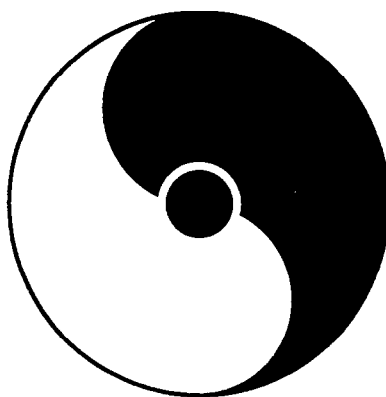


Proceedings of RIKEN BNL Research Center Workshop

Volume 25

CIRCUM-PAN-PACIFIC RIKEN SYMPOSIUM ON “HIGH ENERGY SPIN PHYSICS”

November 3–6, 1999
RIKEN, Wako, Japan



Organizers:

Shunzo Kumano, Toshi-Aki Shibata and Koichi Yazaki

RIKEN BNL Research Center

Building 510, Brookhaven National Laboratory, Upton, NY 11973, USA

Other RIKEN BNL Research Center Proceedings Volumes:

- Volume 24 - Symposium on QCD Physics at RIKEN BNL Research Center - BNL-
- Volume 23 - Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies - BNL-
- Volume 22 - OSCAR II: Predictions for RHIC - BNL-
- Volume 21 - RBRC Scientific Review Committee Meeting - BNL-52568
- Volume 20 - Gauge-Invariant Variables in Gauge Theories - BNL-
- Volume 19 - Numerical Algorithms at Non-Zero Chemical Potential - BNL-52573
- Volume 18 - Event Generator for RHIC Spin Physics - BNL-52571
- Volume 17 - Hard Parton Physics in High-Energy Nuclear Collisions - BNL-52574
- Volume 16 - RIKEN Winter School — Structure of Hadrons —Introduction to QCD Hard Processes— BNL-52569
- Volume 15 - QCD Phase Transitions - BNL-52561
- Volume 14 - Quantum Fields In and Out of Equilibrium - BNL-52560
- Volume 13 - Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration - BNL-66299
- Volume 12 - Quarkonium Production in Relativistic Nuclear Collisions - BNL-52559
- Volume 11 - Event Generator for RHIC Spin Physics - BNL-66116
- Volume 10 - Physics of Polarimetry at RHIC - BNL-65926
- Volume 9 - High Density Matter in AGS, SPS and RHIC Collisions - BNL-65762
- Volume 8 - Fermion Frontiers in Vector Lattice Gauge Theories - BNL-65634
- Volume 7 - RHIC Spin Physics - BNL-65615
- Volume 6 - Quarks and Gluons in the Nucleon - BNL-65234
- Volume 5 - Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density - BNL-65105
- Volume 4 - Inauguration Ceremony, September 22 and Non-Equilibrium Many Body Dynamics - BNL- 64912
- Volume 3 - Hadron Spin-Flip at RHIC Energies - BNL-64724
- Volume 2 - Perturbative QCD as a Probe of Hadron Structure - BNL-64723
- 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 Kenkyusho” (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

The Circum-Pan-Pacific Riken Symposium on High Energy Spin Physics was held at Oukouchi Memorial Hall in Riken from November 3 through 6, 1999. It was held as a joint meeting of the 2nd Circum-Pan-Pacific Symposium on High Energy Spin Physics and the 3rd of the series of Riken Symposia related to the RHIC-SPIN.

The 1st Circum-Pan-Pacific Symposium on High Energy Spin Physics was held at Kobe in 1996 and the RHIC-SPIN Riken Symposia had been held every two years since 1995.

As Prof. Ozaki mentioned in his talk at the beginning of this meeting, the RHIC was ready for the first beam, physics experiments scheduled in 2000, and the RHIC-SPIN would start in 2001. It was therefore considered to be very timely for the researchers in the field of high energy spin physics to get together, clarifying the present status of the field and discussing interesting and important topics as well as experimental subjects to be pursued. It is especially important for the success of the RHIC-SPIN project that the researchers in the neighboring countries surrounding the Pacific are actively involved in it. This is why the above two series were joined in this symposium.

The subjects discussed in the symposium include: Hard processes probing spin-structure functions, polarization mechanisms in high energy reactions, lattice studies of polarized structure functions, theoretical models for the nucleon and its spin structure, RHIC and RHIC-SPIN projects, results and future projects of existing experimental facilities.

Totally 73 scientists participated in the symposium, 27 from abroad and 46 from Japan. It consisted of 13 main sessions, with 33 invited and contributed talks, and 4 discussion sessions covering recent experimental and theoretical developments and important topics in high energy spin physics and closely related fields.

The meeting was successful with excellent talks and lively discussions, which we owe to all the participants. The excursion to the traditional city, Kawagoe, and the banquet there were also enjoyable.

The symposium was sponsored by the Institute of Physical and Chemical Research (RIKEN) in general and the RIKEN-BNL Research Center and the RIKEN Accelerator Laboratory in particular. We are grateful to them for their generous supports. Special thanks are due to Ms. Kishino and Ms. Kiyama for their excellent secretarial works and to young staffs and students for their help during the symposium.

Shunzo Kumano, Toshi-Aki Shibata and Koichi Yazaki

Status of RHIC

Presentation at
Circum-Pan-Pacific RIKEN Symposium on
"High Energy Spin Physics"

Wako, Saitama, Japan
November 3, 1999

Satoshi Ozaki
Brookhaven National Laboratory

Brookhaven Science Associates
U.S. Department of Energy

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RHIC Project Mission

DOE's Flagship Research Facility for Nuclear Physics Research
Extraordinary Tool for Extra-ordinary Science

NSF Long Range Plan 1989

CD1: May 1986

K01: January 1991

K02: January 1991

K03: January 1992

Rings Completed 1/99

Commissioning Began 5/99

CD4: August 12, 1999

TEC = \$ 486.9M

TPC = \$ 616.5M

Uses Existing Tunnel, Exp. Halls,
and He Refrigerator

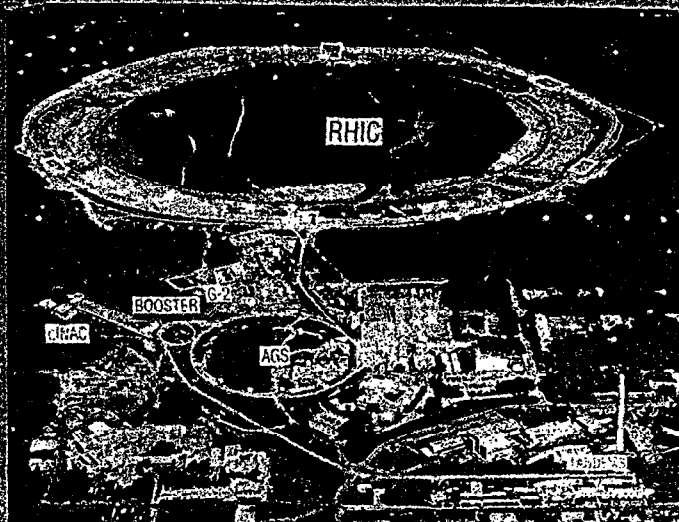
AGS Complex as Injector

The Capital Replacement Value of the Completed RHIC Facility > \$1B

RIKEN-BNL Collaboration ~\$10M for Spin Physics

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The Collider Commissioning Status

Dryogenic System

Blue Ring Cooled to Operating Temperature (4-6 K) on May 26

Yellow Ring Cool-down to 4-6 K on July 14

Beam Commissioning

Permission to Commission with Low Intensity Beam on June 24

Established Closed Orbit in Blue Ring

Captured, Stored, and Accelerated Beams in Blue Ring

Stored Beam Life ~ 45 min.

Establish Closed Orbit and Captured Beams in Yellow Ring

Runs Ended on August 16th

DOE CD4 (Critical Decision 4) [Begin Operating]: Approved on August 12

The First Year (FY 2000) Operation:

Begin in January 2000 with Ring Cool-down: Nominally 30 Weeks



Collider Status Evaluation

Post-Commissioning Run Period: September 16-17, 1999

- Collider Fundamentally Sound in its Design and in its Construction
- Some Deficiencies to Be Corrected and Some Repairs to Be Made
 - He Refrigerator Isolation Valves
 - He Leaks in Cryogenic Valve Boxes
 - Deformation of Bore Tube Bellows From 22 Atms Pressure Tests, Resulting in a Tight Aperture
 - Completion of Magnet Power Supplies Installation
 - Improvement of Control and Diagnostics Tool and Adjustment and Improvement of Quench Protection Systems, and Some QA Issues
 - Commission Storage RF System
- Transfer of Commissioning and Operations Responsibility from RHIC Project to Collider Accelerator Department

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Preliminary Schedule for FY 2000 Operation

Program Element	FY 2000													Oct
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	
AGS-Booster-Tandem Startup		■			↑									
RHIC Cryo Maintenance	■	■	■		RHIC Shield Walls Up									
RHIC Cryo Cooldown				■										
RHIC Cryo Operation					■	■	■	■	■	■	■	■	■	
RHIC Systems Test (Ramping etc, no beam)					■	■								
RHIC Bellows Procurement	■	■	■											
RHIC Cryo Warmup														
RHIC Bellows Fix	■	■	■											
RHIC Cryo Standby														
RHIC Startup with beams					■	■	■							
RHIC Research with colliding beams						■	■	■	■	■	■	■	■	
AGS Fe 0.6-1 GeV/n (SEB-NASA)	■													
AGS 25 GeV/c Protons (FEB-E821)				■	■	■								
*AGS 25 GeV/c Protons (FEB-E951/E938)											◀	◀		
Shutdown	■	■										■	■	

