BNL-52612
Formal Report

Proceedings of RIKEN BNL Research Center Workshop

Volume 29

FUTURE TRANSVERSITY MEASUREMENTS

September 18–20, 2000

Organizing Committee:

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkysho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD and RHIC physics through the nurturing of a new generation of young physicists.

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are seven Fellows and nine post docs in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the academic year 1999-2000; this program will increase to include eleven theorists in the next academic year, and, in the year after, also be extended to experimental physics. In addition, the Center has an active workshop program on strong interaction physics, about ten workshops a year, with each workshop focussed on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time.

The construction of a 0.6 teraflop parallel processor, which was begun at the Center on February 19, 1998, was completed on August 28, 1998.

T. D. Lee
September 29, 2000

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

CONTENTS

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Most abstracts and talks are available online at
http://thy.phy.bnl.gov/www/riken/trans_work/abstracts/abstract.html

Introduction

The RIKEN-BNL Research Center workshop on "Future Transversity Measurements" was held at BNL from September 18-20, 2000. The main goal of the workshop was to explore future measurements of transversity distributions. This issue is of importance to the RHIC experiments, which will study polarized proton-proton collisions with great precision. One of the workshop's goals was to enhance interactions between the DIS community at HERA and the spin community at RHIC in this field.

The workshop has been well received by the participants; the number of 69 registered participants demonstrates broad interest in the workshop's topics. The program contained 35 talks and there was ample time for lively discussions. The program covered all recent work in the field and in addition some very elucidating educational talks were given.

At the workshop the present status of the field was discussed and it has succeeded in stimulating new experimental and theoretical studies (e.g. model calculations for interference fragmentation functions (IFF), IFF analysis at DELPHI). It also functioned to focus attention on the open questions that need to be resolved for near future experiments. In general, the conclusions were optimistic, i.e. measuring the transversity functions seems to be possible, although some new experimental hurdles will have to be taken.

Both the RHIC and the DIS community have clearly recognized the need for further investigations and collaboration. In order to stimulate and monitor further progress two future meetings have been scheduled; the first in Zeuthen (Summer 2001) and the second in Frascati (Fall 2002).

We are hopeful that such joint efforts eventually will result in mapping out the full spin structure of nucleons. We are optimistic that this RBRC workshop and its follow-up meetings will stimulate the necessary activities that will make transversity measurements a reality.

Daniel Boer

Matthias Grosse Perdekamp

WELCOME

Nicholas P. Samios

It is a pleasure to welcome you on behalf of RBRC Management to this workshop on Future Transversity Measurements. It is indeed an auspicious time. The Relativistic Heavy Ion Collider, RHIC, is in operation having provided Gold Gold interactions at two energies 65 Gev/nucleon cd 130 Gev/nucleon. Four experiments have taken data with accumulated luminosities of 3-6 inverse micro barns. This is equivalent to millions of triggers and thousands of events.

Two results have already been submitted to Physical Review Letters for publication. The first letter by Phobos measured the charge particle multiplicity per unit of pseudo regularly, indicating a substantial increase, over that observed at the SPS, and larger than that observed in proton antiproton interactions at higher energies. The STAR collaboration publication involved measuring charge particle elliptic flow, yielding values again larger than that observed at the SPS and approaching the hydro limit. Both publications are indications of the richness and exciting physic possibilities that RHIC promises. Of particular interest to this group is the progress of the polarized proton spin program at RHIC. Polarized protons have been accumulated in the AGS complex and injected into RHIC. These polarized protons have been also moderately accelerated in RHIC and their polarization measured by newly constructed polarimeters. A siberian snake has been inserted in the RHIC lattice and activated. Its performance has been measured with polarized protons and the response was as expected. Accolades to the accelerator physicists who made this possible. As you are aware, the spin program requires four snakes the status of the remaining three being one is completed and the other two almost done. All four snakes are expected to be in the machine for the next run which is expected to begin in March 2001. In the following year, the eight rotators, which are in the process of being built, will be inserted into RHIC for the 2002 run.

It is indeed an exciting time. I am impressed with this large turnout for this workshop and I am looking forward to the ensuing interesting talks and discussions.

September 2000

The first RHIC machine run*

T. Roser
Collider-Accelerator Department, Brookhaven National Laboratory
Upton, N.Y. 11973, USA

The Brookhaven Relativistic Heavy Ion Collider (RHIC) is the first hadron accelerator and collider consisting of two independent rings. It is designed to operate over a wide range of beam energies and with particle species ranging from polarized protons to heavy ions. Construction of the Brookhaven Relativistic Heavy Ion Collider (RHIC)was officially completed last year and and this year saw a highly successful commissioning and first operations period.

An integrated luminosity of at least 3 inverse micro barns were delivered during this first run to each of the four RHIC experiments BRAHMS, PHENIX, PHOBOS, and STAR. The goal for next years run is to achieve full design luminosity. Possible future upgrade options are also discussed that could increase RHIC Au-Au luminosity up to a factor of 40.

A limited commissioning effort with polarized protons is also planned for this year. With a single Siberian snake and polarimeter installed in one of the two RHIC rings injection and acceleration of polarized beam will be tested. Collisions of polarized protons at a beam energy of 100 GeV are planned for next year.

*Work performed under the auspices of the U.S. Department of Energy

The first RHIC machine run

FY2000 RHIC heavy ion run

RHIC polarized proton commissioning and plans

RHIC luminosity upgrade plans

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Thomas Roser
Transversity Workshop
September 18-20, 2000

TR-1

Parameters and goals for RHIC RUN2000

- 60 bunches per ring ✓
- 5×10^8 Au/bunch ✓
- Longitudinal emittance: 0.3 eVs/nucleon/bunch ✓
- Transverse emittance at storage: 15 π μm (norm, 95%) ✓
- Initial storage energy: $\gamma = 70$ [66 GeV/nucl.] ✓ (This energy is below the lowest quench of any DX magnet)
- Lattice at injection and acceleration: $\beta^* =$ 3 m @ 2, 4, 8, and 12 o'clock
  $\beta^* =$ 8 m @ 6 and 10 o'clock
- Lattice at storage and collision: $\beta^* =$ 3 m @ 2, 4, 8, and 12 o'clock
  $\beta^* =$2- 8 m @ 6 and 10 o'clock
- Luminosity: 2×10^{25} cm^{-2} s^{-1} ✓
- Integrated luminosity: a few $(\mu b)^{-1}$ ✓

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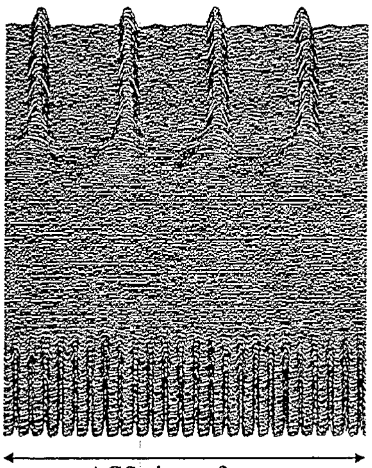
TR-2

RF bunch merging in AGS

- 4 × 6 bunches injected from Booster
- Debunch / rebunch into 4 bunches at AGS injection
- Final longitudinal emittance: 0.3 eVs/nuc./bunch
- Achieved 4×10^9 Au ions in 4 bunches at AGS extraction on 8/4/00



AGS circumference

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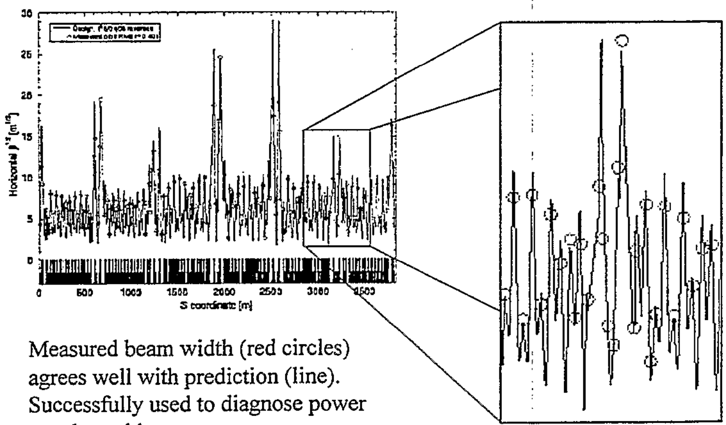
TO 2

RHIC beam measurements



Measured beam width (red circles) agrees well with prediction (line). Successfully used to diagnose power supply problem.

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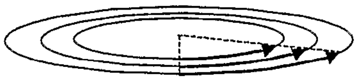
TR-4

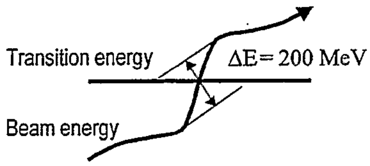
Transition energy crossing

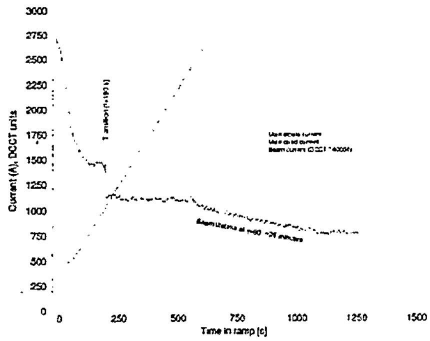
RHIC is first superconducting, slow ramping accelerator to cross transition energy:



Slow and fast particles remain in step.
⇨ increased particle interaction (space charge)
⇨ short, unstable bunches

Cross unstable transition energy with radial energy jump:





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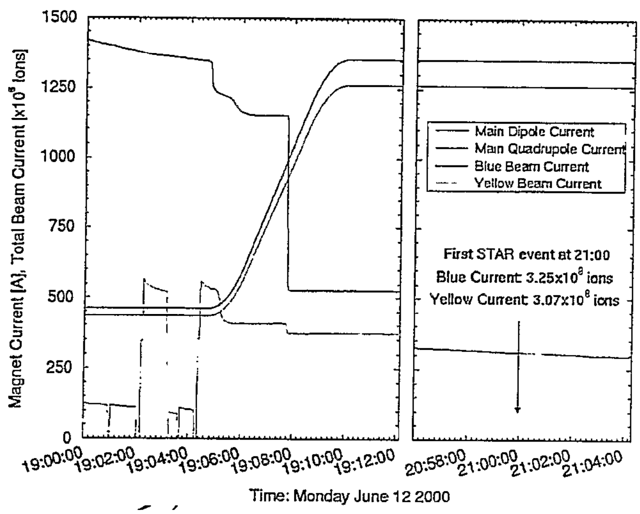
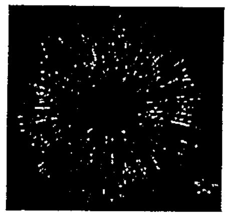
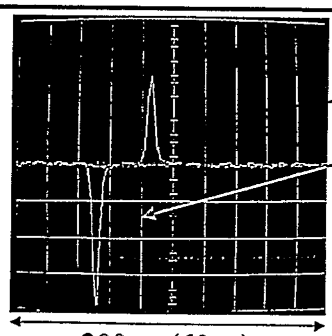
Ramp to first collision





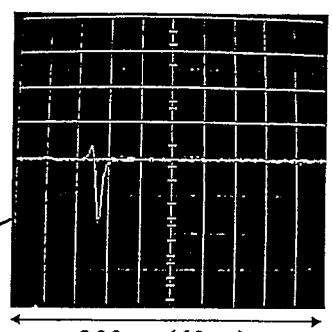
Bringing beams into collision



Beam in blue ring

Beam in yellow ring

200 ns (60 m)



Beams in collision at the interaction regions

200 ns (60 m)

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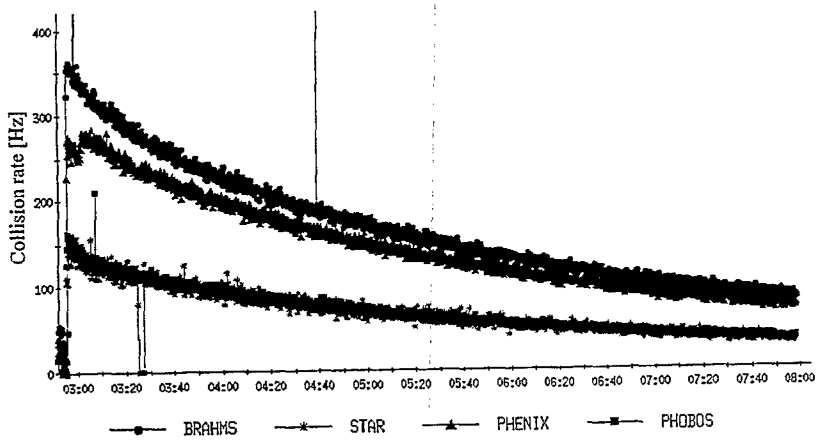
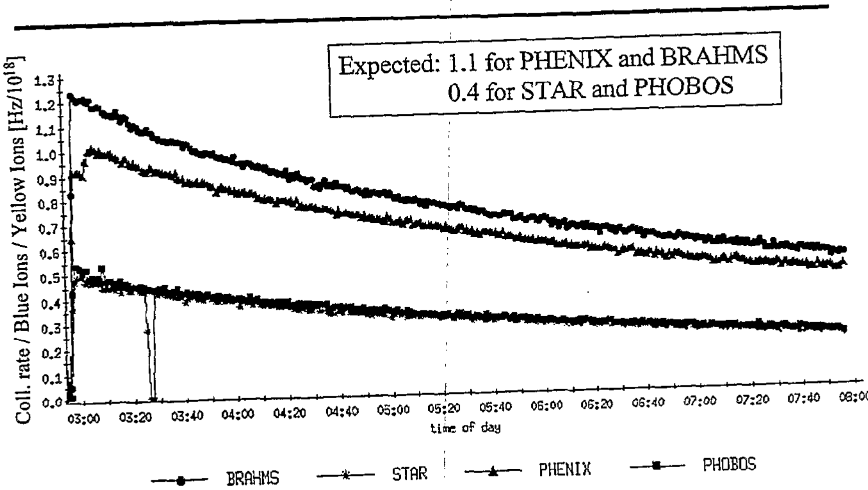
Collision rate at detectors



Specific luminosity



Parameters and goals for RHIC RUN2001

- Transition energy jump quadrupole power supplies installed
- 60 bunches per ring with 1×10^9 Au/bunch
- Storage energy: $\gamma = 107$ [100 GeV/nucl.]
- All bipolar power supplies installed:
  - Lattice at injection and acceleration: $\beta^* = 10$ m at all IR's
  - Lattice at storage and collision: $\beta^* = 2\text{-}10$ m at all IR's
- Luminosity goal: 2×10^{26} cm^{-2} s^{-1} (design luminosity)
- Availability: ≈ 75 %
- Machine efficiency: ≈ 50 %

FY2000 commissioning plan

June-July 2000: (independent of RHIC operation)

- New pol. source (OPPIS) commissioned and beam transp. through linac: 65% polarization measured at 200 MeV polarimeter, 200 μA and 300 μs beam pulse (4×10^{11} polarized protons)

August 2000: (during RHIC Au stores)

- Accelerate single bunch (10^{11} pol. pr. / bunch) in Booster and AGS to $G\gamma = 46.5$ ($\gamma = 25.94$) ✓
- Commission coupled spin resonance crossing using horizontal rf dipole.

September 2000: (dedicated RHIC operation)

- Inject 6 bunches (+ − + − + −) into RHIC blue ring with snake off. ✓
- Commission pC polarimeter and measure vertical polarization ✓
- Turn on snake and measure radial polarization ✓
- Accelerate and measure polarization

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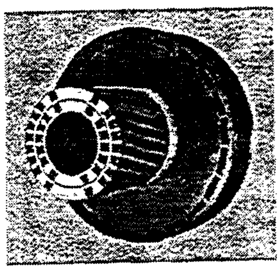
First Siberian Snake in RHIC Tunnel

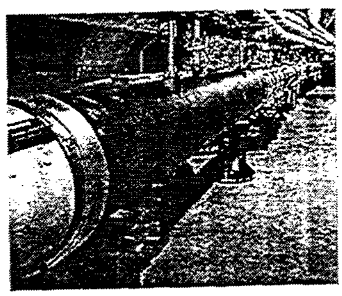
Siberian Snake: 4 superconducting helical dipoles, 4Tesla, 2 m long with full 360° twist

⇨ Acceleration of spin polarized protons beams in RHIC

⇨ Beam studies in September 2000

Funded by RIKEN, Japan
Designed and constructed at BNL





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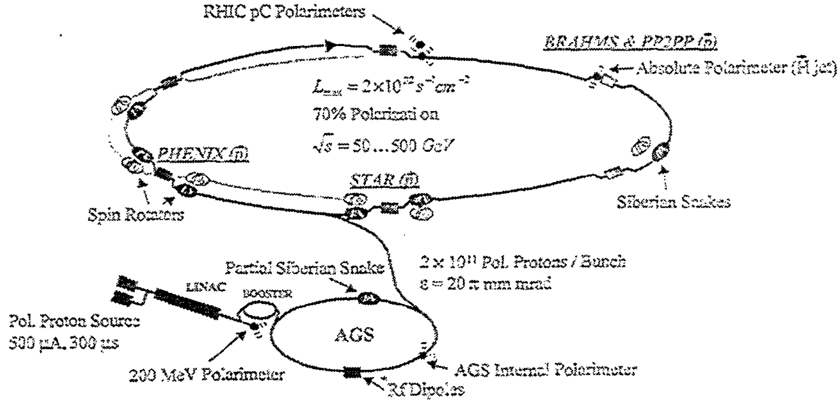
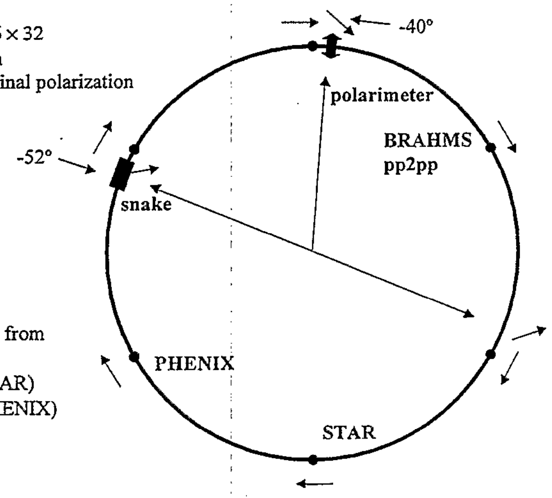
Polarized proton collisions in RHIC



Single Snake in RHIC (E ≤ 100 GeV)

At E = 100.53 GeV: $G\gamma = 192 = 6 \times 32$
$\rightarrow$ all IP's have same polarization
For snake axis at -52° $\rightarrow$ longitudinal polarization



For $\Delta p/p = \pm 0.001$max. deviation from long. polarization:
$32 \times \Delta p/p \times 360° = \pm 12°$ [0.98] (STAR)
$64 \times \Delta p/p \times 360° = \pm 24°$ [0.91] (PHENIX)

Polarized proton status and plans

FY2000 run:

- Single Siberian snake and pC polarimeter installed in blue ring
- New polarized proton source: ~ 10^{12} pol. protons/pulse
- Goal: Accelerate polarized beam in blue ring

FY2001 run:

- All four Snakes and pC polarimeters installed in blue and yellow ring
- Goal: 100 GeV×100 GeV collision with long. pol. at interaction regions
  Accelerate polarized beam to 250 GeV

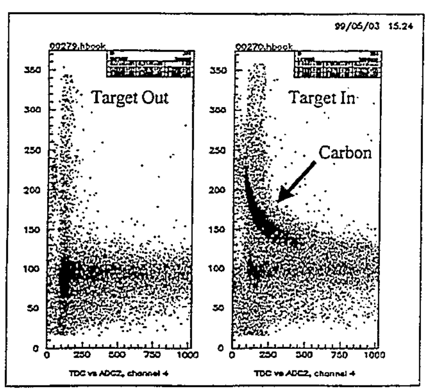
FY2002 run:

- All eight spin rotators installed
- Goal: 250 GeV×250 GeV collision with long. pol. at STAR and PHENIX

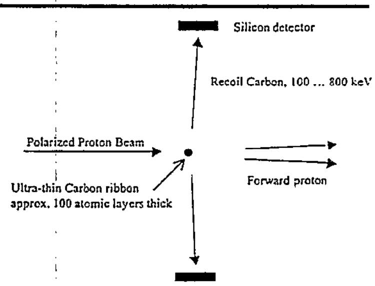
FY2003 run:

- Polarized hydrogen jet target for absolute polarimetry installed

Proton-Carbon CNI Polarimeter (AGS E950)



ADC distribution



- 2-3% energy independent analyzing power for small-angle elastic scattering in the Coulomb-Nuclear Interference (CNI) region
- Slow recoil Carbon detected in between bunch crossings
- Fiber target allows for polarization profile measurement

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Polarized Hydrogen Jet Target

- pC polarimeter is used as fast relative polarization monitor and was calibrated in AGS at 22 GeV to about 15 %.
- Polarized hydrogen jet target allows for absolute beam polarization measurement:

$$P_{\mathrm{Beam}} = P_{\mathrm{Target}} \frac{N_{B\uparrow T\uparrow} - N_{B\downarrow T\uparrow} + N_{B\uparrow T\downarrow} - N_{B\downarrow T\downarrow}}{N_{B\uparrow T\uparrow} - N_{B\downarrow T\uparrow} - N_{B\uparrow T\downarrow} + N_{B\downarrow T\downarrow}}$$

- Jet target thickness of 3×10^{11} cm^{-2} achievable (HERMES, PINTEX, NIKHEF)
- Jet polarization measurable to better than 3% using Stern-Gerlach method
- Collaboration started with Wisconsin, IUCF, and Amsterdam

Pol. H jet target at Bates from NIKHEF

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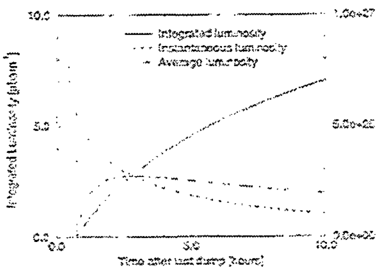
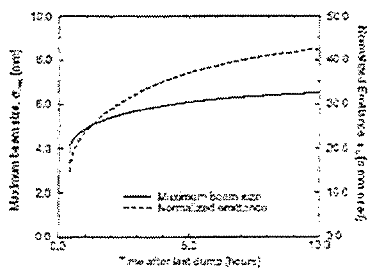
RHIC design luminosity

$$L = \frac{3 f_{rev}\gamma}{2} \frac{N_b N^2}{\varepsilon\beta^*} = 9\ldots1\times10^{26}\, cm^{-2}s^{-1} \text{ over 10 hours}$$

$$N_b = 60\,; N = 1\times10^9; \varepsilon = 15\ldots40\pi\,\mu m; \beta^* = 2m$$





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Luminosity upgrade possibilities

- 'Enhanced' luminosity possible with existing machine:
  - Increase number of bunches to 120
  - Decrease β* from 2 m to 1m
- Further luminosity upgrades:
  - Decrease β* further with modified optics
  - Increase bunch intensity
  - Decrease beam emittance
- Last two (three) items are limited by intra-beam scattering and require beam cooling at full energy!

Beam Cooling at RHIC Storage Energy

- Electron beam cooling of RHIC beams:
  - Bunched electron beam requirements (prelim.):
    100 GeV gold beams: E= 54 MeV I= 3 A peak / 10 mA average
    250 GeV pol. protons: E=135 MeV I=25 A peak / 86 mA average
  - Requires high brightness, high power, energy recuperating superconducting linac, almost identical to Infra-Red Free Electron Laser at TJNAF
  - Collaboration with BINP, Novosibirsk, on the development of RHIC electron cooling
  - $\times$ 10 luminosity increase possible (prelim.)
- Stochastic cooling of low intensity gold beams may also be possible.
- However: hadron beam cooling at high energy has not been achieved anywhere!

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Summary

- Highly successful first RHIC heavy ion run completed
- Commissioning of polarized proton acceleration in RHIC ongoing
- Full design Au luminosity and collisions of polarized protons are planned for FY 2001
- RHIC Au luminosity upgrade:
  - with existing machine: $\times$ 4
  - with full energy electron cooler: $\times$ 10 possible

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1

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RHIC Experimental Review

W.A. Zajc
Columbia University

Thanks to:

M. Baker, W. Busza, J. Harris, M. Lisa,
J. Nagle F.Videbaek, S. White

2

Why is RHIC?

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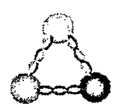
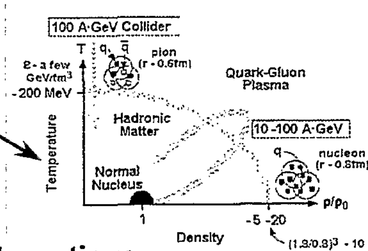
- To understand fundamental aspects of the strong interaction:
  - Where does the proton get its spin?



  - How does nuclear matter "melt"?



- We have a theory of the strong interaction:

$$\boxed{L = i\bar{\psi}D\psi - \frac{1}{4}\widetilde{F}_a^{\ \mu\nu}F^a_{\ \mu\nu} - \bar{\psi}\hat{M}\psi}$$

It works well except when the interaction is strong!

Connections

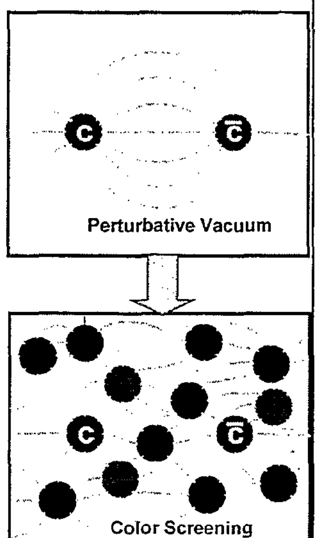
- QCD is a fundamental theory valid in both the weak and the strong coupling limit
- Both aspects are important at RHIC:
  - Initial state in ion-ion collisions determined by low-x gluons
  - Thermalization determined by interplay between
    - (Relatively) few hard gluons carrying most of the energy
    - "Bath" of numerous but very soft gluons (Baier, Mueller, Schiff and Son)
  - Final state multiplicities very sensitive to saturation in gluon distributions
- Subtle connections between
  - Chiral symmetry of QCD
  - Effective field theories of pion-nucleon interaction
  - Spin structure of the nucleon
  - Chiral symmetry restoration in heavy ion collisions

➡ "To know the inside of the proton, you must know the outside of the proton" (R. Mawhinney)

➡ "Deconfinement is chirality by other means" (with apologies to Clauswitz)

Making Something from Nothing

- Explore non-perturbative "vacuum" by *melting it*
  - Temperature scale $T \sim \hbar/(1\,fm) \sim 200\,\mathrm{MeV}$
  - ➡ Particle production
  - ➡ Our 'perturbative' region is filled with
    - gluons
    - quark-antiquark pairs
  - ➡ A Quark-Gluon Plasma (QGP)
- Experimental method:
  Energetic collisions of heavy nuclei
- Experimental measurements:
  Use probes that are
  - Auto-generated
  - Sensitive to all time/length scales



Previous Attempts

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- **First attempt at QGP formation *was* successful (~10^{10} years ago)**
- **Since then:**

  Much of physics has been devoted to exploration of
  "***Matter in unusual conditions***"

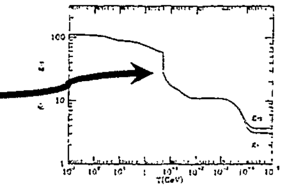
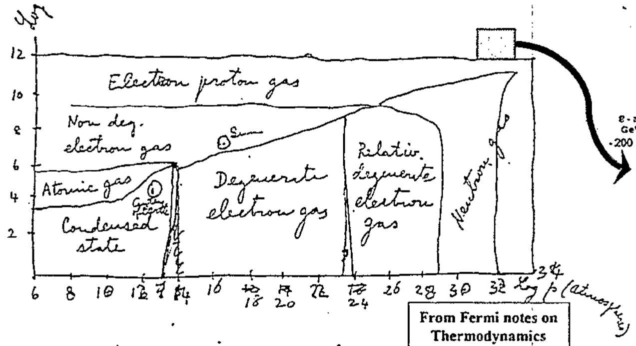
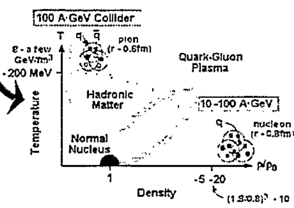


Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory

The Early Universe, Kolb and Turner



From Fermi notes on Thermodynamics



RHIC's Experiments

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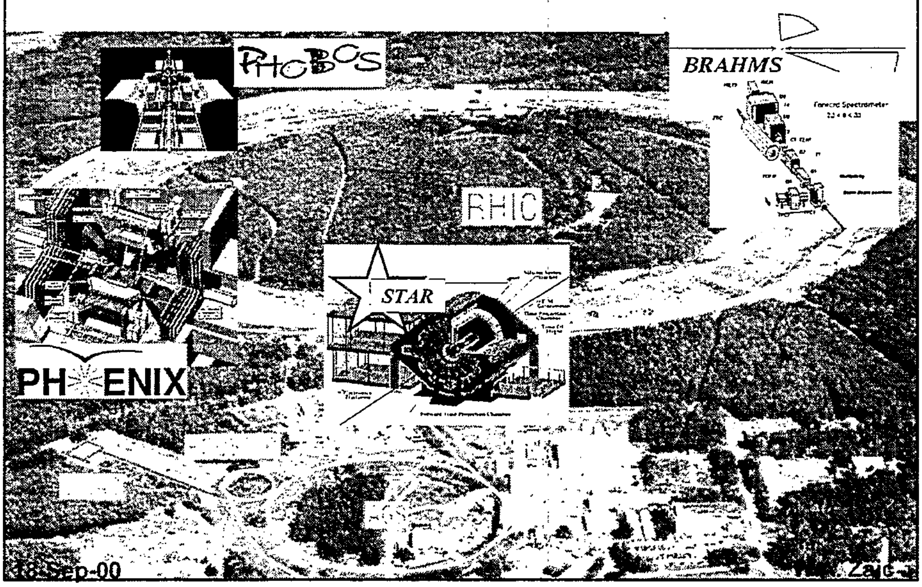

What's Different from "Ordinary" Colliders?

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- Obviously:
  - Multiplicities
  - (Cross sections)
- But also:
  - Hermeticity requirements
  - Rates
  - Low pT physics
  - High pT physics
  - Signals

Hermeticity

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- A key factor in "most" collider detectors
  - Goal of essentially complete event reconstruction
  - Discovery potential of missing momentum/energy now well established
- In heavy ion physics
  - $dN_{ch}/dy \sim 1000$
  - ➡ exclusive event reconstruction "unfeasible"
  - But
    - Seeking to characterize a *state of matter*
    - Large numbers ➡ statistical sampling of phase space a valid approach

Low p_T matters

9

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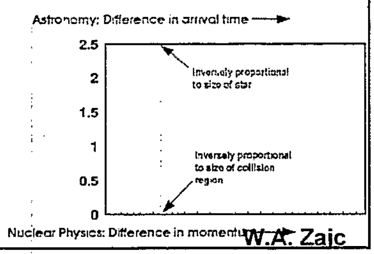
- Search for a phase transition in *hadronic* matter
  - Characteristic scale $\Lambda_{QCD} \sim 200$ MeV
  - Flavor dynamics crucial both to transition and to its signatures
- Heavy ion physics takes place in *phase* space
  - Coordinate space as important as momentum space
  - Measure via identical particle correlations (aka HBT)

Low pT Particle Identification (PID) is crucial to QGP Physics



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(PID) Acceptances

10

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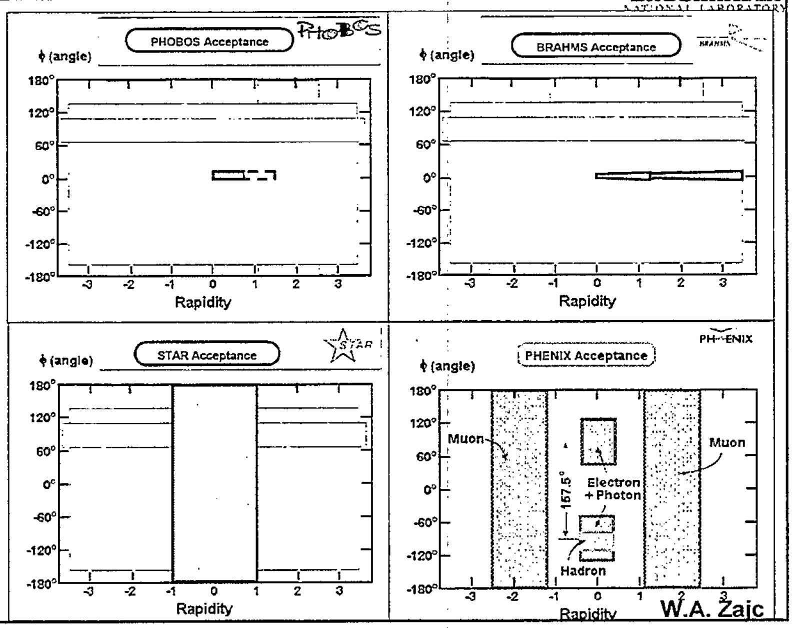

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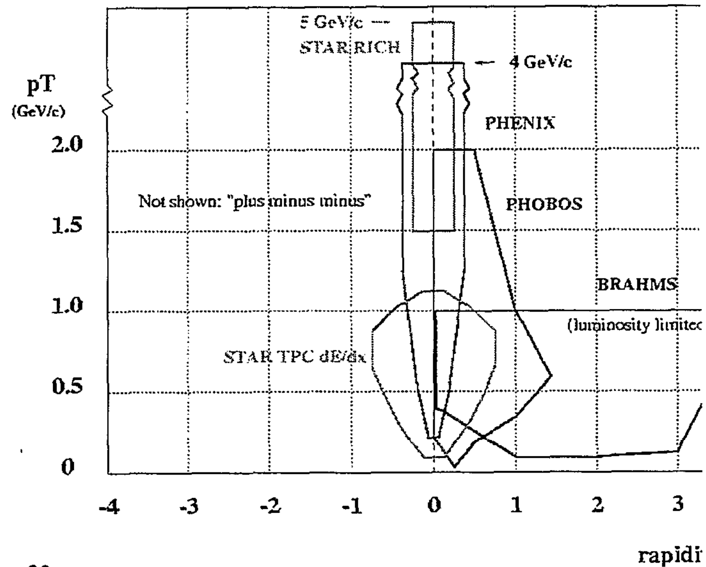
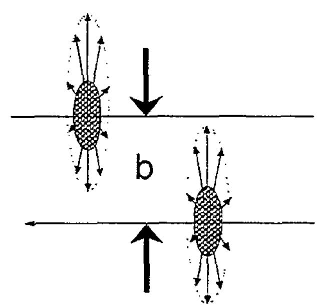
PID Overlaps

sketch of p/pbar acceptances (year 1)



Other Differences

- Event characterization
  - Impact parameter b is well-defined in heavy ion collisions
  - Event multiplicity predominantly determined by collision geometry
  - Characterize this by global measures of multiplicity and/or transverse energy
- Models
  - HEP has SM
    - ➡ Reliable predictions of baseline phenomena
  - HI has only Sub-SM's...
    - ◆ Even the baseline physics at RHIC and beyond is intrinsically unknown



BRAHMS

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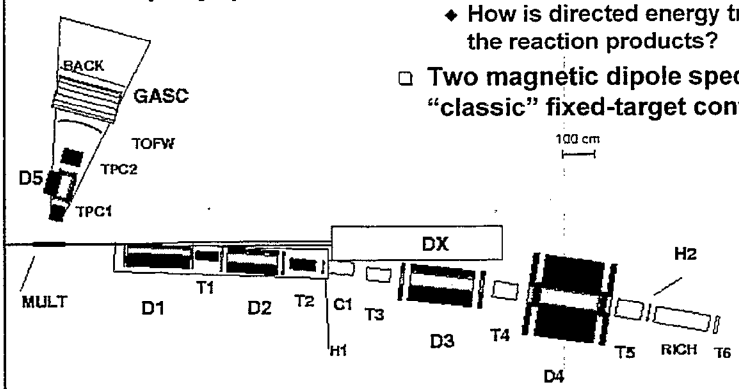
An experiment with an emphasis:

- Quality PID spectra over a broad range of rapidity and p_T
- Special emphasis:
  - Where do the baryons go?
  - How is directed energy transferred to the reaction products?
- Two magnetic dipole spectrometers in "classic" fixed-target configuration

Mid rapidity spectrometer



Forward spectrometer

BRAHMS Details

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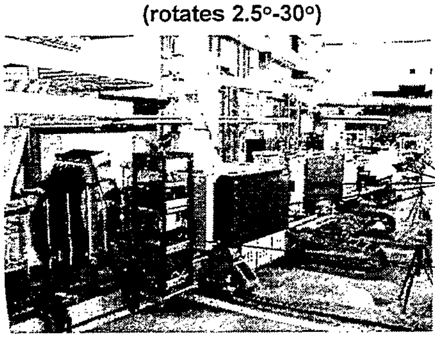
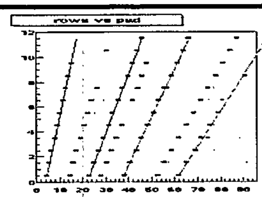
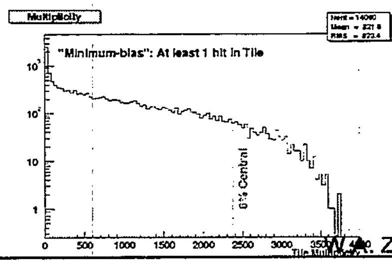
Forward Spectrometer

(rotates 2.5°-30°)





- TPC's: T1 and T2
- DC's: T3,T4,T5 (not connected)
- Magnets: D1,D2,D3,D4
- ToF Hodoscopes: H1, H2
- Cerenkov Counter: C1
- RICH:



STAR

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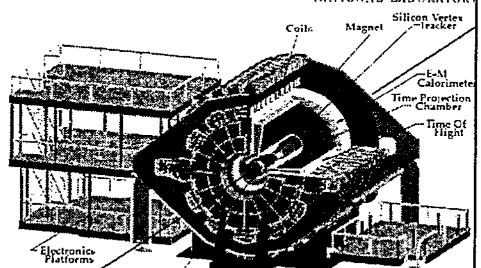
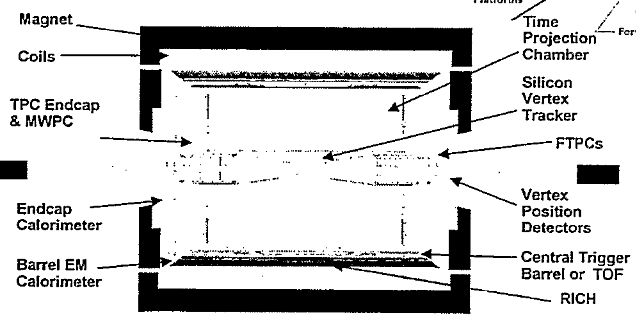


Year 1: Magnet, TPC, CTB, ZDC, RICH



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STAR Event

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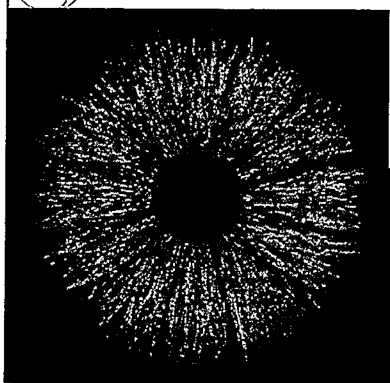
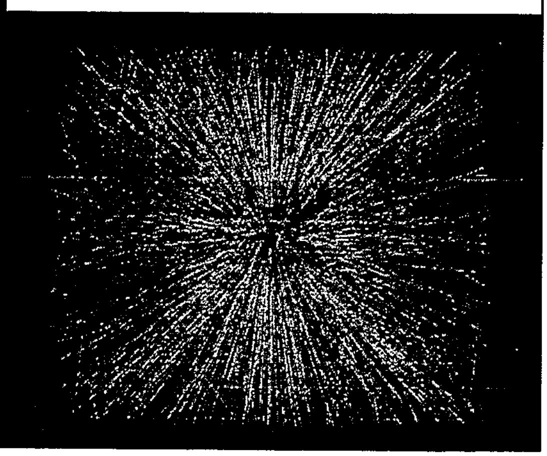


Data Taken June 25, 2000.

Pictures from Level 3 online display.



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Elliptic Flow

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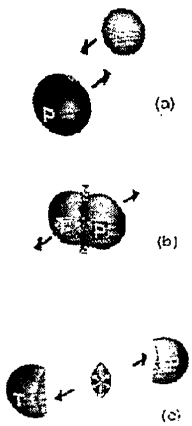
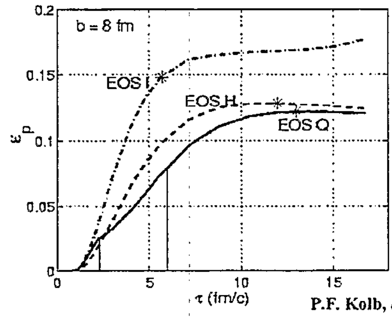


- Spatial anisotropy in non-central collisions & response of the system to early pressure → emission anisotropy
- Elliptic flow predictions from hydro/transport models sensitive to underlying dynamics of initial system



P.F. Kolb, *et al*, (QM99)

- A natural measurement for STAR

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Centrality Dependence of Elliptic Flow

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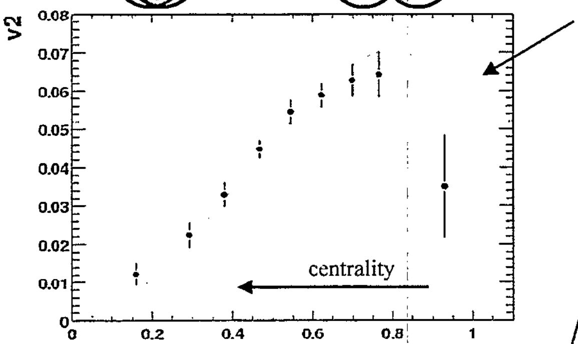
Differential measure of response to initial geometry

PRELIMINARY

(scaled) spatial asymmetry



STAR

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PHENIX

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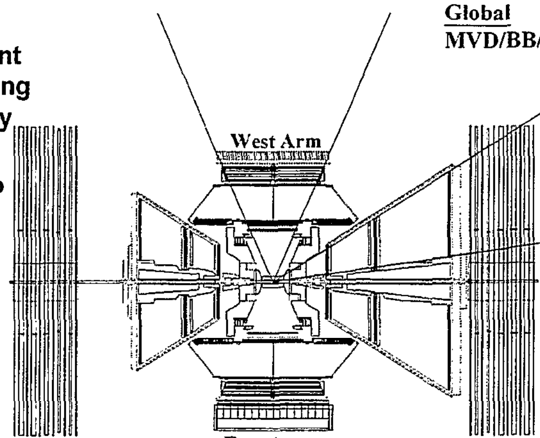
- An experiment with something for everybody
- A complex apparatus to measure
  - Hadrons
  - Muons
  - Electrons
  - Photons

Executive summary:
- *High* resolution
- *High* granularity



Global
MVD/BB/ZDC

Muon Arms
Coverage (N&S)
$-1.2 < |y| < 2.3$
$-\pi < \phi < \pi$
$\Delta M(J/\psi) = 105 MeV$
$\Delta M(\gamma) = 180 MeV$

3 station CSC
5 layer MuID ($10X_0$)
$p(\mu) > 3 GeV/c$

Central Arms
Coverage (E&W)
$-0.35 < y < 0.35$
$30^\circ < |\phi| < 120^\circ$
$\Delta M(J/\psi) = 20 MeV$
$\Delta M(\gamma) = 160 MeV$

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Approaches to QGP Detection

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1. Deconfinement
   - $R(\Upsilon) \sim 0.13$ fm $< R(J/\Psi) \sim 0.3$ fm $< R(\Psi') \sim 0.6$ fm
   - ⇨ Electrons, Muons
2. Chiral Symmetry Restoration
   - Mass, width, branching ratio of Φ to e^+e^-, K^+K^- with $\delta M < 5$ Mev:
   - ⇨ Electrons, Muons, Charged Hadrons
   - Baryon susceptibility, color fluctuations, anti-baryon production:
   - ⇨ Charged hadrons
   - DCC's, Isospin fluctuations:
   - ⇨ Photons, Charged Hadrons
3. Thermal Radiation of Hot Gas
   - Prompt γ, Prompt γ^* to e^+e^-, $\mu^+\mu^-$:
   - ⇨ Photons, Electrons, Muons
4. Strangeness and Charm Production
   - Production of K^+, K^- mesons:
   - ⇨ Hadrons
   - Production of Φ, J/Ψ, D mesons:
   - ⇨ Electrons, Muons
5. Jet Quenching
   - High pT jet via leading particle spectra:
   - ⇨ Hadrons, Photons
6. Space-Time Evolution
   - HBT Correlations of $\pi^\pm \pi^\pm$, $K^\pm K^\pm$:
   - ⇨ Hadrons

Summary: Electrons, Muons, Photons, Charged Hadrons

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PHENIX Design

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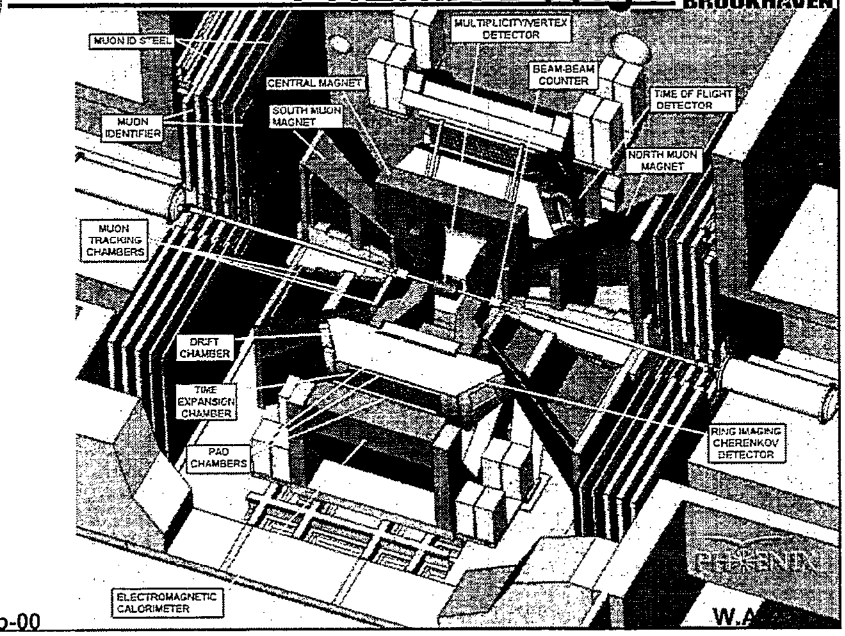

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PHENIX Results

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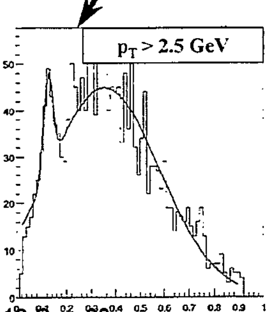
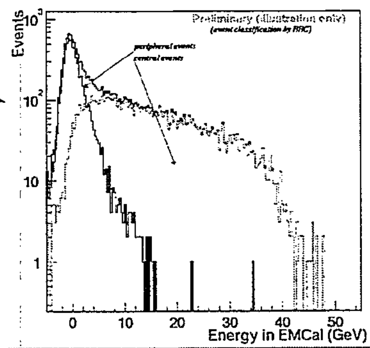
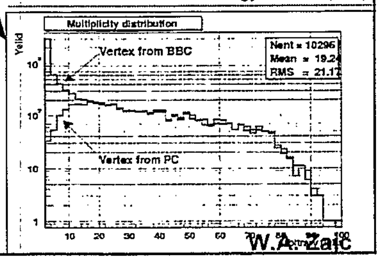
(A sampler)

- Transverse energy spectrum
- Charged multiplicity distribution
- π^0 peak
  (towards a p_T spectrum)







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PHOBOS

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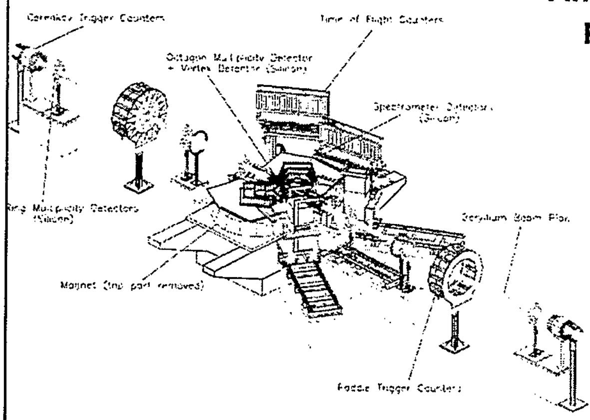

An experiment with a philosophy:

- Global phenomena
  - ➡ large spatial sizes
  - ➡ small momenta
- Minimize the number of technologies:
  - All Si-strip tracking
  - Si multiplicity detection
  - PMT-based TOF
- Unbiased global look at very large number of collisions (~10^9)

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PHOBOS Results

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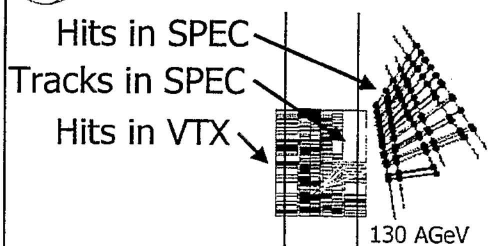
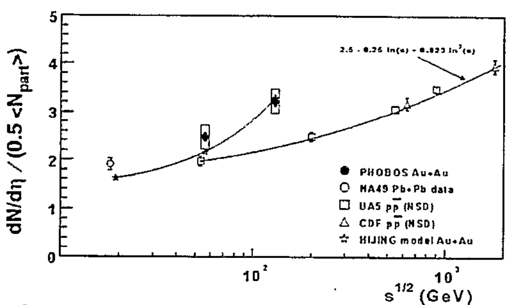


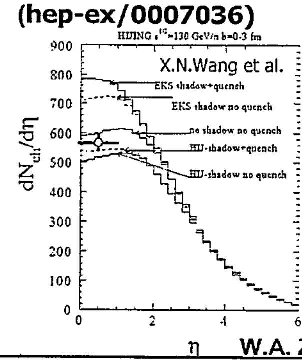
First results on $dN_{ch}/d\eta$

- for central events
- At E_{CM} energies of
  - 56 Gev
  - 130 GeV

(per nucleon pair)

To appear in PRL (hep-ex/0007036)





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Implications of PHOBOS Results

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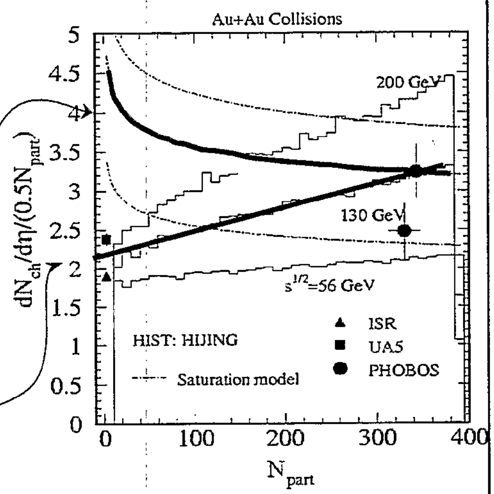
- Constrains (determines!) maximum multiplicities at RHIC energies
- Does not constrain centrality dependence of same
- Does not (quite) distinguish between
  - "Saturation" models, dominated by gg →g
  - "Cascade" models, dominated by gg →gg, gg →ggq



(X.N. Wang and M. Gyulassy, nucl-th/0008014)

Determining N_{PART}

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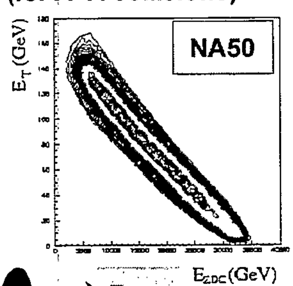
Best approach *(for fixed target!)*:

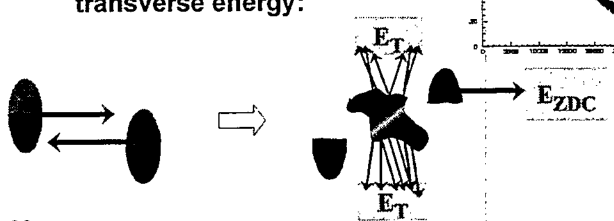
- Directly measure in a "zero degree calorimeter"

$$N_{PART} \approx 2\times\left[A-\frac{E_{ZDC}}{E_{PerNucleon}}\right]$$

(for A+A collisions)



- Strongly (anti)-correlated with produced transverse energy:



RHIC ZDC's

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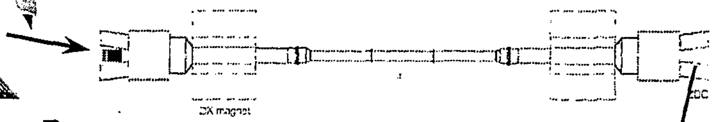
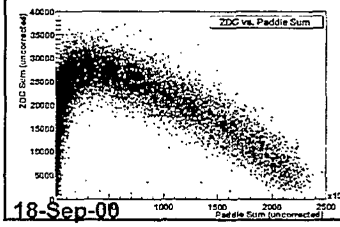
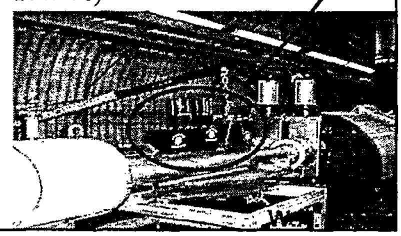
- ZDC ◷ Zero Degree Calorimeter
- Goals:
  - Uniform luminosity monitoring at all 4 intersections
  - Uniform event characterization by all 4 experiments



- Process:
  - Correlated Forward-Backward Dissociation
  - $\sigma_{tot} = 11.0$ Barns (+/- few %)





Summary

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- The initial physics run of RHIC:
  - Validated the various approaches of each experiment
  - Has provided all four experiments with quality data sets
  - Has led to new physics results
  - Will lead to many more results
    - DNP: October 4-7, 2000
    - Quark Matter (January, 2001)
    - PRL
- Prospects for Year-2 promise even more:
  - Increased luminosity
  - New detection channels
- And beyond:
  - P-A
  - Polarized p-A
  - Tagged p-p, for example: p+p $\rightarrow$ n + (π^+ + p)

    $\hookrightarrow$ D-Y + X

RIKEN/RHIC/BNL Physics

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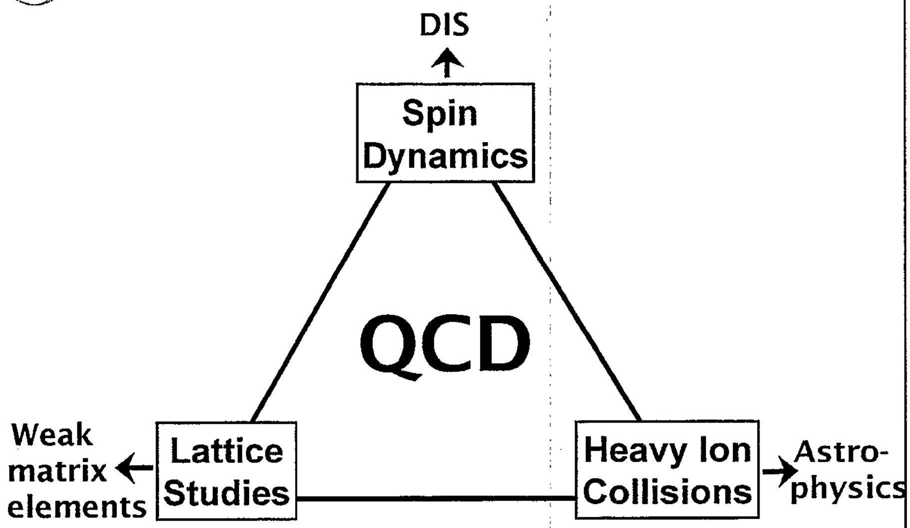

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RHIC Luminosity

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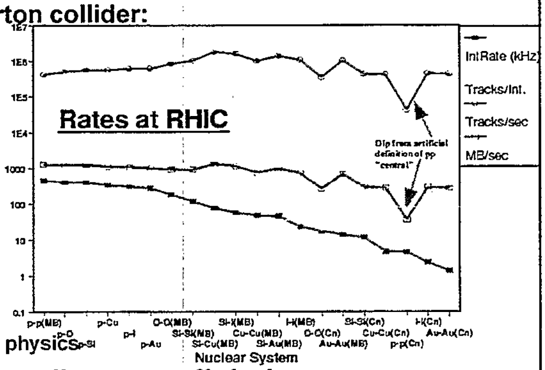
- It's high!
- It's an equal opportunity parton collider:
- Can accelerate essentially all species
  - Designed for p-p to Au-Au
  - Asymmetric collisions (esp. p-A) allowed
  - Good news / bad news:
    - Permits many handles on systematics
    - Permits *in situ* measurements of "background" p-p and p-A physics



➡ ***Detectors must handle unparalleled dynamic range in rates and track densities***

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Jet Physics at RHIC

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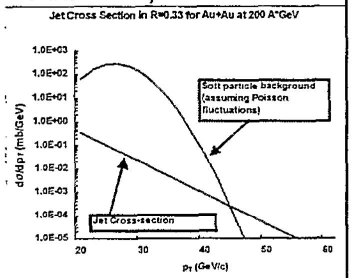
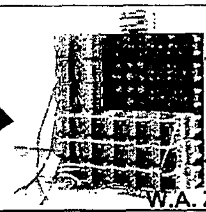
- Tremendous interest in hard scattering (and subsequent energy loss in QGP) at RHIC
  - Predictions that dE/dx ~ (amount of matter to be traversed)
  - Due to non-Abelian nature of medium
- But:
  - "Traditional" jet methodology fails at RHIC
  - Dominated by the soft background:
    - For a typical jet cone R = 0.33 ($R^2 = \Delta\Phi^2 + \Delta\eta^2$) have
      $\langle n_{SOFT} \rangle \sim 64$
      $\langle E_T \rangle \sim 25$ GeV
    - *Fluctuations* in this soft background swamp any jet signal for pT < ~ 40 GeV:
- Solution:
  - Let R ✱~0 (PHENIX $\Delta\eta \times \Delta\phi = 0.01 \times 0.01$)
  - Then use high p_T leading particles





Screening by the QGP

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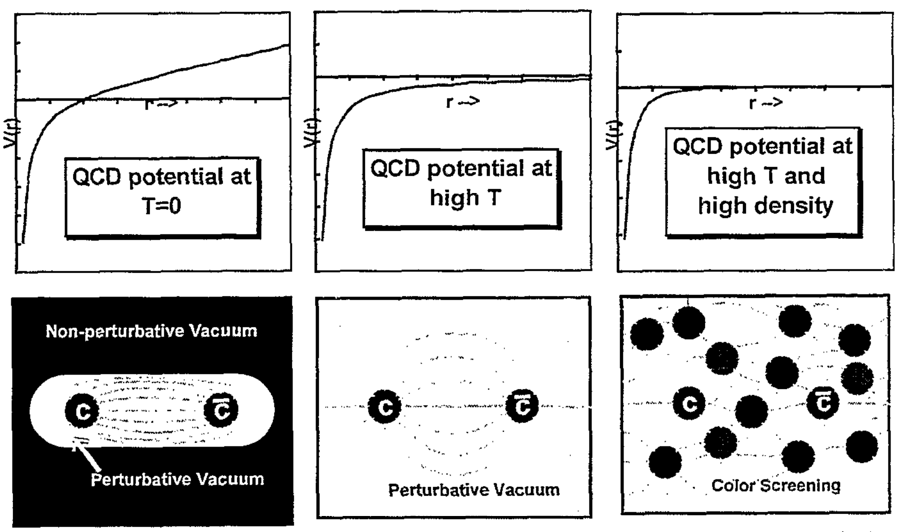
In pictures:



PHOBOS Details

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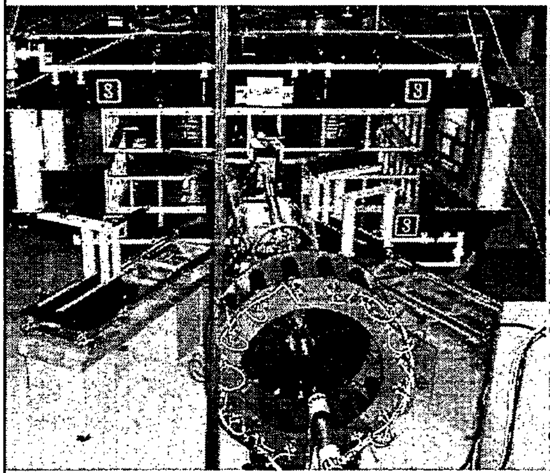

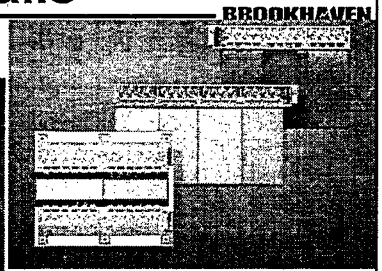

- Si tracking elements
  - 15 planes/arm
  - Front: “Pixels” (1mm x 1mm)
  - Rear: “Strips” (0.67mm x 19mm)
  - 56K channels/arm
- Si multiplicity detector
  - 22K channels
  - $|\eta| < 5.3$

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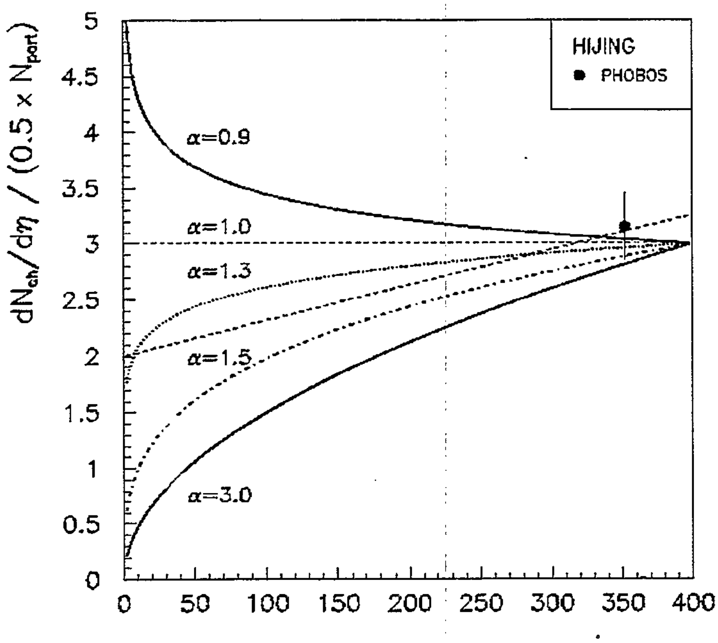


TRANSVERSITY A PRIMER

R.L. JAFFE
RIKEN-BNL
SEPT 2000

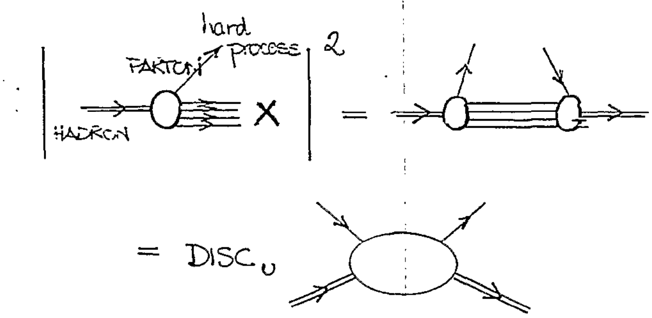
Longitudinal spin ≡ helicity
is familiar in deep inelastic physics

Some transverse asymmetries are
known from hadron scattering

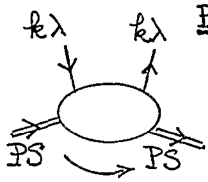
Transversity is rather poorly known

Purpose of this talk: Simple, pedagogical introduction to transversity in deep inelastic processes.

1 BASIC DIS PROCESS



Parton distribution and fragmentation functions are forward.



PS ⇒ PS

Because they originate in square of amplitude.

★ $\vec{S} \parallel \vec{P}$ & $\vec{q}$ ($\vec{q}$ defines deep inelastic process)

Quark and gluon helicity distributions etc.

★ $\vec{S} \perp \vec{P}$ & $\vec{q}$

Quark transversity distribution

2. TRANSVERSE ASYMMETRY ≡ HELICITY FLIP

$$\Delta\sigma_\perp \equiv \sigma(\vec{S}_\perp) - \sigma(\vec{S}_\top)$$

$$|\perp\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right)$$

$$|\top\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle - |-\rangle\right)$$

$\hat{x}$-eigenstates in terms of helicity ($\hat{z}$) eigenstates

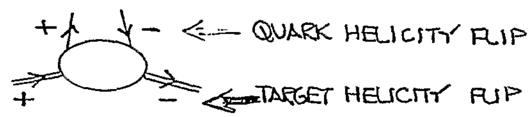
$$\sigma(\vec{S}) \propto \langle \vec{S} | \ldots | \vec{S} \rangle$$

Remember squared amplitude.

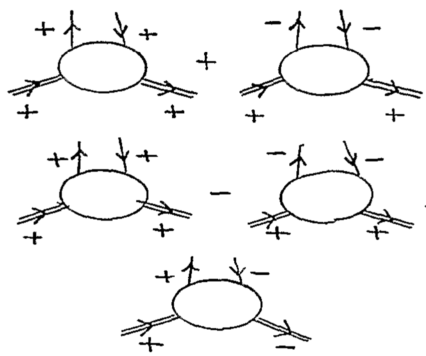
$$\Delta\sigma_\perp \propto \langle\perp|\ldots|\perp\rangle - \langle\top|\ldots|\top\rangle$$

$$\propto \tfrac{1}{2}\{\langle+| + \langle-|\}\ldots\{|+\rangle + |-\rangle\}$$
$$- \tfrac{1}{2}\{\langle+| - \langle-|\}\ldots\{|+\rangle - |-\rangle\}$$
$$\propto \langle+|\ldots|-\rangle + \langle-|\ldots|+\rangle$$

transverse asymmetry = helicity flip.



Other allowed (by symmetries), independent parton distributions



$\Rightarrow q_\uparrow + q_\downarrow$ — $q(x,Q^2)$

$\Rightarrow q_\uparrow - q_\downarrow$ — $\Delta q(x,Q^2)$

$\Rightarrow \delta q(x,Q^2)$

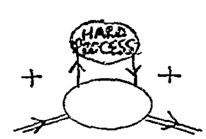
3. HELICITY & CHIRALITY & SELECTION RULES

★ HELICITY = CHIRALITY FOR MASSLESS ON-SHELL QUARKS

CORRECTIONS: MASS $m/\sqrt{Q^2}$; OFF-SHELL $\sqrt{\langle k^2\rangle/Q^2}$ } TWIST-3 SMALL IN **DIS**

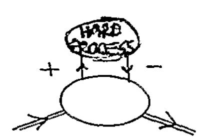
(ACTUALLY HELICITY = − CHIRALITY @ TWIST-3)

$q(x,Q^2)$, $\Delta q(x,Q^2)$ } CHIRAL EVEN



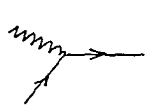
✓

$\delta q(x,Q^2)$ CHIRAL ODD



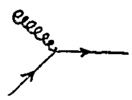
?

· CHIRALITY IN QCD & STANDARD MODEL



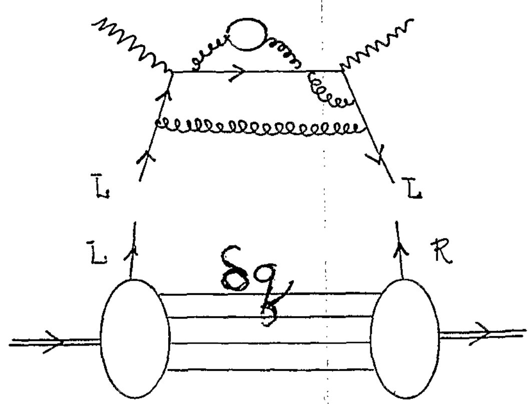
γ, $W^\pm$, Z^0 } $\bar{\psi}\gamma_\mu\psi \to \bar{L}\gamma_\mu L + \bar{R}\gamma_\mu R$; $\bar{\psi}\gamma_\mu\gamma_5\psi \to \bar{L}\gamma_\mu L - \bar{R}\gamma_\mu R$

All electroweak probes preserve chirality



$\bar{\Psi}\gamma_\mu \frac{\lambda^a}{2}\Psi \longrightarrow \bar{L}\gamma_\mu \frac{\lambda^a}{2} L + \bar{R}\gamma_\mu \frac{\lambda^a}{2} R$

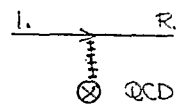
All perturbative QCD couplings preserve chirality



?

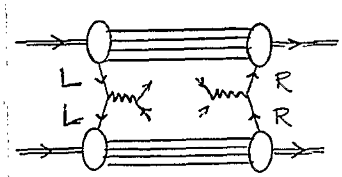
* Transversity appears to decouple from all hard processes ?

* Why isn't δq identically zero ? Because parton distributions involve soft-QCD, where chiral symmetry is spontaneously broken

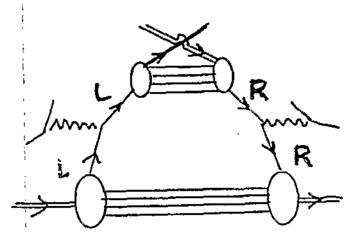


AVOID DECOUPLING BY COMBINING TWO CHIRAL ODD DISTRIBUTIONS

* Drell-Yan & related
  two chiral odd distribution functions



* Single particle inclusive DIS
  one distribution function
  one fragmentation function



PROCESSES SENSITIVE TO TRANSVERSITY MUST INVOLVE AT LEAST TWO OBSERVED HADRONS

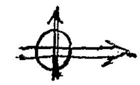
- DY: TWO POLARIZED INITIAL NUCLEONS
- SPI DIS: INITIAL NUCLEON, FINAL HADRON

4 PROPERTIES OF TRANSVERSITY AS F.A.Q.

- PARTON INTERPRETATION ?

Nucleon at P_∞ polarized $\perp$

$\delta q = q_\perp - q_\top$



- OPERATORS ?

$\Delta q \sim$ axial charges $\sim \bar{q}\vec{\gamma}\gamma_5 q$ (chiral even)

$\delta q \sim$ tensor charges $\sim \bar{q}\sigma^{oj}\gamma_5 q$ (chiral odd)

- WHY ARE Δq & δq DIFFERENT ?

AND ARE RELATED BY SEQUENCE OF BOOSTS & ROTATIONS

* But boosts & rotations don't commute

* If quarks were non-relativistic

$$\bar{q}\vec{\gamma}\gamma_5 q \rightarrow q^\dagger \vec{\sigma} q$$

$$\bar{q}\sigma^{oj}\gamma_5 q \rightarrow q^\dagger \sigma^j q$$

$$\delta q \Rightarrow \Delta q$$

So difference between Δq & δq measures relativistic nature of quarks in nucleon.

- WHAT IS ANALOG OF SPIN SUM RULE ?

$$\int_0^1 dx \left(\delta q^a(x,Q^2) - \delta\bar{q}^a(x,Q^2)\right) = \text{FLAVOR } a \text{ TENSOR CHG.}$$

UNKNOWN FROM ELECTROWEAK DECAYS, BUT CALCULATE ON LATTICE

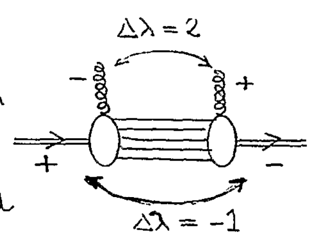
Compare

$$\int_0^1 dx \left(\Delta q^a(x,Q^2) + \Delta\bar{q}^a(x,Q^2)\right) = \text{FLAVOR } a \text{ AXIAL CHG.}$$

MOSTLY MEASURABLE IN β-DECAY

- MIXING WITH GLUE ?

No gluon transversity for nucleon because only $\lambda = \pm 1$ allowed for gluons ($\lambda = 0$ is only possible for off-shell gluons $\Rightarrow \sqrt{\langle k_\perp^2\rangle / Q^2}$)



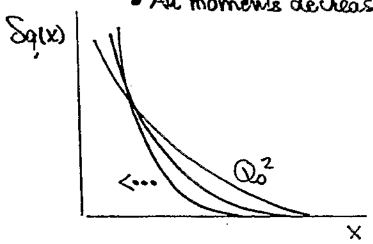
No mixing with glue (note exception for spin-1 target !)

- EVOLUTION ?

Transversity evolves like a non-singlet quark distribution (eg. xF_3) except even lowest moment decreases w/ Q^2

$$\int_0^1 dx\, x^n \left(\delta q(x,Q^2) - (-1)^n \delta\bar{q}(x,Q^2)\right) \sim (\log Q^2)^{-\gamma_n}$$

All $\gamma_n > 0$
- No mixing
- All moments decrease



- BOUNDS FROM POSITIVITY ?

Together q, Δq & δq form a matrix in helicity (quark) space. Matrix is positive definite at every Q^2 for each flavor of quark & antiquark (at least thru L.O.)

$$\mathcal{A} \sim \begin{pmatrix} q+\Delta q & \delta q \\ \delta q & q-\Delta q \end{pmatrix}$$

POSITIVITY $\quad |\Delta q| \le q \quad$ well known

$\quad |\delta q| \le q \quad$ obvious

$\quad 2|\delta q| \le q + \Delta q \quad$ Soffer (not so obvious)

SATURATION OF SOFFER ?
- ★ FOR EACH FLAVOR, NOT FOR SUM
- ★ INCONSISTENT w/ EVOLUTION. COULD APPLY TO Q_0^2, BUT WHY ?

- INTUITION ON TRANSVERSITY ?

? Non-relativistic $\Delta q \cong \delta q$

? Bag $\quad \psi \propto \begin{pmatrix} f(r) \\ i\vec{\sigma}\cdot\hat{r}\, g(r) \end{pmatrix}$

$\Delta q \sim \int r^2 dr \left(f^2 - \frac{1}{3} g^2\right) \qquad$ So $\delta q \gtrsim \Delta q$!

$\delta q \sim \int r^2 dr \left(f^2 + \frac{1}{3} g^2\right)$

? Glue, flavor, etc

Consider $\int dx\,(\delta q^a - \delta \bar{q}^a) \longrightarrow$ tensor charge

- No mixing with glue, no axial anomaly
- Pure valence (charge conjugation odd)

Suggest δq might conform to pre-spin-crisis picture of spin

$$\sum_{u,d,s} \delta q_a \sim 0.6$$

$$\delta u - \delta d \sim 1.25 \quad , \quad \delta s \sim 0$$

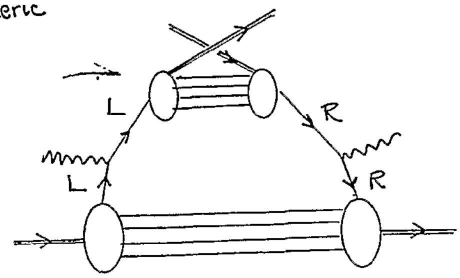
$$\delta u + \delta d \sim 0.6$$

so, striking contrast to $\Delta u, \Delta d, \Delta s$.

5. FILTERING FOR TRANSVERSITY

Access transversity via chiral odd fragmentation function

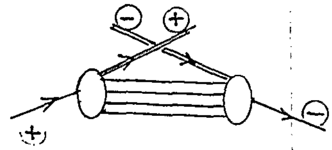
Generic



What sort of process in fragmentation will select transversity distribution?

- Must be chiral odd
- Which means quark helicity flip at leading twist
- Or quark helicity conserving at twist-3.

• SPIN-½ FRAGMENT



Must observe transverse polarization of fragment

* Only Λ-hyperon is available

$$e\vec{P}_\perp \longrightarrow e'\vec{\Lambda}_\perp X$$

Parity violating decay measures Λ-spin

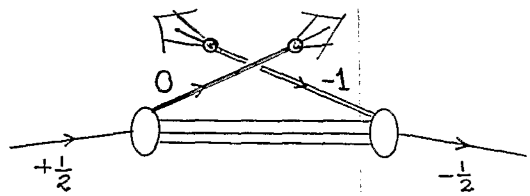
Drawbacks: u dominates proton
s dominates Λ
baryons are rare in current frag's.

SPIN-1 FRAGMENT

ρ-meson

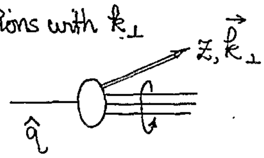
Alas: no way to measure its spin!

• COHERENT PRODUCTION OF HELICITY 0 & 1 SYSTEM !



Final state fragment must be superposition of helicity zero and 1. Sounds hard. Possibly easy!

*** Pions with $k_\perp$



$\Rightarrow$ Pion orbital motion decomposed wrt. $\hat{q}$

$$\langle 0 | q | \pi X \rangle = a_0(z, k_\perp^2) + \underline{\underline{\cos\phi}}\, a_1(z, k_\perp^2) + \ldots$$

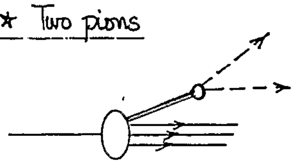
ϕ is defined w.r.t. quark transverse spin

Square and select interference (as $\cos\phi$ depend.)

Signature $\langle \vec{S}_\perp \cdot \vec{q} \times \vec{k}_\perp \rangle$

*** Two pions

Jaffe, Jin, Tang



$$\langle 0 | q | \pi\pi X \rangle = \hat{a}_0(z, m^2) + \hat{a}_1(z, m^2) + \dots$$

Again square and look for transversity signal

$$\langle \vec{S}_\perp \cdot \vec{k}_1 \times \vec{k}_2 \rangle$$

target spin

pion momenta

(Important issues of final state interactions for both examples.)

CONSIDERABLE OPTIMISM!

STAY TUNED TO TALKS THROUGHOUT WORKSHOP.

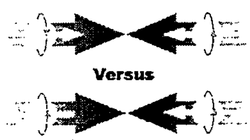
The RHIC Spin Program

Future Transversity Measurements
September 18-20, 2000

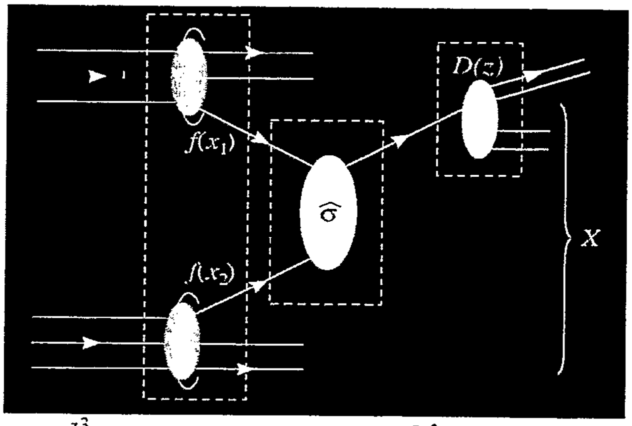
Naohito Saito
RIKEN and RIKEN BNL Research Center

Spin Physics at RHIC

- Utilize Spin Asymmetries to pin down
  - Spin Structure of the Nucleon
    - Proton Spin Sum Rule
    - Transversity Distributions
  - Spin Dependence of Fundamental Interactions
    - Parity Violating Interaction
    - CP Violation in Quark Sector and Higgs Sector
  - Spin Dependence of Fragmentation
    - Interference Fragmentation Function



Hadron-Hadron Collision

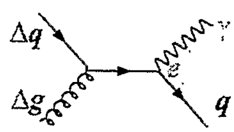


•Universality
→$f(x)$, σ, $D(z)$ are Transferable from one measurement to another!

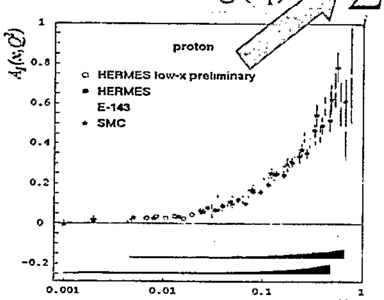
$$E\frac{d^3\sigma}{dp^3}=\sum_{i,j}\int f_i(x_1)f_j(x_2)\frac{d\hat{\sigma}}{dt}D(z)dP$$

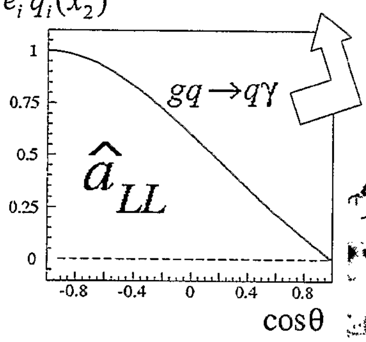
Example: Prompt Photon Production

- **Gluon Compton Dominance**
  - **No fragmentation function at LO**



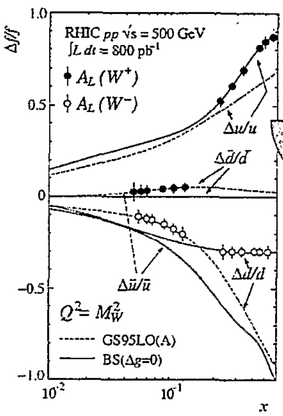
$$A_{LL}=\frac{\Delta g(x_1)}{g(x_1)}\otimes\frac{\sum_i e_i^2\Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)}\otimes a_{LL}(gq\to q\gamma)$$



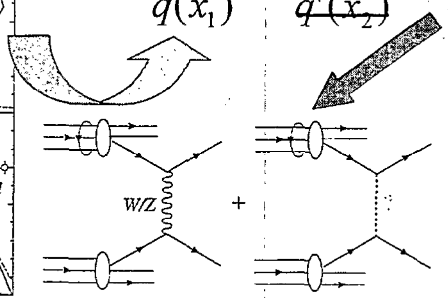


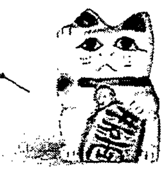
Example-2: Parity Violation in Jet

- In the SM, "Weak" is the only source of PV



$$A_L = \frac{\Delta q(x_1)}{q(x_1)} \otimes \cancel{\frac{q'(x_2)}{q'(x_2)}} \otimes \frac{\Delta\hat{\sigma}}{\hat{\sigma}}$$

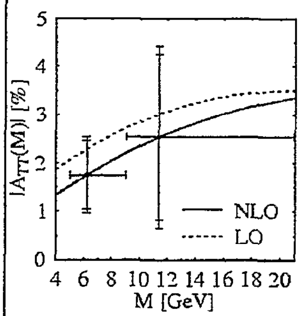


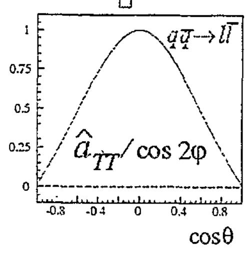


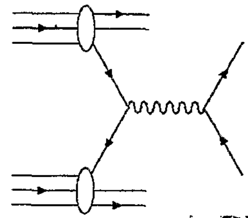
Example-3: A_{TT} (A_{NN}) for Drell-Yan

- One way to measure Transversity Distribution

$$A_{TT} = a_{TT} \frac{\sum_i e_i^2 \delta q(x_1)\delta\bar{q}(x_2) + (1 \leftrightarrow 2)}{\sum_i e_i^2 q(x_1)\bar{q}(x_2) + (1 \leftrightarrow 2)}$$



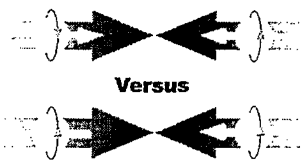




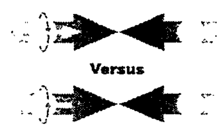
Spin Asymmetries

- A_{LL}: Double Longitudinal Spin Asymmetry
  - cross section asymmetry

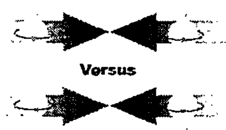
$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$



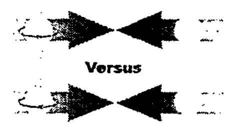
A_L:cross section asymmetry



A_{TT}:cross section asymmetry

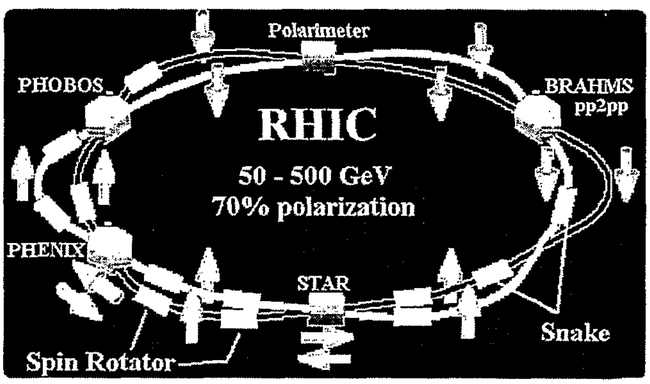


A_N:azimuthal asymmetry



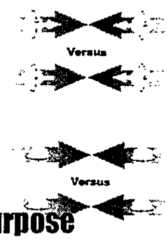
RHIC Spin Project : RIKEN BNL Collaboration (1995~)

- Polarized Collider Facility
  - Siberian Snake & Spin Rotator for PHENIX & STAR
  - PHENIX Upgrade for Spin Physics: Muon, EMC, Trigger etc
- RIKEN BNL Research Center (1997~)



RHIC Spin Phase-I

- **Original Plan**
  - A_{LL} at 200 GeV; 320 pb^{-1}; 2001-2002
  - A_{LL} at 500 GeV; 800 pb^{-1}; 2003-
  - A_{TT} and more...
- **Revision Undergoing...possible option**
  - $A_T(A_N)$ in earlier stage for commissioning purpose
    - ~5pb^{-1} proposed by STAR
  - Inclusion of short A_{TT} run at 200 GeV before 500 GeV run
    - ~30 pb^{-1} proposed by PHENIX
- **RSC Meeting in Kyoto [October 13-14]**
- **Phase-II Discussion is also undergoing...**
  - Energy & Luminosity upgrade

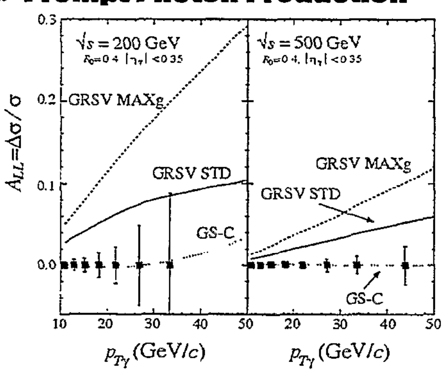


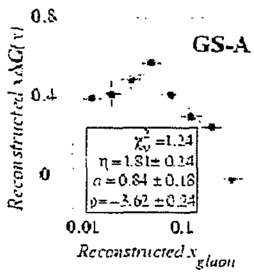
Spin Structure Studies at RHIC

- **Gluon Polarization Δg**
  - Prompt Photon/Jet/Pion/Charm/Bottom
- **Flavor-tagged Quark Polarization**
  - Drell-Yan [$W/Z/\gamma^*$] / Pion
- **Transversity**
  - Drell-Yan [γ^*/Z] / Pion-pair/ Single Spin Asymmetries

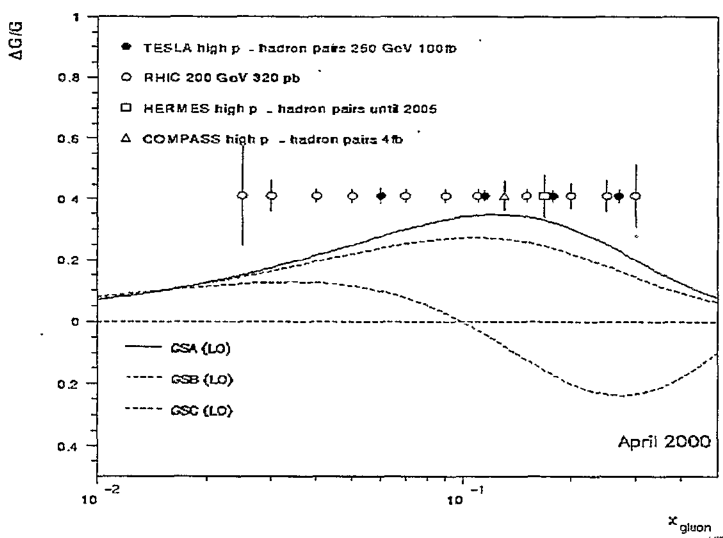
Gluon Polarization $\Delta g(x)$

- **Poorly Determined**
  - **E704 [π^0 / multi-γ] / pQCD analysis of pol-DIS data / HERMES unlike-sign π pair**
- **Prompt Photon Production**



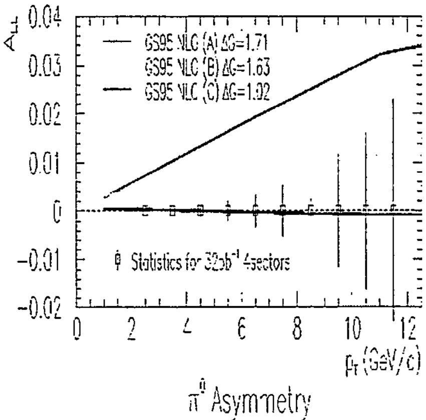


Comparison with Other Exp.



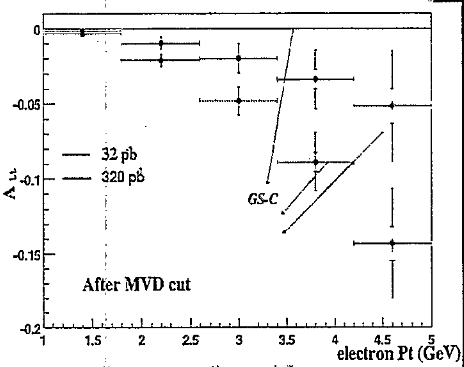
More Gluon Measurements - 1

- **Pion Production**



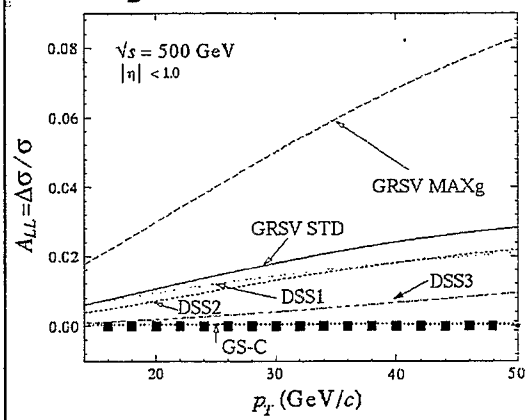
π^0 Asymmetry

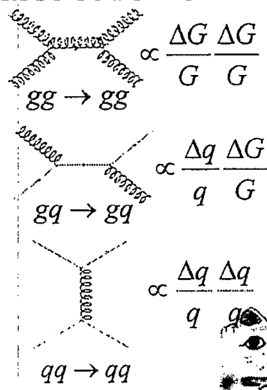
- **Charm/Bottom Production**



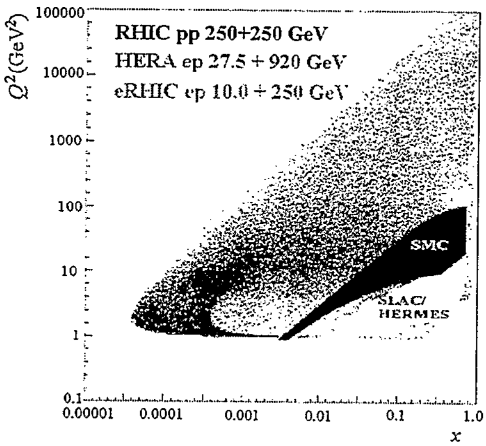
Gluon Polarization and Jet Production

- **Very Sensitive and Powerful Measurement!**





Kinematical Coverage: (x, Q^2)



- **Kinematical Coverage will be greatly enlarged !**
- **Advantageous for Global QCD Analysis.**

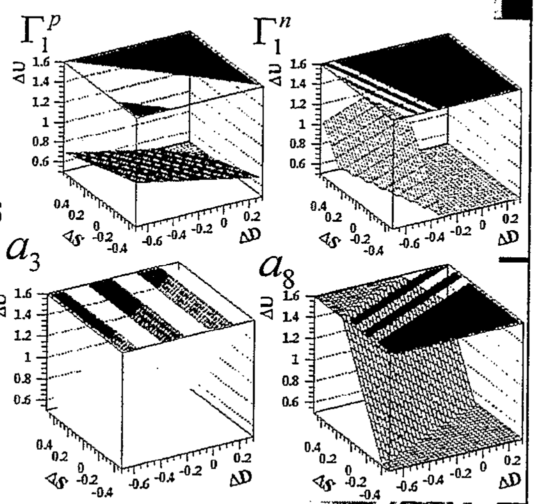
What Do We Know About Quark Polarization?

- Γ_1^p **and** Γ_1^n

$$\Gamma_1^p = \frac{4}{18}\Delta U + \frac{1}{18}\Delta D + \frac{1}{18}\Delta S$$

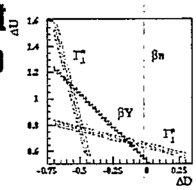
- **Additional Constraints**
  - **Axial vector coupling of octet baryon = assuming flavor** SU(3)

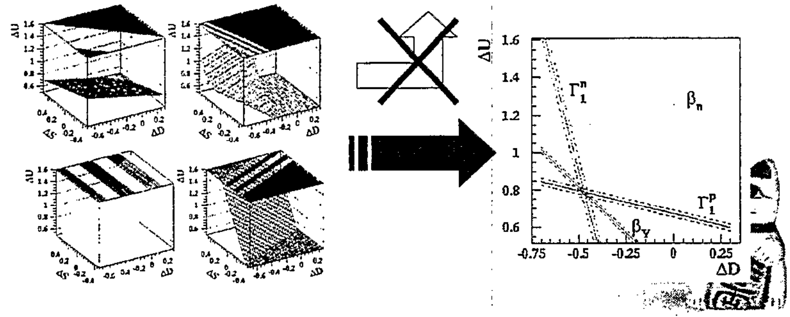
$$a_3 = \Delta U - \Delta D$$
$$a_8 = \Delta U + \Delta D - 2\Delta S$$



Pin Down ΔU, ΔD, ΔS

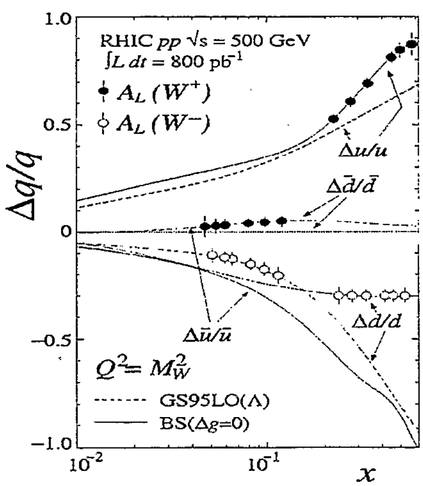
- **Information independent from $\Gamma_1{}^p$ and $\Gamma_1{}^n$ will help**
  - **e.g. ΔU or ΔD**



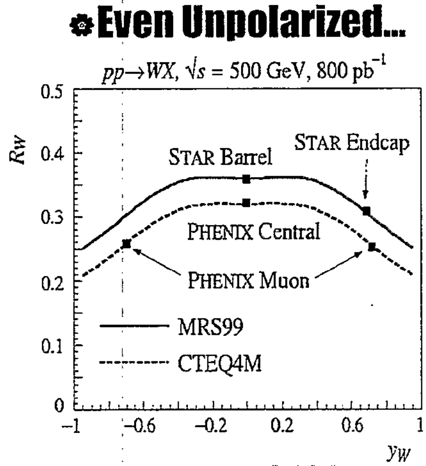


Flavor-Tagged Quark Polarization

- **Parity Violation in W production**

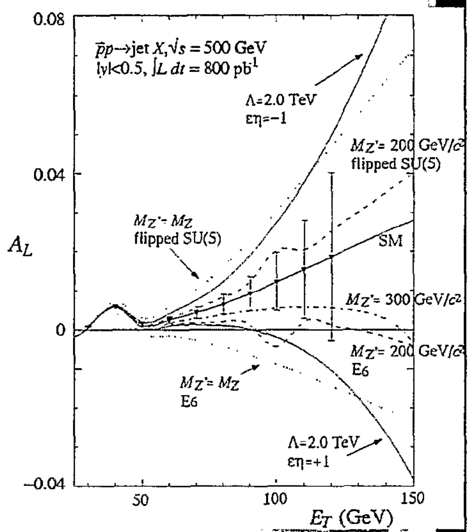


- **Even Unpolarized...**



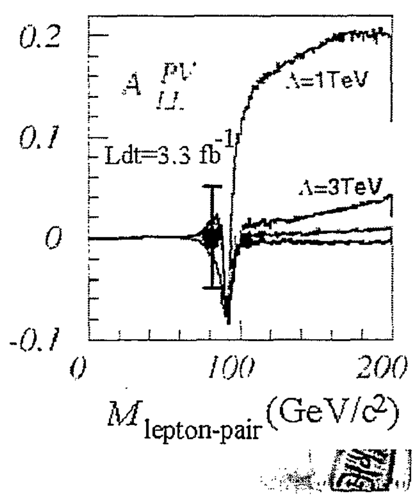
Searches for New Physics

- Interference of New Physics and Weak will result in <u>Anomalous PV</u>
  - Compositeness
    - Run II Limit 4.1 TeV (100 fb-1)
    - RHIC 3.2 fb-1 : 4.4 TeV
  - Leptophobic Z'



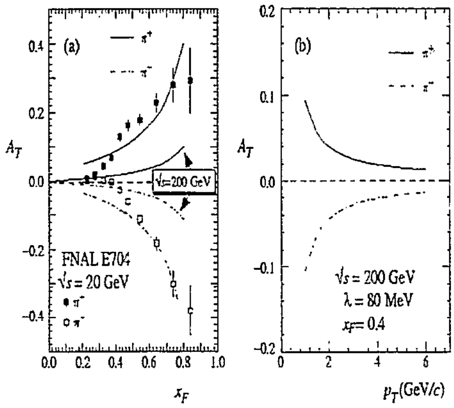
New Physics Search in Di-lepton

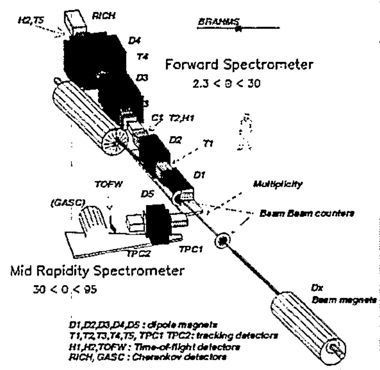
- Compositeness
  - Less Sensitivity than jet production
  - Luminosity & Energy upgrade will help!
- Common Issues
  - Precision of Theory Predictions
    - NLO
    - Polarized PDF



Single Transverse Spin Asymmetry

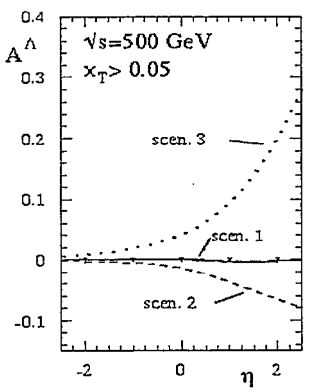
- Several Models
- BRAHMS fits best!





Spin Dependence in Fragmentation

- Longitudinal Spin Transfer Measurement in Lambda Production



$$A_{LL}^{if} = \frac{\Delta f_i}{f_i} \otimes a_{LL}^{if} \otimes \frac{\Delta D_i^{\Lambda}}{D_i^{\Lambda}} (i = u, d, s, g\ldots)$$

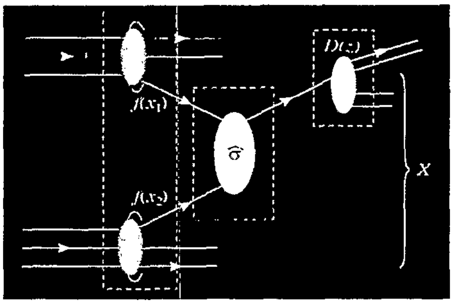
Theory

Our Measurements

Needs of Global Analysis

- We always measure convoluted quantities

- Inter-exp and exp-theory "spin network" is needed.



$$E\frac{d^3\sigma}{dp^3}=\sum_{i,j}\int f_i(x_1)f_j(x_2)\frac{d\hat{\sigma}}{dt}D(z)dP$$

Summary

- RHIC Spin Program has just started with Successful Spin Commissioning at RHIC!
- Upcoming Physics Program includes:
  - Spin Structure of the Nucleon
    - Helicity and Transversity Distributions
  - New Physics Search
  - Spin Dependence of Fragmentation
- Needs of "Spin Network" Addressed

AZIMUTHAL ASYMMETRIES IN HARD SCATTERING PROCESSES[1]

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In my contribution I start with the distribution functions measured in deep inelastic scattering. At leading order in an expansion in powers of $1/Q$ the quark structure of a proton is described by a set of three functions, $f_1^q(x, \ln \mu^2)$, $g_1^q(x, \ln \mu^2)$ and $h_1^q(x, \ln \mu^2)$ [1, 2, 3, 4]. The functions depend on the lightcone momentum fraction $x = p^+/P^+$, where p is the quark momentum and P the hadron momentum and have a logarithmic scale dependence described by the evolution equations; they exist for each flavor indicated by q, $q = u, d, s, \ldots$.

The functions f_1^q and g_1^q appear in the structure functions of deep inelastic scattering as a flavor sum weighted with quark charges squared. The functions h_1^q cannot be measured in inclusive leptoproduction. Being chirally odd [4], it requires e.g. a 1-particle inclusive measurement or Drell-Yan scattering. These processes have in common that two hadrons are involved and hence two soft parts enter in the description of the cross section, at least under suitable experimental conditions, most importantly the presence of a hard scale.

The three functions f_1^q, g_1^q and h_1^q are an independent set of functions describing the leading quark structure of hadrons. To 'calculate' them from QCD requires solving the bound state problem for the proton. To better understand their meaning, one can arranged them in a 4×4 matrix in quark-nucleon space. From such a representation one easily reads off the interpretation and one can obtain positivity conditions [5, 6]. Gluon distribution functions [2, 7] can also be looked at as soft parts appearing in hard scattering processes, but they enter only at higher order, e.g. in the evolution of the distribution functions.

In semi-inclusive deep inelastic scattering (and also in high-energy hadron-hadron scattering) transverse momentum of partons provides new possibilities to probe hadron structure [8, 9]. For instance for fragmentation into pions a transverse momentum dependent fragmentation function enters describing the decay of a transversely polarized quark into pions [10]. The transverse directions reappear in the transverse momentum of the produced hadron, in particular its azimuthal dependence [11]. Using the beforementioned matrix representation one can arrange the transverse momentum dependent functions in a matrix, being a 2×2 matrix (quark helicities) for spin 0 and a 4×4 matrix for spin 1/2 hadrons. Using the matrix representation one again can derive bounds [6]. In the case of spin 0 (or unpolarized) hadrons the transverse momentum dependent function is both chirally odd and T-odd. The latter implies that it is only nonzero if time reversal cannot be used as a constraint, such as is the case for fragmentation functions [12, 13, 14, 15, 16]. The analysis of transverse momentum of partons can be extended straightforwardly to spin 1 hadrons [17] and gluons [18]. We discuss some examples [19, 20, 21, 22]

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BNL, 18.09.2000

AZIMUTHAL ASYMMETRIES IN HARD SCATTERING PROCESSES

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- 'Deep' structure of hadrons
- Semi-inclusive leptoproduction and intrinsic transverse momenta
- Examples in leptoproduction
- Gluon distribution and fragmentation functions
- Examples in hadron-hadron scattering
- Summary and conclusions

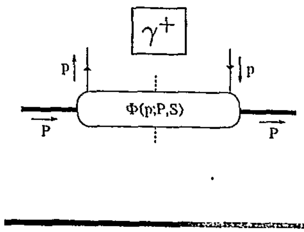
'DEEP' STRUCTURE OF HADRONS

(LEADING) QUARK DISTRIBUTION FUNCTIONS

Hadron structure enters hard processes via quark distribution functions corresponding to lightcone quark-quark correlators.

$$\Phi_{ij}(x) = \int \frac{d\xi^-}{2\pi}\, e^{ip\cdot\xi}\, \langle P,S|\overline{\psi}_j(0)\psi_i(\xi)|P,S\rangle\Big|_{\xi^+=\xi_T=0}$$

Leading part can be considered as a quark production matrix
For an unpolarized/spin 0 hadron:



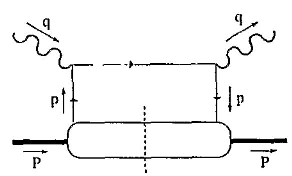
$$\sim M^{(\mathrm{prod})} = \begin{array}{cc} \begin{pmatrix} f_1 & 0 \\ 0 & f_1 \end{pmatrix} & \begin{array}{c} \mathrm{R} \\ \mathrm{L} \end{array} \\ \begin{array}{cc} \mathrm{R} & \mathrm{L} \end{array} & \end{array}$$

- Examples of hard processes: DIS or DY
- Yellow entries only relevant at subleading ($\propto 1/Q^{t-2}$) order, leaving only two "good" fields with chiralities right and left
- The distribution function f_1 depends on the (lightcone) fractional momentum $x = p^+/P^+$ of a quark in a hadron
- In DIS one can access distributions at $x_B = Q^2/2P\cdot q$
  In DY one can access distributions at $x_A = P_A\cdot q/P_A\cdot P_B$

SOFT PARTS IN HARD PROCESSES

Large scale Q leads in a natural way to the use of lightlike vectors: $n_+^2 = n_-^2 = 0$ and $n_+\cdot n_- = 1$

$$\left.\begin{array}{l} q^2 = -Q^2 \\ P^2 = M^2 \\ 2\,P\cdot q = \frac{Q^2}{x_B} \end{array}\right\} \longleftrightarrow \left\{\begin{array}{l} P = \frac{x_B M^2}{Q\sqrt{2}}\,n_- + \frac{Q}{x_B\sqrt{2}}\,n_+ \\ \\ q = \frac{Q}{\sqrt{2}}\,n_- - \frac{Q}{\sqrt{2}}\,n_+ \end{array}\right.$$



part	'components' $-$	$+$	
HARD	$\sim Q$	$\sim Q$	
$H\to q$	$\sim 1/Q$	$\sim Q$	$\to \int dp^- \ldots$

Note: the lightlike vectors may be rescaled into dimensionful vectors $\hat{p} = (Q/x_B\sqrt{2})n_+$ and $\hat{n} = (x_B\sqrt{2}/Q)n_-$

$$P = \hat{p} + \frac{M^2}{2}\,\hat{n}$$
$$q = -x_B\,\hat{p} + \frac{Q^2}{2x_B}\,\hat{n}$$

(LEADING) QUARK STRUCTURE IN A NUCLEON

For a **spin 1/2** hadron (e.g. nucleon) the quark distributions functions enter again in a quark production matrix. Omitting the higher twist entries one obtains in quark⊗nucleon spin space

$$M^{(\mathrm{prod})} = \begin{array}{cc} \left(\begin{array}{cccc} f_1+g_1 & 0 & 0 & 2\,h_1 \\ 0 & f_1-g_1 & 0 & 0 \\ 0 & 0 & f_1-g_1 & 0 \\ 2\,h_1 & 0 & 0 & f_1+g_1 \end{array}\right) & \begin{array}{c} \textcircled{R}\rightarrow \\ \leftarrow\textcircled{R} \\ \textcircled{L}\rightarrow \\ \leftarrow\textcircled{L} \end{array} \\ \begin{array}{cccc} \textcircled{R}\rightarrow & \leftarrow\textcircled{R} & \textcircled{L}\rightarrow & \leftarrow\textcircled{L} \end{array} & \end{array}$$

- The functions exist for every quark flavor: $f_1^q(x) = q(x)$, $g_1^q(x) = \Delta q(x)$, $h_1^q(x) = \delta q(x)$
- The three distribution functions are in principle independent!
- Positivity gives $f_1 \geq 0$ and $|g_1(x)| \leq f_1(x)$ but also the more stringent (**Soffer**) bound

$$|h_1(x)| \leq \frac{1}{2}\left(f_1(x) + g_1(x)\right)$$

- The function h_1 is chirally odd and is not accessible in DIS

g_1 AND h_1 UNDER ROTATIONS

Effects of changing basis:

$$M^{(\mathrm{prod})} = \begin{array}{cc} \left(\begin{array}{cccc} f_1+g_1 & 0 & 0 & 2\,h_1 \\ 0 & f_1-g_1 & 0 & 0 \\ 0 & 0 & f_1-g_1 & 0 \\ 2\,h_1 & 0 & 0 & f_1+g_1 \end{array}\right) & \begin{array}{c} \textcircled{R}\rightarrow \\ \leftarrow\textcircled{R} \\ \textcircled{L}\rightarrow \\ \leftarrow\textcircled{L} \end{array} \\ \begin{array}{cccc} \textcircled{R}\rightarrow & \leftarrow\textcircled{R} & \textcircled{L}\rightarrow & \leftarrow\textcircled{L} \end{array} & \end{array}$$

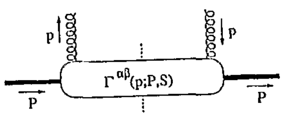
$$M^{(\mathrm{prod})} = \left(\begin{array}{cccc} f_1+h_1 & 0 & 0 & g_1+h_1 \\ 0 & f_1-h_1 & g_1-h_1 & 0 \\ 0 & g_1-h_1 & f_1-h_1 & 0 \\ g_1+h_1 & 0 & 0 & f_1+h_1 \end{array}\right)$$

(LEADING) GLUON DISTRIBUTION FUNCTIONS

Leading gluon distribution functions correspond to lightcone correlators with transverse fields

$$\Gamma^{+\alpha;+\beta}(x) = \int \frac{d\xi^-}{2\pi}\, e^{ip\cdot\xi}\, \langle P,S|F^{+\alpha}(0)F^{+\beta}(\xi)|P,S\rangle\Big|_{\xi^+=\xi_T=0}$$

This can be considered as a gluon production matrix
For an spin 0 or unpolarized hadron:



$$\sim M^{(\mathrm{prod})} = \begin{pmatrix} G(x) & 0 \\ 0 & G(x) \end{pmatrix}$$

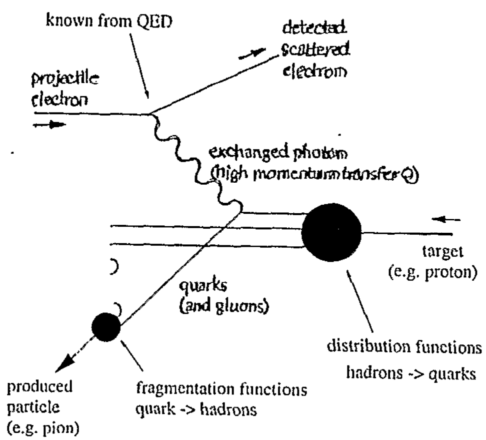
For a spin 1/2 hadron (e.g. nucleon) in gluon⊗nucleon spin space

$$M^{(\mathrm{prod})} = \begin{pmatrix} G+\Delta G & 0 & 0 & 0 \\ 0 & G-\Delta G & 0 & 0 \\ 0 & 0 & G-\Delta G & 0 \\ 0 & 0 & 0 & G+\Delta G \end{pmatrix}$$

SEMI-INCLUSIVE LEPTOPRODUCTION and INTRINSIC TRANSVERSE MOMENTA

SEMI-INCLUSIVE LEPTOPRODUCTION

- Inclusive DIS $\longleftrightarrow$ $q(x) = f_1^q(x)$, $G(x)$ via evolution
- Polarization $\longleftrightarrow$ $\Delta q(x) = g_1^q(x) = q_R(x) - q_L(x)$, $\Delta G(x)$

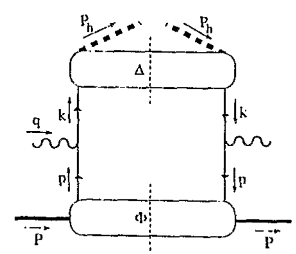


- SIDIS $\longleftrightarrow$ tagging to get f_1^q and g_1^q for $q = u, d, s, c$
- Polarimetry $\longleftrightarrow$ measure $\delta q(x) = h_1^q(x) = q_\uparrow(x) - q_\downarrow(x)$
- Azimuthal dependence $\longleftrightarrow$ study intrinsic quark k_T
- Single spin asymmetries $\longleftrightarrow$ T-odd fragmentation functions

SOFT PARTS IN HARD PROCESSES

Large scale Q leads in a natural way to the use of lightlike vectors: $n_+^2 = n_-^2 = 0$ and $n_+ \cdot n_- = 1$

$$\left.\begin{array}{l} q^2 = -Q^2 \\ P^2 = M^2 \\ P_h^2 = M_h^2 \\ 2\,P\cdot q = \frac{Q^2}{x_B} \\ 2\,P_h\cdot q = -z_h\,Q^2 \end{array}\right\} \longleftrightarrow \left\{\begin{array}{l} P_h = \frac{z_h\,Q}{\sqrt{2}}\,n_- + \frac{M_h^2}{z_h\,Q\sqrt{2}}\,n_+ \\ q = \frac{Q}{\sqrt{2}}\,n_- - \frac{Q}{\sqrt{2}}\,n_+ + q_T \\ P = \frac{x_B\,M^2}{Q\sqrt{2}}\,n_- + \frac{Q}{x_B\sqrt{2}}\,n_+ \end{array}\right.$$

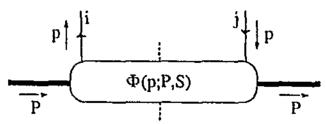


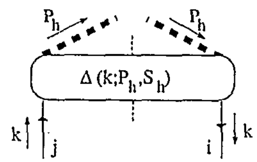
	$-$	$+$	
$q \to h$	$\sim Q$	$\sim 1/Q$	$\to \int dk^+ \ldots$
HARD	$\sim Q$	$\sim Q$	
$H \to q$	$\sim 1/Q$	$\sim Q$	$\to \int dp^- \ldots$

Three external momenta $(P,\, P_h,\, q)$ $\to$ transverse direction relevant

$$q_T = q + x_B\,P - \frac{P_h}{z_h} = -\frac{P_{h\perp}}{z_h}$$

SOFT PART IN SIDIS





Hard inclusive (polarized) deep inelastic leptoproduction involves the soft part Φ integrated over all momenta except $p^+ \equiv x\,P^+$

$$\Phi_{ij}(x) = \int \frac{d\xi^-}{2\pi}\, e^{ip\cdot\xi}\, \langle P,S|\overline{\psi}_j(0)\psi_i(\xi)|P,S\rangle \Big|_{\xi^+=\xi_T=0}$$

Hard semi-inclusive (polarized) deep inelastic lepton-hadron scattering involves soft part Φ integrated over p^- with $p^+ \equiv x\,P^+$ and p_T

$$\Phi_{ij}(x,p_T) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3}\, e^{ip\cdot\xi}\, \langle P,S|\overline{\psi}_j(0)\psi_i(\xi)|P,S\rangle \Big|_{\xi^+=0}$$

Fragmentation into a hadron involves soft part integrated over k^- leaving $P_h^- = zk^-$ and $P_{h\perp} = -zk_T$

$$\Delta_{ij}(z,k_T) = \int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3}\, e^{ik\cdot\xi}\, \langle 0|\psi_i(\xi)|P_h,X\rangle\langle P_h,X|\overline{\psi}_j(0)|0\rangle \Big|_{\xi^-=0}$$

(LEADING) QUARK FRAGMENTATION FUNCTIONS

Quark fragmentation functions into unpolarized or spin 0 hadrons relevant in hard scattering processes are specific entries in the quark decay matrix in Dirac space

$$M^{(\mathrm{dec})} = \begin{array}{cc} \left(\begin{array}{cc} D_1 & i\frac{|k_T|\,e^{-i\phi}}{M_h}\,H_1^\perp \\ -i\frac{|k_T|\,e^{+i\phi}}{M_h}\,H_1^\perp & D_1 \end{array}\right) & \begin{array}{c} \mathrm{R} \\ \mathrm{L} \end{array} \\ \begin{array}{cc} \mathrm{R} & \qquad\qquad \mathrm{L} \end{array} & \end{array}$$

- Examples of hard processes: e^+e^- annihilation and SIDIS
- Yellow entries only relevant at subleading ($\propto 1/Q^{t-2}$) order
- In quark decay time reversal invariance cannot be used $\longrightarrow$ T-odd fragmentation functions, in this case $H_1^\perp$
- The functions D_1 and $H_1^\perp$ depend on the ratio of (lightcone) momenta $z = P_h^-/k^-$ and on the transverse momentum of the quark wrt hadron (k_T)
- In SIDIS one can access the fragmentation functions at $z_h = P\cdot P_h/P\cdot q$ and $P_{h\perp} = -z_h\,k_T$
- The function $H_1^\perp$ is chiral-odd!

FULL QUARK & HADRON SPIN STRUCTURE

Quark distributions accessible including azimuthal asymmetries

$$
\begin{array}{cccc}
(\mathrm{R})\!\rightarrow & \leftarrow\!(\mathrm{R}) & (\mathrm{L})\!\rightarrow & \leftarrow\!(\mathrm{L})
\end{array}
$$

$$
\begin{pmatrix}
f_1 + g_{1L} & \frac{|p_T|}{M}\, e^{i\phi}\, g_{1T} & \frac{|p_T|}{M}\, e^{-i\phi}\, h_{1L}^{\perp} & 2\,h_1 \\
\frac{|p_T|}{M}\, e^{-i\phi}\, g_{1T} & f_1 - g_{1L} & \frac{|p_T|^2}{M^2}\, e^{-2i\phi}\, h_{1T}^{\perp} & -\frac{|p_T|}{M}\, e^{-i\phi}\, h_{1L}^{\perp} \\
\frac{|p_T|}{M}\, e^{i\phi}\, h_{1L}^{\perp} & \frac{|p_T|^2}{M^2}\, e^{2i\phi}\, h_{1T}^{\perp} & f_1 - g_{1L} & -\frac{|p_T|}{M}\, e^{i\phi}\, g_{1T} \\
2\,h_1 & -\frac{|p_T|}{M}\, e^{i\phi}\, h_{1L}^{\perp} & -\frac{|p_T|}{M}\, e^{-i\phi}\, g_{1T} & f_1 + g_{1L}
\end{pmatrix}
$$

- Transverse momentum dependence requires 2 hadrons: SIDIS/DY
- Transverse momentum dependent functions relate to twist three, but appear at leading order in $1/Q$
- T-odd functions appear as imaginary parts of off-diagonal entries for fragmentation functions: $G_{1T}+i\,D_{1T}^{\perp}$ and $H_{1L}^{\perp}+i\,H_1^{\perp}$ New bounds (see BBHM, PRL 58 (2000) 712)
- Straightforward extensions for gluons, spin 1 hadrons, ...

