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Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 25

RHIC SPIN

October 6–8, 1999

Organizing Committee:

Les Bland, Mike Tannenbaum, Aki Yokosawa,
Yousef Makdisi, Naohito Saito, Thomas Roser, Bob Jaffe,
Jacques Soffer (cochair), and Gerry Bunce (cochair)

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Volume 22 - OSCAR II: Predictions for RHIC - BNL-
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Volume 6 - Quarks and Gluons in the Nucleon - BNL-65234
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Volume 1 - Open Standards for Cascade Models for RHIC - BNL-64722

Preface to the Series

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

For the first year, the Center will have only a Theory Group, with an Experimental Group to be structured later. The Theory Group will consist of about 12-15 Postdocs and Fellows, and plans to have an active Visiting Scientist program. A 0.6 teraflop parallel processor will be completed at the Center by the end of this year. In addition, the Center organizes workshops centered on specific problems in strong interactions.

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 a proceedings, which can therefore be available within a short time.

Thanks to Brookhaven National Laboratory and to the U.S. Department of Energy for providing the facilities essential for the completion of this work.

T.D. Lee
July 4, 1997

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Introduction

Welcome! This RHIC Spin Workshop is the 1999 "annual" meeting of the RHIC Spin Collaboration, and the second to be hosted at Brookhaven and sponsored by the RIKEN BNL Research Center. The previous meetings were at Brookhaven (1998), Marseille (1996), MIT in 1995, Argonne 1994, Tuscon in 1991, and the Polarized Collider Workshop at Penn State in 1990. As noted last year, the Center provides a home for combined work on spin by theorists, experimenters, and accelerator physicists. This proceedings, as last year, is a compilation of 1 page summaries and 5 selected transparencies for each speaker. It is designed to be available soon after the workshop is completed. Speakers are welcome to include web or other references for additional material.

The RHIC spin program and RHIC are rapidly becoming reality. RHIC has completed its first commissioning run, as described here by Steve Peggs. The first Siberian Snake for spin has been completed and is being installed in RHIC. A new polarized source from KEK and Triumf with over 1 milliampere of polarized H^- is being installed, described by Anatoli Zelenski. We have had a successful test of a new polarimeter for RHIC, described by Kazu Kurita and Haixin Huang. Spin commissioning is expected next spring (2000), and the first physics run for spin is anticipated for spring 2001.

The purpose of the workshop is to get everyone together about once per year and discuss goals of the spin program, progress, problems, and new ideas. We also have many separate regular forums on spin. There are spin discussion sessions every Tuesday, now organized by Naohito Saito and Werner Vogelsang. The spin discussion schedule and copies of presentations are posted on http://riksg01.rhic.bnl.gov/rsc. Speakers and other spinners are encouraged to come to BNL and to lead a discussion on your favorite idea. We also have regular polarimeter and snake meetings on alternate Thursdays, led by Bill McGahern, the lead engineer for the accelerator spin effort (Thomas Roser is the spokesperson). Waldo Mackay, the Project Manager for spin, leads a weekly accelerator meeting on spin issues on Wednesdays. Finally, Phenix, STAR, and the pp2pp Collaboration have regular collaboration meetings including spin, and spin working groups.

Our agenda is organized around the physics topics:

Opening session—RHIC and detector progress and plans

Gluon polarization

Quark polarization

Transverse spin

Accelerator session

Future spin possibilities at RHIC

Polarimetry for RHIC.

The Organizing Committee for this meeting was Les Bland, Bob Jaffe, Yousef Makdisi, Thomas Roser, Naohito Saito, Mike Tannenbaum, Aki Yokosawa, Jacques Soffer (cochair) and Gerry Bunce (cochair). The secretary for the meeting was Fern Simes, and we would like to thank Fern for an excellent, smooth operation! We also thank the RIKEN BNL Research Center for its support, and Brookhaven National Laboratory and the U.S. Department of Energy for providing facilities. DOE and NSF support for RHIC and also RHIC spin, and the support of RIKEN for the spin components and the Center have made the upcoming spin physics at RHIC a reality.

Gerry Bunce

WELCOMING ADDRESS

T.D. LEE

RIKEN BNL Research Center

October 6, 1999

This is an important and auspicious week at Brookhaven: first the RHIC dedication and now the RBRC Workshop on RHIC Spin. I am very happy to welcome all of you.

It may be appropriate for me to relate to you what George Uhlenbeck told me, some forty years ago, in the fifties, about the discovery of the electron spin.

Discovery of (Spin)$_{\text{electron}}$

1924 Stoner - Pauli multiplicity / orbit. $= 2$

1925 Uhlenbeck & Goudsmit $\text{Spin}_e = \frac{1}{2}$

To explain the Zeeman effect $g = 2$

Ehrenfest : Great idea. Write it up & talk to Lorentz

Lorentz : Must think.
(a wk. later, $m r_e v = \frac{1}{2}$, $r_e = \frac{e^2}{m_e}$)
$v = \frac{1}{2e^2}$? !

Ehrenfest : good paper, already in print
(Physica)

Bohr $\xrightarrow[\text{by train}]{\text{Leiden}}$ Heisenberg + Pauli said:
a missing factor 2 in the
fine structure formula

Uhlenbeck + Goudsmit: What factor 2

Einstein (visiting Leiden): Yes, there is a
missing factor $\frac{1}{2}$

1926 L. Thomas: Thomas precession

To have the "right" idea

at the "RIGHT" time

Now, how about the nucleon spin?

RHIC SPIN PLANS

D.I.LOWENSTEIN
BROOKHAVEN NATIONAL LABORATORY

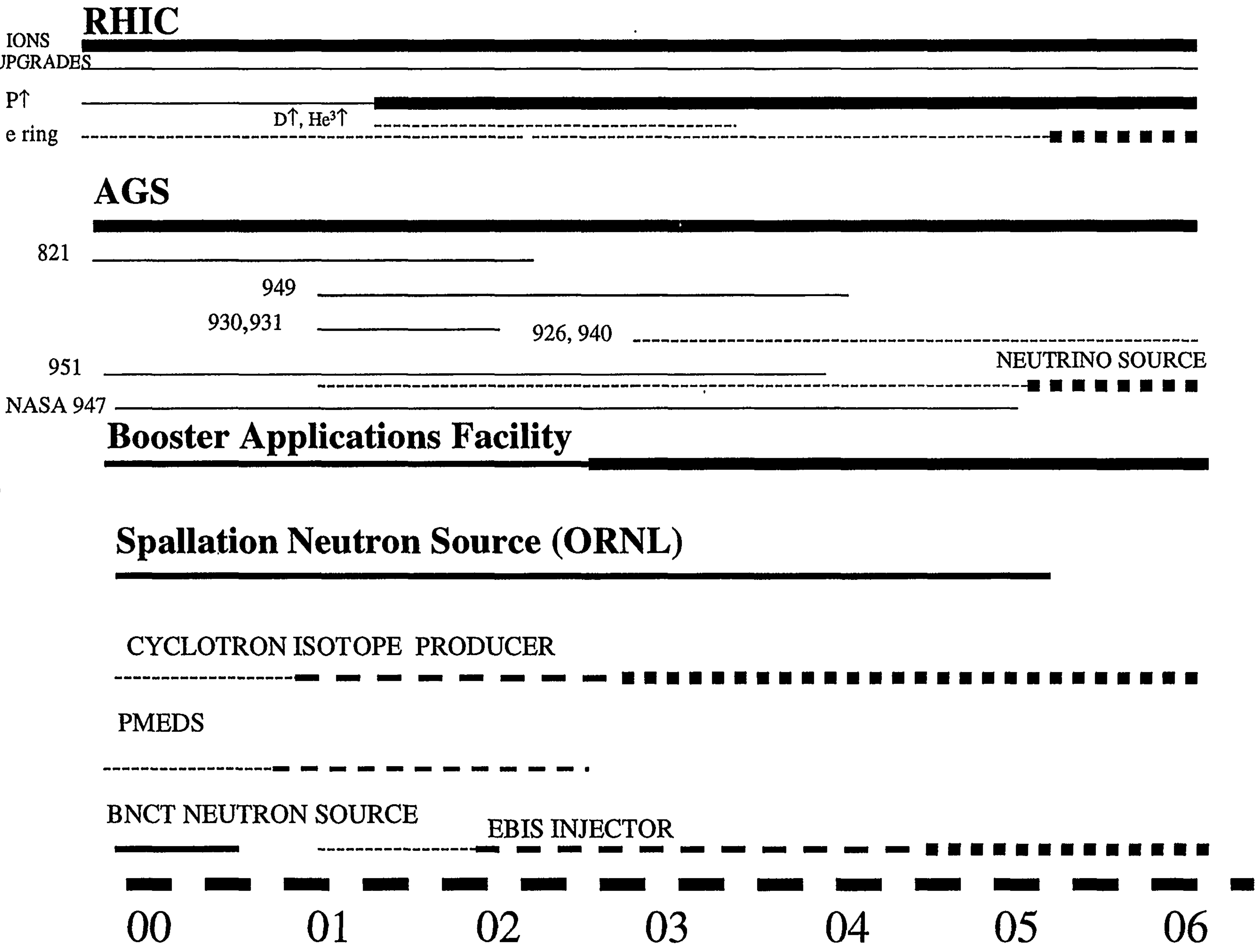
PRESENTED
TO
RHIC SPIN WORKSHOP
OCTOBER 6, 1999

RHIC SPIN

- SPIN PHYSICS IS AN INTEGRAL PART OF THE RHIC PHYSICS PROGRAM
  - MACKAY, PEGGS AND ZELENSKI HAVE THE DETAILS OF CONSTRUCTION AND COMMISSIONING
  - PHYSICS OPERATIONS WILL START AS SOON AS THE MACHINE IS READY AND THE EXPERIMENTS ARE READY
  - THE SCHEDULING OF THE SPIN PROGRAM WILL BE DRIVEN BY THE EXPERIMENT REQUESTS TO TOM KIRK
  - A BALANCE WILL BE STRUCK BETWEEN IONS & $P\uparrow$

- THE CHALLENGE TO THE SPIN COMMUNITY

- WHAT SHOULD WE BE FOCUSING UPON NEXT?
  - AN ELECTRON RING IS BEING CONSIDERED FOR THE ION PROGRAM
  - IS THERE A “MUST DO” CASE FOR THE PHYSICS?
  - WHAT ABOUT $e\uparrow p\uparrow$?
  - ION SOURCES OF $D\uparrow$ AND $He^{3}\uparrow$ ARE BEING CONSIDERED
  - SHOULD THE ENERGY BE PUSHED TO 350 GeV?
  - DETECTORS
    - UPGRADES
    - NEW


RHIC
IONS
UPGRADES
P↑
D↑, He³↑
e ring
AGS
821
949
930,931
926, 940
951
NEUTRINO SOURCE
NASA 947
Booster Applications Facility
Spallation Neutron Source (ORNL)
CYCLOTRON ISOTOPE PRODUCER
PMEDS
BNCT NEUTRON SOURCE
EBIS INJECTOR
00
01
02
03
04
05
06

10/6/99

Talk: Introduction and Status of Polarized Protons at RHIC
Speaker: Waldo MacKay, BNL waldo@bnl.gov

Abstract:

In order to collide polarized protons, the RHIC project will have two snakes in each ring and four rotators around each of two interaction regions. Two snakes on opposite sides of each ring can minimize depolarization during acceleration by keeping the spin tune at a half. Since the spin quantization axis is normally along the vertical direction in a flat ring, spin rotators must be used around an interaction point to have longitudinal polarization in a collider experiment. Each snake or rotator will be composed of four helical dipoles to provide the required rotation of spin with minimal transverse orbit excursions in a compact length of 10m. The basic helical dipole is a superconducting magnet producing a transverse dipole field which is twisted about the magnet axis through 360° in a length of 2.4m.

Particular slides:

1. Spin Resonances and Siberian Snakes

2. Layout of rotators and snakes in RHIC

3. Solution of magnetic field in cylindrical coordinates

4. Field measurements of a helical dipole.

5. Summary and Comments.

For more information see: http://www.rhichome.bnl.gov/RHIC/Spin

Spin Resonances and Siberian Snakes

Spin Tune ν_{sp} **: Number of 360° Spin Rotations per Turn**

Depolarizing Resonance Condition:

Number of Spin Rotations per Turn
= Number of Spin Kicks per Turn

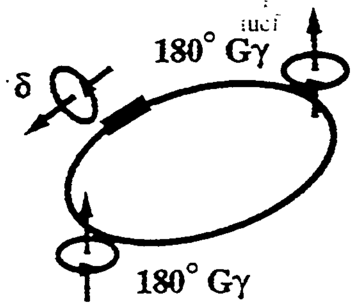
Only Vertical Field

$$\begin{pmatrix} G\gamma = 1.79 \\ \gamma = E/m \end{pmatrix} \quad \begin{array}{lllll} G\gamma & = & \nu_{sp} & = & n \\ G\gamma & = & \nu_{sp} & = & n \pm \nu_y \end{array}$$

Imperfection

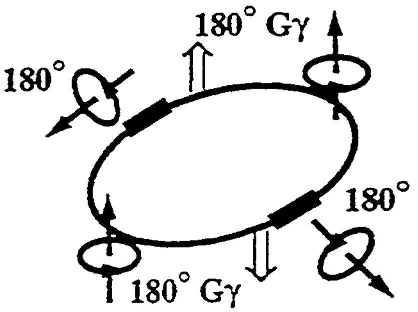
Intrinsic

Local Spin Rotators (Siberian Snakes)



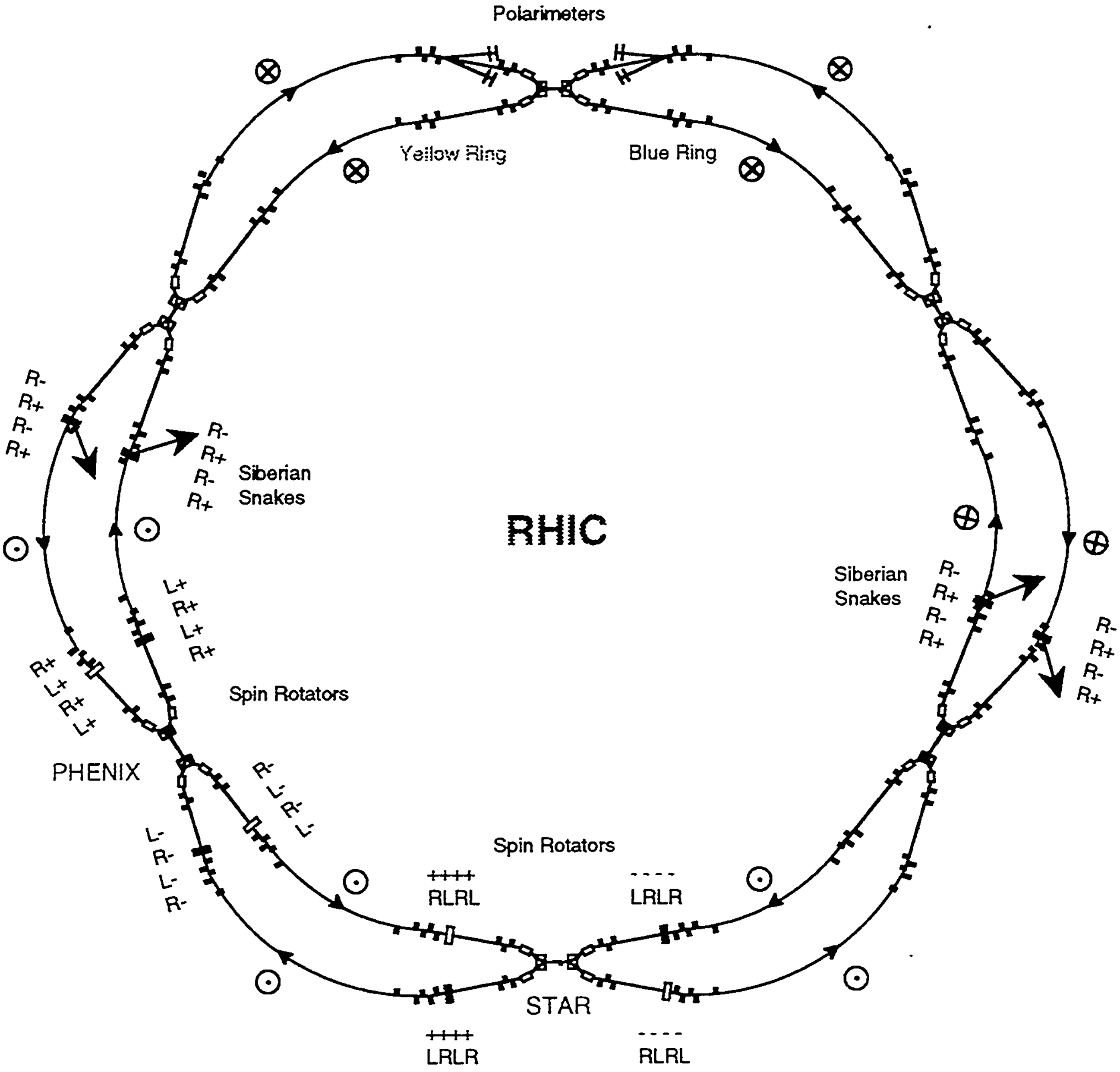
$$\boxed{\cos(180^\circ \nu_{sp}) = \cos(\delta/2) \bullet \cos(180^\circ G\gamma)}$$

- $\delta \neq 0^\circ \rightarrow \nu_{sp} \neq n$ ⇒ **No Imperfection Resonances...**
  Partial Siberian Snake (AGS)
- $\delta = 180^\circ \rightarrow \nu_{sp} = 1/2$ ⇒ **No Imperfection and**
  No Intrinsic Resonances...
  Full Siberian Snake



Two Siberian Snakes (RHIC)

- $\nu_{sp} = 1/2$, **Stable Vertical Polarization**



Rotators = Hor field (at ends), + = radially "out," - = radially "in"
Snakes = Ver field (at ends), + = "up," - = "down"

The Helical Dipole Field

Laplace's Equation (cylindrical coordinates) for the scalar potential:

$$\frac{\partial^2\Phi}{\partial r^2}+\frac{1}{r}\frac{\partial\Phi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\Phi}{\partial\phi^2}+\frac{\partial^2\Phi}{\partial z^2}=0.$$

Separation of variables, $\Phi = R(r)Q(\phi)Z(z)$, gives

$$\begin{aligned}\frac{d^2R}{dr^2}+\frac{1}{r}\frac{dR}{dr}-\left(k^2+\frac{\nu^2}{r^2}\right)R &= 0,\\ \frac{d^2Q}{d\phi^2}+\nu^2Q &= 0,\\ \frac{d^2Z}{dz^2}+k^2Z &= 0.\end{aligned}$$

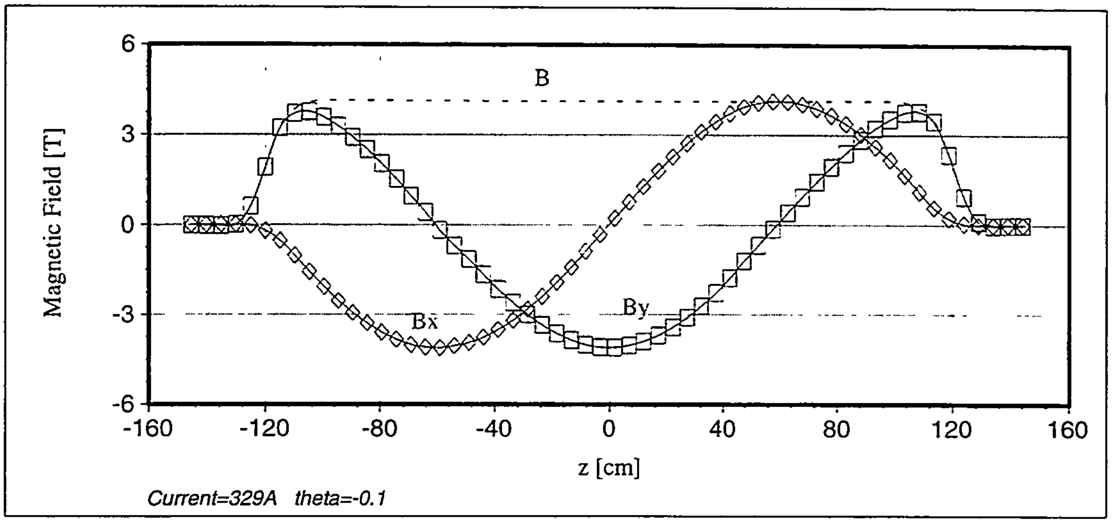
Note:

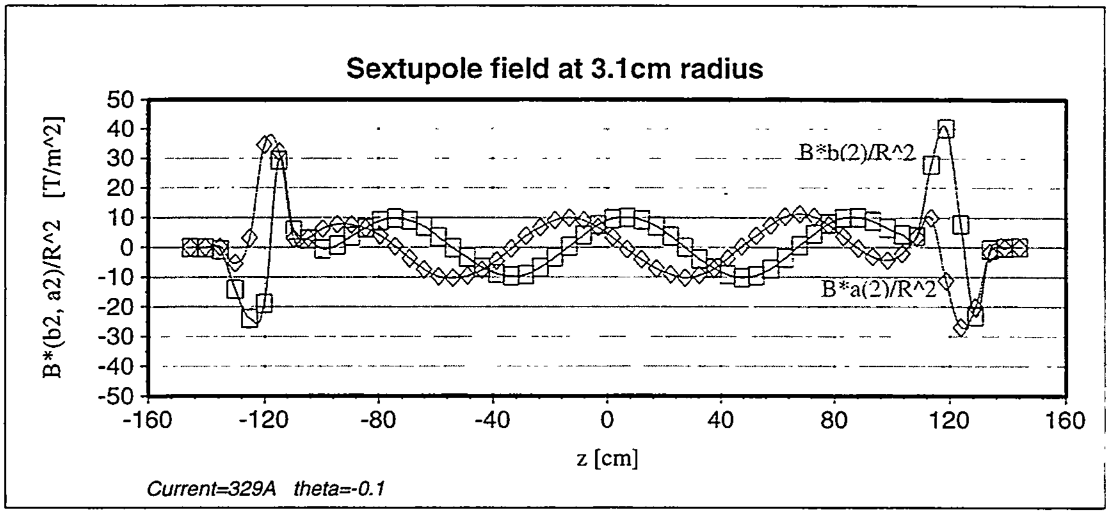
- Repeat period of helical field: $\lambda = 2\pi/|k|$
- $\nu = 1$ since central dipole field repeats after $\phi = 2\pi$
- Assume B_0 points vertically upward at $z = 0$
- $\vec{B} = -\nabla\Phi$ gives...

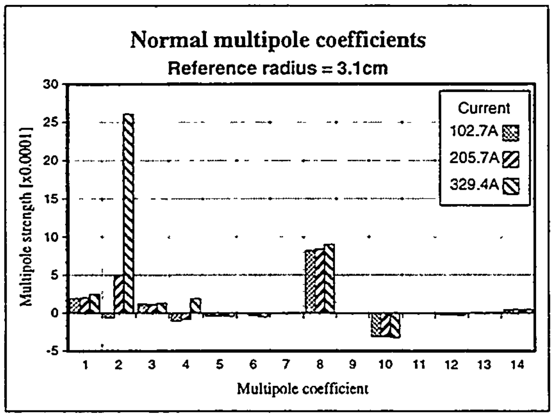
$$\begin{aligned}B_r &= 2B_0[I_0(kr)-\frac{I_1(kr)}{kr}](\cos kz\sin\phi-\sin kz\cos\phi)\\ B_\phi &= 2B_0\frac{I_1(kr)}{kr}(\cos kz\cos\phi+\sin kz\sin\phi)\\ B_z &= -2B_0I_1(kr)(\cos kz\cos\phi+\sin kz\sin\phi)\end{aligned}$$

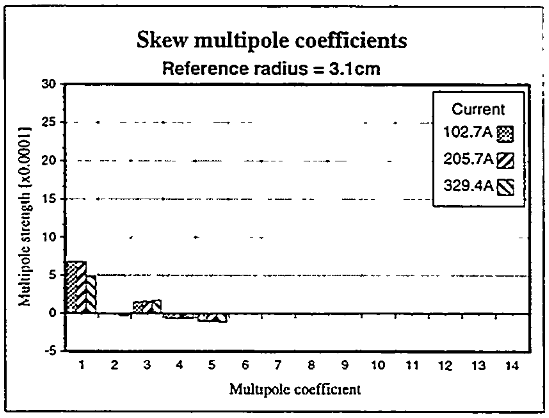
Look at $B_x = B_r\cos\phi - B_\phi\sin\phi$, $B_y = B_r\sin\phi + B_\phi\cos\phi$ and expand these fields near the longitudinal axis (x, y small); then,

$$\begin{aligned}B_x &\approx -B_0\left\{[1+\frac{k^2}{8}(3x^2+y^2)]\sin kz-\frac{k^2}{4}xy\cos kz\right\}\\ B_y &\approx B_0\left\{[1+\frac{k^2}{8}(x^2+3y^2)]\cos kz-\frac{k^2}{4}xy\sin kz\right\}\\ B_z &\approx -B_0k\left\{1+\frac{k^2}{8}(x^2+y^2)\right\}[x\cos kz+y\sin kz]\end{aligned}$$


Magnetic Field [T]
6
3
0
-3
-6
-160
-120
-80
-40
0
40
80
120
160
z [cm]
B
Bx
By
Current=329A theta=-0.1


Sextupole field at 3.1cm radius
B*(b2, a2)/R^2 [T/m^2]
50
40
30
20
10
0
-10
-20
-30
-40
-50
-160
-120
-80
-40
0
40
80
120
160
z [cm]
B*b(2)/R^2
B*a(2)/R^2
Current=329A theta=-0.1


Normal multipole coefficients
Reference radius = 3.1cm
Multipole strength [x0.0001]
30
25
20
15
10
5
0
-5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Multipole coefficient
Current
102.7A
205.7A
329.4A


Skew multipole coefficients
Reference radius = 3.1cm
Multipole strength [x0.0001]
30
25
20
15
10
5
0
-5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Multipole coefficient
Current
102.7A
205.7A
329.4A

Summary and Comments

Snakes & rotators can be built from helical dipoles
- 4 helices per snake/rotator
- desired field strength (4T)
- acceptable field quality
- integrated B is small (full 360° twist of helix)
- short enough to fit in RHIC (2.4m / helix)

Cold test of each helix

Cold mass of first snake is completed
- cryostat is being assembled.

Plan to install the first snake before Dec. 1999
- second snake ~Mar. 2000.

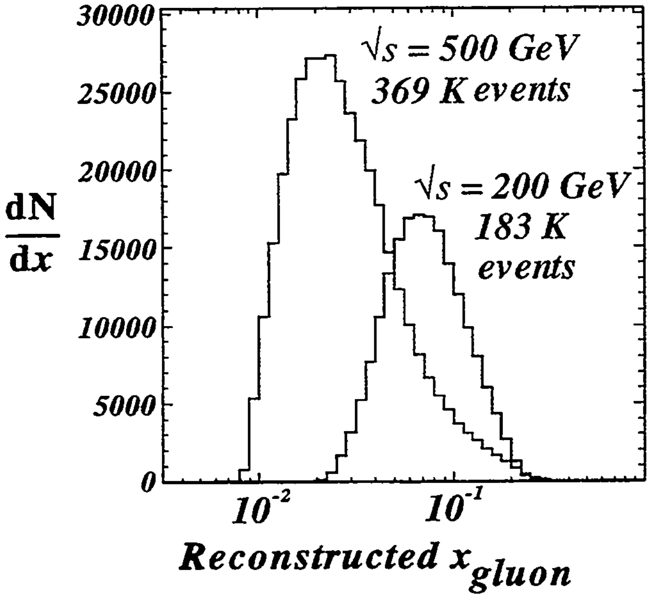
Long-Term Overview of STAR Spin Program

⇒ *full BEMC + full EEMC + "enhanced"* $\mathcal{L}_{\vec{p}\text{-}\vec{p}}$

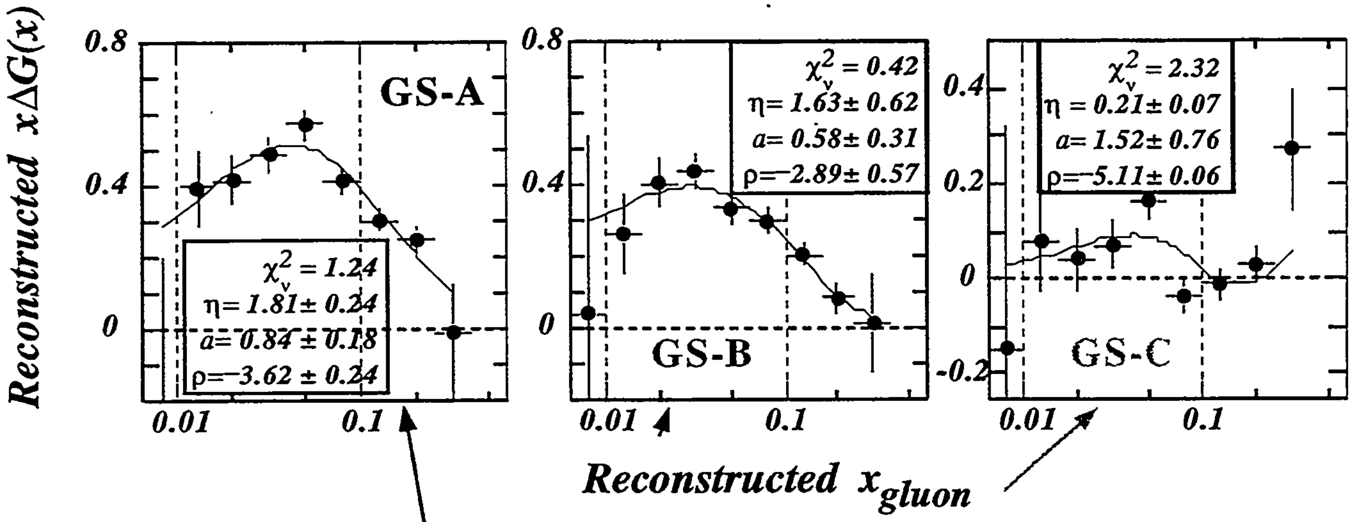
S. Vigdor

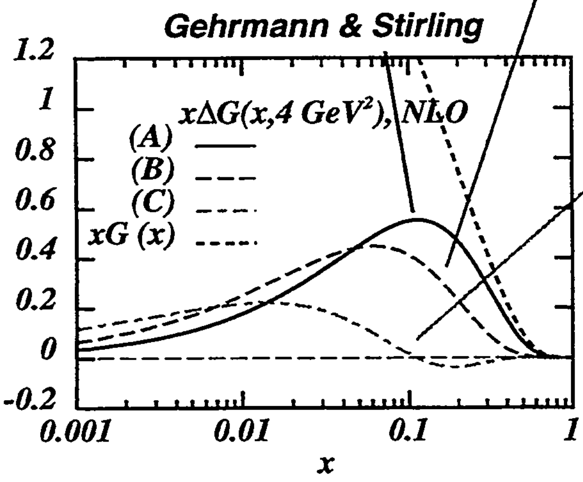
EXPERIMENT	**SIMUL'N STATUS**
Probes of Baryon Spin Structure:	
1) $\Delta G(x)$ in $\vec{p}$: direct extraction for $0.01 \le x_g \le 0.3$, via $\vec{p}+\vec{p} \to \gamma + jet + X$ @ $\sqrt{s} = 200$ GeV + 500 GeV	** see talks by Bland, Balewski
2) $\Delta G(x)$ sensitivity in A_{LL} for inclusive jet and dijet production	*
3) $\Delta\bar{u}$ vs. $\Delta\bar{d}$ in $\vec{p}$ via A_L^{PV} for $\vec{p}+\vec{p} \to W^{\pm} + X \to e^{\pm} + X$ @ $\sqrt{s} = 500$ GeV	* see talk by Ogawa
4) transversity in $\vec{p}$ via A_{TT} for inclusive Z^0 or jet production, or via 3-fold correlations in $\vec{p}_{\perp} + p \to \rho^0 + X \to \pi^+ + \pi^- + X$	
5) sensitivity to $\vec{\Lambda}^0$ spin structure via polarized fragmentation functions: D_{LL} for $\vec{p}_L + p \to \vec{\Lambda} + X \to p + \pi^- + X$ @ high p_T and z	
Essential Calibration/Credibility Checks:	
6) $A_T \to 0$? for high-p_T jet, photon production	
7) sensitivity to Δq at $x_q \gtrsim 0.2$ via $\vec{p}+\vec{p} \to$ dijet + X A_{LL} @ mid-rapidity and moderately high p_T	just starting
Beyond the Standard Model ?	
8) A_{LL}^{PV} in hard ($p_T \gtrsim 50$ GeV/c) inclusive jet prod'n	

$\vec{p} + \vec{p} \rightarrow \gamma + jet + X$ *with STAR + EEMC at*
$\sqrt{s} = 200\ GeV\ (320\ pb^{-1}) + \sqrt{s} = 500\ GeV\ (800\ pb^{-1})$



*Recent simulation results, including proper DGLAP evolution + several different $\Delta G(x,Q^2)$ models, show that BEMC + EEMC + 200 GeV + 500 GeV are **all essential** to cover a sufficient x_{gluon} range (0.01 - 0.30) to constrain the extrapolation to $x \rightarrow 0$, needed to determine $\Delta G \equiv \int_0^1 \Delta G(x)\, dx$ to a precision ≈ ± 0.5.*

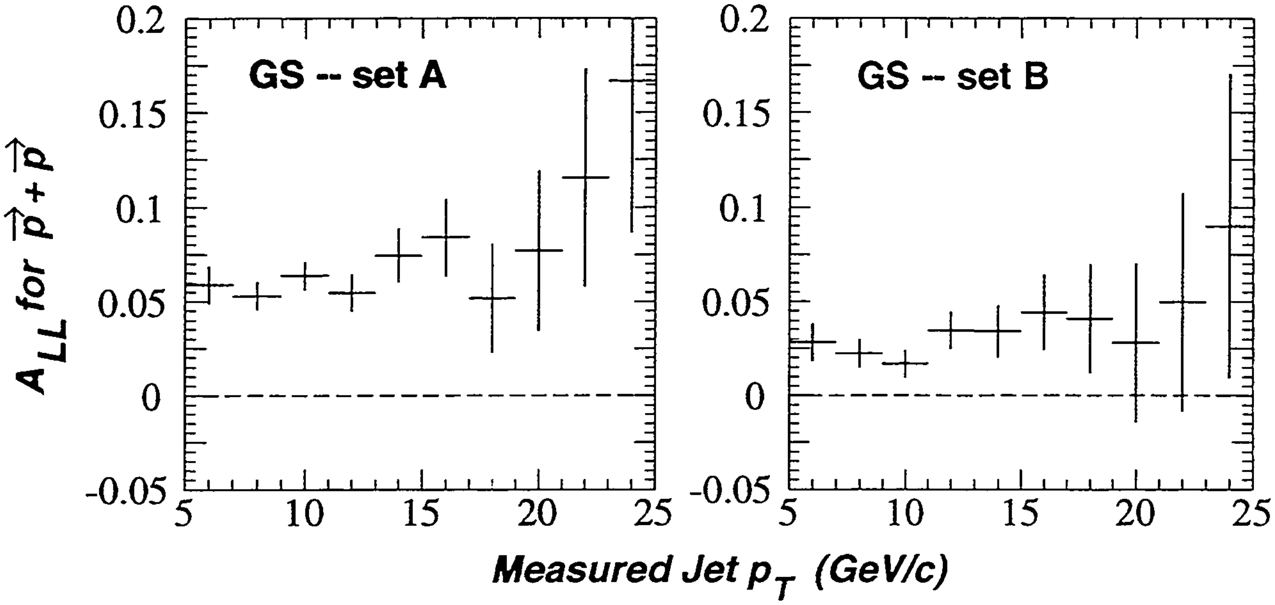


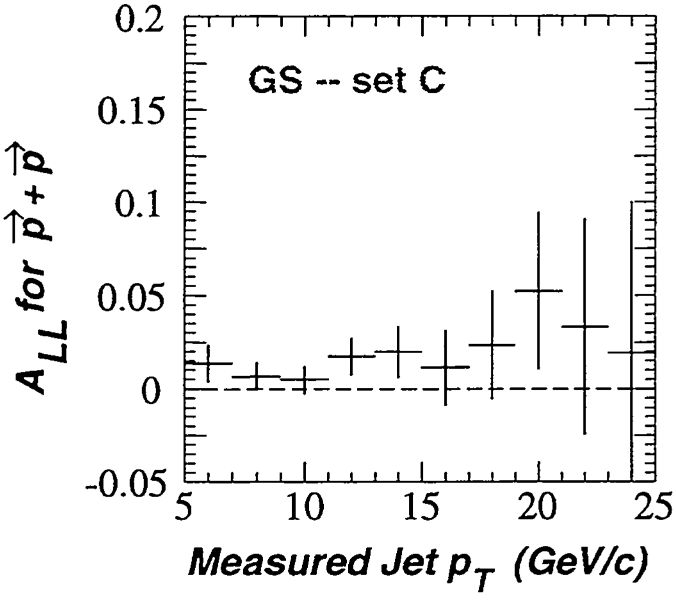


There are small systematic errors that arise from simplifying assumptions made in a direct reconstruction of ΔG from the measured asymmetries. These errors depend on $\Delta G(x,Q^2)$, but can be corrected in an iterative analysis with the aid of simulations. Analysis of STAR's coincidence data with varying kinematic cuts is important to test the simulations.

Sensitivity of Inclusive Jet Asymmetries to $\Delta G(x)$ for RHIC Year 2 (2000-01) $\vec{p} + \vec{p}$ Running at STAR

$\vec{p} + \vec{p} \rightarrow jet + X$, $\sqrt{s} = 200\ GeV$, $\int \mathcal{L}\, dt = 1\ pb^{-1}$





Simulation assumes:

- *Year 2 STAR Geometry*
  $\Rightarrow$ *42 BEMC modules in west end*
  $0 < \phi < 4.4$; $0 < \eta < 1$
- ***Jet Trigger from BEMC***
  $\Rightarrow \sum E_T > 5\ GeV$ *over at least one BEMC patch of size* $(\Delta\eta = 1) \times (\Delta\phi = 0.84)$
- ***Include only jets that are ≈ fully contained within BEMC***
  $\Rightarrow (0.35 < \eta_{jet} < 0.65) \times (0.35 < \phi_{jet} < 4.05)$

The PYTHIA-generated event sample that passes the trigger comprises: ≈ 60% q+g scattering, ≈ 25% q+q scattering, ≈ 15% g+g scattering

Can STAR Dijet Sample be Filtered to Yield Sensitivity to $\Delta q(x)$?

GOAL: 1) ***Essential*** contact with $\overrightarrow{\text{DIS}}$ results as credibility check on RHIC Spin program (earlier and at much higher rate than $W^{\pm}$ prod'n !)

2) If rate sufficient, could provide ***in situ*** relative polarimeter for product of ***longitudinal*** beam polarizations ***at the detector*** and with normal trigger !

FOCUS: q + q scattering near $\theta^* \sim \pi/2$ *($\Rightarrow \hat{a}_{LL} \approx$ 0.4)* and with $x(q_1) \approx x(q_2) \gtrsim 0.2$ *($\Rightarrow \Delta q / q \gtrsim$ 0.3)* $\Rightarrow A_{LL}(\vec{p}-\vec{p}) \sim 0.04$.

NEED: dijet events with $p_T \gtrsim$ ***20 GeV/c*** @ $\sqrt{s}$ ***= 200 GeV***, both near $\eta_{jet} \approx 0.$

EXPLORING Methods to Enhance q + q over q + g, g + g :

1) Exploit PDF differences: $x_1 \approx x_2 \gtrsim 0.2$ $[\Rightarrow f_{qq} \approx 0.25]$

2) Exploit ***q*** vs. ***g*** fragmentation differences via cuts on:

a) jet core -- large ΣE_T in narrow EMC patch [e.g., $(\Delta\eta=0.25) \times (\Delta\phi=0.2)$ enhances qq by factor ≈ 1.5]

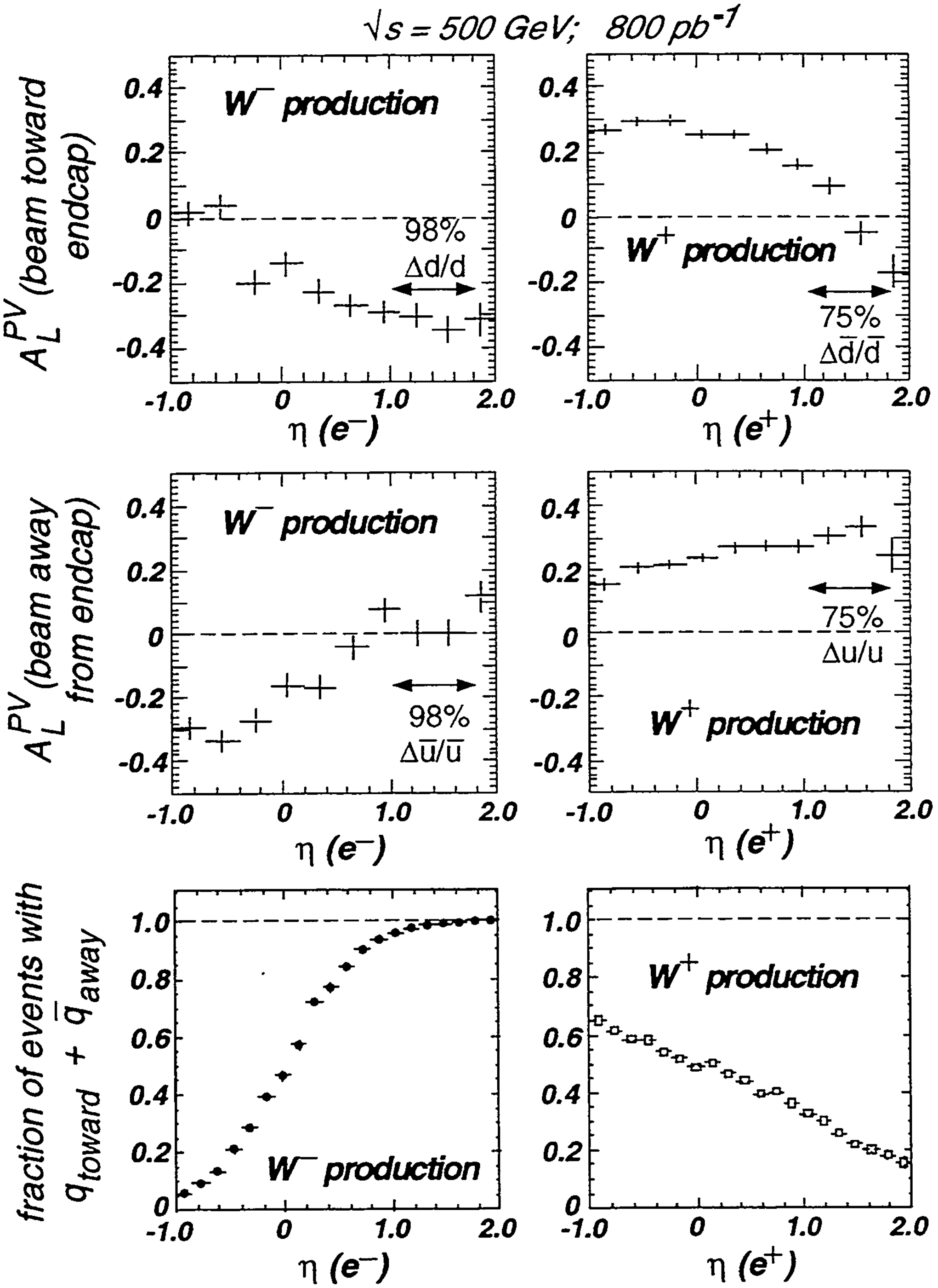
b) leading hadron energy -- $z_{\text{leading}} \gtrsim 0.3$ favors q over g by factor ≈ 2

c) charged particle multiplicity in jet -- ≈ 2 × greater for g jets, according to OPAL and DELPHI 3-jet analyses

QUESTIONS: 1) Can we reach ~ 80% q+q enrichment in sample at useful rate for polarimetry?

2) How reliable is emerging understanding of q vs. g fragmentation?

Measurement of parity-violating single-spin asymmetries for $\vec{p}+\vec{p}\to W^{\pm}+X\to e^{\pm}+X$ in the endcap region allows cleanest separation of antiquark $(\Delta\bar{q}/\bar{q})$ from quark $(\Delta q/q)$ polarizations



W$^{\pm}$ both produced L-handed ⇒

e^{-} emitted preferentially along W^{-} momentum

e^{+} emitted preferentially opposite W^{+} momentum

⇒ W^{-} case gives especially clean quark-antiquark separation

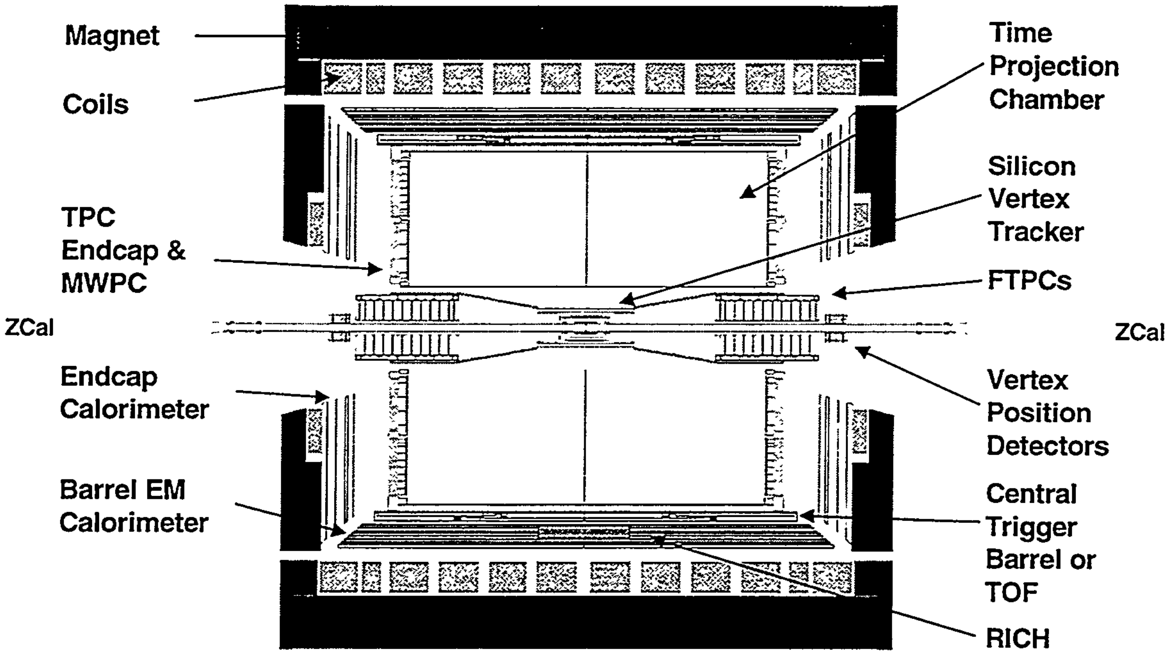
Possible Timeline for STAR Spin Program

RHIC Ops. Year	Assumed Equipm't Status	Physics + Technical Focus
1	Only unpol'd p + p; 4-6 BEMC modules	Calibrate baseline detector + several installed BEMC modules.
2	~ 1 pb^{-1} $\vec{p}+\vec{p}$ @ $\sqrt{s}$ = 200 GeV; ~ 1/3 BEMC; spin rotators @ STAR?	A_T in hard collisions → 0 ? Develop RHIC polarimetry & BEMC calib'n; First glimpse of A_{LL} for inclusive jet $\Rightarrow \Delta G(x)$ sensitivity.
3	~ 30 pb^{-1} $\vec{p}+\vec{p}$ @ $\sqrt{s}$ = 200 GeV; ~ 2/3 BEMC; all rotators installed	A_{LL} for dijet prod'n $\Rightarrow$ sensitivity to ΔG, Δq; First useful stat. sample of γ, γ + jet prod'n; Develop TPC pileup reject algorithms.
4	~ 200 pb^{-1} $\vec{p}+\vec{p}$ @ $\sqrt{s}$ = 200 GeV + ~ 200 pb^{-1} @ 500 GeV; ~ full BEMC + 1/2 EEMC; full Level 3 "filtering"	Full program @ 200 GeV + EEMC calib'n; First data @ 500 GeV to test rate capability + pileup rejection + W production bkgds.
5	> 200 pb^{-1} @ $\sqrt{s}$=200 GeV > 300 pb^{-1} @ $\sqrt{s}$=500 GeV full BEMC + EEMC	Complete $A_{LL}(\gamma + \text{jet})$ for $\Delta G(x)$ @ 200 GeV; $A_L^{PV}(W^{\pm}, Z^0)$, $A_{LL}^{PV}(p_T^{jet} > 50$ GeV/c) @ 500 GeV.

The STAR Spin Program, Status

Geary Eppley, for the STAR Collaboration
October 6, 1999

The STAR experiment at RHIC is a '4π' general-purpose detector capable of carrying out a broad experimental program during both heavy ion and polarized proton operation. The principal components of STAR that are important for spin are the time projection chamber (TPC), the electromagnetic calorimeters, and the trigger. STAR identifies electrons, photons, and jets. STAR cannot identify muons and does not measure missing E_T. The components of the STAR detector sit in a 0.5 Tesla solenoidal magnetic field. The magnetic field has been mapped to a precision of 1-2 Gauss.



TPC

Charge deposited in the TPC drifts from the center $z = 0$ towards the endplane of the cylinder in each half of the TPC. Tracks out to $|\eta|= 1$ cross all 45 pad rows and there is acceptable p_T resolution to $|\eta|\sim 1.5$. The maximum drift time in the TPC is 40 μs and this will generate pileup in the TPC. At the highest luminosity pp running, the mean number of inelastic collisions per crossing is about 1. Since the time between beam crossings is 107 ns, the data read out from the TPC will be approximately the size of a central AuAu event. The out-of-time pileup tracks will need to be ignored to perform analysis on these events and will also need to be purged to reduce the event size so that data may be captured at the rate of 15-20 Hz needed for the spin program.

The TPC is read out by a switched capacitor array. The potential total data volume is 137k pads times a maximum of 512 time slices. This readout takes 10 ms hence there is 1% dead time for each event read out of the TPC. Since the STAR spin program requires a large integrated luminosity, efficient triggering prior to TPC readout is required to minimize dead time.

Barrel EMC

The barrel EMC covers 2π in ϕ and $|\eta| < 1$. The 4800 towers are 0.05, 0.05 $(\Delta\eta, \Delta\phi)$. The lead-scintillator calorimeter contains 21 layers and is 18 radiation lengths in depth. There is also a 36k channel gaseous strip shower maximum detector to separate electrons from hadrons and gammas from π^0's. The EMC response is supplied to the first level trigger (Level 0) as 300 logical trigger towers 0.2, 0.2 $(\Delta\eta, \Delta\phi)$. The response of the highest tower in each trigger tower is also supplied to provide an efficient electron, photon trigger. Four of 120 total barrel EMC modules have been installed on the detector and production is continuing. A final DOE review is scheduled for spring 2000. See: www.star.bnl.gov/STAR/html/emc_l/emc.html.

Endcap EMC

The endcap EMC covers 2π in ϕ and $1.07 < \eta < 2.0$. The tower size is 0.05, 0.1 $(\Delta\eta, \Delta\phi)$ at low η and 0.1, 0.1 at high η. It is a 24 layer lead-scintillator calorimeter 21 radiation lengths in depth. It includes a 7200 channel scintillating strip shower maximum detector for superior electron-hadron and gamma-π^0 separation. It has a more aggressive design than the barrel shower max to handle the increased energies encountered in the endcap. The endcap EMC was recently approved as an NSF project. There is a test beam run for a prototype module at SLAC in October 1999. An engineering review is planned in early 2000. See: www.iucf.indiana.edu/Experiments/STAR/www_bnl/outline.html and www.iucf.indiana.edu/Experiments/STAR/www_publications/cdr.ps.gz

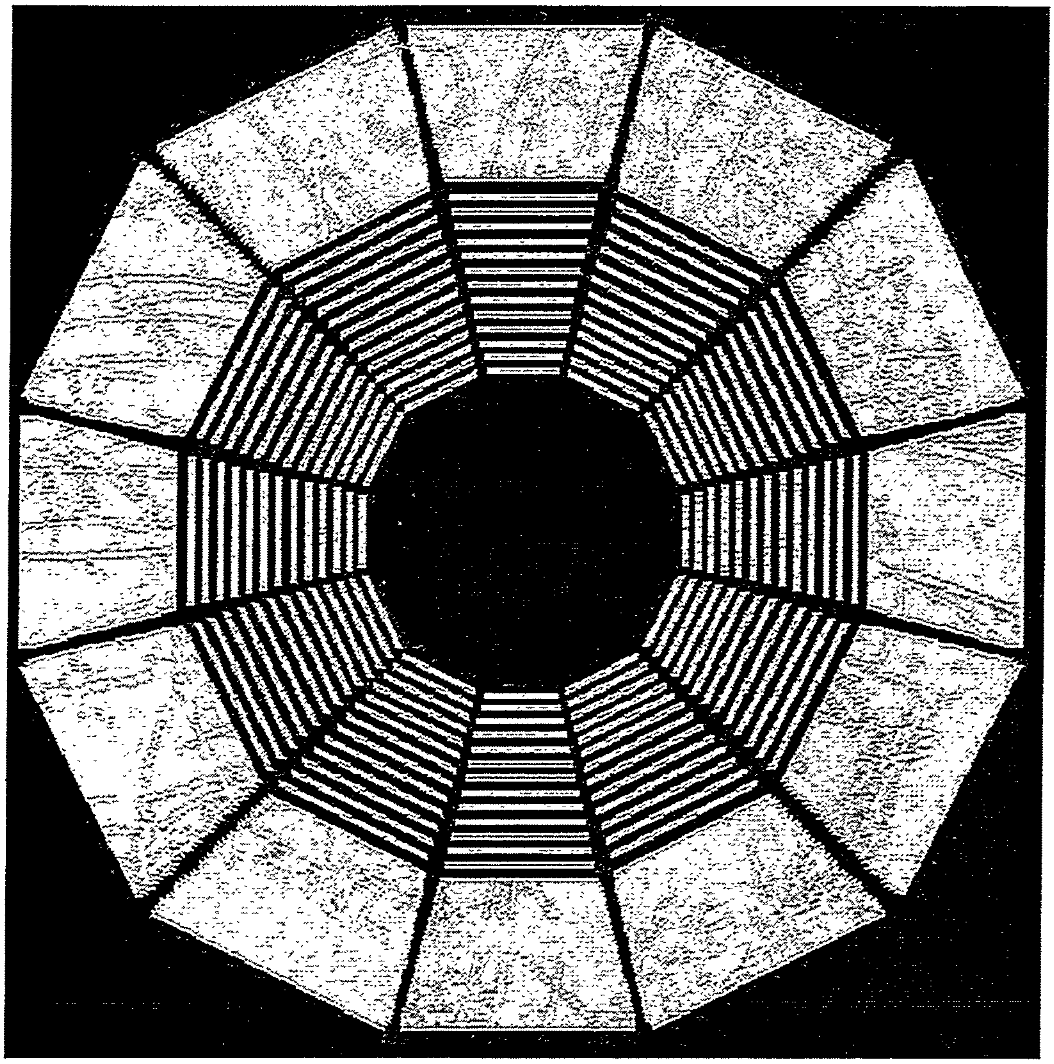
Trigger

The fast detectors that are able to provide information to the early trigger levels are the central trigger barrel (CTB) -- 240 scintillating slats covering 2π in ϕ and $|\eta| < 1$, the multi-wire proportional chamber (MWC) -- the endcaps of the TPC $1 < |\eta| < 2$ providing a trigger readout of four η divisions for each TPC sector, and the barrel and endcap EMCs. The Level 0 decision time is 1.5 μs and Level 0 receives input from the CTB, MWC, and the EMC trigger towers. The expected trigger rate for spin running is ~100 Hz. The Level 1 decision time is 100 μs and Level 1 receives input from Level 0. Level 2 receives information from Level 1 and more detailed information from the calorimeters. The expected output trigger rate in spin running is 15-20 Hz.

The Level 3 trigger operates after the full TPC read out is available. It can handle an event rate up to 50 Hz. The principal use for Level 3 in spin running is to remove pileup in the TPC. This will allow data capture of pp events up to 50 Hz. The likely desirable data capture rate for spin is 15-20 Hz.

Engineering Run

The STAR detector underwent a 3-month engineering run in the beam line May 17 – August 17, 1999. The components available for commissioning included the TPC, CTB, DAQ (75%), zero degree calorimeters (ZDC), and the slow controls system. Tens of thousands of cosmic ray events with full, half, and no magnetic filed were recorded. A few hundred beam-something events were also recorded. All detector components performed well in the test.



Beam-something event, TPC pad view. Run 3002 July 27, 1999.

Year 1

The year 1 run begins December 1999. In addition to the components available this summer, STAR will include a Level 0 trigger, online monitor and control system, Level 3 trigger (partial), MWC, full DAQ, and 4 barrel EMC modules.

Years 2-5

Year 2 will see the addition of the silicon drift vertex detector (SVT), forward TPCs, Level 1 and 2 triggers, additional Level 3 capacity, and ~30 barrel EMC modules. Construction of the barrel EMC will be ongoing and it should be fully complete by year 5 (2003). The first half of the endcap EMC is expected in year 4 with completion in year 5.

The STAR detector is nearly ready for the initial spin physics program now and will be ready to record the first polarized pp collisions beginning in year 2.

Progress of PHENIX Spin Program

Naohito Saito

The institute of Physical and Chemical Research (RIKEN)
Wako, Saitama, 351-0198, Japan
and
RIKEN BNL Research Center
Brookhaven National Laboratory
Upton, NY 11973

Abstract

The PHENIX detector system is going to be completed soon: base-line detector including electromagnetic calorimeter will be rolled in February, 2000 to be ready for the physics run from April. The Muon Arms are under construction to be in time for the 2nd year of operation. In addition to detector construction, we, the PHENIX spin physics working group are working on the various issues, namely measurements of $\Delta g(x)$, flavor decomposition of $\Delta q(x)$, and transversity distribution $\Delta_T q(x)$. The sensitivity of PHENIX measurements to these distributions is updated.

Progress of PHENIX Spin Program

RHIC Spin Collaboration meeting,
October 6-8, 1999

Outline:
- PHENIX Spin Program
- PHENIX Status
- Measurements
  - $\Delta g(x)$, $\Delta q(x)$, $\Delta_T q(x)$
- Summary

Naohito Saito
RIKEN / RIKEN BNL Research Center

PHENIX Spin Program

- Spin Structure of the Nucleon
  - $-\Delta g(x)$: Gluon polarization via γ,π^0,heavy quark productions
  - $-\Delta\overline{q}(x)$: Anti-quark polarization via Drell-Yan (W,Z,γ*)
  - $-\Delta_T q(x), \Delta_T \overline{q}(x)$: Quark transversity
- Symmetry Tests
  - parity violating effects, e.g. compositeness
- QCD Selection Rule
  - switch off gluon; a_{TT}/a_{LL}<<1
- Single Transverse Spin Asymmetry A_N
  - large at lower Energy; higher-twist? ; k_T asymmetry?

PHENIX Spin PWG

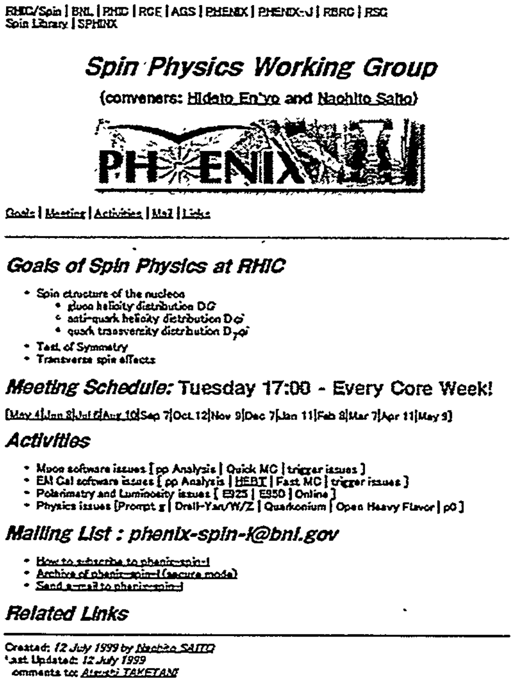
physics issues

- Measurements of $\Delta g(x)$
  - prompt photon production -> EMcal
  - inclusive π^0 production -> EMcal
  - heavy flavor production -> Muon+EMcal
  - Quarkonium production ->Muon+EMcal
- Measurements of $\Delta q(x)$
  - Dreall-Yan/W/Z production ->Muon+EMcal
- Measurements of $\Delta q_T(x)$
  - Drell-Yan?
  - two pions?

PHENIX Spin PWG

experimental issues

- Muon
  - offline software
  - simulations
    - Quick MC
- EMcal
  - offline software
  - HEBT
  - Trigger
  - Simulations
    - Fast MC
- Luminosity/Polarimetry
  - spin specific online issues
  - bunch-by-bunch luminosity and polarization monitoring



RHIC/Spin | BNL | RHIC | RCF | AGS | PHENIX | PHENIX-J | RBRC | RSC
Spin Library | SPHINX

Spin Physics Working Group

(conveners: Hideto En'yo and Naohito Saito)

Goals | Meeting | Activities | Mail | Links

Goals of Spin Physics at RHIC

- Spin structure of the nucleon
  - gluon helicity distribution DG
  - anti-quark helicity distribution Dq̄
  - quark transversity distribution $D_T q$
- Test of Symmetry
- Transverse spin effects

Meeting Schedule: Tuesday 17:00 - Every Core Week!

[May 4|Jun 8|Jul 6|Aug 10|Sep 7|Oct 12|Nov 9|Dec 7|Jan 11|Feb 8|Mar 7|Apr 11|May 9]

Activities

- Muon software issues [pp Analysis | Quick MC | trigger issues]
- EM Cal software issues [pp Analysis | HEBT | Fast MC | trigger issues]
- Polarimetry and Luminosity issues [E925 | E950 | Online]
- Physics issues [Prompt g | Drell-Yan/W/Z | Quarkonium | Open Heavy Flavor | p0]

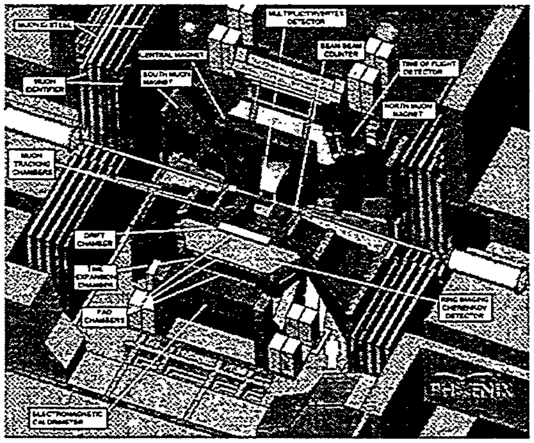
Mailing List : phenix-spin-l@bnl.gov

- How to subscribe to phenix-spin-l
- Archive of phenix-spin-l (secure mode)
- Send e-mail to phenix-spin-l

Related Links

Created: *12 July 1999* by *Naohito SAITO*
Last Updated: *12 July 1999*
Comments to: *Atsushi TAKETANI*

PHENIX Year-1 Status



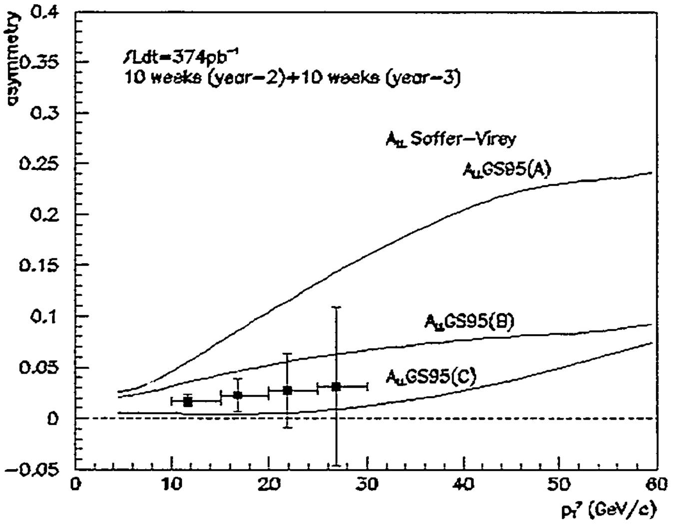
- After roll-in of East Arm:
  - Global:
    - MVD/BB/ZDC
  - East Arm
    - All subsystem mounted
    - >50% read out
  - West Arm
    - EMCal / RICH / DC / PC1
    - ~25% read out
  - Spin Specific Devices
    - EMcal-Level1 Trigger
    - Bunch-by-bunch scaler for luminosity monitor

* South Muon Arm will be ready for year-2, North for year-3 to be ready for 500 GeV!

Prompt Photon A_{LL} and ΔG

Yuji Goto and Alexander Bazilevsky

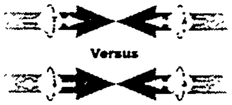
- Model Calculation with PYTHIA and BS/GS95 @200 GeV
- BS ΔG>2
- GSA ΔG=1.71
- GSB ΔG=1.63
- GSC ΔG=1.02

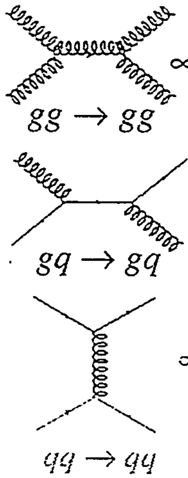


Inclusive π^0 Production

- Mixture of gg, gq, and qq scattering
  - gg dominates at low-p_T, gq dominates at mid-p_T

    →sensitive to gluon polarization



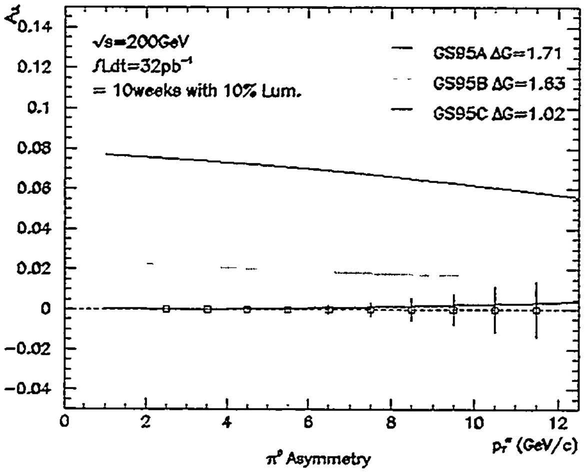


$$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$$

$$\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$$

$$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$$

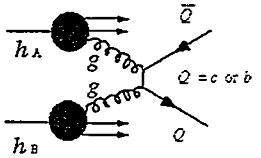
Model Predictions on A_{LL}

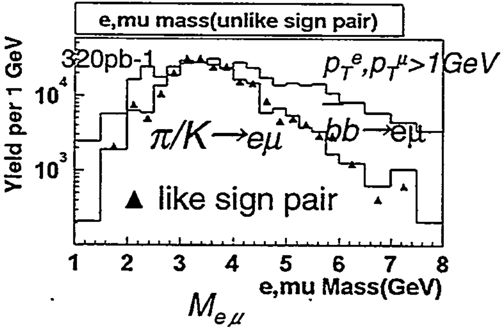


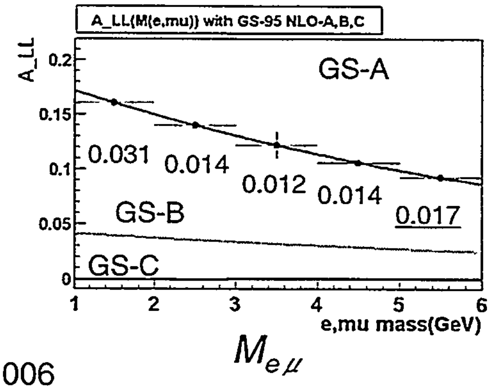
Open Heavy Flavor Production

study by Hiroki Sato with μ-software team

- Charm and bottom production
  - dominated by
  - can be identified with high-mass e-μ pairs





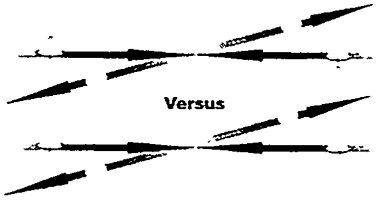


$N_{bb\to e\mu}$~100k events→ δA_{LL}(stat.)~ 0.006

$N_{\pi/K\to e\mu}$ ~60k events

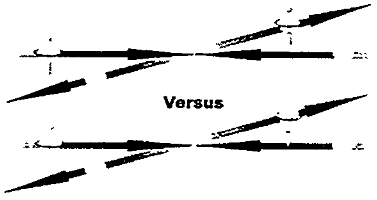
Transversity Measurements

- Double Transverse Spin Asymmetry



$$A_{TT} = \Delta_T q_i(x) \otimes \Delta_T q_i(x) \otimes a_{TT}$$

- Transverse Spin Transfer Asymmetry



$$A_{TT}^{if} = \Delta_T q_i(x) \otimes \Delta \hat{q}_T(z) \otimes a_{TT}^{if}$$

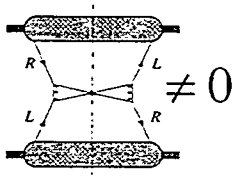
↑

Need "quark spin analyzer"

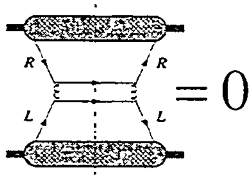
Double Transverse Spin Asymmetry

- Jet Production
  - asymmetry is small
    - only exchange & annihilation channels have non-zero asymmetry
    - gluon does not contribute
  - $A_{TT}/A_{LL}= 0$ unless $\Delta g(x)=0$

(QCD selection rule: Jaffe-NS PLB382(96)165)



exchange channel

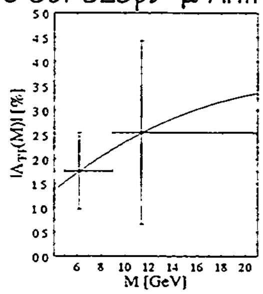


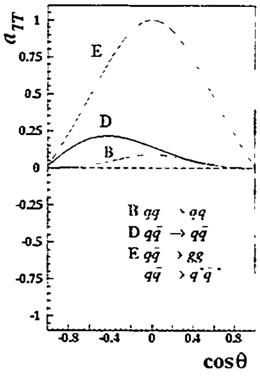
direct channel

- Drell-Yan Production of Lepton Pairs :PHENIX μ ->
  - largest partonic asymmetry
  - concerns
    - rates
    - other processes to contribute to dimuon channels = open heavy flavor

O.Martin et al. PRD57(98)3084

PHENIX 200 GeV 320pb^{-1} μ-Arm

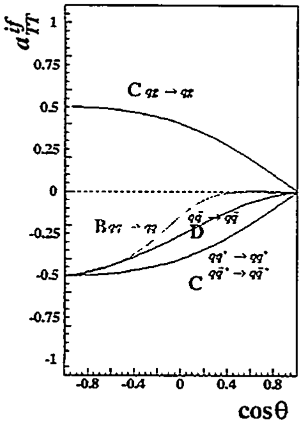




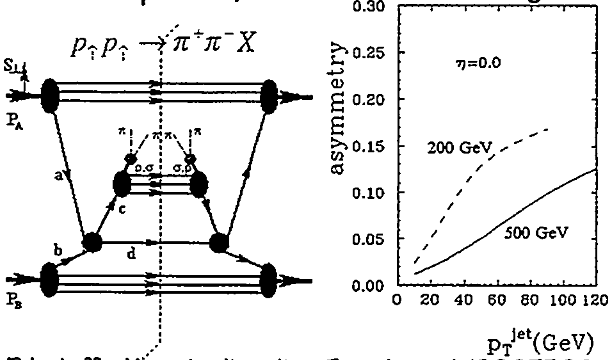
Transverse Spin Transfer Asymmetry

$$A_{TT}^{if} \propto \Delta_T q \otimes a_{TT}^{if} \otimes \Delta_T \hat{q}$$

- Reasonably Large partonic asymmetry => Only need quark spin analyzer



- Quark Spin Analyzer Candidates I
  - two pion@ρ-σ interference region



R.L Jaffe, Xuemin Jin, Jian Tang hep-ph/9807560

- Quark Spin Analyzer Candidates II
  - hint from HERMES ϕ asymmetry

*Matthias Grosse-Perdekamp's work in progress

Summary

- PHENIX is getting ready for Spin Physics from year-2 including core subsystems for Spin Physics
  - year-2/3 : constraints on $\Delta g(x)$ is high priority
  - spin-flavor structure studies with W
  - transversity studies
- Still a lot to do!

The *PP2PP* Spin Program

A. Penzo

(For the PP2PP Collaboration)

Among the approved experiments at RHIC, PP2PP (R7) is aiming to measure pp elastic scattering in a new energy range ($50 \le \sqrt{s} \le 500$ GeV), overlapping with the highest ISR energies and extending well into the $\bar{p}p$ colliders' region.

PP2PP is planning to run in year 2001:

- **initially the $|t|$-range [$0.006 \le |t| \le 1.5$ (GeV/c)^2] can be measured with standard beam tune ($\beta^* = 10$ m and $\varepsilon = 20\ \pi$);**
- **a special beam tune ($\beta^* = 195$ m and $\varepsilon = 5\ \pi$) will give coverage of the range [$0.0004 \le |t| \le 0.12$ (GeV/c)^2] in the CNI region.**

A jet target, integrated with the PP2PP setup, will match the same kinematical regions with recoil detectors and cover the energy range ($6.5 \le \sqrt{s} \le 22.5$ GeV). The combination of forward and recoil detectors will provide *full selection* of elastic events.

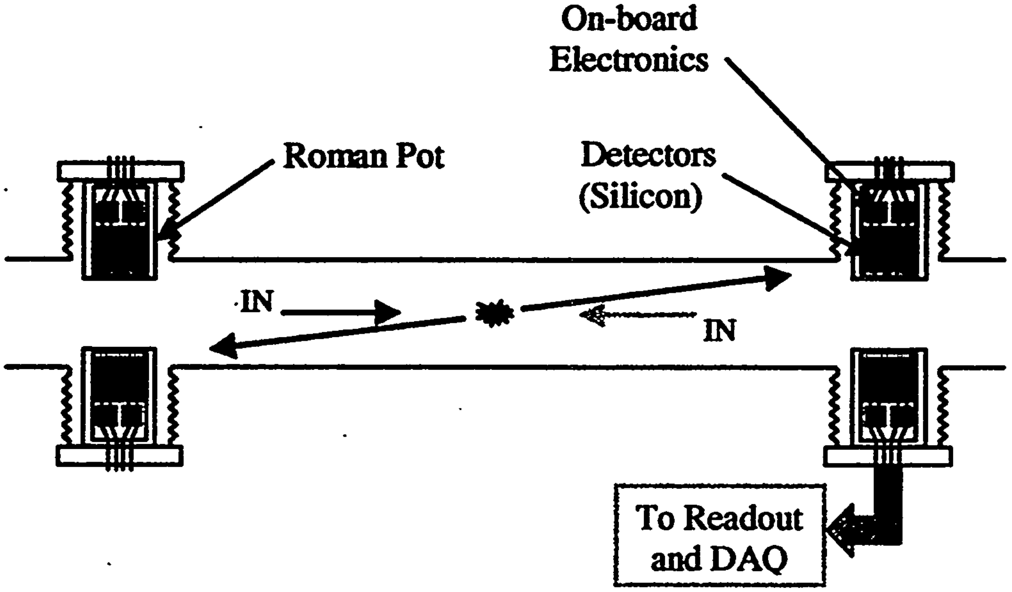
In this configuration, PP2PP will be able to measure the absolute polarization of the RHIC proton beams to 5% accuracy, thus contributing to the precision of all RHIC spin experiments.

Ways of extending the $|t|$- range to higher values [up to $|t| \approx 5 - 10$ (GeV/c)^2] have been studied, and are in principle feasible, both in collider and fixed- target modes.

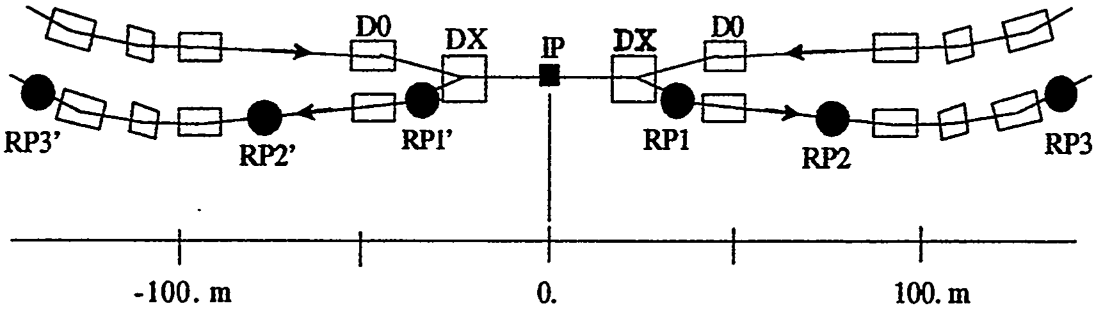
The PP2PP main goal is to extensively map the diffractive regime of the strong interaction over an unprecedented wide range of $\sqrt{s}$ and $|t|$, in order to probe the emerging features of the Pomeron, in terms of QCD concepts, and to explore its spin dependence.

Experimental Method at Hadron Colliders

Roman pot location is determined by parallel to point focusing.