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Polarized Beam Collider
Status
BNL-BNL Collaboration
DOE-AEE Project

Collisions of Polarized Protons

ES-A-500 GeV 2×10^{11} Pol. Protons / Bunch
 $\epsilon = 20 \pi$ mm mrad

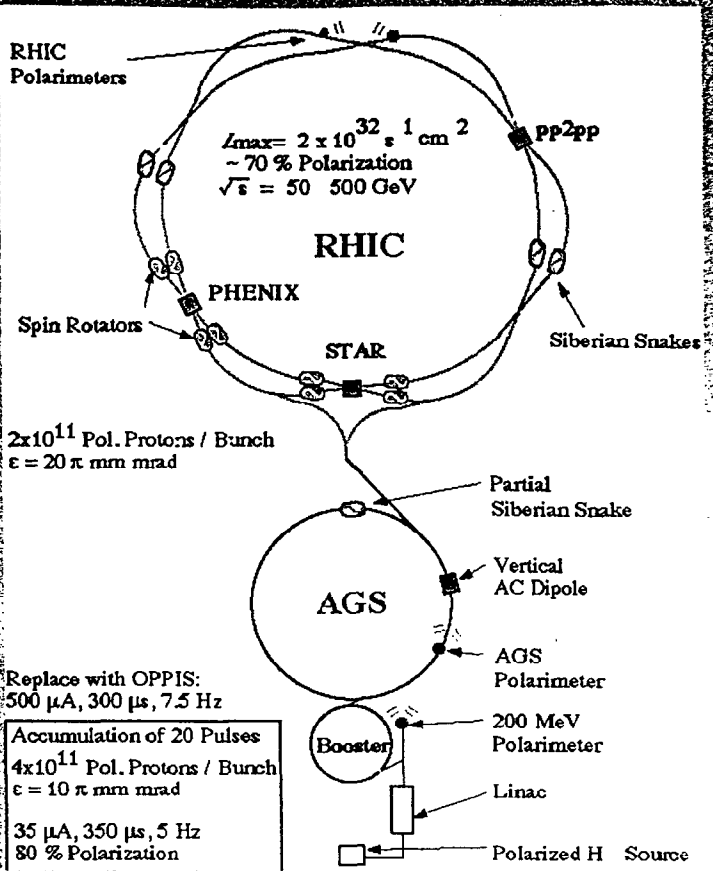
Now Embraced in US NP Program

AGS
Accelerates Polarized Protons

RHIC
Four Siberian Snakes and
Eight Spin Rotators

One Snake Completed in Oct. 1999

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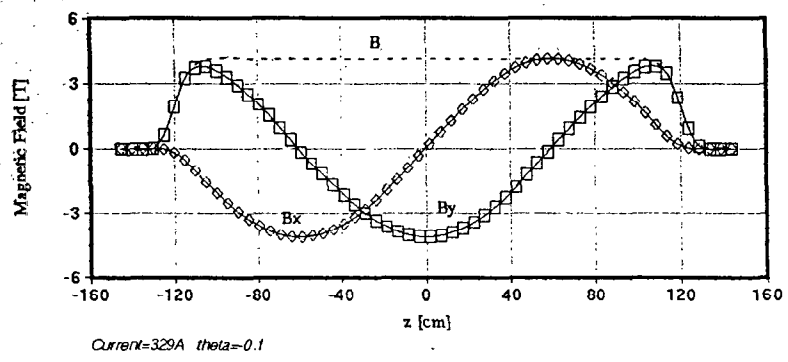


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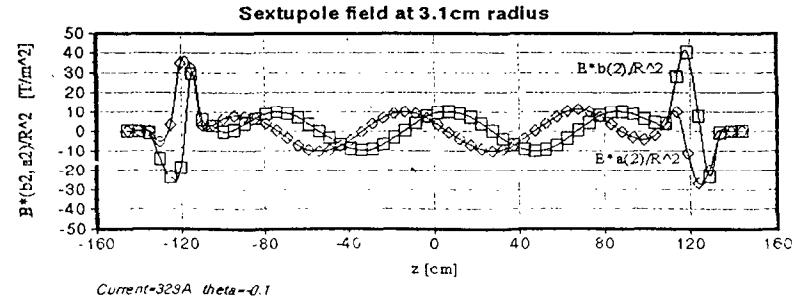


Helical Dipole Performances II

B_x and B_y vs Z



Sextupole at 3.1 cm Radius vs Z





The Detector Status

\$ 115M of Trust Fund for Initial Complement of Detectors

Majority Policy Decision by BNL HE/NP PAC

Two Large Scale Detectors: STAR and PHENIX

Two Small Scale Detectors: PHOBOS and BRAHMS

The Trust Fund was Leveraged Well:

- Supported Construction of Basic Detector Systems
- Significant Foreign Contributions: Cash, In-kind, and Intellectual
- DOE Funding for Additional Experimental Equipment (AEE)

Detectors Were at Respective Collision Points for Commissioning:

- Degree of Instrumentation Varied from Detector to Detector
- Observed Beam-Gas Events in the Commissioning Runs
- Further Instrumentation being Added for the First Year Physics

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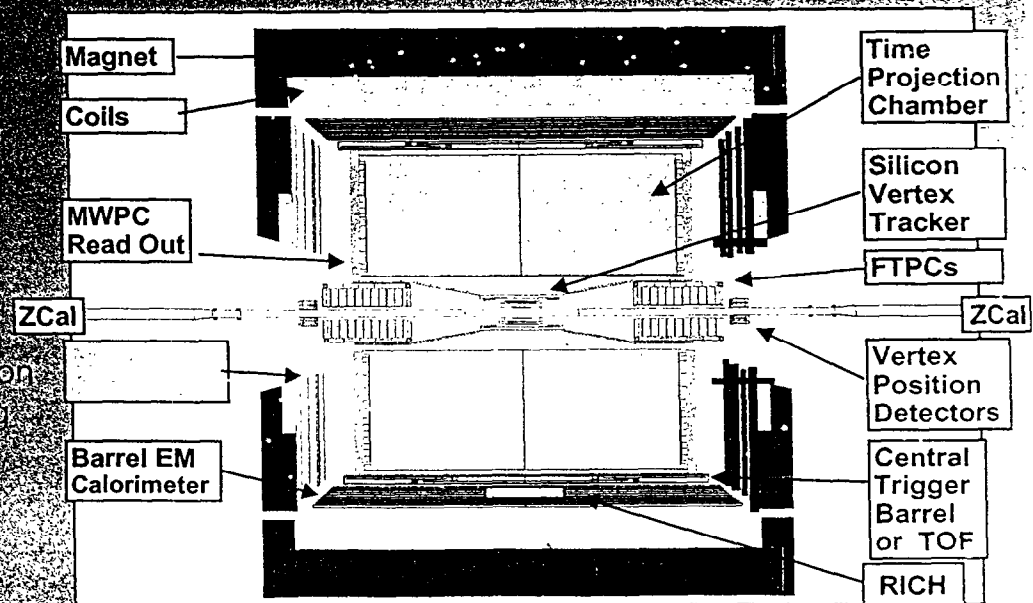
Evolution of STAR Detector

Solenoidal
Geometry

Large Solid Angle
Tracking with
Cylindrical TPC

Particle Identification
by dE/dX Sampling

Event-by-event
Recording of
Hadrons and Jets

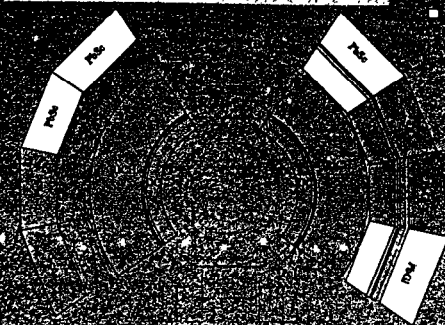


In Place for 1999 for 2000+ for 2001

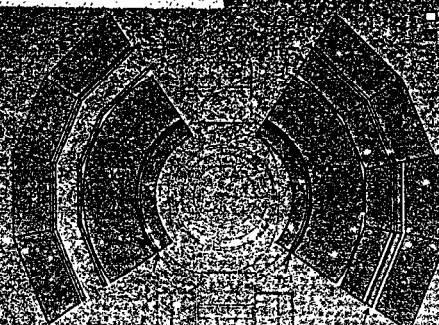


Evolution of PHENIX Configuration

YEAR 1 (FY2000) Run



YEAR 2 Run



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Summary and Conclusions

- RHIC is Now in Commissioning Phase
- The "Beam Test" Indicates that the Collider is Fundamentally Sound in Its Design and Construction
- STAR, PHENIX, PHOBOS and BRAHMS Made Good Progress in the Detector Construction, and Participated in the "Beam Test" Using Part of Their Detectors
- Work is in Progress to Install Punch-listed Items, Repair Damages, Remedy Deficiencies in Power Supply Control Scheme, etc.
- Installation of Additional Detector Instrumentation in Progress
- Plan for the FY-2000 Operation is to Start with Cool-down in January 2000, System Tests with and without Beams for 1 - 2 months, and Collisions of Au Beams in Spring.
- Operation with Polarized Protons is Planned for FY2001, with Accelerator Study Beginning in FY2000

PHENIX for the First Spin Collider RHIC

Hideto En'yo*

for the PHENIX collaboration

Physics Department, Kyoto University, Kyoto 606, Japan

Acceleration of polarized protons in Relativistic Heavy Ion Collider (RHIC) is to provide unique tools to study the spin structure of nucleon, covering the $\sqrt{s}$ region from 50 GeV to 500 GeV with proton polarization of 70 %. At 500 GeV the luminosity of $2 \times 10^{32} \text{cm}^{-2} \text{sec}^{-1}$ is expected. PHENIX, one of the two major detectors at RHIC, is going to investigate this new field of spin physics through the measurements of leptons and photons to probe possible spin carriers in the nucleon. Overview of the PHENIX spin program is presented and the expected physics outcomes are discussed.