RELATIONS IMPOSED BY LORENTZ INVARIANCE

$$
\begin{aligned}
\Phi(x) \;=\; & \frac{1}{2}\left\{ f_1\, \not{n}_+ + \lambda\, g_1 \gamma_5\, \not{n}_+ + h_1\, \frac{[\not{S}_T,\, \not{n}_+]\gamma_5}{2} \right\} \\
& + \frac{M}{2P^+}\left\{ e + g_T\, \gamma_5\, \not{S}_T + \lambda\, h_L\, \frac{[\not{n}_+,\, \not{n}_-]\gamma_5}{2} \right\} \\
\text{T-odd} \quad & + \frac{M}{2P^+}\left\{ f_T\, \epsilon_T^{\rho\sigma} S_{T\rho}\gamma_\sigma - i\,\lambda\, e_L\, \gamma_5 + h\, \frac{i\,[\not{n}_+,\, \not{n}_-]}{2} \right\}
\end{aligned}
$$

$$
\begin{aligned}
\frac{1}{M}\,\Phi_\partial^\alpha(x) \;=\; & \frac{1}{2}\left\{ g_{1T}^{(1)}\, S_T^\alpha\, \gamma_5\, \not{n}_+ + \lambda\, h_{1L}^{\perp(1)}\, \frac{[\not{n}_+, \gamma^\alpha]\gamma_5}{2} \right. \\
\text{T-odd} \quad & \left. + f_{1T}^{\perp(1)}\, \epsilon_T^{\alpha\beta} S_{T\beta}\, \not{n}_+ + h_1^{\perp(1)}\, \frac{i\,[\not{n}_+, \gamma^\alpha]}{2} \right\}
\end{aligned}
$$

$$
g_{1T}^{(1)} = g_{1T}^{(1)}(x) \equiv \int d^2p_T\, \frac{p_T^2}{2M^2}\, g_{1T}(x, p_T)
$$

From the most general (covariant) form for $\langle\overline{\psi}(0)\,\psi(\xi)\rangle$:

$$
\underbrace{g_T - g_1}_{g_2} = \frac{d}{dx}\, g_{1T}^{(1)} \qquad \underbrace{h_L - h_1}_{\frac{1}{2}h_2} = -\frac{d}{dx}\, h_{1L}^{\perp(1)}
$$

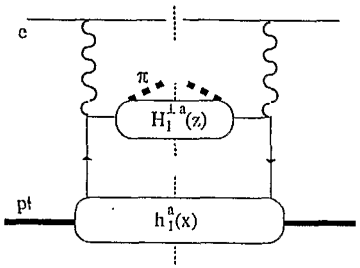
T-odd
$$
f_T = -\frac{d}{dx}\, f_{1T}^{\perp(1)} \qquad h = -\frac{d}{dx}\, h_1^{\perp(1)}
$$

EXAMPLES IN LEPTOPRODUCTION

WHERE DO THE FUNCTIONS SHOW UP

- twist t of correlation functions
  $\Rightarrow$ behavior $(1/Q)^{t-2}$
- k_T-dependent functions
  $\Rightarrow$ azimuthal dependence $(\phi_\ell, \phi_h, \phi_S)$
- cross sections are chirally even
  Examples: $\propto f_1 \otimes D_1$
  $\propto h_1 \otimes H_1$
  $\propto e \otimes H_1^\perp$
  $\propto m\, f_1 \otimes H_1^\perp$
- # of spin vectors is even in case of a T-even combination
  Examples: $\propto \lambda_e\, S_L\, g_1 \otimes D_1$
  $\propto \lambda_e\, |S_T|\, g_{1T}^{(1)} \otimes D_1$
  $\propto |S_T|\, |S_{hT}|\, h_1 \otimes H_1$
- # of spin vectors is odd in case of a T-odd combination (single spin asymmetries)
  Examples: $\propto \lambda_e\, e \otimes H_1^\perp$
  $\propto S_L\, h_L \otimes H_1^\perp$
  $\propto S_L\, h_{1L}^\perp \otimes H$
  $\propto |S_T|\, h_1 \otimes H_1^\perp$
  $\propto |S_T|\, f_{1T}^\perp \otimes D_1$

MEASURING h_1 VIA A SINGLE SPIN ASYMMETRY



J. Collins, NPB 396 (1993) 161

$$\left\langle \frac{Q_T}{M_\pi} \sin(\phi_h^\ell + \phi_S^\ell) \right\rangle_{OTO} = \frac{2\pi\alpha^2 s}{Q^4} |S_T| \, 2(1-y) \sum_{a,\bar{a}} e_a^2 \, x_B \, h_1^a(x_B) H_1^{\perp(1)a}(z_h)$$

How large can $H_1^{\perp(1)}(z)$ become?

$$|H_1^{\perp(1)}(z, -z\boldsymbol{k}_T)| = |\frac{\boldsymbol{k}_T^2}{2M_\pi^2} H_1^{\perp}(z, -z\boldsymbol{k}_T)| \leq \frac{|\boldsymbol{k}_T|}{2M_\pi} D_1(z, -z\boldsymbol{k}_T)$$

With assumption

$$D_1(z, -z\boldsymbol{k}_T) = D_1(z) \frac{R_\pi^2(z)}{\pi z^2} e^{-\boldsymbol{k}_T^2 R_\pi^2}$$

one finds

$$|H_1^{\perp(1)}(z)| \leq \underbrace{\frac{\sqrt{\pi}}{4 M_\pi R_\pi(z)}}_{\mathcal{O}(1)} D_1(z)$$

GLUON DISTRIBUTION AND FRAGMENTATION FUNCTIONS

FULL GLUON & HADRON SPIN STRUCTURE

Gluon distributions accessible including azimuthal asymmetries

$$
\begin{pmatrix}
G+\Delta G_L & \frac{|p_T|e^{-i\phi}}{M}\,\Delta G_T & -\frac{|p_T|^2 e^{-2i\phi}}{2M^2}\,H^\perp & 0 \\
\frac{|p_T|e^{+i\phi}}{M}\,\Delta G_T & G-\Delta G_L & 0 & -\frac{|p_T|^2 e^{-2i\phi}}{2M^2}\,H^\perp \\
-\frac{|p_T|^2 e^{+2i\phi}}{2M^2}\,H^\perp & 0 & G-\Delta G_L & -\frac{|p_T|e^{-i\phi}}{M}\,\Delta G_T \\
0 & -\frac{|p_T|^2 e^{+2i\phi}}{2M^2}\,H^\perp & -\frac{|p_T|e^{+i\phi}}{M}\,\Delta G_T & G+\Delta G_L
\end{pmatrix}
$$

- Transverse momentum dependence requires 2 hadrons: SIDIS/DY
- Bounds from positivity, e.g.

$$|H^{\perp(1)}| \le \sqrt{(G+\Delta G_L)(G-\Delta G_L)} \le G$$

$$|\Delta G_T^{(1)}| \le \frac{|p_T|}{2M}\sqrt{(G+\Delta G_L)(G-\Delta G_L)} \le \frac{|p_T|}{2M} G$$

- Interpretation of H as helicity flip amplitudes or differences of linearly polarized gluon densities

FULL GLUON & HADRON SPIN STRUCTURE

Gluon FF accessible including azimuthal asymmetries
for a spin 0 or unpolarized hadron

$$
\begin{pmatrix}
\hat G(z,-zk_T) & -\frac{|k_T|^2 e^{-2i\phi}}{2M^2}\,\hat H^\perp \\
-\frac{|k_T|^2 e^{+2i\phi}}{2M^2}\,\hat H^{\perp *} & \hat G(z,-zk_T)
\end{pmatrix}
$$

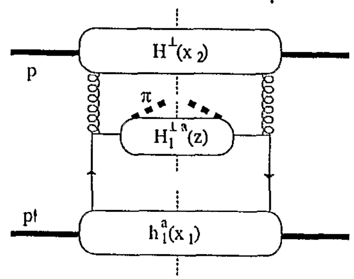
for a spin 1/2 hadron

$$
\begin{pmatrix}
\hat G+\Delta\hat G_L & \frac{|k_T|e^{-i\phi}}{M}\,\Delta\hat G_T^* & -\frac{|k_T|^2 e^{-2i\phi}}{2M^2}\,\hat H^\perp & -i\,\frac{|k_T|^3 e^{-2i\phi}}{2M^3}\,\Delta\hat H_T^\perp \\
\frac{|k_T|e^{+i\phi}}{M}\,\Delta\hat G_T & \hat G-\Delta\hat G_L & -i\,\frac{|k_T|e^{-i\phi}}{M}\,\Delta\hat H_T & -\frac{|k_T|^2 e^{-2i\phi}}{2M^2}\,\hat H^{\perp *} \\
-\frac{|k_T|^2 e^{+2i\phi}}{2M^2}\,\hat H^{\perp *} & i\,\frac{|k_T|e^{+i\phi}}{M}\,\Delta\hat H_T & \hat G-\Delta\hat G_L & -\frac{|k_T|e^{-i\phi}}{M}\,\Delta\hat G_T \\
i\,\frac{|k_T|^3 e^{+2i\phi}}{2M^3}\,\Delta\hat H_T^\perp & -\frac{|k_T|^2 e^{+2i\phi}}{2M^2}\,\hat H^\perp & -\frac{|k_T|e^{+i\phi}}{M}\,\Delta\hat G_T^* & \hat G+\Delta\hat G_L
\end{pmatrix}
$$

T-odd functions (appearing as imaginary functions) are included except $\hat G_T$ and $\Delta\hat H_L^\perp$, which appear as imaginary parts: $\mathcal{I}m\,\Delta\hat G_T = \hat G_T$ and $\mathcal{I}m\,\hat H_\perp = \Delta\hat H_L^\perp$

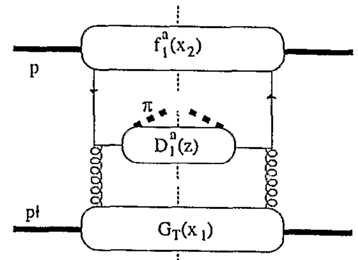
EXAMPLES IN HADRON-HADRON SCATTERING

Three ways to get a single spin asymmetry:
Note: one of the soft parts must be asymptotic ($\propto \alpha_s/|p_T|^2$)



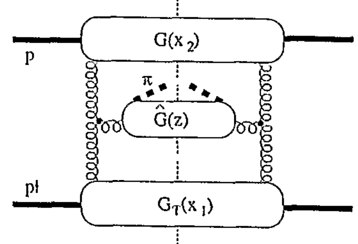
analogy of Collins asymmetry in ℓH

$$\propto \sin(\phi_\pi + \phi_S)\,(h_1^a \times H^{\perp}) \times (H_1^{\perp a})$$



other single-spin asymmetries
(a la Sivers effect)

$$\propto \sin(\phi_\pi - \phi_S)\,(G_T \times f_1^a) \times (D_1^a)$$



$$\propto \sin(\phi_\pi - \phi_S)\,(G_T \times G) \times (\hat{G})$$

SUMMARY AND CONCLUSIONS

Inclusive leptoproduction

- Quark DF $f_1^q(x)$ and $\bar{f}_1^q(x)$ for $q = u, d, s, c$
- Chirality distributions $g_1^q(x)$ and $\bar{g}_1^q(x)$
- Sum rules ($\rightarrow$ moments of DF) and evolution (coupling to gluons)
- Gluon distributions, $G(x)$ and $\Delta G(x)$
- Higher twist distributions ($\rightarrow$ quark-gluon correlations)

Semi-inclusive leptoproduction

1. **Flavor sensitivity** ...
2. **Full forward spin structure** ...
3. **Full spin structure (with k_T)** ...

Hadroproduction

1. **Full spin structure (with k_T) accessible** ...
2. **Need for specific situations** ...

Semi-inclusive leptoproduction

1. **Flavor sensitivity**
   - Production via (favored) FF: $u \to \pi^+$, $\bar{u} \to \pi^-$, ...

$$\sum_q e_q^2 f_1^q(x) \Rightarrow \sum_q e_q^2 D_1^{q\to h}(z)\, f_1^q(x)$$

   - Gluon DF via charm production
2. **Full forward spin structure**
   - Access to chiral-odd DF h_1^q (need transverse pol.)
   - No mixing with gluons under evolution for chiral-odd DF
3. **Full spin structure**
   - p_T-dependent DF $\Rightarrow$ QCD dynamics (cf. higher twist)
   - Obtained from azimuthal dependence, in most cases requiring also polarization
   - T-odd FF (for spin 0 and 1/2 necessarily p_T-dependent) appear in single-spin asymmetries
   - The FF $H_1^\perp$ (chiral-odd and T-odd) can be used to access h_1^q via single-spin asymmetries

Hadroproduction

1. **Full spin structure (with k_T)**
   - Access to chiral-odd DF h_1^q (need transverse pol.)
   - ... and many more functions obtained by looking at azimuthal dependences, in most cases requiring also polarization
2. **Need for specific situations**
   - lepton pair production (Drell-Yan)
   - Single-spin asymmetries pointing to production via T-odd fragmentation functions

Q^2-Evolution of the Transversity Distributions: Theory update

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In this talk I will discuss the characteristic features of the Q^2-evolution of the transversity distribution $\delta q(x, Q^2)$ in comparison with that of the helicity distribution $\Delta q(x, Q^2)$. Owing to the chiral-odd nature of the transversity distribution, it does not mix with the gluon distributions. Accordingly, $\delta q(x, Q^2)$ always obeys nonsinglet-like evolution equation. The difference in the anomalous dimension (or equivalently the splitting function) between $\delta q(x, Q^2)$ and $\Delta q(x, Q^2)$ leads to striking difference in the evolution in the small x-region. This feature is even more conspicuous in the NLO evolution than in the LO evolution.

Formalism of the evolution

Transversity distribution $\delta q(x,\mu^2)$, or $h_1(x,\mu^2)$

Light-cone correlation

$$\delta q(x,\mu^2) = \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS_\perp | \bar{\psi}(0) \gamma^\perp \gamma^+ \gamma_5 \underbrace{[0\,\xi^-]}_{\text{Gauge link}} \psi(\xi^-)\Big|_{\mu^2} |PS_\perp\rangle$$

IF $\gamma^\perp\gamma^+\gamma_5 \to \underline{\gamma^+\gamma_5}$: helicity (Long. pol.) distribution

$\Delta q(x,\mu^2)$ or $g_1(x,\mu^2)$

$\to \underline{\gamma^+}$: Unpol. distribution

$q(x,\mu^2)$ or $f_1(x,\mu^2)$

- Support at $|x| < 1$
- $\psi \to C\bar{\psi}^T$ defines anti-quark distribution $\delta\bar{q}$
  $\delta\bar{q}(x,\mu^2) = -\delta q(-x,\mu^2)$
- Defined for each quark-flavor
  $\delta q^a(x,\mu^2)$ $a = u, d, s, \cdots$

Evolution in the moment space

$$\begin{aligned}
\mathcal{M}_n[\delta q(\mu^2)] &\equiv \int_{-1}^{1} dx\, x^n\, \delta q(x,\mu^2) \\
&= \int_0^1 dx\, x^n [\delta q(x,\mu^2) + (-1)^{n+1} \delta\bar{q}(x,\mu^2)] \\
&\equiv \delta q_n(\mu^2) + (-1)^{n+1} \delta\bar{q}_n(\mu^2) \\
&= \frac{1}{2(P^+)^{n+1}} \langle PS_\perp | \underbrace{\bar{\psi}(0)\gamma^\perp\gamma^+\gamma_5 (iD^+)^n \psi(0)\Big|_{\mu^2}}_{= \, O_n(\mu^2)} |PS_\perp\rangle
\end{aligned}$$

Study of μ^2-dep. of $O_n(\mu^2)$ gives μ^2-dep. of $\delta q^\pm(x,\mu^2) = \delta q(x,\mu^2) \pm \delta\bar{q}(x,\mu^2)$ by inverse Mellin transform back to x-space.

We need to work on renormalization of

$$O_n(\mu^2) = \underbrace{Z_n^{-1}(\mu)}_{\text{renormalization constant}} \underbrace{O_n^B}_{\text{Bare op. of } O_n(\mu)}$$

RG equation

$$\alpha_s \equiv \frac{g^2}{4\pi}$$

$$\mu \frac{d}{d\mu} O_n(\mu) + \gamma_n(\mu) O_n(\mu) = 0$$

$$\gamma_n(\mu) \equiv \frac{d \ln Z_n(\mu)}{d \ln \mu} = \underbrace{\frac{\alpha_s(\mu)}{4\pi} \gamma_n^{(0)}}_{\substack{\text{LO} \\ \text{1-loop}}} + \underbrace{\left(\frac{\alpha_s(\mu)}{4\pi}\right)^2 \gamma_n^{(1)}}_{\substack{\text{NLO} \\ \text{2-loop}}} + \cdots$$

Anomalous dim. for $O_n(\mu)$

Up to NLO, RG eq. is solved to give

$$\delta q_n^{\pm}(Q^2) = \delta q_n^{\pm}(\mu^2) R_n^{\pm}(Q^2, \mu^2) \qquad \delta q_n^{\pm}(\mu^2) = \delta q_n(\mu^2) \pm \delta \bar{q}_n(\mu^2)$$

$$R_n^{\pm}(Q^2, \mu^2) \equiv \left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu^2)}\right)^{\gamma_n^{(0)}/2\beta_0} \left[1 + \frac{\alpha_s(Q^2) - \alpha_s(\mu^2)}{4\pi} \frac{\beta_1}{\beta_0} \left(\frac{\gamma_n^{(1)\pm}}{2\beta_1} - \frac{\gamma_n^{(0)}}{2\beta_0} \right) \right]$$

with $\alpha_s(\mu^2) = \dfrac{4\pi}{\beta_0 \ln(\mu^2/\Lambda^2)} \left[1 - \dfrac{\beta_1 \ln \ln (\mu^2/\Lambda^2)}{\beta_0^2 \ln(\mu^2/\Lambda^2)} \right]$

$$\beta_0 = 11 - \frac{2}{3} N_f \qquad \beta_1 = 102 - \frac{38}{3} N_f$$

★ RG eq. is equivalent to DGLAP eq. :

$$\frac{d}{d \ln \mu} \delta q(x, \mu^2) = \int_x^1 \frac{dy}{y} P\left(\frac{x}{y}\right) \delta q(y, \mu^2)$$

with $P(z) = \dfrac{\alpha_s}{4\pi} P^{(0)}(z) + \left(\dfrac{\alpha_s}{4\pi}\right)^2 P^{(1)}(z) + \cdots$ Splitting function

$$\gamma_n^{(i)} = - \int_0^1 dz\, z^n P^{(i)}(z) \qquad i = 0, 1, \cdots$$

Remarks

(1) Physical cross sections are convolutions of parton distributions and partonic hard cross section H.

e.g.

$$\sigma(Q^2) \sim H(Q, \tfrac{Q}{\mu}, \alpha_s(\mu), x) \otimes q(x, \mu^2)$$

- Separation not unique → "Scheme"
- Both have to be calculated in the same scheme
- $H(Q, \frac{Q}{\mu}, \alpha_s(\mu), x)$: calculable in P-QCD if $\mu^2 > \Lambda_{QCD}^2$.

  LO : Scheme independent.

  NLO : First scheme dependence

(2) Flavor singlet part of $q^a(x, \mu^2)$ and $\Delta q^a(x, \mu^2)$ mix with Gluon distributions

Ano. dim becomes 2×2 matrix

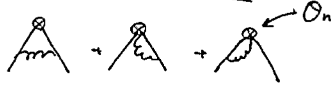
$\gamma_n \to (\gamma_n)_{ij}$ so is DGLAP eq.

(3) $\delta q(x, \mu^2)$: chiral-odd

→ no mixing with gluon distribution

Evolution eq. is Nonsinglet-like.

LO evolution of $\delta q(x,\mu^2)$



$$\gamma_n^{h(0)} = 2C_F\left(1 + 4\sum_{j=2}^{n+1}\frac{1}{j}\right)$$ Artru-Mekhfi (90)

$$\gamma_n^{NS(0)} = 2C_F\left(1 - \frac{2}{(n+1)(n+2)} + 4\sum_{j=2}^{n+1}\frac{1}{j}\right) \qquad C_F = \frac{4}{3}$$

$\uparrow$

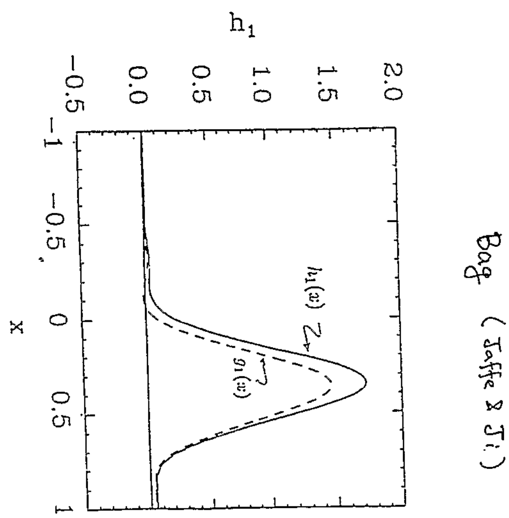
Nonsinglet part of $q(x,\mu^2)$ & $\Delta q(x,\mu^2)$

$\gamma_n^{h(0)} > \gamma_n^{NS(0)}$ for all n especially for small n.

$\Rightarrow$ Evolution of $\delta q(x,\mu^2)$ diffrent from $q^{NS}(x,\mu^2)$ and $\Delta q^{NS}(x,\mu^2)$ <u>especially at</u> small x.

No mixing with gluon distribution to all orders.

1-loop ex.



V. Barone, Phys. Lett. B409 ('97) 499

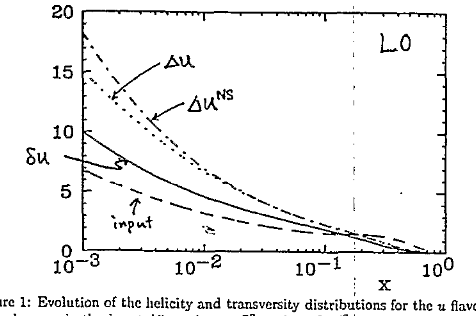


Figure 1: Evolution of the helicity and transversity distributions for the u flavor. The dashed curve is the input $h_1^u \equiv \Delta u$ at $Q_0^2 = 0.23$ GeV^2 taken from the GRV [17] parametrization. The solid (dotted) curve is h_1^u (Δu) at $Q^2 = 25$ GeV^2. The dot-dashed curve is the result of the evolution of h_1^u at $Q^2 = 25$ GeV^2 driven by P_{qq}, *i.e.* with the term δP_h turned off in P_h.

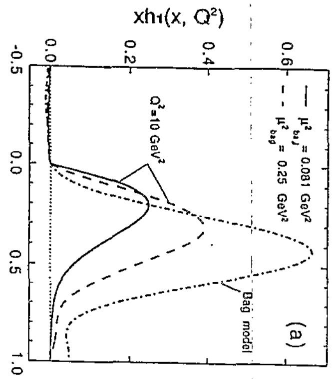


Fig.1(a)

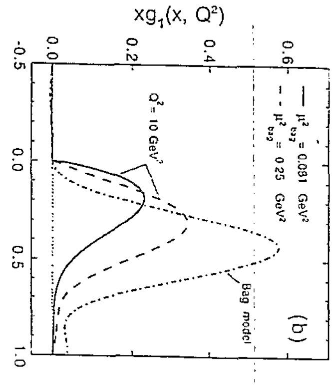


Fig.1(b)

(97)

NLO evolution ($\overline{MS}$)

- Vogelsang, (lightcone gauge)
- Hayashigaki–Kanazawa–Koike (Feynman gauge)
- Kumano–Miyama (Feynman)

$$\delta q_n^{\pm}(\mu^2) = \delta q_n(\mu^2) \pm \delta \bar{q}_n(\mu^2)$$

$$\delta q_n^{\pm}(Q^2) = R_n^{\pm}(Q^2\mu^2)\, \delta q_n^{\pm}(\mu^2)$$

$$R_n^{\pm}(Q^2\mu^2) \equiv R_n^{qq}(Q^2\mu^2) \pm R_n^{q\bar{q}}(Q^2\mu^2)$$

($\because$) NLO anomalous dim. takes the form :

$$\gamma_n^{(1)} = \underbrace{\gamma_n^{qq(1)}}_{\ln n + \left(\frac{1}{n+1}\right)^k} + (-1)^{n+1} \underbrace{\gamma_n^{q\bar{q}(1)}}_{\left(\frac{1}{n+1}\right)^k}$$

$$\Longrightarrow \begin{cases} \delta q_n(Q^2) = \frac{1}{2} R_n^{qq}(Q^2\mu^2)\, \delta q_n(\mu^2) + \frac{1}{2} R_n^{q\bar{q}}(Q^2\mu^2)\, \delta \bar{q}_n(\mu^2) \\ \delta \bar{q}_n(Q^2) = \frac{1}{2} R_n^{q\bar{q}}(Q^2\mu^2)\, \delta q_n(\mu^2) + \frac{1}{2} R_n^{qq}(Q^2\mu^2)\, \delta \bar{q}_n(\mu^2) \end{cases}$$

Evolution of $\bar{q}(x\mu^2)$ receives effects of $q(x\mu^2)$

→ **flavor symmetric sea distribution at μ^2 gives flavor symmetry violation at $Q^2 > \mu^2$.**

BUT $R_n^{q\bar{q}}(Q^2\mu^2)$ gives ~~small~~ effect.
(tiny)

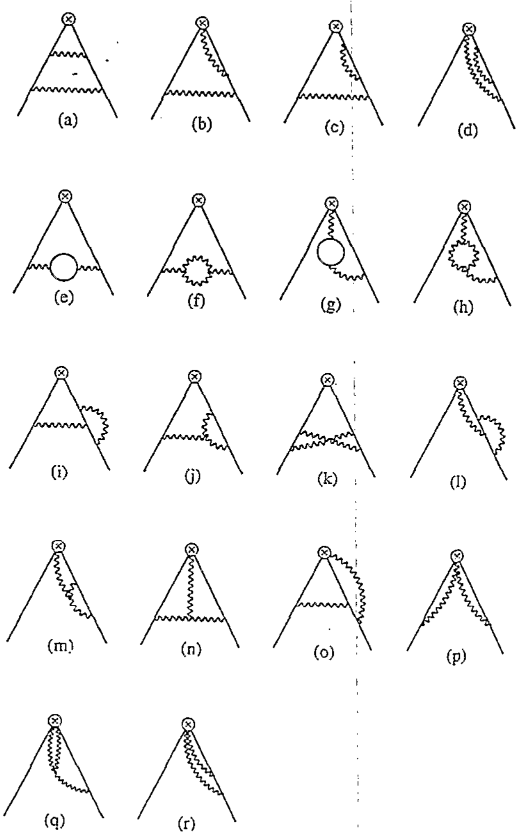


Fig.2

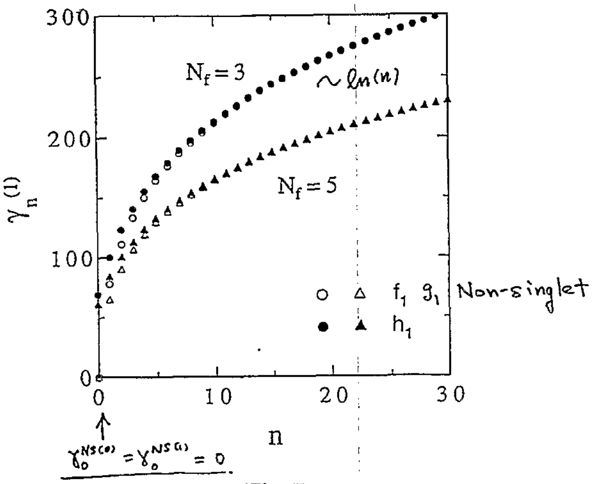
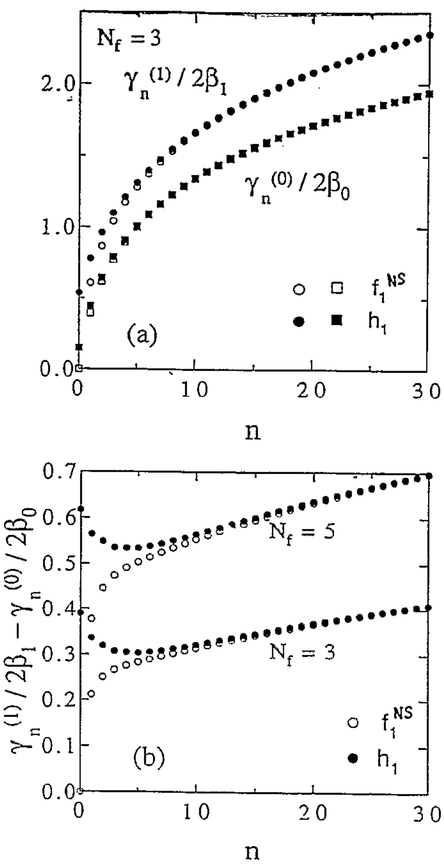


Fig.7

★ $\gamma_n^{h(1)} > \gamma_n^{NS(1)}$ for all n, especially at small n.

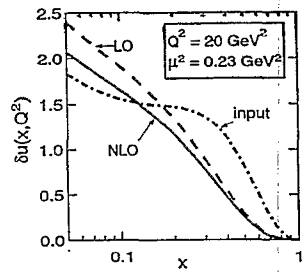
→ difference in small-x behavior



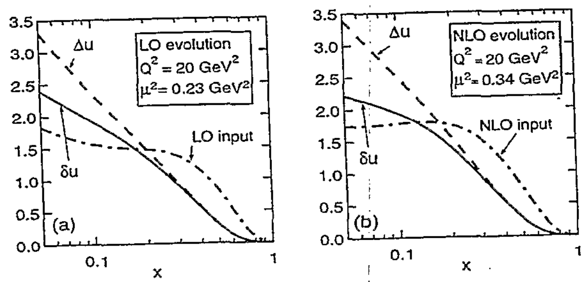
$N_f = 3$
$\gamma_n^{(1)} / 2\beta_1$
$\gamma_n^{(0)} / 2\beta_0$
f_1^{NS}
h_1
(a)
n
$\gamma_n^{(1)} / 2\beta_1 - \gamma_n^{(0)} / 2\beta_0$
$N_f = 5$
$N_f = 3$
f_1^{NS}
h_1
(b)
n

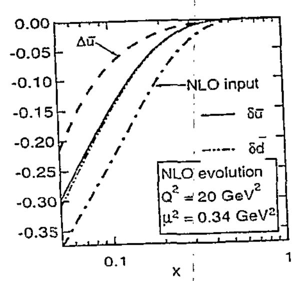
Fig.8

Hayashigaki - Kanazawa - Koike hep-ph/9710421 (DESY-Zeuthen proc



input = GRSV g_1-dist.



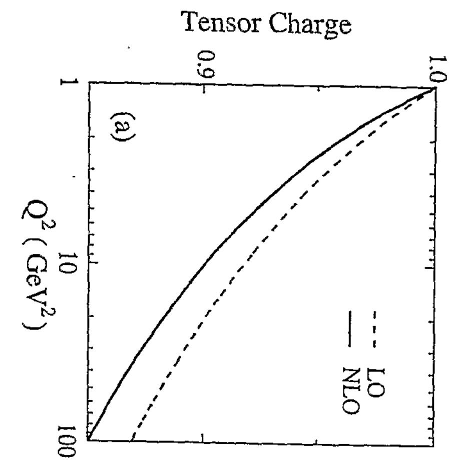


$n=0$: Tensor charge vs. axial charge

$$\int_{-1}^{1} dx\, \delta q(x,\mu^2) = \int_0^1 dx\left[\delta q(x,\mu^2) - \delta\bar q(x,\mu^2)\right]$$
$$= \langle PS_\perp | \bar\psi\, i\gamma_5\sigma^{\perp +}\psi\,|_{\mu^2}| PS_\perp\rangle \frac{1}{p^+}$$
$$\equiv \delta q(\mu^2) \quad \text{tensor charge}$$

$$\int_{-1}^{1} dx\, \Delta q(x,\mu^2) = \int_0^1 dx\left[\Delta q(x,\mu^2) + \Delta\bar q(x,\mu^2)\right]$$
$$= \langle PS_\parallel | \bar\psi\, \gamma^+\gamma_5\psi\,|_{\mu^2}| PS_\parallel\rangle \frac{1}{p^+}$$
$$\equiv \Delta q(\mu^2) \quad \text{axial charge}$$

$\Delta q^{NS}(\mu^2) = \Delta q^{NS}$ μ^2- independent!



- Soffer's inequality

$$2|\delta q^a(x\,Q^2)| \le q^a(x\,Q^2) + \Delta q^a(x\,Q^2) \qquad (*)$$

- Inequality for each quark and anti-quark flavor.
  (NOT necessarily true for valence or nonsinglet distributions.)
- Correct in Parton model.
- In QCD, scheme dependent. (Goldstein et al.)

IF $(*)$ is realized at $Q^2 = Q_0^2$, how is it modified by QCD evolution?

$\overline{MS}$:

$$\gamma_n^{h(i)} > \gamma_n^{NS(i)} \quad (i=0,1) \quad \text{for all } n$$

or $\quad \delta P^{(i)}(z) < P^{(i)}(z) \quad (i=0,1) \quad 0<z<1.$

$\rightarrow$ It is maintained at $Q^2 > Q_0^2$
(becoming more conspicuous at high Q^2.)

Mixing with gluon distribution in r.h.s of $(*)$ does not change the situation numerically.
(Martin et al, Vogelsang, Bourrely et al.)

■ Small-x behavior by DGLAP eq.

Position of the rightmost singularity of γ_n
$\rightarrow$ Asymptotic $x \to 0$ behavior

LO ($\gamma_n^{(0)}$)

$n = -1$ for $q^{NS}(x\,Q^2)$ and $\Delta q^{NS}(x\,Q^2)$
$\rightarrow$ $q^{NS}(x\,Q^2),\ \Delta q^{NS}(x\,Q^2) \underset{x\to 0}{\sim} \text{const.}$

$n = -2$ for $\delta q(x\,Q^2)$
$\rightarrow$ $\delta q(x\,Q^2) \underset{x\to 0}{\sim} x$

NLO ($\gamma_n^{(1)}$)

$n = -1$ for $q^{NS}(x\,Q^2)$ and $\Delta q^{NS}(x\,Q^2)$
$\rightarrow$ $q^{NS}(x\,Q^2),\ \Delta q^{NS}(x\,Q^2) \underset{x\to 0}{\sim} \text{const}$

$n = -1$ for $\delta q(x\,Q^2)$
$\rightarrow$ $\delta q(x\,Q^2) \underset{x\to 0}{\sim} \text{const.}$

different

Comparable with Regge asymptotics (BFKL)
(Kirschner-Mankiewicz-Schäfer-Szymanowski Z. Phys. C74 (97) 501)

Summary

(1) Both LO and NLO evolutions of $\delta q(x\,\mu^2)$ are very different from those of $\Delta q(x\,\mu^2)$ at small x.

$n = 0$ case
tensor charge $\delta q(\mu^2)$ is μ^2-dep.
$\leftrightarrow$ (nonsinglet) axial charge

(2) Soffer's inequality

$$2\,|\delta q^a(x\,Q^2)| \le q^a(x\,Q^2) + \Delta q^a(x\,Q^2) \quad ?$$

IF sattisfied at $Q^2 = Q_0^2$, it is preserved at $Q^2 > Q_0^2$.

(3) NLO correction to LO evolution is quite large.
BUT it has to be combined with the NLO correction to the hard cross sections.

e.g. Martin et al (PRD57 (98) 3084) studied NLO effect in A_{TT} in Drell-Yan.
$\rightarrow$ modest but nonnegligible NLO effect.

Q^2 evolution of transversity distributions: applications

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ABSTRACT

We discuss Q^2 evolution of various transversity distributions with emphasis on the numerical analysis part [1]. The transversity evolution equation is now available not only for the leading-order (LO) [2] but also for the next-to-leading order (NLO) [3].

First, numerical solution of the evolution equation is discussed for the transversity distribution $\Delta_T q$. Dividing the variables x and Q^2 into small steps, we solve the integrodifferential equation by the Euler method in the variable Q^2 and by the Simpson method in the variable x. We provide a FORTRAN program for the Q^2 evolution and devolution of the transversity distribution [1]. Using the program, we show LO and NLO evolution results of the valence-quark distribution $\Delta_T u_v + \Delta_T d_v$ and the singlet distribution $\sum_i(\Delta_T q_i + \Delta_T \bar{q}_i)$. Because the results are very different from longitudinally-polarized ones, the evolution difference could be another important test of perturbative QCD in spin physics.

It is also interesting to find a finite flavor asymmetric distribution $\Delta_T \bar{u} - \Delta_T \bar{d}$ due to the NLO evolution effects [4, 1]. However, the magnitude of the perturbative contribution is very small, so that the asymmetric distribution has to be investigated together with nonperturbative mechanisms in the similar way to the unpolarized case [5]. Although the longitudinal distribution $\Delta \bar{u} - \Delta \bar{d}$ will be investigated, for example, at RHIC in W production processes, the transversity distribution $\Delta_T \bar{u} - \Delta_T \bar{d}$ cannot be measured by the W production due to the chiral-odd property. As an alternative way, the proton-deuteron Drell-Yan process is proposed [6]. We find theoretically that it is an appropriate way for finding $\Delta_T \bar{u} - \Delta_T \bar{d}$.

References

[1] M. Hirai, S. Kumano, and M. Miyama, Comput. Phys. Commun. 108 (1998) 38; 111 (1998) 150. Our evolution program could be obtained upon email request. For details, see http://www-hs.phys.saga-u.ac.jp/program.html.

[2] X. Artru and M. Mekhfi, Z. Phys. C45 (1990) 669.

[3] S. Kumano and M. Miyama, Phys. Rev. D56 (1997) 2504; A. Hayashigaki, Y. Kanazawa, and Y. Koike, Phys. Rev. D56 (1997) 7350; W. Vogelsang, Phys. Rev. D57 (1998) 1886.

[4] O. Martin, A. Schäfer, M. Stratmann, and W. Vogelsang, Phys. Rev. D57 (1998) 3084.

[5] S. Kumano, Phys. Rep. 303 (1998) 183.

[6] S. Kumano and M. Miyama, Phys. Lett. B497 (2000) 149.

* kumanos@cc.saga-u.ac.jp, http://www-hs.phys.saga-u.ac.jp.

Q^2 evolution of transversity distributions: applications

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Talk at the workshop on
Future Transversity Measurements
Sept. 18-20, 2000, BNL, USA

Sept. 18, 2000

- Contents -

Q^2 evolution of transversity distributions

- numerical analysis
- flavor asymmetric distribution
- Drell-Yan cross section

related topic
(pd Drell – Yan for finding $\Delta_T\bar{u} - \Delta_T\bar{d}$)

References

- M. Hirai, SK, M. Miyama, Comput. Phys. Commun. 108 (1998) 38; 111 (1998) 150
- SK, M. Miyama, Phys. Lett. B 497 (2000) 149

Drell-Yan process $\vec{p} + \vec{p} \to \mu^+ \mu^- + X$

Spin asymmetry

$$A_{S_A S_B} = \frac{\sigma(S_A, S_B) - \sigma(S_A, -S_B)}{\sigma(S_A, S_B) + \sigma(S_A, -S_B)}$$

Longitudinal

$$A_{LL} = \frac{\sum_a e_a^2\, g_1^a(x)\, g_1^{\bar{a}}(y)}{\sum_a e_a^2\, f_1^a(x)\, f_1^{\bar{a}}(y)}$$

Transverse

$$A_{TT} = \frac{\sin^2\theta \cos(2\varphi)}{1 + \cos^2\theta} \frac{\sum_a e_a^2\, h_1^a(x)\, h_1^{\bar{a}}(y)}{\sum_a e_a^2\, f_1^a(x)\, f_1^{\bar{a}}(y)}$$

θ, φ: polar and azimuthal angles of the lepton momentum with respect to beam in the c.m. frame of the lepton pair

DGLAP evolution equation for transversity distributions

"nonsinglet type"

$$\frac{\partial}{\partial(\ln Q^2)} \Delta_T q\,(x, Q^2) = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y}\, \Delta_T P\left(\frac{x}{y}\right) \Delta_T q\,(y, Q^2)$$

numerical solution

- $x \longrightarrow$ divided into $2N_x$ steps
- $t = \ln Q^2 \longrightarrow$ divided into N_t steps

$$\frac{\partial}{\partial t} f(x, t) \;\Rightarrow\; \frac{f(x_i, t_{j+1}) - f(x_i, t_j)}{\delta t}$$

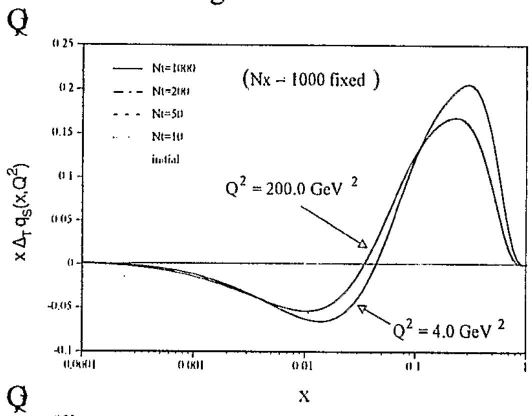
$$\int dz\, f(z) \;\Rightarrow\; \sum_{k=2,4,\ldots}^{2N_x} \frac{\delta z}{3} \left[f(z_{k-1}) + 4 f(z_k) + f(z_{k+1}) \right]$$

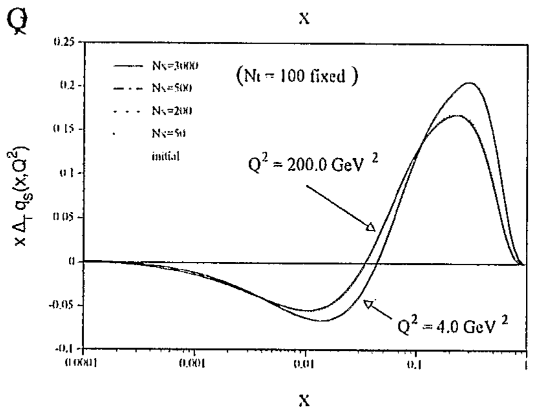
see Comput. Phys. Commun. 111 (1998) 150

Our evolution program could be obtained upon email request: see http://www-hs.phys.saga-u.ac.jp/program.html.

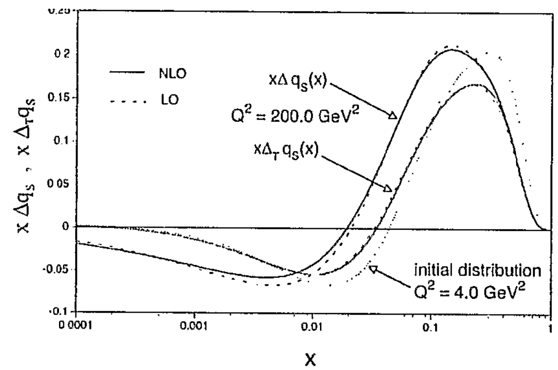
Numerical accuracy

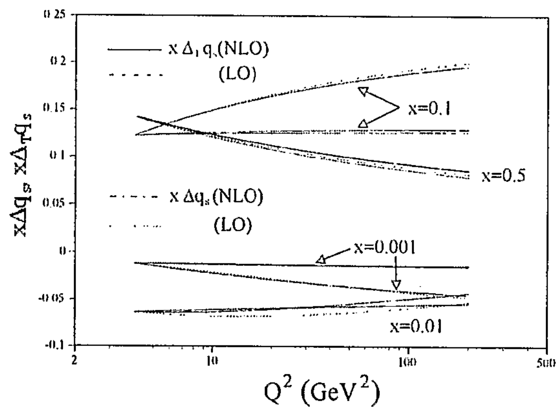
initial=GS-A singlet



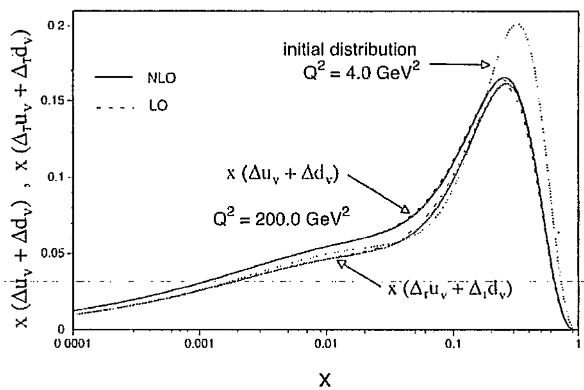


Q^2 evolution of longitudinally polarized and transversity distributions





Q^2 evolution of polarized valence-quark distributions



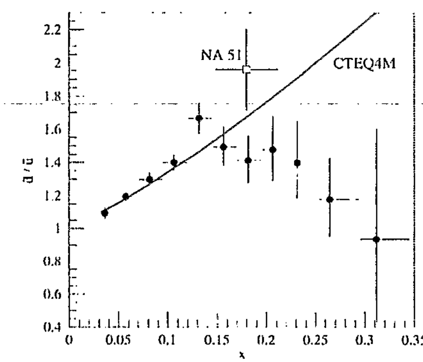
$\bar{u}/\bar{d}$ asymmetry

- Gottfried sum (NMC $S_G = 0.235 \pm 0.026$)

$$S_G = \int_0^1 \frac{dx}{x}\,[F_2^{\mu p}(x) - F_2^{\mu n}(x)]$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 dx\,[\bar{u}(x) - \bar{d}(x)]$$

- Drell-Yan p-n asymmetry (NA51, E866)



(from hep-ex/9803011)

see SK, Phys. Rep. 303 (1998) 183

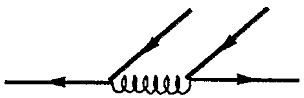
Perturbative QCD contribution

$$\frac{\partial}{\partial(\ln Q^2)}\, q^{\pm}(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\, P_{q^{\pm}}\!\left(\frac{x}{y}\right) q^{\pm}(y,Q^2)$$

where $q^{\pm} = q \pm \bar{q}\,,\ \ P_{q^{\pm}} = P_{qq} \pm P_{q\bar{q}}$

on the transversity, see Martin, Schäfer, Stratmann, and Vogelsang, Phys. Rev. D57 (1998) 3084.

$P_{q\bar{q}} = 0$ in LO
$\neq 0$ in NLO



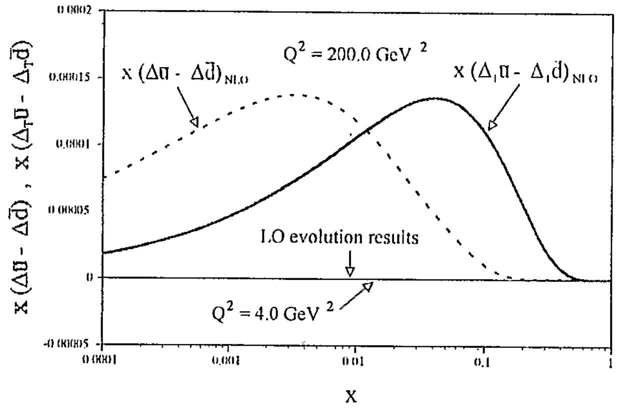
$$(\bar{u} - \bar{d})_{pQCD} = 0 \ \text{ in LO}$$
$$\neq 0 \ \text{ in NLO}$$

$$(\bar{u} - \bar{d})_{pQCD} << (\bar{u} - \bar{d})_{nonperturbative}$$

we expect $(\Delta_T\bar{u} - \Delta_T\bar{d})_{pQCD} << (\Delta_T\bar{u} - \Delta_T\bar{d})_{nonpert.}$

$\Delta_T\bar{u} - \Delta_T\bar{d}$ in perturbative QCD

assume $\Delta_T\bar{u} - \Delta_T\bar{d} = \Delta\bar{u} - \Delta\bar{d}$ at $Q^2 = 4$ GeV^2



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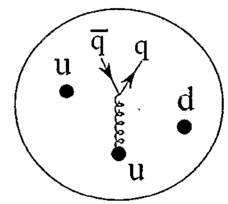
Nonperturbative mechanisms for the $\Delta_T\bar{u}$ / $\Delta_T\bar{d}$ asymmetry

- Virtual meson clouds
- Pauli exclusion principle
- ...

Pauli exclusion principle (unpolarized)



2 (spin) X 3 (color) = 6 states

- 2 of 6 states are occupied for u-quark
- 1 of 6 for d-quark

4 u-quarks and 5 d-quarks can be accomodated.

↓

naive counting estimate: $\bar{u} / \bar{d} = 4 / 5$

Pauli exclusion principle (polarized)

Bourrely, Buccela, Soffer

in a naive quark model

$$|p_+> = \frac{1}{\sqrt{6}}\left[2\,|u_+u_+d_-> - |u_+u_-d_+> - |u_-u_+d_+>\right]$$

$$\downarrow$$

$$u_+ = \frac{5}{3}\ ,\ u_- = \frac{1}{3}\ ,\ d_+ = \frac{1}{3}\ ,\ d_- = \frac{2}{3}$$

suppose $\dfrac{u_s^\downarrow - u_s^\uparrow}{u_v^\uparrow - u_v^\downarrow} = \dfrac{d_s - u_s}{u_v - d_v}$

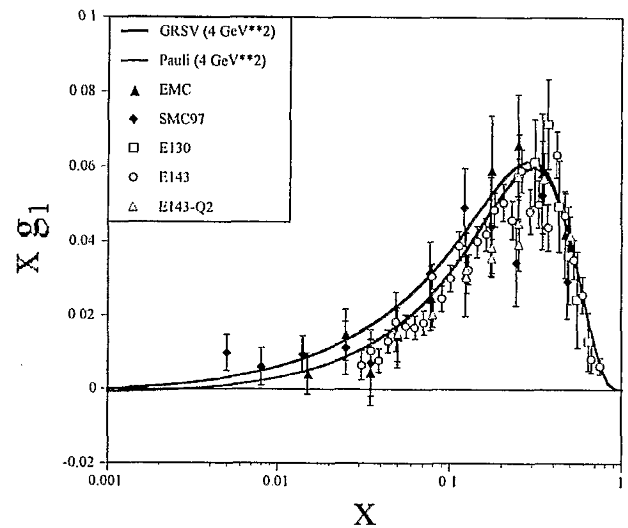
$$\Delta_{(i)}\bar{u} = u_s^\uparrow - u_s^\downarrow = -\frac{d_s - u_s}{u_v - d_v}\left(u_v^\uparrow - u_v^\downarrow\right) \approx -0.13$$

in the same way

$$\Delta_{(i)}\bar{d} = d_s^\uparrow - d_s^\downarrow = -\frac{d_s - u_s}{u_v - d_v}\left(d_v^\uparrow - d_v^\downarrow\right) \approx +0.05$$

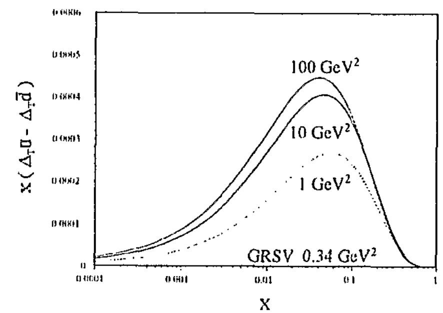
$\Delta\bar{u}$ / $\Delta\bar{d}$ asymmetry effects on g_1

- GRSV ($\Delta\bar{u} = \Delta\bar{d}$) at $Q^2 = 0.34\ \mathrm{GeV}^2 \rightarrow Q^2 = 4\ \mathrm{GeV}^2$
- Pauli ($\Delta\bar{u} \neq \Delta\bar{d}$) at $Q^2 = 0.34\ \mathrm{GeV}^2 \rightarrow Q^2 = 4\ \mathrm{GeV}^2$

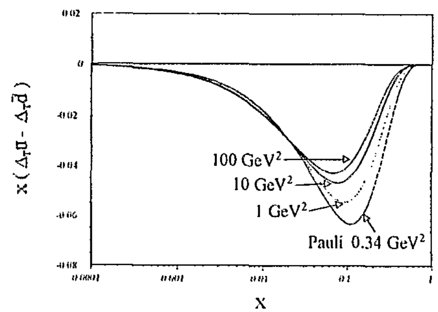


Q^2 dependence of $\Delta_T\bar{u} - \Delta_T\bar{d}$

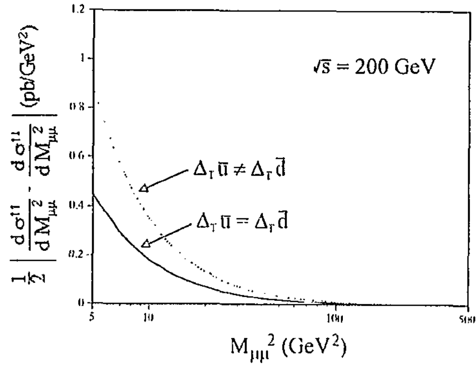
initial $(\Delta_T\bar{u} - \Delta_T\bar{d})_{GRSV} = 0$ at $Q^2 = 0.34$ GeV^2

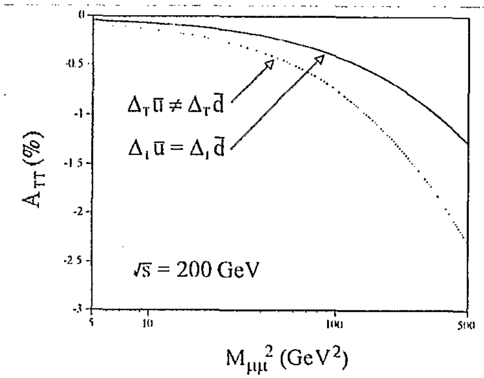


initial $(\Delta_T\bar{u} - \Delta_T\bar{d})_{Pauli} \neq 0$ at $Q^2 = 0.34$ GeV^2

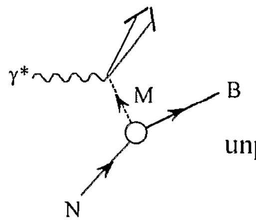


$\Delta_T\bar{u} / \Delta_T\bar{d}$ asymmetry effects on Drell-Yan cross section





Meson-cloud model



unpolarized : e.g. $\pi^+(u\bar{d})$

$\downarrow$

$\bar{d}$ excess : $\bar{u} - \bar{d} < 0$

ρ contribution to $\Delta\bar{u} - \Delta\bar{d}$

Fries–Schäfer (1998)

$$\Delta\bar{q}(x,Q^2) = \sum_\lambda \int_x^1 \frac{dy}{y}\, f^\lambda_{MNB}(y)\, \Delta\bar{q}_{M,\lambda}(x/y,Q^2)$$

polarized : e.g. $\rho^+(u\bar{d})$

$\downarrow$

$\Delta\bar{d}$ excess : $\Delta\bar{u} - \Delta\bar{d} < 0$

Proton-deuteron Drell-Yan for finding $\Delta_T\bar{u} - \Delta_T\bar{d}$

$$R_{pd} \equiv \frac{\Delta_{(T)}\sigma^{pd}}{2\,\Delta_{(T)}\sigma^{pp}} \qquad \text{where } \Delta_{(T)} = \Delta \text{ or } \Delta_T$$

$$= \frac{\sum_a e_a^2 \left[\Delta_{(T)}q_a(x_1)\Delta_{(T)}\bar{q}_a^d(x_2) + \Delta_{(T)}\bar{q}_a(x_1)\Delta_{(T)}q_a^d(x_2)\right]}{2\sum_a e_a^2 \left[\Delta_{(T)}q_a(x_1)\Delta_{(T)}\bar{q}_a(x_2) + \Delta_{(T)}\bar{q}_a(x_1)\Delta_{(T)}q_a(x_2)\right]}$$

- neglect nuclear effects in the deuteron
- assume isospin symmetry

$$x_F = x_1 - x_2$$

- $x_F \to +1$ region

$$R_{pd}(x_F \to 1) = \frac{\sum_a e_a^2 \left[\Delta_{(T)}q_{v,a}(x_1)\Delta_{(T)}\bar{q}_a^d(x_2)\right]}{2\sum_a e_a^2 \left[\Delta_{(T)}q_{v,a}(x_1)\Delta_{(T)}\bar{q}_a(x_2)\right]}$$

$$= 1 - \frac{\left[4\Delta_{(T)}u_v(x_1) - \Delta_{(T)}d_v(x_1)\right]\left[\Delta_{(T)}\bar{u}(x_2) - \Delta_{(T)}\bar{d}(x_2)\right]}{8\Delta_{(T)}u_v(x_1)\Delta_{(T)}\bar{u}(x_2) + 2\Delta_{(T)}d_v(x_1)\Delta_{(T)}\bar{d}(x_2)}$$

suppose $\Delta_{(T)}u_v(x \to 1) \gg \Delta_{(T)}d_v(x \to 1)$

$$R_{pd}(x_F \to 1) = 1 - \left[\frac{\Delta_{(T)}\bar{u}(x_2) - \Delta_{(T)}\bar{d}(x_2)}{2\,\Delta_{(T)}\bar{u}(x_2)}\right]_{x_2 \to 0} = \frac{1}{2}\left[1 + \frac{\Delta_{(T)}\bar{d}(x_2)}{\Delta_{(T)}\bar{u}(x_2)}\right]_{x_2 \to 0}$$

$$\Delta_{(T)}\bar{u} = \Delta_{(T)}\bar{d} \;\Rightarrow\; R_{pd}(x_F \to 1) = 1$$

if $\Delta_{(T)}\bar{u}$, $\Delta_{(T)}\bar{d} < 0$ $\quad |\Delta_{(T)}\bar{u}| < |\Delta_{(T)}\bar{d}| \;\Rightarrow\; R_{pd}(x_F \to 1) > 1$

$\quad |\Delta_{(T)}\bar{u}| > |\Delta_{(T)}\bar{d}| \;\Rightarrow\; R_{pd}(x_F \to 1) < 1$

- $x_F \to -1$ region

$$R_{pd}(x_F \to -1) = \frac{\left[4\Delta_{(T)}\bar{u}(x_1) + \Delta_{(T)}\bar{d}(x_1)\right]\left[\Delta_{(T)}u_v(x_2) + \Delta_{(T)}d_v(x_2)\right]}{8\Delta_{(T)}\bar{u}(x_1)\Delta_{(T)}u_v(x_2) + 2\Delta_{(T)}\bar{d}(x_1)\Delta_{(T)}d_v(x_2)}$$

suppose $\Delta_{(T)}u_v(x \to 1) \gg \Delta_{(T)}d_v(x \to 1)$

$$R_{pd}(x_F \to -1) = \frac{1}{2}\left[1 + \frac{\Delta_{(T)}\bar{d}(x_1)}{4\,\Delta_{(T)}\bar{u}(x_1)}\right]_{x_1 \to 0}$$

$$\Delta_{(T)}\bar{u} = \Delta_{(T)}\bar{d} \;\Rightarrow\; R_{pd}(x_F \to -1) = \frac{5}{8} = 0.625$$

if $\Delta_{(T)}\bar{u}$, $\Delta_{(T)}\bar{d} < 0$ $\quad |\Delta_{(T)}\bar{u}| < |\Delta_{(T)}\bar{d}| \Rightarrow R_{pd}(x_F \to -1) > 0.625$

$\quad |\Delta_{(T)}\bar{u}| > |\Delta_{(T)}\bar{d}| \Rightarrow R_{pd}(x_F \to -1) < 0.625$

Numerical analysis

$$r_{\bar{q}} \equiv \frac{\Delta_{(T)}\bar{u}}{\Delta_{(T)}\bar{d}} = 0.7,\ 1.0,\ \text{or } 1.3 \quad \text{at } Q^2 = 1\ \text{GeV}^2$$

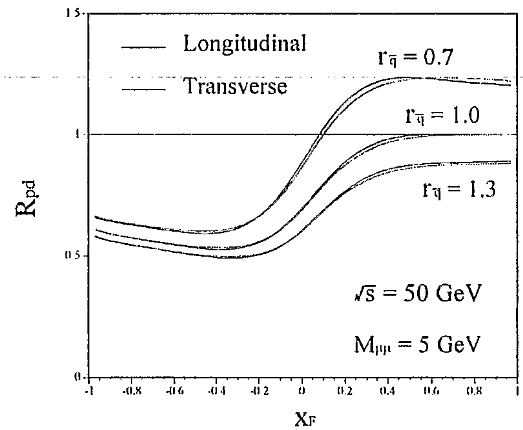
$M_{\mu\mu} = 5$ GeV, $\sqrt{s} = 50$ GeV

parton distributions: LSS–99 at $Q^2 = 1$ GeV^2

$Q^2 = 1$ GeV^2 evolution $\Rightarrow$ $Q^2 = M_{\mu\mu}^2$

$$\Rightarrow\; R_{pd} \equiv \frac{\Delta_{(T)}\sigma^{pd}}{2\,\Delta_{(T)}\sigma^{pp}}$$

assume $\Delta_T q(x) = \Delta q(x)$ at $Q^2 = 1$ GeV^2

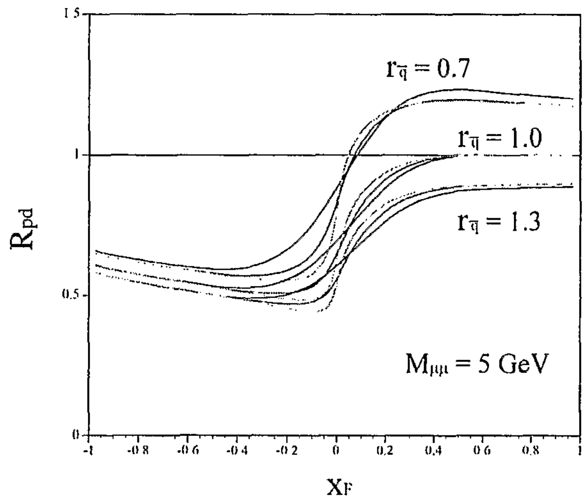


c.m. energy dependence

— $\sqrt{s}$ = 50 GeV

— 200 GeV

500 GeV



Summary

- NLO analysis of $\Delta_T q$ is now possible
- Δq and $\Delta_T q$ evolution results are very different

  → Q^2 evolution of transversity distributions is important for testing pQCD in spin physics.

- Q^2 evolution produces $\Delta_T \bar{u} \neq \Delta_T \bar{d}$

  → need to investigte $\Delta_T \bar{u} - \Delta_T \bar{d}$ with nonperturbative models

  → pd Drell–Yan for $\Delta_T \bar{u} - \Delta_T \bar{d}$?

Drell-Yan Muon Pair Production @ RHIC[1]

Marco Stratmann

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The framework for analyzing the rapidity dependence of the transverse double spin asymmetry A_{TT} for the Drell-Yan process in NLO of QCD is briefly presented. It is discussed how one can make use of NLO results available in the literature obtained within an 'off-shell' regularization method [W. Vogelsang and A. Weber, Phys. Rev. **D48** (1993) 2073] by transforming them to the commonly used $\overline{\mathrm{MS}}$ scheme in which also the NLO splitting functions have been calculated recently. Only by combining NLO parton densities and partonic cross sections in the *same* scheme one obtains physical cross sections (and asymmetries) independent of details of the regularization procedure used in the NLO calculation.

For our numerical estimates LO and NLO input transversity distributions are obtained by saturating Soffer's inequality at a low bound-state like scale $Q_0 \simeq 0.6\,\mathrm{GeV}$ using the unpolarized (helicity) densities by GRV (GRSV). The chosen input numerically preserves Soffer's inequality under Q^2 evolution in NLO in the $\overline{\mathrm{MS}}$ scheme which, however, cannot be demonstrated in general as constraints on the parton level are obscured by their scheme dependence.

Results are presented both for the rapidity dependent as well as integrated spin asymmetries A_{TT} at $\sqrt{S} = 200$ and $500\,\mathrm{GeV}$. Since it is essential that *both* muons are detected experimentally the influence of the limited muon acceptance of the PHENIX detector, $1.2 \leq |y_{\mu^\pm}| \leq 2.4$, on measurements of A_{TT}, i.e., on the achievable statistical accuracy, is discussed in some detail. In particular, it turns out to be difficult, if not impossible, to measure the rapidity dependence of A_{TT} which in principle would be expected to be sensitive to the shape of $\delta q \cdot \delta \bar{q}$. The prospects for the rapidity integrated A_{TT} are somewhat better for not too large values of the dimuon mass M.

Finally, it should be kept in mind that our estimates represent some *upper* bound on A_{TT} within our framework and that A_{TT} would be reduced by a factor of four if Soffer's inequality turns out to be saturated only by 50% rather than fully. On the other hand, it may turn out that saturation takes place at a somewhat higher scale than the one chosen for our analyses which can, e.g., for an input at $Q_0 = 1.0\,\mathrm{GeV}$, lead to values of A_{TT} twice as large as the ones presented here. Therefore A_{TT} in Drell-Yan still seems to be a channel worthwhile to look at to pin down the transversity densities at RHIC.

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[1]work done in collaboration with O. Martin, A. Schäfer, and W. Vogelsang
references: Phys. Rev. **D57** (1998) 3084; Phys. Rev. **D60** (1999) 117502

Drell-Yan Muon Pair Production @ RHIC

Marco Stratmann
(Regensburg)

- **Drell-Yan process up to NLO QCD**
- **Numerical analysis**:
  - model for transversity densities δq
  - detector angular acceptance (PHENIX)
  - transverse double-spin asymmetries
- **Conclusions**

together with O. Martin, A. Schäfer, W. Vogelsang
[Phys. Rev. *D57* (1998) 3084; *D60* (1999) 117502]

• Drell-Yan process up to NLO QCD

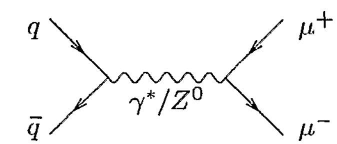
general problem: $\nexists$ 'transversity' gluons

$\rightsquigarrow$ all asymmetries $A_{TT} = d\delta\sigma/d\sigma$ strongly diluted by gluon induced processes in $d\sigma$

$\rightsquigarrow$ need process *w/o* gluon contribution in LO

best candidate: Drell-Yan process Ralston, Soper; Ji
Cortes, Pire, Ralston; Artru, Mokhfi; Ji; Jaffe

chirality flip ✓
M: dimuon mass
y: dimuon rapidity
ϕ: azimuth [$\phi = 0 \leftrightarrow \uparrow$ spin dir.]



$$\frac{d\delta\sigma}{dM\,dy\,d\phi} = \underbrace{\sum_q e_q^2}_{\uparrow} \int dx_1 dx_2 \left[\delta q(x_1,\mu_f^2)\delta\bar{q}(x_2,\mu_f^2) + (1 \leftrightarrow 2)\right] \frac{d\delta\hat{\sigma}}{dM\,dy\,d\phi}$$

electroweak effects
$e_q^2 + e_q G_F \ldots + G_F^2 \ldots$
$\gamma \quad \gamma Z^0 \quad Z^0$

defined as
$(d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow})/2$

'problem': non-trivial ϕ dependence of $d\delta\hat{\sigma}$

$d\delta\hat{\sigma} \simeq \cos(2\phi) \rightsquigarrow \int_0^{2\pi} d\phi\, d\delta\hat{\sigma} = 0$

$\rightsquigarrow$ define $\left(\int_{-\pi/4}^{\pi/4} - \int_{\pi/4}^{3\pi/4} + \int_{3\pi/4}^{5\pi/4} - \int_{5\pi/4}^{7\pi/4}\right) d\phi$

Cortes, Pire, Ralston

In LO:

$$\frac{d\delta\hat{\sigma}^{(0)}}{dM\,dy\,d\phi} = \frac{2\alpha_{em}^2}{9SM}\cos(2\phi)\,\delta(x_1 - \underbrace{x_1^{\min}}_{\sqrt{\tau}e^{y}})\,\delta(x_2 - \underbrace{x_2^{\min}}_{\sqrt{\tau}e^{-y}})$$

where $\tau \equiv M^2/S$

$\leadsto$ best suited observable: $A_{TT}(M, y)$

y dependence of A_{TT} $\leftrightarrow$ scan of $\delta q(x_1)\delta\bar{q}(x_2)$

$\leftrightarrow$ *shape* of δq

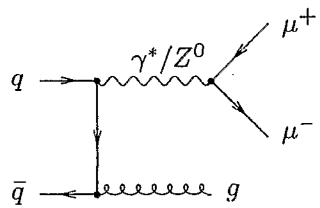
[y integrated $A_{TT}(M)$ 'only' probes very existence of δq]

Why NLO?

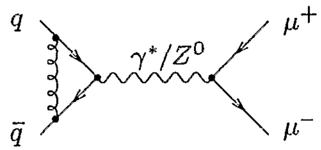
- $\triangleright$ Drell-Yan known for sizable K-factor
- $\triangleright$ reduced dependence on unphysical scales μ_f, μ_r
- $\triangleright$ non-vanishing p_T of muon pair

To do:

real corrections:
[unpol.: also $qg \to q\mu^+\mu^-$]



virtual corrections:



Technical complication:

have to keep azimuthal angle ϕ *un*integrated
[cumbersome when using n *dimensional regularization*]

$\leadsto$ 1st calculation done with *gluon mass* as regulator
Vogelsang, Weber

available NLO results:

$$\frac{d\delta\hat{\sigma}}{dM\,d\phi} \qquad \frac{d\delta\hat{\sigma}}{dM\,dy\,d\phi} \qquad \frac{d\delta\hat{\sigma}}{dM\,dp_T\,d\phi}$$

$\uparrow$
pheno. less relevant:
LO $q\bar{q} \to \mu^+\mu^-$ does not
contribute ($p_T = 0$)

but NLO splitting functions δP_{qq} are in $\overline{\text{MS}}$
Vogelsang; Koike et al.; Kumano, Miyama

$\leadsto$ scheme *independence* requires $d\delta\hat{\sigma}$ in $\overline{\text{MS}}$

Transformation off-shell $\to$ $\overline{\text{MS}}$ scheme:

everything can be deduced from

$$(\delta)C_{q\bar{q},\overline{\text{MS}}} - (\delta)C_{q\bar{q},\text{off-shell}}$$

i.e. 'total DY' $d(\delta)\hat{\sigma}/dM\,d\phi$ for the *unpolarized* case
[$C_{q\bar{q},\overline{\text{MS}}}$: Altarelli et al.; Furmanski et al.; $C_{q\bar{q},\text{off-shell}}$: Kubar et al.]

$\leadsto$ $\overline{\text{MS}}$ results for $d\delta\hat{\sigma}$ $\quad\checkmark$

[2nd calc. of $d\delta\hat{\sigma}$ uses *dimensional reduction* — Contogouris et al.
results agree after transformation to $\overline{\text{MS}}$ — Kamal; Vogelsang]

- <u>Numerical analysis</u>

Modeling transversity densities δq

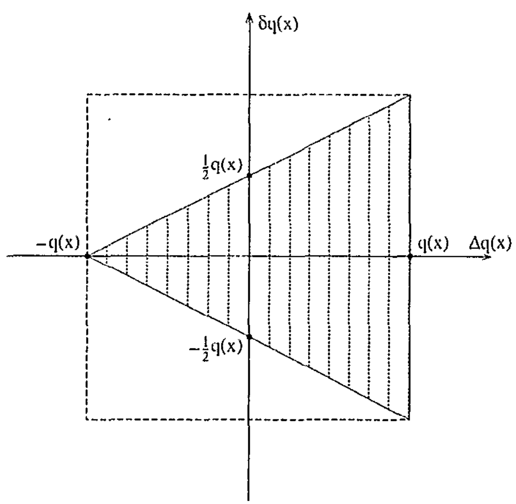
δq unmeasured $\rightsquigarrow$ have to rely on theoretical prejudices

helpful constraint: Soffer inequality

$$\underbrace{\left|\delta q(x,\mu^2)\right|}_{\text{unknown}} \;\le\; \frac{1}{2}\left[\underbrace{q(x,\mu^2) + \Delta q(x,\mu^2)}_{\text{known (more or less)}}\right]$$

$\rightsquigarrow$ upper bounds for δq and spin asymmetries A_{TT}

Soffer's inequality is *more restrictive* than $|\delta q| \;\le\; q$:



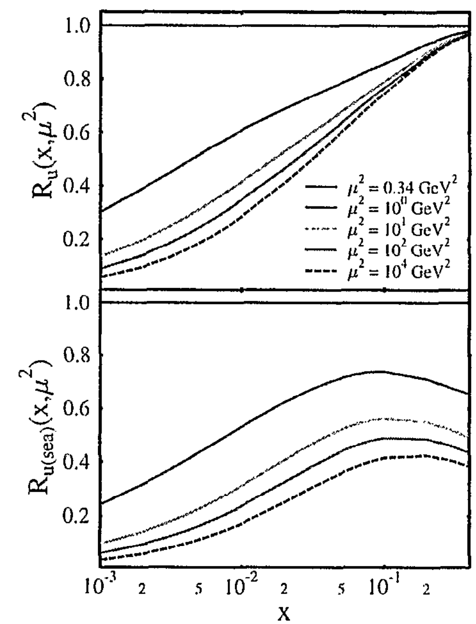
$\rightsquigarrow$ frequently used models based on $\delta q = \Delta q$ at some initial scale $\mu = Q_0$ Scopetta, Vento; Miyama; ...
violate bound if $\Delta q \le -\frac{1}{3} q$

$\rightsquigarrow$ for our estimates of A_{TT} we *saturate* Soffer's ineq. at $Q_0 \simeq 0.6\,\text{GeV}$ using GRV (q) and GRSV (Δq)

Is Soffer's inequality valid *beyond* the leading order?

PDF's are scheme-dependent ($\leftrightarrow$ unphysical) in NLO
$\rightsquigarrow$ constraints on parton level are *not* relevant anymore
[similarly: 'positivity' at work for $|\Delta\sigma| \le \sigma$ *not* $|\Delta f| \le f$]

However, in $\overline{\text{MS}}$ it *usually* works out ...



[remark: *analytical* proof of the inequality in NLO ($\overline{\text{MS}}$) by Bourrely et al. is flawed: $|\Delta P_{ij}| \le P_{ij}$ not fulfilled in $\overline{\text{MS}}$ for $q \to g$
$\rightsquigarrow$ $|\Delta f| \not\le f$ under certain conditions]

Detector angular acceptance for PHENIX

Motivation: theoretical predictions can be misleading if detector effects are not included

Example: Drell-Yan muon pairs @ PHENIX
have to detect *both* muons to get mass M
but only endcaps detect muons: $1.2 \leq |y_{\mu^\pm}| \leq 2.4$

$\rightsquigarrow$ try to include muon acceptance in A_{TT} estimates:
take *fully* differential $d(\delta)\sigma$ [only available in LO so far]
and define acceptance as

$$(\delta)\varepsilon(M,y) \equiv \frac{\int_{\text{detector PS}} dp_T^1 d\phi^1 \; d(\delta)\sigma/dM\,dy\,dp_T^1 d\phi^1}{\int_{\text{full PS}} dp_T^1 d\phi^1 \; d(\delta)\sigma/dM\,dy\,dp_T^1 d\phi^1}$$

important feature: $\delta\varepsilon \neq \varepsilon$

$\rightsquigarrow$ 'distorted' asymmetries: $A_{TT}^{\text{exp}} > A_{TT}$ for $\delta\varepsilon > \varepsilon$ and vice versa

Estimates of statistical errors for A_{TT}:

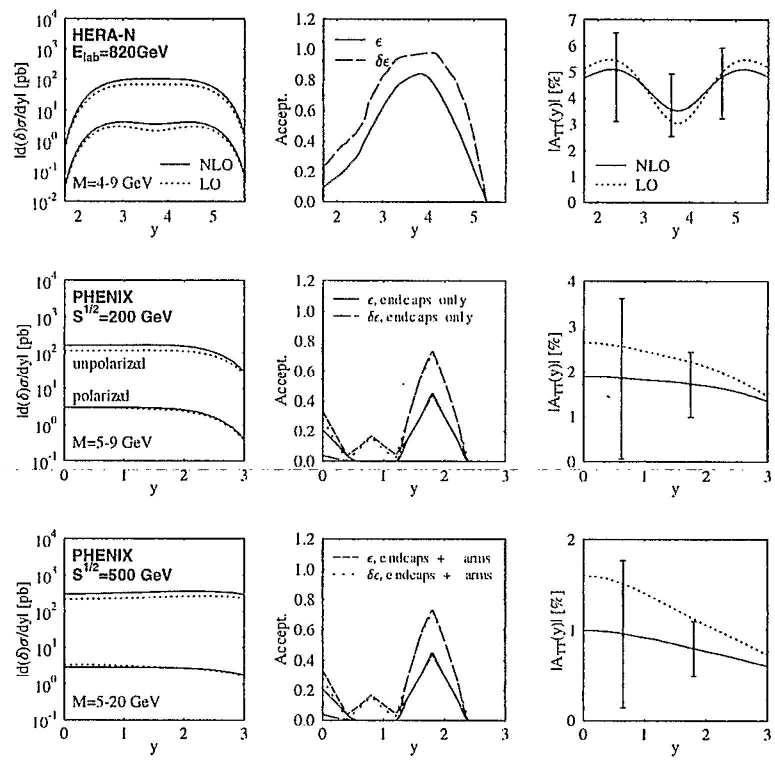
$$\text{stat. error} \simeq \frac{1}{P_A P_B \sqrt{\mathcal{L} \int \varepsilon \; d\sigma}}$$

plus rescaling by $A_{TT}/A_{TT}^{\text{exp}}$

use: $P_A = P_B = 0.7$; $|p_\mu| > 2\,\text{GeV}$ (get rid of background) ;
$\mathcal{L} = 320\ (800)\,\text{pb}^{-1}$ for $\sqrt{S} = 200\ (500)\,\text{GeV}$

Some estimates for A_{TT}

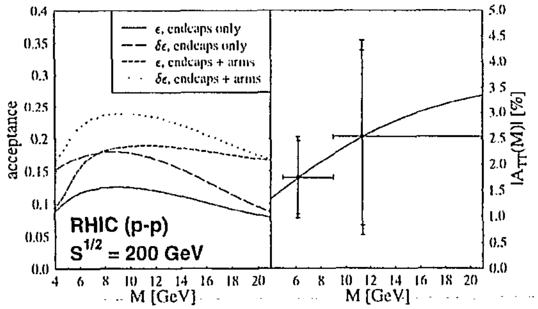
(I) M integrated $\int_{M_1}^{M_2} dM$; differential in y

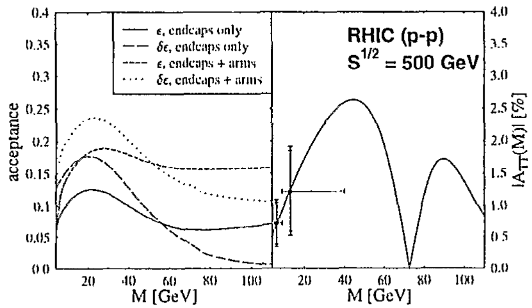


extra 'feature': hypothetical muon arms $|y_{\mu^\pm}| \leq 0.35$
'error bars' for low y bin *with* arms only

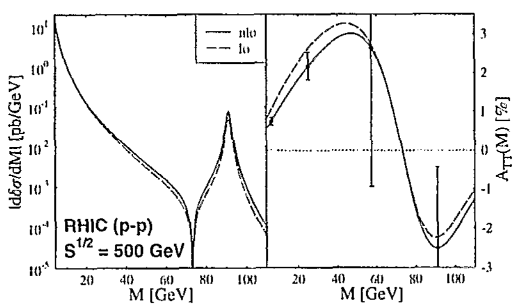
HERA-N: possible future *fixed target* exp. at HERA
'errors' for $\mathcal{L} = 240\,\text{pb}^{-1}$ Korotkov, Nowak

(II) rapidity y integrated; differential in dimuon mass M





... and for a perfect 4π-detector:



- Conclusions

▷ limited muon acceptance threatens to make a measurement of A_{TT} elusive at PHENIX in particular for $A_{TT}(y, M) \leftrightarrow$ *shape* of δq

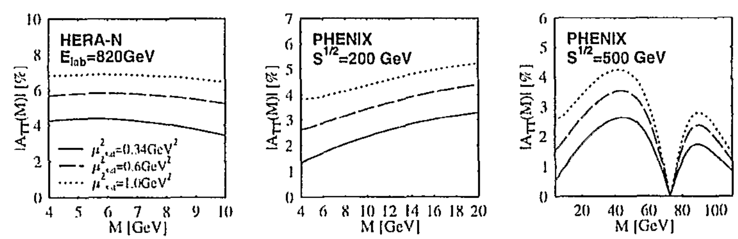
▷ $A_{TT}(M)$ still promising $\leftrightarrow$ proves very existence of δq

BUT one should keep in mind that our estimates are upper bounds for A_{TT}, i.e., most optimistic:

▷ if Soffer's inequality is only 50% saturated all A_{TT}'s would be *down* by a factor of four

On the other hand, if saturation takes place at a *higher* scale Q_0 than assumed, all A_{TT}'s would be *up*

▷ for example $A_{TT}(M)$ with $Q_0^2 = 0.34, 0.6, 1\,\text{GeV}^2$:



Jet Production with Transversely Polarized Proton Beams[†]

W. Vogelsang

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The currently most promising methods of measuring transversity at RHIC suffer either from low event rates (Drell-Yan dimuon production; see talk by M. Stratmann), or from the fact that they involve a presently unknown fragmentation function sensitive to transverse polarization, such as the Collins or the interference fragmentation functions. In this talk, we therefore reinvestigate the possibilities that arise in studies of jet (or, leading hadron) production with transversely polarized proton beams at RHIC. It should be mentioned right away that, also here, there is an immediate drawback: as is well-known, there is no transversity gluon distribution, so reactions like jet production, that proceed to a substantial part through participation of gluon partons in the unpolarized case, are bound to have small transverse double-spin asymmetries [1, 2]. In addition, it turns out that the transversely polarized subprocess asymmetry for the $qq \to qq$ reaction, relevant for jet production, is color-suppressed as $1/N_c$ [1, 2], whereas the channel $q\bar{q} \to q\bar{q}$ involves antiquarks in the initial state, and is thus likely to give a small contribution for pp collisions. On the other hand, jets (or leading hadrons) are produced very copiously at RHIC, resulting in small expected statistical errors on the spin asymmetries, and it is interesting to see whether the spin asymmetry might be large enough to be visible in experiment.

In this talk we consider two "jet" reactions as examples. The first one is the production of pion pairs. Here it is interesting to consider certain combination of cross sections, in particular [3],

$$\sigma^{\pi^+\pi^+} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+} + \sigma^{\pi^-\pi^-} \,,$$

for which at lowest order all reactions with gluons in the final state and, hence, for the unpolarized case the reactions $qg \to qg$ and $gg \to gg$, are eliminated. In this way, one might hope to circumvent the problem of suppression of the spin asymmetry due to gluonic contributions in its denominator. Indeed, the resulting 'double' asymmetry,

$$\tilde{A}_{TT} \equiv \frac{\Delta_T\sigma^{\pi^+\pi^+} - \Delta_T\sigma^{\pi^+\pi^-} - \Delta_T\sigma^{\pi^-\pi^+} + \Delta_T\sigma^{\pi^-\pi^-}}{\sigma^{\pi^+\pi^+} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+} + \sigma^{\pi^-\pi^-}} \,,$$

turns out to be sizable, becoming as large as $\sim 10\%$ in certain regions of transverse momenta of the pions. However, the analysis of the statistical error to be expected for $\tilde{A}_{TT}$ reveals that it will be impossible to use this quantity for measurements of transversity at RHIC. One finds that the statistical error is not only, as usually the case, proportional to the inverse of the square root of the counting rate,

$$\delta(\tilde{A}_{TT}) \propto \left(\sigma^{\pi^+\pi^+} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+} + \sigma^{\pi^-\pi^-}\right)^{-1/2} \,,$$

but rather to

$$\delta(\tilde{A}_{TT}) \propto \left(\sigma^{\pi^+\pi^+} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+} + \sigma^{\pi^-\pi^-}\right)^{-1/2} \sqrt{\frac{\sigma^{\pi^+\pi^+} + \sigma^{\pi^+\pi^-} + \sigma^{\pi^-\pi^+} + \sigma^{\pi^-\pi^-}}{\sigma^{\pi^+\pi^+} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+} + \sigma^{\pi^-\pi^-}}} \,.$$

The additional factor is obviously very large and renders $\delta(\tilde{A}_{TT})$ much bigger than $\tilde{A}_{TT}$ itself.

Another channel we consider is single-inclusive jet production. Here of course all subprocesses with initial-state gluons contribute in the unpolarized cross section, so we expect small transverse-spin asymmetries. On the other hand, jets will be produced at RHIC at very large rates, and experience from the unpolarized case, where the comparison between theory and data works extremely well, indicate that we have a very good understanding of jet physics. For our numerical estimates of the transverse-spin asymmetry we model the transversity densities by following [4] to assume saturation of Soffer's inequality [5] at the low input scale of the 'radiative parton model' [6, 7]. We find that the asymmetry A_{TT} for single-inclusive jet production at RHIC is indeed small, of the order $5 \cdot 10^{-4}$ to $3 \cdot 10^{-3}$. On the other hand, the expected statistical errors on A_{TT} are considerably smaller and indicate that a measurement of transversity in this channel should be successful, provided the systematic uncertainties can be reduced to a level similar to the statistical ones. It turns out that, for our model transversity densities, the asymmetry is mainly driven by the $q\bar{q}$ annihilation reaction for $p_T^{\rm jet} < 40$ GeV, and by qq scattering for larger jet transverse momenta. Results for A_{TT} in jet production were also presented in [2].

[†]Work done in collaboration with D. de Florian and M. Stratmann.

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Jet Production with Transversely Polarized Proton Beams

Werner Vogelsang

RIKEN-BNL Research Center

BNL, 18 September 2000

(with D. de Florian and M. Stratmann)

Motivation :

- most promising reactions sensitive to transversity involve unknown fragmentation functions; measure products like

  $$" \delta q \otimes \tilde{D} "$$

  (and, even worse, combinations thereof)

- trouble is that 'standard pdf processes' (say, in pp) all have problems :
  - Drell-Yan : low rates, $\delta \bar{q}$ small ?
  - dir. photons, jets, inclusive hadrons,... : gluonic contrib. in unpol. case $\longrightarrow A_{TT}$ small (see : Artru & Mekhfi; Ji; Jaffe & Saito; earlier talks today)

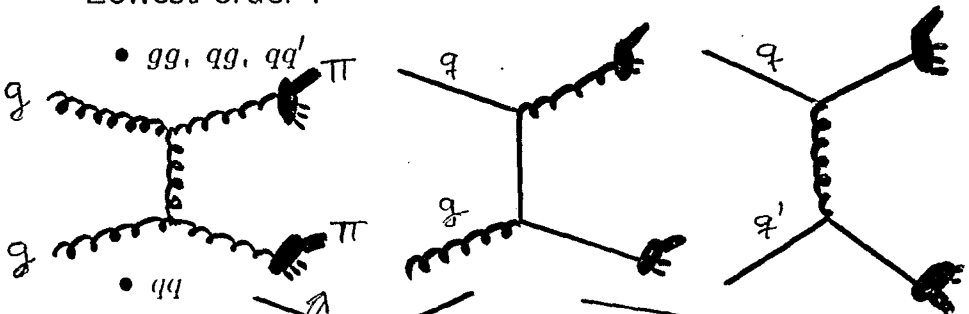
- On the other hand, some of these reactions have enormous rates at RHIC
  - makes measurement of even small A_{TT} possible, as far as statistics is concerned
  - might allow to pick regions where qg and gg channels are less dominant

- consider here two channels:
  pairs of high-p_T pions   single jets

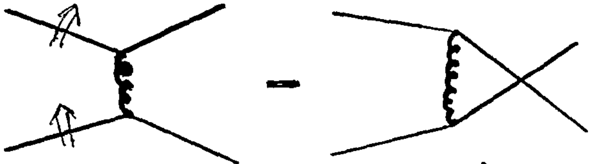
High-p_T pions, $pp \to \pi(p_T)\pi(p_T{}')X$

Lowest order :

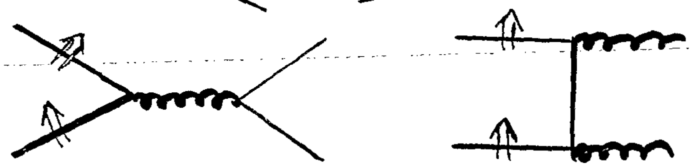
- gg, qg, qq'



- qq



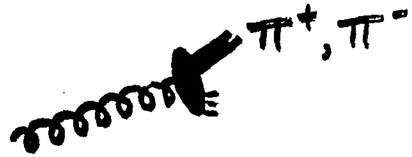
- $q\bar{q}$



problems : (Artru,Mekhfi; Ji; Jaffe,Saito)

- only $q\bar{q}$, and interference of qq graphs, contribute for transversity
- for qq, interference is suppressed by $1/N_C$
- generally, transverse spin gives extra factor $\sim \sin^2\theta \cos(2\varphi)$

Old idea : (Fontannaz,Mantrach,Pire,Schiff)

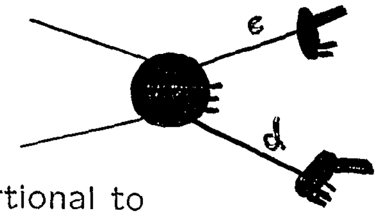


$$D_g^{\pi^+} = D_g^{\pi^-}$$

therefore, consider

$$\sigma^{\pi^+\pi^+} + \sigma^{\pi^-\pi^-} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+}$$

(with pions in opposite azimuthal hemispheres)



is proportional to

$$\ldots \otimes \left(D_c^{\pi^+} - D_c^{\pi^-}\right) \otimes \left(D_d^{\pi^+} - D_d^{\pi^-}\right)$$

$\longrightarrow$ eliminates qg and $gg \to gg$ (not $gg \to q\bar{q}$)

'Double asymmetry'

$$A_{TT} \equiv \frac{\Delta_T\sigma^{\pi^+\pi^+} + \Delta_T\sigma^{\pi^-\pi^-} - \Delta_T\sigma^{\pi^+\pi^-} - \Delta_T\sigma^{\pi^-\pi^+}}{\sigma^{\pi^+\pi^+} + \sigma^{\pi^-\pi^-} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+}}$$

indeed sizable. However, statistical error

$$\delta(A_{TT}) \propto \sqrt{\frac{\sigma^{\pi^+\pi^+} + \sigma^{\pi^-\pi^-} + \sigma^{\pi^+\pi^-} + \sigma^{\pi^-\pi^+}}{\left(\sigma^{\pi^+\pi^+} + \sigma^{\pi^-\pi^-} - \sigma^{\pi^+\pi^-} - \sigma^{\pi^-\pi^+}\right)^2}}$$

Jet Production

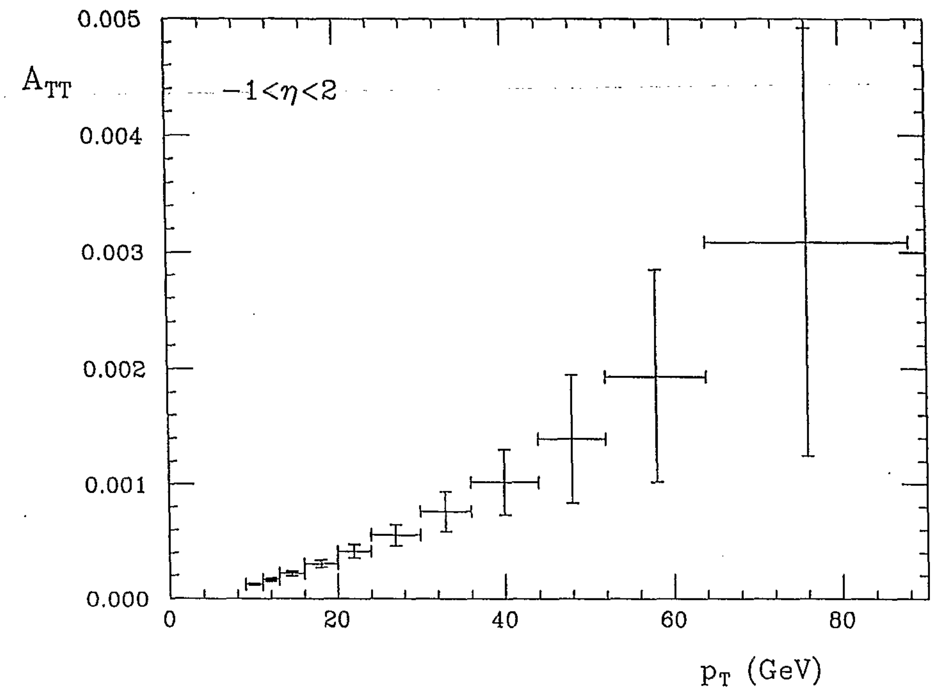
(see also Jaffe & Saito)

- expect small asymmetries
- extremely good statistical accuracy at $\sqrt{s} = 500$ GeV (recall, $A_{LL} \longrightarrow \Delta g$!)
- have very good understanding of jet physics (cf. Tevatron jet data) (better than fragmentation fcts.)

This study :

- δq, $\delta \bar{q}$ through saturation of Soffer's inequality at $\mu_{\text{GRV}} \approx 0.6$ GeV (cf. Stratmann's talk)
  - admittedly, somewhat optimistic
  - could have saturation at higher scale !
  - Jaffe & Saito use $\delta q(x, Q^2) = \Delta q(x, Q^2)$
- unpolarized pdfs : GRV (94)
- lowest order only; fact./ren. scales $\mu = p_T^{\text{jet}}$
- $\sqrt{s} = 500$ GeV, $\mathcal{L} = 800$ pb^{-1}

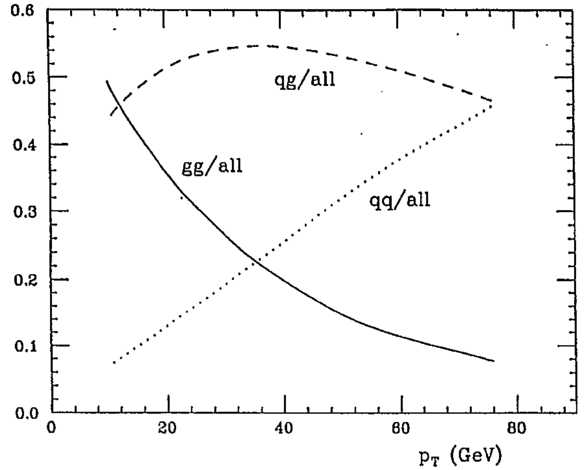
A_{TT} in single-inclusive jet production :

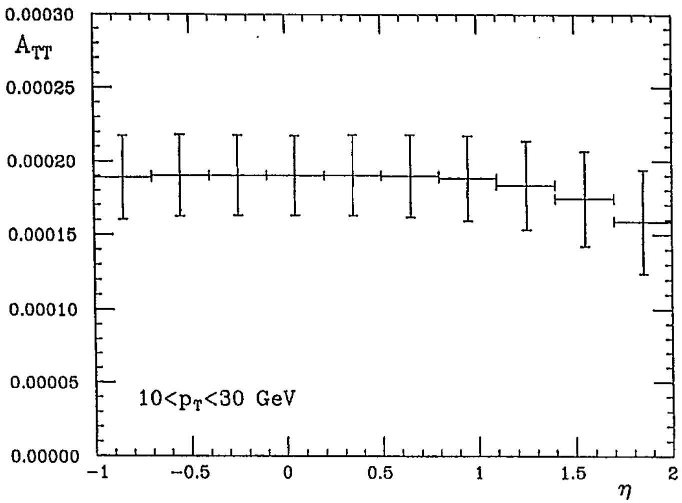


Relative importance of subprocesses :

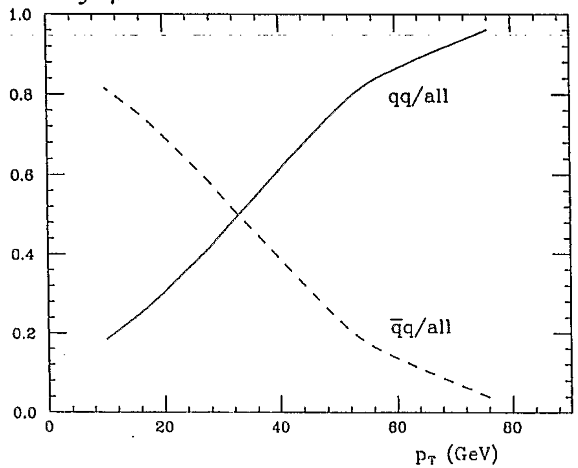
Rapidity dependence in two p_T bins :

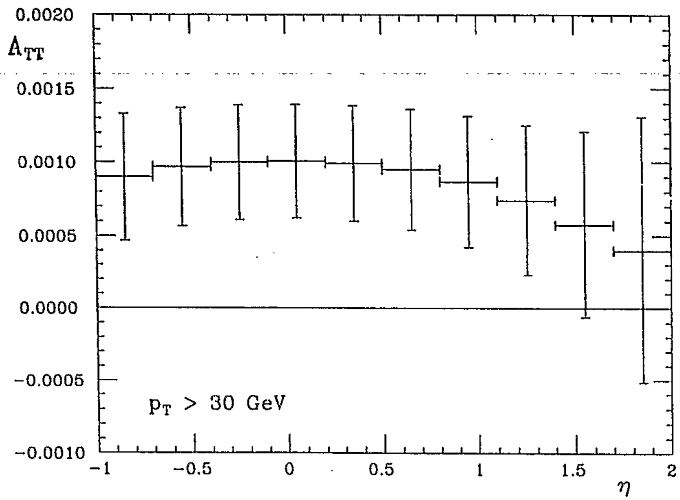
unpolarized :



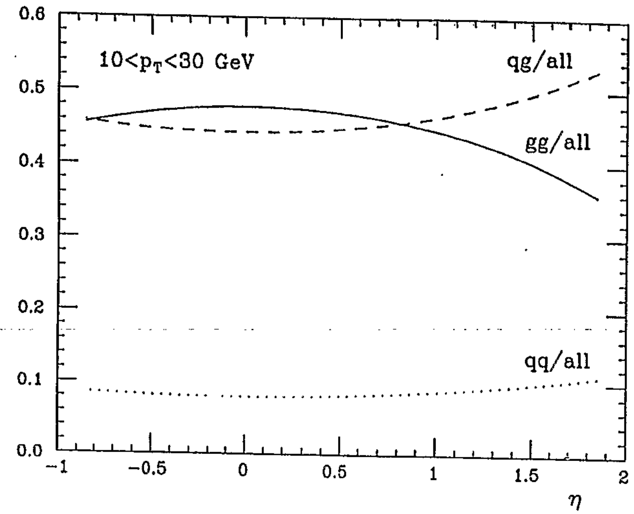


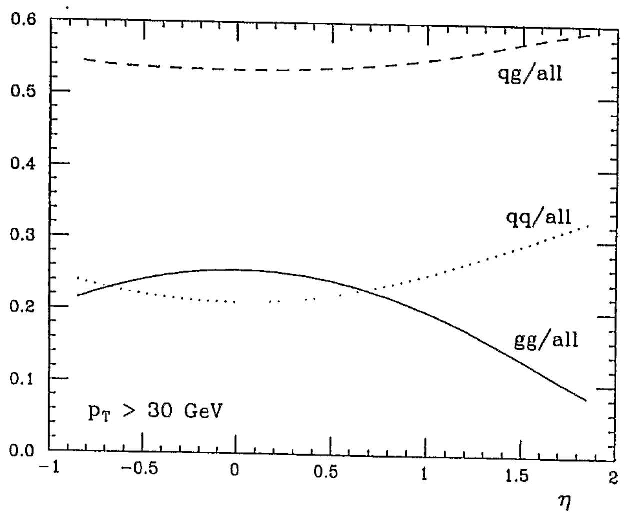
transversely polarized :





Relative importance of subprocesses vs. η :

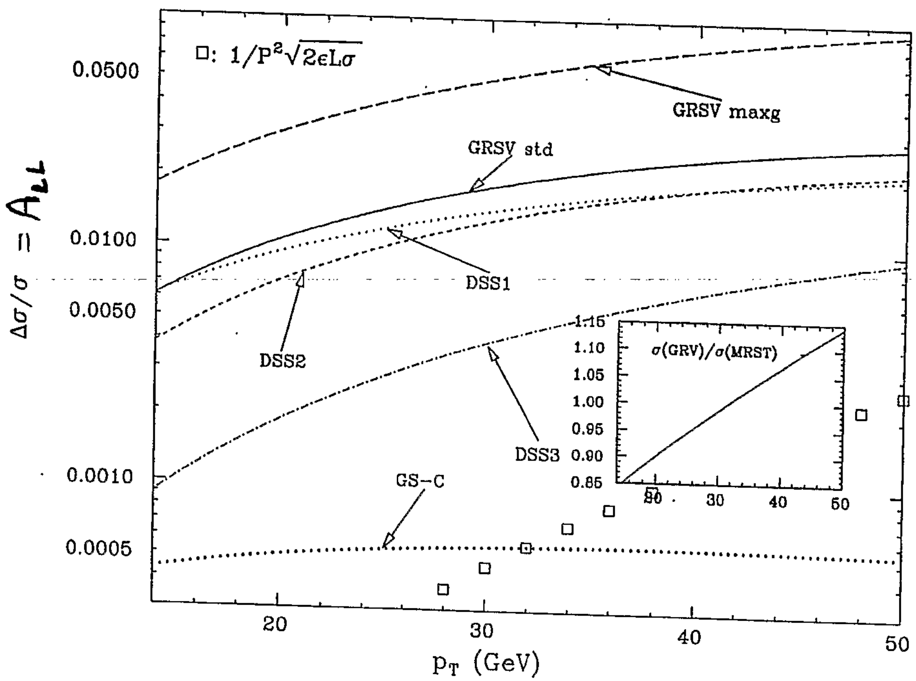




Conclusions

- not all is lost for measuring transversity at RHIC through 'standard processes' !
- jets :
  - small A_{TT}
  - high statistical power
  - theory :
    study scale dependence,
    calculate NLO corrections, ...

A_{LL} in single-inclusive jet production :



Results on Azimuthal Asymmetries from DIS Experiments

H.Avakian **
INFN-LNF/YerPhI
For HERMES Collaboration

Abstract

First measurements of single-spin asymmetries (SSA) in azimuthal distributions in $\ell p \to \ell' \pi X$ processes, with unpolarized leptons and polarized protons, were recently reported by HERMES [1] and by SMC [2] collaborations.

Significant x and $P_\perp$ dependences of $\sin\phi$ moment in the cross section ($A_{UL}^{sin\phi}$) are observed at HERMES for π^+ and π^0 production on a longitudinally polarized hydrogen target.

Single-spin asymmetries in azimuthal distributions of hadrons in polarized deep inelastic scattering are also measured in the wide range of γ^* momentum fraction carried by the final hadron.

In the transition region from semi-inclusive to semi-exclusive processes these asymmetries are found to be significant and have different behavior for neutral and charged pions.

Issues discussed in this contribution include:

- Extraction of $\sin\phi$ moment of SIDIS cross section as a function of different kinematic variables
- Detector related background (acceptance, efficiencies)
- Physics related background (semi-exclusive asymmetries and $\sin 2\phi$ moments).
- Outlook

References

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** **Talk presented by W.-D. Nowak DESY, Zeuthen**

Results on Azimuthal Asymmetries from DIS Experiments

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- Introduction
- Single-Spin Asymmetries
  - ▷ semi-incl $\pi \Rightarrow$ New polarised DF and FF
  - ▷ π^0 versus $\pi^\pm$
  - ▷ exclusive limit
- Summary-outlook

* Talk presented by W.-D. Nowak, DESY Zeuthen

Single Spin Asymmetries

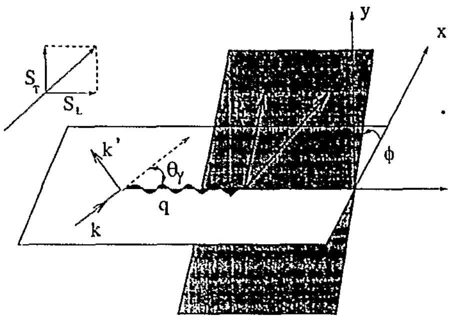
- Double Spin Asymmetries:
  Polarized Beam and Target.
- Single Spin Asymmetry (SSA)
  Polarized Beam or Target.
  - ▷ transverse quark polarization densities
  - ▷ fragmentation of polarized quarks
  - ▷ intrinsic transverse momentum of quarks
  - ▷ GPDF (SPDF, OFPDF..).
  - ▷ higher Twists

Accessible through measurements of

- Azimuthal distributions of hadrons and photons in semi-inclusive and semi-exclusive DIS.

Semi-Inclusive DIS

$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \hat{\sigma}^{eq\to eq} \otimes D^{q\to h},$$



Chiral odd, T-even DF

$\Downarrow$

Chiral-odd T-odd FF

$\Downarrow$

SSA

Naive parton models, non interacting collinear parton
Parity, Angular momentum, Helicity Cons. $\Rightarrow$ SSA $= 0$

SSA originates from multi-parton correlation and intrinsic quark transverse momentum k_T.

Azimuthally weighted cross Sections

$$\sigma^{eH\to ehX} = \sigma_0 + \sigma_1 \sin\phi + \sigma_2 \cos\phi + \sigma_3 \sin 2\phi + \ldots$$

$$\sigma_i = \sigma_i^{UU} + \sigma_i^{UL} + \sigma_i^{LU} + \sigma_i^{UT} + \ldots$$

Unpolarized (U), longitudinally polarized (L) and transversely polarized (T) beam/target

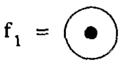
When the cross section is integrated over ϕ of hadrons the single-spin asymmetries (UL,LU,UT ...) vanish in leading order.

$$A_{UL}^{\sin\phi} \equiv \sigma_1^{UL}/\sigma_0 \equiv 2\langle \sin\phi \rangle_{UL}$$

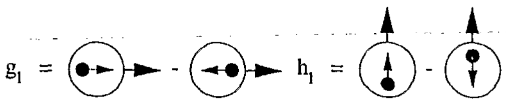
defines the $\sin\phi$ term in the cross section for unpolarized beam and longitudinally polarized target.

Classification of Distribution Functions

The leading twist (subscript:1) description of the nucleon involves 3 types of Distribution Function (+ others at higher level)

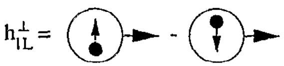


Unpolarized quark in unpolarized nucleon.



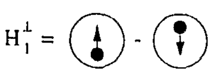
Longitudinal quark in longitudinally and transverse quark in transversely polarised nucleon.

After introduction of transverse momentum of quarks ($p_\perp$):



Transverse quark in longitudinal ~~and longitudinal quark in transversely~~ polarised nucleon.

h_1 is chiral odd $\rightarrow$ can be observed only in combination with another chiral odd structure $\rightarrow$ Collins FF.



Contributions to $\sin\phi$

$$< \sin\phi >_{UL} \quad \propto \quad S_L \frac{2(2-y)}{Q\sqrt{1-y}} \sum_{a,\bar{a}} e_a^2 x h_L^a(x) H_1^{\perp a}(z)$$

$$< \sin\phi >_{UT} \quad \propto \quad S_T(1-y) \sum_{a,\bar{a}} e_a^2 h_1^a(x) H_1^{\perp a}(z)$$

$S_T \propto \sin\theta_\gamma \approx \frac{2Mx_B}{Q}\sqrt{1-y}$,
h_L: twist-3 DF

In HERMES kinematics and with a *longitudinally* polarized target (above shown) contribution from the S_L term is expected to dominate($\sim 75\%$).

Azimuthally weighted Asymmetries

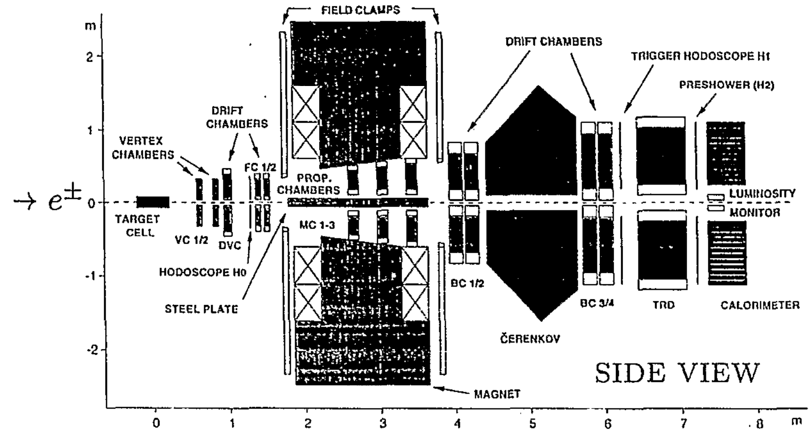
The analyzing powers for beam (target) longitudinal polarization are evaluated as

$$A^{W}_{LU(UL)} \equiv \frac{\frac{L^{\uparrow}}{L^{\uparrow}_{P}} \sum_{i=1}^{N^{\uparrow}} W(\phi_i) \; - \; \frac{L^{\downarrow}}{L^{\downarrow}_{P}} \sum_{i=1}^{N^{\downarrow}} W(\phi_i)}{\frac{1}{2}[N^{\uparrow} \; + \; N^{\downarrow}]} \qquad (1)$$

the $\uparrow$ / $\downarrow$ denotes positive/negative helicity of the lepton (target), L and L_P are luminosity and lumi weighted polarizations.

$W(\phi) = \sin\phi, \sin 2\phi, \sin 3\phi, \cos\phi, \cos 2\phi \ldots$

The HERMES Experiment at DESY



- Beam: transversely self-polarized 27.6 GeV $e^{\pm}$-beam of HERA, rotated to longitudinal spin orientation at the HERMES IP; $P_{\text{beam}} \approx 0.55 \pm 0.02$
- Target: cooled open-ended storage cell inside the beam pipe, longitudinally polarized pure (^{1}H, D, ^{3}He) gas atoms of $(7-33) \times 10^{13}$ nucleons/cm^2; $P_{\text{H}} = 0.88 \pm 0.04$, $P_{\text{D}} \approx P_{\text{H}}$, $P_{\text{He}} = 0.46 \pm 0.02$
- Tracking forward dipole magnet spectrometer with 57 chamber planes ($40\,\text{mrad} < \theta < 220\,\text{mrad}$); resolution: $\delta\theta < 0.6$ mrad. $\delta p/p < 1.5\%$
- Particle ID: threshold Cerenkov detector, TRD, preshower, lead-glass calorimeter; e/h misidentification $< 0.4\%$
- Fast Trigger scintillator hodoscopes H0 H1 H2; calorimeter energy threshold (3.5) GeV

Data selection

Table 1: The HERMES experiment

Target	hydrogen
Polarization	0.86 ± 0.05 (longitudinal)
Acceptance in θ_x	$-0.17 < \theta_x < 0.17$
Acceptance in θ_y	$0.04 < \lvert\theta_y\rvert < 0.14$
DIS cuts	$Q^2 > 1$ $W^2 > 4$ $y < 0.85$
Cuts on hadrons	$z > 0.2$
$\pi^\pm$	$4.9 < E_\pi < 14 GeV$
π^0	$E_\gamma > 1.0 GeV, \quad 0.1 < M_{\gamma\gamma} < 0.17 GeV$

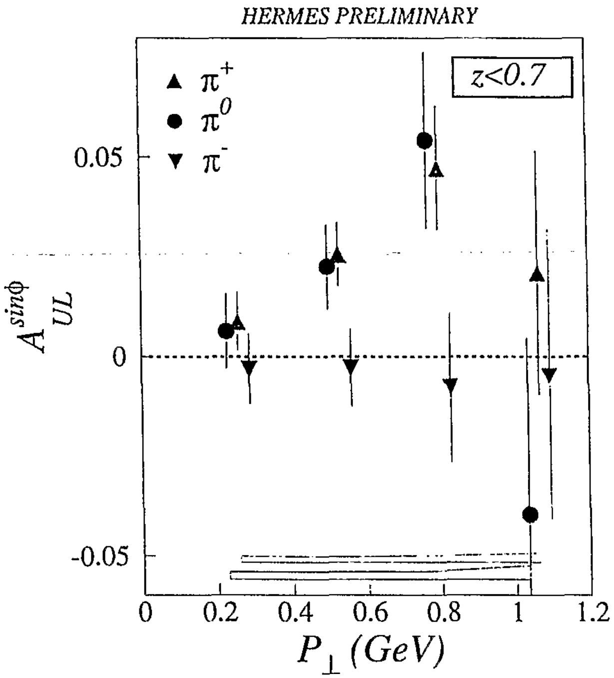
Acceptance and efficiency:

◦ θ_y cut has major influence on the acceptance

Acceptance generated $\sin\phi$ terms:

- Direct: generated $\sin\phi$ term is negligible (MC)
- Indirect: generated $\sin\phi$ (through the $\cos\phi$ term in the acceptance and $\sin 2\phi$ single spin term in the cross section) is under control.

SSA A_{UL}: $P_\perp$ dependence

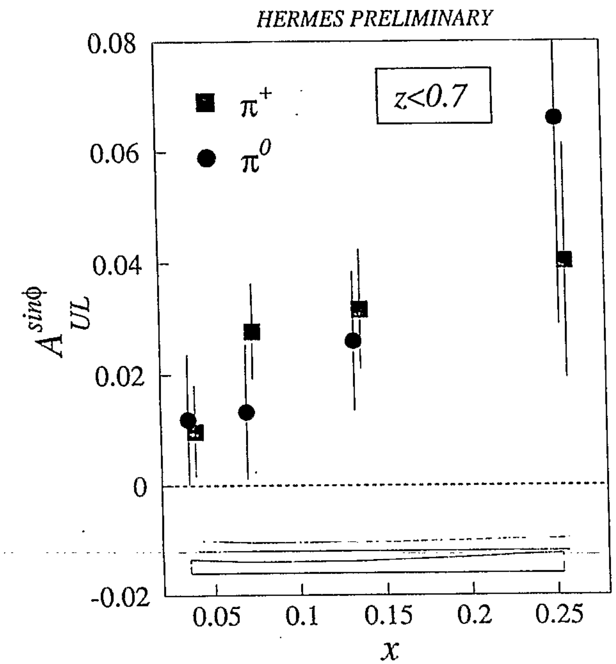


in simple model: $H_1^\perp / D_1 \propto \frac{M_c p_\perp z}{M_c^2 z^2 + p_\perp^2}$

$M_c \sim 1 GeV$, D_1 is the unpolarized fragmentation function, $H_1^\perp$ the polarized "Collins" fragmentation function.

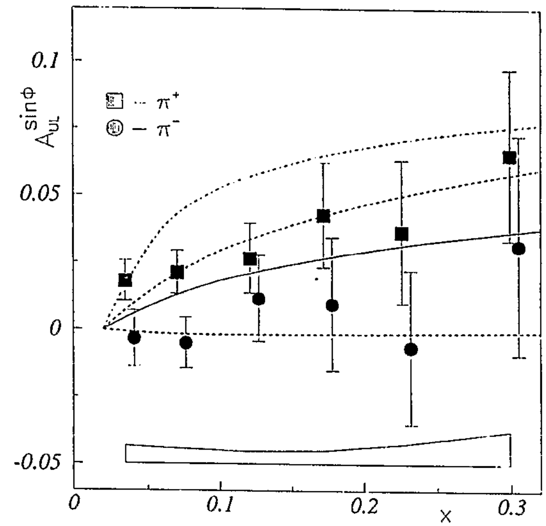
$\pi^\pm$ data published in *A. Airapetian et al. Phys. Rev. Lett. 84 (2000) 4047*

SSA $\mathcal{A}_{UL}$: x dependence



- consistent behaviour of π^+ and π^0.
- behaviour consistent with increase suggests that the sea contribution does not dominate the effect.

Comparison with theory for $\pi^{\pm}$

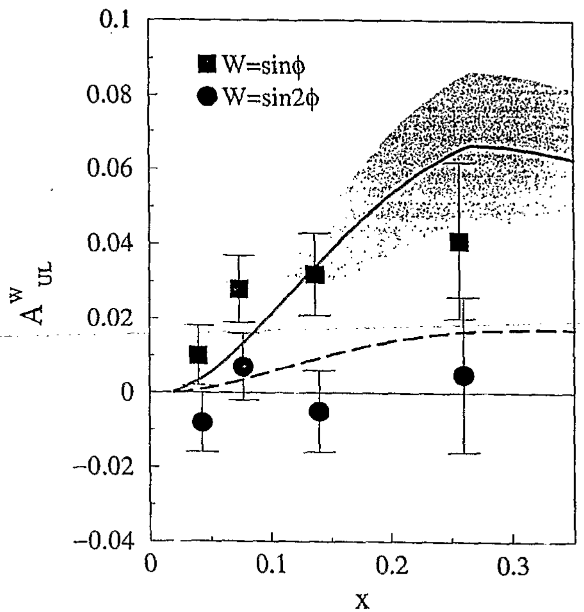


Curves (Kotzinian et al. NP A666,290 2000) correspond to different approximations for h_1 ($h_1 = 0.5(g_1 + f_1)$ for upper and $h_1 = g_1$) and $H_1^{\perp}$ ($M_c = 0.3$ for lower and $M_c = 0.7$).

$$\pi^+ \quad \mathcal{A}_{UL}^{sin\phi} \quad \propto \quad \frac{4}{9} h_L^u \mathbf{H}_1^{\perp \mathbf{u} \to \pi^+} + \frac{1}{9} h_L^d H_1^{\perp d \to \pi^+}$$

$$\pi^- \quad \mathcal{A}_{UL}^{sin\phi} \quad \propto \quad \frac{4}{9} h_L^u H_1^{\perp u \to \pi^-} + \frac{1}{9} h_L^d \mathbf{H}_1^{\perp \mathbf{d} \to \pi^-}$$

Comparison with theory: *sin2ϕ* & *sinϕ*



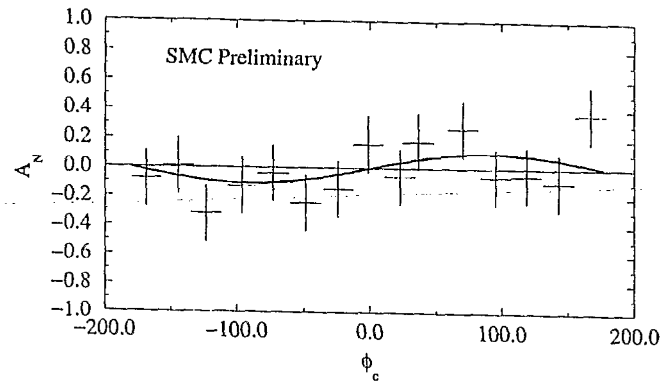
Efremov et. al hep-ph/0001119: ($H_1^\perp$ from DELPHI)

- only the favored fragmentation functions $D_1^{a/\pi}$ and $H_1^{\perp a/\pi}$
- $\langle H_1^\perp(z)/z\rangle = \langle H_1^\perp(z)\rangle/\langle z\rangle$ with $\langle z\rangle = 0.41$
- $\langle P_{h\perp}\rangle \approx \langle p_T\rangle \approx 0.4\,GeV$
- GRV parameterization for $f_1^a(x)$
- h_1 calculated in chiral soliton model

Other Experiments

SMC SSA on *transversely* polarized target

Bravar, DIS99



Best fit value from SMC data:

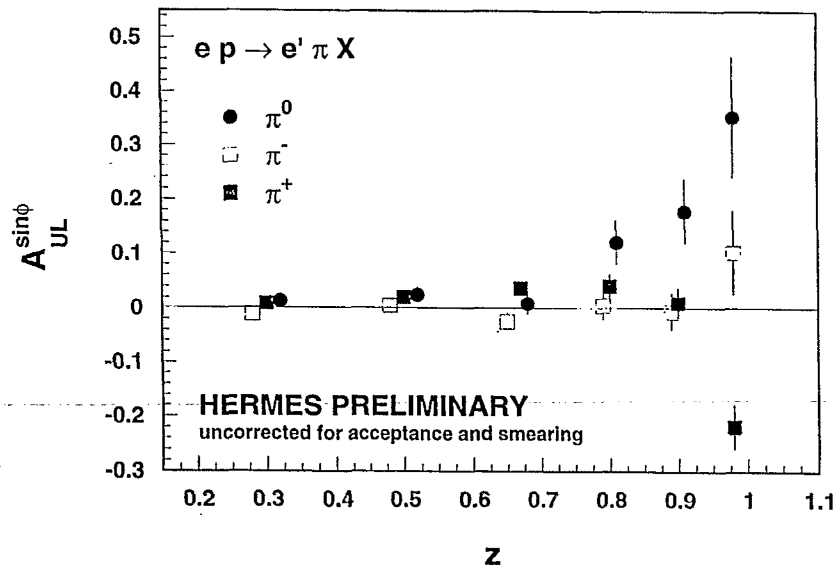
$A_N = 0.11 \pm 0.06$

is consistent with HERMES measurements on *longitudinally* polarized target and also the estimate of the analyzing power given by DELPHI (Efremov et. al)

$$\left|\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle}\right| = (0.063 \pm 0.020)$$

SSA: z-dependence

→ Large SSA in semi-exclusive and exclusive region for π^+ and π^0



→ SIDIS → "SEDIS" → GPDF

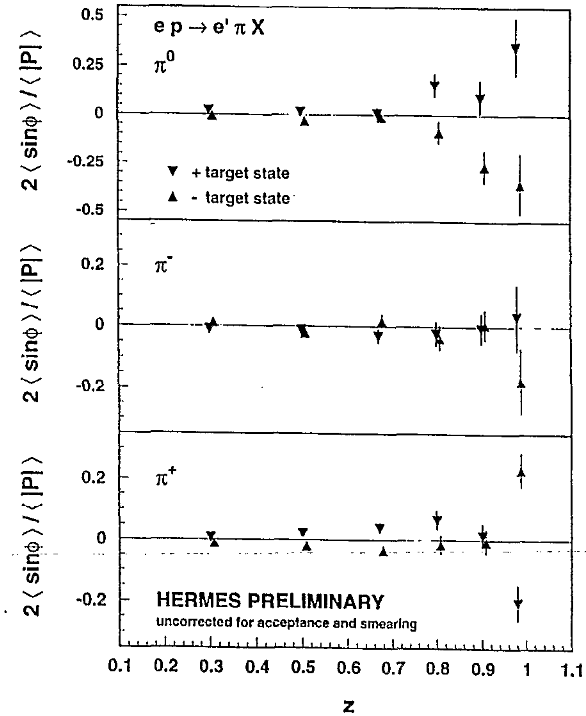
Possible sources for sign flip in π^+ SSA:

▷ HT in SIDIS (Boglione & Mulders)

▷ $A_{UT}^{\sin\phi}(\pi^+\Delta^0) \approx -0.3\, A_{UT}^{\sin\phi}(\pi^+ n)$ (Frankfurt & Co.)

Single Spin Asymmetries for pions

HERMES SSA for separate target spin states



$\sigma_1 = \sigma_1^{UU} + \sigma_1^{UL} + \sigma_1^{LU}$

∘ **significant contribution for π^+ and π^0 from σ_1^{UL}.**

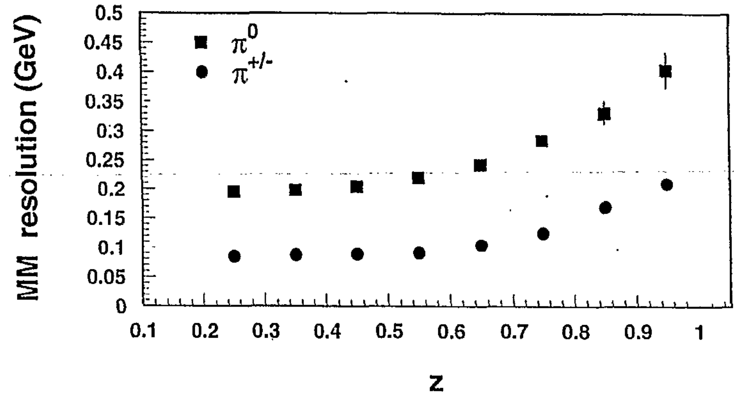
Pions in exclusive limit

Different behavior of π^0 and $\pi^\pm$

- Worse resolution for missing mass for π^0 ($\rightarrow$ fig.)
- Suppression of exclusive π^0 production on proton with respect to π^+(as seen by HERMES)

$\rightarrow$ π^0 in exclusive limit presumably dominated by pure SIDIS events.

HERMES missing mass resolutions



Missing parts of mosaic

- The role of higher twists ($z > 0.7$) and exclusive scattering ($z \approx 1$) in SIDIS

  $\Rightarrow$ need theoretical coverage of full z range

  $\Rightarrow$ need link between SIDIS HT and hard exclusive scattering
- Find kinematic limits (z, Q^2) where SIDIS is still dominating semi-exclusive production.
- Interpretation of SSA differences for charged and neutral pions

Summary

- **Significant x and $P_\perp$ dependence of $A_{UL}^{sin\phi}$ observed for π^+ and π^0 SIDIS.**
- **Different behavior for charged and neutral pions in exclusive limit (z→1).**

Improvements in HERMES Detector

- **RICH $\Rightarrow$ clean π and K samples**
- **Λ wheel $\Rightarrow$ improved exclusivity criteria**

Outlook

- **Transversely polarized target (2000+)**
  - ▷ **transversity, h_1**
  - ▷ **Collins fragmentation function**
  - ▷ **2-pion production [Jaffe]**
- **Separation of contributions from different distribution functions through measurements of other moments ($\cos\phi$, $\cos 3\phi$, $\sin 3\phi$...)**

Investigation of single spin asymmetries in semi-inclusive pion electroproduction

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The azimuthal single target-spin asymmetries for π^+ production in semi-inclusive deep inelastic scattering of leptons off longitudinally polarized protons are evaluated using two main approaches available in the literature (see, e.g. Ref. [1]). It is shown that the approximation where the twist-2 *transverse* quark spin distribution in the *longitudinally* polarized nucleon is small enough to be neglected leads to a consistent description of all existing asymmetries observed by the HERMES experiment. A possibility to access the transverse distribution function through the measurement of single spin azimuthal asymmetry in semi-inclusive single pion leptoproduction on a transversely polarized target is also discussed.

There are two main approaches in the literature which aim at explaining the experimental data:

(i) The approximation where the twist-2 *transverse* quark spin distribution in the *longitudinally* polarized nucleon, $h_{1L}^{\perp(1)}(x)$, is considered small enough to be neglected [2–5]. This results in good agreement with the Bjorken-x behavior of the $sin\phi$ and $sin2\phi$ asymmetries observed at HERMES. Note, that this does not require the twist-3 interaction-dependent part of the fragmentation function, $\tilde{H}(z)$, to be zero.

(ii) The approximation where the contribution of the interaction-dependent twist-3 term, $\tilde{h}_L(x)$, in the distribution function $h_L(x)$ is assumed to be negligible, but $\tilde{H}(z)$ is not constrained [3].