RHIC Intersection Region with PP2PP Basic CB Setup



Detectors

Silicon strip detectors are our choice. They will provide:

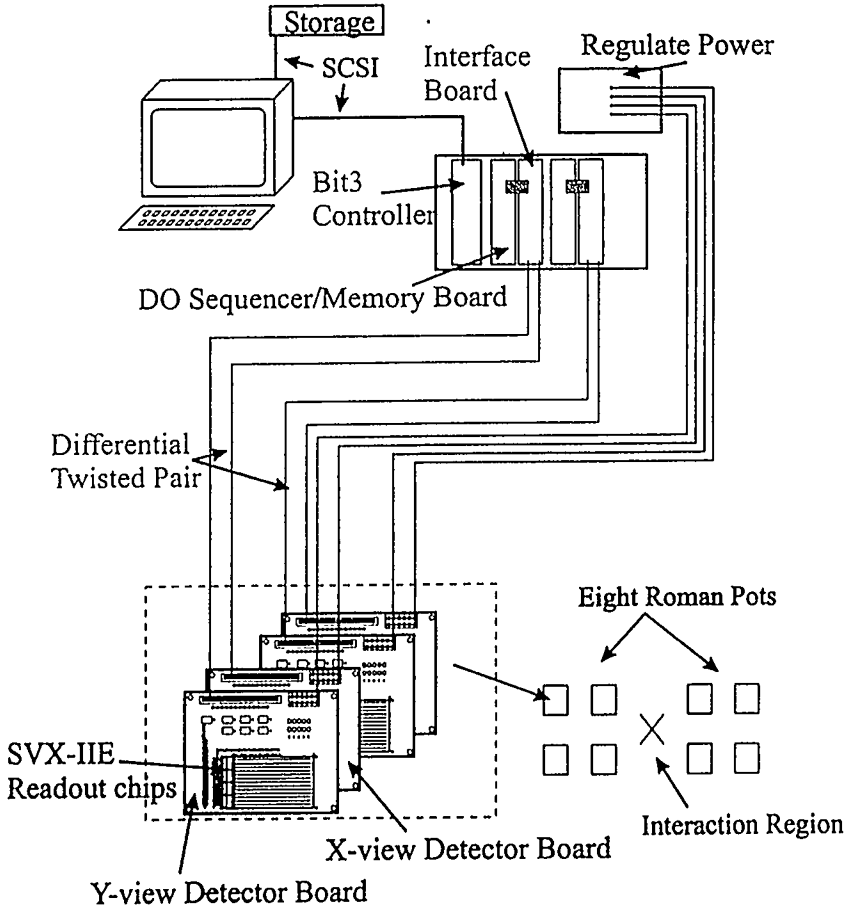
- uniformity of efficiency ~ 0.1% not to dominate errors on σ_{tot} and ρ;
- small dead area between the sensitive part of the detector and the beam 0.5mm
- many detector layers with high efficiency;
- small cell size to limit occupancy per readout channel;
- in the CNI region good detector resolution is needed:

$$\delta t << 10^{-4} GeV^2 (bins) \Rightarrow \delta y \approx 0.1mm$$

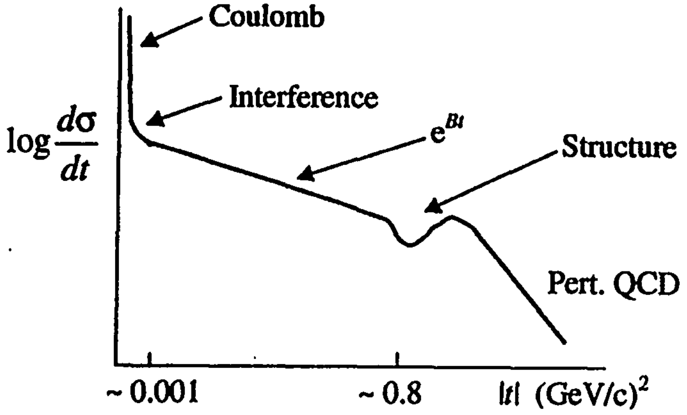
- in the dip region detector resolution set by momentum reconstruction (δp/p ~ 1%) and vertex size (y* ~ 1mm):

$$\delta y \approx 0.2mm$$

PP2PP Readout and Power Scheme (For One Roman Pot)



Elastic Scattering Cross Section



1. Coulomb Region $\frac{d\sigma}{dt} \sim \frac{1}{t^2}$ – Normalization ($\mathcal{L}$)
2. Coulomb – Nuclear Interference – "ρ" Value

} Small *t*

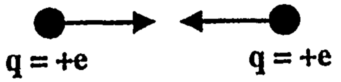
3. Diffraction $\frac{d\sigma}{dt} \sim e^{Bt}$ – σ_{tot}
4. Structure Region – Peaks & Bumps

} Medium *t*

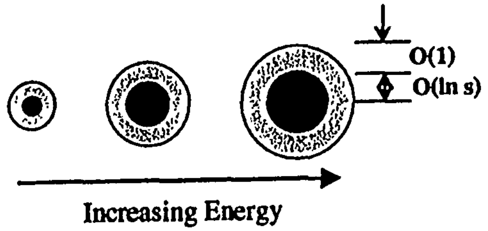
5. Large $|t| \gtrsim 5$ GeV^2 – Pert. QCD Large *t*

There are three regimes in elastic scattering:

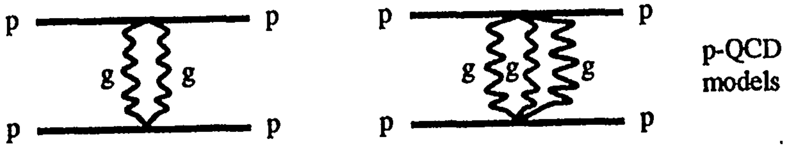
I. Coulomb Scattering, small *t* – protons are point-like



II. Diffraction, medium *t*: – proton has a size and "some" structure



III. QCD Regime, large *t*: – quarks, point-like constituents of protons scatter by exchanging gluons



In order to explain the observed features of ***pp*** elastic scattering, in addition to **Reggeon** exchange, an exchange of the **Pomeron (*gg*)**, a **double Pomeron** and a **Odderon (*ggg*)** exchange is needed to explain the structure of elastic cross section, **dσ/dt**

Polarized beams

With transversely polarized protons and measuring of $\Delta\sigma_{tot}$, A_N, A_{NN} we will determine .
L. Trueman et. al PRD 59, 114010 (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}:

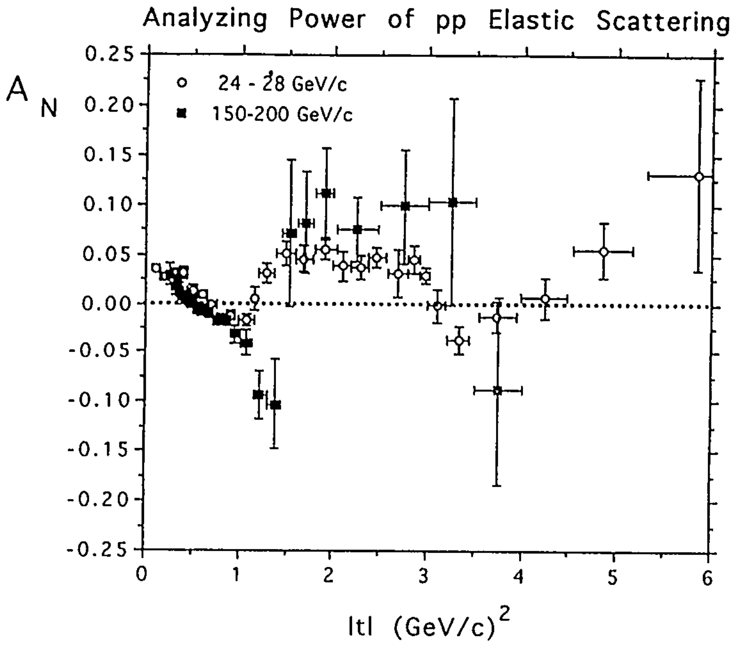
$$A_{NN} = \frac{1}{P_1 P_2 \cos^2\phi}\frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

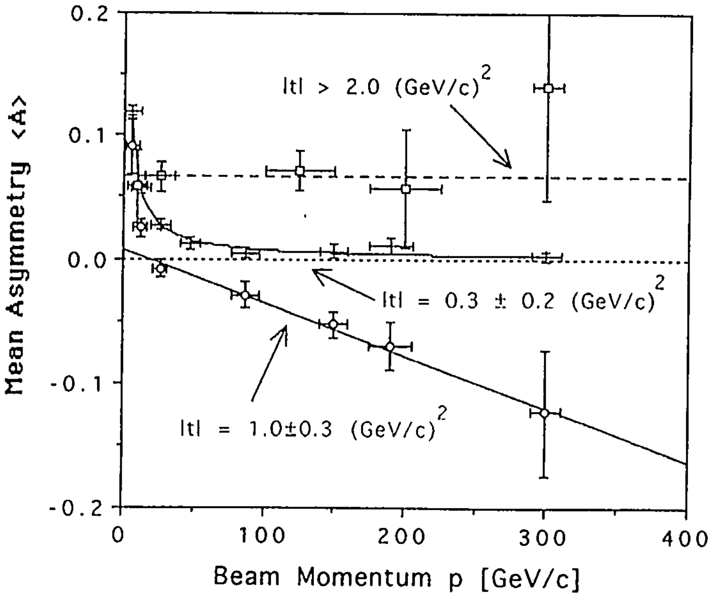
(P_i is beam polarization, ϕ is scattering azimuth)

As there are NO SPIN ROTATORS at 2 o' clock, in principle NO LONGITUDINAL POLARIZATION for PP2PP...

However it MIGHT BE POSSIBLE at some SPECIFIC ENERGY with an appropriate configuration of snakes and spin rotators...

[TO BE STUDIED]





Spin-off of PP2PP program: RHIC polarimetry

- **RHIC beam energies: new domain for polarimetry;**
- **No reaction in this energy range has been measured (or calculated) with accuracy better than 5% ;**
- **Only useful guideline E-704 at FNAL:**
  - 200 GeV polarized proton beam from Λ^0 decay; $(\alpha_\Lambda = 0.642 \pm 0.013)$
  - CNI $pp \rightarrow pp$, $pA \rightarrow p\pi^0 A$, $pp \rightarrow \pi X$;
- **New approach:** ***self - calibrating*** **polarimeter**

Possible in pp → pp with jet target (polarized/ unpolarized):

$$A_N (p\uparrow p \rightarrow pp) \equiv A_N (pp\uparrow \rightarrow pp) \equiv P_R (pp \rightarrow pp\uparrow)$$

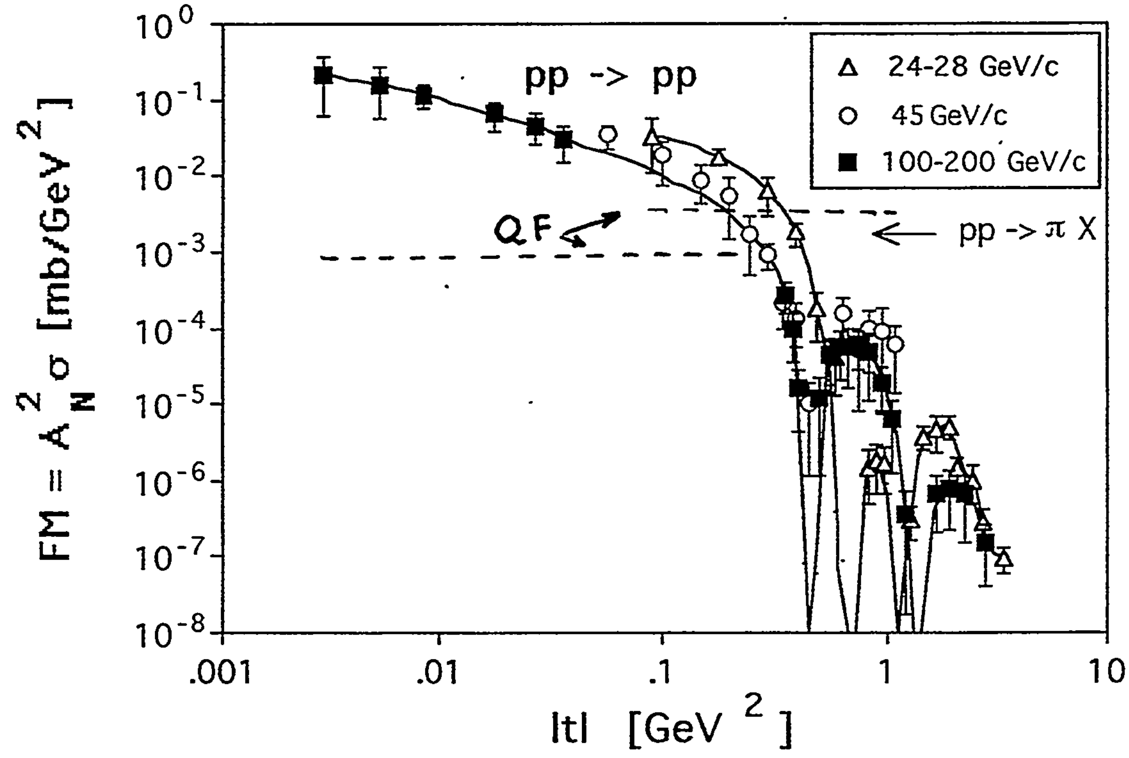
(T-invariance + Pauli principle)

Existing data (25 - 300 GeV/c) and models suggest 3 |t| - regions:

a - CNI $[10^{-3} \leq |t| \leq 10^{-2}\ (\mathrm{GeV/c})^2]$: $A_N \approx +5\%$, very large dσ/dt;

b - small-|t| $[0.1 \leq |t| \leq 0.4\ (\mathrm{GeV/c})^2]$: $A_N \approx +3\%$, large dσ/dt;

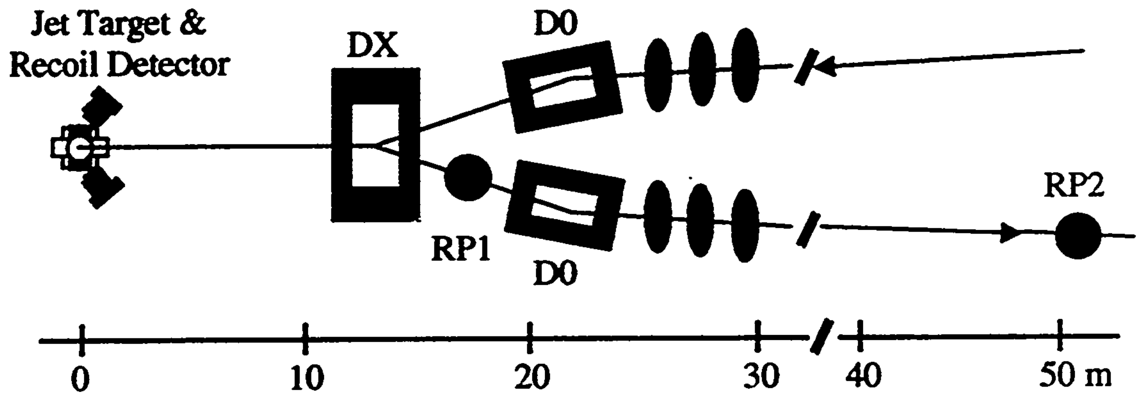
c - medium-|t| $[0.8 \leq |t| \leq 1.2\ (\mathrm{GeV/c})^2]$: $A_N \approx -10\%$, small dσ/dt;



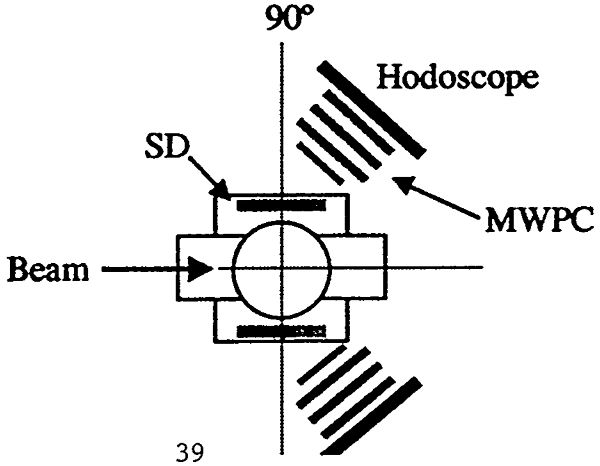
Day one PP2PP Setup with Jet Target and Recoil Detectors

More than one p_{beam} at RHIC, 100 GeV/c and 250 GeV/c proton beams, will allow us to take data at two √s points.

At luminosity $4\text{x}10^{30}$ $\text{cm}^{-2}\text{sec}^{-1}$, 200 hrs data on tape to acquire 1000 evts/0.02 GeV^2/c^2 bin will be needed.



Jet Target and Recoil Detector



Status and Plans

Our goal is to be ready for running in spring of 2001.

1. Experiment has scientific approval.
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;
   - worked with the European groups to secure a polarized and unpolarized jet target for pp2pp and RHIC spin program.

In order to meet the our goal the following in FY 1999 through FY 2001 is desired:

1. FY 1999 finish design and prototyping of the Roman pots, Si strip detectors and of the inelastic detector system.
2. FY 2000 construction and commissioning of detectors, Roman pots, design jet target interface, work on the interface with BRAHMS.
3. FY 2001 installation of the experiment at RHIC including jet target.

More collaborators are welcome!

Direct photon experimental results and issues [1]

Monique Werlen

The direct photon high-p_T data are essential to extract the gluon distribution function $G(x, Q^2)$ whose precise knowledge is mandatory for any gluon polarisation studies.

1 Data versus theory current status

The comparison between full next-to-leading (NLO) calculations and the direct photon production experimental data is quite puzzling. If both low $\sqrt{s}$ UA6/WA70 and high $\sqrt{s}$ ISR data are compatible with the theory, the intermediate $\sqrt{s}$ E706 results disagree (slide 1, hep-ph/9811382). In regions where perturbative calculations are stable vs scale variations, the disagreement is in the relative normalization. Either the $\sqrt{s}$ dependence of the theory is inadequate, but then the correction to the theory would have a complex pattern, rather small for ISR (high $\sqrt{s}$), large for E706 (central $\sqrt{s}$) and back to small for the UA6/WA70 data (low $\sqrt{s}$), or the experimental results are not compatible. In this context, it is worth noting that, for all experiments, the π^0 cross sections have a $\sqrt{s}$ dependence in rough agreement with NLO predictions (slide 2, hep-ph/9910252) and that UA6 data lead to a precise measurement of α_s (slide 3, PLB 452,206) in good agreement with the average world value.

2 Soft gluons resummation

E706 restores the compatibility with the theory by invoking an additional k_T smearing effect. Apparently this was motivated by the k_T measured in di-photons experiments. This effect is well reproduced by the theory through the soft gluons resummation (see the photon pair p_T dependence slide 4) as in Drell-Yan processes. But the analogy between single photon and di-photons processes has no real theoretical foundations for this issue (Catani, Les Houches 99 workshop). Soft gluons resummation effects in direct photon are important at large x_T when large scales are used (slide 5, hep-ph/9903436 hep-ph/9910252). However they don't explain the E706 data on Be, especially at low p_T where non perturbative effects may play a role and where experimental background is high. Although the fragmentation contribution is small in direct photon measurements (contrary to π^0!), the resummation of the fragmentation terms is needed to have a complete theoretical framework.

3 Experimental systematics

The evaluation of systematic uncertainties is tricky and a detailed study of their estimation in the E706 high statistics data has not been published yet. So from what one knows, comparing WA70, UA6 and E706 (low statistics but for energy scale), one can note that:

- the absolute energy scale precision is good: all experiments have achieved 0.5%-0.6%
- the azimuthal distribution for WA70 has systematic uncertainties between 8% and 16% for low p_T (trigger). Uniformity of calorimeter and good calibration are crucial!
- the background to direct photon candidates (mainly from π^0) is large, about 2/3 at low p_T for E706. This is the main part of systematics for WA70 and UA6.
- Symmetry around $y = 0$ is verified but only within the overall systematic uncertainties.
- the ambiguities from projective calorimeter read-out (x-y for WA70 and UA6, r-ϕ for E706) are raised through a rough third coordinate only in WA70 and UA6.

4 Outlook

A precise direct photon measurement at RHIC will contribute to clarify the current data vs theory understanding, in particular, by measuring the $\sqrt{s}$ dependence. A more reliable gluon distribution function will therefore be produced which is necessary for the polarisation physics at RHIC and for LHC whose initial state, although at a lower x and higher Q^2 region, is dominated by gluon-gluon interactions. Better insight will be brought by a cross check between the low-x gluon from direct photon and from low mass high p_T Drell-Yan pairs.

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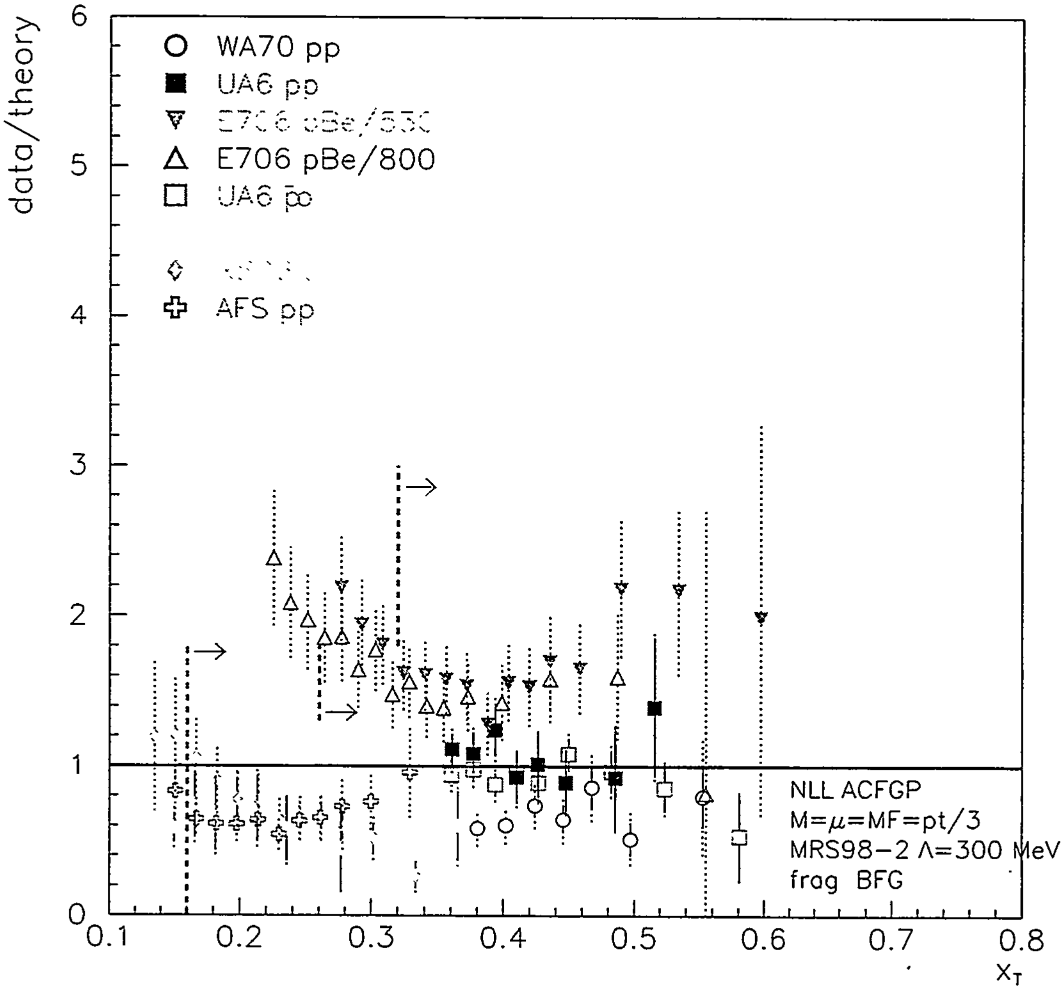
[1] Full set of transparencies available at http://www-iphe.unil.ch/~mwerlen/

Data/Theory MRS 98-2 scales $p_T/3$



Arrows: perturbative predictions "STABLES" vs scale

WA70, ISR: overestimated

UA6 : good agreement

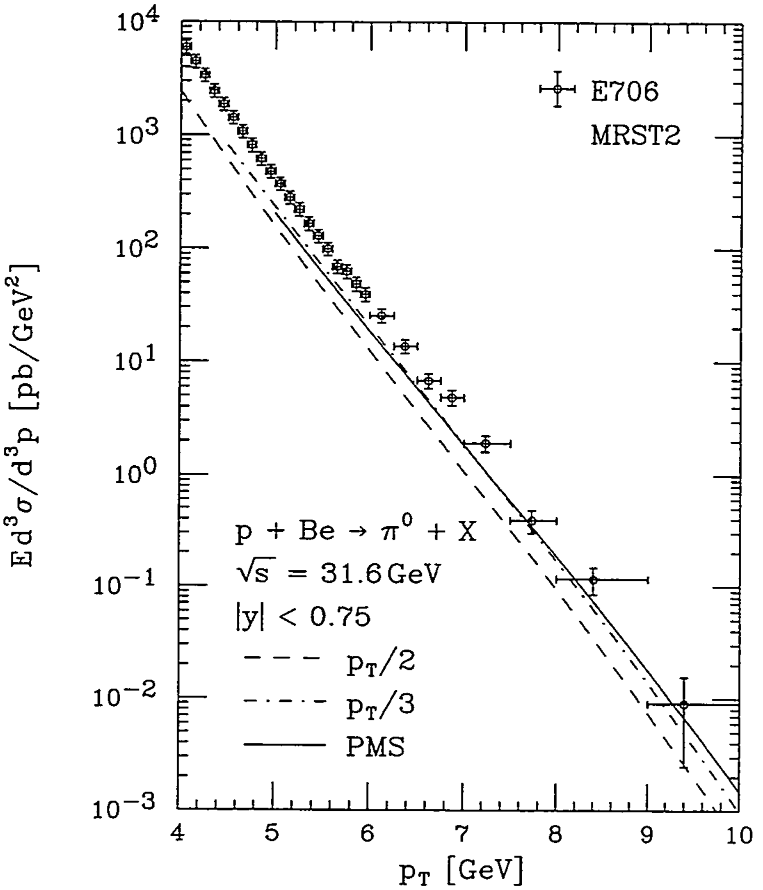
E706: underestimated by 50 to 100%

Possible experimental problems?

Or theory misses the $\sqrt{s}$ dependence?

π^0 phenomenology (hep-ph/9910252)

(Aurenche, Fontannaz, Guillet, Kniehl, M.W.)



$z = E_{\pi^0}/E_{fragmenting\ parton} \approx 0.8$

BKK fragmentation (no constraining data for $z > 0.8$)

ln(1.-z) resummation not available

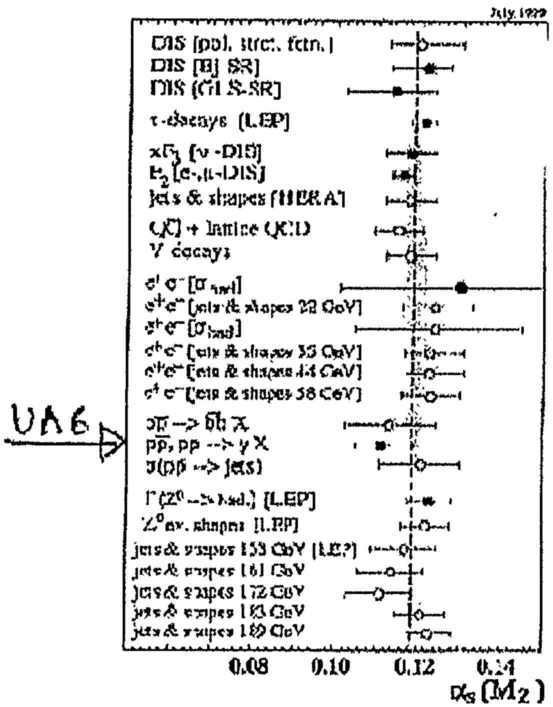
partly approximated with PMS scales

NLL $p_T/2 < \mu = M = M_F < p_T/3$ close to NLL PMS

with scales $p_T/3$: Data/theory ($x_T > 0.3$) $\approx$ 1.4 (UA6), $\approx$ 1.7 (WA70), $\approx$ 1.7 (E706/530),$\approx$ 1.2 (E706/800)

Data sets compatible.

Summer 1999 world average α_s



- From S. Bethke (private communication) average of all 25

$$\alpha_s(M_Z) = 0.119 \pm 0.004$$

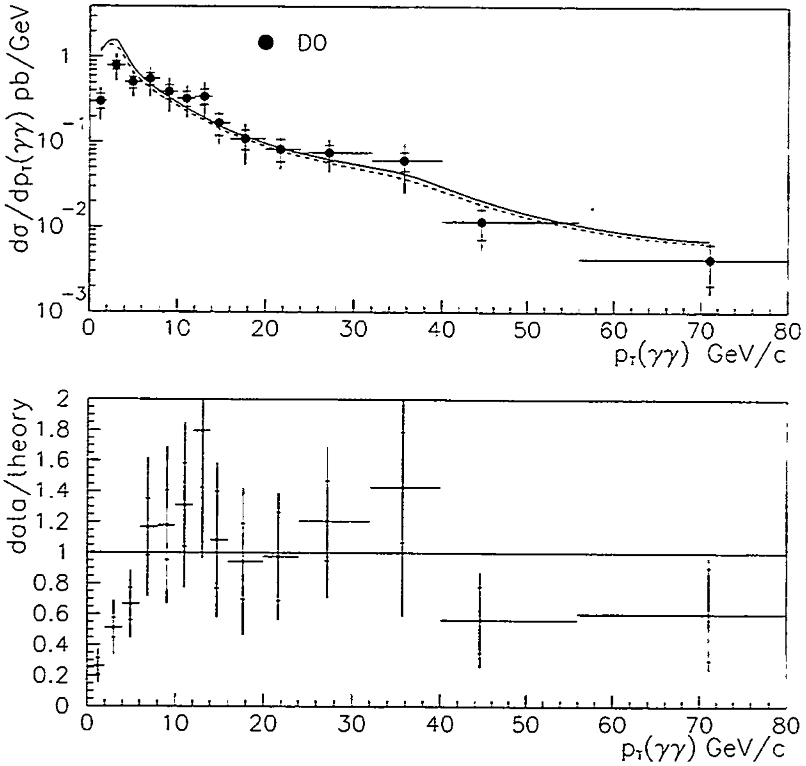
- average based only on complete NNLO QCD results (filled circles in plot)

$$\alpha_s(M_Z) = 0.119 \pm 0.003$$

- excellent consistency between low and high energy, DIS, $\bar{p}p$ and e^+e^-, etc.
- Minimal change from previous world average (hep-ex/9812026)
  - $\alpha_s(M_Z) = 0.119 \pm 0.004$ or
  - $\alpha_s(M_Z) = 0.120 \pm 0.005$ excluding lattice

Two photons at Tevatron:$p_T(\gamma\gamma)$

- D0 preliminary (Wei Chen thesis) $p\bar{p} \to \gamma\gamma$
- $p_T(\gamma_1) > 14$ GeV $\quad p_T(\gamma_2) > 13$ GeV
- isolation cut: $E_T < 2$ GeV in $R = 0.4$ cone
- compared to NLO predictions
  (partonic generator DIPHOX, Binoth, Guillet, Pilon, M.W.)



→ resummation needed when p_T of the pair tends to zero

M.W., RSC workshop, Oct. 1999, sl.4

Soft gluons resummation in direct photon

Resummation when x_T tends to 1 (large double logs)

Catani, Mangano,Nason JHEP9807,024

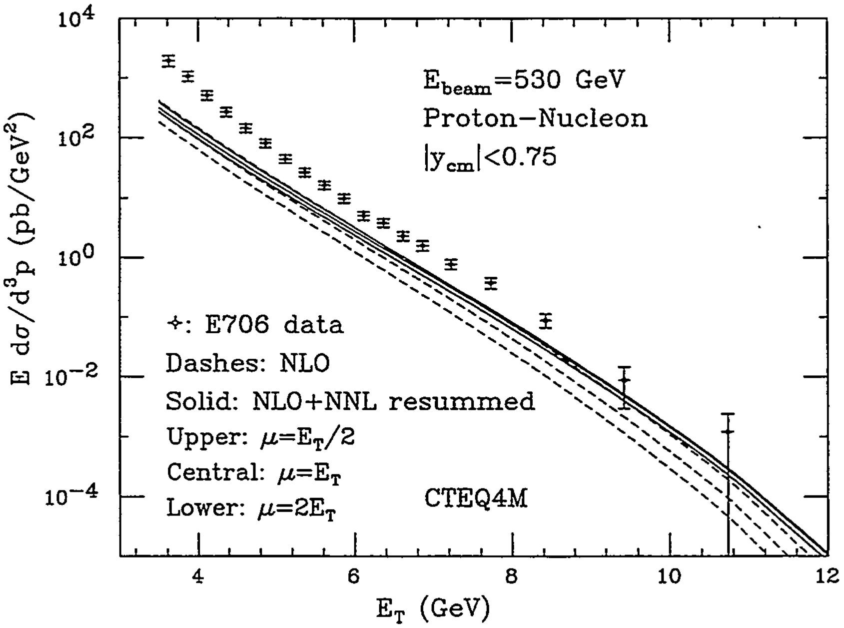
Laenen, Oderda, Sterman PLB438,173

phenomenology

Catani et al., JHEP9903,025 (hep-ph/9903436)

J.Owens, FNAL workshop; Kidonakis, hep-ph/9905480

Catani, Mangano, Nason, Oleari, Vogelsang



Main corrections at large x_T (decreasing with scale)

does not help data/theory at small x_T for E706

i.e. does not solve the "k_T problem"

Resummation of fragmentation terms not available

k_T Issues

M.J.Tannenbaum
BNL/PHENIX
October 8, 1999

- k_T is related to the net transverse momentum of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high p_T photons, or the $\gamma+$ Jet pair for direct photon production.
- In leading order QCD or the Quark-Parton model, all the above pairs are coplanar with the incident beam axis: $k_T = 0$.
- However, early Drell-Yan and inclusive high p_T particle studies showed that k_T was measurable and non-zero. Systematic measurements were made at the ISR and Fermilab.
- Some experimentalists and theorists may view the issue of k_T differently—Experimentalists: multi-soft gluon, Gaussian;
Theorists: Hard-NLO gluons, power-law.
- The definitive work on k_T, actually on the p_T distribution of Drell-Yan pairs was made by G. Altarelli, R. K. Ellis and G. Martinelli in Phys. Lett. **151B**, 457 (1985), based on the ISR measurements. $\Rightarrow$ should be incorporated into event generators.
- The effect of k_T on the Gluon Spin structure function is mainly that it leads to an uncertainty in the value of Bjorken x of the inclusive direct photon measurements. Altarelli's work can be used to predict k_T at $\sqrt{s} = 200$ GeV and shows that $x_T = 2p_T/\sqrt{s}$ estimates x to within 3-4% in the range of interest.

Yuji Goto's Pythia Results

On the following page I show Yuji Goto's results from Pythia relevant to knowing the structure function x value for a direct photon of transverse momentum p_T detected in PHENIX at $\sqrt{s} = 200$ GeV. The naive answer is

$$x_1 = x_2 = x_T = p_T/(\sqrt{s}/2) \tag{1}$$

The reason for the Jacobian peak at $\theta^* = 90°$ in the constiuent c.m. system for detection at $\theta = 90°$ in the $p - p$ c.m. system is that in the constituent c.m. system the momentum of the photon is $p^* = \sqrt{\hat{s}}/2$ and the transverse momentum of the photon (in both systems) is $p_T = p^* \sin\theta^*$, so that for a direct photon at p_T in PHENIX, the constituent c.m. energy $\hat{s}$ is

$$\sqrt{\hat{s}} = 2\,p_T/\sin\theta^* \quad . \tag{2}$$

Since the cross section drops steeply as a function of $\hat{s}$ (think about the mass dependence in Drell-Yan), while the angular distribution varies only by a factor of 2-3 as $\cos\theta^*$ varies from 0.0 to 0.5 [see QCD subprocess angular distributions slide] and is actually much flatter for QCD-compton (varies a factor of 2 from 0.0 to 0.75, see below), the Jacobean peak strongly prefers the minimum $\hat{s}$ for a given p_T.

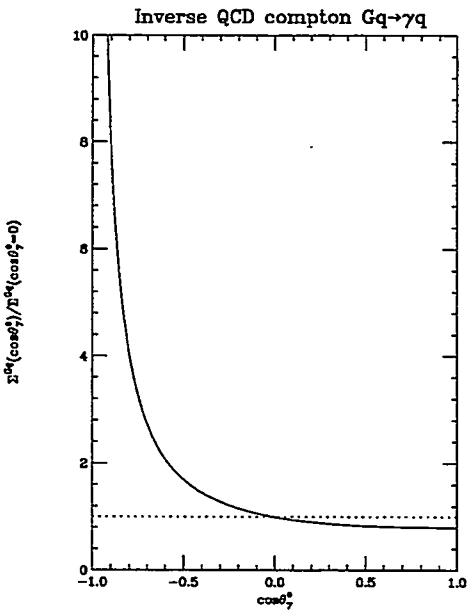
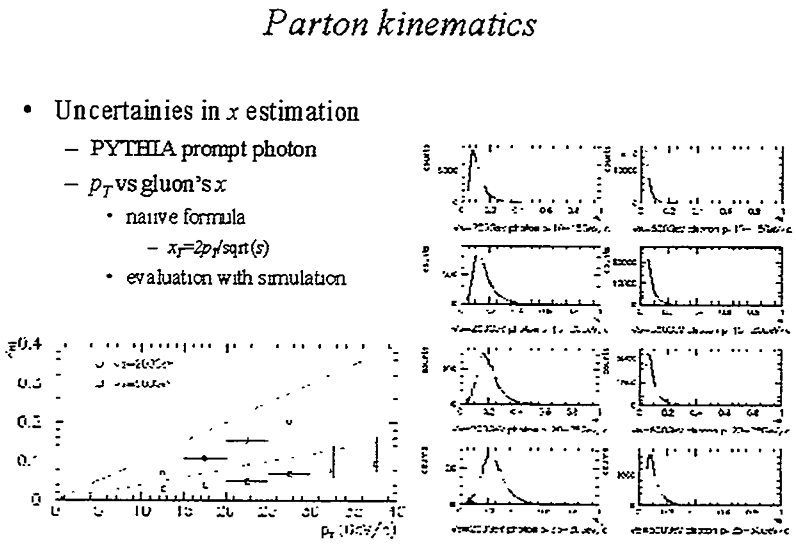


Figure 1: QCD compton subprocess angular distribution. This must be symmetrized unless you can tell a quark from a gluon

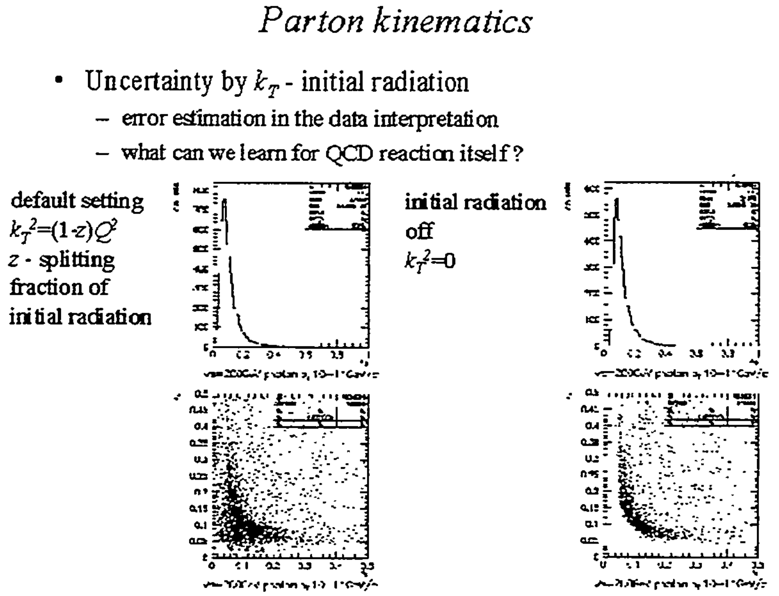
Yuji's Pythia Plots

♡ Yuji's results show 1) $x \ll x_T$, 2) there is no Jacobean peak: the condition $x_1 x_2 = \hat{s}/s = x_T^2$ is not satisfied in PYTHIA, unless $k_T = 0$, 3) about 1/2 the p_T of the photon seems to be due to motion towards the observer !!!



Parton kinematics

- Uncertainies in x estimation
  - PYTHIA prompt photon
  - p_T vs gluon's x
    - naive formula
      - $x_T=2p_T/\text{sqrt}(s)$
    - evaluation with simulation



Parton kinematics

- Uncertainty by k_T - initial radiation
  - error estimation in the data interpretation
  - what can we learn for QCD reaction itself ?

default setting
$k_T^2=(1\text{-}z)Q^2$
z - splitting
fraction of
initial radiation

initial radiation
off
$k_T^2=0$

Figure 2: see `http://www.phenix.bnl.gov/WWW/publish/goto/HardWS/` for better quality

k_T is not a parameter, it can be measured

• In leading order QCD or the Quark-Parton model, the net transverse momentum $\langle p_T \rangle_{\text{pair}} = \sqrt{2} \times \langle k_T \rangle$, of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high p_T photons, or the $\gamma+$ Jet pair for direct photon production is zero. All the above pairs should be coplanar with the incident beam axis.

• However, early Drell-Yan and inclusive high p_T particle studies showed that k_T was measurable and non-zero.

♡ The history of k_T is worth reviewing as k_T was predicted to be zero by theorists, but was discovered to be non-zero by experimentalists. The CCHK experiment [M. Della Negra, et al., Nucl. Phys. **B127**, 1 (1977)] discovered that back-to-back jets had considerable out of plane transverse momentum p_{out}, and proposed that this was due to transverse momentum of partons inside a proton.

♡ This was elaborated by Feynman, Field and Fox, [Nucl. Phys. **B128**, 1, (1997), Phys Rev. **D18**, 3320 (1978)] who introduced the k_T phenomenology of a parton in a proton, which they discussed in terms of 'intrinsic transverse momentum' from confinement which would be constant as a function of x and Q^2, and NLO effects due to hard gluon emission which would vary with x and Q^2, but they used an constant 'effective' k_T to 'explain' the available measurements.

♡ A subsequent ISR experiment, CCOR, showed that k_T for jet-pairs was roughly the same as for Drell-Yan and increased similarly with $\sqrt{s}$ (and p_T) i.e. was not constant. See Fig. 1 in [Ap1].

• The definitive theoretical work on a calculation of k_T in QCD, actually on the p_T distribution of Drell-Yan pairs, was made by G. Altarelli, R. K. Ellis and G. Martinelli in [Phys. Lett. **151B**, 457 (1985)], inspired by the ISR measurements.

Correct k_T for $\sqrt{s} = 200$ GeV

♡ Altarelli, et al., predicted (in 1985) the value of $\langle p_T \rangle_{\rm pair}$ (which they called $\langle q_T \rangle$) for Drell-Yan pairs, which we have seen is the same as for di-hadrons. Interestingly, their predictions go to 200 GeV where the predicted $\langle q_T \rangle = \sigma_{\rm 2partons,2d} = 3.5 \pm 0.2$ GeV/c.

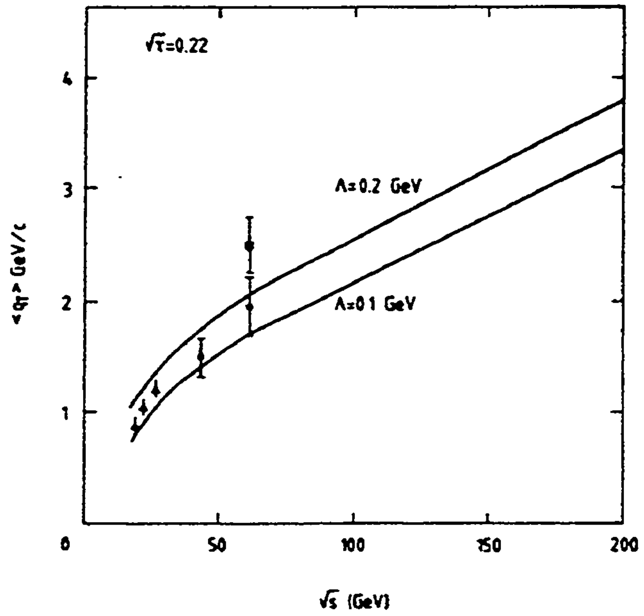


Figure 6: $\langle q_T \rangle$ vs $\sqrt{s}$ at fixed $\sqrt{\tau} = x_1 x_2 = 0.22$. Data shown are ISR and FNAL Drell-Yan. The curves are the theoretical predictions obtained using $\Lambda = 0.1 - 0.2$ GeV. No intrinsic q_T is included. At large values of $\sqrt{s}$, $\langle q_T \rangle$ increases linearly with $\sqrt{s}$. At smaller values, deviations from the linear law are visible, which are due to soft gluon and scaling violation pre-asymptotic effects

♡ Recall from above that

$$\langle k_T \rangle = \langle p_T \rangle_{\rm pair}/\sqrt{2} = 2.5 \text{ GeV/c} \qquad (28)$$

$$\sqrt{\langle k_T^2 \rangle} = \langle k_T \rangle \times 2/\sqrt{\pi} = 2.82 \text{ GeV/c} \qquad (29)$$

Finally, from Eq. 20 the Gaussian smearing is:

$$\sigma_{\gamma,\rm 1d} = k_T/2 = \sigma_{\rm 1parton,2d}/2 = 1.41 \text{ GeV/c}. \qquad (30)$$

Conclusions

♡ There are two important things to note:

◇ $\sigma_{\gamma,1d} = 1.41$ GeV/c is **much less** than exhibited by PYTHIA.

◇ The direct γ cross section from our proposal has an exponential value $b \simeq 0.40$ between 10 and 20 GeV/c, giving a shift in the p_T spectrum by

$$b\,\sigma^2_{\gamma,1d}/2 = 0.4 \text{ GeV/c} \tag{31}$$

- This means that at $\sqrt{s} = 200$ GeV/c, x_T is an excellent estimator of Bjorken x to $\approx 3-4\%$ and therefore **PHTHIA's treatment of k_T is WRONG**
- **Of course, to get the Physics Correct, we should all try to measure k_T at RHIC.**

THIS IS MY ANALYSIS
IT SHOULD SERVE AS A CHALLENGE FOR SOMEONE ELSE
TO DO BETTER!

Angular Momentum in QCD

Brookhaven October 1999

R.L. Jaffe

- ⋆ $\Delta\Sigma \approx 0.2 - 0.3$
- ⋆ In some sense $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$
- ⋆ After considerable struggle, we know
  - What ΔG is
  - How to measure it
- ⋆ L_Q and L_G have been poorly understood.
  - Definition?
  - Gauge invariance? Uniqueness?
  - Distribution in $x_{\rm BJ}$?
  - Measure?
- ⋆ My object – review $\Delta\Sigma$ and ΔG, then confront L_G and L_Q.

Outline

$\boxed{1}$ Ideal parton distributions

$\boxed{2}$ Quark and gluon spin

$\boxed{3}$ Looking for orbital angular momentum I

- What can be learned from structure of QCD angular momentum tensor?

$\boxed{4}$ Looking for orbital angular momentum II

- Parton distributions of orbital angular momentum

$\boxed{5}$ Conclusions and Outlook

Thanks to

Sergei Bashinsky, Xiangdong Ji, Aneesh Manohar

- Background

  RLJ, Spin, Twist and Hadron Structure in Deep Inelastic Processes Lectures in *Erice 1995, The spin structure of the nucleon.*

  RLJ & A. Manohar, Nucl. Phys. B337 (1990) 509.

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  I. Balitsky & V. Braun, Phys. Lett. B267 (1991) 405.

- Orbital Angular Momentum

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  P. Hoodbhoy, X. Ji, and W. Lu hep-ph/9804337.

  X. Ji, Phys. Rev. Lett. 78 (1997) 610.

  S. Bashinsky & RLJ hep-ph/9804397

  P. Hagler & A. Schafer hep-ph/9802362.

  A. Harindranath & R. Kundu hep-ph/9802406.

  S. Scopetta & V. Vento hep-ph/9901324.

  O. Martin Phys. Lett. B448 (1999) 99.

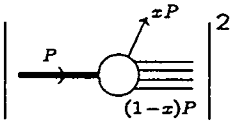
$\boxed{1}$ Ideal Parton Distributions

⋆ A parton distribution

$$f(x_{\rm Bj}) = \sum_X \delta\left(P_X^+ - (1-x_{\rm Bj})P^+\right)\left|\langle X|\psi_+(0)|P\rangle\right|^2$$

$P_X^+ - (1-x_{\rm Bj})P^+$
light-cone momentum distribution

$\psi_+(0)$
"good" component of quark field

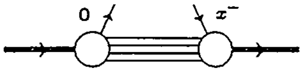


- Probability
- Selects out special direction, $\sqrt{2}P^+ = P^0 - P^3$ determined by experiment
- Distribution in $x_{\rm Bj}$
- Q^2 dependence suppressed (throughout much of this talk)

⋆ In coordinate space

$$f(x_{\rm Bj}) = \frac{1}{2\pi}\int dx^- e^{iP^+x^-x_{\rm Bj}}\langle P|\psi_+^\dagger(0)\psi_+(x^-)|P\rangle\Big|_{\underline{x}=0}$$

where $\underline{x} = (x^+, \vec{x}_\perp)$



- ⋆ Gluon Spin – once controversial, now benign(!)
  - A nearly ideal distribution
    - ⋆ Moments ($n > 0$) of $\Delta G \Leftrightarrow$ local, gauge invariant operators.
    - ⋆ Inverse Mellin transform gives bi-local light-cone Fourier transform (Manohar)

$$\begin{aligned}\Delta G(x_{\mathrm{Bj}}) &= i\int \frac{d\xi^-}{4\pi x_{\mathrm{Bj}}P^+}\exp i x_{\mathrm{Bj}}P^+\xi^- \times \\ &\times \ \langle PS|\,\underline{F^{+\lambda}(0)}\mathcal{I}(0,x^-)\underline{\tilde{F}^{+}_{\lambda}(\xi^-)}\ |PS\rangle\end{aligned}$$

- ⋆ where $\mathcal{I}(0,\xi^-) = \mathrm{P}\{\exp i\int_0^{x^-} dy^\mu A_\mu(y)\}$
- ⋆ and $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\tau}F^{\lambda\tau}$
- ⋆ ($\mathrm{n^{th}}$) moment of ΔG ($\int dx\, x^{n-1}\Delta G$) must be operator of spin-n. Requires factor $1/x_{\mathrm{Bj}}P^+$.

---

2 Quark and Gluon Spin

- ⋆ Quark Spin – once controversial, now benign
  - An ideal distribution

$$\Delta q_a(x_{\mathrm{Bj}}) = \int \frac{d\xi^-}{2\pi\sqrt{2}} e^{i x_{\mathrm{Bj}}P^+\xi^-}\langle PS|q^\dagger_{+a}(0)\gamma^5 q_{+a}(\xi^-)\ |PS\rangle$$

in $A^+ = 0$ gauge.

- Sum rule

$$\begin{aligned}\int_{-1}^{1} dx\Delta q_a(x,Q^2) &= \Delta q_a(Q^2) \\ &\propto \langle P,S|\bar{q}\gamma_\mu\gamma^5 q|P,S\rangle \\ \sum_a \Delta q_a(Q^2) &= \Delta\Sigma(Q^2)\end{aligned}$$

- Probability distributions

$$\Delta q_a(x) = q_a^{\uparrow}(x) - q_a^{\downarrow}(x)$$

- Complications of higher order pQCD. $\Delta q_a(x,Q^2)$ develops scheme dependence beyond lowest order. "Adler-Bardeen" = "anomalous" scheme versus (say) $\overline{\mathrm{MS}}$. A matter of history. Beyond the considerations important at this time for orbital angular momentum.

- ⋆ Summary of an ideal partonic distribution

1 Weighted light-cone momentum probability distribution (weighted by spin, flavor, transversity, etc), with direct physical interpretation in ∞-momentum frame field theory;

2 Manifestly gauge invariant bi- (or multi-) local light-cone Fourier transform;

3 Moments $\Rightarrow$ local, gauge invariant operators of definite twist, recognizable as generators of expected symmetries.

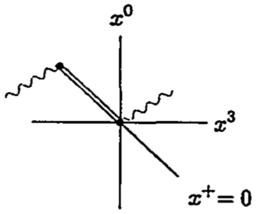
- ⋆ Parton distributions exist for all the components of the angular momentum in QCD, but
- ⋆ But some of them are less than ideal!

$$f(x_{\mathrm{Bj}}) = \frac{1}{2\pi}\int dx^- e^{iP^+x^-x_{\mathrm{Bj}}}\langle P|\psi_+^\dagger(0)\psi_+(x^-)|P\rangle\Big|_{\tilde{x}=0}$$

- Gauge invariance? Written in $A^+ = 0$ gauge, restore manifest g.i.

$$\psi_+^\dagger(0)\psi_+(x^-) \Longrightarrow \psi_+^\dagger(0)\left\{\mathrm{P}\exp i\int_0^{x^-} dy^\mu A_\mu(y)\right\}\psi_+(x^-)$$

where $\{\cdots\}$ is a Wilson link.



- Lorentz invariance?
  $\psi_+^\dagger(0)\cdots\psi_+(x^-) \equiv \bar{\psi}(0)\gamma^+\cdots\psi(x^-)$

  γ^+x^- and all else is boost invariant along x^3 direction.
- Local operators?

$$\int_{-1}^{1} dx\, x^{n-1} f(x) = A_n$$

where A_n are local operators in (gauge covariant) Taylor expansion of $\psi_+^\dagger(0)\cdots\psi_+(x^-)$

- Define first moment
  - ⋆ Analytic continuation in n equivalent to direct integration of $\Delta G(x_{\rm Bj})$

$$\Delta G = \frac{1}{2P^+}\int d\xi^- \epsilon(\xi^-) \langle PS|F^{+\lambda}(0)\mathcal{I}(0,x^-)\tilde{F}^+_\lambda(\xi^-)\,|PS\rangle$$

where $\epsilon(x) = \begin{cases} 1 \text{ for } x > 0 \\ -1 \text{ for } x < 0 \end{cases}$

- So in general gauges, the operator corresponding to gluon spin is non-local!
- However, in $A^+ = 0$ gauges it reduces to local operator

$$\Delta G \xrightarrow{A^+=0} \frac{1}{P^+}\langle PS|A^1F^{+2} - A^2F^{+1}|PS\rangle$$

- Identical to generator M_G^{+12} obtained from symmetry analysis
- Also identical to anomalous (Kogut-Susskind) current in $A^+ = 0$ gauge.
- Note, not $\vec{A} \times \vec{E}$ (naive, gauge variant gluon spin)– see Chen & Fang hep-ph/9802346 and Ji & Hoodbhoy hep-ph/9908275

3 Looking for orbital angular momentum – I

I. First approach was to examine the symmetry generators ($M^{\mu\nu\lambda}$) to find gauge invariant operators with physical correspondence to OAM.

Partial success. RLJ, Manohar, Ji

- ⋆ G. I. operators for quark spin and quark OAM.
- ⋆ Only "total", no insight into $x_{\rm Bj}$ distributions.
- ⋆ No G. I. operators for gluon spin or gluon OAM.
- ⋆ Learned of importance of off forward parton distributions, DVCS, etc.

II. More recent and also successful approach is to formulate the appropriate symmetry transformations on the null plane (x^-=0).

Bashinsky, RLJ
Hägler, Schäfer, & collaborators
A. Harindranath & R. Kundu

- ⋆ G. I. parton distributions for quark and gluon spin and OAM!
- ⋆ Integrated quark and gluon spin distributions coincide with $M^{\mu\nu\lambda}$ analysis.
- ⋆ Parton OAM operators are different from those inferred from $M^{\mu\nu\lambda}$ analysis, and simpler.
- ⋆ Phenomenological studies have begun.
- ⋆ Experimental measurement is problematic.

I. What can be learned from QCD angular momentum tensor?

Look for operators whose expectation values yield components of angular momentum.

Relate to integrals over parton distributions?

No guarantee (1) that interactions drop out or (2) that individual pieces are gauge invariant.

Analog of Momentum Sum Rule for $T^{\mu\nu}$

Standard symmetry analysis RLJ & Manohar

Noether analysis ⇒ $\mathcal{M}^{\mu\nu\lambda}$

Another approach ⇒ $\tilde{\mathcal{M}}^{\mu\nu\lambda} = x^\nu T^{\mu\lambda} - x^\lambda T^{\mu\lambda}$ which is manifestly concerved (since T is symmetric) and generates Lorentz Transformations

However neither has an interpretable form.

Find appropriate Belinfante "superpotential" ⇒ $M^{\mu\nu\lambda}$

$$J^{\nu\lambda} = \int d^3x\, M^{0\nu\lambda} \quad \text{generates Lorentz trans.}$$

In QCD find four terms that contribute to rotation generators, Magnetic moment is forward matrix element of operator with explicit factor of $\vec{x}$

$$\vec{\mu} = F_2(0)\vec{S} = \frac{\int d^3x \langle P,S|\,\frac{1}{2}\vec{x}\times\vec{j}(\vec{x})|P,S\rangle}{\langle P|P\rangle}$$

But clearly, to extract $F_2(0)$ an experiment must be done with $q^\mu \neq 0$

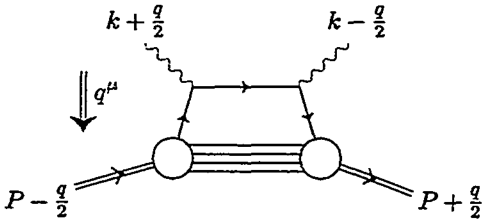
$$F_2(0) \propto \frac{\partial}{\partial q^\nu}\langle P+q/2,S|\; j_\mu(0)\,|P-q/2,S\rangle\Big|_{q=0}$$

⋆ Note: This momentum transfer q is not the momentum of the virtual photon in DIS. It is the momentum transfer to the nucleon line in

$k^2 \to -\infty$

$k\cdot P \to \infty$

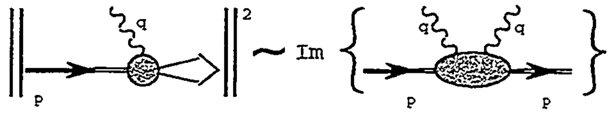
$q^\mu \to 0$



- Why is orbital angular momentum so much harder to measure than spin?

  The explicit appearance of $\vec{x}$ forces one off the forward direction.

  ⋆ Standard deep inelastic scattering is strictly forward



  ⋆ But $\vec{x}$ requires derivative with respect to momentum transfer.

  Example: compare charge and magnetic moment

$$\langle P+q/2,S|\; j_\mu(0)\;|P-q/2,S\rangle = 2P_\mu F_1(0) \;+\; 2i\epsilon_{\mu\alpha\beta\gamma}P^\alpha q^\beta S^\gamma F_2(0) + \mathcal{O}(q^2)$$

  Charge is a forward matrix element

$$Q = F_1(0) = \frac{\int d^3x \langle P|\,j^0(\vec{x})\,|P\rangle}{\langle P|P\rangle}$$

- Internal quark and gluon terms

  Quark term is gauge invariant and coincides with integral of parton distribution.

  Gluon term is not gauge invariant, but $\{+12\}$ component coincides with integral of parton distribution in $A^+ = 0$ gauge.

- Improvement in gauge invariance Ji

$$\begin{aligned} M^{\mu\nu\lambda} &= \frac{i}{2}\bar\psi\gamma^\mu(x^\lambda D^\nu - x^\nu D^\lambda)\psi && \text{quark OAM}\\ &+ \tfrac{1}{2}\epsilon^{\mu\nu\lambda\sigma}\bar\psi\gamma_\sigma\gamma_5\psi && \text{quark spin}\\ &+ 2\,\mathrm{Tr}\left\{F^{\mu\alpha}(x^\lambda D^\nu - x^\nu D^\lambda)A_\alpha\right\} && \text{gluon OAM}\\ &+ \mathrm{Tr}\left\{F^{\mu\lambda}A^\nu - F^{\mu\nu}A^\lambda\right\} && \text{gluon spin}\\ &+ \text{terms that do not contribute to } J^{\nu\lambda} \end{aligned}$$

  - Quark OAM term is now g.i.
  - Ji explains how to measure quark OAM through DVCS
  - Initiates study of off-forward parton distributions
  - Gluon operators remain non-g.i.
  - Unsatisfactory

$$\begin{aligned} M^{\mu\nu\lambda} &= \frac{i}{2}\bar\psi\gamma^\mu(x^\lambda\partial^\nu - x^\nu\partial^\lambda)\psi\\ &+ \tfrac{1}{2}\epsilon^{\mu\nu\lambda\sigma}\bar\psi\gamma_\sigma\gamma_5\psi\\ &+ 2\,\mathrm{Tr}\left\{F^{\mu\alpha}(x^\lambda\partial^\nu - x^\nu\partial^\lambda)A_\alpha\right\}\\ &+ \mathrm{Tr}\left\{F^{\mu\lambda}A^\nu - F^{\mu\nu}A^\lambda\right\}\\ &+ \text{terms that do not contribute to } J^{\nu\lambda} \end{aligned}$$

- Convective quark and gluon terms

  Generic form (a la fluid dynamics)

$$\sum_k \Pi_k(\vec{x}\times\vec{\nabla})\Phi_k$$

  not gauge invariant

  explicit factor of $\vec{x}$

$\boxed{4}$ Looking for orbital angular momentum – II

II. Parton distributions of orbital angular momentum

S. Bashinsky & RLJ
A. Harindranath & R. Kundu
P. Hägler & A. Schäfer
O. Martin

Based primarily on the work by S. Bashinsky, hep-ph 9804397

- ⋆ Anticipate significance of space direction $x^3 \to x^-$ which defines parton model.

  Operators $(\Delta\Sigma, \Delta G, L_Q, L_G)$ identified with generators of rotations about $\hat{P}^3$.
- ⋆ Define the gauge invariant fields corresponding to quark or gluon partons with "momentum" $q^+ = x_{\mathrm{Bj}} P^+$.
- ⋆ Study parton field transformations under rotations about $\hat{P}^3$.
- ⋆ Parton distributions are corresponding Noether charges.

- Take stock

  ⇑ $\Delta\Sigma$ – measure through sum rules in polarized DIS.

  ⇑⇑ L_Q – measure (in principle) $\frac{1}{2}\Delta\Sigma + L_Q$ in DVCS where L_Q is Ji's covariant operator.

  ⇑⇑ $L_G + \Delta G$ – measure (in principle) in DVCS.

  ⇑⇑ Possible equipartition theorem, limiting size of J_q and J_g.

  ⇓⇓ No place for ΔG – no gauge invariant operator.

  ⇓⇓ No physical interpretation for covariant L_G.

  ⇓⇓ No generalization of L_Q or L_G to $L_Q(x_{\mathrm{Bj}})$. Is the Bjorken-x distribution of orbital angular momentum meaningful?

  ⇓ No general understanding of what quantities may or may not appear as parton distributions.

  ⇓ No simple connection to partons in $A^+ = 0$ gauge. [As exists for analogous analysis of $T^{\mu\nu}$].

- Equipartition

  Analogous to quark and gluon momentum partition as $\ln Q^2 \to \infty$

$$J_q \equiv L_Q + \frac{1}{2}\Delta\Sigma \longrightarrow \frac{1}{2}\frac{3n_f}{16+3n_f} \approx \frac{1}{2}$$

$$J_g \equiv L_G + \Delta G \longrightarrow \frac{1}{2}\frac{16}{16+3n_f} \approx \frac{1}{2}$$

- Strong constraints if valid at accessible Q^2

  If equipartition applies and $\Delta\Sigma \approx 0.2 - 0.3$, then only missing link is ΔG. But does it apply? No way to know without additional measurement, eg. of L_Q.

- Observation on scheme dependence.

  In $\overline{MS}$ scheme

$$\frac{1}{2} = L_Q + \frac{1}{2}\Delta\Sigma + L_G + \Delta G$$

  In anomalous scheme

$$\frac{1}{2} = (L_Q + \frac{\alpha}{4\pi} n_f \Delta G) + \frac{1}{2}(\Delta\Sigma - \frac{\alpha}{2\pi} n_f \Delta G) + L_G + \Delta G$$

  Merely a shuffle between terms.

- Insight from this approach

  ⋆ Evolution of Ji's decomposition

  Ji, Tang, Hoodbhoy
  Ratcliffe

  - Leading order evolution

$$\frac{d}{dt}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} = \frac{\alpha}{2\pi}\begin{pmatrix}0 & 0 \\ \frac{3}{2}C_f & \frac{1}{2}\beta_0\end{pmatrix}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix}$$

$$\frac{d}{dt}\begin{pmatrix}L_Q \\ L_G\end{pmatrix} = \frac{\alpha}{2\pi}\begin{pmatrix}-\frac{4}{3}C_f & \frac{1}{3}n_f \\ \frac{4}{3}C_f & -\frac{1}{3}n_f\end{pmatrix}\begin{pmatrix}L_Q \\ L_G\end{pmatrix} + \frac{\alpha}{2\pi}\begin{pmatrix}-\frac{2}{3}C_f & \frac{1}{3}n_f \\ -\frac{5}{6}C_f & -\frac{11}{2}\end{pmatrix}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix}$$

  - Conservation of total

$$\frac{d}{dt}J = \frac{d}{dt}\left\{\Delta\Sigma + \Delta G + L_Q + L_G\right\} = 0$$

- ⋆ Keeps close contact with $A^+ = 0$ gauge but maintains explicit gauge invariance.
- ⋆ Associate "parton observables" directly with appropriate space time transformations.
- ⋆ Obtain partonic definitions of all four terms in the angular momentum sum rule as functions of x_{Bj}.
- ⋆ Anomalous dimensions and Q^2 evolution can be studied relatively easily.
- ⋆ Alas, so far, no one has discovered a way to observe the x_{Bj} distributions of $L_Q(x_{Bj})$ and $L_G(x_{Bj})$ defined in this way.

Re-examine: What is a parton?

> A field quantum which has a definite x_{Bj} in $A^+ = 0$ gauge.

- Eigenstate of translation in x^- direction has definite k^+,

$$\psi(k^+, \underline{x}) \qquad \underline{x} = (x^+, \vec{x}_\perp)$$

$$T_-(a)\psi(k^+, \underline{x}) = e^{-ik^+a}\psi(k^+, \underline{x})$$

where $T_-(a)$ is translation by a along the x^- direction.

- Generalize out of $A^+ = 0$ gauge. Parton is eigenstate of <u>gauge covariant translation.</u>

$$T_-(a)\psi(x) = U(x, x + a^-)\psi(x + a^-)$$

where $T_-(a)$ is "gauge covariant translation operator"

$$U(x, x + a^-) = \mathcal{P}\left(\exp ig \int_{x+a^-}^{x} d\xi_\mu \; A^\mu(\xi)\right)$$

> Parton observables must commute with T_-, because T_- defines x_{Bj}

- Generalize to gluons
- Look among physically motivated transformations, including rotations, to find observables which commute with T_-.
- Noether charges which commute with T_- (which carry x_{Bj} as a parameter) $\Leftrightarrow$ parton distributions!
- So a candidate observable is a gauge invariant Noether charge that can be diagonalized simultaneously with x_{Bj}.

Gluons, residual gauge invariance, and formalism

- Partonic quanta

$$\begin{array}{llll} T_-^q(a^-) & : \; \psi(x) & \rightarrow & U(x, x + a^-)\, \psi(x + a^-) \,, \\ T_-^g(a^-) & : \; D_\lambda(x) & \rightarrow & U(x, x + a^-)\, D_\lambda(x + a^-)\, U(x + a^-, x) \,, \end{array}$$

Infinitesmal form

$$\delta_-^q \psi = a^- D_- \psi \,,$$
$$\delta_-^g A_\lambda = a^- F_{-\lambda} \quad \Rightarrow \quad \delta_-^g A^+ = 0 \,.$$

Leaves A^+ invariant, so can fix gauge $A^+ = 0$. Notation **bold face** denotes fields in $A^+ = 0$ gauge.

$$\delta_-^q \boldsymbol{\psi} = a^- \partial_- \boldsymbol{\psi} \,,$$
$$\delta_-^g \mathbf{A}_\lambda = a^- \partial_- \mathbf{A}_\lambda \,.$$

Decomposition into partonic quanta,

$$\boldsymbol{\psi}(x) = \int \frac{dk^+}{2\pi}\, e^{-ik^+x^-} \tilde{\boldsymbol{\psi}}(k^+, \underline{x}) \,,$$
$$\mathbf{A}_\lambda(x) = \int \frac{dk^+}{2\pi}\, e^{-ik^+x^-} \tilde{\mathbf{A}}_\lambda(k^+, \underline{x})$$

$\tilde{\boldsymbol{\psi}}(k^+, \underline{x})$ and $\tilde{\mathbf{A}}_\lambda(k^+, \underline{x})$ are the parton fields out of which partonic observables can be built and then transformed into any other gauge—

$$\begin{array}{lll} \psi(x) & = & e^{i\alpha(x)} \boldsymbol{\psi}(x) \\ A_\lambda(x) & = & e^{i\alpha(x)} (\mathbf{A}_\lambda(x) + \frac{i}{g}\, \partial_\lambda) e^{-i\alpha(x)} \,, \end{array}$$

The gauge parameter, $\alpha(x)$ is left invariant by T_-,

$$T_-^q(a^-), T_-^g(a^-) \; : \; \alpha(x) \; \rightarrow \; \alpha(x) \,.$$

therefore the parton decomposition of quark and gluon fields in an arbitrary gauge can be obtained first in $A^+ = 0$ gauge and then transforming with α.

Parton densities from light-cone symmetry analysis.

The following expressions are the forms of manifestly gauge invariant quantities, written in $A^+ = 0$ gauge.

$$\begin{aligned}
\Sigma(x_{\mathrm{Bj}}) &\sim \mathrm{lft}\left[\psi_+^\dagger(x^\perp)\gamma^5\psi_+(x^\perp+\xi^-)\right]\\
L_q(x_{\mathrm{Bj}}) &\sim \mathrm{lft}\left[\psi_+^\dagger(x^\perp)(x^1 i\mathcal{D}_2 - x^2 i\mathcal{D}_1)\psi_+(x^\perp+\xi^-)\right]\\
\Delta G(x_{\mathrm{Bj}}) &\sim \mathrm{lft}\left[F^{+\lambda}(x^\perp)\epsilon^{+-}{}_\lambda{}^\chi A_\chi(x^\perp+\xi^-)\right]\\
L_g(x_{\mathrm{Bj}}) &\sim \mathrm{lft}\left[F^{+\lambda}(x^\perp)(x^1 i\mathcal{D}_2 - x^2 i\mathcal{D}_1)A_\lambda(x^\perp+\xi^-)\right]
\end{aligned}$$

where lft means "light-cone Fourier transform"

$$\begin{aligned}
&\mathrm{lft}\left[\phi_1(x^\perp)\phi_2(x^\perp+\xi^-)\right]\\
\equiv\ &\frac{\int d\xi^- d^2x^\perp \exp i x_{\mathrm{Bj}} P^+\xi^- \langle P|\phi_1(x^\perp)\phi_2(x^\perp+\xi^-)|P\rangle}{2\pi\sqrt{2}\,\left(\int d^2x^\perp\right)}
\end{aligned}$$

and $\mathcal{D}_\mu$ is derivative gauge covariant with respect to residual gauge symmetry once $A^+ = 0$ gauge have been fixed.

- The RGT covariant derivative $\mathcal{D}$ occurs naturally in Bashinsky's formalism.

Application to angular momentum

All pieces (quark & glue, spin & orbit) of the angular momentum about the $\hat{e}_3$-axis separately commute with T_-

$$\begin{aligned}
\Sigma &: \quad \delta_\Sigma\tilde{\psi} \equiv i\epsilon\gamma^0\gamma^3\gamma^5\tilde{\psi}\ ;\\
L_Q &: \quad \delta_{L_Q}\tilde{\psi} \equiv -\epsilon(x^1\mathcal{D}_2 - x^2\mathcal{D}_1)\tilde{\psi}\ ;\\
\Delta\tilde{G} &: \quad \delta_{\Delta G}\tilde{G}_\lambda \equiv \epsilon(\delta^1_\lambda\delta^\chi_2 - \delta^2_\lambda\delta^\chi_1)\tilde{G}_\chi\ ;\\
L_G &: \quad \delta_{L_G}\tilde{G}_\lambda \equiv -\epsilon(x^1\mathcal{D}_2 - x^2\mathcal{D}_1)\tilde{G}_\lambda\ .
\end{aligned}$$

These results agree with canonical light-front quantization. [But the insight was worth the struggle.]

- How can a derivative appear in a partonic observable?

  A typical observable is a lightcone fourier transform of a bilinear product of fields ≡ lft

$$q(x_{\mathrm{Bj}}) \sim \mathrm{lft}\left[\psi_+^\dagger(x^\perp)\psi_+(x^\perp+\xi^-)\right]$$

  How to add a derivative (like you need for orbital angular momentum)?

  - ⋆ $\partial_\perp$? $\quad \mathrm{lft}\left[\psi_+^\dagger(x^\perp)\partial_\perp\psi_+(x^\perp+\xi^-)\right]$

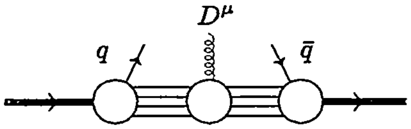
    Sorry! Not gauge invariant!

  - ⋆ $D_\perp$? $\quad \mathrm{lft}\left[\psi_+^\dagger(x^\perp)D_\perp\psi_+(x^\perp+\xi^-)\right]$

    Sorry! $D_\perp$ depends on a space time point,

    $$\mathrm{lft}\left[\psi_+^\dagger(x^\perp)D_\perp(x^- + \eta^-)\psi_+(x^\perp+\xi^-)\right]$$

    Sorry! Now this must be fourier transformed with respect to η^-. It's a function of 3-active parton lines.



  - ⋆ $\mathcal{D}_\perp$? $\quad \mathrm{lft}\left[\psi_+^\dagger(x^\perp)\mathcal{D}_\perp(x^\perp)\psi_+(x^\perp+\xi^-)\right]$

    Aha! $\mathcal{D}_\perp(x^\perp)$ does not depend on a lightcone interval and therefore does not introduce another dynamical field.

- Residual, transverse, gauge invariance

  Actually we spoke too soon in claiming physical significance for $\tilde{\psi}(k^+,\underline{x})$ and $\tilde{\mathrm{A}}_\lambda(k^+,\underline{x})$ because setting $A^+ = 0$ doesn't completely fix the gauge, and observables must be invariant under the residual gauge transformations.

  Residual gauge group are transformations (RGT) generated by $\alpha(\underline{x})$ where phase α is independent of x^+

$$\begin{aligned}
\tilde{\psi}(k^+,\underline{x}) &\rightarrow e^{i\alpha(\underline{x})}\tilde{\psi}(k^+,\underline{x})\ ,\\
\tilde{A}_\lambda(k^+,\underline{x}) &\rightarrow e^{i\alpha(\underline{x})}(\tilde{A}_\lambda(k^+,\underline{x}) + \tfrac{2\pi i\delta(k^+)}{g}\,\partial_\lambda)e^{-i\alpha(\underline{x})}\ .
\end{aligned}$$

  Decompose $\tilde{A}_\lambda$ into a piece that transforms homogeneously under RGT, and remainder that sits at $k^+ = 0$,

$$\tilde{A}_\lambda(k^+,\underline{x}) \equiv 2\pi\delta(k^+)\mathcal{A}_\lambda(\underline{x}) + \tilde{G}_\lambda(k^+,\underline{x})\ ,$$

  So, now under RGT,

$$\begin{aligned}
\mathcal{A}_\lambda(\underline{x}) &\rightarrow e^{i\alpha(\underline{x})}(\mathcal{A}_\lambda(\underline{x}) + \frac{i}{g}\,\partial_\lambda)e^{-i\alpha(\underline{x})}\\
\tilde{G}_\lambda(k^+,\underline{x}) &\rightarrow e^{i\alpha(\underline{x})}\tilde{G}_\lambda(k^+,\underline{x})e^{-i\alpha(\underline{x})}\ .
\end{aligned}$$

  The gauge field of the residual gauge group, $\mathcal{A}_\lambda(\underline{x})$ is the light cone average of A_λ in $A^+ = 0$ gauge

$$\mathcal{A}_\lambda(\underline{x}) = \frac{1}{\int dx^-}\int dx^-\mathrm{A}_\lambda(x)\ .$$

  which vanishes when $\mathrm{A}_\lambda \rightarrow 0$ as $x^- \rightarrow \infty$

- Partonic fields

  So the building blocks for observables – gauge invariant Noether charges that commute with x_{Bj} are $\tilde{\psi}(k^+,\underline{x})$, $\tilde{G}_\lambda(k^+,\underline{x})$, $\mathcal{A}_\lambda(\underline{x})$ which appears in RGT gauge covariant derivative

$$\mathcal{D}_i \equiv \partial_i - ig\mathcal{A}_i,$$

$$\int d^3x M^{12++\cdots+} = S^{++\cdots+} \quad \text{usual quark spin}$$
$$+L_Q^{++\cdots+} \quad \text{covariant derivatives}$$
$$+\Delta L_Q^{++\cdots+} \quad \text{new operators}$$

$$S^{++\cdots+} \propto \int d^3x \bar{\psi}\gamma^+ \frac{\Sigma^3}{2} iD^+ iD^+ \cdots iD^+ \psi$$

$$\begin{aligned} L_Q^{++\cdots+} \propto & \int d^3x \bar{\psi}\gamma^+ (x^1 iD^2 - x^2 iD^1) iD^+ iD^+ \cdots iD^+ \psi \\ & + \int d^3x \bar{\psi}\gamma^+ iD^+ (x^1 iD^2 - x^2 iD^1) iD^+ \cdots iD^+ \psi \\ & + \cdots \\ & + \int d^3x \bar{\psi}\gamma^+ iD^+ iD^+ \cdots iD^+ (x^1 iD^2 - x^2 iD^1) \psi \end{aligned}$$

$$\begin{aligned} \Delta L_Q^{++\cdots+} \propto & \int d^3x \bar{\psi}\gamma^+ (x^1\gamma^2 - x^2\gamma^1) igF^{\rho+}\gamma_\rho iD^+ \cdots iD^+ \psi \\ & + \cdots \\ & + \int d^3x \bar{\psi}\gamma^+ iD^+ \cdots iD^+ (x^1\gamma^2 - x^2\gamma^1) igF^{\rho+}\gamma_\rho \psi \end{aligned}$$

- $L_Q^{++\cdots+}$ is not related to the parton distribution of orbital angular momentum
- $\Delta L_Q^{++\cdots+}$ is not interpretable

It is not surprising that off-forward, deeply virtual Compton scattering is sensitive to

$$\vec{x} \times \{\text{Twist-2, spin-n operators}\}$$

Specifically

$$M^{\alpha\beta\mu_1\mu_2\cdots\mu_n} \equiv x^\alpha T^{\beta\mu_1\mu_2\cdots\mu_n} - x^\beta T^{\alpha\mu_1\mu_2\cdots\mu_n}$$

where

$$T^{\alpha\mu_1\mu_2\cdots\mu_n} \equiv \mathcal{S}\left(\bar{\psi}\gamma^\alpha iD^{\mu_1} iD^{\mu_2} \cdots iD^{\mu_n}\psi\right)$$

is the standard twist two quark operator tower of DIS.

But the invariant matrix elements associated with these operators do not correspond to the angular momentum.

Two problems

- Transverse covariant ($D_\perp$) appear.
- Transverse indices appear on γ matrices – no interpretation at all.

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5 Conclusions and Outlook

The Dilemma of Orbital Angular Momentum
Easy to state, hard to resolve:

- What can be interpreted cannot be measured.
- What can be measured cannot be interpreted.

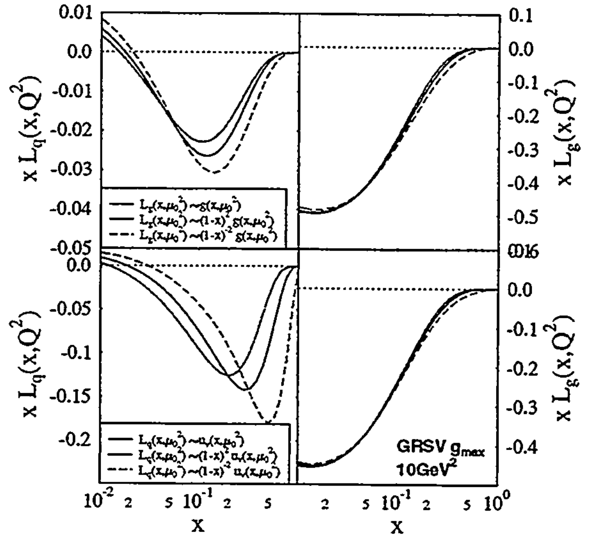
First part should be clear:
The light-cone parton distributions of orbital angular momentum developed by Bashinksky, Hägler et al. and Ravindranath et al. are the correct objects to call orbital angular moemntum. But we know no processes to which they couple.

The second part is less clear:

Ji et al show how to measure higher spin generalizations of

$$x^\lambda T^{\mu\nu} - x^\nu T^{\mu\lambda}$$

where $T^{\mu\nu}$ is the quark piece of the energy momentum tensor.



PHENIX Gluon Polarization Sensitivities and Issues

Yuji Goto, *RIKEN*

We aim at direct measurement of the gluon polarization at PHENIX in the polarized proton collision. This is performed by using gluon+quark and gluon+gluon reactions. The central arm of the PHENIX detector covers central rapidity region, and the muon arm covers forward region to detect many channels of physics signal from these reactions. In the central arm, we detect prompt photon and π^0. In the muon arm, we detect heavy flavor productions which include both quarkonia production and open heavy flavor production.

There is fine–segmented EM calorimeter (EMCal) subsystem in the central arm which covers rapidity region $|\eta| < 0.35$ and 180° azimuthal angle. It consists of lead–scintillator sampling calorimeter (PbSc) and lead glass calorimeter (PbGl). Both have fine granularity about 0.01 radian per tower in both rapidity and azimuthal direction, which gives us good $\pi^0 \rightarrow 2\gamma$ identification capability up to $p_T \sim 30$ GeV/c.

The prompt photon is detected by the EMCal subsystem. Theoretically, the prompt photon production is a clean channel to be interpreted because it is dominated by the gluon Compton process. By measuring asymmetry, A_{LL}, of the prompt photon production in the polarized proton collision, we can deduce the gluon polarization, $\Delta G/G$, by using knowledge of the quark polarization from polarized DIS experiments and calculable asymmetry of the gluon Compton process. Experimentally, detection of the prompt photon is challenging because of many background events mainly from $\pi^0 \rightarrow 2\gamma$ decay.

We are studying sensitivities of our measurements using PYTHIA event generator. Here, we show theoretical and experimental dilution of the asymmetry measurement. For the gluon polarization measurement, what we want is only the asymmetry of the gluon Compton process. Other processes work to dilute the asymmetry. Theoretically, we need evaluation of annihilation process and bremsstrahlung. Experimentally, background photons dilute it. If we apply isolation cut, dilution rate is decreased according to its cut efficiency.

In inclusive photon measurement in the PHENIX EMCal subsystem, there is another uncertainty to obtain the gluon polarization. Because we cannot reconstruct parton kinematics of each event in the inclusive measurement, we are required to use estimated mean values of the kinematic variables. It causes smearing resolution for the gluon polarization measurement. In order to avoid this uncertainty, we can use fitting with Q^2 evolution for the measured asymmetry of the prompt photon. We can include smearing resolution in the fitting procedure to evaluate the measured asymmetry.

To summarize issues of the gluon polarization measurement using the prompt photon, first, we need background evaluation both theoretically and experimentally. In this evaluation, we can utilize other measurements in the PHENIX detector, e.g. weak boson measurement to estimate annihilation process contribution and π^0 measurement for the background photon estimation. We also need study of the fitting procedure to deduce the gluon polarization.

The muon arm covers forward rapidity region $1.2 < |\eta| < 2.4$ and 360° azimuthal angle. It consists of magnets, tracking chambers, and muon identifier. By detecting di–muon in the muon arm, we can identify J/Ψ and measure its production asymmetry. As for open heavy flavor production, the most clean channel is electron–muon coincidence channel. At high $M_{e\mu}$ region, background events from π/K decays are small enough. These background events can be estimated by measuring like–sign pair of electron–muon. We have good enough precision to distinguish several polarized parton distribution functions with different value of the gluon polarization.