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Spin Physics at RHIC

RHIC = polarized parton collider

- Spin Structure of Nucleon

- $1/2 = (1/2)\Delta\Sigma + \Delta G + L_q + L_g$

- ΔG : gluon polarization

- $\Delta\bar{q}$: Anti-quark polarization

- New Structures

- h_1 : transversity

- Test of pQCD

- Use asymmetries sensitive ONLY to the higher orders (A_N at high P_T etc.)

- NEW TOOL to study hadronic processes

- W, Z @ 500 GeV

- flavor sensitive studies of the structure functions

- $c\bar{c}/b\bar{b}$

- • Production mechanism

- Spin in the fragmentation

?QCD triumph?

or

?beyond ?

Measurements of ΔG ($gq \rightarrow \gamma X$)

A. Vazile
Y. Goto

• Background reduction

– segmentation

$$\pi^0 \rightarrow \gamma_{\text{isolate}} + \gamma_{\text{merged}}$$

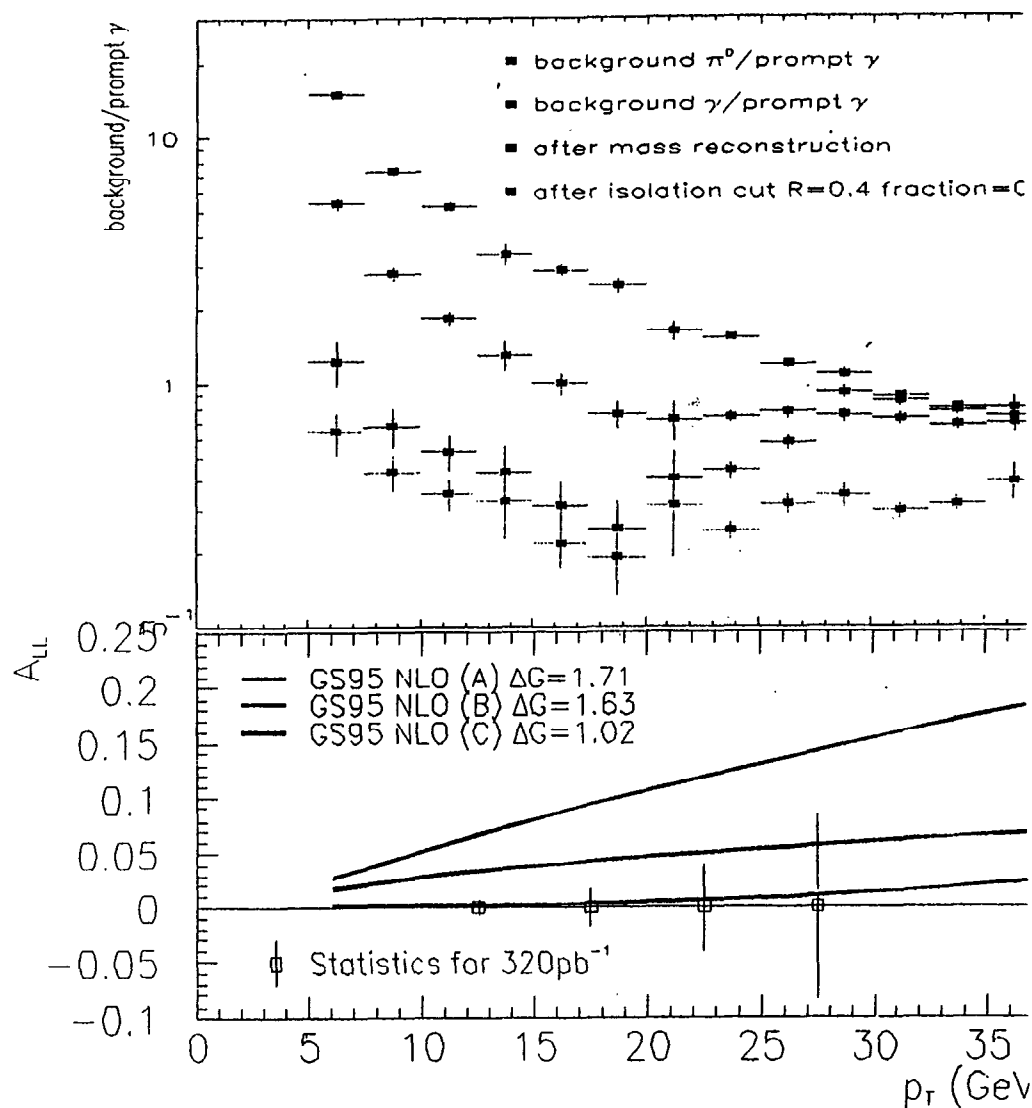
– prompt γ + decay γ

– mass reconstruction π^0

– isolation cut

- $R=0.4$, E-fraction=5%

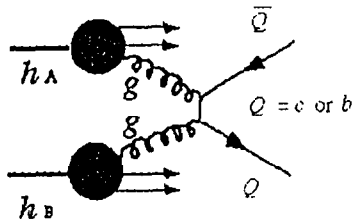
$\Rightarrow$ See A. Vazilevsky's talk



Prompt γ Asymmetry

3-Nov-99

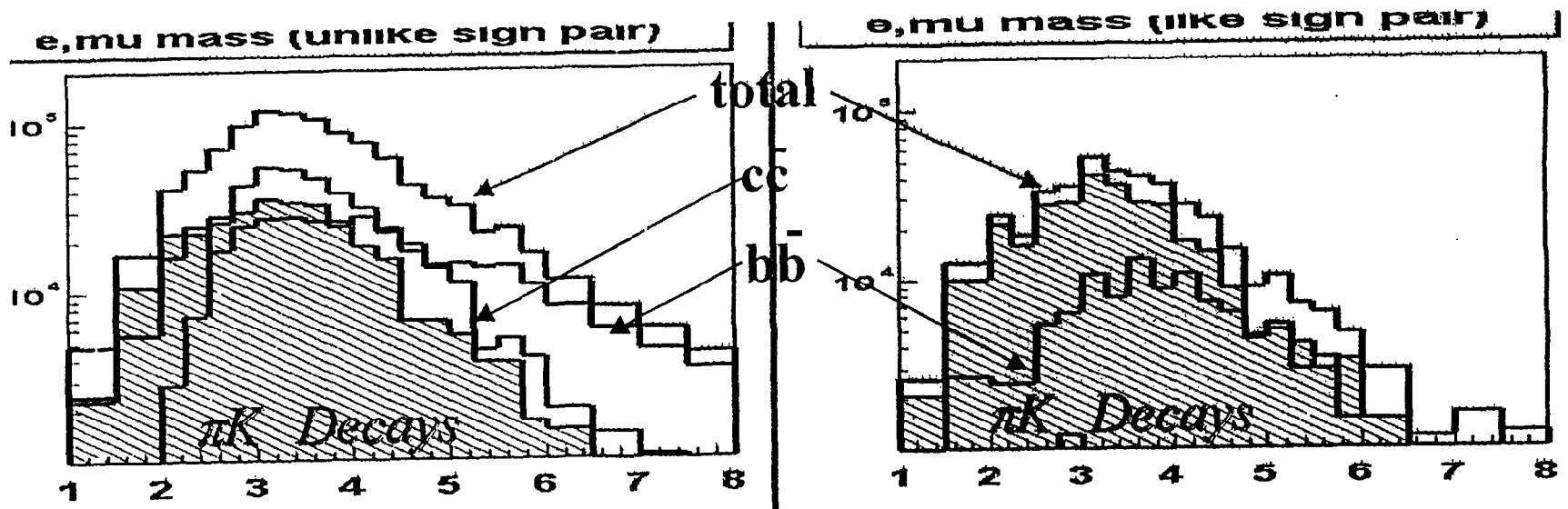
Hideto En'yo, Kyoto University



Measurements of ΔG

$$gg \rightarrow Q\bar{Q} \rightarrow e\mu$$

- $e\mu$ coincidence enhance the leptons from heavy quarks
- 320/pb provides 120k $b\bar{b}$, 100k $c\bar{c}$, 100k hadronic decays
- Like sign pair (also includes signal from $b\bar{b}$) gives fine estimation for the background effects