Another approximation, where only the twist-2 distribution and fragmentation functions are used, i.e. the interaction-dependent twist-3 parts of distribution and fragmentation functions are neglected, was proposed earlier [7,8]. For certain values of parameters this results in good agreement with the HERMES data [9]. However, it leads to the inconsistency that all T-odd fragmentation functions would be required to vanish [10,11]. Thus, we do not consider it.

The transversity distribution $h_1(x)$ measures the probability to find a transversely polarized quark in a transversely polarized nucleon (see, e.g., Ref. [12]). One of the possibilities to access the transversity in one-hadron inclusive deep inelastic scattering off

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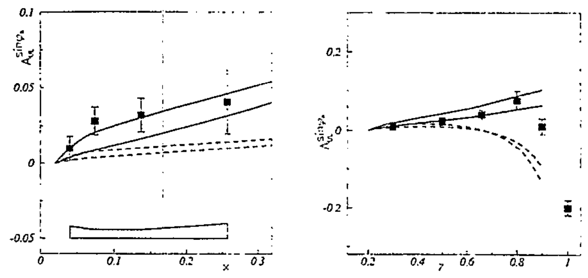

Figure 1. The single target-spin asymmetry $A_{UL}^{\sin\phi}$ for π^+ production as a function of Bjorken-x and z, evaluated using $M_C = 2m_\pi$ and $\eta = 0.8$. The results obtained within approaches (i) and (ii) are denoted by pairs of full and dashed lines, respectively. For each approach two curves are presented corresponding to $h_1 = g_1$ (lower curve) and $h_1 = (f_1 + g_1)/2$ (upper curve). HERMES data are from Ref. [9,13].

transversely polarized nucleons is to measure the azimuthal angular dependences in the production of spin-0 or (on average) unpolarized hadrons, which shows up as $\sin(\phi_h + \phi_S)$ dependence [14], where ϕ_S is the azimuthal angle of the target spin vector.

In Fig. 2 the curves have been calculated by integrating over the HERMES kinematic range. From Fig. 2 one can see that the single transverse-target-spin asymmetry expected to be quite large. At HERMES kinematics ($\langle x\rangle \approx 0.1, \langle z\rangle \approx 0.4$) it amounts to $(4 \div 7)\%$. The HERMES experiment using a transversely polarized proton target will be able to extract $h_1(x)$ in a simple way proposed in Ref. [15]. Actually, the combined results of HERMES (on transversely polarized target) and COMPASS should give quite precise information on transverse distribution functions soon.

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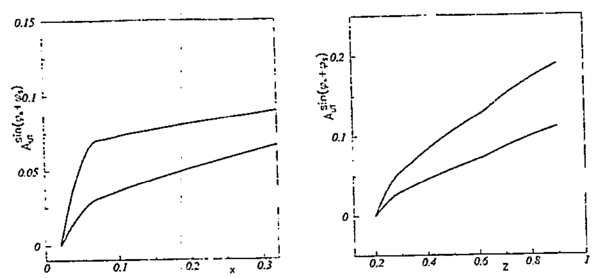

Figure 2. The single target-spin asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$ for π^+ production as a function of Bjorken-x and z, evaluated using $M_C = 2m_\pi$ and $\eta = 0.8$. Two curves are corresponded to $h_1 = g_1$ (lower curve) and $h_1 = (f_1 + g_1)/2$ (upper curve).

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Investigation of single spin asymmetries in semi-inclusive electroproduction:

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- Single-spin asymmetries in SIDIS
- Treatment of azimuthal asymmetries [1]
- Access to Transversity
- Problems / Comments
- Conclusion

[1] tree-level up to order $1/Q$

Azimuthal Asymmetries

Longitudinally Polarized Target

THE $\sin\varphi$ and $\sin 2\varphi$ moments in SIDIS cross section one can define as weighted integrals over the transverse momentum of the observed hadron: Kotzinian, 95; Mulders, Tangerman, 96; Kotzinian, Mulders '97

$$\left\langle \frac{|P_{hT}|}{M_h}\sin\varphi \right\rangle = \frac{\int d^2P_{hT}\,\frac{|P_{hT}|}{M_h}\cdot\sin\varphi\,(d\sigma^+ - d\sigma^-)}{\int d^2P_{hT}\,(d\sigma^+ + d\sigma^-)},$$

$$\left\langle \frac{|P_{hT}^2|}{MM_h}\sin 2\varphi \right\rangle = \frac{\int d^2P_{hT}\,\frac{|P_{hT}^2|}{MM_h}\cdot\sin 2\varphi\,(d\sigma^+ - d\sigma^-)}{\int d^2P_{hT}\,(d\sigma^+ + d\sigma^-)}.$$

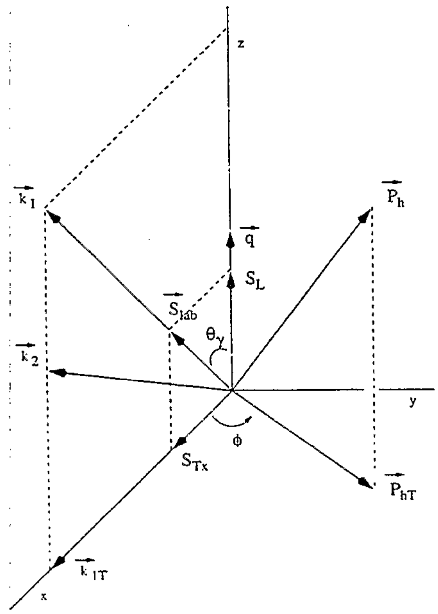
$$A_{UL}^{\sin\varphi} \approx \frac{2M_h}{\langle P_{hT}\rangle}\cdot\left\langle \frac{|P_{hT}|}{M_h}\cdot\sin\varphi \right\rangle.$$

$$A_{UL}^{\sin 2\varphi} \approx \frac{2MM_h}{\langle P_{hT}^2\rangle}\cdot\left\langle \frac{|P_{hT}^2|}{MM_h}\cdot\sin 2\varphi \right\rangle.$$

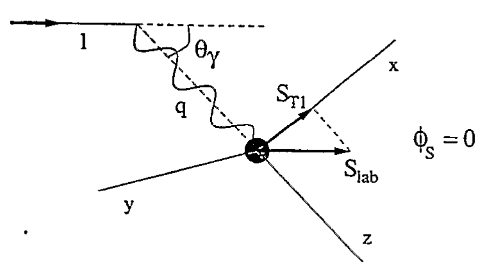
$lN \to l'hX$

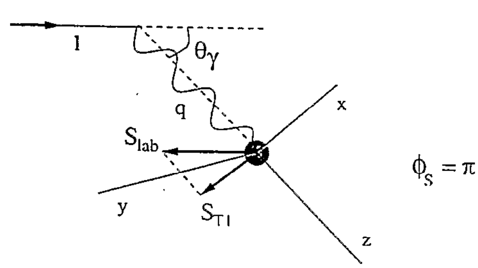
Kinematics

$$x_B = \frac{(Q^2)}{2(Pq)}, \quad y = \frac{(Pq)}{(Pk_1)}, \quad z_h = \frac{(PP_h)}{(Pq)}.$$



Kinematics





Single-Spin Asymmetries

Longitudinally Polarized Target

Subleading in $1/Q$

$$\left.\begin{aligned} A_{UL}^{\sin\phi_h} \sim \frac{M}{Q} S_L \ h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)} \\ + \frac{M}{Q} S_L \ \tilde{h}_L \otimes H_1^{\perp(1)} \end{aligned}\right\} \frac{M}{Q} S_L \ x h_L^{(x)} z \cdot H_1^{\perp(1)}$$

$$- \frac{M}{Q} S_L \ h_{1L}^{\perp(1)} \otimes \frac{\tilde{H}}{z}$$

$$+ \underbrace{\overbrace{\sin\theta_\gamma}^{\sim M/Q} S_{lab}}_{S_{Tx}} \ h_1 \otimes H_1^{\perp(1)}$$

Note:
- color blue denotes twist-2; color green Twist-3
- superscript (1) indicates *weighted* DF's and FF's:

$$H_1^{\perp(1)}(z_h) = z_h^2 \int d^2 k_T \left(\frac{k_T^2}{2M_h^2} \right) H_1^\perp(z_h, z_h^2 k_T^2),$$

$$h_{1L}^{\perp(1)}(x) = \int d^2 p_T \left(\frac{p_T^2}{2M^2} \right) h_{1L}^\perp(x, p_T^2),$$

p_T (k_T) is the initial (final) partons intrinsic transverse momentum.

Azimuthal Asymmetries

$$\left\langle \frac{|P_{hT}|}{M_h} \sin\varphi \right\rangle = \frac{1}{I_0} \left[I_{1L} + I_{1T} \right]$$

$$\left\langle \frac{|P_{hT}^2|}{MM_h} \sin 2\varphi \right\rangle = \frac{1}{I_0} \left[8 S_L (1-y) h_{1L}^{\perp(1)}(x) \cdot z^2 H_1^{\perp(1)}(z) \right]$$

$$I_0 = (1 + (1-y)^2) f_1 D_1$$

$$I_{1L} = 4 S_L \frac{M}{Q} (2-y) \sqrt{1-y} \left[-2 h_{1L}^{\perp(1)} z H_1^{\perp(1)} + \right.$$
$$\left. + x \tilde{h}_L(x) \cdot z H_1^{\perp(1)} - h_{1L}^{\perp(1)} \cdot \tilde{H}(z) \right]$$

$$I_{1T} = 2 S_{Tx} (1-y) h_1(x) \cdot z H_1^{\perp(1)}(z)$$

I_{1L} can rewrite also in this way:

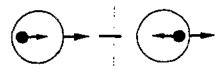
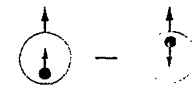
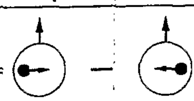
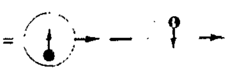
$$I_{1L} = 4 S_L \frac{M}{Q} (2-y) \sqrt{1-y}$$
$$\left[x \underline{h_L(x) z H_1^{\perp(1)}} - h_{1L}^{\perp(1)} \cdot \tilde{H} \right]$$

The functions with superscript (1) denote P_T^2- and k_T^2- moments of DF's and FF's respectively:

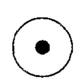
$$h_{1L}^{\perp(1)}(x) = \int d^2 P_T \left(\frac{P_T^2}{2M^2} \right) h_{1L}^\perp(x, P_T^2)$$

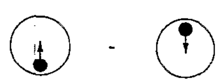
$$H_{1}^{\perp(1)}(z) = z^2 \int d^2 k_T \left(\frac{k_T^2}{2M_h} \right) H_1^\perp(z, z^2 k_T^2)$$

Distribution Functions

$g_1(x)$	Twist-2	$h_1(x)$
$g_1 =$ 	Approximations: NRL: $h_1 = g_1$; SUL: $h_1 = (f_1 + g_1)/2$	$h_1 =$ 
$g_T = + \frac{g_{1T}^{(1)}}{x} + \tilde{g}_T$	Twist-3 Twist-2 Twist-3 (Int.dep.)	$h_L = -2\frac{h_{1L}^{\perp(1)}}{x} + \tilde{h}_L$
$\tilde{g}_T = 0$	QPM	$\tilde{h}_L = 0$
$g_{1T} =$ 	Approximations: W-W $h_{1L}^{\perp(1)} = -x^2 \int_x^1 dy \frac{h_1(y)}{y^2}$	$h_{1L}^{\perp} =$ 
$g_2 = (g_T - g_1) = \frac{d}{dx} g_{1T}^{(1)}$	Twist-3 Derivation of Twist-2	$h_2 = 2(h_L - h_1) = -\frac{d}{dx} h_{1L}^{\perp(1)}$

Fragmentation Functions

$D_1 =$  Probability of finding hadron h in a quark

$H_1^{\perp} =$  The different production probability of unpolarized hadron from a transversely polarized quark

Chiral-odd, "Time-reversal-odd", Twist-2

COLLINS ANSATS:
FOR THE ANALYZING POWER OF TRANSVERSELY POLARIZED QUARK FRAGMENTATION FUNCTION

Collins, 93
Kotzinian, Mulders;

$$A_C(z, k_T^2) = \frac{|k_T|\, H_1^{\perp}(z, k_T^2)}{M_h \cdot D_1(z, k_T^2)} = \eta \cdot \frac{M_C |k_T|}{M_C^2 + k_T^2},$$

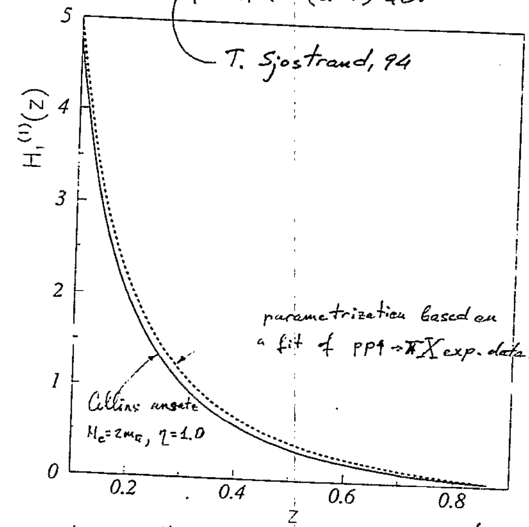
Where η, in principle could be z-dependent,
$M_C \to 2m_\pi \div M_p$.

Fragmentation function

$$H_1^{\perp(1)}(z) = D_1(z)\cdot\frac{M_c}{2M_h}\cdot\left(1-M_c^2R^2\int_0^\infty dx\cdot\frac{e^{-x}}{x+M_c^2R^2}\right)$$ Kotzinian, Mulders, 97

$R^2 \equiv \frac{z^2}{\langle z^2k_T^2\rangle}$; $\left\{\begin{array}{l}\langle z^2k_T^2\rangle = (0.36)^2\,GeV^2\\ \langle p_T^2\rangle = (0.44)^2\,GeV^2\end{array}\right.$ $\Rightarrow$ $\langle P_T\rangle = 0.56\,GeV$, $\langle P_{hT}^2\rangle = 0.165\,GeV^2$

T. Sjostrand, 94



At use: $M_c=2m_\pi$, $\eta=0.6$. * May indicate possible contributions of T-odd Distribution func. in $pp\uparrow\to\pi X$!

Approaches

There are three main approaches*:

- **I** The Wandzura-Wilczek like approximation, where ONLY twist-2 DF's and FF's are used, i.e. the interaction-dependent twist-3 parts are neglected.
  IT leads, however, to the inconsistency that all T-odd fragmentation functions would be required to vanish.
  Kotzinian, et.al, 00
  Efremov, et.al., 00

- **II** The approximation where the twist-2 transverse quark distribution in the longitudinally polarized nucleon, $h_{1L}^{\perp(1)}(x)$, is considered small enough to be neglected.
  This does not require $\tilde{H}(z)=0$.
  Boglione, Mulders, 00
  Efremov, 00
  De Sanctis, Nowak, KO, 00
  D. Boer, 99

- **III** The approximation where the contribution of the interaction-dependent twist-3 term, $\tilde{h}_L(x)$, in the DF's $h_L(x)$ is neglected, BUT $\tilde{H}(z)$ is NOT constrained.
  Boglione, Mulders, 00

*THE NATURE OF SIN φ SSA IN ALL CASES the SAME. it related to T-odd FRAGMENTATION FUNCTIONS KO-1C

I: $A_{UL}^{\sin\phi_h}$ and $A_{UL}^{\sin 2\phi_h}$

Wandzura-Wilczek in *both* DF's and FF's

All Twist-3 = 0 !

$$A_{UL}^{\sin\phi_h} \sim \frac{M}{Q} S_L h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)}$$

$$+ \underbrace{\overbrace{\sin\theta_\gamma}^{\sim M/Q} S_{lab}}_{S_{Tx}} h_1 \otimes H_1^{\perp(1)} \quad (\sim 25\%)$$

$$A_{UL}^{\sin 2\phi_h} \sim S_L h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)}$$

Note: $\tilde{h}_L(x) = 0, \quad \tilde{H}(z) = 0$ $\quad h_{1L}^{\perp(1)}(x) = x^2 \int_x^1 dy \, \frac{h_1(x)}{y^2}.$

II: Theoretical conjecture

"Reduced twist-3": $h_{1L}^{\perp(1)}(x) \approx 0$

Twist-2 DF $h_{1L}^{\perp}(x, p_T)$, non-zero itself, vanishesat any x when integrated over intrinsic transverse momenta.
Then: $\tilde{h}_L(x) = h_1(x)$, i.e. *only* twist-2 remains.

$$A_{UL}^{\sin 2\phi_h} = 0$$

$$(\sim 25\%)$$

$$A_{UL}^{\sin\phi_h} = \frac{M}{Q} S_L h_1 \otimes H_1^{\perp(1)} + \underbrace{\overbrace{\sin\theta_\gamma}^{\sim M/Q} S_{lab}}_{S_{Tx}} h_1 \otimes H_1^{\perp(1)}$$

$\tilde{H}(z) = 0$ $\quad h_L(x) = \tilde{h}_L(x) = h_1(x)$

III: $A_{UL}^{\sin\phi_h}$ and $A_{UL}^{\sin 2\phi_h}$

Wandzura-Wilczek in DF's only

Wandzura-Wilczek like Approach: neglect interaction-dependent twist-3 part: $\tilde{h}_L(x) = 0$ (in parton model vanishes). Then $h_{1L}^{\perp(1)}(x) = -x^2 \int_x^1 dy \frac{h_1(y)}{y^2}$.

$$A_{UL}^{\sin\phi_h} \sim \frac{M}{Q} S_L \; h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)}$$

$$\underline{-\frac{M}{Q} S_L \; h_{1L}^{\perp(1)} \otimes \frac{\tilde{H}}{z}}$$

$$+ \underbrace{\overbrace{\sin\theta_\gamma}^{\sim M/Q} S_{lab}}_{S_{Tx}} \; h_1 \otimes H_1^{\perp(1)} \quad (\sim 50\%)$$

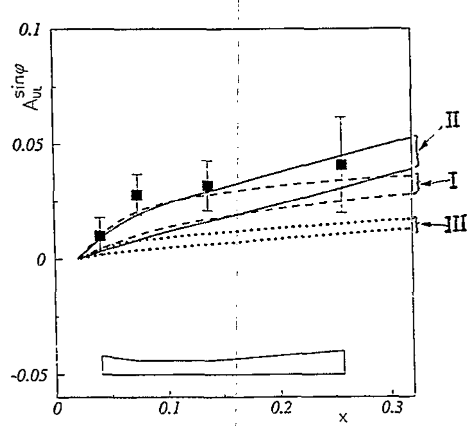
$$A_{UL}^{\sin 2\phi_h} \sim S_L \; h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)}$$

Note: $\tilde{H}(z) = z\frac{d}{dz}(zH_1^\perp(z))$ is the interaction dependent twist-3 part of $H = -2zH_1^\perp(z) + \tilde{H}$.

Single-Spin Asymmetries

Longitudinally polarized Target

Subleading in $1/Q$

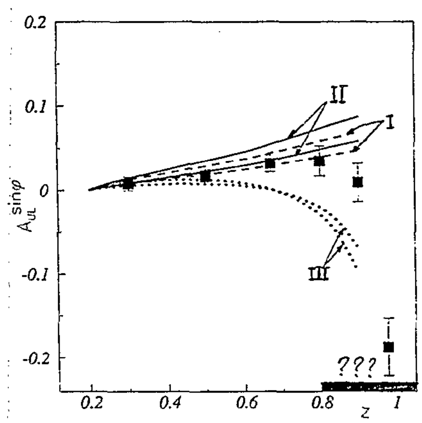


The single target-spin asymmetry $A_{UL}^{\sin\phi}$ for π^+ production as a function of Bjorken-x, evaluated using $M_C = 2m_\pi$ and $\eta = 0.6$. The results obtained within approaches (I), (II), and (III) are denoted by pairs of full dashed and dotted lines, respectively. For each approach two curves are presented corresponding to $h_1 = g_1$ (lower curve) and $h_1 = (f_1 + g_1)/2$ (upper curve). Data are from HERMES

Single-Spin Asymmetries

Longitudinally polarized Target

Subleading in $1/Q$



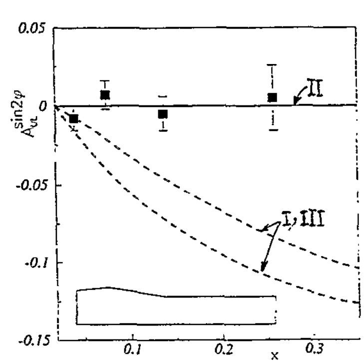
The single target-spin asymmetry $A_{UL}^{\sin\phi}$ for π^+ production as a function of z evaluated using the same parameters as in HERMES preliminary data (the error bars correspond to the statistical uncertainties only).

Single-Spin Asymmetries

Longitudinally polarized Target

Leading in $1/Q$

$$A_{UL}^{\sin 2\phi_h} \sim S_L \; h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)}$$



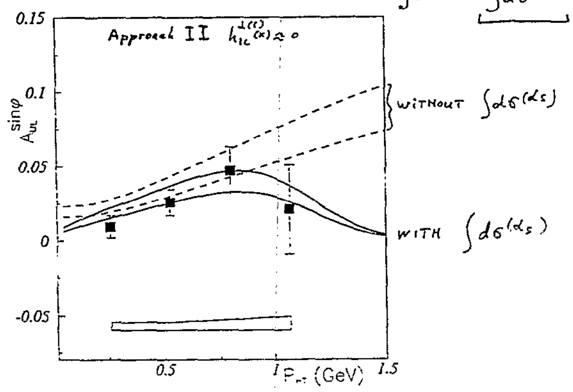
The single target-spin asymmetry $A_{UL}^{\sin 2\phi}$ for π^+ production as a function of Bjorken x, evaluated using the same parameters as before. Note that the line at $A_{UL}^{\sin 2\phi} = 0$ corresponds to the result of approach (II), the curves of the approaches (I) and (III) coincide and are both denoted by dashed curves for the two cases considered for h_1. Data are from HERMES.

Single-Spin Asymmetries

Longitudinally polarized Target

Subleading in $1/Q$

$A_{UL}^{\sin\varphi} = 2\langle\sin\varphi\rangle = \dfrac{\int d\sigma^{(NP)} \sin\varphi}{\int d\sigma^{(NP)} + \int d\sigma^{(\alpha_s)}}$



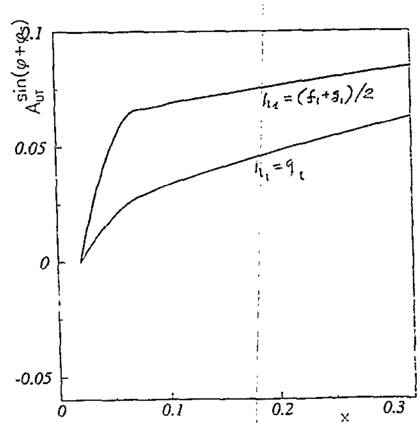
P_{hT} dependence of the $A_{UL}^{\sin\phi}$ asymmetry for π^+ electroproduction off longitudinally polarized protons evaluated using $M_C = 2m_\pi$ and $\eta = 0.6$. Full lines correspond to results where the perturbative contribution is taken into account in the denominator, while dashed ones are without this contribution. For each case two curves are presented corresponding to $h_1 = g_1$ (lower curve) and $h_1 = (f_1 + g_1)/2$ (upper curve). HERMES data are from HERMES.

Single-Spin Asymmetries

Transversely Polarized Target

Leading in $1/Q$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim S_T h_1 \otimes H_1^{\perp(1)}$$

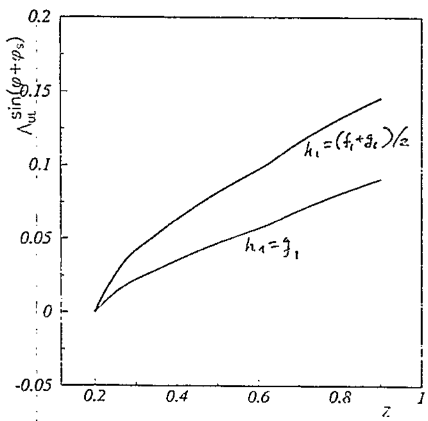


Single-Spin Asymmetries

Transversely Polarized Target

Leading in $1/Q$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim S_T h_1 \otimes H_1^{\perp(1)}$$



Transverse distributions from SSA

$$A_{UT} = P_T D_{nn} \frac{\sum_q e_q^2\, h_1^q(x)\cdot H_1^{\perp(1)q}(z)}{\sum_q e_q^2\, f_1^q(x)\cdot D_1^q(z)}$$

Korotkov, Nowak, KO. 99

Efremov, .. 00

$P_T \to$ target polarization

$$D_{nn} = \frac{1-y}{1-y+y^2/2}$$

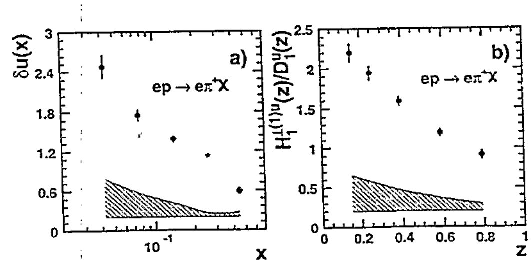
For u-quark

$$A_{UT} = P_T D_{nn} \cdot \frac{h_1^u(x)}{f_1^u(x)} \cdot \frac{H_1^{\perp(1)u\to\pi}(z)}{D_1^{u\to\pi}(z)}$$

Assuming $h_1^u(x_0) = g_1^u(x_0)$ one can solve the problem of normalization.

Korotkov, Nowak, KO., 99

Then



$h_1^u(x)$

a) the transversity distribution $\underbrace{\delta u(x)}$, and b) the ratio of the fragmentation functions $H_1^{\perp(1)u}(z)$ and $D_1^u(z)$ as it would be measured by HERMES with a proton target. The asterisk in a) shows the normalization point.

Conclusion

- The $\sin\varphi$ and $\sin 2\varphi$ SSA in SIDIS are evoluated using three main approaches available in the literature and compared with recent HERMES data
- The approximation $h_{1L}^{\perp(1)}(x) \approx 0$ gives a consistent description of both $A_{UL}^{\sin\varphi}(x)$ and $A_{UL}^{\sin 2\varphi}(x)$. It also describe well the z-dependence in the semi-inclusive channel and P_{hT}-dependence of $A_{UL}^{\sin\varphi}$.
- Predictions for x and z dependences of $A_{UT}^{\sin(\varphi+\varphi_S)}$ are given: $4 \div 5\%$ at HERMES energies.
- A method is shown how to determine the "transversity" from the SSA in SIDIS in case of transversely polarized target.

Problems / Comments

- in $A_{UL}^{\sin\varphi}(z)$:

  How describe the transition from semi-inclusive to exclusive?

- To measure the weighted SSA Will be much easy / realistic

  Experiment $\rightleftarrows$ models

- In approach III: to be consistent with $\tilde{H}(z)$; take into account $\tilde{h}_L(x)$ as well (full twist-3).

  For example the Bag model!

The role of h_1 in azimuthal and single spin asymmetries

M. Boglione

Division of Physics and Astronomy, Faculty of Science, Free University
De Boelelaan 1081, NL-1081 HV Amsterdam, the Netherlands

Because of its chiral-odd nature, the "transversity" distribution function h_1 is particularly hard to measure. In fact, in cross-sections it can only appear in association with a second chiral odd distribution or fragmentation function: another $h_1(x)$ distribution function, as in Drell Yan scattering, or a chiral odd fragmentation function, like the Collins function usually indicated by $\Delta^N D(z)$ or by $H_1^{\perp(1)}(z)$. In my talk I present the results of some work done in the last few years in collaboration with M. Anselmino, E. Leader, P.J. Mulders and F. Murgia, aimed at the study of these functions [1–6].

Single spin asymmetries are absolutely crucial tools since they are strictly related to two "hot" topics:

1. The role of the intrinsic transverse momentum k_T (i.e. the momentum of the parton relative to that of the parent hadron) in both the dynamics and the kinematics of the process (single spin asymmetries are zero when k_T effects are neglected)
2. The existence of distribution and/or fragmentation functions which do not fulfill time reversal invariance (single spin asymmetries are zero unless at least one of the functions is T-odd).

Experimental data on single spin asymmetries are only just starting to be available, but some important work has already been done relaying on a very accurate measurement of the single spin asymmetry of pions, semi-inclusively produced in $p^{\uparrow}p$ scattering [7]. From a fit of these data we were able to determine, through an appropriate parameterisation which takes into account Soffer bounds and positivity constraints, the transversity functions h_1 and the Collins function $\Delta^N D$, a chiral odd k_T dependent fragmentation function which describes the fragmentation of a polarized quark into an unpolarized hadron (a pion in our case) [4].

Both functions play an important role in several DIS azimuthal spin asymmetries. The knowledge on h_1 and $\Delta^N D$ gained by performing such a fit allows us, for example, to give interesting predictions [5] of DIS single spin asymmetries which are presently being measured: HERMES and SMC have recently presented experimental data which are in very good agreement with our predictions [8].

An other interesting way of gathering information on the h_1 distribution function is by considering the semi-inclusive production of transversely polarized Λ and $\bar{\Lambda}$ in deep inelastic scattering. I present the results of our calculations and our estimates, based on various sets of polarized fragmentation functions recently proposed [6].

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[1] M. Anselmino, M. Boglione, F. Murgia, *Phys. Lett.* **B362**, 164, (1995).
[2] M. Anselmino, M. Boglione, F. Murgia, *Phys. Rev.* **D60**, 054027, (1999)
[3] M. Boglione and P.J. Mulders, *Phys. Rev.* **D60**, 054007 (1999).
[4] M. Boglione and E. Leader, *Phys. Rev.* **D61**, 114001 (2000).
[5] M. Boglione and P.J. Mulders, *Phys. Lett.* **B478**, 114, (2000).
[6] M. Anselmino, M. Boglione, F. Murgia, *Phys. Lett.* **B362**, 164, (1995).
[7] D.L. Adams *et al*, *Phys. Lett.* **B261**, 201 (1991) and *Phys. Lett.* **B264**, 462 (1991).
[8] HERMES Collaboration, A. Airapetian *et al.*, hep-ex/9910062.

The role of h_1 in azimuthal and single spin asymmetries

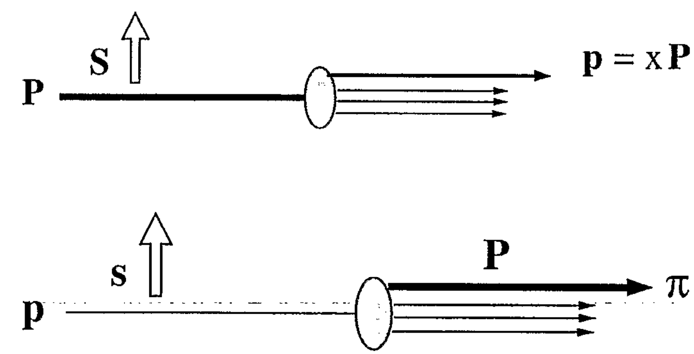
M. Boglione

vrije Universiteit amsterdam

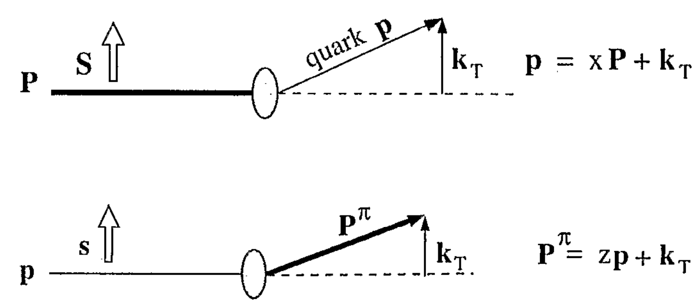
FOM

- * Determination of the transversity h_1 and the Collins function $\Delta^N D$ from $p^\uparrow p \to \pi X$
- * The role of h_1 and $\Delta^N D$ in DIS spin asymmetries
- * Λ and $\bar{\Lambda}$ polarization in polarized DIS

Collinear Kinematics



Intrinsic transverse momentum contribution



Correlation functions fulfill hermiticity, parity and charge conjugation symmetries.
What about time-reversal symmetry ?

DISTRIBUTION PROCESS $\vert P>_{in}$	$\Longrightarrow$	$\vert P>_{out} = \vert P>_{in}$ single particle one moment only
	T	
FRAGMENTATION PROCESS $\vert P_h, X>_{out}$	$\Longrightarrow$	$\vert P_h, X>_{in} = e^{i\delta_{hX}} \vert P_h, X>_{out}$ phase shift

SINGLE SPIN ASYMMETRIES ARE NON-ZERO	only if	EITHER ϕ OR Δ CONTAIN T-ODD FUNCTIONS

Distribution functions

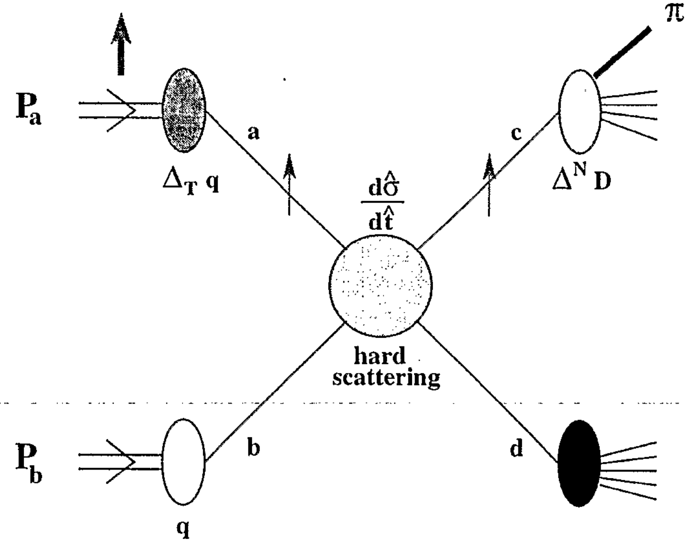
$$
\begin{aligned}
q(x) &= f_{q/p}(x) = f_1(x) \\
\Delta q(x) &= g_1(x) \\
\Delta_T q(x) &= h_1(x) \\
\Delta^N f_{q/p^\uparrow}(x, \boldsymbol{k}_T) &= 2\,\frac{|\boldsymbol{k}_T|\sin\phi}{M}\, f_{1T}^{\perp}(x, \boldsymbol{k}_T)
\end{aligned}
$$

where ϕ is the azimuthal angle of the quark transverse momentum

Fragmentation functions

$$
\begin{aligned}
D(z) &= D_1(z) \\
\Delta D(z) &= G_1(z) \\
\Delta^N D(z, \boldsymbol{k}_T)\, d^2\boldsymbol{k}_T &= -2\,\frac{|\boldsymbol{k}_T|\sin\phi}{M_h}\, H_1^{\perp}(z, \boldsymbol{k}'_T)\, d^2\boldsymbol{k}'_T
\end{aligned}
$$

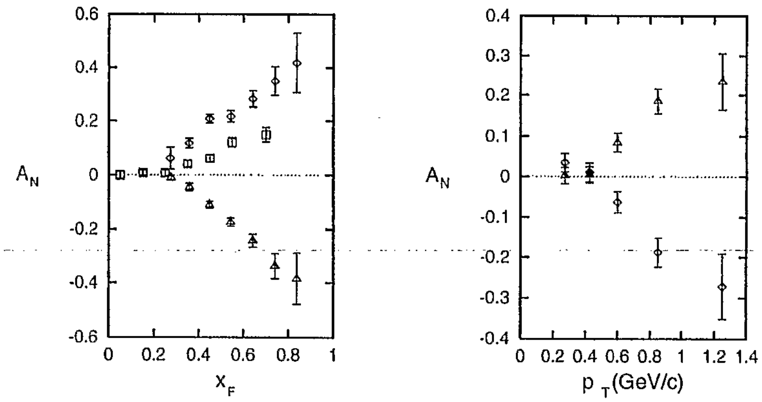
where ϕ is the relative azimuthal angle of the outgoing hadron momentum.



$$\boxed{p^{\uparrow}\, p \longrightarrow \pi\, X}$$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{2\, d\sigma^{unp.}}$$

Single spin asymmetries are $\sim$ 0 at partonic level in COLLINEAR configuration.



HOW CAN WE ACCOUNT FOR SUCH A BIG ASYMMETRY AS EXPERIMENTS DELIVER ?

135

Possible explanations

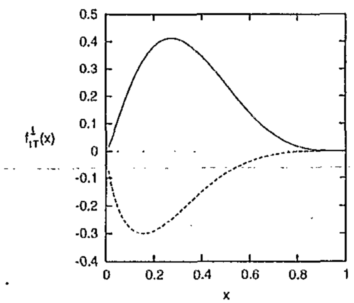
Sivers and Collins mechanisms

- Consider non collinear configurations

$$
- k_T \text{ effects in } \begin{cases} \text{distribution functions} & \to \text{Sivers} \\ \text{(initial state)} & \\ \text{fragmentation functions} & \to \text{Collins} \\ \text{(final state)} & \end{cases}
$$

Sivers mechanism:
Scattering via an unpolarized quark

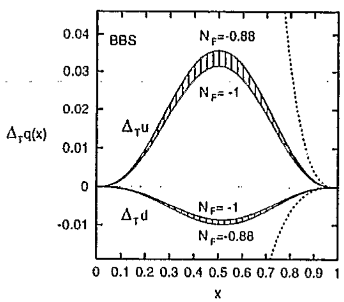
$$\sigma \;\propto\; f_1 \otimes f_{1T}^{\perp} \otimes D_1$$

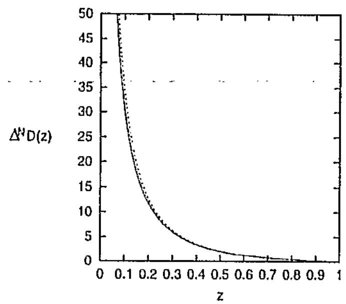


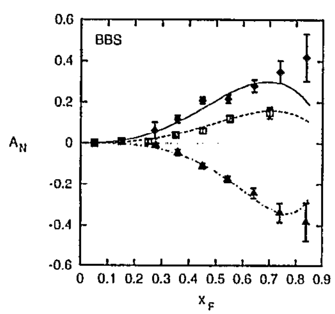
M. Anselmino, M. Boglione, F. Murgia, Phys. Lett. B 362 (1995) 164

Collins mechanism:
Scattering via a transversely polarized quark

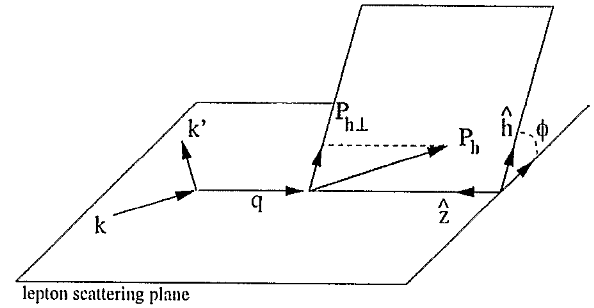
$$\sigma \;\propto\; f_1 \otimes h_1 \otimes H_1^{\perp}$$







M. Boglione, E. Leader, Phys. Rev D 61 (2000) 114001



$$\langle W\rangle_{\underbrace{P_e P_H P_h}_{\uparrow}} \equiv \int d\phi^\ell\, d^2\boldsymbol{q}_T\, \underbrace{W}_{\uparrow}\, \frac{d\sigma_{P_e P_H}}{dx_B\, dy\, dz_h\, d\phi^\ell\, d^2\boldsymbol{q}_T}$$

$$(O, L, T) \qquad\qquad W(Q_T, \phi_h^\ell, \phi_S^\ell, \phi_{S_h}^\ell)\;,$$

e.g.

$$\langle 1\rangle_{OOO} = \frac{2\pi\alpha^2\, s}{Q^4}\, x_B \left(1 + (1-y)^2\right) \sum_{a,\bar{a}} e_a^2\, f_1^a(x_B)\, D_1^a(z_h)$$

Transversely polarized target (leading order)

Use the functions $f_{1T}^{\perp}$, h_1 and $H_1^{\perp}$ determined by fitting the single spin asymmetry A_N in $p^{\uparrow}p \to \pi X$ to calculate the corresponding azimuthal single spin asymmetry in $\ell p^{\uparrow} \to \pi^{+} X$

$$\left\langle \frac{Q_T}{M}\,\sin(\phi_h^\ell - \phi_S^\ell)\right\rangle_{OTO} = \frac{2\pi\alpha^2\,s}{Q^4}\,|S_T|\left(1-y+\frac{1}{2}y^2\right)\sum_{a,\bar a} e_a^2\,x_B\,f_{1T}^{\perp(1)a}(x_B)\,D_1^a(z_h)$$

$$\left\langle \frac{Q_T}{M_h}\,\sin(\phi_h^\ell + \phi_S^\ell)\right\rangle_{OTO} = \frac{2\pi\alpha^2\,s}{Q^4}\,|S_T|\,2(1-y)\sum_{a,\bar a} e_a^2\,x_B\,h_1^a(x_B)\,H_1^{\perp(1)a}(z_h)$$

M. Boglione, P.J. Mulders,
Phys. Rev. D 60 (1999) 054007

Longitudinally polarized target

Leading:

$$\left\langle \frac{Q_T^2}{4MM_h}\,\sin(2\phi_h^\ell)\right\rangle_{OLO} = -\frac{4\pi\alpha^2\,s}{Q^4}\,\lambda\,(1-y)\times\sum_{a,\bar a} e_a^2\,x_B\,h_{1L}^{\perp(1)a}(x_B)\,H_1^{\perp(1)a}(z_h)$$

Subleading:

$$\left\langle \frac{Q_T}{M}\,\sin(\phi_h^\ell)\right\rangle_{OLO} = \frac{4\pi\alpha^2\,s}{Q^4}\,\lambda\,(2-y)\sqrt{1-y}\,\frac{2M_h}{Q}\times\sum_{a,\bar a} e_a^2\left\{x_B\,h_{1L}^{\perp(1)a}(x_B)\,\frac{\tilde H^a(z_h)}{z_h} + x_B\left(2h_{1L}^{\perp(1)a} - x_B\,h_L^a(x_B)\right)\,H_1^{\perp(1)a}(z_h)\right\}$$

$$\boxed{\frac{\tilde{H}(z)}{z} = \frac{d}{dz}\left(z\, H_1^{\perp(1)}\right)}$$

Approximation 1:

$$h_{1L}^{\perp(1)}(x) \approx 0$$

$$\begin{aligned} h_L(x) &= h_1(x) \\ \tilde{h}_L(x) &= h_1(x) - 2x \int_x^1 dy\, \frac{h_1(y)}{y^2} \end{aligned}$$

Approximation 2:

$$\tilde{h}_L(x) \approx 0$$

$$\begin{aligned} h_L(x) &= 2x \int_x^1 dy\, \frac{h_1(y)}{y^2} \\ h_{1L}^{\perp(1)}(x) &= -x^2 \int_x^1 dy\, \frac{h_1(y)}{y^2} = -\frac{1}{2}\, x\, h_L \end{aligned}$$

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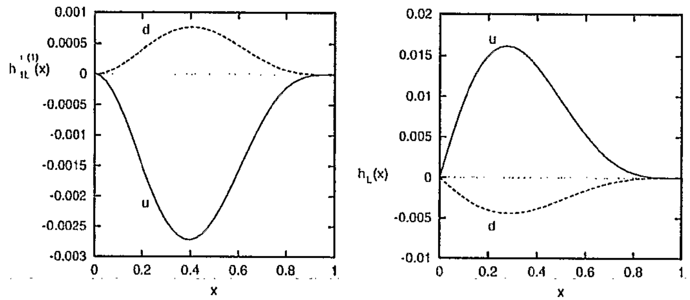
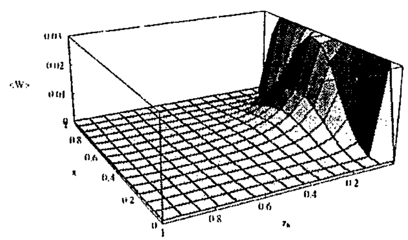
Use h_1 and $H_1^{\perp}$ from spin asymmetry A_N in $pp^{\uparrow} \to \pi X$ and h-distributions in approximation $\tilde{h}_L = 0$



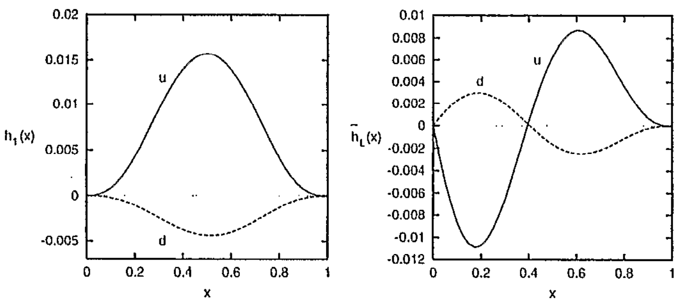
Calculate for $\ell p^{\uparrow} \to \pi^+ X$



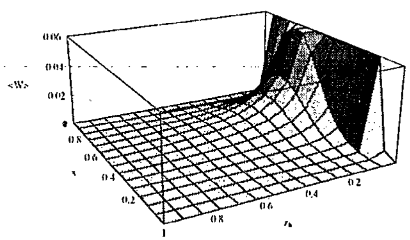
$$\left\langle \frac{Q_T}{M} \sin(\phi_h^{\ell}) \right\rangle_{OLO}$$

$$\propto -\sum_{a,\bar{a}} e_a^2 \Big[x_B \text{ [illegible] } (x_B)\, \frac{\tilde{H}^a(z_h)}{z_h} - x_B^2\, h_L^a(x_B)\, H_1^{\perp(1)a}(z_h) \Big]$$

Use h_1 and $H_1^\perp$ from spin asymmetry A_N in $pp^\uparrow \to \pi X$ and h-distributions in approximation $\tilde{h}_{1L}^{\perp(1)} = 0$



Calculate for $\ell p^\uparrow \to \pi^+ X$



$$\left\langle \frac{Q_T}{M}\,\sin(\phi_h^\ell)\right\rangle_{OLO}$$

$$\propto -\sum_{a,\bar a} e_a^2 \Big[x_B \;[\text{illegible}]\; (x_B)\,\frac{\tilde{H}^a(z_h)}{z_h} - x_B^2\, h_L^a(x_B)\, H_1^{\perp(1)a}(z_h)\Big]$$

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Measure the Λ polarization in $\ell p \to (\Lambda + \bar\Lambda)X$ by looking at the angular distribution of the $\Lambda \to p\pi$ decay (in the Λ helicity rest frame)

$$\boxed{\begin{aligned} P_z^{(0,-S_L)} &= P_z^{(0,+)} = \\ &= \frac{\sum_q e_q^2 \Delta q(x) \Delta D_{B/q}(z)}{\sum_q e_q^2 q(x) D_{B/q}(z)} = \frac{\sum_q e_q^2 g_1^q(x) G_1^q(z)}{\sum_q e_q^2 f_1(x) D_1(z)} \\ &\overset{\Lambda+\bar\Lambda}{\Longrightarrow} \frac{\Delta Q'(x)}{Q(x)}\frac{\Delta D_{\Lambda/s}(z)}{D_{\Lambda/q}(z)} = \frac{\Delta Q'(x)}{Q(x)}\frac{G_1^s(z)}{D_1(z)} \end{aligned}}$$

where

$$D_{\Lambda/u} = D_{\Lambda/d} = D_{\Lambda/s} = D_{\Lambda/\bar u} = D_{\Lambda/\bar d} = D_{\Lambda/\bar s} \equiv D_{\Lambda/q}$$

$$\Delta D_{\Lambda/u}(z, Q_0^2) = \Delta D_{\Lambda/d}(z, Q_0^2) = N_u\, \Delta D_{\Lambda/s}(z, Q_0^2)$$

and

$$\begin{aligned} Q &\equiv 4(u+\bar u) + (d+\bar d) + (s+\bar s) \\ \Delta Q &\equiv 4(\Delta u+\Delta\bar u) + (\Delta d+\Delta\bar d) + (\Delta s+\Delta\bar s) \\ Q' &\equiv [4(u+\bar u) + (d+\bar d)]\, N_u + (s+\bar s) \\ \Delta Q' &\equiv [4(\Delta u+\Delta\bar u) + (\Delta d+\Delta\bar d)]\, N_u + (\Delta s+\Delta\bar s) \end{aligned}$$

$$
\begin{aligned}
P_z^{(S_L,0)} &= P_z^{(+,0)} = \\
&= \frac{\sum_q e_q^2 q(x)\Delta D_{B/q}(z)}{\sum_q e_q^2 q(x) D_{B/q}(z)}\hat{A}_{LL} = \frac{\sum_q e_q^2 f_1^q(x) G_1^q(z)}{\sum_q e_q^2 f_1(x) D_1(z)}\hat{A}_{LL} \\
&\overset{\Lambda+\bar{\Lambda}}{\Longrightarrow} \frac{Q'(x)}{Q(x)}\frac{\Delta D_{\Lambda/s}(z)}{D_{\Lambda/q}(z)}\hat{A}_{LL}(y) = \frac{Q'(x)}{Q(x)}\frac{G_1^s(z)}{D_1(z)}\hat{A}_{LL}(y)
\end{aligned}
$$

$$
\begin{aligned}
P_z^{(s_L,\mp S_L)} &= P_z^{(+,\pm)} = \\
&= \frac{\sum_q e_q^2[q(x)\hat{A}_{LL}(y) \pm \Delta q(x)]\Delta D_{B/q}(z)}{\sum_q e_q^2[q(x) \pm \hat{A}_{LL}(y)\Delta q(x)]D_{B/q}(z)} = \\
&= \frac{\sum_q e_q^2[f_1(x)\hat{A}_{LL}(y) \pm g_1^q(x)]G_1^q(z)}{\sum_q e_q^2[f_1(x) \pm \hat{A}_{LL}(y) g_1^q(x)]D_1(z)} \\
&\overset{\Lambda+\bar{\Lambda}}{\Longrightarrow} \frac{Q'(x)\hat{A}_{LL}(y) \pm \Delta Q'(x)}{Q(x) \pm \Delta Q(x)\hat{A}_{LL}(y)}\frac{\Delta D_{\Lambda/s}(z)}{D_{\Lambda/q}(z)} \\
&= \frac{Q'(x)\hat{A}_{LL}(y) \pm \Delta Q'(x)}{Q(x) \pm \Delta Q(x)\hat{A}_{LL}(y)}\frac{G_1^s(z)}{D_1(z)}
\end{aligned}
$$

where

$$\hat{A}_{LL}(y) = \frac{d\hat{\sigma}_q^{\uparrow\uparrow} - d\hat{\sigma}_q^{\uparrow\downarrow}}{d\hat{\sigma}_q^{\uparrow\uparrow} + d\hat{\sigma}_q^{\uparrow\downarrow}} = \frac{y(2-y)}{1+(1-y)^2}$$

TRANSVERSE POLARIZATION

$$
\begin{aligned}
P_y^{(0,S_N)} &= -P_x^{(0,S_S)} = \\
&= \frac{\sum_q e_q^2 \Delta_T q(x)\Delta_T D_{B/q}(z)}{\sum_q e_q^2 q(x) D_{B/q}(z)}\hat{D}_{NN}(y) \\
&\propto \frac{\sum_q e_q^2 h_1^q(x) H_1^{\perp(1)}(z)}{\sum_q e_q^2 f_1(x) D_1(z)}\hat{D}_{NN}(y) \\
&\overset{\Lambda+\bar{\Lambda}}{\Longrightarrow} \frac{\Delta_T Q'(x)}{Q(x)}\frac{\Delta_T D_{\Lambda/s}(z)}{D_{\Lambda/q}(z)}\hat{D}_{NN}(y) \\
&\propto \frac{\Delta_T Q'(x)}{Q(x)}\frac{H_1^{\perp(1)s}(z)}{D_1(z)}\hat{D}_{NN}(y)
\end{aligned}
$$

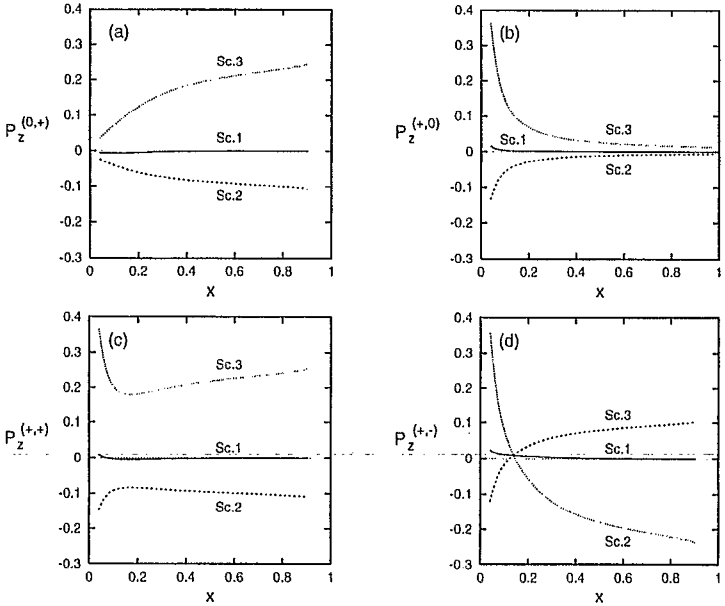
where

$$
\begin{aligned}
\Delta_T Q' &\equiv [4(\Delta_T u + \Delta_T \bar{u}) + (\Delta_T d + \Delta_T \bar{d})]\, N_u + (\Delta_T s + \Delta_T \bar{s}) = \\
&= [4(h_1^u + h_1^{\bar{u}}) + (h_1^d + h_1^{\bar{d}})]\, N_u + (h_1^s + h_1^{\bar{s}})
\end{aligned}
$$

and

$$\hat{D}_{NN}(y) = \frac{d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\uparrow} - d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\downarrow}}{d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\uparrow} + d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\downarrow}} = \frac{2(1-y)}{1+(1-y)^2}$$

1. $N_u = 0$, the whole Λ spin is carried by the s quark
2. $N_u = -0.2$, as suggested by $SU(3)$ flavour symmetry and g_1^p first moment experimental data
3. $N_u = 1$, all light quarks contribute equally to the Λ polarization

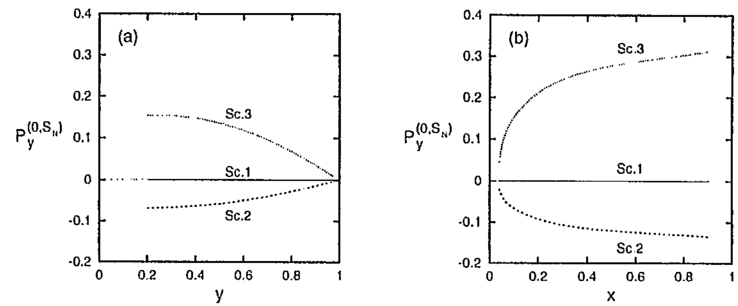


$P_z^{(0,+)}$, $P_z^{(+,0)}$, $P_z^{(+,+)}$ and $P_z^{(+,-)}$ as a function of x at fixed values of $Q^2 = 1.7$ (GeV/c)^2 and $z = 0.5$, for three different scenarios.

$$\Delta_T u = \frac{1}{2}(u + \Delta u), \qquad \Delta_T d = \frac{1}{2}(d + \Delta d)$$

$$\Delta_T \bar{q} = \Delta_T s = 0$$

$$\Delta_T D_{\Lambda/s} = \Delta D_{\Lambda/s}$$



(a), $P_y^{(0,S_N)}$ as a function of y at fixed $x = 0.1$ and $z = 0.5$;
(b), $P_y^{(0,S_N)}$ as a function of x at fixed $Q^2 = 1.7$ (GeV/c)^2 and $z = 0.5$

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Polarized lepton, unpolarized nucleon target

$$
\begin{aligned}
(\sigma_{+0}^{(\Lambda+\bar\Lambda)})_p - (\sigma_{+0}^{(\Lambda+\bar\Lambda)})_n &= \frac{1}{3}(u+\bar u - d - \bar d)\Delta D_u^{\Lambda+\bar\Lambda} \\
(\sigma_{+0}^{(\Lambda-\bar\Lambda)})_p - (\sigma_{+0}^{(\Lambda-\bar\Lambda)})_n &= \frac{1}{3}(u_v - d_v)\Delta D_u^{\Lambda-\bar\Lambda}
\end{aligned}
$$

$$
\begin{aligned}
(\sigma_{+0}^{(\Lambda+\bar\Lambda)})_p + (\sigma_{+0}^{(\Lambda+\bar\Lambda)})_n &= \frac{1}{9}[5(u+\bar u + d + \bar d)\Delta D_u^{\Lambda+\bar\Lambda} \\
&\quad +2(s+\bar s)\Delta D_s^{\Lambda+\bar\Lambda}] \\
(\sigma_{+0}^{(\Lambda-\bar\Lambda)})_p + (\sigma_{+0}^{(\Lambda-\bar\Lambda)})_n &= \frac{1}{9}[5(u_v + d_v)\Delta D_u^{\Lambda-\bar\Lambda} + \\
&\quad +2(s-\bar s)\Delta D_s^{\Lambda-\bar\Lambda}]
\end{aligned}
$$

M. Anselmino, M. Boglione,
U. D'Alesio, E. Leader, F. Murgia,
In preparation

Unpolarized lepton, polarized nucleon target

$$
\begin{aligned}
(\sigma_{0+}^{(\Lambda+\bar\Lambda)})_p - (\sigma_{0+}^{(\Lambda+\bar\Lambda)})_n &= \frac{1}{3}(\Delta u+\Delta\bar u - \Delta d - \Delta\bar d)\Delta D_u^{\Lambda+\bar\Lambda} \\
(\sigma_{0+}^{(\Lambda-\bar\Lambda)})_p - (\sigma_{0+}^{(\Lambda-\bar\Lambda)})_n &= \frac{1}{3}(\Delta u_v - \Delta d_v)\Delta D_u^{\Lambda-\bar\Lambda}
\end{aligned}
$$

$$
\begin{aligned}
(\sigma_{0+}^{(\Lambda+\bar\Lambda)})_p + (\sigma_{0+}^{(\Lambda+\bar\Lambda)})_n &= \frac{1}{9}[5(\Delta u+\Delta\bar u + \Delta d + \Delta\bar d)\Delta D_u^{\Lambda+\bar\Lambda} \\
&\quad +2(\Delta s+\Delta\bar s)\Delta D_s^{\Lambda+\bar\Lambda}] \\
(\sigma_{0+}^{(\Lambda-\bar\Lambda)})_p + (\sigma_{0+}^{(\Lambda-\bar\Lambda)})_n &= \frac{1}{9}[5(\Delta u_v + \Delta d_v)\Delta D_u^{\Lambda-\bar\Lambda} + \\
&\quad +2(\Delta s-\Delta\bar s)\Delta D_s^{\Lambda-\bar\Lambda}]
\end{aligned}
$$

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Unpolarized lepton, TRANSVERSELY polarized nucleon target

$$\boxed{\begin{aligned}(\sigma_{0+}^{(\Lambda+\bar\Lambda)})_p - (\sigma_{0+}^{(\Lambda+\bar\Lambda)})_n &= \frac{1}{3}(\Delta_T u - \Delta_T d)\Delta_T D_u^{\Lambda+\bar\Lambda} \\ (\sigma_{0+}^{(\Lambda-\bar\Lambda)})_p - (\sigma_{0+}^{(\Lambda-\bar\Lambda)})_n &= \frac{1}{3}(\Delta_T u_v - \Delta_T d_v)\Delta_T D_u^{\Lambda-\bar\Lambda}\end{aligned}}$$

$$\boxed{\begin{aligned}(\sigma_{0+}^{(\Lambda+\bar\Lambda)})_p + (\sigma_{0+}^{(\Lambda+\bar\Lambda)})_n &= \frac{1}{9}[5(\Delta_T u + \Delta_T d)\Delta_T D_u^{\Lambda+\bar\Lambda} \\ (\sigma_{0+}^{(\Lambda-\bar\Lambda)})_p + (\sigma_{0+}^{(\Lambda-\bar\Lambda)})_n &= \frac{1}{9}[5(\Delta_T u_v + \Delta_T d_v)\Delta_T D_u^{\Lambda-\bar\Lambda}\end{aligned}}$$

where

$$\Delta_T q \equiv \Delta_T q + \Delta_T \bar q \equiv h_1^q + h_1^{\bar q}$$

$$\Delta_T q_v \equiv \Delta_T q - \Delta_T \bar q \equiv h_1^q - h_1^{\bar q}$$

and we have taken

$$\Delta_T s = \Delta_T \bar s = 0$$

M. Anselmino, M. Boglione,
U. D'Alesio, E. Leader, F. Murgia,
In preparation

Single spin asymmetries are an important tool to learn about distribution and fragmentation functions, and ultimately to study the spin content of nucleons.

The study of the angular distribution of the $\Lambda \to p\pi$ decay allows a simple and direct measurement of the spin properties of the quark hadronization.

Spin-flavour decomposition of polarized SIDIS could allow a considerable step forward in the study of the soft distribution and fragmentation processes if cross sections rather than asymmetries were available.

Interplay between theoretical modeling and experimental work is crucial.

QCD solution(s) to an ancient puzzle: large transverse spin asymmetries.

Elliot Leader
Imperial College, London
(in collaboration with M.Boglione, Vrije Universiteit, Amsterdam)

The very large asymmetries (up to 30-40%) under reversal of the direction of the transverse spin of the polarized proton in semi-inclusive reactions like pp-->hX has long been a puzzle, since ,in the standard approach the basic underlying PQCD parton-parton asymmetry vanishes in LO, and is negligibly small in higher order.

Three different SOFT mechanisms have been suggested as the origin of these aymmetries.

Consider a proton with momentum P and spin vector S.

1) In the Sivers mechanism the number density of quarks of momentum xP + k_T depends upon S via a term S.(P * k_T).

However, such a term violates time-reversal invariance and is not considered further.

2) Surprisingly, the analogous effect (the Collins mechanism) in the fragmentation of a quark of momentum p and spin vector s into a hadron of momentum zp + k_T CAN depend upon s via s.(p * k_T) without violating time reversal invariance.

3) The Efremov-Teryaev and Qiu-Sterman mechanisms require the introduction of a higher twist correlated density giving the joint probability of finding a quark with momentum xp and a gluon with momentum yp in the proton.

The achievement of a non-zero asymmetry requires taking seriously the existence of a pole in the perturbative quark or gluon propagator. Since confinement implies the absence of a pole in the complete propagators, this may be a contentious issue.

We concentrate on the Collins mechanism in p + p --> pion + X (with --> over the first p). The asymmetry depends upon a convolution of the quark transverse spin density [Delta_T q](x) and the Collins fragmentation function [Delta_N D_pion/q](z, k_T) . A vital role is played by the Soffer bound

| [Delta_Tq](x) | < 1/2 (q(x) + Deltaq(x))

and the positivity bound

| [Delta_ND_pion/q] | < 2D_pion/q

where the RHS is the unpolarized fragmentation function.

The main results are:

1) It is impossible to fit the pi(-) data if a standard (negative) polarized Deltad(x) is used in the RHS of the Soffer bound for [Delta_Td](x).

2) A fit is possible if Deltad(x) obeys the PQCD rule that

Deltad(x) --> d(x) as x-->1, i.e. changes sign and becomes positive as x-->1.

3) This has dramatic consequences for the NEUTRON g_1(x) at large x.

4) We obtain the first ever information on [Delta_Tu](x) and [Delta_Td](x) and on [Delta_ND_pion/q](z) in a consistent theoretical treatment.

5) The results are surprising. The magnitudes of [Delta_Tu](x) and [Delta_Td](x) are much smaller than would be expected in a non-relativistic treatment. And the first moments are much smaller than lattice or QCD sum rule estimates .
On the other hand, the magnitude of [Delta_ND_pion/q] is large, almost saturating the positivity bound.

6) In all the above mechanisms the intrinsic transverse momentum is essential and the asymmetry will vanish when

| p_T^pion | >> | k_T |

where k_T is the intrinsic transverse momentum of either the quark in the proton or of the pion in the fragmenting quark.

We are at present studying a more careful treatment of the kinematics in the reaction.

SEMI-INCLUSIVE HADRON-HADRON SINGLE TRANSVERSE SPIN ASYMMETRIES : THE IMPLICATIONS FOR $\Delta_T q(x)$

AND

FOR $g_1^n(x)$.

ELLIOT LEADER, Imperial College, London.

(IN COLLABORATION WITH ELENA BOGLIONE)

1) COLLINS MECHANISM AS EXPLANATION OF LARGE ASYMMETRIES IN

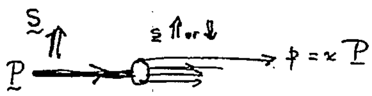
$$p^{\uparrow} + p \to \pi + X$$

2) CRUCIAL ROLE OF SOFFER BOUND AND CONSEQUENCES FOR $g_1^n(x)$

3) PUZZLING ASPECTS OF RESULTS.

3) TRANSVERSE POLARIZED DENSITY $\Delta_T q(x)$

(Sometimes called $h_1(x)$ or $\delta q(x)$)



$q_\uparrow(x)$, $q_\downarrow(x)$ = NUMB. DENSITY .... WITH TRANSVERSE SPIN ALONG ($\uparrow$) OR OPPOSITE ($\downarrow$) TO NUCEON $\underset{\sim}{S} \Uparrow$

$$\Delta_T q(x) \equiv q_\uparrow(x) - q_\downarrow(x)$$

N.B. 1) CANNOT MEASURE VIA DIS WITH TRANSVERSELY POLD. TARGET.

2) $g_2(x)$ DOES NOT TELL YOU ABOUT $\Delta_T q(x)$.

THREE INDEPENDENT FUNCTIONS, ALL OF EQUAL IMPORTANCE :

$$q(x), \quad \Delta q(x), \quad \Delta_T q(x)$$

HOW CAN YOU DETERMINE $\Delta_T q(x)$?

a) MOST DIRECTLY IN DRELL-YAN USING A TRANSVERSELY POLD. TARGET:

$$p + p^{\Uparrow} \longrightarrow l^+ l^- + X$$

AND MEASURING ASYMMETRY UNDER $\Uparrow \rightarrow \Downarrow$

HAS NEVER BEEN DONE ----

BUT RHIC WILL DO IT !

b) IN SEMI-INCLUSIVE HADRON-HADRON REACTIONS WITH TRANSVERSELY POLD. TARGET

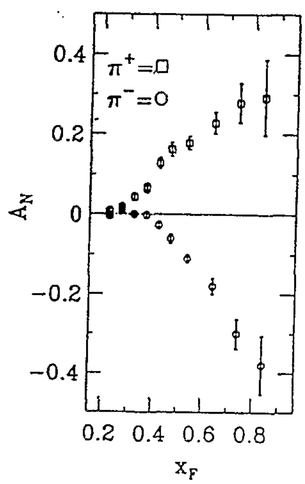
NEEDS — A NEW THEORETICAL IDEA

MAY BE — RESOLUTION OF ANCIENT PUZZLE.

MASS OF DATA ON

$$A^{\Uparrow} + B \rightarrow C + X \qquad \text{MEASURE} \quad A_N = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}$$

SOME EXAMPLES OF DATA :—



$p^{\uparrow} p \rightarrow \pi^{\pm} X$ at. 200 GeV/c.

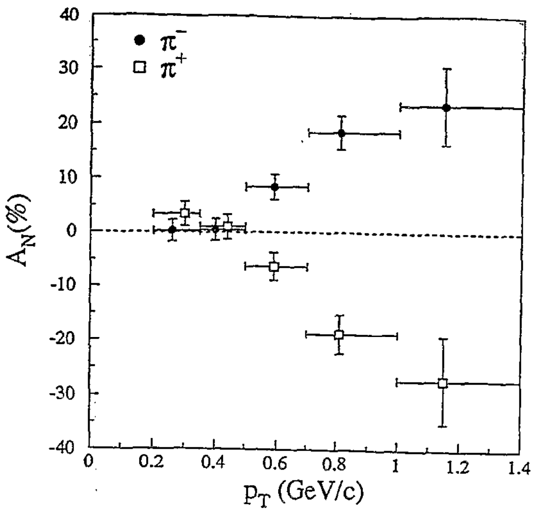


FIG. 2. A_N data as a function of p_T for π^- (full circles) and π^+ (open squares) in the x_F range of 0.2–0.9. For clarity the first two π^- (π^+) data points are offset by −.02 (+.02) GeV/c.

$$\bar{p}^{\uparrow} p \to \pi^{\pm} X \quad \text{at} \quad 200 \ \text{GeV/c}$$

SEE THAT :—

a) ASYMMETRIES ARE LARGE!

b) INCREASE WITH p_T

c) INCREASE WITH x_F

d) SEEM INDEPENDENT OF ENERGY

e) OCCUR IN VARIETY OF REACTIONS.

* FOR ≈ 25 YEARS NO THEORETICAL EXPLANATION

* PERTURBATIVE QCD SEEMS TO GIVE ZERO

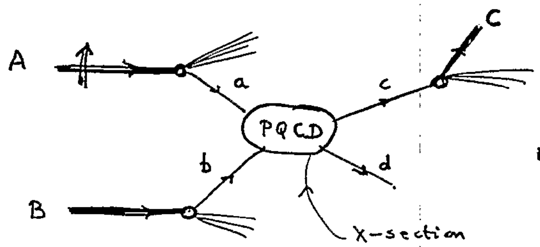
SHALL DISCUSS :—

1) EXPLANATION MAY BE PQCD + NEW SOFT MECHANISM (COLLINS)

2) GIVES INFORMATION ABOUT $\Delta_T q(x)$.

3) SURPRISINGLY, THIS HAS INTERESTING IMPLICATIONS FOR $\Delta q(x)$

Standard parton approach.



NOT Feynman Diag.

Asymmetry at parton level ($\hat{a}_N$) is zero in LO.

e.g. $q_a^{\Uparrow} + q_b \rightarrow q_c + q_d$

$$\hat{a}_N \propto \mathrm{Im}\left\{ (\text{NON-FLIP})^* \, (\text{SINGLE-FLIP}) \right\}$$

ZERO BECAUSE NO HELICITY-FLIP IN PQCD

ALSO ZERO BECAUSE REAL in LO.

Higher order in PQCD ??

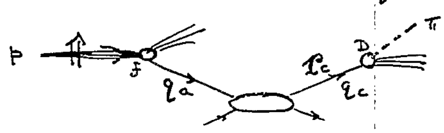
$$\hat{a}_N = \alpha_s \frac{m_q}{\sqrt{\hat{s}}} f(\theta^*)$$

Much too small !

Other mechanisms : $p^\uparrow p \rightarrow \pi^\pm X$

Concentrate only on partons in polarized hadron (proton).

Dominant process is quark $\rightarrow \pi$.



Proceed blindly ....

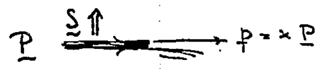
$$d\sigma^{\Uparrow} - d\sigma^{\Downarrow} = \left[f_{q_a/p^{\Uparrow}} - f_{q_a/p^{\Downarrow}} \right] \cdot \hat{\sigma} \cdot D^{\pi/q}_{\text{unpol'd}}$$

$$+ \left[f_{q_a^{\uparrow}/p^{\Uparrow}} - f_{q_a^{\downarrow}/p^{\Uparrow}} \right] \cdot \Delta\hat{\sigma} \cdot \left[D_{\pi/q_c}(p_c) - D_{\pi/q_c}(-p_c) \right]$$

WHAT IS POSSIBLE?

1) WITH USUAL COLLINEAR KINEMATICS.

$$f_{q/p^{\Uparrow}} - f_{q/p^{\Downarrow}} = 0$$

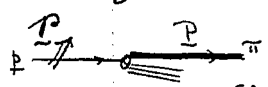


ONLY $\begin{cases} 1 \text{ PSEUDO-VECTOR} \\ 1 \text{ VECTOR.} \end{cases}$

CANNOT CONSTRUCT SCALAR WHICH DEPENDS ON $\underline{S}$ AND $\underline{P}$

ALSO

$$D_{\pi/q}(\underline{\mathcal{P}}) - D_{\pi/q}(-\underline{\mathcal{P}}) = 0$$

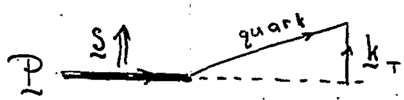


AGAIN ONLY $\begin{cases} 1 \text{ PSEUDO-VECTOR} \\ 1 \text{ VECTOR.} \end{cases}$

CANNOT CONSTRUCT SCALAR.

$\therefore$ ZERO ASYMMETRY.

2) WITH INTRINSIC TRANSVERSE MOMENTUM



$$p^{\text{quark}} = x\underline{P} + \underline{k}_T$$

$$f_{q/p(\underline{S})}(x, \underline{k}_T) = f(x, k_T) + \tilde{f}(x, k_T)\, \underline{S}\cdot(\underline{P}\times\underline{k}_T)$$

$$\Rightarrow \quad f_{q/p^{\Uparrow}} - f_{q/p^{\Downarrow}} \neq 0 \quad \text{(SIVERS)}$$

BUT VIOLATES TIME REVERSAL INVARIANCE !

AND

$$\underline{P}^{\pi} = z\,p + \underline{k}_T^{\pi}$$

$$D_{\pi/q(\underline{\mathcal{P}})}(z, \underline{k}_T^{\pi}) = D_{\pi/q}(z, k_T^{\pi}) + \Delta_N D_{\pi/q}(z, k_T^{\pi})\, \underline{\mathcal{P}}\cdot(p\times\underline{k}_T^{\pi})$$

Sometimes called $H_1^{\perp}$

$$\Rightarrow D_{\pi/q}(\boldsymbol{P}) - D_{\pi/q}(-\boldsymbol{P}) \neq 0$$

(COLLINS)

SURPRISINGLY THIS DOES NOT VIOLATE TIME REVERSAL.

HENCE

$$d\sigma^{\Uparrow} - d\sigma^{\Downarrow} = \overbrace{\left[f_{q_a/p^{\Uparrow}} - f_{q_a/p^{\Downarrow}} \right]}^{\to 0} \cdot \hat{\sigma} \cdot D^{\pi/q}_{\text{unpold}}$$

$$+ \quad \left[f_{q_a^{\Uparrow}/p^{\Uparrow}} - f_{q_a^{\Downarrow}/p^{\Uparrow}} \right] \cdot \Delta\hat{\sigma} \cdot \left[D_{\pi/q_c}(\boldsymbol{P}_c) - D_{\pi/q_c}(-\boldsymbol{P}_c) \right]$$

$$= \left[\Delta_T\, q_a \right] \cdot \left[\frac{d\hat{\sigma}}{d\hat{t}}(a^{\Uparrow} b \to c^{\Uparrow} d) - \frac{d\hat{\sigma}}{d\hat{t}}(a^{\Uparrow} b \to c^{\Downarrow} d) \right] \cdot$$

$$\cdot \left[\Delta_N D_{\pi/c} \right]$$

IN FULL DETAIL :-

$p^{\Uparrow} p \to \pi^{+,-,0}\, X$

$$d\sigma^{\Uparrow} - d\sigma^{\Downarrow} \propto \int dx_a\, dx_b\, d^2 p_T$$

$$\times \underbrace{q(x_b)}_{\text{KNOWN}} \underbrace{\Delta_T q(x_a)}_{\text{NEW}} \underbrace{\left[\frac{d\hat{\sigma}}{d\hat{t}}(a^{\Uparrow} b \to c^{\Uparrow} d) - \frac{d\hat{\sigma}}{d\hat{t}}(a^{\Uparrow} b \to c^{\Downarrow} d) \right]}_{\text{KNOWN}}$$

$$\times \underbrace{\Delta^N D_{\pi/c}(z, p_T)}_{\text{NEW}}$$

Measure $\displaystyle A_N = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}$

A_N LARGE, ESPECIALLY AT LARGE x_F ....

BUT MUST HAVE

$$\left| \Delta^N D_{\pi/c} \right| \leq 2 D_{\pi/c}$$

and Soffer Bound

$$\left| \Delta_T q(x) \right| \leq \tfrac{1}{2} \left[q(x) + \Delta q(x) \right]$$

HOW IMPORTANT IS THE SOFFER BOUND?

TYPICAL PICTURE OF $\Delta u(x)$, $\Delta d(x)$:

$\Delta u(x)$ IS POSITIVE EVERYWHERE

$\therefore$ $u(x) + \Delta u(x)$ IS BIG

$\therefore$ RHS OF SOFFER BOUND IS BIG

$\therefore$ NOT RESTRICTIVE ON $\Delta_T u(x)$.

BUT

$\Delta d(x)$ IS (USUALLY) NEGATIVE EVERYWHERE

$\therefore$ $d(x) + \Delta d(x)$ IS SMALL

$\therefore$ RHS OF SOFFER BOUND IS SMALL

$\therefore$ HIGHLY RESTRICTIVE ON $\Delta_T d(x)$

HOWEVER -----

π^+ COME MAINLY FROM u

π^- COME MAINLY FROM d

BUT

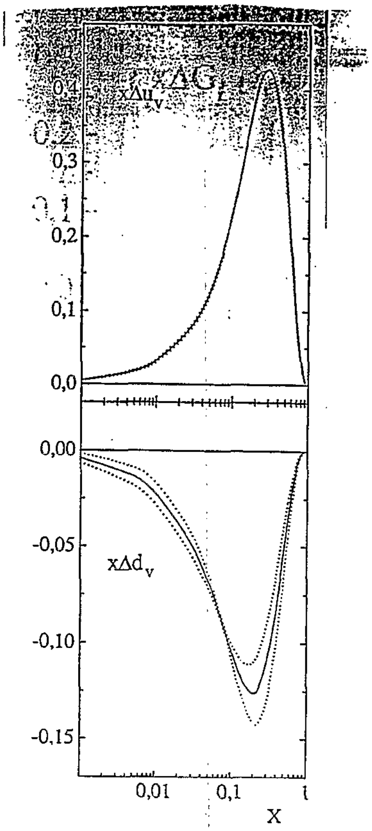
$$A_N^{\pi^-} \approx - A_N^{\pi^+}$$

SUGGESTS MAY BE TROUBLE WITH SOFFER

EXAMPLE : USE GEHRMANN – STIRLING

$\Delta u(x)$, $\Delta d(x)$ TO BOUND

$\Delta_T u(x)$ AND $\Delta_T d(x)$ (F.S)



Leader, Sidorov, Stamenov
fit to Pol'd. DIS.

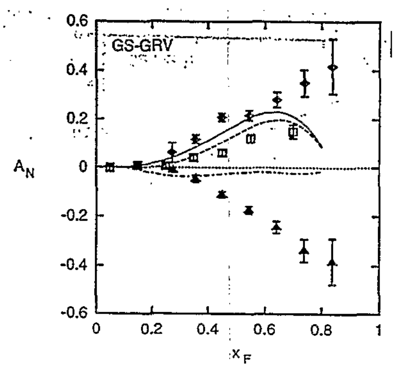


FIG. 1. Single spin asymmetry for pion production in the process $p^{\uparrow}p \to \pi X$ as a function of x_F obtained by using the GS-GRV [13,14] sets of distribution functions. The solid line refers to π^+ the dashed line to π^0 and the dash-dotted line to π^-.

RESULT : TOTAL FAILURE

$$\chi^2_{D.O.F} = 25 \ !$$

CAN WE ESCAPE THIS DILEMMA ?

A SURPRISING ESCAPE ROUTE !

OLD PQCD ARGUMENT, FOR QUARKS, ANTIQUARKS, GLUONS

$$\frac{\Delta q(x)}{q(x)} \longrightarrow 1 \quad \text{AS} \quad x \longrightarrow 1$$

$\Longrightarrow$ ALL $\Delta q(x)$ POSITIVE AT LARGE x

ALMOST ALL FITS TO POLD. DIS $\Delta d(x)$ IGNORE THIS. WHY ? Usual statement :–

1) INCOMPATIBLE WITH DGLAP EVOLUTION.
2) DATA DEMANDS NEGATIVE $\Delta d(x)$

BUT ---

1) DGLAP NOT VALID AS $x \longrightarrow 1$
(APPROACHING EXCLUSIVE REGION)
2) DATA DO NOT EXIST AT REALLY LARGE x

SO, TRY TO IMPOSE $\frac{\Delta q(x)}{q(x)} \longrightarrow 1$ AS $x \to 1$. IN DIS.

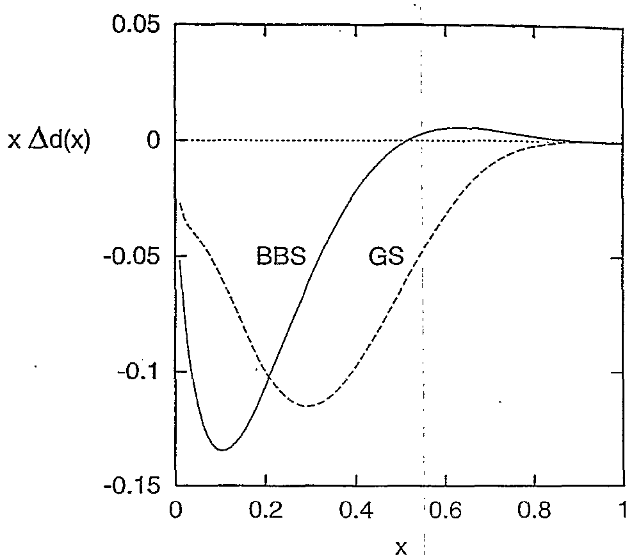
DONE BY BRODSKY, BURKHARDT, SCHMIDT (BBS)

O.K. ... BUT ROUGH TREATMENT — NO EVOLUTION.

IMPROVED BY LEADER, SIDOROV, STAMENOV (LSS) TO INCLUDE EVOLUTION.

FIT TO POLD. DIS QUITE GOOD.

COMPARE $\Delta d(x)$ IN GS AND BBS :



SEE THAT THE RHS OF SOFFER BOUND WILL NOT BE SO SMALL AT LARGE x FOR THE BBS CASE.

CONSEQUENCE IN $\vec{p}p \to \pi X$ IS DRAMATIC !

SIMPLIFICATIONS AND PARAMETRIZATION.

1) ASYMMETRY LARGEST AT LARGE x_F

$\Rightarrow$ LARGE x IMPORTANT

$\therefore$ USE ONLY u AND d QUARKS

2) LARGE $x_F \Rightarrow$ LARGE z IN FRAGMENTATION

$\therefore$ ASSUME $u \to \pi^+$, $d \to \pi^-$ ONLY

3) PARAMETRIZE SO THAT SOFFER BOUND IS AUTOMATICALLY RESPECTED.

$$\Delta_T q(x) = N_q \left[\frac{x^a (1-x)^b}{\dfrac{a^a b^b}{(a+b)^{a+b}}} \right] \left\{ \frac{1}{2}\left[q(x) + \Delta q(x) \right] \right\}$$

CONSTANT WITH $|N_q| \leq 1$

FUNCTION WHOSE MODULUS ≤ 1

SOFFER BOUND

$$\Delta_N D(z) = N_F \left[\frac{z^\alpha (1-z)^\beta}{\dfrac{\alpha^\alpha \beta^\beta}{(\alpha+\beta)^{\alpha+\beta}}} \right] \left\{ 2 D(z) \right\}$$

$|N_F| \leq 1$

KNOWN

RESULT ----

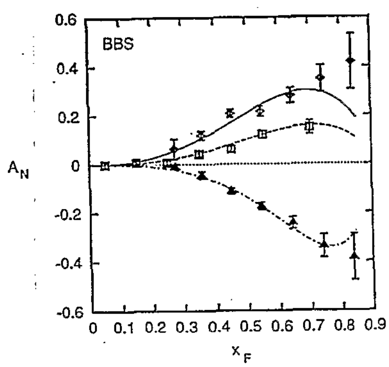
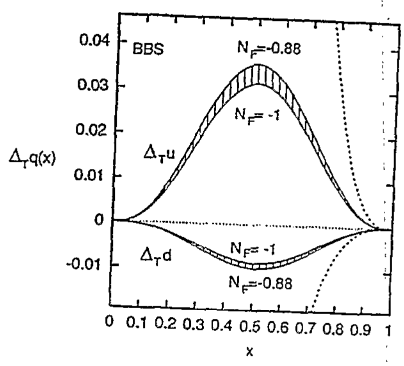


FIG. 7. The single spin asymmetry for pion production in the process $p^\uparrow p \to \pi X$ as a function of x_F, obtained by using the BBS [18] distribution functions. The solid line refers to π^+, the dashed line to π^0 and the dash-dotted line to π^-.

$$\chi^2_{D.O.F.} = 1.45$$



First ever determination of $\Delta_T u$, $\Delta_T d$

Note: 1) Magnitude much smaller than naive N.Rel. estimates.†

2) Sign of $\Delta_T u$ chosen to agree with SU(6) wave-function

† for non-large values of x.

DISCUSSION AND QUESTIONS

1) INFLUENCE ON $g_1^n(x)$ AT LARGE x

a) FOR $\Delta_T d(x)$ NOT TO BE "KILLED" BY SOFFER BOUND SEEMS TO REQUIRE

$$\Delta d(x)/d(x) \to 1 \quad \text{AS} \quad x \to 1$$

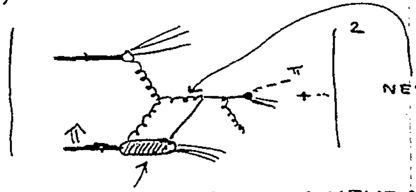
b) THIS IMPLIES $\Delta d(x)$ MUST CHANGE SIGN AND BECOME POSITIVE AT LARGE x.

c) IMPORTANT CONSEQUENCE FOR $g_1^n(x)$: (fig)

2) a) THE MAGNITUDES OF $\Delta_T u(x)$, $\Delta_T d(x)$ ARE SURPRISINGLY SMALL! (RHIC?!?)

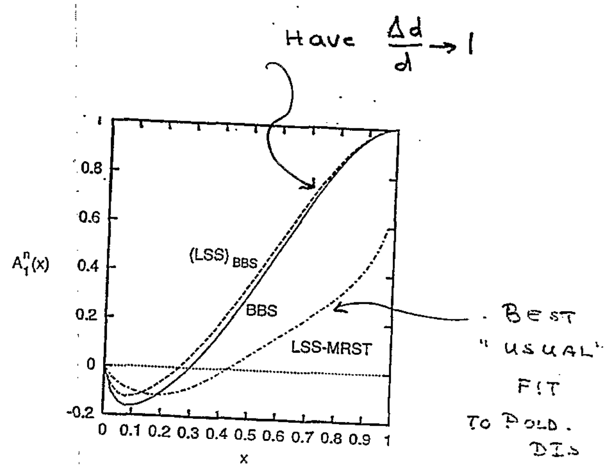
b) CANNOT FIT A_N AT LARGEST x_F

c) ARE OTHER MECHANISMS IMPORTANT?



WHY DO WE BELIEVE IN THE NAIVE POLE IN THE GLUON PROPAGATOR ??
(Efremov, Teryaev ; Sterman, Qiu)

EL-26


Have $\frac{\Delta d}{d} \to 1$
$A_1^n(x)$
(LSS) BBS
BBS
LSS-MRST
x
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
-0.2 0 0.2 0.4 0.6 0.8 1
BEST "USUAL" FIT TO POLD. DIS

Single Transverse Spin Asymmetries in Hadronic Reactions

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In the last years our group[1] has developed a phenomenological approach to the study of single transverse spin asymmetries for semi-inclusive particle production in hadronic collisions at high-energies and moderately large p_T [1]-[5].

This approach is basically an attempt to generalize the usual pQCD formalism for the study of $AB \to CX$ processes at high energies and large p_T, with the inclusion of spin and intrinsic transverse momentum effects in the partonic distribution and/or fragmentation functions. A new class of twist-2, nonperturbative, spin and $\mathbf{k}_\perp$ dependent distributions need to be introduced, which might be responsible for the sizeable single spin asymmetries measured experimentally in the past years (mostly at large, positive x_F). As it is well known, in fact, pQCD at leading twist and with collinear partonic configuration gives negligible single spin asymmetries and is not able to explain these experimental results.

The new, spin and $\mathbf{k}_\perp$ dependent distributions originate from soft, non-perturbative dynamics, which induces correlations between the intrinsic transverse momentum of, e.g., an unpolarized parton(hadron) inside(produced in the fragmentation of) a transversely polarized hadron(parton); this in turn results in an azimuthal asymmetry for the $\mathbf{k}_\perp$ dependence of the parton(hadron) probability distribution. The same is true when the transversely polarized particle is the final parton(hadron).

These distributions are not calculable from first principles in pQCD. However, a simple parameterized form can be derived by performing a fitting procedure to the best available experimental data. After that, if the general pQCD scheme is valid, factorization and universality should allow to use these parameterizations to give *predictions* for different processes. This procedure is completely analogous to that followed for the usual unpolarized, $\mathbf{k}_\perp$-integrated, parton distribution/fragmentation functions.

It can be shown that at leading twist there are four possible spin and $\mathbf{k}_\perp$ dependent contributions involving partons/hadrons with spin $S = 1/2$:

- $\Delta^N f_{q/p^\uparrow}(x,\mathbf{k}_\perp) = f_{q/p^\uparrow}(x,\mathbf{k}_\perp) - f_{q/p^\downarrow}(x,\mathbf{k}_\perp) = f_{q/p^\uparrow}(x,\mathbf{k}_\perp) - f_{q/p^\uparrow}(x,-\mathbf{k}_\perp)$, and $\Delta^N f_{q^\uparrow/p}(x,\mathbf{k}_\perp)$, in the distribution functions;
- $\Delta^N D_{h/q^\uparrow}(z,\mathbf{k}_\perp)$ and $\Delta^N D_{h^\uparrow/q}(z,\mathbf{k}_\perp)$, in the fragmentation process.

Notice that all these functions are $\mathbf{k}_\perp$-odd: this means that we must keep trace of the $\mathbf{k}_\perp$ dependence also in the elementary partonic cross sections, otherwise integration

[1] The work presented here has been done in collaboration with M. Anselmino, M. Boglione, D. Boer, U. D'Alesio.

over intrinsic momentum always will lead to vanishing results for convolution integrals. Furthermore, all the functions are T-odd, which requires initial(final) state interactions. However, while final state interactions are clearly present in the fragmentation process, initial state interactions are more difficult to accomodate: they could spoil the factorization scheme and the universality of the corresponding distributions ($\Delta^N f_{q/p^\uparrow}$, $\Delta^N f_{q^\uparrow/p}$). Finally, the functions involving transversely polarized partons ($\Delta^N f_{q^\uparrow/p}$, $\Delta^N D_{h/q^\uparrow}$) are chiral-odd, and always must appear coupled with some other chiral-odd contribution; e.g. the process $p^\uparrow p \to \pi X$ could involve $\delta q(x) \otimes \Delta^N D_{h/q^\uparrow}(z)$.

Depending on the specific process considered, two or more of these functions can contribute simultaneously. However, as a first step all phenomenological studies performed at present consider one of these contributions at a time. Of special interest are those processes where one of the contributions can be expected to be dominant; in this case one can hope to get precise information on this contribution, to be used in the study of more complicate processes.

For example, in the process $p^\uparrow p \to \gamma X$ only contributions from the partonic distributions can obviously be present. Analogously, in semi-inclusive DIS one can imagine that the contributions in the fragmentation process are dominant.

In any case, it is clear that only an extensive research program which compares and analyzes simultaneously all the physical processes which are (or could be in the near future) experimentally accessible may help us to really disentangle among the several competing contributions and the different proposed theoretical approaches.

Based on these considerations, in the last years we have studied several processes involving the so-called Sivers ($\Delta^N f_{q/p^\uparrow}$) [1, 2] and Collins ($\Delta^N D_{h/q^\uparrow}$) [3, 4] functions; more recently, we have also considered processes where $\Delta^N f_{q^\uparrow/p}$ and $\Delta^N D_{h^\uparrow/q}$ could be relevant [5].

In this contribution I will present in details the results of our research program for two interesting processes: $p^\uparrow p \to \pi X$ (Sivers effect only) and $pp \to \Lambda^\uparrow X$.

1) $p^\uparrow p \to \pi X$

Starting from the general formalism described above, it is easy to show that in this case there are three possible twist-two functions contributing: $\Delta^N f_{q/p^\uparrow}(x,\mathbf{k}_\perp)$, $\Delta^N f_{q^\uparrow/p}(x,\mathbf{k}_\perp)$, and $\Delta^N D_{\pi/q^\uparrow}(z,\mathbf{k}_\perp)$. Notice that sizeable single spin asymmetries have been measured in the large, positive x_F region. From this point of view, the contribution from $\Delta^N f_{q^\uparrow/p}(x,\mathbf{k}_\perp)$ somehow disentangles from the other two. In fact, this effect comes from the unpolarized, target hadron, and should give non-negligible contributions only in the large, *negative* x_F region. On the other hand, $\Delta^N f_{q/p^\uparrow}(x,\mathbf{k}_\perp)$ (the Sivers function) and $\Delta^N D_{\pi/q^\uparrow}(z,\mathbf{k}_\perp)$ (the Collins function) could both be relevant in this kinematical regime. As already mentioned, however, the first phenomenological studies take into account only one of these contributions at a time. Here we concentrate on the Sivers effect, since Collins effect for this process will be discussed in details elsewhere in this workshop (see the contribution by E. Leader). For a discussion of Collins effect in our approach see ref.s [3, 4].

We have first performed a fit to the experimental results from the E704 Collaboration at Fermilab [6]. The quality of the fit is good and the parameterizations obtained for the Sivers function (for u and d quarks) are quite reasonable. These parameterizations show that in order to reproduce the experimental results, the ratio $\Delta^N f_{q/p^\uparrow}/f_q$ must be positive for u quarks and negative for d quarks; it must grow in size when the parton momentum fraction x increases, up to around 0.4-0.5 for large x values.

Using these parameterizations, we can give results for A_N vs. x_F, at fixed $p_T = 1.5$ GeV, for other interesting processes, in the same kinematical regime covered by the E704 experiment. Examples are: $\bar{p}^\uparrow p \to \pi X$, $p^\uparrow p \to \gamma X$, $p^\uparrow p \to K_S X$, etc.

We also discuss in some details the p_T dependence of our results and give some predictions for $A_N(p^\uparrow p \to \pi X)$ in the kinematical regime of interest for RHIC experiments.

It is interesting to notice that the p_T behaviour of A_N seems to be quite different in the kinematical regimes of FNAL-E704 and RHIC experiments ($\sqrt{s} \sim 20$ GeV and $\sqrt{s} \sim 200$ GeV, respectively). In the E704 case, our predictions show a mild dependence on (a small decrease with) p_T in the range $1.5 < p_T < 4.0$ GeV. In the case of RHIC our results show a stronger dependence on p_T.

2) $pp \to \Lambda^\uparrow X$

Hyperon polarization in unpolarized $p-p$, $p-A$ collisions is a longstanding problem for particle physics and pQCD. The huge amount of experimental data collected for the Λ particle can be summarized as follows [7]: the Λ polarization is negative and can be as large as 30% in size. As a function of p_T, $|A_N|$ starts from zero and grows as p_T increases, up to $p_T \sim 1$ GeV. For larger p_T, $|A_N|$ seems to show a "plateau behaviour", up to the highest reachable p_T values. The value of $|A_N|$ in the plateau region increases almost linearly with x_F. On the contrary, $A_N(\bar{\Lambda})$ seems to be compatible with zero, at least in the range $0 \le x_F \le 0.3$.

One point of interest in our theoretical approach is that we can find a common origin for single spin asymmetries in $p^\uparrow p \to \pi X$ and $pp \to \Lambda^\uparrow X$ processes. In our scheme, in fact, we can get contributions to transverse Λ polarization, $A_N(pp \to \Lambda^\uparrow X)$, from the following twist-two functions: $\Delta^N f_{q^\uparrow/p}(x, \mathbf{k}_\perp)$ (from the initial unpolarized protons), and $\Delta^N D_{\Lambda^\uparrow/q}(z, \mathbf{k}_\perp)$ (which we call "polarizing fragmentation function").

However, since there is some experimental evidence that the mechanism responsible for hyperon polarization should be in the fragmentation process, as a first step we have considered only the contribution from the function $\Delta^N D_{\Lambda^\uparrow/q}(z, \mathbf{k}_\perp)$. This assumption can be tested by looking at Λ polarization in semi-inclusive DIS [8].

We have performed a fit to the experimental data available for Λ and $\bar{\Lambda}$ polarization (with $p_T > 1$ GeV and $x_F > 0$), in order to derive a parameterization for $\Delta^N D_{\Lambda^\uparrow/q}(z)$. Results of our fit and details of the parameterizations are shown. Once more, one seems to be able to reproduce with good accuracy all the main features of the experimental results with very reasonable parameterizations for the twist-two polarizing fragmentation function, $\Delta^N D_{\Lambda^\uparrow/q}$. In particular, it results that $\Delta^N D_{\Lambda^\uparrow/u,d} < 0$, $\Delta^N D_{\Lambda^\uparrow/s} > 0$, and $|\Delta^N D_{\Lambda^\uparrow/u,d}| < \Delta^N D_{\Lambda^\uparrow/s}$. These conclusions are almost independent of the particular set of unpolarized Λ fragmentation functions adopted, which are also known with relatively low accuracy.

The results presented here are very encouraging: they show that in our approach it seems possible to reproduce most of the available experimental results (with $p_T > 1$ GeV and $x_F > 0$) by using quite reasonable parameterizations for the new twist-two, $\mathbf{k}_\perp$ dependent distribution/fragmentation functions. We are also able to give predictions for several other processes which could be investigated in running and/or proposed experimental set-ups (RHIC, Rampex, SMC, HERMES, HERA-N, etc.).

In particular, RHIC experiments should allow a detailed investigation of several of the processes considered, particularly in the almost unexplored high-energy, large p_T regime, where our models are expected to be more reliable and could be tested more severely.

At present we are still at the beginning of our full phenomenological program. Among other things, one needs to consider in a more refined way the $\mathbf{k}_\perp$ kinematics, which in the present analysis is treated in a simplified way; one should look to what happens when two (or more) of these polarized, $\mathbf{k}_\perp$ dependent functions are at work simultaneously, which makes the analysis much more complicate.

However, it seems that in near future we will be able to test in details our approach (and similar and/or competing ones) and learn a lot about the mechanism(s) responsible for single spin asymmetries at moderately large p_T. RHIC experiments will play a fundamental role on this respect, particularly in extending the p_T range available, a crucial point for testing pQCD-based approaches.

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[4] M. Anselmino, F. Murgia, *Phys. Lett.* **B483** (2000) 74.
[5] M. Anselmino, D. Boer, U. D'Alesio, F. Murgia, e-print Archive: hep-ph/0008186.
[6] See D.L. Adams *et al.* (E704 Collaboration), *Phys. Lett.* **B264** (1991) 462; *Phys. Rev. Lett.* **77** (1996) 2626; *Phys. Rev. Lett.* **78** (1997) 4003, and references therein.
[7] For a review of data see, *e.g.*, K. Heller, in Proceedings of Spin 96, C.W. de Jager, T.J. Ketel and P. Mulders, Eds., World Scientific (1997).
[8] M. Anselmino, D. Boer, U. D'Alesio, F. Murgia, work in progress.

SINGLE TRANSVERSE SPIN ASYMMETRIES IN HADRONIC REACTIONS

M. Anselmino, Torino; D. Boer, BNL; M. Boglione, Amsterdam; U. D'Alesio, Cagliari; J. Hansson, Gävle-Sweden; E. Leader, London.

- Sketch of the approach.
  A generalization of pQCD formalism for inclusive hadronic processes, $AB \to CX$, including spin and transverse momentum, $\vec{k}_\perp$, effects in the partonic distribution and/or fragmentation functions.

- Results (fits/predictions).
  - $p^\uparrow(\bar{p}^\uparrow)\, p \to \pi, K, \gamma\; X$
  - $\ell p^\uparrow \to \pi X$
  - $\ell p^\uparrow \to \ell' \pi X$
  - $pp \to \Lambda^\uparrow X$

- Conclusions and outlook.

The approach

- Inclusive hadronic processes at large p_T, $AB \to CX$.
  pQCD, factorization theorems, at leading twist and in collinear configuration, give for the unpolarized cross section

$$E_C \frac{d\sigma^{AB\to CX}}{d^3 p_C} = \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{\pi z} f_{a/A}(x_a) f_{b/B}(x_b) \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}} D_{C/c}(z)$$

- pQCD results hold with polarized particles as well.
  Ex:
  $$A, S_A + B, S_B \longrightarrow C + X$$

$$E_C \frac{d\sigma^{A,S_A+B,S_B\to C+X}}{d\vec{p}_C} = \sum_{abcd} \sum_{\substack{\lambda_a\lambda'_a;\lambda_b\lambda'_b \\ \lambda_c\lambda'_c;\lambda_d\lambda_C}} \int \frac{dx_a\, dx_b}{\pi z} \frac{1}{16\pi \hat{s}^2}$$

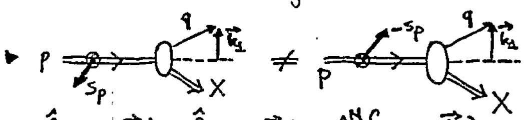
$$\times\, \rho^{a/A,S_A}_{\lambda_a\lambda'_a} f_{a/A}(x_a)\; \rho^{b/B,S_B}_{\lambda_b\lambda'_b} f_{b/B}(x_b)$$

$$\times\, \hat{M}_{\lambda_c\lambda_d;\lambda_a\lambda_b} \hat{M}^*_{\lambda'_c\lambda_d;\lambda'_a\lambda'_b} D^{\lambda_c\lambda'_c}_{\lambda_C\lambda_C}(z)$$

- No single transverse spin asymmetries A_N at leading twist and collinear partonic configuration.

- In a generalized approach (including partonic $\vec{k}_\perp$) a set of new (non perturbative), twist-2, spin and $\vec{k}_\perp$ dependent partonic distr. and fragm. functions may in principle lead to sizeable values of A_N.

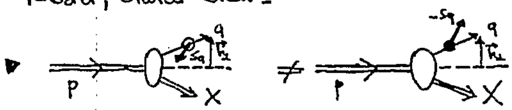
■ Partonic distribution functions.



- $\hat{f}_{q/p^\uparrow}(x,\vec{k}_\perp) - \hat{f}_{q/p^\downarrow}(x,\vec{k}_\perp) = \Delta^N f_{q/p^\uparrow}(x,\vec{k}_\perp)$ $\quad [f_{1T}^\perp]$

$\hookrightarrow \hat{f}_{q/p^\uparrow}(x,\vec{k}_\perp) - \hat{f}_{q/p^\uparrow}(x,-\vec{k}_\perp)$

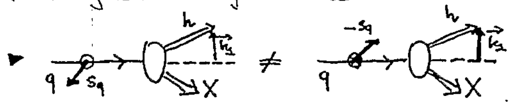
T-odd, chiral-even.



- $\hat{f}_{q^\uparrow/p}(x,\vec{k}_\perp) - \hat{f}_{q^\downarrow/p}(x,\vec{k}_\perp) = \Delta^N f_{q^\uparrow/p}(x,\vec{k}_\perp)$ $\quad [h_1^\perp]$

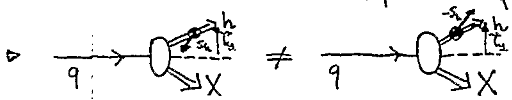
T-odd, chiral-odd $\Rightarrow [\Delta^N f_{q^\uparrow/p} \otimes \Delta_T D]$

■ Fragmentation functions.



- $\hat{D}_{h/q^\uparrow}(z,\vec{k}_\perp) - \hat{D}_{h/q^\downarrow}(z,\vec{k}_\perp) = \Delta^N D_{h/q^\uparrow}(z,\vec{k}_\perp)$ $\quad [H_1^\perp]$

T-odd, chiral-odd $\Rightarrow [\Delta_T q \otimes \Delta^N D_{h/q^\uparrow}]$



- $\hat{D}_{h^\uparrow/q}(z,\vec{k}_\perp) - \hat{D}_{h^\downarrow/q}(z,\vec{k}_\perp) = \Delta^N D_{h^\uparrow/q}(z,\vec{k}_\perp)$ $\quad [D_{1T}^\perp]$

T-odd, chiral-even

■ Example 1: $p^\uparrow p \to \pi X$

$$N[A_N] = E_\pi \frac{d\sigma^{p^\uparrow p\to\pi X}}{d\vec{p}_\pi} - E_\pi \frac{d\sigma^{p^\downarrow p\to\pi X}}{d\vec{p}_\pi}$$

$$= \sum_{abcd} \int \frac{dx_a\, dx_b}{\pi z} \Big\{ \int d^2\vec{k}_\perp \underbrace{\Delta^N f_{a/p^\uparrow}(x_a,\vec{k}_\perp)} f_{b/p}(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(x_a,x_b;\vec{k}_\perp) D_{\pi/c}(z)$$

$$+ \int d^2\vec{k}'_\perp h_1^{a/p}(x_a) f_{b/p}(x_b) \Delta_{NN}\hat{\sigma}(x_a,x_b;\vec{k}'_\perp) \underbrace{\Delta^N D_{\pi/c^\uparrow}(z,\vec{k}'_\perp)}$$

$$+ \int d^2\vec{k}''_\perp h_1^{a/p}(x_a) \underbrace{\Delta^N f_{b^\uparrow/p}(x_b,\vec{k}''_\perp)} \Delta'_{NN}\hat{\sigma}(x_a,x_b;\vec{k}''_\perp) D_{\pi/c}(z) \Big\}$$

- $\Delta_{NN}\hat{\sigma} = \dfrac{d\hat{\sigma}^{a^\uparrow b\to c^\uparrow d}}{d\hat{t}} - \dfrac{d\hat{\sigma}^{a^\uparrow b\to c^\downarrow d}}{d\hat{t}}$; double spin asymmetries for the partonic process
- $\Delta'_{NN}\hat{\sigma} = \dfrac{d\hat{\sigma}^{a^\uparrow b^\uparrow\to cd}}{d\hat{t}} - \dfrac{d\hat{\sigma}^{a^\uparrow b^\downarrow\to cd}}{d\hat{t}}$

Note: all $\Delta^N f$, $\Delta^N D$ are $k_\perp$-odd; we must keep $k_\perp$ effects somewhere else in the convolution integral (see cross-sections above);
this makes the overall effect on physical observables a twist-3 effect.

■ Example 2: $pp \to \Lambda^{\uparrow} X$

$$N[P_y(\Lambda)] = E_\Lambda \frac{d\sigma^{pp\to\Lambda^{\uparrow}X}}{d\vec{P}_\Lambda} - E_\Lambda \frac{d\sigma^{pp\to\Lambda^{\downarrow}X}}{d\vec{P}_\Lambda}$$

$$= \sum_{abcd} \int \frac{dx_a\, dx_b}{\pi z} \Big\{ \int d^2\vec{k}_\perp\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, \frac{d\hat{\sigma}}{d\hat{t}}(x_a, x_b; \vec{k}_\perp)\, \underline{\Delta^N D_{\Lambda^{\uparrow}/c}(z, \vec{k}_\perp)}$$

$$+ \int d^2\vec{k}'_\perp\, \underline{\Delta^N f_{a^{\uparrow}/p}(x_a, \vec{k}'_\perp)}\, f_{b/p}(x_b)\, \Delta_{NN}\hat{\sigma}(x_a, x_b; \vec{k}'_\perp)\, \Delta_T D_{\Lambda/c}(z)$$

$$+ \int d^2\vec{k}''_\perp\, f_{a/p}(x_a)\, \underline{\Delta^N f_{b^{\uparrow}/p}(x_b, \vec{k}''_\perp)}\, \Delta'_{NN}\hat{\sigma}(x_a, x_b; \vec{k}''_\perp)\, \Delta_T D_{\Lambda/c}(z) \Big\}$$

- $\Delta_{NN}\hat{\sigma} = \frac{d\hat{\sigma}^{a^{\uparrow}b\to c^{\uparrow}d}}{d\hat{t}} - \frac{d\hat{\sigma}^{a^{\uparrow}b\to c^{\downarrow}d}}{d\hat{t}}$
- $\Delta'_{NN}\hat{\sigma} = \frac{d\hat{\sigma}^{ab^{\uparrow}\to c^{\uparrow}d}}{d\hat{t}} - \frac{d\hat{\sigma}^{ab^{\uparrow}\to c^{\downarrow}d}}{d\hat{t}}$

Process	$\Delta^N f_{q/p^{\uparrow}}$ $f_{1T}^{\perp}$	$\Delta^N f_{q^{\uparrow}/p}$ $h_1^{\perp}$	$\Delta^N D_{h/q^{\uparrow}}$ $H_1^{\perp}$	$\Delta^N D_{h^{\uparrow}/q}$ $D_{1T}^{\perp}$
$p^{\uparrow}p \to \pi X$	yes	yes ($x_F<0$)	yes	no
$p^{\uparrow}p \to \gamma X$	yes	yes ($x_F<0$)	no	no
$p^{\uparrow}p \to \ell^-\ell^+ X$	yes	yes ($x_F<0$)	no	no
$\ell p^{\uparrow} \to \pi X$	no?	no	yes	no
$\ell p^{\uparrow} \to \ell' \pi X$	no?	no	yes	no
$pp \to \Lambda^{\uparrow} X$	no	yes	no	yes
$\ell p \to \ell' \Lambda^{\uparrow} X$	no	no?	no	yes
$\nu p \to \ell \Lambda^{\uparrow} X$	no	no?	no	yes
$\ell p^{\uparrow} \to \ell' \gamma X$	no?	no	no	no

■ Results for $p^\uparrow p \to \pi X$ [illegible]

$x_F \gtrsim 0.4$

▸ Sivers effect only $\left[\Delta^N f_{a/p^\uparrow}(x_a, \vec{k}_\perp)\right]$ $\quad x_a > x_F$

- Take only valence u,d quark contributions.
- Parametrize

$$\Delta^N f_{a/p^\uparrow}(x, \langle k_\perp \rangle) = \frac{\langle k_\perp \rangle}{M} N_a \, x^{\alpha_a} (1-x)^{\beta_a}$$

- $\dfrac{\langle k_\perp \rangle}{M} = 0.47\, x^{0.68} (1-x)^{0.48}$ $\quad$ (fit to theoretical estimates Stirling, Roberts)

$\vdash$ 6 parameters $\dashv$

- Fix N_a, α_a, β_a $(a = u, d)$ with best fit to exp. data for $p^\uparrow p \to \pi X$ from E704 Collab.

$$\Delta^N f_{u/p^\uparrow} = 6.90\, x^{2.02} (1-x)^{4.06}$$

$$\Delta^N f_{d/p^\uparrow} = -2.34\, x^{1.44} (1-x)^{4.62}$$

- $f_{a/p}(x)$: MRSG set $\qquad$ CTEQ, GRST98

$D_{\pi/c}(z)$: Binnewies et al. set $\qquad$ Greco-Rolli, Indumathi et al.

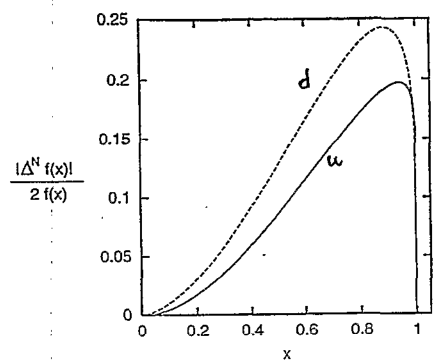


Figure 4: The ratio between $|\Delta^N f_{val}|$ and twice the valence unpolarized distribution function f, Eq. (29), as a function of x. The solid line refers to u quarks and the dashed line to d quarks. Notice that in both cases $|\Delta^N f|/2f \to 0$ for $x \to 1$.

Note: $|\Delta^N f| / (2f) \leq 1$

Exp. data : E704 Collab.

$p^{\uparrow}p \to \pi X$

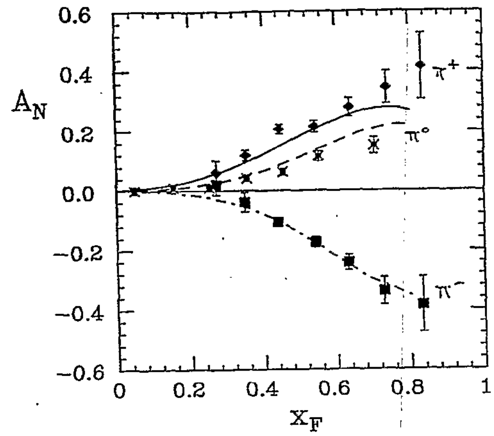


Fig. 1: Fit of the data on A_N for the process $p^{\uparrow}p \to \pi X$ [1], with the parameters given in Eq. (9); the upper, middle, and lower sets of data and curves refer respectively to π^+, π^0, and π^-.

$P_{Lab} = 200$ GeV/c $\quad 0.7 \leq p_T \leq 2$ GeV/c

$x_F = 2p_L/\sqrt{s}$

Theoretical curves : $p_T = 1.5$ GeV/c
Sivers effect only ($\Delta^N f_{q/p^{\uparrow}} \neq 0$)

Exp. data : E704 Collab., PRL 77, 2626 (1996)

$\bar{p}^{\uparrow}p \to \pi X$

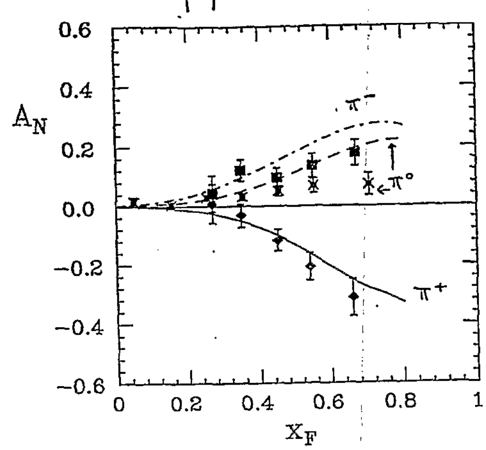


Fig. 2: Single spin asymmetries A_N for the process $\bar{p}^{\uparrow}p \to \pi X$ [2]; the lower, middle, and upper sets of data and curves refer respectively to π^+, π^0, and π^-.

$P_{Lab} = 200$ GeV/c $\quad 0.5 \leq p_T \leq 2.0$ GeV/c

$x_F = 2p_L/\sqrt{s}$

Theor. curves : $p_T = 1.5$ GeV/c
Sivers effect ($\Delta^N f_{q/p^{\uparrow}} \neq 0$) only.

$p^{\uparrow}p \to K^0_S X$

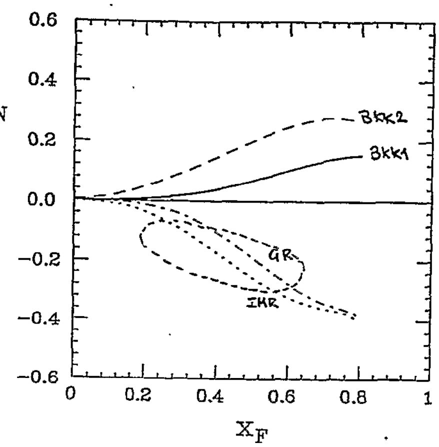


Fig. 8: Predicted single spin asymmetries for the process $p^{\uparrow}p \to K^0_S X$; kinematical conditions are the same as for the pion case, at $p_T = 1.5$ GeV/c. Notations for the theoretical curves are the same as in Fig. 7.

$\sqrt{s} \simeq 20$ GeV

$p_T = 1.5$ GeV/c

Sivers effect $(\Delta^N f_{q/p^{\uparrow}} \neq 0)$ only

Exp. data: E704 Collab., PLB 345, 569 (1995)

$p^{\uparrow}(\bar{p}^{\uparrow})\, p \to \gamma X$

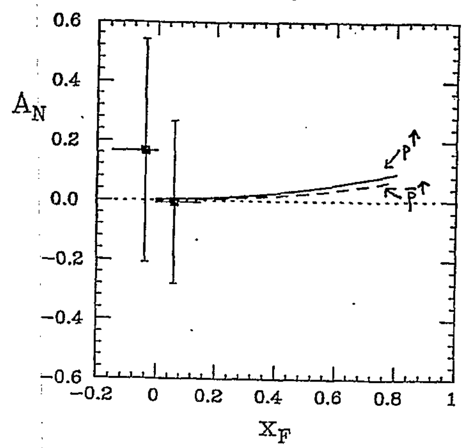


Fig. 4: Single spin asymmetry for the process $p^{\uparrow}(\bar{p}^{\uparrow})\, p \to \gamma X$; experimental data, at $|x_F| \le 0.15$ and $2.5 < p_T < 3.1$ GeV/c, are from Ref. [21]. The curves show our corresponding theoretical predictions at $p_T = 2.5$ GeV/c; the solid curve refers to the $p^{\uparrow}p \to \gamma X$ process, the dashed curve to the $\bar{p}^{\uparrow}p \to \gamma X$ case.

$p_{Lab} = 200$ GeV/c $\quad 2.5 < p_T < 3.1$ GeV/c

$|x_F| \le 0.15$

Theor. curves: $p_T = 2.5$ GeV/c

Sivers effect $(\Delta^N f_{q/p^{\uparrow}} \neq 0)$ only

Exp. data: E704 Collab, PRD53, 4747 (1996) –

$p^{\uparrow} p \to \pi^0 X$

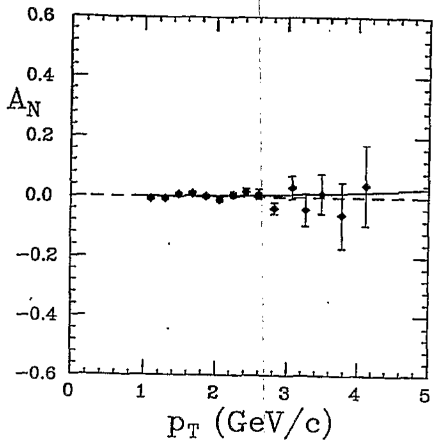


Fig. 3: Single spin asymmetry for the process $p^{\uparrow} p \to \pi^0 X$ at fixed x_F, as a function of p_T; experimental data, at $|x_F| \leq 0.15$, are from Ref. [20]; the solid curve shows our corresponding theoretical prediction at $x_F = 0$.

$P_{lab} = 200$ GeV/c $\quad |x_F| \lesssim 0.15$

Theor. curves: $x_F = 0$

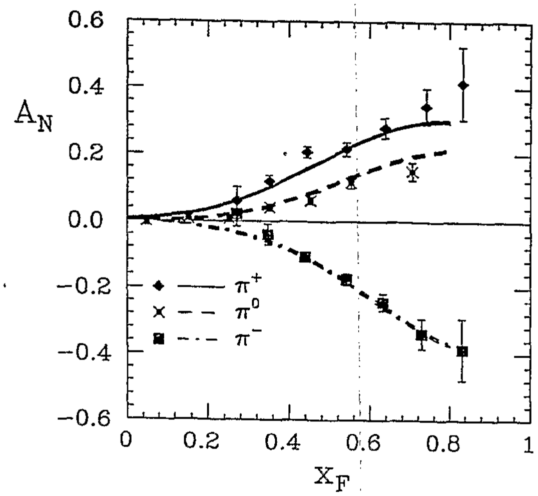
Sivers effect ($\Delta^N f_{q/p^{\uparrow}} \neq 0$) only

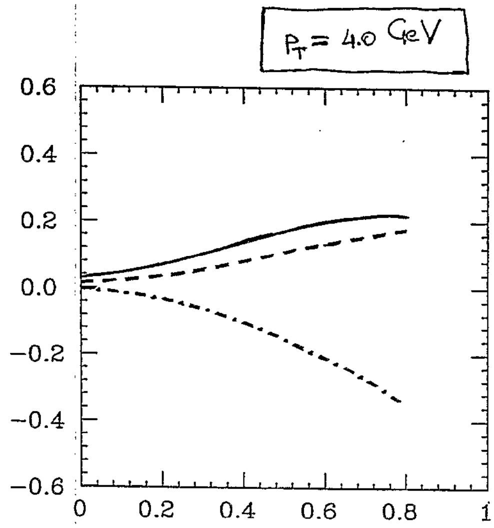
M. Anselmino, U. D'Alesio, FM

$\sqrt{s} \simeq 20$ GeV

$\boxed{p_T = 1.5 \text{ GeV}}$

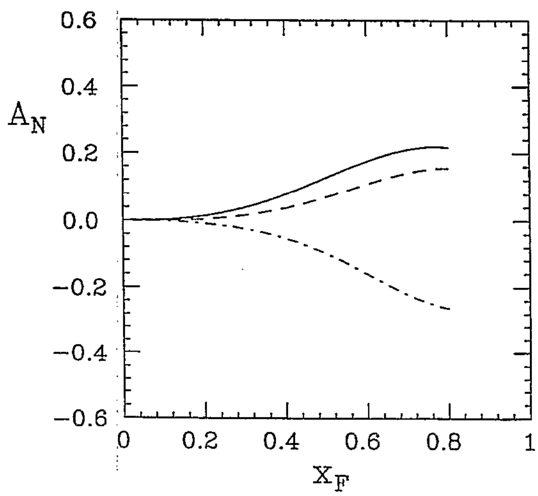
MRST99 pdf





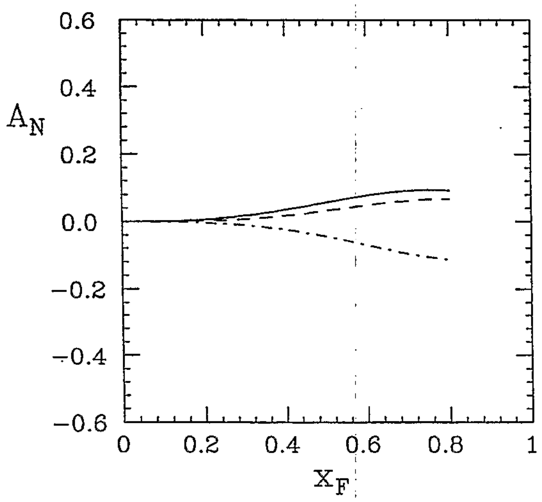
$p^{\uparrow}p \to \pi X$ - RHIC Kinematics

$\sqrt{s} \simeq 200$ GeV $\quad p_T = 1.5$ GeV



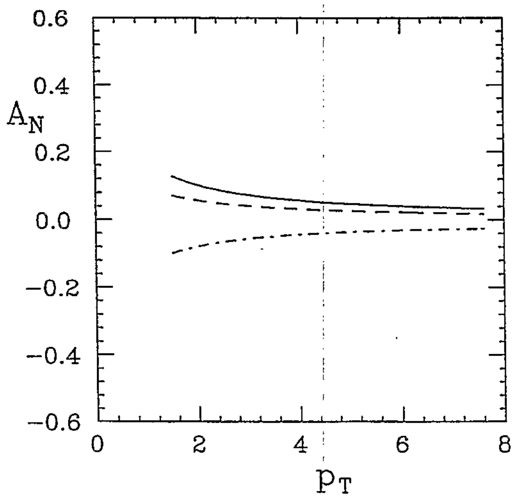
$p^{\uparrow}p \to \pi X$ – RHIC kinematics

$\sqrt{s} \simeq 200$ GeV $\quad p_T = 4.0$ GeV



$p^{\uparrow}p \to \pi X$ – RHIC kinematics

$\sqrt{s} \simeq 200$ GeV , $x_F = 0.5$



■ $pp \to \Lambda^\uparrow X \;\to\; P_y(\Lambda)$

M. Anselmino
D. Boer
U. D'Alesio, FM
hep-ph/0008186

- $$N[P_y(\Lambda)] \sim \sum_{abcd} \int \frac{dx_a\, dx_b}{\pi z}$$

$$\times \Big\{ \int d^2\vec{k}_\perp\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, \frac{d\hat\sigma}{d\hat t}(x_a, x_b; \vec{k}_\perp)\, \Delta^N D_{\Lambda^\uparrow/c}(z, \vec{k}_\perp) \qquad (\mathrm{I})$$

$$+ \int d^2\vec{k}'_\perp\, \Delta^N f_{a^\uparrow/p}(x_a, \vec{k}'_\perp)\, f_{b/p}(x_b)\, \Delta_{NN}\hat\sigma(x_a, x_b; \vec{k}'_\perp)\, \Delta_T D_{\Lambda/c}(z) \qquad (\mathrm{II})$$

$$+ \int d^2\vec{k}''_\perp\, f_{a/p}(x_a)\, \Delta^N f_{b^\uparrow/p}(x_b, \vec{k}''_\perp)\, \Delta'_{NN}\hat\sigma(x_a, x_b; \vec{k}''_\perp)\, \Delta_T D_{\Lambda/c}(z) \Big\} \qquad (\mathrm{III})$$

- Consider the $x_F > 0$ region;

- III should be relevant at $x_F < 0$;
- experimental evidence that hyperon polarization is somewhat independent of the nature of the hadronic target $\Rightarrow$ mechanism responsible for the polarization is in the hadronization process.