Prompt Photon Production

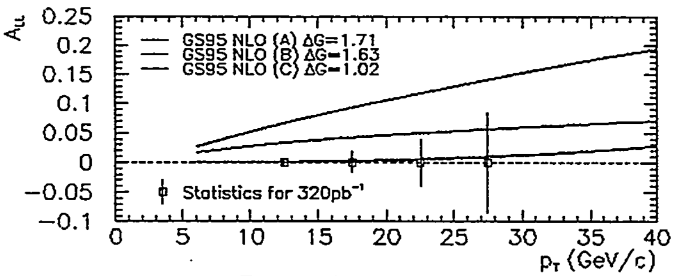
- Yield

320 pb^{-1} 800 pb^{-1}

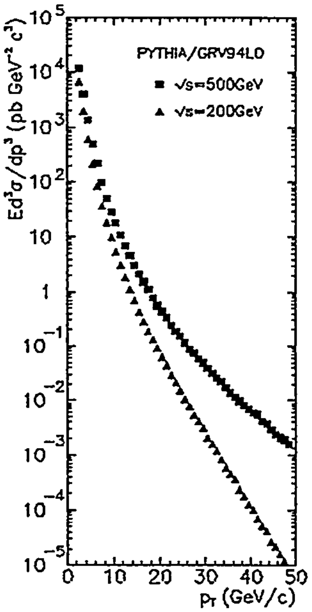
	$\sqrt{s} = 200$GeV			$\sqrt{s} = 500$GeV		
Photon p_T	Yield	Errors on A_{LL}	Errors on $\Delta G/G$	Yield	Errors on A_{LL}	Errors on $\Delta G/G$
10 - 15 GeV/c	1.0×10^5	0.0062	0.046	9.0×10^5	0.0022	0.045
15 - 20 GeV/c	1.3×10^4	0.0168	0.089	1.8×10^5	0.0059	0.059
20 - 25 GeV/c	2.7×10^3	0.0376	0.171	5.3×10^4	0.0081	0.081
25 - 30 GeV/c	5.9×10^2	0.0799	0.309	1.9×10^4	0.0115	0.115
30 - 35 GeV/c				7.7×10^3	0.0141	0.141
35 - 40 GeV/c				3.3×10^3	0.0198	0.198

120K events 1,160K events

- Asymmetry



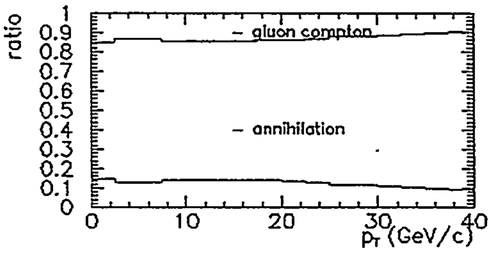
Prompt γ Asymmetry



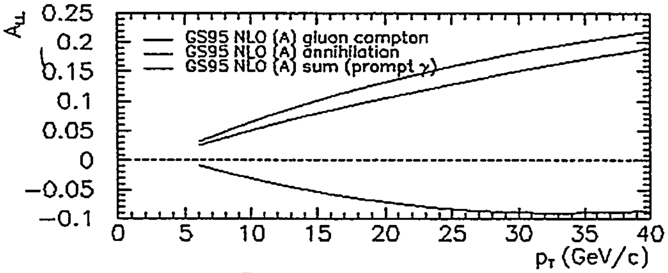
Prompt Photon Asymmetry

- PYTHIA leading order prompt photon production
  - gluon compton process 80-90%
  - annihilation process 10-20%
- Asymmetry dilution by annihilation
  - $a_{LL} = -1$

Asymmetry
~15% dilution



no isolation cut

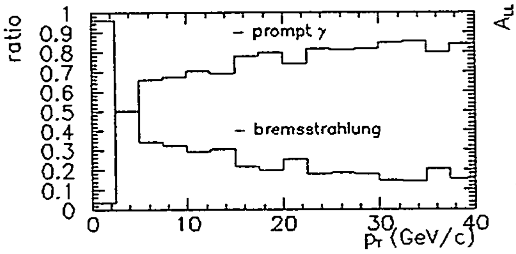


Prompt γ Asymmetry

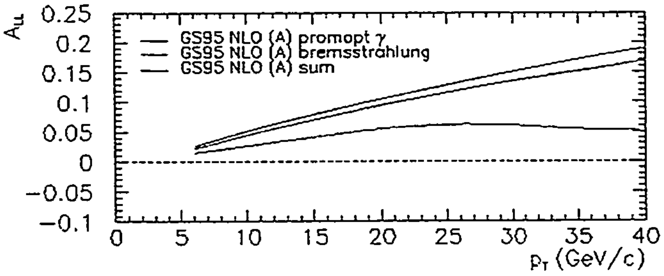
Prompt Photon Asymmetry

- PYTHIA leading order prompt photon + bremsstrahlung
  - prompt photon leading order 70-85%
  - bremsstrahlung 15-30%
- Asymmetry dilution by bremsstrahlung

Asymmetry
~10% dilution



no isolation cut

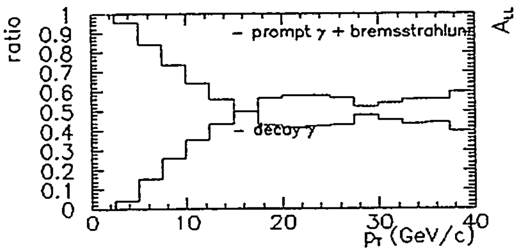


Prompt γ Asymmetry

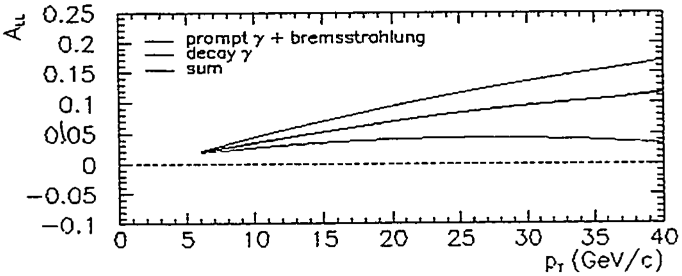
Prompt Photon Asymmetry

- PYTHIA prompt photon + decay photon
  - decay photon - background
  - before background reduction
- Asymmetry dilution by decay photons

Asymmetry
~30% dilution



no cut

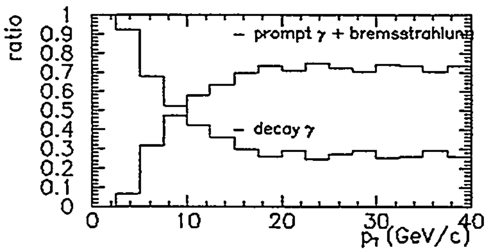


no isolation cut

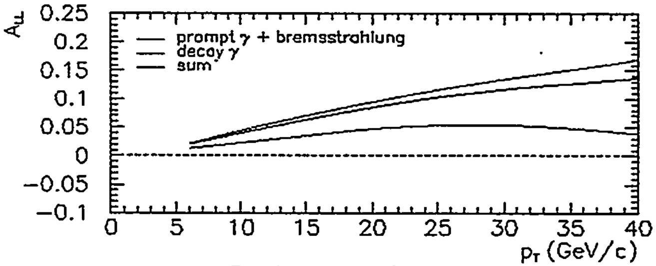
Prompt Photon Asymmetry

- PYTHIA prompt photon + decay photon
  - after background reduction
    - mass reconstruction
    - isolation cut R=0.4, fraction=5%
- Asymmetry dilution by decay photons
  - recovered
  - more recovery by requiring stricter condition

Asymmetry
~20% dilution



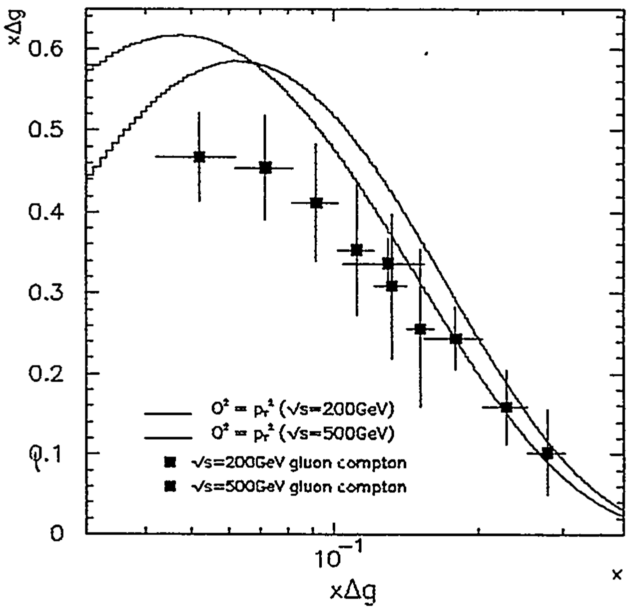
R=0.4 fraction=0.05



R=0.4 fraction=0.05

Gluon Polarization Sensitivity

- $x \cdot \Delta G$ derived from
  - gluon compton photon
  - statistical error for
    - *sqrt(s)=200GeV 320pb^{-1}*
    - *sqrt(s)=500GeV 800pb^{-1}*
- assuming
  - $x_g = x_T = 2p_T/sqrt(s)$
  - $cos(\theta^*)=0$
- Deviation from input $x \cdot \Delta G$ lines
  - fitting will be done on A_{LL} data considering these smearing effects



π^0 Production

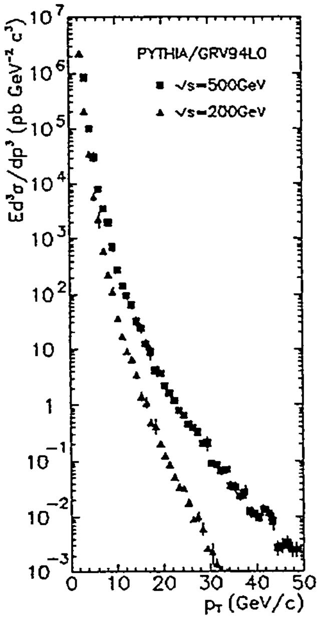
- Yield

  32 pb^{-1}

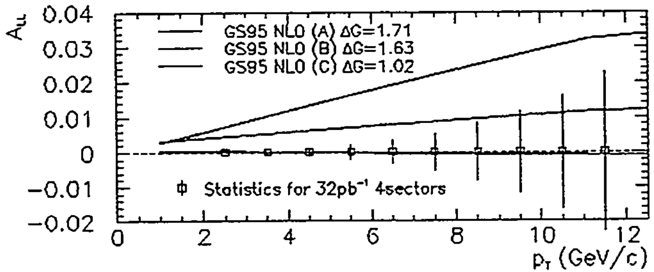
  400M events

π^0 p_T	$\sqrt{s} = 200\text{GeV}$	
	Yield	δA_{LL}
2 - 3 GeV/c	3.3×10^8	1.1×10^{-4}
3 - 4 GeV/c	4.3×10^7	3.1×10^{-4}
4 - 5 GeV/c	8.8×10^6	6.9×10^{-4}
5 - 6 GeV/c	2.3×10^6	1.3×10^{-3}
6 - 7 GeV/c	7.4×10^5	2.4×10^{-3}
7 - 8 GeV/c	3.5×10^5	3.4×10^{-3}
8 - 9 GeV/c	1.3×10^5	5.6×10^{-3}
9 - 10 GeV/c	6.8×10^4	7.8×10^{-3}
10 - 11 GeV/c	3.1×10^4	1.2×10^{-2}
11 - 12 GeV/c	2.1×10^4	1.4×10^{-2}

Table 1: π^0 yield



- Asymmetry

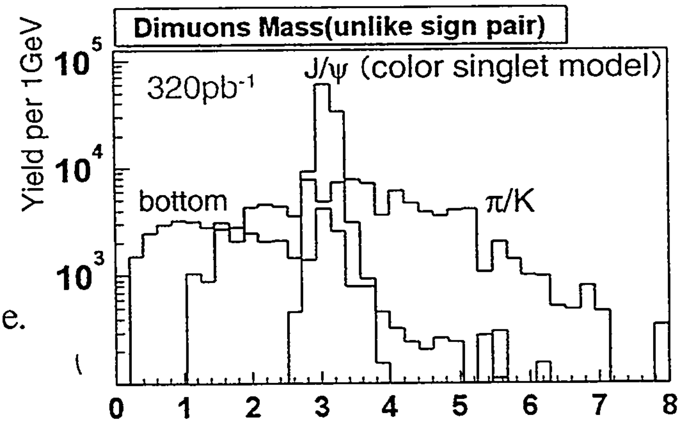


π^0 Asymmetry

J/ Ψ Production

- Di-muon measurement
- Signal
  - $N_{J/\psi}(p_T > 2\text{GeV}) \sim 120\text{k}$ events
  - $\delta A_{LL}^{J/\Psi}(\text{stat.}) \sim 0.006$
- Background
  - $N_{\pi K}/N_{J/\psi} \sim 0.15$
  - $\delta A_{LL}^{\pi K} \sim 0.007$
  - $\delta A_{LL}^{J/\Psi}(\text{syst.}) \sim 0.001$
- Excellent asymmetry measurement will be done.

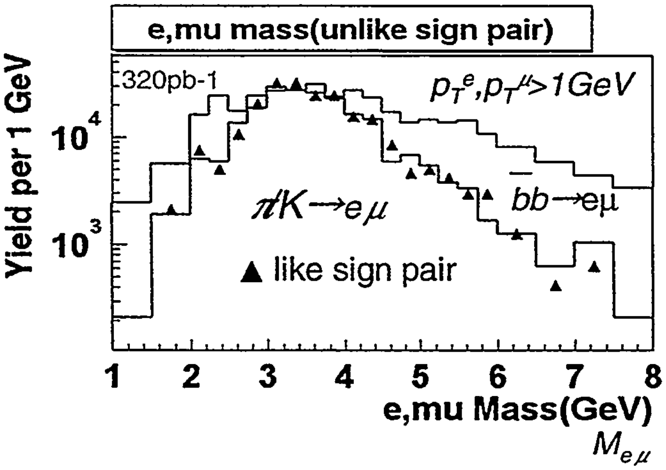
Hiroki Sato's studies



Open Heavy Flavor Production

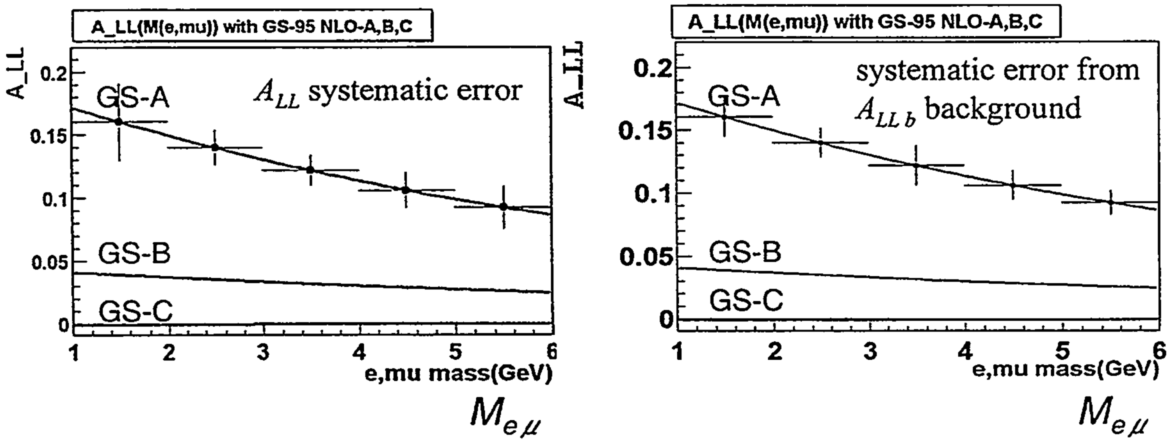
- eμ coincidence
- Signal
  - $N_{bb\to e\mu} \sim$ 100k events
  - δA_{LL}(stat.) ~ 0.006
- Background
  - $N_{\pi K\to e\mu} \sim$ 60k events
  - δA_{LL}(syst.) ~ 0.006
- Good signal/b.g. + good b.g. estimation

Hiroki Sato's studies



Sensitivity of e μ Coincidence

Hiroki Sato's studies



STAR Gluon Polarization Measurements

L.C. Bland, *Indiana University*

One of the primary objectives of the RHIC spin program is to determine the integral contribution (ΔG) gluons make to the proton's spin. Possibly the best way to achieve this objective is to study large transverse momentum ($p_T > 10$ GeV/c) photon production spin asymmetries (A_{LL}) in the collisions of polarized protons at high energies. The general features that make this process attractive for determining ΔG are summarized in Fig. 1a. The 'sensitivity' of the STAR detector, using the reaction $\vec{p} + \vec{p} \rightarrow \gamma + jet + X$, to different models of the polarized gluon distribution function, $\Delta G(x)$, is shown in Fig. 1b. The displayed quantities are further described below.

Studying inclusive γ production at midrapidity ($\eta \approx 0$) will provide some insight into the gluon helicity distribution, $\Delta G(x)$, but is not ideal. First, there is only an approximate relationship between the measured $p_{T,\gamma}$ and the initial state partonic kinematics. For fixed $p_{T,\gamma}$, the quark and gluon momentum fractions ($x_{q(g)}$) fall along a hyperbolic locus. Within the parton shower model, as represented in PYTHIA, the hyperbolic locus is broadened by a transverse momentum (k_T) that varies from event to event (Fig. 2a). Hence, when $\eta_\gamma \approx 0$, the event-averaged momentum fractions are $\bar{x}_q \approx \bar{x}_g \approx x_T = 2p_{T,\gamma} / \sqrt{s}$, and the average photon scattering angle in the partonic CM is $\pi/2$. This does not provide the optimal 'analyzer' of the gluon polarization. Detecting forward photons ($1 < \eta_\gamma < 2$) improves the performance of the gluon 'spin analyzer' by emphasizing asymmetric qg scattering ($x_q > x_g$), and by probing smaller values of x_g, thereby improving the determination of the integral ΔG.

Detection of the away-side jet in coincidence with a forward γ eliminates most of the ambiguities about the initial-state kinematics (Fig. 2b). The event-by-event determination of the partonic kinematics enables a direct extraction [1] of $\Delta G(x)$ from the measured A_{LL} by employing the leading order pQCD relationship, $A_{LL} \approx \Delta G(x_g) / G(x_g) \cdot A_1^p(x_q) \cdot \hat{a}_{LL}(\vartheta^*)$. The efficacy of this method is shown in Fig. 1b for simulated 'direct photon' events, including both qg Compton scattering and $q\bar{q}$ annihilation. The latter process reduces the magnitude of A_{LL} for a given $\Delta G(x)$.

Naturally, other backgrounds, including the production of $\pi^0(\eta^0)$ mesons which subsequently decay into photon pairs (that are difficult to distinguish from single photons at very high energies), and so-called 'fragmentation photons', must be considered. Detailed comparison [2] between published data and the yields simulated for these processes by PYTHIA provide some confidence that the severity of these backgrounds at RHIC can be established. The background magnitudes, after all gating conditions have been imposed, are shown in Fig. 3. Contributions to the photon yield from these backgrounds will result in a smaller magnitude A_{LL} for a given $\Delta G(x)$ (Fig. 4).

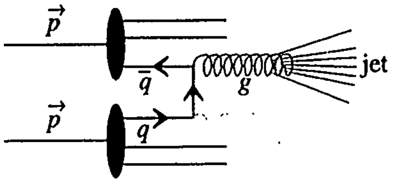
Finally, to establish the contribution gluons make to the proton's spin, the first moment of $\Delta G(x)$ must be determined, requiring an extrapolation of $\Delta G(x)$ to x_g values not probed in the experiment, the most serious limitation being the cutoff at small x_g. By studying photon production spin asymmetries at two collision energies ($\sqrt{s} = 200$ and 500 GeV) the range of x_g probed at RHIC is sufficient to minimize extrapolation errors, as shown in Fig. 5.

[1] L.C. Bland, hep-ex/9907058 (1999).

[2] L.C. Bland, in *RIKEN Workshop on Event Generators for RHIC Spin Physics*, (March, 1999).

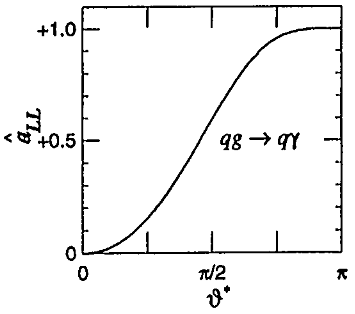
Advantages of $\vec{p}+\vec{p}\rightarrow\gamma+jet+X$ for determining ΔG

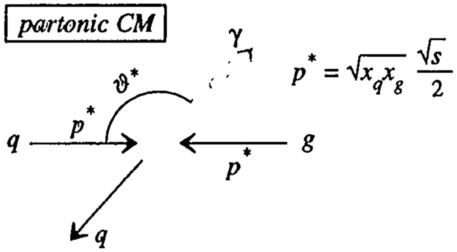
1) Gluon Compton scattering dominates direct photon production



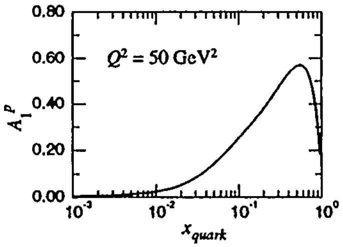
$q+\bar{q}\rightarrow\gamma+g$ makes only ~10% contribution to direct photon yield in pp collisions

2) *Large asymmetry for gluon Compton scattering when photon is detected in direction of incident quark.*





3) *Large quark polarization for $x_q > 0.2$*



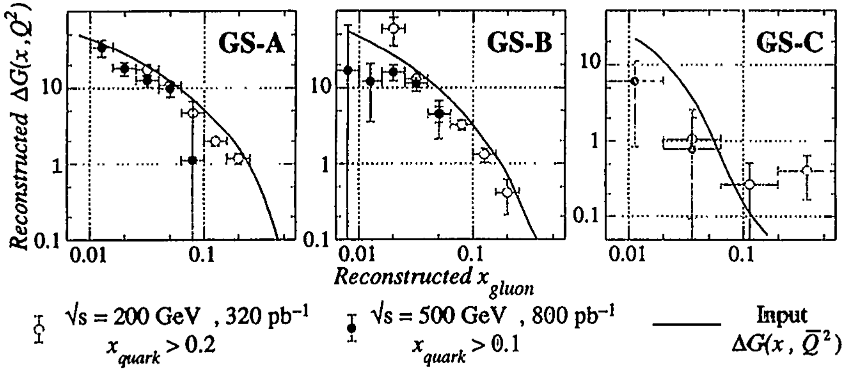
4) *Possibility to reconstruct the initial-state partonic kinematics when both the photon and jet are detected in coincidence.*

Fig. 1a

STAR spin

Sensitivity to $\Delta G(x)$ with STAR (full barrel and endcap EM calorimeter)

$\vec{p}+\vec{p}\rightarrow\gamma+jet+X$ with 3 models of $\Delta G(x)$ (PRD 53, 6100)

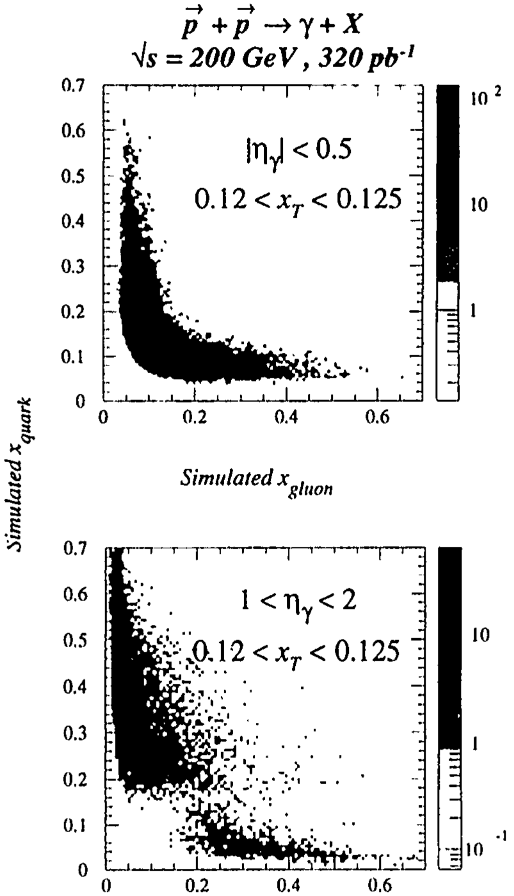


Endcap EM cal ⇒
- *much greater sensitivity to small-x gluons and large-x quarks than for midrapidity γ*

photon + jet coincidences ⇒
- *single dominant partonic process ($qg\rightarrow\gamma q$)*
- *initial-state partonic kinematics reconstruction*
- *selection of events with large 'effective analyzing power' ⇒ $x_{quark} > 0.2$*
- *possibility of directly reconstructing $\Delta G(x)$ from measured A_{LL}*

END RESULT ⇒
- *Determine the integral contribution gluons make to proton spin to accuracy ± 0.5*

Fig. 1b



Inclusive direct photons ⇒

- averaging over initial state partonic kinematics
- at midrapidity,

$$\bar{x}_{quark} \approx \bar{x}_{gluon} \approx x_T = \frac{2p_T}{\sqrt{s}}$$

Forward direct photons ⇒

- emphasis on asymmetric qg collisions $x_{quark} > x_{gluon}$

Need to detect the coincident "away-side" jet to determine the initial-state kinematics.

Fig. 2a

Partonic Kinematics Reconstruction

$$x_1 = \frac{x_T}{2}\,(e^{+\eta_\gamma} + e^{+\eta_{jet}})$$

$$x_T = \frac{2p_{T,\gamma}}{\sqrt{s}}$$

$$x_2 = \frac{x_T}{2}\,(e^{-\eta_\gamma} + e^{-\eta_{jet}})$$

$$\Rightarrow \quad x_{gluon} = \min\,[x_1, x_2]$$

$$x_{quark} = \max\,[x_1, x_2]$$

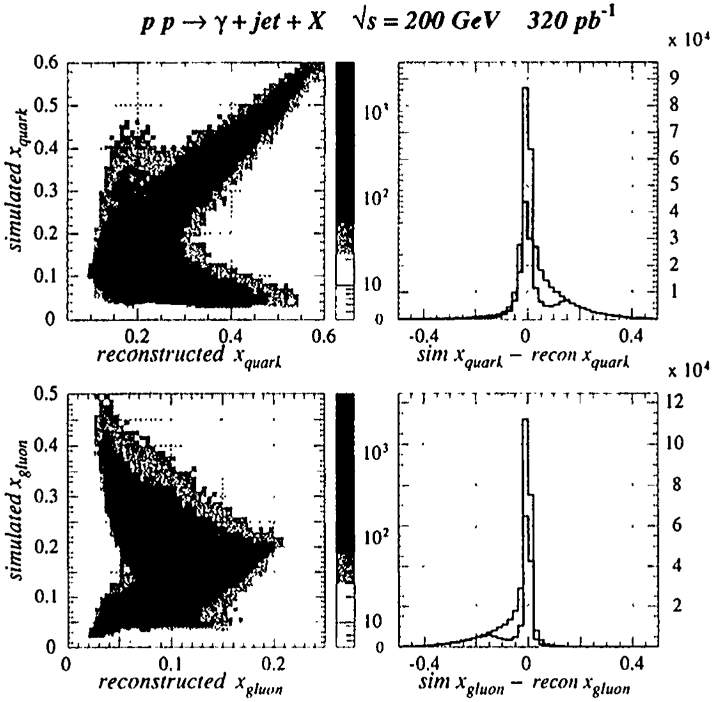
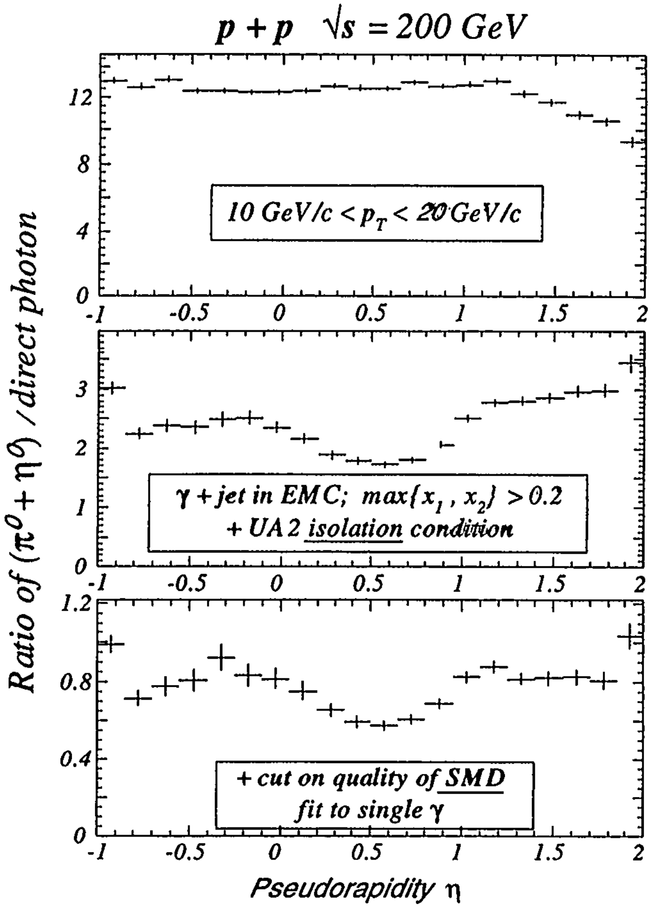


Fig. 2b

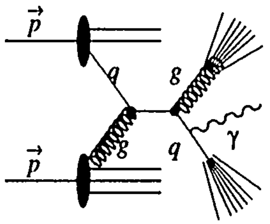
$\pi^0 + \eta^0$ Background Suppression for $\vec{p} + \vec{p} \rightarrow \gamma + jet + X$
(PYTHIA 5.7 simulations)



Remaining background to be subtracted by measuring A_{LL} for samples that pass and fail SMD cut

⇒ increased errors on $\Delta G(x)$ by factor 1.5 - 2.0

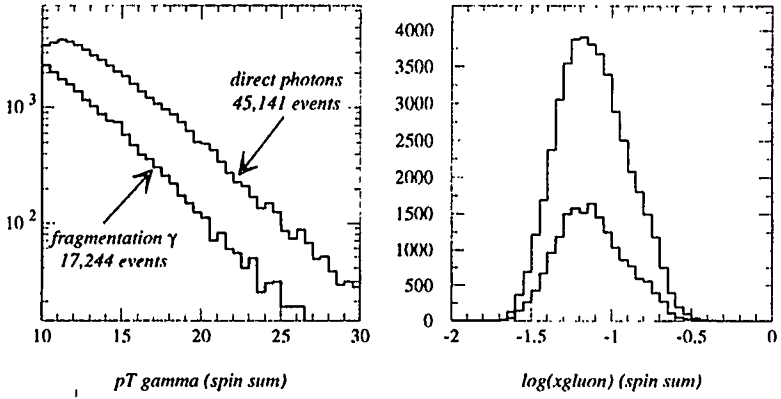
What are the contributions from higher-order processes?



From calculations (Gordon & Vogelsang), we should expect important contributions to the photon yield from higher-order processes.

PYTHIA includes only LO pQCD processes. Higher-order effects are modeled via 'parton showers'. The above process is contained within PYTHIA via so-called 'fragmentation photons'. Comparison between $p + \bar{p} \rightarrow \gamma + 2\ jet$ data and the PYTHIA 'fragmentation' photon yield has been made by the CDF group at $\sqrt{s} = 1.8\ TeV$ (PRD 57, 67). Good agreement is found.

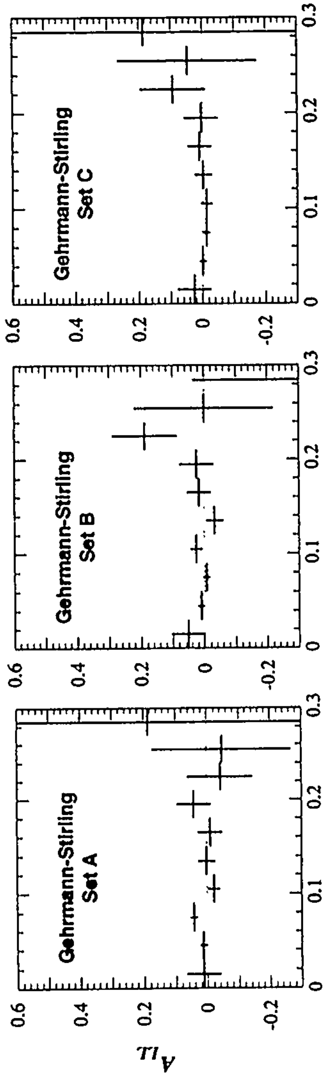
$p + p \rightarrow \gamma + jet + X \quad \sqrt{s} = 200\ GeV \quad 75\ pb^{-1}$ (PYTHIA 5.7)
(includes UA2 isolation condition)



⇒ *a larger radius isolation cone is* ***essential*** *to reduce the yield from 'fragmentation photons'*

Fig. 3

$\vec{p} + \vec{p} \rightarrow \pi^0(\eta^0) + jet + X$
$\sqrt{s} = 200\ GeV,\ 50\ pb^{-1}$



Reconstructed x_{gluon}

Event sample is subjected to direct photon cuts:

$10 < p_T < 20\ GeV/c$
$-1 < \eta_\pi < 2$
$-0.3 < \eta_{jet} < 1.3$
UA2 isolation condition

⇒ • Substantially smaller magnitude A_{LL} than for direct photons.
→ remnant background will dilute the photon asymmetries

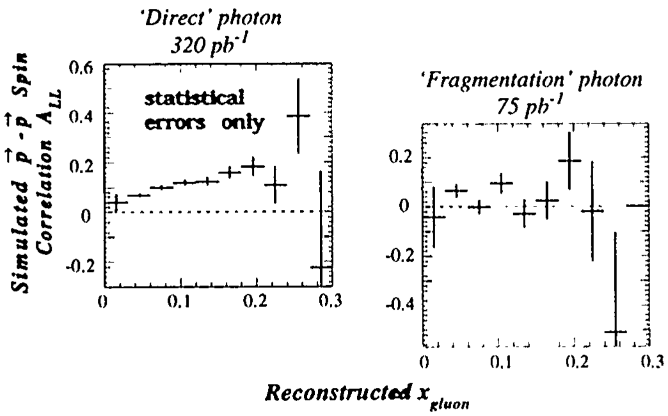
• Minimal dependence on $\Delta G(x)$
→ minimize systematic errors for statistical corrections

What is the influence of 'fragmentation photons' on polarization observables?

Cuts applied to simulation:

$10 < p_{T,\gamma} < 20$ GeV/c
UA2 isolation condition
$-0.3 < \eta_{jet} < 1.3$ (for leading jet)
$\max[x_1, x_2] > 0.2$
$-1 < \eta_\gamma < 2$ (barrel + endcap EMC)

$$\vec{p}\,\vec{p} \rightarrow \gamma + jet + X \quad \sqrt{s} = 200\ GeV$$



⇒ *expect a small dilution of A_{LL} from fragmentation photons*

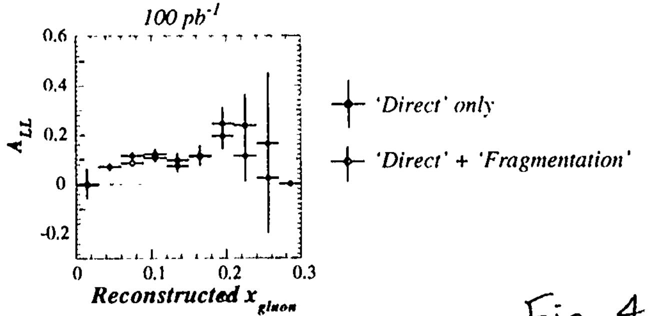
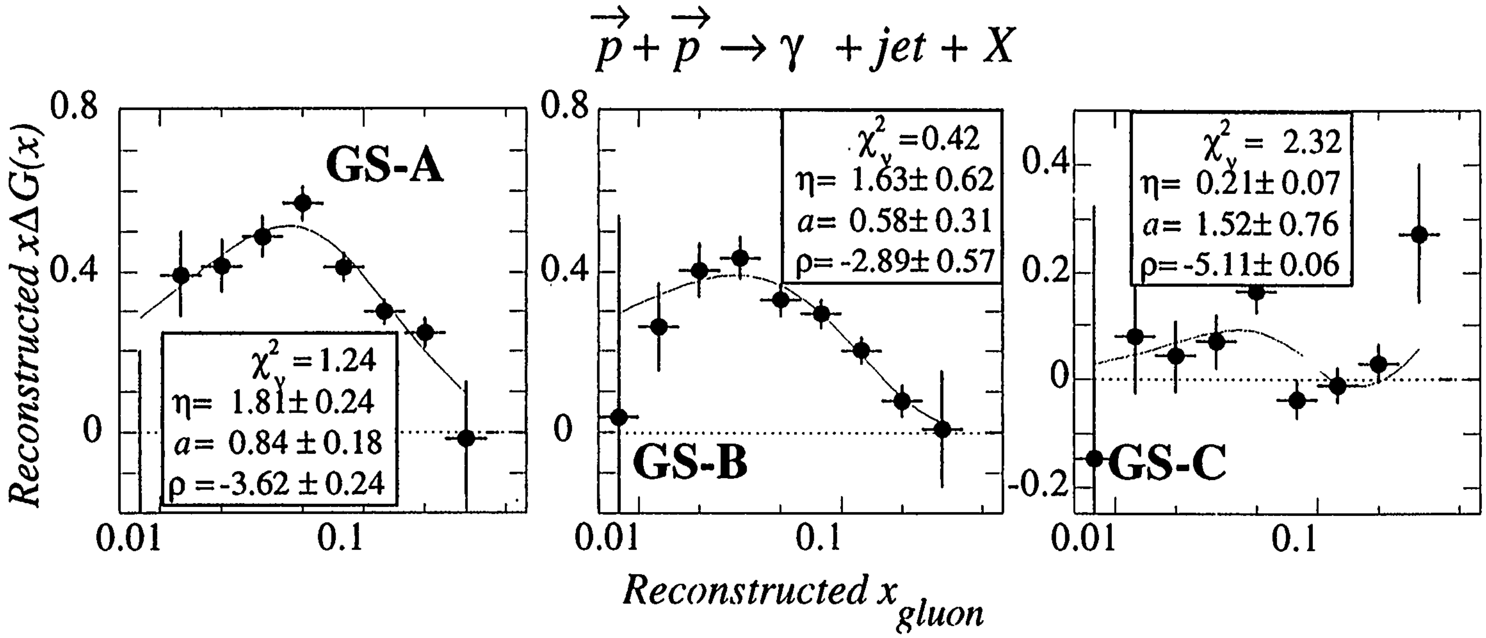


Fig. 4



Fit reconstructed $x\Delta G(x) = \eta A x^a (1-x)^b [\, 1 + \rho x^{1/2} + \gamma x \,]$.

A is chosen so that $\eta = \int_0^1 \Delta G(x)\, dx$.

In the fit, b and γ are fixed.

- A combined data sample at $\sqrt{s}$ = 200 & 500 GeV is essential to minimize extrapolation errors in determining the integral contribution gluons make to the proton's spin.
- Additional corrections are essential to obtain input value of η.

Fig. 5

Rate Capabilities for STAR for Spin

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for STAR Collaboration
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The base line of the spin physics program at STAR relies on measurements of direct photon or W-events in the $p+p$ collisions. Small cross sections for those processes ($\sim 10^5$ background/signal ratio) requires enhanced luminosity running at RHIC. The raw event rate of 4–12 MHz will be reduced to 4–60 Hz by setting a threshold on the electromagnetic calorimeter (EMC) "high towers" and "trigger towers".

Due to the 40 microseconds drift time of the STAR time projection chamber (TPC) on top of the trigger event, a few thousand of background tracks from the early/late bunch crossings ($\sim$ 700) will pile-up. In order not to exceed the band width of the acquisition system, the data volume must be reduced in flight by means of the pileup rejection procedure, described in the talk.

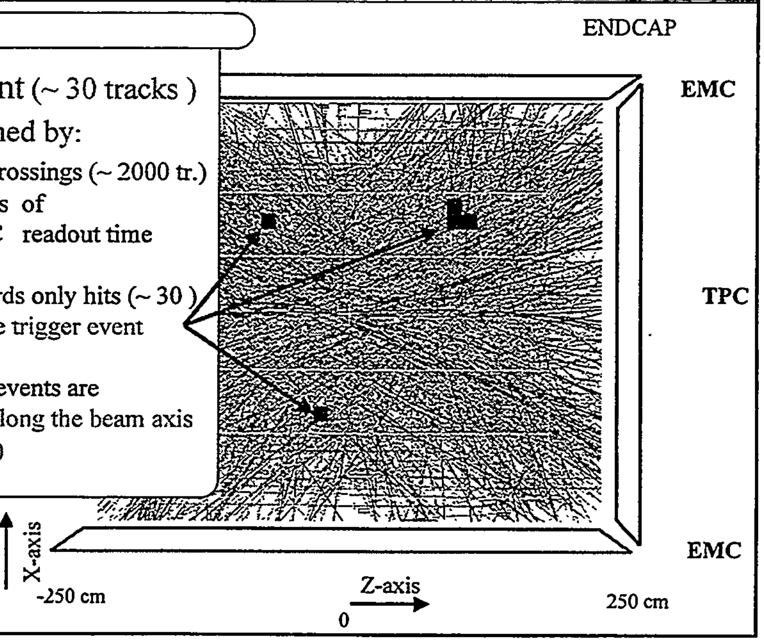
Since the EMC towers are fast detectors, they record only hits from the trigger event. The reconstructed TPC tracks matched to EMC hits are used to determine the vertex associated with the trigger event to an accuracy of 1 cm.

Since the tracks from the pile-up events are displaced along the whole beam axis ($\sim$ 400 cm), only a small fraction of them will coincide with the reconstructed vertex and all others may be rejected. To preserved some tracks from the trigger event arising from the decay of long-lived primaries, tracks matched to the EMC towers are also retained.

Despite the significant reduction of the number of the TPC hits ($\sim$ 1/50) the information about the trigger event is preserved. The quality of the reconstructed partonic kinematics is still dominated by the hadronization process rather then by the limitation of the detector or data acquisition.

Piled up Tracks Reconstructed in TPC

Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999



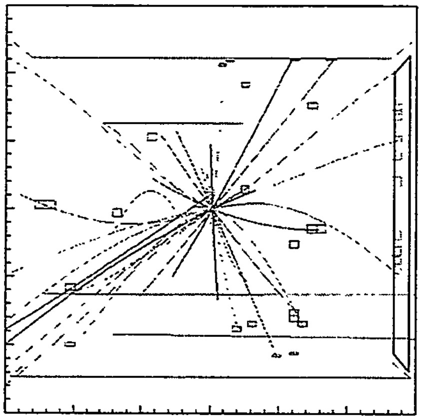
p+p event (~ 30 tracks)
screened by:
720 bunch crossings (~ 2000 tr.) during 40μs of the TPC readout time

- EMC records only hits (~ 30) from the trigger event
- the pileup events are displaced along the beam axis (± 200 cm)

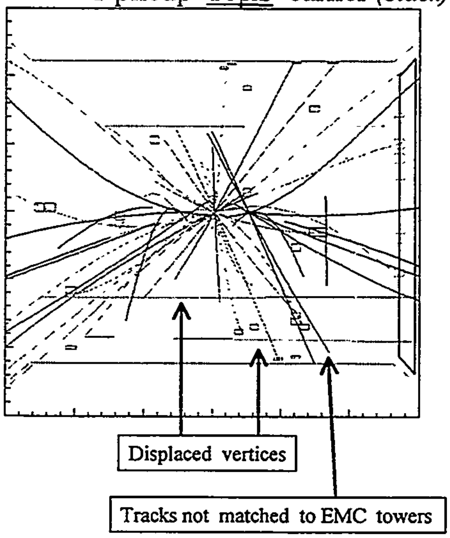
Example of 2 piled up events

Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999

p+p event
(p_T >10 GeV) @ 200 GeV



The same p+p event
+ 1 pileup 10μs earlier *(black)*



Color coding :
- green p_T <500 MeV/c
- blue $p_T \in$ [0.5, 1] GeV/c
- red p_T >1 GeV/c

Vertex Finder - Method

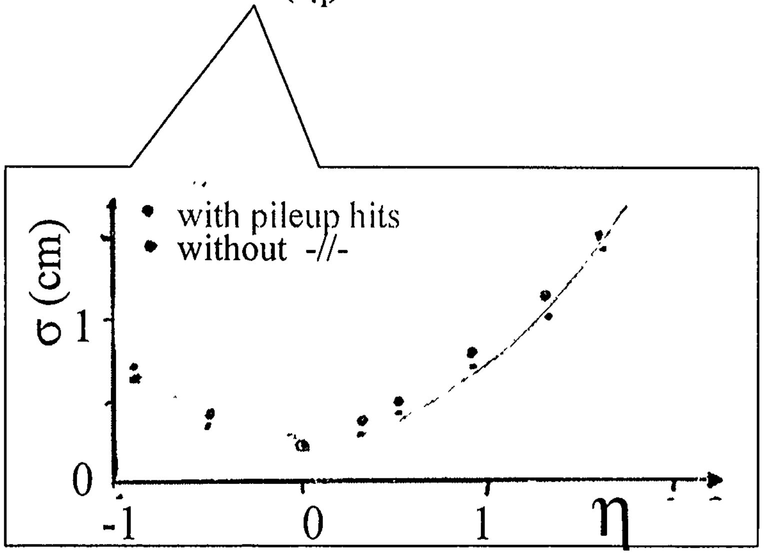
Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999

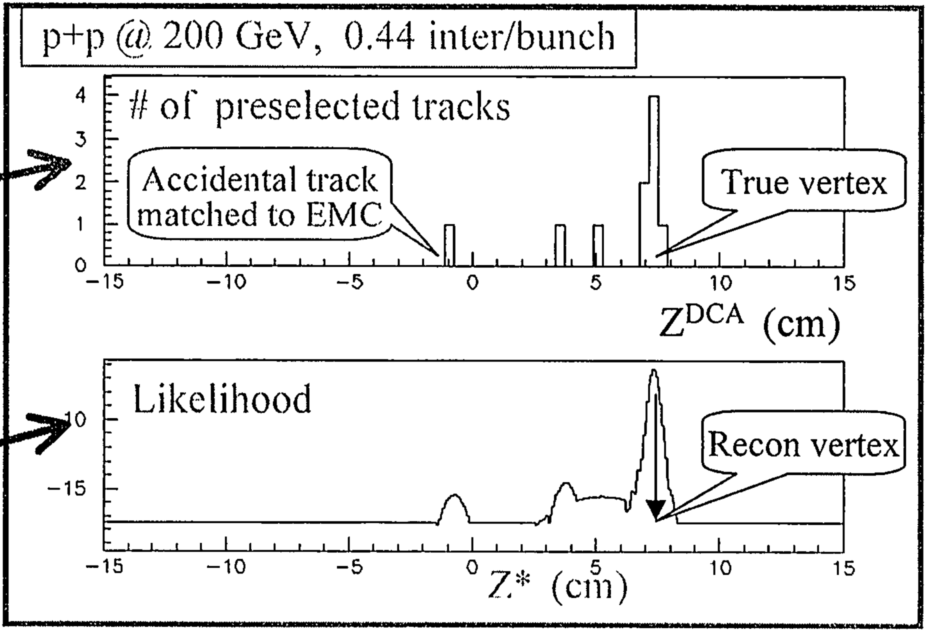
Goal: Identify vertex (Z*) for the trigger event

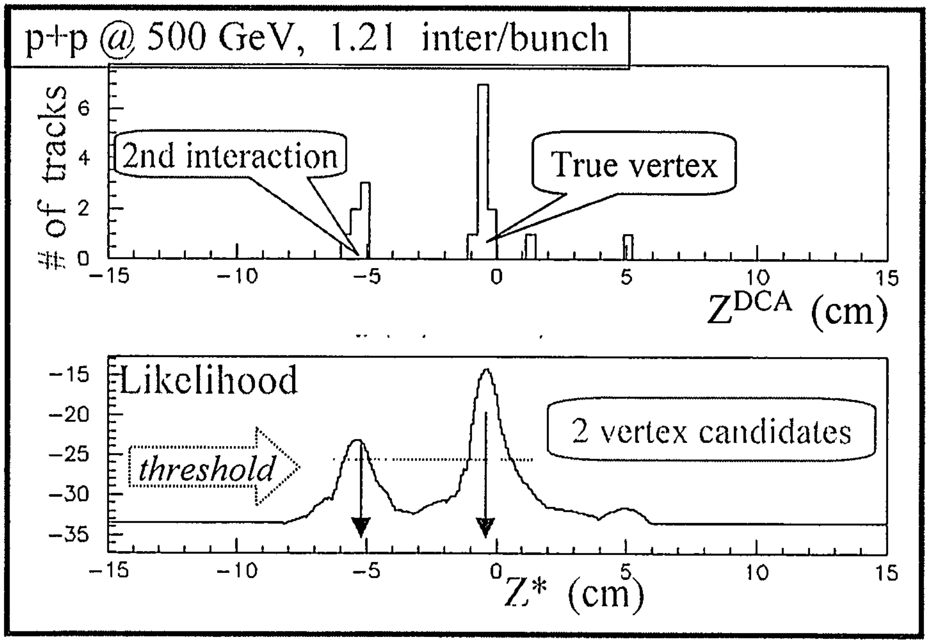
Method:

- **reconstruct** all tracks in TPC
- **preselect tracks** from trigger event:
  - # TPC clusters >20 (of 45)
  - $R_{XY}^{DCA} < 1.3$ cm (primary track)
  - $| Z^{DCA} | < 15$ cm (diamond size)
  - track matched with EMC tower
- find maximum of the **likelihood(Z*)**

$$\ln \mathbf{L(Z^*)} \equiv \sum_i \frac{(Z_i^{DCA} - Z^*)^2}{\sigma(\eta_i)^2}$$, truncated at $\Delta Z > 2\sigma_i$





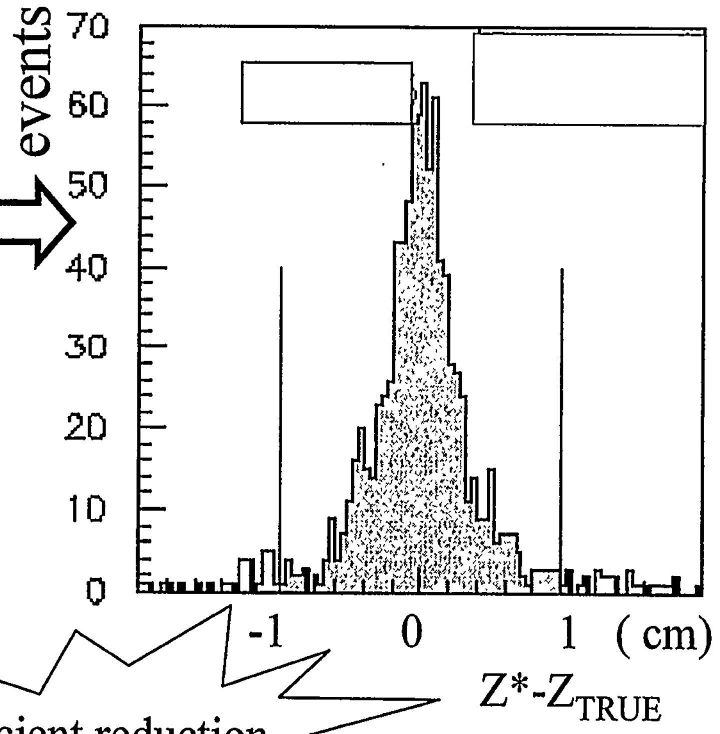


Vertex Finder - Performance

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

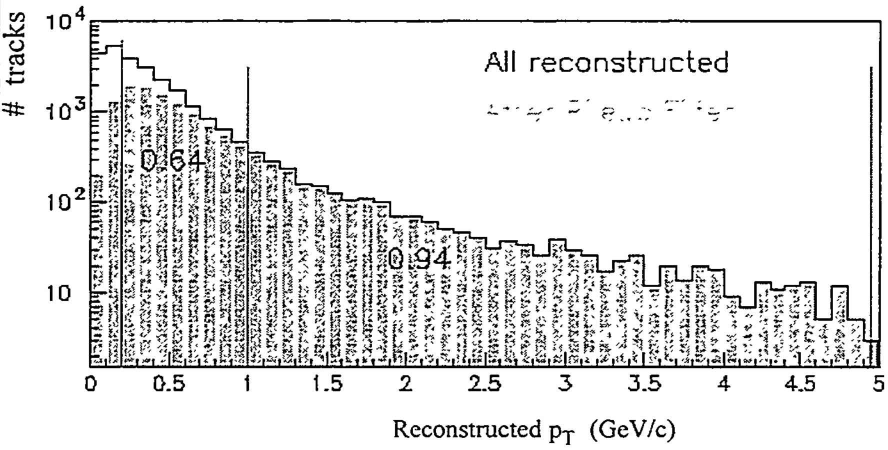
Pileup Filter

*) ±RMS

Do the tracks associated with this vertex include the physics ?

High p_T tracks preserved

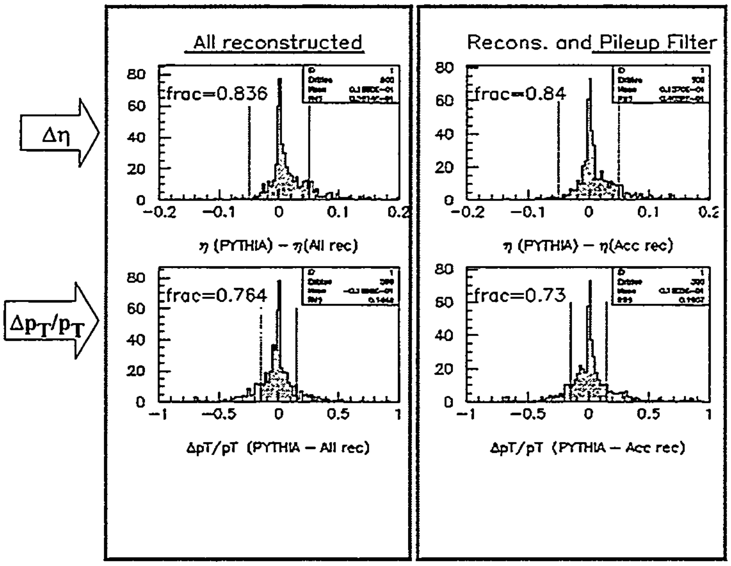
Jan Balewski, IUCF
RHIC spin workshop
BNL, October 6-8, 1999



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

~ 1%

~ 3%

p+p @ 200 GeV , $p_T > 10$ GeV/c, $\eta_q \in [1.0 , 1.3]$

A Next-to-Leading Order pQCD Analysis of $g_1(x, Q^2)$

RHIC Spin Workshop 1999 @ BNL
October 6, 1999

Abhay.Deshpande@Yale.Edu
On behalf of the Spin Muon Collaboration at CERN

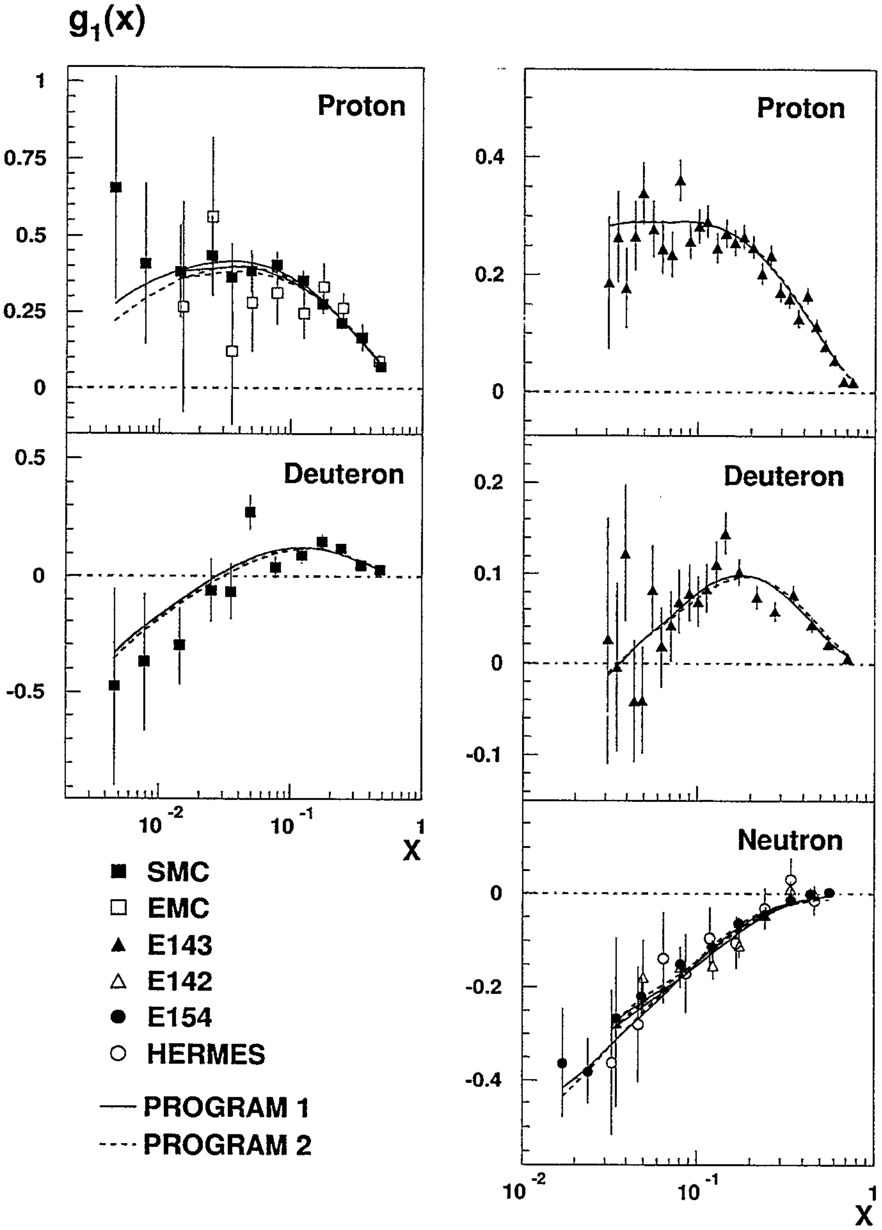
This analysis:

- Is NOT most up-to-date!
  SMC, B. Adeva *et al.*, PR D 112002, December 1998
  Does not have data from later publications by E155 (p,d) and HERMES (p) but is still relevant!
- IS the last published result on polarized gluon distribution by an experimental collaboration with complete uncertainty estimate.
- Suggests the directions for future measurements of gluon distribution

---

Students @ SMC (in time-order of participation): D. Fasching (Northwestern), G. Garcia (Santiago,Spain), A. Ogawa (Nagoya), **Y. Miyachi** (Nagoya) & E. Sichtermann (NIKHEF)

Fit Result



133 Data points (CERN,SLAC,DESY Experiments)

10 Free parameters

$\chi^2 = 116.1$ calculated using only statistical errors on the data

Evaluation of Systematic Errors:

- Experimental sources:
  - Systematic uncertainty on measured $A_1^{\mathrm{p,d,n}}(x, Q^2)$ data points For each data set: systematic uncertainties added in quadrature $\Longrightarrow$ Repeat QCD fits with $A_1 \pm \delta_{\mathrm{syst}} A_1$
  - F_2 and R parameterization: Upper and lower limits of the parametrizations Repeat the QCD fits
  - Maximum deviations from best fit added in quadrature to get total experimental systematic uncertainty
- Theoretical sources: Related to the uncertainties on other inputs in to the pQCD analysis procedure:
  - Factorization and Renormalization scales $\Longrightarrow$ Change by a factor of 2 (high and low), repeat fit...
  - Value of $\alpha_s(M_Z^2)$, the strong coupling constant $\Longrightarrow 0.118 \pm 0.003$
  - Functional form of initial parton distribution
    $\Longrightarrow$ Change, repeat fit, see difference w.r.t. best fit
    $\Longrightarrow$ Change initial Q_i^2, repeat fit, see difference...
  - Others of smaller consequence:
    - * $a_8 = 0.575 \pm 0.016$
    - * Quark mass thresholds
    - * ...
  - Maximum deviations from best fit added in quadrature to get total theoretical systematic uncertainty

Sources of Uncertainty

Nucleon	Γ_1^{fit}	Total Exp. Sys.	Total Theory
Proton	0.122	+0.007	+0.007
		-0.011	-0.024
Deuteron	0.025	+0.006	+0.006
		-0.010	-0.020
Neutron	-0.068	+0.007	+0.005
		-0.011	-0.020

Theoretical Sys. Sources Separated

Nucleon	Scale	α_s	PDFF	Others
Proton	+0.005	+0.002	+0.004	+0.002
	-0.024	-0.004	-0.001	-0.002
Deuteron	+0.003	+0.001	+0.004	+0.001
	-0.020	-0.003	-0.001	-0.001
Neutron	+0.002	+0.001	+0.005	+0.001
	-0.020	-0.003	-0.001	-0.001

Experimental Sys. Sources Separated

Nucleon	SMC	E154	E143	Other Exp.
Proton	+0.005	+0.005	+0.000	0.001
	-0.008	-0.005	-0.004	-0.002
Deuteron	+0.004	+0.005	+0.000	+0.001
	-0.008	-0.005	-0.004	-0.002
Neutron	+0.005	+0.005	+0.000	+0.001
	-0.008	-0.005	+0.004	-0.002

Systematic uncertainties from theoretical sources larger than those from experimental sources

Uncertainties and measured/unmeasured x regions

Measured x region

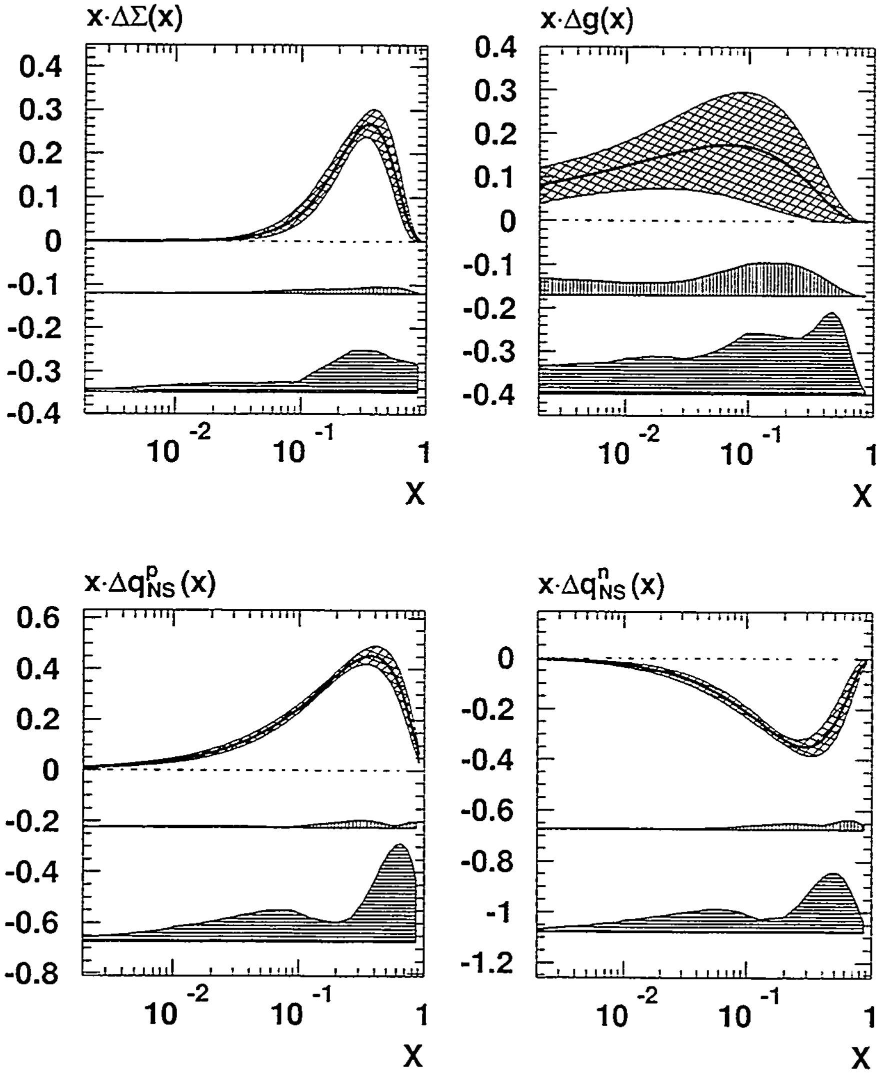
Nucleon	$\int_{0.003}^{0.8} g_1^{\text{data}}(x, Q_0^2)dx$	$\int_{0.003}^{0.8} g_1^{\text{fit}}(x, Q_0^2)dx$
Proton	$0.130 \pm 0.003 \pm 0.005 \pm 0.004$	0.132
Deuteron	$0.036 \pm 0.004 \pm 0.003 \pm 0.002$	0.040
Neutron	$-0.054 \pm 0.007 \pm 0.005 \pm 0.004$	-0.048

Unmeasured low and high x regions

$\int g_1^{\text{fit}}(x, Q_0^2)dx$	$0.0 < x < 0.003$	$0.8 < x < 1.0$
Proton	$-0.012^{+0.014}_{-0.025}$	$0.003^{+0.001}_{-0.001}$
Deuteron	$-0.015^{+0.010}_{-0.023}$	$0.000^{+0.000}_{-0.001}$
Neutron	$-0.020^{+0.010}_{-0.026}$	$0.000^{+0.001}_{-0.001}$

Uncertainty from the low x unmeasured region largest!

QCD Fit Results: Polarized Parton Distributions



- The singlet and nonsinglet quark distribution functions known reasonably well.
- The polarized gluon distribution function is largely unknown!

Results: $\eta_g = \int_0^1 \Delta g(x) dx$

First moment of the polarized gluon distribution at $Q^2 = 1$ GeV^2

$$\eta_g = \int_0^1 \Delta g(x)\mathrm{d}x = 0.99^{+0.99}_{-0.31}(\mathrm{stat})^{+0.42}_{-0.22}(\mathrm{exp.syst})^{+1.43}_{-0.45}(\mathrm{theory})$$

- η_g is largely unknown
- New DIS data from SLAC and HERMES reduces the statistical and experimental systematic uncertainty by a small amount, but this does nothing to the theoretical uncertainty
- Largest sources of uncertainty:
  Theoretical and related to unknown **low-x** behavior of g_1
  - Functional form of initial parton distribution function
  - Unknown factorization and renormalization scale
  - Uncertainty in value of $\alpha_s(M_Z^2)$
- Needs measurements over larger kinematic range
  $\Longrightarrow$ Possible future experiments with *Polarized* $\vec{e}\cdot\vec{p}$ scattering with HERA or/and with RHIC-$\vec{e}\cdot\vec{p}$ Collider
  (Talks by S. Peggs & A. Deshpande, October 8th)

- Measure η_g through photon-gluon fusion (PGF) where gluon enters at **leading order**
  $\Longrightarrow$ HERMES at DESY (R. Kaiser)
  $\Longrightarrow$ RHIC-Spin at BNL (this session)
  $\Longrightarrow$ COMPASS at CERN (A. Bravar)

Physics Results from Hermes
Gluon Polarization

Ralf Kaiser - Desy/Zeuthen
On Behalf Of The Hermes Collaboration

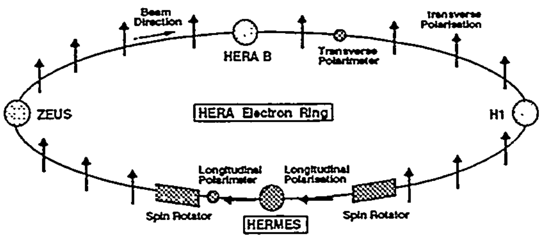
RHIC Spin Workshop, BNL, October 1999

- The HERMES Experiment
- Spin Asymmetry in the Photoproduction of Pairs of High-p_T Hadrons
- Extraction of $\Delta G/G$

Results are based on the data taking periods 1996-1997 of the Hermes experiment at Hera

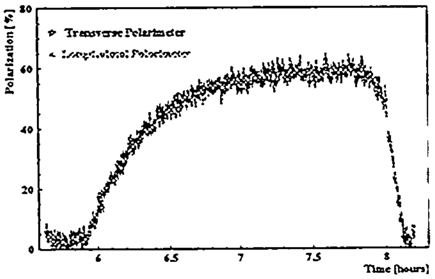
Measurement of the Spin Asymmetry in the Photoproduction of Pairs of High-p_T Hadrons at HERMES, hep-ex/9907020, submitted to Phys.Rev.Lett.

Polarized Electrons in Hera



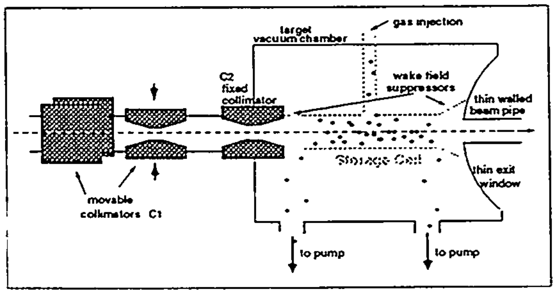
Sokolov-Ternov-Effect:

$$P(t) = \frac{8\sqrt{3}}{15}\left(1 - e^{-\frac{t}{\tau_P}}\right)$$



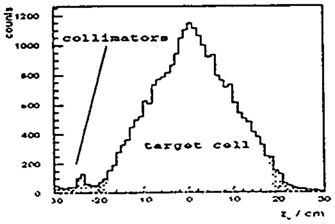
Polarization measured by two Compton polarimeters. $< P >= (55 \pm 2_{sys})\%$

Internal Polarized Gas Target

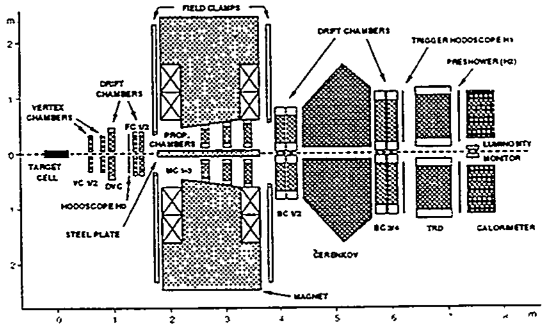


H,D target: atomic beam source based on Stern-Gerlach separation
high target density: $7.6 \cdot 10^{13}$ atoms/cm^2

polarization measured with a Breit-Rabi-polarimeter. $< P >= (88 \pm 4_{sys})\%$



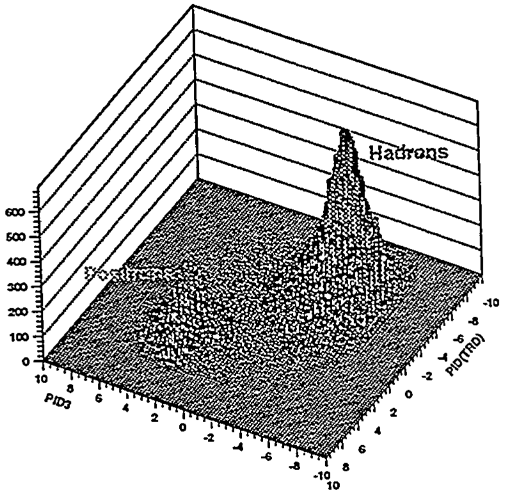
Hermes Spectrometer



Magnet:	$\int B_y dz = 1.3$ Tm
Tracking system:	$\sigma(\Theta) = 0.6$ mrad
	$\sigma(p)/p = 0.7 \ldots 1.4\,\%$ for leptons
PID System:	Calorimeter, Preshower, TRD, Cerenkov

In 1998 the threshold Cerenkov detector has been replaced by a RICH detector.

Particle Identification



$$PID3 = \log_{10}\left(\frac{\mathcal{L}^e_{cal}\mathcal{L}^e_{pre}\mathcal{L}^e_{cer}}{\mathcal{L}^h_{cal}\mathcal{L}^h_{pre}\mathcal{L}^h_{cer}}\right)$$

99% electron identification efficiency with < 1% hadron contamination (for DIS events).

Why measure spin asymmetries of pairs of high-p_T hadrons?

The physics goal is the measurement of the gluon polarization ΔG.

⇒ subprocess with gluons required

⇒ photon-gluon fusion $\gamma g \to q\bar{q}$ is an evident candidate

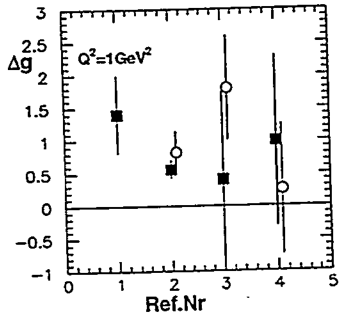
⇒ tagging of photon-gluon fusion through pairs of high-p_T hadrons at low energies (too low for jets)

[Bravar, Harrach, Kotzinian. Phys.Lett.B421:349-359,1998]

ΔG from $g_1(x, Q^2)$ Evolution

In NLO QCD the polarized structure function $g_1(x,Q^2)$ of the nucleon is related to the polarized quark, antiquark, and gluon distributions $\Delta q(x,Q^2)$, $\Delta\bar{q}(x,Q^2)$, and $\Delta G(x,Q^2)$:

$$g_1 = \frac{1}{2}\sum_q^{N_f} e_q^2\left[(\Delta q + \Delta\bar{q})\otimes\left(1+\frac{\alpha_s}{2\pi}\Delta C_q\right)+\frac{\alpha_s}{2\pi}\Delta G\otimes\Delta C_G\right]$$



1 Altarelli et al., 1998
2 Leader et al., 1998
3 E154, 1997
4 SMC, 1998

[Presented by R. Windmolders at DIS-99.]

open circles: $\overline{MS}$ scheme,
full squares: AB scheme.

errors are statistical and systematic errors in quadrature; theoretical uncertainty is not included in the errors of (2).

Experimental Technique

Measure the cross section asymmetry

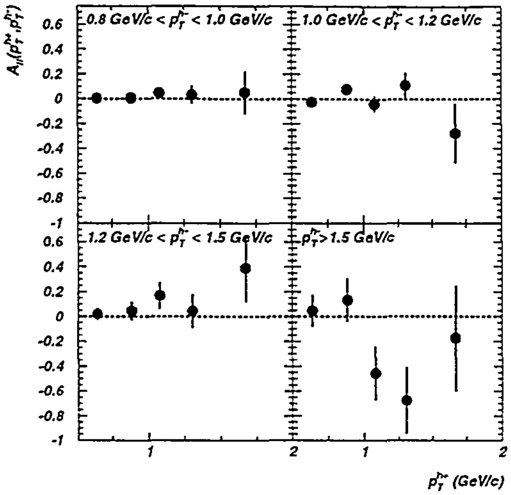
$$A_{\parallel} = \frac{N^{\uparrow\downarrow}L^{\uparrow\uparrow} - N^{\uparrow\uparrow}L^{\uparrow\downarrow}}{N^{\uparrow\downarrow}L_p^{\uparrow\uparrow} + N^{\uparrow\uparrow}L_p^{\uparrow\downarrow}}$$

$N^{\uparrow\uparrow(\uparrow\downarrow)}$;	number of oppositely charged hadron pairs for different target-beam spin orientations
$L^{\uparrow\uparrow(\uparrow\downarrow)}$	luminosities
$L_p^{\uparrow\uparrow(\uparrow\downarrow)}$	luminosities weighted by $P_T \cdot P_B$

Require:

- at least two hadrons (h^+, h^-) in spectrometer
- for both hadrons $p > 4.5$ GeV and $p_T > 0.5$ GeV
- $M(2\pi) > 1.0$ GeV, to remove ρ and ϕ
- quasi-real photoproduction: no scattere e^+ required. $\langle Q^2\rangle = 0.06$ GeV^2

MEASURED ASYMMETRY $A_{\parallel}(p_T^{h^+}, p_T^{h^-})$

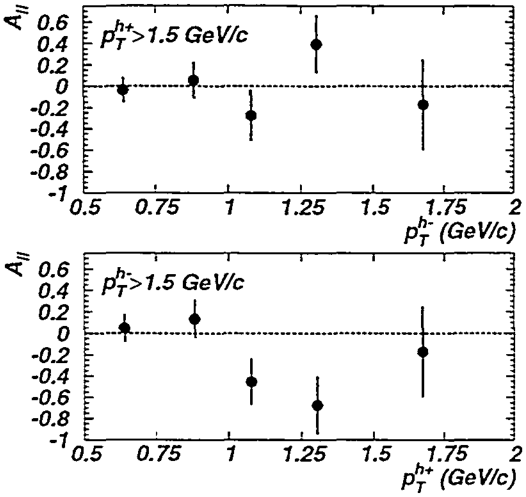


SYSTEMATIC ERROR ≈ 8% OF MEASUREMENT

CHECKS THAT HAVE BEEN PERFORMED ON THE DATA:

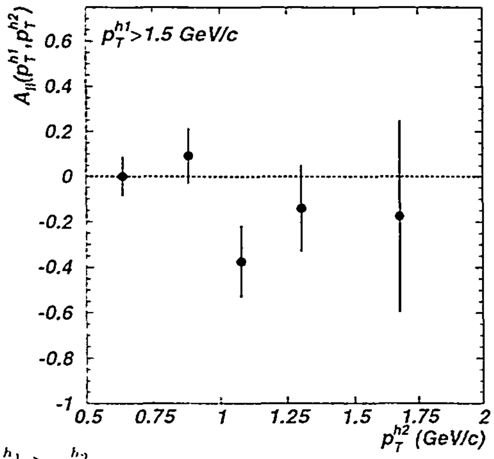
- e^+/h^+ MISIDENTIFICATION
- PARTICLE IDENTIFICATION CUT VARIATION
- MOMENTUM CUT VARIATION
- CONSISTENT RESULT OBTAINED USING IDENTIFIED PIONS ONLY

ASYMMETRY IN REGION OF INTEREST



THE TWO MEASUREMENTS ARE STATISTICALLY CONSISTENT, BUT THE DATA SUGGEST A LARGER ASYMMETRY WHEN THE TRANSVERSE MOMENTUM OF THE NEGATIVE HADRON IS HIGHER.

COMBINED h^+, h^- ASYMMETRY



$p_T^{h_1} > p_T^{h_2}$

IN THE REGION $p_T^{h_1} > 1.5$ GeV, $p_T^{h_2} > 1.0$ GeV ($p_T^{h_1} > p_T^{h_2}$) A NEGATIVE ASYMMETRY $A = -0.28 \pm 0.12(stat.) \pm 0.02(syst.)$ IS OBSERVED. IN CONTRAST TO THE POSITIVE ASYMMETRIES MEASURED IN SEMI-INCLUSIVE DIS.

WITHOUT THE REQUIREMENT $p_T^{h_1} > 1.5$ GeV THE ASYMMETRY IS CONSISTENT WITH ZERO.

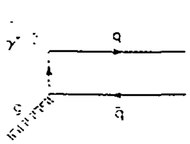
CONTRIBUTIONS FROM SUBPROCESSES

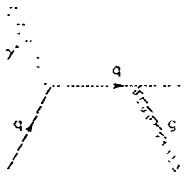
- LOWEST ORDER DIS
  ⇒ SUPPRESSED BY HIGH-p_T REQUIREMENT

- INTERACTION VIA THE HADRONIC STRUCTURE OF THE PHOTON DESCRIBED BY THE VMD → ASSUMED TO HAVE NEGLIGIBLE SPIN ASYMMETRY

- NON-RESONANT HADRONIC ($q\bar{q}$) ANOMALOUS PHOTON STRUCTURE
  → MAY BE NEGLECTED ACCORDING TO SCHULER/SJOSTRAND

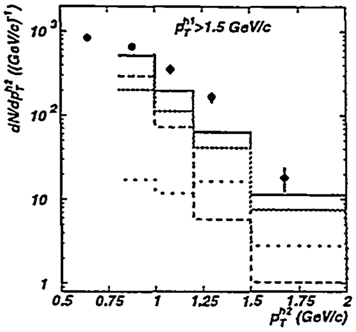
- TWO FIRST ORDER QCD PROCESSES (DIRECT) WHICH DESCRIBE THE INTERACTION OF A POINTLIKE PHOTON. THESE ARE PHOTON GLUON FUSION (PGF) AND THE QCD COMPTON EFFECT (QCDC).





MC-Data Comparison

PYTHIA 5.724 WITH $\hat{p}_T^{\min} = 0.5$ GeV. JETSET FRAGMENTATION TUNED TO HERMES SIDIS DATA.



SOLID: PGF, DASHED: QCDC, DOTTED: VMD

- p_T-DEPENDENCE SIMILAR BUT SIGNIFICANTLY SMALLER IN MAGNITUDE (AGREEMENT IS BETTER FOR DEFAULT JETSET FRAGMENTATION PARAMETERS)
- POSSIBLY CONTRIBUTIONS FROM HIGHER-ORDER QCD PROCESSES AND/OR CONTRIBUTIONS FROM HARD INTERACTIONS OF THE HADRONIC STRUCTURE OF THE PHOTON (SIMULATION OF THE DIRECT QCD PROCESSES IS RESTRICTED TO LO).
- GOOD AGREEMENT FOR THE DISTRIBUTIONS IN OTHER KINEMATIC VARIABLES, E.G. AZIMUTHAL ANGLE BETWEEN THE TWO HADRONS AND $\Delta p_T = |\vec{p}_T^{h^-}| - |\vec{p}_T^{h^+}|$.