3-Nov-99

Hideto En'yo, Kyoto University

Measurements of Δq , $\Delta \bar{q}$ at PHENIX

Parity violating single Asymmetry

unpolarized distribution $\times$ polarized distribution

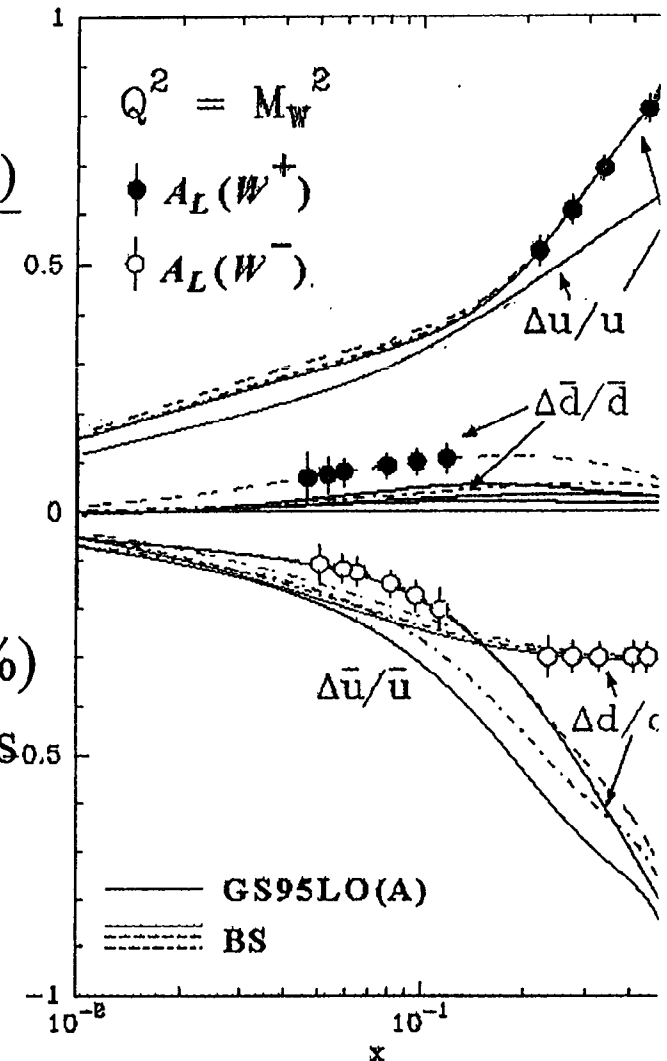
$$A_L^{W^+} = \frac{\Delta u(x_a, M_W^2) \bar{d}(x_b, M_W^2) - \Delta \bar{d}(x_a, M_W^2) u(x_b, M_W^2)}{u(x_a, M_W^2) \bar{d}(x_b, M_W^2) + \bar{d}(x_a, M_W^2) u(x_b, M_W^2)}$$

- $\bar{d}$ small at high $x \rightarrow \Delta u/u$ ($\Delta d/d$ for W^-)
flavor selected valence quark polarization
 $\rightarrow \Delta \bar{d}/\bar{d}$ ($\Delta \bar{u}/\bar{u}$ for W^-) determination

Major background is Z decay (20%)

systematic error will be minimized ($\sim 1\%$)

with A_L^Z ($\sim 20\%$) and $\sigma(Z)$ measurements



Conclusions (*Time Table towards discovery*)

- PHENIX construction on going
 - Y2000 Spring E&W Central Arms ready for the first Au-Au collisions
 - Y2000 Summer South Muon Arm ready for the first polarized collisions
 - Y2001 Summer North Muon Arm ready for the 500GeV running
 - PHENIX High rate capability
 - PHENIX Powerful particle IDs for pQCD probes
- Y2001, The first measurements of helicity asymmetry will be performed @200GeV. Sizable ΔG generates *surprises* in the High $p_T \pi^0$, High $p_T \mu$, J/ψ data.
- Y2002, Statistics will be much improved @200GeV, ensuring the *determination of ΔG* in direct γ and $e-\mu$ coincidence data. “Spin Crisis” will hopefully be solved by them.
- Y200?, Weak Bosons will be produced at RHIC, the NEW “flavor sensitive” tool for the *anti-quark/quark polarization* and unpolarized structure function of anti-quark measurements.
- And **beyond...**

Spin Physics with the STAR detector

L.C. BLAND*, for the STAR collaboration

Department of Physics, Indiana University, Bloomington, IN USA

The STAR detector will bring unique capabilities to the study of $\vec{p} + \vec{p}$ collisions up to total center of mass energies of 500 GeV at RHIC. The large acceptance of the time projection chamber and the electromagnetic calorimeter enable STAR to observe jets, and to detect photons and electrons in important regions of phase space. The premier experiments of the STAR spin program are discussed in this contribution. Photon + jet coincidence measurements will provide the world's best determination of the contribution gluons make to the proton's spin. Detection of the daughter electrons and positrons from $W^\pm$ decay will enable the determination of the polarization of the $q\bar{q}$ sea within the proton.

*E-mail address: bland@iucf.indiana.edu

Prompt Photon Reconstruction in PHENIX.

Alexander Bazilevsky

RIKEN-BNL Research Center

Prompt Photon production in hadronic collisions is a good probe to investigate the structure of the nucleon. We're going to measure ΔG , gluon polarization in the proton, using polarized pp collisions at RHIC. For this purpose we're going to use Central Arm of the PHENIX setup. Its main component – Electromagnetic Calorimeter (EMCal) – is a key detector for Prompt Photon reconstruction and background reduction. Its characteristics have been thoroughly investigated in Test Beam runs at AGS (BNL) and SPS (CERN). Their parameterizations have been then used for simulation of the EMCal response to different particles, including π^0 mass resolution, Shower Profile analysis efficiencies for high p_t π^0 identification and hadronic background suppression.

The results presented are based on the PYTHIA 5.7 generator. The expected p_t range for Prompt Photon production asymmetry measurements is 5-30 GeV for $\sqrt{s} = 200$ GeV and 320 pb^{-1} . The main contributors to Prompt Photon production are Compton and Annihilation processes.

Charged hadron background will be suppressed by the Tracking System of PHENIX. Nevertheless based just on the EMCal response and Shower Profile analysis we can suppress the hadronic background > 500 times for $p_t > 5$ GeV. Another background source is photons primarily from π^0 decays. For $p_t > 25$ GeV the main contributor is π^0 's with merged photons.

One of the techniques to reduce the photon background level is mass reconstruction. It concerns π^0 's giving both photons in the detector acceptance. Another one is Isolation Cut using the fact that Prompt Photons are usually well isolated from the final state hadrons. Standard approach is to draw a cone around photon, sum the energy in it and require it to be less than certain fraction of the Prompt Photon energy (Fixed Isolation). Another approach (Smooth Isolation) is to consider the accepted energy E_{tot} in the cone to be a function of cone radius R : $E_{\text{tot}}(R) \rightarrow 0$ for $R \rightarrow 0$, E_{tot} is permitted to be large for big R (S.Frixione, Phys.Let. B429(1998), 369). This approach seems to us more advantageous: since the Fixed Isolation can accept only small amount of energy (usually 5-10%) in rather big cone (usually $R=0.5-1$), its efficiency for Prompt Photon reconstruction may deteriorate due to effects like:

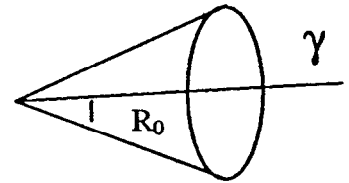
1. Electronic noise: in the cone with $R=0.5$ there are about 5000 EMCal cells. Even small electronic noise can give a contribution to E_{tot} in the cone;
2. The particles which are not from the Vertex (magnet iron etc.) and ones from the other collision in the same event (for $\sqrt{s} = 500$ GeV 50% of all events are expected to be multiple collision) may also contribute to the E_{tot} in the cone.

Background: Photons

Isolation Cut (just a few points – work is in progress)

- Will suppress Bremsstrahlung, π^0 's with merged photons, π^0 's with one photon lost

Isolation Cone around photon: $R_0 = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
 η - pseudorapidity, ϕ - azimuthal angle



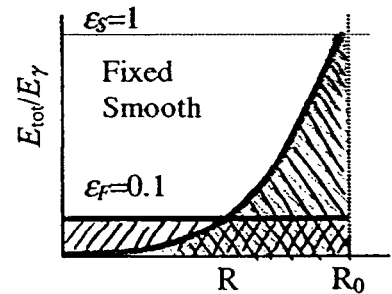
Require the energy deposited in the Cone E_{tot} to be less than certain fraction of the photon energy $\varepsilon \cdot E_\gamma$

1. Fixed isolation

$$E_{tot} < \varepsilon_F \cdot E_\gamma \quad \text{in the Cone with } R_0$$

2. Smooth isolation (S.Frixione, Phys.Let.B429(1998),369)

$$E_{tot}(R) < \varepsilon_S \cdot E_\gamma \cdot \left(\frac{1 - \cos R}{1 - \cos R_0} \right) \quad \text{for all } R < R_0$$



- Fixed Isolation Cut accepts only small amount of energy (usually $\varepsilon_F \sim 0.05 \div 0.1$) in the rather big Cone (usually $R_0 \sim 0.5 \div 1.0$)
- Smooth Isolation accepted amount of energy depends on the Cone radius R :

$$E_{tot}(R) \rightarrow 0 \quad \text{for } R \rightarrow 0$$

$$E_{tot} \text{ is permitted to be large for big } R \text{ (usually } \varepsilon_S \sim 1)$$

Background: Photons

Isolation Cut (just a few points – work is in progress)

Fixed or Smooth ?