→ As a first step we only consider term I in $P_y(\Lambda)$.

■ May be tested in $\ell p \to \Lambda^\uparrow X$.

- A significant amount (20–30%) of Λ's come from the decay $\Sigma^0 \to \Lambda\gamma$. We consider effective, inclusive Λ fragmentation functions (true also for unpolarized ff).

- Most of the exp. data are for pA scattering. We adopt a simple incoherent model, neglecting nuclear effects (but we have checked that nuclear effects leave results for P_Λ almost unchanged.

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- $$\left\langle \frac{k_\perp(z)}{M} \right\rangle = K z^a (1-z)^b$$
- $$\Delta^N D_{\Lambda^\uparrow/q} = N_q z^{c_q} (1-z)^{d_q} \frac{D_{\Lambda/q}(z)}{2} \qquad \left(|\Delta^N D| \le \frac{D}{2} \right)$$
- $D_{\Lambda/q}(z)$:

1) de Florian, Stratmann, Vogelsang; $D_{\Lambda/u} = D_{\Lambda/d} = D_{\Lambda/s}$.
   Note: actually for $\Lambda + \bar\Lambda$; but
   $$P_{\Lambda+\bar\Lambda} = \left(P_\Lambda + \frac{d\sigma^{\bar\Lambda}}{d\sigma^\Lambda} P_{\bar\Lambda}\right)\left(1 + \frac{d\sigma^{\bar\Lambda}}{d\sigma^\Lambda}\right)^{-1} \simeq P_\Lambda$$
   since $d\sigma^\Lambda \gg d\sigma^{\bar\Lambda}$ and $P_{\bar\Lambda} \sim 0$.

2) Indumathi, Mani, Rastogi; $D_{\Lambda/u} = D_{\Lambda/d} \ll D_{\Lambda/s}$

3) Boros, Londergan, Thomas; low scale, no evolution.

- MRST99 pdf

p-Be, $\sqrt{s} \simeq 82$ GeV
$\sqrt{s} \simeq 116$ GeV

K. Heller et al., PRL 51, 2025 (83)
B. Lundberg et al., PRD 40, 3557 (89)
E.J. Ramberg et al., PLB 338, 403 (94)

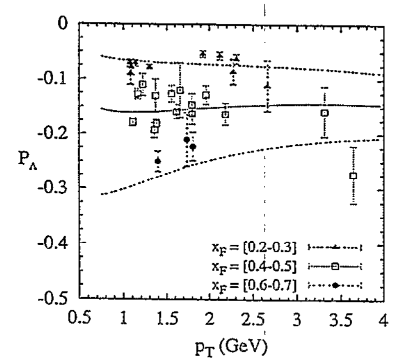

Fig. 1: Our best fit to P_Λ data from p–Be reactions, as a function of p_T and for different x_F bins, as indicated in the figure. Only some of the bins are shown; see Fig. 2 for complementary bins. The experimental results, [37]-[39], are collected at two different c.m. energies, $\sqrt{s} \simeq 82$ GeV and $\sqrt{s} \simeq 116$ GeV. For each x_F-bin, the corresponding theoretical curve is evaluated at the mean x_F value in the bin, and at $\sqrt{s} = 80$ GeV; the results change very little with the energy. See the text for further details.

p-Be, $\sqrt{s} \simeq 82$ GeV
$\sqrt{s} \simeq 116$ GeV

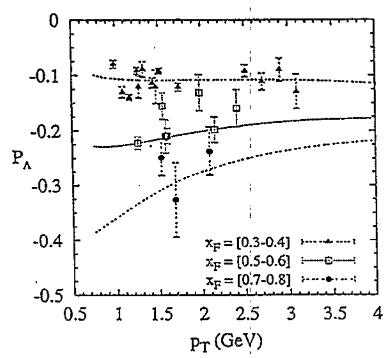

Fig. 2: Our best fit to P_Λ data from p–Be reactions, as a function of p_T and for different x_F bins, as indicated in the figure. Only some of the bins are shown; see Fig. 1 for complementary bins. The experimental results,[37]-[39], are collected at two different c.m. energies, $\sqrt{s} \simeq 82$ GeV and $\sqrt{s} \simeq 116$ GeV. For each x_F-bin, the corresponding theoretical curve is evaluated at the mean x_F value in the bin, and at $\sqrt{s} = 80$ GeV; the results change very little with the energy. See the text for further details.

p-Be, $\sqrt{s} \simeq 82$ GeV
$\sqrt{s} \simeq 116$ GeV

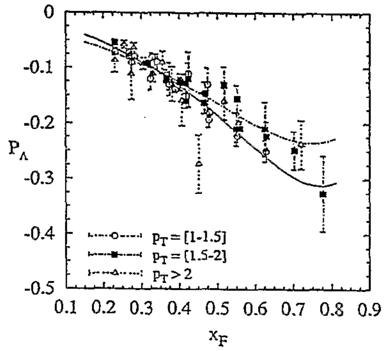

Fig. 3: P_Λ data for p–Be reactions, as a function of x_F and for different p_T bins, as indicated in the figure. The data are collected at two different c.m. energies, $\sqrt{s} \simeq 82$ GeV and $\sqrt{s} \simeq 116$ GeV, [37]-[39]. The two theoretical curves, evaluated at $\sqrt{s} = 80$ GeV, correspond to $p_T = 1.5$ GeV/c (solid) and $p_T = 3$ GeV/c (dot-dashed).

p-p — A.M. Smith et al., PLB 185, 209 (87)

$p_T \geq 0.96$ $\langle p_T \rangle = 1.1$ GeV

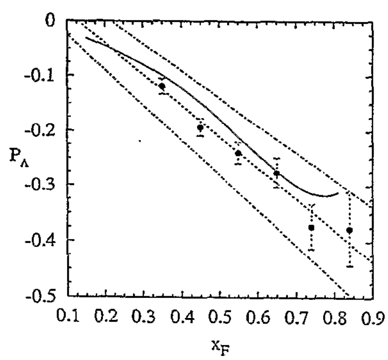

Fig. 4: Experimental results for P_Λ in p–p reactions, as a function of x_F, from Ref. [36]. All data with $p_T \geq 0.96$ GeV/c are collected, and $\langle p_T \rangle = 1.1$ GeV/c. Also shown is a linear fit to the data, taken from Ref. [36] (central line); the upper and lower dot-dashed lines show the corresponding fit error band. The solid curve shows the theoretical computation, at $p_T = 1.1$ GeV/c, with all parameters fixed as in Eqs. (28) and (29).

p-Be $\sqrt{s} \simeq 82$ GeV

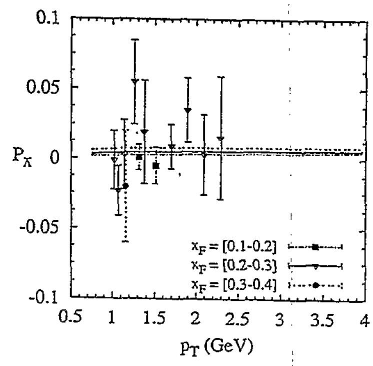

Fig. 5: Our best fit to $P_{\bar{\Lambda}}$ data from p–Be reactions, as a function of p_T and for different x_F bins, as indicated in the figure. The experimental results [36, 38] are collected at the c.m. energies $\sqrt{s} \simeq 82$ GeV. For each x_F-bin, the corresponding theoretical curve is evaluated at the mean x_F value in the bin, and at $\sqrt{s} = 80$ GeV; the results change very little with the energy.

$D_{\Lambda/q}$: Indumathi et al.

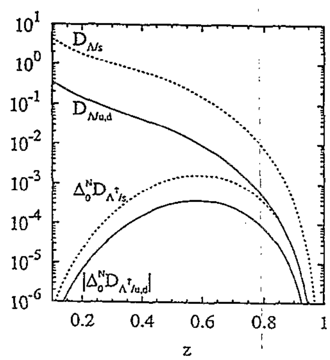

Fig. 6: Plot of $|\Delta_0^N D_{\Lambda^\uparrow/u}|$ ($= |\Delta_0^N D_{\Lambda^\uparrow/d}|$) and $\Delta_0^N D_{\Lambda^\uparrow/s}$, as given by Eq. (27) with the best fit parameters (28) and (29). For comparison we also show the unpolarized fragmentation functions $D_{\Lambda/u}$ ($=D_{\Lambda/d}$) and $D_{\Lambda/s}$ [42].

Note Whatever the set of unpolarized Λ ff's used, a good fit to data requires:

1) $\Delta^N D_{\Lambda^\uparrow/u,d} < 0$; $\Delta^N D_{\Lambda^\uparrow,s} > 0$

2) $\Delta^N D_{\Lambda^\uparrow/s} > |\Delta^N D_{\Lambda^\uparrow/u,d}|$

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Conclusions

- General approach to single spin asymmetries in inclusive, semi-inclusive particle production; spin and intrinsic transverse momentum effects in distribution and/or fragmentation functions.
- New, non perturbative, twist-2 functions are required ($\Delta^N f_{q/p\uparrow}$, $\Delta^N f_{q^\uparrow/p}$, $\Delta^N D_{h/q^\uparrow}$, $\Delta^N D_{h^\uparrow/q}$). Depending on the process considered, one or more of them can be involved simultaneously.
- Several processes have been studied assuming that one of them gives the relevant contribution. Available exp. data were used to parametrize it, then make predictions for other related processes.
- Next steps:
  - more refined treatment of $k_\perp$ effects (need models for explicit $k_\perp$-dependence of $\Delta^N f$, $\Delta^N D$; gaussian ?).
  - what happens when two of the $\Delta^N f$, $\Delta^N D$ are at work? Need refined, combined analysis of semi-inclusive DIS and pp processes; increase number of parameters.
  - More data, at different energies, larger p_T, good separation of x_F and p_T dependence. (RHIC, Ramper, ...)
  - More exp. results for semi inclusive DIS ($\ell p^\uparrow \to \ell' \pi X$, $\ell p \to \Lambda^\uparrow X$, ...)

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MEASURING TRANSVERSITY WITH SPIN-ONE HADRONS

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We analyze one-particle inclusive DIS in the case when a spin-1 hadron (such as a vector meson) is observed in the final state. We consider only leading order contributions in $1/Q$, but we include transverse momentum of partons. We identify five asymmetries where the transversity distribution $h_1(x_B)$ appears multiplied by new fragmentation functions or moments of them.

To describe the production of spin-one hadrons in DIS we need to introduce two soft correlation functions, describing the quark distribution in the spin-1/2 target and the hadronization of a quark into the final state spin-1 hadron. In leading order in $1/Q$ we are concerned only with the quark-quark correlation functions Φ and Δ. The correlation function Φ has been already widely studied in the literature (see e.g. [1]). The function Δ is defined as (using Dirac indices α and β)

$$\Delta_{\alpha\beta}(k, P_h, S_h, T_h) = \int \frac{d^4\xi}{(2\pi)^4} e^{+ik\xi} \langle 0|\psi_\alpha(\xi)|P_h, T_h\rangle\langle P_h, T_h|\bar{\psi}_\beta(0)|0\rangle. \quad (1)$$

Here, k is the momentum of the quark decaying into an outgoing hadron after being struck by a virtual photon. The vector P_h is the momentum of the outgoing hadron, S_h is its spin vector and T_h is its spin tensor, needed to the full description spin-one polarization [2]. In the hadronic tensor we need the integrated correlation function

$$\Delta(z, k_T) = \frac{1}{4z} \int dk^+ \, \Delta(k, P_h, S_h, T_h)\Big|_{k^- = \frac{P_h^-}{z};\, k_T = \frac{P_{h\perp}}{z}}. \quad (2)$$

which can be decomposed using 18 different fragmentation functions [3]. Five of them are chiral odd and as such they are possible candidates to connect to the transversity distribution function.

The cross-section of semi-inclusive deep-inelastic scattering is

$$\frac{d\sigma(l + \vec{H} \to l' + h + X)}{dx\, dz\, dy} = \frac{\pi\alpha^2}{Q^4} \frac{y}{2z} L_{\mu\nu}\, 2MW^{\mu\nu}, \quad (3)$$

where x, z and y are the usual scaling variables and $L_{\mu\nu}$ is the lepton tensor. The hadronic tensor $W^{\mu\nu}$ can be written as

$$2MW^{\mu\nu} = 2z\, \mathrm{Tr}\, [2\Phi(x)\gamma^\mu 2\Delta(z)\gamma^\nu]. \quad (4)$$

By substituting the full structure of Φ and Δ into Eq. (4) and using the resulting hadronic tensor in Eq. (3), we can calculate the cross section for a transversely polarized target.

From the experimental point of view, it is necessary to reconstruct the spin-one particle momentum and polarization by studying its decay products. For instance, one has to isolate pion couples coming from the decay of primary ρ mesons. The polarization analyzing powers can then be expressed in terms of the azimutal and polar angles of one of the pions. Because of the parity-conserving character of the decay, only tensor polarization analyzing powers are different from zero.

To single out the contributions containing the transversity distribution function a transversely polarized target is needed. Then, azimutal asymmetries can be defined as

$$\langle W\rangle_{UT}(x_B, y, z_h) = \int d\phi_\pi^\ell\, d\phi^\ell\, d^2\boldsymbol{P}_{h\perp}\, W \left(\frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\phi^\ell\, dx_B\, dz_h\, dy\, d^2\boldsymbol{P}_{h\perp}}\right) \quad (5)$$

where ϕ^ℓ is the azimutal angle of the electron scattering plane, ϕ_ρ^ℓ, φ_S^ℓ and ϕ_π^ℓ are the azimutal angles with respect to the scattering plane of the outgoing ρ, of the transverse spin of the target and of one of the decay pions, respectively.

The following asymmetries containing the transversity distribution can then be observed:

$$\langle \sin(\phi_\pi^\ell + \varphi_S^\ell)\rangle_{UT} = \frac{4\pi^2\alpha^2 s}{Q^4} x_B\, |S_T|\,(1-y)\,|\sin 2\theta_\pi| \sum_a e_a^2\, h_1^a(x_B)\, H_{1LT}^a(z_\rho) \quad (6)$$

$$\left\langle \frac{Q_T}{M_h} \sin(2\phi_\pi^\ell + \phi_S^\ell - \phi_\rho^\ell)\right\rangle_{UT} = \frac{8\pi^2\alpha^2 s}{Q^4} x_B\, |S_T|\,(1-y)\, \sin^2\theta_\pi \sum_a e_a^2\, h_1^a(x_B)\, H_{1TT}^{(1)a}(z_\rho) \quad (7)$$

$$\left\langle \frac{Q_T}{M_h} \sin(\phi_S^\ell + \phi_\rho^\ell)\right\rangle_{UT} = \frac{8\pi^2\alpha^2 s}{Q^4} x_B\, |S_T|\,(1-y) \sum_a e_a^2\, \frac{(1 - 3\cos\theta_\pi)}{2}\, h_1^a(x_B)\, H_{1LL}^{\perp(1)a}(z_\rho) \quad (8)$$

$$\left\langle \frac{Q_T^2}{M_h^2} \sin(\phi_S^\ell + 2\phi_\rho^\ell - \phi_\pi^\ell)\right\rangle_{UT} = \frac{8\pi^2\alpha^2 s}{Q^4} x_B\, |S_T|\,(1-y)\,|\sin 2\theta_\pi| \sum_a e_a^2\, h_1^a(x_B)\, H_{1LT}^{\perp(2)a}(z_\rho) \quad (9)$$

$$\begin{aligned}\left\langle \frac{Q_T^5}{4M^2 M_h} \sin(\phi_S^\ell + 3\phi_\rho^\ell - 2\phi_\pi^\ell)\right\rangle_{UT} &= \frac{8\pi^2\alpha^2 s}{Q^4} x_B\, |S_T|\,(1-y)\, \sin^2\theta_\pi \\ &\times \sum_a e_a^2 \Bigg[h_1^a(x_B)\, H_{1TT}^{\perp(4)a}(z_\rho) + 4\left(\frac{M_h}{M}\right)^2 h_1^{(1)a}(x_B)\, H_{1TT}^{\perp(3)a}(z_\rho) \\ &+ 10\left(\frac{M_h}{M}\right)^2 h_{1T}^{\perp(2)a}(x_B)\, H_{1TT}^{\perp(3)a}(z_\rho)\Bigg], \end{aligned} \quad (10)$$

where θ_π is the angle between the direction of the outgoing meson and the direction of the decay pion as measured in the meson's rest frame.

1. See e.g. P.J. Mulders, R.D. Tangerman, Nucl. Phys. B 461 (1996) 197.
2. C. Bourrely, E. Leader, J. Soffer, Phys. Rep. 59 (1980) 95.
3. A. Bacchetta, P.J. Mulders, Phys. Rev. D 62, 114004.

MEASURING TRANSVERSITY WITH SPIN-ONE HADRONS

A. Bacchetta

P.J. Mulders

vrije Universiteit *amsterdam*

- Spin one in correlation functions
- Vector meson decay
- Asymmetries and transversity

Extent of this analysis

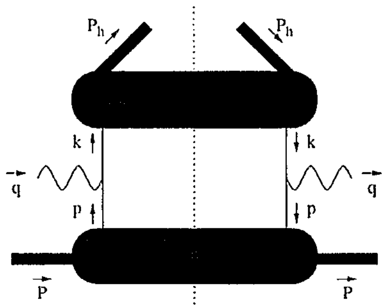
- Leading order in 1/Q
- Tree level
- Including intrinsic transverse momentum
- Including (naive) time-reversal odd contributions

Very essential bibliography

- P. Hoodbhoy, R.L. Jaffe, A. Manohar, NPB **312** (1988) 571
- X. Ji, PRD **49** (1994) 114
- A. B., P.J. Mulders, `hep-ph/0007120`, PRD

- P.J. Mulders, R.D. Tangerman, NPB **461** (1996) 197
- D. Boer, P.J. Mulders, PRD **57** (1998) 5780
- A. B., M. Boglione, A. Henneman, P.J. Mulders, PRL **85** (2000) 712

$$\mathrm{d}\sigma(l + H \to l' + h + X) \propto L_{\mu\nu}\, W^{\mu\nu}$$



$$\boxed{2MW^{\mu\nu} \propto \mathrm{Tr}\left[\Phi(x_{_B})\, \gamma^\mu\, \Delta(z_h)\, \gamma^\nu\right]}$$

$$x_{_B} = \frac{Q^2}{2\,P\cdot q} \qquad z_h = \frac{2\,P_h\cdot q}{Q^2}$$

$$\boxed{\begin{aligned} 2MW^{\mu\nu} \;\propto\; & \int \mathrm{d}^2\boldsymbol{p}_T\, \mathrm{d}^2\boldsymbol{k}_T\, \delta^2(\boldsymbol{p}_T + \boldsymbol{q}_T - \boldsymbol{k}_T) \times \\ & \mathrm{Tr}\left[\Phi(x_{_B}, \boldsymbol{p}_T)\, \gamma^\mu\, \Delta(z_h, \boldsymbol{k}_T)\, \gamma^\nu\right] \end{aligned}}$$

$$\boldsymbol{q}_T = -\frac{P_{h\perp}}{z_h}$$

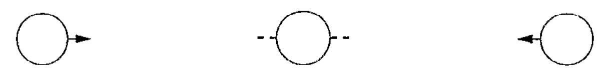
The correlation function can be written as a function of the spin vector S and the spin tensor T of the hadron

$$\Phi_{ij}(p, P, S, T) = \int \frac{\mathrm{d}^4\xi}{(2\pi)^4}\, \mathrm{e}^{\mathrm{i}p\cdot\xi} \langle P, S, T | \bar{\psi}_j(0) \psi_i(\xi) | P, S, T\rangle$$

or as a matrix in the hadron's helicity space

$$\Phi_{ij;\Lambda\Lambda'}(p, P) = \int \frac{\mathrm{d}^4\xi}{(2\pi)^4}\, \mathrm{e}^{\mathrm{i}p\cdot\xi} \langle P, \Lambda | \bar{\psi}_j(0) \psi_i(\xi) | P, \Lambda'\rangle$$

where Λ and Λ' are hadron's helicities (1,0,-1)

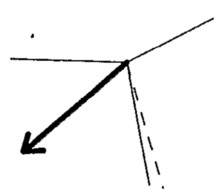


The connection between the two forms is done by means of the spin density matrix

$$\boxed{\begin{aligned} \Phi(p, P, S, T) &= \rho(S,T)_{\Lambda'\Lambda}\, \Phi_{ij;\Lambda\Lambda'}(p, P) \\ &= \mathrm{Tr}\left[\rho(S,T)\, \Phi(p, P)\right] \end{aligned}}$$

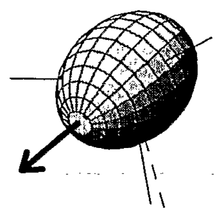
Spin 1/2

$$S = \begin{pmatrix} S_T^x \\ S_T^y \\ S_L \end{pmatrix}$$



Spin 1

$$T = \frac{1}{2}\begin{pmatrix} -\frac{2}{3}S_{LL} + S_{TT}^{xx} & S_{TT}^{xy} & S_{LT}^{x} \\ S_{TT}^{xy} & -\frac{2}{3}S_{LL} - S_{TT}^{xx} & S_{LT}^{y} \\ S_{LT}^{x} & S_{LT}^{y} & \frac{4}{3}S_{LL} \end{pmatrix}$$



Density matrix

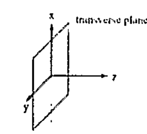
$$\rho(S) = \frac{1}{2}(\mathbf{1} + S_i\,\sigma_i) \qquad \rho(S,T) = \frac{1}{3}\left(\mathbf{1} + \frac{3}{2}S_i\,\Sigma_i + 3\,T_{ij}\,\Sigma_{ij}\right)$$

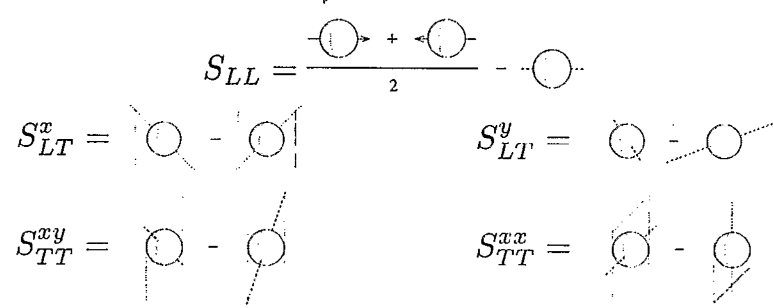
Degree of polarization

$$0 \le \sqrt{S^2} \le 1 \qquad 0 \le \sqrt{\frac{3}{4}S^2 + \frac{3}{2}T^{ij}T_{ij}} \le 1$$

$P\left(m_{(\theta,\varphi)}\right)$ = probability of finding a state with spin-component m along the direction specified by θ and φ

$$\boxed{\begin{aligned}
S_{LL} &= \frac{1}{2}P\left(1_{(0,0)}\right) + \frac{1}{2}P\left(-1_{(0,0)}\right) - P\left(0_{(0,0)}\right),\\
S_{LT}^{x} &= P\left(0_{(-\frac{\pi}{4},0)}\right) - P\left(0_{(\frac{\pi}{4},0)}\right),\\
S_{LT}^{y} &= P\left(0_{(-\frac{\pi}{4},\frac{\pi}{2})}\right) - P\left(0_{(\frac{\pi}{4},\frac{\pi}{2})}\right),\\
S_{TT}^{xx} &= P\left(0_{(\frac{\pi}{2},-\frac{\pi}{4})}\right) - P\left(0_{(\frac{\pi}{2},\frac{\pi}{4})}\right),\\
S_{TT}^{xy} &= P\left(0_{(\frac{\pi}{2},\frac{\pi}{2})}\right) - P\left(0_{(\frac{\pi}{2},0)}\right).
\end{aligned}}$$





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Available Dirac structures:

$\mathbf{1},\ \gamma_5,\ \gamma^\mu,\ \gamma^\mu\gamma_5,\ \mathrm{i}\sigma^{\mu\nu}\gamma_5$

Available Lorentz structures:

$p,\ P,\ S,\ T$

General decomposition

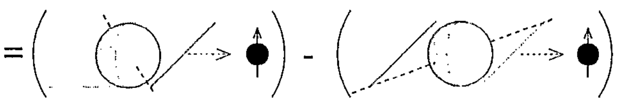
Leading order in $\frac{1}{Q}$

$$\Phi(x) =$$
$$f_1(x)\, \not{n}_+ + g_1(x)\gamma_5\, \not{n}_+ S_L + h_1(x)\, \not{n}_+ \gamma_\nu \gamma_5 S_T^\nu$$
$$+ f_{1LL}(x)\, \not{n}_+ S_{LL} + h_{1LT}(x)\, \not{n}_+ \gamma_\nu \gamma_5\, \varepsilon_\perp^{\nu\rho} S_{LT\,\rho}$$

$$\Phi(x; \boldsymbol{p}_T) =$$
$$\ldots + h_{1LL}^\perp(x, p_T^2)\, \not{n}_+ \gamma_\nu \frac{p_T^\nu}{M} S_{LL}$$
$$+ h'_{1LT}(x, p_T^2)\, \not{n}_+ \gamma_\nu \gamma_5\, \varepsilon_\perp^{\nu\rho} S_{LT\,\rho}$$
$$+ h_{1LT}^\perp(x, p_T^2)\, \not{n}_+ \gamma_\nu \frac{p_T^\nu}{M} \frac{\boldsymbol{S}_{LT} \cdot \boldsymbol{p}_T}{M}$$
$$+ h'_{1TT}(x, p_T^2)\, \not{n}_+ \gamma_\nu\, \gamma_5 \varepsilon_T^{\nu\rho} S_{TT\,\rho\sigma} \frac{p_T^\sigma}{M}$$
$$+ \mathrm{i} h_{1TT}^\perp(x, p_T^2)\, \not{n}_+ \gamma_\nu \frac{p_T^\nu}{M} \frac{\boldsymbol{p}_T \cdot \boldsymbol{S}_{TT} \cdot \boldsymbol{p}_T}{M^2} + \ldots$$

Without transverse momentum $\Rightarrow$ 5 FUNCTIONS

h_1 χ-odd

$h_{1LT} =$  χ-odd T-odd

With transverse momentum $\Rightarrow$ 18 FUNCTIONS

h_{1LL} χ-odd T-odd

h'_{1LT} χ-odd T-odd

h'_{1LL} χ-odd T-odd

$h_{1LL}^\perp$ χ-odd T-odd

$h_{1LL}^\perp$ χ-odd T-odd

By merging together the two dimensional parton chirality space with the two dimensional target helicity space, we obtain the full scattering matrix $M = (\Phi\gamma^+)^T$

$$\begin{pmatrix}
f_1 + g_1 + \frac{f_{1LL}}{2} & 0 & 0 & 0 & \sqrt{2}\,(h_1 + \mathrm{i}h_{1LT}) & 0 \\
0 & f_1 - f_{1LL} & 0 & 0 & 0 & \sqrt{2}\,(h_1 - \mathrm{i}h_{1LT}) \\
0 & 0 & f_1 - g_1 + \frac{f_{1LL}}{2} & 0 & 0 & 0 \\
0 & 0 & 0 & f_1 - g_1 + \frac{f_{1LL}}{2} & 0 & 0 \\
\sqrt{2}\,(h_1 - \mathrm{i}h_{1LT}) & 0 & 0 & 0 & f_1 - f_{1LL} & 0 \\
0 & \sqrt{2}\,(h_1 + \mathrm{i}h_{1LT}) & 0 & 0 & 0 & f_1 + g_1 + \frac{f_{1LL}}{2}
\end{pmatrix}$$

When one measures a longitudinal spin asymmetry

$$\boxed{\frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}} = \frac{g_1}{f_1 + \frac{1}{2} f_{1LL}}}$$

then to extract g_1 we need to know also

$$\boxed{\frac{d\sigma^{\rightarrow} + d\sigma^{\leftarrow} - d\sigma^{0}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow} + d\sigma^{0}} = \frac{2\, f_{1LL}}{3\, f_1}}$$

cf. Hoodboy, Jaffe, Manohar, Nuc. Phys. B 312, 571

$$f_{1LL} \equiv -\frac{2}{3}\, b_1$$

Exactly the same happens with transversely polarized hadrons and transversity.

The only spin-one hadronic target is the deuteron: in the hypothesis of independent scattering on the two nucleons, f_{1LL} is small, but how much ?

The decomposition of Δ can be carried out in the same way.
Only some replacements are needed:

$x \quad M$

$P \quad p$

$P^+ \quad \not{n}_+$

$f_1 \quad g_1 \quad h_1$

REPLACE [redacted]

We also need to replace

$S_{hL} \quad S_{hT}^i$

$S_{hLL} \quad S_{hLT}^i \quad S_{hTT}^{ij}$

REPLACE [redacted]

since in a cross section we observe

$$\boxed{\Delta(k, P_h, A_h^i, A_h^{ij}) = \mathrm{Tr}\left[R_h^{(\text{decay})}(A_h^i, A_h^{ij})\,\Delta(k, P_h)\right]}$$

The analyzing powers depend on the details of the final-state hadron decay.

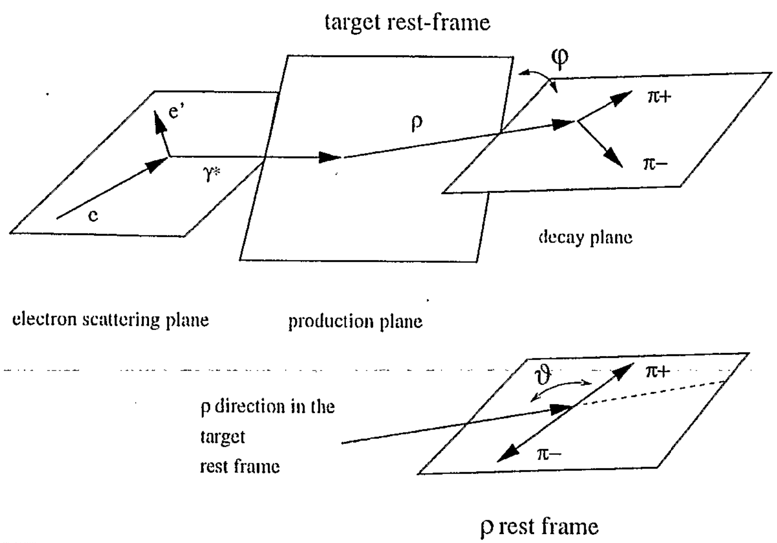
$$R_h^{(\text{decay})}(A_h) = \frac{1}{4\pi}\left(\mathbb{1} + \frac{3}{2}\,\Sigma_i\, A_h^i + 3\,\Sigma_{ij}\, A_h^{ij}\right)$$

For $\rho \to \pi^+\pi^-$

$$A_h^i = 0$$

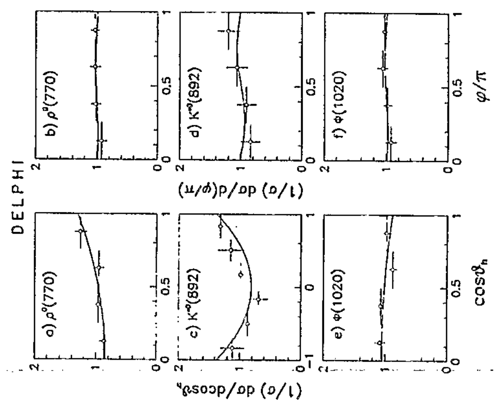
$$A_h{}^{ij} = \frac{1}{3}\delta^{ij} - \hat{p}_{\text{cm}}^i \hat{p}_{\text{cm}}^j.$$

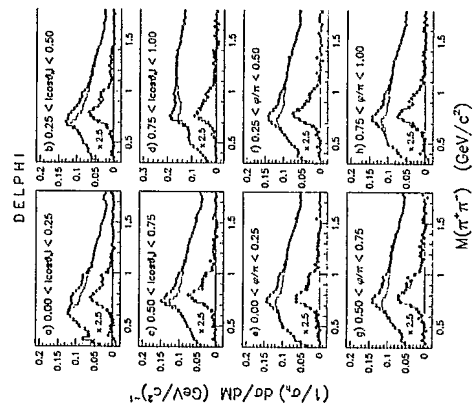
direction of pion in ρ rest-frame



$$
\begin{aligned}
A_{LL} &= -\tfrac{1}{2}\left(\cos^2\theta + \cos 2\theta\right)\\
A_{LT}^{x} &= -\sin 2\theta\ \cos\varphi\\
&\qquad A_{LT}^{y} = -\sin 2\theta\ \sin\varphi\\
A_{TT}^{xx} &= -\sin^2\theta\ \cos 2\varphi\\
&\qquad A_{TT}^{xy} = -\sin^2\theta\ \sin 2\varphi
\end{aligned}
$$

Delphi collaboration Phys. Lett. B 406, 271





Measurement of decay distribution seems to be feasable

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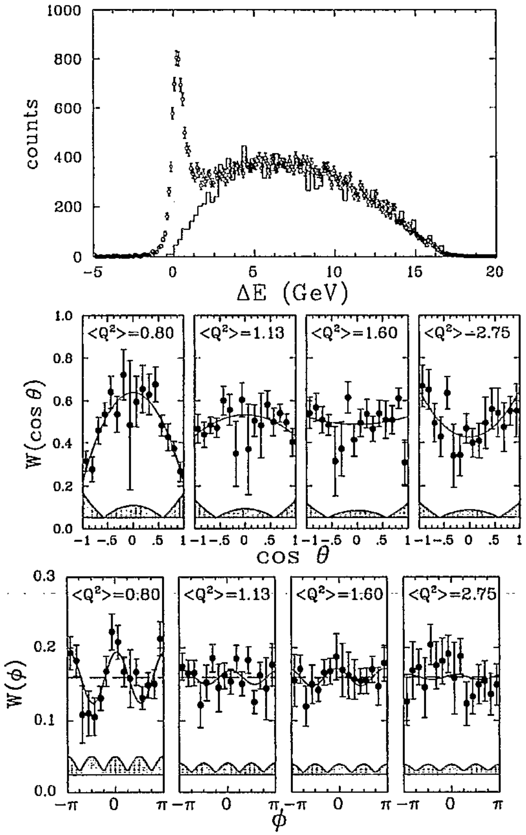
Hermes collaboration hep-ex/0002016

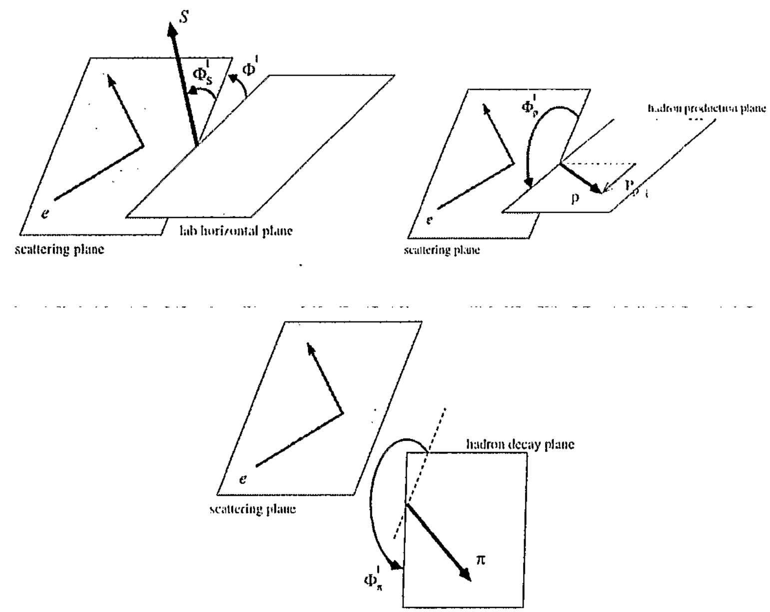
(Zeus collaboration Eur. Phys. J. C 12, 393)



Measurement of decay distribution seems to be feasable

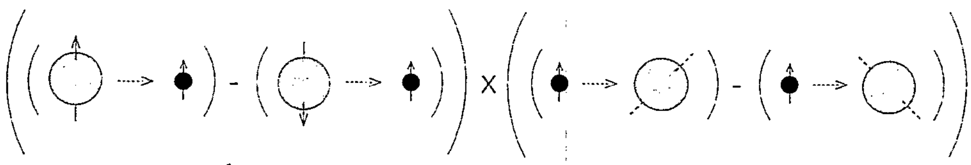
$$\langle W \rangle_{UT}(x_B, y, z_\rho) = \int \mathrm{d}\phi^\ell\, \mathrm{d}^2\boldsymbol{P}_{\rho\perp}\, W \left(\frac{\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow}{\mathrm{d}\phi^\ell\, \mathrm{d}x_B\, \mathrm{d}z_\rho\, \mathrm{d}y\, \mathrm{d}^2\boldsymbol{P}_{\rho\perp}} \right)$$

$$W = W\left(\frac{|P_{\rho\perp}|}{z}, \phi^\ell_\rho, \phi^\ell_S, \phi^\ell_\pi\right)$$



$$\left\langle \sin\left(\phi_\pi^\ell + \phi_S^\ell\right)\right\rangle_{UT} \;\propto\; \sin|2\theta_\pi| \sum_a e_a^2\, h_1^a(x_B)\, H_{1LT}^a(z_\rho)$$

χ-odd T-odd



h_1 $\times$ H_{1LT}

cf. X. Ji, Phys. Rev. D 49, 114

$$H_{1LT} \equiv \hat{h}_{\bar{1}}$$

$$\left\langle \frac{|P_{\rho\perp}|}{2\,z\,M_h}\,\sin\left(2\phi_\pi^\ell + \phi_S^\ell - \phi_\rho^\ell\right)\right\rangle_{UT} \;\propto\; \sin^2\theta_\pi \sum_a e_a^2\, h_1^a(x_B)\, H_{1TT}^{(1)a}(z_\rho)$$

$$\left\langle \frac{|P_{\rho\perp}|}{2\,z\,M_h}\,\sin\left(\phi_S^\ell + \phi_\rho^\ell\right)\right\rangle_{UT} \;\propto\; \frac{1}{2}\left(1 - 3\cos\theta_\pi\right) \sum_a e_a^2\, h_1^a(x_B)\, H_{1LL}^{\perp(1)a}(z_\rho)$$

$$\left\langle \frac{|P_{\rho\perp}|^2}{2\,z^2\,M_h^2}\,\sin\left(\phi_\pi^\ell - \phi_S^\ell - 2\phi_\rho^\ell\right)\right\rangle_{UT} \;\propto\; |\sin 2\theta_\pi| \sum_a e_a^2\, h_1^a(x_B)\, H_{1LT}^{\perp(2)a}(z_\rho)$$

$$\left\langle \frac{|P_{\rho\perp}|^3}{4\,z^3\,M_h^3}\,\sin\left(2\phi_\pi^\ell - \phi_S^\ell - 3\phi_\rho^\ell\right)\right\rangle_{UT} \;\propto\; \sin^2\theta_\pi \sum_a e_a^2\, h_1^a(x_B)\, H_{1TT}^{\perp(3)a}(z_\rho)$$

The variety of possibilities in this process includes 5 observables at leading order in $\frac{1}{Q}$ to measure the transversity distribution h_1.

This process allows the first chance of observing a time-reversal odd fragmentation function at first order in $\frac{1}{Q}$ and without including intrinsic transverse momentum effects.

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? Are there reasons to believe that these T-odd functions are different from zero? Is it possible to provide simple models of them?

? What is the relation with the more general case of two-pion production?

Why Interference Fragmentation Functions ?

Rainer Jakob
Fachbereich Physik, Universität Wuppertal, Germany

In this talk the conceptual problems of building explicite models for one-hadron inclusive T_N-odd fragmentation functions (FFs) are discussed. Understanding the basic obstacles in incorporating final state interactions (FSI), exemplified for the case of the spectator model, leads naturally to the consideration of two-hadron interference FFs, for which FSI are much easier to model.
Following the reasons for the failure of attempts to invent simple models for one-hadron T_N-odd FFs is rather illustrative, and may explain why there are only parameterizations, but no explicite model calculations available, for instance, for the Collins function.
The reasoning takes the following steps:

- A classification scheme of transverse momentum dependent FFs with regard to their partonic and hadronic spin/helicity information, their chiral symmetry properties, and their behavior under so-called naive time-reversal (T_N) is briefly discussed (cf. contribution by Piet Mulders and references therein).
- The class of T_N-odd FF which can be non-vanishing only in the presence of FSI is of particular interest. A prominent function is the so-called "Collins function", $H_1^\perp(z, \mathbf{k}_\mathrm{T})$, which is a potential chiral-odd partner in a measurement of the quark transversity function, h_1, from azimuthal asymmetries in one-hadron inclusive hard scattering processes.
- The modeling of one-hadron T_N-odd FFs faces severe problems which are discussed. Different cases are considered where the observed hadron interacts with
  a. hadrons in the target remnant jet (factorization breaking)
  b. an effective external potential (generally breaks transl./rotational invariance)
  c. hadrons within the same jet (simple ansätze can be redefined into a vertex).

  For the latter class of FSI the technical problems are exemplified in a simple toy model using the general properties of the FFs and the general classification scheme. The example reveals that a phase difference between different reaction channels is necessary, but not sufficient to produce T_N-odd FF.

A more detailed discussion can be found in [1,2]. A calculation of T_N-odd two-hadron interference FFs is presented in an accompanying talk by Marco Radici.

Acknowledgment: This contribution is based on work done in collaboration with Andrea Bianconi, Sigfrido Boffi, Marco Radici. I acknowledge discussions on the subject with Daniël Boer, Piet Mulders and Joao Rodrigues.

[1] A. Bianconi, S. Boffi, R. Jakob and M. Radici, Phys. Rev. **D62** (2000) 034008.

[2] A. Bianconi, S. Boffi, R. Jakob and M. Radici, Phys. Rev. **D62** (2000) 034009.

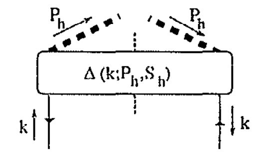
Why Interference Fragmentation Functions ?

Rainer Jakob
Fachbereich Physik, Universität Wuppertal

- ♧ transverse momentum dependent $\mathrm{FF}^{q\to h\,X}$
- ♠ problems to model (interference) $\mathrm{FF}^{q\to h\,X}$
- ♣ two hadron interference $\mathrm{FF}^{q\to h_1\,h_2\,X}$

based on work with:
Andrea Bianconi, Sigfrido Boffi, Marco Radici,
Daniel Boer, Piet Mulders, Joao Rodrigues

Fragmentation Functions describe $q \to h + X$



hadronic ME of bilocal quark operator Soper, Collins, Jaffe

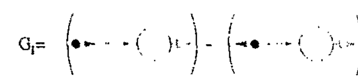
quark-quark correlation function (one hadron)

$$\Delta_{ij}(k,P_h,S_h) = \sum_X \int \frac{d^4x}{(2\pi)^4}\, e^{ik\cdot x} \times \langle 0|\psi_i(x)|P_h,S_h;X\rangle\langle P_h,S_h;X|\overline{\psi}_j(0)|0\rangle$$

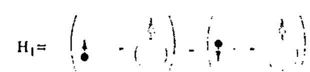
$$\Delta^{[\Gamma]}(z) = \frac{1}{4z}\int dk^+\, d^2\mathbf{k}_T\ \mathrm{Tr}(\Delta\,\Gamma)\Big|_{k^-=P_h^-/z}$$

$$\Delta^{[\gamma^-]}(z) = D_1(z)$$

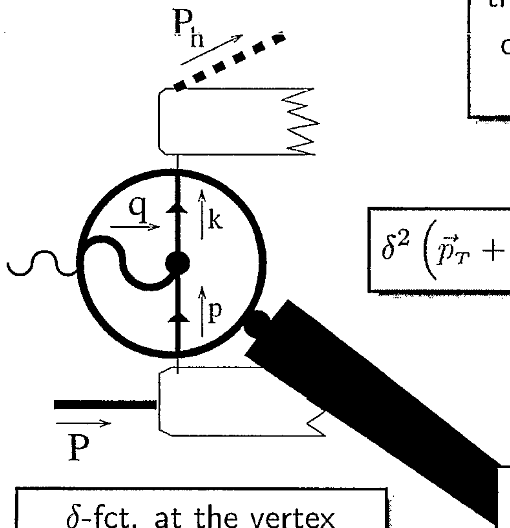
$$\Delta^{[\gamma^-\gamma_5]}(z) = \lambda_h\ G_1(z)$$



$$\Delta^{[i\sigma^{\alpha -}\gamma_5]}(z) = S^{\alpha}_{hT}\ H_1(z)$$



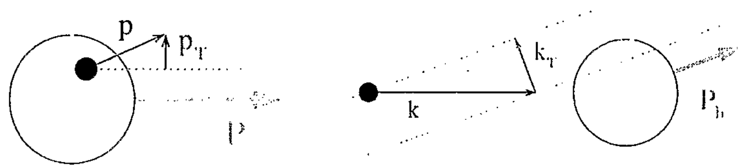
with λ_h helicity, S^{α}_{hT} transv.comp. of spin vector



transverse momentum of quarks relative to parent hadrons

$$\delta^2\left(\vec{p}_T + \vec{q}_T - \vec{k}_T\right)$$

δ-fct. at the vertex couples transverse momentum components $\Longrightarrow$ $\dfrac{d\sigma}{d\ldots d^2\vec{q}_T}$ sensitive to $\vec{p}_T$, $\vec{k}_T$



$$\int d^2p_T\, f_1(x,\vec{p}_T^{\,2}) = f_1(x) \qquad \int d^2k'_T\, D_1(x,\vec{k}_T^{\prime\,2}) = D_1(x)$$

FF dependent on parton transverse momentum:

$$\Delta^{[\gamma^-]}(z_h,\vec{k}_T) = D_1(z_h,\vec{k}_T^{\prime 2}) + \frac{\epsilon_{T ij} k_T^i S_{hT}^j}{M_h} D_{1T}^{\perp}(z_h,\vec{k}_T^{\prime 2})$$

$$\Delta^{[\gamma^-\gamma_5]}(z_h,\vec{k}_T) = \lambda_h\, G_{1L}(z_h,\vec{k}_T^{\prime 2}) + \frac{\vec{k}'_T\cdot\vec{S}_{hT}}{M_h} G_{1T}(z_h,\vec{k}_T^{\prime 2})$$

$$\Delta^{[i\sigma^{i-}\gamma_5]}(z_h,\vec{k}_T) = S_{hT}^i\, H_1(z_h,\vec{k}_T^{\prime 2}) + \frac{\epsilon_T^{ij} k_{Tj}}{M_h} H_1^{\perp}(z_h,\vec{k}_T^{\prime 2}) + \frac{\lambda_h k_T^i}{M_h} H_{1L}^{\perp}(z_h,\vec{k}_T^{\prime 2}) + \frac{\left(k_T^i k_T^j - \frac{1}{2}\vec{k}_T^2\delta_{ij}\right) S_{hT}^j}{M_h^2} H_{1T}^{\perp}(z_h,\vec{k}_T^{\prime 2})$$

with $\vec{k}'_T = -z_h\vec{k}_T$

8 FFs at leading order

$\boxed{FF(z)}$ dependent on momentum fraction z only

quark spin	$\Delta^{[\Gamma]}$	T_N-even U	T_N-even L	T_N-even T	T_N-odd / FSI U	T_N-odd / FSI L	T_N-odd / FSI T
u	γ^-	$D_1(z)$	–	–	–	–	–
ℓ	$\gamma^-\gamma_5$	–	$G_1(z)$	–	–	–	–
t	$i\sigma^{i-}\gamma_5$	–	–	$H_1(z)$	–	–	–

$\boxed{FF(z, k_T)}$ with transverse momentum dependence

quark spin	$\Delta^{[\Gamma]}$	T_N-even U	T_N-even L	T_N-even T	T_N-odd / FSI U	T_N-odd / FSI L	T_N-odd / FSI T
u	γ^-	D_1	–	–	–	–	$D_{1T}^\perp$
ℓ	$\gamma^-\gamma_5$	–	G_{1L}	G_{1T}	–	–	–
t	$i\sigma^{i-}\gamma_5$	–	$H_{1L}^\perp$	$H_{1T}, H_{1T}^\perp$	$H_1^\perp$	–	–

$\boxed{\text{blue FF = chiral odd}}$ possible 'partner for transversity'

RJ

September 2000

there are problems to model (interference) $\text{FF}^{q \to h\, X}$

"T_N-odd" used in the sense:

$\boxed{\text{"... would be forbidden by time reversal invariance if there were no FSI ..."}}$

necessary condition for non-zero T_N-odd FF:

$\boxed{\text{interference of two channels with different phase}}$

possible models

after hadronization

FSI between hadrons

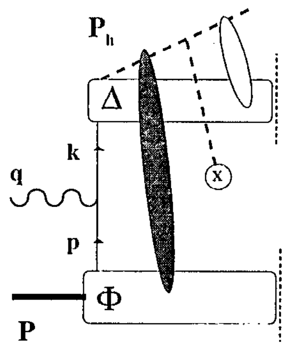
before hadronization

parton's 'feel' the presence of other partons

$\to$ dressed quark propagator

problems to model FSI leading to T_N-odd FF

possible residual interactions between hadrons in the final state



dark blob factorization breaking

dashed line averaged external potential

→ breaks rotational and translational invariance

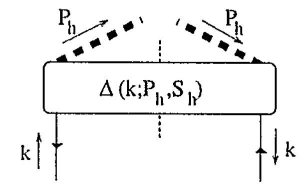
unless simplified model (not 'rich' enough for T_N-odd FF)

light blob interaction with residual fragments in jet

→ requires non-trivial microscopic modifications of the hadron wave function

otherwise, it can be reabsorbed in the vertex

properties of correlation function



hermiticity:

$$\gamma_0\,\Delta^\dagger(k;P_h)\,\gamma_0 = \Delta(k;P_h)$$

parity invariance:

$$\gamma_0\,\Delta(\tilde{k};\tilde{P}_1,\tilde{P}_2)\,\gamma_0 = \Delta(k;P_1,P_2)$$

time-reversal invariance: (if applicable)

$$\left(\gamma_5 C\,\Delta(\tilde{k};\tilde{P}_1,\tilde{P}_2)\,C^\dagger\gamma_5\right)^* = \Delta(k;P_1,P_2)$$

where $\tilde{k} = (k^0, -\vec{k})$ and $C = i\,\gamma^2\,\gamma^0$.

most general ansatz (for $S_h = 0$)

$$\Delta = B_1 M_h + B_2\,\not{P}_h + B_3\,\not{k} + \frac{B_4}{M_h}\sigma_{\mu\nu}P_h^\mu k^\nu$$

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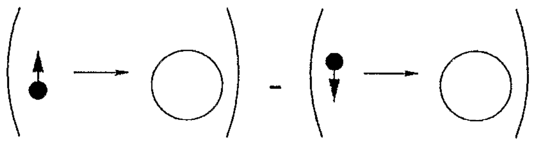
for instance 'Collins function' $H_1^\perp$ is T_N-odd

$H_1^\perp =$ 

$$\begin{cases} \Delta = B_1 M_h + B_2 \not{P}_h + B_3 \not{k} + \dfrac{B_4}{M_h} \sigma_{\mu\nu} P_h^\mu k^\nu \\ \Delta^{[i\sigma^{i-}\gamma_5]} = \ldots + \dfrac{\epsilon_T^{ij} k_{Tj}}{M_h} H_1^\perp \end{cases}$$

$$\Downarrow$$

$$H_1^\perp(z_h, \vec{k}_T'^2) = \frac{P_h^-}{z_h} \int dk^+ \int dk^- \, \delta\left(k^- - \frac{P_h^-}{z_h}\right) [-B_4]$$

and would be forbidden by time-reversal invariance if there were no final state interactions

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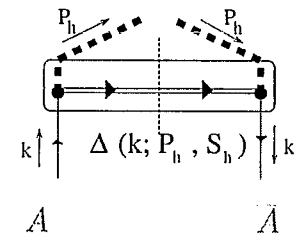


for illlustration only:

simple toy model: scalar spectator

$$\Delta \equiv \tilde{\Delta} \, \delta\left((P_h - k)^2 - M_D^2\right)$$

$$\tilde{\Delta} = \frac{-i}{\not{k} - m} \underbrace{u(P_h)\, \overline{u}(P_h)}_{(\not{P}_h + M_h)} \frac{-i}{\not{k} - m}$$

$$= A_1 M_h + A_2 \not{P}_h + A_3 \not{k} + \frac{(A_4 = 0)}{M_h} \sigma_{\mu\nu} P_h^\mu k^\nu$$

- assume: $A \to A + e^{i\phi} A$ (uniform damping)

$$\Rightarrow \quad \tilde{\Delta} = 2(1 + \cos\phi)\, A\bar{A} \ \Rightarrow \ A_4 = 0$$

phase is necessary but not sufficient !

- assume: $A \to A + e^{i\phi} \not{k} A$

$$\Rightarrow \quad \tilde{\Delta} = (A_1 + B_1 \cos\phi) M_h + A_2 \not{P}_h + (A_3 + B_3 \cos\phi) \not{k} + \frac{B_4 \sin\phi}{M_h} \sigma_{\mu\nu} P_h^\mu k^\nu$$

sufficient (but can be redefined into the vertex !)

two hadron interference FF

- two (!!) leading hadrons detected in the same jet
- interference of two channels with different phases can produce T_N-odd FF

J.C. Collins and G.A. Ladinski, hep-ph/9411444

two pions (chiral sigma model)

- independent production
- production via σ-'resonance'

R.L. Jaffe, Xuemin Jin, Jian Tang,

P.R.L. **80** (98) 1166; P.R. **D57** (98) 5920

two pions (known phase shifts)

- s-wave 'resonance' (σ)
- p-wave resonance (ρ)

A.Bianconi, S.Boffi, R.Jakob, M.Radici,

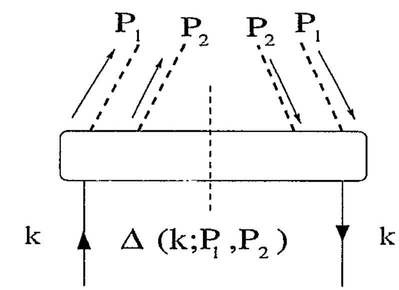
PRD 62 (2000) 034009 and 034008

pion & proton (spectator model)

- indepedent production
- production via ρ-resonance

two-hadron FF

definition of hadronic matrix element



$$\Delta(k; P_1, P_2) = \sum_X \int \frac{d^4\xi}{(2\pi)^4} \int \frac{d^4 P_X}{(2\pi)^4}\, e^{ik\cdot\xi}$$

$$\times \langle 0|\psi_i(\xi)|h_1, h_2, X\rangle \langle X, h_1, h_2|\overline{\psi}_j(0)|0\rangle$$

much easier to model the FSI between the two hadrons

(but not with the rest of the jet)

properties and more details → talk by **Marco Radici**

Calculation of T-odd fragmentation functions in semi-inclusive processes

M. Radici
I.N.F.N. - Sezione di Pavia - Italy

The study of the nonperturbative features of quark and gluon dynamics inside hadrons is based on information extracted from distribution and fragmentation functions. At leading order, the state of a quark with respect to a dominant longitudinal direction is parametrized by three functions: the momentum f_1, the helicity g_1 and the spin-transverse distributions h_1 (or transversity). The first two ones are rather well known from experiments, while h_1 is chiral-odd and, therefore, unaccessible in inclusive processes. The possibility to detect more exclusive channels allows for a larger set of fragmentation functions (FF) in the final state, among which there are possible chiral-odd partners that could allow extraction of the transversity.

These classes of FF are also odd with respect to a special transformation, the naive time-reversal [1]. In other words, they are forbidden in absence of final-state interactions (FSI) and are called "T-odd". Therefore, they are interesting objects by themselves because they represent a tool to microscopically study the phenomena occurring in the final jet and leading to the detected particles. From this perspective, it is certainly not convenient to consider semi-inclusive processes where just one leading hadron is detected, because it requires the ability of describing the whole jet dynamics. It is easier to assume the jet as a spectator and consider two leading hadrons to be detected [2].

By generalizing the Collins-Soper light-cone formalism [3] for fragmentation into multiple hadrons and in analogy with semi-inclusive hard processes involving one detected hadron in the final state [4], the cross section for two-hadron semi-inclusive emission is a linear combination of projections $\Delta^{[\Gamma]}$ by specific Dirac structures Γ, where Δ is the quark-quark correlation function describing the decay of a quark with momentum k into two hadrons P_1, P_2, namely

$$\Delta_{ij}(k;P_1,P_2) = \sum_X \int \frac{d^4\zeta}{(2\pi)^4}\, e^{ik\cdot\zeta} \langle 0|\psi_i(\zeta)\, a^\dagger_{P_2}\, a^\dagger_{P_1}|X\rangle\, \langle X|a_{P_1}\, a_{P_2}\, \overline{\psi}_j(0)|0\rangle\ . \tag{1}$$

The projections involve integration over the (hard-scale suppressed) light-cone component k^+ and, consequently, ζ is light-like [2]. The sum in Eq. (1) runs over all the possible intermediate states involving the two final hadrons P_1, P_2. Since the three external momenta k, P_1, P_2 cannot all be collinear at the same time, we choose for convenience the frame where the total pair momentum $P_h = P_1 + P_2$ has no transverse component.

When $\Gamma = \gamma^-, \gamma^-\gamma_5, i\sigma^{i-}\gamma_5$, four different interference FF appear at leading twist, $D_1, G_1^\perp, H_1^\perp, H_1^\sphericalangle$, that depend on how much of the fragmenting quark momentum k is carried by the hadron pair ($z = z_1 + z_2$), on the way this momentum is shared inside the pair ($\xi = z_1/z$ and $1-\xi = z_2/z$), and on the "geometry" of the pair, namely on the transverse relative momentum of the two hadrons ($\mathbf{R}_T^2$) and on the relative orientation between the pair plane and the quark jet axis, i.e. on the transverse momentum of the quark $\mathbf{k}_T$ with respect to the P_h^- direction and the scalar product $\mathbf{k}_T \cdot \mathbf{R}_T$.

The different Dirac structures Γ are related to different spin states of the fragmenting quark and lead to the nice probabilistic interpretation at leading order [2]: D_1 is the probability for an unpolarized quark to produce a pair of unpolarized hadrons; $G_1^\perp$ is the difference of probabilities for a longitudinally polarized quark with opposite chiralities to produce a pair of unpolarized hadrons; $H_1^\sphericalangle$ and $H_1^\perp$ both are differences of probabilities for a transversely polarized quark with opposite spins to produce a pair of unpolarized hadrons. $G_1^\perp$, $H_1^\sphericalangle$ and $H_1^\perp$ are (naive) "T-odd" and do not vanish only if there are residual interactions in the final state. In this case, the constraints from time-reversal invariance cannot be applied. $G_1^\perp$ is chiral even; $H_1^\sphericalangle$ and $H_1^\perp$ are chiral odd and can, therefore, be identified as the chiral partners needed to access the transversity h_1. Given their probabilistic interpretation, they can be considered as a sort of "double" Collins effect [5].

In order to make quantitative predictions, we adopt the formalism of the spectator model, specializing it to the emission of a hadron pair. The basic idea is to replace the sum over the complete set of intermediate states in Eq. (1) with an effective spectator state with a definite mass M_D, momentum

P_D. Consequently, the correlator simplifies to

$$\Delta_{ij}(k;P_1,P_2) \sim \frac{\theta(P_D^+)}{(2\pi)^3}\,\delta\left((k-P_h)^2-M_D^2\right)$$
$$\langle 0|\psi_i(0)|P_1,P_2,D\rangle\langle D,P_2,P_1|\overline{\psi}_j(0)|0\rangle\,, \qquad (2)$$

where the additional δ function allows for a completely analytical calculation of the Dirac projections $\Delta^{[\Gamma]}$. For the hadron pair being a proton and a pion with invariant mass the mass of the Roper resonance, results have been published in Ref. [1]. In this case, the spectator state has the quantum numbers of a scalar or axial diquark. FSI arise from the interference between the direct production and the decay of the Roper resonance. For the hadron pair being two pions with invariant mass in the range $[m_\rho-\Gamma_\rho, m_\rho+\Gamma_\rho]$ with $m_\rho = 768$ MeV and $\Gamma_\rho \sim 250$ MeV, the spectator state becomes an on-shell quark with mass $m_q = 340$ MeV. Naive "T-odd" FF now arise from the interference between the direct production of the two π, which exchange a quark in t channel, and the decay of the ρ. We have explicitly checked that the former contribution reproduces the experimental transition probability for $\pi-\pi$ production in the relative S-channel, while the latter one is known to do the same job in the relative P-channel. Hence, we believe this choice represents most of the $\pi-\pi$ strength for invariant mass in the considered interval.

By defining specific Feynman rules for the $\rho\pi\pi$, $q\pi q$ and $q\rho q$ vertices, we perform actual calculations of the interference FF with microscopical ingredients. Cut-offs are introduced in the vertices to exclude large virtualities of the quark while keeping the asymptotic behaviour of FF at large z consistent with the quark counting rule. We infer the vertex form factors from previous works on the spectator model [6]. However, there numbers should be taken as indicative, since the ultimate goal is to verify that nonvanishing "T-odd" FF occur at leading twist, particularly when integrating on some of the kinematical variables and possibly washing all interference effects out.

Results of analytical calculation of Eq.(2) show that $H_1^\perp = 0$ and $H_1^{\sphericalangle} = -2m_q G_1^\perp/m_\pi$, where m_q is the quark mass. After integrating over $\mathbf{k}_T, \mathbf{R}_T^2$ while keeping $\mathbf{R}_T$ in the horizontal plane of the lab (usually identified with the scattering plane), we still get nonvanishing $H_1^{\sphericalangle}(z,M_h)$ and $G_1^\perp(z,M_h)$.

The cross section for the deep-inelastic scattering of an unpolarized electron on a polarized proton target where two pions are detected in the final state, contains, after integrating all the transverse dynamics $(\mathbf{P}_{hT},\mathbf{k}_T,\mathbf{R}_T^2)$, an unpolarized contribution proportional to $D_1(z,M_h)$ and a term proportional to $H_1^{\sphericalangle}(z,M_h)$ which depends on the transverse target polarization S_T. Therefore, by flipping the polarization of the target, it is possible to build the following azimuthal asymmetry

$$\mathcal{A} \propto \frac{S_T}{2m_\pi}\sin(\phi_{R_T}+\phi_{S_T})\,\frac{h_1(x)}{f_1(x)}\,\frac{H_1^{\sphericalangle}(z,M_h)}{D_1(z,M_h)}\,, \qquad (3)$$

where ϕ_{R_T},ϕ_{S_T} are the azimuthal angles of $\mathbf{R}_T,\mathbf{S}_T$ with respect to the scattering plane, respectively. The asymmetry shows indeed the familiar sinusoidal azymuthal dependence. Noteworthy is the factorization of the chiral-odd, naive "T-odd" $H_1^{\sphericalangle}$ from the chiral-odd transversity h_1. Therefore, such asymmetry measurement allows for the extraction of h_1 using a model input for the FF.

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[2] Bianconi A., Boffi S., Jakob R., and Radici M., *Phys. Rev.* D **62**, 034008 (2000).

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[6] Jakob R., Mulders P.J., and Rodrigues J., *Nucl. Phys.* A **626**, 937 (1997).

Calculation of T-odd fragmentation functions in semi-inclusive processes

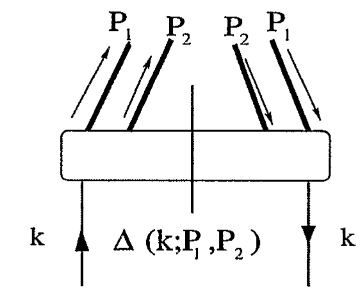
Marco Radici

I.N.F.N. - Pavia

based on work with
A. Bianconi, S. Boffi, D. Boer, R. Jakob

Transversity, BNL., 18-20 Sept. 2000

$lH \to l'h_1h_2X$ at leading order , $S_R = 0$



$$\Delta(k;P_1,P_2) = \sum_X \int \frac{d^4\xi}{(2\pi)^4} \int \frac{d^4P_X}{(2\pi)^4}\, e^{ik\cdot\xi}\, \langle 0|\psi(\xi)|P_1,P_2,X\rangle \langle X,P_2,P_1|\overline{\psi}(0)|0\rangle$$

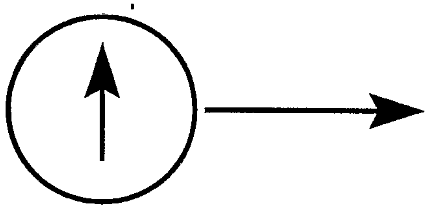
$$= C_1\,(M_1+M_2) + C_2\,\not{P}_1 + C_3\,\not{P}_2 + C_4\,\not{k} + \frac{C_5}{M_1}\sigma_{\mu\nu}P_1^\mu k^\nu + \frac{C_6}{M_2}\sigma_{\mu\nu}P_2^\mu k^\nu + \frac{C_7}{M_1+M_2}\sigma_{\mu\nu}P_1^\mu P_2^\nu + \frac{C_8}{M_1M_2}\gamma_5\epsilon_{\mu\nu\rho\sigma}\gamma^\mu P_1^\nu P_2^\rho k^\sigma$$

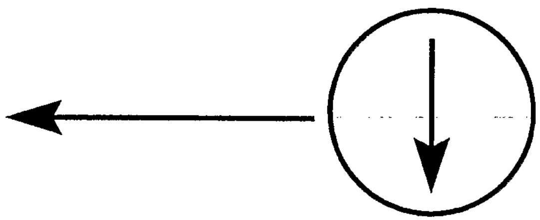
Hermiticity $\Longrightarrow$ $C_i^* = C_i$; $i = 1-4, 5-8$

Time-reversal inv. $\Longrightarrow$ $\begin{cases} C_i^* = C_i & i = 1-4 \\ C_i^* = -C_i & i = 5-8 \end{cases}$

no FSI $\Longrightarrow$ $C_5 = C_6 = C_7 = C8 = 0$!

Naive Time-reversal invariance

$| \, i \, , f > \; =$ 

$| \, -i, \; -f > \; =$ 

Time-rev. inv. $\longrightarrow \; | \, T_{i\,f} \, |^2 = | \, T_{-f\,-i} \, |^2$

$| \, T_{i\,f} \, |^2 - \; | \, T_{-i\,-f} \, |^2$

$\nearrow$ = 0 Naive Time-rev. inv.

$\searrow$ $\neq$ 0 T-odd effects

Kinematics

$$P_h = P_1 + P_2 = \left[P_h^-, P_h^+, 0_T\right] \qquad k = \left[\frac{P_h^-}{z_h}, z_h \frac{k^2 + \vec{k}_T^2}{2P_h^-}, \vec{k}_T\right]$$

$$z_h = \frac{P_1^- + P_2^-}{k^-} = z_1 + z_2 \qquad P_1 = \left[\xi P_h^-, \frac{M_1^2 + R_T^2}{2\xi P_h^-}, R_T\right]$$

$$\xi = \frac{z_1}{z_2} \qquad P_2 = \left[(1-\xi)\, P_h^-, \frac{M_2^2 + R_T^2}{2(1-\xi)\, P_h^-}, -R_T\right]$$

$$\tau_h = k^2 \; ; \qquad M_h^2 = P_h^2 = \frac{M_1^2 + \vec{R}_T^2}{\xi} + \frac{M_2^2 + \vec{R}_T^2}{1-\xi}$$

$$\sigma_h = 2P_h \cdot k = \frac{M_1^2 + \vec{R}_T^2}{z_h\, \xi} + \frac{M_2^2 + \vec{R}_T^2}{z_h\, (1-\xi)}$$

$$\sigma_d = 2(P_1 - P_2) \cdot k = 4R \cdot k =$$

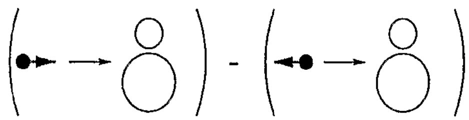
$$\frac{M_1^2 + \vec{R}_T^2}{z_h\, \xi} - \frac{M_2^2 + \vec{R}_T^2}{z_h\, (1-\xi)} + z_h (2\xi - 1)(\tau_h + \vec{k}_T^2) - 4\, \vec{k}_T \cdot \vec{R}_T$$

$$\begin{aligned} \Delta^{[\Gamma]} &= \frac{1}{4 z_h} \int dk^+ \int dk^- \, \delta\left(k^- - \frac{P_h^-}{z_h}\right) \, \mathrm{Tr}[\Delta\Gamma]\Big|_{\vec{k}_T} \\ &= \int d\sigma_h d\tau_h \, \delta\left(\tau_h + \vec{k}_T^2 - \frac{\sigma_h}{z_h} + \frac{M_h^2}{z_h^2}\right) \frac{\mathrm{Tr}[\Delta\Gamma]}{8 z_h P_h^-} \\ &= \Delta^{[\Gamma]}(z_h, \xi, \vec{k}_T^2; M_h^2, \sigma_d \to \vec{k}_T \cdot \vec{R}_T) \end{aligned}$$

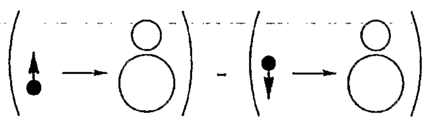
Fragmentation Functions at leading order

- $\Delta^{[\gamma^-]}(z_h, \xi, M_h^2, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = D_1(z_h, \xi, M_h^2, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T)$

- $\Delta^{[\gamma^- \gamma_5]}(z_h, \xi, M_h^2, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = \dfrac{\epsilon_T^{ij} R_T^i k_{Tj}}{M_1 M_2} G_1^\perp$

$G_1^\perp =$ 

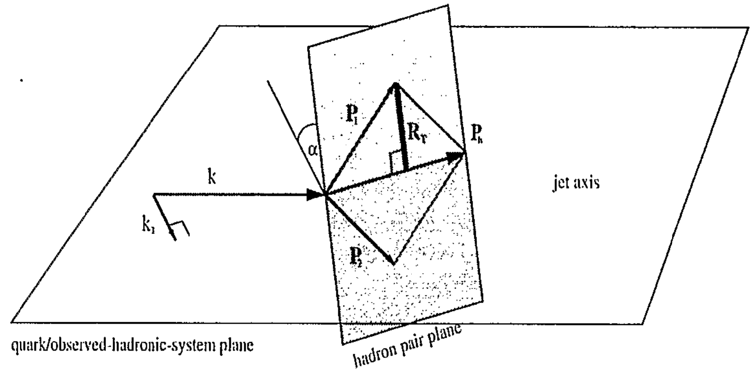
- $\Delta^{[i\sigma^{i-} \gamma_5]}(z_h, \xi, M_h^2, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = \dfrac{\epsilon_T^{ij} R_{Tj}}{M_1 + M_2} H_1^{\sphericalangle} + \dfrac{\epsilon_T^{ij} k_{Tj}}{M_1 + M_2} H_1^\perp$

$H_1^\perp =$ 

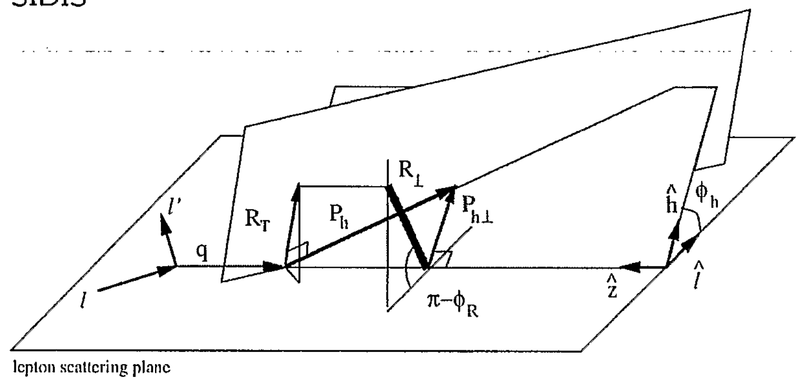
$\Longrightarrow$ "double Collins effect": $H_1^\perp$, $\boxed{H_1^{\sphericalangle}}$

Kinematics

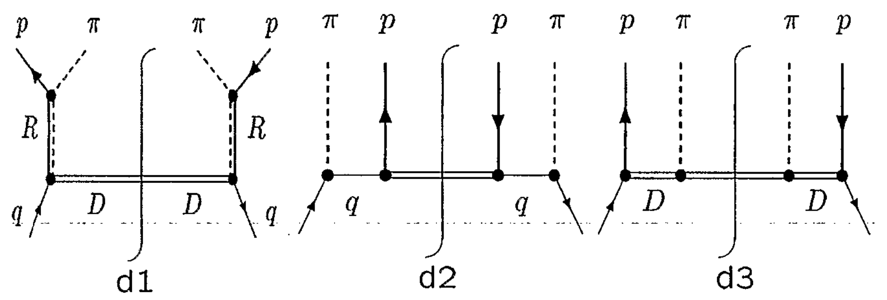
$\Delta^{[\Gamma]}(z_h, \xi, M_h^2, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T)$



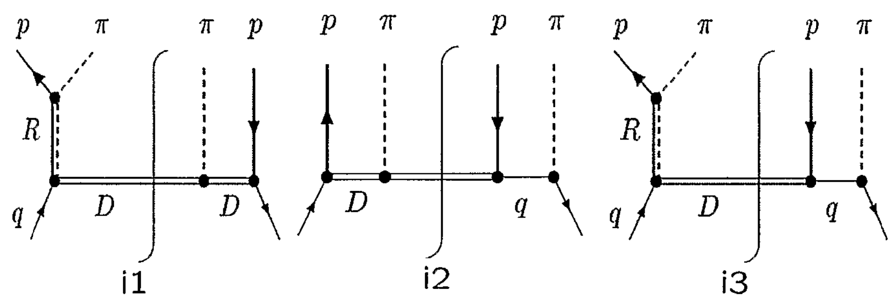
SIDIS



$lH \to l'(R \to p\pi)X$ at leading order



diagonal diagrams



interference diagrams

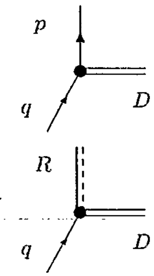
Spectator Model

$$|X\rangle \sim |D_f(qq)\ ,\ P_D^2 = M_D^2\rangle\ ;\ f = S, A \to D_S \equiv S, D_A \equiv A$$

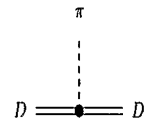
$$\Delta = \frac{\theta(P_D^+)}{(2\pi)^3}\,\delta\left((k-P_h)^2 - M_D^2\right)\ \langle 0|\psi(0)|\pi, p, D\rangle\langle D, p, \pi|\overline{\psi}(0)|0\rangle$$

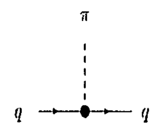
Vertices :

$$\begin{cases} \Upsilon^{\mathbf{qSp}} \equiv \Upsilon^{\mathbf{qSR}} = N_{qD}\, \mathbb{1}\, \dfrac{\tau_h - m_q{}^2}{|\tau_h - \Lambda_N{}^2|^2} \\ (\Upsilon^{\mathbf{qAp}})^\mu \equiv (\Upsilon^{\mathbf{qAR}})^\mu = \dfrac{N_{qD}}{\sqrt{3}}\,[\gamma_5\gamma^\mu]\,\dfrac{\tau_h - m_q{}^2}{|\tau_h - \Lambda_N{}^2|^2} \end{cases}$$



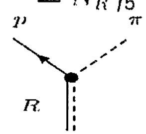
$$(\Upsilon^{\mathbf{A\pi A}})_{\mu\nu} = f_{D\pi D}\,\epsilon_{\mu\nu\rho\sigma}\,p_1^\rho p_2^\sigma \qquad \Upsilon^{\mathbf{q\pi q}} = N_{q\pi}\gamma_5 \frac{\tau_h - m_q^2}{|\tau_h - \Lambda_\pi{}^2|}$$





Propagators :

$$\Upsilon^{\mathbf{p\pi R}} = N_R\gamma_5$$

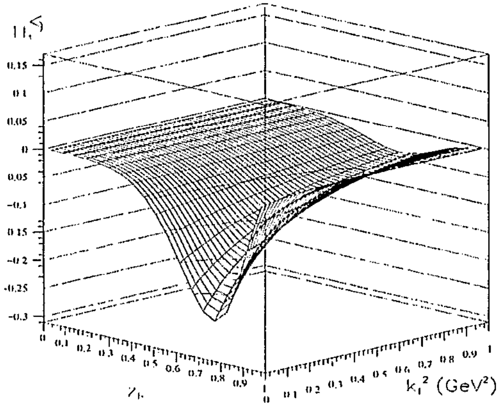


quark $\dfrac{\mathrm{i}}{\not{k} - m_q}$

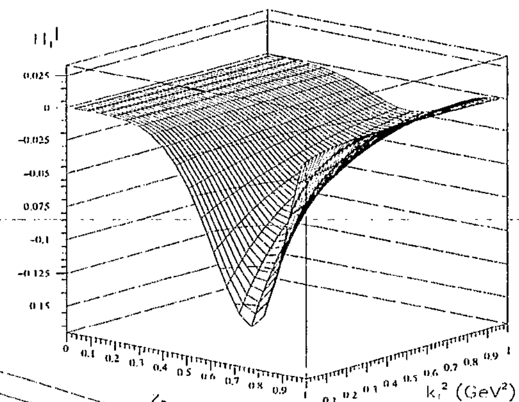
Roper $\dfrac{\mathrm{i}\,(\not{P}_h + M_R)}{P_h^2 - M_R{}^2 + \mathrm{i}M_R\Gamma_R}$

Diquark $S \to \dfrac{\mathrm{i}}{P_D^2 - M_S{}^2}\ ;\ A \to \dfrac{\mathrm{i}}{P_D^2 - M_A{}^2}\left(-g^{\mu\nu} + \dfrac{P_D^\mu P_D^\nu}{P_D^2}\right)$

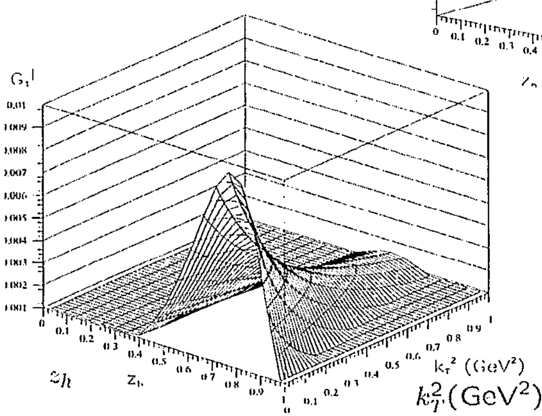
- $M_h = M_R = 1.44$ GeV
- $\vec{k}_T \cdot \vec{R}_T = 0$
- $R_T^2(\xi) \geq 0 \Rightarrow 0.5 \leq \xi \leq 0.9$



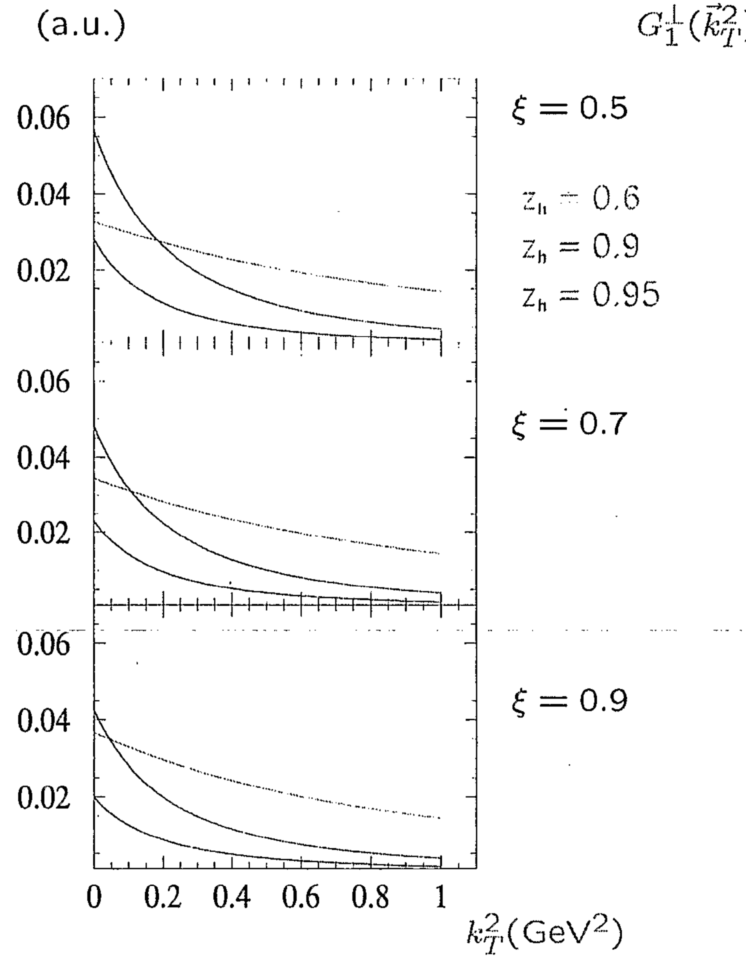
$H_1^{\sphericalangle}(z_h, \xi = 0.7, \vec{k}_T^2)$



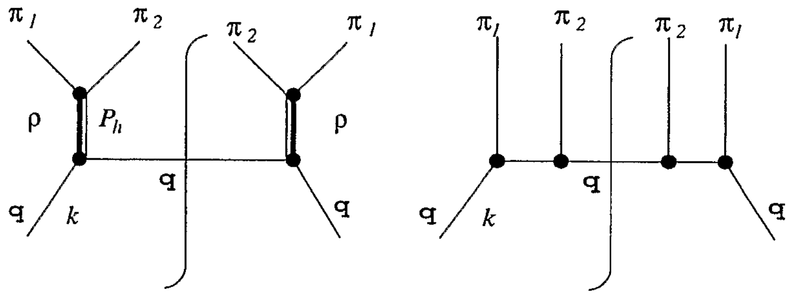
$H_1^{\perp}(z_h, \xi = 0.7, \vec{k}_T^2)$



$G_1^{\perp}(z_h, \xi = 0.7, \vec{k}_T^2)$

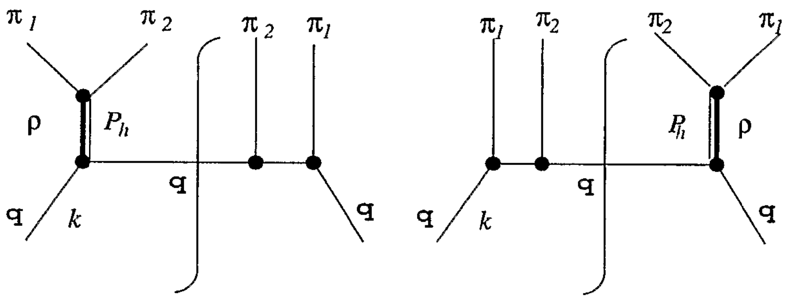


$lH \to l'\pi^+\pi^- X$ at leading order



d1 d2

diagonal diagrams



i1 i2

interference diagrams

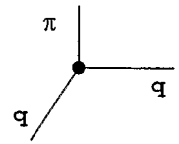
Spectator Model

$|X\rangle \sim |q\ ,\ (k-P_\pi)^2 = m_q^2\rangle\ ;\ k - P_\pi \equiv k_\pi$

$$\Delta = \frac{\theta(k_\pi^+)}{(2\pi)^3}\, \delta\left(k_\pi^2 - m_q^2\right)\ \langle 0|\psi(0)|\pi^+,\pi^-,q\rangle\langle q,\pi^+,\pi^-|\overline{\psi}(0)|0\rangle$$

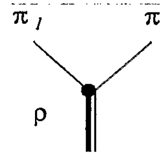
Vertices

$$(\Upsilon^{\rho\pi\pi})^\mu = f_{\rho\pi\pi}\ R_h^\mu\ ;\ \frac{f^2_{\rho\pi\pi}}{4\pi} = 2.84 \pm 0.50$$



$$\Upsilon^{q\pi q} = \frac{N_{q\pi}}{\sqrt{2}}\frac{1}{|\kappa^2 - \Lambda_\pi^2|^{\frac{3}{2}}}[\gamma_5]\ ;\ \kappa = \tau_h,\ k_\pi$$

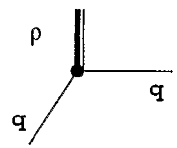
$N_{q\pi} = 2.564\text{GeV}^2\ ;\ \Lambda_\pi = 0.4\text{GeV}$



$$(\Upsilon^{q\rho q})^\mu = \frac{N_{q\rho}}{\sqrt{2}}\frac{1}{|\tau_h - \Lambda_\rho^2|^{\frac{3}{2}}}[\gamma^\mu]$$

$$N_{q\rho} = \left(\frac{1}{26}\ \frac{N^4_{q\pi}}{f^2_{\rho\pi\pi}}\ \frac{|m_q^2 - \Lambda_\rho^2|^3}{|m_q^2 - \Lambda_\pi^2|^6}\right)^{\frac{1}{2}}$$

$\Lambda_\rho = 0.5\text{GeV}$



ρ propagator

$$\frac{1}{P_h^2 - m_\rho{}^2 + \mathrm{i} m_\rho \Gamma_\rho}\ \left(-g^{\mu\nu} + \frac{P_h^\mu P_h^\nu}{P_h^2}\right)$$

$$m_\rho = 0.768\text{GeV}\ ;\ \Gamma_\rho = \frac{f^2_{\rho\pi\pi}}{4\pi}\frac{m_\rho}{12}\left(1 - \frac{4m_\pi^2}{m_\rho^2}\right)^{\frac{3}{2}}$$

Plot of interf. fragm. functions
for $u \to \pi^+ + \pi^-$

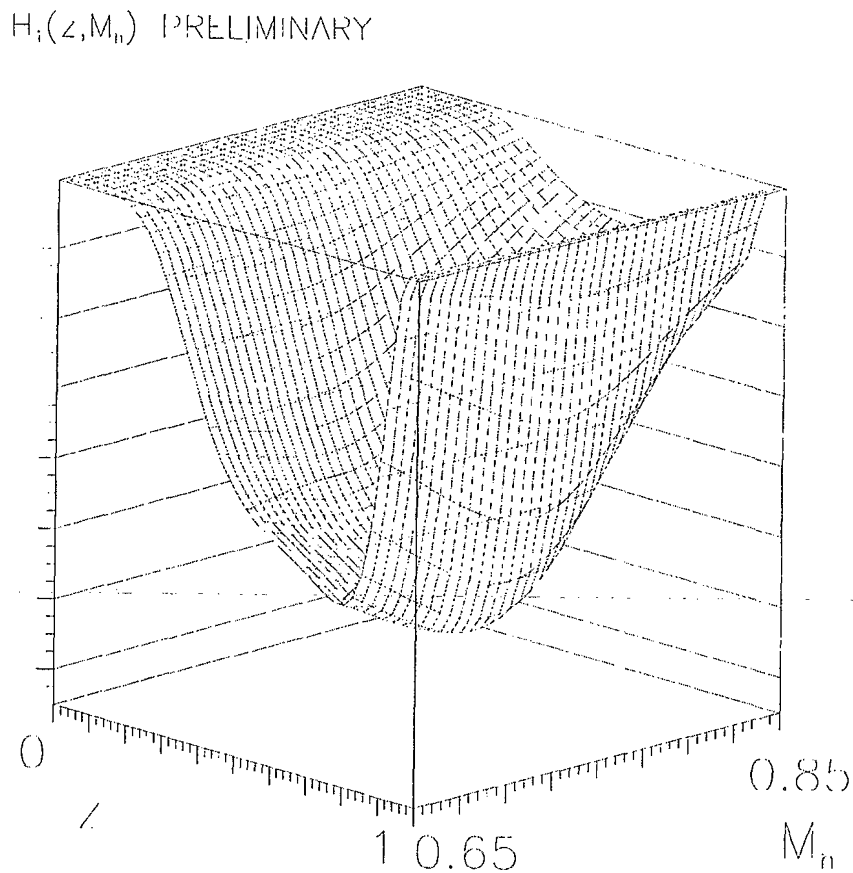
- $H_1^\perp(z_h, \xi, M_h, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = 0$

- $H_1^{\sphericalangle} = -m_q \, \dfrac{m_{\pi_1} + m_{\pi_2}}{m_{\pi_1} m_{\pi_2}} \, G_1^\perp$

- $\vec{R}_T^2(\xi) = \xi(1-\xi)M_h^2 - (1-\xi)m_{\pi_1}^2 - \xi m_{\pi_2}^2 \geq 0$
  $\Rightarrow \ \xi_{min} \leq \xi \leq \xi_{max}$
  $\phi_{R_T} = 0$ deg

- $\displaystyle\int d\vec{k}_T \int_{\xi_{min}}^{\xi_{max}} d\xi \ D_1(z_h, \xi, M_h, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = \ D_1(z_h, M_h)$
  $\displaystyle\int d\vec{k}_T \int_{\xi_{min}}^{\xi_{max}} d\xi \ G_1^\perp(z_h, \xi, M_h, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = \ G_1^\perp(z_h, M_h)$
  $\displaystyle\int d\vec{k}_T \int_{\xi_{min}}^{\xi_{max}} d\xi \ H_1^{\sphericalangle}(z_h, \xi, M_h, \vec{k}_T^2, \vec{k}_T \cdot \vec{R}_T) = \ H_1^{\sphericalangle}(z_h, M_h)$

- $m_q = 0.34$ GeV ; $m_{\pi_1} = m_{\pi_2} = 0.135$ GeV



How to disentangle h_1?

$$\frac{d\sigma}{x dy dz_h \, d\xi \;\, d^2\vec{q}_T \;\, d^2\vec{R}_T} = K L_{\mu\nu}\, W^{\mu\nu} \left\{ \begin{array}{l} \displaystyle\int d\vec{p}_T d\vec{k}_T \; \delta(\vec{p}_T + \vec{q}_T - \vec{k}_T) \\ \qquad\qquad \mathrm{w}(\vec{p}_T, \vec{k}_T) \;\, \mathrm{DF}(x, \vec{p}_T) \\ \qquad \mathrm{FF}\;(\mathrm{z}_h, \xi, \; M_h \;, \vec{k}_T^2, \vec{k}_T \cdot \; \vec{R}_T \;) \end{array} \right.$$

- $R_T^2(\xi, M_h)$; $\phi_{R_T} = 0$ deg $\Longrightarrow \int d\vec{q}_T \int_{\xi_{min}}^{\xi_{max}} d\xi$

$$\frac{d\sigma}{dx dy dz_h \; dM_h} = K \Big\{ \quad \mathrm{A(y)} \;\, \mathrm{f}_1(x) \widetilde{D}_1(z_h, M_h) +$$

$$\mathrm{B(y)} \; \frac{|\vec{S}_T|}{m_{\pi_1} + m_{\pi_2}} \sin(\; \phi_{R_T} \; + \; \phi_{S_T} \;) \;\; h_1(x) \;\;\; \widetilde{H}_1^{\sphericalangle}(z_h, M_h) \; +$$

$$\mathrm{C(y)} \;\; \lambda_e \lambda \quad \mathrm{g}_1(x) \;\, \widetilde{D}_1(z_h, M_h) \Big\}$$

$$\frac{d\mathcal{A}_{\;OT}}{dx dy dz_h \; dM_h} = \frac{B(y)}{A(y)} \quad \frac{|\vec{S}_T|}{m_{\pi_1} + m_{\pi_2}} \sin(\; \phi_{R_T} \; + \; \phi_{S_T} \;) \; \frac{h_1(x)}{f_1(x)} \; \frac{\widetilde{H}_1^{\sphericalangle}(z_h, M_h)}{\widetilde{D}_1(z_h, M_h)}$$

Summary

- Interest in interf. fragm. functions (intFF) for hadronization in 2 hadrons at leading order
  [Phys. Rev. **D62** (2000) 034008]
- Calculations of intFF, e.g.
  - $lH \to l'p\pi X$ [Phys. Rev. **D62** (2000) 034009]
  - $lH \to l'\pi^+\pi^- X$ in progress
  - insight into hadronization and FSI through microscopical model
- Disentangle transversity at leading order
  - e.g. $l\vec{H} \to l'\pi^+\pi^- X$
- Extend calculations to other processes, e.g.
  - $e^+e^- \to h_1 h_2 X$
  - $e^+e^- \to h_1 h_2 h_3 h_4 X$
  - $pp \to h_1 h_2 X$
- Q_o^2 scale $\to$ evolution ?
  - but diquark model is comparable with GRV param. or EMC data, when available
    [see Jakob *et al.*, N.P. **A626** (1997) 937]

Soft pions in hard reactions

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There are several examples of hard reactions in which a pair of soft pions is produced. Examples are semi-inclusive reactions and hard exclusive reactions. In the case of hard semi-inclusive pion pair production the fragmentation function corresponding to the interference of $C = +$ and $C = -$ two pion states is accompanied by the transversity distribution in the nucleon. This in principle allows to measure the transversity in such reactions [1]. To do this one needs an information about two pion fragmentation functions (2πFF). As the invariant mass of a pion pair is low one can apply the methods of chiral perturbations theory in order to constrain 2πFF.

In my talk I demonstrated how these methods work for the two-pion distribution amplitude (2πDA) [2]. This object appears in QCD description of hard exclusive reaction and it characterizes the transition of small transverse size quark-antiquark pair into a pair of soft pions. I showed that one can prove new soft pion theorems for 2πDA which relate this object to the DA of a single pion which is measured in other hard reactions [3]. Furthermore the dependence of the 2πDA on the invariant mass of the produced pions can be fixed in terms of known $\pi\pi$ scattering phase shifts. Using these results one is able to constrain considerably 2πDA what allows in turn to make predictions for hard exclusive reactions with productions of two pions [4]. Interesting interference phenomena in hard exclusive production of pion pairs were considered recently in ref. [5]

Analogous methods can be also applied to the 2πFF in order to fix properties of this new object. This would help to extract the transversity distribution in the nucleon from data on hard semi-inclusive production of pion pairs.

[1] R.L. Jaffe, X. Jin, J. Tang, Phys. Rev. Lett. **80** (1998) 1166.
[2] M. Diehl, T. Gousset, B. Pire, and O. V. Teryaev, Phys. Rev. Lett. **81**, (1998) 1782.
[3] M. V. Polyakov, Nucl. Phys. B **555** (1999) 231.
[4] B. Clerbaux, M. V. Polyakov, Nucl. Phys. A **679** (2000) 185.
[5] B. Lehmann-Dronke, A. Schaefer, M. V. Polyakov and K. Goeke, *"Angular distributions in hard exclusive production of pion pairs,"* hep-ph/0012108.

SOFT PIONS IN HARD REACTIONS

M. V. POLYAKOV

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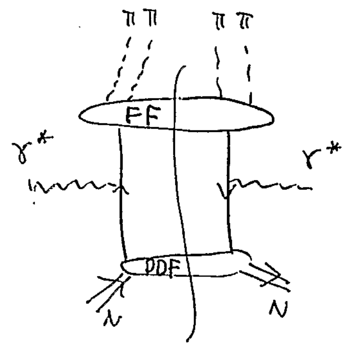
1. HOW CHIRAL DYNAMICS CAN HELP US TO ANALYSE DATA ON HARD REACTIONS?

2. WHAT CAN WE LEARN about CHIRAL LAGRANGIAN FROM HARD REACTIONS?

2π IN SIDIS AND TRANSVERSITY



Idea to use INTERFERENCE OF C=+1 & C=−1 ππ states to access transversity
/ Collins, Heppelmann, Ladinsky '94
Jaffe, Jin, Tang '98 /

$$\sum_X \int dz^+ e^{ik^- z^+} \langle 0 | \psi_i(z) | \pi(p_1)\pi(p_2) X \rangle_{out} \times {}_{out}\langle \pi(p_1)\pi(p_2) X | \bar{\psi}_j(0) | 0 \rangle \Big|_{z^2=0}$$

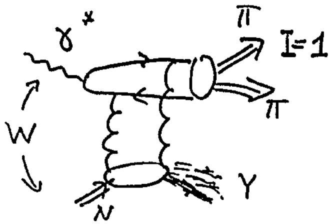
$\Longrightarrow$ CHIRALLY odd FF $H_1^{\sphericalangle}$, H_1^{+}

/ Bianconi, Boffi, Jakob, Radici '99 /

$$\frac{d\sigma(\gamma^* N \to \pi\pi X)_{OT}}{d\Omega\, dx\, d\zeta\, \underbrace{d^2 P_\pi^\perp}_{\hookrightarrow\, dm_{\pi\pi}}} \sim |S_\perp| |P_\pi^\perp| \sum_f e_f^2\, h_1(x)\, H_1^{\sphericalangle}(z, \zeta, m_{\pi\pi})$$

TRICK: UNDER T-transformation $|\pi\pi\rangle_{out} \to |\pi\pi\rangle_{in}$ and for a many particle state. $|\ \rangle_{out} \neq |\ \rangle_{in}$

FIRST EXAMPLE: two-pion hard production at small x_{Bj} ("ρ-meson" prod'n)

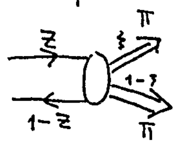


$\leftarrow$ C-parity minus

$M^2_{\pi\pi} \ll Q^2 \sim W^2$

$M_Y^2 \ll Q^2$

Non-perturbative object: 2π WF



} soft

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$$\Phi_{2\pi}(z,\zeta,m_{\pi\pi}) = \int \frac{d\lambda}{2\pi} e^{i\lambda z (P\cdot n)} \times$$

$$\times \langle \pi(P_1)\pi(P_2)|_{out} \, \bar{\psi}(\lambda n) \not{n} \psi(0) | 0 \rangle$$

cf $H^*(z,\zeta,m_{\pi\pi})$

$n^2 = 0$; $P^\mu = p_1^\mu + p_2^\mu$

$$\zeta = \frac{n\cdot p_1}{n\cdot P}$$

$$\frac{d\sigma}{dt} \sim \left| \int \frac{dz}{z(1-z)} \Phi_{2\pi}(z,\zeta,m_{\pi\pi}) \right|^2 \left| x_{Bj}\, G^{\text{skewed}}(x_{Bj}) \right|^2$$

c.f. $\left| \int \frac{dz}{z(1-z)} \phi_\rho(z) \right|^2$ —"— standard formula

CLOSER LOOK AT $\Phi_{2\pi}$

$$\Phi_{2\pi}(z,\zeta,m_{\pi\pi}) = 6z(1-z) \sum_{n=0}^{\infty} \sum_{\ell=1}^{n+1} B_{n\ell}(m_{\pi\pi}) \times$$

$$\times\, C_n^{3/2}(2z-1)\, P_\ell(2\zeta-1)$$

conformal spin $\nearrow$ $\quad$ $\uparrow$ orbital momentum

Evolution

$$B_{n\ell}(m_{\pi\pi};Q^2) = \left(\frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)}\right)^{\gamma_n} \cdot B_{n\ell}(m_{\pi\pi}, Q_0^2)$$

$\gamma_0 = 0 \qquad \gamma_{2,4,\dots} > 0$

asymptotically

$$\Phi_{2\pi}(z,\zeta,m_{\pi\pi}) = 6z(1-z)\cdot(2\zeta-1)\cdot B_{01}(m_{\pi\pi}) \cong$$

fixed by normalization

$$\int_0^1 dz\, \Phi(z,\zeta,m_{\pi\pi}) = F_\pi^{e.m.}(m_{\pi\pi})\cdot(2\zeta-1)$$

$$\cong 6z(1-z)(2\zeta-1)\, F_\pi^{e.m.}(m_{\pi\pi})$$

$\uparrow$ measured with high accuracy in $e^+e^- \to 2\pi$ at low energies

Soft pion theorems for $\Phi_{2\pi}$

In the limit $\zeta \to 0, 1$ & $m_{\pi\pi} \to 0$

$p^{\mu}_{1(2)} \to 0 \Leftarrow$ soft pion

/Weinberg '67/

Generically:

$$\lim_{p^\mu \to 0} {}_{out}\langle \pi(p) A | \mathcal{O} | B \rangle_{in} = \frac{i}{f_\pi} \langle A | \mathcal{O}^{\text{chirally rotated}} | B \rangle$$

/Teryaev, M.V.P. '98/

$$\Phi_{2\pi}(z, \zeta, m_{\pi\pi}) \xrightarrow[m_{\pi\pi}\to 0]{\zeta \to 0,1} \varphi_\pi(z) = 6z(1-z)\left[1 + a_2^\pi C_2^{3/2}(2z-1) + \dots\right]$$

↑ pion WF, probed in $\gamma^*\gamma \to \pi$, $F_\pi^{em}(Q^2 \to \infty)$, etc.

$$\boxed{a_2^\pi = B_{21}(0) + B_{23}(0)}$$

Let us move up in $m_{\pi\pi}$!

↑ $\pi\pi$ scattering amplitude $\Rightarrow$

$\Rightarrow \Phi_{2\pi}$ gets imaginary part

/Watson '56/

$$\mathrm{Im}\, B_{nl}(m_{\pi\pi}) = \mathrm{tg}\left[\delta_l(m_{\pi\pi})\right] \cdot \mathrm{Re}\, B_{nl}$$

↑ $\pi\pi$ scattering phase shifts – well measured

$\Rightarrow$ Dispersion relations

Omnès solutions /Omnès '58/

$$B_{nl}(m_{\pi\pi}) = B_{nl}(0) \cdot f_{nl}(m_{\pi\pi})$$

constrained by soft pion theorems

↑ Omnès functions studied by "chiral community"

$$\ln f_{nl}(m_{\pi\pi}) = \sum_{k=1}^{N_s} C_{nl}^{(k)} m_{\pi\pi}^{2k} + \frac{m_{\pi\pi}^{2N_s}}{\pi} \int_{\text{threshold}}^{\infty} \frac{ds}{s^{N_s}} \frac{\delta_l(s)}{s - m_{\pi\pi}}$$

Subtraction coefficients $C_{nl}^{(k)}$ are related to coupling constants of Effective Chiral Lagrangian. E.g.

$C_{01}^{(1)} \sim L_9$ of Gasser & Leutwyler

The better we know **EChL** the better $f_{nl}(m_{\pi\pi})$ are constrained!

$C_{10}^{(1)}$ & $C_{12}^{(1)}$ are related to terms of EChL describing interaction of soft pions with gravity!

$$\mathcal{L} = \alpha_1 R^{\mu\nu}\, \mathrm{tr}(\partial_\mu U \partial_\nu U^+) + \alpha_2 R\, \mathrm{tr}(\partial_\mu U \partial^\mu U^+)$$

↑ curveture

Resonances

Near a resonance with spin ℓ:

$$\delta_\ell(m_{\pi\pi}\sim m_R) = \mathrm{arctg}\left[\frac{\Gamma_\ell m_R}{m_{\pi\pi}^2 - m_R^2}\right]$$

Using Omnès solution one gets:

$$\Phi_{2\pi}(z,\zeta, m_{\pi\pi}\sim m_R) = \Phi_R(z)\cdot P_\ell(2\zeta-1)$$

e.g.

$$\Phi_\rho(z) = i\,6z(1-z)\Big[\underbrace{f_{01}(m_\rho)}_{\overset{\parallel}{F_\pi^{e.m.}(m_\rho)}} + B_{21}(0)\, f_{21}(m_\rho)\, C_2^{3/2}(2z-1) + \Big]$$

$$\Phi_\rho(z) = i\,6z(1-z)\cdot F_\pi^{e.m.}(m_\rho)\left[1 + \frac{B_{21}(0)}{F_\pi^{e.m.}(m_\rho)}\, f_{21}(m_\rho)\, C_2^{3/2}(2z-1) + \right]$$

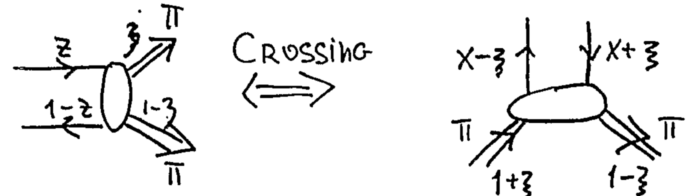
c.f. $\Phi_\rho(z) = f_\rho\; 6z(1-z)\left[1 + a_2^\rho\; C_2^{3/2}(2z-1) + \dots\right]$

$$f_\rho = \underbrace{i\,F_\pi^{e.m.}(m_\rho)}_{\text{well measured}}\;;\quad a_2^\rho = B_{21}(0)\,\underbrace{\frac{f_{21}(m_\rho)}{F_\pi^{e.m.}(m_\rho)}}_{\text{also known from low-energy physics}}$$

$B_{21}(0)$: We can measure in hard reactions

How?

CROSSING



WF SPD in the pion

Skewed Parton Distrbutions are related to 2π WF by Crossing

$\Rightarrow$ technically Sommerfeld–Watson transformation /Shuvaev + MVP '2001?/

$$B_{N\,N+1}(0) = \frac{2}{3}\,\frac{2N+3}{N+2}\int_0^1 dx\, x^N q_\pi(x)$$

$q_\pi(x)$: quark distributions in the pion $\Rightarrow$ appear in DY.

$\Phi_{2\pi}$

- $\xrightarrow{\text{soft pion th.}}$ WF of the pion
- $\longrightarrow$ WF of resonance
- $\xrightarrow{\text{Crossing}}$ PARTON DISTRIBUTIONS IN THE PION (including SPDs)
- $\xrightarrow{\text{Watson th.}}$ $\pi\pi$ scattering phases
- $\longrightarrow$ Effective Chiral Lagrangian
- $\longrightarrow$ Omnès functions

$\Phi_{3\pi} \longrightarrow U_A(1)$ axial anomaly

NEW LOOK!!!

THE SAME CAN BE SAID ABOUT FF like $H_1^{\sphericalangle}$, $H_1^{\perp}$

HOW TO PROBE $\Phi_{2\pi}$?

Idea: Shape of $m_{\pi\pi}$ spectrum

$$\frac{dN}{dm_{\pi\pi}} = \int \frac{dz}{z(1-z)} \Phi_{2\pi}(z,\zeta,m_{\pi\pi}) \otimes \text{BARYON STRUCTURE}$$

from Novosibirsk experiment. Barkov et al.

$$\frac{dN}{dm^2_{\pi\pi}} \propto \left(1-\frac{4m_\pi^2}{m^2_{\pi\pi}}\right)^{3/2} \left|F_\pi^{e.m.}(m_{\pi\pi})\right|^2 \times \left(1+D_1(m_{\pi\pi})\right)^2 + \frac{3}{7}\left(1-\frac{4m_\pi^2}{m^2_{\pi\pi}}\right)^{7/2} D_2^2(m_{\pi\pi})$$

$$D_1 = B_{21}(0)\, e^{+C_{21}^{(1)} m^2_{\pi\pi}} - \frac{6\, m_\pi^2}{m^2_{\pi\pi}} B_{23}(0)\, e^{C_{23}^{(1)} m^2_{\pi\pi}}$$

$$D_2 = B_{23}(0)\, e^{C_{23}^{(1)} m^2_{\pi\pi}}$$

we fit

constants of EChL

$\Rightarrow$ $a_2^\pi = B_{21}(0) + B_{23}(0)$ – soft pion theorems

$a_2^\rho = B_{21}(0)\, e^{C_{21} m_\rho^2}$

$$\int_0^1 dx\, x^2 \left(q_\pi(x) - \bar{q}_\pi(x)\right) = \frac{6}{7} B_{23}(0)$$

B. CLERBAUX + MVP

RESULTS OF THE FIT

$a_2^{\pi} = 0.02 \pm 0.50$ @ 21 GeV^2

0.14 ± 0.09 A. Schmedding & O. Yakovlev '99 $\gamma^* \gamma \to \pi$

$0.12 \pm 0.07^{+0.05}_{-0.07}$ V. BRAUN, A. Khodjamirian M. Maul '99 $F_\pi^{e.m.}(Q^2 \to \infty)$

-0.1 Bolz et al. '97

$\int_0^1 dx\, x^2 (q_\pi(x) - \bar{q}(x)) = 0.15 \pm 0.35$

0.085 ± 0.05 P.J. Sutton et al. '92 πN DY data

0.10 ± 0.02 C. Best et al. '97 Lattice

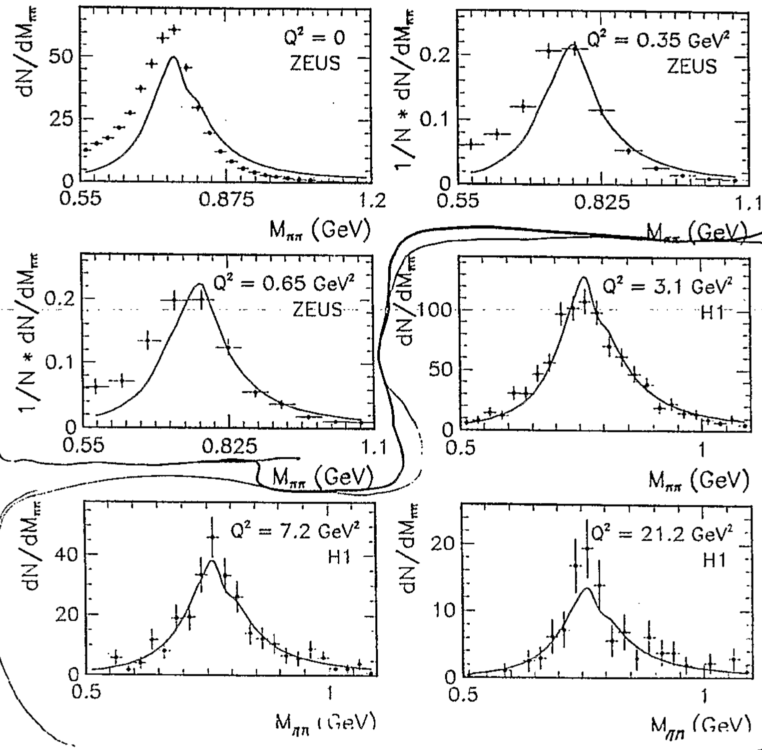
$u_2^P = -0.10 \pm 0.20$

0.12 ± 0.06 P. Ball & V. BRAUN '96 QCDSR

0.05 ± 0.01 S. Mikhailov '98 A. BAKULEV QCDSR

~ -0.1 MVP '98 instantons

soft REGIME $\chi^2/dof \sim$ hundreds



hard regime $\chi^2/dof \sim 1$

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CONCLUSION

WITH HELP OF CHIRAL DYNAMICS
(SOFT PION THEOREMS, CROSSING,
LOW-ENERGY EXP. DATA, ETC)
ONE CAN, IN PRINCIPLE, FIX
CHIRALLY-Odd FF FROM THE SHAPE
OF $\dfrac{d\sigma(\gamma^* N \to \pi\pi X)}{d\, m_{\pi\pi}}$

$\Rightarrow$ access TO h_1

$\Rightarrow$ NEW KNOWLEDGE ON CHIRAL LAGRANGIAN

$\Rightarrow$ NEW "PLAYGROUND" FOR LOW ENERGY MODELS OF QCD.

Status of Fragmentation Function Analysis at DELPHI

Oliver Passon
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BUGH-Wuppertal
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In order to access the chiral odd transversity distribution an other chiral odd partner is needed to construct a even cross section. Following the proposal by Jaffe [1] the two pion interference fragmentation function is a candidat for this. This presentation reports the status of the anaysis which tries to extract this fragmentation function out of DELPHI Z data.

In trying to extract the two-pion-interference-fragmentation-function (2πIFF) I proceeded in the following steps:

1. **select two jet events**
   A cut Thrust>0.95 was performed.

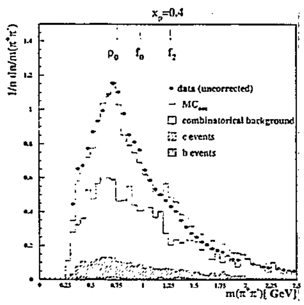


Figure 1: Invariant mass spectrum of the selected pion pairs. Here a rather restrictive x_p cut of 0.4 was performed. Above the background (like-sign, normalized to fit the tail) the ρ resonance can be seen clearly, although its shape is distorted by K^* and ω reflections. At the time beeing no pion ID was performed.

2. **remove heavy quark events**
   Standard strategies for removing b-quark events exist. They exploit live time differences of the weakly decaying B-hadrons, which give raise to a secondary vertex. The performed cut into a suitable variable removes 80% of all b-quark events.

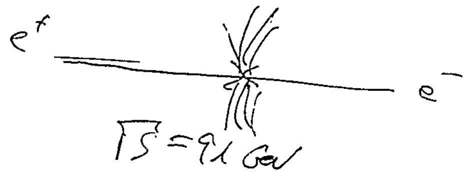
3. **select pion pairs in each jet**
   The pion pairs where demanded to carry a substantial fraction of the beam momentum, x_p. Different selections where tried out (between 20 and 40%). Additionally the helicity angle between the pion pairs was a selection criteria: $-0.7 < \cos\theta < 0.7$. This cut removes pion pairs which share the momentum very unequally. You end up with the distribution for the invariant mass of the pion pairs as shown in Fig. 1. As can be read of this plot the mass resolution of DELPHI is clearly better than 50 MeV (the binning of this distribution). The actual value is known to lie between 30 and 40 MeV (depending on the x_p cut). Thus it is possible to bin into different mass regions (below and above m_ρ) as suggested by the authors of [1].

4. **histogram the angle between the planes spanned by each pion pair**
   Following a suggestion by Bob Jaffe I looked into the angle between the planes spanned by a pion pair in *each* jet. In the course of the workshop it became clear that this angle does not carry the information we are interested in. More promissing seem to be the approaches developed in [2] and [3]. The discussion and work continues.

[1] R.L.Jaffe et al. *Interference Fragmentation Functions and the Nucleon's Transversity* hep-ph/9709322
[2] X.Artru and J.Collins *Measuring transverse spin correlations 4-particle correlations in $e^+e^- \to 2$ jets* hep-ph/9504220
[3] D.Boer *Azimuthal Asymmetries in Hard Scattering Processes* PHD-Thesis VU Amsterdam, 1998

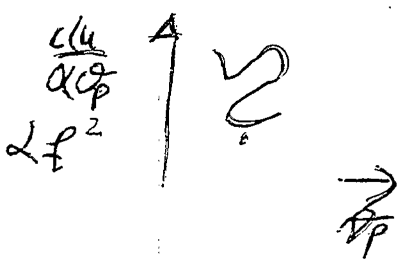
Status of Fragmentation Function Analysis at DELPHI

Oliver Passon
Wuppertal



The Method:

1. look for **two-jet** events
2. **remove** heavy quark events
3. pair $\pi^+\pi^-$ pairs in **each** jet
4. each $\pi^+\pi^-$ pair defines a **plane**, look into the distribution of the angles **between** this planes
5. bin masses below and above m_ρ ($\approx$ 770 MeV)



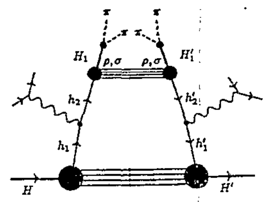


FIG. 1. Hard scattering diagram for $\pi^+\pi^-(K\bar{K})$ production in the current fragmentation region of electron scattering from a target nucleon. In perturbative QCD the diagram (from bottom to top) factors into the products of distribution function, hard scattering, fragmentation function, and final state interaction. Helicity density matrix labels are shown explicitly.