Extraction of $\Delta G/G$

$$A_{\|} \approx (A_{\mathrm{PGF}} f_{\mathrm{PGF}} + A_{\mathrm{QCDC}} f_{\mathrm{QCDC}}) D$$

f_{PGF}, f_{QCDC}: UNPOLARIZED SUBPROCESS FRACTIONS
D: VIRTUAL PHOTON DEPOLARIZATION FACTOR

$$A_{\mathrm{PGF}} \approx \langle \hat{a}_{PGF}(\gamma G \to q\bar{q}) \rangle \langle \frac{\Delta G}{G} \rangle$$

$$A_{\mathrm{QCDC}} \approx \langle \hat{a}_{QCDC}(\gamma q \to qG) \rangle \langle \frac{\Delta q}{q} \rangle$$

HARD SUBPROCESS ASYMMETRIES DIRECTLY CALCULABLE IN LO QCD: $\hat{a}_{\mathrm{PGF}} = -1$, $\hat{a}_{\mathrm{QCDC}} \approx 0.5$

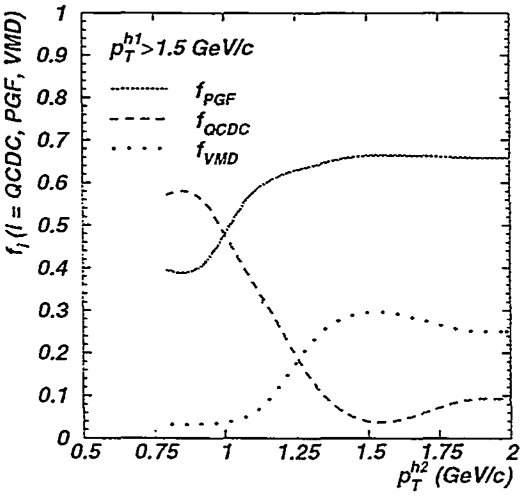
$$A_{\|} \approx \left(\hat{a}_{\mathrm{PGF}} \frac{\Delta G}{G} f_{\mathrm{PGF}} + \hat{a}_{\mathrm{QCDC}} \frac{\Delta q}{q} f_{\mathrm{QCDC}} \right) D,$$

AFTER APPROPRIATE AVERAGING OVER THE SELECTED KINEMATICS:

$$\frac{\Delta G}{G} = \frac{A_{\|} - \langle \hat{a}_{\mathrm{QCDC}} \rangle \frac{\Delta q}{q} f_{\mathrm{QCDC}} \langle D \rangle}{\langle \hat{a}_{\mathrm{PGF}} \rangle f_{\mathrm{PGF}} \langle D \rangle}.$$

$\langle \hat{a}_{\mathrm{QCDC}} \frac{\Delta q}{q} D \rangle = 0.15$, $\langle D \rangle = 0.93$

Extracted Subprocess Fractions

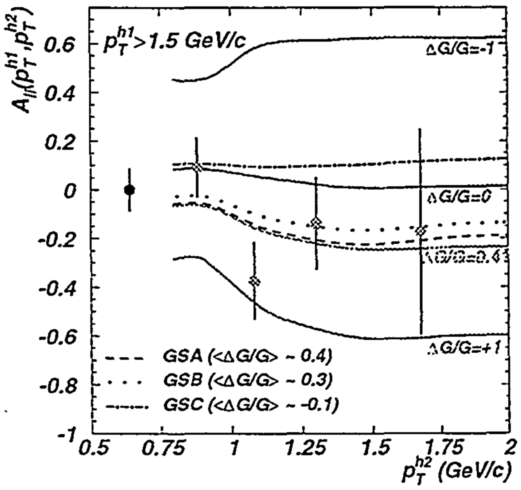


$$f_{PGF} + f_{QCDC} + f_{VMD} = 1$$

$\hat{a}_{\mathrm{PGF}} = -1$ $\hat{a}_{\mathrm{QCDC}} \approx 0.5$

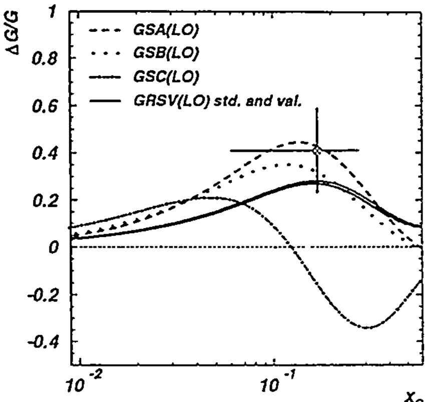
THE OBSERVED ASYMMETRY $A_{\|}$ IS LARGE AND NEGATIVE WHERE PGF IS EXPECTED TO DOMINATE.

Sensitivity of the Asymmetry to $\Delta G/G$



MC PREDICTIONS FOR $\Delta G/G = \pm 1$ (LOWER/UPPER SOLID CURVES), $\Delta G/G = 0$ (MIDDLE SOLID CURVE), AND THE PHENOMENOLOGICAL LO QCD FITS (DASHED, DOTTED AND DOT-DASHED CURVES).

EXTRACTED $\Delta G/G$



LO QCD FITS EVALUATED AT $Q^2 = 2$ GeV^2.

$$\langle \Delta G/G \rangle = 0.41 \pm 0.18 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$$

WITH $0.06 < x_G < 0.28$, $\langle x_G \rangle = 0.17$

- UNKNOWN THEORETICAL UNCERTAINTY ARISES FROM POSSIBLE DEFICIENCIES IN THE USED MC MODEL.
- SIGNIFICANT CONTRIBUTION FROM A NEGLECTED PROCESS WITH A LARGE NEGATIVE SPIN ASYMMETRY NECESSARY TO ALTER THE PRINCIPAL CONCLUSION THAT $\langle \Delta G/G \rangle$ AT $\langle x_G \rangle = 0.17$ IS POSITIVE.

SUMMARY AND OUTLOOK

◇ NEGATIVE ASYMMETRY IN PHOTOPRODUCTION OF PAIRS OF HIGH-p_T HADRONS $A_{\parallel} = -0.28 \pm 0.12$ (stat.) ± 0.02 (syst.) FOR $p_T^{h_1} > 1.5$ GeV/c, $p_T^{h_2} > 1.0$

◇ FIRST ATTEMPT FOR A DIRECT MEASUREMENT OF $\Delta G(x)$.

◇ INTERPRETATION IN FRAMEWORK OF LO QCD MODEL: $\langle \Delta G/G \rangle$ IS POSITIVE $\langle \Delta G/G \rangle = 0.41 \pm 0.18$ (stat.) ± 0.03 (syst.) AT $\langle x_G \rangle = 0.17$ AND SCALE $\langle \hat{p}_T^2 \rangle = 2.1$ GeV^2.

◇ FUTURE: MAY 2000. STATISTICS ON POLARIZED DEUTERIUM - TWICE THE PRESENT STATISTICS ON HYDROGEN.

- → CHECK DIFFERENCE BETWEEN LEADING h^+ AND LEADING h^-
- → IMPROVE STATISTICAL SIGNIFICANCE OF THE RESULT
- → TRY TO IMPROVE THEORETICAL UNDERSTANDING

The COMPASS Experiment at

ALESSANDRO BRAVAR
Universität Mainz
RICH Spin Workshop
BNL, 6 - 8 October 1999

The COMPASS Collaboration

Common Muon and Proton Apparatus
for Structure and Spectroscopy

Belgium, Finland, Germany, India, France
Israel, Italy, Japan, Poland, Russia,
Switzerland, USA

Bielefeld, Bochum, Bonn, Calcutta, CERN, BNL,
Dubna, Erlangen, Freiburg, Heidelberg,
Helsinki, Mainz, Miyazaki, Mons, Moscow,
Munich, Nagoya, Protvino, Saclay, Tel Aviv,
Torino, Trieste, Warsaw

- 28 Institutes
- ~ 170 Physicists

Physiscs with Polarized Muons & Targets

- $\Delta G/G$ GLUON POLARIZATION
  open charm
  hidden charm
  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 ($x_F < 0$)
  fracture functions
- EXCLUSIVE PROCESSES
  elastic vector mesons (ρ^0, ϕ, J/Ψ)
  deep virtual compton scattering
- …

Physiscs with Hadron Beams

HADRON STRUCTURE

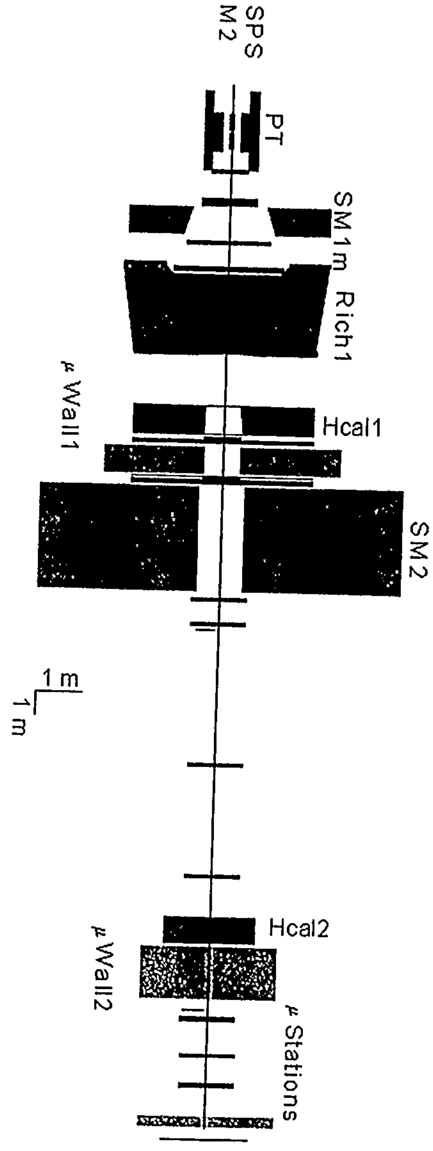
- Polarizabilities in Primakoff reactions (π, K, p)

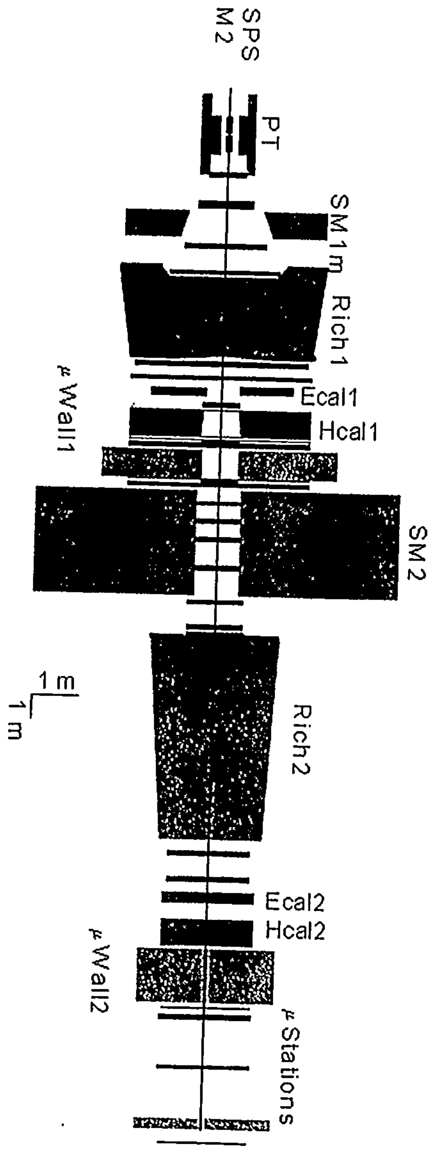
LIGHT QUARK SPECTROSCOPY AND GLUONIC STATES

- Search for glueballs in Pomeron - Pomeron scattering
- Search for hybrids / exotic states

CHARMED HADRONS

- production phenomena (π, K, p beams)
- semileptonic decays
- leptonic decays
- precision measurements of c - baryon lifetimes
- production and spectroscopy of cc - baryons (Ξ_{cc}, Ω_{cc})





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% $\langle P \rangle / N \sim 16$ deuteron ^{6}LiD P~50% $\langle P \rangle / N \sim 25$

$\int_{1y} \mathcal{L}\, dt = 2\ fb^{-1}$/year (incl. 25% eff.)

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

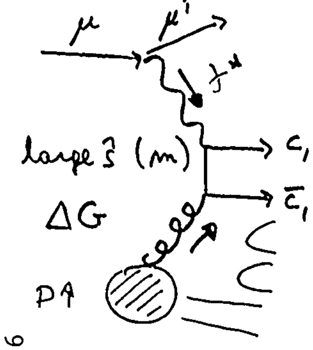
ECALs, HCALs

TRIGGER photo-production $Q^2 \sim 0$; $y > 0.$

DIS $Q^2 > 0.5$; $y > 0.1$

HOW: POLARIZED $\ell\uparrow p\uparrow$ SCATTERING
FOR PROCESSES INITIATED BY GLUONS (PGF)
IN DIS & $Q^2 \sim 0$ PHOTO-PROD. LIMIT

- HEAVY FLAVORS (c, b)

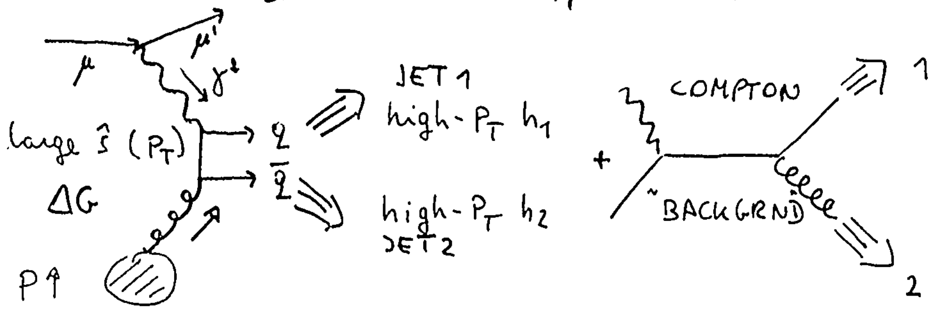


$$A_{LL} \sim \langle a_{LL}^{PGF} \rangle \langle \frac{\Delta G}{G} \rangle \cdot \frac{1}{D}$$

$$\delta \langle \frac{\Delta G}{G} \rangle \sim \langle a_{LL}^{PGF} \rangle^{-1} \cdot \delta A_{LL}$$

$$\delta A_{LL} \sim \frac{1}{\sqrt{N}} \cdot \frac{1}{P_T} \cdot \frac{1}{P_B} \cdot \frac{1}{D}$$

- DI-JETS & CORR. HIGH-P_T HADRONS



$$A_{LL} \sim \langle a_{LL}^{PGF} \rangle \langle \frac{\Delta G}{G} \rangle R + \langle a_{LL}^{COMPT} \rangle \langle \frac{\Delta u}{u} \rangle (1-R) \qquad R = \frac{\sigma^{PGF}}{\sigma^{TOT}}$$

↳ "subtract" COMPTON:
. additional uncertainty on $\langle \frac{\Delta G}{G} \rangle$

OPEN CHARM & PGF

O.C. WELL DESCRIBED BY PHOTON-GLUON FUSION

CLEAN HARD PROCESS
ONE LARGE SCALE $\hat{s}$
$\hat{s} \geq 4 m_c^2 \sim 10 \text{ GeV}^2$

$$\Delta \sigma^{\gamma p \to c\bar{c}} \propto \int \Delta G \, \Delta\hat{\sigma}$$

OPEN CHARM PRODUCTION

- LARGE CROSS SECTION, $\sim 1\%$ of $\sigma_{TOT}^{\gamma p}$ @100G
- NO (LARGE) DIFFRACTIVE CONTRIB.
- (ALMOST) NO CONSTITUENT CHARM
- SMALL CONTRIB. RESOLVED PHOTON (Few %)

POLARIZED

$$\hat{\sigma}^{\uparrow\uparrow} \neq \hat{\sigma}^{\uparrow\downarrow} \longrightarrow \Delta G$$

γg SUB PROCESS KNOWN
UNPOLARIZED
POLARIZED $\Big\rangle$ NLO

LEPTO PRODUCTION

$$\sigma^{\mu p \to c\bar{c}} = \Gamma(E; Q^2, \nu) \cdot \frac{\sigma^{\gamma p \to c\bar{c}}}{[1 + Q^2/M_0^2]^2} \leftarrow \gamma\text{-prod.}$$

$$\Gamma = \gamma^* \text{ flux} \sim \alpha_{EM} Q^{-2} \nu^{-1}$$

Rate Estimates for 100 GeV Beam

PROPOSAL!

Signal: $D^0 \to K\pi$ and $D^{*+} \to D^0 \pi_s^+$ ONLY
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\hookrightarrow K\pi$

$$N_s^{D^0} = \int \mathcal{L}\,dt \times \sigma^{\mu p \to c\bar{c}} \times \frac{N^{D^0+\overline{D^0}}}{N^{cc}} \times B.R. \times \varepsilon_{det.,tar.}$$

$$= 4.3 \times 10^{37} \mathrm{cm}^{-2}\mathrm{day}^{-1} \times 1.9\,\mathrm{nb} \times 1.2 \times 4\% \times 23\%$$

$$= 900 \text{ Events/day:} \quad D^{*+} \to D^0 \pi^+_{soft} \approx 300 \text{ Events/day}$$

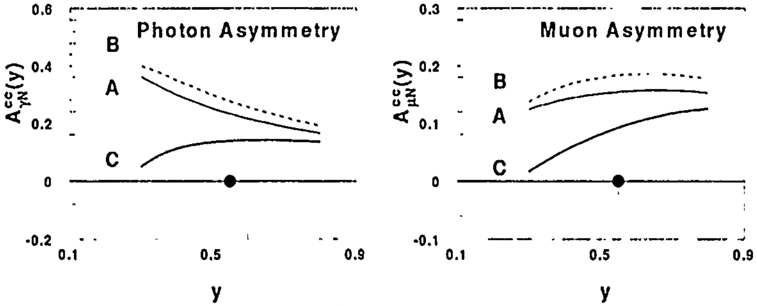
Background:

$$N_{Bkg}^{D^0} = \int \mathcal{L}\,dt \times \sigma^{\mu p}_{tot} \times \varepsilon_{accidental.,det.,tar.}$$

$$= 4.3 \times 10^{37} \mathrm{cm}^{-2}\mathrm{day}^{-1} \times 460\,\mathrm{nb} \times 1.6 \times 10^{-4}$$

$$= 3400 \text{ Events/day:} \quad D^{*+} \to D^0 \pi^+_{soft} \approx 0 \text{ Events/day}$$

$\rightsquigarrow \; \delta A^{c\bar{c}}_{\gamma p} \approx 0.051 \quad \rightsquigarrow \; \delta\left(\frac{\Delta G}{G}\right) \approx 0.14$ (after 2★ years)



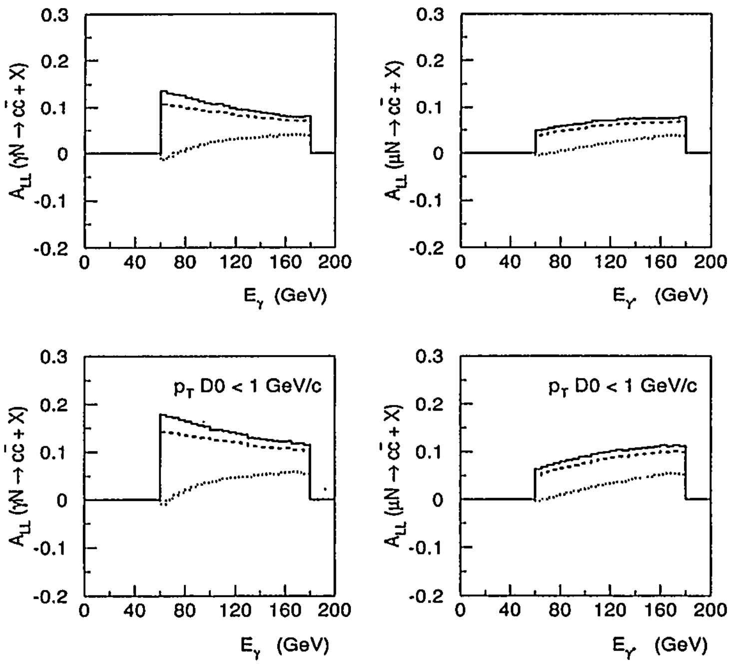
(gluon helicity distribution: Gehrmann & Stirling (1995))

★ additional kinematic contraints (p_T) on PGF $\rightsquigarrow \; \delta\left(\frac{\Delta G}{G}\right) \lesssim 0.10$

$A_{LL}^{\gamma^* N \to c\bar{c}}$ & $A_{LL}^{\mu N \to c\bar{c}}$ for 200 GeV μ's @ LO

$$A_{LL}^{\gamma^* N \to c\bar{c}} = \frac{1}{D} \cdot A_{LL}^{\mu N \to c\bar{c}} = \frac{1}{D} \cdot \frac{\Delta\sigma^{\mu N \to c\bar{c}}}{\sigma^{\mu N \to c\bar{c}}}$$

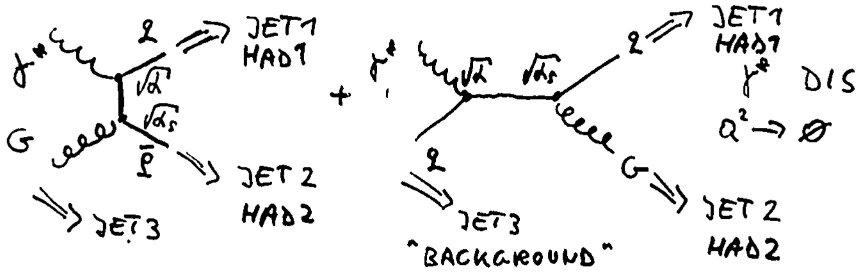
$D \equiv$ depolarization factor



INPUTS: polarized pdf: Gehrmann and Stirling, PRD 53 (96) 6100.
unpolarized pdf: Martin, Roberts, and Stirling, PLB 354 (95) 155.

G and $\underline{\Delta G}$ from DI-JETS and HIGH P_T CORRELATED HADRONS

L.O. (α_s) QCD DIAGRAMS FOR 2 JET PRODUCTION



$$\Delta\sigma^{HH} = \int_{PH.S} \Delta q(x)\, \Delta\hat{\sigma}^{L.O.}\, \overset{=0}{\cancel{D_q^{HH}}} \;+$$

$$\Delta G(\eta)\, \Delta\hat{\sigma}^{PGF}\left[D_{q\bar{q}}^{HH} + 1 \leftrightarrow 2\right] \;+$$

$$\Delta q(\eta)\, \Delta\hat{\sigma}^{COM}\left[D_{qG}^{HH} + 1 \leftrightarrow 2\right]$$

SCALE ~ $\sum p_T^2$ (~ 10 GeV^2 for high p_T had)

η - MOMENTUM FRACTION

q MOSTLY u QUARKS (charge & $\eta \sim 0.1$)

$$A_{LL}^{HH} = \frac{\Delta\sigma^{HH}}{\sigma^{HH}} \sim \langle a_{LL}^{PGF}\rangle \left\langle \frac{\Delta G}{G} \right\rangle \frac{\sigma^{PGF}}{\sigma^{TOT}} +$$

$$\langle a_{LL}^{COM}\rangle \left\langle \frac{\Delta u}{u} \right\rangle \frac{\sigma^{COM}}{\sigma^{TOT}}$$

TO EXTRACT (Δ)G MUST "SUBTRACT" COMPTON BKG

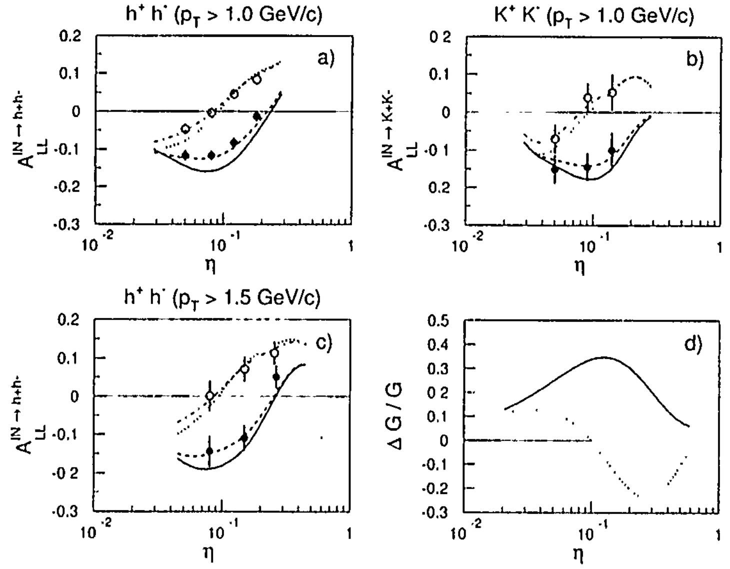
$$\frac{\sigma^{PGF}}{\sigma^{COM.}} = f(\eta, Q^2) \propto \frac{G(\eta, Q^2)}{u(\eta, Q^2)}$$

$A_{LL}^{lN \to h^+h^-}$ correlated high − p_T hadrons

Expectations for 200 GeV μ's with ^{6}Li^{2}H target

$\int Ldt = 2\text{fb}^{-1} \equiv 1$ year of COMPASS

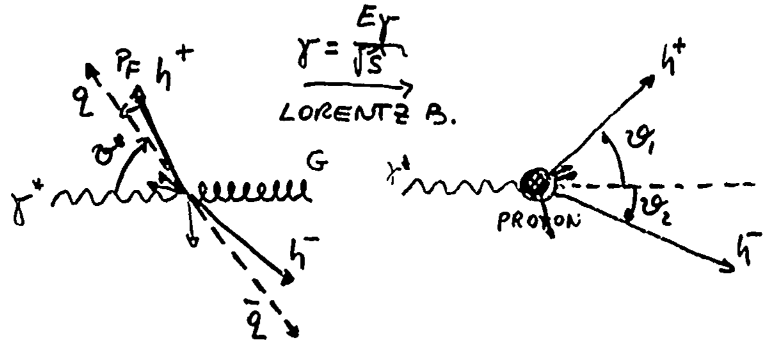
Bravar, von Harrach, and Kotzinian, PLB 421 (98) 349.



$\Rightarrow \delta\left(\frac{\Delta G}{G}\right) \sim 5$ % for each data point

dominated by systematics !

KINEMATICS



C.M. FRAME LAB. FRAME

$$P_T^* = \varrho\, p^* \sin\vartheta^* \quad \longrightarrow \quad P_T = P_T^* = \varrho\, p^* \sin\vartheta^*$$

$$P_L^* = \varrho\, p^* \cos\vartheta^* \quad \longrightarrow \quad P_L = \;= \gamma\, \varrho\, p^* (\pm\cos\vartheta^* + 1) \quad (\beta = 1)$$

p^* - mom. of quark

$(1-\varrho)$ - mom. fraction of quark carried by hadron $(q \to h)$

EXTRACT η - MOM. FRACT. OF GLUON

$$\tan\vartheta^{\pm}_{LAB} = \frac{P_T^{\pm}}{P_L^{\pm}} = \frac{\sin\vartheta^*}{\gamma\,(\pm\cos\vartheta^* + 1)} \qquad \gamma = \frac{E_{\gamma^*}}{\sqrt{s}}$$

$$\tan\vartheta^+_{LAB} \cdot \tan\vartheta^-_{LAB}$$

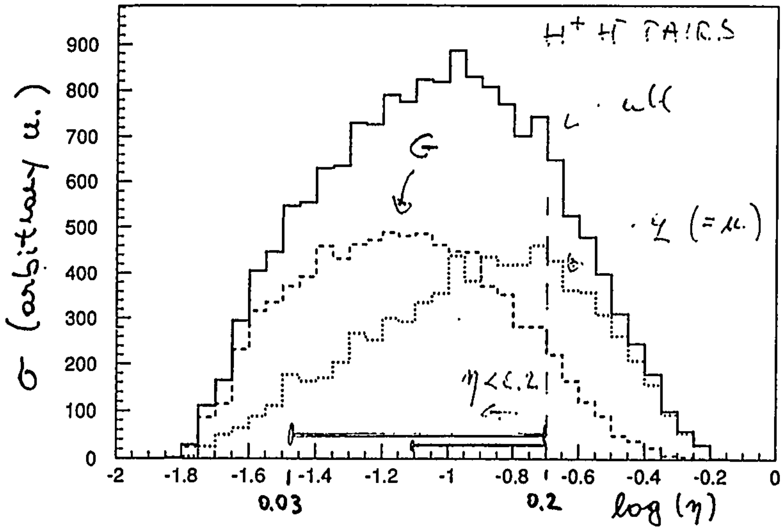
$$\hat{s} = E_{\gamma^*}^2 \cdot \tan\vartheta^+_{LAB} \cdot \tan\vartheta^-_{LAB}$$

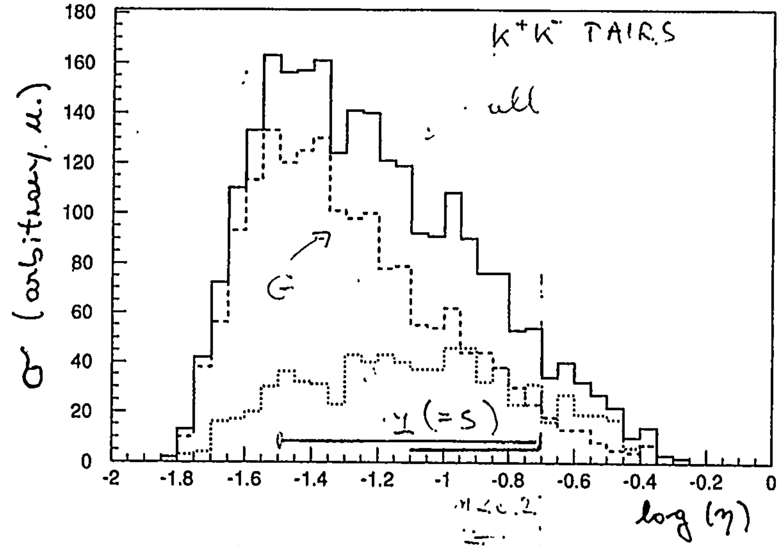
$$\eta = \frac{\hat{s} + Q^2}{2M\, E_{\gamma^*}}$$

EXTRACT $\cos\vartheta^*$ - SCATTERING ANGLE IN C.M.

$$\cos\vartheta^* = (\tan\vartheta^+_{LAB} - \tan\vartheta^-_{LAB}) / (\tan\vartheta^+_{LAB} + \tan\vartheta^-_{LAB})$$

GLUON DISTRIBUTIONS





INPUT: GRV 94 LO

SELECTIONS: $P_T^{\pm} > 1$ GeV, $x_F^{\pm} > 0$, $\Delta\varphi = 180° \pm 30°$

Semi-Inclusive Results from the Spin Muon Collaboration (SMC)

Jörg Pretz
Yale University, New Haven, CT
on behalf of the Spin Muon Collaboration

A measurement and analysis of semi-inclusive asymmetries for positively and negatively charged hadrons from deep inelastic scattering of longitudinally polarised muons on polarised protons and deuterons in the range $0.003 < x < 0.7$ of the Bjorken variable and for a momentum transfer $Q^2 > 1$ GeV^2 is presented. From these asymmetries and the SMC inclusive spin asymmetries we determine the polarised quark distributions of valence quarks, $\Delta u_v(x)$ and $\Delta d_v(x)$, and non-strange sea quarks, $\Delta\bar{q}(x)$, at Q^2=10 GeV^2. Combining all SMC data we find for the first moments $\int_0^1 \Delta u_v(x)\mathrm{d}x = 0.92 \pm 0.11 \pm 0.07$, $\int_0^1 \Delta d_v(x)\mathrm{d}x = -0.53 \pm 0.15 \pm 0.07$ and $\int_0^1 \Delta\bar{q}(x)\mathrm{d}x = -0.02 \pm 0.05 \pm 0.02$, where we assumed $\Delta\bar{u}(x) = \Delta\bar{d}(x) =: \Delta\bar{q}(x)$. The first moments for the valence quarks are consistent the with first moments deduced in LO from SU(3) matrix elements F and D assuming a flavor symmetric sea ($\Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta s(x) = \Delta\bar{s}(x)$).

The x-range covered corresponds to 90% for the u_v quarks and 84% for the d_v quarks ($\int_{0.003}^{0.7} u_v(x)dx = 1.80$, $\int_{0.003}^{0.7} d_v(x)dx = 0.84$), i.e. the extrapolated region at low x amounts only to 10% and 16% for the u_v and d_v quarks respectively. The low x extrapolation was obtained from fits to our data using different parameterizations of the polarized quark distributions and using parameterizations obtained from fits to inclusive data.

We also determine for the first time the second moments of the valence distributions $\int_0^1 x\Delta q_v(x)\mathrm{d}x$ which we find consistent with recent Lattice QCD calculations.

These results are published in Phys. Lett. B420 (1998) 180.

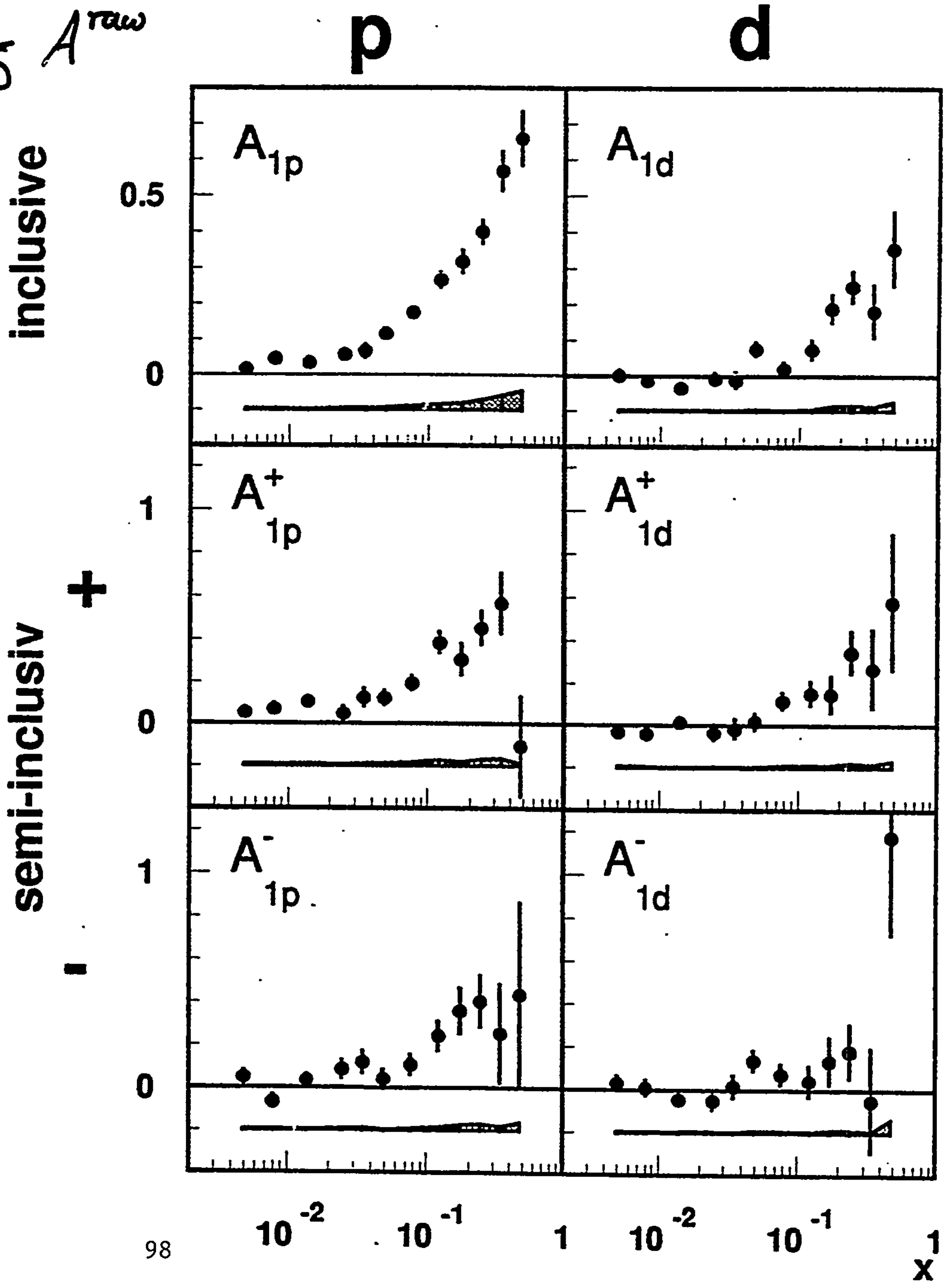
Asymmetries

$Q^2 > 1\ \mathrm{GeV}^2,\ z = \frac{E_{had}}{\nu} > 0.2$

$1.3 < Q^2 < 60\ \mathrm{GeV}^2,\ \langle Q^2 \rangle = 10\ \mathrm{GeV}^2$

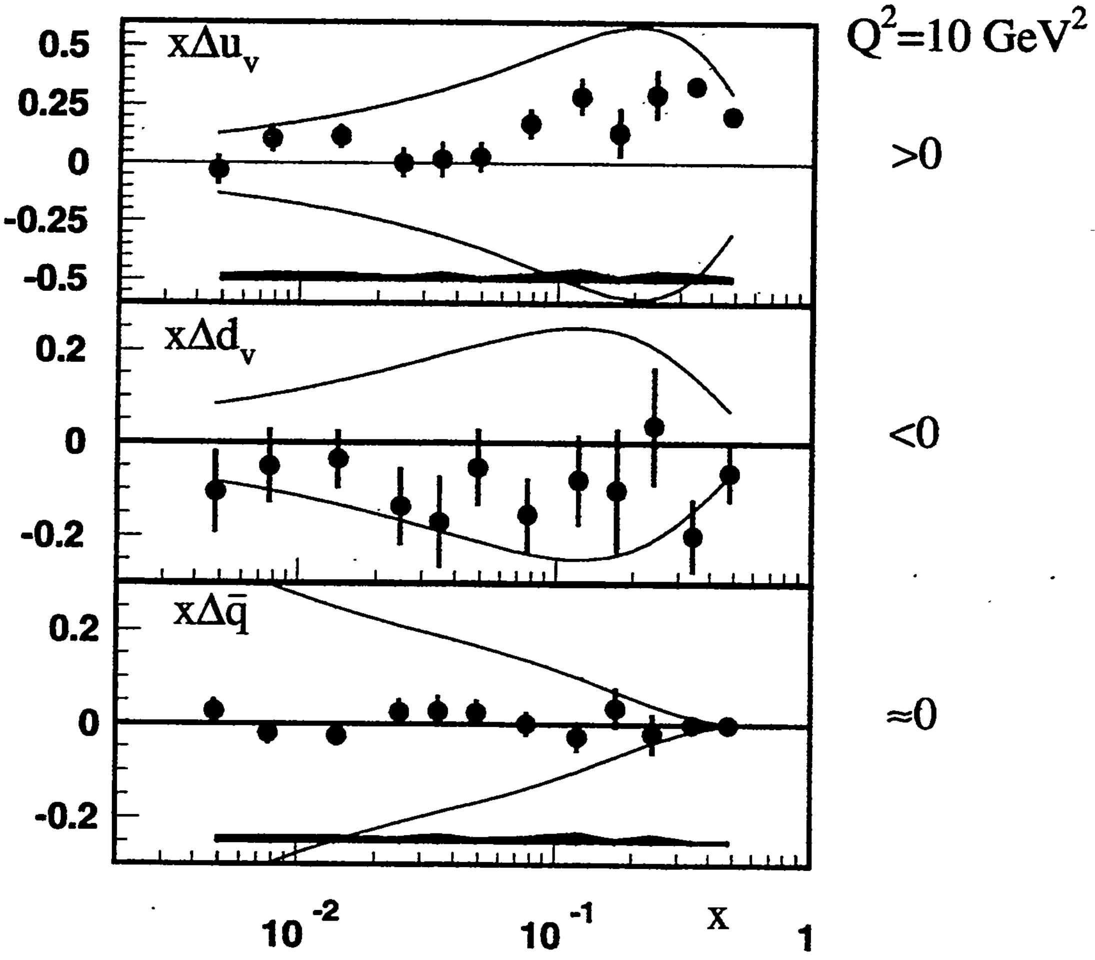
$0.003 < x < 0.7$

$A = \frac{1}{P_B P_T f D} A^{raw}$

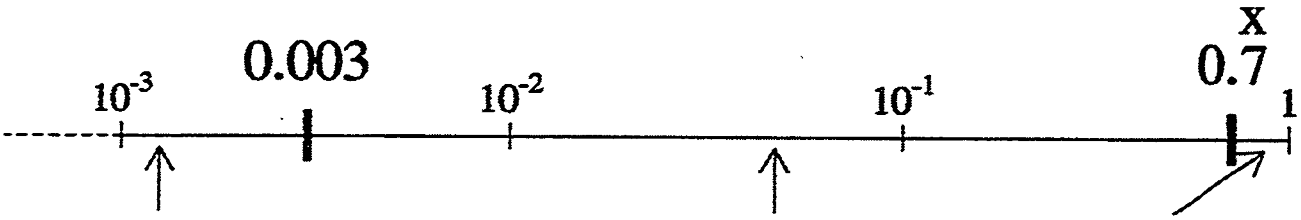


$\Delta u_v, \Delta d_v \& \Delta \bar{q}$

$x(q^{\uparrow} - q^{\downarrow}) = x\Delta q(x)$ (points)
$x(q^{\uparrow} + q^{\downarrow}) = xq(x)$ (lines)
unpolarized quark distributions (GRV)
$|\Delta q(x)| < q(x)$



Integrals $\int_0^1 \Delta q(x) dx$



fits to semi-incl. data and
parameterizations obtained
from inclusive data

measured

negligible
because unpol.
dist. are small

$\int dx$	0-0.003	0.003-0.7	0 - 1
Δu_v	0.04 ± 0.04	$0.73 \pm 0.10 \pm 0.07$	$0.77 \pm 0.10 \pm 0.06$
Δd_v	-0.05 ± 0.05	$-0.47 \pm 0.14 \pm 0.08$	$-0.52 \pm 0.14 \pm 0.09$
$\Delta \bar{q}$	0.00 ± 0.02 (syst.)	$0.41 \pm 0.04 \pm 0.03$ (stat) (syst.)	$0.01 \pm 0.04 \pm 0.03$ (stat) (syst)

$\Delta\Sigma = \Delta u_v + \Delta d_v + 6\Delta\bar{q} = 0.26 \pm 0.07 \pm 0.03$
at $Q^2 = 10 \mathrm{GeV}^2$,
published in PLB 420 (1998) 180

<u>syst. error:</u> unknown fragm. functions, P_B, P_T, ...
Assuming $\Delta\bar{u} = \Delta\bar{d} = \eta\Delta s = \eta\Delta\bar{s}$ and varying η
in the range $0.25 < \eta < 1.5$ changes $\int \Delta u_v(x)dx$ by 0.006
⇒ sensitive to **non** starnge quarks only

Comparison with ...

... baryon decays

Assumptions:

(1) $SU_f(3)$ sym. sea $(\Delta\overline{u} = \Delta\overline{d} = \Delta s = \Delta\overline{s})$

(2) $SU_f(3)$ sym. in $(\Delta u_p = \Delta d_n\ , \Delta u_p = \Delta s_{\Xi^0}, \ldots\ )$
baryon octet

$$\Rightarrow g_A^{n\rightarrow p} = \int \Delta u_v - \Delta d_v\, dx\ , \quad g_A^{\Xi^0\rightarrow\Lambda} = \int \Delta u_v + \Delta d_v\, dx$$

	strongly depend on (1) & (2)	SMC
$\int \Delta u_v(x)\, dx =$	0.92 ± 0.02	$0.77 \pm 0.10 \pm 0.08$
$\int \Delta d_v(x)\, dx =$	-0.34 ± 0.02	$-0.52 \pm 0.14 \pm 0.09$

... lattice QCD

2nd moments of the valence distributions

	M. Glöckler et al. hep-ph / 9708270	SMC
$\int x\, \Delta u_v(x)\, dx =$	0.189 ± 0.008	$0.155 \pm 0.018 \pm 0.010$
$\int x\, \Delta d_v(x)\, dx =$	-0.046 ± 0.003	$-0.056 \pm 0.026 \pm 0.011$

Summary

- $\Delta u_v(x) > 0$, $< \Delta u_v/u_v > \approx$ 50 %
  polarisation increasing with x

  $\Delta d_v(x) < 0$, $< \Delta d_v/d_v > \approx -$ 50 %

  $\Delta\overline{q}(x) \approx 0$, $2 \int \Delta\overline{q}(x)\, dx = 0.02 \pm 0.10$

  $\updownarrow$

  $\int \Delta s(x) + \Delta\overline{s}(x)\, dx = -0.11 \pm 0.03$

- first direct measurement of
  polarised quark distributions

- good agreement
  1st moments ↔ baryon decay constants
  2nd moment ↔ lQCD

PHYSICS RESULTS FROM HERMES
POLARIZED QUARK DISTRIBUTIONS

RALF KAISER - DESY/ZEUTHEN
ON BEHALF OF THE HERMES COLLABORATION

RHIC SPIN WORKSHOP, BNL, OCTOBER 1999

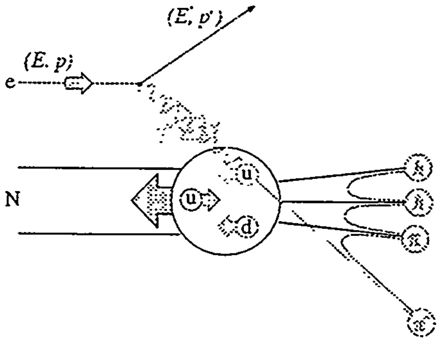
- SEMI-INCLUSIVE DEEP INELASTIC SCATTERING
- POLARIZED QUARK DISTRIBUTIONS
- COMPARISON TO PREDICTIONS
- OUTLOOK

RESULTS ARE BASED ON THE DATA TAKING PERIODS 1995-1997 OF THE HERMES EXPERIMENT AT HERA.

Flavor Decomposition of the Polarized Quark Distributions in the Nucleon from Inclusive and Semi-inclusive Deep-inelastic Scattering, HEP-EX/9906035, TO BE PUBLISHED IN PHYS. LETT. B

SEMI-INCLUSIVE DIS

IN SEMI-INCLUSIVE DEEP INELASTIC SCATTERING A HADRON h IS DETECTED IN COINCIDENCE WITH THE SCATTERED LEPTON.



- SELECT HADRONS FROM THE CURRENT FRAGMENTATION REGION BY CUTS ON $z = E_h/\nu > 0.2$ AND $x_F = 2p_L^*/W \geq 0.1$
- IN LO QCD (ASSUMING SPIN INDEPENDENCE OF FRAGMENTATION):

$$\frac{g_1^h}{F_1^h}(x, Q^2) = \frac{\int_{z_{min}}^1 dz \sum_q e_q^2 \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)}{\int_{z_{min}}^1 dz \sum_q e_q^2 q(x, Q^2) \cdot D_q^h(z, Q^2)}$$

$(\Delta q)q$: (POLARIZED) QUARK DISTRIBUTION
D_q^h: FRAGMENTATION FUNCTION

EXPERIMENTAL DETERMINATION OF g_1/F_1

THE RATIO

$$\frac{g_1^{(h)}}{F_1^{(h)}} = \frac{\sum_q e_q^2 \Delta q \cdot D_q^h}{\sum_q e_q^2 q \cdot D_q^h}$$

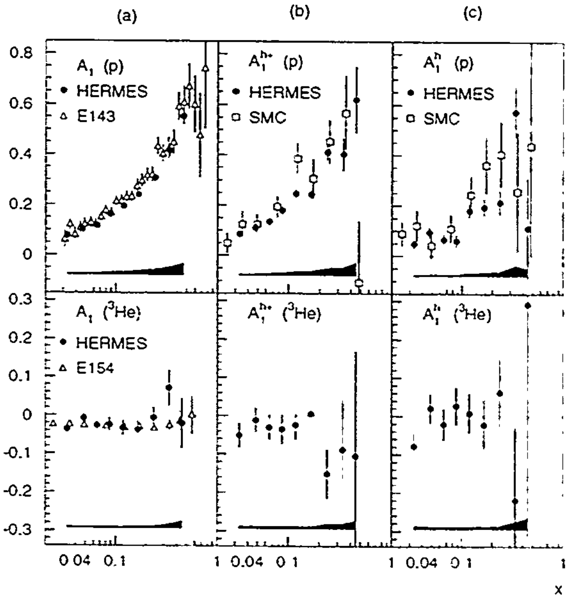
IS RELATED TO THE MEASURED LEPTON NUCLEON ASYMMETRY $A_{\|}^{(h)}$ BY

$$\frac{g_1^{(h)}}{F_1^{(h)}} = \frac{1}{1 + \eta\gamma} \left[\frac{A_{\|}^{(h)}}{D} + \gamma(\gamma - \eta) \cdot \frac{g_2^{(h)}}{F_1^{(h)}} \right]$$

FROM THE ASSUMPTION $g_2^{(h)} = 0$ FOLLOWS

$$A_1^{(h)} = \frac{g_1^{(h)}}{F_1^{(h)}} = \frac{A_{\|}^{(h)}}{D(1 + \eta\gamma)}$$

SEMI-INCLUSIVE ASYMMETRIES



(a) INCLUSIVE ASYMMETRIES IN COMPARISON TO SLAC
(b) SEMI-INCLUSIVE ASYMMETRIES FOR POSITIVELY CHARGED HADRONS IN COMPARISON TO SMC
(c) SEMI-INCLUSIVE ASYMMETRIES FOR NEGATIVELY CHARGED HADRONS IN COMPARISON TO SMC

DATA ARE GIVEN AT MEAN Q^2 OF EACH x BIN
[illegible]

Δq-EXTRACTION

- REWRITE PHOTON-NUCLEON ASYMMETRY

$$A_1^h(x,z) = \sum_q \left[\underbrace{\frac{e_q^2\, q(x)\cdot D_q^h(z)}{\sum_{q'} e_{q'}^2\, q'(x)\cdot D_{q'}^h(z)}}_{P_q^h(x,z)} \cdot \frac{\Delta q(x)}{q(x)} \right]$$

- PURITY $P_q^h(x,z)$ GIVES PROBABILITY THAT A QUARK $q(x)$ WAS STRUCK WHEN A HADRON $h(z)$ IS DETECTED
- PURITIES ARE SPIN-INDEPENDENT QUANTITIES (FRAGMENTATION PROCESS SPIN-INDEPENDENT)
- DEFINE

$$\vec{A} = \begin{pmatrix} A_1^{h_1(x)} \\ \dots \\ A_1^{h_m(x)} \end{pmatrix} \quad \mathcal{P} = \left[P_q^{h_i}(x)\right]_{mn} \quad \vec{Q} = \begin{pmatrix} \Delta q_1(x)/q_1(x) \\ \dots \\ \Delta q_n(x)/q_n(x) \end{pmatrix}$$

WHERE $P_q^h(x) = \int_{z_{min}}^{1} P_q^h(x,z)\, dz$

- TO EXTRACT QUARK POLARIZATIONS SOLVE

$$\vec{A} = \mathcal{P}\vec{Q}$$

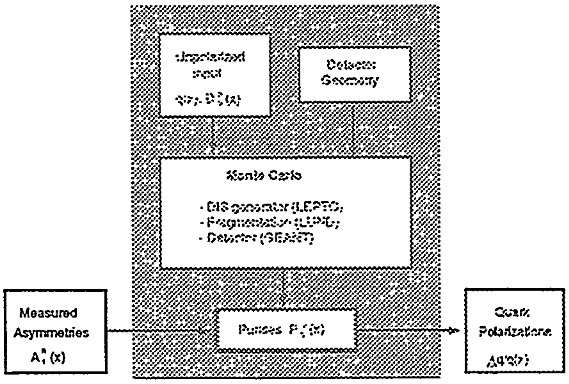
WHERE DO THE PURITIES COME FROM ?

- SMC: PURITIES

$$P_q^h(x,z) = \frac{e_q^2\, q(x)\cdot D_q^h(z)}{\sum_{q'} e_{q'}^2\, q'(x)\cdot D_{q'}^h(z)}$$

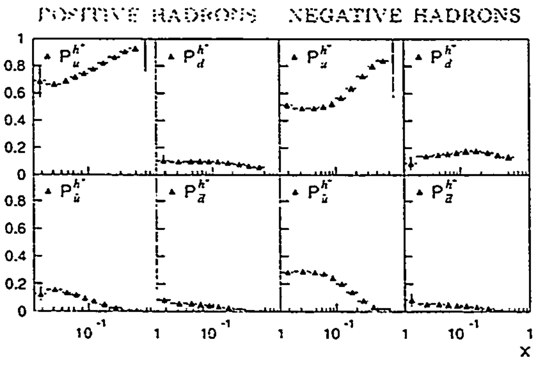
ARE DERIVED FROM MEASURED $D_q^h(z)$ AND PARAMETERIZATIONS OF $q(x)$.

- HERMES:



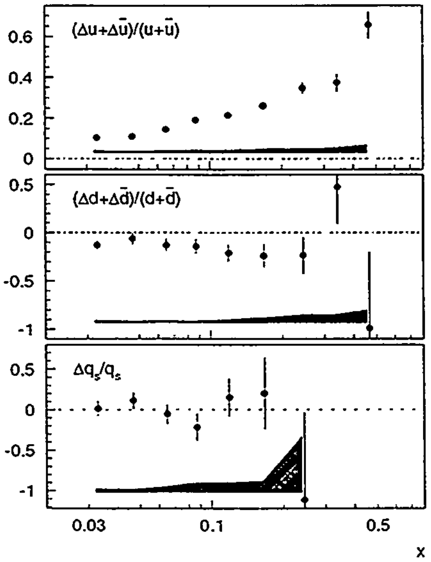
PURITIES

PURITIES $P^{h^\pm}_{u,\bar{u},d,\bar{d}}$ FOR A PROTON TARGET:



- h^+, h^--ASYMMETRIES ON THE PROTON DOMINATED BY $\Delta u(x)$
- SENSITIVITY TO $\Delta d(x) = \Delta u_n(x)$ VIA NEUTRON (^3He) DATA
- SENSITIVITY TO $\Delta\bar{u}, \Delta\bar{d} \approx 10\%$ FOR $x \leq 0.2$

FLAVOR DECOMPOSITION



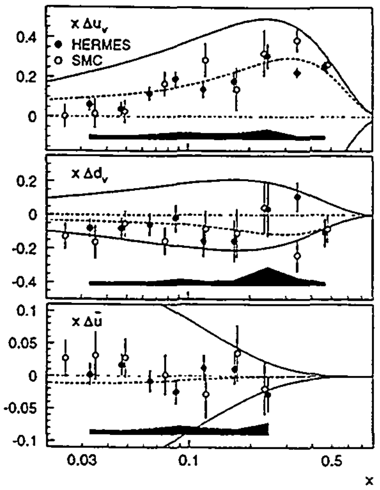
FLAVOR DECOMPOSITON OF QUARK POLARIZATIONS AS A FUNCTION OF x AT MEASURED Q^2.

SEA ASSUMPTION (1):

$\frac{\Delta q_s}{q_s} = \frac{\Delta u_s}{u_s} = \frac{\Delta d_s}{d_s} = \frac{\Delta \bar{u}_s}{\bar{u}_s} = \frac{\Delta \bar{d}_s}{d_s} = \frac{\Delta s}{s} = \frac{\Delta \bar{s}}{\bar{s}}$

— DIRECT DETERMINATION OF Δs NOT YET POSSIBLE FROM THESE DATA

VALENCE AND SEA QUARK DISTRIBUTIONS



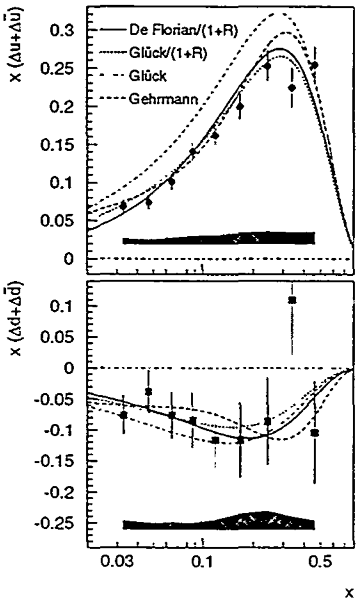
POLARIZED VALENCE AND SEA QUARK DISTRIBUTIONS AT $Q^2 = 2.5$ GeV^2 COMPARED TO SMC IN THE HERMES RANGE OF x.

SOLID LINE: POSITIVITY LIMIT

DOTTED LINE: GEHRMANN/STIRLING (GLUON A, LO).

SMC SEA ASSUMPTION (2):
$\Delta u_s = \Delta d_s = \Delta s = \Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s}$.

COMPARISON TO PARAMETERIZATIONS



DE FLORIAN AND GLÜCK PARAMETRIZATIONS CORRECTED BY A FACTOR OF $(1 + R)$ TO ALLOW FOR DIRECT COMPARISON.

INTEGRALS OVER MEASURED RANGE

INTEGRALS OVER THE MEASURED RANGE OF x ARE OBTAINED AS

$$\Delta q = \sum_i \left(\frac{\Delta q}{q}\bigg|_i \int_{x_i}^{x_{i+1}} q(x)dx \right)$$

WHERE $(\Delta q/q)|_i$ IS CONSTANT WITH EACH BIN $[x_i, x_{i+1}]$.

	HERMES	SMC
Δu_v	0.52±0.05 ± 0.08	0.59±0.08 ± 0.07
Δd_v	−0.19±0.11 ± 0.13	−0.33±0.11 ± 0.09
$\Delta\bar{u}$	−0.01±0.02 ± 0.03	0.02±0.03 ± 0.02
$\Delta\bar{d}$	−0.02±0.03 ± 0.04	0.02±0.03 ± 0.02
$\Delta\bar{s}$	−0.01±0.02 ± 0.02	0.01±0.03 ± 0.02

COMPARISON OF HERMES AND SMC INTEGRALS IN THE HERMES x-RANGE OF $0.023 \le x \le 0.6$. ALL VALUES GIVEN AT $Q^2 = 2.5$GeV^{-2}.

⇒ HERMES AND SMC RESULTS ARE IN AGREEMENT

SPIN CONTRIBUTIONS COMPARISON TO PREDICTIONS

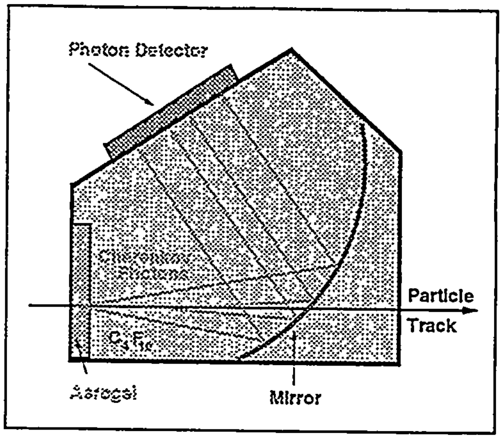
	TOTAL INTEGRAL	PREDICTION	
$\Delta u + \Delta\bar{u}$	0.57±0.02 ± 0.03	0.66±0.03	SU(3)
$\Delta d + \Delta\bar{d}$	−0.25±0.06 ± 0.05	−0.35±0.03	SU(3)
$\Delta s + \Delta\bar{s}$	−0.01±0.03 ± 0.04	−0.08±0.02	SU(3)
Δq_0	0.30±0.04 ± 0.09	0.23±0.04	SU(3)
Δq_3	0.84±0.07 ± 0.06	1.01±0.05	BJORKEN
Δq_8	0.33±0.10 ± 0.11	0.46±0.03	F& D
Δu_v	0.57±0.05 ± 0.08	0.84±0.05	LATTICE
Δd_v	−0.22±0.11 ± 0.13	−0.25±0.02	LATTICE

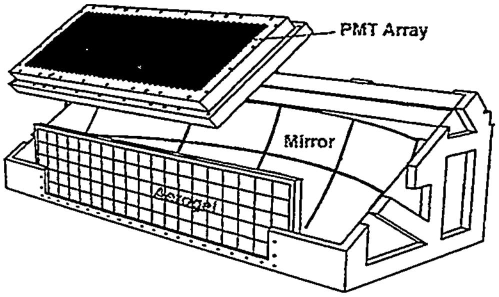
- FLAVOR SEPARATED FIRST MOMENTS DIFFER FROM SU(3) PREDICTIONS, BUT THE UNCERTAINTIES DO NOT ALLOW A STATEMENT WHETHER SU(3) FLAVOR SYMMETRY IS VIOLATED.
- $\Delta q_0 = \Delta u + \Delta d + \Delta s$ AGREES WELL WITH THE SU(3) PREDICTION.
- $\Delta q_3 = \Delta u - \Delta d$ IS IN AGREEMENT WITH THE BJORKEN SUM RULE.
- $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$ IS LOWER THAN THE PREDICTION, BUT STILL CONSISTENT.
- Δu_v OVERESTIMATED BY QUENCED LATTICE QCD

SUMMARY

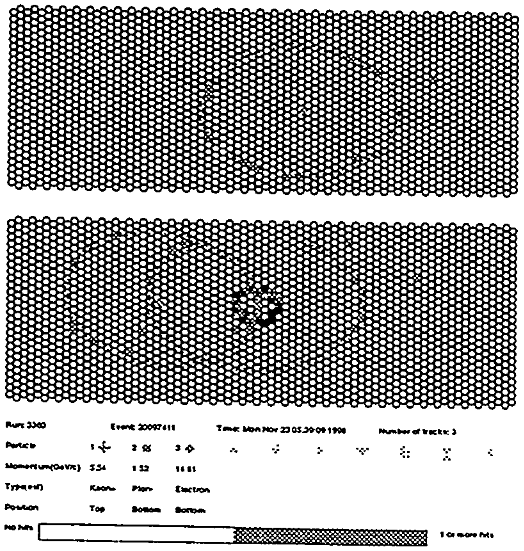
- ◇ $A_1^{(h)}$ MEASURED ON ^{3}He AND ^{1}H TARGETS
- ◇ POLARIZATION FOR u QUARKS POSITIVE, FOR d QUARKS NEGATIVE AND FOR SEA QUARKS COMPATIBLE WITH ZERO
- ◇ SINGLET COMBINATION Δq_3 AGREES WITH BJORKEN SUM RULE
- ◇ FLAVOR SEPARATED FIRST MOMENTS DIFFER FROM INCLUSIVE RESULTS BASED ON $SU(3)_f$ SYMMETRY
- ◇ OCTET COMBINATION Δq_8 LOWER THAN THE VALUE OF $3F - D$ PREDICTED USING $SU(3)_f$, BUT STILL CONSISTENT

THE HERMES RICH

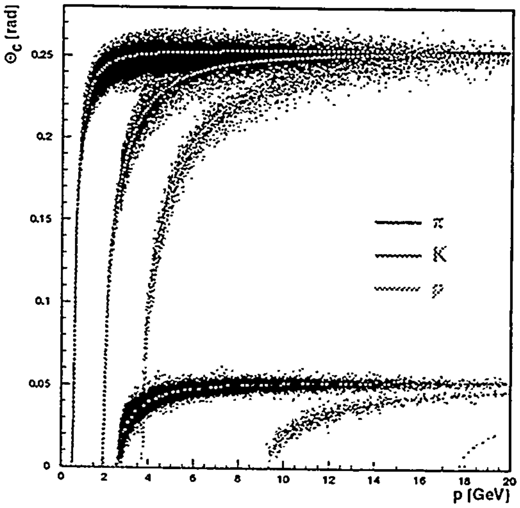




CHARM MESON CANDIDATE



HERMES RICH - AVERAGE ANGLES



⇒ DESIGN RESOLUTION REACHED FOR GAS AND AEROGEL (WITHIN 10%).

OUTLOOK

◇ IMPROVED PRECISION FOR $\Delta d(x)$ WITH DEUTERIUM TARGET

◇ π, K, p ASYMMETRIES AND FRAGMENTATION FUNCTIONS FROM RICH DATA

◇ SEPARATION OF LIGHT AND STRANGE SEA POLARIZATION

Flavor asymmetry of polarized parton distributions in Drell-Yan processes

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ABSTRACT

First, we discuss polarized proton-deuteron (pd) Drell-Yan processes in order to investigate new spin structure of a spin-1 hadron and also flavor asymmetry in polarized antiquark distributions. Our general formalism indicates that there exist many structure functions; however, the number is reduced if the cross section is integrated over the dilepton transverse momentum $\vec{Q}_T$ [1]. A parton-model analysis suggests that one of the structure functions should be related to the tensor polarized distributions [2]. There are some experimental possibilities at FNAL, HERA, and RHIC to study the polarized pd reactions.

Next, using our pd Drell-Yan formalism, we discuss the relation between the ratio of the pd Drell-Yan cross section to the proton-proton (pp) one $\Delta_{(T)}\sigma_{pd}/2\Delta_{(T)}\sigma_{pp}$ and the flavor asymmetry in polarized light-antiquark distributions. The asymmetry in the unpolarized distributions is now an established fact [3]; however, little is known in the polarized case. The results in Ref. [4] indicate that the difference between the pp and pd cross sections is valuable for finding not only the flavor asymmetry in longitudinally polarized antiquark distributions but also the one in transversity distributions. Because the flavor asymmetry in the transversity distributions cannot be found in W production processes and inclusive lepton scattering due to the chiral-odd property, it is important that we point out the possibility of using the pd/pp ratio.

References

[1] S. Hino and S. Kumano, Phys. Rev. D59 (1999) 094026.

[2] S. Hino and S. Kumano, Phys. Rev. D60 (1999) 054018.

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

[4] S. Kumano and M. Miyama, hep-ph/9909432.

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Purposes for polarized proton-deuteron Drell-Yan

- New spin structure of spin-1 hadrons

  tensor distribution (b_1)

  no theoretical description
  for polarized pd Drell-Yan
  until recently

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

  unpolarized case (established fact)

  ⟶ polarized (totally unknown)

- possibly at RHIC ? (or FNAL, HERA)

Spin asymmetries in the parton model $\left(\int d\vec{Q}_T \text{ case}\right)$

Unpolarized cross section

$$\left\langle \frac{d\sigma}{dx_A\, dx_B\, d\Omega} \right\rangle = \frac{\alpha^2}{4\,Q^2}\,(1+\cos^2\theta)\,\overline{W}_T$$
$$= \frac{\alpha^2}{4\,Q^2}\,(1+\cos^2\theta)\,\frac{1}{3}\sum_a e_a^2\,\left[f_1^a(x_A)\, f_1^{\bar{a}}(x_B) + f_1^{\bar{a}}(x_A)\, f_1^a(x_B) \right]$$

Spin asymmetries

$$A_{LL} = -\frac{\overline{V}_T^{LL}}{4\,\overline{W}_T} = \frac{\sum_a e_a^2\,\left[g_1^a(x_A)\, g_1^{\bar{a}}(x_B) + g_1^{\bar{a}}(x_A)\, g_1^a(x_B) \right]}{\sum_a e_a^2\,\left[f_1^a(x_A)\, f_1^{\bar{a}}(x_B) + f_1^{\bar{a}}(x_A)\, f_1^a(x_B) \right]}$$

$$A_{(T)T} = A_{T(T)} = A_{TT}^{\parallel} = \frac{\sin^2\theta\,\cos 2\phi}{1+\cos^2\theta}\,\frac{\overline{U}_{2,2}^{TT}}{\overline{W}_T}$$
$$= \frac{\sin^2\theta\,\cos(2\phi)}{1+\cos^2\theta}\,\frac{\sum_a e_a^2\,\left[h_1^a(x_A)\, h_1^{\bar{a}}(x_B) + h_1^{\bar{a}}(x_A)\, h_1^a(x_B) \right]}{\sum_a e_a^2\,\left[f_1^a(x_A)\, f_1^{\bar{a}}(x_B) + f_1^{\bar{a}}(x_A)\, f_1^a(x_B) \right]}$$

$$A_{TT}^{\perp} = \tan(2\phi)\, A_{TT}^{\parallel}$$

$$A_{UQ_0} = \frac{\overline{V}_T^{UQ_0}}{\overline{W}_T} = \frac{\sum_a e_a^2\,\left[f_1^a(x_A)\, b_1^{\bar{a}}(x_B) + f_1^{\bar{a}}(x_A)\, b_1^a(x_B) \right]}{\sum_a e_a^2\,\left[f_1^a(x_A)\, f_1^{\bar{a}}(x_B) + f_1^{\bar{a}}(x_A)\, f_1^a(x_B) \right]}$$

$$A_{LT} = A_{TL} = A_{UT} = A_{TU} = A_{TQ_0} = A_{UQ_1} = A_{LQ_1}$$
$$= A_{TQ_1} = A_{UQ_2} = A_{LQ_2} = A_{TQ_2} = 0$$

Advantage of the hadron reaction ($b_1^{\bar{a}}$ measurements)

$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2\, f_1^a(x_A)\, b_1^{\bar{a}}(x_B)}{\sum_a e_a^2\, f_1^a(x_A)\, f_1^{\bar{a}}(x_B)}$$

p-d asymmetry R$_{pd}$ $(x_F \to 1)$

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

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

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

if $\Delta_{(T)}\bar{u} < 0$

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

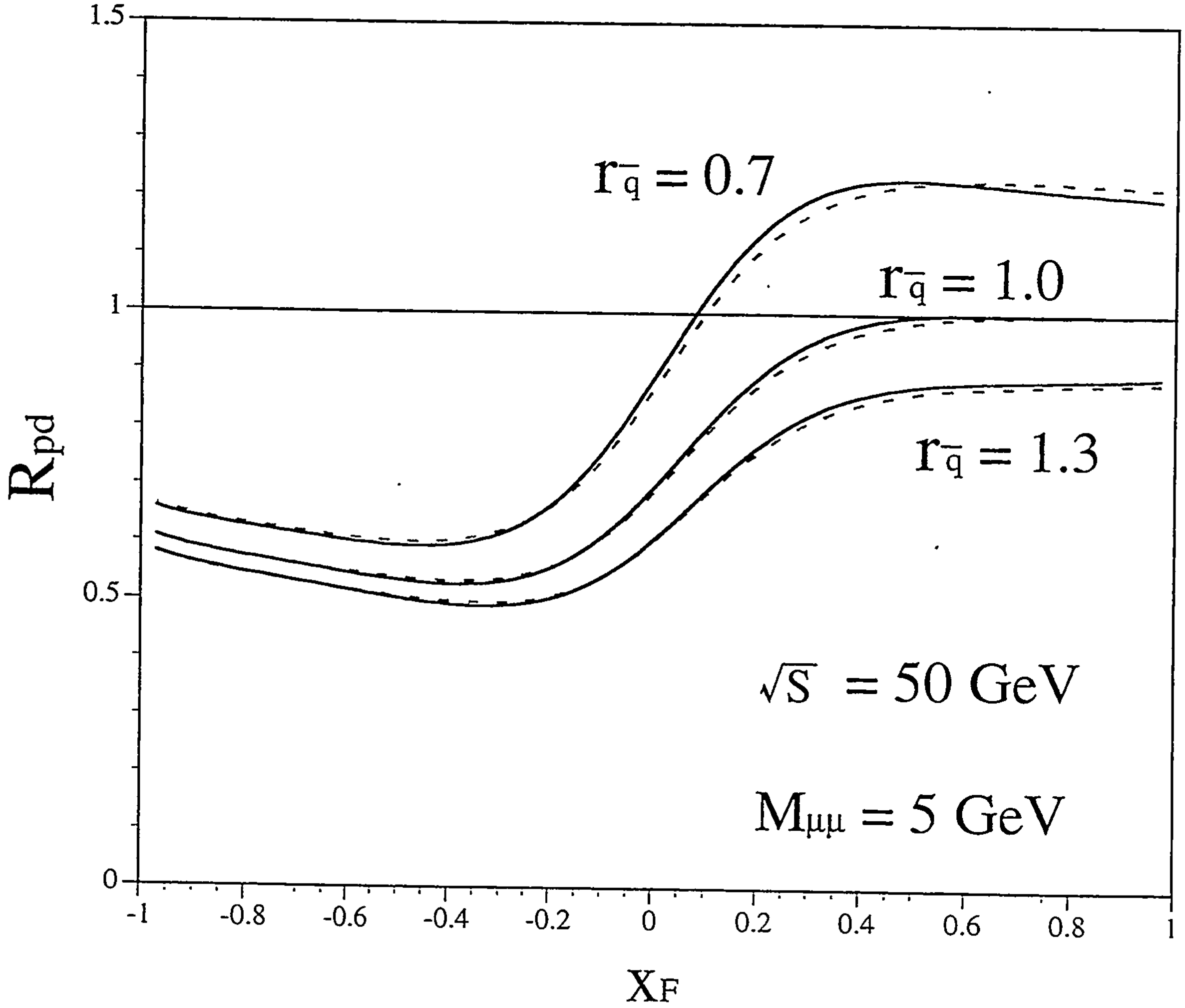
$$\Delta_{(T)}\bar{u} < \Delta_{(T)}\bar{d} \quad \Rightarrow \quad R_{pd}(x_F \to 1) < 1$$

Rpd (LO evolution)

—— Longitudinal

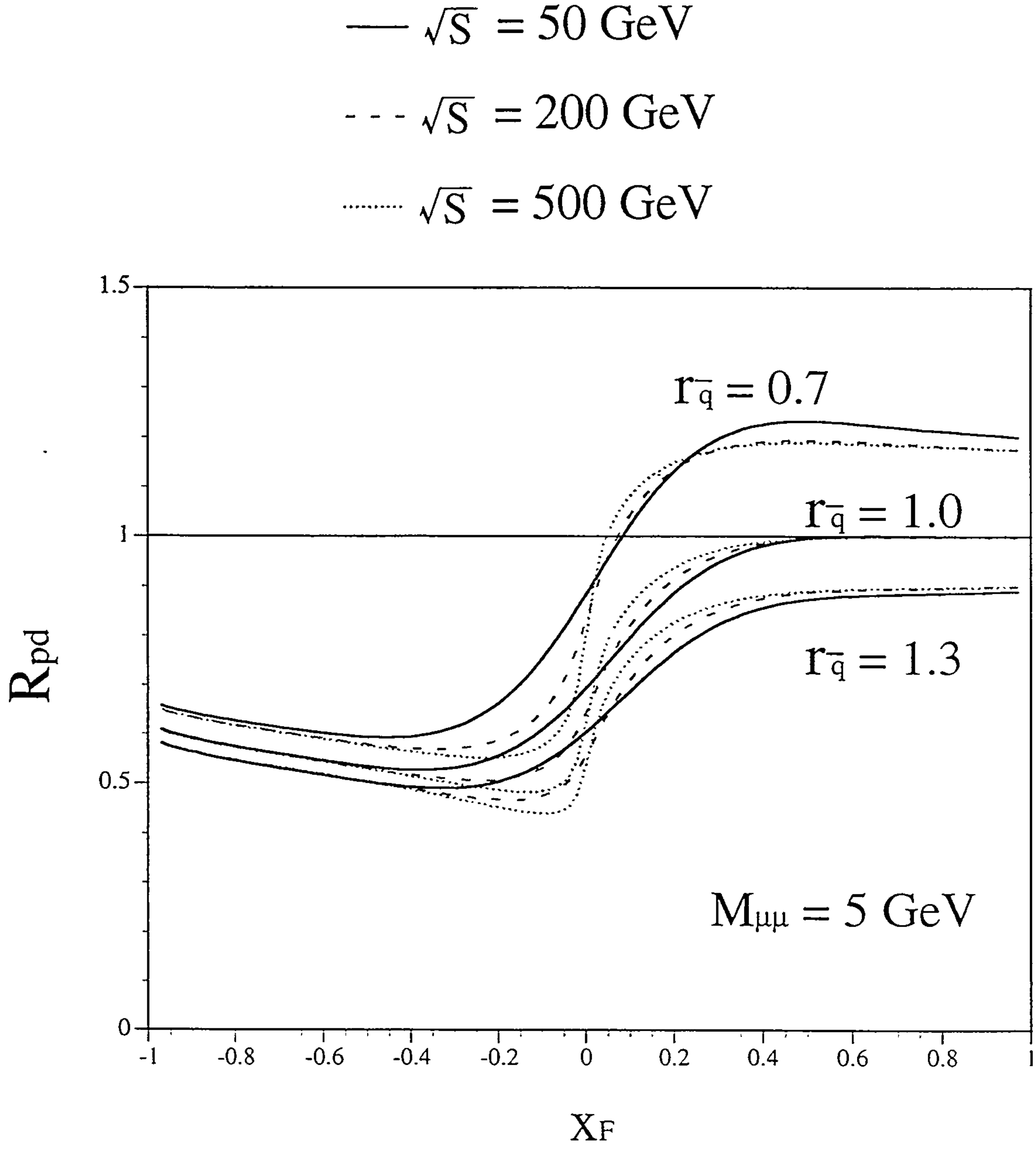
- - - - Transverse

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



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

Rpd (c.m. energy dependence)



Summary

- P, T, H ⟶ many structure functions in $\vec{p} + \vec{d} \rightarrow \mu^+\mu^- + X$

- New functions ⟶ **tensor** structure (measured by quadrupole spin asymmetries)

- b_1 and **particularly** $\bar{b}_1$ can be measured by A_{UQ_0}.

- $R_{pd} = \frac{\Delta_{(T)}\sigma^{pd}}{2\,\Delta_{(T)}\sigma^{pp}}$ **is useful** for finding $\frac{\Delta_{(T)}\bar{u}}{\Delta_{(T)}\bar{d}}$ especially at $x_F \rightarrow 1$.

- The above point is important in the **transversity,** for which W production and inclusive lepton scattering do not provide information.

- **Future possibility** at RHIC !?
(FNAL, HERA)

Discussion on Quark Polarization Measurements

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Abstract

We discuss the possible ways to measure quark polarizations in the proton with flavor decomposition. Since polarized deep-inelastic scattering is the only source of information on the quark polarization, we only know the linear combination of them weighted by electric charge-squared. Using charged current scattering at higher energies either *pp* or *ep*, it should be possible to decompose into each flavor.

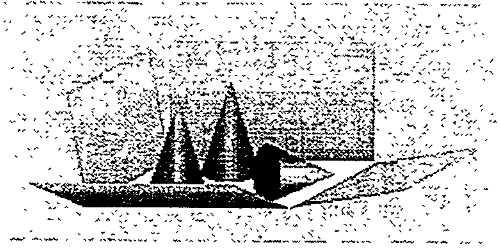
These transparencies were used to initiate the discussion. Some comments and questions raised at the meeting were also included.

Why Interpretation?

- Because we want to come to a universal view of hadron induced reactions.
  - "polarized gluon distribution" $\Delta g(x)$ is relevant to $pp \to HX$ not $\Delta g(x)+L_g(\text{“}x\text{”})$
- So we want to interpret the results in
  - Gauge Invariant Framework, if possible
  - QPM, the most widely accepted model which have been playing crucial role in the SM

Discussion of Quark Polarization Measurements

RHIC Spin Collaboration meeting,
October 6-8, 1999



Naohito Saito

RIKEN / RIKEN BNL Research Center

What we know from pol-DIS?

- Three different styles:
  - SMC style:
    - 4-indep. Functions: $\Delta\Sigma(x)$, $\Delta q^p{}_{NS}(x)$, $\Delta q^p{}_{NS}(x)$, $\Delta g(x)$
    - quark part equiv. to:

$$a_0(x)=\Delta u(x)+\Delta d(x)+\Delta s(x)$$
$$a_3(x)=\Delta u(x)\text{-}\Delta d(x)$$
$$a_8(x)=\Delta u(x)+\Delta d(x)\text{-}2\Delta s(x)$$

equiv to : $\Delta u(x), \Delta d(x), \Delta s(x)$

  - ABFR(Altarelli, Ball, Forte, Ridolfi) style:
    - similar to SMC but assumes: $a_3(x) \propto a_8(x)$
  - PDF-style:
    - 4-indep. Functions: $\Delta u_V(x)$, $\Delta d_V(x)$, $\Delta s(x)(= \Delta u_{sea}(x)= \Delta d_{sea}(x))$, $\Delta g(x)$

Why do we need $\Delta d(x)$?

$$A_1^p(x)=\frac{g_1^p(x)}{f_1^p(x)}=\frac{\sum_i e_i^2\Delta q_i(x)}{\sum_i e_i^2 q_i(x)}$$

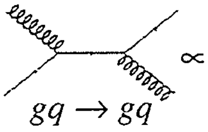
- Examples:
  - Prompt Photon
    - gluon Compton:

$$A_{LL}(p_T)=a_{LL}(qg\to\gamma q)\cdot\frac{\Delta g(x)}{g(x)}\cdot\frac{\sum_i e_i^2\Delta q_i(x)}{\sum e_i^2 q_i(x)};i=u,\overline{u},d,\overline{d},s,\overline{s}\ldots$$

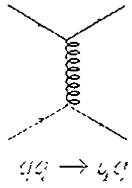
    - annihilation:

$$A_{LL}(p_T)=a_{LL}(q\overline{q}\to\gamma g)\cdot\frac{\sum_i e_i^2\Delta q_i'(x)\Delta\overline{q}_i(x)}{\sum_i e_i^2 q_i(x)\overline{q}_i(x)};i=u,\overline{u},d,\overline{d},s,\overline{s}\ldots$$

  - Jet Production:



$$\propto\frac{\Delta q}{q}\frac{\Delta G}{G}$$



$$\propto\frac{\Delta q}{q}\frac{\Delta q}{q}$$

What we can do?

- Semi-inclusive DIS
- W
- Drell-Yan
- High-pT jet?
- W+charm?
- Gamma+charm?

- Experimental feasibility:
  - rate, background
- Theory basis:
  - FAQ: factorization OK?
  - pQCD

- Comments and questions at the meeting
  - CC in eP collision (mentioned by Bob in the discussion)
  - u in $p = d$ in n?
  - ^{3}He+p collision at 240 GeV+ 350 GeV possible?
  - Hi-pt DY to look at $g(x)$, $\Delta g(x)$ ...

What used in unpolarized case?