Smooth Isolation Cut is less severe for the Prompt Photons

- Smooth Isolation Cut is less sensitive to the noise

In the Cone with $R=0.5$ there are ~5000 EMCal cells (towers); even small electronic noise in each cell may give considerable contribution to the E_{tot} in the Cone

- Smooth Isolation Cut is less sensitive to background particles which are not from the Vertex (Magnet iron etc.)

It deteriorates the reconstruction efficiency for Prompt Photons after Isolation Cut

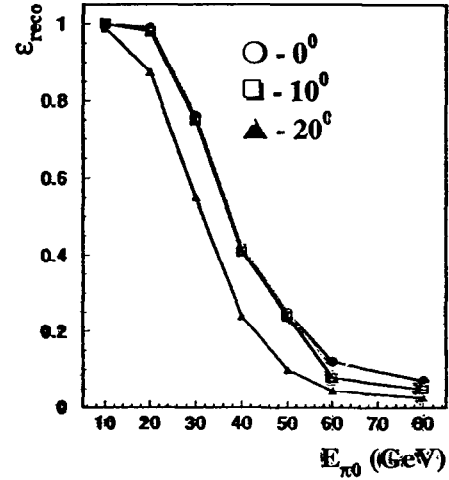
- Smooth Isolation Cut is less sensitive to the multiple collision in single event

Following slide

Background: π^0 , merged γ 's

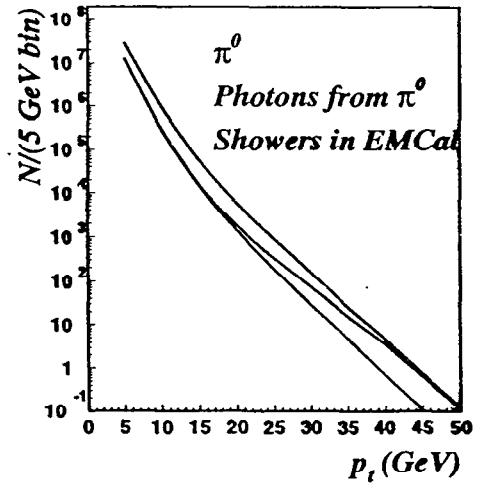
Shower Profile Analysis

- Up to $E_{\pi^0}=20$ GeV ($d_{\gamma\gamma}\approx 1.3$ cells) - photons separated perfectly
- $E_{\pi^0}=35$ GeV ($d_{\gamma\gamma}\approx 0.75$ cells) - 50% efficiency of two photon identification
- For $\theta > 10^\circ$ efficiency worsens due to longitudinal shower fluctuation in the projection on the EMCal surface



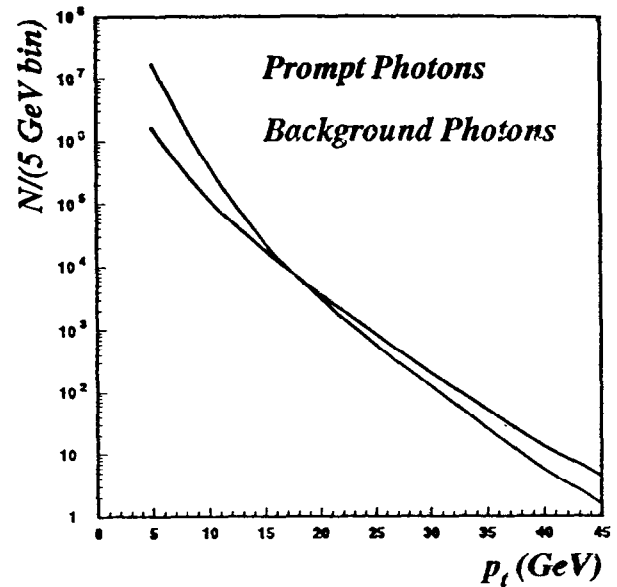
π^0 's in QCD Jets ($\sqrt{s}=200\text{GeV}$, 320pb^{-1})

- Because of the shower merging in the EMCal the background level increases for $p_t > 20$ GeV

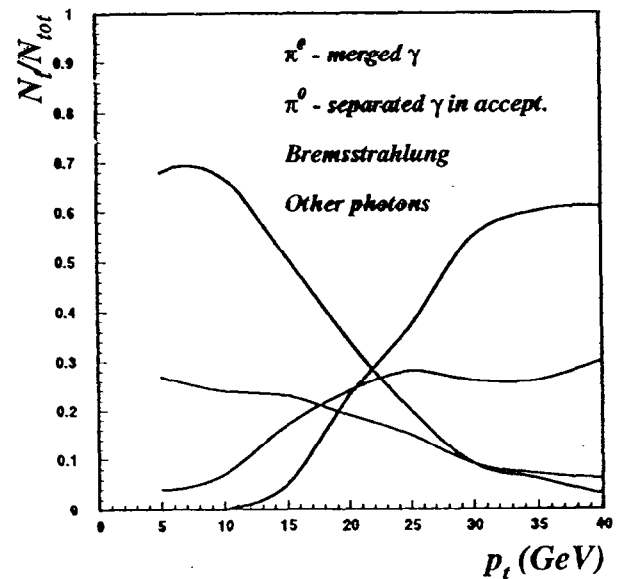


Background: Photons

- Background Photons dominate over Prompt Photons with $p_t < 20$ GeV/c



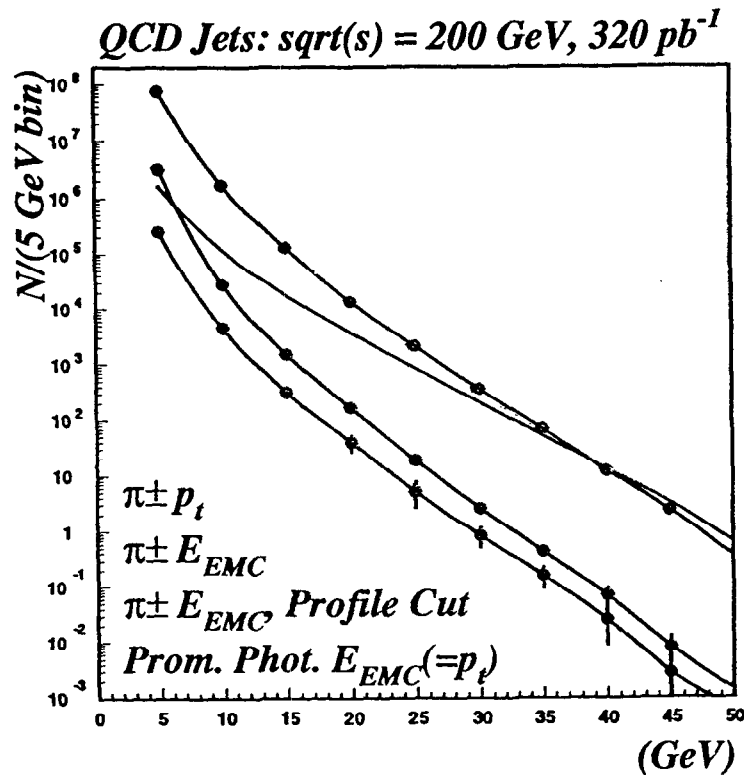
- For $p_t > 20$ GeV/c the main contributors to the Background are Bremsstrahlung and π^0 with merged photons



Background: Hadrons

QCD Jets: $\sqrt{s}=200\text{GeV}$, 320pb^{-1}

Using Tracking System we will suppress Charged Hadrons but
...EMCal itself can do it successfully:



- EMCal itself can considerably suppress the charged hadron background – about 500 times for each p_t bin

EMCal – the only device that detects $n, \bar{n}$. They make a contribution to the background showers in the EMCal primarily in $E_{EMC} < 10 \text{ GeV}$. They are also effectively suppressed by Shower Profile Cut.

Total and Differential Cross Sections and Polarization Effects in Proton-Proton Elastic Scattering at RHIC

Wlodek Guryn

for pp2pp (R7) collaboration

Brookhaven National Laboratory, Upton, NY 11973, USA

The physics program, the setup, and the performance of an experiment to measure elastic scattering of polarized protons at the Relativistic Heavy Ion Collider (RHIC) are described. In the medium t range, diffractive region, with four momenta transferred $0.006 < -t < 1.5(\text{GeV}/c)^2$, the experiment will address one of the main, unsolved problems in particle and nuclear physics: long-range QCD and confinement. In the small t range, Coulomb Nuclear Interference (CNI), $0.0004 < -t < 0.12(\text{GeV}/c)^2$, the experiment will, in a model-independent way, test general analytical properties of scattering amplitudes: analyticity, unitarity, and crossing symmetry. In addition, by measuring single spin asymmetries such as A_N , double spin correlation parameter A_{NN} , and cross section difference $\Delta\sigma_T = \sigma_{tot}(\uparrow, \downarrow) - \sigma_{tot}(\uparrow, \uparrow)$, we will be able to determine the helicity amplitudes ϕ . Those amplitudes are not well known at this time, so their systematic study at RHIC will help understand spin structure of nucleon and the exchanged mediator of the force, Pomeron and Odderon. A polarized gas jet target added to the setup will expand the physics capabilities to cover the fixed-target range of energies, giving centre of mass (cms) energy range $7 < \sqrt{s} < 500\text{GeV}$.