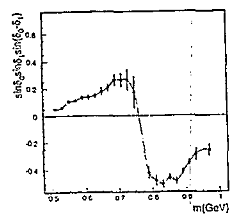
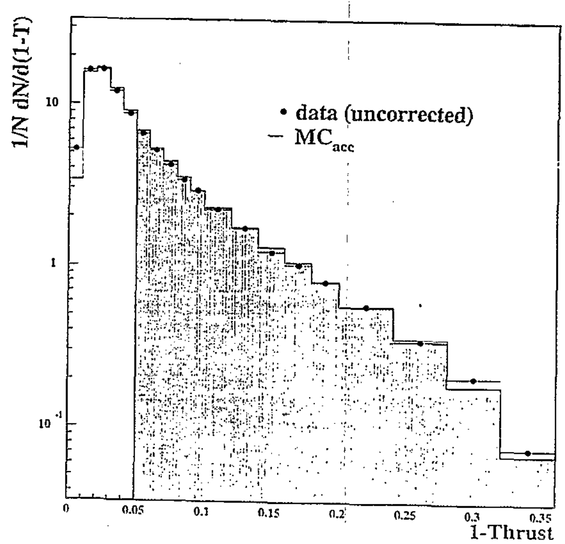
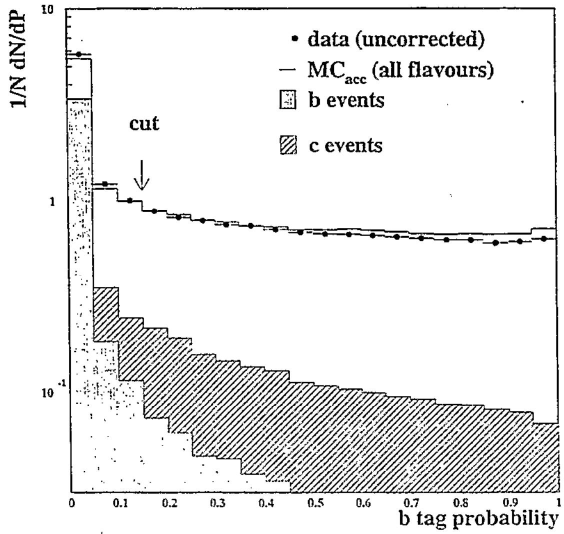


FIG. 2. The factor, $\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)$, as a function of the invariant mass m of two-pion system. The data on $\pi\pi$ phase shifts are taken from Ref. [15]

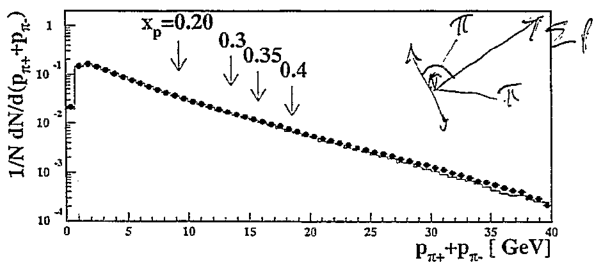
Step 1: look for two-jet events

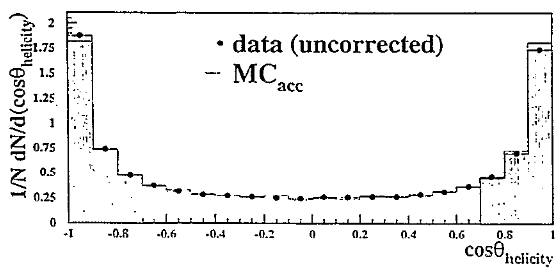


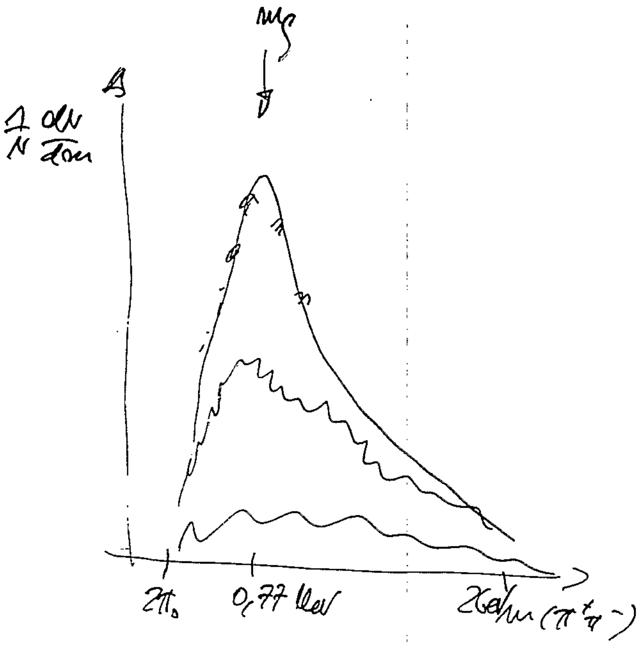
Step 2: remove b-quark events



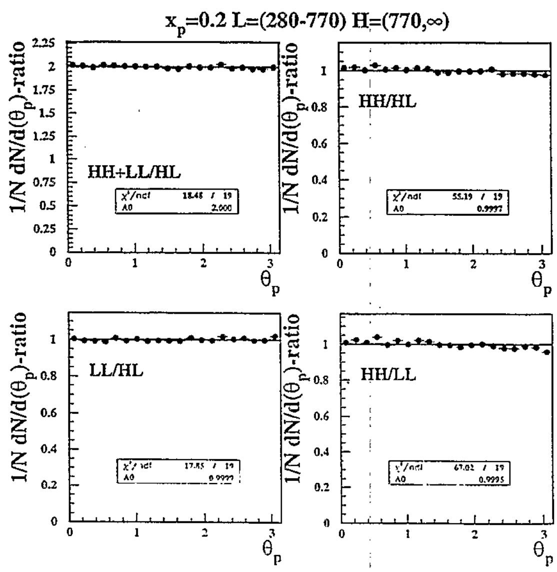
Step 3: pair $\pi^+\pi^-$ pairs in each jet





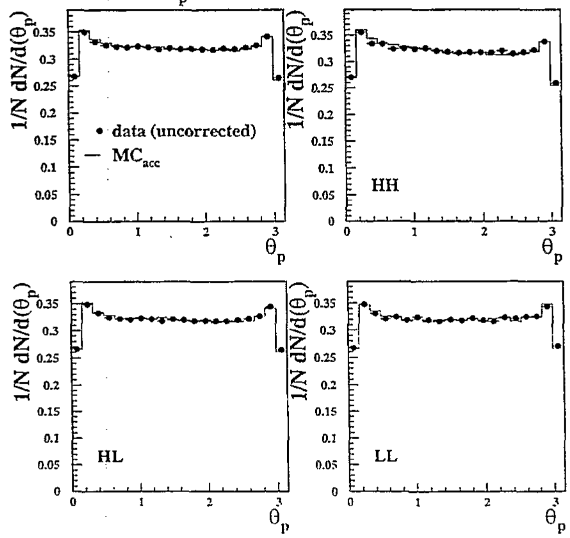


Step 4/5: distribution of angle between the planes



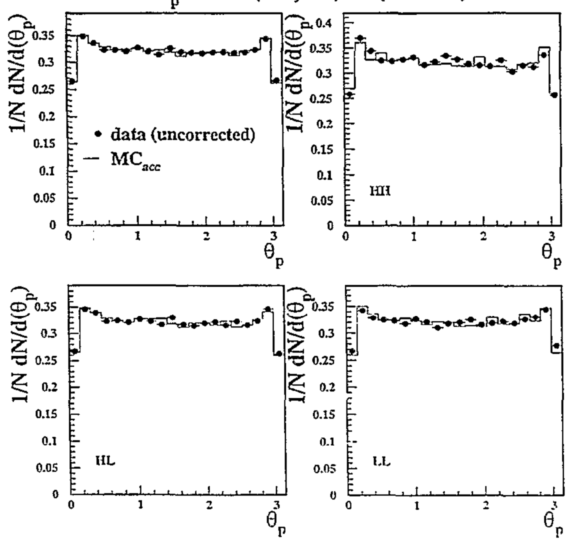
Step 4/5: distribution of angle between the planes

x_p=0.2 L=(280-770) H=(770,∞)



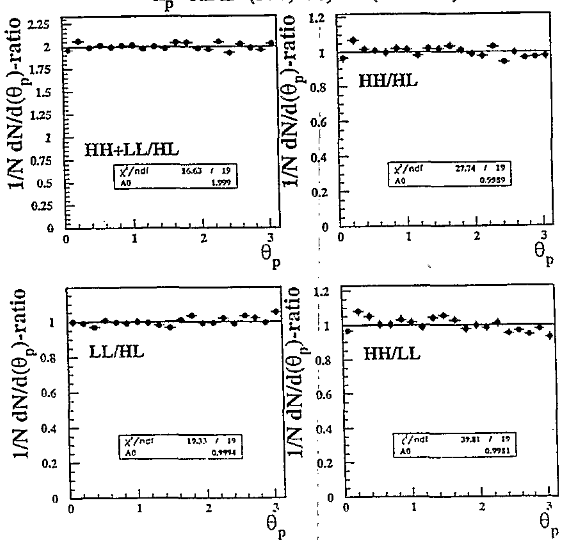
Step 4/5: distribution of angle between the planes

x_p=0.2 L=(570,770) H=(770-970)



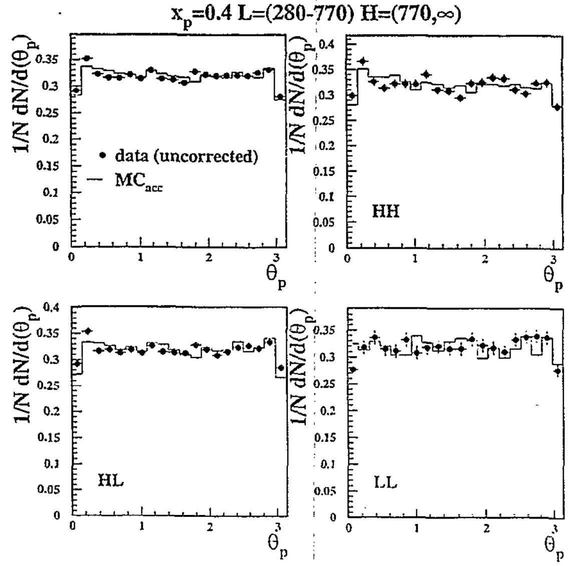
Step 4/5: distribution of angle between the planes

x_p=0.2 L=(570,770) H=(770-970)

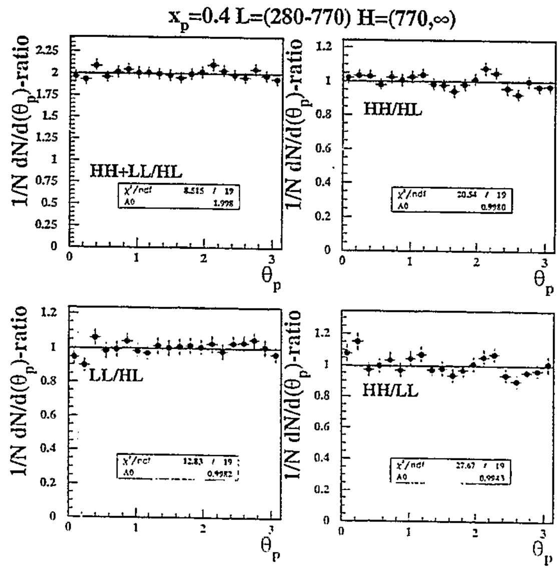


Step 4/5: distribution of angle between the planes

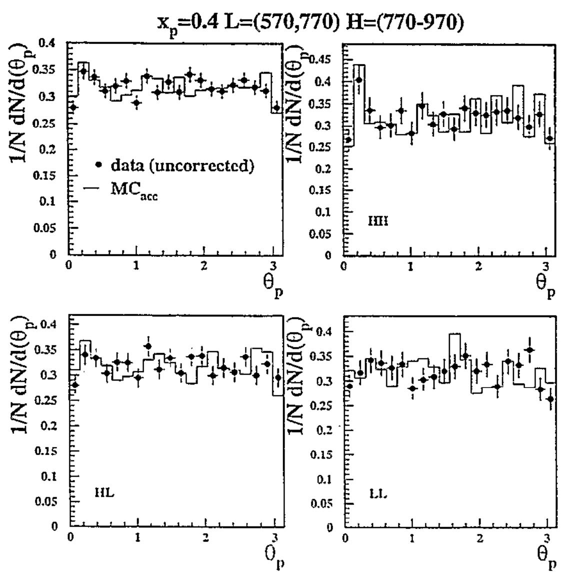
x_p=0.4 L=(280-770) H=(770,∞)



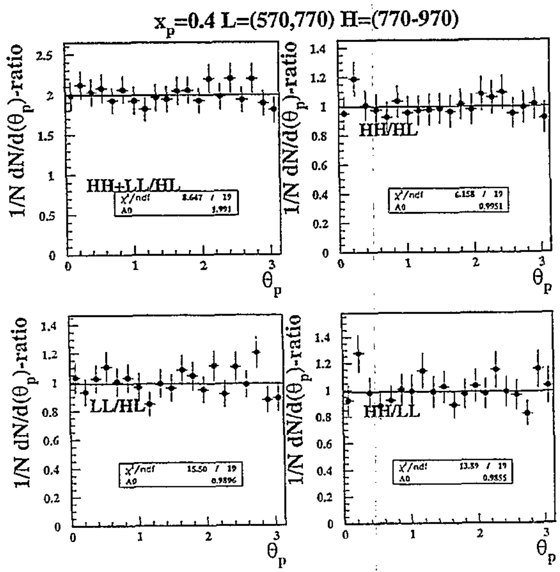
Step 4/5: distribution of angle between the planes



Step 4/5: distribution of angle between the planes

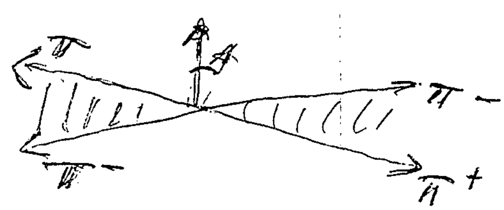


Step 4/5: distribution of angle between the planes



Summary and Outlook

- data of $\approx 2 \times 10^6$ hadronic Z decays used to investigate IFF
- no signal seen: the effect seems to be very tiny
- possible improvements:
  - use information on particle ID in order to get rid of K^* reflections etc.
  - include 91-93 data



Collins Fragmentation Function from LEP data?

Daniël Boer

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Upton, New York 11973, U.S.A.

I will discuss a Collins effect driven $\cos(2\phi)$ asymmetry in electron-positron annihilation into two almost back-to-back pions [1], which in principle can be determined from existing LEP data. Such a determination of the Collins effect fragmentation function would be useful for the extraction of the transversity distribution function from other processes.

I will demonstrate that transverse momentum dependent azimuthal spin asymmetries, like the above mentioned Collins effect asymmetry, generally suffer from suppression due to Sudakov factors. This means that tree level estimates of such asymmetries tend to overestimate the magnitude. Moreover, this Sudakov suppression increases with energy. This was forseen by Collins [2] and a first quantitative example (a double transverse spin asymmetry in vector boson production) was given in Ref. [3].

A brief review is given of a factorization theorem [4] for cross sections differential in a transverse momentum much smaller than the large scale(s) in the process. The distribution and fragmentation functions occuring in such factorized cross section expressions are functions of the transverse momentum of the partons and therefore allow for effects that relate transverse spin and transverse momentum, such as the Collins effect. This effect can appear at leading twist, or more precisely, does not give rise to explicit suppression by inverse powers of a large energy scale (Q). Nevertheless, Sudakov factors arising from resummation of soft gluon radiation corrections, lead to a suppression that increases with energy (in the example of Ref. [3] effectively as $\log^2 Q$ or to slightly less good approximation as a fractional power $Q^{0.6}$ in the range between $Q = 10 - 100$ GeV).

I will show explicitly that the inclusion of Sudakov factors in the $\cos(2\phi)$ asymmetry at $Q = M_Z$ cause a suppression by at least an order of magnitude compared to tree level. Therefore, this Sudakov suppression casts some doubt on the actual determination [5] of the Collins fragmentation function from LEP data. Numerically it is found that the Collins function obtained by using a tree level expression will approximately increase by a factor of 5 if Sudakov factors are taken into account and if the same analyzing power (a function of the Collins function squared) is to be obtained. The resulting (average) Collins function is likely to be too large to be compatible with the Collins fragmentation function obtained from asymmetries at lower energy, considering the fact that all the moments of chiral-odd functions are expected to decrease with energy (which is for instance the case for the transversity function h_1).

In a similar determination of the interference fragmentation functions from LEP data (electron-positron annihilation into two back-to-back pion pairs) neither Sudakov nor power suppression occurs, which is therefore a more promising option.

[1] D. Boer, R. Jakob, P.J. Mulders, Nucl. Phys. B 504 (97) 345; Phys. Lett. B 424 (98) 143.
[2] J.C. Collins, Nucl. Phys. B 396 (93) 161.
[3] D. Boer, Phys. Rev. D 62 (00) 094029.
[4] J.C. Collins, D.E. Soper, Nucl. Phys. B 193 (81) 381; Acta Phys. Polon. B16 (85) 1047;
J.C. Collins, D.E. Soper, G. Sterman, Nucl. Phys. B 250 (85) 199.
[5] A.V. Efremov, O.G. Smirnova, L.G. Tkachev, Nucl. Phys. B (Proc. Suppl.) 74 (99) 49.

Collins Fragmentation Function from LEP data?

Daniël Boer
RIKEN-BNL Research Center

- Brief overview of factorization and transverse momentum
- Collins effect in electron-positron annihilation
- Effects of Sudakov factors
- Implications and conclusions

Factorization and transverse momentum

Leading twist (LT) factorization theorem:

$$\frac{d\sigma}{d\Omega dx_1 dx_2} = \sum_{a,b} \int_{x_1}^{1} dx \int_{x_2}^{1} d\bar{x}\, f_1^a(x)\, \frac{d\hat{\sigma}_{ab}}{d\Omega dx d\bar{x}}\, \overline{f}_1^b(\bar{x})$$

For $|q_T| \equiv Q_T \ll Q$ (Collins, Soper & Sterman, NPB 250 (1985) 199)

$$\frac{d\sigma}{d\Omega dx_1 dx_2 d^2 q_T} = Y(x_1, x_2, Q, Q_T) +$$

$$\sum_{a,b} \int_{x_1}^{1} dx \int_{x_2}^{1} d\bar{x} \int d^2 k_T\, d^2 p_T\, f_1^a(x, k_T)\, \frac{d\hat{\sigma}_{ab}}{d\Omega dx d\bar{x} d^2 q_T}\, \overline{f}_1^b(\bar{x}, p_T)$$

$Y(x_1, x_2, Q, Q_T)$ becomes important only when $Q_T \sim Q$

$$\frac{d\hat{\sigma}}{d\Omega dx d\bar{x} d^2 q_T} = H(x, \bar{x}, p_T, k_T, q_T; Q) \int \frac{d^2 b}{(2\pi)^2}\, e^{-ib\cdot(p_T + k_T - q_T)}\, e^{-S(b)}$$

$e^{-S(b)}$ is a Sudakov form factor (exponentiation rather than cancellation of soft gluon contributions)

Factorization and transverse momentum

$$\frac{d\hat{\sigma}}{d\Omega dx d\bar{x} d^2 q_T} = H(x, \bar{x}, p_T, k_T, q_T; Q) \int \frac{d^2 b}{(2\pi)^2}\, e^{-ib\cdot(p_T + k_T - q_T)}\, e^{-S(b)}$$

Transverse momentum dependence of the hard part will lead to $1/Q$ suppression (in contrast to intrinsic transverse momentum)
One can perform a collinear expansion of the hard part

$$H(x, \bar{x}, p_T, k_T, q_T; Q) \approx H(x, \bar{x}; Q)$$

At tree level:

$$\int \frac{d^2 b}{(2\pi)^2}\, e^{-ib\cdot(p_T + k_T - q_T)}\, e^{-S(b)} \to \delta^2(p_T + k_T - q_T)$$

Need to consider: transverse momentum dependent functions
Ralston & Soper, NPB 152 (1979) 109

$$\Phi(x) \to \Phi(x, p_T)$$
$$\Delta(z) \to \Delta(z, k_T)$$

Leads to many azimuthal asymmetries, even unpolarized ones

e^+e^-: D.B., Jakob & Mulders, NPB 504 (97) 345; PLB 424 (98) 143

Collins & Soper, NPB 194 (1982) 445

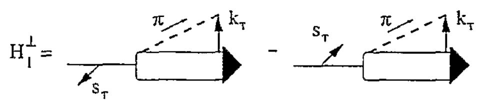
$$\Delta_{ij}(k) = \sum_X \int \frac{d^4z}{(2\pi)^4}\, e^{ik\cdot z} \langle 0|\psi_i(x)|P,S;X\rangle\langle P,S;X|\overline{\psi}_j(0)|0\rangle$$

The unpolarized fragmentation correlation function $\Delta(z)$ is parameterized as

$$\Delta(z) = D_1(z)\,\frac{\gamma^+}{4}$$

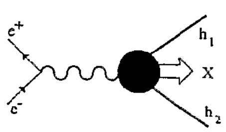
and $\Delta(z, k_T)$ as

$$\Delta(z, k_T) = D_1(z, k_T)\,\frac{\gamma^+}{4} + iH_1^\perp(z, k_T)\,\frac{\not{k}_T\gamma^+}{4}$$



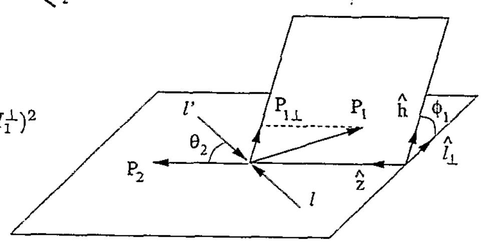
Apart from experimental indications that the Collins effect is nonzero at low energies (HERMES, SMC) and that it can account for the $pp^\uparrow \to \pi X$ SSA [see other talks at this workshop], there is also LEP data...

Collins effect in $e^+e^- \to \pi^+\pi^- X$



$e^+ + e^- \to \pi^+ + \pi^- + X$

$\langle\cos(2\phi_1)\rangle \propto (H_1^\perp)^2$



D.B., Jakob & Mulders, NPB 504 (97) 345; PLB 424 (98) 143

A confirmation of this asymmetry would confirm the Collins effect, without the need of polarization

A first indication of a nonzero correlation comes from a preliminary analysis of the 91-95 LEP1 data (DELPHI) by Efremov, Smirnova & Tkatchev, NPB (Proc. Suppl.) 79 (1999) 554

Collins effect in $e^+ e^- \to \pi^+ \pi^- X$

Problem is that the asymmetry expression used is the tree level result

$$\frac{d\sigma(e^+e^- \to \pi^+\pi^- X)}{d\Omega dz_1 dz_2 d^2 q_T} \propto \{1 + \cos(2\phi_1) A(q_T)\}$$

with $(q_T^2 \equiv Q_T^2 \ll Q^2)$

$$A(q_T) \equiv \frac{B(y)\, \sum_a c_2^a\, \mathcal{F}\left[\left(2\, q_T\!\cdot\! p_T\; q_T\!\cdot\! k_T \,-\, q_T^2\, p_T\!\cdot\! k_T\right) H_1^\perp \overline{H}_1^\perp\right]}{Q_T^2 M_1 M_2\; A(y)\, \sum_a c_1^a\, \mathcal{F}\left[D_1 \overline{D}_1\right]}$$

$$\begin{aligned} A(y) &= \left(\frac{1}{2} - y + y^2\right) \stackrel{cm}{=} \frac{1}{4}\left(1 + \cos^2\theta_2\right) \\ B(y) &= y\,(1-y) \stackrel{cm}{=} \frac{1}{4}\sin^2\theta_2 \end{aligned}$$

$$\begin{aligned} c_1^a &= \left({g_V^a}^2 + {g_A^a}^2\right) \\ c_2^a &= \left({g_V^a}^2 - {g_A^a}^2\right) \end{aligned}$$

Beyond tree level

At tree level the convolutions are defined as follows:

$$\mathcal{F}\left[D\overline{D}\right] \equiv \int d^2k_T\, d^2p_T\, \delta^2(p_T + k_T - q_T) D^a(z_1, k_T^2) \overline{D}^a(z_2, p_T^2)$$

Beyond tree level and hence, beyond the range of intrinsic transverse momentum one has to take into account the effect of resummed perturbative QCD corrections

Resummation of soft gluons into Sudakov form factors results in a replacement (Collins, Soper & Sterman)

$$\delta^2(p_T + k_T - q_T) \to \int \frac{d^2b}{(2\pi)^2}\, e^{-ib\cdot(p_T + k_T - q_T)}\, e^{-S(b,Q)}$$

$$S(b,Q) = \int_{b_0^2/b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[A(\alpha_s(\mu))\,\ln\frac{Q^2}{\mu^2} + B(\alpha_s(\mu))\right]$$

Beyond tree level

Tree level:

$$\mathcal{F}\left[D\overline{D}\right] \equiv \int d^2k_T\, d^2p_T\, \delta^2(p_T + k_T - q_T) D^a(z_1, k_T^2)\overline{D}^a(z_2, p_T^2)$$

Inclusion of the Sudakov form factor leads to

$$\mathcal{F}\left[D\overline{D}\right] = \frac{1}{2\pi}\int_0^\infty db\, b\, J_0(bQ_T)\, e^{-S(b)}\, \tilde{D}(z_1, b)\, \tilde{\overline{D}}(z_2, b)$$

Collins (NPB 396 (1993) 161): "*The effect [of Sudakov form factors] is to broaden the transverse momentum distribution as Q increases, but in a spin-independent way: the broadening is due to recoil against the transverse momentum of soft gluon emission. This will have the effect of diluting the spin asymmetry [...].*

Sudakov form factors in polarized scattering: Weber (NPB 382 (1992) 63; NPB 403 (1993) 545)

Estimating the asymmetry

Assume Gaussian transverse momentum dependence:

$$D_1(z, z^2k_T^2) = D_1(z)\, R^2 \exp(-R^2k_T^2)/\pi z^2$$

we find

$$A(q_T) \equiv \frac{B(y)\, \sum_a\, c_2^a\, H_1^{\perp a}(z_1)\, \overline{H}_1^{\perp a}(z_2)}{4M^4R^4\, A(y)\, \sum_a\, c_1^a\, D_1^a(z_1)\, \overline{D}_1^a(z_2)}\, \mathcal{A}(Q_T)$$

where

$$\mathcal{A}(Q_T) \equiv M^2\, \frac{\int_0^\infty db\, b^3\, J_2(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}{\int_0^\infty db\, b\, J_0(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}$$

Here we introduce the usual b regulator: $b_* = b/\sqrt{1 + b^2/b_{\max}^2}$ and the nonperturbative Sudakov factor of Ladinsky-Yuan (PRD 50 (94) R4239), which uses $b_{max} = 0.5\,\text{GeV}^{-1}$ and leads to

$$S_{NP}(b) = 2.05\, b^2 \qquad \text{at } Q = 90\,\text{GeV}$$

We restrict to S_{LL}

Gaussian form of $H_1^\perp(z, \boldsymbol{k}_T)$

One might be inclined to assume the maximally allowed function by saturating the bound satisfied by $H_1^\perp$

$$|\boldsymbol{k}_T|\, H_1^\perp(z, |\boldsymbol{k}_T|) \leq z\, M_h\, D_1(z, |\boldsymbol{k}_T|)$$

producing a $1/|\boldsymbol{k}_T|$ behavior of $H_1^\perp(z, \boldsymbol{k}_T)$. However, this is not consistent with the fact that the Collins effect should vanish in the limit $\boldsymbol{k}_T \to 0$.

Often used is an Ansatz based on a simple model by Collins

$$\frac{H_1^\perp(z, k_T^2)}{D_1(z, k_T^2)} = \eta\, \frac{M_C M_\pi}{k_T^2 + M_C^2}$$

For the present purpose, the additional fall-off with $1/k_T^2$ on top of the Gaussian fall-off is not needed.

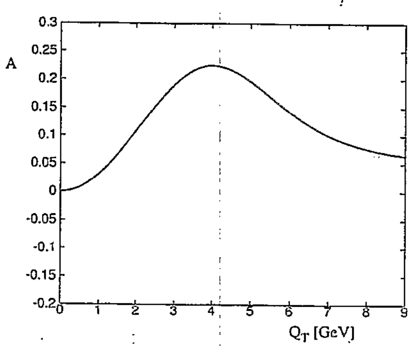
We will restrict to a Gaussian fall-off and assume the simple form

$$H_1^\perp(z, k_T^2) = c(z)\, D_1(z, k_T^2)$$

Implications

$$\mathcal{A}(Q_T) \equiv M^2\, \frac{\int_0^\infty db\, b^3\, J_2(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}{\int_0^\infty db\, b\, J_0(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}$$

$\mathcal{A}(Q_T)$
$Q^2 = M_Z^2$



Features:

- Kinematic zero at $Q_T = 0$ as expected
- Maximum of 0.22 at $Q_T = 4\,\text{GeV}$

Comparison to tree level

Efremov *et al.* NPB (Proc. Suppl.) 74 (99) 49; 79 (99) 554

$$\frac{d\sigma}{d\cos\theta_2 d\phi_1} \propto \left(1 + \frac{6}{\pi}\left[\frac{H_1^{q\perp}}{D_1^q}\right]^2 \frac{v_q^2 - a_q^2}{v_q^2 + a_q^2}\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cdot\cos(2\phi_1)\right)$$

$$\frac{d\sigma}{d\cos\theta_2 d\phi_1} \propto \left(1 + A\left[\frac{H_1^{\perp a}(z_1)}{D_1^a(z_1)}\right]^2 \frac{g_V^{a\,2} - g_A^{a\,2}}{g_V^{a\,2} + g_A^{a\,2}}\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_1)\right)$$

Note: numerator and denominator have separate $\sum_a$

$$\left.\begin{array}{rcl} A^{\mathrm{efr}} & = & 6/\pi \\ A^{(0)} & = & 1/(2M^2R^2) \end{array}\right\} \Longrightarrow \left\{\begin{array}{lcl} R^2 & \sim & 13\,\mathrm{GeV}^{-2} \\ \langle p_T^2\rangle & \sim & (270\,\mathrm{MeV})^2 \end{array}\right.$$

$$A^{\mathrm{sud}} = 0.07$$

If $A^{\mathrm{efr}} = 6/\pi$ yields $\overline{|H_1^\perp/D_1|} = 6\% \pm 2\%$,

then $A^{\mathrm{sud}} = 0.07$ yields $\overline{|H_1^\perp/D_1|} = 30\% \pm 10\%$ [too large?]

Conclusions

- Leading twist factorization at $Q_T^2 \ll Q^2$ requires distribution and fragmentation functions as a function of transverse momentum
- Sudakov factors need to be included
- In the Collins effect $\cos(2\phi)$ asymmetry in $e^+e^- \to \pi^+\pi^- X$ a strong suppression due to Sudakov factors was demonstrated.
- This is relevant at $Q \sim M_Z$ and casts some doubt on the actual determination of the Collins fragmentation function from LEP data
- Tree level estimates tend to overestimate transverse momentum dependent azimuthal asymmetries

TRANSVERSITY MEASUREMENT WITH THE PHENIX DETECTOR AT RHIC

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The PHENIX collaboration at Brookhaven National Laboratory will probe the spin structure of the proton in polarized proton-proton collisions at the Relativistic Heavy Ion Collider. Initial data taking is planned for 2001 with longitudinally polarized proton beams at $\sqrt{s} = 200$ GeV. Measurements of transverse spin asymmetries will provide access to the currently unknown transversity distributions δq. We discuss a proposal by Jaffe, Jin and Tang to access transversity distributions at RHIC through two meson interference fragmentation in the ρ/σ invariant mass region.

1 Introduction

High energy, deeply inelastic lepton-nucleon and hadron-hadron scattering cross sections can be described with the help of three independent nucleon helicity amplitudes. Measurements of the nucleon structure functions $F_1(x, Q^2)$ -the helicity average- and $g_1(x, Q^2)$ -the helicity difference-, have explored the helicity conserving part of the cross sections with great experimental accuracy. In contrast, no information is presently available on the helicity flip amplitude. The absence of experimental measurements is a consequence of the chiral-odd nature of the helicity flip amplitude and the related "transversity quark distributions", $\delta q(x, Q^2)$, which prevents the appearance of helicity flip contributions at leading twist in inclusive DIS experiments. Transversity distributions were first discussed by Ralston and Soper [1] in Drell-Yan scattering of two transversely polarized hadrons. In Drell-Yan processes the transverse double spin asymmetry, A_{TT}, is proportional to $\delta q \delta \bar{q}$ with even chirality.

Transverse single spin asymmetries $A^{\perp}$ (e.g. unpolarized leptons on transversely polarized nucleon targets) in *semi-inclusive* DIS and pp scattering may offer an alternative way to observe helicity flip contributions at leading twist. This possibility relies on the presence of quark fragmentation functions, $H_1^{\perp}$, which are sensitive to the quark polarization in the final state and possess the necessary negative chirality. The asymmetries $A^{\perp}$ are proportional to $\sum_q \delta q \times a_t^f \times H_1^{\perp}$, where a_t^f are the transversity dependent partonic initial-final-state asymmetries which can be calculated from pQCD.

For example, Collins suggested that in semi-inclusive single pion production the quark spin direction might be reflected in the azimuthal distribution of a final state pion[3]. Collins further demonstrated that the symmetry properties of the process do not require the proposed fragmentation function $H_1^{\perp}$ to be identical to zero. The current interest in transversity distributions results from a recent HERMES result[5] and a preliminary SMC result[6], which suggest that Collins's function $H_1^{\perp}$ and the transversity distribution function δq in fact are different from 0.

In the following we discuss a proposal by Collins, Heppelmann and Ladinsky[4] and more recently, Jaffe, Jin and Tang[7] to utilize two meson interference fragmentation in order to access the transversity distributions.

2 Transversity at RHIC

Originally the transverse double spin asymmetry, A_{TT}, in the Drell-Yan process, $A_{TT} \sim \delta q \delta \bar{q}$, was viewed as a good candidate for a measurement of the transversity distribution functions at RHIC. Unfortunately, a recent analysis[2] estimates A_{TT} to about $1-2\%$ with statistical errors comparable to the asymmetry itself for a projected measurement at RHIC. At present the proposal of Collins et.al. [4] and Jaffe et.al. [7] to utilize chiral odd two pion interference fragmentation processes appears to be the most promising approach to measure transversity at RHIC. In order to access the transversity distribution functions through this channel, it will be necessary to know the associated fragmentation functions. While currently unmeasured it should be possible in principle to extract this functions from existing e^+e^- data at LEP.

The relevant process at RHIC is pion pair production in pp scattering with one proton transversely polarized. For example, in the ρ/σ invariant mass region interference occurs between two pions in a superposition of s-wave and p-wave states. The spin analyzing power of this process is different from 0 in intervals of only a few 100 MeV above and below the ρ-mass and changes sign at the ρ-mass[8]. Therefore, it will be important that PHENIX possesses sufficient invariant mass resolution to observe the invariant mass dependence of the analyzing power. The invariant mass resolution for pion pairs in the ρ-mass region is shown in Fig. (1) and the *RMS* of the distribution is 12 MeV. The excellent mass resolution will make it possible to observe the expected sign change of the asymmetry providing a powerful tool to study acceptance related systematic errors.

The measurement will use the PHENIX central detector arms which cover the pseudo rapidity interval $|\eta| < 0.35$. A combination of tracking chambers will give good momentum resolution: $\Delta p/p \approx 2\%$ at $p = 10$ GeV. TOF measurements, a Time Expansion Chamber in combination with the EMC and the RICH will provide particle ID over are large momentum range. In order to estimate experimental sensitivities a first study was carried out at the event generator level including PHENIX detector acceptances and a parametrizations of the PHENIX central arm momentum resolution. The results using an integrated luminosity of 32 pb^{-1} are compared to asymmetry projections from Tang[8] in Fig. (1). The error bars shown in the plot represent statistical errors only. The asymmetries in Fig. (1) were obtained using upper bounds for the relevant distribution and fragmentation functions and represent an optimistic upper limit[8]. Further studies, including full PHENIX detector simulations and using new model calculations of the analyzing power are underway.

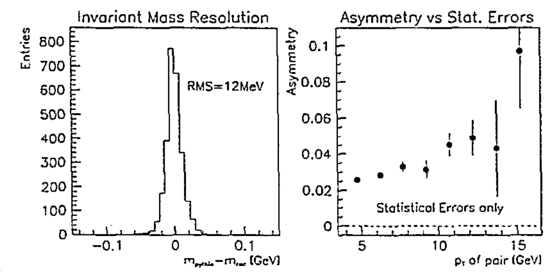


Figure 1: Left plot: The invariant mass resolution for pion pairs in the ρ-mass region. Right plot: Maximum transverse single spin asymmetries compared to statistical errors, $\int L dt = 32\,\mathrm{pb}^{-1}$.

References

1. J. Ralston, D.E. Soper, Nucl. Phys. B152, 109 (1979).
2. O. Martin et al., Phys. Rev. D60, 117502 (1999).
3. J.C. Collins, Nucl. Phys. B396, 161 (1993).
4. J.C. Collins, S.F. Heppelmann and G.A. Ladinsky, Nucl. Phys. B 420, 565 (1994); J.C. Collins and G.A. Ladinsky, preprint PSU-TH-114, hep-ph/9411444; J.C. Collins, proceedings of the RHIC Spin Workshop, October 6 - 8, 1999, p. 158.
5. HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 84, 4047 (2000).
6. A. Bravar, for the SMC Collaboration, Nucl. Phys. (Proc. Suppl.) B79, 520 (1999).
7. R.L. Jaffe et al., Phys. Rev. Lett. 80, 1166 (1998); Phys. Rev. D57, 5920 (1998).
8. J. Tang, hep-ph/9807560 and J. Tang, Thesis, MIT (1999).

Transversity Measurement with PHENIX

- PHENIX
- Nucleon transversity through final state interaction in

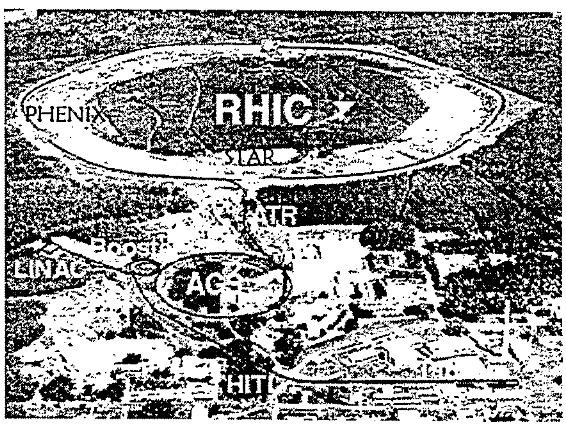
$$p^{\uparrow} p \rightarrow \pi^{+}\pi^{-} + X$$

- Experimental issues

  Invariant Mass Resolution

  Rates

RHIC as polarized Proton Collider



RHIC accelerates 60 polarized proton bunches to 250 GeV. Collision are possible in different polarization states:

BRAHMS, PHOBOS, (PP2PP)

Single and double transverse spin asymmetries.

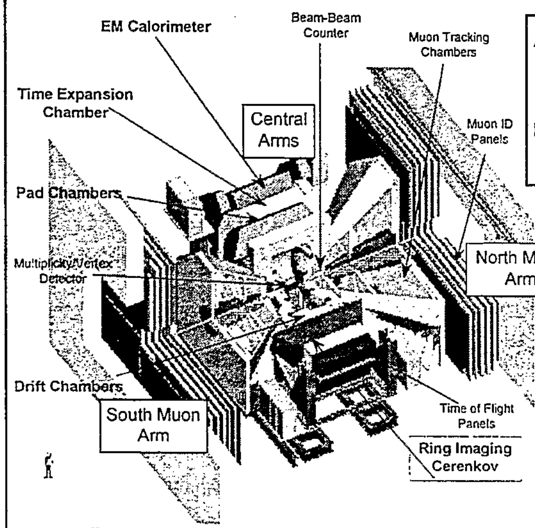
PHENIX and STAR

Single and double transverse and longitudinal spin asymmetries -> Competition between longitudinal and transverse spin program.

$$\left.\begin{array}{l} \text{at } \sqrt{s} = 200 \text{ GeV}, \int_{1\text{year}} L\,dt = 320 \text{ pb}^{-1} \\ \text{at } \sqrt{s} = 500 \text{ GeV}, \int_{1\text{year}} L\,dt = 800 \text{ pb}^{-1} \end{array}\right\}$$

Use 10% of first year at full luminosity for exploratory run with transverse polarization -> 2002, 2003?

The PHENIX Detector

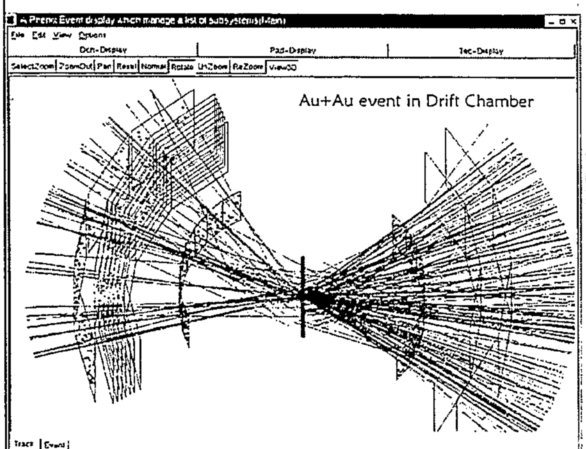


Acceptance : $30 \le |\phi| \le 120, |\eta| \le 0.35$
$\Rightarrow$ no jet reconstruction

Rate Capability : Raw Rate ≤ 12 MHz
Accepted Rate = 12kHz

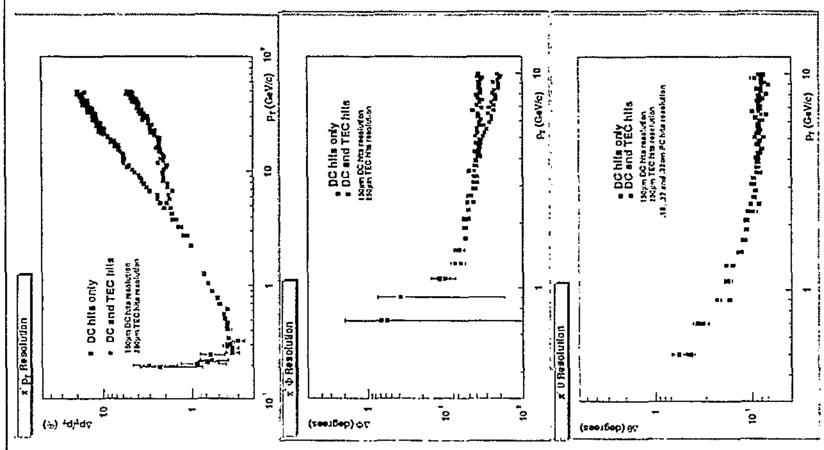
RICH Thresholds for different Species	
p-ID	p [GeV]
e	0.013
π	3.5
K	12.3
p	23.5

Momentum Resolution

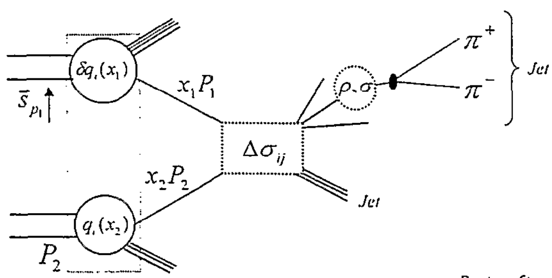


Momentum Resolution in the Central Arm	
p [GeV]	Δp [MeV]
1	6
3	36
5	90
10	200

PHENIX Momentum and Angular resolution



Nucleon transversity through final state interaction at RHIC

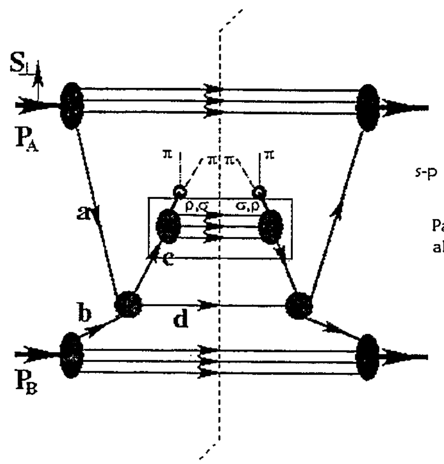


$$\frac{d^7\sigma_H\left(pp^\uparrow \rightarrow \pi^+\pi^- X\right)}{dx_1 dx_2 dt dz dm^2 d\cos\theta d\varphi} \propto \underbrace{\delta q(x_1)\cdot q(x_2)}_{\text{Proton Structure}} \cdot \underbrace{\boxed{\frac{d^3\sigma(q_1q_2 \rightarrow q_3q_4)}{dx_1dx_2dt}}}_{\text{Hard Scattering Process}}$$

$$\underbrace{\frac{d^2\mathcal{M}}{dzdm^2}}_{\text{Interference Fragmentation}} \cdot \underbrace{\frac{d^2\mathcal{D}}{d\cos\theta d\varphi}}_{\text{Pion Fragmentation}}$$

Jian Tang, Thesis MIT, June 1999
R. Jaffe, X. Jin, J. Tang Phys. Rev. D57 (1999)5920
X. Ji, Phys. Rev. D49 (1994)114
J. Collins, S. Heppelmann, G. Ladinsky, Nucl Phys. B420 (1994)565

Interference fragmentation $\boxed{\dfrac{d^2\mathcal{M}}{dz\,dm^2}}$

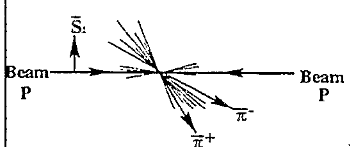


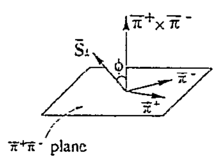
s-p wave interference fragmentation:

Parton emits ρ/σ followed by absorption of σ/ρ a forming a parton

Transverse Single Spin Asymmetry

(Tang. Thesis, MIT)



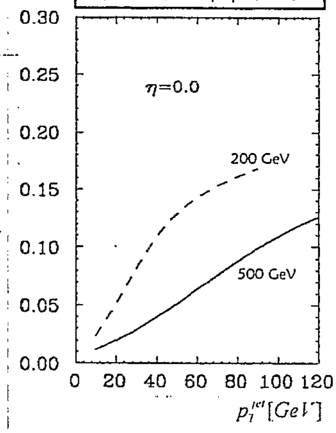


$N^{\uparrow}$ Pion Pair Yield,
$\sin\delta_l$: Two Pion Phase Shifts
$\delta q(x)$: Transversity quark DFs
$\delta\hat{q}(z)$: Pol. Fragmentation Func.

$$A_\perp = \frac{1}{P_{beam}}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}} = -\frac{\sqrt{6}\pi}{4}\boxed{\sin\delta_0\sin\delta_1\sin(\delta_0-\delta_1)\cdot\cos(\phi)}\cdot\frac{[\delta q(x_1)\cdot G(x_2)\cdot\delta\hat{q}_I(z)]\delta\hat{\sigma}^{qg}_{gg}+\ldots}{[G(x_1)\cdot G(x_2)]\delta\hat{\sigma}^{gg}_{gg}+\ldots\}\cdot[\sin^2\delta_0\hat{q}_0(z)+\sin^2\delta_1\hat{q}_1(z)]}$$

Maximum Asymmetry

$\eta = 0, m_{\rho,\sigma} = 0.83$ GeV, $\cos\phi = 1$
$\delta\hat{q}_I^2 = 4\hat{q}_0\hat{q}_1/3,\ 2|\delta q| \le q + \Delta q$



Interference Fragmentation

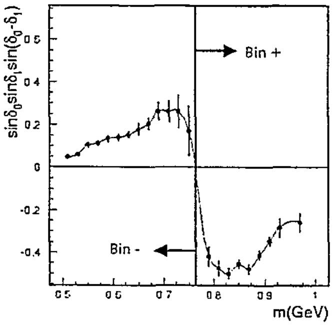
$$\frac{d^2\mathcal{M}}{dz\,dm^2} \propto \sin\delta_0 e^{i\delta_0}\left(\kappa\cdot\hat{q}_I(z)+\lambda\cdot\delta\hat{q}_I(z)\right)\sin\delta_1 e^{-i\delta_1}+\dots$$

s-wave

p-wave

Strong interaction π,π phase shifts

Where:
$\kappa = I\otimes\bar{\eta}_0,\ \lambda=\sigma_+\otimes\bar{\eta}_- + \sigma_-\otimes\bar{\eta}_+$
$\hat{q}_I(z),\delta\hat{q}_I(z)$: spin average and difference fragmentation functions



P. Estabrooks and A.D. Martin, Nucl. Phys. B79 (1974)301

Non-vanishing "support" only in the ρ mass region!

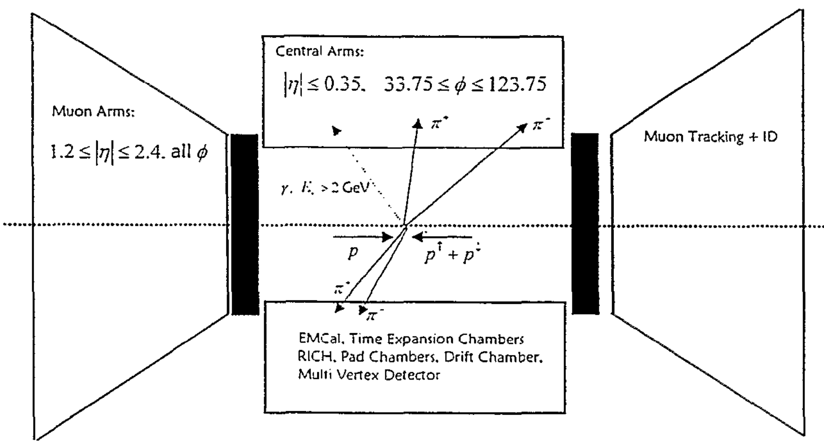
- Sufficient mass Resolution?
- Great for systematics!

PHENIX-Measurement

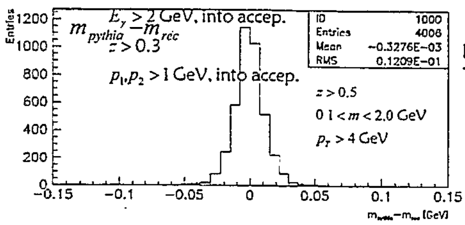
Trigger: Tag $\pi^{+,-}$ in RICH and Jet Mul in EMCal

Reconstruct invariant mass of pion pairs

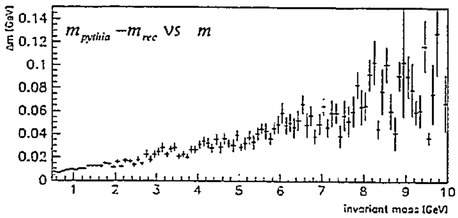
Form single spin asymmetry $A_{exp}=\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$



Invariant Mass Resolution



RMS=12 MeV



Nice! (required for Phi...)

Expected Rate

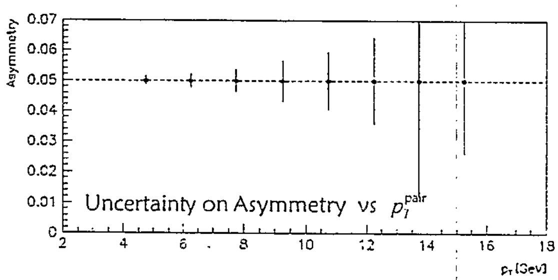
Example:

$E_{\pi_1,\pi_2} > 4$ GeV

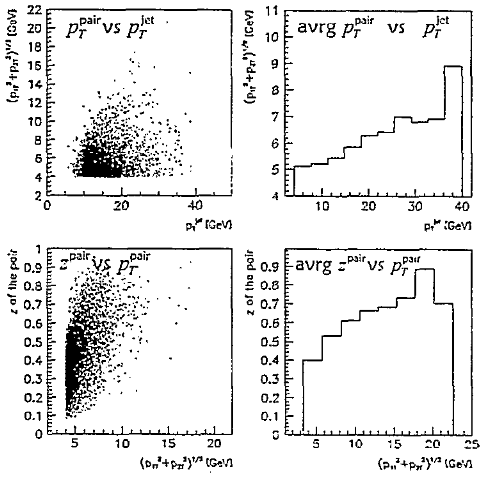
$\sqrt{p_{1T}^2 + p_{2T}^2} > 4$ GeV

800 MeV $< m <$ 950 MeV

5.2 Million events in 32 pb^{-1}
15% with pair after cuts

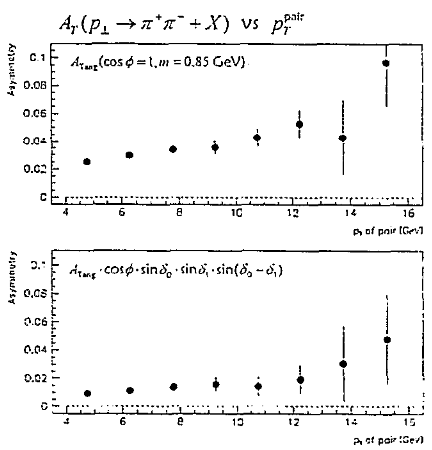


Kinematics



➡ Cannot reconstruct Event Kinematics

Projected Asymmetry (For 1 week of running)



$\int L dt = 32 pb^{-1}$

$E_{\pi_1,\pi_2} > 4$ GeV

$\sqrt{p_{1T}^2 + p_{2T}^2} > 4$ GeV

800 MeV $< m <$ 950 MeV

➡ Small aymmetry below 5% but good rate!

Conclusions

- Transversity can be probed using Interference Fragmentation Functions
- Momentum Resolution and Statistics are sufficient
- Good Control of Systematic Errors
- Fragmentation Functions are (currently) unknown

Transversity at STAR

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The question of how the spin degrees of freedom in the nucleon are organized has still not been fully answered even after recent polarized deep inelastic scattering experiments.

The transvesity is the last missing part among the 3 quark distributions at leading twist. While helicity average and difference distributions were well measured by DIS, helicity flip distribution is harder to access, since it's chiral odd and have to couple with other chiral odd fragmentation function to be measured. SMC and Hermes reported non-zero asymmetries, which suggest that transversity is not small. Transversity is also interesting, since absence of gluon transversity and one may expect naive parton model works, which did not work for longitudinal case.

Among a few proposed way to measure transversity, looking at 2 pions correlation at ρ, σ mass region in a jet at pp collision with one proton polarized transvesely, which was proposed by Jaffe et al [1] seems to be most promising.

The Relativistic Heavy Ion Collider(RHIC) will accelerate polarized proton beams. The STAR detector, although originally designed for heavy ion physics, has excellent capability for spin physics as well.

One of the biggest advantage of the STAR for this measurement is large acceptance which allow us to do jet measurement. The asymmetry is function of 5 kinematics valuables, p_t^{jet}, η^{jet}, $z = E^{pair}/E^{jet}$, m_{pair} and $cos(\phi)$ where ϕ is angle between proton polarization axis and of normal vector of $\pi^+\pi^-$ plane. Therefore it is very important to measure asymmetry as function of all these valuables, to check models on fragmentation as well as to see x_{bj} dependences of transversity. STAR detector has good enough mass resolution, also capable to measure jets. With integrated luminosity of 32/pb at $\sqrt{s} = 200GeV$, which is 1 week of running at design luminosity, STAR may start measuring sizable asymmetry, although realistic sensitivity estimation has to wait LEP data analysis of fragmentation functions.

[1] R.L.Jaffe et al., Phys. Rev. Let. 80, 1166(1998); Phys. Rev. D57, 5920 (1998);

Transversity at STAR

Akio Ogawa
Penn State Univ

2000 Sep 19
RIKEN BNL Research Center Workshop

Spin Physics at STAR

Gluon Polarization:
- Direct Photon — $qg \rightarrow q\gamma$ photon gluon compton scattering
- Direct Photon + jet
- Jet — $qg / gg / qq \rightarrow Jet + Jet$
- Jet + Jet

Quark / Anti-Quark Polarization :
- W production — $q\bar{q} \rightarrow W^{\pm} \rightarrow e^{\pm}$

Transversity :
- Pion pair correlation
- Dijet?

Parity Violating Asymmetry:
- Search for New Physics

Nucleon's Transversity

Leading twist quark distribution

$$F = \frac{q}{2} I \times I + \frac{\Delta q}{2} \sigma_3 \times \sigma_3 + \frac{\delta q}{2} (\sigma_+ \times \sigma_- + \sigma_- \times \sigma_+)$$

Longitudinal Spin Distribution $p^{\rightarrow} \Rightarrow \; : \; \Delta q = q^{\rightarrow} - q^{\leftarrow}$

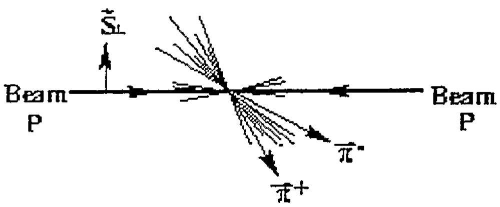
Transversity $p^{\uparrow} \Rightarrow \; : \; \delta q = q^{\uparrow} - q^{\downarrow}$

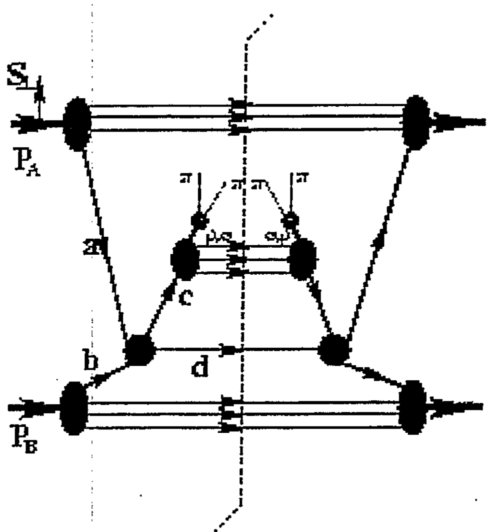
No gluon contribution
Helicity flip
Soffer Inequality $2|\delta q| \leq q + \Delta q$
Last missing piece at leading twist

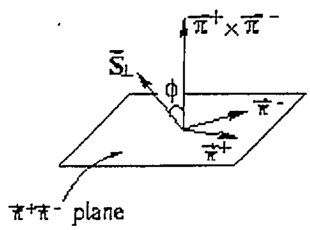
$$P^{\uparrow} + P \rightarrow \pi^+ + \pi^- + X$$

↳ Jet

$$A \propto \vec{S} \cdot (\vec{\pi}^+ \times \vec{\pi}^-) = \cos\phi$$







Need mass to have helicity flip
Need chiral odd interaction to have Collins effect

Two meson production

$$A=\frac{\sigma^{-\Uparrow+}-\sigma^{+\Uparrow-}}{\sigma+\sigma}=\frac{\sum\delta q\otimes q\otimes\delta\sigma\otimes\delta D}{\sum q\otimes q\otimes\sigma\otimes D}$$

$$=\frac{\sqrt{6}\pi}{4}$$ [redacted] [redacted] mass

$$\otimes\frac{\sum_{qg\to qg,\bar{q}g\to\bar{q}g\ldots}\delta\hat{\sigma}\cdot\delta q_a(x_a)\otimes q_b(x_b)\quad P_t,\eta\quad\otimes\delta\hat{q}_I(z)}{\sum_{gg\to q\bar{q},qg\to qg\ldots}\hat{\sigma}\cdot q_a(x_a)\otimes q_b(x_b)\quad\otimes\{\sin^2\delta_0\hat{q}_0(z)+\sin^2\delta_1\hat{q}_1(z)\}}$$

Phase Shift $\sin\delta_0\sin\delta_1\sin(\delta_0-\delta_1)$ is known

ρ,σ

$\hat{q}_0(z),\hat{q}_1(z)$

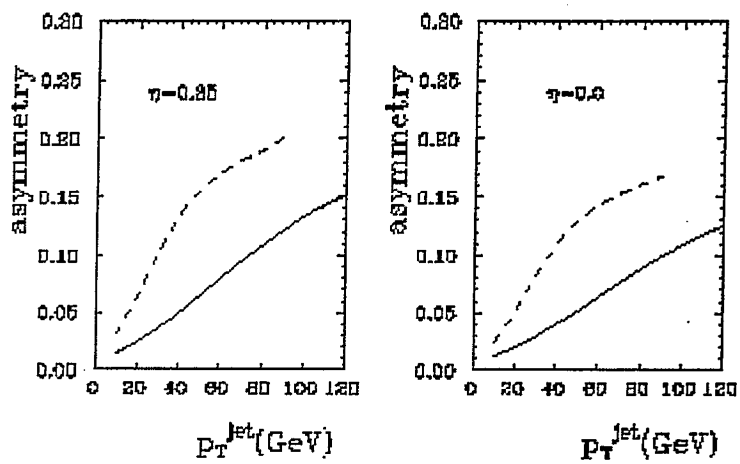
$\delta\hat{q}_I(z)$ }unknown

In Jian Tang paper, assume { $\delta\hat{q}_I(z)=\frac{3}{4}\hat{q}_0(z)\hat{q}_1(z)$ Schwartz Inequality Limit

$\hat{q}_0(z)=\hat{q}_1(z)$

No z dependence

Asymmetries predicted by Jian Tang for pp at sqrt(s) 200/500 GeV

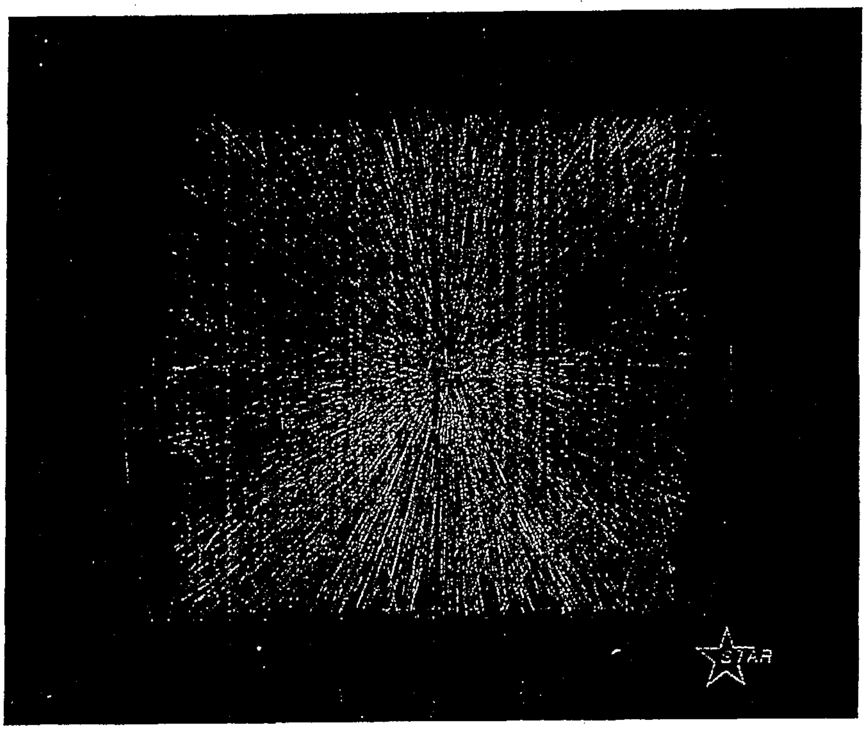


What is the prediction at η=1.0~1.3?

FIG. 1. The single spin symmetry as function of p_T^{jet} for two-pion production in pp collision at $\sqrt{s}=500$ GeV(solid) and $\sqrt{s}=200$ GeV(dashes) (pseudo-rapidity $\eta=0.0$ and $\eta=0.35$).

This model is an optimistic estimation:
saturate Soffer & Schwartz inequality, mass=0.8 (at max asymmetry)

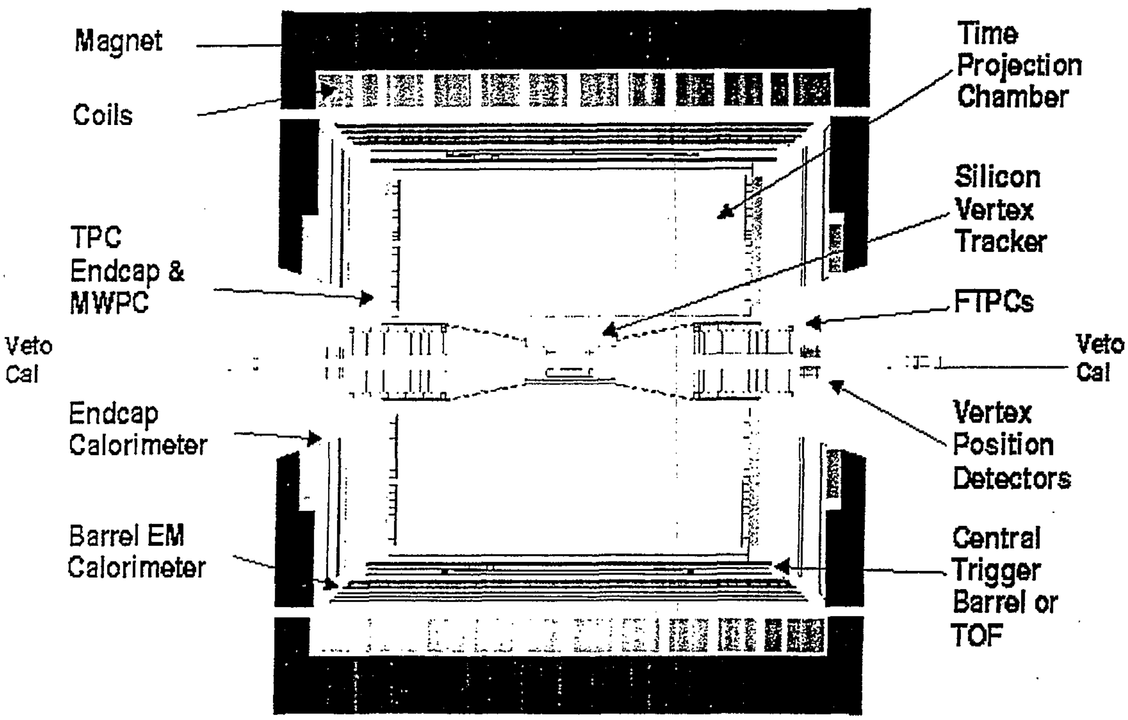
STAR detector



A central AuAu even at 130GeV

An-7

STAR detector



Experiment	STAR, polarized pp
Location	RHIC as polarized pp collider, BNL
Web Page	http://www.star.bnl.gov
Run Schedule	First run in 2001
Contact for Transversity	Akio Ogawa (akio@bnl.gov)
Polarization States	Single and double longitudinal and transverse asymmetries
Energy & polarization	$50 < \sqrt{s} < 500$ GeV, 70%
Expected Luminosity	$\int L dt = 320\ \mathrm{pb}^{-1}$/year at $\sqrt{s} = 200$ GeV
	$\int L dt = 800\ \mathrm{pb}^{-1}$/year at $\sqrt{s} = 500$ GeV
Acceptance	Charged particles $-2.0 < \eta < 2.0$, $0 < \phi < 2\pi$
	Electrons, photons $-2.0 < \eta < 1.0$, $0 < \phi < 2\pi$
	Jets $-1.3 < \eta < 0.3$, $0 < \phi < 2\pi$
Particle Id	EMC : electro/hadron, photon/π^0
	dE/dx(TPC) π/K : $p < 0.6$, K/P : $p < 1.2$GeV
	dE/dx(TPC+SVT) π/K : $p < 0.8$, K/P : $p < 1.5$GeV
	TOF π/K : $p < 1.3$, K/P : $p < 2.4$GeV
	RICH π/K : $p < 3$, K/P : $p < 5$GeV
Invariant Mass Res.	RMS$\sim$ 16 MeV at $2 < p_t < 10$ GeV and at ρ^0 mass
Momentum Resolution	$\Delta p_T/p = 1.5\%$ at 0.2 GeV
	$\Delta p_T/p = 3.5\%$ at 10 GeV
Vertex Resolution	$\Delta x, y \sim 1mm, \Delta z \sim 1cm$

STAR detector for Transversity measurement

Wide acceptance :

Jet measurements ~25-30% Et resolution

check Z dependence

check Pt & Rapidity dependence

Good invariant mass resolution: 2-5 % at 800MeV

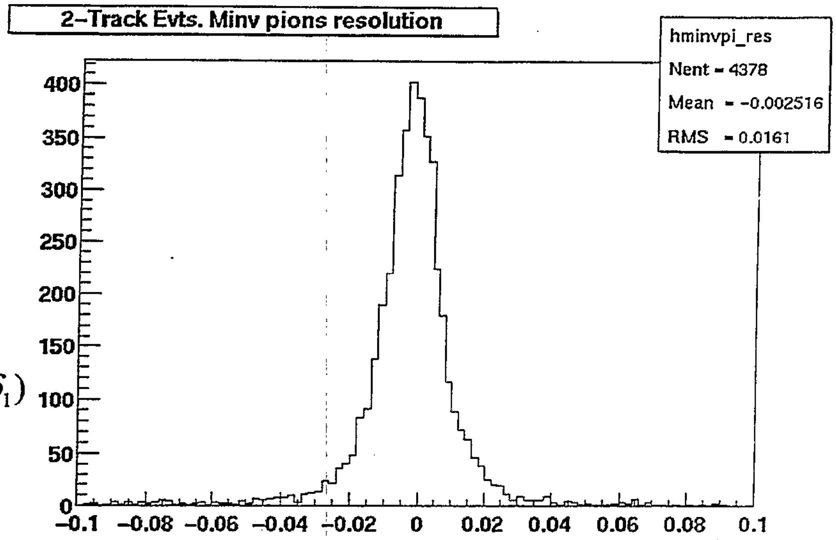
STAR is a working detector!

But slow: Need good triggers at high luminosity

TPC has 40usec drift time : pile up events

STAR-RCF bandwidth (20Mb/sec) : L3 data volume reduction

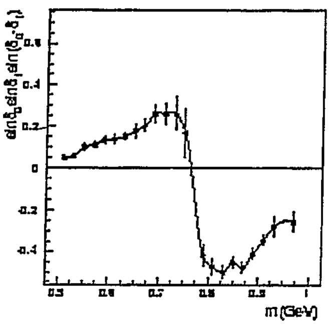
No PID at high pt :~10% Kaon/proton



A factor

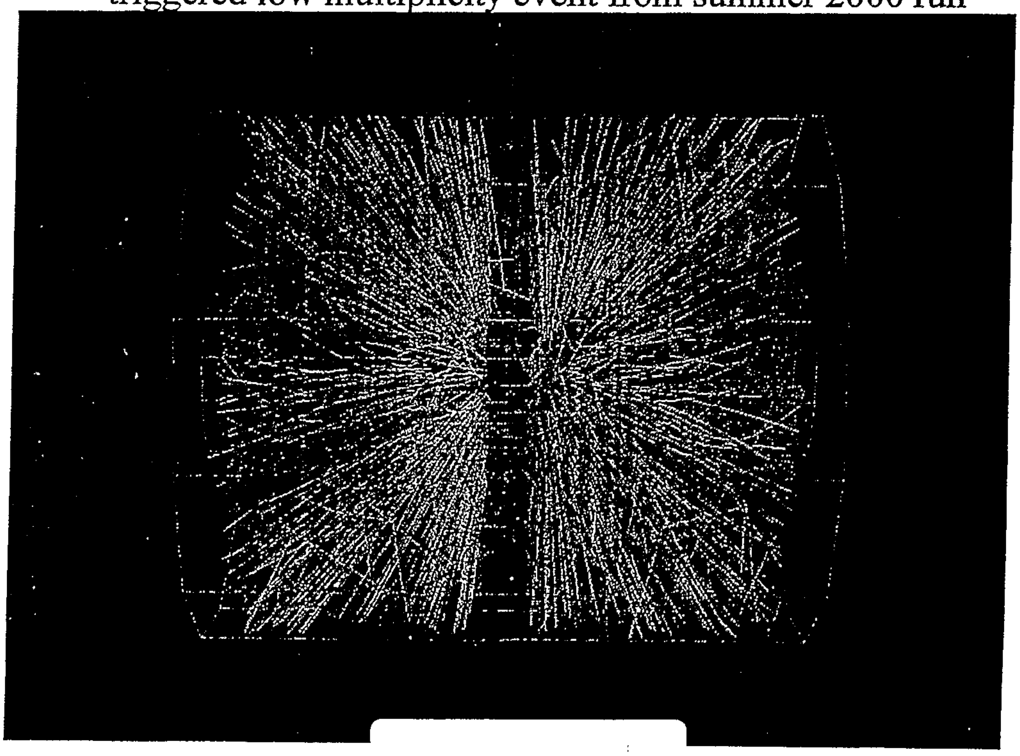
$\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)$

from Phase Shifts
as function of
invariant mass

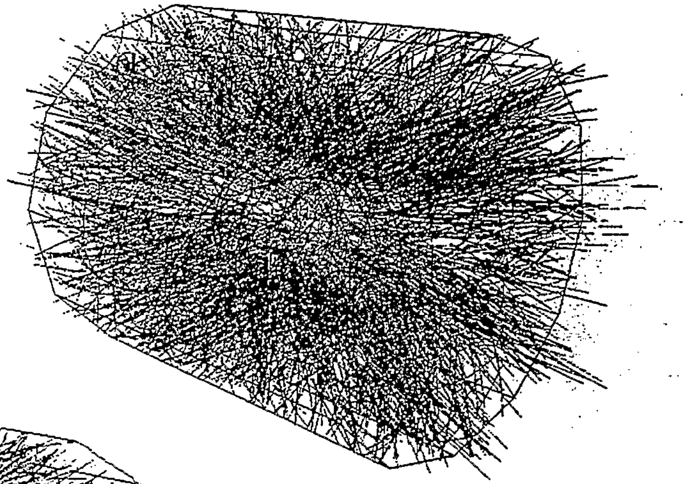


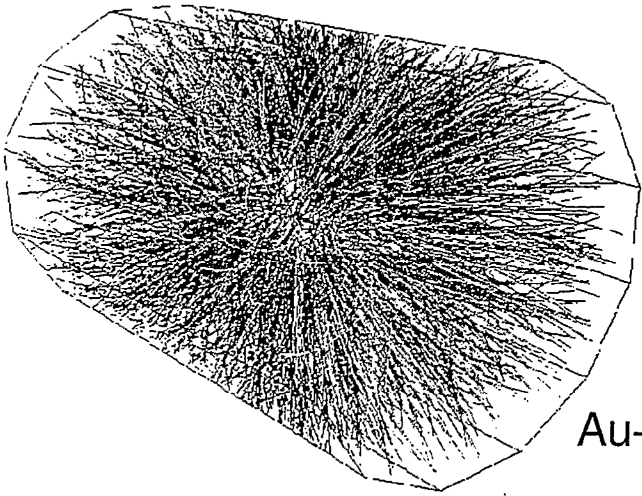
Invariant mass resolution of STAR
for Pt = 2-10 GeV pair around
mass ~ 0.8 GeV

Overlapped (pile up) AuAu high multiplicity event on top of
triggered low multiplicity event from summer 2000 run



P+P
at highest luminosity
with pile up events
~4000 tracks



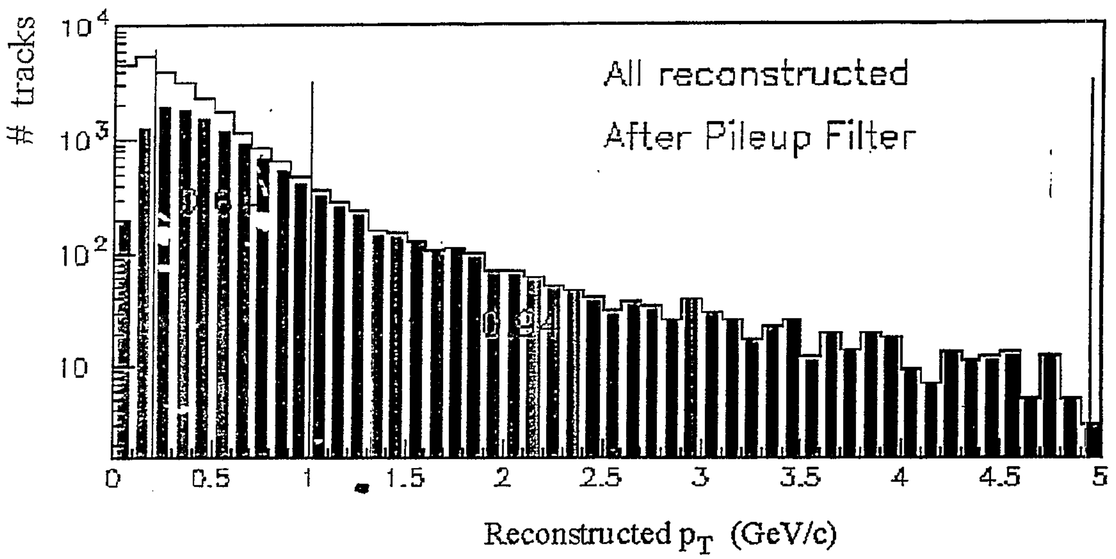


Reconstructed
TPC tracks

Au+Au central Event

High p_T tracks preserved

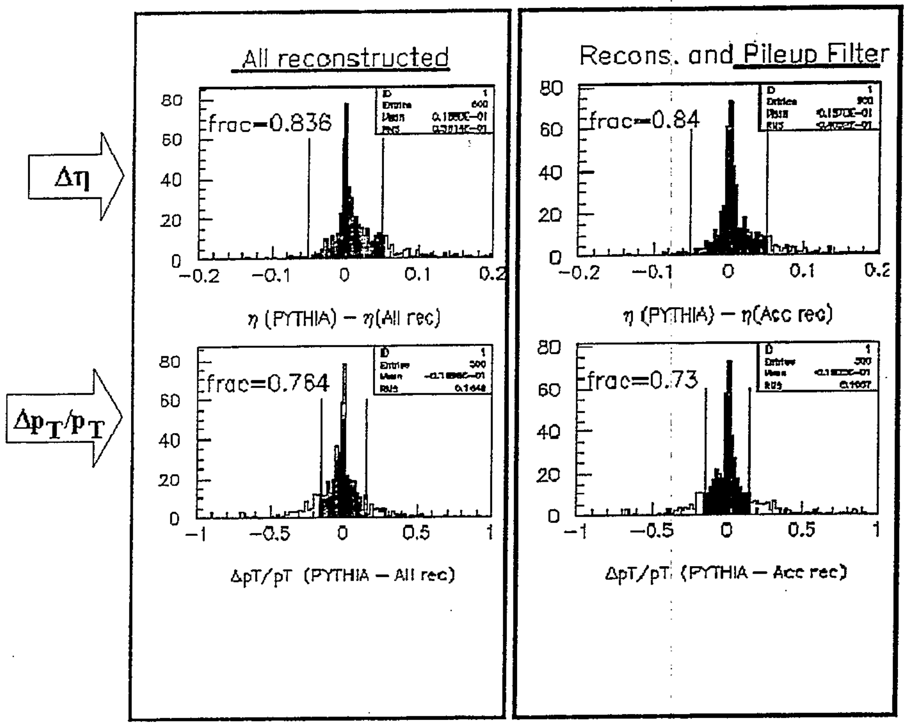
Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999



Tested with p+p @200 GeV , $\eta_q \in [1.0, 1.3]$

Test of Pileup Filter with full background

Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999



Events "lost" due to the pileup filter

$\Delta\eta$: ~1%

$\Delta p_T/p_T$: ~3%

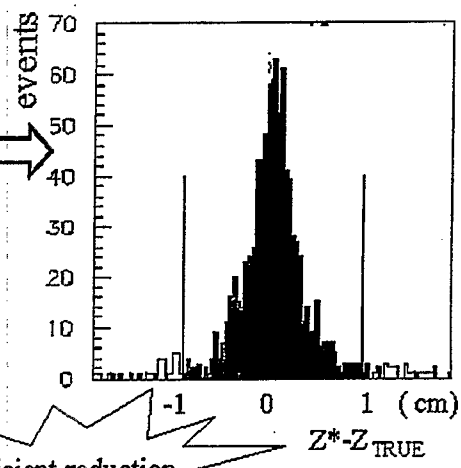
p+p @ 200 GeV, $p_T > 10$ GeV/c, $\eta_q \in [1.0, 1.3]$

Vertex Finder - Performance

Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999

For 88% of events $|\Delta Z| < 1$ cm
(out of 400 cm TPC length)

Tested with p+p @200 GeV, $\eta_q \in [1.0, 1.3]$



Pileup Filter accepts tracks:
- $|Z_i^{DCA} - Z^*| < 4\sigma_i$

or
- matched to the EMC towers

Sufficient reduction of data volume

	Trigger event	with pileup hits
All reconstructed tracks	27 ± 13*)	2,070 ± 170
Tagged tracks	13 ± 6	43 ± 12

*) ±RMS

Pileup Filter

Do the tracks associated with this vertex include the physics ?

STAR Trigger

Level 0 Trigger — EMC $1.0(\eta) \times 0.8(\phi)$ trigger patch
- see only 1/3 of total energy at L0 trigger
- bias towards EM rich events
- → Look at the other side of triggered jet

CTB/MWC multiplicity trigger

Level 3 Trigger — TPC tracking available
- DAQ to tape speed depends on data size
  - Data size reduction at L3
  - Possibly selecting invariant mass / z / $\cos\phi$

$Au + Au \rightarrow Au + Au + \rho^0$

event taken 2000 summer

STAR trigger first year:

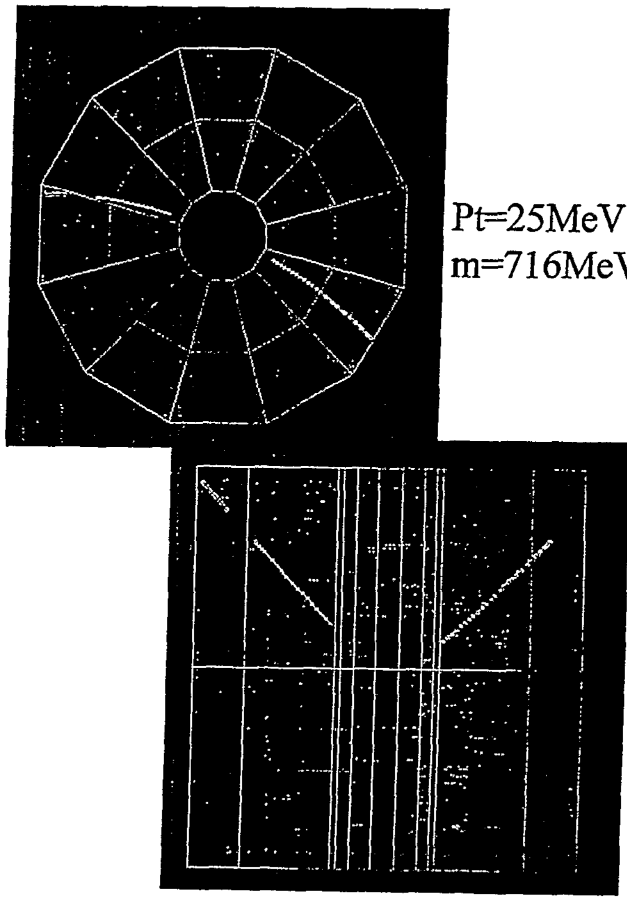
L0 trigger worked >50Hz

Topological L0 trigger
(CTB North South coincidence
+ multiplicity cut)
20 -30Hz

Trigger -DAQ - RCF worked at
~ 30Hz

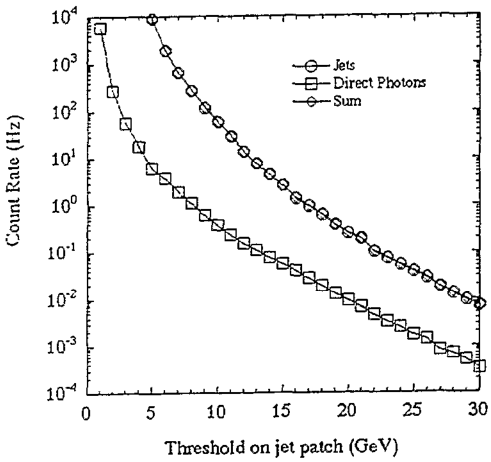
L3 reconstructed tracks at
~50Hz

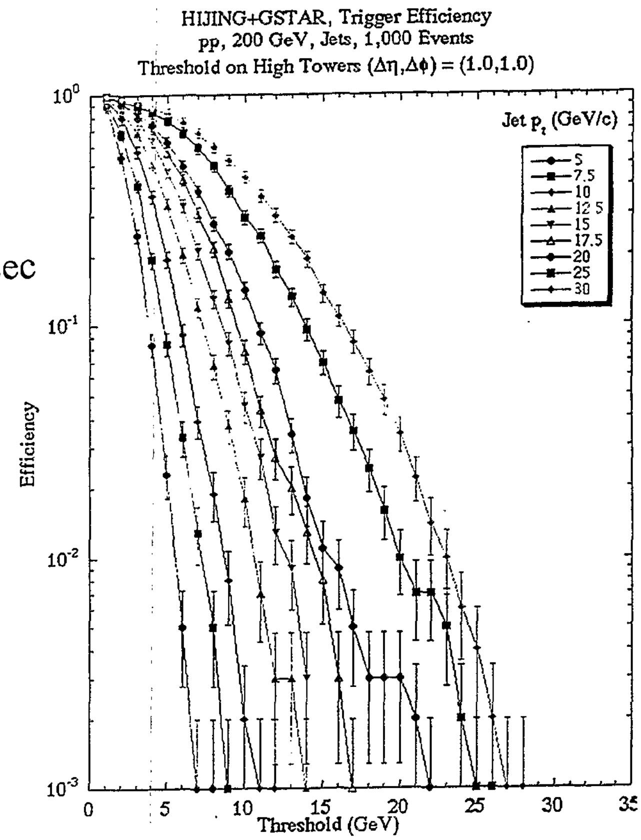
L3 reduction to
~ 2Hz



Pt=25MeV
m=716MeV

L0 Trigger
Rate and efficiency
at 200GeV
& L = 8 10^31/cm^2/sec





Signal Estimation

Luminosity, triggering, polarization, length of data taking

Cuts : Find jets (EM+charged hadrons) in $-0.3 < \eta < 0.3$
Any 2 opposite charged particle pairs within a jet
Pt > 0.3GeV
$-1 < \eta < 1$
0.5 < mass < 1.0GeV

Bins : cos ϕ, mass, z , Pt_jet , η _jet

A scenario

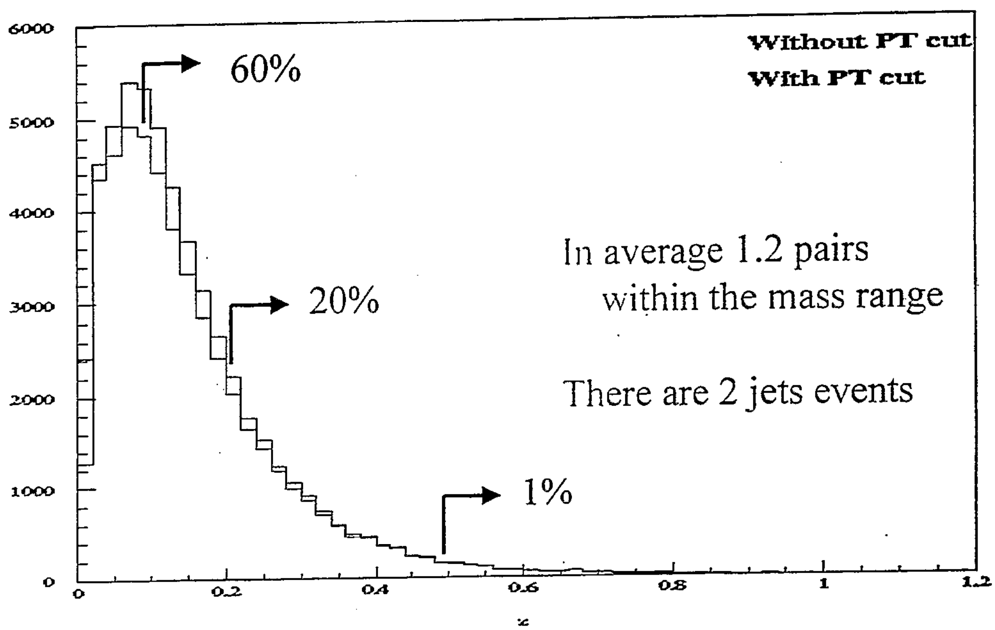
Year 2002 or 2003
L = 8 10^31 /cm^2/sec
L0 (EMC Jet) Trigger with threshold ~ 10GeV
Only using north/south (not top/bottom)
with L3 data size reduction
→ ~15Hz to tape
1 week run, 50% machine time ~ 32/pb

	Hz	300K sec Total
Jet Events	15	4.5M
pt<10		~2M
10<pt<20		~2M
20<pt		~0.4M

Beam Polarization	0.7
cosϕ integral	0.5
	0.35

82K events = 1% error on A

Number of pairs / Event vs Z



Conclusion

STAR can measure 2 pion asymmetry

Can see dependence on mass , $\cos\phi$, z, Pt_jet , η _jet
Many handles to check models

Is low x = high η = endcap EMC interesting for transversity?

Fragmentation function is needed to extract transversity

STAR Detector

Tracking:
- 0.5Tesla solenoid magnet
- Time Projection Chamber
- Silicon Vertex Detector
- Forward TPC

Calorimeter:
- Electoromagnetic Calorimeter
- Shower Max Detector
- Pre Shower Detector

Trigger:
- Central Trigger Barrel
- TPC endcap MWPC
- (- Vertex Position Detector)
- Zero Degree Calorimeter

Particle ID
- dE/dx at TPC/SVT
- (- TOF)
- RICH
- EMC/SMD/PreShower

TRANSVERSE SPIN FROM FIXED TARGET TO RHIC

(BRAHMS & Co.)

A. BRAVAR
UNI. MAINZ
BNL 19 Sept. Y2K

ELASTIC SCATTERING A_{N}, A_{NN} → large t → CNI region

TOTAL x-SECTION $\Delta\sigma_T = \sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow)$

INCLUSIVE PROCESSES @ LARGE x_F

→ PION (MESON) ASYMMETRIES A_N → π^+/π^-, K^+/K^-

HYPERONS A_Λ (P_0)

SPIN TRANSFER D_{NN}

INCLUSIVE PROCESSES CENTRAL REGION

DIFFRACTIVE PROCESSES (i.e. $pp \to \Lambda K p$)

HEAVY FLAVORS (CHARM)

NEW ENERGY DOMAIN

$\sqrt{s}$ up to 500 vs. 20 in F.T.

$\hookrightarrow \sqrt{s}$ DEP ?

EXTEND KINEMATICAL COVERAGE

in particular higher P_T up to $P_T \sim 5$ GeV

IMPROVE / COMPLEMENT EXISTING DATA

NEW CHANNELS ?

EXISTING RHIC EXPERIMENTS

(WITH MODEST UPGRADES ?) CAN STUDY

MESON ASYMMETRIES (A_N) UP TO 5+ GeV

BRAHMS & CO. vs. STAR & PHENIX

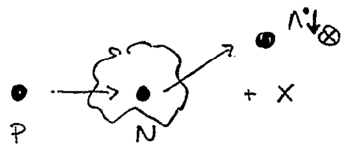
(+) RUN ALL TIME TRANSVERSE POLARIZATION

(−) LOWER $\mathcal{L} \sim 10^{31}$

(+) ACCESS FORWARD REGION (large x_F)

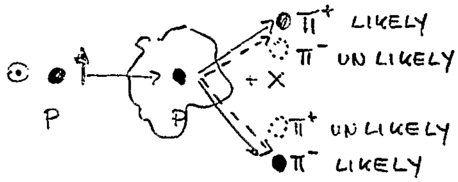
(?) MODEST UPGRADES

TRANSVERSE SPIN EFFECTS IN INCLUSIVE PRODUCTION



$P_\Lambda < \emptyset$

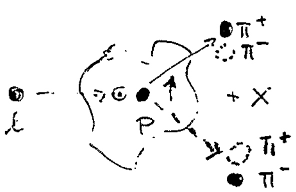
1976 @ FNAL



$A_N^{\bar{p} \to \pi^+} \gtrsim \emptyset$

$A_N^{\bar{p} \to \pi^-} \lesssim \emptyset$

90's @ FNAL

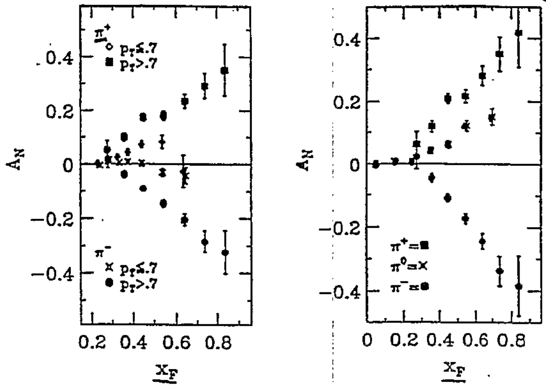


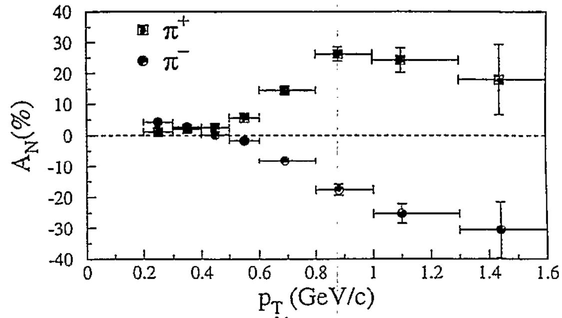
$A_N \neq \emptyset$?

$\hookrightarrow \frac{\Delta q}{q} \sim \frac{h_1}{F_1}$

$A_N : p\uparrow + p \to \pi^{+/-} + X$

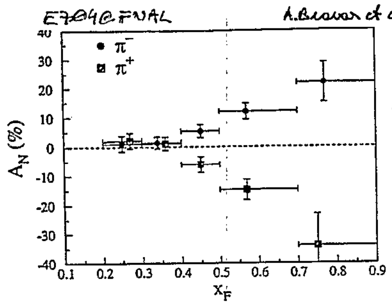
E704 @ FNAL — D.L. Adams et al. (PLB '91)

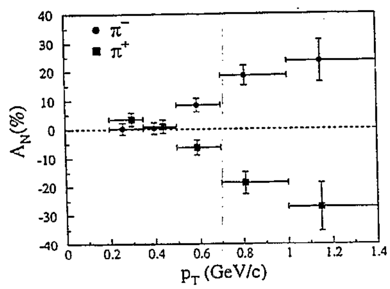


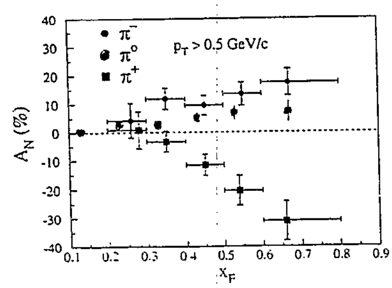


$A_N : \bar{p}\uparrow + p \to \pi^{+/-} + X$

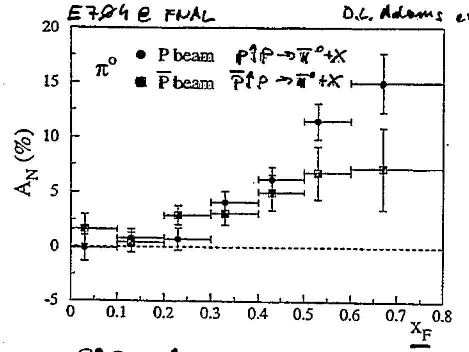
E704 @ FNAL — A.Bravar et al. (PRL '96)



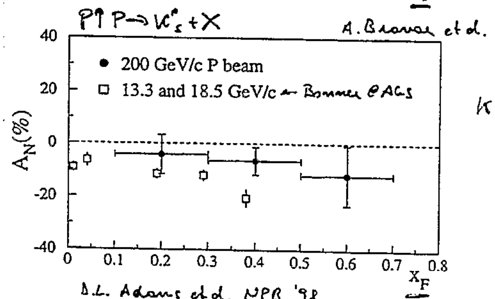




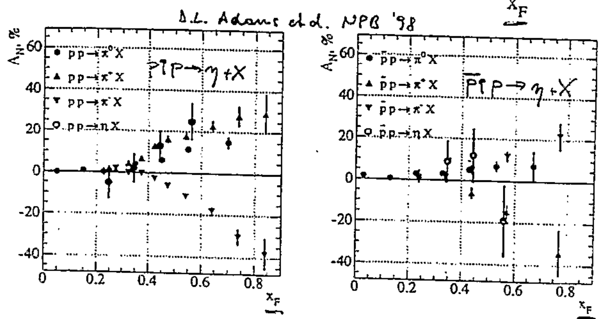
AB-6a



π^0



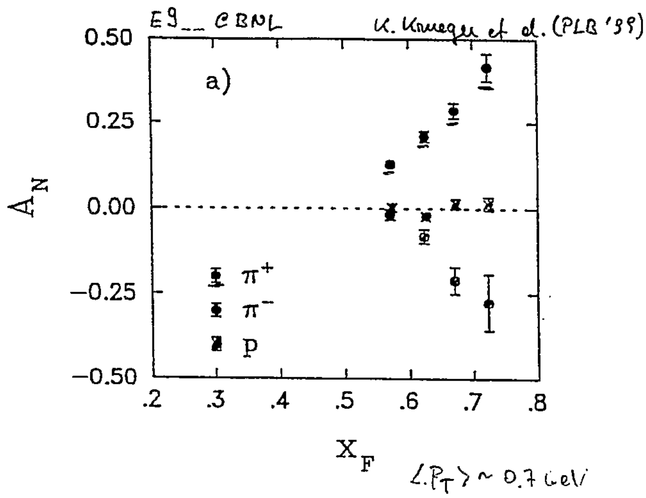
K^0_s



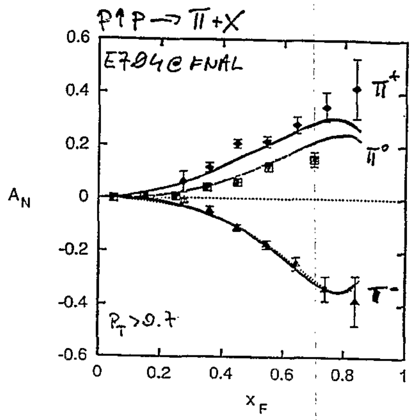
η

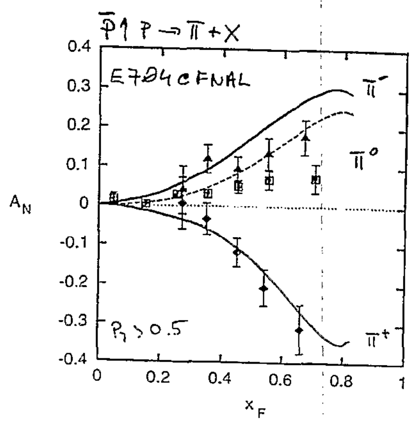
AB-7

$P\uparrow C \to \pi^{+/-} + X$ (at 21.7 GeV)



M. Anselmino et al.





$$A_N\,(\bar{p}^{\uparrow} p \to \pi^+/\pi^- + X) \simeq \frac{1}{P_B\langle\cos\phi_V\rangle}\,\frac{N_L - N_R}{N_L + N_R}$$

THEORY MEETS EXPERIMENT (finally!)

J. Qiu & G. Sterman hep-ph/9806356 PRD 59 014004

E704 @ FNAL

$P_T > 0.7$

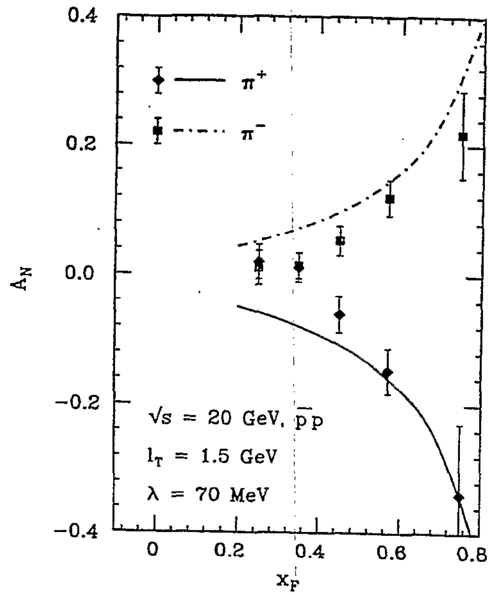
PREDICTION

A_N decreases with P_T increasing @ $P_T > 3-5$ GeV

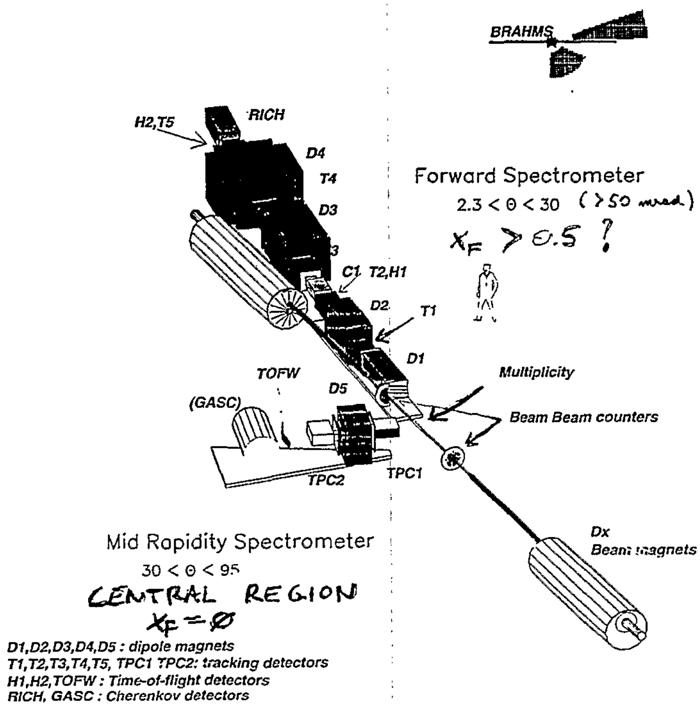
$x_F \sim x_B$; for $x_F \gtrsim 0.5$

$$\frac{d\sigma^{\pi^+}}{dx_F} \sim (1-x_F)^3$$

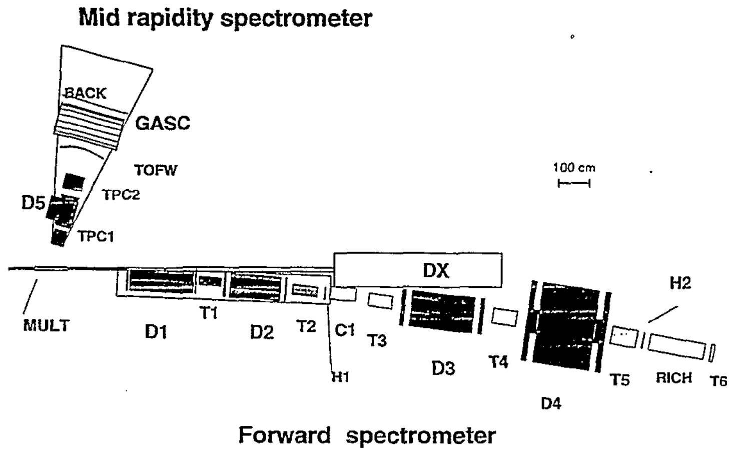
$$u(x) \sim (1-x)^3$$

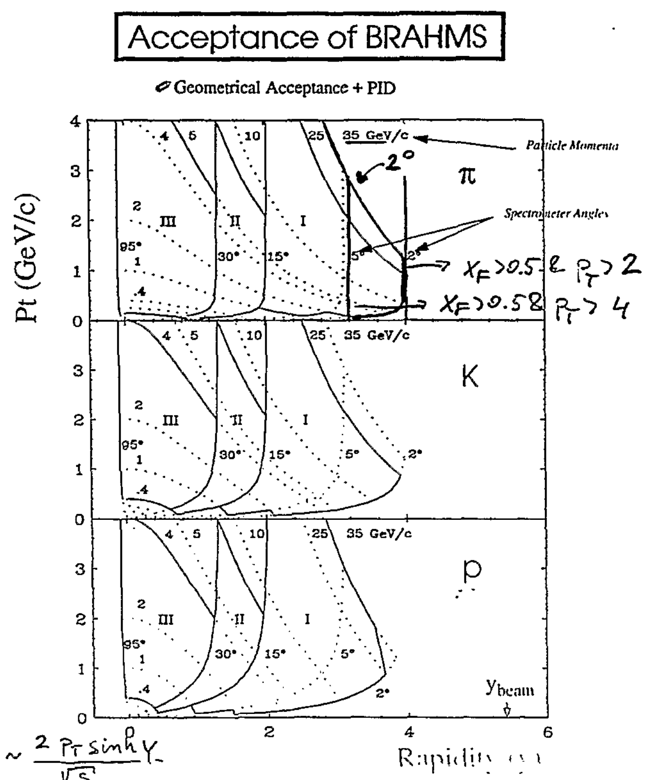


π+
π−
√s = 20 GeV, p̄p
l_T = 1.5 GeV
λ = 70 MeV
A_N
x_F



BRAHMS
H2,T5
RICH
D4
T4
D3
C1 T2,H1
D2
T1
D1
Forward Spectrometer
2.3 < θ < 30 (>50 mrad)
x_F > 0.5 ?
Multiplicity
Beam Beam counters
TOFW
D5
(GASC)
TPC2
TPC1
Dx
Beam magnets
Mid Rapidity Spectrometer
30 < θ < 95
CENTRAL REGION
x_F = ∅
D1,D2,D3,D4,D5 : dipole magnets
T1,T2,T3,T4,T5, TPC1 TPC2: tracking detectors
H1,H2,TOFW : Time-of-flight detectors
RICH, GASC : Cherenkov detectors





$x_F \sim \frac{2 P_T \sinh y}{\sqrt{s}}$

Region I : With the full Forward Arm
Region II : With the D1 - D2 (Forward Arm) Complex alone
Region III : With the Mid Rapidity Arm

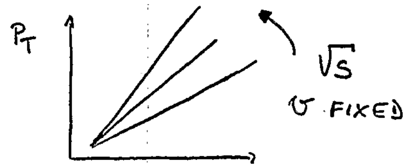
$\Delta\varphi \sim 1^\circ$

AB-1/c

MEASURE AT FIXED ANGLE ϑ

$P_T \sim P_L \cdot \vartheta$

$x_F \sim P_L / P_B$



$x_F > 0.5$ & $\vartheta > 50$ mrad (BRAHMS)

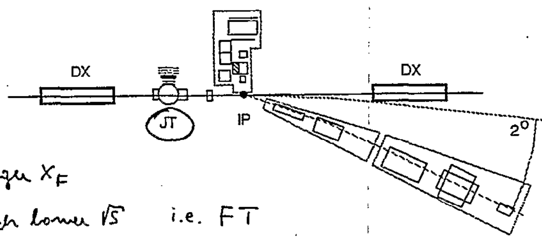
	$\sqrt{s}$	P_z	P_T^{min}
50+50	100	> 25	1.25
100+100	200	> 50	2.50
250+250	500	> 125	6.25
FIXED TARGET	≤ 20	x_F up to 0.7–0.8	P_T up to 1.5–2.0

* X-SECTION DROPS VERY QUICKLY WITH P_T
* NO (LITTLE) OVERLAP WITH F.T. DATA

[redacted] Jet Target at 2 o' clock

a) PP2PP design location at 2 o' clock (implementation of high-β optics)

b) Integration with BRAHMS



(+) larger x_F

(−) much lower $\sqrt{s}$ i.e. FT

• BRAHMS - 2 spectrometers:

a) Mid-Rapidity Spectrometer (30°≤Θ ≤95°)
b) Forward Spectrometer (2.3°≤Θ ≤30°)

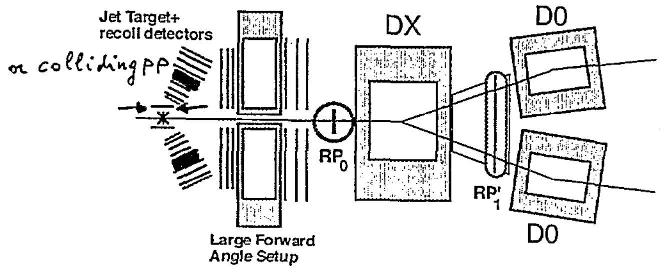
• Jet target 5-6 m *upstream* IP :

1 - Clearance of BRAHMS MRS;
2 - Acceptance to BRAHMS FS ?
(Low beam momenta)

• Charged particles' inclusive production;
• Large |t| elastic scattering ?
• Diffractive production ....

Large acceptance setup

Large Forward Angle Setup



(+) large acceptance forward region

(−) new setup

OUTLOOK

- MESON ASYMMETRIES (A_N) CAN BE STUDIED WITH EXISTING RHIC EXPT.
- LARGE X_F - P_T COVERAGE FOR $\underline{P_T > 2.5}$
  ↳ (−) NO (LITTLE) OVERLAP WITH F.T.
- MODEST UPGRADES:
  - EXTEND P.I.D.
  - TRIGGER SYSTEM
  - ECALS FOR π^0 ?
- DETAIL STUDY OF RATES (YIELDS) NEEDED BEFORE ASSESSING FEASABILITY.
- SYSTEMATIC EFFECTS (also A_{NN})

Transverse Physics with PP2PP experiment at RHIC

Wlodek Guryn

ABSTRACT

We shall describe the setup, performance and physics program of an experiment to measure elastic scattering of transversely polarized protons at the Relativistic Heavy Ion Collider, RHIC. By measuring transverse spin asymmetries like $A_N(t)$, $A_{NN}(t)$ at moderate values of four momentum transfer -t and of the difference in cross sections $\sigma(\uparrow\uparrow) - \sigma(\uparrow\downarrow)$, we will be able to determine the helicity amplitudes ϕ_i, which describe elastic scattering. Those amplitudes are not well known at this time. In particular the hadronic spin flip amplitude ϕ_5 is of interest and can be determined by measuring elastic scattering in the Coulomb Nuclear Interference (CNI) region. A systematic study of helicity amplitudes at RHIC will lead to understanding of spin structure of nucleon and of the exchanged mediator of the force, Pomeron and Odderon. There are many models, but the real theory is still missing. By measuring elastic scattering in the non-perturbative regime of QCD, experiment will address one of the main, unsolved problems in particle and nuclear physics: long range QCD and confinement. In small range of four-momentum transferred, CNI, 0.0004<-t<0.12 $(\text{GeV/c})^2$ one tests in a model independent way, general analytical properties of scattering amplitudes: analyticity, unitarity and crossing symmetry. In the diffractive region, with four momenta transfer 0.006< -t <1.5 $(\text{GeV/c})^2$, one studies dynamics of long range strong interactions. The polarization observables will give access to spin degrees of freedom, which help distinguish between different nucleon structure models, like quark diquark model of the proton and its appropriate wave function of the proton. Elastic scattering of pd, p?d, dd, $p^?He^4$ can be measured without changes to the setup. By appropriate design of the veto system and an additional trigger condition, the experiment will also measure single diffraction dissociation

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September 18 - 20, 2000
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Transverse Spin at pp2pp

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Outline of the Talk

1. PP2PP experiment with p and $p^{\uparrow}$.
2. Program with transversely polarized beams
3. Summary

Total and Differential Cross Sections, and Polarization Effects in pp Elastic Scattering at RHIC

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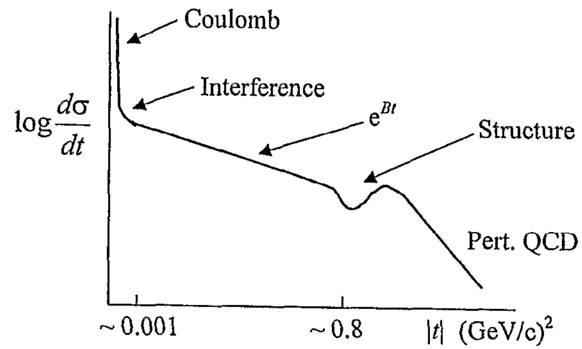
Elastic Scattering Cross Section



1. Coulomb Region $\frac{d\sigma}{dt} \sim \frac{1}{t^2}$ – Normalization (□) } Small t
2. Coulomb – Nuclear Interference – "ρ" Value } Small t
3. Diffraction $\frac{d\sigma}{dt} \sim e^{Bt}$ – σ_{tot} } Medium t
4. Structure Region – Peaks & Bumps } Medium t
5. Large $|t|$ □ 5 GeV^2 – Pert. QCD Large t

PP2PP PHYSICS PROGRAM

Studying total and elastic cross sections played a crucial role in particle and nuclear physics, in particular pp and $p\bar{p}$ experiments extend to the highest *s*. **Elastic scattering has been measured at every accelerator,** for every *s* energy available.

The main goal of the experiment is to map in great detail the spin dependence of the proton-proton interaction over a wide range of s and $|t|$, $50\leq\sqrt{s}\leq500$ GeV, $4\mathrm{x}10^{-4}\leq|t|\leq1.5$ GeV^2. In order to understand the features of the exchange mechanism (Pomeron), in terms of QCD concepts.

Polarization observables $A_N, A_{NN}, (A_{LL})$ will give access to spin degrees of freedom, which distinguish between **different nucleon structure models**; e.g. the three-quark model of the proton versus the quark-diquark model of the proton.

By measuring **spin asymmetries A_N, A_{NN}, A_{LL},** we will be able to determine the **helicity amplitudes** ϕ_i, which describe the dynamics of nucleon-nucleon elastic scattering, and which are poorly known at best:

$\phi_1 \sim \langle ++|M|++\rangle$ $\phi_2 \sim \langle --|M|++\rangle$ $\phi_3 \sim \langle +-|M|+-\rangle$

$\phi_4 \sim \langle +-|M|-+\rangle$ $\phi_5 \sim \langle ++|M|+-\rangle$

Their measurement will shed light on the exchange mechanism (Pomeron) including its spin dependence.

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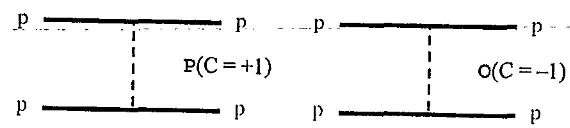
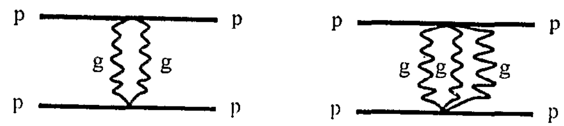
1. **Proton constituent quark structure through A_N, being sensitive to hadronic spin flip in CNI region, is sensitive quark – diquark proton structure:**

2. **The spin dependance of nucleon-nucleon interactions and determine features of the Pomeron in terms of QCD concepts and its spin dependence.**



Non-pert QCD

3. **Large-$|t|$ region, for tests of pQCD:**



Pert. QCD

P(C = +1)   O(C = –1)

Other topics done with the same experimental setup:

- **Diffractive *pp* scattering** can be done, with four momenta transfer $|t|<1.5$ GeV^2, where one studies the dynamics of long-range strong interactions.

- **Elastic scattering of pd, $p^{\uparrow}d$, dd, $p^{\uparrow 4}$He** can be measured with the **same experimental setup.**

These measurements challenge strong interaction theory, since they involve the application of QCD in a kinematical region where non-perturbative effects are important.

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Polarized beams

With transversely polarized protons and measuring of $\Delta\sigma_{tot}$, A_N, A_{NN} we will determine helicity amplitudes $\phi_i(s,t)$:

$$\phi_1 \sim <++|\mathbf{M}|++> \qquad \phi_2 \sim <--|\mathbf{M}|++> \qquad \phi_3 \sim <+-|\mathbf{M}|+->$$

$$\phi_4 \sim <+-|\mathbf{M}|-+> \qquad \phi_5 \sim <++|\mathbf{M}|+->.$$

1. **THE ODDERON AND SPIN DEPENDENCE OF HIGH-ENERGY PROTON-PROTON SCATTERING. E. Leader, T.L. Trueman. Phys.Rev.D61:077504,2000**

2. **THE SPIN DEPENDENCE OF HIGH-ENERGY PROTON SCATTERING. N.H. Buttimore, B.Z. Kopeliovich, E. Leader, J. Soffer, T.L. Trueman Phys.Rev.D59:14010,1999**

- the difference of σ_{tot} as function of pure initial transverse spin:

$$\Delta\sigma_{tot} = \sigma_{tot}(\uparrow\downarrow) - \sigma_{tot}(\uparrow\uparrow)$$

- the analyzing power, A_N:

$$A_N = \frac{1}{P\cos\phi}\frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

- and the double-spin correlation parameter, A_{NN}:

$$A_{NN} = \frac{1}{P_1 P_2 \cos^2\phi}\frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

(P_i is beam polarization, ϕ is scattering azimuth

Physics Goals

We shall study systematically *pp* elastic scattering with polarized and unpolarized beams $p_{lab} < 250$ GeV/c and in both colliding beam mode and fixed target mode, using a polarized gas jet target.

The four-momentum transferred *-t* is sub-divided in two kinematic ranges:

1. Medium *t* region, **day one pp running**, no special conditions required:

$$0.006 < |t| \leq 1.5 \ (\mathrm{GeV}/c)^2$$

- evolution of dip structure observed at the ISR in $d\sigma_{el}/dt$;
- *s* and t dependence of the nuclear slope, ***b***.

2. Coulomb Nuclear Interference (**CNI**) region:

$$0.0004 < |t| < 0.12 \ (\mathrm{GeV}/c)^2$$

- *s* dependence of σ_{tot} and $d\sigma_{el}/dt$;
- ratio of real to imaginary part of the forward scattering amplitude, ρ;
- nuclear slope parameter of the *pp* elastic scattering,

PHYSICS PROGRAM

1. By measuring **spin asymmetries** A_N, A_{NN}, A_{LL}, we will be able to determine the **helicity amplitudes** ϕ_i, which describe elastic scattering. They are not well known now.

$$\phi_1 \sim \langle ++|\, M \,|++\rangle \qquad \phi_2 \sim \langle --|\, M \,|++\rangle \qquad \phi_3 \sim \langle +-|\, M \,|+-\rangle$$

$$\phi_4 \sim \langle +-|\, M \,|-+\rangle \qquad \phi_5 \sim \langle ++|\, M \,|+-\rangle.$$

2. **Polarization observables will give access to spin degrees of freedom,** which distinguish between different nucleon structure models, like quark diquark model of the proton and its appropriate wave function of the proton.

3. **In the medium *t* region,** with four momenta transfer $|t|<1.5\mathrm{GeV}^2$, we will study the dynamics of long range strong interactions, the non-perturbative regime of QCD. Hence, the experiment will address one of the main, unsolved problems in particle and nuclear physics: **long range QCD** and confinement.

4. By appropriate design of the veto system and an additional trigger condition, the experiment will also measure **single diffraction dissociation.**

5. **In the small momentum transferred |t| region,** one tests in a model independent way, general analytical properties of scattering amplitudes: analyticity, unitarity crossing symmetry.

6. Using the same detectors and an additional magnet in the IR for momentum reconstruction will allow measurement of elastic scattering **in large *t* region,** hence tests of **pQCD** calculations.

For small scattering angles the protons follow the accelerator lattice, hence one can use the transport matrix to relate the position at the detection point to the scattering angle at the collision point:

$$y_{\det} = \sqrt{\beta/\beta^*}\left(\cos\Phi + \alpha^* \sin\Phi\right)y^* + \sqrt{\beta\beta^*}\left(\sin\Phi\right)\Theta_{SC}$$

or:

$$y_{\det} = a_{11}\, y^* + L_{eff}\, \Theta_{SC}.$$

The optimum condition, called parallel to point focusing, is when $a_{11} = 0$ and L_{eff} is large. So that for small Θ_{SC} one gets large displacement at the detection point, with no sensitivity to y*.

The smallest **t** expressed in terms of beam parameters is:

$$t_{min} \propto \frac{k^2 \varepsilon p^2}{\beta^*}$$

This implies the need for **large β* and small ε.**

(In order to reach Coulomb region special tune, β* = **195 m** and low emmitance ε = **5π**, are required.)

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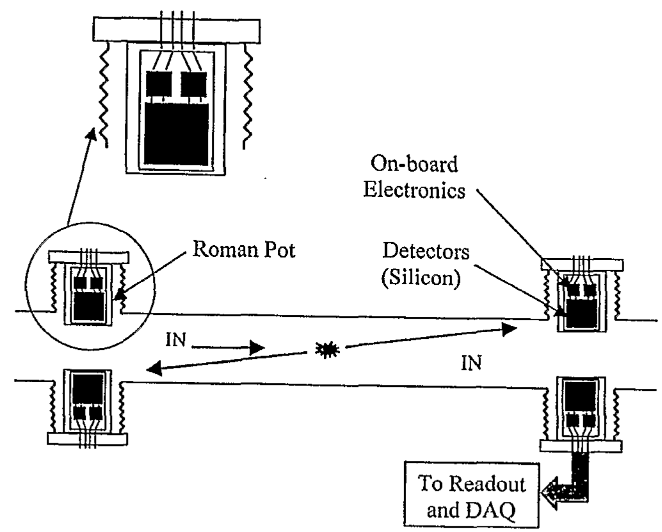
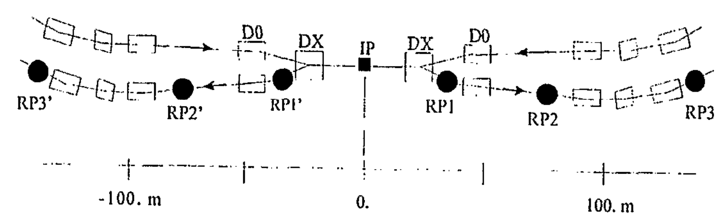
Roman pot location is determined by parallel to point focusing.



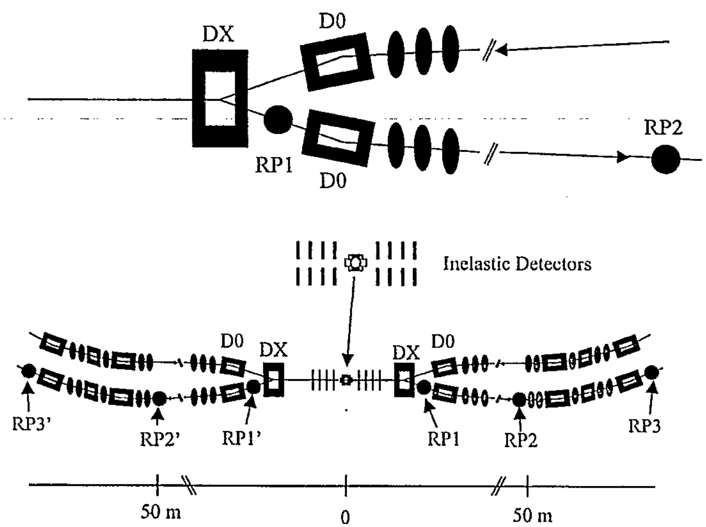
RHIC Intersection Region with PP2PP Basic CB Setup



Day one PP2PP Setup

More than one p_{beam} at RHIC, 100 GeV/c and 250 GeV/c proton beams, will allow us to take data at two $\sqrt{s}$ points.

At luminosity 4×10^{30} $cm^{-2}sec^{-1}$, 200 hrs data on tape to acquire 1000 evts/0.02 GeV^2/c^2 bin will be needed.



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Detectors

Silicon strip detectors are our choice. They will provide:

- uniformity of efficiency ~ 0.1% not to dominate errors on σ_{tot} and ρ;
- small dead area between the sensitive part of the detector and the beam 0.5mm
- many detector layers with high efficiency;
- small cell size to limit occupancy per readout channel;
- in the CNI region good detector resolution is needed:

$$\delta t << 10^{-4}\, GeV^2 (bins) \Rightarrow \delta y \approx 0.1mm$$

- in the dip region detector resolution set by momentum reconstruction ($\delta p/p$ ~ 1%) and vertex size (y^* ~ 1mm):

$$\delta y \approx 0.2mm$$

Status and Plans

Our goal is to be ready for running in spring of 2001.

1. Experiment has scientific approval and has received funding for equipment.

2. Since the approval time we have:

   - optimized the experiment, involving RHIC accelerator group to find placement for detectors (parallel to point focusing;)

   - designed of parts that are critical: Roman pots, detectors;

   - designed the veto system;

1. 2000 finish design and prototyping of the Roman pots, Si strip detectors and of the inelastic detector system.

2. 2001 construction and commissioning of detectors, Roman pots,

Engineering run in Spring of 2001

3. 2002 physics run.

Observations on Factorization

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This talk began with a review of the formalism for collinear factorization, [1] which applies to inclusive hard scattering cross sections involving one or more hard scales. Such cross sections, including those for Drell-Yan, jet and heavy quark production, are convolutions in partonic longitudinal momentum fractions, between parton distribution functions, $\phi_{a/A}$, and hard scattering functions. For inclusive single-particle production at high transverse momentum, fragmentation functions are included. For the latter case, the differential cross section is thus

$$\begin{aligned} d\sigma_{AB\to C(p)} &= \sum_{ijk} \int dx\, dy\, dz\; \phi_{i/A}(x,\mu_F)\; \phi_{j/B}(y,\mu_F) \\ &\quad \times D_{C/k}(z,\mu_F)\; d\hat{\sigma}_{ijk}(xp_A, yp_B, p_C/z, \mu_F, \alpha_s(\mu_F))\;, \end{aligned} \tag{1}$$

where μ_F is the factorization scale, and where $\hat{\sigma}$ is perturbatively calculable. This formalism applies at leading power in the hard scale, for both polarized and unpolarized cross sections. Corrections to the factorization formula itself are suppressed by powers of the hard scale (p_T, etc.).

Parton distributions and fragmentation functions may be expressed as expectation values of nonlocal operators in hadronic states. [2] For example, for the fragmentation function of a quark (referred to the plus direction for convenience)

$$D_{C/f}(z,\mu_F) = \int \frac{d\lambda}{2\pi}\, e^{-i\lambda(p_C^+/z)} \sum_X \langle 0|q(0)|C,X\rangle\, \Gamma\, \langle C,X|\bar{q}(\lambda,0^+,0_\perp)|0\rangle \tag{2}$$

where information on polarization can be incorporated through the choice of the Dirac matrix Γ. These expectations require a renormalization, corresponding to a maximum relative transverse momentum for the observed hadron and parton, or equivalently a cutoff on the transverse distance to the light-cone. The freedom to choose this scale, which corresponds to the factorization scale, leads directly to calculable evolution for the parton distributions.

Factorization may be understood heuristically in terms of the Lorentz transformation properties of classical fields, by an analysis familiar from electrodynamics. [1] The physical electromagnetic field strengths are Lorentz contracted even more strongly than a scalar field, suggesting that factorization holds even to the first nonleading power. [3] In the case of polarized cross sections, however, some of this suppression may be lost, due to the mechanical origin of the orbital angular momentum.

The most basic extension of collinear factorization is to include the transverse momentum degrees of freedom of the partons. [5, 4] The corresponding expectation values are very closely related to the normal parton distributions, so that for quark q in polarized hadron A we have the general form [5]

$$\mathcal{P}_{q/A}(x,k_\perp,s) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3}\, e^{-ixp^+y^- + ik_\perp\cdot y_\perp}\, \langle A(p,s)|\bar{q}(0^+,y^-,y_\perp)\,\Gamma\, q(0)|A(p,s)\rangle\,, \tag{3}$$

where again the choice of Γ determines the spin content of the distribution. In the case of parton distributions at measured k_T, a good deal is known about the summation of logarithms of the transverse momentum. [5]

Dependence on the transverse momentum of partons is power suppressed in inclusive cross sections with *only* hard scales in the final state. When there is in addition a second scale, the k_T distribution of initial-state partons, or final-state hadrons in fragmentation, may become crucial. At the same time, if the cross section remains otherwise inclusive, factorization is not lost. The most familiar example is the Drell-Yan cross section at measured Q_T, but another example is found in the Collins effect, [6] where the expectation of the triple product $\langle s\cdot p_J\times p_\pi\rangle$ acts as a small scale, with p_J and p_π a jet and pion momentum, respectively.

Finally, power suppressed effects may be important, when leading power contributions are small or absent altogether. Examples are multiple scattering in nuclei and chiral-even single-spin asymmetries. [7] Such contributions are, as indicated above, often amenable to collinear factorization. Parton k_T-effects are likely to be important in these cases as well.

References

[1] J.C. Collins, D.E. Soper and G. Sterman, in *Perturbative quantum chromodynamics*, ed. A.H. Mueller (World Scientific, Singapore, 1989).

[2] J.C. Collins and D.E. Soper, *Nucl. Phys.*, **194**, 445 (1982).

[3] J.-W. Qiu and G. Sterman, *Nucl. Phys.* **B353**, 137 (1991).