Martin, Roberts, and Stirling Phys.Rev.D50(1994) 6734

Process/ Experiment	**Leading order subprocess**	**Parton determination**
DIS ($\mu N \to \mu X$) BCDMS, NMC $F_2^{\mu p}, F_2^{\mu n}$	$\gamma^* q \to q$	Four structure functions $\to$ $u + \bar{u}$ $d + \bar{d}$ $\bar{u} + \bar{d}$ s (assumed $= \bar{s}$), but only $\int xg(x)dx \simeq 0.5$ [$\bar{u} - \bar{d}$ is not determined]
DIS ($\nu N \to \mu X$) CCFR (CDHSW) $F_2^{\nu N}, xF_3^{\nu N}$	$W^* q \to q'$	
$\mu N \to c\bar{c}X$ F_2^c, EMC	$\gamma^* c \to c$	$c \approx 0.1s$ at Q_0^2
$\nu N \to \mu^+ \mu^- X$ CCFR	$W^* s \to c$ $\hookrightarrow \mu^+$	$s \approx \frac{1}{2}\bar{u}$ (or $\frac{1}{2}\bar{d}$)
DIS (HERA) F_2^{ep} (H1,ZEUS)	$\gamma^* q \to q$	λ ($x\bar{q} \sim xg \sim x^{-\lambda}$, via $g \to q\bar{q}$)

Process/ Experiment	**Leading order subprocess**	**Parton determination**
$pp \to \gamma X$ WA70 (UA6)	$qg \to \gamma q$	$g(x \approx 0.4)$
$pN \to \mu^+ \mu^- X$ E605	$q\bar{q} \to \gamma^*$	$\bar{q} = ...(1-x)^{\eta_s}$
$pp, pn \to \mu^+ \mu^- X$ NA51	$u\bar{u}, d\bar{d} \to \gamma^*$ $u\bar{d}, d\bar{u} \to \gamma^*$	$(\bar{u} - \bar{d})$ at $x = 0.18$
$p\bar{p} \to WX(ZX)$ UA2, CDF, D0 $\to W^{\pm}$ asym CDF	$ud \to W$	u, d at $x_1 x_2 s \simeq M_W^2 \to$ $x \approx 0.13$ CERN $x \approx 0.05$ FNAL slope of u/d at $x \approx 0.05$

- No neutrino exp for polarized case...

Progress Report to the
Annual RHIC-Spin Collaboration Meeting
BNL, October 7, 1999

How could CP-invariance and physics beyond SM be tested in polarized proton collisions at RHIC?[1]

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Outlook:

- The motivations to search for *CP*-violation at RHIC with polarized protons in modes other than B-decays are presented.
- The measurable single- and double-spin asymmetries which could be an indication of *CP*-violation and new physics in $W^{\pm}$- and Z^0-production by polarized nucleons (and leptons) are discussed.
- The example of a phenomenological extension of SM, which generates the asymmetries of interest, is provided.
- RHIC sensitivity to the "illegal" (in Standard Model) spin correlations is estimated.

Summary:

- In polarized particle collisions, the presence of **two axial vectors** of initial polarizations, **fully controlled** by the experimenters, dramatically increases the number of **available for tests correlations and asymmetries**. This makes high energy colliders with polarized beams to be a powerful tool to **search for** and **study** New Physics beyond the Standard Model, including *CP*-violation at the energy scale of *W*- and *Z*-masses and above.
- The future e^+e^--, $\mu^+\mu^-$-, and particularly $p\bar{p}$-colliders with **two** polarized beams would clearly be the best to search for and study **model independent** *CP*-violation.
- While **not** absolutely unambiguously and model independent, *CP*-violation beyond SM could also be tested in $W^{\pm}$- and Z^0-boson production in **polarized proton** collisions at RHIC by comparison the relative signs of various asymmetries (*if found nonzero*) in (*presumably*) *CP*-conjugate processes at a parton level. In the best scenario of detecting several *CP*-odd and *CP*-even unusual correlations in the same processes, the only alternative to *CP*-violation might be ... even worse: for example, to completely discard the current picture of $W^{\pm}$- and Z^0-production from quark-antiquark annihilation.

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[1] hep-ex/9908050, Submitted to *Nuclear Physics* **B** on July 14, 1999.

EXAMPLE:

Phenomenological interaction Lagrangians:

(*G. L. Kane, G. A. Ladinsky, and C. P. Yuan, Phys.Rev.* ***D45*** *(1992) 124*)

Charged current:

$$\begin{aligned} L_c = & \frac{g}{2\sqrt{2}}\{[W_\mu^- \overline{q}_d \gamma^\mu (f_1^+ + f_1^- \gamma_5) q_u + \text{h.c.}] + & \text{``\underline{Vector}''} \\ & + \frac{1}{\Lambda}[\partial_\nu W_\mu^- \overline{q}_d \sigma^{\mu\nu} (f_2^+ + f_2^- \gamma_5) q_u + \text{h.c.}]\} & \text{``\underline{Tensor}''} \end{aligned}$$

where $\gamma_5 = -i\gamma^0\gamma^1\gamma^2\gamma^3$ and $\sigma^{\mu\nu} = \frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$; Λ is the "natural" energy scale for the "tensor" coupling; q_u and q_d are for the "upper" and "lower" quarks, respectively.

The usual $(V - A)$-interactions correspond to $f_1^+ = f_1^- = 1$, and all $f_{2,3}^\pm = 0$. ***CP*- and *T*-symmetries are broken if any or all $f_i^\pm$ are complex.**

Neutral current:

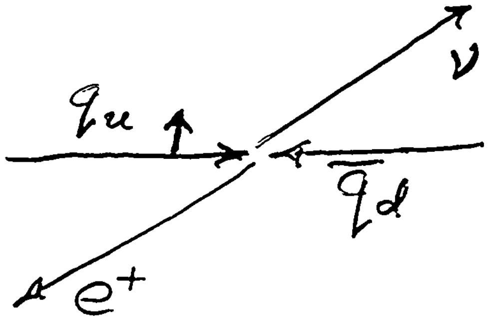
$$L_n = \frac{g}{2\sqrt{2}}\{[Z_\mu^0 \overline{q} \gamma^\mu (f_1^+ + f_1^- \gamma_5) q] + \frac{1}{\Lambda}[\partial_\nu Z_\mu^0 \overline{q} \sigma^{\mu\nu} (f_2^+ + f_2^- \gamma_5) q]\}$$

Formfactors $f_1^\pm$ and f_2^+ are real; ***CP*- and *T*-symmetries are broken with nonzero and purely imaginary formfactor f_2^-:**

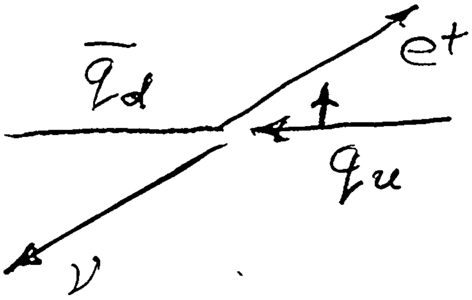
$$f_2^- \equiv i\,\mathrm{Im}(f_2^-) \neq 0$$

Up-Down Asymmetry

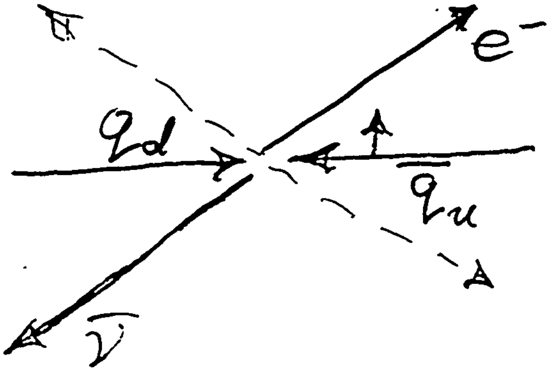
Helicity independent



P



CP

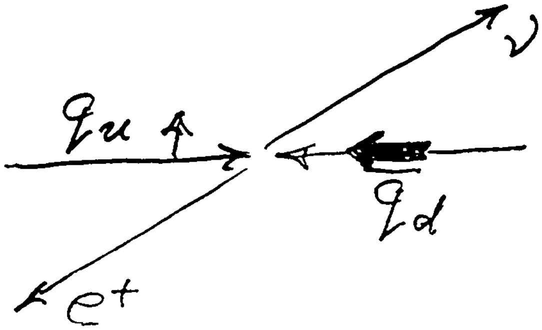


CP-even: same sign

CP-odd: changes sign

$$\boxed{A \sim (\vec{\xi}_\perp \cdot \vec{K})}$$

Helicity dependent



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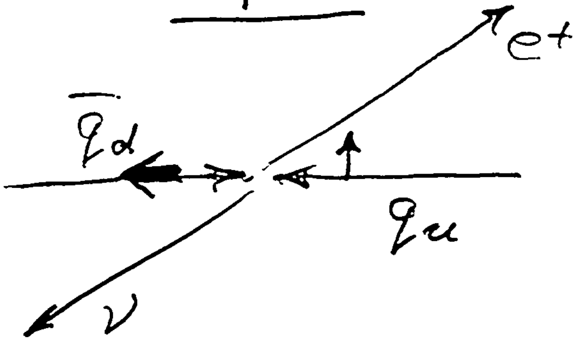
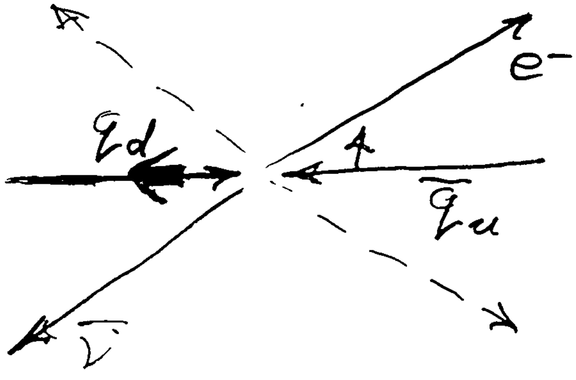


CP



CP-even: changes sign

CP-odd: same sign

$$\boxed{A \sim \lambda(\vec{\xi}_\perp \cdot \vec{K})}$$

$| M_{fi} |^2_{vv}$: "Vector-Vector":

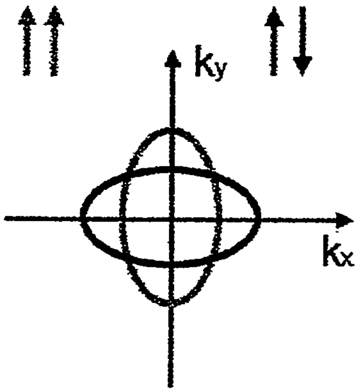
(Potentially) Large double-spin asymmetries:

***T*-even** (and *CP*-even in this particular model): A_{TT}:

Allowed in Z- but strictly prohibited in tree-level V-A W-production

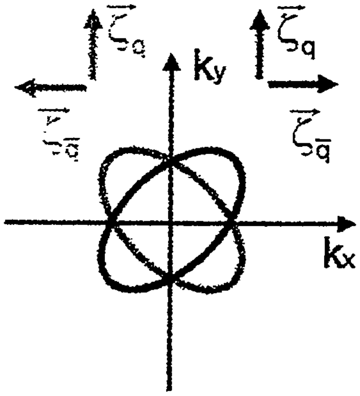
$$A \propto (| f_1^+ |^2 - | f_1^- |^2)\{(\zeta_q^\perp \cdot \boldsymbol{n}_k)(\zeta_{\bar{q}}^\perp \cdot \boldsymbol{n}_k) - \tfrac{1}{2}(\zeta_q^\perp \cdot \zeta_{\bar{q}}^\perp)[1 - (\boldsymbol{n}_p \cdot \boldsymbol{n}_k)^2]\}$$

Parallel spins



± cos 2φ

Perpendicular spins



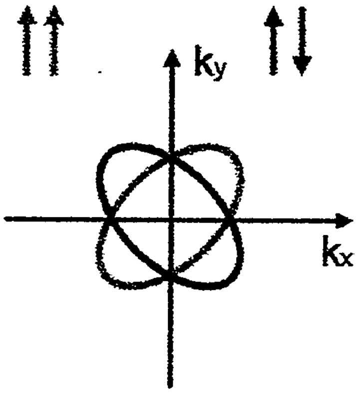
± sin 2φ

***T*-odd** (and *CP*-odd in this particular model): 45° rotated A_{TT}:

Strictly prohibited at tree-level SM for both W- and Z-productions

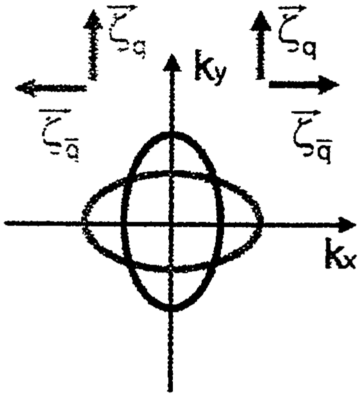
$$A \propto \pm \mathrm{Im}(f_1^+ f_1^{-*})\{\boldsymbol{n}_k \cdot [\zeta_q^\perp \times \boldsymbol{n}_p](\zeta_{\bar{q}}^\perp \cdot \boldsymbol{n}_k) + \boldsymbol{n}_k \cdot [\zeta_{\bar{q}}^\perp \times \boldsymbol{n}_p](\zeta_q^\perp \cdot \boldsymbol{n}_k)\}$$

Parallel spins



± sin 2φ

Perpendicular spins

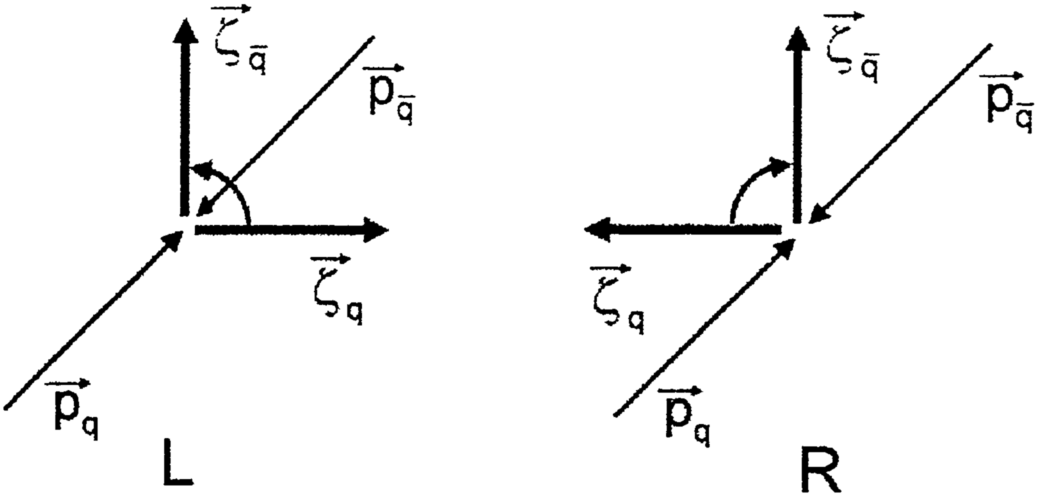


± cos 2φ

$| M_{fi} |^2_{tt}$: "Tensor-Tensor":

(Potentially) Large *T*-odd double-spin asymmetry $\Delta\sigma_\perp$:

$$\frac{d\sigma_\perp}{d\Omega} \propto T\text{-even} + \mathrm{Im}(f_2^+ f_2^{*-})(\boldsymbol{n_p} \cdot [\boldsymbol{\zeta}_q^\perp \times \boldsymbol{\zeta}_{\bar{q}}^\perp])$$



$$\Delta\sigma_\perp = \sigma_\perp^R - \sigma_\perp^L \propto \mathrm{Im}(f_2^+ f_2^{*-})$$

CP-conjugation:

$$\sigma_\perp^R(q_u\overline{q}_d) \overset{CP}{\rightarrow} \sigma_\perp^L(q_d\overline{q}_u) \qquad \sigma_\perp^L(q_u\overline{q}_d) \overset{CP}{\rightarrow} \sigma_\perp^R(q_d\overline{q}_u)$$

Corollary:

***CP*-even** (spurious): $\Delta\sigma_\perp(q_d\overline{q}_u) = -\Delta\sigma_\perp(q_u\overline{q}_d)$

***CP*-odd** (true): $\Delta\sigma_\perp(q_d\overline{q}_u) = +\Delta\sigma_\perp(q_u\overline{q}_d)$

Back to the Earth (Q & A)

Q: What is the expected RHIC sensitivity to "illegal" asymmetries?

A: At *pp*-**interaction level**, it is ~1%.

$W^{\pm}$ and Z^0 event rates at $\sqrt{s} = 500\ GeV$ for $\int L\cdot dt = 800\ pb^{-1}$; Cuts: $P_T^{e,\mu} > 20\,GeV/c$.

(A. Derevschikov, V. Rykov, K. Shestermanov, and A. Yokosawa. *Report to the SPIN-94.*)

	STAR_b	STAR_b1ec	STAR_b2ec
W^+	64,600	71,500	78,400
W^-	15,000	20,600	26,200
Z^0	2,700	4,200	6,200

	PHENIX_1μ	PHENIX_2μ	PHENIX_e
W^+	4,650	9,300	14,900
W^-	5,050	10,100	2,600
Z^0	25	310[1]	120

[1] ~700 without P_T-cut.

Q: How large could be the discussed asymmetries at *pp*-level?

A: ***CP*-odd double-spin:**

~(0.03–0.05)×$\text{Im}(F_1F_2^*)$ where $F_{1,2}$ are for either $f_1^{\pm}$ or $f_2^{\pm} \times M_{W,Z}/\Lambda$, depending on the particular asymmetry.

***CP*-odd single-spin:**

$\sim \sqrt{(0.03-0.05)} \times \text{Im}(f_1f_2) \times M_{W,Z}/\Lambda \sim$
$\sim(0.1\text{–}0.3)\times\text{Im}(f_1f_2^*) \times M_{W,Z}/\Lambda.$

O. Martin, A. Schafer, M. Stratmann, and W. Vogelsang. *Phys. Rev.* **D57**, 3084 (1998)

NEW PARITY VIOLATION EFFECTS

J. Soffer

$$A_L = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} \qquad \vec{p}\vec{p} \to \mu\nu + X \qquad \sqrt{s} = 500 \text{ GeV}$$

$$A_{LL}^{PV} = \frac{\sigma_{--} - \sigma_{++}}{\sigma_{--} + \sigma_{++}}$$

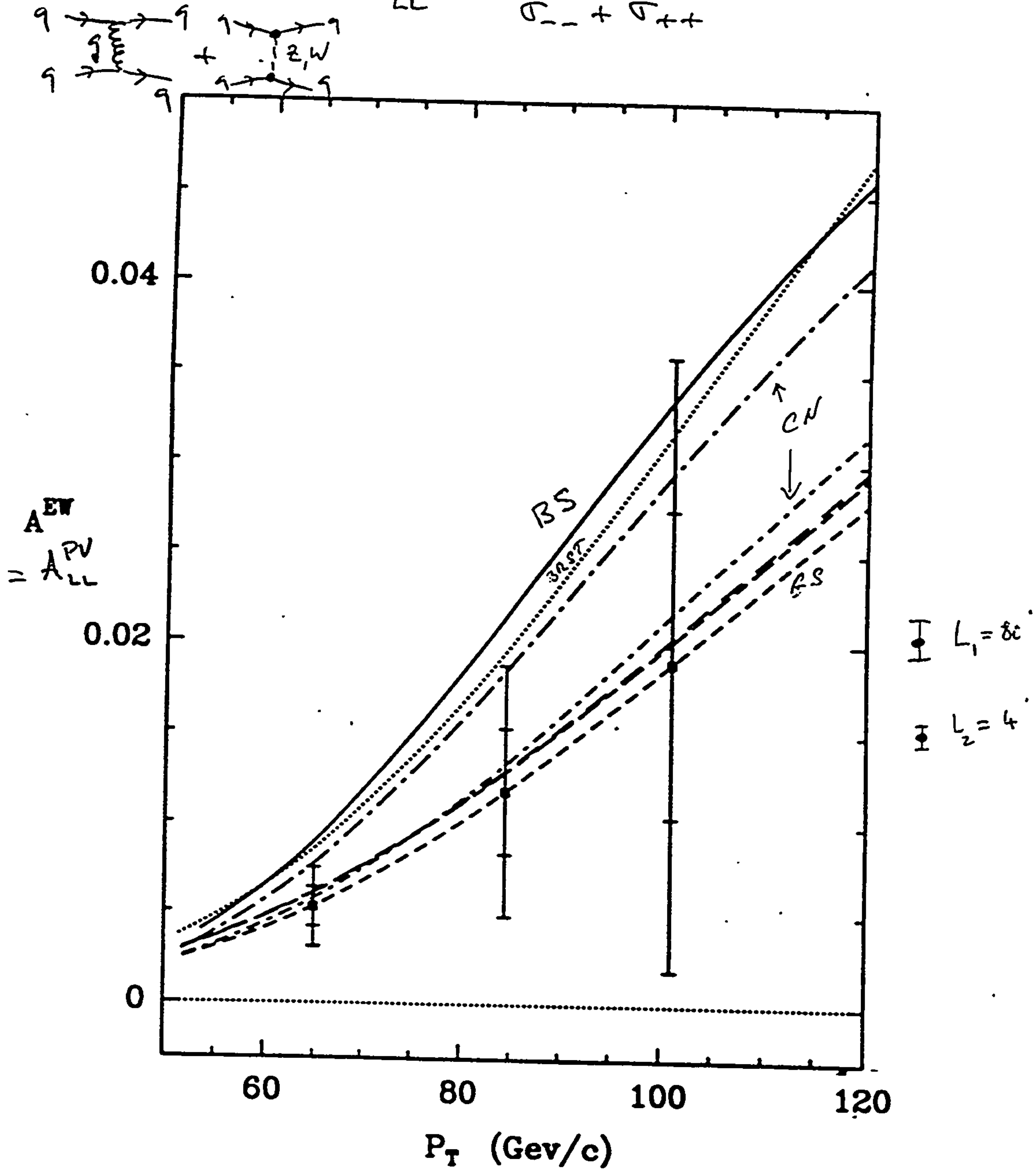


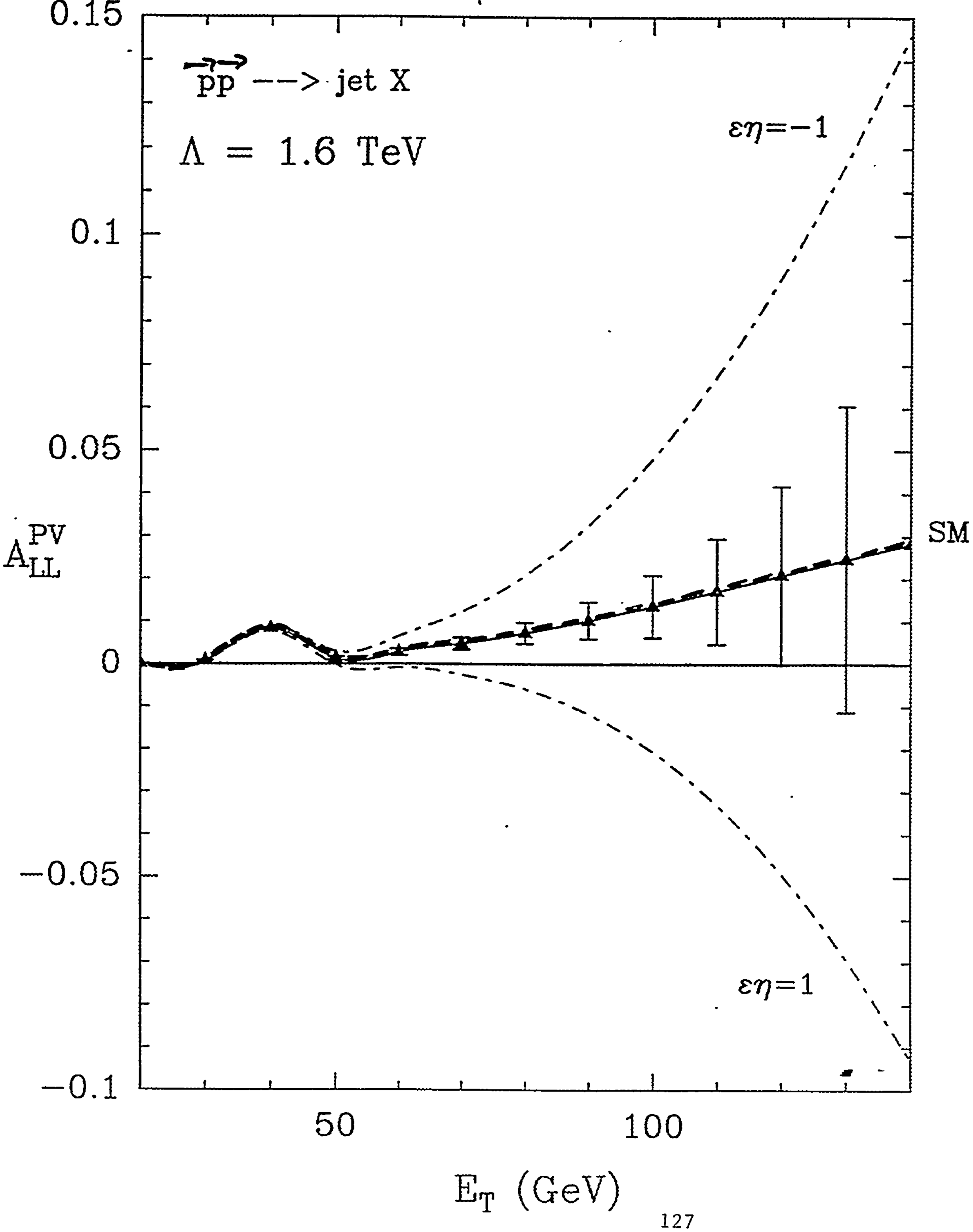
Fig 1

TAXIL, VIREY PL B364 181 (199C)

$$L_{eff} \sim \frac{\varepsilon}{\Lambda^2}\left[\bar{\psi}\gamma_\mu(1-\eta\gamma_5)\psi\right]\left[\bar{\psi}\gamma_\mu(1-\eta\gamma_5)\psi\right]$$

$$d_\mu \; d_\mu$$

P.TAXIL , J.M. VIREY



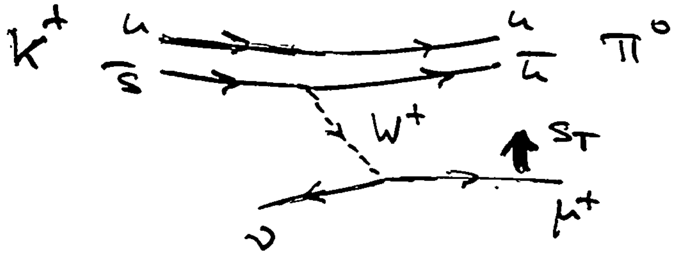
- CP VIOLATING ASYMMETRY FOR W PRODUCTION

$\cancel{CP}$ AT HIGH ENERGY IS A RELEVANT ISSUE

IS $\cancel{CP}$ BEYOND THE STANDARD MODEL DETECTABLE?

AS AN EXAMPLE LET'S CONSIDER CP TESTS IN $K_{\ell 3}$ DECAY $(K \to \pi \ell \nu)$

e.g. THE TRANSVERSE MUON POLARIZATION IN $K^+ \to \pi^0 \mu^+ \nu$



$$S_T^\mu = \frac{Im(f_{++}^* f_{+-})}{|f_{++}|^2 + |f_{+-}|^2}$$ (+, - MUON HELICITI

IN SM ONLY ONE AMPLITUDE f_{+-} WHICH IS REAL SO $S_T = 0$

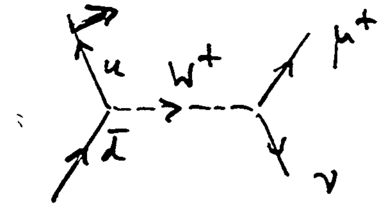
TO MAKE $S_T \neq 0$ CAN POSTULATE THE EXISTEN OF A PURELY IMAGINARY f_{++} MUCH SMALLER THAN f_{+-} AND ORIGINATED FROM A SCALAR EXCHANGE IN ADDITION TO W EXCHANGE

LATEST RESULT FROM E246 AT KEK (EPS-HEP

$$\langle S_T^\mu \rangle = -0.0042 \pm 0.0049 (st) \pm 0.0009 (sys)$$

(NOT FINAL HOPE TO DO BETTER)

A SIMILAR SITUATION IN $p^{\uparrow}p \rightarrow W^{+}X$
WITH A TRANSVERSELY POLARIZED PROTON



LET'S CONSIDER $A_T = \dfrac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$

FOR A ROUGH ESTIMATE OF THE AVERAGE EXPECTED EFFECT

$$\langle A_T \rangle \sim \left\langle \frac{h_1^u}{u} \right\rangle \langle s_T^u \rangle$$

WITH $\langle s_T^u \rangle = \dfrac{\sin\theta_c}{\cos\theta_c} \langle s_T^{\mu} \rangle$ $\left(\frac{\sin}{\cos} \sim 0.25 \right)$

AND $\left\langle \dfrac{h_1^u}{u} \right\rangle = 0.4$ (EFREMOV, GOEKE, POLYAKI
FROM T-ODD AZIMUTHAL
ASYMMETRY IN $ep \rightarrow e\pi^+ X$
HERMES GET $\frac{h_1^u}{u} = 0.48 \pm$

SO WE GET

$$\langle A_T \rangle \sim -4 \cdot 10^{-4}$$

HARD TO DETECT BUT IT COULD BE THAT THE COUPLING OF THE SCALAR IS LARGER TO $(u\bar{d})$ THAN TO $(u\bar{s})$??

ANYWAY IF A LARGE EFFECT IS SEE
THIS WILL BE A BIG DISCOVERY
ANOTHER ONE !!

Spin and the Well-Dressed Quark, presented by John Ralston

There is a subtle problem of interpreting spin-dependent measurements in a gauge theory such as QCD. Contradictions of present interpretation may even force revision of very basic concepts. The difficulty is old, going back to electrodynamics and J. H. Poynting's derivation of a conserved energy flux in Maxwell's theory. Poynting's method is incomplete, because concepts of density of energy, momentum, or angular momentum exist only after specification of Lagrangian coordinates, and cannot be separated from them; even the numerical value changes when coordinates change. Gauge theories with vector potential (A) as coordinate lead by Noether's theorem to expressions for densities of Poincare' symmetry generators that are gauge-dependent. Such quantities cannot be compared directly to experiments, which measure thing that are gauge-independent. This is the source of confusion and debate over spin, orbital angular momentum, and other quantities in QCD.

Since experiments cannot measure quantities conjugate to standard coordinates, perhaps coordinates can be built to match what can be measured. I seek gauge-sector coordinates for which the theory's Poincare' generator densities will be gauge-invariant. Let $T^{\mu\nu} = \Sigma \partial L/\partial\phi_{,\mu}\phi_{,\nu} - g_{\mu\nu}L$ be the energy momentum tensor for ordinary fields ϕ that carry color, and described by Lagrangian density L. The notation is $\phi_{,\mu} = \partial_\mu\phi$. Let $A_\nu^{ab}(e)$ with color indices a, b represent the potential in terms of new fields e and their derivatives. Transferring ordinary derivatives to gauge-covariant derivatives is accomplished if $\delta^{\alpha\beta}A_\nu^{ab} = (\partial A_\alpha^{ab}/\partial\bar{e}_{\lambda,\beta}^{c})\bar{e}_{\lambda,\nu}^{c}$. This is solved by a representation

$$gA^{ab}(e) = -ie_\mu^a\partial\bar{e}_\mu^b.$$

Under a local color transformation $U^{ab}(x), e_\mu^a(x) \rightarrow U^{ab}(x)e_\mu^b(x)$ one finds the derived $A(e)$ transforms like the vector potential. There is a constraint $e_\mu^a\bar{e}_\mu^b = \delta^{ab}$ of geometrical origin, which is invariant under global unitary or orthogonal transformations V on the μ (non-space-time) index. The representation and dimension of V are unspecified, subject to consistency that the δA variations are reproduced by δe's. This implies certain minimum requirements on the number of parameters describing e.

Using the e coordinates it is found that the gauge sector $T_{gauge}^{\mu\nu} = F^{\mu\rho}F_\rho^\nu - g^{\mu\nu}L$ which is the 'Poynting" expression. The quark (ψ) angular momentum density is the one obtained by replacing $\partial\psi$ by $D\psi$, where D is the gauge covariant derivative. The gauge-sector angular momentum is entirely orbital, provided e transforms like a Lorentz scalar, which is the simplest representation. Such expressions have often been postulated improperly for the standard variables, via the illigitimate notion of adding ad-hoc pure divergences that "change nothing". Indeed canonical transformations are implemented by pure divergences, so new coordinates are implied by both the new and previous approaches.

These considerations at the classical level are proper to discussion of symmetries. Apparently the entire theory can also be mapped into the e's at the quantum level; whether this challenging technical problem can lead to a practically useful representation remains to be explored in detail. It is very fascinating that new invariants are allowed with the new coordinates, which can describe quark dressing and concepts such as a mass gap or "gluon mass". Thus the "spin crisis" raises a deeper crisis of interpretation of the gauge-sector. Certainly A is a useful coordinate for perturbation theory. The non-perturbative nature of measurements, however, suggests that diffferent variables transforming like e_μ^a are better suited to the physical interpretation of spin experiments.

For references, see J. P. Ralston, preprints (1997, 1999); *Found. Phys.* (in press); *Proceedings of QCD-ISMD* (Brown University 1999) (in press).

①, 2

SPIN and the Well-Dressed Quark

John Ralston

Belinfante, 1930's rejection prototype

found $T^{\mu\nu}$ electrodynamics not gauge inv.

also not symmetric $T^{\mu\nu} \neq T^{\mu\nu}$

wanted invariance of gauge,

wanted symmetric so to get gravity in,

plus $M^{\mu\nu\lambda} = x^{\lambda} T^{\mu\nu} - x^{\nu} T^{\mu\lambda}$,

... thereby MISSING THE CLASSICAL EXISTENCE of SPIN ...

... added a "pure derivative" and declared it unobservable ...

NO

... → FIND BETER COORDINATES ←

AGAIN: given $L(q,\dot{q})$

$\int d^4x\, \mathcal{L} + \partial^\mu F_\mu$

change $L(q,\dot{q}) \to L + \frac{dF}{dt}$

ACTION $S = \int_1^2 dt\; L + \frac{dF}{dt}$

no effect on equations of motion, blah, blah.

But not trivial, induces canonical transformation

$$p\dot{q} - H(q,p) = P\dot{Q} - K(Q,P) + \frac{\partial F}{\partial q}\dot{q} + \frac{\partial F}{\partial Q}\dot{Q} + \frac{\partial F}{\partial t}$$

$p = \partial F/\partial q$

$P = -\partial F/\partial Q$

YOU MADE A COORDINATE TRANSFORMATION

→ FIND BETTER COORDINATES ←

Given generic fields φ, which may include A

Gauge Invariant $\mathcal{L} = \mathcal{L}(\varphi, \varphi_{;\mu})$ $;\mu = \partial_\mu - A_\mu$

Calculate $T^{\mu\nu} = \sum \frac{\partial \mathcal{L}}{\partial \varphi_{,\mu}} \varphi_{,\nu} - g^{\mu\nu}\mathcal{L}$ $,\mu = \partial_\mu$ notation suppresse, obvious co/contrav

but $\frac{\partial \mathcal{L}}{\partial \varphi_{,\mu}} = \frac{\partial \mathcal{L}}{\partial \varphi_{;\mu}}$

Now assume $A = A(e, e_{,\alpha})$ and add convective A terms

e.g. $\frac{\partial \mathcal{L}}{\partial \bar{e}_{,\mu}} \bar{e}_{,\nu} = \frac{\partial \mathcal{L}}{\partial A^\sigma} \frac{\partial A^\sigma}{\partial \bar{e}_{,\mu}} \bar{e}_{,\nu} = +i \frac{\partial \mathcal{L}}{\partial \varphi_{;\sigma}} \frac{\partial A^\sigma}{\partial \bar{e}_{,\mu}} \bar{e}_{,\nu}$ AND SUM OVER TYPES

Total variation of convection $T^{\mu\nu} = \frac{\partial \mathcal{L}}{\partial \psi_{;\alpha}} (\delta^{\alpha\mu}(\psi_{;\nu} + A_\nu) + \frac{\partial A^\alpha}{\partial \bar{e}_{,\mu}} \bar{e}_{,\nu} + \dots$

$T^{\mu\nu}$ is then a function of gauge derivatives ([illegible] gauge invariant) when

$i\delta^{\alpha\mu} A_\nu = -i\sum \frac{\partial A^\alpha}{\partial \bar{e}_{,\mu}} \bar{e}_{,\nu}$, with $e \to \mathcal{U}e$; $\bar{e}^a e^b = \delta^{ab}$.

NOW SOLVE THIS CONSISTENTLY ..

NEW COORDINATES FOR GAUGE SECTOR

$$e^{a}_{\mu}$$

a ← COLOR, LOCAL
$a = 1 \ldots 3$
SU(3)

μ ← "E-GROUP"
NOT SPACE-TIME
$\mu = 1 \ldots E$

LORENTZ: SCALAR OK (OR AS YOU WISH)

$$e^{a}_{\mu}(x) \to e^{a}_{\mu}(x)' = \mathcal{U}^{ab}_{(x)} e^{b}_{\mu}(x)$$

$$\bar{e}^{a}_{\mu}(x) \to \bar{e}^{a}_{\mu}(x)' = \bar{e}^{b}_{\mu} \mathcal{U}^{\dagger\, ba}_{(x)}$$

$\mathcal{U} \in$ SU(

USEFUL CONSTRUCT "A"(e, ē)

$$g A^{ab} \equiv -i \underbrace{e^{a} \partial \bar{e}}^{b} = +i \partial \underbrace{e^{a} \cdot \bar{e}}^{b}$$

COUPLING CONST → g

↳ 4-vector, Lorentz $\partial = \partial / \partial x^{\alpha}$

↳ not a tensor under color.

TRANSFORM:

$$A \to A' = A(\mathcal{U}e, \bar{e}\mathcal{U}^{\dagger})$$

$$= -i \mathcal{U} \underbrace{e \partial (\bar{e}}\, \mathcal{U}^{\dagger})$$

$$A' = \mathcal{U} A \mathcal{U}^{\dagger} - i \mathcal{U} \partial \mathcal{U}^{\dagger} / g$$

… and not "pure gauge"

NOW TRY IT

MacCullagh-Maxwell of KYMS

$$\mathcal{L} = -\frac{1}{4} F_{\alpha\beta} F^{\alpha\beta}$$

$$\hookleftarrow F^{\alpha\beta}(\partial e, \partial \bar{e}, e \ldots)$$

$$T^{\mu\nu} = \sum \frac{\partial \mathcal{L}}{\partial e_{,\mu}} e_{,\nu} + \frac{\partial \mathcal{L}}{\partial \bar{e}_{,\mu}} \bar{e}_{,\nu} \quad \Leftarrow \text{our coordinates}$$

$$\vdots$$

$$= F^{\mu\alpha} F_{\alpha}{}^{\nu} - g^{\mu\nu} \mathcal{L} \qquad \text{IT WORKS!}$$

NON-ABELIAN? YES, ALREADY DONE.

energy flux of "e's": $\vec{E} \times \vec{B}$

$\uparrow$ appropriate "Trace"

WHAT CAN YOU DO WITH THIS?

• unlimited •

eg.

"STANDARD" PARTON DIST:

$$\langle p,s | \psi(x) P e^{i \int_x^{x'} A \cdot dx} \bar{\psi}(x') | ps \rangle$$

see also Heller, Johnson, Lovell Abcdlle

"WELL DRESSED" DIST:

$$\langle p,s | \psi^a_{(x)} \underbrace{\bar{e}^a(x)\, e^b(x')}_{} \bar{\psi}(x') | ps \rangle$$

$$\hookleftarrow e^{-ig\frac{D \cdot A}{D^2}} + \ldots \quad \Leftarrow \text{easy generalizn to } A^+ = 0$$

IDENTICAL
AT
LEADING
TWIST

ALL ORDERS
ALL TWISTS

5/5

REPAIRING the UMO ★★★

- unidentified
- measurable
- objects

OBJECT	COORDINATES	
$\vec{E}\times\vec{B} \overset{?}{=} \vec{P}/\text{vol}$	photon or gluon? NO gluon/matter? NO e/matter? YES	set not gi
$\bar{\Psi}\gamma^{\mu}(x^{\lambda}D^{\nu}-x^{\nu}D^{\lambda})\Psi \overset{?}{\Rightarrow} \vec{L}/\text{vol}.$	gluon/matter? No e/matter? YES	
but $\int d^3x\, \vec{L}/\text{vol}$ ok		
$\varepsilon^{\mu\nu\lambda\sigma}\bar{\Psi}\gamma_{\sigma}\gamma_{5}\Psi \overset{?}{\Rightarrow} \vec{\text{spin}}/\text{vol}$	quark + anything YES	

A^{ab}_{μ}, the gluon, is a human perturbative coordinate and not "same thing" as QCD itself.

Data transcends human perturbative distinctions. Data is non-perturbative. Spin data forces us to new coordinates beyond the current standard..

SPIN CONFRONTS THE PARADOX.
DEEPEST ISSUES - INNER
vs OUTER GEOMETRY - LIE
IN RESOLUTION

Pion Inclusive An at 21.6 GeV from C and H2

(E925)

ANL, BNL, IHEP Protvino, Indiana U, RIKEN, Kyoto U,
U of Tokyo Penn State, UCLA

Presented by D. Underwood
High Energy Physics
Argonne National Lab

for RHIC SPIN Oct 7, 1999

Measurements of the spin Asymmetry An for p C -> pi+, pi- +X and p p -> pi+, pi- +X are presented. The data on H2 are preliminary. These measurements were made at BNL in 1997 and 1999.

The experimental setup used hodoscopes and ananalyzing magnet. Polarized beam from the AGS was extracted and collimated. Beam intensities of up to 10^7/spill were utilized in the experiment. The inclusive data for the two beam polarizations were normalized to A luminosity monitor. A measurement of pp elastic asymmetry was done simultaneously to normalize the beam polarization. Features of the setup, trigger, analysis, and systematic errors are shown in the transparancies.

It was found that the pion inclusive asymmetry from Carbon is the same as from Hydrogen, within errors. This was contrary to some expectations. Thus, if this process is used in a polarimeter for RHIC, a Carbon target would give absolute polarization as well as a H2 target. A limitation on the Absolute Analyzing power comes from the limited knowledge, about +- 12 %, of the An (pp elastic) used to normalize this experiment.

The structure of the asymmetries for pi+ and pi- vs Xf is remarkably like that found at 200 GeV. The pi + and pi - have the same differences from mirror symmetry at both energies. The structures move as a function of root(S), as also seen in some older, incomplete data from 11 GeV. About a dozen theoretical papers on this type of pion asymmetry do not describe these features in any detail.

E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

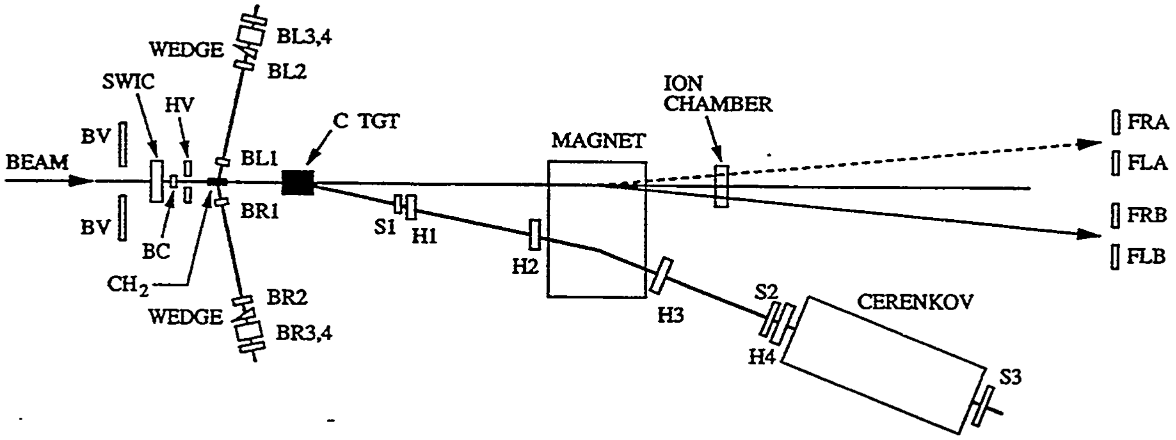
E925 measured $\pi^{\pm}$ and proton inclusive analyzing powers at 21.6 GeV/c, and verified that they are large and have the same signs and general appearance as do the 200 GeV data.

There were two running periods:

November 1997 - Carbon Target PUBLISHED
PLB 459, 412 (1999)

March 1999 - Hydrogen Target PRELIMINARY

Experimental Layout:



The Experiment was done in the B1 line at the AGS.

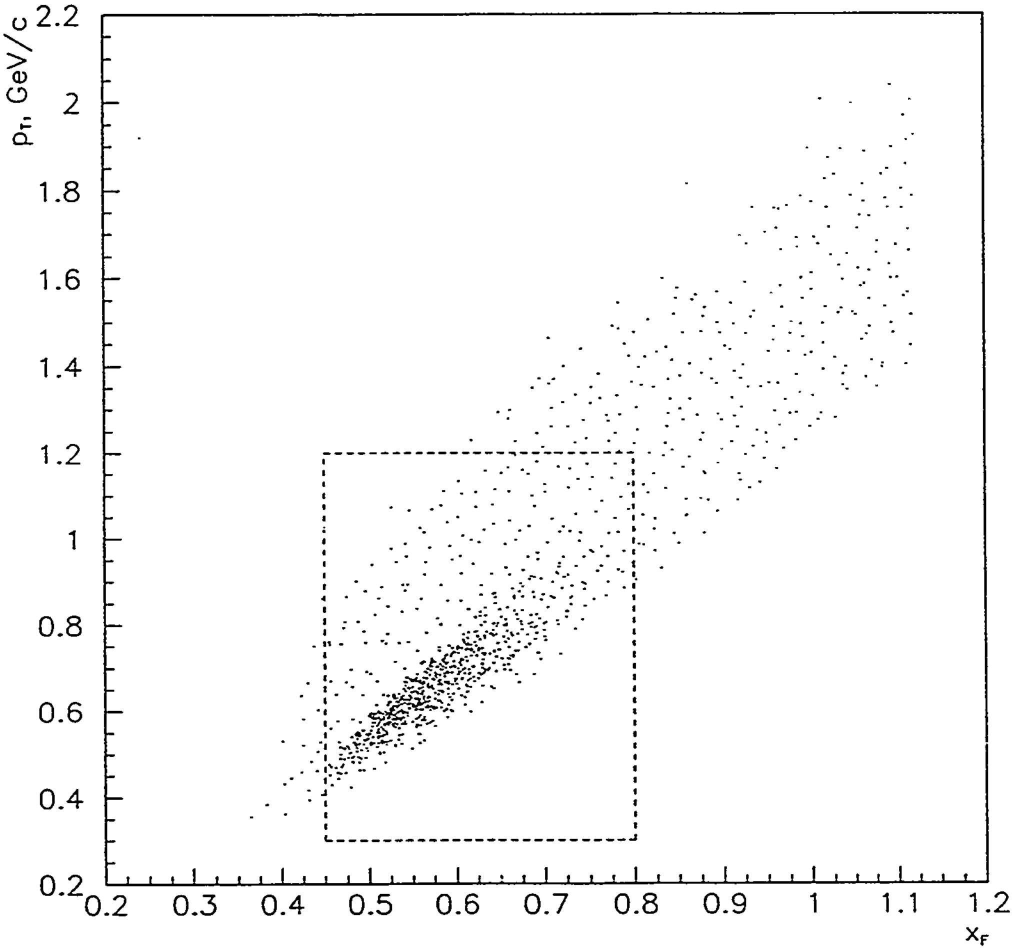
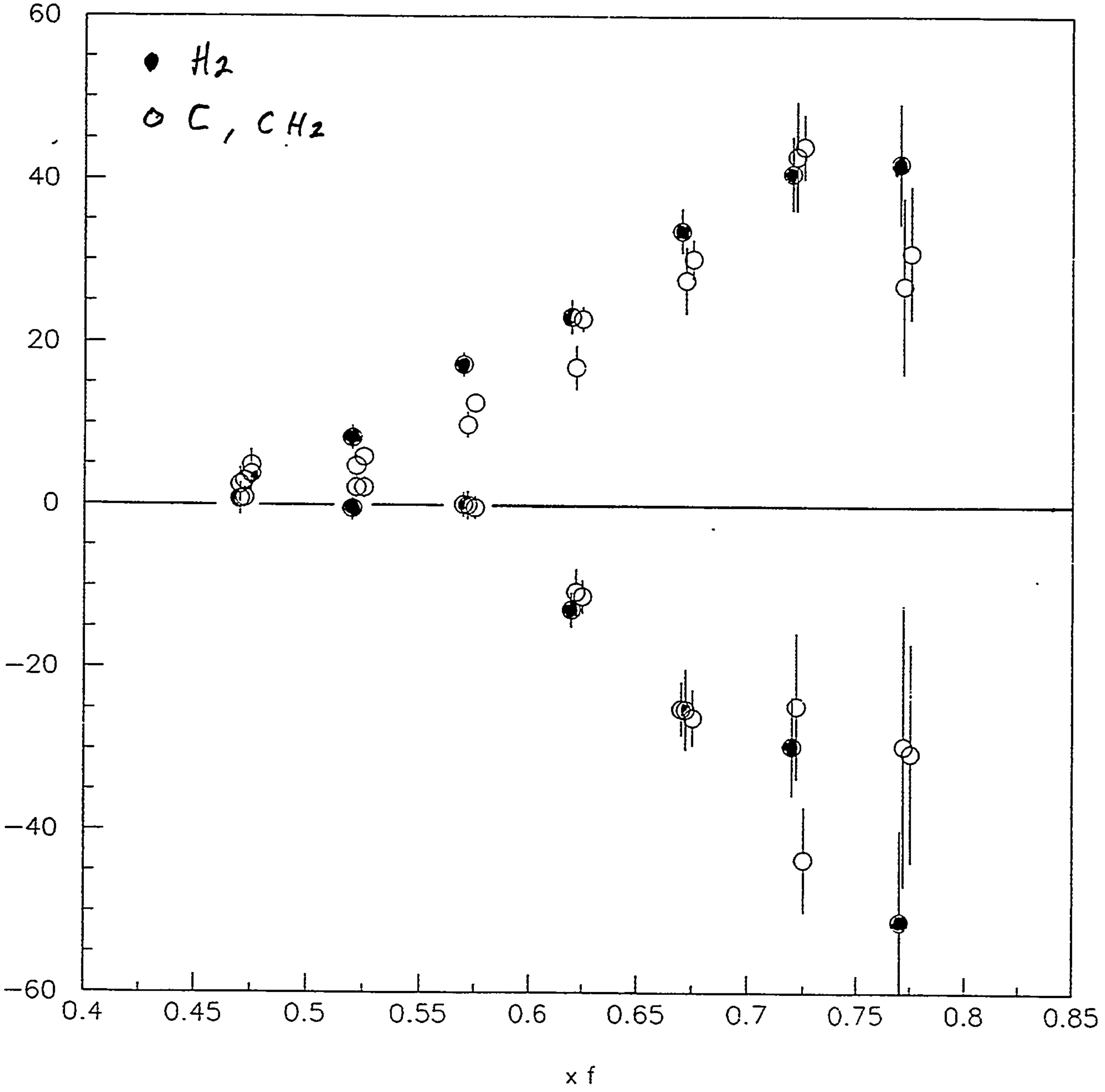


FIG. 15. Scatter plot of x_F vs. p_T. The box indicates the cuts on x_F and p_T. This was the final cut before background subtraction.



MATCH CH_2 99 TO C 97
WITHIN SYSTEMATIC ERRORS
(RE-PROCESSED, RE-BINNED)

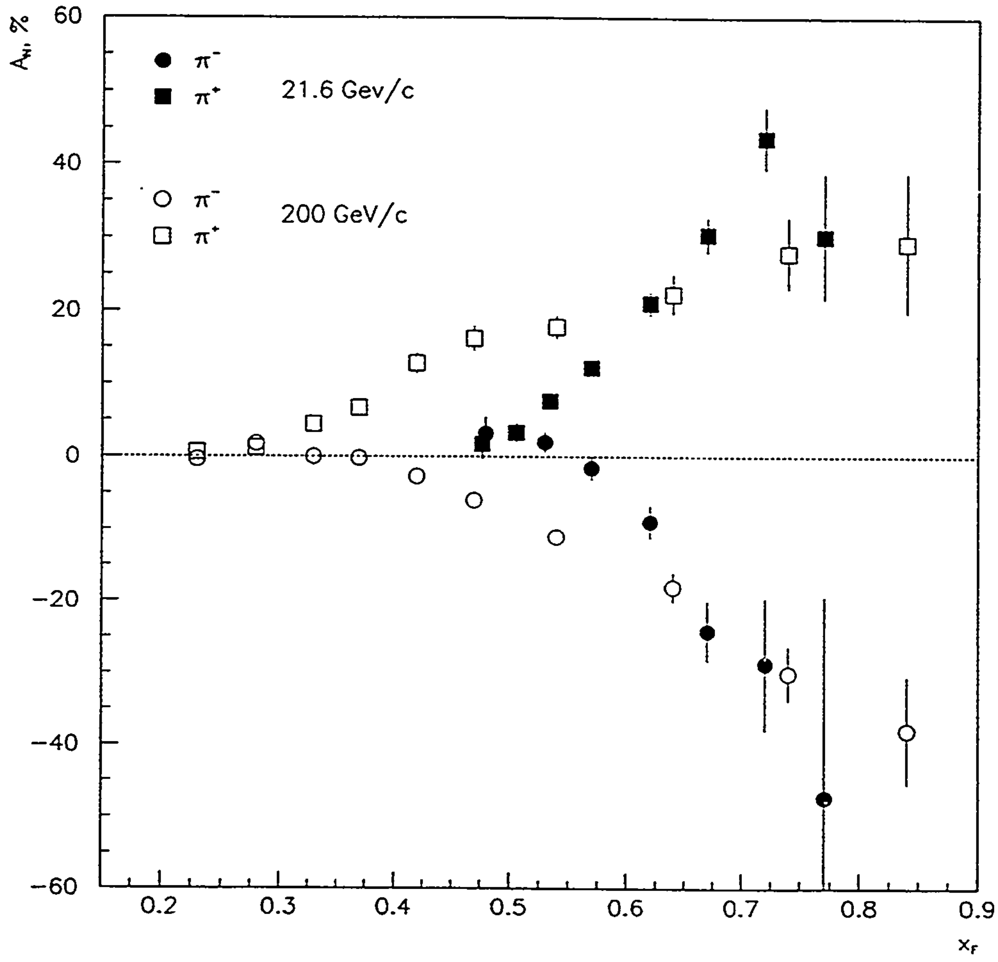


FIG. 21. Comparison of inclusive analyzing powers A_N from 21.6 *GeV/c* and 200 *GeV/c* [1]. H_2

- NOT REALLY MIRROR SYMMETRIC

- RISE FROM 0 POLARIZATION TRAVELS WITH $\sqrt{s}$ (SEE 11 GeV ALSO)

CAN WE LEARN SOMETHING ABOUT THE PHYSICS PROCESS FROM KINEMATICS?

RECENT RESULTS ON INCLUSIVE PION ASYMMETRIES

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Institute for High Energy Physics, 142284Protvino, RF

Recent measurements of the analyzing power done by groups FODS-2, PROZA-M (IHEP, Protvino) and E925(AGS, BNL, Upton) are reviewed.

1. FODS-2 team produced and used the polarized proton beam of 40 GeV/c from Lambda decay(see Table 1, where the E704 polarized beam parameters are presented too for comparison). FODS-2(Fig.1) measured the analyzing powers for pi(+,-), K(+,-) and p, anti p at 40 GeV/c. The particle identification power can be seen in Fig.2 The measured kinematical region was: x_F=0.02-0.11(central region) and p_T=0.7-3.4 GeV/c. For pions and kaons the x_T dependences seem similar to ones seen at E704 in forward direction, while data for p appear not depending on x_T.(see Fig.3-6). FODS-2 plans to increase statistics by 40 times in oncoming runs.

2. PROZA-M collaboration uses the polarized propandiol target installed on 70 GeV/c unpolarized proton beam, The scheme of apparatus is presented in Fig,7, while its mass resolution can be seen in Fig.8. The measured kinematical region was: x_R=x_T=0.2-0.5 and p_T=1.05-2.95 GeV/c for EMC1 and x_R=x_T=0.3-0.4, p_T=1.75-2.35 GeV/c for EMC2. Both EMC1 and EMC2 were installed at 90 degr. in the c.m.s. EMC3 has an acceptance: x_R=0.25-0.5 and p_T=1.7-2.2 GeV/c. While asymmetry for EMC and EMC2 is consistent with zero(Fig.9), EMC3(having x_F around -0.3) shows nonzero negative asymmetry growing with x_R(Fig.10). This is a direct indication that the analyzing power in the polarized proton fragmentation region might be significant. Proza-M plans to extend x_F region up to -0.8 in near future.

3. E925 experiment aimed to measure the analyzing power in the inclusive pion production at the RHIC injection energy 22 GeV. The scheme of detector is presented in Fig. 11. The polarized proton beam of AGS was used and results on analyzing power for hydrogen and carbon are shown in Fig.12. Two important conclusions can be drawn. First asymmetry(sign, magnitude, shape) is the same as at 200 GeV/c. This might be an indication that the analyzing power for inclusive pion production is energy independent. Second analyzing powers on hydrogen and carbon are practically the same.

1. FODS-2 experiment was done on the polarized proton beam of 40 GeV/c produced through the Λ-decay. The main parameters of this beam is presented in Table 1. For comparison in this table the parameters of the E704 setup are included too.

Table 1. The list of parameters of the primary proton beam and the polarized proton beam from Λ-decay for two experimental setups E704 and FODS-2.

Parameters	E704	FODS-2
Primary beam:		
Momentum, GeV/c	800	70
Intensity, protons per spill	(0.3-2)x10 ^{12}	10^{13}
Beam size at the production target, xxy, mm**2	0.8x2	4x2.5
Duration of the spill, sec.	20	1-2
Duty factor, %	33	20
Polarized beam		
Production target, material, xxyxz, mm^3	Be, 1.5x1.5x300	Al, ?x?x300
Momentum, GeV/c	200	40
Momentum bite, %	±10	±4.5
Beam size at final focus(rms), xxy, mm^3	15x15	[redacted] 10.6X 8.1
Angular divergence at final focus, x'xy', $mrad^2$	0.8x0.6	[redacted] 6.5X 6.0
Pion contamination in polarized proton beam, %	±13	[redacted] ± 0,8
Polarization tagging detector,	yes	no
Polarization tagging resolution, %	±11	—
Momentum tagging detector	yes	no
Momentum resolution of the tagging detector, %	±1.5	no
Beam polarimeter:	yes	no
Beam polarization calculated , %	45± 3 [redacted]	39^{+1}_{-3}
Beam polarization measured by the CNI polarimeter, %	41±26	—
Beam polarization measured by Primakoff polarimeter, %	40±9	—
Total polarized protons at target	9×10^6	9×10^6
Tagged polarized protons at target	6×10^6	—
Tagged protons with |P|>35% and <P>=45%	3×10^6	—
Polarization reverse	by system of 8 magnets; any polarization direction.	by movable collimator

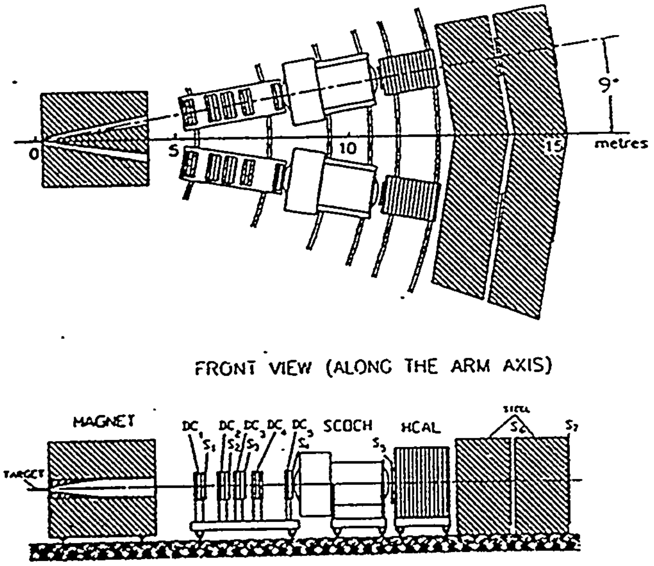


Fig. 1. The schematic layout of FODS-2 spectrometer.

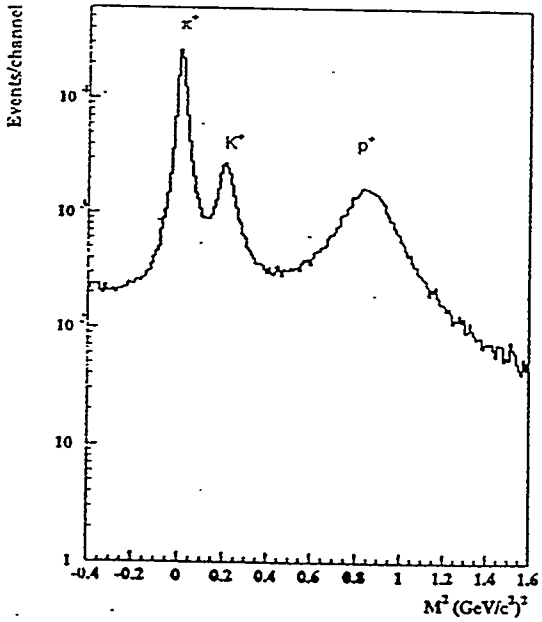


Fig. 2. Mass spectrum of hadrons measured by SCOCH detector.

FODS-2 results

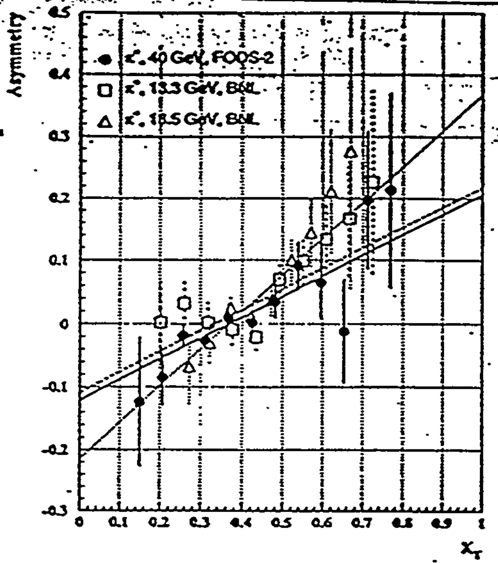


Fig. 3. Comparison of A_N vs x_T for π^+-mesons at 40 GeV, 18.5 and 13.3 GeV [3]. Solid line shows fit (5) for 40 GeV, dashed line – for 13.3 GeV, and dotted line – for 18.5 GeV.

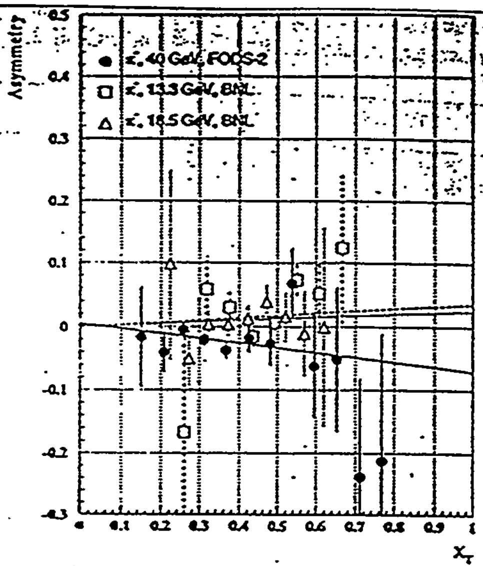


Fig. 4. Comparison of A_N vs x_T for π^--mesons at 40 GeV, 18.5 and 13.3 GeV [3]. Solid line shows fit (5) for 40 GeV, dashed line — for 13.3 GeV, and dotted line – for 18.5 GeV.

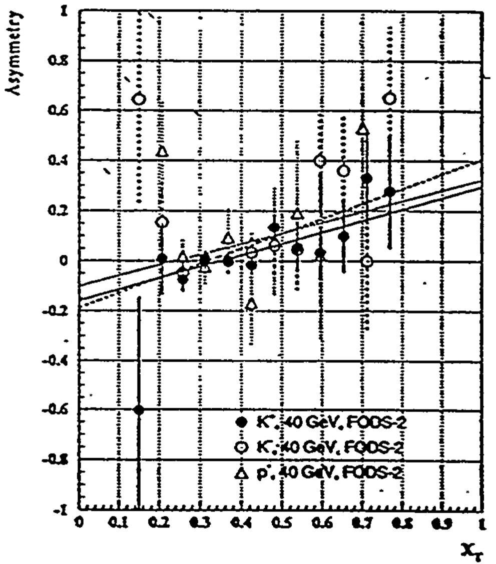


Fig. 5. Single-spin asymmetry vs x_T for K^+, K^--mesons and antiprotons. Solid line shows fit (5) for K^+, dashed line – for K^-, and dotted line – for antiprotons.

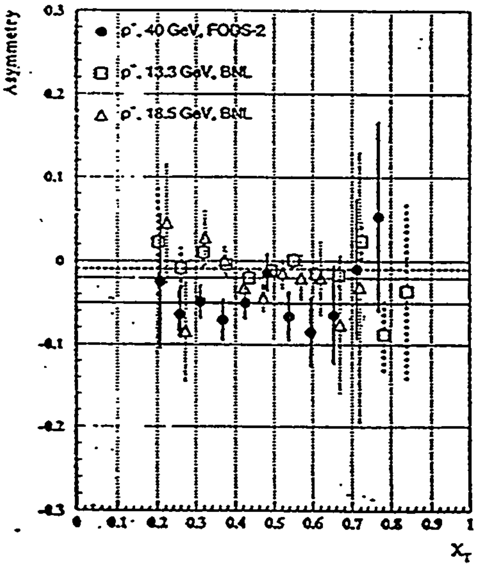


Fig. 6. Comparison of A_N vs x_T for protons at 40 GeV, 18.5 and 13.3 GeV [3]. Solid line shows fit (5) for 40 GeV, dashed line – for 13.3 GeV, and dotted line – for 18.5 GeV.

2. PROZA-M setup

The main goal is to measure the analyzing power in reaction $p+p_T \rightarrow \pi^0 + X$ at 80 GeV/c. Intensity 4×10^6 p/spill, τ(spill)=1sec. Beam size, xxy(rms) = 4×3 mm^2, beam angular divergence x×y = 2×1 mrad(rms). Polarized target: ϕ = 2cm, l = 20cm, propandiol, target polarization 80%. Lead glass calorimeters: EMC1(l=7m, Θ(lab)=9°)contains 480 cnts(24 ×20), EMC2(l=3m, Θ(lab)=9°) 144(12×12), EMC3=EMC2. Standard cell:3.8x3.8×450 mm^3 (18 X_0). High p_T trigger. 500 events/spill. DAQ has 70% efficiency.

Future measurement aims to reach x_F reagion close to -0.8, where expected to see the highest analyzing power(around 30-40% according to E704 data, assuming an energy independence of this observable).

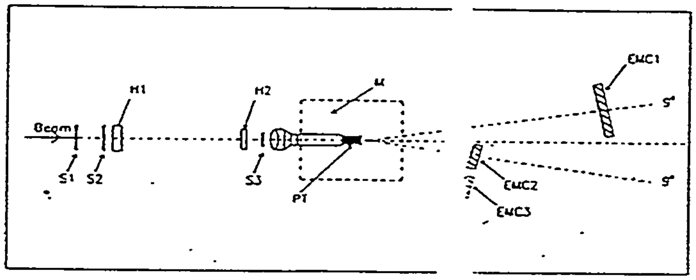


Fig. 7. Diagram of the experimental setup PROZA-M. S1, S2 and S3 are scintillator zero-level trigger counters. H1 and H2 are the two-coordinate hodoscopes. PT is the polarized target. M is the magnet of the target. EMC1, EMC2, and EMC3 are three electromagnetic calorimeters. 9° in Lab. system corresponds to 90° in CM for 70 GeV.

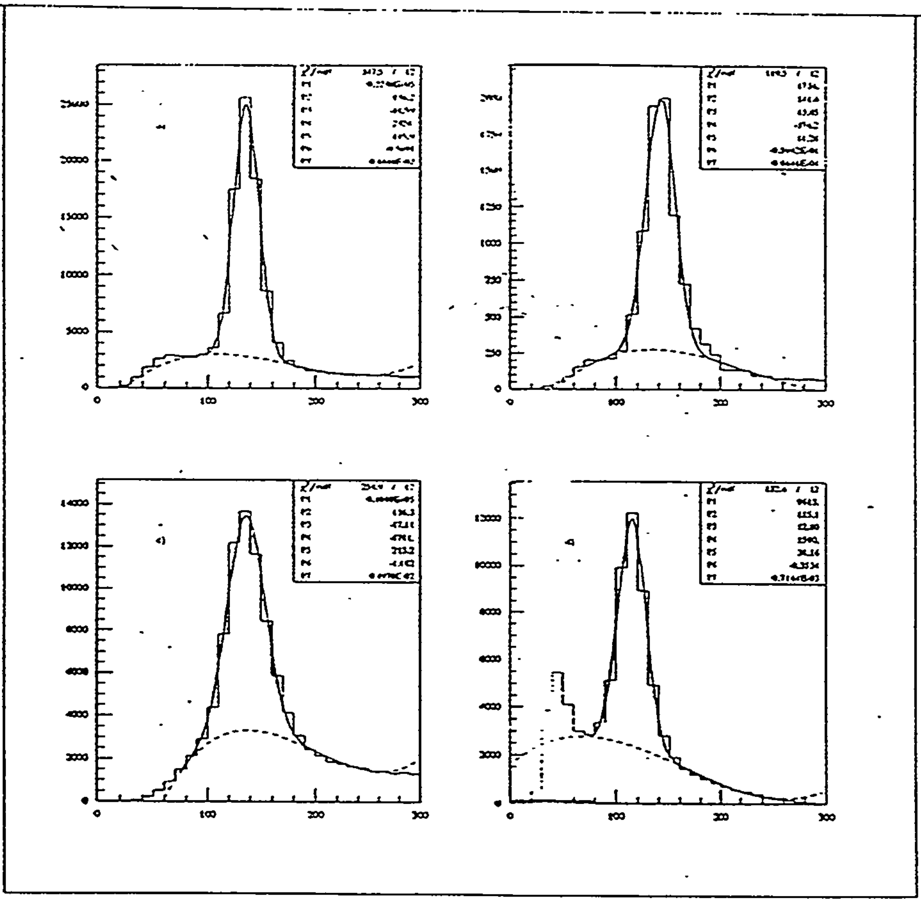
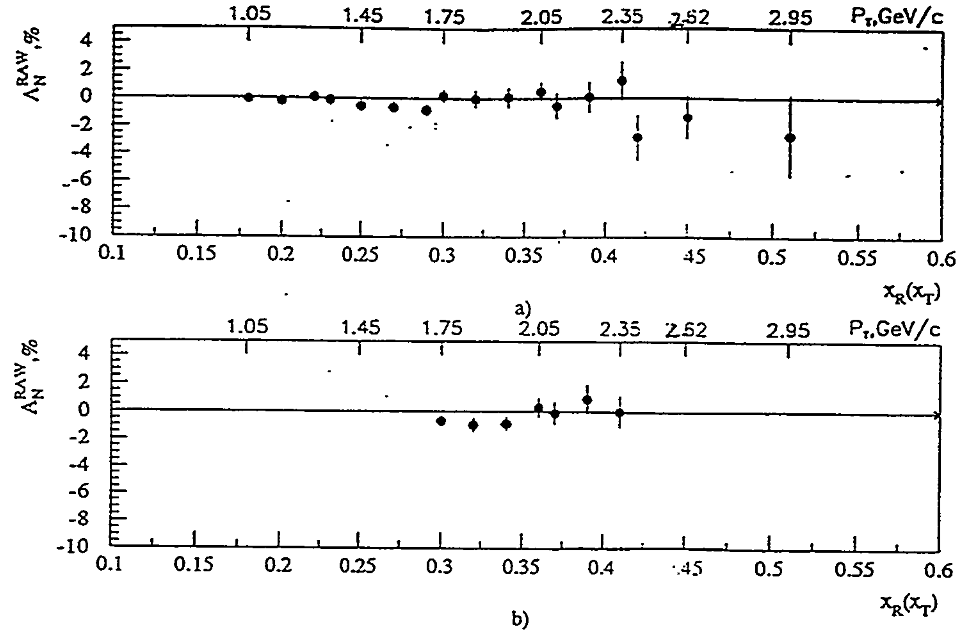


Fig. 8, The two-photon invariant-mass distributions for π^0 production at a) EMC1 for the p_T region from 1.7 to 1.8 GeV/c; b) EMC1 for the p_T region from 2.2 to 2.3 GeV/c; c) EMC2 for the p_T region from 1.7 to 1.8 GeV/c; d) EMC3 for the p_T region from 1.2 to 1.3 GeV/c (after energy scale corrections (see text) the mean mass value has changed from 115 to 129 MeV/c^2).

PROZA-M results



a)

b)

Fig. 9. The raw asymmetry parameter as a function of $x_R(x_T)$ for a) EMC1 and b)EMC2.

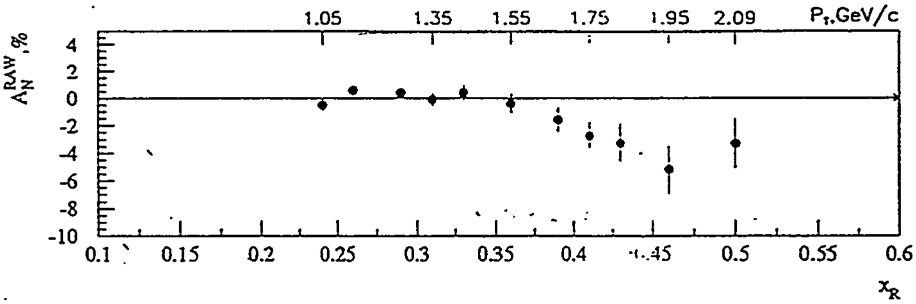
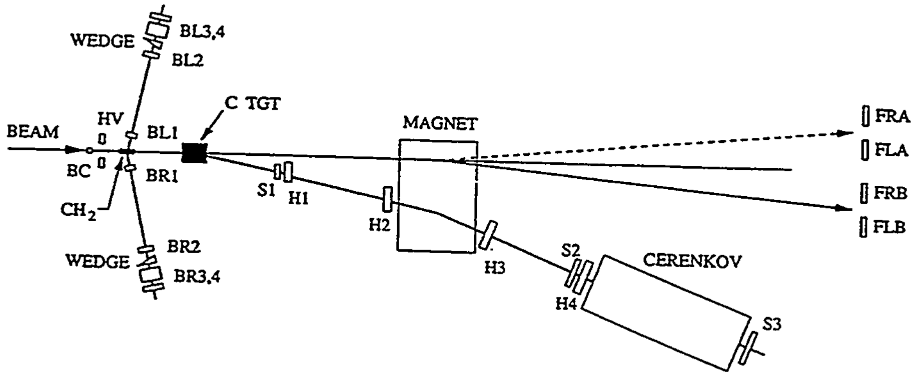


Fig.10 The raw asymmetry parameter as a function of p_T (or x_R) for EMC3.

EXPERIMENT E925, AGS, BNL



E925 results

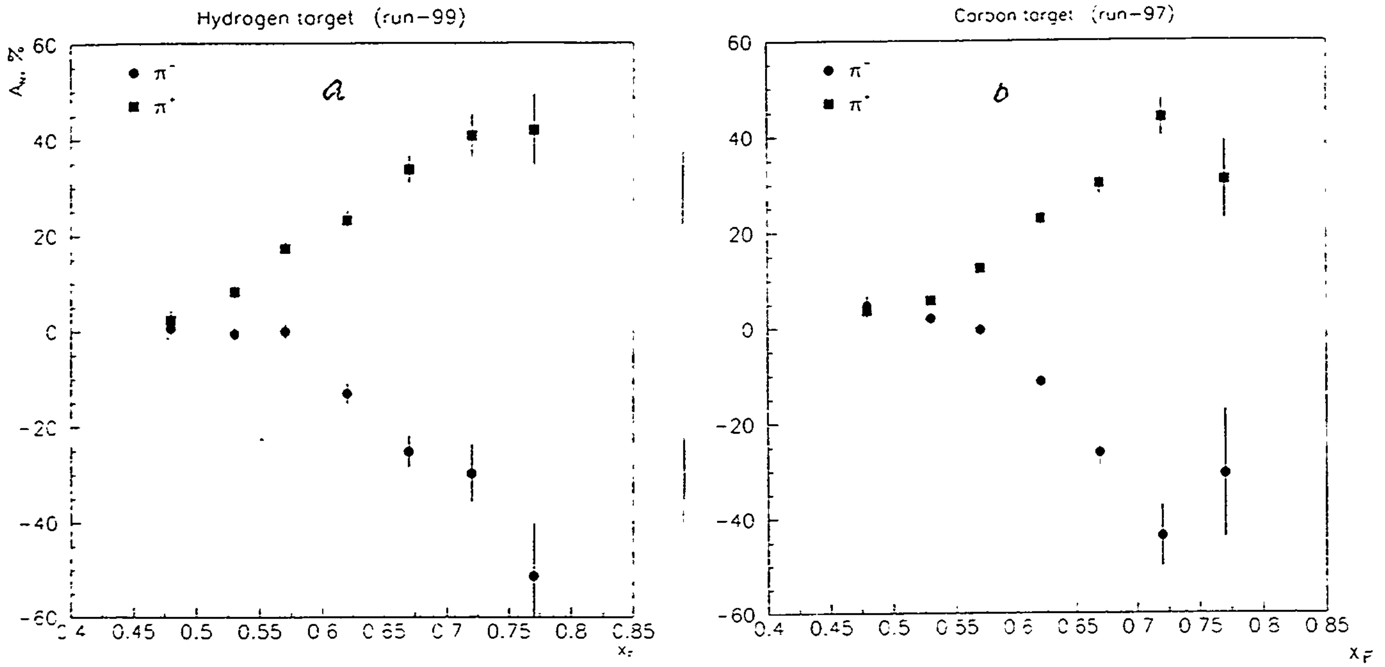


Fig.12. Analyzing power at 22 GeV/c for inclusively produced pi(+) and pi(-): a) on hydrogen, and b) on carbon targets.

Conclusions

Experimental data from FODS-2 relevant to the central region indicate on some interesting spin effects like similar to BNL data x_T dependence, flavour dependence, etc. But one needs more precise measurements by improving the technique of experiment and the statistical precisions.

Experimental data from PROZA-M indicate that the essential spin effect might be present in the polarized proton fragmentation region. In contrary to the E704 the target is polarized instead of the beam. But according to the identity of both colliding protons in both cases the analyzing powers must coincide. It is cruicial to continue such measurements in order to justify the inclusive neutral pion polarimeter at RHIC domain of energy.

Experiment E825 gave an evidence for the similarity of the analyzing powers at 21 and 200 GeV/c. It also shows that the analyzing powers in inclusive pion productions at hydrogen and carbon are practically coinciding.

For polarimetry at RHIC among 3 above experiments only E925 presents a solid base. It is important to make an additional measurements at the intermediate energy between 21 and 200 GeV/c and also around 250 GeV/c(RHIC top energy).

The drawbacks in experiments with polarized beams are not so high accuracy in the beam polarization determination. FODS-2 did not make any experimental measurement of beam polarization. In E925 the precisions in beam polarization measurements were: 1997 run- ±26%, in 1999 run- ±16%. The goal to have a precision ±5% is not yet reached.

PHYSICS RESULTS FROM HERMES

AZIMUTHAL SINGLE SPIN ASYMMETRIES

RALF KAISER - DESY/ZEUTHEN
ON BEHALF OF THE HERMES COLLABORATION

RHIC SPIN WORKSHOP, BNL, OCTOBER 1999

- DISTRIBUTION AND FRAGMENTATION FUNCTIONS
- AZIMUTHAL SINGLE SPIN ASYMMETRIES
- HERMES RESULTS

RESULTS ARE BASED ON THE DATA TAKING PERIODS 1996-1997 OF THE HERMES EXPERIMENT AT HERA

Observation of a Single-Spin Azimuthal Asymmetry in Semi-Inclusive Pion Electro-Production, SUBMITTED TO PHYS.REV.LETT., HEP-EX/99XXXXXX

DISTRIBUTION AND FRAGMENTATION FUNCTIONS

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

THE SEMI-INCLUSIVE DIS CROSS SECTION CAN BE WRITTEN AS THE SUM OVER QUARK FLAVORS q OF CONVOLUTIONS OF DISTRIBUTION FUNCTIONS AND FRAGMENTATION FUNCTIONS.

BASIC ASSUMPTION:
FACTORIZATION IS VALID, I.E. SCATTERING PROCESS AND HADRONIZATION CAN BE REGARDED AS INDEPENDENT.

THE SIMPLEST DISTRIBUTION FUNCTIONS ARE THE UNPOLARIZED PARTON DISTRIBUTION FUNCTIONS $u(x)$, $d(x)$, ETC., ALSO REFERED TO AS f_1^q.