PHYSICS PROGRAM

The main goal of the experiment is to extensively map the diffractive regime of strong interactions over a wide range of s and M in order to probe the emerging features of the Pomeron, in terms of QCD concepts, and to explore its spin dependence.

1. By measuring spin asymmetries A_N , A_{NN} , (A_{LL}), we will be able to determine the helicity amplitudes ϕ_i , which describe elastic scattering. They are not well known now.

$$\phi_1 \sim \langle ++ | M | ++ \rangle \quad \phi_2 \sim \langle -+ | M | ++ \rangle \quad \phi_3 \sim \langle +- | M | ++ \rangle$$

$$\phi_4 \sim \langle +- | M | +- \rangle \quad \phi_5 \sim \langle ++ | M | +- \rangle.$$

2. **Polarization observables will give access to spin degrees of freedom**, which distinguish between different nucleon structure models, like quark diquark model of the proton and its appropriate wave function of the proton.
3. Using polarized jet target the experiment will contribute to understanding and measurement of beam polarization by covering wide range of elastic reactions.

The four-momentum transferred $-t$ is sub-divided in two kinematic ranges:

- 1. In the medium t region, day one pp running, no special conditions required:**

$$0.006 < -t < 1.5 \text{ (GeV/c)}^2,$$

we will study the dynamics of long range strong interactions, the non-perturbative regime of QCD. Hence, the experiment will address one of the main, unsolved problems in particle and nuclear physics: **long range QCD and confinement.**

- **evolution of dip structure observed at the ISR in $d\sigma_{el}/dt$;**
 - **s and t dependence of the nuclear slope, b .**
- 4. In the small momentum transferred $|t|$ region, Coulomb Nuclear Interference (CNI) region:**

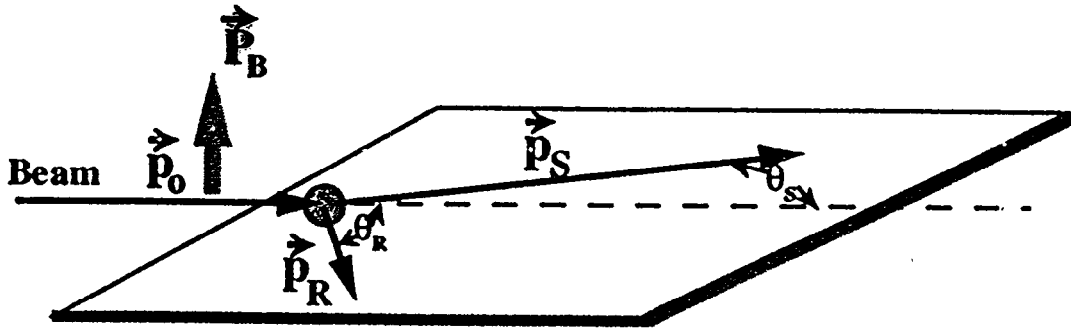
$$0.0004 < -t < 0.12 \text{ (GeV/c)}^2$$

one tests in a model independent way, general analytical properties of scattering amplitudes: analyticity, unitarity crossing symmetry.

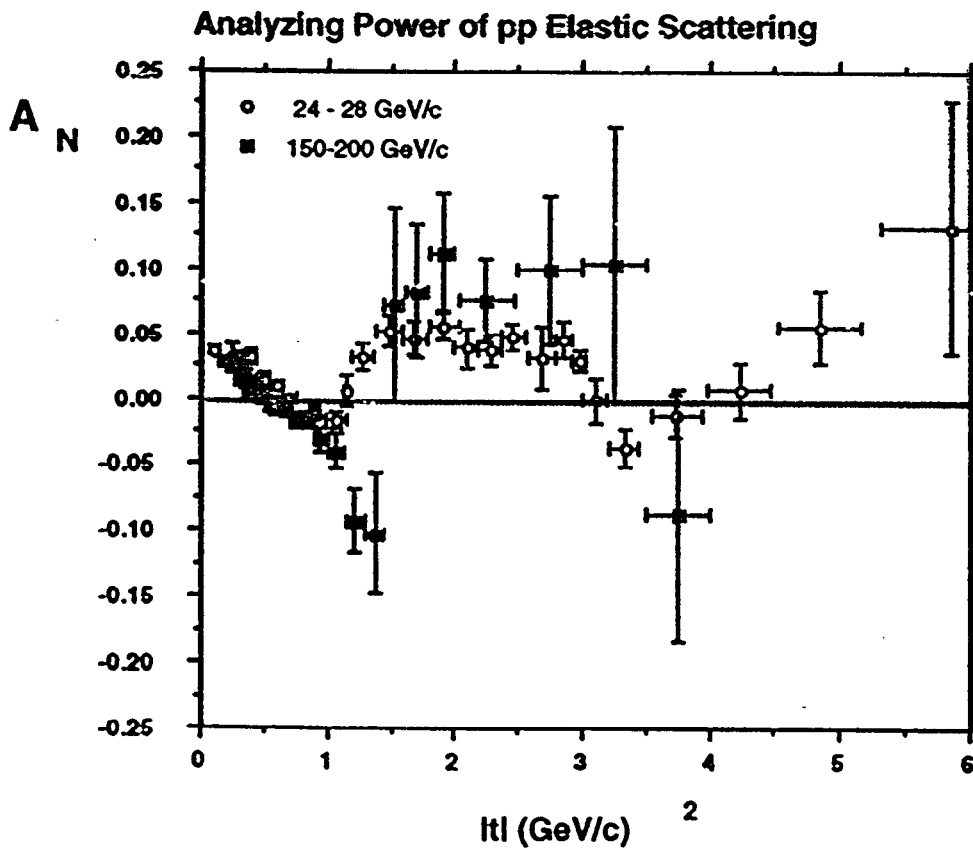
- s dependence of σ_{tot} and $d\sigma_{el}/dt$;
- ratio of real to imaginary part of the forward scattering amplitude, ρ ;
- nuclear slope parameter of the pp elastic scattering,

SPIN EFFECTS in ELASTIC SCATTERING

Polarisation Asymmetry Measurements



$$\begin{aligned} \sigma_{\uparrow} &= \sigma_0 [1 + A_N \vec{p}_B \cdot (\vec{p}_0 \times \vec{p}_S)] \\ \sigma_{\downarrow} &= \sigma_0 [1 - A_N \vec{p}_B \cdot (\vec{p}_0 \times \vec{p}_S)] \end{aligned} \quad A_N = \frac{1}{|\vec{p}_B|} \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$



Wlodek Guryn
 Circum-Pan-Pacific RIKEN Symposium on "High Energy Spin Physics"
 November 3-6, 1999, RIKEN, Wako, Japan

Spin-off of PP2PP: RHIC Polarimetry

1. RHIC energy range presents a new domain for polarimetry. No reaction has been measured (or calculated) with the desire accuracy of better than 5%.
2. Our study shows that the challenge of measuring the polarization of polarized proton beams at RHIC can be achieved by exploiting the basic symmetry properties of the pp elastic scattering process:

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

(T-invariance and Pauli principle)

3. Existing data (25 –300 GeV/c) and models suggest three $\sqrt{s}$ regions:
 - CNI: $10^{-3} \leq \sqrt{s} \leq 10^{-2} \text{ (GeV/c)}^2$, where $A_N \approx 5\%$, very large σ ;
 - Small- $\sqrt{s}$: $0.1 \leq \sqrt{s} \leq 0.4 \text{ (GeV/c)}^2$, where $A_N \approx 3\%$, large σ ;
 - Medium- $\sqrt{s}$: $0.8 \leq \sqrt{s} \leq 1.2 \text{ (GeV/c)}^2$, where $A_N \approx -10\%$, small σ .
4. A polarized jet target, integrated with Roman Pots of the PP2PP setup, will match the same kinematical regions with recoil detectors and cover the energy range, $6.5 < \sqrt{s} < 22.5 \text{ GeV}$. The combination of forward and recoil detectors will provide *full selection* of elastic events.
5. An H₂, molecular-cluster of higher density, can be used as an internal target for polarimetry after the calibration with polarized H jet is done.
 - Forward + recoil detection (full-kinematics constrained pp $\rightarrow$ pp events)
 - Hydrogen gas target (unbiased recoil detection; low background)
 - Self - calibration polarized jet (option included)
 - Cost - effective (redeploying resources and integrating PP2PP infrastructure).