[4] E. Laenen, G. Sterman and W. Vogelsang, hep-ph/0010080.

[5] J.C. Collins and D.E. Soper, *Nucl. Phys.* **193**, 381 (1981).

[6] J. Collins, *Nucl. Phys.* 420, 565 (1994), hep-ph/9305309.

[7] J.-W. Qiu and G. Sterman, *Phys. Rev.* **D59**, 014004 (1999), hep-ph/9806356.

(A FEW) OBSERVATIONS ON FACTORIZATION IN HADRON-HADRON SCATTERING

G. Sterman
BNL
Sept. 19, 00

COLLINEAR FACTORIZATION

hard scale $M = Q$ (DY)
$= p_T$ (1PI)
...

$$d\sigma_{AB\to C(p_T)} = \sum_{ijk} \int dx\, dy\, dz$$
$$\times\ \phi_{i/A}(x,\mu_F)\, \phi_{j/B}(y,\mu_F)$$
$$\times\ D_{C/k}(z,\mu_F)$$
$$\times\ d\hat{\sigma}_{ijk}\left(xp_A, yp_B, \frac{p_C}{z}, \mu_F, \alpha_s(\mu_F)\right)$$

$\sum_{ijk} \leftrightarrow$ parton flavor and spin structures

$$+ \left[\frac{\langle k_T\rangle}{M}\right]^p \quad \begin{array}{l} p \geq 2 \text{ unpol.} \\ p \geq 1 \text{ pol.} \end{array}$$

Matrix elements

$i = f, s$

$$\phi_{q_f,s/A}(x,\mu^2) = \int \frac{dy^-}{2\pi}\, e^{-ixp^+y^-}$$

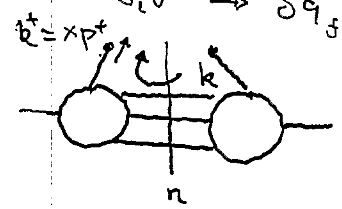
$$\langle A(p,s)|\, \bar{q}_f(y^-)\, \Gamma^{(s)}\, q_f(0)\, |A(p,s)\rangle$$

$\gamma^+ \rightarrow q_f(x)$

$\gamma^+\gamma^5 \rightarrow \Delta q_f$

$s_i\sigma^{+i} \rightarrow \delta q_f \quad \ldots$

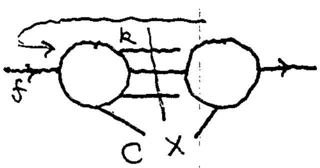
$$= \sum_n \int_{k_\perp^2 < \mu^2} dk^-\, d^2k_\perp$$



$$D_{c/q_f s}(z,\mu^2) = \int \frac{dy^-}{2\pi}\, e^{-i(p_c^+/z)y^-}$$

$$\times \langle 0|\, q_f(0)\, |c\, X\rangle\, \Gamma^{(s)} \times \langle c\, X|\, \bar{q}_f(y^-)\, |0\rangle$$

$$= \sum_X \int$$



$dk^-\, d^2k_\perp$

- Factorization → Evolution

$$F(Q) = \hat{\sigma}\left(\frac{Q}{\mu}, \alpha_s(\mu)\right) \otimes f(\mu, \alpha_s(\mu))$$

μ - factorization scale

$$\mu \frac{dF(Q)}{d\mu} = 0$$

$$\Downarrow$$

splitting fn.

$$\begin{cases} \mu \dfrac{d\hat{\sigma}}{d\mu} = \hat{\sigma} \otimes P(\alpha_s(\mu)) \\ \mu \dfrac{df}{d\mu} = -P(\alpha_s(\mu)) \otimes f \end{cases}$$

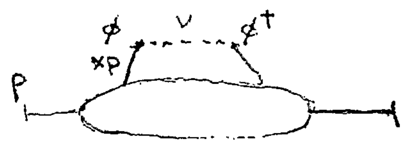
- Parton distribution ↔ Matrix element

$$f_a(x,\mu) = \int d\lambda\, e^{-i\lambda x p \cdot v} \langle p | \phi_a^{+}(\lambda v^{\mu})\, \phi_a(0) | p \rangle$$

$A^{+} = 0$ gauge

$\overrightarrow{p}$ $\overleftarrow{v}$

$$= \int d^2 \ell_\perp \langle p | b^{+}(x v \cdot \ell, \ell_\perp)\, b(x v \cdot \ell, \ell_\perp) | p \rangle$$



GS-4

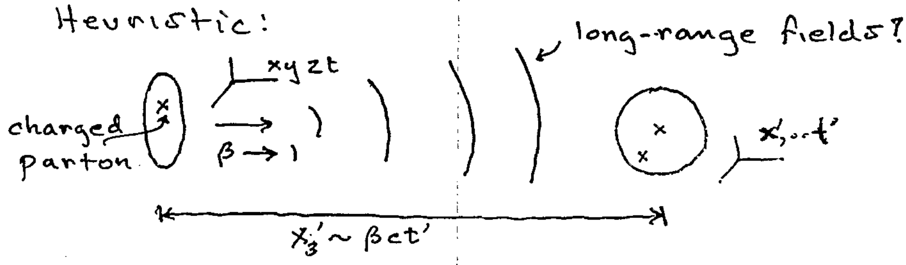
HEURISTICS OF FACTORIZATION
(unpolarized)

7

- Why?

Formal arguments: J. Qiu, G.S. (1991)

Heuristic:



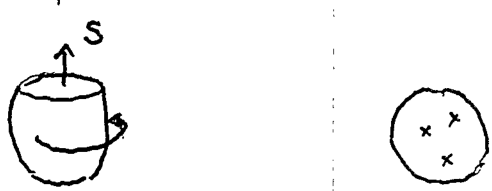
Lorentz Contractions: $\Delta \equiv \beta c t' - x'_3$

field	x frame	x' frame
scalar	$V(x) = \frac{e}{\lvert\vec{x}\rvert}$	$V'(x') = \frac{e}{(x_T^2 + \gamma^2\Delta^2)^{1/2}}$ $\to 1/\gamma$ $\sim$ "ruler"
gauge	$A^-(x) = \frac{e}{\lvert\vec{x}\rvert}$	$A'^-(x') = \frac{e\gamma(1+\beta)}{(x_T^2 + \gamma^2\Delta^2)^{1/2}}$ $\to 1 \gg$ "ruler"
field strength	$E_3(x) = \frac{e}{\lvert\vec{x}\rvert^2}$	$E'_3(x') = \frac{-e\gamma\Delta}{(x_T^2 + \gamma^2\Delta^2)^{3/2}}$ $\to 1/\gamma^2 \ll$ "ruler"

Suggests: Factorization to $O(1/Q^2)$ — not at $1/Q^+$, P^-
(R. Basu, A. Ramalho, G.S. '84)

5-7 (Consistent w/ Doria, Frenkel, Taylor noncancellation in QCD)

But polarized:



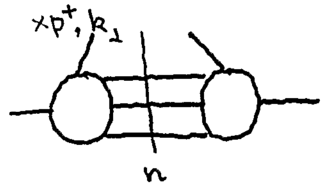
orbital part can only contract as $\frac{1}{\gamma}$

$\Rightarrow$ Factorization to $1/Q$ (only)

FACTORIZATION WITH $k_\perp$-UNINTEGRATED DISTRIBUTIONS

- distributions: Collins + Soper 81

$$\mathcal{P}_{f,s}(x, k_\perp) = \sum_n \int dk^-$$



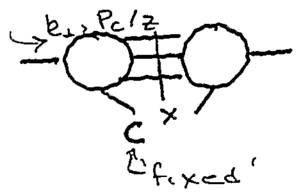
see below for p^+-dependence

$$= \int \frac{dy^- d^2 y_\perp}{(2\pi)^3} e^{-ixp^+y^- + i\underline{k}_\perp \cdot \underline{y}_\perp}$$

$$\cdot \langle A(p,s) |\, \bar{q}_f(0^+ y^- y_\perp)\, \Gamma^{(s)} q(0) \,| A(p,s) \rangle$$

$$\phi_{f,s}(x, \mu) = \int^{\mu} d^2 k_\perp \, \mathcal{P}_{f,s}(x, k_T)$$

$$\mathcal{D}_{f,s}(z, k_\perp) = \sum_X \int dk^-$$



- gauge dependence cancels in cross sections

Factorization at 'fixed k_T'

k_T - dependence power-suppressed unless

two observables

$M \gg m \gtrsim \Lambda_{QCD}$ (!)

Examples:

- $A+B \to V(Q, Q_T) + X$

$$\underset{M}{Q} \gg \underset{m}{Q_T}$$

$$\frac{d\sigma}{dQ^2 d^2Q_T} \sim \mathcal{P}_{i/A}(x, k_T) \otimes \mathcal{P}_{j/B}(y, k'_T) \otimes \hat{\sigma}\, \underbrace{\delta^2(Q_T - k_T - k'_T)}_{\sim \frac{1}{Q_T^2}} + \underbrace{Y}_{\sim Q_T^0}$$

- Collins effect

$$\frac{d\sigma(s_\perp)}{dp_H\, dp^{Jet}} \sim h_1(x, s_\perp) \otimes \hat{\sigma} \otimes \overbrace{\frac{\langle s \cdot p_H \times p_J \rangle}{\langle |p_H \times p_J| \rangle}}^{\text{notation heuristic!}}$$

$M \sim p_H$ or p^{Jet}

$m^2 \sim p_H \times p_J$

- e^+e^-: Collins Soper 81 ... Boer 00

SOME THINGS WE KNOW

- $$\mathcal{P}(x, k_T) \xrightarrow[k_T \to \infty]{} \int_x^1 d\xi \; \phi(\xi, \mu) \cdot C\left(\frac{x}{\xi}, \frac{k_T}{\mu}, \alpha_s(\mu)\right)$$

$$\hookrightarrow \sim \frac{\alpha_s(k_T^2)}{k_T^2}$$

- $\mathcal{P}$ depends on p^+ in <A(p)|

$\hookrightarrow$ suppression at small-$k_\perp$
large-b

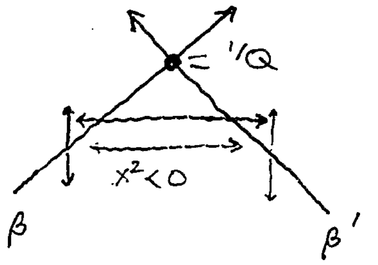
$$\mathcal{P}(x, k_T) \sim \int d^2b \, e^{i k_T \cdot b} \, e^{-S(b,Q)}$$

$Q \leftarrow$ actually $p \cdot n_{gauge}$

$$S(b,Q) \sim c \int_{1/b}^{Q} \frac{d\mu'}{\mu'} \ln \frac{\mu'}{Q} \, \alpha_s(\mu') + \cdots$$

- spin-independent
- the larger p^+, the more initial-state radiation
- but in single-scale cross sections only contributes to higher orders in $\hat{s}$
- moderate k_T not purely perturbative (Laenen Vogelsang Gib) GS

Factorization for
k_T-unintegrated distributions



$\beta^2 \sim \beta'^2 \sim 0$

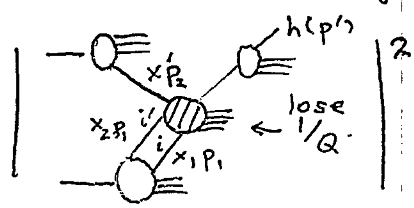
OK at same level as k_T-integrated as long as Q remains large

But: $\hat{\sigma}$ must still be computed with CO kinematics (gauge invariance) to go beyond LO

- Factorization at Nonleading Power

7

(1)



$\sim \sigma_4$

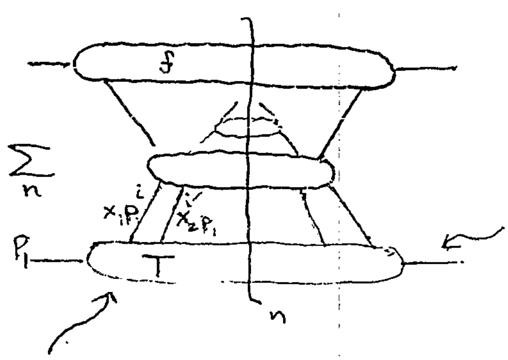
(2)

$$\omega \frac{d\sigma_4}{d^3p'} = \sum_{(ii')jk} \int \frac{dx'}{x'} f_{j/P_2}(x') \int \frac{dz}{z^2} D_{h/k}(z)$$

$$\times \int dx_1 dx_2 dx_3 T_{(ii')/P_1}(x_1, x_2, x_3) \times \hat{\sigma}^{(4)}_{(ii')+j\to k}$$

(3)

$\sigma \sim \sum_n$



nucleus, for us

(4)

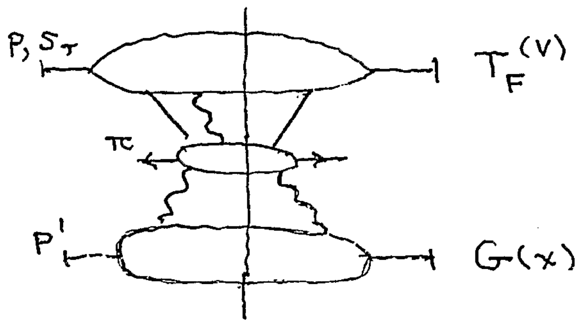
$$T(x_i) = \int \frac{dy_1^- dy_2^- dy_3^-}{(2\pi)^3} e^{ip^+(x_1y_1^- + x_2y_2^- + x_3y_3^-)}$$

$$\times t_{\alpha\beta\gamma s} \langle p | B^+_{i\alpha}(0) \hat{B}^+_{\sigma\beta}(y_3) B_{\sigma\gamma}(y) B_{i\xi}(y) | \ldots$$

R. Ellis, Furmanski, Petronzio (82)
R. Jaffe (82), J. Qiu (90) } DIS

- Typical Contribution to single-spin

$$p\uparrow + p \to \pi + X$$



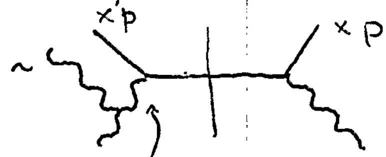
$$T_F^{(V)}(x,x) = \int \frac{dy^-}{4\pi}\, e^{ixp\cdot vy^-} \times \epsilon^{S_T v p \sigma}$$

$$\times \langle P S_T | \bar{\psi}(0)\, \gamma \cdot v \int d\lambda\, F_{\sigma +}(\lambda)\, \psi(y^- v) | P S_T \rangle$$

- Alternatives: chiral odd, fragmentation, k_T-dependent distributions
  - Meng
  - Artru
  - Collins
  - Sivers
  - Boer

$$\Delta\sigma \sim \int dx\, dx'\, T_F^{(V)}(x,x') \cdot \hat{\sigma} \cdot \ldots$$

$\hat{\sigma}(x,x')$

$\sim$ 

$$\frac{1}{x-x'+i\epsilon}$$

$$\int dx'\, T_F^{(V)}(x,x')\, \frac{1}{x-x'+i\epsilon} \sim \pi i\, T_F^{(V)}(x,x) + \text{real}$$

higher order :

- double pole $k^2 \to 0$ cancels
- reverts to previous result for large k^2 without extra logs...

Emphasize

- k_T factorization for two-scale problems OK
- otherwise: k_T effects
  - higher order in $\alpha_S(M)$
  - power-suppressed for NP level ↙ may still be important?
- 'Intrinsic' k_T essential for DY Q_T, azimuthal-dep^ce of fragmentation at large p_T...

Structure Functions and Chiral Odd Quark Distributions in the NJL Soliton Model of the Nucleon

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Inclusive and semi-inclusive processes analyzed via QCD factorization theorems imply that generic cross-section and nucleon structure functions are convolutions of hard-perturbative and soft non-perturbative contributions. For example, at leading twist and lowest order in $\alpha_s(Q^2)$, DIS structure functions are given by

$$F(x,Q^2) = \sum_a \int_x^1 \frac{dy}{y} H_a\left(\frac{x}{y}, \frac{Q^2}{\mu^2}, \alpha_s(\mu)\right) f_{a/P}(y,\mu^2) + \text{remainder}.$$

The hard coefficient functions, $H_a\left(\frac{x}{y}, \frac{Q^2}{\mu^2}, \alpha_s(\mu)\right)$, are calculable in perturbative QCD whereas the soft quark distribution functions, $f_{a/P}(y,\mu^2)$ are defined relative to the scale, μ^2 which factors the hard and soft physics. Alternatively, in DIS, factorization of hard and soft can be expressed via Mellin transform where the "remainder" is an expansion in twist, τ

$$\int_0^1 dx\, x^{n-1}\, F_i\,(y,Q^2) = \sum_\tau C^n_{\tau,i}\,(Q^2/\mu^2, \alpha_s(\mu^2))\, \mathcal{O}^n_{\tau,i}(\mu^2)(\frac{1}{Q^2})^{\frac{\tau}{2}-1}.$$

The logarithmic Q^2 behavior of the target independent coefficient functions, $C^n_{\tau,i}(Q^2/\mu^2, \alpha_s(\mu^2))$ is determined from the renormalization group equations. The reduced matrix elements, $\mathcal{O}^n_{\tau,i}(\mu^2)$, reflect the nonperturbative properties of the nucleon target. The QCD-parton model in conjunction with the factorization theorem enables one to calculate and predict the Q^2 dependence of the hard contribution. On the other hand a nonperturbative approach is needed, *e.g.* lattice QCD, to predict the soft, nonperturbative piece which is measured in asymmetries. Yet, the difficultly of calculating bound state wave functions for the nucleon from first principles has led many to resort to quark model calculations for hadron structure functions [3]. More recently however, calculations have been performed in the context effective field theories of QCD.

From the perspective that hadron structure can be viewed as functions of constituent quark distributions we adopt the Nambu-Jona-Lasinio chiral soliton as a low energy effective field theory for QCD to calculate chiral even and odd quark distribution functions and their corresponding hadron structure functions [1,2]. In this context the factorization parameter,μ^2, plays the role of the intrinsic model scale. At this scale, twist two structure functions don't look like the data since presumably it has contributions from higher twist. To go from the hadronic scale to the experimental scale we first sum the moments without radiative corrections; namely, calculate the structure functions in the Bjorken limit. Subsequently we evolve effective quark distributions via DGLAP scheme and construct nucleon structure functions in terms of charge weighted averages of the constituent quark distribution functions.

The starting in this approach however is not the parton model motivated definition of leading twist quark distribution function: $f_{a/P}(x) = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS|\overline{\psi}^a(0)\Gamma\psi^a(\lambda n)|PS\rangle$ (where $\Gamma = \{\mathbb{1}, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$). Rather, we use the optical theorem, $W^{\mu\nu}(q) = \frac{1}{2\pi}\Im\,(T^{\mu\nu}(q))$, to calculate the absorptive part of the forward virtual Compton amplitude, $T^{\mu\nu}(q) = \int d^4\xi\, e^{iq\cdot\xi}\, \langle p,s|T\,(J^\mu(\xi)J^\nu(0))\,|p,s\rangle$. Here the bilocal current correlation function is unambiguously obtained from the regularized[1] NJL action

$$T\,(J^\mu(\xi)J^\nu(0)) = \frac{\delta^2}{\delta v_\mu(\xi)\,\delta v_\nu(0)}\, \mathrm{Tr}_\Lambda \log\left[i\partial\!\!\!/ - (S + i\gamma_5 P) + \mathcal{Q}\, v\!\!\!/\right]\Big|_{v_\mu=0}.$$

Applying Cutkosky's rules we extract the leading twist pieces of the structure functions in the Bjorken limit: $q^2 \to -\infty$ with $x = -q^2/p\cdot q$ fixed. Starting from the Compton amplitude rather than the QCD-parton model quark-target amplitude yields a self consistent definition of the *regularized quark-target amplitude* or the leading twist constituent quark distribution functions. To leading order in the $1/N_c$ expansion the Compton amplitude in the Bjorken limit is

[1] We use Pauli-Villars regularization since it preserves both the anomaly structure of QCD and the leading scaling behavior hadron structure functions in the Bjorken limit.

$$T_{\mu\nu}(q) = -M_N \frac{N_C}{2} \int \frac{d\omega}{2\pi} \sum_\alpha \int dt \int d^3\xi_1 \int d^3\xi_2 \int \frac{d^4k}{(2\pi)^4}\, e^{i(q_0+k_0)t}\, e^{-i(\vec{q}+\vec{k})\cdot(\vec{\xi}_1-\vec{\xi}_2)}\, \frac{1}{k^2+i\epsilon}$$
$$\times\Big\langle N\Big|\Big\{\left[e^{i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_1)\beta\mathcal{Q}^2_A\gamma_\mu k\!\!\!/\gamma_\nu\Psi_\alpha(\vec{\xi}_2) - e^{-i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_2)\beta\mathcal{Q}^2_A\gamma_\nu k\!\!\!/\gamma_\mu\Psi_\alpha(\vec{\xi}_1)\right] f^+_\alpha(\omega)$$
$$+\left[e^{i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_1)\mathcal{Q}^2_A(\gamma_\mu k\!\!\!/\gamma_\nu)_5\beta\Psi_\alpha(\vec{\xi}_2) - e^{-i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_2)\mathcal{Q}^2_A(\gamma_\nu k\!\!\!/\gamma_\mu)_5\beta\Psi_\alpha(\vec{\xi}_1)\right] f^-_\alpha(\omega)\Big\}\Big|N\Big\rangle, \qquad (0.1)$$

with the spectral functions given by

$$f^\pm_\alpha(\omega) = \sum_{i=0}^2 c_i \frac{\omega \pm \epsilon_\alpha}{\omega^2 - \epsilon^2_\alpha - \Lambda^2_i + i\epsilon} \pm \frac{\omega \pm \epsilon_\alpha}{\omega^2 - \epsilon^2_\alpha + i\epsilon}. \qquad (0.2)$$

Λ_i are the Pauli-Villars regulators and ϵ_α are single particle constituent quark energy levels in the soliton background. The resulting hadronic tensor obtained from Eq. (0.1) bares some resemblance to the parton model and quark model calculations however there is no clear distinction between the quark and anti-quark contributions due to the complicated pole structure that arises from regularization.

Given this prescription the regularization function for the chiral odd distribution functions is self consistently determined by calculating the forward scattering matrix element between transversally polarized nucleons containing a vector and pseudo-scalar current [4]

$$T_\mu = \frac{i}{2}\int d^4x e^{iqx} \langle p, \mathcal{S}_\perp\, |T\,(j_\mu(x)j_5(0) + j_5(y)j_\mu(0))|\, p, \mathcal{S}_\perp\rangle. \qquad (0.3)$$

Now the correlation functions is given by

$$T\,(j_\mu(\xi)j_5(0)) = \frac{\delta^2}{\delta v_\mu(\xi)\,\delta v_5(0)}\,\mathrm{Tr}_\Lambda \log\left[i\partial\!\!\!/ - (S + i\gamma_5 P) + \mathcal{Q}\, v\!\!\!/ + \mathcal{Q}_5\, v_5\right]\Big|_{v_\mu=0}, \qquad (0.4)$$

from which we obtain regularized distributions.

Having completed the calculation of the leading twist chiral even/odd structure functions [1] we find the Soffer inequality is satisfied

$$f^q_1(x) + g^q_1(x) \;\geq\; |2h^q_T(x)|, \qquad (0.5)$$

where the effective quark flavor distributions are $f_1^{(q)}(x,Q^2_0)$, $g_1^{(q)}(x,Q^2_0)$ and $h_T^{(q)}(x,Q^2_0)$ and $q = u,d$ denotes the quark flavors at the low-scale of the model $Q^2 = 0.4\mathrm{GeV}^2$. In addition, we calculate the zeroth moments of the chiral odd distribution functions which are referred to as the isoscalar and isovector nucleon tensor charges,

$$\Gamma^S_T(Q^2) = \frac{18}{5}\int_0^1 dx\;\left[h^p_T\,(x,Q^2)\; + h^n_T\,(x,Q^2)\right] \qquad (0.6)$$

$$\Gamma^V_T(Q^2) = 6\int_0^1 dx\;\left[h^p_T\,(x,Q^2)\; - h^n_T\,(x,Q^2)\right] \qquad (0.7)$$

at both the low scale, $Q^2_0 = 0.4\mathrm{GeV}^2$ and a scale commensurate with experiment, $Q^2 = 4\mathrm{GeV}^2$. These results are compared with other model calculations in addition to lattice results.

I would like to thank Daniel Boer and Matthias Grosse-Perdekamp for the opportunity to speak at the "Future Transversity Measurements" BNL Workshop. I also thank Ms. Tammy Heinz for her efforts in organizing this workshop. Finally I gratefully acknowledge my collaborators on this project, Hebert Weigel, Enrique Ruiz Arriola and Hugo Reinhardt.

[1] L. Gamberg, H. Weigel, and H. Reinhardt, Phys. Rev. D58, 054014 (1998).
[2] H. Weigel, Nucl.Phys. A670 92, (2000) ; H. Weigel and L. Gamberg Nucl.Phys.A 680, 48 (2000), H. Weigel, E. Ruiz Arriola, L. Gamberg, Nucl. Phys. B 560, 383 (1999).
[3] R.L. Jaffe, G.G. Ross, Phys. Lett. B93, 313 (1980).
[4] B.L. Ioffe, A. Khodjamirian, Phys.Rev.D51, 3373(1995).

“Future Transversity Measurements”

Brookhaven National Laboratory, Upton, NY

September 18 – 20, 2000

“Structure Functions and Chiral Odd Quark Distributions in the NJL Soliton Model of the Nucleon”

Leonard Gamberg

University of Oklahoma and University of Pennsylvania

- **Regularization of Quark Distribution Functions in the NJL Chiral Soliton Model**

  L. Gamberg and H. Weigel; In prep.

- **Hadron Structure Functions in a Chiral Quark Model: Regularization, Scaling and Sum Rules** ,

  H. Weigel, Nucl.Phys. **A670** 92, (2000) ; H. Weigel, E. Ruiz Arriola and L. Gamberg; Nucl.Phys. **B560**, 383 (1999).

- **Chiral Odd Structure Functions from a Chiral Soliton** ,

  L. Gamberg , H. Weigel and H. Reinhardt; Phys. Rev. D **58**, 05014 (1998)

- **Nucleon Structure from a Chiral Soliton in the Infinite Momentum Frame,**

  L. Gamberg , H. Weigel and H. Reinhardt; Int.J.Mod.Phys.**A13**, 5519 (1998)

- **Polarized Nucleon Structure Functions within a Chiral Soliton,**

  H. Weigel , L. Gamberg and H. Reinhardt; Phys. Rev. D **55**, 6910 (1997)

Model Structure Functions-“Factorization and OPE Inspired” (Jaffe, Ross; PLB93,313(80), Jaffe, Ji; PRD43,724(91))

- Inclusive and semi-inclusive processes understood and analyzed via QCD Factorization Theorem (Collins et al. (89), Sterman this Workshop).

- Generic cross-section or nucleon structure function written as convolution of hard-perturbative and soft non-perturbative

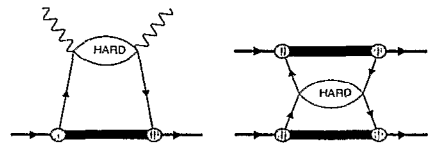


FIG. 2. DIS and cross section for Drell-Yan.

- At leading twist and lowest order in $\alpha_s(Q^2)$

* DIS: $l + p \Rightarrow l' + X$

$$F(x,Q^2) = \sum_a \int_x^1 \frac{dy}{y} H_a\left(\frac{x}{y}, \frac{Q^2}{\mu^2}, \alpha_s(\mu)\right) f_{a/P}(y,\mu^2) + \text{remainder}$$

* Drell Yan: $p + p' \Rightarrow l^+ l^- + X$

$$d\sigma_{a,b} \sim \int_{x_a}^1 \int_{x_b}^1 dy_a dy_b f_{a/P_a}(y_a,\mu^2) H_{ab}\left(\frac{x_a}{y_a}, \frac{x_b}{y_b}, Q^2, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right) \bar{f}_{b/P_b}(y_b,\mu^2)$$

+remainder

- In context of DIS:

  h) **Hard Part:** $H_a\left(\frac{x}{y}, \frac{Q^2}{\mu^2}, \alpha_s(\mu)\right)$ coefficient functions calculable in perturbative QCD.

  s) **Soft Part:** $f_{a/P}(y, \mu^2)$ quark distribution functions defined at a given factorization scale, μ^2 .

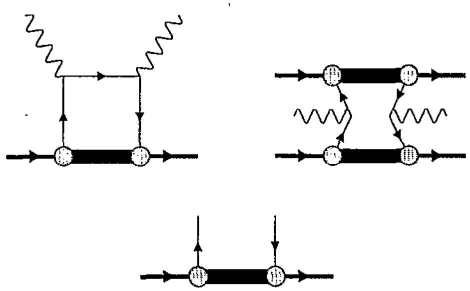


FIG. 3. DIS, Cross section for Drell-Yan, Forward Quark Target Amplitude or $f_{a/P}$.

- At leading twist basic objects of analysis, the forward quark-target scattering amplitude on the light cone (in light-cone gauge)

$$f_{a/P}(x) = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS \left| \bar{\psi}^a(0)\Gamma\psi^a(\lambda n) \right| PS \rangle$$

- Where $\Gamma = \{\mathbb{1}, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$

- **Alternatively**, in DIS factorization **hard** and **soft** express via Mellin transform "remainder" $\longrightarrow$ expansion in **twist**

$$\begin{aligned} \Gamma_n\left(Q^2\right) &= \int_0^1 dx\, x^{n-1}\, F_i\left(y, Q^2\right) \\ &= \sum_\tau C^n_{\tau,i}\left(Q^2/\mu^2, \alpha_s(\mu^2)\right) \mathcal{O}^n_{\tau,i}(\mu^2)\left(\frac{1}{Q^2}\right)^{\frac{\tau}{2}-1} . \qquad (1) \end{aligned}$$

  a) Coefficients, $C^n_{\tau,i}(Q^2/\mu^2, \alpha_s(\mu^2))$; Q^2 dependence from RGE.

  b) Matrix elements, $\mathcal{O}^n_{\tau,i}(\mu^2)$, reflect nonperturbative properties of nucleon.

- **Equivalently**, factorization can be derived from "Optical Theorem" applied to DIS in conjunction with the OPE:

  a) Relates analytic properties of Compton amplitude $T_{\mu\nu}(q)$ to hadronic tensor, $W_{\mu\nu} = \frac{1}{2\pi}\mathrm{Im}\ T_{\mu\nu}$.

  b) Expresses product of currents via OPE; expansion on the light cone ($\xi^2 \rightarrow 0$) $\longrightarrow$ Eq. (1) infinite set of moment sum rules.

- In all pictures factorization scale μ^2 separates hard and soft physics.

QCD-Parton Model vs. Low Energy Models

- QCD-Parton Model in conjunction with the factorization theorem:
  - *) Calculate and predict logarithmic Q^2 dependence of hard piece.
- Low Energy Model:
  - *) Lattice or model calculation to predict soft (measured) piece.
    1) Difficult to obtain nucleon bound state from first principles in QCD and calculate nucleon structure functions.
    2) Led many to calculate model hadron structure functions and effective quark distributions.
    3) Since 1980 gone beyond N.R. quark models to effective low energy quantum field theories of QCD.

STRATEGY

- From perspective that hadron structure can be viewed as functions of constituent quark distributions we adopt Nambu-Jona-Lasinio chiral soliton to calculate chiral even and odd at the scale, μ^2.
- In this context the factorization parameter μ^2 becomes the hadronic model parameter characterizing the intrinsic model scale.
- At model scale twist two structure functions don't look like the data since presumably it has contributions from higher twist.
- In practical terms to go from the hadronic scale to the experimental scale we first
  1) Sum the moments without radiative corrections; namely, calculate the structure functions in the Bjorken limit.
  2) Evolve structure functions and effective quark distributions via DGLAP scheme.

Introduction–Chiral Odd Structure Functions:

- Chiral odd spin–dependent structure functions $h_T(x)$ and $h_L(x)$ suppressed in DIS scattering process

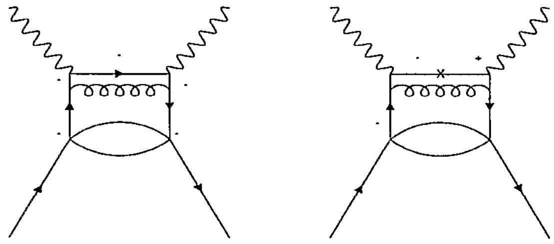


FIG. 4. Suppression of chiral odd distribution in DIS.

- $h_T(x)$ first studied by (Ralston and Soper[NPB152(79)]) in Drell Yan spin asymmetries, while $h_L(x)$ was more recently by Jaffe and Ji.
- Proposal to extract $h_T^q(x)$ ($\equiv \delta q^a(x)$) from Drell Yan dilepton production due to transversally polarized proton beams at RHIC.
- Proposal to measure $h_T^q(x)$ by (Jaffe, Jin, Tang [PRL80,(98)] and many others see conference proceedings....) by analysis of two meson fragmentation in transversally polarized DIS fixed target $eN \to e'\pi^+\pi^- X$ at HERMES(DESY) .

CONSTITUENT QUARKS

- Dealing with constituent quarks. Starting point cannot be the soft/hard factorization-parton model motivated definition of leading twist quark distribution function:

$$f_{a/P}(x) = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS \left| \overline{\psi}^a(0) \Gamma \psi^a(\lambda n) \right| PS \rangle$$

- Necessary to start from the absorptive part of the forward virtual Compton amplitude (Davidson, Arriola PLB(95), Weigel, Arriola, Gamberg NPB (98))

$$T^{\mu\nu}(q) = \int d^4\xi \, e^{iq\cdot\xi} \langle p, s | T \left(J^\mu(\xi) J^\nu(0) \right) | p, s \rangle$$

- Time-ordered product unambiguously from regularized action

$$T \left(J^\mu(\xi) J^\nu(0) \right) = \frac{\delta^2}{\delta v_\mu(\xi) \, \delta v_\nu(0)} \mathrm{Tr}_\Lambda \log \left[i\partial\!\!\!/ - (S + i\gamma_5 P) + Q \, v\!\!\!/ \right] \Big|_{v_\mu = 0}$$

- Extract the leading twist pieces of the structure functions in the Bjorken limit: $\Rightarrow q^- \to \infty \; q^+ \to xP^+$.
- Obtain self consistent definition of regularized quark-target amplitude or the leading twist constituent quark distribution functions.

NJL Chiral Quark-Soliton Model:

- Constructed from NJL Chiral Quark Model of quark flavor dynamics.

  a) Model low energy (non-pert.) gluonic modes via one gluon exchange w/0 kinetic energy term. $\Rightarrow$ "Fermi model of QCD".

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m_0)q + 2G_{\rm NJL}\sum_{i=0}^{3}\left((\bar{q}\frac{\lambda^i}{2}q)^2 + (\bar{q}\frac{\lambda^i}{2}i\gamma_5 q)^2\right).$$

  b) Interaction is dimension six operator. Non-renom. theory.

- $\longrightarrow [G] \sim [M^{-2}]$: Model supplemented with regularization Λ to cut off ultraviolet divergences.

- Hubbard-Stratonivch transformation *i.e.* introduce (generic) auxillary meson field, $\Phi \longrightarrow$ non-local mesonic action

$$Z_{NJL} = \int \mathcal{D}\Phi\, e^{-\frac{i}{2}\int \Phi Q^{-1}\Phi} \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\, e^{-i\int \bar{\psi}(i\partial\!\!\!/ - m_0 - \Phi)\psi}$$

$$\mathcal{A}[S,P] = -iN_c \mathrm{Tr}_\Lambda \log\left[i\partial\!\!\!/ - m_0 - (S + i\gamma_5 P)\right] - \frac{1}{4G_{\rm NJL}}\int d^4x\, \mathrm{tr}\left(\mathcal{M}^\dagger\mathcal{M}\right), \quad (2)$$

- $M = S + iP$, composite scalar (S), pseudoscalar (P) meson.

Regularization

- Define regularization at the level of the effective action.

- Guarantees quantities are regularized "self-consistently".

- Employ Pauli-Villars regularization scheme. Two subtractions necessary to regularize the logarithmic and quadratic divergences.

  (Weigel, Gamberg, Reinhardt PRD58(1998) and Wakamatsu, PRD60(00).)

- Preserves anomaly structure of QCD in the effective theory.

- In context of Structure function calculations

  a) Preserve scaling in Bjorken limit (Davidson, Ruiz-Arriola, PLB348(1995)).

  b) Possible to formulate bosonized NJL model completely in Minkowski space $\Rightarrow$ helpful in applying Cutkosky's rules to obtain the hadronic tensor from the forward Compton amplitude.

Details:

a) With the "PV" conditions:

$$c_0 = 1\,,\ \Lambda_0 = 0,\ \sum_{i=0}^{2} c_i = 0, \quad \text{and}$$

$$\sum_{i=0}^{2} c_i \Lambda_i^2 = 0 \tag{3}$$

b) Take limit $\Lambda_1 \longrightarrow \Lambda_2$, leads to identity

$$\sum_{i=0}^{2} c_i f\left(\Lambda_i^2\right) = f(0) - f\left(\Lambda^2\right) + \Lambda^2 f'\left(\Lambda^2\right) \tag{4}$$

- Couple "external" vector (axial) vector sources Fermion currents

$$i\mathbf{D} = i\partial\!\!\!/ - (S + i\gamma_5 P) + v\!\!\!/ + a\!\!\!/\gamma_5 \quad \text{and}$$

$$i\mathbf{D}_5 = -i\partial\!\!\!/ - (S - i\gamma_5 P) - v\!\!\!/ + a\!\!\!/\gamma_5$$

- Separate functional trace into (un–)regularized γ_5–even (odd)

$$\mathrm{Tr}_\Lambda \log\left[i\partial\!\!\!/ - (S + i\gamma_5 P) + \mathcal{Q}\,v\!\!\!/\right] =$$

$$-i\frac{N_C}{2}\sum_{i=0}^{2} c_i \mathrm{Tr}\log\left[-\mathbf{D}\mathbf{D}_5 + \Lambda_i^2 - i\epsilon\right]$$

$$-i\frac{N_C}{2}\mathrm{Tr}\log\left[-\mathbf{D}\left(\mathbf{D}_5\right)^{-1} - i\epsilon\right].$$

Model Parameters in Pauli-Villars Regularization Scheme (Dynamical Chiral Symmetry Breaking)

- Adjust the cut off Λ as value as well: to produce the physical meson properties $m_\pi = 135\,\mathrm{MeV}$ and $f_\pi = 93\,\mathrm{MeV}$ and $m_K = 494\,\mathrm{MeV}$
- This leaves one free parameter, the constituent quark mass, M_u.
- Cutoff dependence in the $SU(2)$ sector in isospin limit:

$m\,[MeV]$	$\Lambda\,[MeV]$	G_{NJL}	$m^0\,[MeV]$	$-\langle\bar\psi\psi\rangle^{1/3}\,[MeV]$
350	766	8.41	3.85	≈ 215
400	739	8.85	1.87	≈ 211
450	728	9.01	1.02	≈ 209

- **Conditions**

1) Gap Equation, $\frac{\delta \mathcal{A}_{NJL}}{\delta M} = 0 \Rightarrow \frac{1}{2G} = \frac{\langle\bar q q\rangle}{M - m_0}$

$\langle\bar q q\rangle = \lim_{x\to x'} G(x, x') = -4iN_C M \sum_{i=0}^{2} c_i \int \frac{d^4k}{(2\pi)^4}\left[-k^2 + M^2 + \Lambda_i^2 - i\epsilon\right]^{-1}.$

2) Mass-shell condition from Bethe Salpeter Equation,

$\mathcal{A}_{NJL} = \frac{1}{2}\int \frac{d^4q}{(2\pi)^4}\vec\pi(q)\cdot D^{-1}(q^2)\vec\pi(-q) + \mathcal{O}\left(\vec\pi^4\right),\ D^{-1}(q^2) = g^2\left[2N_C q^2 \Pi(q^2) - \frac{1}{2G}\frac{m_0}{m}\right]$

$\Pi(q^2) = -i\sum_{i=0}^{2} c_i \int_0^1 dx \frac{d^4k}{(2\pi)^4}\left[-k^2 - x(1-x)q^2 + m^2 + \Lambda_i^2 - i\epsilon\right]^{-2}$

3) Pion decay constant from PCAC, $\langle\pi(p)|A_\mu(x)|0\rangle = f_\pi p_\mu e^{-ipx}$, $\quad f_\pi = 4N_c M g \Pi\left(m_\pi^2\right)$

The NJL Model Chiral Soliton:

- Non–perturbative meson configuration of hedgehog type

$$\mathcal{M}_{\mathrm{H}}(\boldsymbol{x}) = m \exp\left(i\boldsymbol{\tau}\cdot\hat{\boldsymbol{r}}\Theta(r)\right), \quad U_{\gamma_5} = e^{i\gamma_5\boldsymbol{\tau}\cdot\hat{\boldsymbol{r}}\Theta}.$$

- Functional trace for static configuration

$$\mathcal{A} = \mathrm{Tr}_\Lambda \log(i\partial\!\!\!/ - U_{\gamma_5}) - \frac{1}{4G_{\mathrm{NJL}}}\int d^4x \,\mathrm{tr}\left(U - m^0\right)^\dagger\left(U - m^0\right),$$

- Dirac operator in terms of Hamiltonian, $h = \boldsymbol{\alpha}\cdot\boldsymbol{p} + m\beta U^{\gamma_5}$

- Hedgehog ansatz for $\boldsymbol{r}\Theta(\boldsymbol{r})$ implies that $\longrightarrow$ grandspin

  $\mathbf{G} = \mathbf{t} + \mathbf{j}$ good quantum number: $[h, \mathbf{G}] = 0$

- Eigenvalues and eigen-functions of $h|\psi_\mu\rangle = \epsilon_\mu|\psi_\mu\rangle$ for profile $\Theta(\mathbf{r})$.

- In Pauli Villars scheme, energy functional

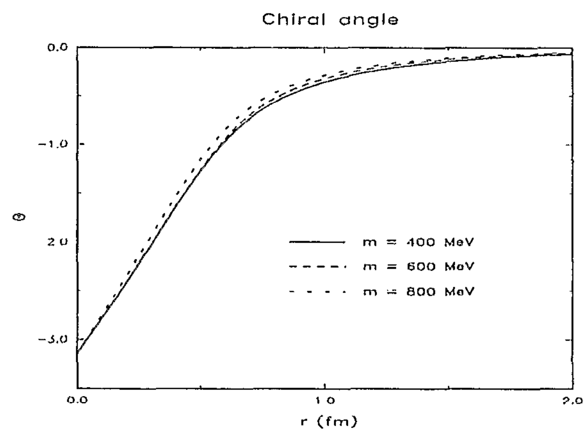
$$E_{\mathrm{tot}}[\Theta] = \frac{N_C}{2}\left(1 - \mathrm{sign}(\epsilon_{\mathrm{val}})\right)\epsilon_{\mathrm{val}} - \frac{N_C}{2}\sum_{i=0}^{2} c_i \sum_{\alpha}\left\{\sqrt{\epsilon_\alpha^2 + \Lambda_i^2} - \sqrt{\epsilon_\alpha^{(0)2} + \Lambda_i^2}\right\}$$
$$+ m_\pi^2 f_\pi^2 \int d^3r \left(1 - \cos(\Theta)\right).$$

"*val*" denotes valence quark level. Distinct level bound in soliton background, *i.e.* $-m < \epsilon_{\mathrm{V}} < m$.

- **Self Consistent Solution**: $\Theta(r)$, is obtained by extremizing $\frac{\delta E[\Theta]}{\delta\Theta} = 0$ while simultaneously determining $\{\psi_\mu(x), \epsilon_\mu\}$ with B.C.

BC) $\mathbf{r} = \mathbf{0}$, $\Theta(0) = -\pi$, $\mathbf{r} = \infty$, $\Theta(0) = 0$.

- The baryonic charge encoded in topological property of the soliton. Distorted meson field and Dirac spectra. Bound quark states appear which carrying baryonic charge of soliton as nucleon (see Alkofer et al. Phys.Rep265(96) and Bochum Reviews).



Nucleon From Chiral Soliton:

- Promote rotation zero modes to time dependent fluctuations about the hedgehog field; $\longrightarrow$ cranking technique in nuclear physics.

$$M(\boldsymbol{x},t) = A(t) M_{\rm H}(\boldsymbol{x}) A^{\dagger}(t) \ ,$$

Collective coordinates $A(t) \in SU(2)$.

- Generates states of good spin and isospin.

- Eigenfunctions of resulting Hamiltonian are Wigner D–functions

$$\langle A|N\rangle = \frac{1}{2\pi} D^{1/2}_{I_3,-J_3}(A) \ ,$$

I_3 and J_3 projection isospin and spin quantum numbers of nucleon.

- Put *ansatz* (5) into the action functional (??) expand in the angular velocities

$$2A^{\dagger}(t)\dot{A}(t) = i\boldsymbol{\tau}\cdot\boldsymbol{\Omega}$$

to quadratic order, $\longrightarrow$ Lagrange function for the collective coordinates.

- Canonical quantization: angular velocity $\boldsymbol{\Omega}$ substituted by nucleon spin operator $\boldsymbol{J} = \alpha^2\boldsymbol{\Omega}$, α^2 moment of inertia.

NJL Model Nucleon Structure Functions

- Define the hadronic tensor for localized field configurations. Demands the restoration of translational invariance.

- Introduce collective coordinate, $\vec{R}$, position of soliton (nucleon) with its momentum, $\vec{p}$ being conjugate to collective coordinate, *i.e.* $\langle \vec{R}|\vec{p}\rangle = \sqrt{2E}\exp\left(i\vec{R}\cdot\vec{p}\right)$.

- $E = \sqrt{\vec{p}^{\,2} + M_N^2}$ denotes the nucleon energy.

- Compton amplitude obtained by averaging over the position of the soliton,

$$\begin{aligned} T^{ab}_{\mu\nu} &= 2iM_N \int d^4\xi \int d^3R\, e^{iq\cdot\xi} \langle p,s|T\left\{J^a_\mu(\xi-R)J^{b\dagger}_\nu(-R)\right\}|p,s\rangle \\ &= 2iM_N \int d^4\xi_1 \int d^3\xi_2\, e^{iq\cdot(\xi_1-\xi_2)} \langle s|T\left\{J^a_\mu(\xi_1)J^{b\dagger}_\nu(\xi_2)\right\}|s\rangle \ . \end{aligned}$$

- The spin–flavor matrix elements evaluated in space of collective coordinates A.

Compton Amplitude in Bjorken Limit

- To obtain the Compton amplitude consider the real

$$\mathcal{A}^{(2,v)}_{\Lambda,\mathrm{R}} = -i\frac{N_C}{4}\sum_{i=0}^{2} c_i \mathrm{Tr}\left\{\left(-\mathbf{D}^{(\pi)}\mathbf{D}^{(\pi)}_5 + \Lambda_i^2\right)^{-1}\left[\mathcal{Q}^2 \not{v}\,(\not{\partial})^{-1}\not{v}\mathbf{D}^{(\pi)}_5 - \mathbf{D}^{(\pi)}(\not{v}\,(\not{\partial})^{-1}\not{v})_5\mathcal{Q}^2\right]\right\}$$

and imaginary

$$\mathcal{A}^{(2,v)}_{\Lambda,\mathrm{I}} = -i\frac{N_C}{4}\mathrm{Tr}\left\{\left(-\mathbf{D}^{(\pi)}\mathbf{D}^{(\pi)}_5\right)^{-1}\left[\mathcal{Q}^2 \not{v}\,(\not{\partial})^{-1}\not{v}\mathbf{D}^{(\pi)}_5 + \mathbf{D}^{(\pi)}(\not{v}\,(\not{\partial})^{-1}\not{v})_5\mathcal{Q}^2\right]\right\}.labelsimple7$$

action expanded to second order in external vector source $\not{v}$

$$T\left(J^{\mu}(\xi)J^{\nu}(0)\right) = \frac{\delta^2}{\delta v_\mu(\xi)\,\delta v_\nu(0)}\left(\mathcal{A}^{(2,v)}_{\Lambda,\mathrm{R}} + \mathcal{A}^{(2,v)}_{\Lambda,\mathrm{I}}\right)$$

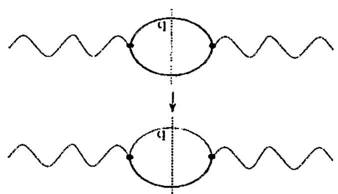


FIG. 5. Taking the Bjorken limit.

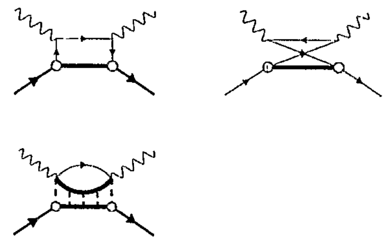


FIG. 6. The Valence and polarized-sea contributions to chiral soliton structure Functions.

- Leading order in $1/N_C$ piece,

$$T_{\mu\nu}(q) = -M_N\frac{N_C}{2}\int\frac{d\omega}{2\pi}\sum_\alpha\int dt\int d^3\xi_1\int d^3\xi_2\int\frac{d^4k}{(2\pi)^4}e^{i(q_0+k_0)t}e^{-i(\vec{q}+\vec{k})\cdot(\vec{\xi}_1-\vec{\xi}_2)}\frac{1}{k^2+i\epsilon}$$
$$\times\Big\langle N\Big|\Big\{\left[e^{i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_1)\beta\mathcal{Q}^2_A\gamma_\mu\not{k}\gamma_\nu\Psi_\alpha(\vec{\xi}_2) - e^{-i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_2)\beta\mathcal{Q}^2_A\gamma_\nu\not{k}\gamma_\mu\Psi_\alpha(\vec{\xi}_1)\right]f^+_\alpha(\omega)$$
$$+\left[e^{i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_1)\mathcal{Q}^2_A(\gamma_\mu\not{k}\gamma_\nu)_5\beta\Psi_\alpha(\vec{\xi}_2) - e^{-i\omega t}\Psi^\dagger_\alpha(\vec{\xi}_2)\mathcal{Q}^2_A(\gamma_\nu\not{k}\gamma_\mu)_5\beta\Psi_\alpha(\vec{\xi}_1)\right]f^-_\alpha(\omega)\Big\}\Big|N\Big\rangle.$$

- With spectral functions $f^{\pm}_\alpha(\omega) = \sum_{i=0}^{2} c_i\frac{\omega\pm\epsilon_\alpha}{\omega^2-\epsilon_\alpha^2-\Lambda_i^2+i\epsilon} \pm \frac{\omega\pm\epsilon_\alpha}{\omega^2-\epsilon_\alpha^2+i\epsilon}$
- Applying Cutkosky's rules yields hadronic tensor ($1/N_c$ corrections)

$$W_{\mu\nu}\xrightarrow{\mathrm{Bj}} -iM_N\frac{N_C}{4}\int\frac{d\omega}{2\pi}\sum_\alpha\int d^3\xi\int\frac{d\lambda}{2\pi}e^{iM_N x\lambda}\Big\langle N\Big|$$
$$\Big\{\left[\bar{\Psi}_\alpha(\vec{\xi})\mathcal{Q}^2_A\gamma_\mu\not{n}\gamma_\nu\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{-i\lambda\omega} - \bar{\Psi}_\alpha(\vec{\xi})\mathcal{Q}^2_A\gamma_\nu\not{n}\gamma_\mu\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{i\lambda\omega}\right]f^+_\alpha(\omega)\Big|_{\mathrm{p}}$$
$$+\left[\bar{\Psi}_\alpha(\vec{\xi})\mathcal{Q}^2_A(\gamma_\mu\not{n}\gamma_\nu)_5\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{-i\lambda\omega} - \bar{\Psi}_\alpha(\vec{\xi})\mathcal{Q}^2_A(\gamma_\nu\not{n}\gamma_\mu)_5\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{i\lambda\omega}\right]f^-_\alpha(\omega)\Big|_{\mathrm{p}}$$
$$+\frac{i\lambda}{4}\left[\bar{\Psi}_\alpha(\vec{\xi})\vec{\tau}\cdot\vec{\Omega}\mathcal{Q}^2_A\gamma_\mu\not{n}\gamma_\nu\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{-i\lambda\omega} + \bar{\Psi}_\alpha(\vec{\xi})\mathcal{Q}^2_A\vec{\tau}\cdot\vec{\Omega}\gamma_\nu\not{n}\gamma_\mu\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{i\lambda\omega}\right]f^+_\alpha(\omega)\Big|_{\mathrm{p}}$$
$$+\frac{i\lambda}{4}\left[\bar{\Psi}_\alpha(\vec{\xi})\vec{\tau}\cdot\vec{\Omega}\mathcal{Q}^2_A(\gamma_\mu\not{n}\gamma_\nu)_5\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{-i\lambda\omega} + \bar{\Psi}_\alpha(\vec{\xi})\mathcal{Q}^2_A\vec{\tau}\cdot\vec{\Omega}(\gamma_\nu\not{n}\gamma_\mu)_5\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{i\lambda\omega}\right]f^-_\alpha(\omega)\Big|_{\mathrm{p}}$$
$$+\sum_\beta\langle\alpha|\vec{\tau}\cdot\vec{\Omega}|\beta\rangle\Big(\left[\bar{\Psi}_\beta(\vec{\xi})\mathcal{Q}^2_A\gamma_\mu\not{n}\gamma_\nu\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{-i\lambda\omega} - \bar{\Psi}_\beta(\vec{\xi})\mathcal{Q}^2_A\gamma_\nu\not{n}\gamma_\mu\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{i\lambda\omega}\right]g^+_{\alpha\beta}(\omega)\Big|_{\mathrm{p}}$$
$$+\left[\bar{\Psi}_\beta(\vec{\xi})\mathcal{Q}^2_A(\gamma_\mu\not{n}\gamma_\nu)_5\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{-i\lambda\omega} - \bar{\Psi}_\beta(\vec{\xi})\mathcal{Q}^2_A(\gamma_\nu\not{n}\gamma_\mu)_5\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{i\lambda\omega}\right]g^-_{\alpha\beta}(\omega)\Big|_{\mathrm{p}}\Big)\Big\}\Big|N\Big\rangle.$$

- Next step, hadronic tensor is contracted with appropriate projectors which in turn provides the structure functions. In the Bjorken limit these projectors become quite simple

f_1	f_2	g_1	$g_T = g_1 + g_2$
$-\frac{1}{2}g^{\mu\nu}$	$-xg^{\mu\nu}$	$\frac{i}{2M_N}\epsilon^{\mu\nu\rho\sigma}\frac{q_\rho p_\sigma}{q\cdot s}$	$\frac{-i}{2M_N}\epsilon^{\mu\nu\rho\sigma}s_\rho p_\sigma$
spin independent	spin independent	$\vec{s}\parallel\vec{q}$	$\vec{s}\perp\vec{q}$

- Unpolarized structure function: In Bjorken limit the Callan–Gross relation, $f_2(x) = 2xf_1(x)$, is automatically fulfilled.
- Using the relevant projection operator given in table I we find the "sea" contribution for the longitudinal polarized structure function

$$
\begin{aligned}
g_1(x) = & -i\frac{M_N[\Theta]N_C}{36}\int\frac{d\omega}{2\pi}\sum_\alpha\int d^3\xi\int\frac{d\lambda}{2\pi}e^{iM_N[\Theta]x\lambda} \\
& \times\Bigg\{\left(\sum_{i=0}^{2}c_i\frac{\omega+\epsilon_\alpha}{\omega^2-\epsilon_\alpha^2-\Lambda_i^2+i\epsilon}\right)_{\rm p}\langle N|I_3|N\rangle \\
& \times\left[\Psi_\alpha^\dagger(\vec{\xi})\tau_3(1-\alpha_3)\gamma_5\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{-i\omega\lambda}+\Psi_\alpha^\dagger(\vec{\xi})\tau_3(1-\alpha_3)\gamma_5\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{i\omega\lambda}\right] \\
& -\frac{30}{\alpha^2[\Theta]}\left[\frac{i\lambda}{4}\left(\frac{\omega+\epsilon_\alpha}{\omega^2-\epsilon_\alpha^2+i\epsilon}\right)_{\rm p}\right. \\
& \times\left[\Psi_\alpha^\dagger(\vec{\xi})\tau_3(1-\alpha_3)\gamma_5\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{-i\omega\lambda}-\Psi_\alpha^\dagger(\vec{\xi})\tau_3(1-\alpha_3)\gamma_5\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{i\omega\lambda}\right] \\
& +\sum_\beta\left(\frac{(\omega+\epsilon_\alpha)(\omega+\epsilon_\beta)}{(\omega^2-\epsilon_\alpha^2+i\epsilon)(\omega^2-\epsilon_\beta^2+i\epsilon)}\right)_{\rm p}\langle\alpha|\tau_3|\beta\rangle \\
& \times\left.\left[\Psi_\beta^\dagger(\vec{\xi})(1-\alpha_3)\gamma_5\Psi_\alpha(\vec{\xi}+\lambda\hat{e}_3)e^{-i\omega\lambda}+\Psi_\beta^\dagger(\vec{\xi})(1-\alpha_3)\gamma_5\Psi_\alpha(\vec{\xi}-\lambda\hat{e}_3)e^{i\omega\lambda}\right]\right\}.
\end{aligned}
$$

Valence Quark Approximation:

- Expectation values of bilocal quark-bilinears appearing in the evaluation of nucleon structure functions expressed as (regularized) sums over bilocal and bilinear combinations of all eigenfunctions Ψ_μ including the Dirac sea states.
- Dominant contributions ($\geq 80\%$) to static nucleon properties (moments of structure functions) stems from the distinct valence level.
- Approximate bilinears by their valence quark contribution.
- Wave-function, induced by the collective rotation $A(t)$, included

$$
\begin{aligned}
\Psi_{\rm v}(x,t) &= e^{-i\epsilon_{\rm v}t}A(t)\left\{\Psi_{\rm v}(x)+\frac{1}{2}\sum_{\mu\neq{\rm v}}\Psi_\mu(x)\frac{\langle\mu|\tau\cdot\Omega|{\rm v}\rangle}{\epsilon_{\rm v}-\epsilon_\mu}\right\} \\
&=: e^{-i\epsilon_{\rm v}t}A(t)\psi_{\rm v}(x).
\end{aligned}
$$

- This replacement of bilocal and bilinear quark fields when computing nucleon structure functions defines valence approximation.

Regularization Function for Chiral Odds

- Self consistently arriving at the correct regularization function structure functions we work from the forward scattering matrix element between transversally polarized nucleons containing a vector and pseudo-scalar current (Ioffe, Khodjamirian PRD51(95))

$$T_\mu = \frac{i}{2}\int d^4x e^{iqx}\langle p, \mathcal{S}_\perp | T\left(j_\mu(x) j_5(0) + j_5(y) j_\mu(0)\right)| p, \mathcal{S}_\perp\rangle \quad (5)$$

- Applying Cutkosky's rules and going to the Bjorken limit on the light cone in the parton model yields,

$$\begin{aligned} Im\, T_\mu &= -\frac{i}{4}\int \frac{d\lambda}{2\pi} e^{i\lambda x}\langle p, \mathcal{S}_\perp |\overline{\psi}(0) i\sigma_{\mu\nu} n^\nu \gamma_5 \psi(\lambda n)| p, \mathcal{S}_\perp\rangle \\ &= h_T \mathcal{S}_{\mu\perp}(x, Q^2) - h_L(x, Q^2) m^2 n_\mu(\mathcal{S}\cdot n) \end{aligned} \quad (6)$$

- Adapting above mentioned technique of calculation

$$T\left(j_\mu(\xi) j_5(0)\right) = \frac{\delta^2}{\delta v_\mu(\xi)\,\delta v_5(0)}\left(\mathcal{A}^{(2,n)}_{\Lambda,\mathrm{R}} + \mathcal{A}^{(2,n)}_{\Lambda,\mathrm{I}}\right) \quad (7)$$

we get regularized distributions (Gamberg, Weigel, in preparation).

OPE-ANALYSIS

- Reveals leading order in $1/Q^2$ transverse chiral even and odd structure function $g_1(x, Q^2)$ and $h_T(x, Q^2)$ purely twist–2, while $g_2(x, Q^2)$ and $h_L(x, Q^2)$ contain twist–2 and –3 contributions spin–dependent gluonic–quark correlations.

$$\lim_{Q^2\to\infty}\int_0^1 dx\, x^n g_1(x, Q^2) = \frac{1}{2}\sum_i \mathcal{O}^n_{2,i} \quad , \quad n = 0, 2, 4, \ldots ,$$

$$\lim_{Q^2\to\infty}\int_0^1 dx\, x^n\, g_2(x, Q^2) = -\frac{n}{2\,(n+1)}\sum_i\left\{\mathcal{O}^n_{2,i} - \mathcal{O}^n_{3,i}\right\}, \; n = 2, 4, \ldots .$$

- Inverse Mellin transform yields

$$g_2(x, Q^2) = -\, g_1(x, Q^2) + \int_x^1 \frac{dy}{y}\, g_1(y, Q^2) + \overline{g}_2(x, Q^2) \quad (10)$$

- One may reformulate this argument to extract the twist–3 piece

$$\overline{g}_2(x, Q^2) \; := \; g_2(x, Q^2) \; - \; g_2^{WW}(x, Q^2)\;, \quad (11)$$

- Similarly for the chiral odds:

$$h_L = 2x\int_x^1 dy \frac{h_T(y, Q^2)}{y^2} + \overline{h}_L(x, Q^2)\;, \quad (12)$$

$$\overline{h}_L(x, Q^2) = h_L(x, Q^2) - h_L^{(2)}(x, Q^2) \quad (13)$$

Valence Contribution to Chiral Odd Structure Functions:

- The nucleon rest–frame (RF) analysis given by Eq. (7) yeilds valence contribution the chiral odds

$$
\begin{aligned}
h_T^{(+)}(x) &= N_C \frac{2M\sqrt{2}}{8\pi} \int d\xi^- \exp(-i\xi^- \frac{Mx}{\sqrt{2}}) \\
&\times \int d^3\boldsymbol{x}_0 \langle \mathcal{S}_\perp | \Psi_+^\dagger(\xi - \boldsymbol{x}_0)\gamma_\perp\gamma_5 \mathcal{Q}^2 \Psi_+(-\boldsymbol{x}_0) | \mathcal{S}_\perp \rangle_{\xi^+ = \xi_\perp = 0} \,. \qquad (14)
\end{aligned}
$$

- Introduce Fourier transforms quark wave functions

$$
\psi\Big(\xi_\perp, \xi_3 = -\frac{\xi^-}{\sqrt{2}}\Big) = \int \frac{d^2p_\perp dp_3}{2\pi^2} \exp\Big[i(\frac{p_3\xi^-}{\sqrt{2}} - \mathbf{p}_\perp \cdot \xi_\perp)\Big] \tilde{\psi}\,(\mathbf{p}_\perp, \mathbf{p}_3) \quad (15)
$$

- Forward/backward moving quark contributions to the transverse and longitudinal chiral odd nucleon structure functions

$$
\begin{aligned}
h_T^{(\pm)}(x) &= \pm N_C \frac{M}{\pi} \int_{p_{\min}^{\mp}}^{\infty} p dp \, d\phi \langle \mathcal{S}_\perp | \tilde{\psi}^\dagger(\boldsymbol{p}_\mp) \\
&\times (1 \mp \alpha_3)\,\gamma_\perp\gamma_5 \mathcal{Q}^2 \tilde{\psi}(\boldsymbol{p}_\mp) | \mathcal{S}_\perp \rangle \; \Big|_{\cos\theta = \frac{(Mx\mp\epsilon)}{p}} \qquad (16)
\end{aligned}
$$

$$
h_L^{(\pm)}(x) = \pm N_C \frac{M}{\pi} \int_{p_{\min}^{\mp}}^{\infty} p dp \, d\phi \langle \mathcal{S}_z | \tilde{\psi}^\dagger(\boldsymbol{p}_\mp) \alpha_3\gamma_0\gamma_5 \mathcal{Q}^2 \tilde{\psi}(\boldsymbol{p}_\mp) | \mathcal{S}_z \rangle \; \Big|_{\cos\theta = \frac{(Mx\mp\epsilon)}{p}} \quad (17)
$$

Evolution and the Infinite Momentum Frame (IMF):

- **Evolution:** Model approximates QCD at a low scale Q_0^2. Evolve to a (larger) Q^2 commensurate with experiment.

- **Support:** Proper support necessary to apply DGLAP evolution.

  1) In Soliton approach baryon states built from localized field configurations. States do not carry good four–momentum: $\longrightarrow$ calculated structure functions do not vanish exactly for $x > 1$ although contributions in $x > 1$ very small.

  2) Boosting to the IMF, common problem of improper support *i.e.* non–vanishing structure functions for $x > 1$, is cured along lines suggested by Jaffe [Ann.Phys.132(81)]

  4) For the quark soliton model, transformation corresponds to boost in the space of the collective coordinate $\boldsymbol{x}_0$

  (Gamberg, Weigel, Reinhardt IJMPA13(98)).

- IMF characterized by the limit $\Omega \longrightarrow \infty$. Transformation matrix for Dirac spinors becomes

$$S(\Lambda) = \sqrt{\frac{p^0+m}{2m}}1 + \sqrt{\frac{p^0-m}{2m}}\alpha_3$$
$$\stackrel{\text{IMF}}{\longrightarrow} S(\Lambda_\Omega) + \mathcal{O}\left(\frac{m}{p^+}\right) \quad \text{with} \quad S(\Lambda_\Omega) = \frac{1}{2}\exp\left(\frac{\Omega}{2}\right)(1+\alpha_3) \ , \qquad (18)$$

- Quark spinors, boosted to IMF

$$\Psi(\xi) \longrightarrow S(\Lambda)\Psi\left(\Lambda^{-1}(\xi - x_0)\right)$$
$$\stackrel{\text{IMF}}{\longrightarrow} \frac{1}{2}(1+\alpha_3)\,\Psi\left(e^{\Omega}(\xi^- - x_0^-), \boldsymbol{x}_\perp - \boldsymbol{\xi}_{0\perp}, \xi^+ = 0\right)\exp\left(\frac{\Omega}{2}\right) \ . \qquad (19)$$

- Leading twist structure functions within the NJL–chiral soliton model become

$$h_T^{(\pm)}(x) = \pm\frac{N_c M}{\pi(1-x)}\int_{p_{\min}}^{\infty} p dp d\varphi$$
$$\times\langle N|\tilde{\psi}^\dagger(\boldsymbol{p}_\mp)\,(1\mp\alpha_3)\,\gamma_\perp\gamma_5 Q^2\tilde{\psi}(\boldsymbol{p}_\mp)|N\rangle\Big|_{\cos\theta=-\frac{M\ln(1-x)\pm\epsilon_V}{p}} \ .$$

- Generally, relation between structure functions in IMF and the RF

$$f_{\text{IMF}}(x) = \frac{\Theta(1-x)}{1-x}f_{\text{RF}}(-\ln(1-x)) \ . \qquad (20)$$

- Lorentz contraction associated with boost to IMF maps infinite line to $x \in [0, 1[$.

Evolution:

- Transverse component $h_T(x, Q^2)$ is pure twist–2.

- Longitudinal piece $h_L(x, Q^2)$; extract the twist–2 component through $h_T(x, Q^2)$ namely, $h_L^{(2)}(x, Q^2) = 2x\int_x^1 dy\, h_T(y, Q^2)/y^2$.

- Twist–2; we restrict ourselves to leading order in α_s because for the twist–3 piece of h_L, the necessary ingredients are not known in next–to–leading order.

- Leading order the Twist–2 structure functions, g_1, g_2^{WW}, h_T and $h_L^{(2)}$: in the evolution differential equation

$$f(x, t+\delta t) = f(x,t) \ + \ \delta t\frac{df(x,t)}{dt} \ , \qquad (21)$$

characterized by the convolution integral,

$$\frac{dq(x,t)}{dt} = \frac{\alpha(t)}{2\pi}[q(x,t)\otimes P_{qq} + g(x,t)\otimes P_{qg}]$$
$$\frac{dg(x,t)}{dt} = \frac{\alpha(t)}{2\pi}[q(x,t)\otimes P_{gq} + g(x,t)\otimes P_{gg}] \qquad (22)$$

Splitting functions for chiral even and odd respectively,

$$
\begin{aligned}
P_{qq}^{even}(z) &= C_R(f)\left(\frac{1+z^2}{1-z^2}\right)_+ \\
P_{qq}^{odd}(z) &= \frac{4}{3}\left[\frac{2}{(1-z)_+} - 2 + \frac{3}{2}\,\delta(z-1)\right] \\
P_{gq}(z) &= C_R(f)[\frac{1+(1-z)^2}{z}] \\
&\text{etc...}
\end{aligned}
\tag{23}
$$

- $C_R(f) = \frac{n_f^2-1}{2n_f}$ for n_f–flavors
- $\alpha_{QCD} = \frac{4\pi}{\beta \log(Q^2/\Lambda^2)}$ and $\beta = (11 - \frac{2}{3}n_f)$
- Employing the "+" prescription yields

$$
\frac{dh^{(2)}(x,t)}{dt} = \frac{\alpha_{QCD}(t)}{2\pi}\Big\{ \left(2 + \frac{8}{3}\log(1-x)\right) h^{(2)}(x,t)
+ \frac{8}{3}\int_x^1 \frac{dy}{y}\left[\frac{1}{1-y}\left(h^{(2)}(\frac{x}{y},t) - yh^{(2)}(x,t)\right) - h^{(2)}(\frac{x}{y},t)\right]\Big\} .
$$

299

Twist Three Piece:

- The admixture of independent quark and quark–gluon operators contributing to the twist–3 portion $\overline{h}_L(x,Q^2)$ grows with n where n refers to the n^{th} moment, $\mathcal{M}_n\left[\overline{h}_L(Q^2)\right]$ of $h_L(x,Q^2)$ [Balitsky et al. PRL 77(96)].
- Leading order evolution only known in the large N_C limit. However such an approach seems particularly suited for soliton models which utilize large N_C arguments.
- Evolution kernel can be constructed that "propagates" the the twist–3 part $\overline{h}(x,Q^2)$ in momentum

$$
\overline{h}_L(x,Q^2) = \int_x^1 \frac{dy}{y} b(x,y;Q^2,Q_0^2)\overline{h}_L(y,Q_0^2) \ . \tag{24}
$$

- $b(x,y;Q^2,Q_0^2)$, obtained by inverting the Q^2 dependence of $\mathcal{M}_n$,

$$
b(x,y;Q^2,Q_0^2) = a(L)\left(\frac{x}{y}\right)^{\rho-1} \sum_{i=0} \left(\ln\frac{y}{x}\right)^{i+\rho-1} \frac{\mathcal{C}_i(L)}{\Gamma(i+\rho)} \tag{25}
$$

Results: Sum Rules

- In order to verify the sum rule for g_A the expression

$$g_A = \frac{N_C}{6}\langle N|2I_3|N\rangle \sum_{i=0}^{2} c_i \sum_\alpha \frac{\epsilon_\alpha}{\sqrt{\epsilon_\alpha^2+\Lambda_i^2}}\langle\alpha|\tau_3\alpha_3\gamma_5|\alpha\rangle\,. \tag{26}$$

has to be compared with the integral $\int_0^\infty dx g_1(x)$.

- We are able to demonstrate Bjorken sum rule

$$\int_0^\infty dx\,(g_1^p(x) - g_1^n(x)) = \frac{1}{6}g_A \tag{27}$$

after taking care of the isospin matrix elements of the nucleon.

- Using rotational invariance in grand–spin space verifies the Burkhardt–Cottingham(70) sum rule $\int_0^\infty dx\, g_2(x) = 0$.

- SLAC-E155x experiment (P. Bosted HiX2000 Proceedings for E155x) measuring the polarized spin structure function $g_2(x, Q^2)$ has compared the data with our model sum rule, $d_2(Q^2) = 3\int dx x^2 \bar{g}_2(x, Q^2)$

	Q_0^2	Q^2	SLAC-E155
$d_2^{(p)}$	0.0074	0.00374	.007 ± .004
$d_2^{(n)}$	0.0039	−0.0019	.004 ± .010

TABLE I. The Q^2 evolution for $d_2(Q^2) = 3\int dx x^2 \bar{g}_2(x, Q^2)$

- In connection with chiral–odd's we calculate the isoscalar and isovector nucleon tensor charges, at low scale, $Q_0^2 = 0.4\text{GeV}^2$ and scale commensurate with experiment, $Q^2 = 4\text{GeV}^2$.

$$\Gamma_T^S(Q^2) = \frac{18}{5}\int_0^1 dx\ \left[h_T^p\left(x,Q^2\right) + h_T^n\left(x,Q^2\right)\right] \tag{28}$$

$$\Gamma_T^V(Q^2) = 6\int_0^1 dx\ \left[h_T^p\left(x,Q^2\right) - h_T^n\left(x,Q^2\right)\right] \tag{29}$$

m (MeV)	350	400	450	Lat.	SR	CQ	QS	Q^2	CM
$\Gamma_T^S(Q_0^2)$	0.80 (0.82)	0.72 (0.76)	0.67 (0.72)	0.61	0.61	1.31	0.69	0.16	0.90
$\Gamma_T^S(Q^2)$	0.73	0.65	0.61	no scale attributed				25.0	0.72
$\Gamma_T^V(Q_0^2)$	0.88 (0.89)	0.86 (0.87)	0.86 (0.85)	1.07	1.37	1.07	1.45	0.16	1.53
$\Gamma_T^V(Q^2)$	0.80	0.78	0.77	no scale attributed				25.0	1.22

TABLE II. Nucleon tensor charges calculated from as a function of constituent quark mass m in the NJL chiral soliton model. Momentum scales are $Q_0^2 = 0.4\text{GeV}^2$ and $Q^2 = 4.0\text{GeV}^2$. Numbers in parenthesis in respective upper rows include the negligible contribution from the polarized quark vacuum. Compared with results from the Lattice [Aoki et al, PRD56,433(97)] QCD sum rules [He et al. PRD52,2960(95)], the constituent quark model with Goldstone boson effects [Suzuki, NPA626,886(97)] and quark soliton model calculation [Kim et al PRD53,R4715(96)] including multiplicative $1/N_C$ corrections violating PCAC in the similar case of the axial vector current [Alkofer, Weigel PLB319,1(93)], confinement model [Barone PLB390,287(97)] with the associated momentum scales (in GeV^2) are shown.

Polarized Nucleon Structure Functions and E143 Data

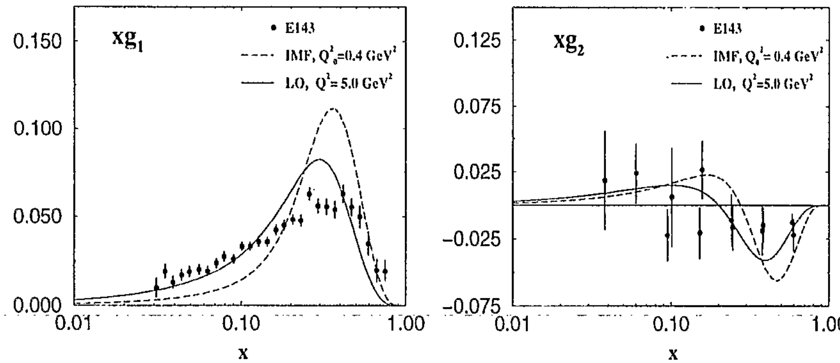


FIG. 7. Model predictions for the polarized proton structure functions xg_1 (left panel) and xg_2 (right panel). The curves labeled 'RF' denote the results as obtained from the valence quark contribution. These undergo a projection to the infinite momentum frame 'IMF' Gamberg(98) and a leading order 'LO' DGLAP evolution . Data are from SLAC E143 Abe et al.(98).

- Having completed the calculation of the leading twist chiral even/odd structure functions we test the Soffer inequality

$$f_1^q(x) + g_1^q(x) \geq |2h_T^q(x)|\,, \tag{30}$$

where the effective quark flavor distributions are $f_1^{(q)}(x,Q_0^2)$, $g_1^{(q)}(x,Q_0^2)$ and $h_T^{(q)}(x,Q_0^2)$ and $q=u,d$ denotes the quark flavors. Find that it is satisfied at the low–scale of the model $Q^2 = 0.4\mathrm{GeV}^2$.

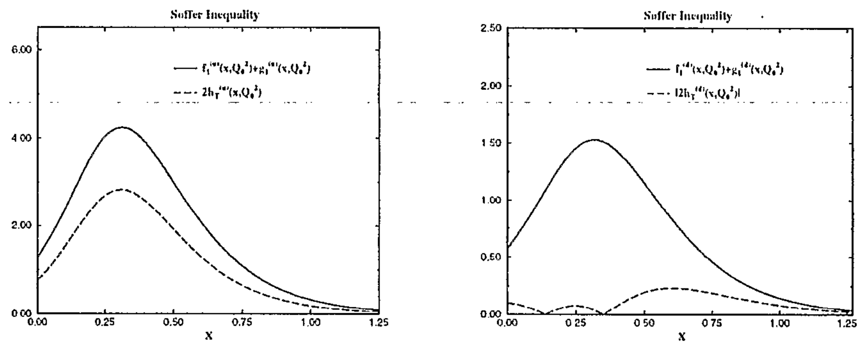


FIG. 8. The Soffer inequality for the chiral even combination $f_1^{(q)}(x,Q_0^2)+g_1^{(q)}(x,Q_0^2)$ (solid line) of the effective up quark (left panel) and down-quark (right panel) distributions and the chiral odd structure function $2\,h_T^{(q)}(x,Q_0^2)$ (long dashed line) for a constituent quark mass of $m_q = 400$MeV, calculated in the nucleon rest frame (RF).

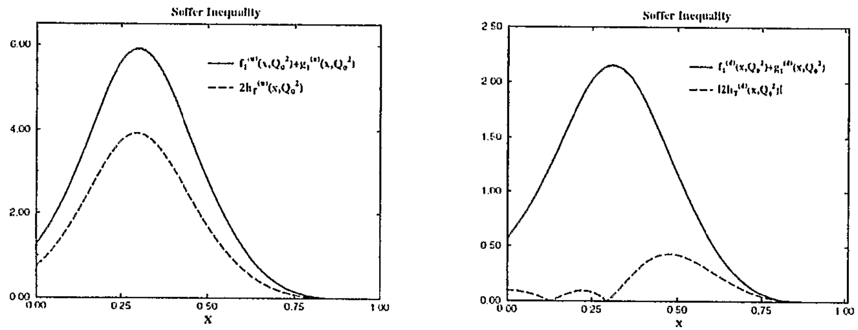


FIG. 9. Same as (8) but in IMF. The transformation prescription is given in eq (20).

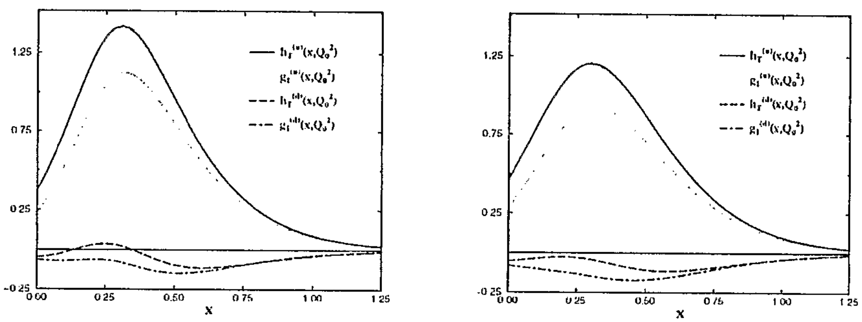


FIG. 10. The valence quark approximation of the transverse chiral odd nucleon distribution function as a function of Bjorken x for the up and down quark flavor content in the rest frame. calculation Also for $g_1(x, Q_0^2)$for the twist 2 polarized structure function. Two values of the constituent quark mass are considered: m = 400MeV (left panel, Fig. 10a) and m = 450MeV (right panel, Fig. 10b).

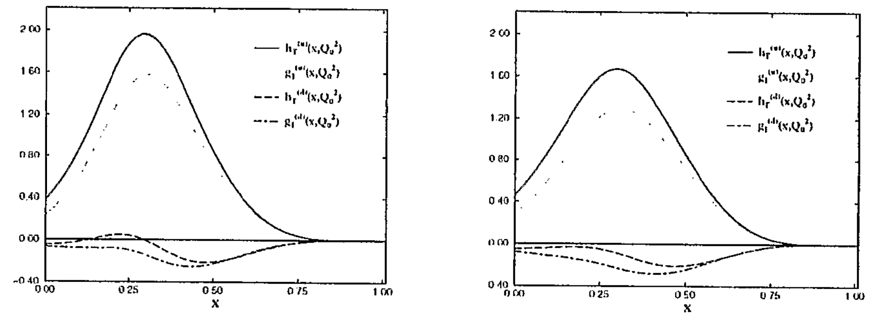


FIG. 11. Same as figure 10 in the IMF (20).

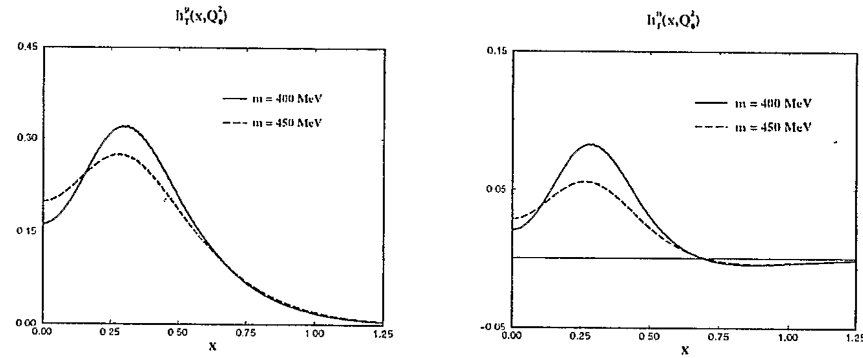


FIG. 12. The valence quark approximation of the transverse chiral odd nucleon structure functions as a function of Bjorken x. Left panel (Fig. 12a): $h_T^p(x, Q_0^2)$ for constituent quark masses m = 400MeV (solid line) and m = 450MeV (long-dashed line). Right panel (Fig. 12b): $h_T^n(x, Q_0^2)$.

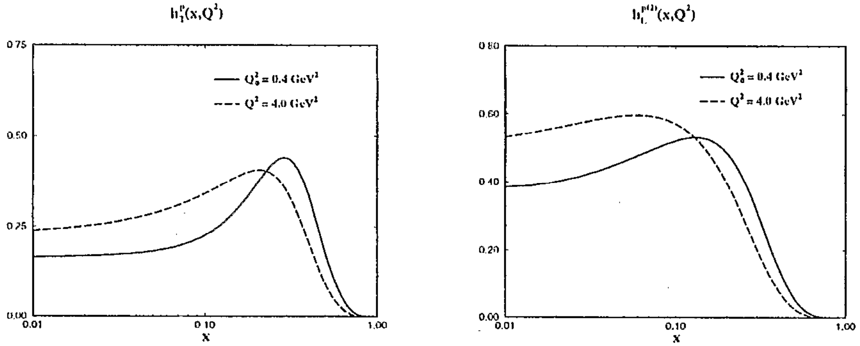


FIG. 13. Left panel (Fig. 13a): The evolution of $h_T^p(x,Q^2)$ from $Q_0^2 = 0.4\mathrm{GeV}^2$ (solid line) to $Q^2 = 4\mathrm{GeV}^2$ (long dashed line) for the constituent quark mass $m = 400\mathrm{MeV}$. Right panel (Fig. 13b): The evolution of the twist 2 contribution to the longitudinal chiral odd structure function, $h_L^{p(2)}(x,Q^2)$ from $Q_0^2 = 0.4\mathrm{GeV}^2$ (solid line) to $Q^2 = 4\mathrm{GeV}^2$ (long-dashed line) for $m = 400\mathrm{MeV}$.

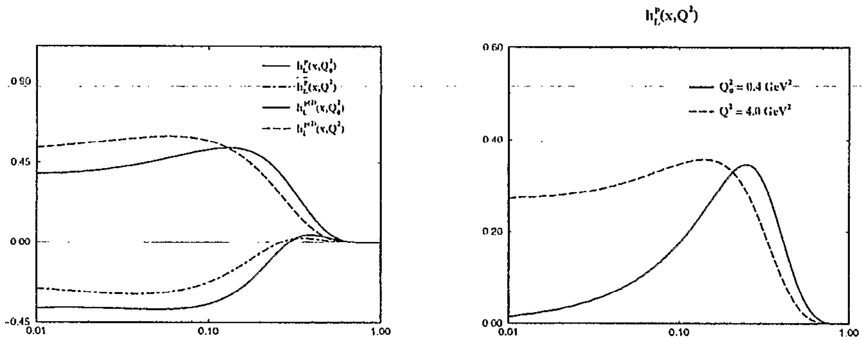


FIG. 14. Left panel (Fig. 14a): The evolution of the twist 3 contribution to the longitudinal chiral odd structure function, $\overline{h}_L^p(x,Q^2)$ along with the corresponding twist-2 piece, $h_L^{p(2)}(x,Q^2)$. Right panel (Fig. 14b): The evolution of $h_L^p(x,Q^2) = h_L^{p(2)}(x,Q^2) + \overline{h}_L^p(x,Q^2)$ from $Q_0^2 = 0.4\mathrm{GeV}^2$ (solid line) to $Q^2 = 4\mathrm{GeV}^2$ (long dashed line) for the constituent quark mass $m = 400\mathrm{MeV}$.

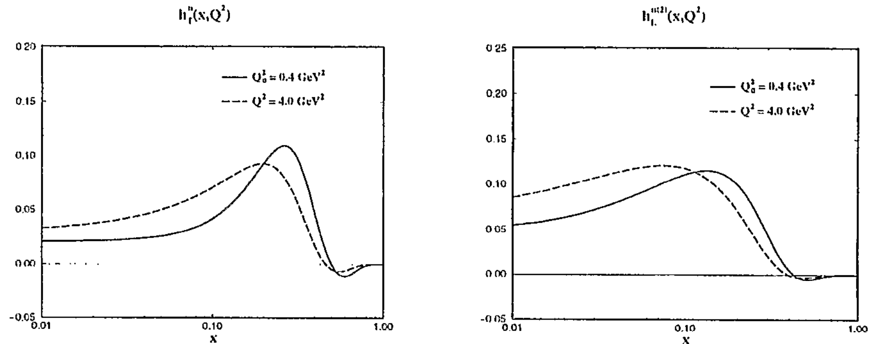


FIG. 15. Left panel (Fig. 15a): The evolution of $h_T^n(x,Q^2)$ from $Q_0^2 = 0.4\mathrm{GeV}^2$ (solid line) to $Q^2 = 4\mathrm{GeV}^2$ (long dashed line) for the constituent quark mass $m = 400\mathrm{MeV}$. Right panel (Fig. 15b): The evolution of the twist 2 contribution to the longitudinal chiral odd structure function, $h_L^{n(2)}(x,Q^2)$ from $Q_0^2 = 0.4\mathrm{GeV}^2$ (solid line) to $Q^2 = 4\mathrm{GeV}^2$ (long-dashed line) for $m = 400\mathrm{MeV}$.

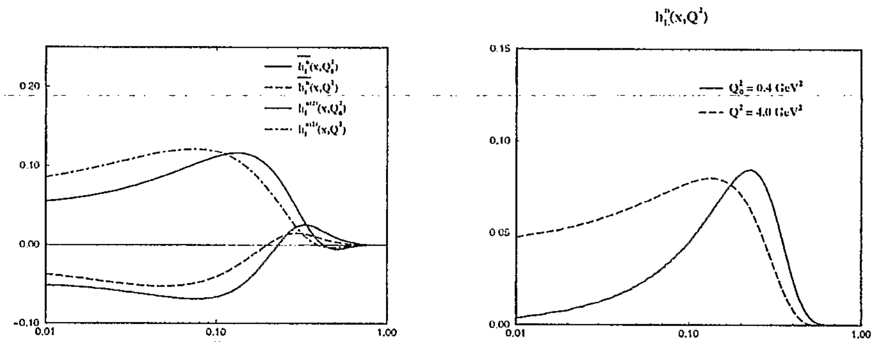


FIG. 16. Left panel (Fig. 16a): The evolution of the twist 3 contribution to the longitudinal chiral odd structure function, $\overline{h}_L^n(x,Q^2)$ along with the corresponding twist 2 piece, $h_L^{n(2)}(x,Q^2)$. Right panel (Fig. 16b): The evolution of $h_L^n(x,Q^2) = h_L^{n(2)}(x,Q^2) + \overline{h}_L^n(x,Q^2)$ from $Q_0^2 = 0.4\mathrm{GeV}^2$ (solid line) to $Q^2 = 4\mathrm{GeV}^2$ (long dashed line) for the constituent quark mass $m = 400\mathrm{MeV}$.

Transversity distributions in the large–N_c limit

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A unique feature of the transversity distributions viz. the tensor charges is the fact that these quantities are related to hadronic matrix elements of *chirally odd* operators in QCD. Since all known low–energy probes of hadrons such as electromagnetic or weak currents are *chirally even*, low–energy experiments normally do not provide any information about chirally odd matrix elements. (An exception is the so-called sigma term, whose effect on hadrons is, however, proportional the small current quark masses.) On the other hand, since chiral symmetry is spontaneously broken in the QCD vacuum, hadrons are expected to react very differently to chirally odd probes as compared to chirally even ones.

In order to obtain estimates of the transversity distributions and the tensor charges one may appeal to the large–N_c limit of QCD. In this limit the low–energy dynamics of QCD can approximately be described by an effective model of massive "constitutent" quarks, interacting with pions in a chirally invariant way [1]. The chiral Lagrangian of the pion field is then obtained by "bosonization" (integration over the quark fields) and gradient expansion (expansion in derivatives of the pion field). This approach reproduces not only the various known chirally invariant structures, it also allows to predict their coefficients in terms of the two basic parameters of the model — the constituent quark mass, M, and the ultraviolet cutoff, Λ. In a similar way one can "bosonize" also QCD color–singlet composite operators, including the chirally odd ones defining the transversity distributions and the tensor charges. (The normalization point of the operators here is of the order of the ultraviolet cutoff, $\Lambda \sim 600\,\mathrm{MeV}$.) One finds that the isovector tensor operator in the chiral Lagrangian is represented by a pionic operator of the form

$$\bar{\psi}\sigma_{\mu\nu}\tau^a\psi \;\rightarrow\; F_T\,\epsilon^{abc}\epsilon_{\mu\nu\rho\sigma}\partial_\rho\pi^b\partial_\sigma\pi^c, \tag{1}$$

and thus of higher order in gradients of the pion field than the isovector axial charge

$$\bar{\psi}\gamma_\mu\gamma_5\tau^a\psi \;\rightarrow\; F_\pi\,\partial_\mu\pi^a \tag{2}$$

The constants F_T and F_π are of different parametric order

$$F_\pi^2 \;\sim\; M^2\log\frac{\Lambda}{M}, \qquad\qquad F_T \;\sim\; \frac{M}{F_\pi^2} \tag{3}$$

i.e., F_π contains a would–be UV divergence while F_T is finite. Thus, the coupling of the flavor non-singlet tensor charge to pions is completely different from that of the axial charge.

The large–N_c limit of QCD also gives rise to a description of the nucleon as a chiral soliton. The chiral quark–soliton model of Ref.[2], in a sense, interpolates between the non-relativistic quark model and the Skyrme model of the nucleon as a soliton of the pion field. This approach can be used to calculate the parton distributions in the nucleon [3].

In the case of the transversity distributions the *isovector* distribution is leading in the $1/N_c$–expansion, while the *isoscalar* one is subleading [4,5]. It is particularly interesting to compare the transverse to the longitudinally polarized distributions. Numerical results show that the isovector transversity *quark* distribution, $\delta u(x) - \delta d(x)$, has approximately the same magnitude and shape as the longitudinally polarized one, $\Delta u(x) - \Delta d(x)$, consistent with the expectations based on the non-relativistic quark model. The corresponding *antiquark* distributions, however, are very different: The transverse polarized one is much smaller than the longitudinally polarized one. This can easily be understood: The antiquark distributions are well described by gradient expansion, and Eqs.(1) and (2) show that the chirally odd operator is suppressed in gradients of the pion field relative to the chirally even one (the same applies for the corresponding operators of higher spin). Thus, we see that qualitative differences between the longitudinally and transverse polarized antiquark distributions can be traced back to the "chiral dynamics" of low–energy QCD.

A discussion of the flavor–singlet longitudinally and transverse polarized distributions, as well as predictions for observable such as spin asymmetries in transverse polarized Drell-Yan pair production (A^{TT}) can be found in Ref.[5].

[1] D. Diakonov and V. Petrov, Nucl. Phys. B 272 (1986) 457.
[2] D. Diakonov, V. Petrov and P. Pobylitsa, Nucl. Phys. B 306 (1988) 809.
[3] D.I. Diakonov, V.Yu. Petrov, P.V. Pobylitsa, M.V. Polyakov and C. Weiss, Nucl. Phys. B 480 (1996) 341; Phys. Rev. D 56 (1997) 4069.
[4] P.V. Pobylitsa and M.V. Polyakov, Phys. Lett. B 389 (1996) 350.
[5] P. V. Pobylitsa, M. V. Polyakov, K. Goeke, P. Schweitzer, D. Urbano, and C. Weiss, Bochum University preprint RUB-TPII-15/00

Transversity distributions in the large-N_c limit

C. Weiss, RIKEN-BNL Workshop, Sep. 18-20, 2000

[with K. Goeke, P.V. Pobylitsa, M.V. Polyakov, P. Schweitzer, D. Urbano]

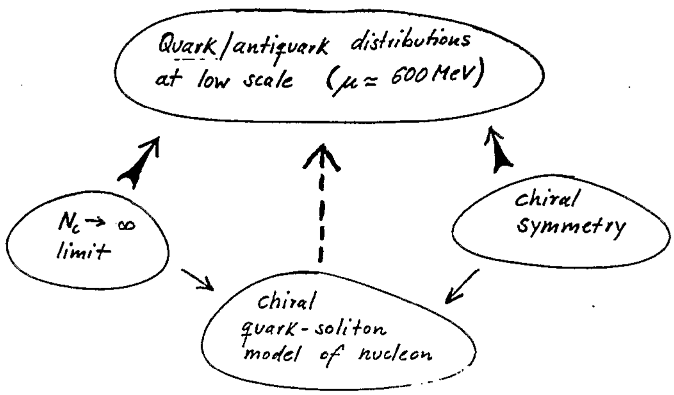
— Transversity distributions $\longleftrightarrow$ chiral (flavor) dynamics

e.g. difference between $\delta\bar{q}$ and $\Delta\bar{q}$ can be understood from chiral symmetry

— Reliable model estimates of δq, $\delta\bar{q}$

Drell-Yan   Semi-inclusive DIS

CW-1



Outline

— Quark/antiquark distributions at large N_c

- q, Δq
- δq
- Inequalities

— Transversity & chiral dynamics

- "bosonization" of tensor charge

— Transversity distributions from the chiral quark-soliton model

Non-rel. quark model $\xleftrightarrow{\text{"interpolates"}}$ Skyrmion

— Estimates of Drell-Yan spin asymmetry A_{TT} ($\rightarrow$ RHIC)

Quark/antiquark distributions at large N_c

- $N_c \to \infty$ limit: Useful methodical tool to analyze non-perturbative phenomena in QCD (properties of hadrons, ...)

"deeper" reason: QCD $\rightarrow$ effective theory of mesons, baryons as solitons ['tHooft, Witten]

Example: Axial couplings of nucleon: $(\bar{\psi}\gamma_\mu\gamma_5\psi)$

$$g_A^{(3)} \sim N_c \qquad (\text{num.: } 1.25$$

$$g_A^{(0)} \sim 1 \qquad \sim 0.2 .. 0.3\,)$$

Note difference isovector $\leftrightarrow$ isoscalar!

Tensor charges: $(\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi)$

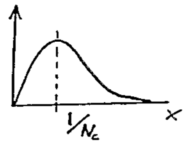
$\delta q^{(3)} \sim N_c$ $\leftarrow$ isovector leading!

$\delta q^{(0)} \sim 1$

- Large-N_c behavior of quark/antiquark distributions 1.2

[Diakonov et al. 96]

Consider $x \sim \frac{1}{N_c}$



unpolarized: $$u(x)+d(x), \quad \bar{u}(x)+\bar{d}(x) \sim N_c^2 \text{ function}(N_c x)$$
$$u - d \qquad \bar{u} - \bar{d} \sim N_c \text{ function}(N_c x)$$

longitud. polarized: $$\Delta u(x) - \Delta d(x), \quad \Delta\bar{u}(x) - \Delta\bar{d}(x) \sim N_c^2 \text{ function}(N_c x)$$
$$\Delta u + \Delta d \qquad \Delta\bar{u} + \Delta\bar{d} \sim N_c \text{ function}(N_c x)$$

leading!

transverse polarized: $$\delta u(x) - \delta d(x), \quad \delta\bar{u}(x) - \delta\bar{d}(x) \sim N_c^2 \text{ function}(N_c x)$$
$$\delta u + \delta d \qquad \delta\bar{u} + \delta\bar{d} \sim N_c \text{ function}(N_c x)$$

suppressed!

> Isovector transversity distribution leading in $^1/_{N_c}$-expansion

- Large-N_c inequality (generalization of Soffer inequalities) 1.3

[Pobylitsa, Polyakov, 00]

$$\frac{1}{2}\left[\frac{u(x)+d(x)}{3} + |\Delta u(x) - \Delta d(x)|\right] \geq |\delta u(x) - \delta d(x)|$$

Only N_c-leading distributions enter!

Transversity and chiral dynamics

Spontaneous breaking of chiral symmetry
→ Pion as Goldstone boson, soft pion theorems, etc.
→ $\langle \bar\psi\psi \rangle \neq 0$, etc.
→ Mass generation
⋮

→ effective low-energy dynamics [Diakonov, Eides 84]

$$\mathcal{L}_{eff} = \bar\psi \left(i\partial\!\!\!/ - M e^{i\gamma_5 \pi^a \tau^a} \right) \psi$$

dynamical quark mass

quarks coupled to pion field

→ Chiral Lagrangian

$$W_{eff}[\pi] \equiv \mathrm{Det}\left[i\partial\!\!\!/ - M e^{i\gamma_5 \pi^a \tau^a} \right]$$

$$= \frac{F_\pi^2}{4} \int d^4x \; \mathrm{tr}\left[\partial_\mu U^+ \partial_\mu U \right] \qquad \text{Weinberg-Lagrangian}$$

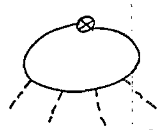
$$+ \ \mathcal{O}(\partial U^4) + \ldots \qquad \text{Gasser-Leutwyler terms}$$

$$+ \ \text{Wess-Zumino term}$$

$$U(x) = e^{i\tau^a \pi^a(x)} \qquad F_\pi^2 \sim M^2 \log \frac{\Lambda_{UV}}{M}$$

"Bosonize" QCD operators $(N_c \to \infty)$:

$\bar\psi \ldots \psi \longrightarrow$



Expand in $\partial_\mu U = \partial_\mu \pi + \ldots$

Axial current: $\bar\psi \gamma_\mu \gamma_5 \tau^a \psi \longrightarrow F_\pi^2 \, \mathrm{tr}\left[\tau^a U^+ \partial_\mu U \right]$

$$\sim F_\pi^2 \, \partial_\mu \pi^a + \ldots$$

$$\left[F_\pi^2 \sim M^2 \log \frac{\Lambda_{UV}}{M} \right]$$

Tensor operator: $\bar\psi \sigma_{\mu\nu} \gamma_5 \psi \rightarrow M \, \varepsilon_{\mu\nu\varrho\sigma} \, \mathrm{tr}\left[\tau^a U^+ \partial_\varrho U \, \partial_\sigma U^+ \right]$

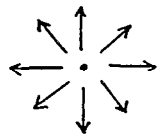
$$\sim M \, \varepsilon_{\mu\varrho\nu\sigma} \, \varepsilon^{abc} \, \partial_\varrho \pi^b \, \partial_\sigma \pi^c$$

$\left.\begin{array}{l}\text{Axial current} \\ \text{Tensor operator}\end{array}\right\}$ of order $\left\{\begin{array}{l}\partial U \\ (\partial U)^2\end{array}\right.$

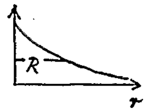
[Isosinglet operators: Higher order in ∂U !]

Nucleon ($N_c \to \infty$)   [Diakonov, Petrov, Pobylitsa 88]

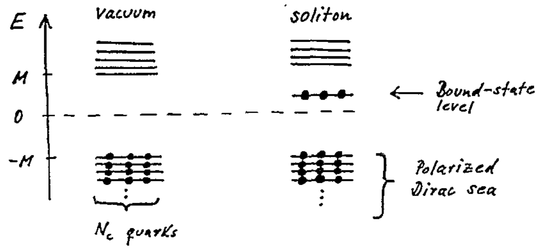
Classical pion field ("soliton")



$\vec{\pi}_{class} \sim \vec{r}$



Quark single-particle levels



Spin / Isospin states ($N, \Delta, \ldots$) from quantization of collective (iso-) rotations (zero modes)

- Model "interpolates":

$R \to 0$: Nonrelativist. quark model

$R \to \infty$: Skyrmion

↳ expand observables in ∂U ?

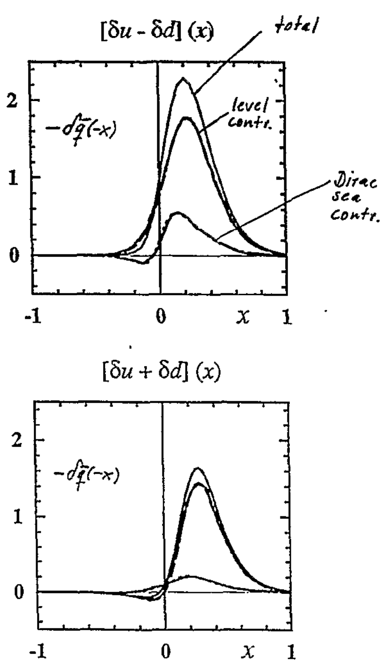


Figure 1 *The isovector (top) and isoscalar (bottom) transversity quark- and antiquark distributions obtained from the chiral quark soliton model. The functions shown here represent $[\delta u \mp \delta d](x)$ at $x > 0$ and $-[\delta\bar{u} \mp \delta\bar{d}](-x)$ at $x < 0$. Dashed lines: Contributions of the bound state level. Dotted lines: Contributions of the Dirac continuum. Solid lines: Total results (sums of bound state level and Dirac continuum)*

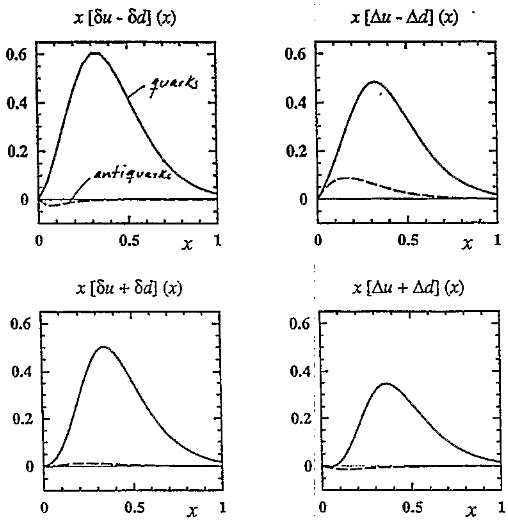


Figure 2: *The total isovector (top row) and isoscalar (bottom row) transverse and longitudinally polarized quark- and antiquark distributions, multiplied by x. Shown are the total results (sum of level and continuum contributions), corresponding to the solid lines in Fig. 1) Solid lines: Quark distributions. Dashed lines: Antiquark distributions*

[P. Pobylitsa et al., RUB-TPII-15/100; to be published]

$\delta\bar{q}(x)$ versus $\Delta\bar{q}(x)$

Consider limit $R \to \infty$ → Expansion in ∂U

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) \approx \frac{F_\pi^2 M_N}{3} \int_{-\infty}^{\infty} \frac{d\tau}{2\pi} \frac{\cos M_N \tau x}{\tau} \times \int d^3z \, tr\left[\tau^3 (-i) \, U_{cl}(\vec{z}+\tau\vec{e}_3) \, U_{cl}^+(\vec{z})\right]$$

$$\delta\bar{u}(x) - \delta\bar{d}(x) \approx \frac{N_c M_N M}{48\pi^3} \int_{-\infty}^{\infty} \frac{d\tau}{2\pi} e^{iM_N\tau x} \int_0^1 d\alpha \int_0^\alpha d\beta \times \int d^3z \, tr\left[\tau^1 \, U_{cl}(\vec{z}-\alpha\tau\vec{e}_3) \, \partial_i U^+(\vec{z}-\beta\tau\vec{e}_3) \, \partial_j U_{cl}(\vec{z})\right] \varepsilon_{ij3}$$

→ $\Delta\bar{q}$, $\delta\bar{q}$ expressed in terms of classical pion field of the nucleon ($N_c \to \infty$) !

$\delta\bar{u}(x) - \delta\bar{d}(x)$ suppressed relative to $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ by $\partial U^2 \sim 1/(MR)^2$

→ $|\delta\bar{u}(x) - \delta\bar{d}(x)| \ll |\Delta\bar{u}(x) - \Delta\bar{d}(x)|$ CW-12

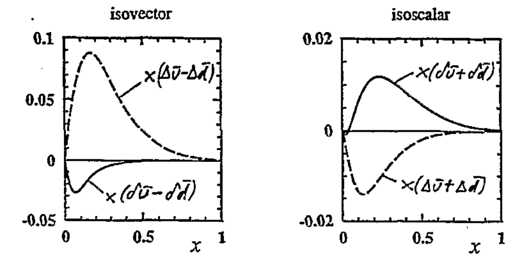


Figure 3: *The transverse and longitudinally polarized antiquark distributions, see Fig. 2. Left: Isovector distributions, $x[\delta\bar{u}-\delta\bar{d}](x)$ and $x[\Delta\bar{u}-\Delta\bar{d}](x)$. Right: Isoscalar distributions, $x[\delta\bar{u}+\delta\bar{d}](x)$ and $x[\Delta\bar{u}+\Delta\bar{d}](x)$. Solid lines: Transversity antiquark distributions Dashed lines: longitudinally polarized antiquark distributions.*

[P. Pobylitsa et al. RUB-TPII-15/00, to be published]

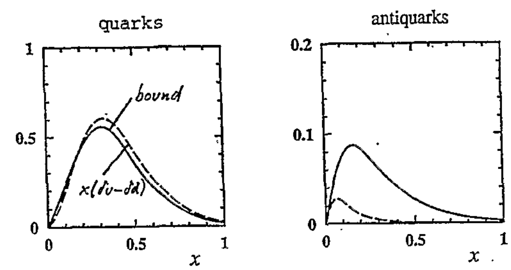


Figure 5: *The large-N_c improved Soffer bound for the quark (left) and antiquark (right) distributions. Dashed lines: $|x[\delta u-\delta d](x)|$. Solid lines: The large N_c Soffer bound $(x[u+d](x)/3+x[\Delta u-\Delta d](x))/2$.* [redacted]

$$\frac{1}{2}\left[\frac{u(x)+d(x)}{3} + |\Delta u(x)-\Delta d(x)|\right] \geq |\delta u(x)-\delta d(x)|$$

[Pobylitsa, Polyakov 00]

Generalized Soffer inequalities ($N_c \to \infty$)

- saturated for quarks
- not saturated for antiquarks

CW-14

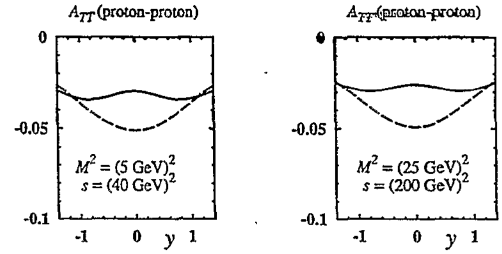


Figure 6: *The transverse spin asymmetry, A_{TT}, Eq.(5.1), in transverse polarized proton–proton collisions, in two different kinematical regions: $s = (40\,\mathrm{GeV})^2, M^2 = (5\,\mathrm{GeV})^2$ (left), and $s = (500\,\mathrm{GeV})^2, M^2 = (25\,\mathrm{GeV})^2$ (right). Solid lines: Asymmetries calculated with the quark- and antiquark distributions computed in the chiral quark-soliton model, cf. Fig.2. For the quark distributions we used the calculated ratios of transverse to longitudinally polarized distributions, Eqs.(4.7) and (4.8), together with the GRSV95 parametrizations [3] for $[\Delta u-\Delta d](x)$ and $[\Delta u+\Delta d](x)$. Dashed lines: Asymmetries obtained assuming that $\delta q(x) \equiv \Delta q(x)$ and $\delta\bar{q}(x) \equiv \Delta\bar{q}(x)$ $(q = u, d)$, using the GRSV95 parametrizations [3] for $\Delta q(x)$ and $\Delta\bar{q}(x)$.*

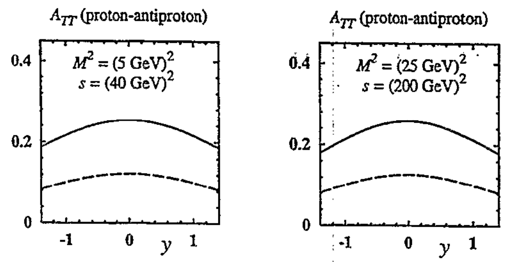


Figure 7: *The transverse spin asymmetry, $A_{TT}^{p\bar{p}}$, Eq.(5.2), in transverse polarized proton-antiproton collisions. The solid and dashed lines correspond to the cases described in Fig.6.*

Summary

- We can actually say A LOT about transversity distributions from well-tested general principles:
  - chiral symmetry
  - large-N_c limit

- Large isovector transversity dist'n $\delta u(x) - \delta d(x)$

- Quark dist'ns: $\delta q(x) \approx \Delta q(x)$

  Antiquark ": $\delta\bar{q}(x)$, $\Delta\bar{q}(x)$ VERY DIFFERENT!

A_{NN} in elastic pp scattering

T.L. Trueman
Workshop on *Future Transversity Measurements* Sept. 18-20, 2000

Brookhaven National Laboratory, Upton, NY 11973, USA

This topic is very different from the others discussed at this workshop. The appropriate language for addressing this "soft" physics is Regge theory which is highly developed and very successful in describing a large variety of processes, but there is not yet a quantitive relation between it and the underlying field theory, QCD. Most of the material here has been presented in published papers or at other conferences. See, in particular, Buttimore, Kopeliovich, Leader, Soffer and Trueman, Phys Rev D 59, 114010 (1999). That paper contains references to all the papers cited but not referenced here.

How big do we expect A_N and A_{NN} to be? Extensive low energy data, mainly from Argonne, give asymmetries in the 5-10 % range. Regge fits to these (Berger et al) are very sensitive to the normal Regge poles which fall away by the time RHIC energies are reached. The Pomeron (as a Regge pole) is included in these fits but its spin dependent coupling are not well-determined. Taking them at face value yields very small remaining asymmetries at RHIC. Later, higher energy data, up to AGS and CERN PS energy show larger and rapidly varying asymmetries at higher values of t. (First transparency) These are not really understood and are not included in the fits of Berger at al.

Only A_N is measured over a wider energy range, up to $300\,GeV/c$ lab momentum. A Regge-inspired fit to the data at $t = -0.15\,GeV/c^2$ is shown in the second transparency. A good fit with an asymptotic value of $2.3 \pm 1.2\%$ is found. If there were no hadronic helicity-flip at all, only the known Coulomb spin flip, the value would be 1%, consistent with this value. It would extrapolate to RHIC as $1/\sigma_{\rm tot}$.

A fit to the E704 data in the CNI region is shown in Transparency 3. It, too, is consistent with pure Coulomb helicity-flip, but with significant error. The hadronic amplutude is taken to have the form $(\rho + i\sigma_{\rm tot})\exp B\,t/2, B \approx 12\,GeV/c^2$ and the Coulomb to be the simple lowest order pole; the fit in the region of t shown is very insensitive to B. It should be valid up to a few tenths of a GeV-squared, but not beyond because both the strong shape and the Coulomb (due to form factors) change from the assumed form. Neverthess, since this is

a workshop I allowed myself to do the following, bogus plot. (Transparency 4.) Using the same form way outside its range of validity, we find it predicts a large peak in A_N, rather near to t-value where the peak is seen in Crabb et al, but even larger in magnitude. That might catch your attention momentarily until you think about it. The lower part of the figure makes it clear what is going on: the extrapolated forms of the strong and Coulomb amplitudes intersect once more at that value of t (their first intersection is responsible for the famous CNI peak at $t \approx -0.003\,GeV^2$). Indeed, the differential cross section implied by this combination of amplitudes is about 2 orders of magnitude below the data at this t -value.There are two points to make from this bogus result: (1) remarkable variations of the spin asymmetries may take place although the underlying amplitudes are slowly varying, and (2) when applied to p-nucleus scattering where the Coulomb piece is enhanced by Z and the strong piece drops much more sharply from diffraction by the larger nucleus, the intersection will take place at a much smaller value of t where the approximations are valid. This is the essence of the calculation of Kopeliovich (hep-ph/9801414) shown in Transparency 5. These show very large asymmetries at small values of t but above the usual CNI range.

The next four transparencies should speak for themselves. Since the "Pomeron" is such a complex object and since, over the RHIC energy range, it may be impossible to separate small power or logarithmic behaviours in the energy, I would like to consider it here as "what is left at high energy" including possible odderon or other yet unheard of contributions. This presents to $pp2pp$ the opportunity to elucidate its nature by studying the spin dependence of its couplings. This also serves as an alternative to the use of comparing reactions with various projectiles, which was essential to Regge phenomenology at lower energy but is not possible at a collider. So factorization and quantum number exchange can be tested provided the spin dependence is large enough to be measured. On can use the "unnatural parity" asymmetries A_{LL} and A_{SS} to search for the presence of Regge singularities near $J = 1$ with quantum numbers $P = C = -(-1)^J$ and $P = -C = -(-1)^J$, respectively. By making phase sensitive measurements in A_{NN} and A_N (see Leader and Trueman, Phys Rev D 61, 077504 (2000)) one can test for the presence of $P = C = (-1)^J = -1$ trajectories, e.g. the "odderon", in a rather sensitive way. Example of these are shown in Transparencies 10 and 11.

Finally we note that use of the Coulomb Nuclear interference and total cross sections for transverse and longitudinally polarized protons enables one to separately get at the real and imaginary parts of all the pp amplitudes near $t = 0$. An example of this is given in the final transparency. There is enormous redundancy here, so much so that in principle one can measure everything without knowing the magnitude of the polarization P, only its direction. This same procedure works also for scattering of unlike particles, for example $p\,He^3$, (Buttimore, Leader and Trueman, in prep.)

A_{NN} in Elastic Proton Proton Scattering

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Talk presented at the RIKEN BNL Research Center Workshop on

Future Transversity Measurements

September 18-20, 2000

Crosbie et al
1981

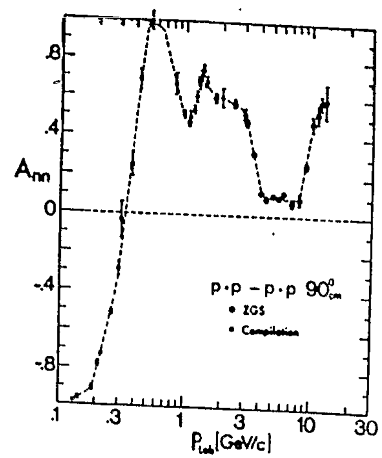


FIGURE 1. Momentum Dependence of Proton-Proton Elastic Spin-Spin Correlation Parameter at 90°_{cm}.

Crabb et al
1990

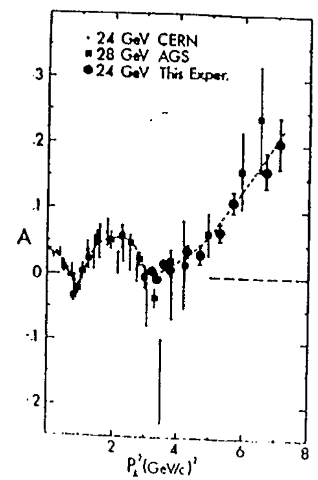
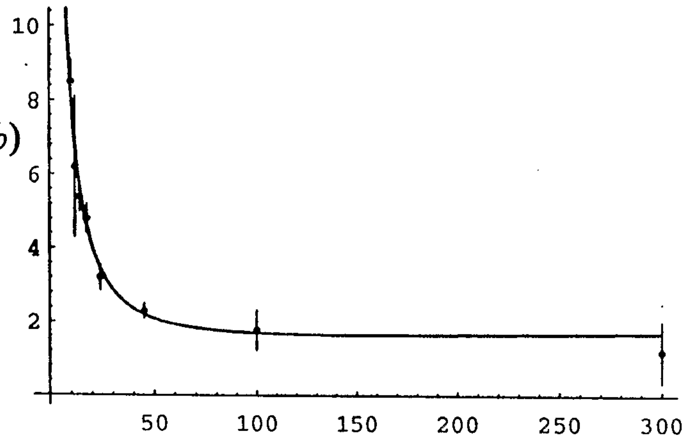


FIGURE 4. Spin Asymmetry in p-p Elastic Scattering at High $P_\perp$.

Energy dependence of P at t = -0.15 GeV^2



Best fit gives asymptotic value 2.3±1.2

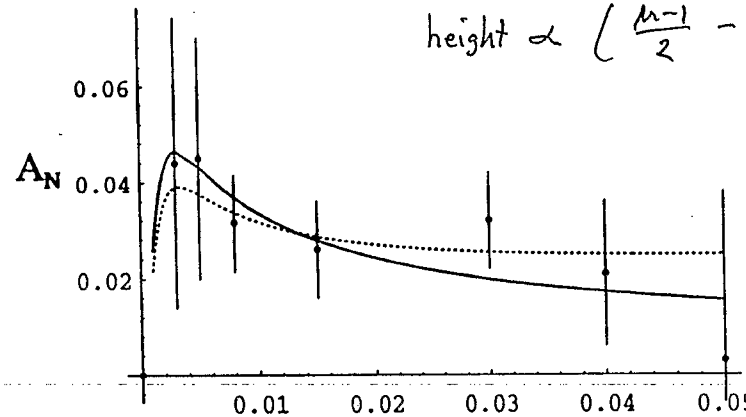
Pure CNI at 300 is 1.1

10 GeV Borghini 1971
11.8 GeV Kramer 1977
14 GeV Borghini 1971
17.5 GeV Borghini 1971
24 Gev Crabb 1977
45 GeV Gaudot 1976
100 GeV Snyder 1978
300 GeV Snyder 1978

Best fits to 704 data with and without Im(τ) = 0

$\phi_5 = \tau \frac{\sqrt{-t}}{m} \phi_+$

height $\propto \left(\frac{\mu-1}{2} - \tau \right)$

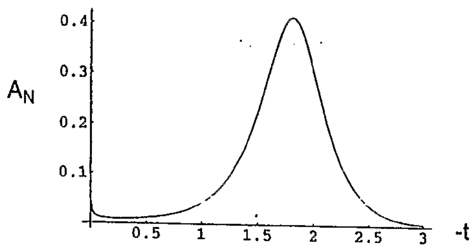


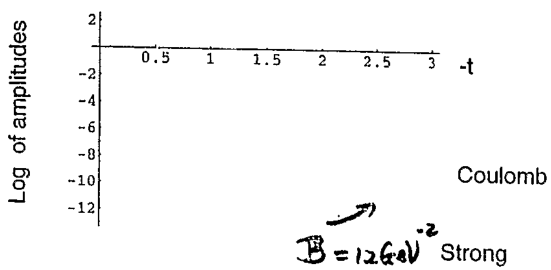
———— $\tau = 0.0 \pm 0.15$

·········· $\tau = 0.2 + 0.03\,I \pm (0.3 + 0.01 i)$

(Also use notation $\phi_5 = r_5 \frac{\sqrt{-t}}{m} \mathrm{Im}\,\phi_+$

so $\tau \approx \mathrm{Im}\, r_5$)





$$F_c(q^2) = \frac{1}{A}\int d^2b\, e^{i\vec{q}\cdot\vec{b}}\, T(b)$$

$$F_H(q^2) = \frac{1}{2\sigma_{tot}^{pA}}\int d^2b\, e^{i\vec{q}\cdot\vec{b}}\left[1 - e^{-\frac{1}{2}\sigma_{tot}^{pN} T(b)}\right]$$

$$T(b) = \int_{-\infty}^{\infty} dz\, \rho_A(b,z) = \text{"nuclear thickness"}$$

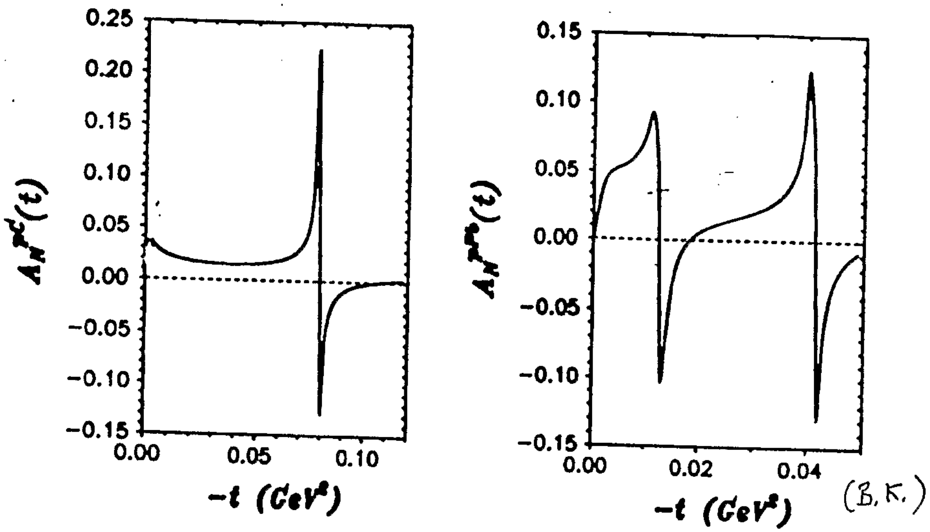


Figure 3: *Asymmetry in polarised proton scattering on carbon and lead, calculated using (12).* pure CNI

If $\tau_A \neq$ scale shifts throughout by factor

$$\left(1 - \frac{2\tau_A}{\mu - 1}\right)$$

Physics of A_{NN} etc. ?

Appropriate language is Regge theory

What is the Pomeron?

"That which is left at high energy"

Began life in 1960's as a simple Regge pole at $J=1$ when $t=0$.