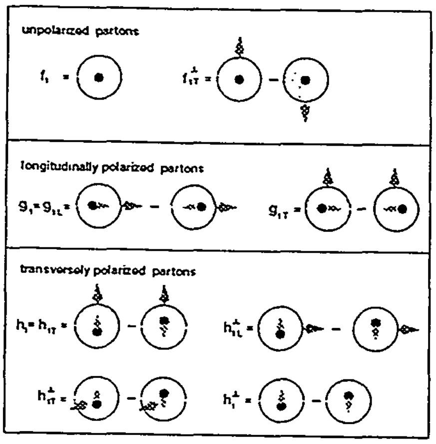
THE SIMPLEST FRAGMENTATION FUNCTION IS THE UNPOLARIZED FAVORED FRAGMENTATION FUNCTION D_1.

BUT THERE IS MORE ...

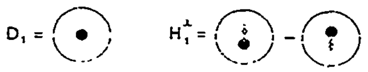
DISTRIBUTION AND FRAGMENTATION FUNCTIONS

TRANSVERSE POLARIZATION ADDS QUITE A FEW DISTRIBUTION FUNCTIONS TO THE WELL KNOWN UNPOLARIZED f_1 AND LONGITUDINAL g_1: THE TRANSVERSE h_1 AND A VARIETY OF MORE COMPLEX FUNCTIONS [RALSTON, 1979].

(SUBSCRIPT 1 $\doteq$ TWIST 2, SUPERSCRIPT $\perp \doteq p_T$(PARTON)>0):



THE SAME IS TRUE FOR THE FRAGMENTATION FUNCTIONS:



CLASSIFICATION OF DISTRIBUTION AND FRAGMENTATION FUNCTIONS

Distributions (T-even)				Distributions (T-odd)			
$\Phi^{[\Gamma]}$		chirality		$\Phi^{[\Gamma]}(x,k_T)$		chirality	
		even	odd			even	odd
twist 2	U	f_1		twist 2	U		$h_1^{\perp}$
	L	g_1	$h_{1L}^{\perp}$		L		
	T	g_{1T}	h_1 $h_{1T}^{\perp}$		T	$f_{1T}^{\perp}$	
twist 3	U	$f^{\perp}$	e	twist 3	U		h
	L	$g_L^{\perp}$	h_L		L	$f_L^{\perp}$	e_L
	T	g_T $g_T^{\perp}$	h_T $h_T^{\perp}$		T	f_T	e_T

Fragmentation			
$\Delta^{[\Gamma]}$		chirality	
		even	odd
twist 2	U	D_1	$H_1^{\perp}$
	L	G_{1L}	$H_{1L}^{\perp}$
	T	G_{1T} $D_{1T}^{\perp}$	H_1 $H_{1T}^{\perp}$
twist 3	U	$D^{\perp}$	E H
	L	$G_L^{\perp}$ $D_L^{\perp}$	E_L H_L
	T	G_T $G_T^{\perp}$ D_T	E_T H_T $H_T^{\perp}$

[JAFFE, MULDERS, ...]

FUNCTIONS IN BLUE ARE RELEVANT FOR THE PRESENT HERMES MEASUREMENT.

PHYSICS GOALS

- UNDERSTAND POLARIZATION EFFECTS IN THE FRAGMENTATION PROCESS AND
- MEASURE CHIRAL-ODD DISTRIBUTION FUNCTIONS AND T-ODD FRAGMENTATION FUNCTIONS

SINGLE SPIN ASYMMETRIES DEPEND ONLY ON THE POLARIZATION OF THE BEAM OR THE TARGET. THEY APPEAR TO BE DUE TO INITIAL AND/OR FINAL STATE INTERACTIONS.

CHIRAL ODD DISTRIBUTION AND T-ODD FRAGMENTATION FUNCTIONS CAN LEAD TO SINGLE SPIN ASYMMETRIES (SSA) IN POLARIZED HARD PROCESSES.

⇛ LOOK FOR A CORRELATION BETWEEN THE AZIMUTHAL DISTRIBUTIONS OF THE PRODUCED HADRONS AND THE (TRANSVERSE OR LONGITUDINAL) TARGET POLARIZATION.

SINGLE SPIN ASYMMETRIES (SSA) IN DIFFERENT PROCESSES

SINGLE SPIN ASYMMETRIES

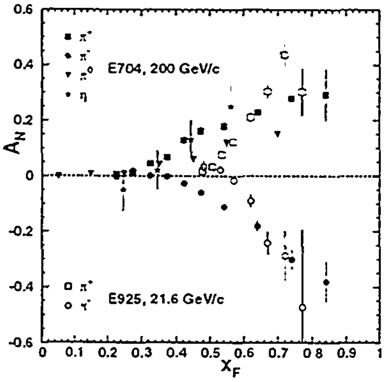
$$A_N = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}$$

MIGHT ORIGINATE IN QCD FROM THE DISTRIBUTION FUNCTION (DF), THE ELEMENTARY SCATTERING PROCESS (ESP) OR THE FRAGMENTATION FUNCTION (FF).

	A_N ORIGINATES FROM ...		
PROCESS	DF	ESP	FF
$l + p^\uparrow \to l + \pi^\pm + X$	$A_N \approx 0$	$A_N = 0$	$A_N \neq 0$
$p + p^\uparrow \to \pi^\pm + X$	$A_N \neq 0$	$A_N \approx 0$	$A_N \neq 0$
$p + p^\uparrow \to ll + X$ $p + p^\uparrow \to W^\pm + X$ in the fragmentation region of $p^\uparrow$	$A_N \neq 0$	$A_N \approx 0$	$A_N = 0$
$Z^0 \to$ 2-jet decays	$A_N = 0$	$A_N = 0$	$A_N \neq 0$

SSA - EXPERIMENTAL STATUS

- FNAL E704 BNL E925
  $p + p^\uparrow \to \pi^{\pm,0} + X$ A_N UP TO 40 %



- DELPHI $\cos 2\phi$ IN $Z^0 \to$ 2-jet
  $\left|\frac{\int_{0.2}^{1} H_1^\perp(z)\, dz}{\int_{0.2}^{1} D_1(z)\, dz}\right| = 6.3 \pm 1.7\%(\text{stat.})$
- SMIC $\mu + \vec{p} \to \mu + h^\pm + X$
  $A_N^{h^+} = 0.11 \pm 0.06$

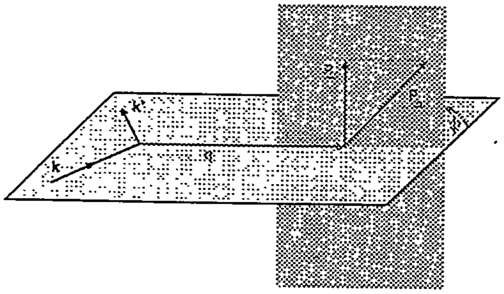
HERMES - THE EXPERIMENT

$$\vec{l} + \vec{p} \to l + \pi^\pm + X$$

BEAM ENERGY BEAM POLARIZATION	27.56 GeV 0.55 ± 0.04 (LONG.)
TARGET TARGET POLARIZATION	HYDROGEN 0.86 ± 0.05 (LONG.)
ACCEPTANCE IN θ_x ACCEPTANCE IN θ_y	$-1.7 < \theta_x < 1.7$ $0.4 < \lvert\theta_y\rvert < 1.4$
DIS CUTS	$Q^2 > 1$ $W^2 > 4$ $y < 0.85$
CUTS ON FINAL HADRONS	$z > 0.2$ $P_\perp > 0.05$
IDENTIFIED π^+ IDENTIFIED π^-	$\sim 110,000$ $\sim 80,000$

AZIMUTHAL SINGLE SPIN ASYMMETRIES - KINEMATICS

SINGLE SPIN ASYMMETRIES DEPEND ONLY ON THE SPIN OF EITHER THE BEAM OR THE TARGET. THEY APPEAR AS DEPENDENCES OF THE CROSS SECTION ON THE AZIMUTHAL ANGLE ϕ.



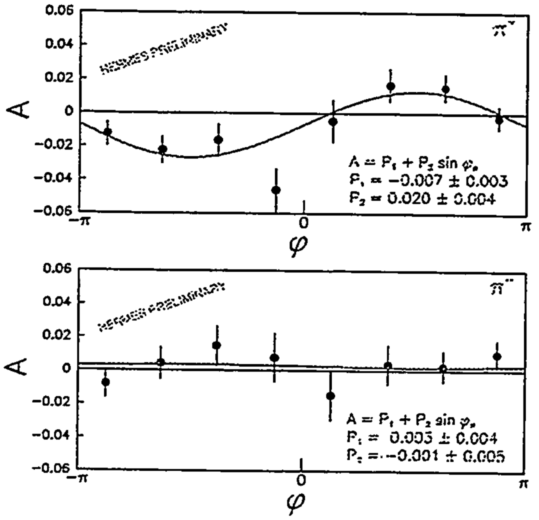
IN THE CASE OF LONGITUDINAL TARGET POLARIZATION THE AZIMUTHAL ANGLE ϕ IS THE ANGLE BETWEEN THE ELECTRON SCATTERING PLANE AND THE PROJECTION OF THE HADRON MOMENTUM $P_\perp$ PERPENDICULAR TO THE VIRTUAL PHOTON MOMENTUM q.

AZIMUTHAL SINGLE SPIN ASYMMETRIES

UNPOLARIZED BEAM, LONGITUDINALLY POLARIZED TARGET:

$$A(\phi) = \frac{1}{P_T}\frac{N^{\Uparrow}(\phi) - N^{\Downarrow}(\phi)}{N^{\Uparrow}(\phi) + N^{\Downarrow}(\phi)}$$

WHERE $N^{\Uparrow(\Downarrow)}(\phi)$ ARE NUMBERS OF PIONS IN A ϕ BIN FOR TWO OPPOSITE TARGET SPIN STATES AND P_T IS THE TARGET NUCLEON POLARIZATION.



AZIMUTHALLY WEIGHTED ASYMMETRIES

ANALYSIS USES AZIMUTHALLY WEIGHTED MOMENTS OF CROSS SECTIONS:

$$\langle W\rangle_{BT}^{\Uparrow(\Downarrow)} = \int W(\phi)\, dN^{\Uparrow(\Downarrow)}$$

$B,T =$ U (UNPOLARIZED),
L (LONGITUDINALLY POLARIZED)
T (TRANSVERSELY POLARIZED)

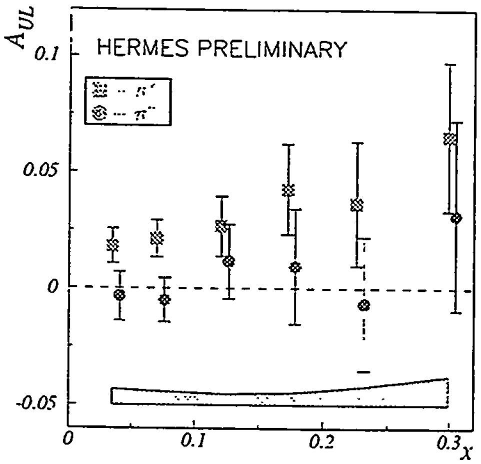
HERE: $W = \sin\phi$.

EXTRACTING ASYMMETRIES:

$$A_{UL} = \frac{\frac{L^{\Uparrow}}{L_T^{\Downarrow}}\langle W^{\Uparrow}\rangle_{UL} - \frac{L^{\Downarrow}}{L_T^{\Uparrow}}\langle W^{\Downarrow}\rangle_{UL}}{\frac{1}{2}\left[\int dN^{\Uparrow} + \int dN^{\Downarrow}\right]}$$

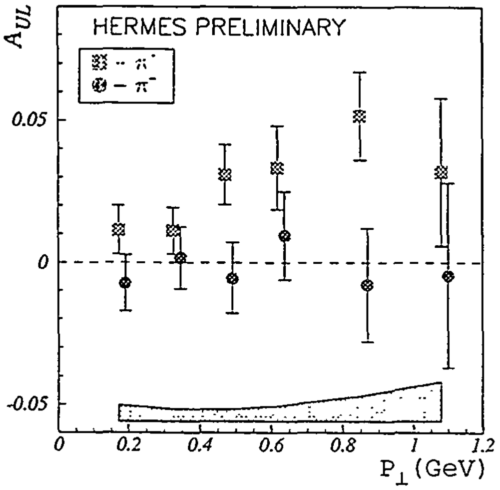
WHERE $\Uparrow$ ($\Downarrow$) DENOTES THE SIGN OF THE TARGET SPIN.

A_{UL}: x-DEPENDENCE



BAND AT THE BOTTOM OF THE PLOT REPRESENTS THE SYSTEMATIC UNCERTAINTY.

$\mathcal{A}_{UL}$: $p_\perp$-DEPENDENCE



BAND AT THE BOTTOM OF THE PLOT REPRESENTS THE SYSTEMATIC UNCERTAINTY.

A_{UL}: RESULTS

	π^+
$A_{UL}^{\sin\phi}$	$0.022 \pm 0.005 \pm 0.003$
$A_{UL}^{\sin 2\phi}$	$-0.002 \pm 0.005 \pm 0.010$
$A_{LU}^{\sin\phi}$	$-0.005 \pm 0.008 \pm 0.004$
	π^-
$A_{UL}^{\sin\phi}$	$-0.002 \pm 0.006 \pm 0.004$
$A_{UL}^{\sin 2\phi}$	$-0.005 \pm 0.006 \pm 0.005$
$A_{LU}^{\sin\phi}$	$-0.007 \pm 0.010 \pm 0.004$

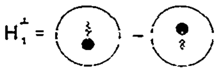
ONLY THE AYMMETRY $A_{UL}^{\sin\phi}(\pi^+)$ IS SIGNIFICANTLY DIFFERENT FROM ZERO, ALL OTHERS ARE COMPATIBLE WITH ZERO.

$\mathcal{A}_{UL}$: INTERPRETATION

$$\begin{aligned}
\mathcal{A}_{UL}^{\sin\phi} \sim\ & \frac{M}{Q} S_L\ h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)} && T2 \otimes T2 \\
& + \frac{M}{Q} S_L\ \tilde{h}_L \quad \otimes H_1^{\perp(1)} && T3 \otimes T2 \\
& - \frac{M}{Q} S_L\ h_{1L}^{\perp(1)} \otimes \frac{\tilde{H}}{z} && T2 \otimes T3 \\
& + \sin\theta_\gamma S_{lab}\ h_1 \quad \otimes H_1^{\perp(1)} && T2 \otimes T2
\end{aligned}$$

$$\mathcal{A}_{UL}^{\sin 2\phi} \sim S_L\ h_{1L}^{\perp(1)} \otimes H_1^{\perp(1)} \qquad T2 \otimes T2$$

- SUBSCRIPT 1 DENOTES TWIST-2; WITHOUT SUBSCRIPT: TWIST-3.
- SUPERSCRIPT (1) INDICATES k_T WEIGHTED DISTRIBUTION AND FRAGMETATION FUNCTIONS:
  $H_1^{\perp(1)}(z_h) = z_h^2 \int d^2k_T \left(\frac{k_T^2}{2M_h^2}\right) H_1^{\perp(1)}(z_h, z_h^2 k_T^2)$
- $\tilde{H}(z) = z\frac{d}{dz}(zH_1^\perp(z))$



SUMMARY AND OUTLOOK

◇ AZIMUTHAL SINGLE SPIN ASYMMETRIES IN SEMI-INCLUSIVE PION ELECTRO-PRODUCTION HAVE BEEN OBSERVED FOR THE FIRST TIME.

◇ THE $\sin\phi$-WEIGHTED AZIMUTHAL ASYMMETRY IS FOUND TO BE SIGNIFICANT FOR π^+ PRODUCTION $0.022 \pm 0.005(stat.) \pm 0.003(syst.)$ WHILE IT IS CONSISTENT WITH ZERO FOR π^- PRODUCTION.

◇ THE $\sin 2\phi$ WEIGHTED ASYMMETRIES FOR $\pi^\pm$ PRODUCTION ARE CONSISTENT WITH ZERO.

◇ THE $x-$ AND p_T-BEHAVIOURS OF $A_{UL}^{\sin\phi}$ ARE IN AGREEMENT WITH EXPECTATIONS BASED ON THE COLLINS MODEL FOR FRAGMENTATION.

◇ ADDITIONAL DATA ON A DEUTERIUM TARGET EXIST, BUT HAVE NOT YET BEEN ANALYZED.

◇ AFTER HERA LUMINOSITY UPGRADE TAKE DATA ON A TRANSVERSELY POLARIZED TARGET TO MEASURE TRANSVERSITY h_1.

Transverse spin distribution and fragmentation functions

Daniël Boer
RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973

In this talk I will focus on the transverse spin distribution and fragmentation functions, which parametrize transverse spin effects in hard scattering processes. Even though little is known experimentally on most of these functions, single transverse spin experiments have been performed. For instance, deep inelastic scattering of an electron off a transversely polarized hadron has been investigated at SLAC and by SMC. In this experiment one is sensitive to the chiral-even, T-even distribution function g_T, which appears in the cross section suppressed by a power of the hard scale. On the other hand, the leading twist, chiral-odd, T-even distribution function h_1 (also called transversity distribution function) has not been studied experimentally yet, but it can be measured in Drell-Yan scattering of two transversely polarized protons at RHIC.

Large single transverse spin asymmetries have been observed in the process $p\,p^{\uparrow} \to \pi\,X$. For the description of this process one also needs fragmentation functions, including T-odd functions which are expected to arise due to final state interactions. The description of this specific process in terms of transverse spin distribution and fragmentation functions will lead to power suppressed single spin asymmetries, unless one takes into account the transverse momentum of the partons, see e.g. [1].

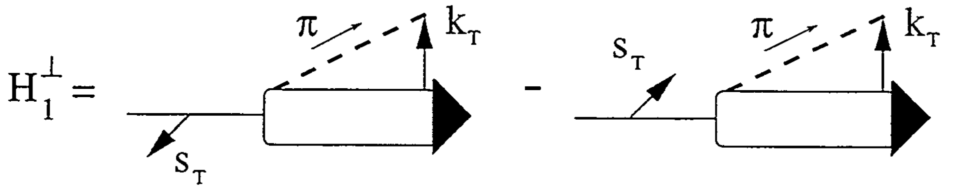
Especially the T-odd functions with transverse momentum dependence might be relevant for the description of single transverse spin asymmetries, since these functions link the transverse momentum and transverse spin (of either quarks or hadrons) with a specific handedness. The different functions will lead to distinct angular dependences. Hence, by studying the angular dependences of asymmetries (and their transverse momentum dependence) one investigates the connection between transverse spin and transverse momentum of quarks and hadrons directly. This is a most promising way to unravel the origin(s) of transverse spin asymmetries. This is for instance demonstrated by a recent result by the HERMES Collaboration [2]. They reported a $\sin\phi$ asymmetry in the process $e\,\vec{p} \to e'\,\pi^+\,X$, where the target has a polarization along the electron beam direction and ϕ is the angle of the transverse momentum of the pion with respect to the lepton scattering plane. This asymmetry is expressed in terms of a chiral-odd, T-odd fragmentation function with transverse momentum dependence, the Collins effect function $H_1^{\perp}$ [3]. We find that the contribution from the target spin transverse to the virtual photon direction can be equally important as the longitudinal contribution and it even becomes dominant for larger x and smaller y values (see also [4] for a discussion on this topic).

Finally, I will briefly discuss the other leading twist, T-odd, transverse momentum dependent fragmentation function, the chiral-even function called $D_{1T}^{\perp}$, which is relevant for transversely polarized Λ production, for instance in $p\,p \to \Lambda^{\uparrow}X$.

[1] D. Boer, Phys. Rev. D 60 (1999) 014012.
[2] H. Avakian, Proceedings of DIS99 conference in DESY-Zeuthen.
[3] J.C. Collins, Nucl. Phys. B 396, 161 (1993).
[4] A.M. Kotzinian *et al.*, hep-ph/9908466.

Transverse Spin and Transverse Momentum

Study the transverse momentum dependence of the asymmetries
The T-odd effects link transverse momentum and transverse spin with a certain handedness, like e.g. the Collins effect:

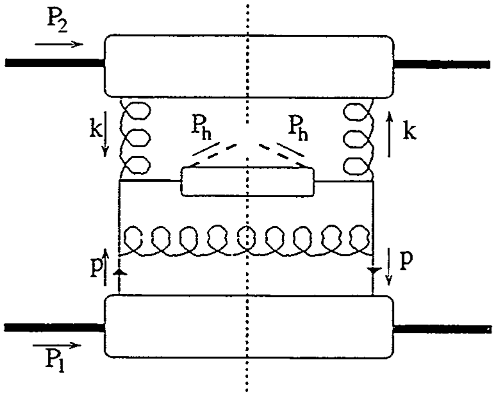


Expected to arise due to final state interactions between π and X

Can lead to the single spin asymmetry at leading order:

$A_T \sim h_1(x_1) \otimes f_1(x_2) \otimes H_1^{\perp}(z, \boldsymbol{k}_T)$

Anselmino, Boglione & Murgia
(PRD 60 (99) 054027)

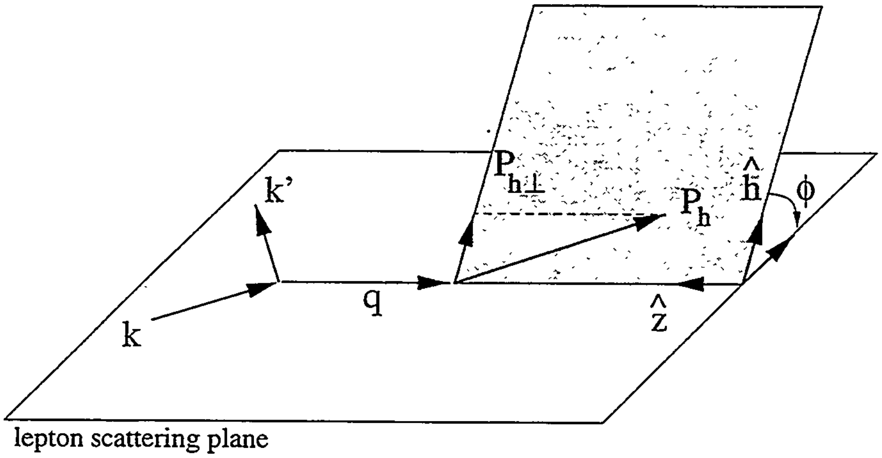


Other possible explanations:

- Soft gluon or fermion poles (Qiu & Sterman, PRL 67 (1991) 2264)
- Transverse momentum dependent T-odd distribution functions ($f_{1T}^{\perp}$ Sivers; Anselmino *et al.*; $h_1^{\perp}$ D.B. & Mulders)

HERMES Asymmetry in $e + \vec{p} \to e' + \pi + X$

HERMES reported a $\sin\phi$ asymmetry at DIS99 [Zeuthen, April '99]



In a factorized picture (Mulders & Tangerman, NPB 461 (1996) 197):

$$\mathcal{W}^{\mu\nu} = \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T\, \delta^2(\boldsymbol{p}_T+\boldsymbol{q}_T-\boldsymbol{k}_T)\,\mathrm{Tr}\,(\Phi(x,\boldsymbol{p}_T)\gamma^\mu\Delta(z,\boldsymbol{k}_T)\gamma^\nu)$$

Project out the $\sin(\phi)$ dependence from the cross section:

$$A_{P_eP_H} \equiv \int d^2\boldsymbol{P}_{h\perp}\,\frac{|\boldsymbol{P}_{h\perp}|}{zM}\,\sin(\phi)\,\frac{d\Delta\sigma_{P_eP_H}(\vec{\ell}\vec{H}\to\ell' hX)}{dxdzdyd\phi_\ell d^2\boldsymbol{P}_{h\perp}}$$

HERMES Asymmetry in $e + \vec{p} \to e' + \pi + X$

We assume one flavor ($u \to \pi^+$) and neglecting a term M_π / M

Polarization of the target is in the lepton scattering plane

$$
\begin{aligned}
A_{OL} &\propto \lambda\, 2(2-y)\sqrt{1-y}\, \frac{M}{Q}\, x\, h_L(x)\, H_1^{\perp(1)}(z) \\
A_{OT} &\propto |\boldsymbol{S}_\perp|\, (1-y)\, h_1(x)\, H_1^{\perp(1)}(z) \\
A_{LO} &\propto \lambda_e\, 2y\sqrt{1-y}\, \frac{M}{Q}\, x\, e(x)\, H_1^{\perp(1)}(z) \overset{WW}{\propto} \frac{m_u}{Q} \approx 0
\end{aligned}
$$

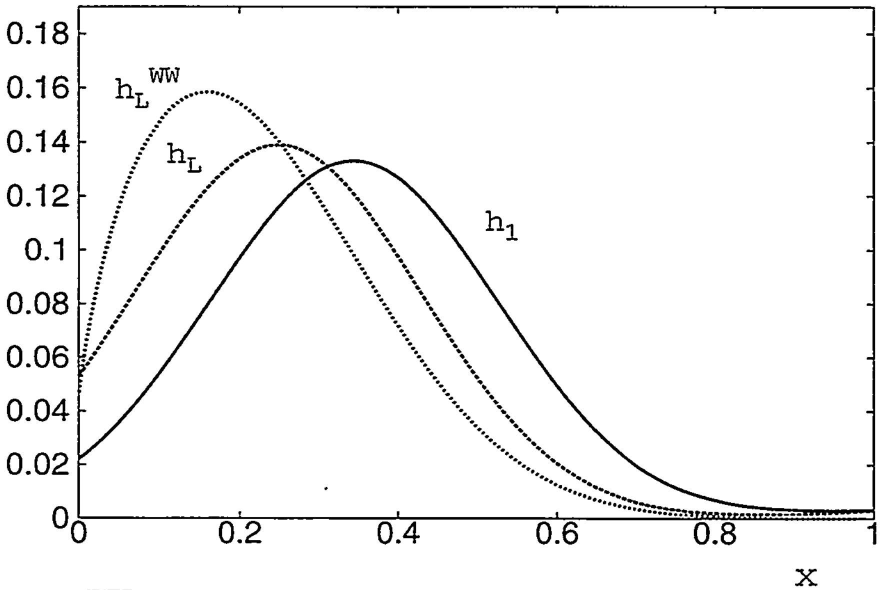
where $H_1^{\perp(1)}(z) = z^2 \int d^2\boldsymbol{k}_T \boldsymbol{k}_T^2 H_1^\perp(z, \boldsymbol{k}_T)$

HERMES:
Polarization of the target is along the electron beam direction
This is a combination of L and T, depending on y

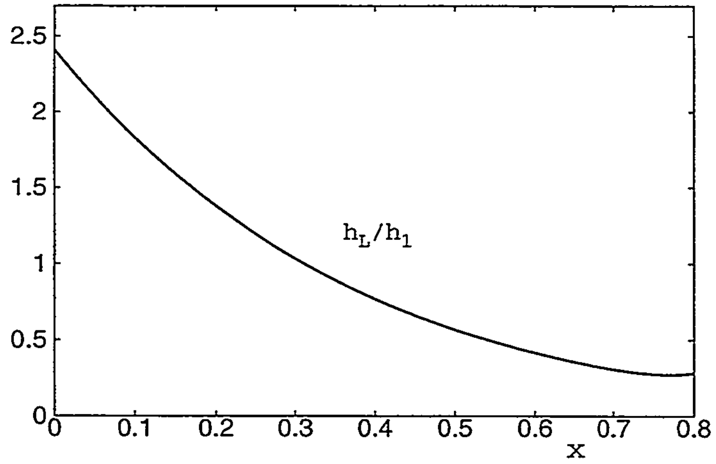
We find

$$
\frac{|\boldsymbol{S}_\perp|}{\lambda} = \sqrt{1-y}\, \frac{2Mx}{Q} \qquad \Longrightarrow \qquad \frac{A_{OL}}{A_{OT}} = \frac{2-y}{1-y}\, \frac{h_L(x)}{h_1(x)}
$$

HERMES Asymmetry in $e + \vec{p} \to e' + \pi + X$



Bag model



For $0.2 < y < 0.8$:

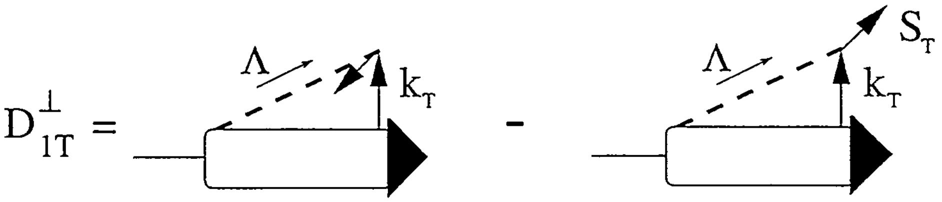
$$2\,\frac{h_L}{h_1} < \frac{A_{OL}}{A_{OT}} < 6\,\frac{h_L}{h_1}$$

Conclusion: For larger x, but small y, $A_{OT} \gtrsim A_{OL}$

Kotzinian *et al.*, hep-ph/9908466: A_{OL} is dominant contribution to the asymmetry; A_{OT} contributes only 20 to 25 % (for $0 < x < 0.3$)

Transversely Polarized Λ Production

The other leading twist T-odd fragmentation function with transverse momentum dependence is $D_{1T}^{\perp}$:



Mulders & Tangerman, NPB 461 (1996) 197

This is the analogue of the Sivers effect function (PRD 41 (1990) 83)

Application to transversely polarized Λ production
(Anselmino, D.B. & Murgia, in preparation)

Remark: In charged current exchange processes chiral-odd functions like $h_1, H_1^{\perp}$ cannot be accessed; $D_{1T}^{\perp}$ is chiral-even.

Consequences for RHIC Spin Program of Results from SMC and HERMES

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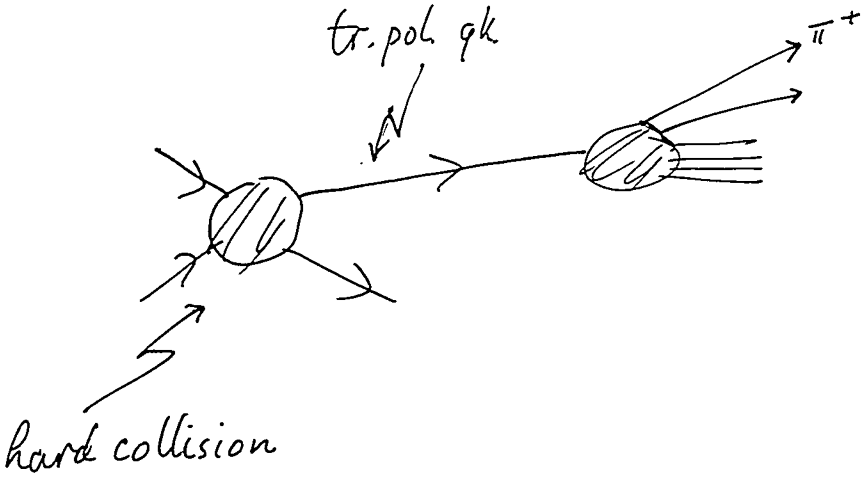
Abstract

Recently, SMC and HERMES have reported measurements of the azimuthal distribution of hadrons in the current quark jet in deep-inelastic scattering. This distribution is therefore likely to have a substantial analyzing power for the transverse spin of the quark initiating the jet. A corresponding process at RHIC can be found in the production of jets in collisions of unpolarized protons on transversely polarized protons. One is to look for a spin-dependence of the azimuthal distribution of leading $\pi^+\pi^-$ pairs around the jet axis.

Fragmentation of transversely polarized quark



Spin-sensitive observables include

1. Azimuthal d/n of $\pi^+\pi^-$ (&c) about jet axis (JCC, Heppelmann & Ladinsky, NP B420, 565 (1994))

$$D(z) \quad + \quad |\vec{S}_T| \sin(\phi_t - \phi_s) \times \Delta D(z \cdots)$$

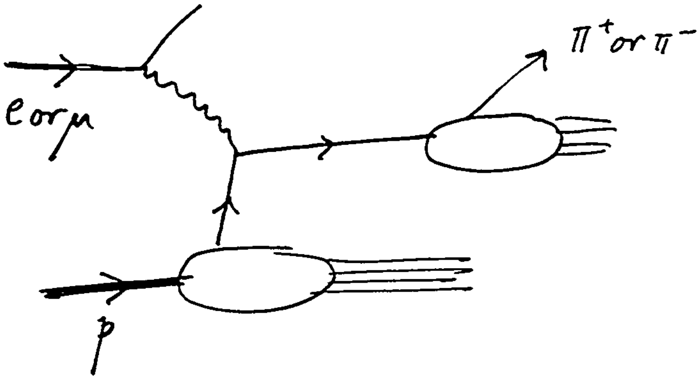
2. Azimuthal d/n of π^+ (&c) about jet axis. (JCC, NP B396, 161 (1993))

Notes

1. Need $\underline{\underline{2}}$ momenta to define ϕ.
2. T-odd observable — need non-trivial final-state phases & interference
   — e.g. s-p wave (Jaffe, Jin & Tang, PRL 80, 1166 (1998))
3. Probes chiral symmetry breaking in dynamics.
4. Leading particles in jet are best.

Data (all preliminary)

DIS:



Transversely polarized p

⇒ transversely polarized struck quark

⇒ $1 + \text{const.} \sin\phi$ distribution for hadron about jet axis.

1. SMC : $\mu p^{\text{transverse}}$: DIS99
http://www.ifh.de/~dis99p/WGROUP4/wg4-03.ps.gz

2. HERMES: $ep^{\text{Long.}}$: DIS99
http://www.ifh.de/~dis99p/WGROUP4/wg4-04.ps.gz
In $\gamma^* p$ frame, transverse spin $\simeq \sqrt{\frac{4M^2x^2}{Q^2}(1-y)}$ × Long. spin
Higher-twist effect!

SMC

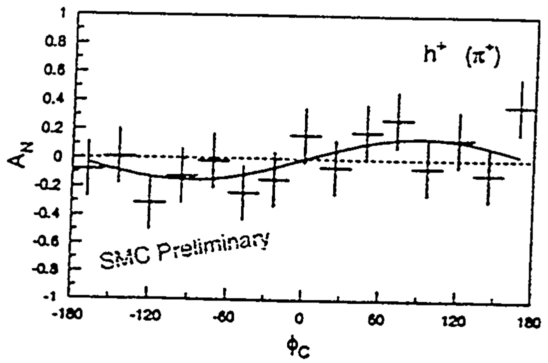
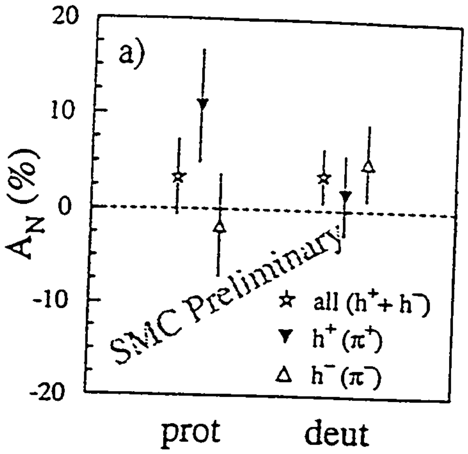


Figure 2. ϕ_c azimuthal distributions for positive hadrons produced off transversely polarized protons with a $(Const+A_N \sin\phi_c)$ fit superimposed.



π^+ : $A_N = (11 \pm 6)\%$

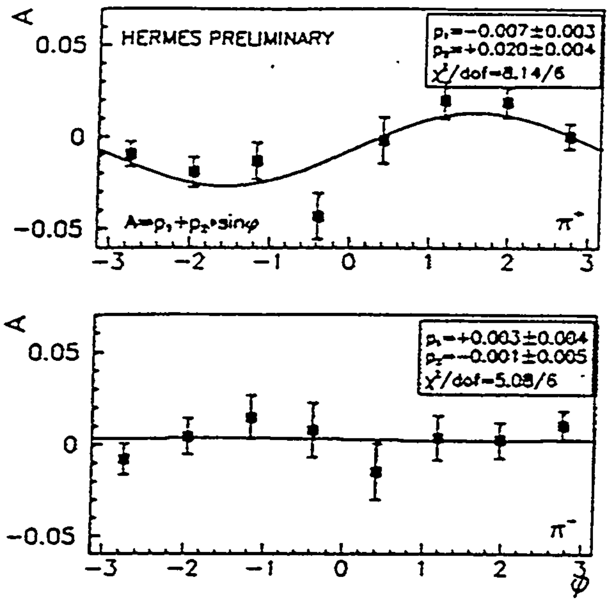
π^- : $A_N = (-2 \pm 6)\%$

$\langle x \rangle \simeq 0.08$ & $\langle Q^2 \rangle \simeq 5\,GeV^2$.

$\boxed{z > 0.25}$ $\langle z \rangle \simeq 0.45$

$$\frac{\text{Transversity d/n}}{\text{Total}} \times \frac{\text{frag. asym.}}{\text{total}} \times \text{xsect. factor} \sim 10\%$$

6



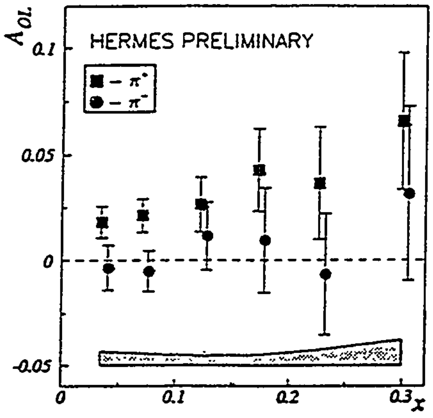


Figure 3. Target spin analyzing power in the *sinφ* moment (A_{OL}) as a function of Bjorken x, for π^+ (squares) and π^- (circles) . Error bars show the statistical uncertainties and the band represents the systematic uncertainties.

π^+: $A_{OL} = (2{\cdot}2 \pm 0{\cdot}4 \pm 0{\cdot}4)\%$

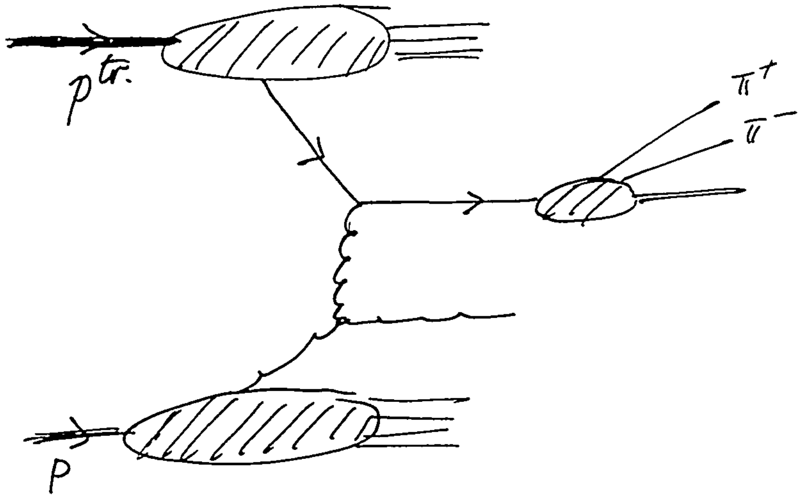
π^- $(-0{\cdot}1 \pm 0{\cdot}5 \pm 0{\cdot}4)\%$

$Q > 1\,\text{GeV}$, $W > 2\,\text{GeV}$

$z > 0{\cdot}2$

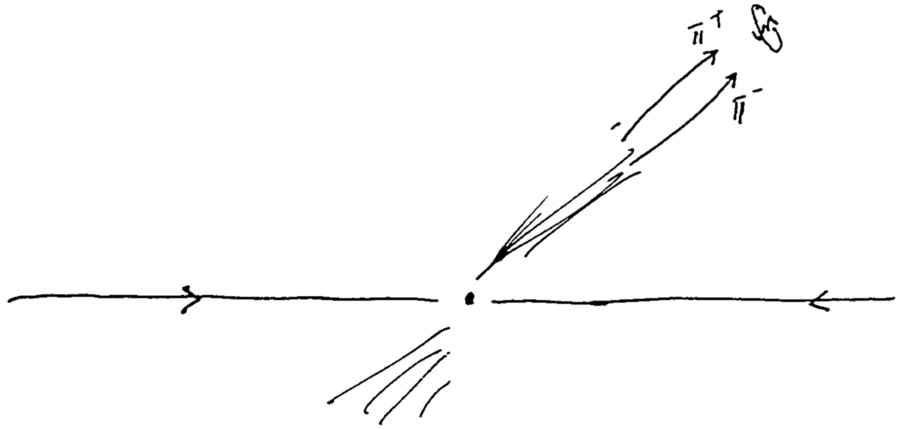
Expect suppression by $\sim \frac{2Mx}{Q}$ rel. to SMC.

RHIC



$$p^{\uparrow} + p \longrightarrow \text{jet} + X$$
$$\quad \hookrightarrow \pi^+\pi^- + \cdots$$

Measure azimuthal d/n of $\pi^+\pi^-$ around jet axis



9

Subprocesses: $q\,q \longrightarrow q\,q$ ✓

$q\,g \longrightarrow q\,g$ ✓

$g\,q \longrightarrow g\,q$ X Not spin asym.

$g\,g \longrightarrow g\,g$ or $q\bar{q}$ X

Where? 1. Large p_T jet — forward w.r.t. polarized beam, preferably
(eg. 30GeV+

What? 2. $\pi^+ \& \pi^-$ tracks — must measure charge

How much? 3. ~10% asymmetry (pdf × hard scatter × frag)
see JCC, Heppelmann & Ladinsky

Need how many events? ~10^4 ?
(Work in progress — Akio Ogawa)

Transverse spin asymmetries in Drell-Yan

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RIKEN - SPIN, October, 7, 1999

It is well-known that asymmetries are very important in spin physics, since they are sensitive to spin density functions and/or to higher twists. In the present talk we consider two kinds of asymmetries in Drell-Yan events generated by collisions of an unpolarized proton beam with a transversely polarized one, i. e.,

$$p^{\uparrow}p \longrightarrow \mu^{+}\mu^{-}X.$$

The two-asymmetries - muon helicity asymmetry and left-right asymmetry - are sensitive to twist-3 terms. Helicity asymmetry is related to the transversity function h_1. Left-right asymmetry is produced by a soft gluon contribution and it has already been calculated by other two authors, who do not agree on the final formula. Our approach is different from the one currently followed in the literature, but the functions we obtain in our calculation correspond to those used in preceding papers on the subject.

First of all we adopt the QCD improved parton model, showing that the result may be partly predicted also by geometrical considerations. Transverse momentum plays an essential role in helicity asymmetry, which depends on the transverse momentum dependent transversity function. On the other hand the left-right asymmetry vanishes in parton model.

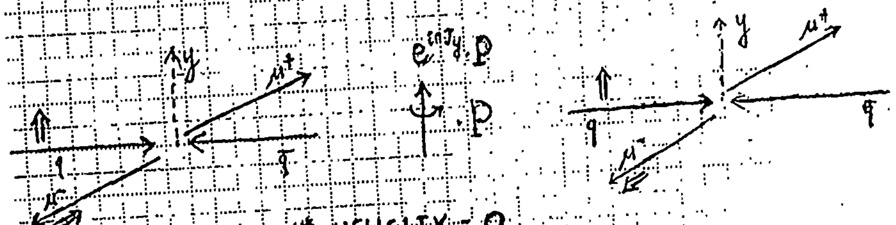
Moreover we calculate, in tree approximation, the one-gluon correction to parton model. We write this correction term as a convolution of elementary amplitudes with parton densities: we adopt an axial gauge, in order to keep the validity of the parton description. Since we must guarantee gauge invariance, we write also the overall hadronic tensor according to quantum field theory, which contains the covariant derivative. This tensor results to be proportional to the sum of the hadronic tensors that we have obtained by considering separately the parton model and the one-gluon correction. In this way we can also establish some symmetry properties of the correlation functions, which considerably simplify our calculations. Developing calculations, we obtain a T-even and a T-odd combination of such functions. In particular the T-odd distribution functions are characterized by the so-called soft gluon pole; this term is essential to left-right asymmetry, which is of order 1%. On the contrary the one-gluon correction does not contribute to helicity asymmetry, which is estimated to be $(1-4)\%$ and may be used for detrmining h_1.

2- ASYMMETRY PREDICTIONS IN PARTON MODEL

GEOMETRICAL CONSIDERATIONS

i) TRANSVERSE MOMENTUM NEGLECTED

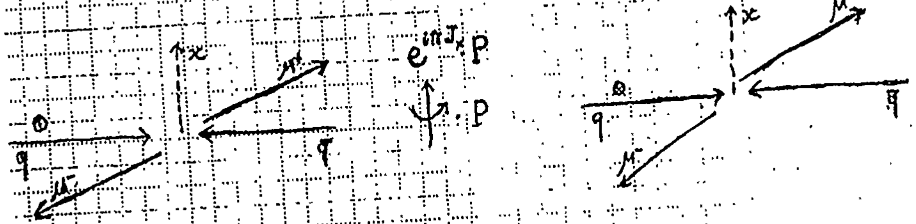
HELICITY ASYMMETRY



AVERAGE γ^* HELICITY = 0

$\boxed{A_1 = 0}$

LEFT - RIGHT ASYMMETRY



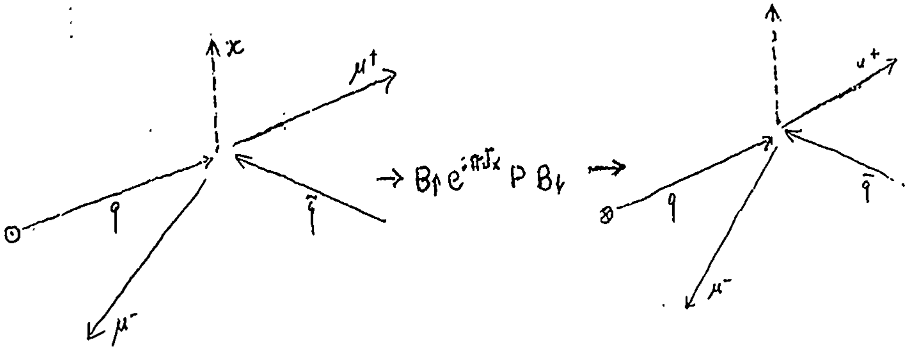
$\boxed{A_2 = 0}$

ii) TRANSVERSE MOMENTUM CONSIDERED

QCD IMPROVED PARTON MODEL:

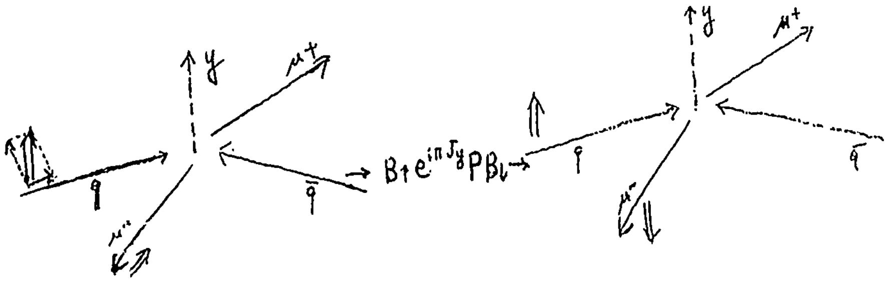
D. Sivers: Phys. Rev. D41, 83 (1990); 261 (1991)

LEFT - RIGHT ASYMMETRY



$\boxed{A_2 = 0}$ (twist-3 ; g = 0)

HELICITY ASYMMETRY



AVERAGE γ^* HELICITY ≠ 0

$\boxed{A_1 \neq 0}$ (twist-3 ; g = 0)

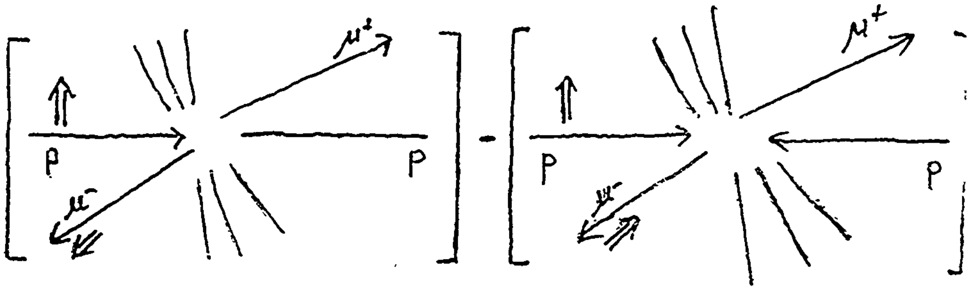
1-DEFINITION OF ASYMMETRIES

A) MUON HELICITY ASYMMETRY

$\mu^- \longrightarrow e^- \bar{\nu}_e \, \nu_\mu \;\Rightarrow\; N_\mu^{(r)} - N_\mu^{(l)}$ MEASURABLE

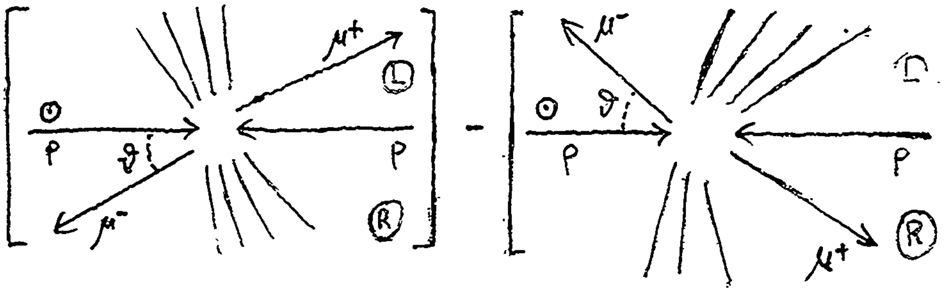
BOLLINI et al. : Nucl. Instr. Meth. 204, 333 (1983)

$$A_1 = \frac{d\sigma_r - d\sigma_l}{d\sigma_r + d\sigma_l} \; :$$

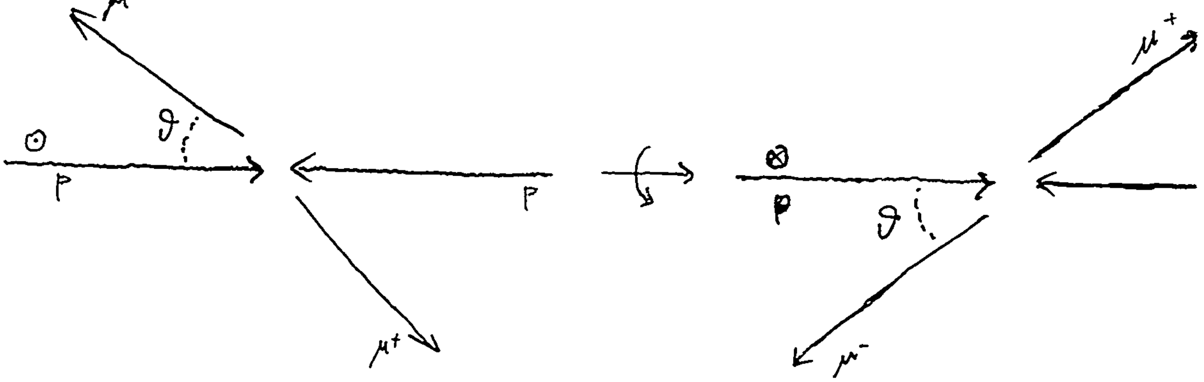


B) LEFT-RIGHT ASYMMETRY(*)

$$A_2 = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \; :$$



NOTICE :



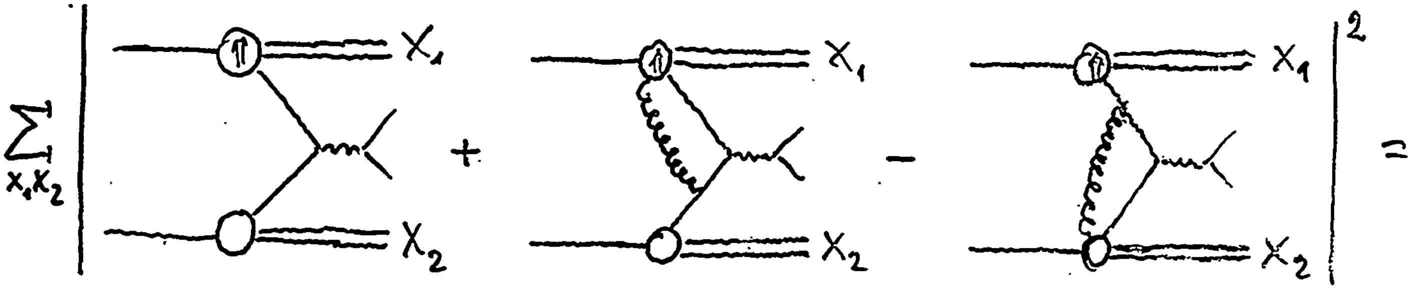
(*) N. HAMMON ET AL. : PHYS. LETT. B 390, 409 (1997)

D. BOER ET AL. : PHYS. REV. D 57, 3057 (1998)

3-QCD FIRST ORDER CORRECTIONS

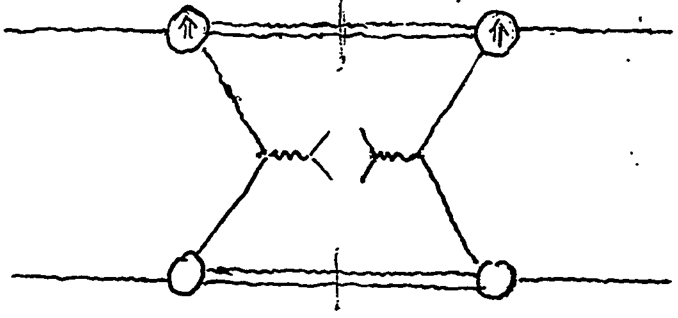
APPROX.: TREE ; TWIST 3

INTERFERENCE :



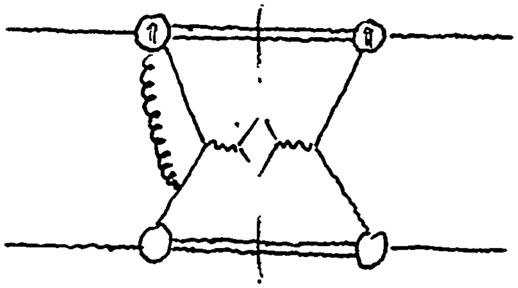
TWIST 2,3 ($\vec{P}_\perp$)

=

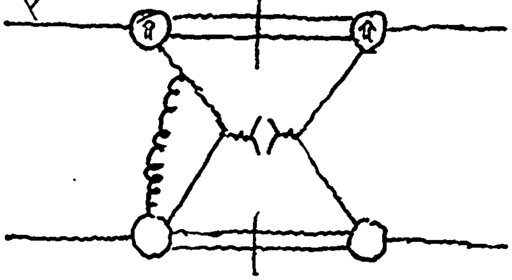


+

TWIST 3 ($\cancel{\vec{P}_\perp}$)



+ c. c. −



− c. c.

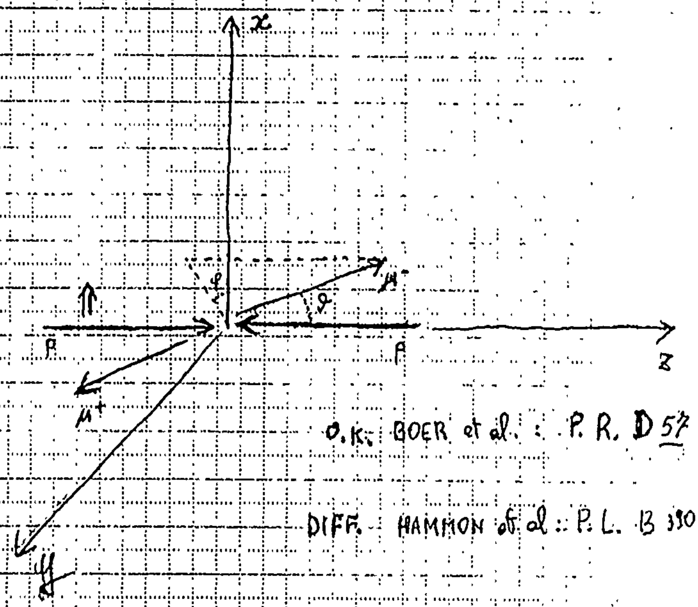
$$+ \mathcal{O}(\text{TWIST } 4)$$

AXIAL GAUGE

4 - ASYMMETRIES

A) LEFT - RIGHT ASYMMETRY

$$A_2 = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = g \frac{\sum_{f=1}^{3} e_f^2 \left(\tilde{\delta}_1 Q^f + \tilde{\delta}_2 Q^f\right)}{\sum_{f=1}^{3} e_f^2 Q^f} \frac{\sin 2\vartheta \cos\varphi}{1+\cos^2\vartheta} \frac{\sqrt{s}\, M_p}{2 q^2}$$



O.K.: BOER et al. : P.R. D $\underline{57}$ (1998) 3057

DIFF. HAMMON et al.: P.L. B 390 (1997) 409

$$Q^f = \int d^2 p_{1\perp} \left[q^f(x_1, \vec{p}_{1\perp}^{\,2})\, \bar{q}^f(x_2, \vec{p}_{2\perp}^{\,2}) + (q \leftrightarrow \bar{q}) \right]$$

$$\tilde{\delta}_1 Q^f = \int d^2 p_{1\perp} \left[C_{(1)}^{f1R}(x_1, \vec{p}_{1\perp}^{\,2}; x_1, \vec{p}_{1\perp}^{\,2})\, \bar{q}^f(x_2, \vec{p}_{2\perp}^{\,2}) + (q \leftrightarrow \bar{q};\ c \leftrightarrow \bar{c}) \right]$$

$$\tilde{\delta}_2 Q^f = \int d^2 p_{1\perp} \left[C_{(1)}^{f2R}(x_2, \vec{p}_{2\perp}^{\,2}; x_2, \vec{p}_{2\perp}^{\,2})\, \bar{q}^f(x_1, \vec{p}_{1\perp}^{\,2}) + (q \leftrightarrow \bar{q};\ c \leftrightarrow \bar{c}) \right] \boxed{A_2 \sim 1\,\%}$$

B) HELICITY ASYMMETRY

$$A_1 = \frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\sigma_\uparrow + d\sigma_\downarrow} = \frac{\sum_f e_f^2\, \delta Q^f}{\sum_f e_f^2\, Q^f} \frac{\cos\vartheta}{2(1+\cos^2\vartheta)} + O(g^2) + O(\text{Twist } 4)$$

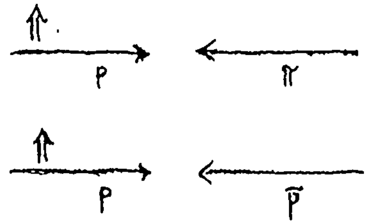
$$\boxed{A_1 \sim 1\text{-}4\%}$$

$$Q^f = \int d^2 p_{1\perp} \left[q^f(x_1, \vec{p}_{1\perp}^{\,2})\, \bar{q}^f(x_2, \vec{p}_{2\perp}^{\,2}) + (q \leftrightarrow \bar{q}) \right]$$

$$① \ \delta Q^f = \int d^2 p_{1\perp} \frac{\vec{s}\cdot\vec{p}_{1\perp}}{|\vec{p}_1|} \left[\delta q^f(x_1, \vec{p}_{1\perp}^{\,2})\, \bar{q}^f(x_2, \vec{p}_{2\perp}^{\,2}) - \delta \bar{q}^f(x_1, \vec{p}_{1\perp}^{\,2})\, q^f(x_2, \vec{p}_{2\perp}^{\,2}) \right.$$

$$\boxed{h_1^f(x) = \int d^2 p_\perp\, \delta q^f(x, \vec{p}_\perp^{\,2})}$$

HOW TO EXTRACT δq^f, $\delta \bar{q}^f$?



$$② \ \delta Q_\pi^f = \int d^2 p_{1\perp} \frac{\vec{s}\cdot\vec{p}_{1\perp}}{|\vec{p}_1|} \left[\delta q^f(x_1, \vec{p}_{1\perp}^{\,2})\, \bar{q}_\pi^f(x_2, \vec{p}_{2\perp}^{\,2}) - \delta \bar{q}^f(x_1, \vec{p}_{1\perp}^{\,2})\, q_\pi^f(x_2, \vec{p}_{2\perp}^{\,2}) \right]$$

δq^f, $\delta \bar{q}^f$ CAN BE FOUND BY DECONVOLUTING THE SYSTEM ①-② OF INTEGRAL EQS.

5. CONCLUSIONS

HELICITY ASYMM.	LEFT-RIGHT ASYMM.
$\left(i\,\partial_\mu \delta_{ij} + \cancel{g\,\lambda^a_{ij} A^a_\mu}\right) S^\mu$	$\left(\cancel{i\,\partial_\mu \delta_{ij}} + g\,\lambda^a_{ij} A^a_\mu\right) \bar{S}^\mu$
S_μ = PAULI - LUBANSKI 4-VECTOR ;	$\bar{S}_\mu = \varepsilon_{\mu\nu\rho\sigma}\, P_1^\nu P_2^\rho S^\sigma$

P_1, P_2 = 4-MOMENTA OF PROTONS

$A_1 \sim (1 - 4)\%$	$A_2 \sim 1\%$
SENSITIVE TO h_1	SENSITIVE TO THE SOFT-GLUON POLE OF A T-ODD FUNCTION

Maximum polarization from the AGS[1]

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Over the last decade several improvements have been made to increase the polarization of the proton beam at the AGS [1]. A solenoidal partial snake was installed to overcome all imperfection resonances in the energy range of the AGS [2]. Polarization losses have been observed due to coupling depolarizing resonances mainly excited by the solenoid field of this snake. To reduce this polarization losses the solenoid has to be replaced by a dipole partial snake. Different magnet arrangements to realize such a type of snake are under consideration. The rf dipole concept to preserve polarization at intrinsic resonances has been demonstrated at the AGS for the first time [3]. At strong intrinsic resonances, adiabatic spin flips can be excited to preserve the polarization during resonance crossing. For weak intrinsic resonances it is possible to change the optics during acceleration to suppress intrinsic spin harmonics [4]. A further major improvement is the installation of a new polarized source which will provide mA currents of polarized beam with a polarization up to 80% [5].

After all this upgrades it will be possible to provide a polarized proton beam with a polarization of more than 70% from the AGS to be injected into RHIC.

References

[1] T. Roser, Proc. of the Workshop on Polarized Protons at High Energies, Hamburg (1999).

[2] H. Huang at al., Phys. Rev. Lett. **73**, 2982 (1994).

[3] M. Bai et al., Phys. Rev. E **56**, 6002 (1997).

[4] A. Lehrach at al., 'Suppressing Intrinsic Spin Harmonics at the Cooler Synchrotron COSY', submitted to Nucl. Instrum. Methods A.

[5] A.N. Zelenski, Proc. of PAC99, 106 (1999).

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[1] Work performed under the auspices of the U.S. Department of Energy

Depolarizing Resonances at AGS

1. imperfection

$\gamma G = 5,6, \ldots$

→ 5% solenoidal partial snake

2. intrinsic

$\gamma G = kP \pm \nu_y$

P (GeV/c)	γG	ε_R	P_{fi}
4.5	$0 + \nu_y$	0.0061	- 0.42
8.0	$24 - \nu_y$	0.0002	0.995
10.8	$12 + \nu_y$	0.0024	0.45
14.3	$36 - \nu_y$	0.0051	- 0.26
17.1	$24 + \nu_y$	0.0004	0.90
20.5	$48 - \nu_y$	0.0006	0.95
23.4	$36 + \nu_y$	0.011	- 0.77
26.8	$60 - \nu_y$	0.064	- 0.993

→ 18 Gm rf dipole

3. couple

$\gamma G = 0 + \nu_x, 12 + \nu_x, 36 \pm \nu_x$

4. higher order

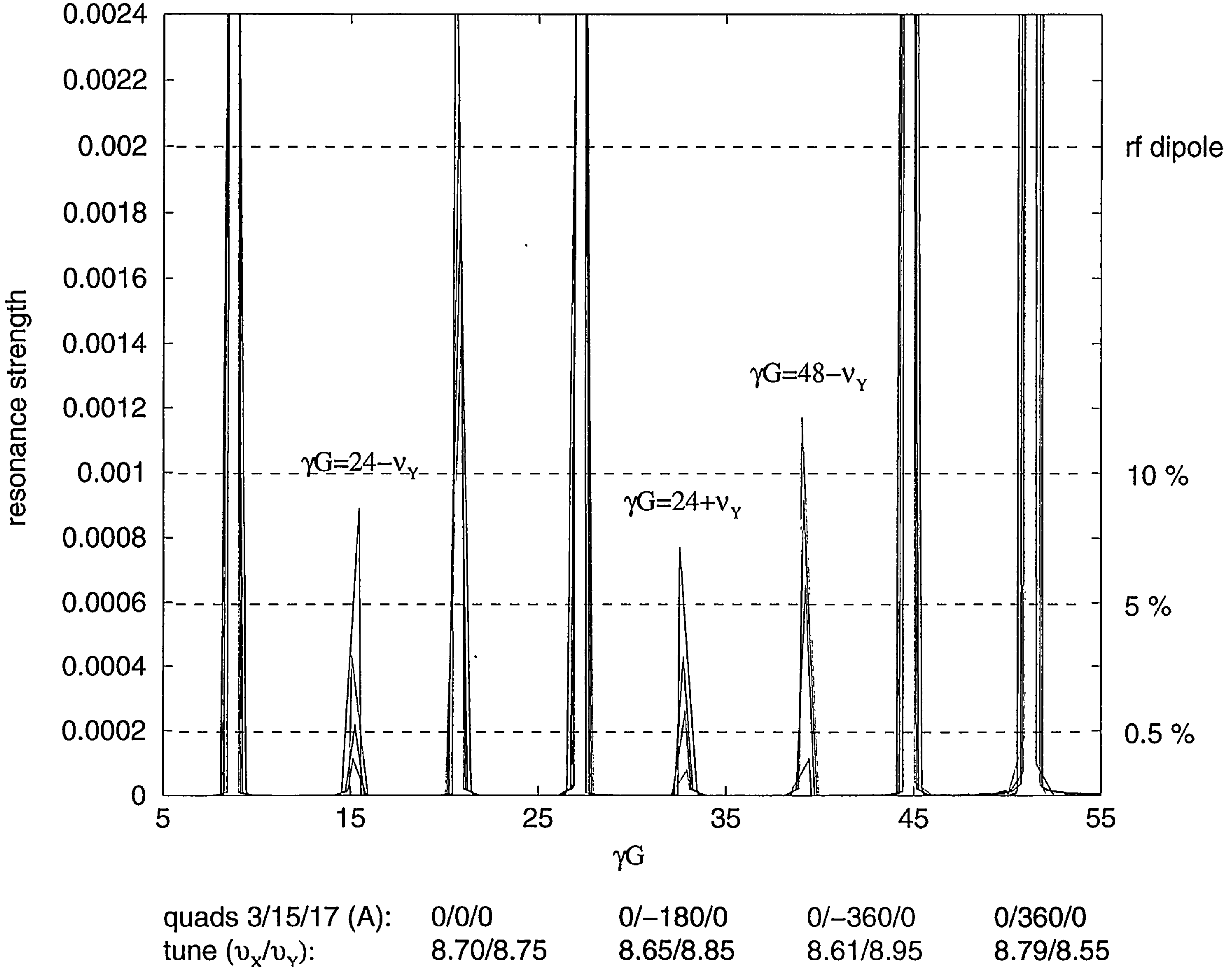
$\gamma G = 60 - \nu_y - 9$

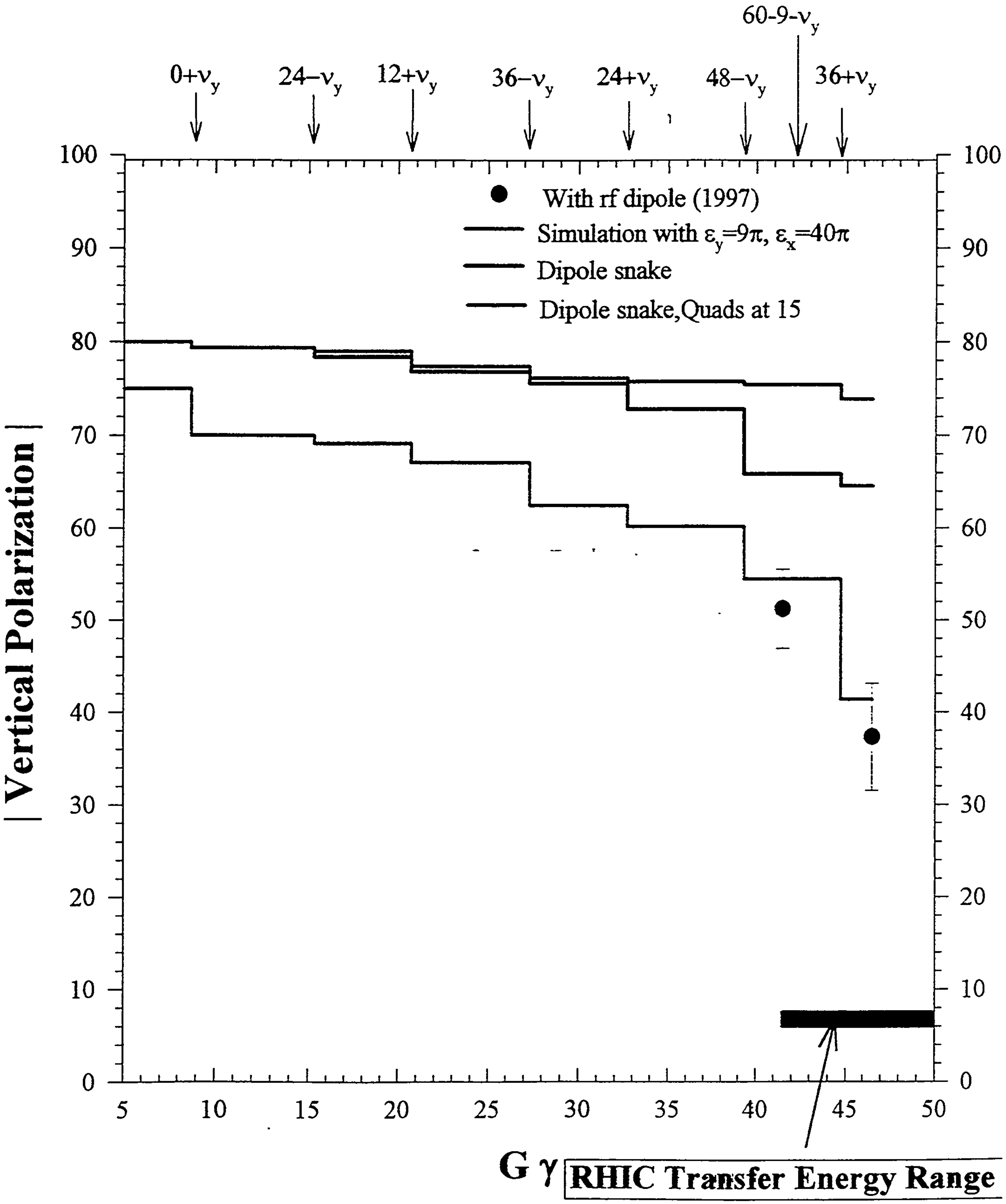
→ $\approx 41\ \%$ at $\gamma G = 46.5$

AGS Partial Snake designs

	Total Length	Magnetic field		Magnet length	Filed integral		Xmax	Ymax
	[m]	1.5 GeV [T]	22 GeV [T]	[m]	1.5 GeV [Tm]	22 GeV [Tm]	[cm]	[cm]
Helical	2.64	1.350	1.610	1.786	2.41	2.88	1.90	1.80
7 Dipoles	2.61	1.519	1.950	1.706	2.59	3.33	2.52	3.58
6 Dipoles	2.75	1.530	1.964	1.600	2.45	3.14	1.59	4.18
5 Dipoles	2.72	1.508	1.936	2.118	3.19	4.10	1.63	3.87
4 Dipoles	2.55	1.535	1.971	2.100	3.22	4.14	1.94	4.83

Intrinsic Resonances at AGS




60-9-ν_y
0+ν_y
24−ν_y
12+ν_y
36−ν_y
24+ν_y
48−ν_y
36+ν_y
With rf dipole (1997)
Simulation with ε_y=9π, ε_x=40π
Dipole snake
Dipole snake,Quads at 15
| Vertical Polarization |
0
10
20
30
40
50
60
70
80
90
100
5
10
15
20
25
30
35
40
45
50
G γ
RHIC Transfer Energy Range

Conclusion / Outlook

1.) new polarized source

improving factor:

1.07

2.) dipole partial snake

improving factor:

1.48

3.) quads at position 15

improving factor:

1.14

→

≈ 74% polarization from AGS

RF Dipole Studies and Plans in the AGS and RHIC

Abstract

Mei Bai

Brookhaven National Laboratory

RF dipole with horizontally oriented oscillating dipole field is a very useful tool in spin manipulation. One application is to overcome intrinsic spin resonance due to the vertical betatron oscillation around the closed orbit. This method was successfully applied in the recent AGS polarized proton experiments[1] where full spin flip was achieved at crossing three strong intrinsic spin resonances of $0+\nu_z$, $12+\nu_z$ and $36-\nu_z$. In the experiments, the amplitude of the RF dipole oscillating field was slowly ramped from zero to the desired value before the resonance was encountered and then ramped down to zero after the resonance was crossed. This adiabatic manipulation eliminated the transverse beam emittance growth.

RF dipole can also be used to induce an adiabatic full spin flip in high energy accelerators where full snake system is installed to overcome both imperfection resonance and intrinsic resonance. This is often desired by physics experiments to reduce the systematic errors. The full spin flip is obtained by slowly ramping the RF dipole frequency through the spin precession frequency. In RHIC, two RF dipoles with fields oriented in horizontal and vertical plane will be installed. The RF dipole with horizontal field will be used as a spin flipper. Both magnets will also be used to obtain coherent betatron oscillations for the purpose of beam dynamic diagnosis and studies.

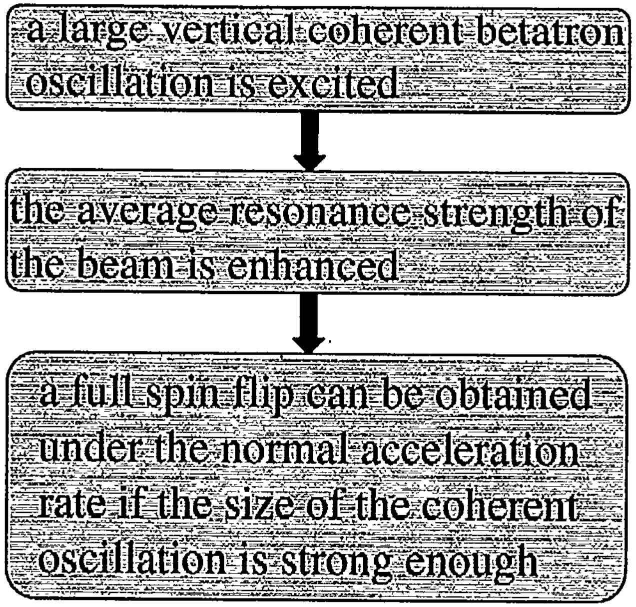
References:

[1] M. Bai et al., Phys. Rev. Lett. 80, 4673 (1998)

[2] T. Roser, Handbook of Accelerator Physics and Engineering, edited by A. Chao and M. Tigner.

- Applications of RF dipole in spin manipulation
  - overcoming intrinsic spin resonance by adiabatically inducing a coherent spin flip
    - Intrinsic spin resonance
      - » comes from vertical betatron oscillation
      - » locates at $G\gamma = mP + n\nu_z$
      - » strength is proportional to the size of the betatron oscillation
      - » beam polarization after crossing an isolated intrinsic resonance depends on the average resonance strength over all the particles in the beam.

- In the presence of a horizontal RF dipole field oscillating at a frequency close to the vertical betatron oscillation frequency,

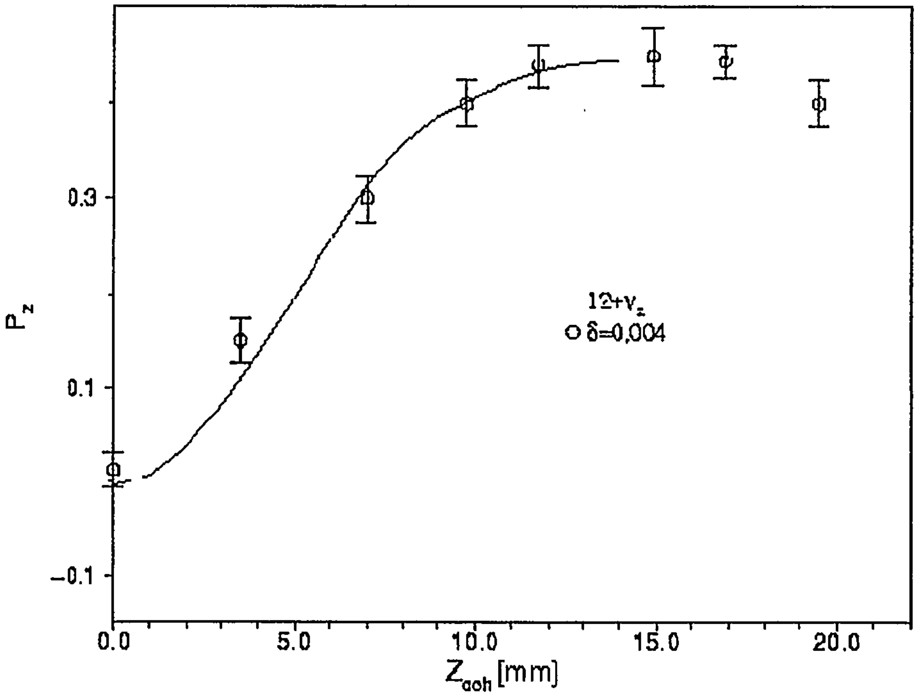


a large vertical coherent betatron oscillation is excited

the average resonance strength of the beam is enhanced

a full spin flip can be obtained under the normal acceleration rate if the size of the coherent oscillation is strong enough

- using an RF dipole to induce a full spin flip at intrinsic spin resonance $12+\nu_z$



- Spin flipper -- use an RF dipole to induce a spin flip in the presence of full snake(s)

An RF dipole with horizontal oriented oscillating dipole field induces an artificial spin resonance at the location of ν_m,

$$\nu_m = \frac{RF\ dipole\ field\ oscillation\ frequency}{beam\ revolution\ frequency}$$

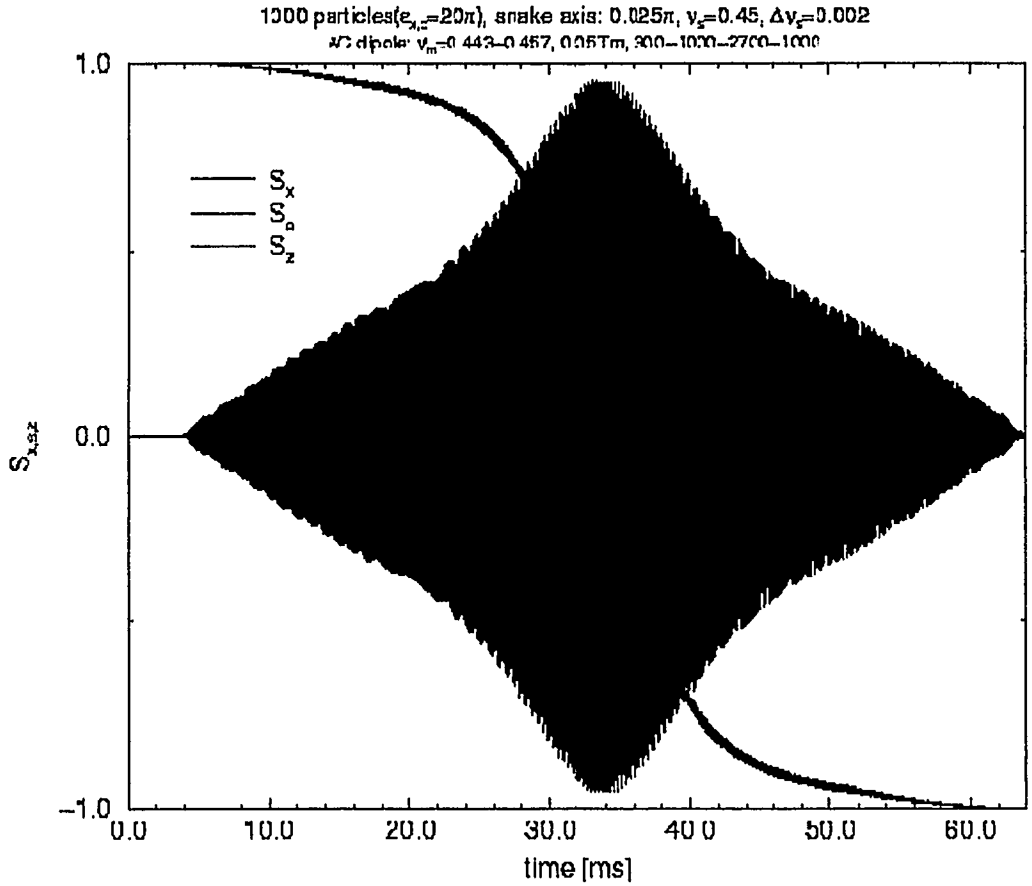
Its strength is:

$$\varepsilon = \frac{1 + G\gamma}{4\pi}\frac{B_m L}{B\rho}$$

To achieve more than 99% spin flip, the frequency ramping rate of the RF dipole has to satisfy:

$$\alpha = \frac{d\nu_m}{d\theta} < 0.295\ |\varepsilon|^2$$

» tracking result with a beam of 1000 particles



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Beam polarization distributions for RHIC[1]

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In order to calculate the distribution of the beam polarization in a circular accelerator, the invariant spin field has to be calculated. The invariant spin field $\vec{n}(\vec{z})$ depends on the position $\vec{z}$ of the particle in the six dimensional phase space. A particle with the initial spin $\vec{s}_i$ at the phase space position $\vec{z}_i$ has the final spin $\vec{s}_f$ and is transported to the phase space point $\vec{z}_f$ during one turn in the accelerator. If $T_{t=1}$ is the one turn spin transfer matrix, then for every phase space point $\vec{z}_i$ a spin field vector $\vec{n}(\vec{z}_i)$ exists such that

$$\vec{n}(\vec{z}_f) = T_{t=1} \cdot \vec{n}(\vec{z}_i). \tag{1}$$

The spin follows the invariant spin field if the motion of the spin is adiabatic. The invariant spin field in a high energy accelerator can vary substantially across the beam. This decreases the amount of polarization provided to experiments and makes the polarization dependent on the position in phase space. One method to calculate the invariant spin field is stroboscopic averaging [1], which is based on multi-turn tracking and averaging of the spin viewed stroboscopically from turn to turn at one position in the ring. The invariant spin field has also been studied using a method called adiabatic anti-damping [2], which is very similar to the method presented here.

In this study the motion of the particle and spin is adiabatically excited with coherent betatron oscillations using an rf dipole [3]. The calculation of the invariant spin field close to an intrinsic spin resonance is delicate, because the influence of the rf dipole on the spin motion is not negligible. The modulation tune of the rf dipole has to be moved very close to the betatron frequency in order to keep the effect of the rf dipole on the spin motion small. With respect to the amount of polarization that can be provided to experiments at RHIC, the invariant spin field is investigated at the interaction point of the PHENIX experiment. For the experimental proof of this calculation, a polarimeter has been proposed which is able to measure sideways polarization. Not only for spin dynamics calculation but also from the experiments' point of view, it is important to calculate and measure the invariant spin field. This effect will likely exclude certain energy ranges in the vicinity of spin resonances from being used for spin experiments at RHIC.

References

[1] G.H. Hoffstätter et al., Phys. Rev. E **54**, 4240 (1996).

[2] M. Vogt et al., Proc. of EPAC 98, 1362 (1998).

[3] A. Lehrach, AGS/RHIC/SN No. 81.

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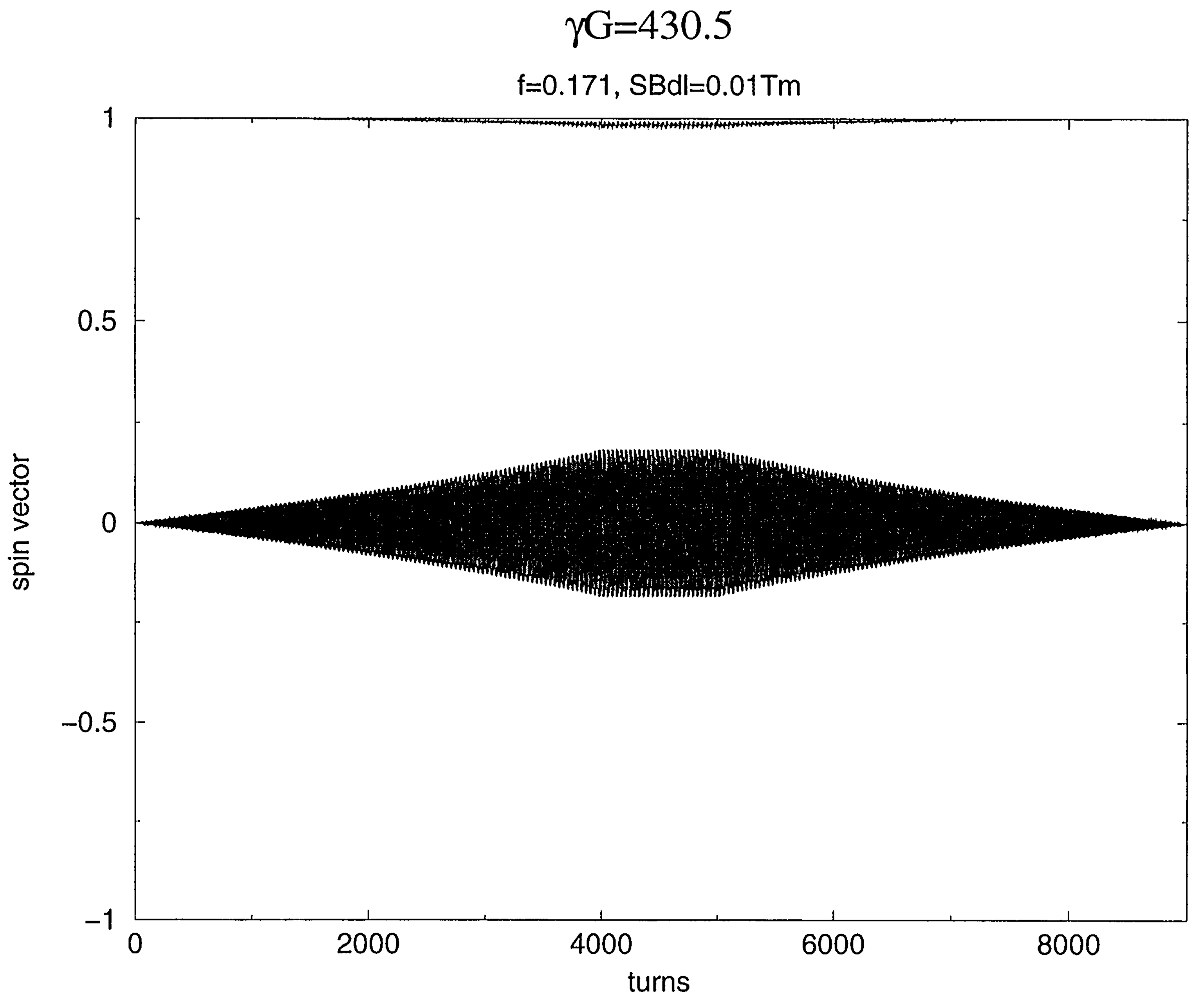
[1] Work performed under the auspices of the U.S. Department of Energy

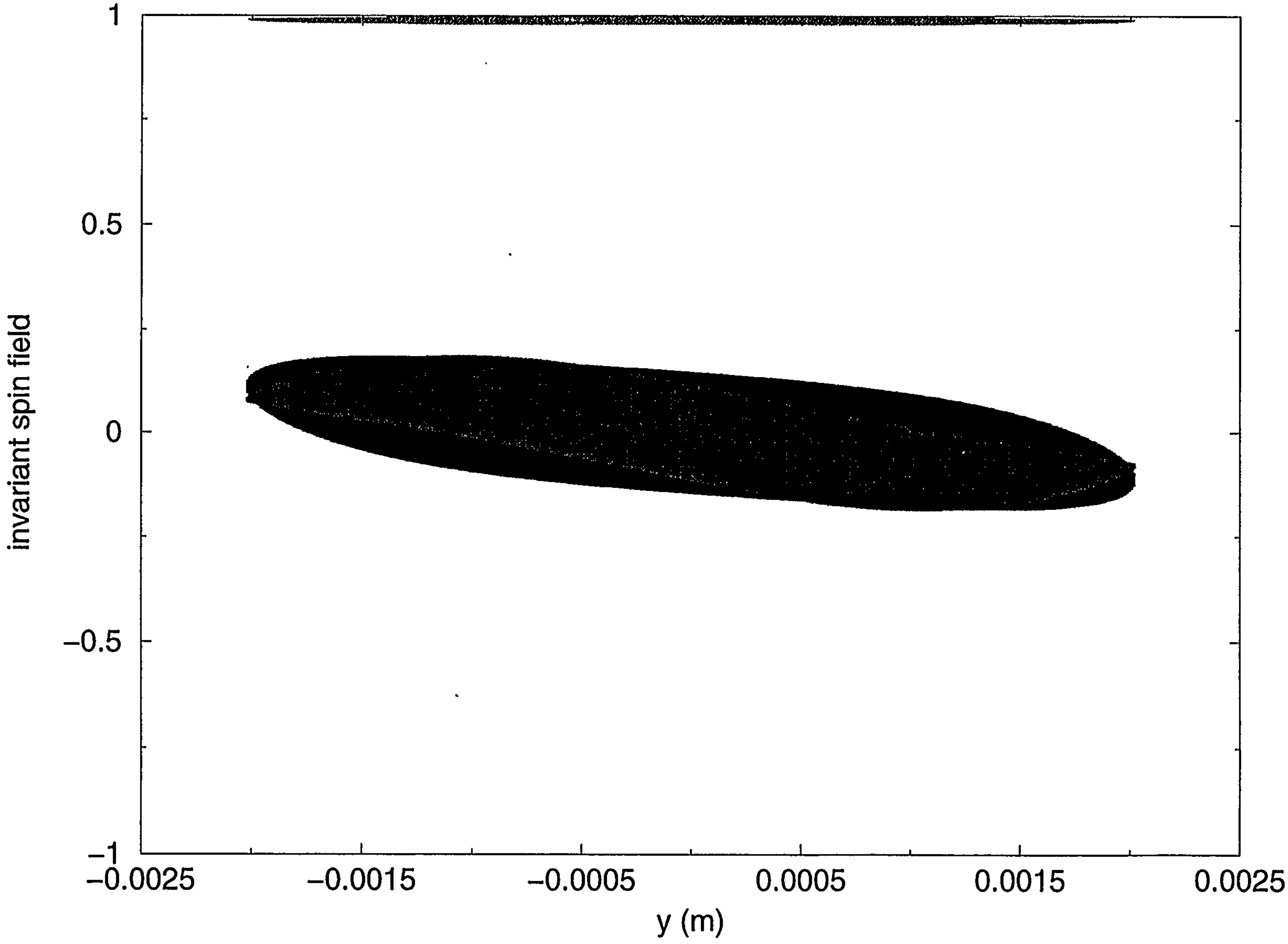
invariant spin field

- **$\vec{z}$: position of particle in longitudinal and transversal phase space**
- **$T_{t=1}(\vec{z})$: one turn spin transfer matrix**

particle is transported from $\vec{z}_i$ to $\vec{z}_f$ during one turn, for each $\vec{z}_i$:

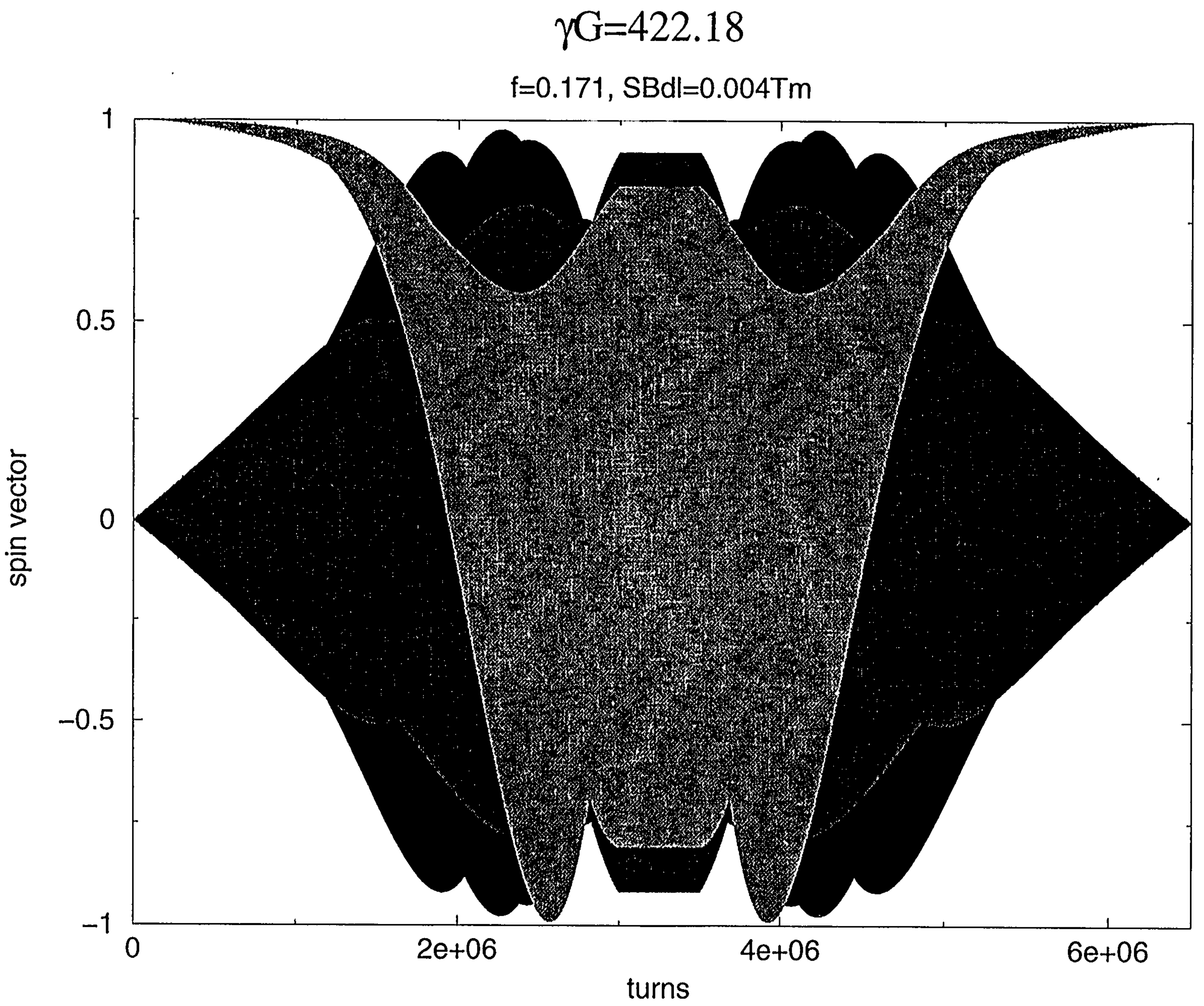
$$\boxed{\vec{n}(\vec{z}_f) = T_{t=1}(\vec{z}_i)\ \vec{n}(\vec{z}_i)}$$

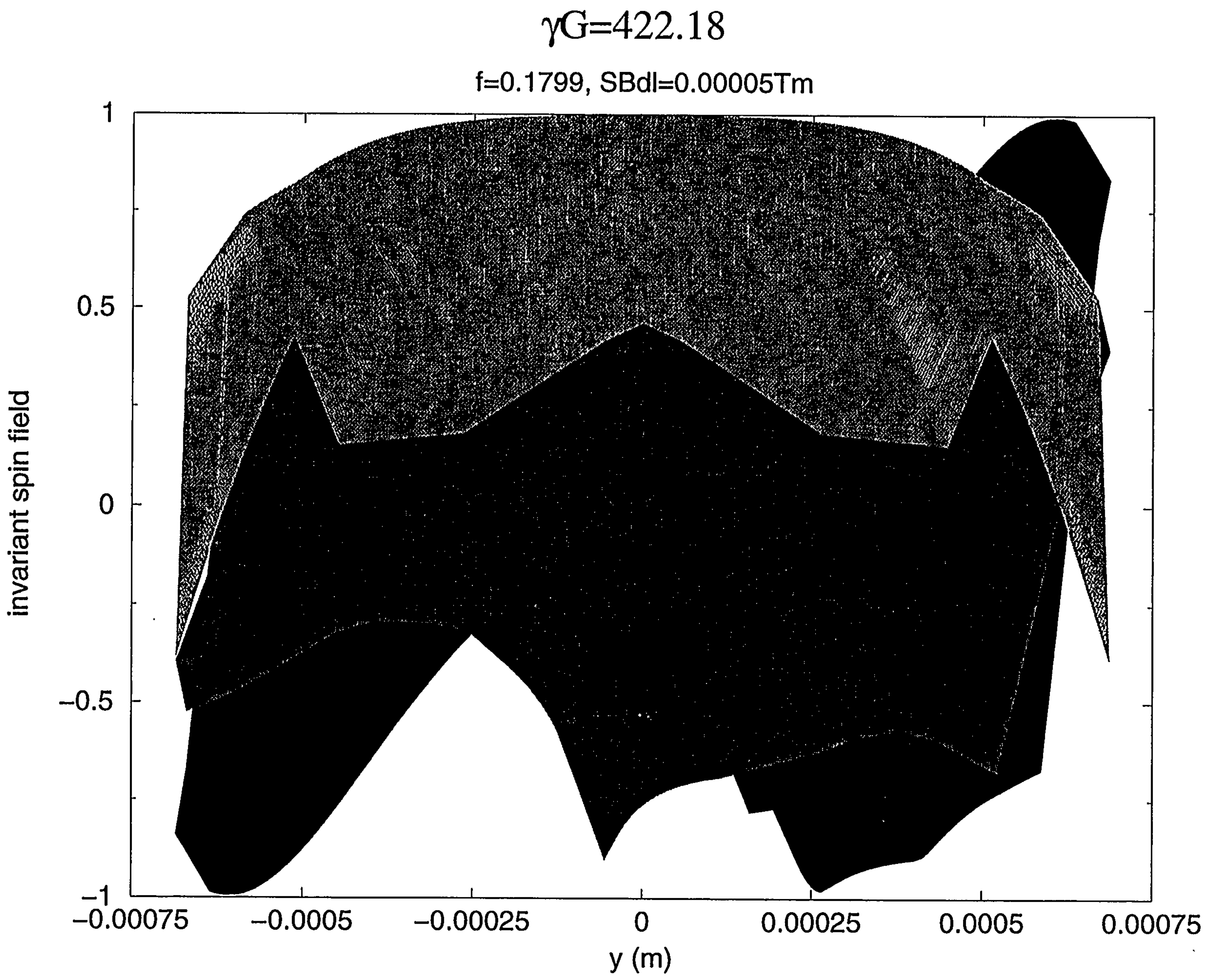

γG=430.5
f=0.171, SBdl=0.01Tm
spin vector
1
0.5
0
−0.5
−1
0
2000
4000
6000
8000
turns



γG=430.5

f=0.171, SBdl=0.01Tm


γG=422.18
f=0.171, SBdl=0.004Tm
spin vector
1
0.5
0
−0.5
−1
0
2e+06
4e+06
6e+06
turns


γG=422.18
f=0.1799, SBdl=0.00005Tm
invariant spin field
1
0.5
0
−0.5
−1
−0.00075
−0.0005
−0.00025
0
0.00025
0.0005
0.00075
y (m)

Optically Pumped Polarized H^- Ion Source (OPPIS) for RHIC

A.N.Zelenski, INR Moscow/TRIUMF

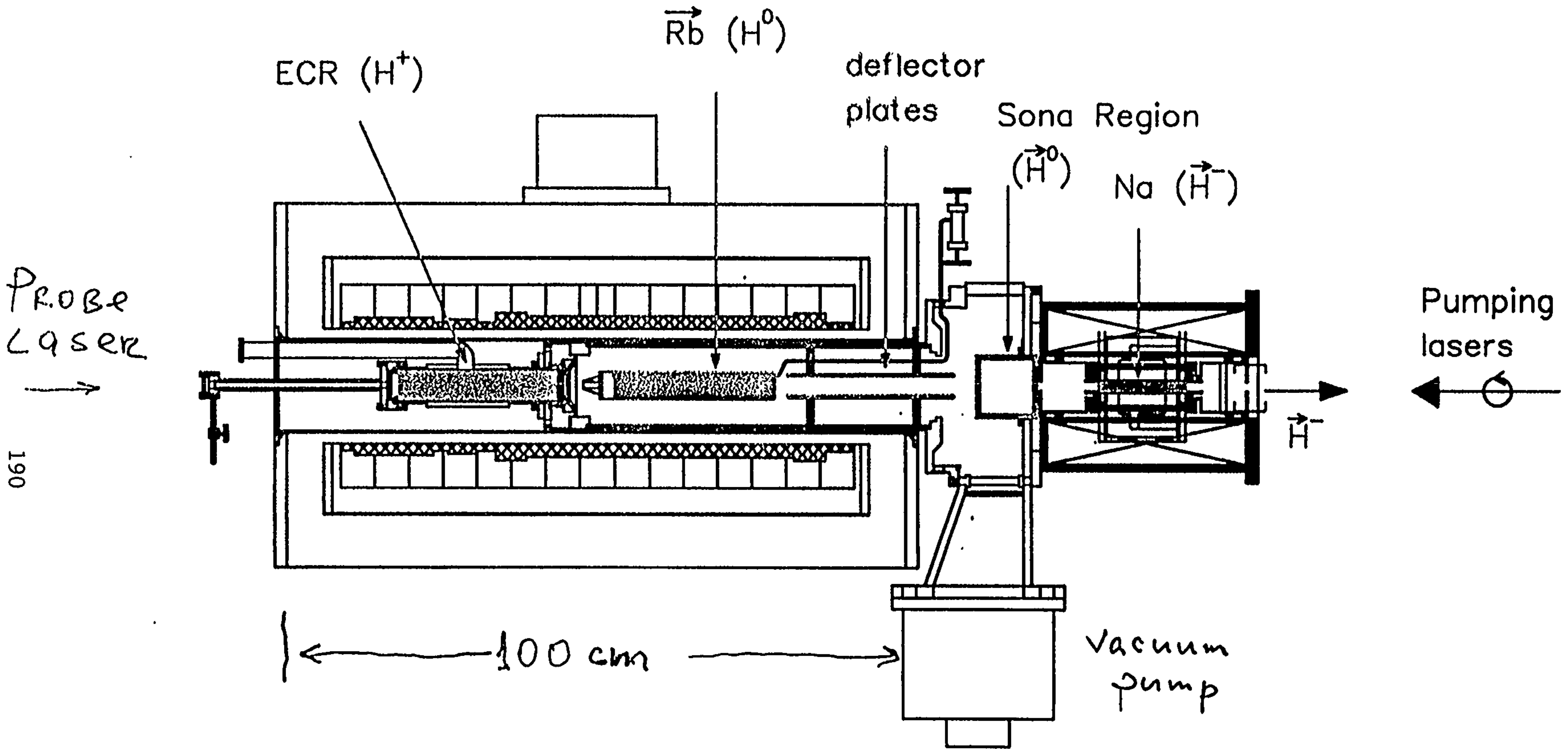
The polarized ion source for RHIC must produce in excess of 0.5 mA H ion current during a 300 us pulse, or current duration > 150 mA μs, within a normalized emittance of less than 2π mm mrad (see Table 1). This current corresponds to $9 \cdot 10^{11}$ particle/pulse. Assuming 50% beam losses in the LEBT,RFQ, LINAC, and injection to the AGS booster, that gives $4.5 \cdot 10^{11}$ polarized protons per booster bunch and finally $2 \cdot 10^{11}$ protons for the RHIC bunch. The KEK OPPIS upgrade had been comleted at TRIUMF and source was delivered to BNL on September 21, for installation at the RHIC injector.

An ECR primary proton source was upgraded from 18 GHz to 28 GHz. A new sodium-jet ionizer was developed to reduce sodium losses, increase current and polarization. The cell is floated and biased to - 32 kV, which allowed to accelerate primary 3.0 keV beam to 35 keV for injection to RFQ. A long pulse laser system based on solid -state Ti:Sapphire and LiSAF crystalls was developed to produce up to 400 us polarized beam pulse duration. In excess of 1.5 mA H^- ion current of 85-90% polarization within 1.8 π mm mrad normalized emittance was obtained as a result of current and polarization optimization (see Table 1). The OPPIS installation, construction of new LEBT , laser facilities and Lamb-shift polarimeter is now in progress at BNL.

Table I. OPPIS FOR RHIC

		specified	**achieved**
H^- ion current,	**(mA)**	**0.5**	**1.5**
Polarization,	**(%)**	**80**	**85- 90**
Emittance,	**(π mm mrad)**	**2.0**	**1.8**
Current duration,	**(mA us)**	**150**	**600**
Repetition rate,	**(Hz)**	**7.5**	**7.5**
Beam energy,	**(keV)**	**35**	**35**

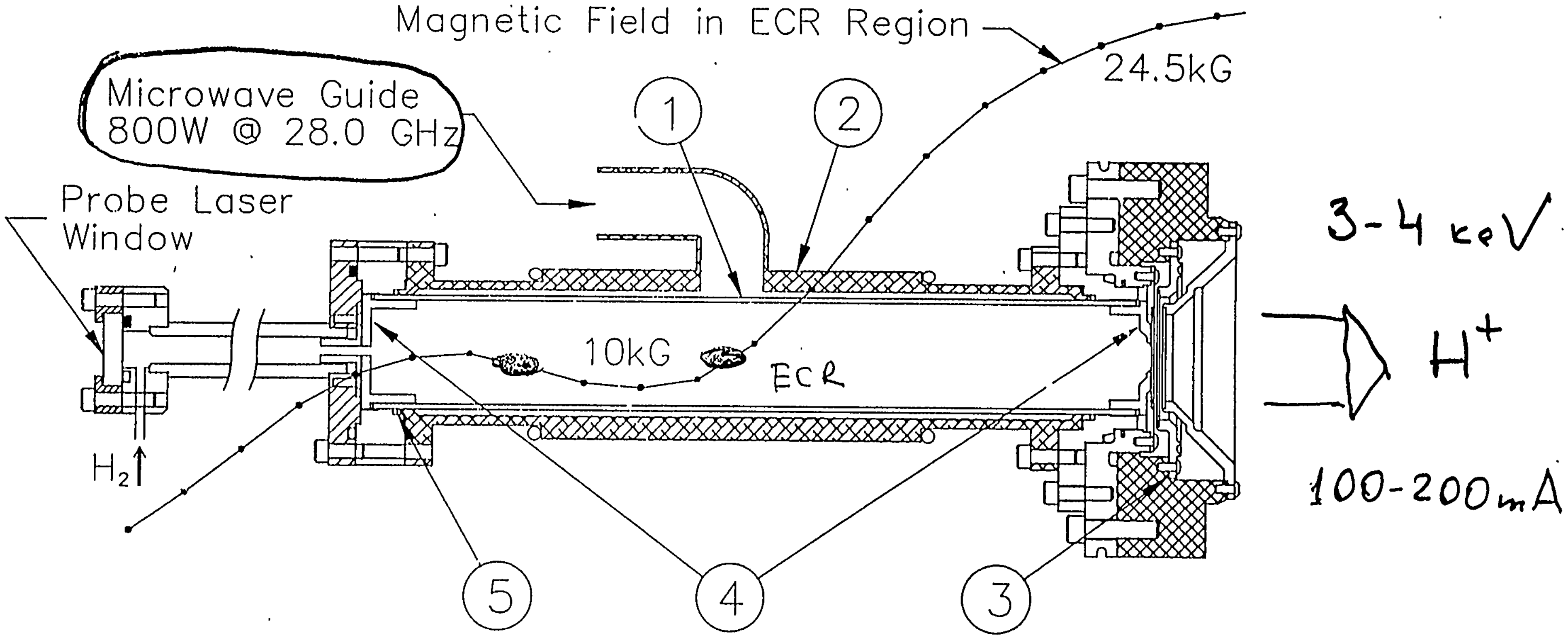
THE TRIUMF Optically Pumped Polarized $\vec{H}^-$ Ion Source (OPPIS).



OPPIS delivers 30-40% of the beamtime for "Parity" experiment at TRIUMF.

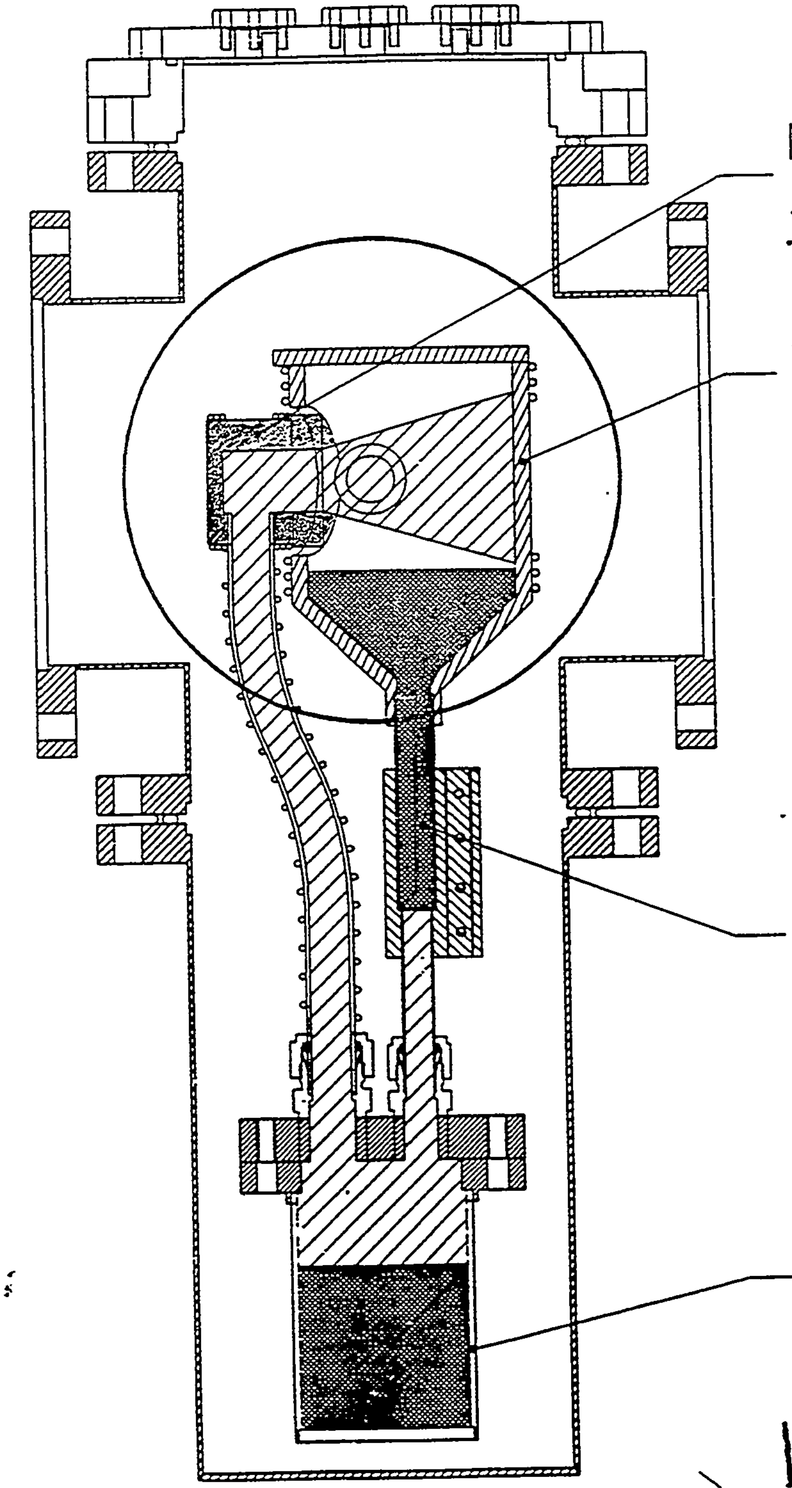
18 GHz → 28 GHz ECR H^+

ECRFIGUR.PS
.DWG
.DSK

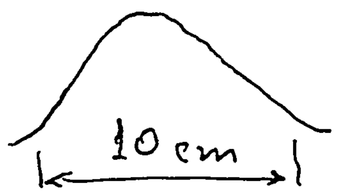


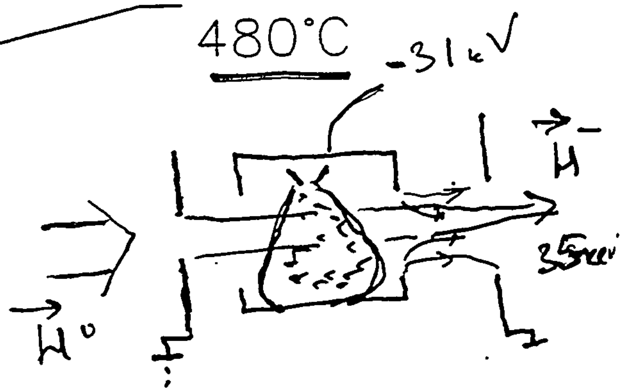
THe TRIUMF OPPIS ECR primary proton source

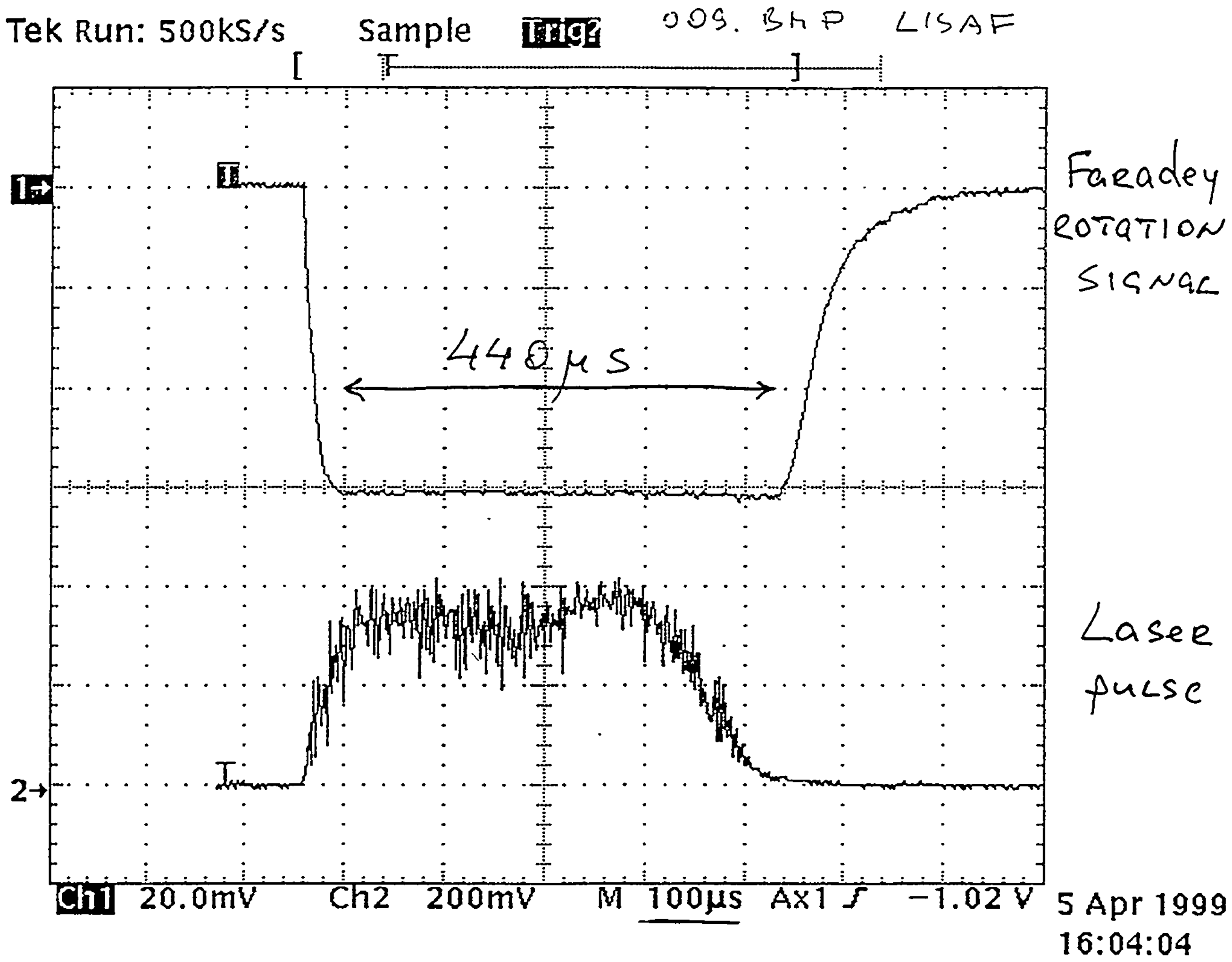
SODIUM JET IONIZER CELL



Sodium density profile





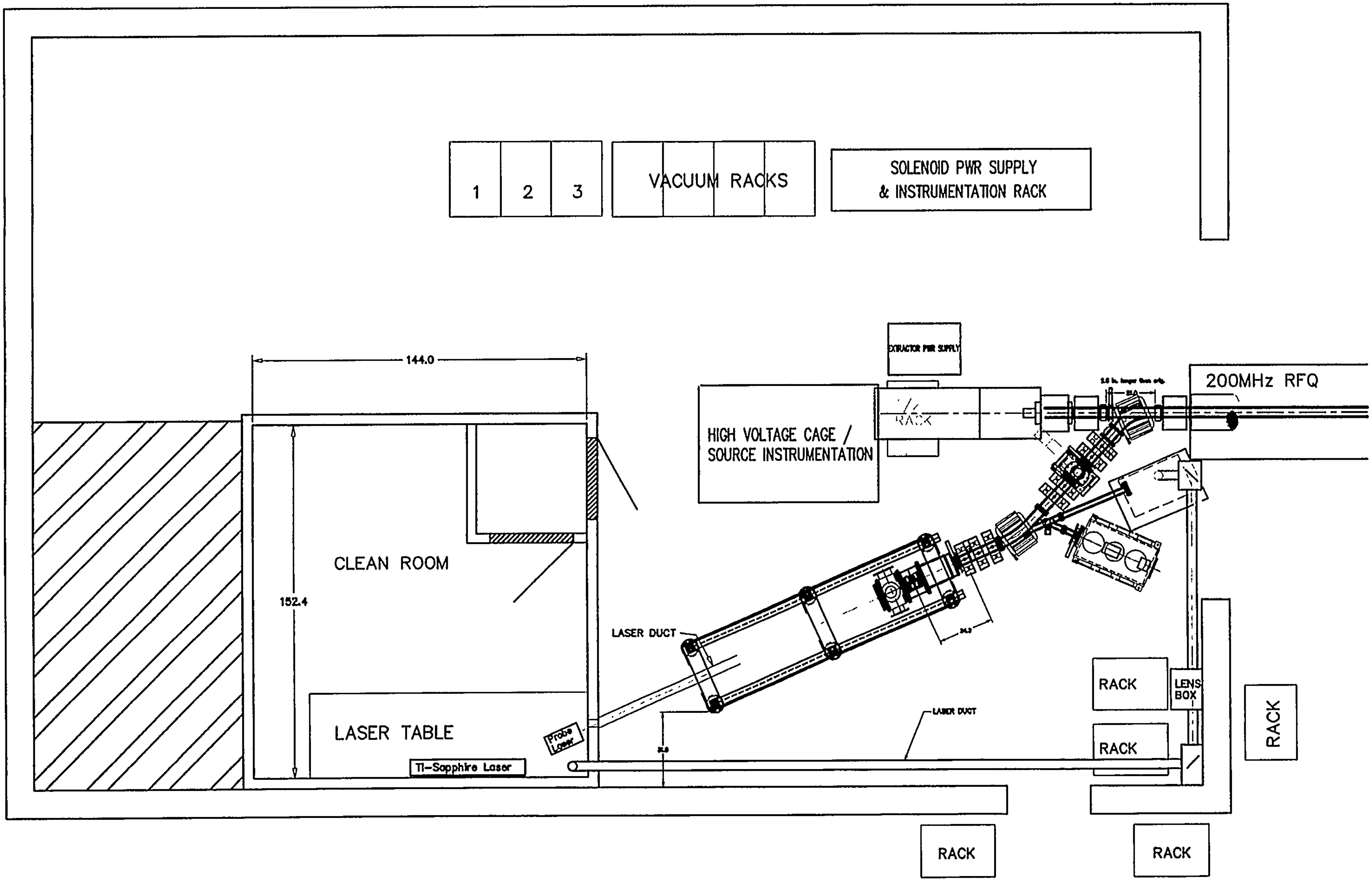


Optical pumping by LiSAF laser.

LiSAF ⟷ $LiSrAlF_6 : Cr^{3+}$

Laser power : $\frac{80\ mJ}{400\ \mu s} \sim 200\ W$

OPPIS Layout at BNL



Bunch Polarization, Variations, and Other Systematic Issues

Thomas Roser

Brookhaven National Laboratory

Measuring high precision asymmetries using polarized proton collisions at RHIC will require a high luminosity but will also pose new challenges to controlling systematic errors. Systematic errors can be caused by beam parameter variations that are either correlated or uncorrelated with the sign of the bunch polarization. Although a typical measurement of an asymmetry will be an average over many collisions even uncorrelated beam parameter variations can cause large fluctuations in the asymmetry measurement since filling RHIC will freeze in a certain random correlation for the whole store. The following three steps should minimize systematic errors due to beam parameter variations:

- Measure polarization and luminosity bunch-by-bunch (bunch pair by bunch pair) and correct individual asymmetries

- Measure each asymmetry four times: no flip, spin flip first beam, spin flip second beam (both beams flipped), spin flip first beam back (only second beam flipped); and then take the appropriate average.

- Recog beams to get new combination of bunch pairs as often as possible and then average over asymmetries.

Spin filling pattern in RHIC

$$\boxed{A_{LL}^{8} = \frac{1}{P^2}\,\frac{N_{++}+N_{--}-N_{+-}-N_{-+}}{N_{++}+N_{--}+N_{+-}+N_{-+}}}$$

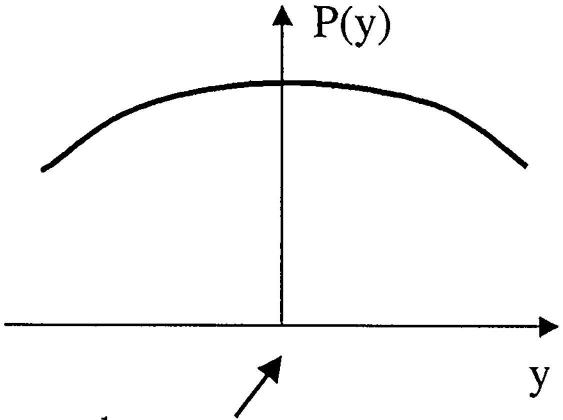
With 60 bunches per ring -> 15 groups of 8 bunches

$$\boxed{A_{LL} = \left\langle A_{LL}^{8} \right\rangle}$$

No systematic errors if all bunches are identical except for the sign of the polarization.

Bunch parameter variations

Possible beam variations both correlated and uncorrelated with spin sign from source and acceleration:



- Bunch intensity (0th moment)
- Bunch emittance (2nd moment)
- Polarization (0th moment)
- Amplitude dependent polarization (2nd moment)

Note: Odd moments will not survive beam acceleration or storage because of non-zero betatron tune spread.
Even bunch parameter variations uncorrelated with spin sign remain constant during a RHIC fill.

Compensation for bunch variations

- Bunch polarizations measured with ring polarimeters
- Bunch pair luminosities measured over same time period as bunch pair events
- Reduces systematic errors and fluctuations in asymmetry

$$A_{LL}^{8} = \frac{\frac{N_{++}}{L_{++}} + \frac{N_{--}}{L_{--}} - \frac{N_{+-}}{L_{+-}} - \frac{N_{-+}}{L_{-+}}}{\frac{(P_5P_6+P_7P_8)}{2}\left(\frac{N_{++}}{L_{++}} + \frac{N_{--}}{L_{--}}\right) + \frac{(P_1P_2+P_3P_4)}{2}\left(\frac{N_{+-}}{L_{+-}} + \frac{N_{-+}}{L_{-+}}\right)}$$

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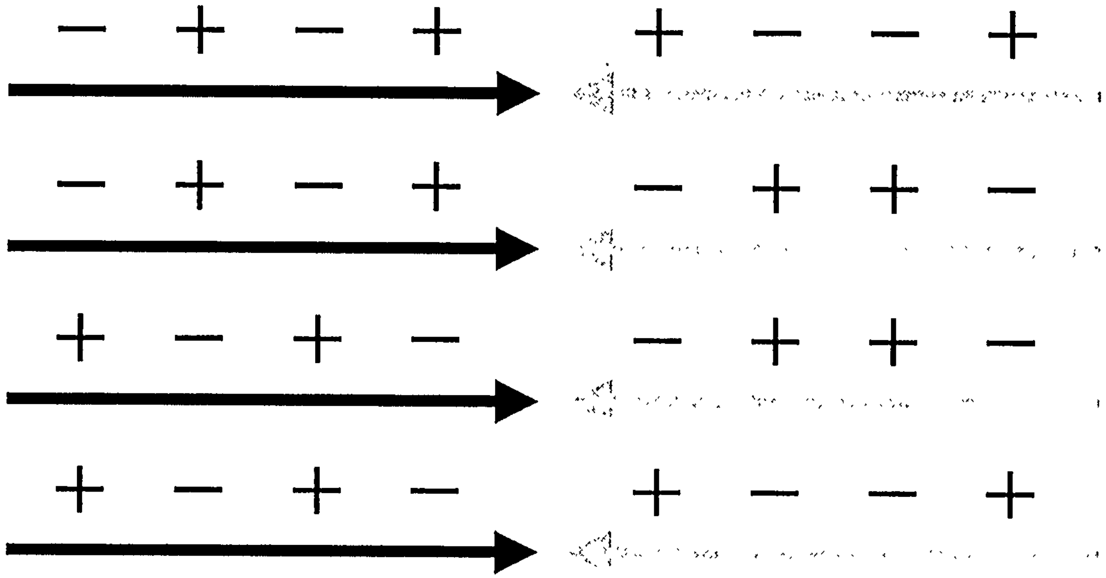
Spin flipping

Systematic correlations and beam parameter fluctuations are effectively suppressed by periodic spin flipping:



$$A_{LL}^{8}(\uparrow\uparrow)$$

$$A_{LL}^{8}(\uparrow\downarrow) = -A_{LL}^{8}(\uparrow\uparrow)$$

$$A_{LL}^{8}(\downarrow\downarrow) = A_{LL}^{8}(\uparrow\uparrow)$$

$$A_{LL}^{8}(\downarrow\uparrow) = -A_{LL}^{8}(\uparrow\uparrow)$$

$$\boxed{\left\langle A_{LL}^{8} \right\rangle = A_{LL}^{8}(\uparrow\uparrow) - A_{LL}^{8}(\uparrow\downarrow) + A_{LL}^{8}(\downarrow\downarrow) - A_{LL}^{8}(\downarrow\uparrow)}$$

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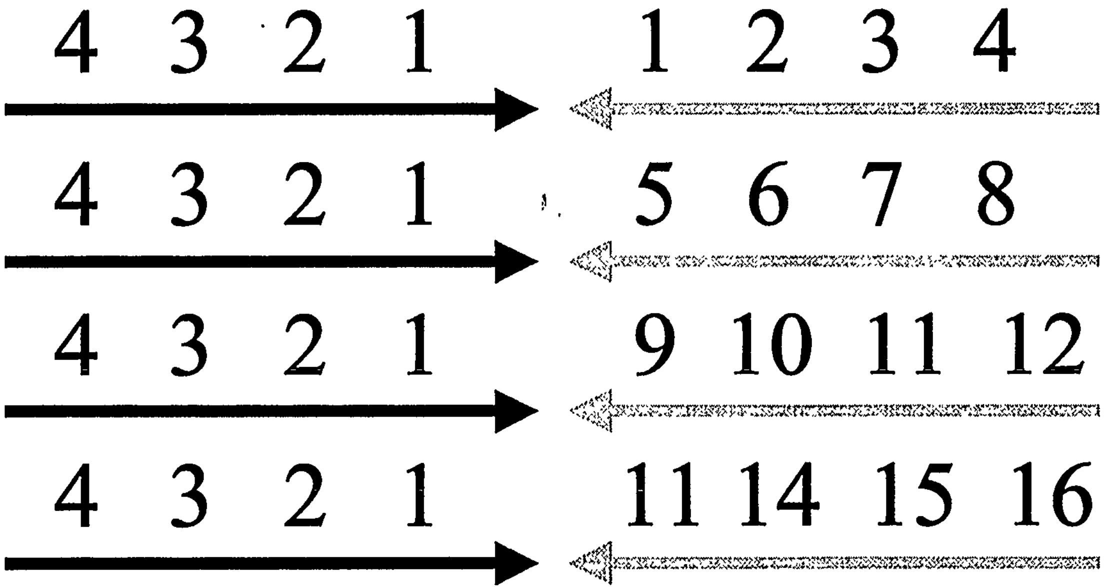
Recogging

The effect of beam parameter variations is randomized during a fill by frequent recogging:



4 3 2 1 → ← 1 2 3 4

4 3 2 1 → ← 5 6 7 8

4 3 2 1 → ← 9 10 11 12

4 3 2 1 → ← 11 14 15 16

$$\boxed{\left\langle A_{LL}^{8} \right\rangle = \frac{1}{N}\sum_{i=1}^{N} A_{LL}^{8}\left(cog_{i}\right)}$$

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Physics With A Polarized $\vec{e} \cdot \vec{p}$ Collider

Abhay Deshpande[1]
abhay.deshpande@yale.edu

RHIC Spin Workshop, BNL
October 8, 1999

Outline of the talk:

- Motivation: Need for Polarized $\vec{e} \cdot \vec{p}$ Collider
  - Recent results
  - Open questions
  - An $e \cdot p$ collider already exists!
- Physics With Polarized HERA
- Concluding remarks
  A Case for Polarized HERA

- Other possibilities:
  - An electron storage ring in the RHIC tunnel
    RHIC-$\vec{e} \cdot A$ and RHIC-$\vec{e} \cdot \vec{p}$
    $\Longrightarrow$ Comments.

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1997 Workshop on Physics With Polarized Protons at HERA

http://www.desy.de/~gehrt/heraspin

Conveners: A. De Roeck & T. Gehrmann

DESY-Proceedings-1998-01, February 1998

1999 Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities

http://www.desy.de/heraspin

Organizers: D. Barbar, A. De Roeck, V. W. Hughes, & F. Willike

Extremely active participation from BNL's machine physics groups and RHIC Spin: Phenix and Star Collaborations

---

PARTICIPANTS

G. Altarelli	(CERN)	T. Gehrmann	(DESY)	M. Maul	(Regensburg)
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J. Ellis	(CERN)	S. Manayenkov	(St. Petersburg)	S. Willfahrt	(Karlsruhe)
J. Feltesse	(Saclay)	L. Mankiewicz	(Munich)	R. Windmolders	(Mons)
S. Forte	(INFN-Torino)	O. Martin	(Regensburg)	M. Wobisch	(Aachen)

General Aim: Improve up on the 1996 Workshop Studies ⟹ Detector level physics studies; Explore new topics; Development of Tools: MC Generators, Detector Simulations; Address technical issues: Polarized Sources, Accelerator Issues, Proton Beam Polarimetry

Polarized $\vec{e} \cdot \vec{p}$ scattering @ HERA

Spin measurements in the kinematic region

- Q^2 : $0 \longrightarrow \quad \sim 5 \times 10^4$ GeV^2
  Photoproduction $\longrightarrow$ high Q^2
  Present $Q^2_{\mathrm{MAX}} \sim 100$ GeV^2
- $10^{-5} \leq x \leq 0.6$
  Low $x \Longrightarrow 0.002 \leq x_g \leq 0.2$
  Present $x_{\mathrm{MIN}} \sim 10^{-3}$

Polarized HERA Machine Parameters (assumed for workshop studies)

- $E_{\mathrm{p}} \sim 820$ GeV; Polarization $\sim 70\%$
- $E_{\mathrm{e}} \sim 27.5$ GeV; Polarization $\sim 70\%$
- Polarization Measurement Uncertainties
  $\Delta P_e/P_e \sim 5\%$; $\Delta P_p/P_p \sim 5\%$
- High Luminosity Lumi-Upgrade: ~ 170 pb^{-1}/year
- ZEUS and H1 Detectors

(Have Already!) (Not Yet!)

Physics Topics: 1997/99 Workshops

- Polarized Structure Functions g_1, g_5, g_2 $\surd\surd$
- Polarized Gluon Distribution ΔG:$\surd\surd$
  - NLO-pQCD fits of g_1
  - Di-Jet events in DIS
  - 2-Track events in DIS
  - Combined fits: g_1 + Di-Jets
  - Photoproduction
- Polarized semi-inclusive measurements $\surd$
- Polarized parton distribution in photon Δq^{γ} $\surd\surd$
- Diffraction/Vector Meson
- DHG Sum rule: $(\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow})$ at $Q^2 = 0$$\surd\surd$
- $(W^{\pm}, Z^0)$ Production
- High Q^2 anomaly → polarized HERA$\surd\surd$
- Target fragmentation $\surd\surd$
- Λ Polarization $\surd$
- Deeply virtual polarized Compton scattering $\surd$
- $\vec{p}\vec{p}$ scattering with HERA-$\vec{N}$ $\surd\surd$

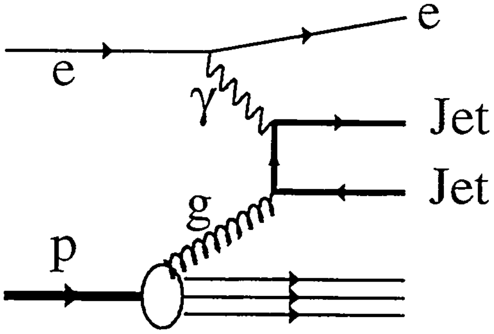
Green: Not good; $\surd$: Good; $\surd\surd$: Very Good

Measurement of $\Delta G(x, Q^2)$ and its first moment...

Numerous approaches possible at HERA

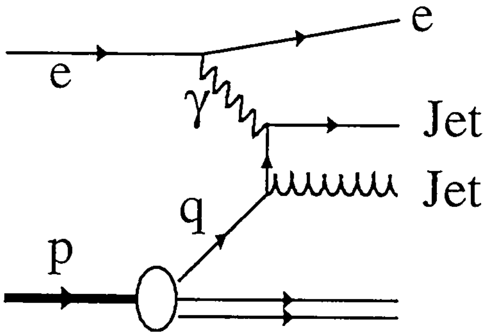
- "Indirect Determination": ΔG from NLO fits to g_1
- "Direct Determination": Photon Gluon Fusion in DIS and Photoproduction $\Longrightarrow$ ΔG appears at LO

Signal



Photon Gluon Fusion

Background



QCD-Compton

DIS:

- ΔG from 2-Jet Events (LO) in DIS
- ΔG from 2-High-p_T tracks with opposite azimuthal angle in DIS
- ΔG from combined QCD fit of g_1 and Jets in DIS

Photoproduction

- ΔG from Jets & High-p_T in photoproduction

A Case For Polarized HERA

- Behavior of $g_1(x, Q^2)$ at lowest x and highest Q^2 range $\Longrightarrow$ unique
- Measurement of $\Delta G(x, Q^2)$ in the largest x_g range using many approaches
- Polarized parton distributions in photons from photoproduction $\Longrightarrow$ unique
- Direct determination of $\Delta q_V = \Delta q - \Delta \bar{q}$ via charged current events
- Spin Physics beyond standard model... and more
- $N\vec{N}$ and $\vec{N}\vec{N}$ scattering at $\sqrt{s} \sim 40$ GeV with HERA-$\vec{N}$
- Measurements complementary to other future spin experiments

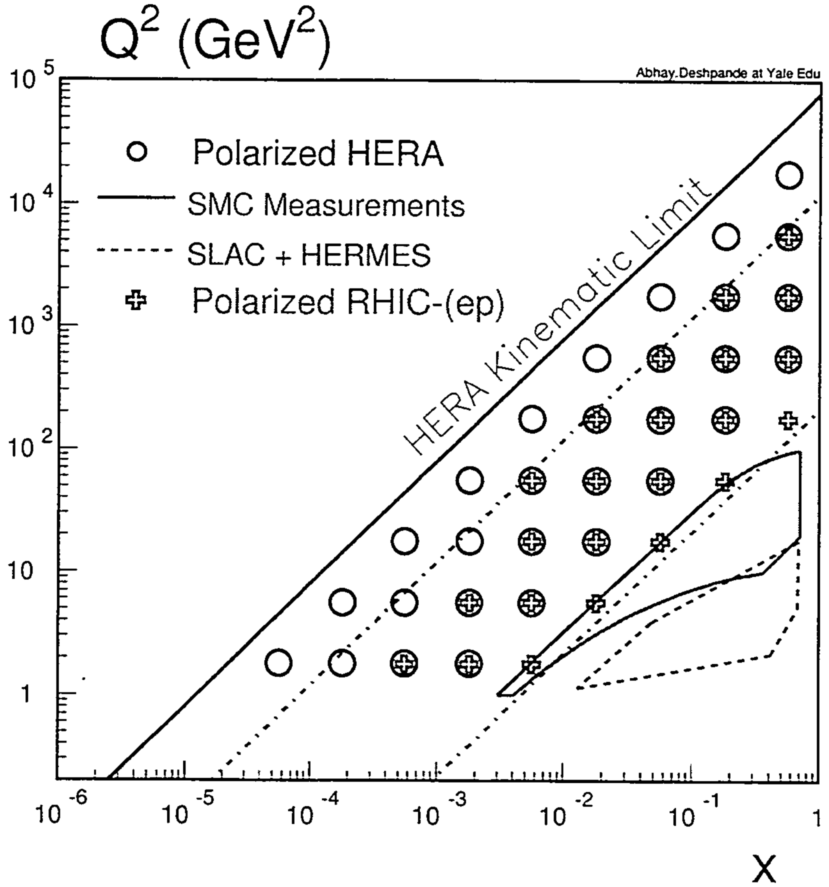
We have at HERA

- High energy electron and proton beams and people who know them!
- Electron beam already polarized! Polarization measurement $\Delta P/P \leq 5\%$
- Two working collider detectors and people who know them!

It would be unfortunate not to polarize the proton beam!

An Electron Ring in RHIC Tunnel

- **Possible 10-12 GeV electron ring in RHIC tunnel (??)** $\Longrightarrow$ **Will enable** $e \cdot A$ **and** $\vec{e} \cdot \vec{p}$ **scattering**
- $\vec{e} \cdot \vec{p}$ **with** $\sqrt{s} \sim 100$ **GeV** $\Longrightarrow$ **A Mini-Hera**
  Recall for HERA $\sqrt{s} \sim 300$ **GeV**



- **Physics program similar to Polarized HERA. Luminosity??...Detector issues: Modify presently available? Build New?**
- **Dedicated studies needed.**

WORKSHOP ANNOUNCEMENT SOON

SYSTEMATICS FOR POLARIZATION MEASUREMENTS

H. Spinka

High Energy Physics Division
Argonne National Laboratory, Argonne, Illinois 60439, USA

The number of events detected in a polarimeter depends on many factors. Assuming the polarimeter can detect particles to the left (L) and right (R) of the beam with approximately equal acceptance, then a simple set of equations can be written for the number of these detected events. The important factors include the analyzing powers (A_L, A_R), beam intensity for a particular pulse or bunch ($B_\pm$), beam polarization ($P_\pm$), and a product of acceptance and efficiency ($d\Omega_L$, $d\Omega_R$). It is assumed that the beam, target, and detector efficiency are constant, independent of bunch or pulse or polarization sign. In this case, the equations can be solved with small systematic error for the average of the beam polarization times the average analyzing power

$$PA = [(P_+ + P_-)/2] \times [(A_L + A_R)/2].$$

However, the systematic error is non-negligible for real polarimeters when it is attempted to measure the polarization of a single pulse or spill. The limitations are described in this talk.

Systematic errors become more important when the product of efficiency and solid angle ($d\Omega$) varies and is correlated with beam polarization sign. An example is given where the beam or target moves left to right or the efficiency changes to give values of $d\Omega_L$ and $d\Omega_R$ correlated with polarization sign. In order to keep systematic effects small compared to statistical uncertainties, there can be stringent requirements on such changes, as shown in the example.

Finally, even monitoring of luminosity at two interaction regions can supply information about changes in $d\Omega$ or the luminosity monitors, as described in this talk. This fact will make collaboration between the different RHIC detectors important to study such effects.

This work was supported in part by the U.S. Department of Energy, contract no. W-31-109-ENG-38.

INTRODUCTION

SYSTEMATIC ERRORS IN BEAM POLARIZATION MEASUREMENTS MAY DOMINATE STATISTICAL UNCERTAINTIES UNDER SOME CIRCUMSTANCES. CAUTION IN THE DESIGN AND VARIOUS CROSS CHECKS ARE REQUIRED TO MINIMIZE AND MEASURE THESE SYSTEMATIC EFFECTS.

SOME PROBLEMS TO CONSIDER:

- **Polarimeter arms not perfectly symmetric**
  - Different L, R rates, even for unpolarized beams
  - Different L, R analyzing powers from asymmetric backgrounds or imperfect alignment
  - Changing rates or analyzing powers – hardware variations and rapidly changing $A_N(\theta)$ or $d\sigma/d\Omega\,(\theta)$.

- **Beam bunches not perfectly equal**
  - Different intensity
  - Different polarization
  - Varying phase space

- **Polarimeter target not "constant"**
  - Variations in position
  - Changing thickness
  - Differing composition

AN EXAMPLE

DETECTOR EFFICIENCY, OR
TARGET POSITION, OR
BUNCH POSITION, OR...

} CHANGES THAT ARE CORRELATED WITH POLARIZATION SIGN CAN GIVE "FAKE" ASYMMETRIES.

IN THIS CASE, DIFFERENT EQUATIONS MUST BE CONSIDERED TO ACCOUNT FOR VARIATIONS IN "$d\Omega$". (IGNORE DIFFERENCES BETWEEN $A_L^{(j)}, A_L^{(k)}$ AND BETWEEN $A_R^{(j)}, A_R^{(k)}$.)

$$L_+^{(j)} = N B_+^{(j)} \underline{\underline{d\Omega_L^{(j)}}} \left(1 + P_+^{(j)} A_L\right)$$

etc.

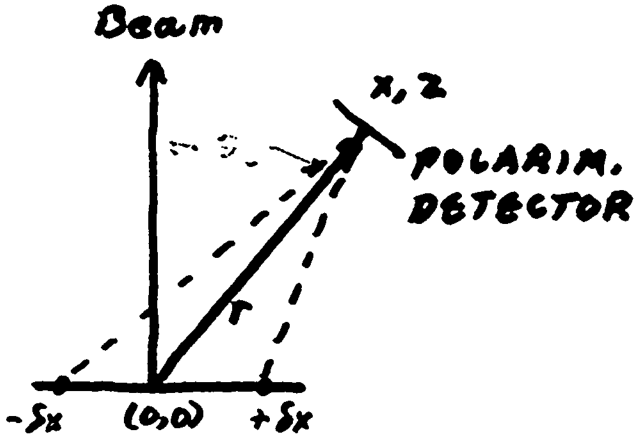
$$\varepsilon_{\Omega L}^{(jk)} = \frac{d\Omega_L^{(j)} - d\Omega_L^{(k)}}{d\Omega_L^{(j)} + d\Omega_L^{(k)}} \qquad \varepsilon_{\Omega R}^{(jk)} = \frac{d\Omega_R^{(j)} - d\Omega_R^{(k)}}{d\Omega_R^{(j)} + d\Omega_R^{(k)}}$$

Then

$$\alpha_1^{(jk)} \simeq PA + \frac{1}{2}\left(\varepsilon_{\Omega L} - \varepsilon_{\Omega R}\right)$$

$$+ \frac{1}{2}\varepsilon_P\left(\varepsilon_{\Omega L} + \varepsilon_{\Omega R}\right) + O(\varepsilon^3)$$

EXTRA TERMS OF ORDER ε, ε^2 HAVE APPEARED.



$$\varepsilon_{\Omega L}^{(jk)} \simeq -\,\varepsilon_{\Omega R}^{(jk)}$$
$$\simeq 2\,\frac{\Delta x}{r}\sin\theta_L$$

FOR THE CNI POLARIMETER, $r \sim 15$ cm, AND $\sin\theta_L \sim 1$ SO IT IS REQUIRED TO HAVE

$$\delta x \ll \frac{r}{2}\,\delta\alpha_q \simeq 0.10 \text{ mm}$$

IN ORDER TO HAVE SYSTEMATIC ERRORS SMALL COMPARED TO STATISTICAL UNCERTAINTIES. (MUST BE CAREFUL OF MECHANICAL VIBRATIONS)

The π-inclusive polarimeter is much less sensitive to this particular systematic error since

$\sin\theta_L$ much smaller
r much larger

BEWARE OF EFFICIENCY CHANGES IN THE DETECTORS OR SPIN DEPENDENT BACKGROUNDS.

SUMMARY

- ESTIMATED STATISTICAL UNCERTAINTIES ON BEAM POLARIZATION FOR SINGLE BUNCHES ARE

$$\delta P_+^{(j)}, \delta P_-^{(k)} \gtrsim \pm 0.05 \qquad \text{CNI}$$
$$\pm 0.01 \qquad \pi\text{-inclusives}$$

- SYSTEMATIC ERRORS FROM $d\Omega_L \neq d\Omega_R$ (ε_A) CAN BE MADE SMALLER THAN STATISTICAL UNCERTAINTIES IF $d\Omega$ IS STABLE (detector efficiencies, target and beam position, ...)

  EFFICIENCIES MUST BE CONSTANT TO $\ll 0.1\%$ FOR TIMES $\gg$ (LO)(220 nsec).

  TARGET POSITION AND THICKNESS, BEAM PHASE SPACE CHANGES MUST NOT BE CORRELATED WITH POLARIZATION SIGN EITHER. THESE ALSO CONTRIBUTE TO "$d\Omega$".

- IT WILL BE DIFFICULT TO ESTIMATE ε_A FROM POLARIMETER DATA.

  This needs to be estimated from simulations of the polarimeter design

- $\sigma(P_+^{(j)})$ and $\sigma(P_-^{(k)})$, assumed to be equal on the average, can be estimated from $\sigma(\alpha_9^{(jk)})$ and statistics.

  This may differ from fill to fill.

  Perhaps cross check with the AGS polarimeter

- $\sigma(\mathcal{E}_\Omega)$ can be estimated from $\sigma(\alpha_9^{(jk)})$, $\sigma(\alpha_{10}^{(jk)})$, and statistics. A nonzero $\sigma(\mathcal{E}_\Omega)$ would indicate systematic errors!

  $\mathcal{E}_\Omega$ and $\sigma(\mathcal{E}_\Omega)$ may be time dependent, and could vary from fill to fill.

- Tests for detector efficiency or beam phase space changes are possible using relative intensities and luminosities, even with unpolarized beam.

  Phase space for bunches that "collide" with some empty bunches may evolve differently within a fill than bunches that only "collide" with full bunches.

The different RHIC detectors should work together to perform some of these checks.

FERMION BOSON COLLISIONS
AND SWIFT PROTON POLARIMETRY

Nigel H. Buttimore

University of Dublin, Trinity College

RIKEN BNL RHIC SPIN MEETING
6–8 October 1999

Summary

The spin asymmetries for proton carbon and proton deuteron elastic scattering are studied at small angles in the context of understanding spin dynamics at high energies for the purposes of measuring the polarization of proton and ion beams. The effects of spin dependence, dispersive spin-independent amplitudes, and the Coulomb phase are addressed in particular. Electromagnetic helicity amplitudes for proton deuteron collisions resulting from single photon exchange have been calculated, those prominent at low momentum transfer and high energy being exhibited. The character of the maximum asymmetry for polarized protons scattering on bosons of low spin is dicussed, focussing on the dependence upon spin and phases that is important for polarimetry.

1. Introduction

QCD expectations of contributions to the spin of a proton from quark and gluon spin and angular momenta require protons with polarization known to 5%

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g \,.$$

The use of scattering in the Coulomb nuclear interference region to generate large neutron polarization has been studied by Schwinger, Phys. Rev. 69, 681 (1946). Polarization in hadron induced processes at RHIC has been considered by Makdisi at Spin96, Amsterdam (p. 107) and polarimetry for polarized proton colliders with a jet target by Penzo et al (p. 810). The spin dependence of high energy proton proton scattering has been examined in the context of a pp polarimeter by NHB, Kopeliovich, Leader, Soffer, Trueman, Phys. Rev. D59, 114010 (1999).

Proton carbon elastic scattering in the interference region has been proposed by Kurita and the E950 Collaboration as a polarimeter for RHIC (see Spin82, Brookhaven, p. 634). A further example of a fermion boson collision process with interesting spin dependence involves small angle proton deuteron scattering with its twelve independent helicity amplitudes. Proton carbon collisions provide a context for a study of the proton deuteron case.

2. Single spin asymmetry for pC

General principles do not require that spin dependence vanishes with increasing energy. A common spin formalism uses helicity amplitudes in terms of which the asymmetry for proton carbon elastic scattering is

$$A_N \;=\; 2\,\mathrm{Im}\,(f_{++}{}^{*}\,f_{+-})\;/\;\left(|f_{++}|^2+|f_{+-}|^2\right)$$

where there is an electromagnetic component $f_j + e^{i\delta} f_j^e$, $(j = ++,\, +-)$ that involves a phase shift $\delta = \alpha\,(Z \ln|2/bt| - Z\gamma + \cdots)$ Cahn, Z. Phys. C15, 253 (1982) resulting from higher order Coulomb effects that involve b, the slope of the differential cross section.

Interference between nonflip amplitudes $f_{++}^{\mathrm{em}}(s,t)$ and $f_{++}(s,t)$ is prominent when $t = t_c = -8\pi Z\alpha/\sigma_{\mathrm{tot}}(\mathrm{pC}) \approx -0.0013$ (GeV/c)^2. The approximate one photon exchange helicity nonflip amplitude at high s and low $|t|$

$$f_{++}^{\mathrm{em}} = \frac{Z\alpha s}{t}\,F_1(t)\,F(t)$$

uses proton Dirac and carbon electromagnetic form factors normalized according to $F_1(0) = 1$ and $F(0) = 1$. The t dependence of the form factor product is similar to the hadronic t dependence of f_{++} at small angles, tending to cancel in an asymmetry. The corresponding helicity flip amplitude,

$$f_{+-}^{\mathrm{em}} = -\frac{Z\alpha s}{\sqrt{-t}}\,\frac{\kappa}{2m}\,F_2(t)\,F(t)$$

involves the Pauli form factor F_2 of the proton. Here $F_2(0) = 1$, the magnetic moment of the proton is $\kappa + 1 = \mu = 2.793$, and m is the proton mass.

3. Asymmetry maximum for pC

The Coulomb phase shift δ of about 11% in the interference region for a carbon target with $Z = 6$ suggests that trigonometric approximations for, eg, $\cos\delta$ should be avoided. Assuming that the hadronic imaginary part has exponential dependence on small t the asymmetry may be written in an approximate two-part form to show the ρ dependence and spin dependence with a numerator

$$\begin{aligned}\frac{m\,A_N}{\sqrt{-t}}\,\frac{16\pi}{\sigma_{\rm tot}^2}\,\frac{d\sigma}{dt}\,e^{-bt} &= [(\mu-1-2\,{\rm Im}\,r)\cos\delta-(\rho-2\,{\rm Re}\,r)\sin\delta]\,\frac{t_c}{t}\\ &\quad -2\,{\rm Re}\,r+2\rho\,{\rm Im}\,r\end{aligned}$$

and a denominator, the scaled unpolarized differential cross section

$$\frac{16\pi}{\sigma_{\rm tot}^2}\,\frac{d\sigma}{dt}\,e^{-bt}=\left(\frac{t_c}{t}\right)^2-2(\rho\cos\delta+\sin\delta)\frac{t_c}{t}+1+\rho^2$$

where the hadronic nonflip ratio is $\rho = {\rm Re}\,f_{++}/{\rm Im}\,f_{++}$ and a kinematically scaled hadronic ratio of the helicity flip amplitude is defined as

$$r = \frac{m}{\sqrt{-t}}\times\frac{f_{+-}}{{\rm Im}\,f_{++}}\,.$$

The maximum of the interference asymmetry near $t_{\rm max} = \sqrt{3}\,t_c$ depends on the parameters ρ, δ, Re r, and Im r, and, to first order in these quantities, it is

$$\frac{4mA_N^{\rm max}}{\kappa\sqrt{-3\,t_{\rm max}}} = 1+\frac{\sqrt{3}}{2}(\rho+\delta)-\frac{2}{\kappa}({\rm Im}\,r-\sqrt{3}{\rm Re}\,r)\,.$$

A negative value of $\rho(s)$ would reduce the asymmetry maximum in pC elastic scattering. A ρ value of -0.2, for example, contributes at the level of -17% to the maximum of A_N in the interference region; and proportionately for other values of ρ. Note the importance of knowing the Bethe phase δ also. A study of the pC differential cross section at interference would provide values of ρ at particular energies. A combined analysis of ${\rm Im}\,r$ and ${\rm Re}\,r$ in the context of the use of analyticity in a dispersion relation could provide further constraints on the hadronic helicity flip amplitude.

Negative C-parity forbids three gluon exchange in pion-nucleon, kaon-nucleon, and pC elastic collisions. A study of multiple gluon exchange would lead to additional understanding of the rôle played by the helicity flip amplitude in pC asymmetries.

4. Spin asymmetry for pd collisions

For proton deuteron elastic scattering the 36 possible helicity amplitudes may be reduced to 12 independent amplitudes under the assumption of time reversal and parity invariance. Of the hadronic amplitudes, $H_i(\lambda'_p, \lambda'_d; \lambda_p, \lambda_d)$ with $\lambda_p = \pm$ and $\lambda_d \in \{+, 0, -\}$, four ($i = 1\text{--}4$) can be non-zero in the forward direction, five ($i = 5\text{--}9$) have $\sqrt{-t}$ single flip dependence, two ($i = 10\text{--}11$) have $-t$ double flip dependence, and $H_{12}(+-;-+)$ has $-t\sqrt{-t}$ dependence. The asymmetry at interference involves the significant amplitudes

$$A_N \;=\; \frac{2\,\mathrm{Im}\,[H_6{}^*\,(H_1 + H_4) + \cdots]}{|H_1|^2 + |H_2|^2 + |H_3|^2 + |H_4|^2 + 2|H_6|^2 + \cdots}$$

where each includes an electromagnetic element related to spin 1/2 and spin 1 electromagnetic currents, Waldenstrøm, Nuovo Cimento 3A, 491 (1971). The one photon exchange helicity amplitudes, calculated by Corbett, MSc TCD 1984, have approximate form (and here $H_2^{\mathrm{em}}(+-;-0)$ is insignificant)

$$H_i^{\mathrm{em}}(+j;+j) = \frac{\alpha s}{t}\,F_1(t)\,F_1^{\mathrm{d}}(t)$$

in the nonflip case labelled by $i = 1,\ 3,\ 4$ for deuteron helicities $j \in \{+,\ 0,\ -\}$, respectively, where $F_1^{\mathrm{d}}(t)$ is a deuteron electromagnetic form factor. The proton single flip amplitudes $H_7^{\mathrm{em}}(++;--)$ and $H_9^{\mathrm{em}}(+0;-0)$ are unimportant, but

$$H_6^{\mathrm{em}}(++;-+) = \frac{\alpha s}{\sqrt{-t}}\,\frac{\kappa}{2m}\,F_2(t)\,F_1^{\mathrm{d}}(t)$$

while the deuteron single helicity flip electromagnetic amplitudes are

$$H_5^{\mathrm{em}}(++;+0) = H_8^{\mathrm{em}}(+0;+-) = \frac{\alpha s}{\sqrt{-2t}}\,F_1(t)\,\frac{1}{2M}\,G_1^{\mathrm{d}}(t)$$

where $G_1^{\rm d}(0)$ is related to $\mu_{\rm d} = 0.8574$, the magnetic moment of the deuteron, and M is the deuteron mass. The double spin flip amplitudes, $H_{10}^{\rm em}(++;+-)$ and $H_{11}^{\rm em}(+0;-+)$, play no rôle in the interference region.

5. Asymmetry maximum for pd

The Coulomb phase shift δ is about 2% in the interference region for a deuteron target. Assuming that the hadronic imaginary part has exponential dependence on t, the proton spin asymmetry shows spin dilution

$$\begin{aligned}\frac{3}{2}\frac{m\,A_N}{\sqrt{-t}}\frac{16\pi}{\sigma_{\rm tot}^2}\frac{d\sigma}{dt}e^{-bt} &= [\mu_{\rm p} - 1 - 2\,{\rm Im}\,r - (\rho - 2\,{\rm Re}\,r)\,\delta]\,\frac{t_c}{t} \\ &\quad - 2\,{\rm Re}\,r + 2\rho\,{\rm Im}\,r\end{aligned}$$

where the unpolarized differential cross section is

$$\frac{16\pi}{\sigma_{\rm tot}^2}\frac{d\sigma}{dt}e^{-bt} = \left(\frac{t_c}{t}\right)^2 - 2(\rho+\delta)\frac{t_c}{t} + 1 + \rho^2 + \cdots$$

with ratio $\rho = {\rm Re}\,H_+/{\rm Im}\,H_+$ referring to the hadronic non-flip amplitude H_+ (an appropriate average of H_1, H_3, and H_4) and a kinematically scaled hadronic ratio of the proton helicity flip amplitude is defined as

$$r \;=\; -\frac{m}{\sqrt{-t}} \times \frac{H_6}{{\rm Im}\,H_+}\,.$$

Again a negative value of $\rho(s)$ would reduce the asymmetry maximum in pd elastic scattering. A detailed study of the pd differential cross section at interference could provide values of ρ at particular energies. Helicity dependent terms could then be isolated and their energy and momentum transfer dependence studied to facilitate the understanding of proton deuteron spin structure at smaller length scales (Kumano, 1999).

I am grateful to Enterprise Ireland for partial support under its International Programme IC/1999/075.

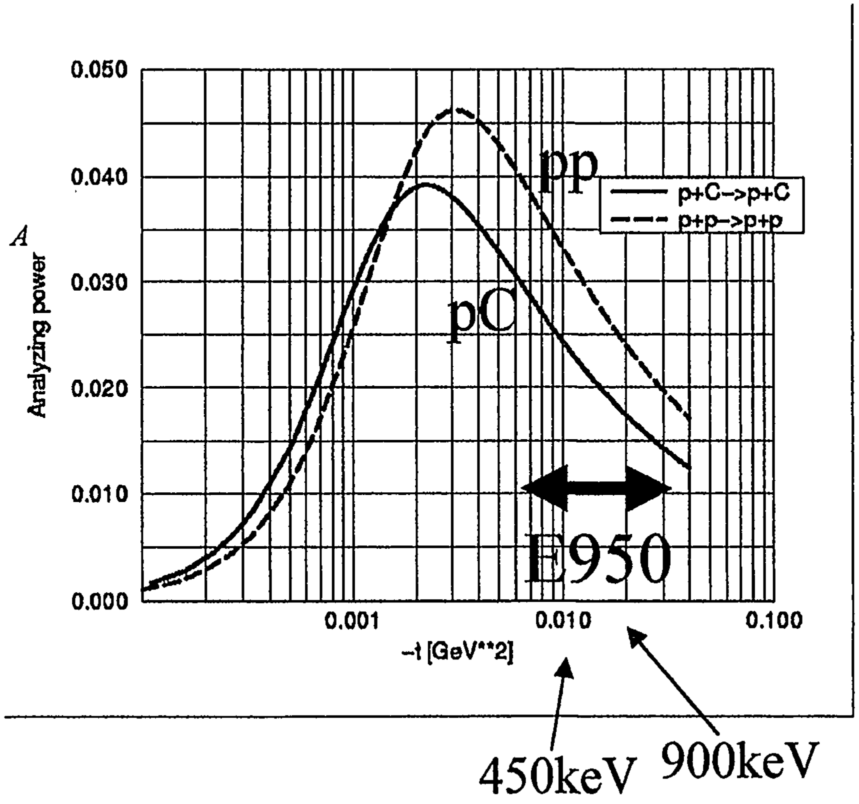
Summary

- The elastic reactions pC, pp, and pd form a sequence of processes with increasingly rich spin structure
- The maximum spin asymmetry at $\sqrt{3}\,t_c$ depends on $\rho(s)$ and the hadronic helicity flip amplitude, as does the optimal figure-of-merit at t_c
- The pC maximum asymmetry, in the absence of spin and ρ effects, is expected to be reduced from the pp value by a factor $\sqrt{6\,\sigma_{\rm tot}({\rm pp})/\sigma_{\rm tot}({\rm pC})}$
- The pd maximum asymmetry, likewise, is expected to be reduced from the pp value by the factor $(2/3)\sqrt{\sigma_{\rm tot}({\rm pp})/\sigma_{\rm tot}({\rm pd})}$ if the pure spin elastic amplitudes, H_1, H_3, and H_4, are equal.
- A study of CNI asymmetries for polarized proton nucleus collisions would offer a considerable increase in the understanding of proton ion spin dependent dynamics. Such knowledge would have significant impact on proton and ion polarimetry.