Quantum numbers of Pomeron pole:

$$C = +1$$
$$P = +1$$
$$I = 0$$
$$(-1)^J = +1$$

Pole couplings factorize:

$$F_{\lambda'\mu';\lambda\mu} \propto \beta_{\lambda'\lambda}\,\beta_{\mu'\mu}$$

$$\Rightarrow \quad \phi_2(s,t) = -\frac{\phi_5^2(s,t)}{\phi_+(s,t)}$$
$$= -\phi_4(s,t)$$
$$\phi_-(s,t) = 0$$

very strong

(Reminder $\phi_\pm = \frac{1}{2}(F_{++++} \pm F_{+-+-})$

5 pp amps. $\ni$ $\phi_2 = F_{++--}$

$\phi_4 = F_{+--+}$

$\phi_5 = F_{+++-}$)

No doubt really much more complicated: cuts, hard vs. soft, ...

Opportunity for $p^\uparrow p^\uparrow \to pp$

What are quantum numbers dominating exchange at RHIC energy?

Q.N.	Amplitude	Reggeons
$P = C = (-1)^J = +1$	$\phi_+, \phi_2 - \phi_4, \phi_5$	$\mathbb{P}, f, a_2 \cdots (2^{++})$
$P = C = (-1)^J = -1$	"	$\mathbb{O}, \rho, \omega \cdots (1^{--})$
320 $P = C = -(-1)^J = +1$	ϕ_-	$a_1\ (1^{++})$
$P = C = -(-1)^J = -1$	"	? $(0^{--}$ exotic$)$
$-P = C = (-1)^J = +1$	$\phi_2 + \phi_4$	$\pi, \eta\ (0^{-+})$
$-P = C = (-1)^J = -1$	"	$b_1\ (1^{+-})$

Dominant contribution to asymmetries.

$A_N \sim \mathrm{Im}(\phi_+ \phi_5^*)$, $A_{NN} \sim \mathrm{Re}(\phi_+ [\phi_2^* - \phi_4^*])$

$A_{LL} \sim \mathrm{Re}(\phi_+ \phi_-^*)$ $\quad A_{LS} \sim \mathrm{Re}(\phi_5 [\underbrace{\phi_- + 2(\phi_2 + \phi_4}_{\text{unnatural parity}}$

$A_{SS} \sim \mathrm{Re}(\phi_+ [\phi_2^* + \phi_4^*])$

A_{LL} tests for ϕ_- $\quad P = C = -(-1)^J$

(Kochelev et al HEP-PH 9911480)

Absence of $P = -C = -(-1)^J \Rightarrow$

$\phi_2(s,t) \approx -\phi_4(s,t) \Rightarrow A_{SS}^{(s,t)} \approx 0$

$\Rightarrow \quad \phi_2(s,t) \to 0$ as $t \to 0$

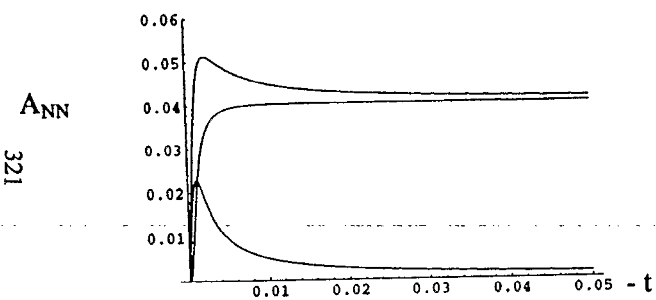
$\Rightarrow \quad A_{NN} \to 0$ "

Presence of $P = C = (-1)^J = -1$ in dominant ϕ_+, ϕ_2, ϕ_5 detectable by phase relations. (Odderon, Leader + Trueman PR D61, 077504)

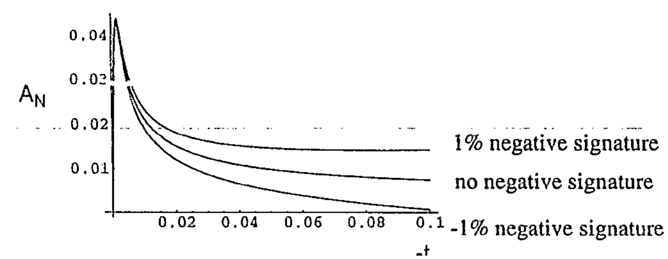
Strong effect in A_N and (via CNI) A_{NN}

Comparison of A_{NN} for various values of r_2:
.02 I (lower), .02 (middle), .02 + .02 I (upper).

$\phi_2 = 2 r_2 \, \mathrm{Im}\, \phi_+$



Sensitivity of A_N to small admixture of $C=P=(-1)^J = -1$ in ϕ_5



no negative signature = pure CNI

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Near $t=0$

CNI term

$$A_{JJ} PP' \frac{d\sigma}{dt} = a_{JJ}\left(\frac{Z\alpha}{t}\right) + \frac{1}{8\pi} b_{JJ}$$

$$+ O(t)$$

pure hadronic term

$$a_{LL} = PP' R_-$$

$$a_{NN} = PP' R_2$$

$$b_{LL} = PP'\left(I_+ I_- + R_2 R_- + R_2^2 + I_2^2\right)$$

so non-linearity allows determination of PP', in principle, using $I_+ = \sigma_{tot}$

$$PP' I_2 = -\tfrac{1}{2} PP' \Delta\sigma_T$$

$$PP' I_- = \tfrac{1}{2} PP' \Delta\sigma_L$$

Cardan invariance of transversity cross sections

X. Artru*

A fermion state of definite momentum and polarisation can be written as $|\mathbf{p}, \lambda, \mathbf{s}_T\rangle$, where λ and $\mathbf{s}_T$ are the expectation values of the helicity and transversity vector, with

$$\mathbf{p} \cdot \mathbf{s}_T = 0, \qquad \lambda^2 + \mathbf{s}_T^2 = 1 \tag{1}$$

In the massive case ($m \neq 0$), $\mathbf{s}_T$ is the transverse part of the spin 4-vector s^μ. In the massless case, the longitudinal part of s^μ becomes infinite, but we can introduce the *transversity 4-vector* s^μ_T, defined up to a "gauge transformation"

$$s^\mu_T \to s^\mu_T + constant \times p^\mu \tag{2}$$

Eq.(1) corresponds to the "gauge" $s^0 = 0$ (†). When a formula for a polarized cross section is given in a covariant way in terms of one or several s^μ, it is possible to make the following check : 1) take the limit of massless fermions and replace s^μ by s^μ_T 2) check that result is invariant under transformation (2).

For masless fermions interacting with vector and/or axial coupling, the exact conservation of chirality lead to the invariance of the cross sections when all the transversity vectors are rotated by a common angle (counted positively according to the "corkscrew rule" about the 3-momentum of each particle). We call this "cardan invariance", by analogy with a mechanical cardan, drawn at the bottom of transparent No 1. Cardan invariance also holds separately for a pair of fermions connected by one internal fermion line in a Feynman diagram, e.g. (f_1, f_1') or (f_2, f_2') in transparent 1.

For the reaction $e^+ e^- \to f \bar{f}$ ($f = e^-, \mu^-, \tau^-$, or light quark), the cardan transformation rotates the transversity of f and $\bar{f}$ in opposite way about the $f - \bar{f}$ axis in the center-of-mass frame. Therefore the transversity correlation is in $\cos(\phi + \phi')$ when φ and ϕ' are counted positively about the *same* oriented axis (transparent No 2).

The derivation in the example where f is an incoming fermion and f' an incoming antifermions is outlined in transparent No 3.

Chiral invariance leads to the invariance of the matrix element under

$$|f\rangle \to \exp(C\gamma_5)|f\rangle, \qquad \langle f| \to \langle f|\exp(-C\gamma_5)$$
$$|\bar{f}\rangle \to \exp(-C\gamma_5)|\bar{f}\rangle, \qquad \langle \bar{f}| \to \langle \bar{f}|\exp(C\gamma_5) \tag{3}$$

for incoming fermions, outgoing fermions, incoming antifermions and outgoing antifermions respectively. For pure imaginary C, we have the cardan rotation of angle $-2\mathrm{Im}(C)$. Taking C to be real, one find a new invariance described below.

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(†) the "gauge" freedom can be understood from $s^\mu = s^\mu_T + (\lambda/m)(p^0/|\mathbf{p}|)(\mathbf{p}^2/p^0, \mathbf{p})$ as a relic of an infinitesimal uncertainty on λ in the limit $m \to 0$.

For a state with nonzero transversity, we can define the parameter χ by

$$\lambda = \pm \tanh\chi, \qquad |\mathbf{s}_T| = 1/\cosh\chi \tag{4}$$

where the + sign is for a fermion, the − sign for an antifermion (χ is called the *chiradity* in transparent 3 by analogy with *rapidity* = tanh[velocity]). The transformation (3) with real C is equivalent to

$$\chi \to \chi + 2C, \qquad \chi' \to \chi' - 2C, \tag{5}$$

with the azimuthes of the transversity vector (but not their norms) left unchanged. Here unprimed quantities refer to f = incoming fermion or outgoing antifermion, primed quantities to f' = outgoing fermion or incoming antifermion. If f and f' are connected by an internal quark line, the quantity

$$\hat{\sigma} \equiv \frac{\text{cross section}}{|\mathbf{s}_T|\,|\mathbf{s}'_T|} \tag{6}$$

is invariant under the transformation (5), which we call a "see-saw" transformation since it changes the expectation values of the chirality in opposite way for f and f'. The denominator in (6) compensates for the change of the norms of the state vectors in Eq.(3) with real C.

Application. Consider the reaction $e^+ e^- \to f \bar{f}$. The totally polarized cross section at the Z^0 peak is given by

$$|\mathbf{s}_T(e^+)| \cdot |\mathbf{s}_T(e^-)| \cdot |\mathbf{s}_T(f)| \cdot |\mathbf{s}_T(\bar{f})| \cdot \frac{d\sigma}{d\Omega} = \frac{|\hat{F}|^2}{64\pi^2 s} \tag{7}$$

with

$$\hat{F} = \frac{G(s)}{2}\left[-u\ (\mathcal{R}_e \mathcal{R}_f^* + \mathcal{L}_e \mathcal{L}_f^*) - t\ (\mathcal{R}_e \mathcal{L}_f^* + \mathcal{L}_e \mathcal{R}_f^*)\right], \tag{8}$$

$$G(s) = \left(\frac{e}{\sin 2\theta_W}\right)^2 \times \left(s - m_{Z^0}^2 + i\, m_{Z^0}\Gamma_{Z^0}\right)^{-1}, \tag{9}$$

$$\mathcal{R}_e \equiv \exp\left(\frac{1}{2}\chi_{e^+} + \frac{1}{2}\chi_{e^-} - i\phi_{e^-}\right) g_R^e, \qquad \mathcal{L}_e \equiv \exp\left(-\frac{1}{2}\chi_{e^+} - \frac{1}{2}\chi_{e^-} - i\phi_{e^+}\right) g_R^e, \tag{10}$$

and analogous notation for $e^- \to f$, $e^+ \to \bar{f}$,

$$g_R^e = 2\sin^2\theta_W = 0.46, \qquad g_L^e = g_R^e - 1$$

$$g_R^u = -\frac{2}{3} g_R^e, \qquad g_L^u = g_R^u + 1, \qquad g_R^d = \frac{1}{3} g_R^e, \qquad g_L^d = g_R^d - 1.$$

Cardan and see-saw invariance of $\hat{F}$ can easily be verified from (8) and (10).

The above formula are relatively simple and can be generalized to the partially polarized case as follows. Suppose that the spin state of an initial (resp. final) particle is only partially fixed (resp. analyzed). The corresponding *density matrix* can be written as

$$\frac{1+a}{2}\, |\bar{\lambda}, \phi\rangle\langle \bar{\lambda}, \phi| + \frac{1-a}{2}\, |\bar{\lambda}, \phi + \pi\rangle\langle \bar{\lambda}, \phi + \pi|, \tag{11}$$

where $\bar{\lambda}$ is the average helicity, ϕ the azimuth of the average transversity $\bar{\mathbf{s}}_T$ and

$$\bar{\lambda}^2 + \bar{\mathbf{s}}_T^2 < 1, \qquad a \equiv \left(1 - \bar{\lambda}^2\right)^{-\frac{1}{2}}\ \bar{s}_T < 1 \tag{12}$$

[for a final particle, replace $(1 \pm a)/2$ by $(1 \pm a)$]. One is led to following receipe :
The partially polarized cross section is obtained from the totally polarized one by multiplying each term of the form $\cos(\cdots \pm\phi_i + \cdots)$, *where fermion n° i is involved, by the corresponding reduction factor* a_i.

I am debtful to Emmanuel Loyer for discussions related to this work.

Tensor Charge and the Electric Dipole Moment

X. Artru*

In the naive nonrelativistic quark model, the quarks in the nucleons are in a S-wave and the magnetic (dipole) moment (MDM) of the nucleon is of the form $\mathrm{MDM}_q \cdot \langle\vec{\sigma}_q\rangle$ (summed over the valence quarks), where MDM_q and $\langle\vec{\sigma}_q\rangle$ are the magnetic moment and the expectation value of the Pauli matrix of the quark. The same should be true for electric dipole moments (EDM), if any. To take into account relativistic effects as well as see quarks, two generalizations of $\langle\vec{\sigma}_q\rangle$ can be considered :

- the axial charge Δq [1], related by a sum rule to the quark helicity distribution,
- the tensor charge δq [2,3], related to the quark transversity distribution.

Arguments are given in favor of the latter [4] :

- Both the tensor charge and the coupling to a MDM or a EDM involve the Dirac matrices $\sigma_{\mu\nu}$
- antiquark contribute with a negative sign to both tensor charge and the nucleon MDM or EDM
- the tensor charge as well as MDM or EDM is a chiral-odd object.
- the tensor charge and the EDM evolve in opposite way with the renormalisation scale [5,6] (the quark transversity is "diluted" at high Q^2 by gluon radiation, the quark EDM is "screened" at low Q^2 by dressing with gluons), so that their product is invariant, as it should be for a physical quantity.

There are, however, "indirect" contributions to the nucleon EDM which are not of the form $\mathrm{EDM}_q \cdot \delta_q$ (see transparent No. 4): For instance, the interaction of a chromo-electric dipole moment (CEDM) of the quark with the internal chromoelectric field can produce a dipole asymmetry $c_q\ \langle\vec{X}_q\rangle$ of the charge density, in a direction parallel to the spin. Similar effects have been predicted to occur in atomic physics and can give a very big enhancement of the ratio (atomic EDM) / (electron EDM) [7]. Also heavy quark loops connected via three gluons to the light quarks can contribute to the nucleon EDM [8,6]. This contribution can not be proportional to δ_q, since the latter is not coupled to gluons [5].

In conclusion, the tensor charge is certainly involved in nucleon electric dipole moment (and magnetic moment [9]), but not in all the possible terms.

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Extended Soffer inequality for $\mathbf{k}_T$ - dependent transversity distribution. Application to single spin asymmmetry in inclusive meson production

X. Artru*

In deriving Soffer's inequality [1]

$$\delta q(x) \leq q^+(x) \tag{1}$$

from positivity, it is assumed that the axis of transverse spin quantification is irrelevant, i.e.

$$\delta_{\hat{\mathbf{x}}} q(x) = \delta_{\hat{\mathbf{y}}} q(x) \equiv \delta q(x) \tag{2}$$

where $\delta_{\hat{\mathbf{y}}} q(x)$ is the distribution of quark polarized in the direction $+\hat{\mathbf{y}}$ minus the distribution of quark polarized in the direction $-\hat{\mathbf{y}}$ in a nucleon polarized in the direction $+\hat{\mathbf{y}}$. In the case of $\mathbf{k}_T$ - dependent quark distribution, the direction of $\mathbf{k}_T$ breaks the rotationnal symmetry about the $\hat{\mathbf{z}}$ direction and the first equality in (2) is lost. The generalization of (1) is then [2]

$$|\delta_{\hat{\mathbf{x}}} q(x, \mathbf{k}_T) + \delta_{\hat{\mathbf{y}}} q(x, \mathbf{k}_T)| \leq 2q^+(x, k_T) \tag{3}$$

For instance, in the toy (quark + scalar-diquark) model of the nucleon (which saturates Soffer's inequality), we have (see Eq. C.4 of Ref.[3]) :

$$\delta_{\hat{\mathbf{y}}} q(x, \mathbf{k}_T) = q^+(x, \mathbf{k}_T) \left(1 + \frac{k_x^2 - k_y^2}{(m_q + x m_N)^2}\right) \tag{4}$$

together with

$$q(x, \mathbf{k}_T) = q^+(x, \mathbf{k}_T) \left(1 + \frac{k_T^2}{(m_q + x m_N)^2}\right) \tag{5}$$

The distributions $\delta_{\hat{\mathbf{x}}} q(x, \mathbf{k}_T)$ and $\delta_{\hat{\mathbf{y}}} q(x, \mathbf{k}_T)$ for $\mathbf{k}_T$ along $\hat{\mathbf{x}}$ can be expressed in terms of the distributions $h_{1T}(x, \mathbf{k}_T)$ and $h_{1T}^{\perp}(x, \mathbf{k}_T)$ adopted in this workshop [4].

Single spin asymmetry in inclusive meson production has been explained [5-7] in terms of $\delta q(x) \equiv 2h_1(x)$ and the *sheared* (or "Collins") *jet effect.* In Ref.[5] the explanation was unconfortable for the following reasons :

a) a large value of $h_1(x)$ and a large sheared jet effect was needed,
b) Soffer's inequality was just satisfied, using data on $g_1(x)$ available at that date (present data are still more constraining). This question is specially discussed in [7].

However, triggering a meson with a large $\mathbf{p}_T$ induces a bias on the intrinsic $\mathbf{k}_T$ of the initial active quark, which will be more likely in the direction of $\mathbf{p}_T$ (see the picture at the bottom of the transparent). Therefore a $\mathbf{k}_T$ - dependent polarized transversity distribution

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should be used instead of the $\mathbf{k}_T$ - integrated one $\delta q(x)$. Assuming that $\mathbf{p}_T$ is in the $\hat{\mathbf{x}}$ direction, and the nucleon polarized in the $\hat{\mathbf{y}}$ direction, we have to replace

$$\frac{\delta q(x)}{q(x)}\, q(x, \mathbf{k}_T)\,, \tag{6}$$

which was effectively used in [5], by $\delta_{\hat{\mathbf{y}}} q(x, \mathbf{k}_T)$.

As suggested by the quark + scalar-diquark model (Eqs.4-5), and considering the trigger bias which makes $\langle k_x^2 \rangle \gg \langle k_y^2 \rangle$, m_N^2 or m_q^2, one guess that the above difficulties a) and b) may be greatly diminished. A new simulation using the $\mathbf{k}_T$ - dependent polarized distribution $\delta_{\hat{\mathbf{y}}} q(x, \mathbf{k}_T)$ should be undertaken to confirm it quantitatively.

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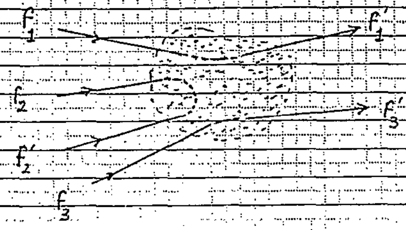
RIKEN BNL WORKSHOP Sept 2000
Future transversity measurement

Cardan invariance (massless fermions) of transversity cross sections

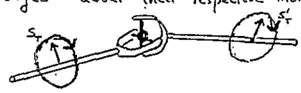


general fermion state : $|\vec{p}, \lambda, \mathbf{s}_T\rangle$

with $\lambda^2 + \mathbf{s}_T^2 = 1$

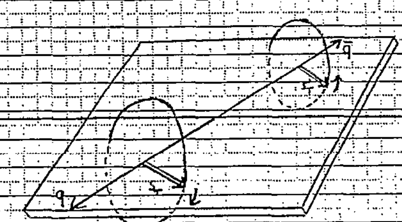
(one can replace S_T by the 4-vector S_T^μ ,
defined up to a "gauge transformation" :
$s_T^\mu \to s_T^\mu + c\, p^\mu$)

Theorem : The $|\text{amplitude}|^2$ is invariant if one rotates the transversities of two connected fermions by a common angle about their respective momenta



XA-1

application to $e^+e^- \to q\bar{q}$



invariant under simultaneous OPPOSITE rotations of $\mathbf{s}_T$ and $\mathbf{s}_T'$

$$\frac{d\hat{\sigma}}{d\Omega} = \left(\frac{d\hat{\sigma}}{d\Omega}\right)_{\text{unpol.}} \left\{ 1 - \hat{a}_{NN} \cos(\varphi + \varphi') \right\}$$

equivalent : $\left\{ 1 + \hat{a}_{NN}\, \mathbf{s}_T \cdot \mathcal{R}\, \mathbf{s}_T' \right\}$

rotation of π about the normal to scattering plane

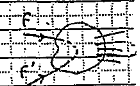
$\Rightarrow$ the quarks remember about the azimuth of the electron with respect to the $q\bar{q}$ axis demonstration

complex numbers

$$|\lambda, s_T\rangle = a|+\rangle + b|-\rangle$$

$$|\lambda', s'_T\rangle = a'|+\rangle + b'|-\rangle$$

• case where f and f' are both ingoing



amplitude $= \langle X | T | f, f' \rangle$

$$|f, f'\rangle = \underbrace{aa'|+\rangle|+\rangle}_{\text{does not contribute}} + ab'|+\rangle|-\rangle + ba'|-\rangle|+\rangle + \underbrace{bb'|-\rangle|-\rangle}_{\text{does not contribute}}$$

"cardan" rotation: $a \to a\, e^{-i\theta/2}$; $b \to b\, e^{+i\theta/2}$

same for a' and b'

$\Downarrow$

$\langle X | T | f f' \rangle$ does not change

"See-saw" invariance

$$\left.\begin{aligned} a &\equiv (\operatorname{ch}\chi)^{-1/2} \exp\left(\frac{\chi - i\varphi}{2}\right) \\ b &\equiv (\operatorname{ch}\chi)^{-1/2} \exp\left(\frac{-\chi + i\varphi}{2}\right) \end{aligned}\right\} \quad \begin{aligned} \lambda &= \tanh \underset{\text{"chiradity"}}{\chi} \\ |s_T| &= \frac{1}{\operatorname{ch}\chi} \end{aligned}$$

For an antifermion, replace χ by $-\chi$

$$\frac{|\text{amplitude}|^2}{\operatorname{ch}\chi \, \operatorname{ch}\chi'} = \text{invariant under opposite "chiradity" shifts of f and } \bar{f}$$

XA-3

$$\overset{\circlearrowleft\ \circlearrowleft}{e^+ e^-} \to \overset{\circlearrowleft\ \circlearrowleft}{f \bar{f}} :$$

$$\frac{d\sigma}{d\Omega} = \frac{|G(s)|^2}{256\pi^2 s} \times \prod_{\text{all particles}} |s_T| \times \mathbf{H}$$

cardan + see-saw invariant

$$\mathbf{H} = A + B\left[u^2 \cos(\varphi_+ - \varphi_- + \varphi_f - \varphi_{\bar{f}}) + t^2 \cos(\varphi_+ - \varphi_- - \varphi_f + \varphi_{\bar{f}})\right] + C \cos(\varphi_+ - \varphi_-) + D \cos(\varphi_f - \varphi_{\bar{f}})$$

with A, B, C, D cardan-invariant ;

for instance : $C = 2tu\, g^e_R\, g^e_L \left[\exp(\chi_f + \chi_{\bar{f}})\, {g^f_R}^2 + \exp(-\chi_f - \chi_{\bar{f}})\, {g^f_L}^2\right]$

electroweak couplings to the Z^0

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Tensor Charge and Electric Dipole Moment :

can we say :

$$\text{EDM}_{\text{nucleon}} = \text{T.C.} \times \text{EDM}_{\text{quark}} \;?$$

recall :

$$\text{T.C.} = \delta q - \delta \bar{q} = \int_0^1 dx \left[\delta q(x) - \delta \bar{q}(x) \right]$$

Naive argument :

quark magnetic moment $\vec{\mathcal{M}} = \mu \, \vec{\sigma}$

" elec. dipole " $\vec{\mathcal{D}} = \text{edm} \, \vec{\sigma}$

$$\Downarrow$$

$$\text{EDM (nucleon)} = \text{E.D.M. (quark)} \times \underbrace{\langle \vec{\sigma}_{\text{quark}} \rangle \cdot \hat{S}_{\text{nucleon}}}_{\text{"spin carried by the quark"}}$$

- Ellis and Flores, G. Karl $\Big\} \rightarrow$ take Δq (axial charge)
- X.A.*, T. Falk et al $\Big\} \rightarrow$ take $\delta q - \delta \bar{q}$ (tensor charge)
- See also de Rújula, CERN-Th-5908/90 ; R. Nag, P.T.P 91 (1994)

* ELFE summer school, Cambridge 1995

XA-5

Arguments in favor of δq (rather than Δq)

- effective e.d.m. lagrangian | tensor charge

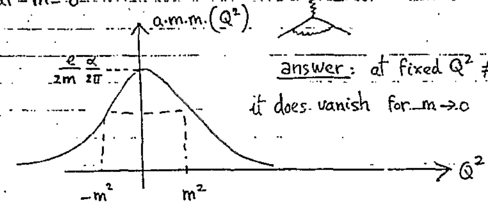
$$\frac{i}{2} (\text{e.d.m.}) \, F^{\mu\nu} \, \bar{\psi} \, \sigma_{\mu\nu} \, \gamma_5 \, \psi \qquad \Big| \qquad \langle N | \int d^3x \; \bar{\psi} \, \sigma_{\mu\nu} \, \psi \, | N \rangle$$

$$\bar{N} \, \sigma_{\mu\nu} \, N$$

- charge conjugation $= -1$
- e.d.m. = chiral - odd interaction

(same for anomalous magnetic moment)

apparent paradox : the m.m.a. of $e^{\pm}$ is $\pm \frac{e}{2m} \frac{\alpha}{2\pi}$.
Naive chirality argument would say that it vanishes at $m = 0$



answer : at fixed $Q^2 \neq 0$, it does vanish for $m \to 0$

- Contrary to the axial charge, the tensor one is scale-dependent:

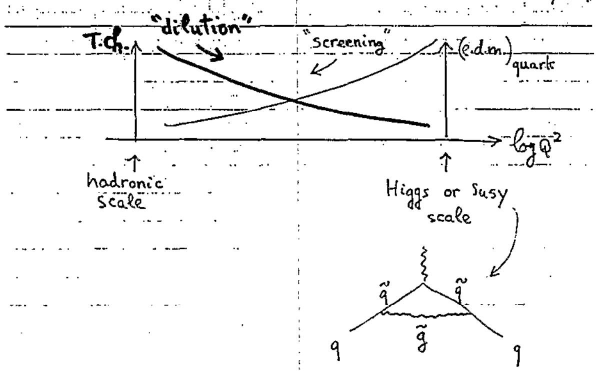
$$\text{T.Ch.} \propto \alpha_s(Q^2)^{\frac{4}{33-2N_f}} \qquad (\text{LLA})$$

Fortunately, the E.D.M. of the quark also evolves:

$$\text{e.d.m.} \propto \alpha_s(Q^2)^{-\frac{4}{33-2N_f}}$$

(See, for instance, de Rújula et al. Phys.Lett. B 245),

so that the E.D.M. of the nucleon is scale-independent.



XA-7

"LESS GOOD" NEWS:

T-violating part of a neutron energy in a constant external field $\mathbf{E}$ (take $\hat{\mathbf{S}} \parallel \mathbf{E}$):

$$\mathcal{W} = \langle \text{neutron} | \int d^3\mathbf{x}\ \psi_q^\dagger(\mathbf{x}) \left\{ -e_q\, \mathbf{E}\cdot\mathbf{X} - (\text{e.d.m.})_q\ \beta\left(\boldsymbol{\Sigma}\cdot\mathbf{E}_{tot} + i\,\boldsymbol{\alpha}\cdot\mathbf{B}_{\underset{\text{"internal"}}{int}}\right)\right\} \psi_q(\mathbf{X}) | \text{neutron} \rangle$$

$$\mathbf{E}_{tot} \equiv \mathbf{E} + \mathbf{E}_{int}, \qquad (\text{e.d.m.})_{\text{neutron}} \equiv -\frac{d\mathcal{W}}{d\mathbf{E}}$$

- term in $\beta\,\boldsymbol{\Sigma}\cdot\mathbf{E}$ $\rightarrow$ $\boxed{(\text{T.C.}) \times (\text{edm})_{\text{quark}}}$
- terms in $\beta\,\boldsymbol{\Sigma}\cdot\mathbf{E}_{int}$ and $\beta\,\boldsymbol{\alpha}\cdot\mathbf{B}_{int}$ $\rightarrow$ permanent P-wave contamination of the internal wave function
  - ↳ non-zero value of $\langle \mathbf{X}_q \rangle$ (Schiff moment)
  - ↳ $\boxed{\text{contribution of the } \mathbf{E}\cdot\mathbf{X} \text{ term}}$
- Such "indirect" contribution also occurs with a chromo-electric dipole moment

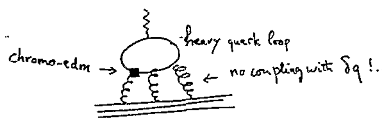
XA-8

– What about the e.d.m. of atoms ?

$$\frac{(\text{e.d.m.})\,(\text{thallium or Cesium})}{(\text{e.d.m.})\,(\text{electron})} \sim 10^{2-3}$$

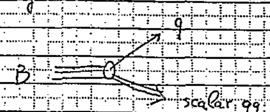
- can only come from the indirect contribution
- the big enhancement comes from a large polarisability of such atoms (see B.P. Das, APCTP Bulletin april 99)

Conclusion
- tensor charge is involved in nucleon electric dipole moment but there are other contributions (indirect, chromo-electric-d.m. ...) (see, e.g. De Rujula et al Phys. Lett. B 245 640 '90).
- it may also be involved in nucleon anomalous magnetic moment (model of X-S Chen hep-ph/98 02 347)



XA-9

Toy model — By-passing Soffer — X. ARTRU RIKEN-BNL workshop Future Transversity measurements Sept 2000



$$\delta q(x) = q^{+}(x) \propto (m + xM)^2$$

→ Soffer saturated (≠ no leakage of quantum information)

- at fixed $\vec{k}_T$ (rotational invariance lost)

orientation of $\perp$ spin

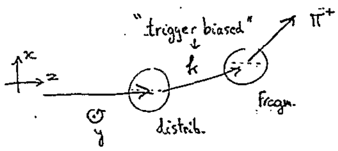
$$\boxed{\delta_x q + \delta_y q \leqslant 2 q^{+}}$$

but $\delta_x q \neq \delta_y q$ type $h_{1T}^{\perp}$

in fact : $\delta_x q(x, \vec{k}_T) \propto (m + xM)^2 + k_x^2 - k_y^2$

(Artru & Mekhfi '90) appendix C

single spin asym. in $\pi^{\pm}$ prod. from $p\,\vec{p}$ collision



trigger bias : $\langle k_x \rangle$ "large" and positive

XA-10

LATTICE CALCULATION of NUCLEON MATRIX ELEMENTS using DOMAIN WALL FERMIONS

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(RBC Collaboration)

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I. Introduction

- (moments of) Nucleon Structure Function and PDF's can be calculated in QCD using Lattice Gauge Theory

- 1^{st} step, calculate lowest moments of g_1 and h_1, Δq and δq, (axial and tensor charges).

- $2 s_\mu \Delta q = \underline{\langle p,s | \bar{q} \gamma_5 \gamma_\mu q | p,s \rangle}$

  $2(s_\mu p_\nu - s_\nu p_\mu)\, \delta q = \underline{\langle p,s | i\bar{q}\, \sigma_{\mu\nu} \gamma_5 q | p,s \rangle}$

  $(s^2 = -1, \quad q = u, d, s)$

  $\sigma_{\mu\nu} = \frac{[\gamma_\mu, \gamma_\nu]}{2}$

(Introduction, cont'd)

exp. value

- $G_A = \Delta u - \Delta d$ 1.267
- $G_V = 1$ (SU(2) flavor sym)
- Singlet Axial Charge (quark "spin" contribution to the proton)

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \lesssim 25\%$$

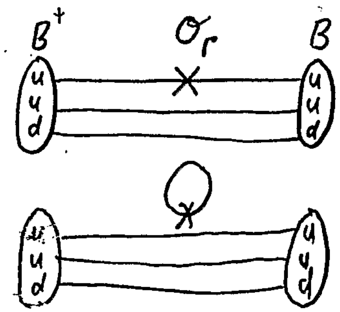
- Tensor Charge

$$\delta\Sigma = \delta u + \delta d + \delta s \qquad —$$

(Introduction, cont'd)

- Need $s^\mu \langle p,s|\bar{q}\,\Gamma_\mu q|p,s\rangle$ in rest frame
- obtain it from correlation function

$$G_\Gamma(t,t') = \mathrm{Tr}\left[(1+\gamma_t)\Gamma_i \sum_{x,y,z} B(x,t)(\bar{q}\,\Gamma_i q)_{y,t} B^\dagger(z,0)\right]$$



t_{source}, t_{sink} Fixed

"connected"

Wick contractions

"disconnected"

$t =$ t_{source} t t_{sink}

- For $t_{sink} \gg t \gg t_{source}$ ("plateau")

$$\langle G_\Gamma(t_{sink}, t, t_{source})\rangle_{gauge} \rightarrow$$

$$s^\mu e^{-M_N(t_{sink}-t_{source})} \frac{\langle 0|B|N\rangle\langle N|\bar{q}\,\Gamma_\mu q|N\rangle\langle N|B|0\rangle}{2M_N}$$

$$G_N(t_{sink}, t_{source}) \rightarrow \frac{\langle 0|B|N\rangle\langle N|B^\dagger|0\rangle}{2M_N} e^{-M_N(t_{si}-}$$

- In this study we use "quenched" gauge ensemble and calculate connected piece only

(Introduction, cont'd)

- Lattice operators must be renormalized

$$O_\Gamma^{cont.}(\mu) = Z_\Gamma(a\mu)\, O_\Gamma^{Latt}(a)$$

- Need Z_A, $Z_T(a\mu)$:

$$\left(\frac{G_A}{G_V}\right)^{cont} = \frac{Z_A G_A^{latt}}{Z_V G_V^{latt}} = \frac{G_A^{latt}}{G_V^{latt}}$$

since $\frac{Z_A}{Z_V} = 1$ for DWF

also, $G_V^{cont} = Z_V G_V^{latt} = 1$

$\therefore Z_V = (G_V^{latt})^{-1}$ good ✓

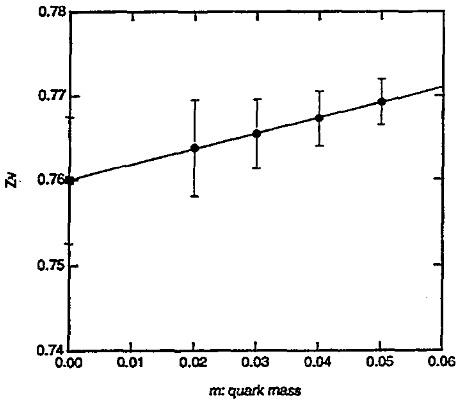
- for δq need Z_T, take from our NPR study of quark bilinears

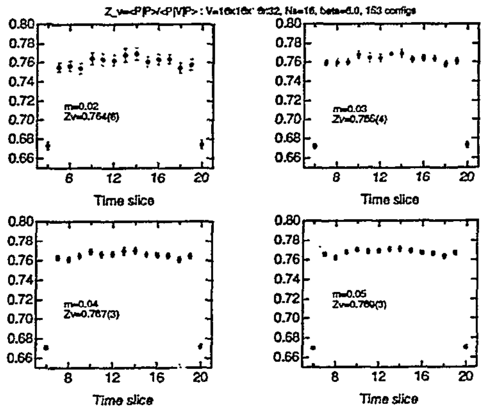
II. Results

Numerical calculations

- RIKEN-BNL-Columbia-KEK QCDSP,
- 150-200 gauge configurations, using a heat-bath algorithm,
- $\beta = 6.0$, $16^3 \times 32 \times 16$, $M_5 = 1.8$,
- source at $t = 5$, sink at 21, current insertions in between.

$Z_V = 1/G_V^{\text{lattice}}$ is well-behaved,

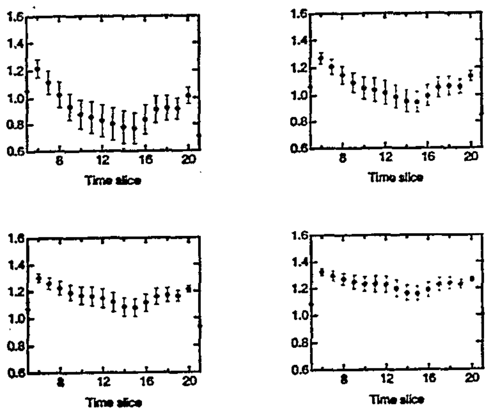


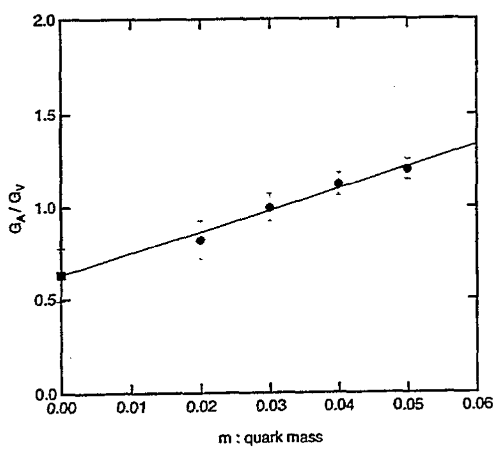


- the value 0.764(6) at $m_f = 0.02$ agrees well with $Z_A = 0.7555(3)$ from $-\langle A_\mu^{\text{conserved}}(t)\bar{q}\gamma_5 q(0)\rangle = Z_A \langle A_\mu^{\text{local}}(t)\bar{q}\gamma_5 q(0)\rangle$ (RBCK hep-lat/0007033),
- linear fit gives $Z_V = 0.760(7)$ at $m_f = 0$.

$$G_A = \Delta u^{conn} - \Delta d^{conn} \qquad (\Delta u^{disc} = \Delta d^{disc})$$

G_A/G_V: averaged in $10 \le t \le 16$,





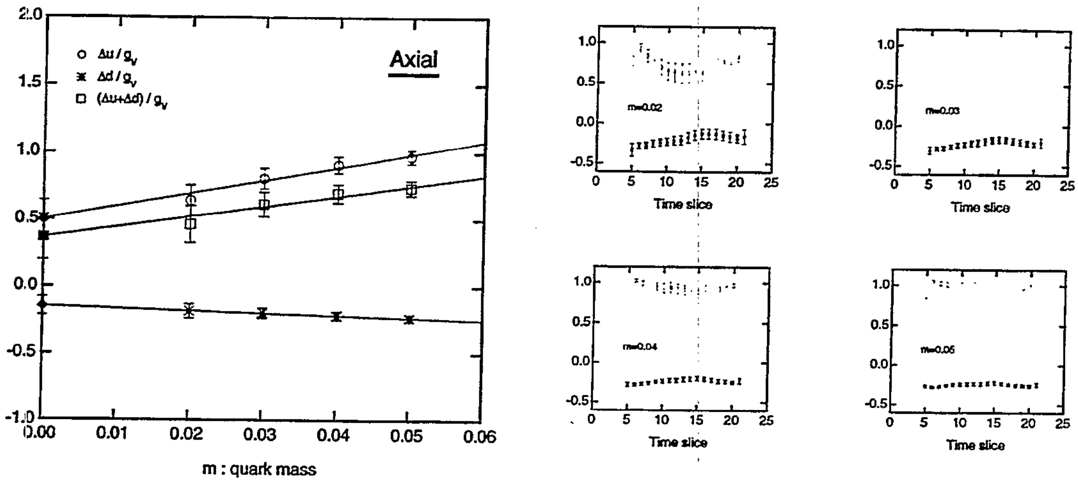
- linear extrapolation yields 0.63(14) at $m_f = 0$.

- $\left(\frac{G_A}{G_V}\right)^{exp.} = 1.267$

X 2 too small!

$$\Delta\Sigma = \overset{con}{\Delta u} + \overset{con}{\Delta d} + \cancel{\Delta s}$$

Δq

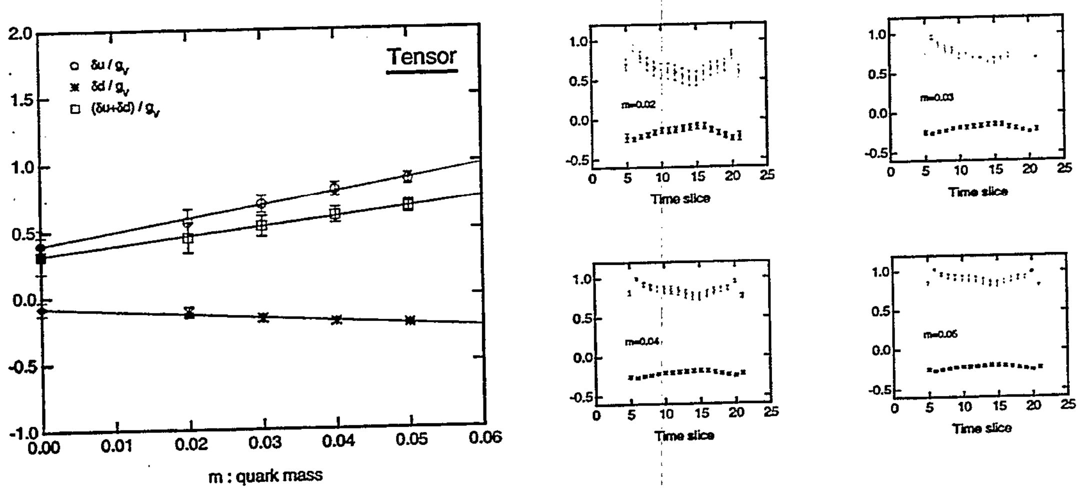


- $\Delta u/G_V = 0.50(14)$ and $\Delta d/G_V = -0.15(7)$ by linear extrapolation to $m_f = 0$.

- $\Delta\Sigma^{exp} \sim .1 - .2$
- $\Delta q^{disc} < 0$ (not included in our calc.)

$$\delta\Sigma = \overset{conn}{\delta u} + \overset{conn}{\delta d} + \cancel{\delta s}$$

δq



- $\delta u/G_V = 0.40(12)$ and $\delta d/G_V = -0.08(5)$ by linear extrapolation to $m_f = 0$,
- a preliminary value for Z_T/Z_A is 1.1(1) [5].

[5] A forthcoming RBCK paper.

Summary:

- Relevant three-point functions are well behaved in DWF,
- $Z_V = Z_A$ is well satisfied, 0.760(7) and 0.7555(3),
- linear extrapolation to $m_f = 0$ gives
  - $G_A/G_V = 0.63(14)$,
  - $\Delta q/G_V = 0.37(17)$,
  - $(\delta q/G_V)^{\text{lattice}} = 0.32(14)$, with a preliminary $Z_T \sim 1.1(1)Z_A$, in progress.
- Further study required to check systematic errors arising from
  - finite lattice volume,
  - excited states (small separation between t_{source} and t_{sink}),
  - quenching (zero modes, absent pion cloud, ...),

  especially in the lighter quark mass region.

- include "disconnected" diagrams

(Transverse Spin) Asymmetries in DVCS.

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The last few years have witnessed an essential progress in the theory of skewed parton distributions (SPDs). The latter enter as functions describing soft scale physics in factorizable processes such as deeply virtual Compton scattering $eN \to e'N'\gamma$, diffractive production of hadrons $eN \to e'N'H$ etc. An SPD is a kind of trinity object which unifies the concept of parton densities, distribution amplitudes and form factors in one function. It possesses a rich structure and carries a wealth of information on hadron constituents. SPDs acquire the definition in terms of a Fourier a transform of light-ray quark (gluon) operators sandwiched between hadronic states with unequal momenta, e.g.

$$\langle P_2|\bar{\psi}(-\lambda n)\gamma_\mu\psi(\lambda n)|P_1\rangle = \int_{-1}^{1} dx e^{-i\lambda x(P_1+P_2)\cdot n} \times \left\{ H(x,\eta,\Delta^2)\bar{U}(P_2)\gamma_\mu U(P_1) + E(x,\eta,\Delta^2)\bar{U}(P_2)\frac{i\sigma_{\mu\nu}\Delta_\nu}{2M}U(P_1)\right\}, \quad (1)$$

where we have performed a decomposition into independent Dirac structures (for the proton) which encode the information about the spin content of the target. As we note, contrary to the conventional parton distributions, SPDs depend on top of hadron momentum fraction x also on the longitudinal t-channel momentum $\eta = (P_2 - P_1)\cdot n/(P_1 + P_2)\cdot n$, the so-called skewedness, and momentum transfer squared $\Delta^2 \equiv (P_2 - P_1)^2$.

A lot of insights has been gained into perturbative properties of SPDs. The evolution equations have been constructed and renormalization group kernels have been calculated in two-loop approximation. The numerical magnitude of these effects is moderate. On the other hand, radiative corrections to DVCS amplitude modify leading order predictions significantly.

The aforementioned definition (1) was given for non-polarized proton. Once it has a polarization there are extra two functions, called $\widetilde{H}$ and $\widetilde{E}$. One can introduce the quark helicity flip SPDs – counterparts of the usual forward quark transversity, — however, they do not contribute neither to DVCS (due to zero quark masses) nor to diffraction. Yet there is a tensor gluon operators which describes gluon helicity flip by two units and provides two further SPDs. The off-forwardness of DVCS favours their presence even for spin one-half hadrons due to possible non-zero orbital momentum of the product. By the same reason the effects of this kind are absent in conventional DIS, but emerge for higher spin targets. Since gluons show up at order $\mathcal{O}(\alpha_s)$ we can neglect them in a first approximation. Thus, the electroproduction cross section will depend in general on four unknown SPDs H, E, $\widetilde{H}$ and $\widetilde{E}$.

For $eN \to e'N'\gamma$ the DVCS amplitude will interfere with the Bethe-Heitler process. Therefore, apart from $|\mathrm{DVCS}|^2$ term we will have $|\mathrm{BH}|^2$ and $\mathrm{BH}^* \cdot \mathrm{DVCS} + \mathrm{BH} \cdot \mathrm{DVCS}^*$. Provided BH would be absent, it will be extremely difficult (or even not possible) to extract any information on SPDs since, first, the cross section would have dependence on SPD^2 and, second, one cannot invert in practice the convolution of an SPD with a perturbative coefficient function. The presence of BH provides a unique opportunity to access SPDs directly. The $|\mathrm{BH}|^2$ is not a problem since it can be removed by forming appropriate asymmetries w.r.t. lepton charge or/and lepton and hadron polarizations. The interference term is a linear function of SPDs multiplied by (known) Dirac and Pauli form factors which parametrize BH amplitude. Various spin asymmetries measure imaginary part of DVCS amplitude and thus, at leading order in QCD coupling constant, SPDs directly for the kinematical situation when momentum fraction equals skewedness $H(\eta,\eta)$. The leading twist asymmetries are dominated by $\cos\phi/\sin\phi$ azimuthal angle dependence, see e.g. [1]. Once twist-three effects are switched on, one generates $\cos(2\phi)/\sin(2\phi)$ structures [2]. The gluon helicity flip effects are isolated by genuine $\cos(3\phi)$ and $\sin(3\phi)$ dependence which arise for non-polarized and longitudinally polarized proton settings, respectively [3]. Numerical estimates of single spin asymmetries show an agreement with the recent results from HERMES [4]. This is a first step of a long way one has to go before one can get the experimental constraints on the skewed parton distribution for different parton helicity components. For this purpose, all possible asymmetries have to be employed as they are sensitive to various combinations of SPDs. We expect more detailed information from the DVCS measurement at Jefferson accelerator facility soon [5].

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BNL / September 20 2000

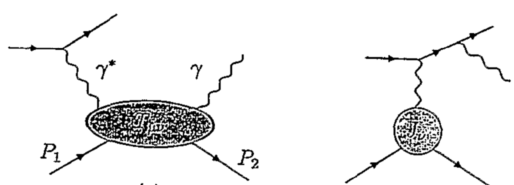
(Transverse Spin) Asymmetries in DVCS.

Andrei Belitsky

(YITP, SUNY Stony Brook)

DVCS:

$$e(k)N(M) \to e(k')N(P_2)\gamma(q_2).$$



(a) (b)

Kinematical variables

$Q^2 \equiv -q_1^2$ large

$x \equiv -q_1^2/(2P_1 q_1)$ fixed

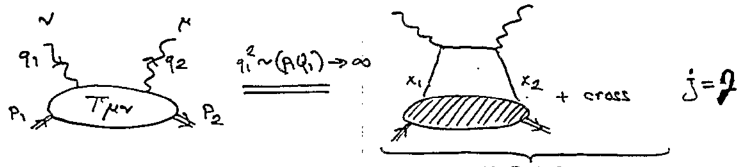
$\Delta^2 = (P_2 - P_1)^2$ small

$y = P_1 \cdot q_1 / P_1 \cdot k = \dfrac{Q^2}{x \cdot s}$

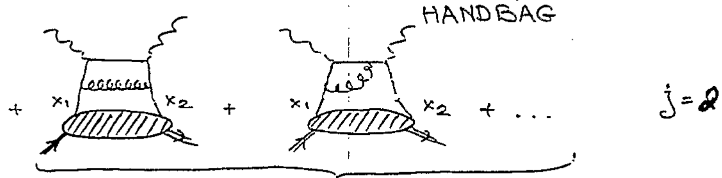
- DVCS amplitude.

$$T_{\mu\nu} \equiv i \int d^4x \, e^{\frac{i}{2}(q_1+q_2)\cdot x} \langle P_2 | T\{ j_\mu(\tfrac{x}{2}) j_\nu(-\tfrac{x}{2}) \} | P_1 \rangle$$

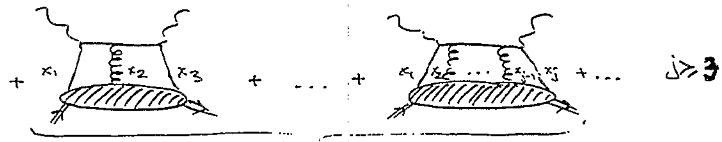
In QCD we write



HANDBAG



HIGHER ORDER CORRECTIONS



HIGHER TWIST CORRECTIONS

$$T_{\mu\nu} = \mathcal{T}_{\mu\nu}(p_i, q_i, \ldots) \sum_{j=2}^{\infty} \left(\frac{\Lambda_{had}^2}{Q^2} \right)^{j-2} \int \{dx_i\} \, T(x_{Bj}, \{x_i\} | ds) \, \mathcal{O}(\{x_i\} | \ldots$$

LORENTZ TENSOR — COEFFICIENT FUNCTION — SPD

+ ...

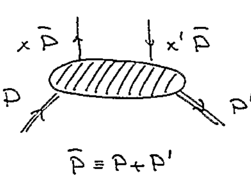
- SPD's & their properties.

Q: What are SPD functions?

A: SPD's are new non-perturbative inputs used in exclusive electro-production processes to paramet-rize hardronic substructure.

Ditles Geyer Möller Robaschik Hořejši '94
Ji '97
Radyushkin '97

Characteristic feature is a non-zero momentum transfer in the t-channel

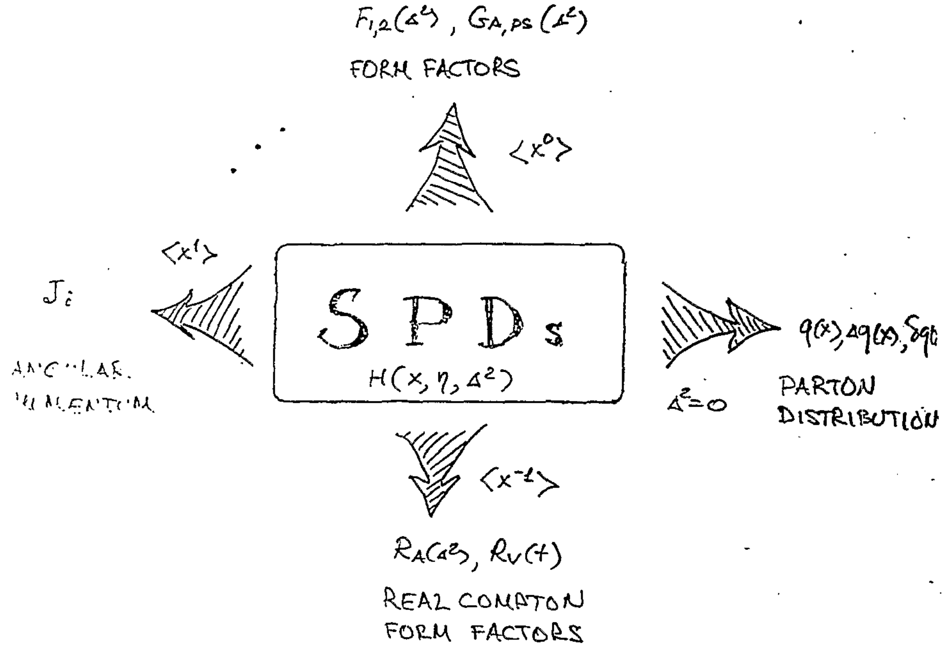


$$= \langle P' | \varphi^\dagger(x') \varphi(x) | P \rangle$$

$$P - P' = \eta \bar{P};$$

$$\bar{P} \equiv P + P'$$

η — skewedness
(sometimes ξ)



- FORM FACTOR DECOMPOSITION

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}(-\tfrac{\lambda}{2} n) \gamma_\mu \psi(\tfrac{\lambda}{2} n) | P \rangle$$

$$= H(x,\eta,\Delta^2)\, \bar{U}(P') \gamma_\mu U(P)$$

$$+ E(x,\eta,\Delta^2)\, \bar{U}(P') \frac{i\sigma_{\mu\nu}\Delta^\nu}{2M} U(P)$$

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \bar{\psi}(-\tfrac{\lambda}{2} n) \gamma_\mu \gamma_5 \psi(\tfrac{\lambda}{2} n) | P \rangle$$

$$= \tilde{H}(x,\eta,\Delta^2)\, \bar{U}(P') \gamma_\mu \gamma_5 U(P)$$

$$+ \tilde{E}(x,\eta,\Delta^2)\, \bar{U}(P')\, i\gamma_5 \frac{\Delta_\mu}{2M} U(P)$$

$O^{val}(x,\eta)$ evolved up to $Q^2 = 100$ GeV^2

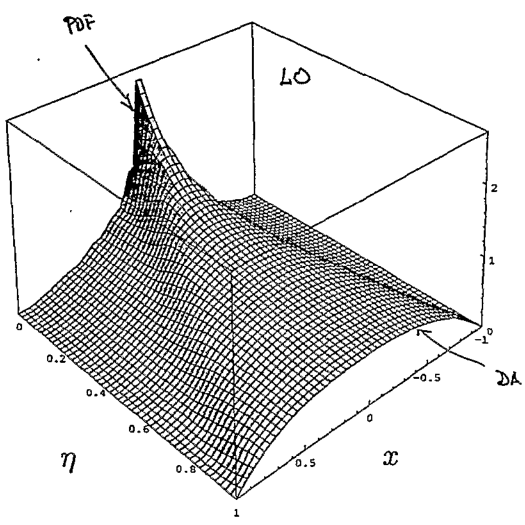


Figure 2: Distribution from Fig. 1 evolved with LO formulae up to $Q^2 = 100\,\mathrm{GeV}^2$.

Model for SPD

For numerical estimate we choose an oversimplified factorized form of distribution:

$$O(X,\xi,\Delta^2,Q^2) = F(\Delta^2)q(X,\xi,Q^2).$$

Here

- $F(\Delta^2)$ is an elastic parton form factor
- $q(X,\xi,Q^2)$ is a non-forward function

The non-forward function for QUARKS is modeled as follows

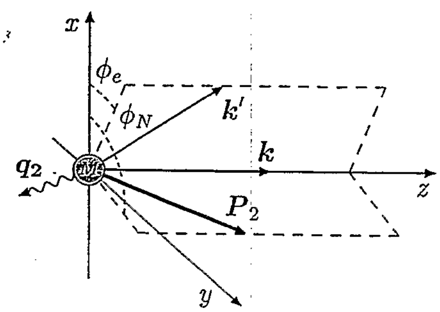
$$q(X,\xi,Q^2) = \int_{-1}^{1} dx \int_{-1+|x|}^{1-|x|} dy\ \delta(X+\xi y - t)\frac{3}{4}\frac{[1-|x|]^2 - y^2}{[1-|x|]^3}\ q(x),$$

with forward quark parton density $q(x)$.
Dipole-type elastic form factor is assumed in estimates

$$F(\Delta^2) \propto \left(1+\frac{\Delta^2}{\Lambda^2}\right)^{-2}$$

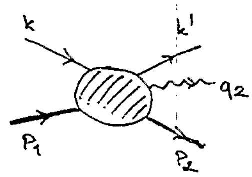
The kinematics of the reaction

in the laboratry frame, i.e. the rest frame of the target



Azimuthal angle

$$\phi_r = \phi_N - \phi_e,$$



Cross section for real photon electroproduction.

$$\frac{d\sigma}{dx\,dy\,d|\Delta^2|\,d\varphi_r} = \frac{\alpha_{em}^3}{8\pi}\,\frac{xy}{Q^2}\left(1+\frac{4M^2x}{Q^2}\right)^{-\frac{1}{2}}\left|\frac{\mathcal{T}}{e^3}\right|^2;$$

as usual

$$y = 1-\frac{E'}{E}\,, \qquad Q^2 = -q_1^2;$$

Here

$$\varphi_r \equiv \varphi_N - \varphi_{e'};$$

$$|\mathcal{T}|^2 = \sum_{\text{spins}}' \left\{ |\mathcal{T}_{VCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{T}_{VCS}\mathcal{T}^*_{BH} + \mathcal{T}^*_{VCS}\mathcal{T}_{BH} \right\}$$

where

$$\mathcal{T}_{BH} = -\frac{e^3}{\Delta^2}\,\varepsilon^*_\mu \underbrace{L_{\mu\nu}}_{\text{leptonic tensor}} J_\nu$$

electron

positron

$$\mathcal{T}_{VCS} = \mp \frac{e^3}{q_1^2}\,\varepsilon^*_\mu \underbrace{T_{\mu\nu}}_{\text{DVCS tensor}}\,\bar{u}(k')\gamma_\nu u(k)$$

and

$$J_\nu = \bar{U}(P_2)\left\{ \underbrace{F_1(\Delta^2)}_{\text{Phase}}\gamma_\nu + i\,\underbrace{F_2(\Delta^2)}_{\text{PAULI}}\,\frac{\sigma_{\nu\tau}\Delta_\tau}{2M} \right\} U(P_1)$$

FORM FACTORS

AB-10

Phase space

$$d\mathcal{M} = \frac{\alpha^3 xy}{8\pi Q^2}\left(1+\frac{4M^2x}{Q^2}\right)^{-1/2} dx\,dy\,d|\Delta^2|\,d\phi_r.$$

Off-forward functions

$$\mathcal{O}(\xi,\Delta^2) = \int_{-1}^{1} dX\,\left\{\frac{Q_i^2}{1-X/\xi-i\epsilon} \mp (X\to -X)\right\} O_i(X,\xi,\Delta^2),$$

with O_i being a given quark (of charge Q_i) skewed parton distribution.

A.B, Müller, Niedermeier, Schäfe

Asymmetries (for $\Delta^2_{\min}/\Delta^2 \ll 1$):

1. Polarized lepton beam and unpolarized target:

$$\Delta_{\rm SL} d\sigma \equiv d\sigma^{\uparrow} - d\sigma^{\downarrow}$$
$$= -\frac{16(2-y)\sqrt{1-x}}{\sqrt{1-y}x\sqrt{-\Delta^2 Q^2}} \sin(\phi_r) {\rm Im}\left\{F_1\mathcal{H}_1 + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2}F_2\mathcal{E}_1\right\} d\mathcal{M}.$$

2. Unpolarized lepton beam and longitudinally polarized target:

$$\Delta_{\rm SLN} d\sigma \equiv d\sigma_{\Uparrow} - d\sigma_{\Downarrow} = \frac{16(2-2y+y^2)\sqrt{1-x}}{\sqrt{1-y}yx\sqrt{-\Delta^2 Q^2}} \sin(\phi_r)$$
$$\times {\rm Im}\left\{\frac{x}{2-x}(F_1+F_2)\mathcal{H}_1 + F_1\widetilde{\mathcal{H}}_1 + \frac{x}{2-x}\left(\frac{x}{2}F_1 + \frac{\Delta^2}{4M^2}F_2\right)\tilde{\mathcal{E}}_1\right\} d\mathcal{M}.$$

3. Unpolarized lepton beam and transversally polarized target: ($\Phi = \{0, \pi\}$):

$$\Delta_{\rm STN} d\sigma \equiv d\sigma_{\rightarrow} - d\sigma_{\leftarrow} = \frac{16(2-2y+y^2)}{\sqrt{1-y}yx(2-x)\sqrt{Q^2M^2}}$$
$$\times\left[\frac{\cos(3\phi_r/2)}{2\pi}(1-x){\rm Im}\left\{2F_2(\mathcal{H}_1+\widetilde{\mathcal{H}}_1) - [(2-x)F_1 - xF_2]\mathcal{E}_1 - xF_1\tilde{\mathcal{E}}_1\right\}\right.$$
$$+\frac{\cos(\phi_r/2)}{2\pi}{\rm Im}\{2(1-x)F_2(\mathcal{H}_1 - \widetilde{\mathcal{H}}_1) - [(2-x)F_1 + xF_2]\mathcal{E}_1$$
$$\left. + x(F_1 + xF_2)\tilde{\mathcal{E}}_1\}\right] d\mathcal{M}.$$

4. Charge asymmetry in unpolarized experiment:

$$\Delta_{\rm C}^{\rm unp} d\sigma \equiv d^{+}\sigma^{\rm unp} - d^{-}\sigma^{\rm unp} = -\frac{16(2-2y+y^2)\sqrt{1-x}}{\sqrt{1-y}yx\sqrt{-\Delta^2 Q^2}}\cos(\phi_r)$$
$$\times {\rm Re}\left\{F_1\mathcal{H}_1 + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2}F_2\mathcal{E}_1\right\} d\mathcal{M}.$$

Charge, single (lepton) spin, single longitudinal and transverse proton spin asymmetries

Azimuthal averaging

$$A_{\rm C} = \left(\int_{-\pi/2}^{\pi/2} d\phi_r \frac{\Delta_{\rm C}^{\rm unp} d\sigma}{d\phi_r} - \int_{\pi/2}^{3\pi/2} d\phi_r \frac{\Delta_{\rm C}^{\rm unp} d\sigma}{d\phi_r}\right) / \left(\int_0^{2\pi} d\phi_r \frac{d^{-}\sigma^{\rm unp} + d^{+}\sigma^{\rm unp}}{d\phi_r}\right)$$

$$A_{\rm SL} = \left(\int_0^{\pi} d\phi_r \frac{\Delta_{\rm SL} d\sigma}{d\phi_r} - \int_{\pi}^{2\pi} d\phi_r \frac{\Delta_{\rm SL} d\sigma}{d\phi_r}\right) / \left(\int_0^{2\pi} d\phi_r \frac{d\sigma^{\uparrow} + d\sigma^{\downarrow}}{d\phi_r}\right)$$

$$A_{\rm SLN} = \left(\int_0^{\pi} d\phi_r \frac{\Delta_{\rm SLN} d\sigma}{d\phi_r} - \int_{\pi}^{2\pi} d\phi_r \frac{\Delta_{\rm SLN} d\sigma}{d\phi_r}\right) / \left(\int_0^{2\pi} d\phi_r \frac{d\sigma_{\Uparrow} + d\sigma_{\Downarrow}}{d\phi_r}\right)$$

$$A_{\rm STN} = \left(\int_{\pi/3}^{2\pi/3} d\phi_r \frac{\Delta_{\rm STN} d\sigma}{d\phi_r} - \int_{2\pi/3}^{5\pi/3} d\phi_r \frac{\Delta_{\rm STN} d\sigma}{d\phi_r}\right) / \left(\int_0^{2\pi} d\phi_r \frac{d\sigma_{\rightarrow} + d\sigma_{\leftarrow}}{d\phi_r}\right)$$

HERMES kinematics: $E = 27.5\mathrm{GeV}$. As a starting point we choose $Q^2 = 6\ \mathrm{GeV}^2$ and the range of $x = 0.1 - 0.4$ and t-channel momentum transfer $-\Delta^2 = 0.1 - 0.5\ \mathrm{GeV}^2$.

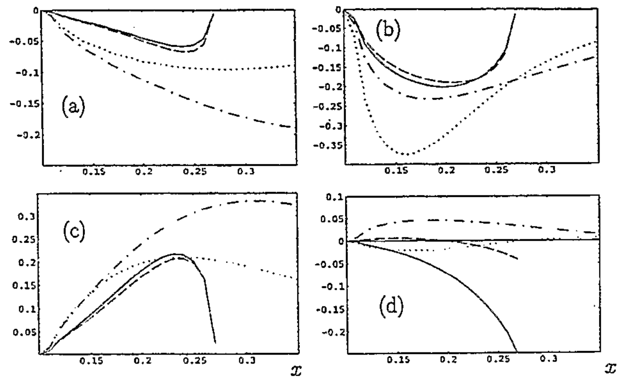
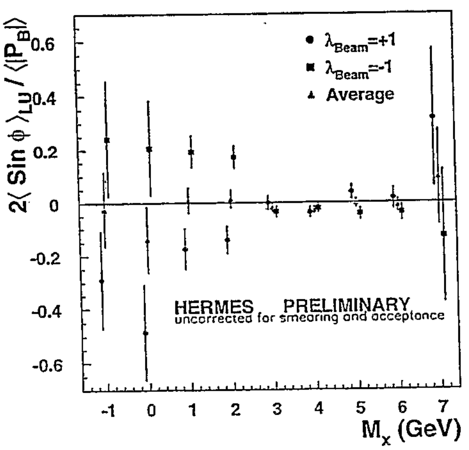


Figure 1: Perturbative leading order results for the charge asymmetry for an unpolarized beam (a), single spin asymmetries for a polarized positron beam (b) and an unpolarized target; as well as for an unpolarized lepton beam and a longitudinally (c) (transversally (d)) polarized proton target versus x, for $Q^2 = 6\ \mathrm{GeV}^2$. The predictions for the model specified in the text are shown as solid (dotted) curves for $\Delta^2 = -0.1(0.5)\ \mathrm{GeV}^2$, respectively. The same model however with neglected spin-flip contributions are presented as dashed (dash-dotted) line for the same values of Δ^2.

H. Avakian for Hermes HAMBURG SEPT. 11, 2000

Azimuthal Asymmetry



$$\frac{2 < sin\phi >_{LU}}{< |P_B| >} = \frac{2\int_0^{2\pi} d\phi\ (d\sigma/d\phi)\ sin(\phi)}{< |P_b| > \int_0^{2\pi} d\phi\ (d\sigma/d\phi)}$$

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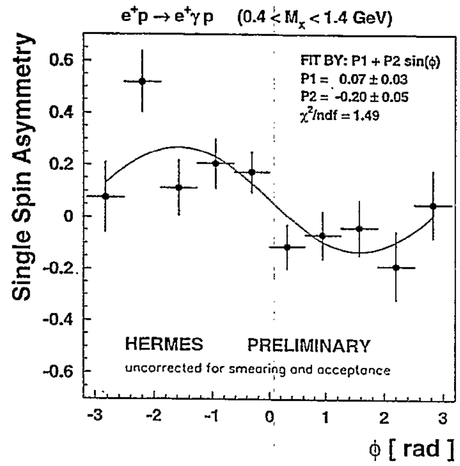
ϕ Dependence of SSA



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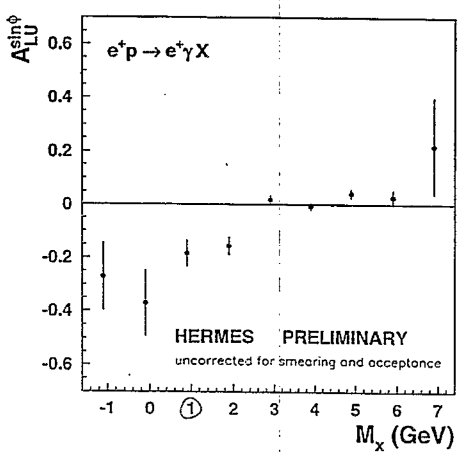
Single Spin Asymmetry



$$A_{LU}^{sin\phi} = \frac{2\int_0^{2\pi} d\phi\,(d\sigma^+/d\phi - d\sigma^-/d\phi)\,sin(\phi)}{<|P_b|> \int_0^{2\pi} d\phi\,(d\sigma^+/d\phi + d\sigma^-/d\phi)}$$

- Off-forward gluonometry...

Diehl et al.
Hoodbhoy, Ji
A.B., Müller

Twist-2 gluon operator

$$g^{\perp}_{\mu\mu'} g^{\perp}_{\nu\nu'} \quad G_{+\mu}(x_1)\, G_{+\nu}(x_2) \qquad\qquad (x_1-x_2)^2=0$$

$$g^{\perp}_{\mu\mu} = 2$$

$$= \frac{1}{2} g^{\perp}_{\mu'\nu'} \left(g^{\perp}_{\mu\nu}\, G_{+\mu}(x_1) G_{+\nu}(x_2) \right)$$

$$+ \frac{1}{2} \epsilon^{\perp}_{\mu'\nu'} \left(\epsilon^{\perp}_{\mu\nu}\, G_{+\mu}(x_1) G_{+\nu}(x_2) \right)$$

$$+ \, \tau^{\perp}_{\mu'\nu';\rho\sigma} \overbrace{\left(\tau^{\perp}_{\mu\nu;\rho\sigma}\, G_{+\mu}(x_1) G_{+\nu}(x_2) \right)}^{\equiv\, {}^{T}\mathcal{O}_{\rho\sigma}} \quad ; \text{ Jaffe, Manohar}$$

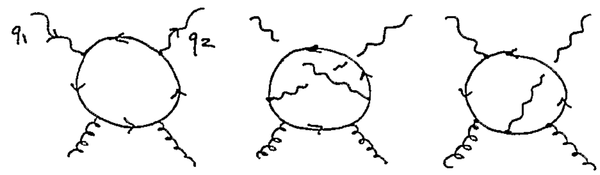
$$\Updownarrow$$

$$\left(\tfrac{1}{2},\tfrac{1}{2}\right) \otimes \left(\tfrac{1}{2},\tfrac{1}{2}\right) = (0,0) \oplus \left((1,0)\oplus(0,1)\right) \oplus (1,1)$$

operator with the same quantum number does not exists in quark sector: NO MIXING

$$\tau^{\perp}_{\mu\nu;\rho\sigma} \equiv \frac{1}{2}\left(g^{\perp}_{\mu\rho} g^{\perp}_{\nu\sigma} + g^{\perp}_{\mu\sigma} g^{\perp}_{\nu\rho} - g^{\perp}_{\mu\nu} g^{\perp}_{\rho\sigma} \right)$$

Contribution to DVCS amplitude



$$T_{\mu\nu} = -\frac{\alpha_s}{\pi} \sum_{i=1}^{N_f} Q_i^2 \int_{-1}^{1} dX\; G^{T}_{\mu\nu}(X,\xi,\Delta^2)\, \sigma(X,-\xi)$$

with

$$G^{T}_{\mu\nu}(X,\xi,\Delta^2) = \frac{4}{P_+} \int \frac{d\lambda}{2\pi}\, e^{i\lambda X P_+} \langle P_2 |\, \mathcal{O}^{T}_{\mu\nu}(\lambda,-\lambda)\, | P_1 \rangle$$

and

$$\sigma(X,\eta) = \frac{1}{(X-\eta+i0)(X+\eta-i0)} \;;$$

Hoodbhoy, Ji
A.B., Müller

NOTE: Coefficient function does NOT CONTAIN $\underline{\text{LOG } Q^2}$

Tensor decomposition

$$G^T_{\mu\nu}(x,\eta,\Delta) = H^T_G(x,\eta,\Delta^2)\,\frac{\tau^{\perp}_{\mu\nu;\alpha\beta}}{2M}\,\frac{\Delta_\alpha q_\gamma}{Pq}\,\bar{U}(P_2)\,i\sigma_{\gamma\beta}U(P_1)$$

$$+\; E^T_G(x,\eta,\Delta^2)\,\frac{\tau^{\perp}_{\mu\nu;\alpha\beta}}{4M^2}\,\Delta_\alpha\,\bar{U}(P_2)\left(\frac{\Delta_\beta \not{q}}{Pq}-\eta\gamma_\beta\right)U(P_1)$$

$P \equiv P_1 + P_2$;

$q \equiv \frac{1}{2}(q_1+q_2)$;

$\Delta \equiv P_2 - P_1$;

$\Delta_\mu \Delta_\nu$ - structure generates a peculiar azimuthal angle dependence in the cross section:

- Unpolarized lepton & proton

  $d\sigma \sim \cos(3\varphi_r)\, d\varphi_r$

- Unpolarized lepton & polarized proton

  $d\sigma \propto \sin(3\varphi_r)\, d\varphi_r$

Weighted cross section A.B, Müller

- $$\frac{1}{2\pi}\int_0^{2\pi} d\varphi_r \cos(3\varphi_r)\,\frac{d\overset{+}{\sigma}-d\overset{-}{\sigma}}{d\varphi_r}$$

$$= 16\sqrt{-\frac{\Delta^2}{Q^2}}\,\frac{\sqrt{(1-x)^3(1-y)}}{xy\,(2-x)^2}\left(1-\frac{\Delta^2_{min}}{\Delta^2}\right)^{3/2}\frac{1}{2M^2}\,\mathrm{Re}\left(F_1\mathcal{E}^T - F_2\mathcal{H}^T\right)$$

- $$\frac{1}{2\pi}\int_0^{2\pi} d\varphi_r \sin(3\varphi_r)\,\frac{d^{+}\sigma_{\rightarrow} - d^{+}\sigma_{\leftarrow}}{d\varphi_r}$$

$$= 16\sqrt{-\frac{\Delta^2}{Q^2}}\,\frac{\sqrt{(1-x)^3(1-y)}}{xy\,(2-x)^2}\left(1-\frac{\Delta^2_{min}}{\Delta^2}\right)^{3/2}\frac{1}{2M^2}\,\mathrm{Im}\left(\mathcal{H}^T + \frac{x}{2}\mathcal{E}^T\right)$$

Here

$$\Delta^2_{min} = -\frac{M^2x^2}{1-x}$$

We CAN access gluon SPD not contaminated by quark effects.

Probing odd chirality at RAMPEX[1]

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RAMPEX[2] is a one-spin experiment on polarized target at the 70-GeV/c proton accelerator in Protvino. The detector was designed to have two arms. The first arm incorporates magnet, proportional chambers, two Čerenkov counters, ECAL1 and HCAL. Now this arm is being tested at the accelerator runs twice a year. Another arm was planned to be a fine-granulated ECAL2. It will be constructed later.

So the existing detectors with the planned second ECAL allow to study one-spin asymmetry in the reaction

$$p + p_{\uparrow} \rightarrow \pi^{\pm} + \pi^{0} + X,$$

which is relevant to the twist-2 chiral-odd quark distribution function $h_1(x)$. Two detected pions are produced in the back-to-back CMS kinematics at large transverse momenta.

The simulation of the process was made with PYTHIA in the chosen kinematic region: $1.5 < p_{T1}, p_{T2} < 2.5\ GeV/c$ under the selection rules that correspond to the RAMPEX triggering, acceptance and detection efficiency.[3]

Fig. 1 shows the integrated luminosity $\int \mathcal{L}dt = 10$ events/pb and the corresponding number of the filtered events (~2000).

The p_T properties of the filtered events are presented on Fig. 2(a,b,c). The errorbars of the asymmetry $A(p_T)$ are plotted in Fig. 2d in red, green and blue for the assumed measured asymmetry values 0.05, 0.10 and 0.20, respectively.

As is seen from Fig. 2d, the reasonable measurements of $A(p_T)$ can be made during the 4-month beam exposition, only if the asymmetry value at $p_T = 1.5 \div 2.5$ GeV/c is equal at least 20%.

---

1) Talk given at the Workshop 'Future Transversity Measurements', BNL, Sept. 18-20, 2000.
2) look at http://rampex.ihep.su/
3) S. Akimenko et al. Proposal of experiment RAMPEX, Preprint IHEP 97-58, 1997.

Lumi

$L = 5.4*10^{31}\ cm^{-2}\ spill^{-1}$

spill = (9+1) s

Run time: 2 months + 2 months

$\sigma = 220$ pb

$\int L dt = 10$ ev/pb

Statistics

$N_{filtered} = 2.2*10^3$ events

Fig. 1. Luminosity and expected statistics at p_T=1.5-2.5 GeV/c.

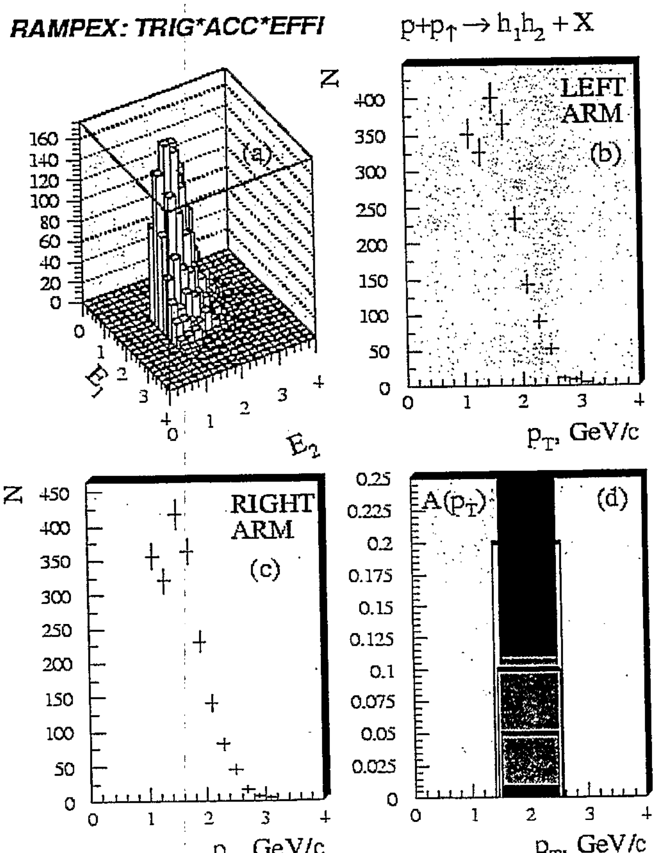

Fig. 2. Kinematics and asymmetry errorbars (see text).

Yu. Arestov

IHEP, Protvino

Probing odd chirality at RAMPEX

Sept. 18-20, 2000
BNL (Transversity)

STATE RESEARCH CENTER OF RUSSIA

INSTITUTE FOR HIGH ENERGY PHYSICS

IHEP 97-58

S. Akimenko, G. Alekseev, Yu. Arestov, V. Belousov, B. Chuiko, V. Grishin, A. Derevschikov, A. Davidenko, S. Erin, V. Kachanov, Yu. Kharlov, V. Khodyrev, A. Konstantinov, V. Medvedev, Yu. Melnik, A. Meschanin, N. Minaev, V. Mochalov, A. Mysnik, A. Pavlinov, D. Patalakha, A. Prudkoglyad, V. Rykalin, P. Semenov, V. Senko, V. Solovianov[1], S. Stepushkin, O. Tsai, N. Ukhanov, A. Ufimtsev, A. Yakutin
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(*St. Peterburg Institute for Nuclear Physics, Gatchina*)

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(*University of Michigan, Ann Arbor, Michigan, USA*)

A STUDY OF ONE-SPIN ASYMMETRIES IN $pp_{\uparrow}$ AND $\pi^{-}p_{\uparrow}$ INTERACTIONS AT 70 AND 40 GEV/C

(Proposal of experiment RAMPEX)

Collaboration Protvino-Dubna-Gatchina-Michigan

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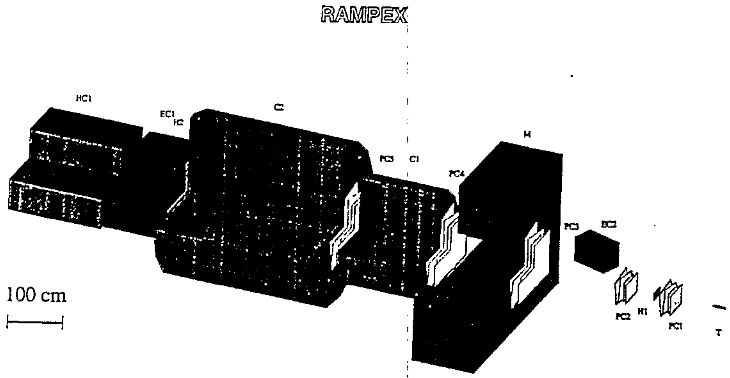
Protvino 1997



4 Experimental setup

Th full version of the experimental setup includes two arms (fig. 7). One arm consists of the magnet spectrometer, two Čerenkov counters Č1, Č2 to identify charged particles, an electromagnetic calorimeter EC1 and a hadron calorimeter HC. The magnet spectrometer consists of the magnet M and five proportional chambers PC1-PC5. In fig. 7 this arm

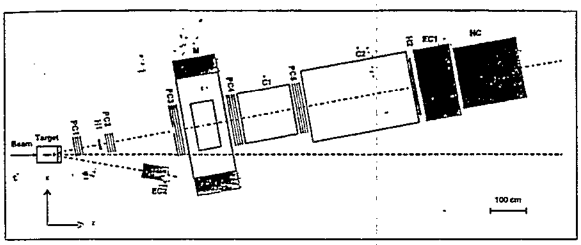


Рис. 7: Layout of experimental setup RAMPEX: PC1–PC5 — blocks of proportional chambers, M — analysing magnet, H1, H2 — trigger hodoscopes, Č1, Č2 — threshold Čerenkov counters, EC1, EC2 — electromagnetic calorimeters, HC — hadron calorimeter.

makes an angle of 9° with the beam line corresponding to 90° in cms. This arm will be also rotated to a smaller angle close to 0° to detect particles with large x_F and to a larger angle to detect particles with negative x_F. Numerical estimations of acceptances and efficiences show that the angle values near 80 and 300 mrad are optimal for these measurements.

The second arm of the setup consists only of the fine-granulated electromagnetic calorimeter EC2 which is placed symmetrically to the beam line and makes angle $-9°$ or smaller.

4.1 Beam.

Existing equipment of the 14th channel allows use of a 40 GeV/c π^- beam with the 1.8% K^- and 0.3% $\bar{p}$ contamination [BRU75] and the 70 GeV/c unpolarized proton beam extracted directly from the accelerator with a bent Si crystal [ASE93]. We assume the pion/proton beam intensity of $5 \cdot 10^6$ in a 1-second spill with a 9-second interval between spills. The size of the pion beam is characterized by the values $\Delta_x = \pm 8$ mm, $\Delta_y = \pm 6$ mm with ± 2.5 mrad and ± 1.5 mrad angular divergences, horizontal and vertical respectively. The momentum uncertainty of the pion beam is defined by $\delta p/p = \pm 2.5\%$ [BRU75].

The transverse size of the proton beam is smaller by a factor of 2, and the angular divergence is smaller than ± 0.3 mrad [ASE93].

PPT

$C_3H_8O_2$ propane-diol

ϕ 20 mm
$\ell = 200$ mm

$\langle P \rangle \approx 80\%$ $83 \div 87\%$

Dilution factor ranges from 6 to 10

Density $9.3 \cdot 10^{24}$ nucleons/cm^2

NH_3 $D = 3$

and the statistical inaccuracies of A_N.

Inclusive π^0 production. Neutral pions are detected with the electromagnetic calorimeters EC1 and EC2. For angles between the beam line and main spectrometer arm of
80 mrad (position 1) and 157 mrad (position 2), the π^0 detection efficiency reaches 40%

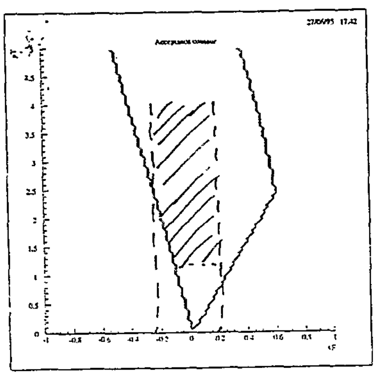


Рис. 16: Acceptance of the experimental setup for $\pi^\pm, K^\pm$

and 10% respectively, as is seen in fig. 19. If π^0's are produced in cms backward hemisphere (300 mrad, position 3) the geometrical efficiency ranges from 1 to 3% at $x_F = -0.2 \div -0.4$.

This figure shows also the two-dimensional distributions for π^0 fluxes in the 100-shift accelerator run for the three angle positions of the calorimeter EC1.

Inclusive production of K_S^0, $\phi(1020)$ and Λ. The unstable hadrons will be detected in the dominant decay channels

$$K_S^0 \to \pi^+\pi^-, \quad \phi \to K^+K^-, \quad \Lambda \to p\pi^-,$$

with the decay probabilities 68.6%, 49.1% 64.1%, respectively. In estimates of the production cross sections, the experimental data on inclusive production of ϕ [AKE77], K_S^0 and Λ [AMM86] were used. The total production cross sections in pp collisions at 70 GeV/c are equal to

$$\sigma(\phi(1020)) = 0.5 \text{ mb}, \quad \sigma(\Lambda) = 3.4 \text{ mb}, \quad \sigma(K_S^0) = 3.1 \text{ mb}$$

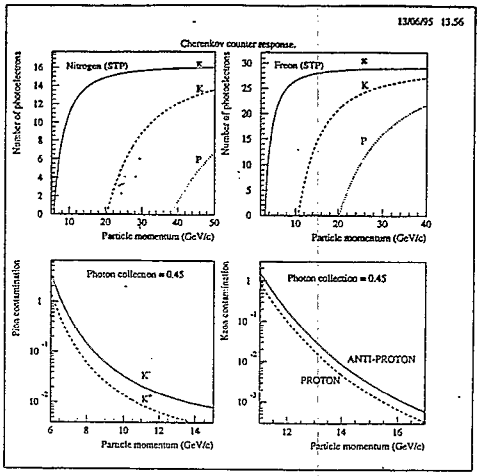


Рис. 9: Calculated properties of the Čerenkov counters

4.4 Charged particle identification.

Particle types for π, K, p and $\bar{p}$ are determined with the help of two threshold multichannel Čerenkov counters Č1 and Č2 which are placed downstream of the magnetic spectrometer. The counter Č1 has 8 channels (4×2) and it is filled with freon-12 at 1 *atm*. The 16-channel counter Č2 (8×2) is filled with the nitrogen also at 1 *atm*. The counters are designed to allow detection of multiple charged signals. Combinations of two counters can identify $\pi^{\pm}$ with momenta $3.1 \div 20$ GeV/c, and $K^{\pm}$ and $p^{\pm}$ from 10 to 20 GeV/c.

The aperture and the length of Č1 are 1.2×0.9 m^2 and 1.5 m. The same characteristics for Č2 are 1.6×0.88 m^2 and 3.0 m.

The counter mirrors are spherical, made of glass with 2 mm thick. The mirrors in counters Č1 and Č2 have sizes 30×50 cm^2 and 25×50 cm^2 respectively. The mirrors are covered with a reflecting layer to obtain maximum light reflection in the region of the PMT sensitivity. At the focus of each mirror a photo-multipiver tube PMT-174,

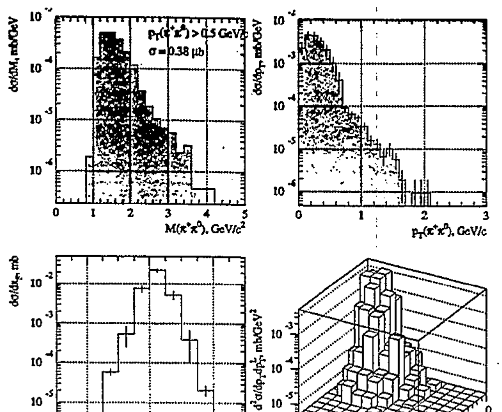


Fig. 21. Differential distributions of the $\pi^+\pi^0$ pair production in the back-to-back kinematics.

8. Status of equipment

The experimental setup is being constructed as a rather universal and flexible one for fixed-target experiments. It allows reasonable detection of charged and neutral particles and, if necessary, strong change of kinematic region of measurements. Two arms provide various possibilities to measure produced particles in the opposite cms hemispheres.

8.1. Acceptance

As the magnet apperture (240 mrad) is much bigger than the the detectors' acceptance (120 mrad) downstream of the magnet, the main spectrometer arm can move – within the magnet acceptance – in zx-plane to cover x_F-range from -0.5 to 0.5 for charged hadrons and from -0.5 to 0.9 for neutral mesons with $p_T < 3$ GeV/c without getting out of the magnet apperture.

hadrons (pions) must be restricted, say, $p_t > 0.3$ GeV/c. The pion longitudinal momenta obey an appropriate condition, for example, $x_F < -0.3$.

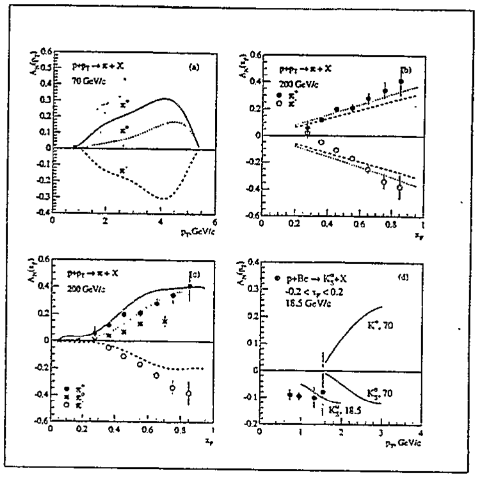


Рис. 4: Model predictions for one-spin asymmetry A_N: a- p_T-dependence of $\pi^{\pm}, \pi^0$ asymmetries at 70 GeV/c in the U-matrix model including the $q\bar{q}$ orbital motion [TRO95]; b- x_F-dependence of the $\pi^{\pm}$ asymmetry at 200 GeV/c in the same model, different curves correspond to different model parameters; c- pion asymmetries at 200 GeV/c in the Berlin model with orbiting valence quarks [BOR95]; d- asymmetries of K^+ and K_S^0-mesons in the model with quark spin flip in colored hadron remnant [ARE91].

One can use two leading particles with momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ to define both the quark axis and the azimuthal angle. This leads to the correlations of type

$$\frac{\mathbf{s}(\mathbf{p}_1 \times \mathbf{p}_2)}{|\mathbf{p}_1 \times \mathbf{p}_2|}.$$

SPIN96, Amsterdam

Rampex Round Table

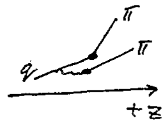
Rampex Physics Program

- measuring twist-3 induced asymmetries
- how to probe chirally-odd parton distr.

(197) Feb. approval

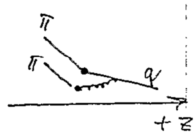
$p\,p_{\uparrow} \to \pi\pi + X$; 70 GeV/c

1° Forward production



unpol. beam

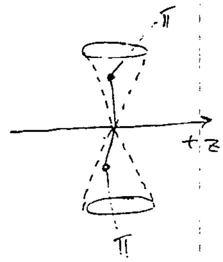
2° Backward production



OK, pol. target

disadvantage: small $p_T \Rightarrow$ possible admixture with pions from beam/target emitting remnants

3° Back-to-back production



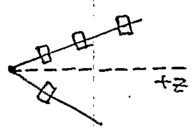
$$\frac{d\sigma}{d\vec{p}_1\, d\vec{p}_2}$$

$(\theta_1^*\ \phi_1^*)$,

$(\theta_2^*\ \phi_2^*)$

$\boxed{\text{PYTHIA User Choises}}$

Kinematics — lab

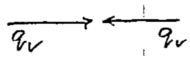


$\theta = 9° \pm \Delta\theta_{acc}$

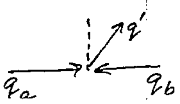
$\Delta\theta_{acc}^R$

$\Delta\theta_{acc}^L$

Subprocess

a) 

val – val

b) 

$\theta_{q'} = \frac{\pi}{2} \pm \underbrace{\Delta\theta_{q'}}_{10°, 20°, 30°}$

$p_T(q') > 2$ GeV/c

Selection

a) $E^*_{\pi^\pm} > 1.5$ GeV tagged by

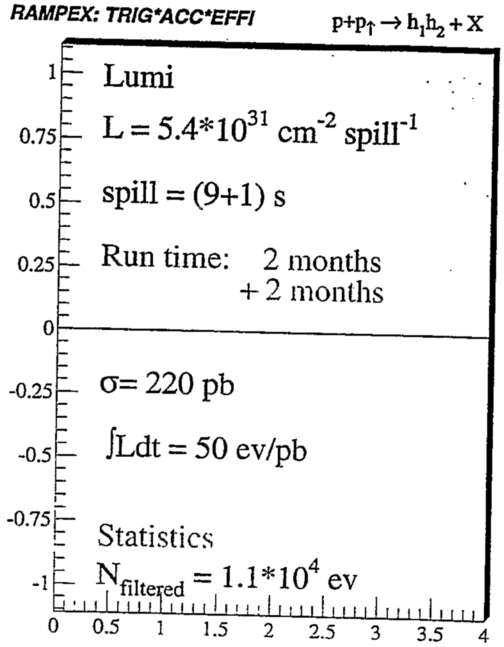
$E^*_{\pi^0} > 1.0$ GeV

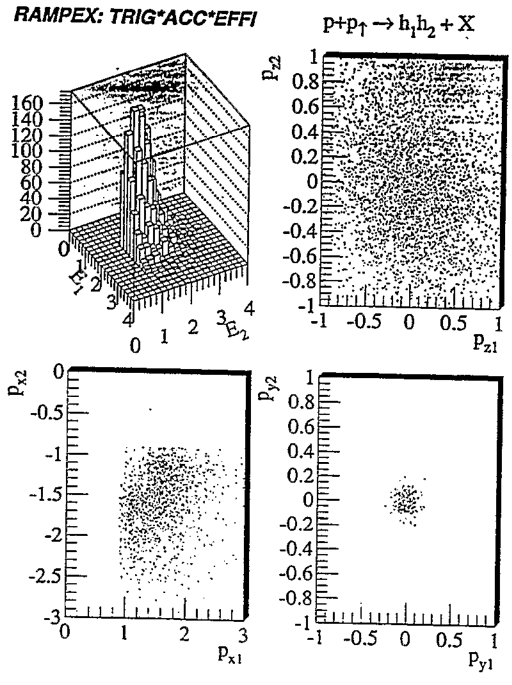
b) vice versa

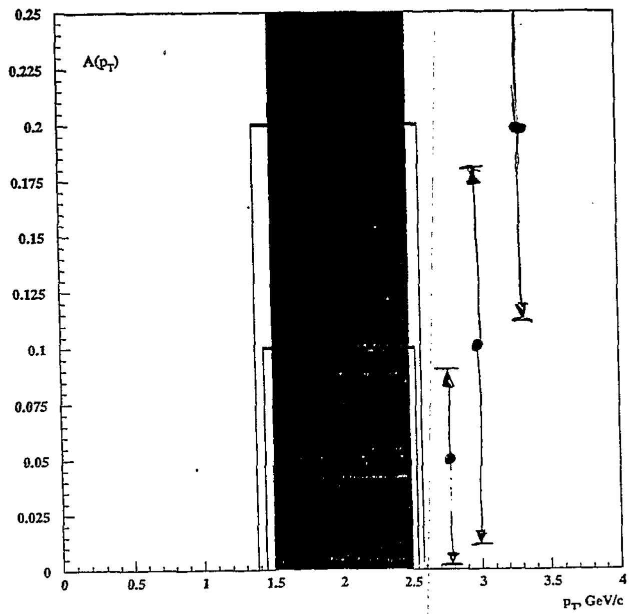
Statistics

10^7 entries in loop

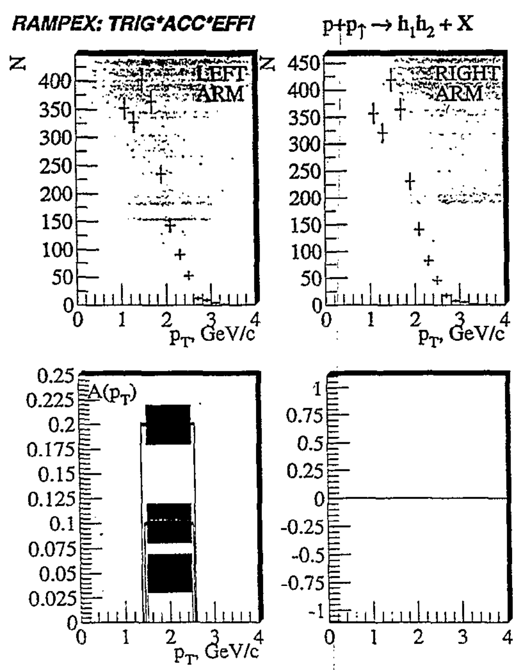
10^4 filtered


RAMPEX: TRIG*ACC*EFFI
p+p↑ → h1h2 + X
Lumi
L = 5.4*10^31 cm^-2 spill^-1
spill = (9+1) s
Run time: 2 months
+ 2 months
σ= 220 pb
∫Ldt = 50 ev/pb
Statistics
N_filtered = 1.1*10^4 ev


RAMPEX: TRIG*ACC*EFFI
p+p↑ → h1h2 + X
E1
E2
pz2
pz1
px2
px1
py2
py1


A(p_T)
p_T, GeV/c

$C_3H_8O_{12}$


RAMPEX: TRIG*ACC*EFFI
p+p↑ → h1h2 + X
LEFT ARM
RIGHT ARM
N
p_T, GeV/c
A(p_T)

CURRENT STATUS

1. RUNS: 2 times a year
   30 days in March-April
   30 days in Oct – Nov

2. Neutral arm WORKS.
   π^0's are taken and handled

3. The charged arm is still being tested.

   DIS2000 web site (U. of Liverpool)

NEAREST RUNS

1. Nov'00
   - π^0 data taking.
   - Testing PC, C_1, C_2, EC1 and HC
   - An attempt to get charged p. tracking

2. March'01 Continuation

Future Transversity Measurements with HERMES

V. A. Korotkov[a,b], W.-D. Nowak[a]

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Physics prospects for the study of the quark transversity distributions $\delta q(x)$ with HERMES using a transversely polarized proton/deuteron target are presented. To evaluate the level of expected statistical accuracy statistics of 7.0 M reconstructed DIS events was assumed. This statistics can be accumulated by HERMES in two years of running starting 2001+. The electron beam and target polarizations were assumed to be $P_B = 50\%$ and $P_T = 75\%$, respectively. Three methods to extract the $\delta q(x)$ distributions were investigated under reasonable input assumptions on the transversity distributions and corresponding polarized fragmentation functions. Twist-3 pion production in SIDIS of longitudinally polarized leptons on transversely polarized protons shows a quite sizeable asymmetry sensitive to the transversity distribution. Two other methods rely on polarimetry for the scattered transversely polarized quark: i) observation of the Collins angle dependence in quark fragmentation and ii) observation of a correlation between the transverse spin of the target nucleon and the normal to the two-meson plane. The size of the asymmetry in the study of two-meson correlations depends on the unknown interference fragmentation function. Using the upper bound of this fragmentation function produces an asymmetry which can be measured at HERMES with sufficient statistical accuracy. The polarized fragmentation function responsible for the Collins effect, $H_1^{\perp(1)}(z)$, was taken to be compatible with results of first measurements by HERMES and DELPHI which showed that it can be quite sizeable. A measurement of the Collins effect asymmetry as a function of two variables, x and z, allows under the assumption of u-quark dominance in the π^+ production to reconstruct the shape for both unknown functions, $\delta u(x)$ and $H_1^{\perp(1)}(z)$, while the relative normalization cannot be fixed without a further assumption. For non-relativistic quarks $\delta q(x) = \Delta q(x)$. Therefore, an assumption that $\delta u(x)$ coincides with $\Delta u(x)$ at small values of Q^2 was made. A study of the evolution of these two functions with Q^2 in LO showed that differences between them are very small up to rather large values of Q^2 in the region of intermediate and large values of x. Hence the assumption $\delta u(x_0) = \Delta u(x_0)$ at $x_0 = 0.25$ was made to resolve the normalization ambiguity. A study of the Collins effect asymmetry in this context allows to conclude that the HERMES experiment is capable to measure simultaneously and with good statistical precision the u-quark transversity distribution $\delta u(x)$ and of the polarized fragmentation function $H_1^{\perp(1)}(z)$.

Future Transversity Measurements with HERMES

V. Korotkov, W.-D. Nowak

Workshop "Future Transversity Measurements"
BNL, September 20, 2000

- Transversity
- Methods to measure
- HERMES Experiment
- Twist-3 Pion Production
- Two-Meson Correlations
- Collins Effect
  - Normalization Ambiguity
  - Polarized fragmentation function
  - Single Target-Spin Asymmetry
  - Projections for Statistical Accuracy
- Summary

Transversity Distribution

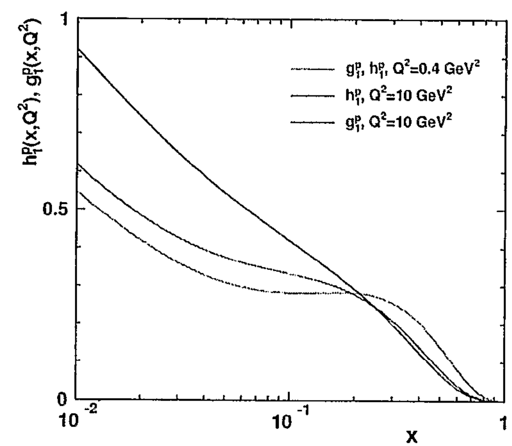
Three twist-2 quark distributions:

- quark number density distribution $q(x, Q^2)$
- quark helicity distribution $\Delta q(x, Q^2)$
- quark transversity distribution $\delta q(x, Q^2)$

For non-relativistic quarks: $\delta q(x) = \Delta q(x)$.

No transversity distribution for gluons. $\Longrightarrow$ $\delta q(x, Q^2)$ does not mix with gluons under QCD evolution.

QCD-evolution of $\delta q(x, Q^2)$ is well established theoretically.
Example for LO evolution of proton structure functions
$g_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x, Q^2)$ and $h_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \delta q_i(x, Q^2)$



Possible methods to measure $\delta q(x)$ in SIDIS

The $\delta q(x, Q^2)$ is a chiral-odd distribution and as such it decouples from all hard processes that involve only one quark distribution (or fragmentation) function.

$$A \sim \sum_i e_i^2 \delta q_i(x) H_1(z)$$

i) Twist-3 pion production in SIDIS (Jaffe, Ji, 93)

ii) Measurement of the transverse polarization of Λ's in the current fragmentation region (Baldracchini,82 Jaffe,96)

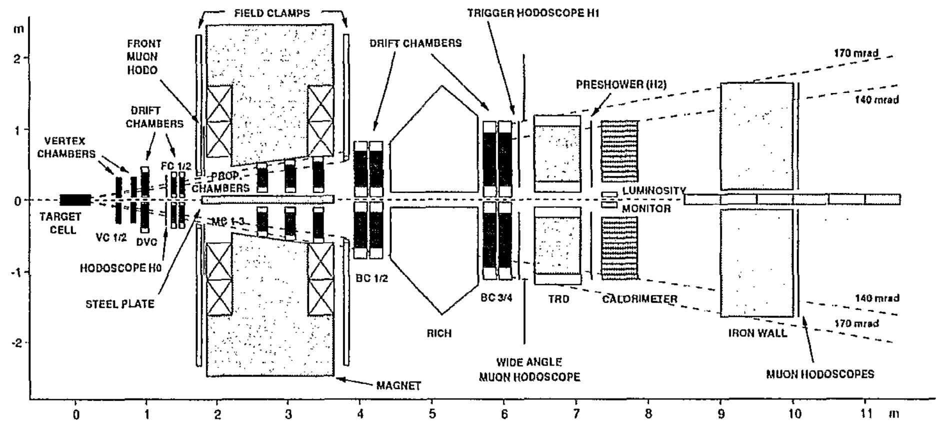
iii) Observation of the Collins effect in quark fragmentation through the measurement of pion single target-spin asymmetries (Collins,93, Kotzinian, 95, Mulders et al,96).

iv) Measurement of correlation between the transverse spin vector of the target nucleon and the normal to the two-meson plane (Jaffe et al.,97)

v) Measurement of spin-1 hadron production in SIDIS (Bacchetta, Mulders)

Methods ii) - v) rely on POLARIMETRY of the scattered transversely polarized quark and require a transversely polarized target only.

The HERMES Spectrometer



- Polarized positrons of energy 27.5 GeV in the HERA storage ring, $P_B = 0.55 \pm 0.02$
- Polarized internal hydrogen gas target, $P_T = 0.86 \pm 0.04$
- Forward spectrometer, $0.04 < \theta < 0.22$ rad.
- Particle ID: RICH (Threshold Čerenkov), TRD, Preshower, Lead Glass Calorimeter.
- Track reconstruction: $\delta P/P = 0.7 \div 1.3\%$, $\delta\theta \leq 0.6$ mrad.

Transversity Analysis at HERMES

$$ep^{\uparrow}(d^{\uparrow}) \to e'\pi X, \quad E = 27.5 \text{ GeV}, \quad P_T = 0.75, \quad P_B = 0.5$$

Statistics expected for 2002+: $7 \cdot 10^6$ reconstructed DIS events

$$Q^2 > 1 \text{ GeV}^2, \quad W > 2 \text{ GeV}, \quad 0.02 < x < 0.7, \quad y < 0.85.$$

From HERMES Monte Carlo program: pion distributions, acceptance.

Cuts for the kinematic variables of the pion:

$$x_F > 0., \quad z > 0.1, \quad P_{h\perp} > 0.05 \text{ GeV} .$$

To simulate A_T, the approximation $\delta q(x) = \Delta q(x)$ was used (relatively low Q^2-values at HERMES)

$Q^2 = 2.5$ GeV^2 (average value for the HERMES)

GS LO parameterization for $\Delta q(x)$

GRV94LO parameterization for $q(x)$

Twist-3 Pion Production is SIDIS

$\vec{e}p^{\uparrow} \to e'\pi X$ (Jaffe, Ji 1993)

$$\frac{d^4\Delta\sigma^h}{dx dy dz d\phi} = \frac{e^4}{4\pi^2 Q^2} \cos\phi\, \gamma\sqrt{1-y}\Big[G_T^h(x,z) - G_1^h(x,z)(1-\frac{y}{2})\Big]$$

$$G_1^h(x,z) = \frac{1}{2}\sum_q e_q^2 \Delta q(x) \hat{q}^h(z),$$

$$G_T^h(x,z) = \frac{1}{2}\sum_q e_q^2 [\Delta_T q(x) \hat{q}^h(z) + \frac{\delta q(x)}{x}\frac{\hat{e}_q^h(z)}{z}]$$

$\hat{q}^h(z)$ — the usual twist-2 FF

$\hat{e}_q^h(z)$ — unknown chiral-odd twist-3 FF

$\Delta_T q(x)$ — contribution of quark q into $g_T(x) = g_1(x) + g_2(x)$.

A simple relation between $\hat{e}(z)$ and $\hat{q}(z)$ has been obtained in the chiral quark model (Ji, Zhu 1993)

$$\hat{e}(z) = z\hat{q}(z)\frac{m_q}{M} \approx \frac{1}{3} z\hat{q}(z)$$

where $m_q \approx \frac{1}{3}M$ is the constituent quark mass.

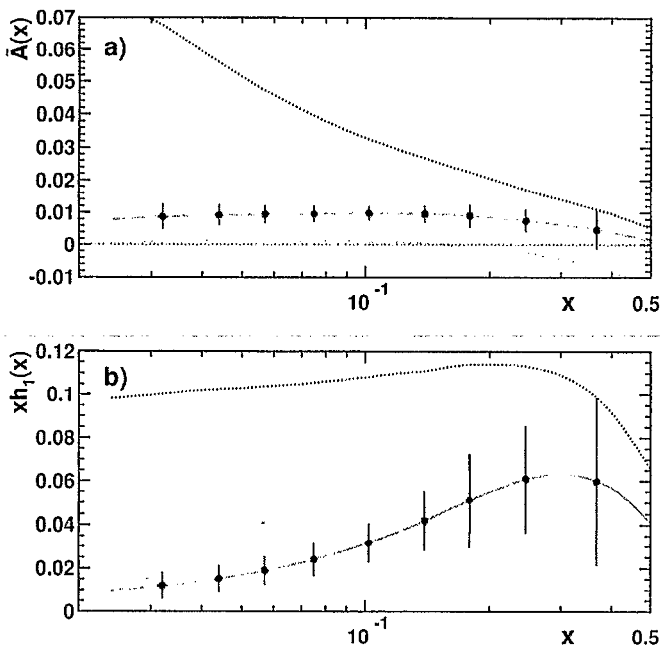
Twist-3 Pion Production at HERMES

We use the asymmetry $\tilde{A}^h(x,y,z) = \frac{1}{\cos\phi} A^h(x,y,z,\phi)$.

A particular simple case is for $\pi^+ + \pi^-$ asymmetry:

$$\tilde{A}^{\pi^+ + \pi^-} = \frac{g_T(x) + \frac{1}{x} h_1(x) r(z) - (1-y/2) g_1(x)}{F_1(x)}$$

where $r(z) = \frac{1}{z}\frac{\hat{e}(z)}{\hat{q}(z)}$ was taken to be 1/3 (Ji, Zhu 1993).



Dashed curves — $\delta q(x) = 0$, dotted curves — saturation of the Soffer's inequality.

Two-Meson Correlation with Transverse Spin

The interference effect between the s- and p-waves of the two-meson system allows the quark's polarization information to be carried through $\vec{k}_+ \times \vec{k}_- \cdot \vec{S}_\perp$. (Jaffe et al., 1998)

For $eN^\uparrow \to e'\pi^+\pi^- X$

$$\mathcal{A}_{\perp T} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2} \cos\phi \, \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)$$
$$\times \frac{\sum_a e_a^2 \delta q_a(x)\, \delta\hat{q}_I^a(z)}{\sum_a e_a^2 q_a(x) \left[\sin^2\delta_0 \hat{q}_0^a(z) + \sin^2\delta_1 \hat{q}_1^a(z)\right]}$$

$\delta\hat{q}_I^a(z)$ — unknown chiral-odd interference quark FF

$\delta_{0,1} = \delta_{0,1}(m^2)$ — strong interaction $\pi\pi$ phase shifts

$\cos\phi = \vec{k}_+ \times \vec{k}_- \cdot \vec{S}_\perp / |\vec{k}_+ \times \vec{k}_-||\vec{S}_\perp|$ — analog of the Collins angle defined by the $\pi^+\pi^-$ system

$\hat{q}_0$ and $\hat{q}_1$ — spin-average FF for the σ and ρ resonances.

The interference FF $\delta\hat{q}_I$ has an upper bound

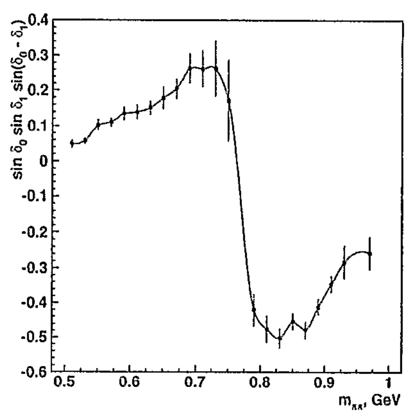
$$\delta\hat{q}_I^2 \leq 4\widehat{q}_0\widehat{q}_1/3$$

for each flavor.

It could be measured in $e^+e^- \to (\pi^+\pi^- X)(\pi^+\pi^- X)$.
Nothing has been published yet.

The final state phase generated by the s-p interference is crucial to the method. If the data are not kept differential in enough kinematic variables, the effect will almost certainly average to zero.

In particular the two-meson invariant mass, m, must be kept differential. The interference averages to about zero when integrating over the mass of the two-pion system due to a factor $\sin(\delta_0 - \delta_1)$.



Two-Meson Correlations at HERMES

For the proton target the asymmetry takes the form:

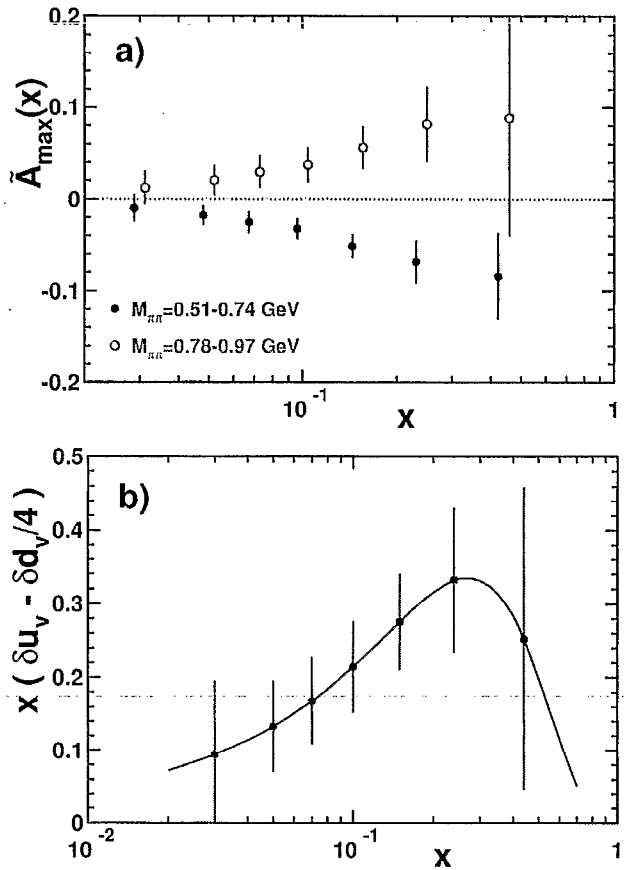
$$\mathcal{A}_{\perp T} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi\ \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)\ \times$$
$$\frac{\delta u_v(x) - \frac{1}{4}\delta d_v(x)}{(u(x)+\bar{u}(x)) + \frac{1}{4}(d(x)+\bar{d}(x))} \cdot \frac{\delta\hat{u}_I(z)}{\sin^2\delta_0\widehat{u}_0(z) + \sin^2\delta_1\widehat{u}_1(z)} \cdot$$

A *maximally* possible asymmetry with $\delta\hat{u}_I^{\,2} = 4\widehat{u}_0\widehat{u}_1/3$.

The maximal asymmetry does not depend on z

$$A_{max}^{ep\to e'\pi^+\pi^- X} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi\,\frac{1}{\sqrt{3}}\sin(\delta_0-\delta_1)$$
$$\times\frac{\delta u_v(x) - \frac{1}{4}\delta d_v(x)}{(u(x)+\bar{u}(x)) + \frac{1}{4}(d(x)+\bar{d}(x))}\,.$$

$$\tilde{A}_{max} = P_T \cdot A_{max}/\cos\phi$$

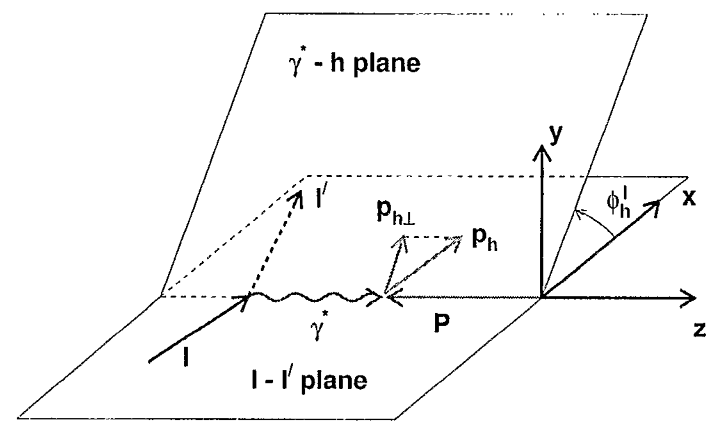


The projected accuracies are the best what could be measured at HERMES. A real level of the accuracy depends on the size of the interference FF $\delta\hat{u}_I(z)$ and of the two-pion FF's $\hat{u}_{0,1}(z)$.

Measurement of $\delta q(x)$ via the Collins effect

Weighted asymmetry [Mulders, Tangermann 96, Kotzinian, Mulders 97]

$$A_T(x,y,z) \equiv \frac{\int d\phi^\ell \int d^2P_{h\perp} \frac{|P_{h\perp}|}{zM_h} \sin(\phi_s^\ell + \phi_h^\ell)\ (d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi^\ell \int d^2P_{h\perp}(d\sigma^\uparrow + d\sigma^\downarrow)}$$



Factorization w.r.t. x and z:

$$A_T(x,y,z) = f \cdot P_T \cdot D_{nn} \cdot \frac{\sum_q e_q^2\ \delta q(x)\ H_1^{\perp(1)q}(z)}{\sum_q e_q^2\ q(x)\ D_1^q(z)}$$

$D_{nn} = (1-y)/(1-y+y^2/2)$ - transverse spin transfer coefficient.

u-quark Dominance in π^+ Production

In a first analysis the assumption of u-quark dominance in the π^+ production is quite reasonable:

i) 70÷90% of π^+ originate from the fragmentation of struck u-quark for a proton target (only slightly smaller for a deuteron target);

ii) Sum rule for T-odd fragmentation functions [Schäfer, Teryaev, 99] → contributions from non-leading parton fragmention is expected to be severely suppressed:

$$\frac{H_1^{\perp(1)d\to\pi^+}(z)}{D_1^{d\to\pi^+}(z)} = \frac{H_1^{\perp(1)\bar{u}\to\pi^+}(z)}{D_1^{\bar{u}\to\pi^+}(z)} = 0$$

iii)

$$\frac{\Delta q_{sea}(x)}{q_{sea}(x)} \ll \frac{\Delta q(x)}{q(x)}$$

Assume

$$\frac{\delta q_{sea}(x)}{q_{sea}(x)} \ll \frac{\delta q(x)}{q(x)}$$

Then

$$A_p^{\pi^+}(x,y,z) = P_T \cdot D_{nn} \cdot \frac{\delta u(x)}{u(x)} \cdot \frac{H_1^{\perp(1)}(z)}{D_1(z)}$$

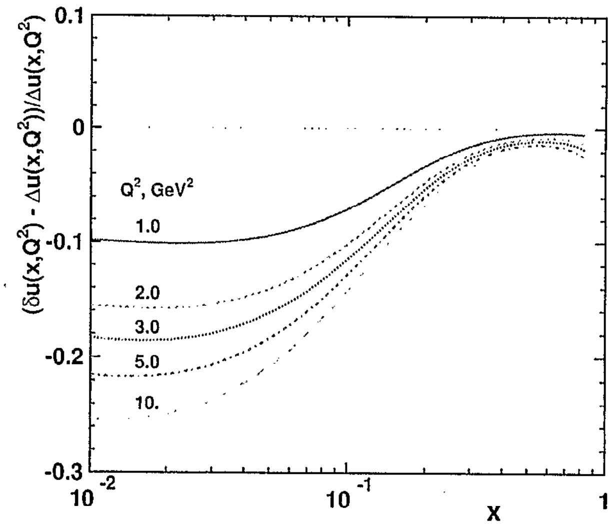
$$A_d^{\pi^+}(x,y,z) = f_D \cdot P_T \cdot D_{nn} \cdot \frac{\delta u(x) + \delta d(x)}{u(x) + d(x)} \cdot \frac{H_1^{\perp(1)}(z)}{D_1(z)}$$

where $f_D = 1 - \frac{3}{2}\omega_D$, $\omega_D = 0.05$

Normalization Ambiguity

The factorized form with respect to x and z allows the simultaneous reconstruction of the SHAPE for both $\delta u(x)$ and $H_1^{\perp(1)}(z)/D_1(z)$, while the relative normalization cannot be fixed without a further assumption.

Use the expectation that $\delta q(x)$ coincides with $\Delta q(x)$ at small Q^2.



The differences are expected to be smallest for intermediate and large x. Hence the assumption

$$\delta q(x_0) = \Delta q(x_0)$$

at $x_0 = 0.25$ was made to resolve the normalization ambiguity.

Polarized Fragment. Function $H_1^{\perp(1)q}(z)$

Experimental indications that $H_1^{\perp(1)q}(z)$ is non-zero:

i) azimuthal correlations between particles from opposite jets in Z decay at DELPHI [A.Efremov et al., 99]
ii) a single target-spin asymmetry measured at HERMES
[PRL **84**, 4047 (2000)]

Analyzing power in transversely polarized quark fragmentation (Collins guess):

$$A_C(z,k_T) \equiv \frac{|k_T| H_1^{\perp q}(z,z^2k_T^2)}{M_h D_1^q(z,z^2k_T^2)} = \frac{M_C\,|k_T|}{M_C^2+|k_T^2|},$$

$M_C \simeq 0.3 \div 1.0$ GeV

Gaussian parameterization for the quark transverse momentum dependence in the unpolarized fragmentation function

$$D_1^q(z,z^2k_T^2) = D_1^q(z)\,\frac{R^2}{\pi\, z^2}\,\exp(-R^2k_T^2),$$

leads to

$$H_1^{\perp(1)q}(z) = D_1^q(z)\frac{M_C}{2M_h}\left(1 - M_C^2R^2\int_0^\infty dx\,\frac{\exp(-x)}{x+M_C^2R^2}\right).$$

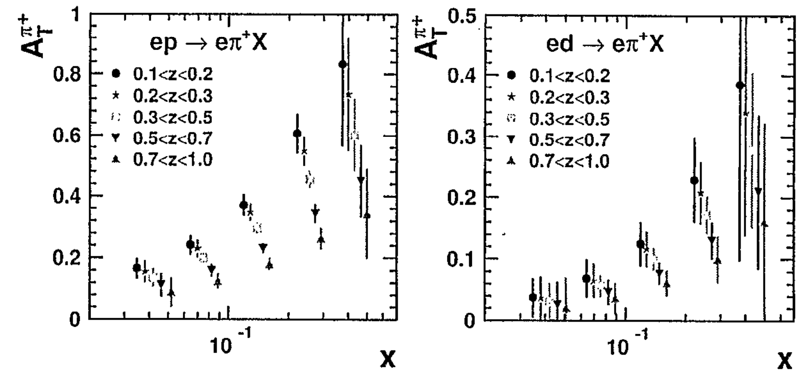
$R^2 = z^2/b^2$

In the following $M_C = 0.7$ GeV and $b^2 = 0.25$ GeV^2
Consistent with the HERMES and DELPHI measurements.

Single Target-Spin Asymmetry

To improve the separation of the struck quark fragm. region, an additional cut $W^2 > 10$ GeV^2 was introduced.

The simulated data were divided into 5x5 bins in (x, z).



The experimental data consist of 25 measured values, as opposed to 9 unknown function values:
4 values for $\delta u(x_i)$ $[\delta u(x_i) + \delta d(x_i)]$ and
5 values for $H_1^{\perp(1)u}(z_j)/D_1^u(z_j)$

The standard procedure of χ^2 minimization was applied to reconstruct the values for both $\delta u(x)$ $[\delta u(x_i) + \delta d(x_i)]$ and $H_1^{\perp(1)u}(z)/D_1^u(z)$ and to evaluate their projected statistical accuracies.