Beauty of CNI

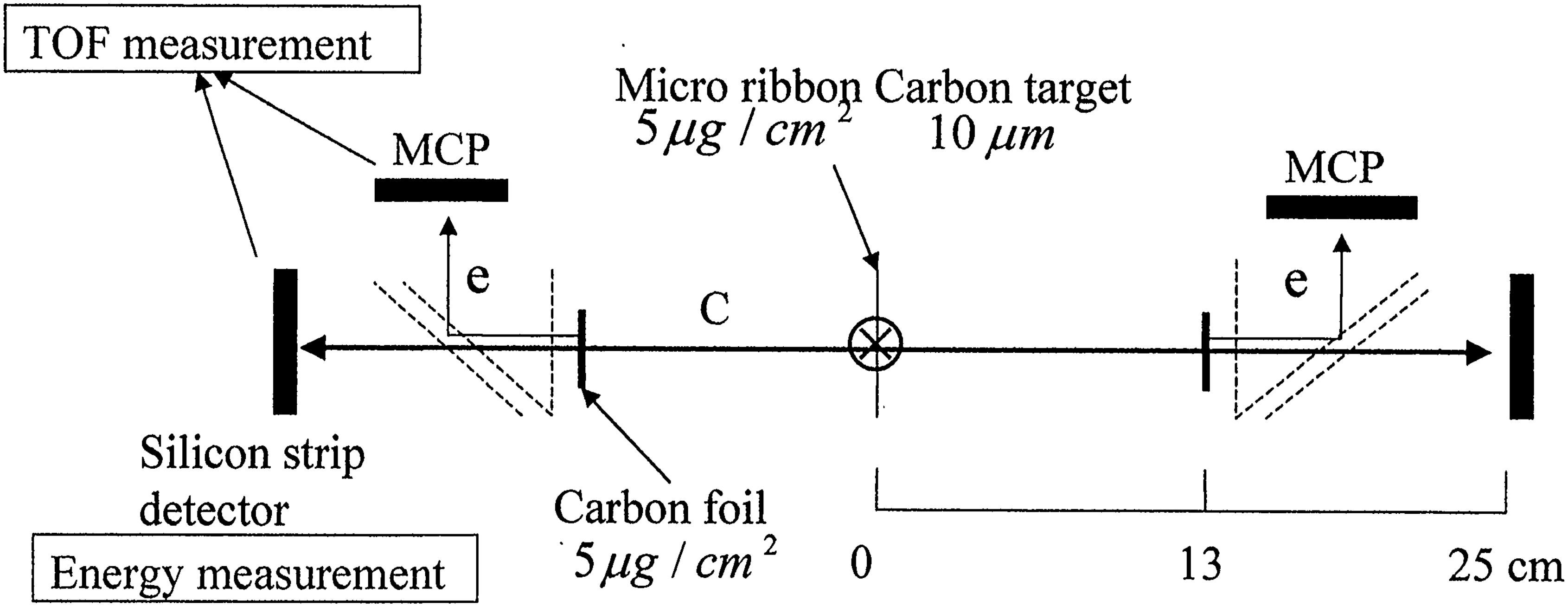
- Asymmetry calculable

- Weak beam momentum dependence



Kazu Kurita/RIKEN, RBRC

Experimental Design



TOF measurement

MCP

Micro ribbon Carbon target

$5 \mu g / cm^2$ $10 \mu m$

MCP

e

C

e

Silicon strip detector

Energy measurement

Carbon foil

$5 \mu g / cm^2$

0

13

25 cm

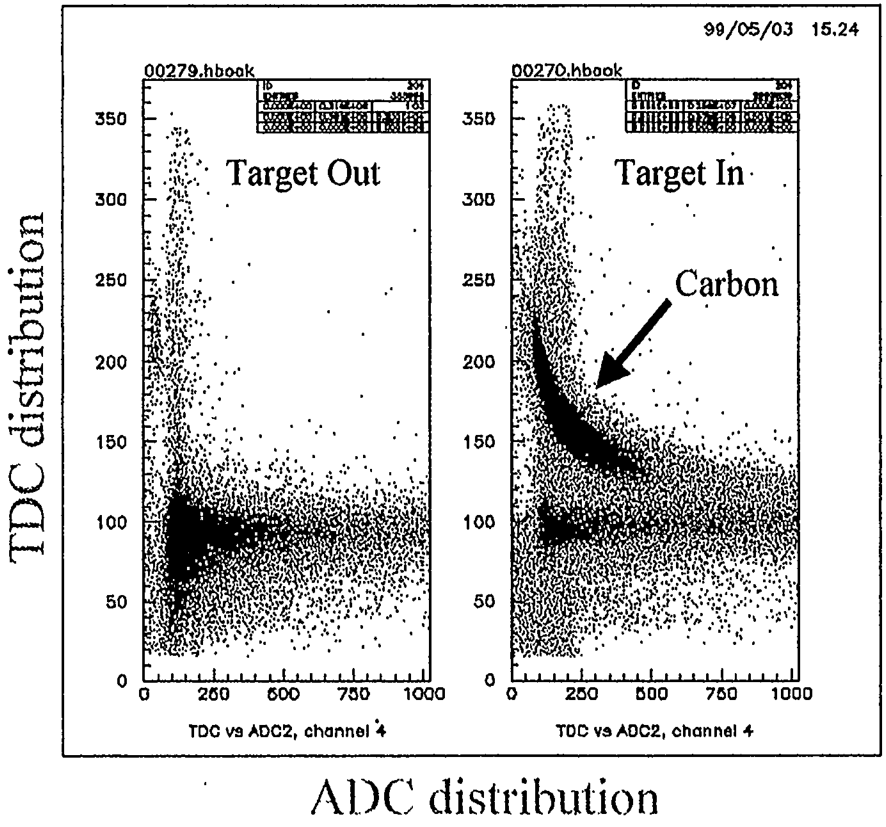
6ch,4mm/strip

surface:bare Si

E950 Detector Arrangement

Si data

- Comparison between target in/out runs gives the evidence of Carbon detection
- target frame is in the beam even with the target out run



Asymmetry

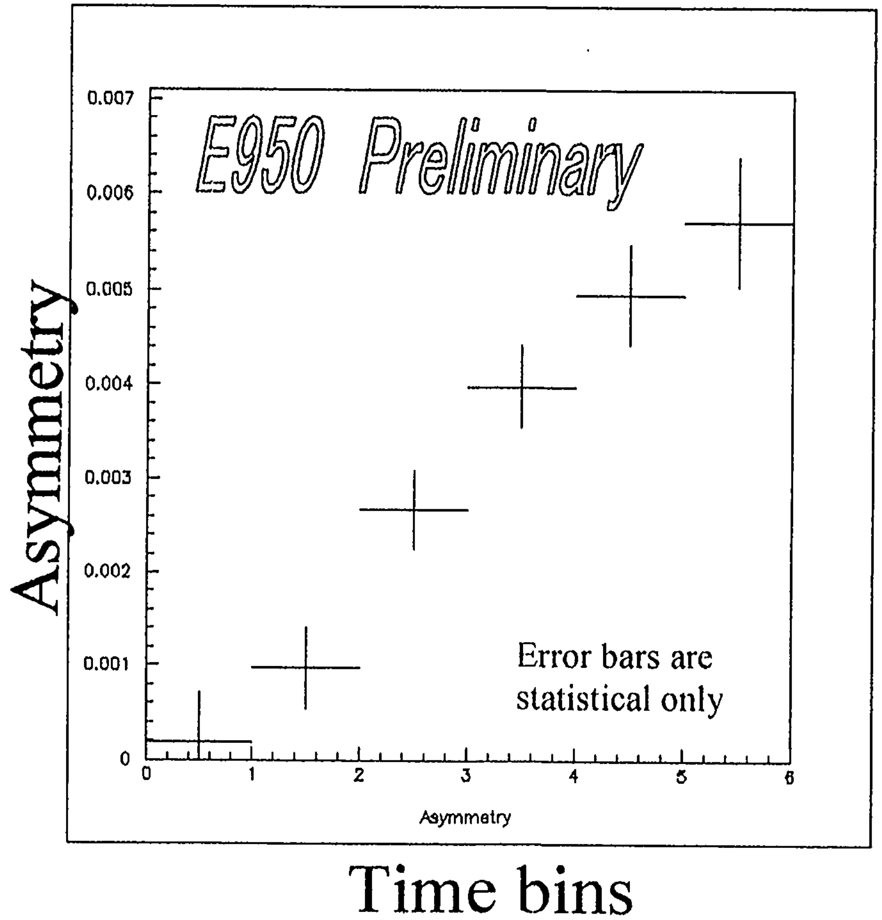
Carbon asymmetry is statistically significant

The physics asymmetry increases with arrival time => consistent with theory

Effect of different discriminator threshold was found to be very small

Asymmetry of prompt is less than 0.001

Other systematic error study is being done



Summary

1, We successfully detected carbon recoils inside the AGS ring

2, We see asymmetry

3, t dependence seems to be qualitatively consistent with theory but we are not ready to compare with theory quantitatively

4, Error from calibration is under evaluation

5, We started the preparation for RHIC pC CNI polarimeter

The RHIC Polarimeter–Preparations

Haixin Huang

Brookhaven National Lab

Abstract

This presentation summarizes the current layout of RHIC CNI polarimeter in one ring. The compact design of 1.5meter long target box hosts two target assemblies(vertical and horizontal) and six detectors, which can scan the beam polarization profiles vertically and horizontally. In foreseeing the limited lifetime of the target, three target ribbon will be used for each target assembly. The target is a 4μ m/cm^2, 6μ m wide carbon ribbon. This kind of target has been used successfully in AGS E950 experiment. A p-Carbon quasi-elastic polarimeter working at injection energy will be installed for cross check purpose and it shares the same target with CNI polarimeter. In the future, a pion polarimeter will be installed in yellow ring, which utilizes five C-magnets and four existing hodoscopes used in E925. By comparing with data taken at 22GeV/c(AGS E925) and 200GeV/c (Fermilab E704), it can provide direct calibration of analyzing power of CNI polarimeter at these two energies.

RHIC Polarimeter Requirement

Short Term RHIC spin program schedule

FY2000: commissioning one ring up to 100GeV with polarized beam

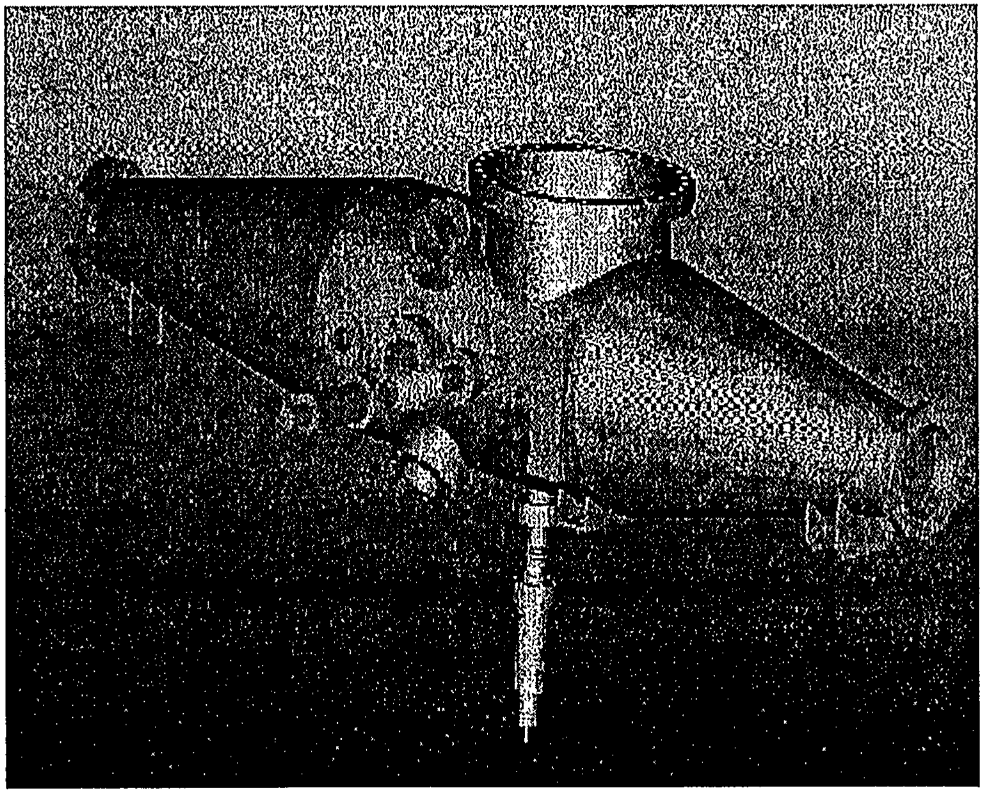
FY2001: Physics run at 100GeV(both rings polarized)

need a fast and reliable polarimeter with 10% relative error in a few minutes or seconds.

RHIC pC CNI Polarimeter Plan

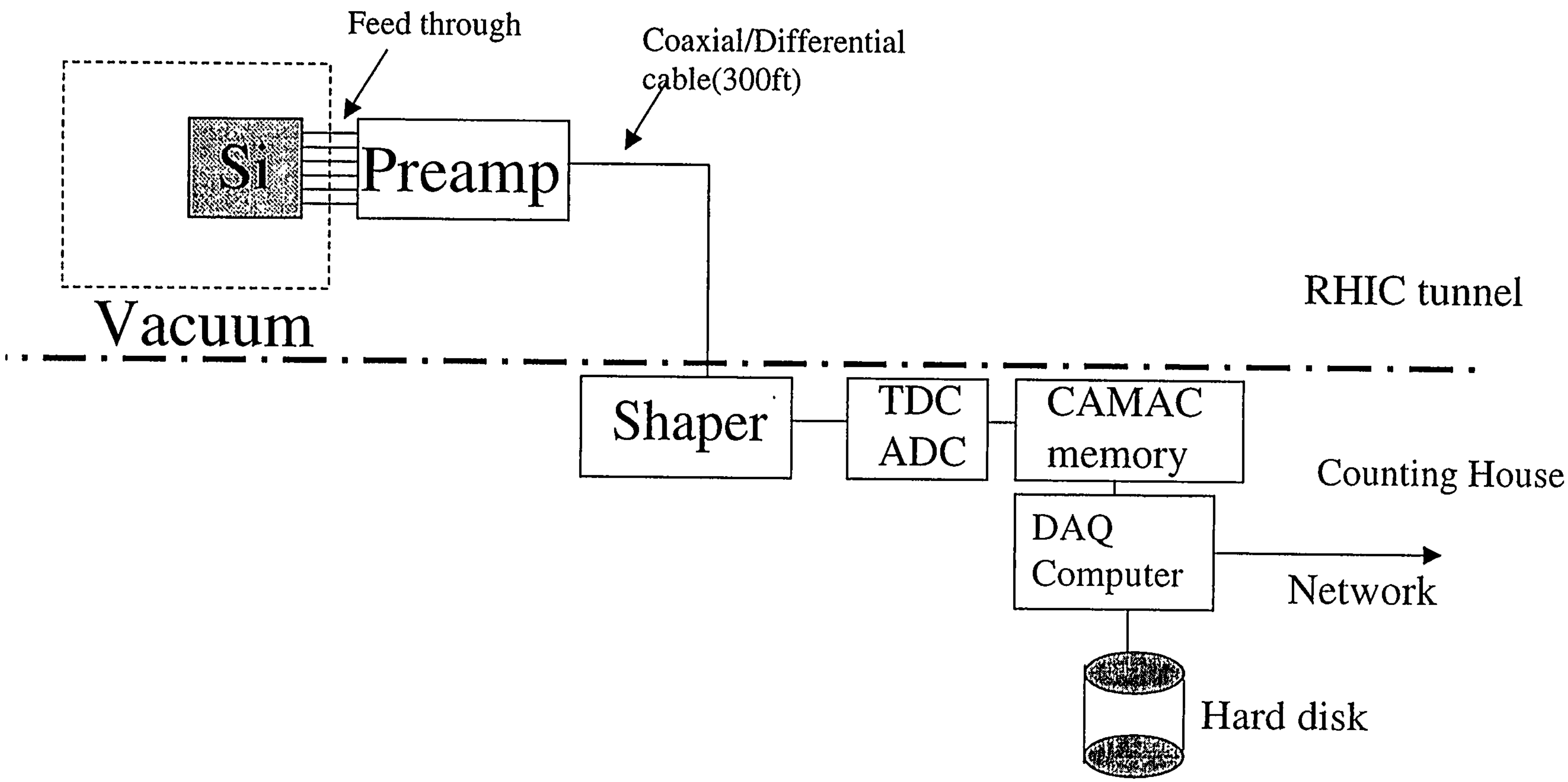
- Installation in the RHIC ring by Mar. 2000
  - Vacuum chamber due at the end of October
  - Target design similar to the AGS one
  - Detector assembly modularized
  - Data Acquisition (remote controllable)
  - Improvement on the electrical noise reduction

pC CNI polarimeter for RHIC



- 1.6m long(5:1 tapering on both ends)
- 17cm radius
- 3 pairs of SSD detectors
- vertical and horizontal targets
- capable of measuring both vertical and horizontal beam polarization profiles

FY2000 Readout Scheme



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RHIC Polarimeter Schedule

FY2000: p+C CNI Polarimeter in blue ring, with a possible p+C elastic scattering polarimeter for injection energy only

FY2001: p+C CNI polarimeters in both rings

$p+C \longrightarrow \pi^- + X$ in one ring

p+p CNI with unpolarized gas jet target(PP2PP)

FY200n: p+p with polarized gas jet target

Physics Asymmetries Using Bunch Polarizations and Crossing Luminosities

Gerry Bunce, BNL and RBRC
RHIC Spin Workshop, October 1999

False asymmetries are always a central concern in spin physics. Often we arrange our experiments to frequently reverse the spin of the beam or target or reverse the spin effect in the apparatus. The beam reversals may take place every accelerator cycle (AGS),every month (electrons for Hermes), or never (muons for SMC).

At RHIC each bunch is prepared independently, allowing us to reverse the spin for adjacent stored bunches, giving spin reversals every 100 nanoseconds. Thus, apparatus acceptance for, say, (++) and (+-) collisions will be identical to high precision. However, we face some new concerns at RHIC: since the bunches are prepared independently, their polarizations can vary as well as numbers of protons in the bunch and emittance of the bunch. Also at RHIC, different pairs of bunches collide at each experiment (actually the same pairs collide at locations 6 "hours" apart—at Phenix and at pp2pp/Brahms for example). The luminosity seen at STAR will not be the same as the luminosity at Phenix, and the average polarization the beams at STAR will not equal the average polarization at Phenix, and neither will equal the average polarization seen by the polarimeters. (The polarimeters will see all bunches, but the experiments only see bunches that collide—some bunches pass the detectors with an empty bunch in the other ring. Strings of empty bunches are needed to abort the beam; we may also want empties to measure background.)

If each experiment measures a relative luminosity for each crossing, and the polarimeters report polarizations for each bunch to the experiments, we can construct effective beam polarizations at the experiments, weighted by crossing luminosity. At Phenix we are preparing electronics to keep track of 4 luminosity monitors, for each crossing, or 480 scalers. This is part of the triggering system so that only "live" luminosity will be monitored. We will also prescale triggers from the luminosity monitors to keep track of the acceptance of the monitors compared to the physics triggers (in the crossing diamond, for example).
The monitors for high luminosity have not been chosen yet. Concerns are saturation for 2 collisions in the same crossing, and statistics since we want to keep track of relative luminosity to 10^{-3} to 10^{-4}. (Note that this is relative to (++) vs. (+-) bunches; the monitor response can change slowly with time.) One approach is to use an inefficient luminosity monitor. We will have 10^{13} crosses in 10^{6} seconds, and we need 10^{8} counts in the monitor. Therefore, the monitor can have 10^{-5} efficiency, which would eliminate saturation concerns. We will also be able to sum energy or multiplicity as luminosity monitors.

Weighted Polarization for RHIC

L_i^+ = luminosity for crossing i, + polarization bunches

P_i^+ = polarization of bunch i, + polarization bunches, from polarimeter

For a single spin asymmetry, A_L,

$P^+ = \Sigma L_i^+ P_i^+ / \Sigma L_i^+$, $P^- = \Sigma L_i^- P_i^- / \Sigma L_i^-$

$P_{avg} = (P^+ + P^-)/2$, $P_{diff} = (P^+ - P^-)/2$

$$\mathbf{A_L = 1/P_{avg} \times (N^+ - N^-) / [(N^+ + N^-) - (N^+ - N^-) \times P_{diff} / P_{avg}]}$$

($N^{+/-}$ are the normalized counts for a physics signal for the +/- bunches respectively, $N^+ = Counts^+ / L^+$, where the counts and luminosity are summed over the + bunches, etc. for N^- .)

For a double spin asymmetry, A_{LL},

$P^{++/--} = (\Sigma P_{ai}^+ P_{bi}^+ L_i^{++} + \Sigma P_{ai}^- P_{bi}^- L_i^{--}) / (\Sigma L_i^{++} + \Sigma L_i^{--})$,

$P^{+-/-+} = (\Sigma P_{ai}^+ P_{bi}^- L_i^{+-} + \Sigma P_{ai}^- P_{bi}^+ L_i^{-+}) / (\Sigma L_i^{+-} + \Sigma L_i^{-+})$

where P_{ai}^+ is the polarization for bunch i of beam a, + bunches,

and L_i^{+-} is the luminosity of crossing i for the combination of +

bunches in beam a and – bunches for beam b, etc.

$P_{avg} = (P^{++/--} + P^{+-/-+}) / 2$, $P_{diff} = (P^{++/--} - P^{+-/-+}) / 2$

$$\mathbf{A_{LL} = 1/P_{avg} x (N^{++/--} - N^{+-/-+}) / [(N^{++/--} + N^{+-/-+}) - (N^{++/--} - N^{+-/-+}) \times P_{diff}/P_{avg}]}$$

and $N^{++/--} = (Counts^{++} + Counts^{--})/(L^{++} + L^{--})$, with $Counts^{++}$ the number

of counts for a physics signal with beams a and b both pol. +.

Polarized Proton Luminosity (1 collision/cross for L=2 x 10^{32})

-Accelerator luminosity measurements => **absolute** luminosity to <10% ??

-No present candidate to monitor luminosity at Phenix with a known cross section for proton-proton collisions => no present second handle on **absolute** luminosity

-Need **4** monitors of **relative** luminosity for polarized protons

> 4 monitors: cross check linearity, not sensitive to beam polarization, both "0°" and "90°" monitors to be sensitive to different crossing diamonds
>
> Possible monitors: subset of Beam-Beam; subset of Emcal; etc. Problems: saturation and accidentals from more than one collision in a cross. This is a work in progress.

-Live relative luminosity is needed => for spin, we need to only count live luminosity, not correct total counts with a livetime fraction

-One approach on polarized proton luminosity monitors—very inefficient monitors to avoid saturation and accidentals:

$$A_{LL} = \frac{1}{P^2} \times \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

-for jet production $N = N_{++} + N_{+-}$ can be 10^6 over entire run of 4 x 10^6 seconds

⇨ statistics of $L = L_{++} + L_{+-} = 10^8$ desired
⇨ out of 10^7 crosses/second, or 4 x 10^{13} crosses
⇨ monitor should be >2.5 x 10^{-6} efficient

-a counter telescope looking at the interaction region is an example

-Another approach: "analog" sum such as multiplicity or energy

The polarized proton monitors have to be decided and built for the 2nd RHIC run—to be continued.

Design Issues for the Luminosity Electronics

-Live luminosity

-4 monitors to cross check for linearity, independence from beam polarization, different acceptance for interaction diamond

-Monitor each crossing: learn about/throw out bad crossings, crossing tag for each trigger, complete flexibility to determine polarization weighted by luminosity. We will have all information on tape that we need in case of a mistake in polarization sign, for example (which happens!). On-line equivalent of a spill monitor. Create beam-beam, beam-gas, gas-beam, and gas-gas monitors and normalization.

-4 x 120 = 480 scalers

-Reset the luminosity scalers for crossing that causes trigger. These 4 scalers are kept with the event information => tape. Each trigger then has incremental flux information from the previous trigger for that crossing. The order of the events on tape is no longer important. By resetting and keeping just the 4 scalers which are for the triggered crossing, the event size is manageable. (Mike Tannenbaum)

-For Level 2 trigger and for data summary tapes, a short scaler record must be passed along if an event is rejected. (Brian Cole)

-Trigger on prescaled luminosity monitors. This gives us information on, for example, the vertex seen by the monitors vs. the vertex seen by the physics triggers. We can then correct for a difference.

-There can be only one busy and deadtime. All detectors participating in physics for which luminosity is needed must be in the same partition. Period.

The electronic design meeting these needs is by Fred Wohn and John Lajoie from Iowa State.

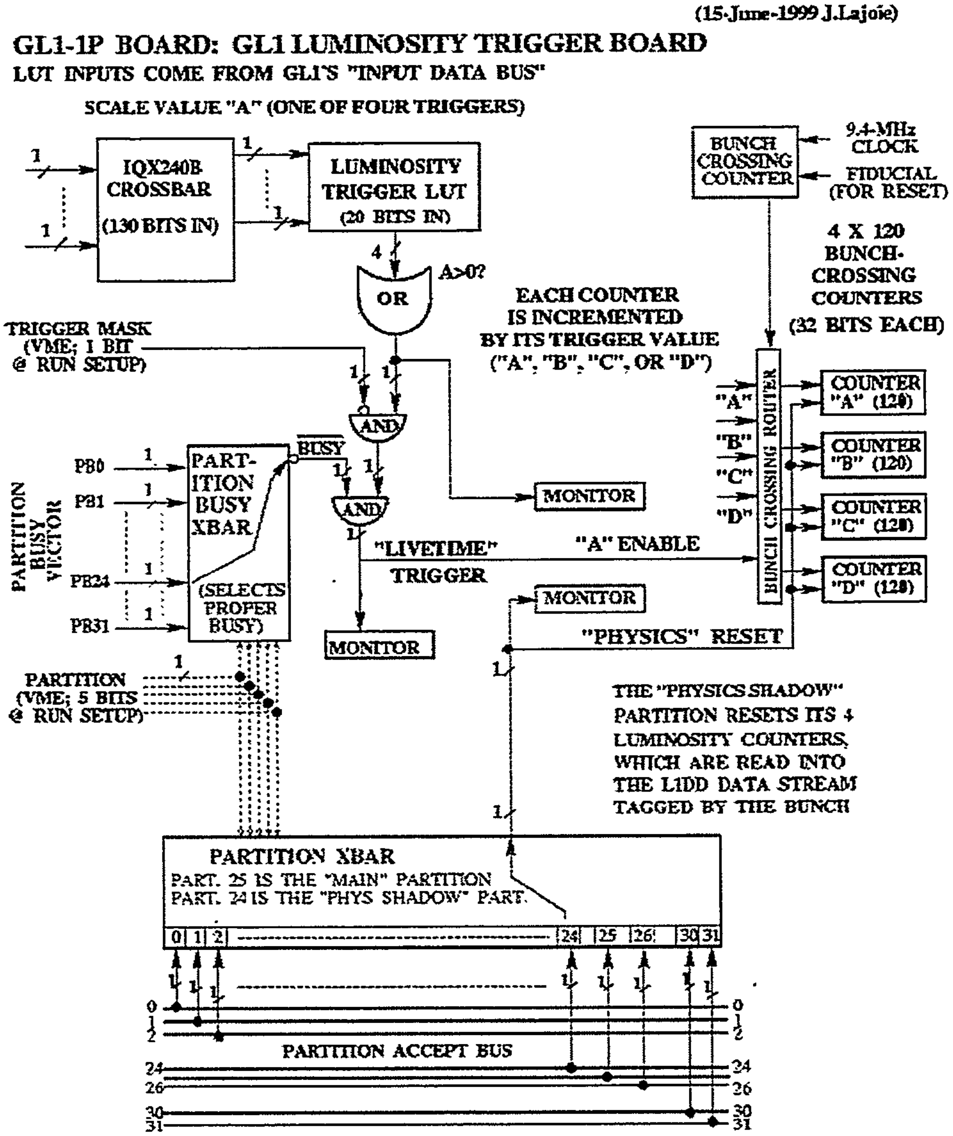


Figure 1: GL1-1P block diagram. Note that the physics shadow partition is used to provide the busy information as well as to reset the luminosity counters on a partition accept for the shadow partition. The "monitor" boxes denote data that can be stored in the diagnostic monitor fifos, and are not part of the GL1-1P algorithm.

np Charge Exchange Polarimetry

E.J. Stephenson, for the E948 collaboration
Indiana University Cyclotron Facility, Bloomington, IN 47408 USA

In order to address concerns about present polarimetry efforts (low analyzing power, cost of setup), we began an exploration of the production of neutral hadrons and an alternative analyzer. The idea arose from measurements below 12 GeV/c of charge exchange n+p scattering at small momentum transfer $-u$ that show typical analyzing powers of $A = 0.6$ [PRL **30**, 1183; PL **31B**, 617; and PRL **45**, 1529]. These measurements would suggest that the best operating point or figure or merit would be in the range $0.2 < -u < 0.4$ $(\mathrm{GeV/c})^2$. In March, 1999, we took data with the 22 GeV/c polarized proton beam at the AGS to test this idea.

As shown in the Figure 1, we assembled a polarimeter mockup consisting entirely of scintillation detectors. This assembly was not designed to measure the n+p charge exchange reaction only, since it had large angular acceptance and poor energy resolution on the forward hadron. It consisted of a left-right pair of recoil scintillators that covered 22°, an angle chosen to include quasi-elastic scattering from a nucleus, and two forward telescopes. The telescopes were each made of 4 lead-scintillator calorimeter bars arranged in a square. In front there was a charged-particle veto detector. In between were two layers of lead with a scintillator in the middle that was designed to mark electromagnetic showers. A trigger consisted of a signal in the recoil detectors on one side in coincidence with a calorimeter signal on the other side.

In analysis, cuts were made to require recoil signals larger than minimum ionizing. A minimum energy was required for each of the four calorimeter bars on each side. This selected events that fell near the intersection of the four bars. A crude estimate suggests that we were sensitive to $0.25 < -u < 0.42$ $(\mathrm{GeV/c})^2$. Events were then divided into four classes (see Figure 2) depending on whether there was a signal in the charged particle veto (charged vs. neutral) and whether there was a signal in the shower scintillator (signal marked electromagnetic, no signal marked hadronic).

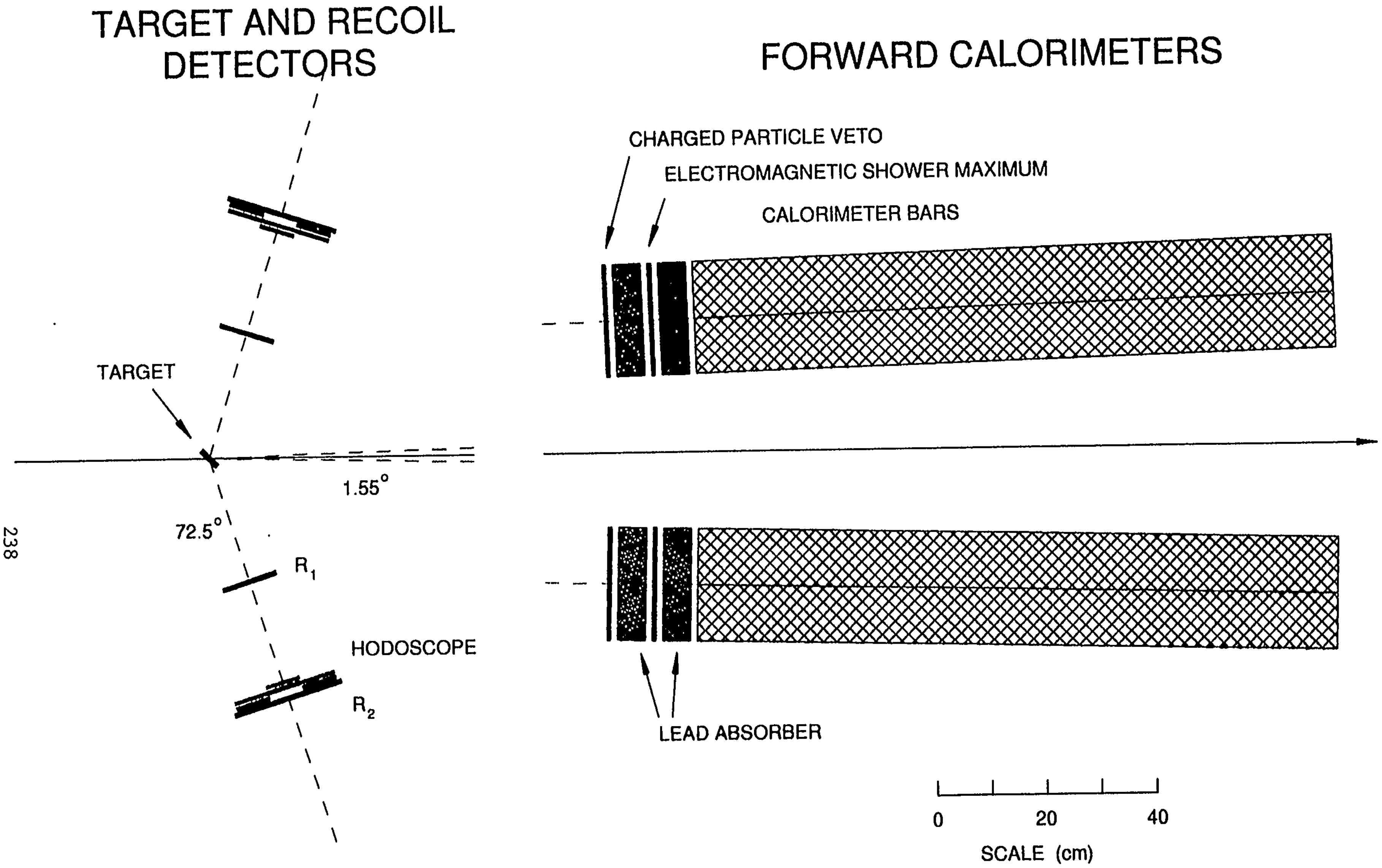
The charged, hadronic events were consistent with a monoenergetic peak whose rate was close to that expected for p+p elastic scattering. As shown in Figure 3, the analyzing power for these events (black dots) was consistent with previous measurements of elastic scattering. The beam polarization of 43% was provided by E925.

The neutral. hadronic events were peaked at a lower calorimeter energy. As shown in the left panel of Figure 4, they exceeded by more than an order of magnitude the rate expected for charge exchange, based on known cross sections. In addition, the analyzing power varied across the calorimeter energy peak, confirming that this distribution arose from the overlap of many reaction processes.

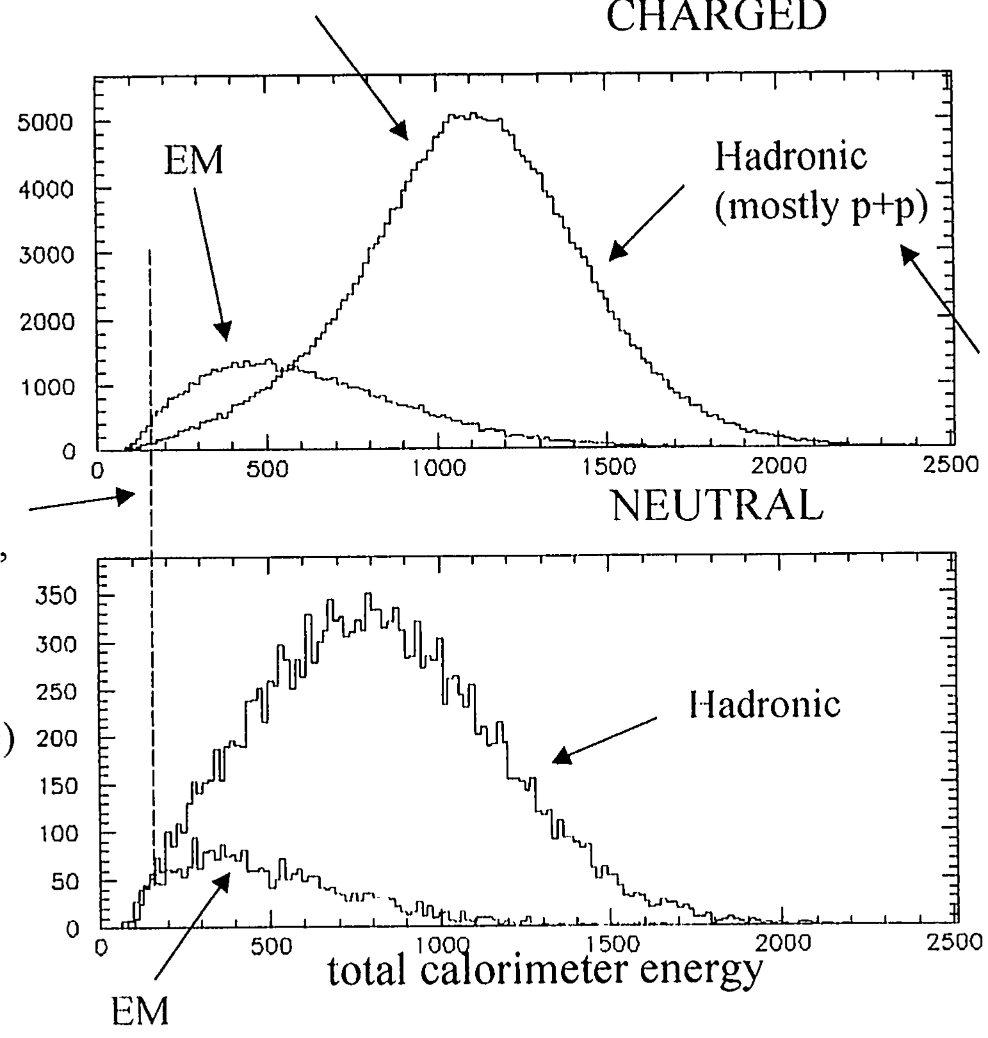
The utility of this as a polarimeter depends on the sensitivity to spin that is shown in the right-hand panel of Figure 4. (The boundaries for the five bins are shown in the left panel.) The maximum analyzing power on carbon, the target most likely to be used at RHIC commissioning, reaches about 10%. Data taken using a CD_2 target shows a larger analyzing power. Subtraction gives the analyzing power for deuterium alone, which reaches 30%. The difference between deuterium and carbon arises in part from a much larger excess of other neutral-producing processes in carbon.

Figure 5 tabulates the figure of merit (σA^2) for a number of target and software cut choices. Within a factor of a few, they are similar, indicating no striking statistical advantage for choosing neutral production over elastic scattering, save for the systematic advantages of a larger spin dependence.

To further develop this option, we would need a better understanding of what reaction processes produce the neutral spectrum, and how the spin dependence would evolve with increasing energy.


TARGET AND RECOIL DETECTORS
FORWARD CALORIMETERS
CHARGED PARTICLE VETO
ELECTROMAGNETIC SHOWER MAXIMUM
CALORIMETER BARS
TARGET
1.55°
72.5°
R1
HODOSCOPE
R2
LEAD ABSORBER
0
20
40
SCALE (cm)

FOUR EVENT CLASSES FOR CD_2 TARGET



peak σ=26%

CHARGED

(mostly p+p)

1.6 times too large if $0.25 < -u < 0.42$ $(GeV/c)^2$

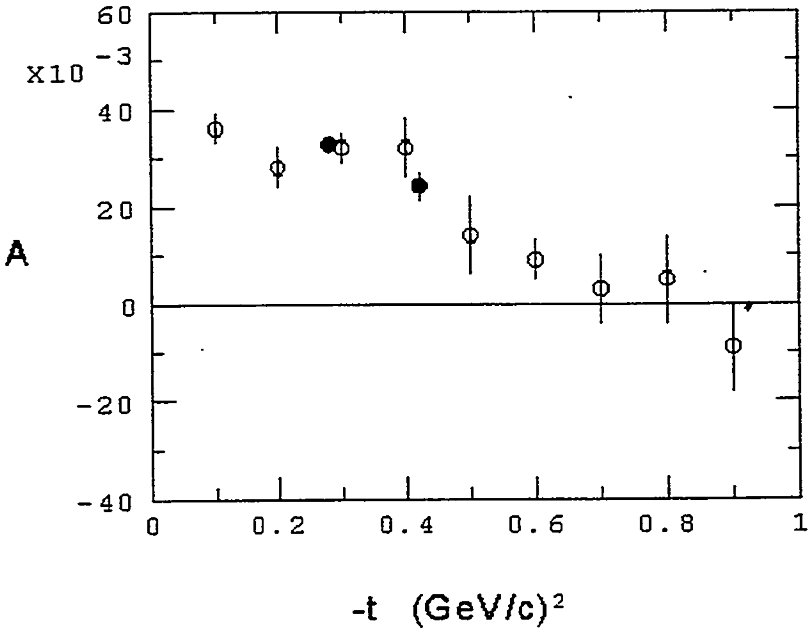
Soft cutoff from minimum energy requirement in calorimeter bars (Without minimum, charged, hadronic peak becomes shoulder on exponential decline)

NEUTRAL

total calorimeter energy

COMPARISON TO ELASTIC SCATTERING ANALYZING POWER

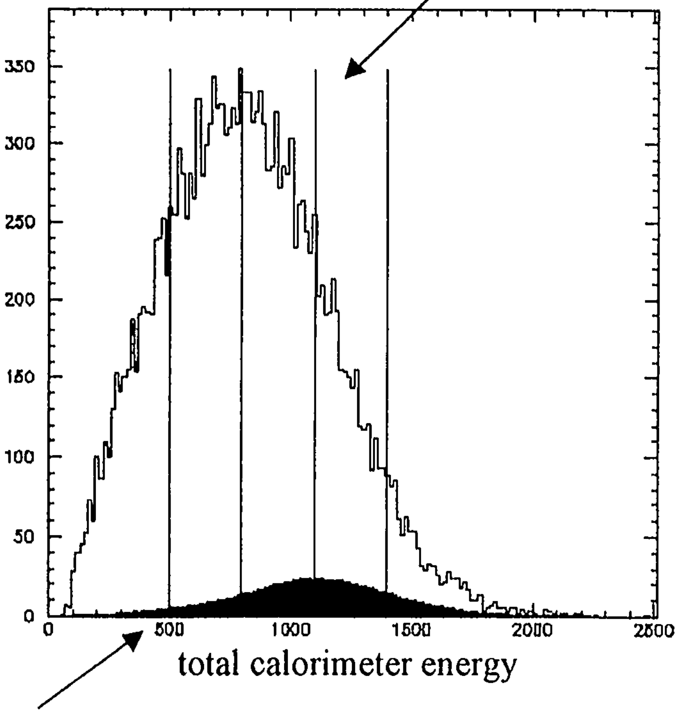
Open circles = data from Crabb at 24 GeV/c



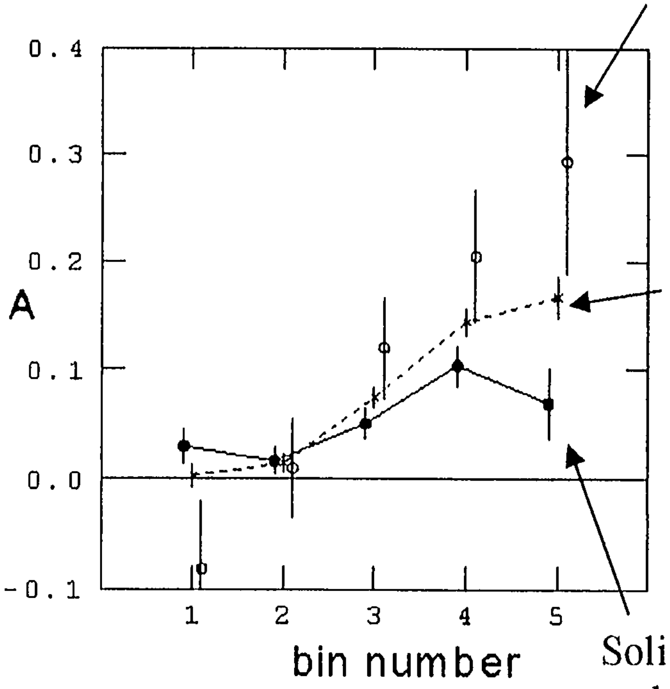
Average beam polarization = 0.425 ∓ 0.055
(preliminary)

"NEUTRAL, HADRONIC" SPECTRUM

The spin dependence changes with calorimeter energy. Results are shown for 5 bins.



This is the "charged, hadronic" spectrum scaled by the ratio of the charge-exchange to the elastic cross section. It is always less than the measured spectrum.



Open circles = deuterium alone

x = CD_2 target

Solid dots = carbon target

FIGURES OF MERIT

(hadronic)

	σ (μb)	A	F. O. M.
charged:			
C	1340	0.0271∓0.0024	0.98
CH_2	4030	0.0273∓0.0025	3.00
CD_2	3445	0.0341∓0.0019	4.01
neutral, full peak:			
C	167	0.0400∓0.0069	0.27
CD_2	245	0.0564∓0.0054	0.78
neutral, upper half of calorimeter energy:			
C	87	0.0610∓0.0096	0.33
CD_2	136	0.1015∓0.0074	1.40
deuterium only:			
charged	1051	0.0387∓0.0079	1.57
neut., all	39	0.0915∓0.0268	0.33
neut., top-E	24	0.1753∓0.0351	0.75
charge-exchange (anticipated):			
	6.2	0.4	0.99

A Polarized Atomic Jet Target for RHIC Polarimetry

H. Kolster[a], **T. Wise**[b]
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[b] *University of Wisconsin, Madison, WI 53706 USA*

Abstract

The advantages of internal polarized targets for the operation in storage rings and their high polarization give a possible basis for the polarimetry at RHIC. The restrictions in the use of an internal target for RHIC polarimetry are given by high reliability and precision with minimum effort. These criteria can be met if the internal target is operated near the high polarization limit –100% polarization– and the analysis of the target polarization is limited to monitoring the performance near this limit. The general design is based on injecting a nuclear polarized beam from an atomic beam source (ABS) [1,2], into the interaction region and then analyzing the beam polarization. Typical beam intensities for standard operation of atomic beam sources are $I = 6 \times 10^{16}\,\mathrm{atoms\,s^{-1}}$ resulting in an equivalent beam pressure of $P_b = 10^{-5}\,\mathrm{mbar}$ in the interaction point with the proton beam. The nuclear polarization of the atomic beam can be achieved by use of an adiabatic transition, which follows the sextupole magnets of the ABS. The atomic jet beam is analyzed in a sequence of an adiabatic transition, a sextupol magnet for separation of electron polarized hyperfine states and a quadrupole mass spectrometer, which functions as a detector for the intensity of the atomic beam [1,3]. Beam blockers, which are installed on axis in the sextupoles in ABS and analyzing magnet block out particles on axis, helping to optimize the rejection efficiency of the sextupoles. Thus a polarized beam can be produced in the interaction point, whose composition of hyperfine states is known with a precision of $\Delta P_a = 2 - \varepsilon_1 + \varepsilon_2$, the sum of the inefficiencies ε of both RF-transitions. The adiabatic transitions can be operated with an efficiency up to $\varepsilon = 99.5\% \pm 1\%$ [1] resulting in high nuclear polarization of the jet beam. The nuclear polarization is then calculated from the occupations of hyperfine states in the beam, $P_2 = n_1 - n_2 - (n_3 - n_4)\cos\theta(B)$ [1,3], where $\theta(B)$ gives the dependence on the magnetic holding field.

The unpolarized background resulting from ballistic flow of molecules from the dissociator into the interaction region and from diffusive flow between the ABS, target, and analyzer chambers give a unpolarized contribution α_0 to the target. High speed pumping on the target chamber and a beam dump in the analyzer chamber help to reduce the pressure and the unpolarized background in the interaction region. Calibration measurements simulate the gas flow into the target chamber and allow to measure the unpolarized background on the percent level [3].

A holding field at the interaction point is required to define the polarization direction of the jet and to decouple the electron and proton spins for atoms in state 2 and 4 (mixed state atoms). At a field value of 250 mT, 5× the critical field for hydrogen atoms, the spins are well decoupled ($\cos\theta(B) \to 1$) and the mixed state polarization approaches 100%. The jet target polarization including the unpolarized background results in $P_T = \alpha_0 \cdot P_a$ with an estimated uncertainty of $\Delta P_a = 0.02$ and $\Delta\alpha_0 = 0.01$ [1,3].

[1] B. Braun, Ph.D. Thesis, Ludwig-Maximilians-Universität München, Germany (1995)
[2] T. Wise, A.D. Roberts, and W. Haeberli, Nucl. Instr. and Meth., A 336 (1993) 410
[3] H. Kolster, Ph.D. Thesis, Ludwig-Maximilians-Universität München, Germany (1998)

MOTIVATION

A. PENZO, PST99, SEPT 1999, ERLANGEN

CONCLUSIONS:

- PP2PP WITH JET ⇒ HYBRID OF COLLIDER & F.T.
- USE OF POLARIZED JET: SIMPLE BUT ESSENTIAL ...
- WE NEED "STANDARD" PERFORMANCE (MAYBE TRIVIAL FOR SPECIALISTS...
- BUT HIGH RELIABILITY AND
- SIMPLICITY OF OPERATION & MAINTEN.

FOR POLARIMETRY ABJ WILL BE USED MINIMUM NECESSARY...

- New approach: *self - calibrating* polarimeter

Possible in pp → pp with jet target (polarized/ unpolarized):

$$A_N(p\uparrow p \to pp) \equiv A_N(pp\uparrow \to pp) \equiv P_R(pp \to pp\uparrow)$$

(T-invariance + Pauli principle)

GOAL: $\frac{\Delta P}{P} \leq 5\%$

A POLARIZED ATOMIC JET TARGET for RHIC POLARIMETRY

H. Kolster
NIKHEF / VU Amsterdam

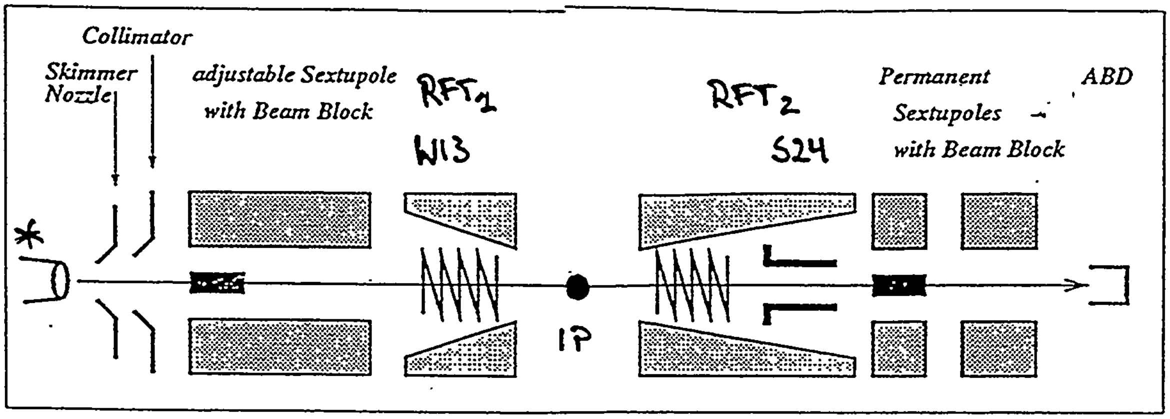
T. Wise
University of Wisconsin - Madison

BNL October 8, 1999

- INTRODUCTION
- THE JET TARGET
  - POLARIZED ATOMIC BEAM
  - MOLECULAR BACKGROUND
- SYSTEMATIC UNCERTAINTIES

ATOMIC BEAM JET TARGET

$$P = \alpha_0 P_a$$



- atomic beam from dissociator *
- sixpole magnets to polarize beam
- RFT_1 (transitions) to change to nuclear polarization
- target holding field to maintain high polarization
- RFT_2 + sixtupole to monitor performance of source

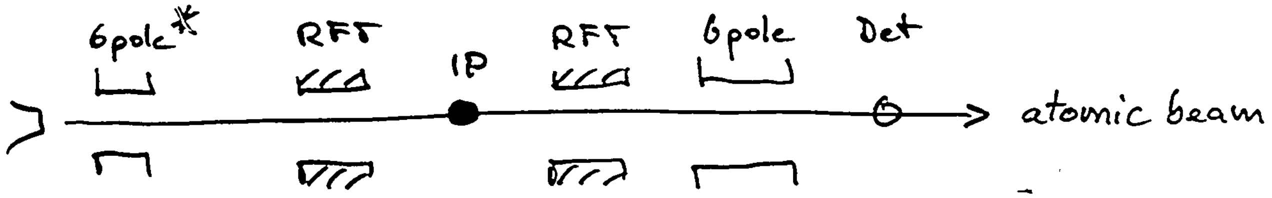
(- calibrations for molecular background)

- Polarized & unpolarized beam
- Detector (ABD) measures intensity of beam

- beam pressure in IP : $P = 10^{-7}$ mbar, $n \sim 10^{11} \frac{\text{atoms}}{\text{cm}^2}$

$\mapsto$ $L = 10^{29}\ \text{cm}^{-2}\text{s}^{-1}$ @ RHIC

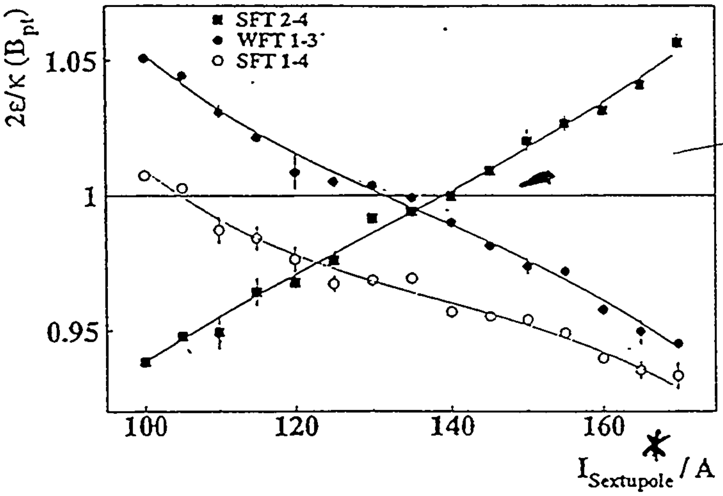
POLARIZED BEAM ANALYSIS



N_i

$$\begin{pmatrix}1\\1\\1\\1\end{pmatrix} \to \begin{pmatrix}1\\1\\0\\0\end{pmatrix} \xrightarrow{1\to3} \begin{pmatrix}0\\1\\1\\0\end{pmatrix} \xrightarrow{2\to4} \begin{pmatrix}0\\0\\1\\1\end{pmatrix} \to \begin{pmatrix}0\\0\\0\\0\end{pmatrix} \quad \Sigma N_i = 0$$

ε_{ij}



$\delta\varepsilon \approx 1.5\%$

Fig. 8.2:
Ostensive efficiencies of the high frequency transitions WFT 1-3, SFT 1-4 and SFT 2 without consideration of the sextupole corrections as a function of the sextupole current. The measured data were fitted with third degree polynomials

not full efficient transitions:

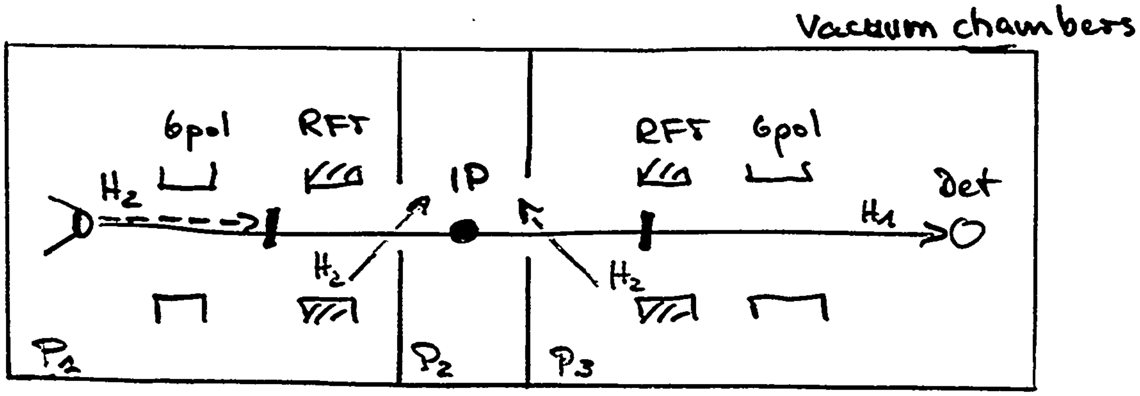
$$\Sigma N_i = 2 - \varepsilon_{13} - \varepsilon_{24} = \delta\varepsilon$$

↳ systematic uncertainty

→ Calculate Polarization in IP:

$$P = \underbrace{\cancel{n_1}}_{\substack{=0\\ \text{beam}\\ \text{blocker}}} - n_3 - (n_2 - \underbrace{\cancel{n_4}}_{\substack{=0\\ \text{beam}\\ \text{blocker}}}) \cos\theta \quad \pm \delta\varepsilon_{(\max)}$$

MOLECULAR BACKGROUND



Pressures P_1, P_2, P_3

- beam dump in detector chamber
- ballistic flow of H_2 blocked
- diffusive and rest gas flows into IP need calibration:

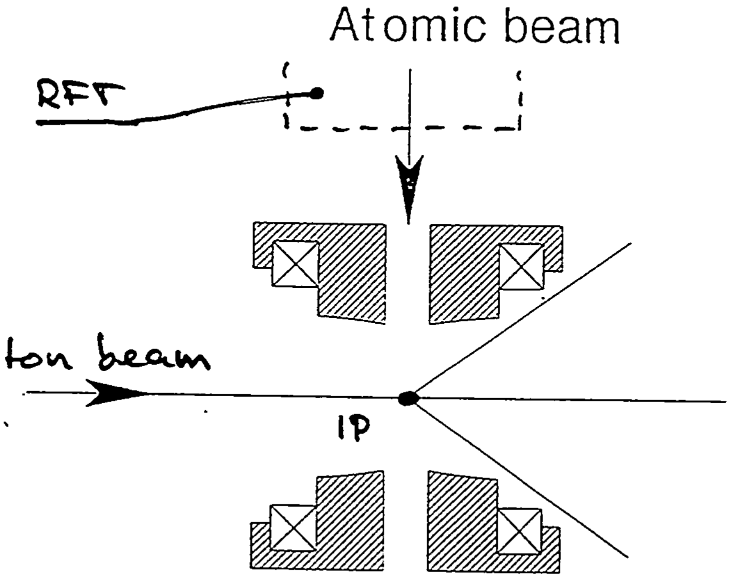
  adjust P_1 and P_3 with unpol gas and ABS off; measure background and subtract.

required: $P_2 \approx 10^{-7}$ mbar atomic beam: $P \approx 10^{-4}$ mbar

↳ correction in per cent range known to 10% → small contribution

MAGNETIC HOLDING FIELD

Transverse magnet, possible design:



(T. Wise)

Limit stray field for RFT with iron yoke.

SUMMARY

- Atomic Beam Jet Target

$I = 10^{16}$ atoms $\cdot s^{-1}$, $P_b \approx 10^{-7}$ mbar
$n \approx 10^{11}$ nucl./cm^2

- Polarization of Target at IP

$$P_T = \alpha_0 \cdot P_a$$

P_a – Atomic beam in high polarization
Limit states $|1\rangle, |2\rangle$ equally pop.
-> Polarization calculated
input : holding field B
=> $\delta P_a \leq 0.02$ possible

α_0 – Reduced molecular background,
beam dump in separate chamber,
calibration ~~f~~of background events
$(P_m = 0)$
=> $\delta \alpha_0 \sim 0.01$ possible

- Intensity monitor in Analyzer (QMS)

Polarimetry at the Experiments

Kenichi Imai
Department of Physics, Kyoto University and RIKEN.

The polarimetry at the experiments, especially PHENIX and STAR, is important because of the following reasons; 1) The beam polarimeter only measures the transverse polarization while the polarization direction will be rotated into the longitudinal direction at the PHENIX and STAR in most cases. 2) There may be a phase space dependence of the beam polarization. 3) The beam polarization is not continuously monitored with the CNI and pion beam polarimeters due to the radiation and heat of the carbon target.

It is important to confirm the operation of the spin rotator. To confirm the fully longitudinally polarized beam, it is sensitive to detect the transverse component of the beam polarization. If any sizable A_T in any reaction process is found and the figure of merit is large enough, then one can use such a process to monitor the transverse polarization in the experiments by themselves. The large A_T was observed only at large X_F (larger than 0.3) with low P_t which is not covered by the PHENIX and STAR. (At high P_t, the figure of merit is very small because of the low event rate even though the A_T is large.)

We propose one method which utilizes an small electro-magnetic calorimeter surrounding the beam pipe to detect π^0s at large X_F, where A_T is expected to be more than 10%. A simulation showed that the transverse component of the beam polarization in both horizontal and vertical directions can be measured at a few % level within several hours.

Possible methods of relative monitor of the longitudinal polarization at the experiments are briefly discussed. If the gluon polarization is relatively large, one can expect a finite A_{LL} even at rather low P_t for the inclusive π^0 at PHENIX and jet at STAR, which will be useful to monitor the product of the two beam polarizations. To monitor the polarization of each beam, one needs a parity violating process such as the deacy of the longitudinally polarized Λ of which polarization is transfered from the proton.

Why we want polarimetry at the experiment

1. Polarization direction at PHENIX and STAR is different from the beam polarimeter.

   1) Selfanalyzing polarization monitor in the experiments both P_L & P_T

   2) confirmation of the spin rotator performance

2. possible phase space dependence of the polarization

   1)

3. Operation of the beam polarimeter is not continuous heat, radiation,

   1)

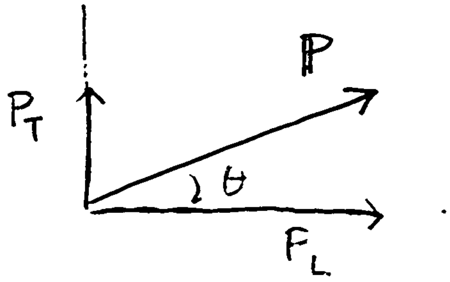
Polarization monitoring P_L , P_T

$\Delta P_T \propto \sqrt{N} A_T$ $\Delta P_{LL} \propto \sqrt{N} A_{LL}$.

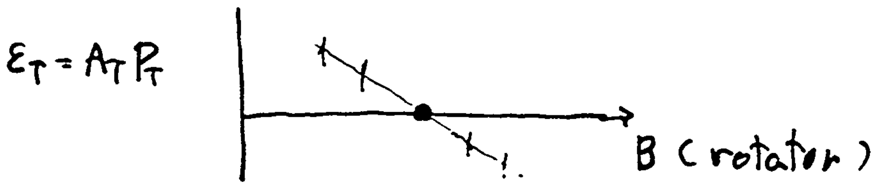
($A_N = 5\%$ $N = 10^5$ events $\Delta P/P \simeq 10\%$)

(high rate process .
on-line analysis .

To confirm pure longitudinal polarization ,
null measurement of $\varepsilon = P_T \cdot A_T$ is sensitive.



$P_T = |P| \sin\theta$, $P_L = |F| \cos\theta$



A_T useful at $\sqrt{s} = 50 \sim 500$ GeV ??

1) inclusive $\pi^{\pm}, \pi^0$ at large X ($x_F > 0.3$)

- PHENIX μ-arm. (hopeless)

- additional π^0 (γ) detector

2) CNI (P-P)

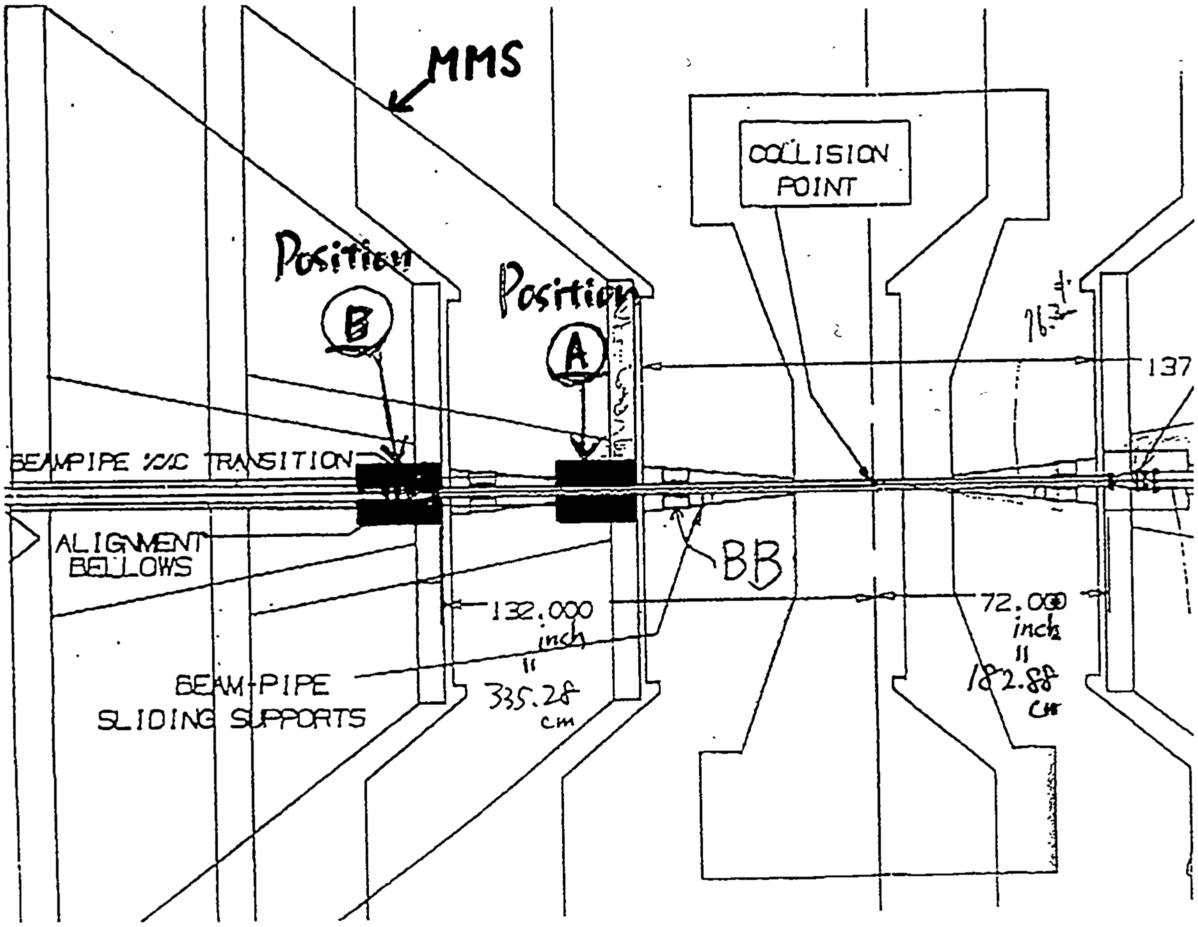
- Roman Pot at PHENIX (STAR)

  (A_{LL} ; $\Delta\sigma_L$ can be measured for pp elastic)

3) any non zero A_T at reasonably high rate?

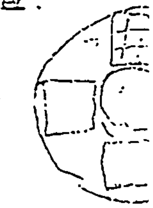
(A_{TT})

$x_F \lesssim 0.1$



3) kinematics

At 200 GeV, the energy of pizero for XF=0.5 is 50 GeV. Two photon separation is about 5mm at position A and 9mm at B. It can be measured as a single cluster of energy in calorimeter.



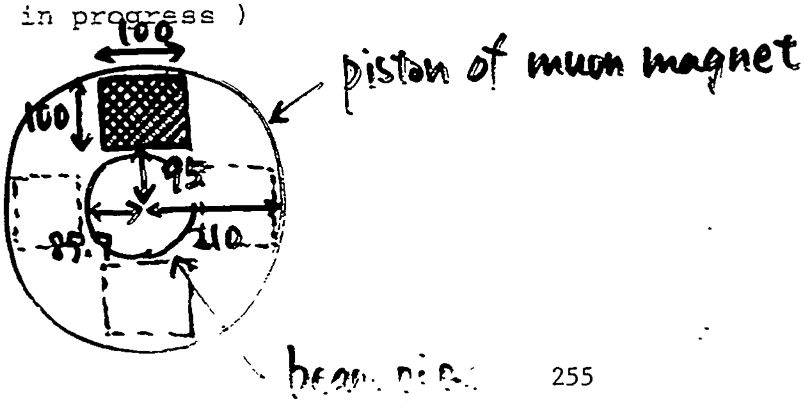
The Pt of the pizero is from 2.6 to 4.9 GeV/c for the position A and from 1.5 to 2.7 GeV/c for B position. The rate is higher for the position B.

4) Calorimeter

The dimension of the calorimeter would be 100x100mm in area and 20 rad. length deep. It is located up, down, left and right around the beam pipe. The rad. length of the material should be as short as possible. For example, $PbWO_4$ or PbF etc. If we make 4x4 block for each calorimeter, we need 64crystal/arm.

5) Rate and precision of spin direction measurement

(in progress)



* Result *

error estimation of polarization determination and trigger ratio

Position A	p_T cut	error estimation	trigger ratio
200GeV	0.5GeV/c	0.065	1.7E+4/sec
	1.5GeV/c	0.075	1.2E+2/sec
	2.5GeV/c	0.132	3.7E+0/sec
500GeV	0.5GeV/c	0.109	1.2E+5/sec
	1.5GeV/c	0.106	2.1E+3/sec
	2.5GeV/c	0.127	1.7E+2/sec

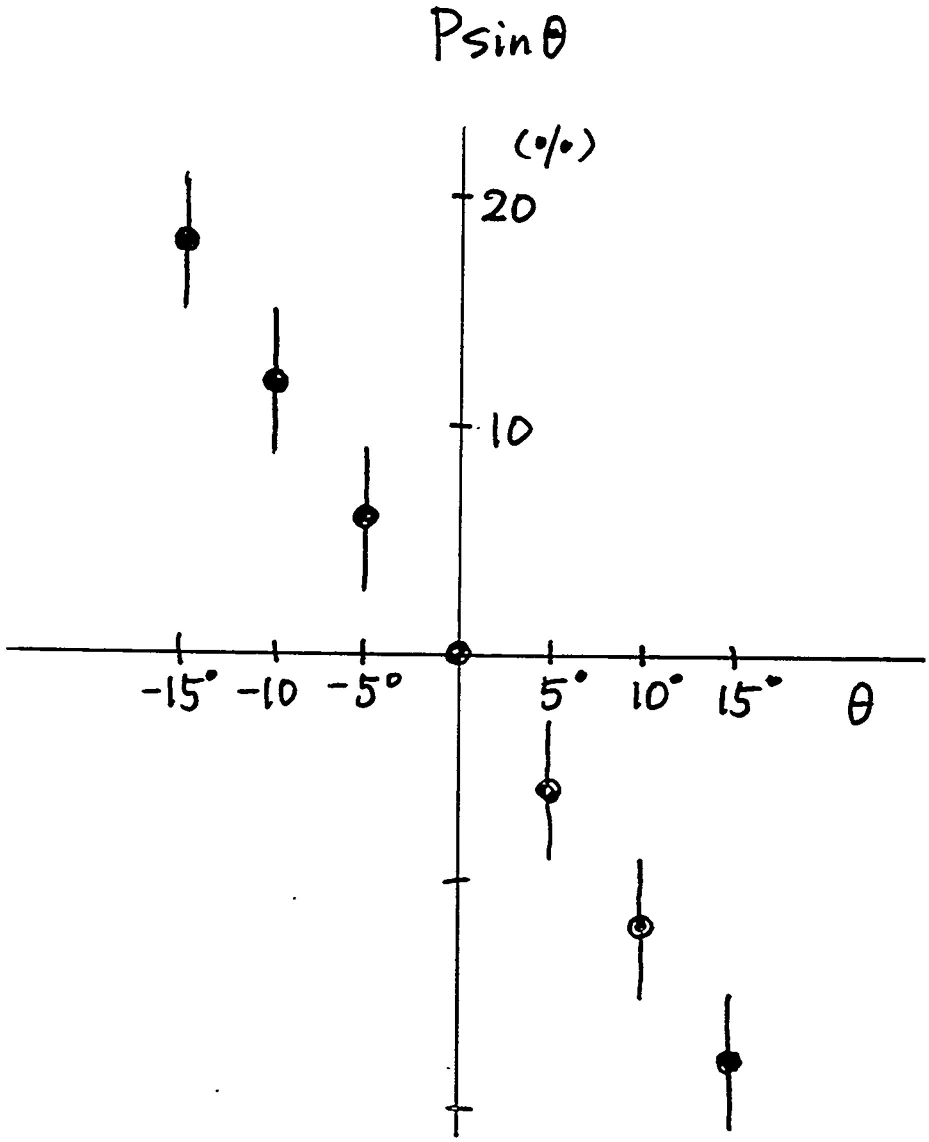
Position B			
200GeV	0.5GeV/c	0.047	9.5E+3/sec
	1.5GeV/c	0.066	2.0E+1/sec
	2.5GeV/c	1.545	1.8E-1/sec
500GeV	0.5GeV/c	0.057	8.0E+4/sec
	1.5GeV/c	0.057	1.1E+3/sec
	2.5GeV/c	0.069	5.9E+1/sec

Crystal

Table 1: Properties of Crystals for Calorimetry at $p\bar{p}$ colliders, compared to BGO

Crystal Type and Properties				
$Bi_4Ge_3O_{12}$	BaF_2	CeF_3	$PbWO_4$	Parameter
7.13	4.88	6.16	8.28	ρ[g/cm^3]
2.15	1.49	1.62	2.30	n
1.12	2:06	1.68	0.85	λ_r[cm]
21.8	29.9	26.2		λ_i[cm]
2.33	3.39	2.63	2.19	Molière Radius [cm]
480	195-220/310	340/300	440/530	λ_{max}[nm]
300	0.8/630	30/5	2.2/9.9/39	τ[ns]
100	16/100	55	4.4	Light Yield [% of BGO]
-1.55		0.14	-1.9	Temperature Dependence [%/°C]
10	$>10^4$	$>10^4$	?	Radiation Hardness [Gy]

20cm = 23.5 X_l


P sin θ
(%)
20
10
-15°
-10
-5°
5°
10°
15°
θ

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AGENDA

RIKEN BNL Research Center

Workshop on RHIC Spin
October 6–8, 1999
Physics Department - Large Seminar Room

**Organizing Committee: Les Bland, Mike Tannenbaum, Aki Yokosawa,
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Jacques Soffer (cochair), and Gerry Bunce (cochair)**

Wednesday, Oct. 6

Opening Session – Session Chair: Jacques Soffer

08:45	T.D. Lee	*Welcome*-(TBC)
09:00	G. Bunce	*Introduction to the RHIC Spin Workshop*
09:15	S. Peggs	*RHIC commissioning in 1999*
09:30	D. Lowenstein	*RHIC plans for 2000*
09:45	W. Mackay	*Intro. and status of pol. protons at RHIC*
10:15		**Coffee**
10:30	S. Vigdor/G. Eppley	*The STAR spin program–overview and status*
11:15	N. Saito	*Progress of the Phenix Spin program*
12:00	A. Penzo	*The pp2pp spin program*
12:30		**Lunch**

Gluon Polarization – Session Chair: Naohito Saito

13:30	M. Werlen	*Direct photon experimental results and issues*
14:15	M. Tannenbaum	k_T *issues*
14:45	R. Jaffe	*Angular momentum in QCD*
15:30		**Coffee**
16:00	Y. Goto	*Phenix gluon polarization sensitivities and issues*
16:30	L. Bland	*STAR gluon polarization measurements*
17:00	J. Balewski	*Rate capabilities for STAR for spin*
17:30	A. Deshpande	*SMC gluon polarization from QCD analysis*
18:00	R. Kaiser	*HERMES results on gluon polarization*
18:30	S. Bravar	*COMPASS plans and sensitivities*
19:00		**End of Session**

Thursday, October 7

Quark Polarization – Session Chair: Les Bland

09:00	J. Pretz	*SMC semi-inclusive results*
09:25	R. Kaiser	*HERMES semi-inclusive measurements of quark pol.*
9:50	A. Ogawa	*W production with STAR*
10:15		**Coffee**
10:45	S. Kumano	*Flavor asymmetry in long.-pol. and transv. distributions*
11:15	N. Saito	*Discussion on quark polarization*
11:30	V. Rykov	*CP tests and physics beyond SM at RHIC*
12:00	J. Soffer	*Comments on physics beyond SM at RHIC*
12:15		**Lunch**

Transverse Spin – Session Chair: Aki Yokosawa

13:30	J. Ralston	*Spin and the well-dressed quark*
14:15	D. Underwood	*Pion asymmetries*
14:45	S. Nurushev	*Recent results on inclusive pion asymmetries*
15:15		**Coffee**
15:45	R. Kaiser	*Hermes azimuthal asymmetry*
16:15	D. Boer	*Transverse spin distribution and fragmentation functions*
16:45	J. Collins	*Consequences to the RHIC spin program of the Hermes results*
17:15	E. Di Salvo	*Transverse spin asymmetries in Drell Yan*
17:45		**End of Session**
19:00		**Conference Dinner (sponsored by RBRC)** **Dockside Restaurant, Port Jefferson**

Friday, October 8

Accelerator Session – Session Chair: G. Bunce

09:00	A. Lehrach	*Maximum polarization from the AGS*
09:15	M. Bai	*rf dipole studies and plans in AGS and RHIC*
09:45	A. Lehrach	*Beam polarization distributions for RHIC*
10:15		**Coffee**
10:45	T. Roser	*Bunch pol., variations, other systematic issues*

Future spin possibilities at RHIC

11:15	S. Peggs	*eA and ep collider studies for RHIC*
11:45	A. Deshpande	*Physics of polarized ep colliders at RHIC and HERA*
12:15		**Lunch**

Polarimetry for RHIC – Session Chair: Yousef Makdisi

13:30	H. Spinka	*Systematics in polarization measurements*
14:15	N. Buttimore	*Fermion boson collisions and swift proton polarimetry*
14:45	K. Kurita	*p-carbon polarimetry–an update*
15:15	H. Huang	*The RHIC polarimeter–preparations*
15:45		**Coffee**
16:15	G. Bunce	*Physics asymmetries using bunch polarizations and crossing lum.*
16:30	E. Stephenson	*np backward scattering polarimetry*
17:00	H. Kolster	*Polarized jet for RHIC polarimetry*
17:30	K. Imai	*Polarimetry at the experiments*
18:00	Y. Makdisi	*Discussion on RHIC polarimetry*
18:30		**Workshop End**

Forthcoming RIKEN BNL Center Workshops

Title:	**Event Generator for RHIC Spin Physics III**
Organizers:	N. Saito and A. Schaefer
Date:	March 6–20, 2000
Title:	**Prediction and Uncertainties for the RHIC Spin Physics Program**
Organizers:	W. Vogelsang and J. Qiu
Date:	March 6–31, 2000

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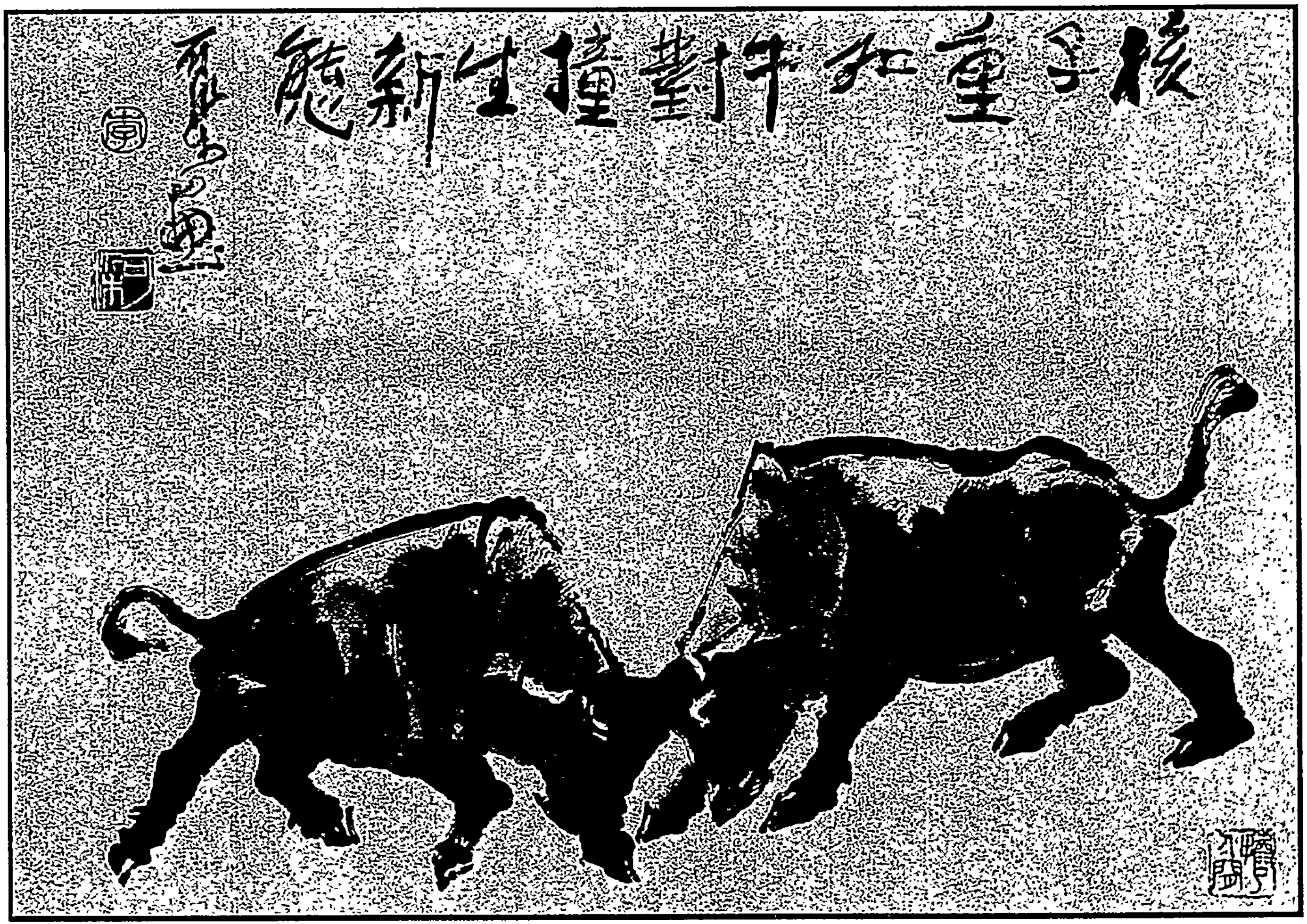
RIKEN BNL RESEARCH CENTER

RHIC SPIN

OCTOBER 6–8, 1999



Li Keran

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Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T. D. Lee

Speakers:

M. Bai
J. Balewski
L. Bland
D. Boer
S. Bravar
G. Bunce
N. Buttimore
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