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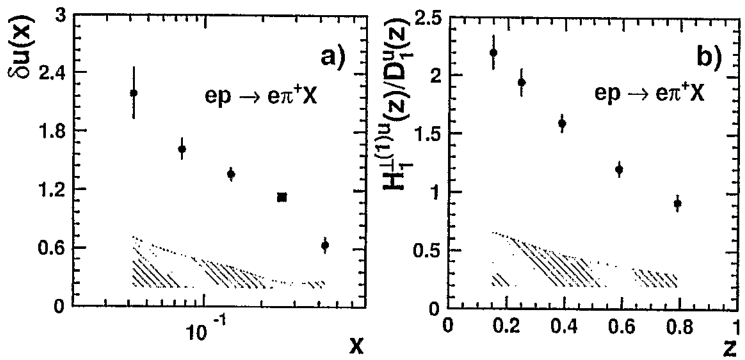
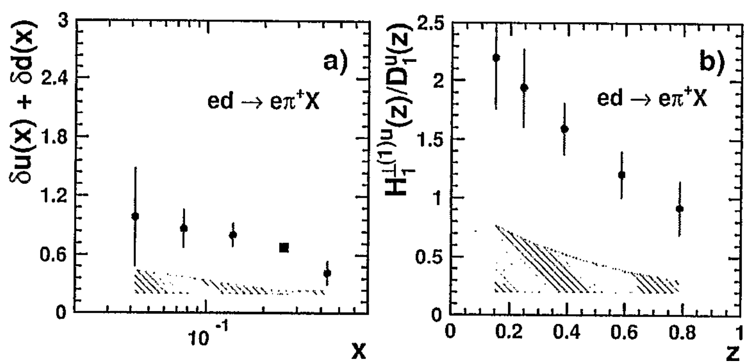
Projections for Statistical Accuracy

Projections for $\delta u(x)$ and $H_1^{\perp(1)u}(z)/D_1^u(z)$ (PROTON target)



Projections for $\delta u(x) + \delta d(x)$ and $H_1^{\perp(1)u}(z)/D_1^u(z)$
(DEUTERON target)



Summary

- There are many methods proposed to measure the transversity. All of them suffer from a necessity to reconstruct two unknown functions simultaneously.
- HERMES can make a statistically rather precise first measurement of $\delta u(x)$ and of the polarized fragmentation function $H_1^{\perp(1)u}(z)$ with a transversely polarized proton target in 2002+ based on a study of the Collins effect
- A study of the twist-3 pion production may offer another measurement of the $h_1(x)$ if the twist-3 fragmentation function $\hat{e}(z)$ is quite sizeable
- In addition the HERMES has a capability to access the transversity distribution via measurements of the two-meson correlations and transverse polarization of Λ's
- We need new high luminosity polarized ℓN experiments to measure the transversity distributions with an accuracy comparable to what we have now for the helicity distributions.

Transversity with COMPASS at CERN

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While transverse spin effects have been studied in hadronic interactions since several decades (for a recent review see [1]), investigations with leptonic probes have started very recently. The probability that a quark spin in a transversely polarized nucleon is oriented parallel (or antiparallel) to the nucleon spin can, in principle, be measured in DIS off a transversely polarized target. This *twist-2* distribution function $h_1(x)$ is different from its longitudinal counterpart $g_1(x)$, among other things because of the different role of the polarized gluons which do not contribute to $h_1(x)$.

However $h_1(x)$ cannot be mesured directly in inclusive DIS because of its odd chirality nature. Alternatively, it can be determined by analyzing the polarization of the *struck* quark, since in the fragmentation process the leading hadron is expected to be polarized or to exhibit an azimuthal asymmetry related to the spin of the fragmenting quark. One method to access $h_1(x)$ uses the (transverse) *spin dependent azimuthal asymmetries* of the leading hadrons around the virtual photon direction. The analyzing power of this process is not yet known, but it is probably large.

A first proposal to study these effects has been made by the HELP group at CERN [2]. A broad experimental program to investigate transverse spin effects in DIS has been proposed recently by the COMPASS collaboration at CERN [3]. COMPASS will complete the commissioning of the apparatus next year (2001). Data taking will also start in year 2001.

According to Collins [4], the fragmentation function for transversely polarized quarks $\mathcal{D}_q^h$ is built up from two pieces, a spin-independent part D_q^h, and a spin-dependent part ΔD_q^h:

$$\mathcal{D}_q^h(z,\vec{p}_q^{\,h}) = D_q^h(z,p_q^h) + \Delta D_q^h(z,p_q^h)\cdot\sin\phi_c \tag{1}$$

The angle ϕ_c, known as 'Collins angle', is the azimuthal angle between the outgoing hadron ϕ_h and the final quark spin $\phi_{S'}$ around the virtual photon momentum, and at leading twist it is given by

$$\phi_c = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi \tag{2}$$

where ϕ_S is the initial quark spin azimuthal angle. Note that $\sin\phi_c$ is the spin component of the final quark normal to the production plane defined by the virtual photon and the outgoing hadron. This is the only single-spin asymmetry allowed by the symmetries conserved in strong interactions.

The spin dependence of the fragmentation function leads to a specific azimuthal dependence for the outgoing leading hadron

$$d\sigma(\phi_c) \sim const\cdot(1 + A_N\sin\phi_c)\, d\phi_c\,. \tag{3}$$

The amplitude A_N of the azimuthal modulation

$$A_N = H(x)\cdot a_c(z,p_T) \tag{4}$$

is proportional to both the transversity distribution, $H(x) = 2x\,h_1(x)\,/\,F_2(x)$, and the *analyzing power* in the polarized quark fragmentation, a_c, known also as *quark polarimeter*. At present, both quantities are unknown, and experimentally one measures their product A_N. Note that $a_c = a_c(Q^2, z, p_T, etc.)$ depends strongly on the selected hadron kinematics. a_c is probably large, in the order of $0.1 \div 0.3$ as suggested by the size of typical asymmetries in soft hadronic processes and recent DIS measurements (SMC, HERMES). In COMPASS different methods will be tried to determine the *quark polarimeter* $a_c(z,p_T)$.

Experimentally, one accesses these effects by selecting the leading (fastest) hadron produced in the event in DIS off a transversely polarized target, and by studying its azimuthal dependence with respect to the ϕ_c angle. The transverse single-spin asymmetry A_N is derived from the measured asymmetry in the yields of hadrons produced opposite in azimuth (ε_N):

$$A_N = \frac{1}{P_T\, f\, D_{NN}}\cdot\varepsilon_N = \frac{1}{P_T\, f\, D_{NN}}\cdot\frac{1}{<\sin\phi_c>}\cdot\frac{N(\phi_c<\pi) - N(\phi_c>\pi)}{N(\phi_c<\pi) + N(\phi_c>\pi)} \tag{5}$$

where P_T and f are the target transverse polarization and dilution factor, respectively. $D_{NN} = 2(1-y)\,/\,(1+(1-y)^2)$ is the transverse spin transfer coefficient (or depolarization factor). In $\gamma^* + q\uparrow\rightarrow q'$ D_{NN} is large at low y and decreases with increasing y. The low y region corresponds also to the large x region, where quarks polarization is expected to be higher. The largest effects appear for $\sin\phi_c = \pm\pi/2$, therefore *left-right* asymmetry w.r.t. final quark spin.

As illustrated in this talk, the asymmetries which will be measured in COMPASS are expected to be many standard deviations from zero [3]; even if the Collins analyzing power should be much smaller than in the parametrization used, the measurement will still be significative. It will bring new insight into the nucleon spin structure.

First results on the transverse spin dependence in semi-inclusive hadron production off transversely polarized targets, $\mu\, p\uparrow\rightarrow\mu' + \pi^\pm + X$, have been obtained by the Spin Muon Collaboration [5]. SMC finds $A_N = 0.11 \pm 0.06$ for π^+'s, and $A_N = -0.02 \pm 0.06$ for π^-'s on the proton target at $< x > \sim 0.08$ and $< Q^2 > \sim 5$ GeV^2. On deuteron, A_N is small for both π^+'s and π^-'s. The data indicate also that A_N increases in magnitude with increasing p_T. Although the statistical precision is limited, mainly because of the large target dilution factor f, indications of transverse spin effects are observed in the data, with an almost 2σ positive effect for π^+'s produced on protons.

References

[1] A. Bravar, *Experimental Overview of Spin Effects in Hadronic Interactions*, plenary talk at SPIN98.

[2] The HELP proposal, CERN/LEPC 93-14, LEPC/P7, Sept. 1993.

[3] The COMPASS proposal, CERN/SPSLC 96-14, SPSC/P297, March 1996

[4] J. Collins, Nucl. Phys. B 396 (1993) 161.

[5] SMC, A. Bravar *et al.*, Nucl. Phys. B (Proc. Suppl.) 79 (1999) 520.

Transversity with the COMPASS Experiment at CERN

ALESSANDRO BRAVAR
Universität Mainz
Transversity Workshop
BNL, 18 - 20 September 2000

AZIMUTHAL DISTRIBUTIONS OF HADRONS IN D. I. S. OFF TRANSVERSELY POLARIZED TARGETS

INCLUSIVE: $\underset{\mu}{\longrightarrow}$ $\uparrow p$ $\to g_2$

SEMI-INCLUSIVE: (more info) $\underset{\mu}{\longleftrightarrow}$ $\uparrow p$ φ_c $\to$ had. (φ_c)

(pol; n. not)

$$d\sigma(\varphi_c) \propto (1 + A_N \sin\varphi_c)\, d\varphi_c$$

$$A_N \to \underline{h_1} \sim \Delta_\perp q$$

azimuthal asymm. $\varphi_c \to \varphi_c + \pi$

$\varphi_c = 90°$ $\downarrow$ $\sin\varphi_c = 1$

left / right asymm. $L(R) \to R(L)$

TRANSVERSITY $h_1(x)$

$$h_1(x) = \frac{1}{2}\sum_f e_f^2 \left[\Delta_\perp q(x) + \Delta_\perp \bar{q}(x)\right] \quad (QPM)$$

$h_1 \neq g_1$ — no gluons
— relativistic

TWIST 2 : not accessible in inclusive D.I.S.

but accessible in semi-inclusive D.I.S.

NEED: transverse target polarisation
measurement struck quark polarisation
(quark polarimeter)

MEASURE

$$\varepsilon_\varphi = \frac{N(\Phi_c) - N(\Phi_c + \pi)}{+}$$ AZIMUTHAL ASYMMETRY

Φ collins

$$= P_T f\, D_{NN}\, H(x)\, a_c \sin\varphi_c$$

quark polarization

quark polarimeter
to be determined elsewhere

$$H(x) \sim \frac{2x\, h_1(x)}{F_2} \sim \frac{\Delta_\perp \mu}{\mu}$$

$a_c \sim 10\% - 30\%$

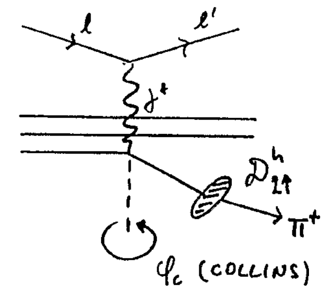
$$a_c = \frac{\Delta_\perp D}{D}$$ NON PERTURBATIVE $\quad a_c = a_c(z, p_T)$

ONE MEASURES $\quad A_N = H \cdot a_c$

to extract h_1 need a_c (how?)

what to expect for A_N: $\frac{\Delta\mu}{\mu} \sim 30\% \rightarrow \lesssim 10\%$

$\ell\, p^\uparrow \rightarrow \ell'\, \pi^{+/-} + X$



$$D^h_{q\uparrow}(z, \vec{p}_q) = D^h_q(z, p_q) + \Delta D^h_q(z, p_q)\cdot \sin\varphi_c$$

$\varphi_c = \varphi_h - \varphi_{s'} \qquad \sin\varphi_c \equiv \perp$ comp $q'^\uparrow$ to $\gamma^* \times \vec{P}_h$

$d\sigma(\varphi_c) \sim (1 + A_N \sin\varphi_c)\, d\varphi_c$ AZIMUTHAL DIST

$$A_N = a_c \cdot H$$

quark "polarimeter" — transversity

$a_c = a_c(z, P_T, W, \dots)$ depends on kinematics !

exp.

$$H = H(x, Q^2) \approx \frac{2x\, h_1(x, Q^2)}{F_2(x, Q^2)} \sim \frac{\Delta\mu_\perp}{\mu}$$

$$A_N = \frac{1}{P_T \cdot f} \cdot \frac{1}{D_{NN}} \cdot \frac{1}{\langle \sin\varphi_c \rangle} \cdot \frac{N(\varphi_c < \pi) - N(\varphi_c > \pi)}{N(\varphi_c < \pi) + N(\varphi_c > \pi)}$$

target polarization

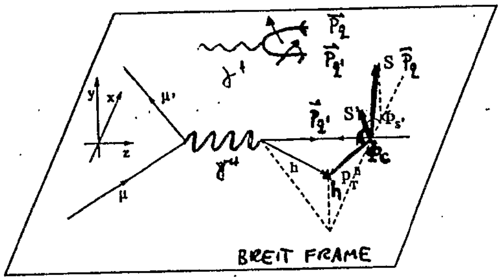
spin transfer coef. in $\gamma^* q\uparrow \rightarrow q'\uparrow \; = 2(1-y)/[1+(1-y)^2]$,

'COLLINS EFFECT' NP B396 ('93) 161

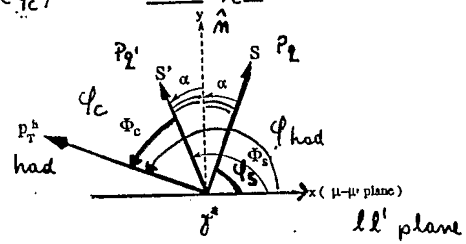
$$\ell\, p^{\uparrow} \to \ell'\, \pi^{+(-)} + X$$

$$\mathcal{D}_{q\uparrow}^{h}(z, p_T) = D_q^h(z, p_T) + \Delta D_q^h(z, p_T)\, \sin \Phi_c$$

$\Rightarrow$ 'SPIN' AZIMUTHAL DIST. 'COLLINS' ANGLE



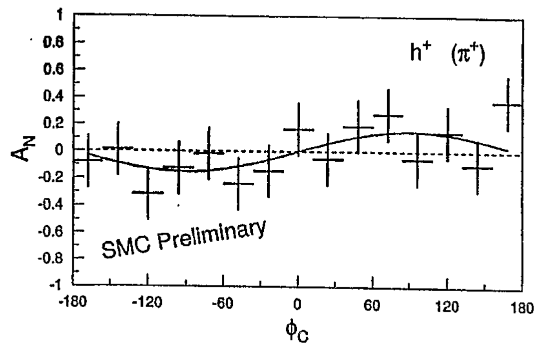
$$\Rightarrow\ d\sigma(\varphi_c) \propto a \cdot \underline{\sin(\varphi_c)} + b$$

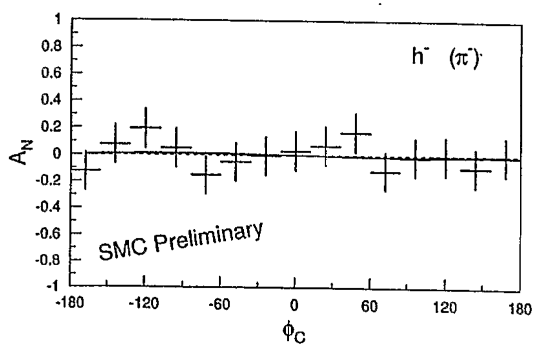


$$P_q' = P_q \cdot D_{NN} \qquad D_{NN} < 1$$

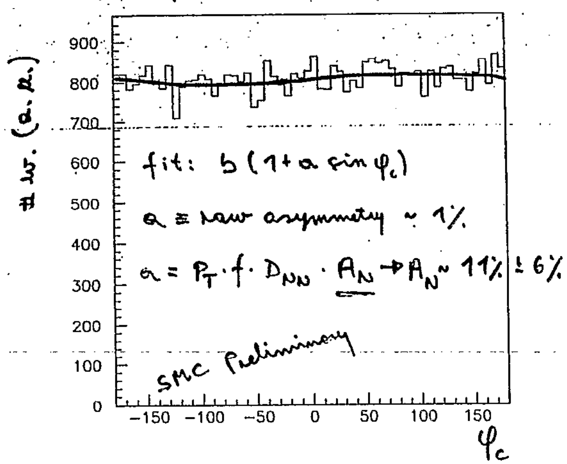
$$\varphi_h - \varphi_{s'} = \varphi_c = \varphi_h + \varphi_s - \pi \quad (\text{also } \varphi_h - \varphi_s \text{ allowed})$$

Azimuthal Hadron Distributions on $p \Uparrow$





$\ell p\uparrow \to \ell' \pi^+ X$



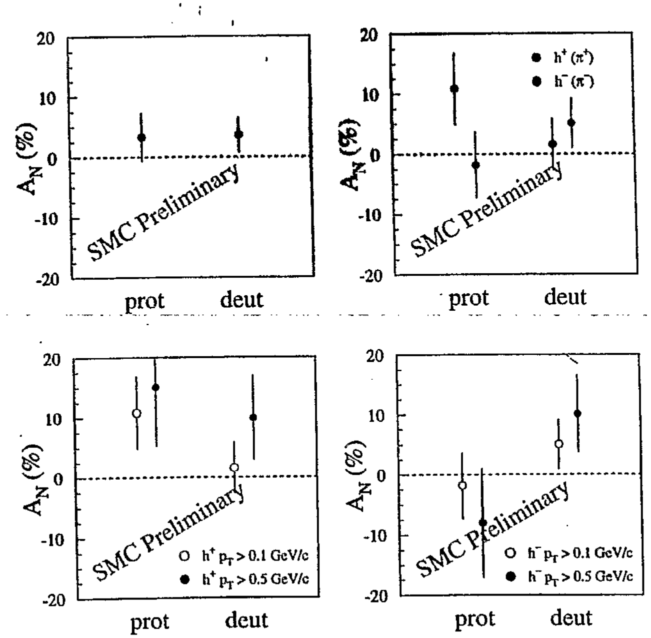
use weight method:

for each event $w_i = P_T \cdot f \cdot D_{NN} \cdot \sin(\varphi_c)_i$

$$A_N = \frac{\sum w_i}{\sum (w_i)^2} \qquad \delta A_N = \frac{1}{\sqrt{\sum_i w_i^2}}$$

The Transverse Single - Spin Asymmetry A_N

SMC, Nucl. Phys. B (Proc. Suppl.) 79 (1999) 520



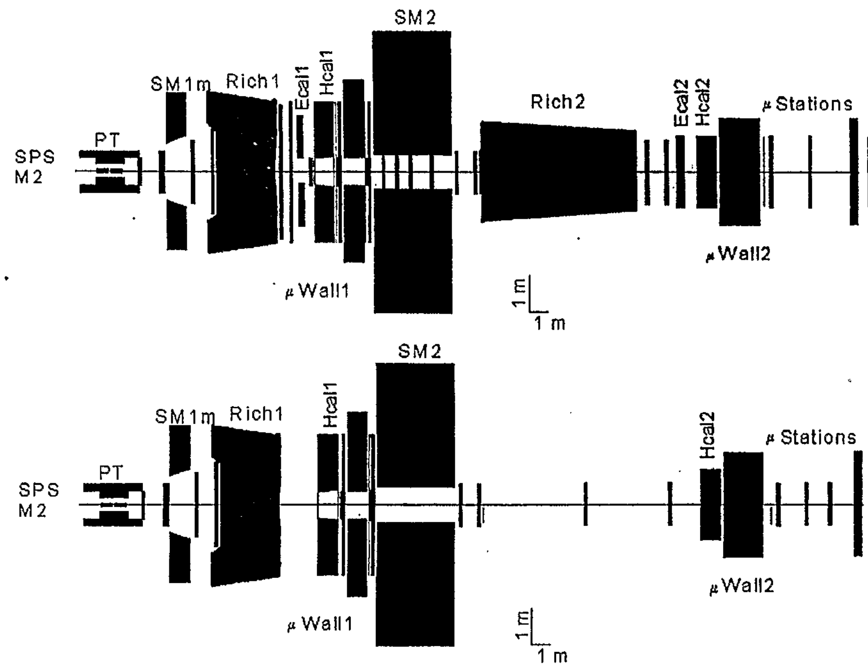
The COMPASS Collaboration

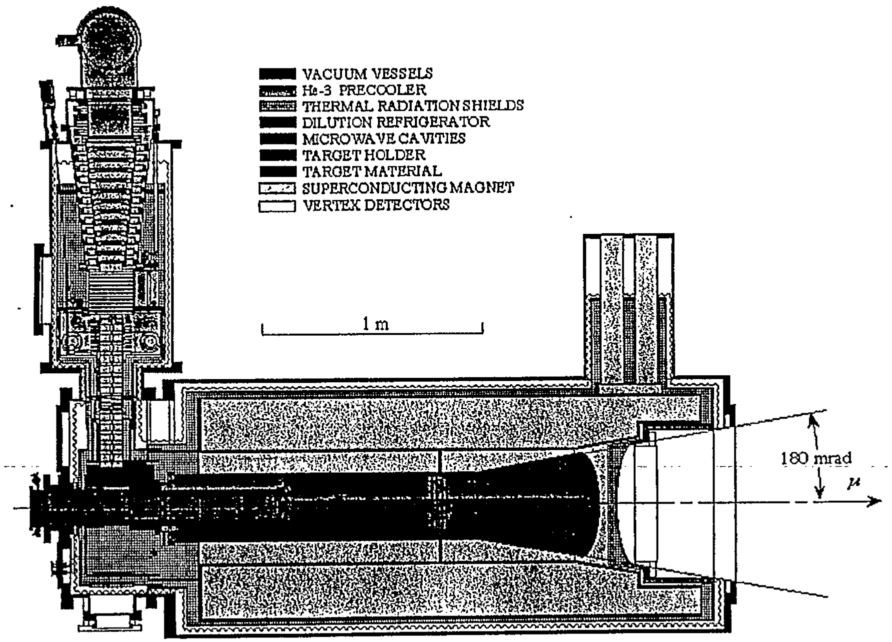
Common **M**uon and **P**roton **A**pparatus
for **S**tructure and **S**pectroscopy

Belgium, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Russia, Switzerland, USA

Bielefeld, BNL, Bochum, Bonn, Calcutta, CERN, Dubna, Erlangen, Freiburg, Heidelberg, Helsinki, Mainz, Miyazaki, Mons, Moscow, Munich, Nagoya, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw

- **28 Institutes**
- **$\sim$ 170 Physicists**





Parameters of Experiment

μ beam: 100 / 190 GeV μ^+ (μ^-)
Pol ~ −80% (+80 for μ^-)
2×10^8 μ/spill (1×10^8 μ/s)

target: proton NH_3 P ~ 90% ⟨P⟩/N ~ 16%
deuteron ^6LiD P ~ 50% ⟨P⟩/N ~ 25%

$\int_{1y} \mathcal{L}\,dt = 2\ fb^{-1}$/year (incl. 25% eff.)
75% LONG. 25% TRANSV. POL.

FULL (4π) COVERAGE OF HADRONS $x_F > 0$

2 STAGE spectrometer (± 180 mrad acc.)
large / small angle
slow / fast particles

PARTICLE ID 2 RICHs 3σ π/K sep. p >
μ-WALLs
ECALs, HCALs

TRIGGER photo-production $Q^2 \to 0$; y > 0.
DIS $Q^2 > 0.5$; y > 0.

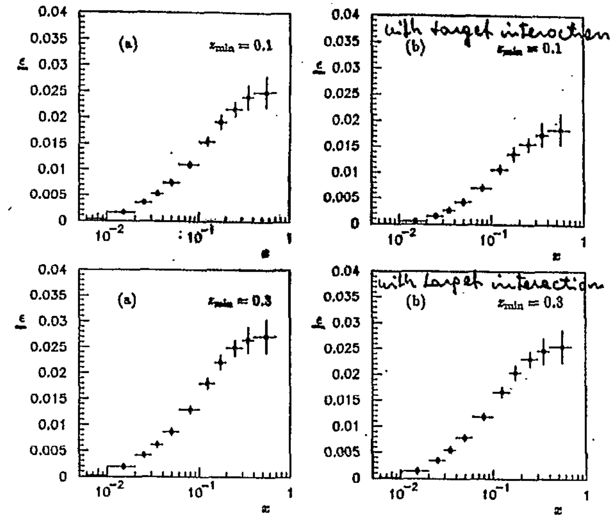
Physiscs with Polarized Muons & Targets

- $\Delta G/G$ GLUON POLARIZATION
  open charm (D^0, D^{*+}, ...)
  hidden charm (J/Ψ, ...)
  high p_T hadrons
- Δu_v, Δd_v, $\Delta\bar{q}$, Δs FLAVOR DECOMPOSITION $g_1(x)$
  semi - inclusive $\pi^\pm, K^\pm, K^{*0}$
- ΔD_q^Λ POLARIZED FRAGMENTATION FUNCTIONS
  Λ, $\bar{\Lambda}$ polarization ($x_F > 0$)
- $h_1(x)$ TRANSVERSITY
  semi - inclusive $\pi^\pm$ with $\perp$ pol. target (azimuthal dep.)
- $g_1(x)$, $g_2(x)$ POLARIZED STRUCTURE FUNCTIONS
  inclusive (high statistics)
- TARGET FRAGMENTATION REGION
  Λ polarization ($x_F < 0$)
- EXCLUSIVE PROCESSES
  elastic vector mesons (ρ^0, ϕ, J/Ψ)
  deep virtual compton scattering
- ...

$\varepsilon = f\, P_T\, D_{NN}\, H(x)\, a_c$ for Leading hadron

$L_? \simeq \frac{2x\, h_1(x)}{F_2(x)}$

1 month on NH_3



x	$z \geq 0.1$		$z \geq 0.3$	
	ϵ	$x \cdot h_1$	ϵ	$x \cdot h_1$
0.006–0.01	0.0004±0.0011	0.005 ±0.013	0.0003±0.0013	0.005 ±0.019
0.01–0.02	0.0016±0.0006	0.010 ±0.004	0.0019±0.0007	0.010 ±0.004
0.02–0.03	0.0035±0.0006	0.017 ±0.003	0.0041±0.0007	0.017 ±0.003
0.03–0.04	0.0053±0.0007	0.024 ±0.003	0.0062±0.0008	0.024 ±0.003
0.04–0.06	0.0075±0.0007	0.032 ±0.003	0.0087±0.0006	0.032 ±0.003
0.06–0.10	0.0110±0.0007	0.048 ±0.003	0.0129±0.0006	0.048 ±0.003
0.10–0.15	0.0154±0.0010	0.065 ±0.005	0.0180±0.0012	0.065 ±0.004
0.15–0.20	0.0192±0.0015	0.077 ±0.006	0.0220±0.0017	0.077 ±0.006
0.20–0.30	0.0216±0.0016	0.081 ±0.006	0.0248±0.0018	0.081 ±0.006
0.30–0.40	0.0239±0.0027	0.071 ±0.008	0.0264±0.0030	0.071 ±0.008
0.40–0.70	0.0249±0.0036	0.046 ±0.007	0.0271±0.0038	0.046 ±0.007

input $h_1 = f_1$

OUTLOOK

- TRANSVERSITY: NEW & RICH FIELD
- INDICATIONS OF LARGE EFFECTS:
  - $\ell \vec{p} \to \ell' + \pi + X$ (HERMES)
  - $\ell p^{\uparrow} \to \ell' + \pi + X$ (SMC)

  Azimuthal $\sin \varphi_c$
  - Z^0 pole Jet Handedness ......

  $a_N \sim 0.1 \div 0.3$
- $A_N \sim a_n \cdot H$

  "precise" determination needed
- COMPASS COMMISSIONING IN Y2K

  COMPLETION OF SETUP IN Y2K+1

  $\hookrightarrow$ PHYSICS
- BROAD PHYSICS PROGRAM
  - MUONS
  - HADRONS

  50 : 50 SHARING

  25% WITH $\perp$ TARGET

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Future Transversity Measurements with TESLA-N

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Physics prospects for the study of the quark transversity distributions $\delta q(x)$ with TESLA-N using a transversely polarized proton and deuteron targets are presented. The TESLA-N project exploits an idea to use one of planned e^+e^- collider TESLA arms to achieve collisions of longitudinally polarized electrons with a solid state fixed target that may be either longitudinally or transversely polarized. Basic parameters of the TESLA-N project are electron beam energy 250 GeV, integrated luminosity 100 fb^{-1} per year. As polarized targets NH_3 ($P_T = 80\%$) and ^6LiD ($P_T = 30\%$) are considered.
The measurement of the azimuthal asymmetries due to the Collins effect in the production of positive and negative pions on proton and deuteron targets as a function of three variables x, Q^2, and z will allow the simultaneous reconstruction of the shapes of the unknown functions $\delta q(x, Q^2)$ (u, d, $\bar{u}$, and $\bar{d}$) and $H_1^{\perp(1)}(z)/D_1(z)$ where flavour independence was assumed for the fragmentation functions ratio. The relative normalization cannot be fixed without a further assumption. This ambiguity can be resolved by relating $\delta q(x)$ to $\Delta q(x)$ in the region of large values of x where the differences between two distributions are expected to be small. It is demonstrated that such approach allows to measure $\delta q(x, Q^2)$ at TESLA-N with statistical accuracies comparable to existing measurements of the helicity distributions. The quark tensor charge can be measured with accuracies of about 0.01 for $\delta u(1GeV^2)$ and 0.02 for $\delta d(1GeV^2)$. Simultaneously, it provides a good measurement of the polarized fragmentation function $H_1^{\perp(1)}(z)$.
In addition, it is shown that TESLA-N has a good capability to access the transversity distributions through a measurement of correlations between the transverse spin of the target nucleon and the normal to the two-meson plane. The projected statistical accuracy is quite encouraging if the interference fragmentation function is not too much suppressed w.r.t. its upper bound.

Future Transversity Measurements with TESLA-N

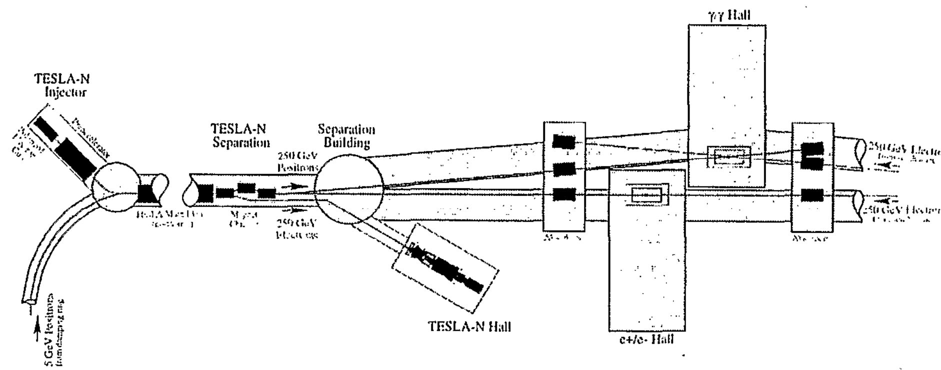
V. Korotkov, W.-D. Nowak

Workshop "Future Transversity Measurements"
BNL, September 20, 2000

- TESLA-N
- $\delta q(x, Q^2)$ Extraction via the Collins Effect
- Asymmetry in the Two-Pion Correlations
- Summary

TESLA-N

The TESLA-N idea: use one of the e^+e^- collider TESLA arms to organize collisions of longitudinally polarized electrons with a solid state fixed target that may be either longitudinally or transversely polarized.



Basic parameters:

- Beam Energy 250 GeV
- Luminosity 100 fb^{-1} per year
- Electron beam polarization 90%
- Proton target: NH_3, $P_T = 80\%$, $f = 0.176$
- Deuteron target: ^6LiD, $P_T = 30\%$, $f = 0.44$

TESLA-N **Study Group**

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Transversity analysis at TESLA-N

— Collins Effect

— Two-Pion Correlations

To estimate the transversity distributions, the helicity distributions at low scale were taken as input (LO GRSV-96, 'stand.')

$$\delta q(x, 0.4GeV^2) = \Delta q(x, 0.4GeV^2)$$

Evoluted to higher Q^2

$$\frac{\partial}{\partial \ln Q^2}\delta q^{\pm}(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi}\delta P_{q^{\pm}}(x) \otimes \delta q^{\pm}(x, Q^2)$$

where $\delta q^{\pm} = \delta q \pm \delta\bar{q}$. In LO

$$\delta P_{q^{\pm}}(x) = C_F[\frac{2x}{(1-x)_+} + \frac{3}{2}\delta(1-x)]$$

Hadron distributions: LEPTO + JETSET

Event cuts: $Q^2 > 1GeV^2$, $W > 2GeV$, $0.05 < y < 0.90$

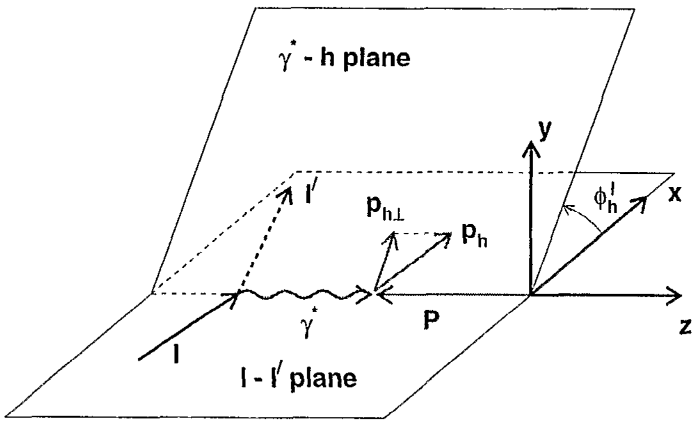
Acceptance: 5 ÷ 175 mrad

Pion variables: $x_F > 0$, $z > 0.1$, $P_{h\perp} > 50MeV$

Measurement of $\delta q(x)$ via the Collins effect

Weighted asymmetry [Mulders, Tangermann 96, Kotzinian, Mulders 97]

$$A_T(x,y,z) \equiv \frac{\int d\phi^\ell \int d^2P_{h\perp} \frac{|P_{h\perp}|}{zM_h} \sin(\phi_s^\ell + \phi_h^\ell)\ (d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi^\ell \int d^2P_{h\perp}(d\sigma^\uparrow + d\sigma^\downarrow)}$$



Factorization w.r.t. x and z:

$$A_T(x,y,z) = f \cdot P_T \cdot D_{nn} \cdot \frac{\sum_q e_q^2\ \delta q(x)\ H_1^{\perp(1)q}(z)}{\sum_q e_q^2\ q(x)\ D_1^q(z)}$$

$D_{nn} = (1-y)/(1-y+y^2/2)$ - transverse spin transfer coefficient.

$$A_T^h(x,y,z) \sim \frac{\sum_q e_q^2\ \delta q(x)\ H_1^{\perp(1)q\to h}(z)}{\sum_q e_q^2\ q(x)\ D_1^{q\to h}(z)} \equiv$$

$$\sum_q \frac{\delta q(x)}{q(x)} \cdot \frac{H_1^{\perp(1)q\to h}(z)}{D_1^{q\to h}(z)} \cdot \frac{e_q^2\ q(x)\ D_1^{q\to h}(z)}{\sum_q e_q^2\ q(x)\ D_1^{q\to h}(z)} \equiv$$

$$\sum_q \frac{\delta q(x)}{q(x)} \cdot \frac{H_1^{\perp(1)q\to h}(z)}{D_1^{q\to h}(z)} \cdot P_q^h(x,z)$$

where

$$P_q^h(x,z) \equiv \frac{e_q^2\ q(x)\ D_1^{q\to h}(z)}{\sum_q e_q^2\ q(x)\ D_1^{q\to h}(z)}$$

Very simple factorized (in respect to x and z) form for the A_T.

Sum rule for T-odd fragmentation functions (Schäfer, Teryaev, 99)

$\to$ contributions from non-leading parton fragmention

is expected to be severely suppressed:

$$\frac{H_1^{\perp(1)d\to\pi^+}(z)}{D_1^{d\to\pi^+}(z)} = \frac{H_1^{\perp(1)u\to\pi^-}(z)}{D_1^{u\to\pi^-}(z)} = \ldots \equiv 0$$

Combined analysis of $A_p^{\pi^+}$,$A_p^{\pi^-}$, $A_d^{\pi^+}$, $A_d^{\pi^-}$

$$A_p^{\pi^+}(x,y,z) \sim \frac{\delta u(x)}{u(x)} \cdot \frac{H_1^{\perp(1)u\to\pi^+}(z)}{D_1^{u\to\pi^+}(z)} \cdot P_{u(p)}^{\pi^+}(x,z) + \frac{\delta\bar{d}(x)}{\bar{d}(x)} \cdot \frac{H_1^{\perp(1)\bar{d}\to\pi^+}(z)}{D_1^{\bar{d}\to\pi^+}(z)} \cdot P_{\bar{d}(p)}^{\pi^+}(x,z)$$

$$A_p^{\pi^-}(x,y,z) \sim \frac{\delta d(x)}{d(x)} \cdot \frac{H_1^{\perp(1)d\to\pi^-}(z)}{D_1^{d\to\pi^-}(z)} \cdot P_{d(p)}^{\pi^-}(x,z) + \frac{\delta\bar{u}(x)}{\bar{u}(x)} \cdot \frac{H_1^{\perp(1)\bar{u}\to\pi^-}(z)}{D_1^{\bar{u}\to\pi^-}(z)} \cdot P_{\bar{u}(p)}^{\pi^-}(x,z)$$

$$A_n^{\pi^+}(x,y,z) \sim \frac{\delta d(x)}{d(x)} \cdot \frac{H_1^{\perp(1)u\to\pi^+}(z)}{D_1^{u\to\pi^+}(z)} \cdot P_{u(n)}^{\pi^+}(x,z) + \frac{\delta\bar{u}(x)}{\bar{u}(x)} \cdot \frac{H_1^{\perp(1)\bar{d}\to\pi^+}(z)}{D_1^{\bar{d}\to\pi^+}(z)} \cdot P_{\bar{d}(n)}^{\pi^+}(x,z)$$

$$A_n^{\pi^-}(x,y,z) \sim \frac{\delta u(x)}{u(x)} \cdot \frac{H_1^{\perp(1)d\to\pi^-}(z)}{D_1^{d\to\pi^-}(z)} \cdot P_{d(n)}^{\pi^-}(x,z) + \frac{\delta\bar{d}(x)}{\bar{d}(x)} \cdot \frac{H_1^{\perp(1)\bar{u}\to\pi^-}(z)}{D_1^{\bar{u}\to\pi^-}(z)} \cdot P_{\bar{u}(n)}^{\pi^-}(x,z)$$

To resolve the normalization ambiguites:

$$\frac{H_1^{\perp(1)u\to\pi^+}}{D_1^{u\to\pi^+}} = \frac{H_1^{\perp(1)d\to\pi^-}}{D_1^{d\to\pi^-}} = \cdots = \frac{H_1^{\perp(1)}}{D_1}$$

$$\delta u(x_0,Q_0^2) = \Delta u(x_0,Q_0^2)$$

OR

fix every quark transversity distributions at some point

$$\begin{aligned}
\delta u(x_0,Q_0^2) &= \Delta u(x_0,Q_0^2)\\
\delta d(x_0,Q_0^2) &= \Delta d(x_0,Q_0^2)\\
\delta \bar{u}(x_0,Q_0^2) &= \Delta \bar{u}(x_0,Q_0^2)\\
\delta \bar{d}(x_0,Q_0^2) &= \Delta \bar{d}(x_0,Q_0^2)
\end{aligned}$$

This allows to reconstruct δu, δd, $\delta\bar{u}$, $\delta\bar{d}$ (x,Q^2) and measure the tensor charges

$$\delta q(Q^2) = \int_0^1 dx(\delta q(x,Q^2) - \delta\bar{q}(x,Q^2))$$

There are predictions from lattice studies.
The nucleon tensor charge

$$\delta\Sigma(Q^2) = \sum_i \int dx(\delta q_i(x,Q^2) - \delta\bar{q}_i(x,Q^2))$$

is calculated to be
0.56 ± 0.09 at $Q^2 = 2$ GeV^2 (S.Aoki et al. 1996) and
0.76 ± 0.07 at $Q^2 = 4$ GeV^2 (Göckeler et al. 1997).

Reconstruction of the $\delta q(x, Q^2)$

Measure the asymmetries at $N_{(x,Q^2)}$ points in (x, Q^2) and at N_z points in z.

$$A_{p,d}^{\pi^+,\pi^-}(x, Q^2, z) = \Phi\left(\frac{\delta q}{q}(x, Q^2),\ \frac{H_1^{\perp(1)}}{D_1}(z),\ P_{p,d}^{q\to\pi}(x, Q^2, z)\right)$$

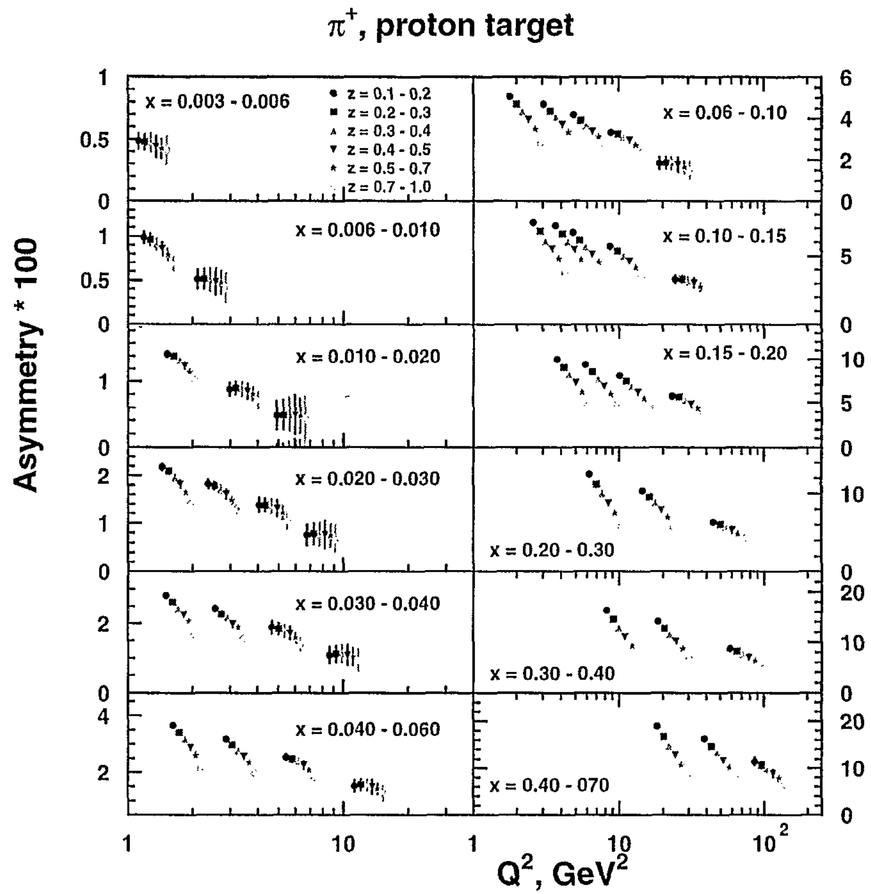
Then we would have
$4N_{(x,Q^2)}N_z$ measurements,
$4N_{(x,Q^2)}$ unknown values of $\delta q(x, Q^2)$ and
N_z unknown values of $\frac{H_1^{\perp(1)}}{D_1}(z)$

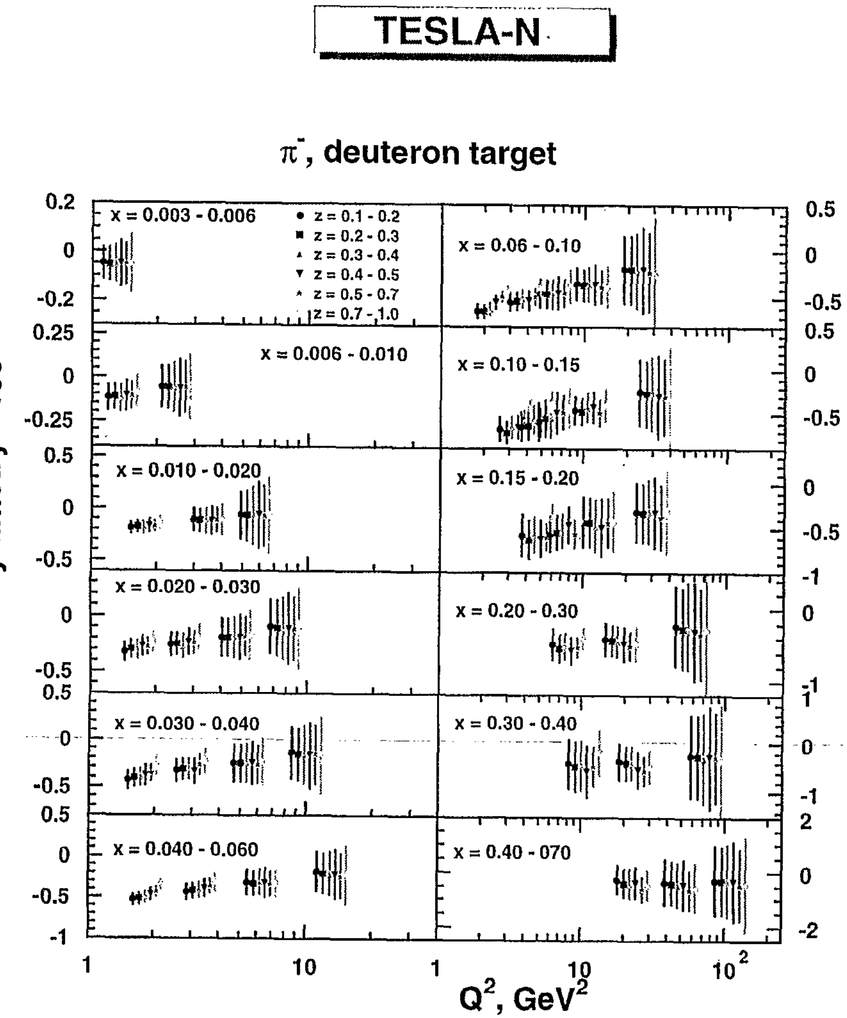
Two methods:

- overconstrained set of coupled equations which one may resolve with a minimization procedure.
- define a parameter-dependent ansatz for every $\delta q(x, Q_0^2)$ and use the LO evolution to fit the unknown parameters and unknown values of $\frac{H_1^{\perp(1)}}{D_1}(z)$ to measured asymmetries.

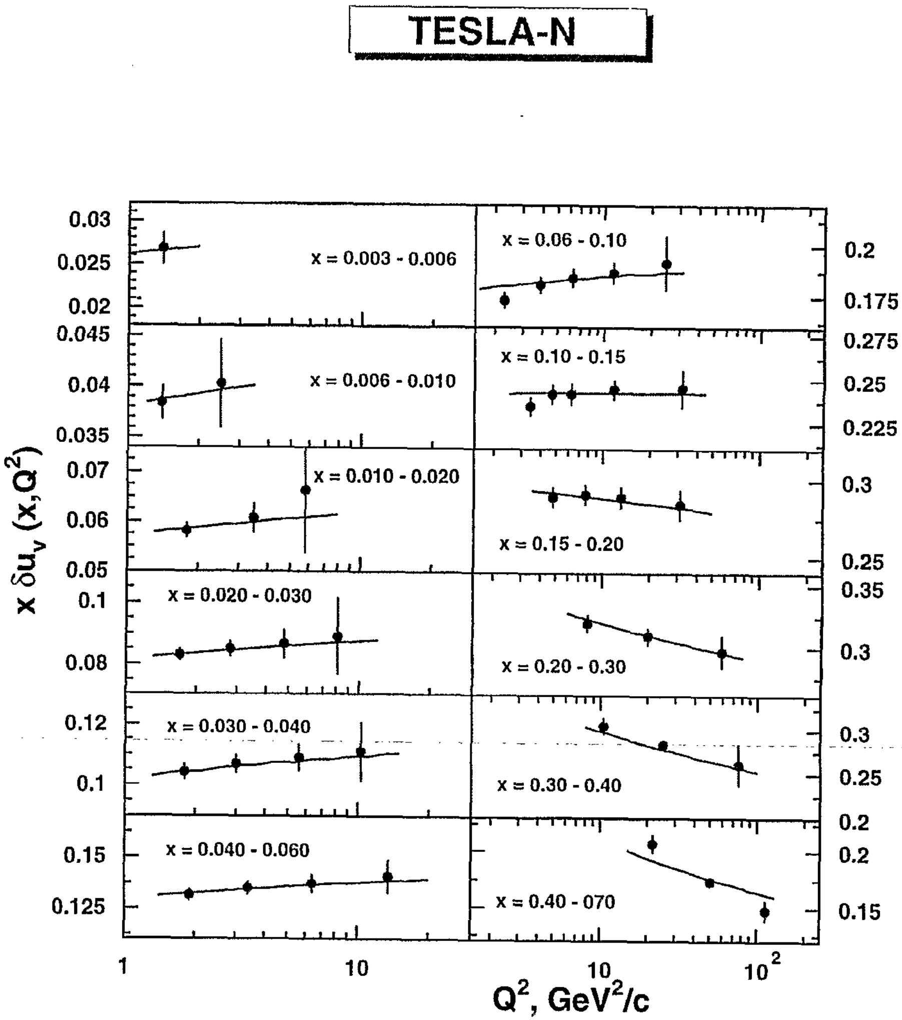
$$\delta q_f(x, Q_0^2) = \eta_f x^{\alpha_f}(1 - x)^{\beta_f}(1 + \gamma_f x + \rho_f\sqrt{x})$$

TESLA-N



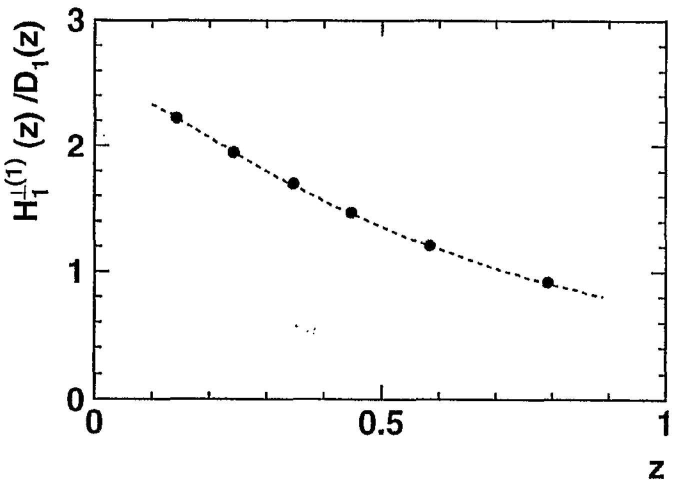


TESLA-N
π^-, deuteron target
x = 0.003 - 0.006
z = 0.1 - 0.2
z = 0.2 - 0.3
z = 0.3 - 0.4
z = 0.4 - 0.5
z = 0.5 - 0.7
z = 0.7 - 1.0
x = 0.006 - 0.010
x = 0.010 - 0.020
x = 0.020 - 0.030
x = 0.030 - 0.040
x = 0.040 - 0.060
x = 0.06 - 0.10
x = 0.10 - 0.15
x = 0.15 - 0.20
x = 0.20 - 0.30
x = 0.30 - 0.40
x = 0.40 - 070
Asymmetry * 100
Q^2, GeV^2



TESLA-N
x = 0.003 - 0.006
x = 0.006 - 0.010
x = 0.010 - 0.020
x = 0.020 - 0.030
x = 0.030 - 0.040
x = 0.040 - 0.060
x = 0.06 - 0.10
x = 0.10 - 0.15
x = 0.15 - 0.20
x = 0.20 - 0.30
x = 0.30 - 0.40
x = 0.40 - 070
$x\,\delta u_v\,(x,Q^2)$
Q^2, GeV^2/c

TESLA-N



LO Fit Results

$$\delta q_f(x, Q_0^2) = \eta_f \frac{1}{N_f(\alpha,\beta,\gamma,\rho)} x^{\alpha_f}(1-x)^{\beta_f}(1+\gamma_f x + \rho_f\sqrt{x})$$

$$N_f(\alpha,\beta,\gamma,\rho) = \int_0^1 x^{\alpha_f}(1-x)^{\beta_f}(1+\gamma_f x + \rho_f\sqrt{x})dx$$

u_v	η	0.873	0.010	0.883	0.011	0.883	0.011
	α	-0.197	0.025	-0.210	0.027	-0.230	0.031
	β	3.672	0.074	3.574	0.080	3.463	0.104
	γ	6.649	0.218	6.549	0.253	6.409	0.302
	ρ	-2.694	0.118	-2.580	0.146	-2.348	0.203
d_v	η	-0.308	0.009	-0.316	0.024	-0.313	0.012
	α	-0.338	0.059	-0.581	0.264	-0.447	0.126
	β	1.423	1.625	2.858	0.798	3.022	0.616
	γ	0.042	0.581	-1.498	7.445	1.668	2.112
	ρ	-0.835	0.702	5.542	7.768	0.080	1.859
$\bar{u}$	η	-0.062	0.002	-0.065	0.003	-0.061	0.002
	α	-0.247	0.035	-0.227	0.044	-0.263	0.049
	β	5.028	0.217	4.828	0.233	4.471	0.391
	γ	0.0		0.0		-2.855	1.553
	ρ	0.0		0.0		1.369	1.130
$\bar{d}$	η	$\bar{d}=\bar{u}$		-0.058	0.008	$\bar{d}=\bar{u}$	
	α			-0.279	0.197		
	β			6.314	2.352		
	γ			0.0			
	ρ			0.0			
χ^2/DoF		1040/966		1036/963		1034/964	

Two-Meson Correlation with Transverse Spin

The interference effect between the s- and p-waves of the two-meson system allows the quark's polarization information to be carried through $\vec{k}_+ \times \vec{k}_- \cdot \vec{S}_\perp$. (Jaffe et al., 1998)

For $eN^\uparrow \to e'\pi^+\pi^- X$

$$\mathcal{A}_{\perp T} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2} \cos\phi \; \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) \times \frac{\sum_a e_a^2 \delta q_a(x)\, \delta\hat{q}_I^a(z)}{\sum_a e_a^2 q_a(x)\left[\sin^2\delta_0 \hat{q}_0^a(z) + \sin^2\delta_1 \hat{q}_1^a(z)\right]}$$

$\delta\hat{q}_I^a(z)$ — unknown chiral-odd interference quark FF

$\delta_{0,1} = \delta_{0,1}(m^2)$ — strong interaction $\pi\pi$ phase shifts

$\cos\phi = \vec{k}_+ \times \vec{k}_- \cdot \vec{S}_\perp / |\vec{k}_+ \times \vec{k}_-||\vec{S}_\perp|$ — analog of the Collins angle defined by the $\pi^+\pi^-$ system

$\hat{q}_0$ and $\hat{q}_1$ — spin-average FF for the σ and ρ resonances.

The interference FF $\delta\hat{q}_I$ has an upper bound

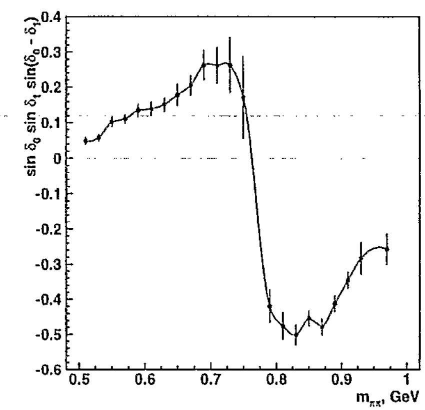
$$\delta\hat{q}_I^2 \leq 4\hat{q}_0\hat{q}_1/3$$

for each flavor.

It could be measured in $e^+e^- \to (\pi^+\pi^- X)(\pi^+\pi^- X)$. Nothing has been published yet.

The final state phase generated by the s-p interference is crucial to the method. If the data are not kept differential in enough kinematic variables, the effect will almost certainly average to zero.

In particular the two-meson invariant mass, m, must be kept differential. The interference averages to about zero when integrating over the mass of the two-pion system due to a factor $\sin(\delta_0 - \delta_1)$.



Two-Pion Correlations at TESLA-N

For a proton target:

$$\mathcal{A}_{\perp T} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi\ \sin\delta_0 \sin\delta_1 \sin(\delta_0-\delta_1) \times$$

$$\frac{\delta u_v(x) - \frac{1}{4}\delta d_v(x)}{(u(x)+\bar{u}(x)) + \frac{1}{4}(d(x)+\bar{d}(x))} \cdot \frac{\delta \hat{u}_I(z)}{\sin^2\delta_0 \hat{u}_0(z) + \sin^2\delta_1 \hat{u}_1(z)} .$$

A *maximally* possible asymmetry with $\delta\hat{u}_I^2 = 4\hat{u}_0\hat{u}_1/3$.

The maximal asymmetry does not depend on z

$$A_{max}^{ep\to e'\pi^+\pi^- X} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi \frac{1}{\sqrt{3}} \sin(\delta_0-\delta_1)$$

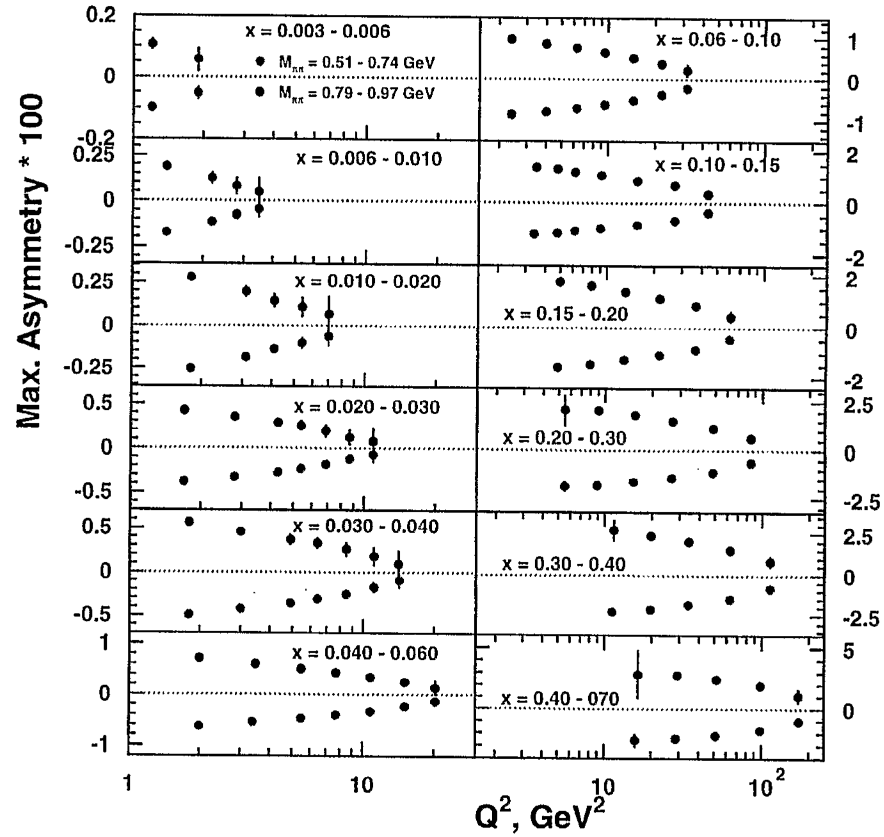
$$\times \frac{\delta u_v(x) - \frac{1}{4}\delta d_v(x)}{(u(x)+\bar{u}(x)) + \frac{1}{4}(d(x)+\bar{d}(x))} .$$

$$A_{max}^{ed\to e'\pi^+\pi^- X} \sim \frac{\delta u_v(x) + \delta d_v(x)}{u(x)+\bar{u}(x) + d(x)+\bar{d}(x)}$$

$$\tilde{A}_{max} = P_T \cdot A_{max}/\cos\phi$$

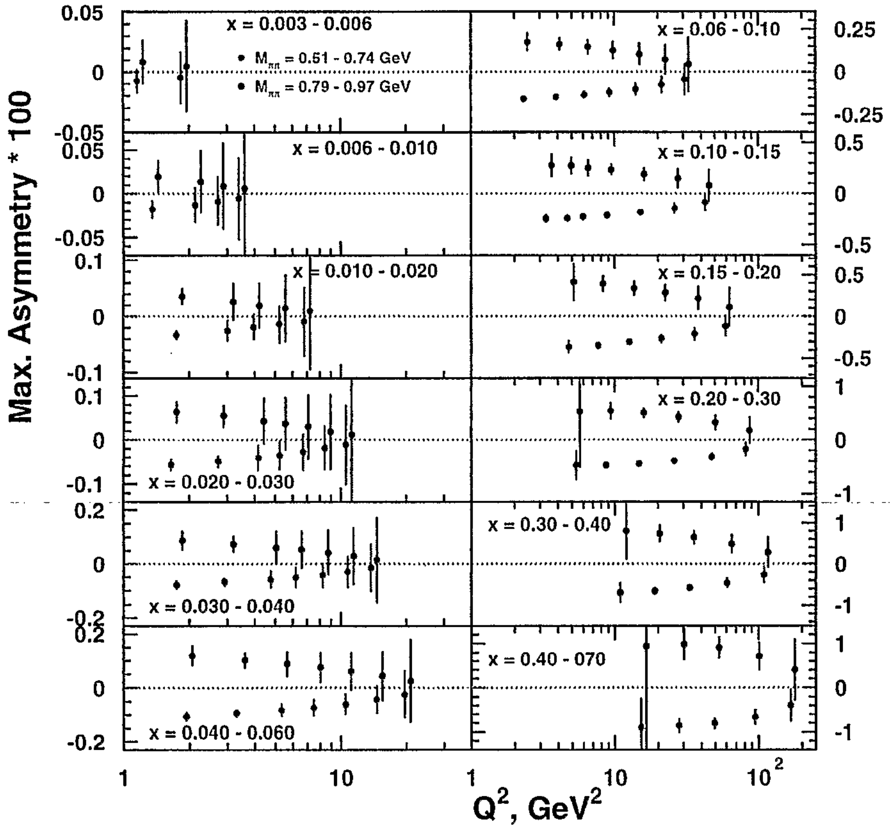
TESLA-N

Two-Pion Correlations, NH_3 Target.



TESLA-N

Two-Pion Correlations, ^6LiD Target.



Summary

- The TESLA-N project, due to its very high luminosity and large c.m. energy, has a big potential to study the quark transversity distributions $\delta q(x, Q^2)$.

- Through the Collins effect in SIDIS $\delta q(x, Q^2)$ can be measured with statistical accuracies comparable to existing measurements of the helicity distributions. The quark tensor charge can be measured with accuracies of about 0.01 for $\delta u(1GeV^2)$ and 0.02 for $\delta d(1GeV^2)$. Simultaneously, it may allow a good measurement of the polarized fragmentation function $H_1^{\perp(1)q}(z)$.

- In addition, the TESLA-N has a good capability to access the transversity distributions through two-meson correlations. The projected statistical accuracy is quite encouraging if the interference fragmentation function is not too much suppressed w.r.t. its upper bound.

- There are additional methods to study the transversity distributions which have not been investigated yet in framework of the TESLA-N project.

Do we understand the fragmentation process at HERMES ?

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Semi-inclusive deep-inelastic scattering and the concept of flavour-tagging has become an important tool in the determination of different parton distributions. However, to apply this technique, the fragmentation process has to be understood. Especially at the relatively low center-of-mass energy of the HERMES experiment ($\sqrt{s} \sim 7$ GeV), two important questions have to be addressed:

- do the hard and the soft processes factorise ?
- can one clearly separate the current and the target fragmentation region ?

Two HERMES measurements support the validity of the factorisation ansatz at HERMES:

1. The measurement of the flavour asymmetry in the light quark sea
At HERMES the flavour asymmetry of the light quark sea has been determined from the ratio of the differences between charged pion yields for proton and neutron targets:

$$r(x,z) = \frac{N_p^{\pi^-} - N_n^{\pi^-}}{N_p^{\pi^+} - N_n^{\pi^+}},$$

where $x = Q^2/2M\nu$ is the Bjorken scaling variable and $z = E^\pi/\nu$ is the fraction of the virtual photon energy carried by the pion. Using the factorised ansatz for semi-inclusive deep-inelastic scattering

$$N^{\pi^\pm}(x,z) \propto \sum_i e_i^2 (q_i(x) D_{q_i}^{\pi^\pm}(z) + \bar{q}_i(x) D_{\bar{q}_i}^{\pi^\pm}(z))$$

one can derive the following expression:

$$\frac{1+r(x,z)}{1-r(x,z)} = \frac{u(x) - d(x) + \bar{u}(x) - \bar{d}(x)}{(u(x) - \bar{u}(x)) - (d(x) - \bar{d}(x))} \cdot \frac{3}{5} \frac{(1 + D_u^{\pi^-}(z)/D_u^{\pi^+}(z))}{(1 - D_u^{\pi^-}(z)/D_u^{\pi^+}(z))},$$

which factorises into two independent functions of x and z and thus can be rearranged to extract the ratio $(\bar{d}(x) - \bar{u}(x))/(u(x) - d(x))$. Plotting the same quantity for fixed values of x as a function of z provides a test of the assumed form of factorisation. No z dependence is seen (see Fig. 1), strongly supporting the assumption of factorisation between the hard scattering process (depending on the parton distributions $q_i(x)$) and the hadronisation of the struck quarks (described by the fragmentation functions $D_q^{\pi^\pm}(z)$). It should be noted however that the statistical precision of the data presented here does not allow to exclude a z dependence of the order of 10-20%.

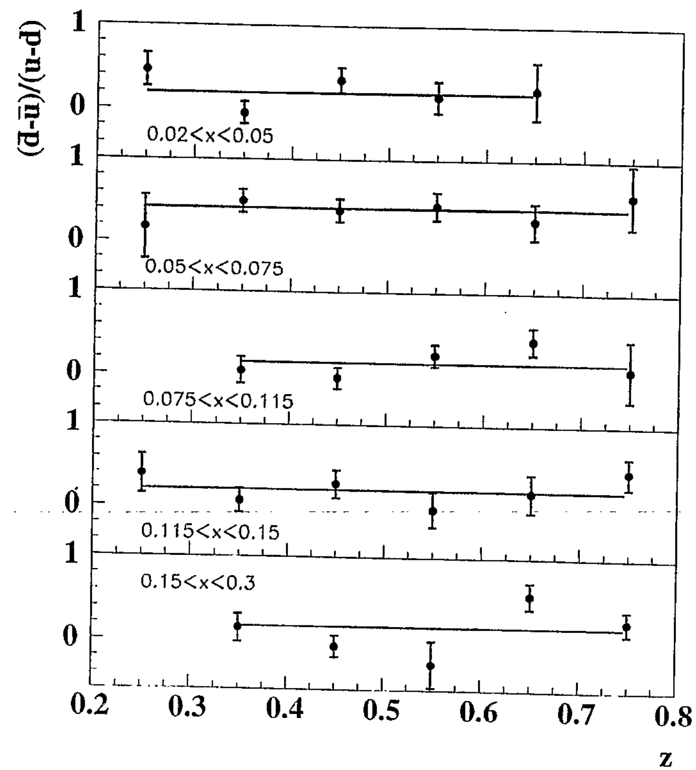

Figure 1: z dependence of $(\bar{d}(x) - \bar{u}(x))/(u(x) - d(x))$ as measured by HERMES

2. The measurement of the pion multiplicity

The differential multiplicity, i.e. the number of pions produced in deep-inelastic scattering, normalised to the total number of inclusive deep-inelastic events has been determined for both neutral and charged pions. As expected from isospin symmetry, the agreement between neutral and charged pions is excellent, at least up $z \sim 0.7$ where a possible contribution from exclusive channels might become important. In Fig. 2 the neutral pion multiplicity as measured at HERMES is compared to the previous EMC measurement as a function of z. As a significant Q^2 dependence of the fragmentation process is expected by perturbative QCD, the HERMES results have been evolved from the average measured Q^2 of 2.5 GeV^2 to the average Q^2 of the EMC experiment ($Q^2 = 25$ GeV^2). The excellent agreement between the two experiments strongly supports the fact that the fragmentation process at HERMES is essentially the same as for the EMC experiment at a much higher center-of-mass energy.

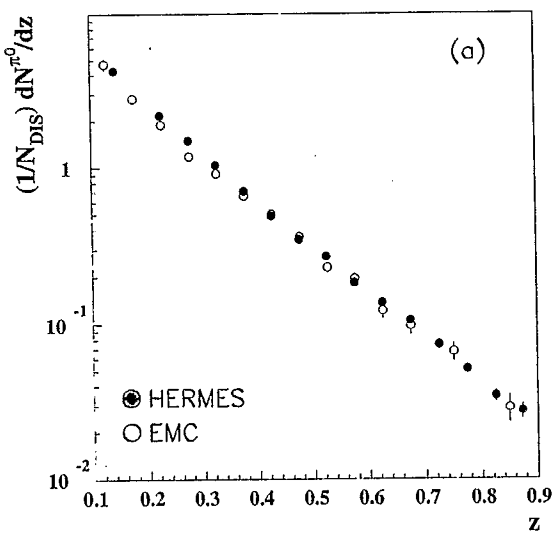

Figure 2: z dependence of neutral pion multiplicities measued by HERMES and EMC

Earlier experiments have reported evidence for an additional x or W dependence of multiplicities measured in deep-inelastic scattering. Fig. 3 shows the charged pion multiplicities for HERMES as a function of x for four different bins in z together with data on charged hadron multiplicities from EMC. All data have been evolved to $Q^2 = 2.5$ GeV^2, the average Q^2 of the HERMES data.

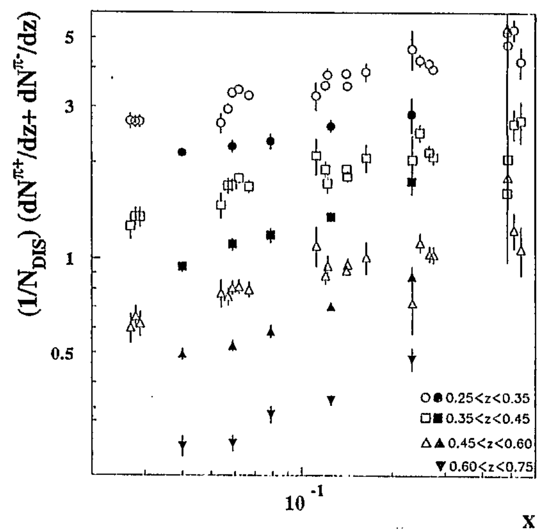

Figure 3: x dependence of charged pion (hadron) multiplicities for fixed values of z as measued by HERMES (pions) and EMC (hadrons)

In this figure the following observations are of interest:

- The difference in the absolute values of the multiplicities seen by HERMES and by EMC is related to the fact that the HERMES data are for pions while the EMC data include all hadrons.
- Both data sets show a significant x dependence which gets stronger as z decreases.
- The slopes in the data from both experiments are consistent even though they were measured at very different kinematics.
- As the mean Q^2 per bin for HERMES only varies between 2.1 and 2.6 GeV^2, the observed x dependence is not generated by Q^2 evolution.

One possible explanation for the observed x dependences might be NLO QCD corrections to the simple LO factorisation form used in the analysis of both the HERMES and the EMC data. Another possibility is the difference between multiplicities and fragmentation functions: while fragmentation functions are expected to depend on z (and Q^2) only, multiplicities might become x dependent because of the presence of the strange sea quarks.

The question if one can clearly separate the current and the target fragmentation region is best demonstrated by a plot of P. Mulders (Fig. 4).

KINEMATICS (W = 5 GeV)

$$\eta = \frac{1}{2}\ln\left(\frac{P_h^-}{P_h^+}\right) = \ln\left(\frac{P_h^-\sqrt{2}}{M_{h\perp}}\right) = -\ln\left(\frac{P_h^+\sqrt{2}}{M_{h\perp}}\right)$$

$$\begin{cases} \text{current}: \eta_{cm} = \ln z + \ln\left(\frac{W}{M_{h\perp}}\right) \\ \text{target}: \eta_{cm} = -\ln z + \ln\left(\frac{W}{M_{h\perp}}\right) \end{cases}$$

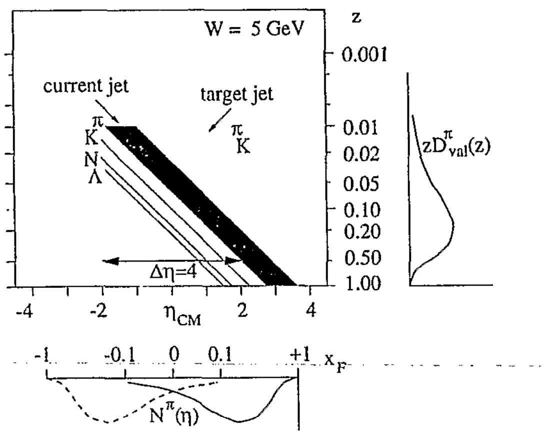

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Figure 4: Separation of current and target fragmentation

The current and the target fragmentation region are reasonably separated if the rapidity difference is larger than about 4. For pions in the HERMES kinematics this corresponds to the requirement of a minimum z value of about 0.2-0.3. As all HERMES analyses of semi-inclusive events used for the extraction of parton distributions have imposed a minimum z value of 0.2, contributions from the target fragmentation region are expected to be very small.

Some remarks about fragmentation functions at low Q^2

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A measurement of transversity densities in processes other than 'Drell-Yan' or $pp \to jets$ usually involves the knowledge of some set of (chiral-odd) fragmentation functions which are unmeasured as well. Therefore a global QCD analysis of various processes measured at different experiments and energies is mandatory to pin down transversity, including its flavor structure, in the future.

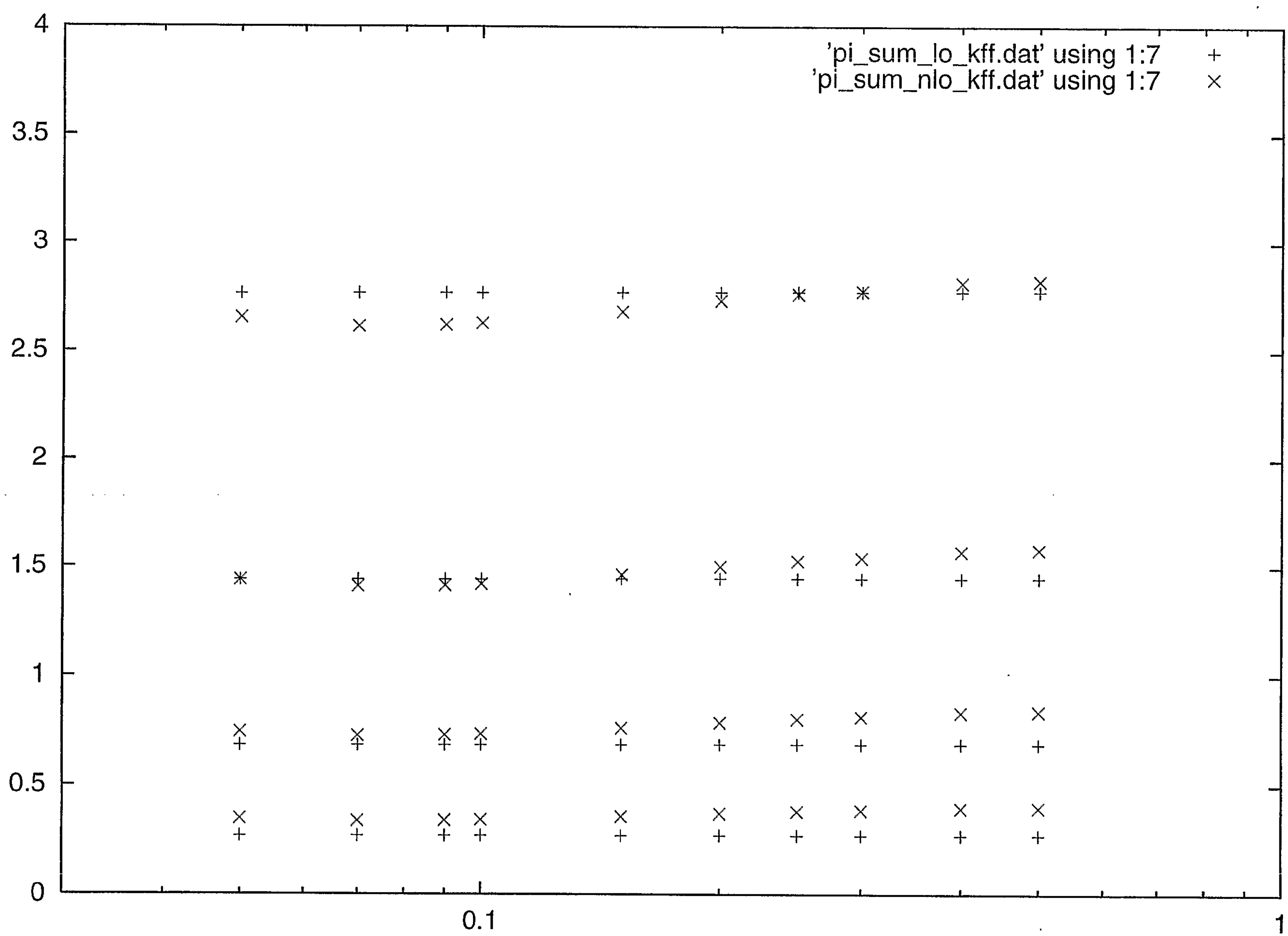
To make such an analysis reliable and theoretically sound, one of the key issues which has to be addressed first is to check whether the QCD framework for fragmentation functions can accommodate available *unpolarized* data for single inclusive charged hadron (mainly pion) production at fixed target energies. This is important since a major part of upcoming measurements with transversely polarized targets will be done at comparatively low fixed target energies (HERMES, COMPASS) where all sorts of problems like large NLO QCD corrections or large higher twist effects may occur. Unless such a relatively 'simple' process as semi-inclusive DIS can be described and theoretically understood within (perturbative) QCD, a reliable extraction of, e.g., chiral odd fragmentation functions in the future from much more involved measurements seems to be elusive.

As a benchmark one can take the available charged hadron (pion) data from EMC, $\langle Q^2 \rangle \simeq 25\,\mathrm{GeV}^2$, and HERMES, $\langle Q^2 \rangle \simeq 2.5\,\mathrm{GeV}^2$. It should be mentioned that both sets of available LO and NLO parametrizations of fragmentation functions, (1): S. Kretzer, Phys. Rev. D62 (2000) 054001, (2): B. Kniehl et al., Nucl. Phys. B582 (2000) 514, are obtained from fits to high precision e^+e^- data at the Z-pole from CERN LEP-I and SLAC SLD. These sets then successfully describe also e^+e^- data from PEP, PETRA, and TRISTAN at much lower energies. However, available scarce low Q^2 SIDIS data were not considered so far because they are much less precise than e^+e^- data. It should be also recalled that in the usual QCD framework the scale dependence of fragmentation functions $D^H(z, Q^2)$ is governed by evolution equations in a similar fashion as for parton densities and that the produced hadron H is treated as a *massless* particle in the same way as target mass corrections are usually neglected in DIS.

When applying the available sets of fragmentation functions in a calculation of SIDIS production of $\pi \equiv \pi^+ + \pi^-$ at $\langle Q^2 \rangle \simeq 2.5\,\mathrm{GeV}^2$ the following observations can be made:

- NLO effects are sizable and, more importantly, manifest themselves in a breaking of the so called '$x - z$' factorization, a feature which is also visible experimentally, e.g., in the HERMES data. In LO (and by assuming that $D_s^\pi = 0$) one expects that the multiplicity $\frac{1}{N_{\mathrm{DIS}}}\frac{dN^\pi(z)}{dz}$ is independent of x and can be directly related to $D_u^\pi = D_d^\pi$. In NLO this simple picture is messed up by $\mathcal{O}(\alpha_s)$ coefficient functions which are non-trivial functions of x *and* z and hence 'relate' parton densities $f(x)$ and fragmentation functions $D(z)$. Unfortunately the agreement between NLO QCD and HERMES data is not too good since the observed 'slopes' w.r.t. x are much more pronounced than predicted by NLO QCD. However, one of the lessons to be learned from this exercise is that a LO analysis seems to be not sufficient at low Q^2, which, of course, considerably complicates the extraction of fragmentation functions from SIDIS data. Similarly, polarized fragmentation functions should be better extracted in a full 'unfolding procedure' using NLO cross sections rather than with the help of an auxiliary 'purity' function based on $x - z$ factorization, i.e., $\Delta f/f(x) \times \Delta D/D(z) \times \Delta\hat{\sigma}/\hat{\sigma}$.
- Both sets of fragmentation functions introduced above have the rather odd feature that they predict sizable kaon and proton fragmentation functions at $\langle Q^2 \rangle \simeq 2.5\,\mathrm{GeV}^2$, presumably because mass effects are not taken into account. This casts some doubt on the applicability of the concept of fragmentation functions at low Q^2. On the other hand, future SIDIS data, for instance from HERMES, may be useful in a more global analysis of fragmentation functions which not only considers e^+e^- data. In this context it should be noted that in SIDIS other flavor combinations of fragmentation functions are probed than in e^+e^- and hence such data contain new vital information which may help to come up with a better theoretical understanding of fragmentation processes.
- Effects of the non-vanishing mass of the produced hadron may play a non-negligible role at small Q^2 or, more precisely, small W^2. For pions, however, even at $\langle Q^2 \rangle \simeq 2.5\,\mathrm{GeV}^2$ mass effects should be still small, which is certainly not true anymore for heavier hadrons. One prominent example where mass effects have to be taken into account to achieve a better agreement with data is Λ production in SIDIS. Finite mass effects can *approximately* be taken into account by introducing a function $\beta = \sqrt{1 - 4M_\Lambda^2/(zW)^2}$ which leads to a 'rescaling' of z.

In addition, low Q^2 SIDIS data may contain a considerable contribution from higher twists [as an example one should keep in mind that all current sets of parton distribution functions fail to describe, e.g., the NMC F_2 data below Q^2 values of about $2 - 4\,\mathrm{GeV}^2$] which can help to explain the residual slope w.r.t. x in the data mentioned above. In any case much more work is needed to obtain a better theoretical understanding of the available data even in the unpolarized case. Also mass effects have to be considered in more detail and more systematically in the future. Upcoming, more precise SIDIS data, e.g., from HERMES, may help to shed some light on the poorly understood fragmentation process. A global analysis of SIDIS and e^+e^- data is perhaps a good idea for the future since SIDIS probes combinations of fragmentation functions which are not accessible in e^+e^- and, hopefully, this leads to a better description of experimental results even at low values of Q^2. However it may turn out that the usual QCD framework for fragmentation functions cannot be applied at all in the low Q^2 region.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Comments on the Sivers vs Collins Mechanisms

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In the Sivers mechanism[1] a transversely polarized nucleon (momentum P and covariant spin vector S_T) produces a quark of momentum $xP + k_\perp$ and the number density of these quarks $f(S_T; x, k_\perp)$ is supposed to depend upon S_T via a term like $S_T \cdot (P \times k_\perp)$.

The Collins mechanism[2] looks remarkably similar. A transversely polarized quark (momentum p and covariant spin vector s_T) fragments into a hadron H with momentum $zp + K_\perp$. The fragmentation function $D(s_T; z, k_\perp$ is supposed to depend upon s_T via a term like $s_T \cdot (p \times K_\perp)$.

Although, diagramatically, these proccesses look almost identical, the expressions for the number density and the fragmentation function are quite different in terms of matrix elements of field operators. Schematically:

$$f \propto < P, S_T|\bar{\psi}\psi|P, S_T >$$
$$= \sum_{allX} < P, S_T|\bar{\psi}|X >< X|\psi|P, S_T >$$

but

$$D \propto \sum_{allX} < 0|\bar{\psi}|H, X >< H, X|\psi|0 >$$

If $|P, S_T >$ is a *free* nucleon entering the hard interaction then time-reversal invariance forbids any dependence of f upon the transverse S_T.

Time-reversal invariance does *not* forbid D from depending on s_T. The key difference is that

$$\sum_{allX} |X >< X| = I$$

commutes with the time reversal operator $\hat{T}$, but

$$\sum_{allX} |H, X >< H, X| \neq I$$

for fixed kinematics of H, and does not commute with $\hat{T}$ if there is an interaction between H and X.

Thus the Sivers mechanism is really forbidden by time-reversal invariance, *unless* the incoming nucleon is not free. How could that be ? Well, in DIS with a proton, the proton and electron certainly interact electrically long before the hard scattering takes place. But this is a negligible $O(\alpha_{em})$ effect, so it is totally ignored.

In Drell-Yan reactions there could be multi-gluon strong interactions between the colliding nucleons before the hard scattering. But if this were an important effect it would be hard to understand why factorization works. Thus we do not believe the Sivers mechanism is responsible for single transverse spin asymmetries.

That is the theoretical picture. But the question should be studied experimentally! A series of tests for the various mechanisms is given in [3] and [4]. In particular, in *fully inclusive* DIS, with a transversely polarized target, there should not be any single spin asymmetry, aside from effects of order $0(\alpha_{em})$.

References

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D. Sivers, *Phys. Rev. D 41*, 83 (1990)

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Towards a global transversity analysis

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In order to measure the transversity function $\delta q(x)$ for both u and d quarks separately, one must overcome the problem that in experiments one always accesses a linear combination with coefficients that are also unknown. These coefficients are either dependent on antiquark transversity functions (expected to be small) or on certain types of fragmentation functions, which are still to be determined. The question I am going to address here is: assuming that one has three types of experiments, namely hadron-hadron collisions (e.g. RHIC), semi-inclusive DIS (e.g. HERMES, COMPASS) and electron-positron annihilation (e.g. LEP), which observables can actually be obtained in the near future such that the transversity functions can be disentangled? For simplicity I will neglect s quark contributions in nucleons and pions, since sea quark transversities are expected to be small.

Interference fragmentation functions

The first possibility is offered by the so-called interference fragmentation functions $\delta\hat{q}_I(z)$. These are expected to be extractable from the process $e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X$, where the pion pairs are in opposite jets.

In order to make use of the interference fragmentation functions, one has to make some assumptions on its flavor dependence. I will discuss two scenario's and a third one will be easy to construct, but leads to similar results as the first scenario. The first scenario is that one assumes that the fragmentation of $u \to \pi^+\pi^- X$ equals the probability of $d \to \pi^+\pi^- X$, which is a reasonable assumption for the unpolarized fragmentation functions and may be expected to hold also for the interference fragmentation functions. In this scenario one thus equates $\delta\hat{q}_I^u(z)$ and $\delta\hat{q}_I^d(z)$ and one can obtain the linear combination:

$$O_1 = a_1\, \delta\hat{q}_I^u(z)\, \delta\hat{q}_I^d(z'), \tag{1}$$

which means: one observable, two unknowns.

In the second scenario we make one more assumption. One first observes that charge conjugation equates $u \to \pi^+\pi^- X$ with $\bar{u} \to \pi^-\pi^+ X$. For the interference fragmentation functions, the sign of the pion charges are irrelevant, as long as one sign is fixed to define a preferred direction (to define the sign of the cross-product observable). Switching the π^+ and π^- position reverses this direction, which results in a sign change in the observable. Taking into account the switching of the position is possible, since one knows that whenever there is a quark on one side, there will be an antiquark on the other side. This effectively leads to $\delta\hat{q}_I^u(z) = -\delta\hat{q}_I^{\bar{u}}(z)$ (a similar relation does not hold for the unpolarized fragmentation functions) and then one could obtain:

$$O_1' = a_1'\, \delta\hat{q}_I^u(z)\, \delta\hat{q}_I^u(z'), \tag{2}$$

*Disclaimer: since I will merely be stating very basic observations, I will refrain from providing references

with only one unknown function. Note that the prime is used to indicate a different scenario, not a different experimental observable. Also, it should be noted that it is assumed here that the unpolarized $\pi^+\pi^-$ fragmentation functions are determined from for instance $e^+e^- \to (\pi^+\pi^-)X$, since these functions enter in the denominator of the asymmetries.

A third possibility is that one assumes only $\delta\hat{q}_I^u(z) = -\delta\hat{q}_I^{\bar{u}}(z)$, but not $\delta\hat{q}_I^u(z) = \delta\hat{q}_I^d(z)$, then one can only obtain:

$$O_1'' = a_1''\, \delta\hat{q}_I^u(z)\, \delta\hat{q}_I^u(z') + b_1''\, \delta\hat{q}_I^d(z)\, \delta\hat{q}_I^d(z'), \tag{3}$$

which again means: one observable, two unknowns. This case will have similar conclusions as the first scenario, so we will not investigate this case explicitly.

From the process $pp^\uparrow \to (\pi^+\pi^-)X$ one obtains in the first scenario

$$O_2 \propto \left(a_2\, \delta q^u(x)\, \delta\hat{q}_I^u(z) + b_2\, \delta q^d(x)\, \delta\hat{q}_I^d(z)\right), \tag{4}$$

which is convoluted with the unpolarized quark or gluon distribution functions, which are known. Also, one knows that the partonic subprocess is purely governed by pQCD, such that $a_2 = b_2$. In the second scenario one obtains

$$O_2' \propto \left(a_2\, \delta q^u(x) - b_2\, \delta q^d(x)\right)\, \delta\hat{q}_I^u(z). \tag{5}$$

From the process $ep^\uparrow \to (\pi^+\pi^-)X$ one obtains similar combinations of functions

$$O_3 \propto \left(a_3\, \delta q^u(x)\, \delta\hat{q}_I^u(z) + b_3\, \delta q^d(x)\, \delta\hat{q}_I^d(z)\right), \tag{6}$$

and

$$O_3' \propto \left(a_3\, \delta q^u(x) - b_3\, \delta q^d(x)\right)\, \delta\hat{q}_I^u(z), \tag{7}$$

but since this is partly QED, we know that $a_3 = 4b_3$.

The three observables O_1, O_2, O_3 contain 4 unknowns $(\delta q^u(x), \delta q^d(x), \delta\hat{q}_I^u(z), \delta\hat{q}_I^d(z))$, thus one needs some additional input which is not easy to obtain as will become clear later. But the three observables O_1', O_2', O_3' contain exactly 3 unknowns $(\delta q^u(x), \delta q^d(x), \delta\hat{q}_I^u(z))$ and therefore allow for the extraction of $\delta q^u(x)$ and $\delta q^d(x)$ separately from $e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X$, $pp^\uparrow \to (\pi^+\pi^-)X$ and $ep^\uparrow \to (\pi^+\pi^-)X$. So if the interference fragmentation functions were obtained from existing LEP data, then other experiments like RHIC, HERMES or COMPASS would (apart from this one input) be able to extract a particular linear combination of $\delta q^u(x)$ and $\delta q^d(x)$ (with known coefficients) from their data.

So far I have discussed what are the options in case one does not know anything about the functions $\delta q^u(x)$ and $\delta q^d(x)$ and just wants to extract them from experiment. In practice, one will assume a standard form for the dependence on the kinematic variables (the light cone momentum fractions) and make a fit to the data. In this case not the complete shape of the functions needs to be obtained from experiment, but only a few parameters governing a plausible shape. So it seems that by measuring different kinematical configurations of the same observable, one can obtain the parameters for the shapes of the unknown functions. However, in both $pp^\uparrow \to (\pi^+\pi^-)X$ and $ep^\uparrow \to (\pi^+\pi^-)X$ this again only works for a particular linear combination of $\delta q^u(x)$ and $\delta q^d(x)$ (assuming the interference fragmentation functions from LEP data are known).

That the LEP data and the future data from other experiments are obtained at different energies is not a problem. The energy dependence of the functions does not form an obstacle, since the evolution of the transversity and interference fragmentation functions are all known. The latter is equal to that of the transversity *fragmentation* function $\delta\hat{q}(z)$, which is clear from the identical operator structure of these two matrix elements. Moreover, at least in LO pQCD the evolution of $\delta\hat{q}(z)$ can be easily related to the evolution of $\delta q(x)$ itself (Gribov-Lipatov reciprocity relation).

On the other hand, unlike unpolarized and longitudinally polarized DIS, where the evolution of structure functions yields additional information, namely on the (unpolarized and polarized) gluon densities, the known evolution of the transversity and interference fragmentation functions offers no such advantage. Since there is no mixing with a gluon density under evolution, the observables O_i evolve purely multiplicatively. But even in the case that there was an additive piece due to mixing with a gluon density, evolution would allow only to differentiate between such a gluon density and again a particular linear combination of the transversity functions.

Hence, neither measuring different kinematical configurations at fixed energy nor varying the energy scale itself, provide additional tools to disentangle the transversity functions for the u and d quark separately. Combining results obtained by different experiments is thus a necessity.

Collins effect fragmentation functions

In analogy to the extraction of the transversity functions by using the interference fragmentation functions, one might consider the use of the so-called Collins fragmentation functions. The observables are very similar, namely $e^+ e^- \to \pi^+ \pi^- X$ (where the pions belong to opposite jets), $p p^\uparrow \to \pi^\pm X$ and $e p^\uparrow \to \pi^\pm X$. This might look like a simpler option: one expects better statistics and also, π^+ and π^- yield different information. However, the theoretical framework is much less clean. One needs to start the analysis of the Collins asymmetries from a different factorization theorem than for interference fragmentation function asymmetries. In the former the description in terms of parton light cone momentum fractions is not sufficient (one is not only dealing with partons that are collinear to the hadrons from which they emerge or to those which they generate in the fragmentation process). The ingredients to evolve the observables involving the Collins functions have not been investigated fully yet. For instance, one has to deal with issues like Sudakov suppression (see my contribution at this workshop). These issues need to be clarified further, before reliable connections between different observables containing the Collins functions can be made.

Other options

The Drell-Yan process $p^\uparrow p^\uparrow \to \ell \bar{\ell} X$ originally viewed as the main experimental method to obtain information on the transversity functions- is expected to be small primarily due to the anti-quark transversity functions. Another possibility for RHIC in particular is the process $p^\uparrow p^\uparrow \to$ jet X (or $p^\uparrow p^\uparrow \to 2$ jets X), in which one can measure the combination

$$O_1 \propto a_1 \left(\delta q^u(x)\, \delta q^u(x') + \delta q^d(x)\, \delta q^d(x')\right) + \dots \quad (8)$$

Here one has to assume that the quark-antiquark contributions (the ellipsis) are negligible or can be reduced considerably by a transverse momentum cut. This would allow for the closed system O_1', O_2', O_4, which requires LEP and RHIC data only. Rates will be high, but the magnitude of the asymmetry itself turns out to be very small (see Werner Vogelsang's contribution at this workshop).

Some other observables like transversely polarized Λ production in $p p^\uparrow \to \Lambda^\uparrow X$ and $e^+ e^- \to \Lambda^\uparrow \overline{\Lambda}^\uparrow X$, have the problem that they introduce yet other unknown functions $(\delta\hat{q}, \delta\hat{\bar{q}})$ and s quark contributions can not be neglected.

If one would use different target or final state hadrons, in order to obtain a flavor decomposition, one also introduces new unknown functions, but in some cases one could argue in favor of an additional symmetry (isospin invariance) to relate different hadrons. But often one would like to test such a symmetry (e.g. in the case of hyperons) rather than just impose it.

Finally, a remark about an important property of chiral odd functions, like the transversity distribution and fragmentation functions, the Collins and the interference fragmentation functions. Chiral odd functions do not couple to charged currents, hence neutrino processes can not be used to extract different flavor combinations. This is another limiting factor.

Conclusion

In conclusion, a flavor decomposition of transversity functions will be difficult to measure, but not impossible. In my opinion, the most plausible scenario appears to be the following. Extraction of the interference fragmentation functions from existing LEP data. Using this input, other experiments can obtain linear combinations of $\delta q^u(x)$ and $\delta q^d(x)$. These linear combinations can then be combined to extract the transversity functions for the u and d quark separately. Once the formalism concerning the Collins fragmentation functions has been established firmly (beyond tree level, that is), then this certainly also offers useful alternatives. All in all, by combining theoretical and experimental efforts to measure the transversity functions, one can be hopeful that in the not too distant future the complete spin state of the proton will finally be mapped out.

Technical Data Sheets for Related Experiments

COMPASS, BRAHMS, HERMES, PHENIX, PHOBOS, RAMPEX, STAR, TESLA-N

Experiment	**BRAHMS**, polarized pp
Location	RHIC - 2O'clock area, BNL
Web Page	http://www.rhic.bnl.gov/BRAHMS
Run Schedule	Transverse polarization in 2001/02
Contact for Transversity	Flemming Videbaek (videbaek@bnl.gov)
	Gerry Bunce (bunce@bnl.gov)
Polarization States	transverse polarization effects
Beam Polarization	$P_{\text{beam}} = 0.7$
Kinematics	$50\,\text{GeV} < \sqrt{s} < 500\,\text{GeV}$
Expected Luminosity	$\int Ldt = 320\,\text{pb}^{-1}/\text{year at } \sqrt{s} = 200\,\text{GeV}$
	$\int Ldt = 800\,\text{pb}^{-1}/\text{year at } \sqrt{s} = 500\,\text{GeV}$
Acceptance:	
Central Arm	$0 < \eta < 1.5$, $\Delta\Omega = 5msr$
Forward Arm	$1.5 < \eta < 4.0$, $\Delta\Omega = 0.8msr$
Momentum Resolution:	
(forward arm only)	$\Delta p/p = 1\%$ at $1 - -25\,\text{GeV}$,
	$\Delta p/p = 2\%$ at $50\,\text{GeV}$,
(Central arm)	$\Delta p/p = 1\%$ up to $4\,\text{GeV}$
Vertex Resolution	$\Delta z \approx 1.0\,\text{cm}$
Particle Identification	$\pi - K$ separation to $\approx 18\,\text{GeV}$
	$K - p$ separation to $\approx 30\,\text{GeV}$

Experiment	**COMPASS** (NA58) polarized mu - p deep inelastic scattering
Location	CERN, Geneva, CH
Web Page	http://wwwcompass.cern.ch
Run Schedule	First physics run with longitudinal polarization in 2001
Contact for Transversity	Anna Martin, anna.martin@cern.ch
Polarization States	Longitudinal beam (mu) polarization
	Longitudinal and transverse target (p) polarization
Kinematics	100 – 200 GeV beam
	x_{Bj}, Q^2 similar to SMC
Expected Luminosity	$\int Ldt = 2\,\mathrm{fb}^{-1}$/year incl. efficiencies
Acceptance	Full acceptance forward hemisphere ($x_F > 0$)
	charged particle reconstruction down to 1 GeV (and less)
Particle Id	π/K separation from 3.5 GeV with RICH
	μ identification (muon walls)
	Electron identification (electromagnetic cal.s)
Momentum Resolution	
Vertex Resolution	$\Delta x,\ \Delta y < 1$ mm, $\Delta z \approx$ few mm
Comments	About 20 % of time with transversely polarized target
	sharing with *hadron* beams

Experiment	**HERMES**, fixed-target polarized ep and ed; unpolarized eA
Location	Hamburg, DESY
Web Page	http://www-hermes.desy.de/
Run Schedule	First Run with Transverse Polarization in 2001
Contact for Transversity	Wolf-Dieter.Nowak@desy.de
Polarization States	Single and double longitudinal and transverse asymmetries
Beam Polarization	$P_B = 50 - 60\%$
Target	internal gas target, H, D, $P_T = 80\%$
Kinematics	$E_e = 27.5\,\mathrm{GeV}$
Expected Luminosity	$\int Ldt = 80\,\mathrm{pb}^{-1}$/year
Acceptance	$\lvert\Theta_x\rvert < 170$ mrad horizontally (magnet bending plane)
	$40 < \lvert\Theta_y\rvert < 140$ mrad vertically
Particle Id	$e^{\pm}$ ($p > 1.5$ GeV), γ ($E > 0.8$ GeV)
	RICH: π (0.5–16 GeV), K (2–16 GeV), p (2–20 GeV)
	TOF: $\pi/K/p$ ($p < 2\,\mathrm{GeV}$)
Invariant Mass Res.	$\sigma = 5.7\,\mathrm{MeV}$ for pion pairs in K_s-mass region
Momentum Resolution	$\Delta p/p = 0.7 \div 1.3\%$
Angular Resolution	$\Delta\theta = 0.6$ mrad
Vertex Resolution	$\Delta t_{xy} = 1$ mm, $\Delta z = 1$ cm

Experiment	**PHENIX**, polarized pp
Location	RHIC as polarized pp collider, BNL
Web Page	http://www.phenix.bnl.gov
Run Schedule	First run with longitudinal polarization in 2001 Exploratory run with transverse polarization in 2002(?)
Contact for Transversity	Matthias Grosse Perdekamp; matthias@bnl.gov
Polarization States	Single and double longitudinal and transverse asymmetries
Peam Polarization	$P_{\text{beam}} = 0.7$
Kinematics	$50\,\text{GeV} < \sqrt{s} < 500\,\text{GeV}$
Expected Luminosity	$\int Ldt = 320\,\text{pb}^{-1}$/year at $\sqrt{s} = 200\,\text{GeV}$ $\int Ldt = 800\,\text{pb}^{-1}$/year at $\sqrt{s} = 500\,\text{GeV}$
Acceptance	Muon arms: $1.2 < \eta < 2.4$, $0 < \phi < 360$ Central arms: $-0.35 < \eta < 0.35$, $33.75 < \lvert\phi\rvert < 123.75$
Particle Id	Muon arms: Muons with more than $\approx 2.0\,\text{GeV}$ Central arms: Electrons, photons ($p_T < 30\,\text{GeV}$), π^0 ($p_T < 30\,\text{GeV}$) $\pi^{+,-}$, ($p_T < 12\,\text{GeV}$)
Invariant Mass Res.	RMS=12 MeV for pairs in ρ-mass region
Momentum Resolution (central arm only)	$\Delta p_T/p = 0.6\%$ at $1\,\text{GeV}$, $\Delta p_T/p = 1.8\%$ at $10\,\text{GeV}$ $\Delta p_T/p = 2.5\%$ at $20\,\text{GeV}$
Vertex Resolution	$\Delta x \approx \Delta y \approx 0.3\,\text{cm}$, $\Delta z \approx 0.5\,\text{cm}$
Comments	Muon arms are downstream of central magnet yoke, no useful acceptance for hadrons in the muon arms

Experiment	**PHOBOS**, polarized pp
Location	RHIC as polarized pp collider, BNL
Web Page	http://phobos-srv.chm.bnl.gov
Run Schedule	Transverse polarization in 2001
Contact for Transversity	Mark Baker (Mark.Baker@bnl.gov)
Polarization States	transverse polarization effects
Beam Polarization	$P_{\text{beam}} = 0.7$
Kinematics	$50\,\text{GeV} < \sqrt{s} < 500\,\text{GeV}$
Expected Luminosity	$\int Ldt = 320\,\text{pb}^{-1}$/year at $\sqrt{s} = 200\,\text{GeV}$ $\int Ldt = 800\,\text{pb}^{-1}$/year at $\sqrt{s} = 500\,\text{GeV}$
Acceptance	Spectrometer: $0 < \eta < 1.5$, $-5 < \phi < 5$ degrees and $-5 < \phi - \pi < 5$ degrees
Invariant Mass Res.	RMS=30 MeV for pairs in ρ-mass region
Momentum Resolution (central arm only)	$\Delta p/p = 1\%$ at $1\,\text{GeV}$, $\Delta p/p = 2.5\%$ at $10\,\text{GeV}$ $\Delta p/p = 5\%$ at $20\,\text{GeV}$
Vertex Resolution	$\Delta x \approx \Delta y \approx \Delta z \approx 0.05\,\text{cm}$

Experiment	**RAMPEX**, $pp_{\uparrow}$ at 70 GeV/c, polarized target
Location	IHEP, Protvino
Web Page	http://rampex.ihep.su/
Run Schedule	First Run with π^o detection in March 2000; next run with π^o – Fall 2000; first charge particle detection – March 2001.
Contact for Transversity	Yuri Arestov, arestov@rampex.ihep.su
Polarization States	Single transverse asymmetries
Kinematics	$1 < p_{T1},\ p_{T2} < 3.5$ GeV/c in back-to-back kinematics
Expected Luminosity	$\int \mathcal{L}dt = 2500\,\mathrm{nb}^{-1}$/two months*
Acceptance	Two arms corresponding to the production at 90^o in CMS
Particle Id	Two Cerenkov counters; ECAL; HCAL (trigger) $\pi^{\pm}$ at $p = 3 \div 20$ GeV/c; $K^{\pm}$, $p^{\pm}$ at $p = 10 \div 20$ GeV/c
Invariant Mass Res.	RMS=4.5 MeV for ϕ meson
Momentum Resolution	$\Delta p/p = 1.7 \cdot 10^{-3} p + 2 \cdot 10^{-3}$
Vertex Resolution	–
Comments	currently the 2nd arm consists of ECAL only; 1st arm is assembled of magnet spectrometer, five blocks of PC', two Č's, ECAL and HCAL.

$*$ – corrected for the number of polarized protons in the target.

Experiment	**STAR**, polarized pp
Location	RHIC as polarized pp collider, BNL
Web Page	http://www.star.bnl.gov
Run Schedule	First run in 2001
Contact for Transversity	Akio Ogawa (akio@bnl.gov)
Polarization States	Single and double longitudinal and transverse asymmetries
Energy & polarization	$50 < \sqrt{s} < 500$ GeV, 70%
Expected Luminosity	$\int Ldt = 320\,\mathrm{pb}^{-1}$/year at $\sqrt{s} = 200$ GeV $\int Ldt = 800\,\mathrm{pb}^{-1}$/year at $\sqrt{s} = 500$ GeV
Acceptance	Charged particles $-2.0 < \eta < 2.0,\quad 0 < \phi < 2\pi$ Electrons, photons $-2.0 < \eta < 1.0,\quad 0 < \phi < 2\pi$ Jets $-1.3 < \eta < 0.3,\quad 0 < \phi < 2\pi$
Particle Id	EMC : electro/hadron, photon/π^0 dE/dx(TPC) $\pi/K : p < 0.6,\ K/P : p < 1.2$GeV dE/dx(TPC+SVT) $\pi/K : p < 0.8,\ K/P : p < 1.5$GeV TOF $\pi/K : p < 1.3,\ K/P : p < 2.4$GeV RICH $\pi/K : p < 3,\ K/P : p < 5$GeV
Invariant Mass Res.	RMS$\sim$ 16 MeV at $2 < p_t < 10$ GeV and at ρ^0 mass
Momentum Resolution	$\Delta p_T/p = 1.5\%$ at 0.2 GeV $\Delta p_T/p = 3.5\%$ at 10 GeV
Vertex Resolution	$\Delta x, y \sim 1mm, \Delta z \sim 1cm$

Experiment	**TESLA-N**, fixed-target polarized ep and ed; unpolarized eA
Location	DESY, Hamburg
Web Page	http://www.ifh.de/hermes/future/
Run Schedule	First Run in 2010+
Contact for Transversity	Wolf-Dieter.Nowak@desy.de
Polarization States	Single and double longitudinal and transverse asymmetries
Beam Polarization	$P_B = 90\%$
Target	NH_3, polarization $P_T = 80\%$, dilution $f = 0.176$
	LiD, polarization $P_T = 30\%$, dilution $f = 0.44$
Kinematics	$E_e = 250\,\mathrm{GeV}$, possibly also $30 \ldots 50$ GeV
Expected Luminosity	$\int L dt = 100\,\mathrm{fb}^{-1}/\mathrm{year}$
Acceptance	$5 < \theta < 175$ mrad
Particle Id	ECAL, TRD, RICH
Momentum Resolution	$\Delta p/p = 0.5\%$
Angular Resolution	$\Delta\theta = 0.3$ mrad

Some notation relevant to the workshop's topics

Classification of transverse momentum dependent quark distribution and fragmentation functions for spin-0 and spin-1/2 hadrons by P.J. Mulders:

DISTRIBUTIONS (T-even)			
		chirality	
		even	odd
twist 2	U	$\boldsymbol{f}_1$	
	L	$\boldsymbol{g}_{1L}$	$h_{1L}^{\perp}$
	T	g_{1T}	$\boldsymbol{h}_1$ $h_{1T}^{\perp}$
twist 3	U	$f^{\perp}$	$\boldsymbol{e}$ [1]
	L	$g_L^{\perp}$	$\boldsymbol{h}_L$ [1]
	T	$\boldsymbol{g}_T$ [1] $g_T^{\perp}$	h_T $h_T^{\perp}$

DISTRIBUTIONS (T-odd)			
		chirality	
		even	odd
twist 2	U	–	$h_1^{\perp}$
	L	–	–
	T	$f_{1T}^{\perp}$	–
twist 3	U	–	$\boldsymbol{h}$
	L	$f_L^{\perp}$	$\boldsymbol{e}_L$
	T	$\boldsymbol{f}_T$	e_T

FRAGMENTATION			
		chirality	
		even	odd
twist 2	U	$\boldsymbol{D}_1$	$H_1^{\perp}$
	L	$\boldsymbol{G}_{1L}$	$H_{1L}^{\perp}$
	T	G_{1T} $D_{1T}^{\perp}$	$\boldsymbol{H}_1$ $H_{1T}^{\perp}$
twist 3	U	$D^{\perp}$	$\boldsymbol{E}$ $\boldsymbol{H}$
	L	$G_L^{\perp}$ $D_L^{\perp}$	$\boldsymbol{E}_L$ $\boldsymbol{H}_L$
	T	$\boldsymbol{G}_T$ $G_T^{\perp}$ $\boldsymbol{D}_T$	E_T H_T $H_T^{\perp}$

U, L, T denote the hadron polarization state
All DFs depend on x and $\boldsymbol{k}_T$
All FFs depend on z and $\boldsymbol{k}_T$
Upon integration over $\boldsymbol{k}_T$ only the functions in boldface remain, with a name change for:

$g_1(x) \equiv \int d^2\boldsymbol{k}_T\, g_{1L}(x, \boldsymbol{k}_T)$
$G_1(z) \equiv \int d^2\boldsymbol{k}_T\, G_{1L}(z, \boldsymbol{k}_T)$

Other commonly used notation (often with flavor and/or hadron labels)

$f_1(x)$	$\to$	$q(x)$		
$g_1(x)$	$\to$	$\Delta q(x)$		
$h_1(x)$	$\to$	$\delta q(x)$	$\Delta_T q(x)$	
$D_1(z)$	$\to$	$\hat{q}(z)$	D_a^H	$\hat{f}_1(z)$ [1]
$G_1(z)$	$\to$	$\Delta\hat{q}(z)$	$\Delta D_a^H(z)$	$\hat{g}_1(z)$ [1]
$H_1(z)$	$\to$	$\delta\hat{q}(z)$		$\hat{h}_1(z)$ [1]
$E(z)$	$\to$	$\hat{e}_1(z)$ [1]		
$H(z)$	$\to$	$\hat{e}_{\bar{1}}(z)$ [1]		
$D_T(z)$	$\to$	$\hat{g}_{\bar{T}}(z)$ [2]		
$E_L(z)$	$\to$	$\hat{h}_{\bar{L}}(z)$ [2]		
$f_{1T}^{\perp}$	$\to$	$\Delta^N f_{a/h^{\uparrow}}$ [3]		[Sivers effect]
$h_1^{\perp}$	$\to$	$\Delta^N f_{a^{\uparrow}/h}$ [3]		
$D_{1T}^{\perp}$	$\to$	$\Delta^N D_{h^{\uparrow}/a}$ [3]		
$H_1^{\perp}$	$\to$	$\Delta^N D_{h/a^{\uparrow}}$ [3]	$\Delta\hat{D}_{H/a}$ [4]	[Collins effect]

Comments: we ignored twist 4 functions and gluon DFs and FFs
The above does not give the exact translation; there are often kinematic factors between two functions describing the same matrix elements

The originally proposed names are often not commonly used. E.g.
Ralston & Soper (NPB 152 (79) 109): h^T for h_1
Baldracchini *et al.* (Fortschritte der Physik 30 (81) 505): $\delta_2 D$ for h_1
Artru & Mekhfi (ZPC 45 (90) 669): $\Delta_1 q(x)$ for h_1

See also Bukhvostov *et al.*; Efremov & Teryaev for more notation

Interference Fragmentation Functions:

A. Bianconi, S. Boffi, R. Jakob, M. Radici, PRD 62 (2000) 034008:

Interference Fragmentation Functions			
		chirality	
		even	odd
twist 2	U	$\boldsymbol{D}_1$	–
	L	$G_1^{\perp}$	–
	T	–	$H_1^{\perp}$ $\boldsymbol{H}_1^{\sphericalangle}$

U, L, T now denote the quark polarization state
All IFFs depend on $z_1, z_2, \boldsymbol{k}_T$ and $\boldsymbol{R}_T$
Upon integration over $\boldsymbol{k}_T$ only the functions D_1 and $H_1^{\sphericalangle}$ remain

Other commonly used notation

$D_1(z_1, z_2, \boldsymbol{R}_T) \rightarrow \quad \hat{q}_I(z)$ [5] $\quad \hat{F}_1(z, l)$ [2]
$H_1^{\sphericalangle}(z_1, z_2, \boldsymbol{R}_T) \rightarrow \quad \delta\hat{q}_I(z)$ [5] $\quad \hat{H}_1(z, l)$ [2]

Spin-1 hadron DFs and FFs:

See Bacchetta & Mulders, hep-ph/0007120;
For spin-1 DFs, see also Hino & Kumano, PRD 60 (99) 054018;
For spin-1 FFs, see also Ref. [2]

References

[1] R.L. Jaffe, X. Ji, PRL 71 (93) 2547

[2] X. Ji, PRD 49 (94) 114

[3] See papers by Anselmino, Boglione, Murgia *et al.*

[4] J.C. Collins, NPB 396 (93) 161

[5] R.L. Jaffe, X. Jin, J. Tang, PRL 80 (98) 1166

FUTURE TRANSVERSITY MEASUREMENTS
September 18-20, 2000
A RIKEN BNL Research Center Workshop

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Future Transversity Measurements

September 18-20, 2000

A RIKEN BNL Research Center Workshop

Brookhaven National Laboratory

Upton, NY, 11973

Agenda

Monday September 18

Morning Session (Large Seminar Room, Physics Bldg.510)

8:30 Coffee and Registration (Foyer, Large Seminar Room)

9:30 - 10:40 Chair: Gerry Bunce

Welcome	Nicholas Samios	10min
The First RHIC Machine Run	Thomas Roser	30min
RHIC Experimental Review	Bill Zajc	30min

11.00 - 12:15 Chair: George Igo

Transversity: A Primer	Bob Jaffe	45min
The RHIC Spin Program	Naohito Saito	30min

Afternoon Session (Room B, Berkner Hall)

14:00 - 16:00 Chair: Bob Jaffe

Azimuthal Asymmetries in Hard Scattering Processes	Piet Mulders	30min
Evolution of Transversity Distributions:		
Theory Update	Yuji Koike	30min
Applications	Shunzo Kumano	30min

16:30-18:30 Chair: Piet Mulders

Drell-Yan Muon Production at RHIC	Marco Stratmann	15min
Pion Pair Production with Transversely Polarized Beams	Werner Vogelsang	15min
Results on Azimuthal Asymmetries from DIS Experiments	Wolf-Dieter Nowak	30min
Investigation of Single Spin Asymmetries in SIDIS	Karo Oganessyan	30min

Tuesday September 19

Morning Session (Room B, Berkner Hall)

8:00-9:00 Breakfast (Room A, Berkner Hall)

9:00-10:45 Chair: Daniel Boer

The role of h_1 in Azimuthal and Single Spin Asymmetry	Elena Boglione	30min
Transverse Single-Spin Asymmetries in Semi-Inclusive Hadron-Hadron Reactions	Elliot Leader	30min
Single Transverse Spin Asymmetries in Hadronic Reactions	Francesco Murgia	30min

11:15-12:45 Chair: Elliot Leader

Transversity Measurements Using Spin One Hadrons	Alessandro Bacchetta	20min
Why Interference Fragmentation Functions?	Rainer Jakob	20min
Calculation of T-odd Fragmentation Functions in Semi-Inclusive Processes	Marco Radici	20min

Afternoon Session (Room B, Berkner Hall)

14:15-16:00 Chair: Aram Kotzinian

Production of Soft Pions in Hard Reactions	Maxim Polyakov	30min
Status of Fragmentation Function Analysis at DELPHI	Oliver Passon	20min
Collins Fragmentation Function from LEP Data?	Daniel Boer	20min

16:30-18:00 Chair: Wolf-Dieter Nowak

Transversity at PHENIX	Matthias Grosse Perdekamp	20min
Transversity at STAR	Akio Ogawa	20min
Transverse Spin Program for PHOBOS and BRAHMS	Sandro Bravar	20min
Transverse Spin at pp2pp	Wlodek Guryn	20min

19:30 Workshop Dinner at the Dockside in Port Jefferson

Wednesday September 20

Morning Session (Room B, Berkner Hall)

8:00-9:00 Breakfast (Room A, Berkner Hall)

9:00-10:45 Chair: Larry Trueman

Factorization in Hadron-Hadron Scattering	George Sterman	30min
Chiral Odd Quark Distributions and Structure Functions in the Chiral Soliton Model of the Nucleon	Leonard Gamberg	30min
Transversity Distributions in the Large-N_c limit	Christian Weiss	30min

11:15 - 12:45 Chair: George Sterman

A_NN in Elastic Proton Proton Scattering	Larry Trueman	20min
Tensor Charge and Electric Dipole Moment	Xavier Artru	20min
Tensor Charge from Lattice Calculations	Tom Blum	20min
Transverse Spin Asymmetries in DVCS	Andrei Belitsky	20min

Afternoon Session (Room B, Berkner Hall)

14:00 - 15:30 Chair: Yousef Makdisi

RAMPEX: Probing Odd Chirality	Yuri Arestov	20min
Future Transversity Measurements with HERMES	Vladislav Korotkov	20min
Future Transversity Measurements at COMPASS	Sandro Bravar	20min
Future Transversity Measurements with TESLA N	Vladislav Korotkov	20min

16:00 - 17:00 Chair: Wolf-Dieter Nowak

Discussion on Global Transversity Analysis
(Daniel Boer, Abhay Deshpande, Matthias Grosse Perdekamp, Werner Vogelsang)

For information please contact:

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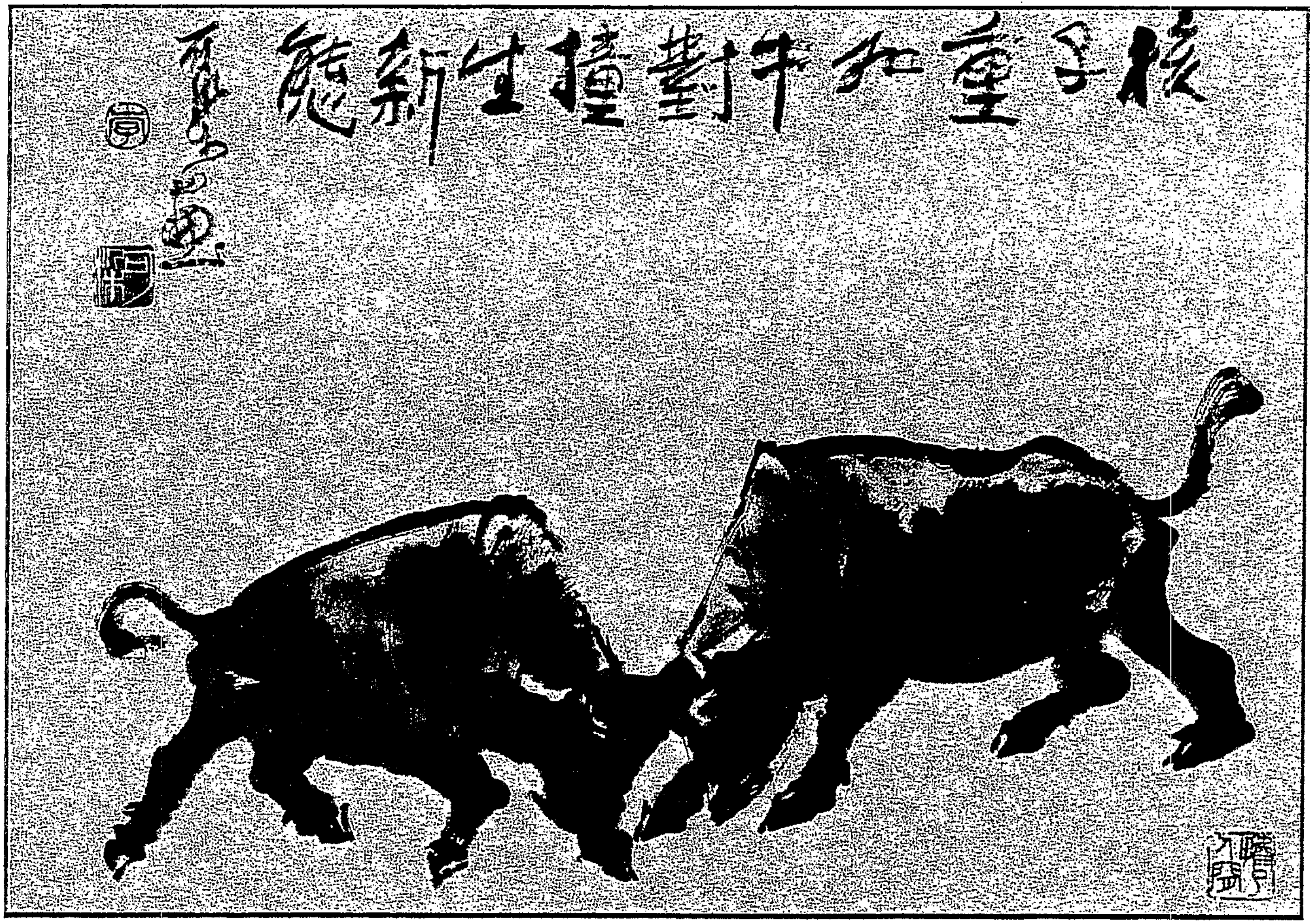
RIKEN BNL RESEARCH CENTER

FUTURE TRANSVERSITY MEASUREMENTS

SEPTEMBER 18–20, 2000



Li Keran

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Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T. D. Lee

Speakers:

Y. Arestov	X. Artru	A. Bacchetta	A. Belitsky
T. Blum	D. Boer	M. Boglione	A. Bravar
A. Bruell	L. Gamberg	M. Grosse Perdekamp	W. Guryn
R.L. Jaffe	R. Jakob	Y. Koike	V. Korotkov
S. Kumano	E. Leader	P.J. Mulders	F. Murgia
W.-D. Nowak	K. Oganessyan	A. Ogawa	O. Passon
M.V. Polyakov	M. Radici	T. Roser	N. Saito
N.P. Samios	G. Sterman	M. Stratmann	T.L. Trueman
W. Vogelsang	C. Weiss	W.A. Zajc	

Organizers: Daniel Boer & Matthias Grosse Perdekamp

Scientific Advisors: Robert L. Jaffe, Piet Mulders, Wolf-Dieter Nowak