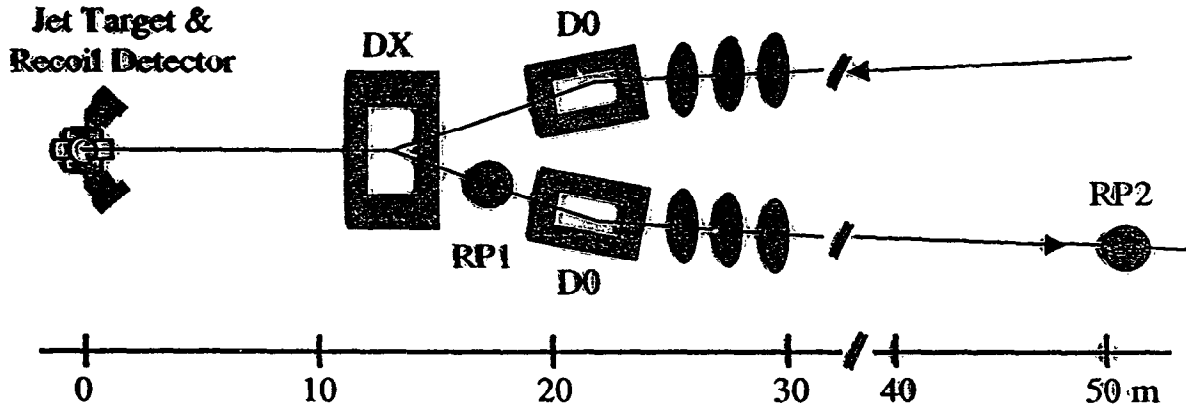
Wlodek Guryn

Circum-Pan-Pacific RIKEN Symposium on "High Energy Spin Physics"
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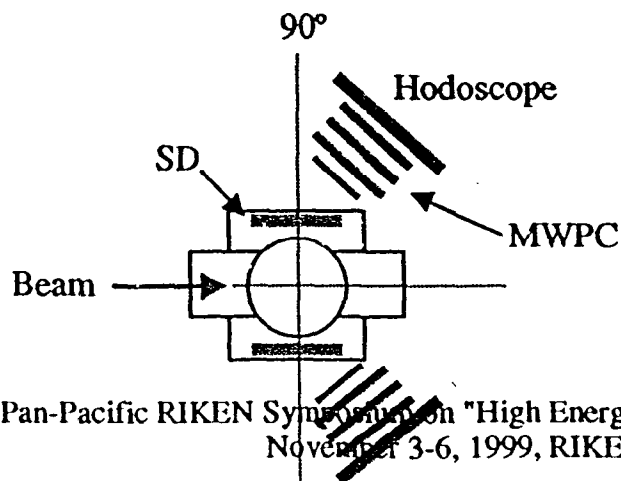
Day one PP2PP Setup with Jet Target and Recoil Detectors

More than one p -beam at RHIC, 100 GeV/c and 250 GeV/c proton beams, will allow us to take data at two $\sqrt{s}$ points.

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



Jet Target and Recoil Detector



Wlodek Guryń
Circum-Pan-Pacific RIKEN Symposium on "High Energy Spin Physics"
November 3-6, 1999, RIKEN, Wako, Japan

Transverse polarization 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 polarization distribution and fragmentation functions, which parametrize transverse spin effects in hard scattering processes. Although 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, 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 $pp^\uparrow \rightarrow \pi X$. 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, studying the angular dependences of asymmetries (and their transverse momentum dependence) 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 $e\vec{p} \rightarrow e' \pi^+ X$, 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]. A striking feature is that the contribution from the target spin transverse to the virtual photon momentum contributes also at subleading order in M/Q , even though the relevant functions (h_1 and $H_1^\perp$) are leading twist functions. We find from a bag model calculation that the latter contributes much less to the measured asymmetry, i.e. for $0 < x < 0.3$, than the longitudinal component, as was already observed in Ref. [4]. However, it can be equally important and it even becomes dominant for larger x and smaller y values.

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 $pp \rightarrow \Lambda^\uparrow X$.

[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

The T-odd effects link transverse momentum and transverse spin with a certain handedness, like e.g. the Collins effect:

$$H_1^\perp = \text{[Diagram 1]} - \text{[Diagram 2]}$$

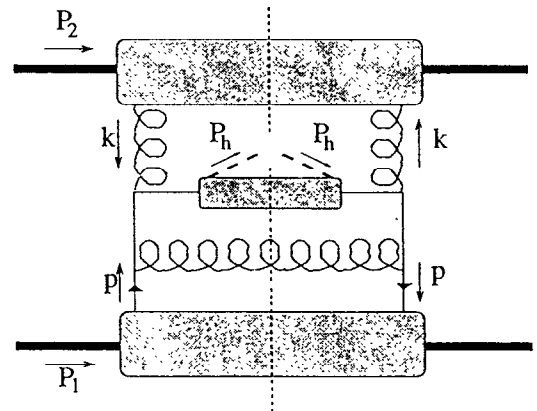
The diagram shows the definition of the Collins function $H_1^\perp$ as the difference between two cross-sections. In the first cross-section, a transversely polarized target (shaded rectangle) with spin vector S_T (pointing down and to the left) produces a pion π with transverse momentum k_T (pointing up). In the second cross-section, the target has the same spin S_T but is rotated, and the pion π is produced with transverse momentum k_T pointing in the opposite direction.

Expected to arise due to final state interactions between π and X

Can lead to $pp^\uparrow \rightarrow \pi X$ asymmetry at leading order:

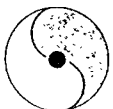
$$A_T \sim h_1(x_1) \otimes f_1(x_2) \otimes H_1^\perp(z, k_T)$$

Anselmino, Boglione & Murgia
(PRD 60 (99) 054027)



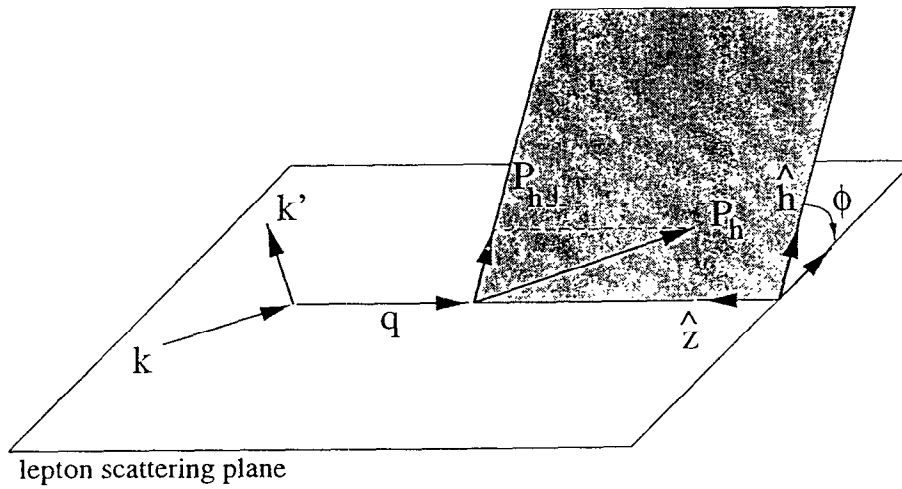
Other possible explanations:

- 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 $e + \vec{p} \rightarrow e' + \pi + X$

HERMES reported a $\sin \phi$ asymmetry at DIS99 [Zeuthen, April '99]

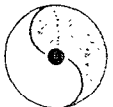


In a factorized picture (Mulders & Tangerman, NPB 461 (1996) 197):

$$\mathcal{W}^{\mu\nu} = \int d^2 \mathbf{p}_T d^2 \mathbf{k}_T \delta^2(\mathbf{p}_T + \mathbf{q}_T - \mathbf{k}_T) \text{Tr}(\Phi(x, \mathbf{p}_T) \gamma^\mu \Delta(z, \mathbf{k}_T) \gamma^\nu)$$

Project out the $\sin(\phi)$ dependence from the cross section:

$$A_{P_e P_H} \equiv \int d^2 \mathbf{P}_{h\perp} \frac{|\mathbf{P}_{h\perp}|}{zM} \sin(\phi) \frac{d\Delta\sigma_{P_e P_H}(\vec{\ell} \vec{H} \rightarrow \ell' h X)}{dx dz dy d\phi_\ell d^2 \mathbf{P}_{h\perp}}$$



HERMES Asymmetry in $e + \vec{p} \rightarrow e' + \pi + X$

We assume one flavor ($u \rightarrow \pi^+$) and neglecting a term M_π/M

Polarization of the target is in the lepton scattering plane

$$A_{OL} \propto \lambda 2(2-y)\sqrt{1-y} \frac{M}{Q} x h_L(x) H_1^{\perp(1)}(z)$$

$$A_{OT} \propto |\mathbf{S}_\perp| (1-y) h_1(x) H_1^{\perp(1)}(z)$$

$$A_{LO} \propto \lambda_e 2y\sqrt{1-y} \frac{M}{Q} x e(x) H_1^{\perp(1)}(z) \stackrel{WW}{\propto} \frac{m_u}{Q} \approx 0$$

where $H_1^{\perp(1)}(z) = z^2 \int d^2\mathbf{k}_T \mathbf{k}_T^2 H_1^\perp(z, \mathbf{k}_T)$

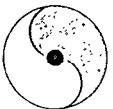
HERMES:

Polarization of the target is along the electron beam direction

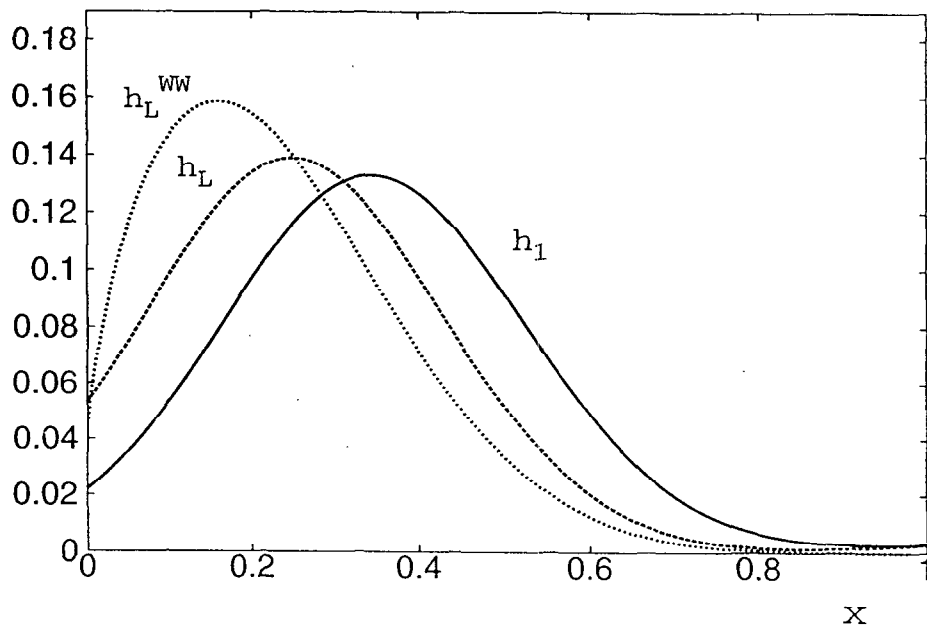
This is a combination of L and T , depending on y

We find

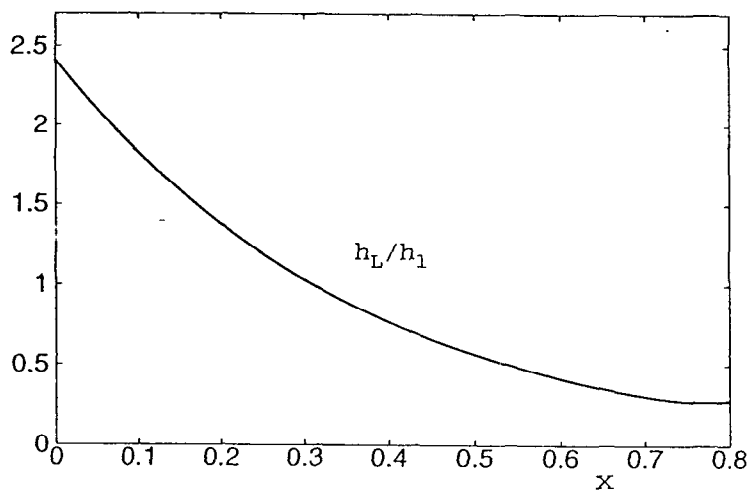
$$\frac{|\mathbf{S}_\perp|}{\lambda} = \sqrt{1-y} \frac{2Mx}{Q} \quad \Rightarrow \quad \frac{A_{OL}}{A_{OT}} = \frac{2-y}{1-y} \frac{h_L(x)}{h_1(x)}$$



HERMES Asymmetry in $e + \vec{p} \rightarrow e' + \pi + X$



Bag model

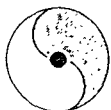


For $0.2 < y < 0.8$:

$$2 \frac{h_L}{h_1} < \frac{A_{OL}}{A_{OT}} < 6 \frac{h_L}{h_1}$$

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 $D_{1T}^\perp$:

$$D_{1T}^\perp = \text{[Diagram 1]} - \text{[Diagram 2]}$$

Mulders & Tangerman, NPB 461 (1996) 197

This is the analogue of the Sivers effect function (PRD 41 (1990) 83)

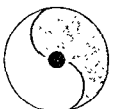
Application to transversely polarized Λ production

(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.

These T -odd functions satisfy the sum rules

$$\begin{aligned} \text{Schäfer-Teryaev} \quad & \sum_h \int dz \, z \, H_1^{\perp(1)}(z) = 0 \\ & \sum_h \int dz \, z \, D_{1T}^{\perp(1)}(z) = 0 \end{aligned}$$



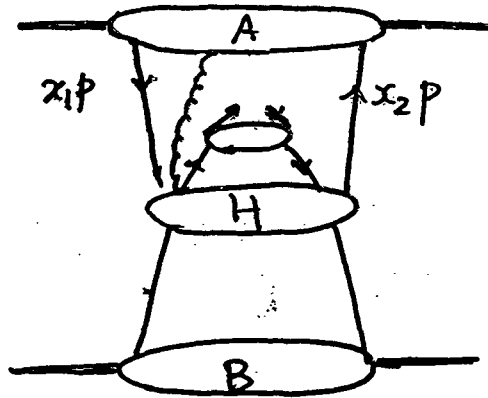
Single-Transverse Spin Asymmetry for Pion Production at RHIC

Y. Kanazawa and Yuji Koike

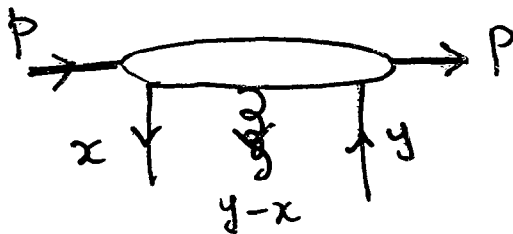
Department of Physics, Niigata University,
Ikarashi, Niigata 950-2181, Japan

A formula for the single transverse spin asymmetry in the large- p_T pion production in the nucleon-nucleon collision is derived. We focus on the chiral-odd contribution where the transversity distribution and the chiral-odd spin-independent twist-3 distribution contributes. This contribution is expected to give rise to a large effect at $x_F \rightarrow -1$.

Twist-3 effects



Twist-3 distributions = quark-gluon correlation



$$\vec{P} \parallel +\hat{e}_z$$

$$p^+ \neq 0 \quad n^- = \frac{1}{p^+}$$

$$p^2 = n^2 = 0, \quad p \cdot n =$$

$$T_F(x, y) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x} e^{i\mu(y-x)}$$

$$\times \langle ps | \bar{\psi}(0) \Gamma \underline{F}^{\alpha\beta}(\mu n) n_\beta \psi(\lambda n) | ps \rangle$$

$$T_D(x, y) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x} e^{i\mu(y-x)}$$

$$\times \langle ps | \bar{\psi}(0) \Gamma \underline{D}^{\alpha}(\mu n) \psi(\lambda n) | ps \rangle$$

$$\Gamma = \gamma_\mu, \gamma_\mu \gamma_5, \sigma_{\mu\nu}, 1, \gamma_5$$

Classification of $T_F(x_1, x_2)$: 4-independent twist-3 distribution

$$T_{(T)}^{\mu\nu\alpha}(x_1, x_2) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle ps | \bar{\Psi}(0) \sigma^{\mu\nu} i \gamma_5 F^{\alpha\beta}(\mu n) n_\beta \Psi(\lambda n) | ps \rangle$$

$$= \underline{i} M(S \cdot n) \{ (g^{\mu\alpha} p^\nu - g^{\nu\alpha} p^\mu) - p^\alpha (n^\mu p^\nu - n^\nu p^\mu) \} T_F^{(T)}(x_1, x_2) \\ + M(p^\mu \epsilon^{\nu\alpha\beta\lambda} - p^\nu \epsilon^{\mu\alpha\beta\lambda}) p_\lambda n_\beta T_F^{(S)}(x_1, x_2) + \dots \quad \leftarrow S_{11}$$

$\leftarrow$ spin average

$$T_{(V)}^{\mu\alpha}(x_1, x_2) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle ps | \bar{\Psi}(0) \gamma^\mu F^{\alpha\beta}(\mu n) n_\beta \Psi(\lambda n) | ps \rangle$$

$$= p^\mu \epsilon^{\alpha\nu\kappa\lambda} p_\nu n_\kappa S_{\perp\lambda} T_F^{(V)}(x_1, x_2) + \dots \quad \leftarrow S_{\perp}$$

$$T_{(A)}^{\mu\alpha}(x_1, x_2) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle ps | \bar{\Psi}(0) \gamma^\mu \gamma_5 F^{\alpha\beta}(\mu n) n_\beta \Psi(\lambda n) | ps \rangle$$

$$= \underline{i} p^\mu S_{\perp}^\alpha T_F^{(A)}(x_1, x_2) + \dots \quad \leftarrow S_{\perp}$$

(cf. Kodaira & To
P.T.P. '91)

N.B.

① $T_F^{(i)} (i = V, A, T, S)$ are real.

② $T_F^{(i)}(x_1, x_2) = T_F^{(i)}(x_2, x_1) \quad (i = V, S)$

$T_F^{(i)}(x_1, x_2) = -T_F^{(i)}(x_2, x_1) \quad (i = A, T)$

③ Similar classification for $T_D(x_1, x_2)$.

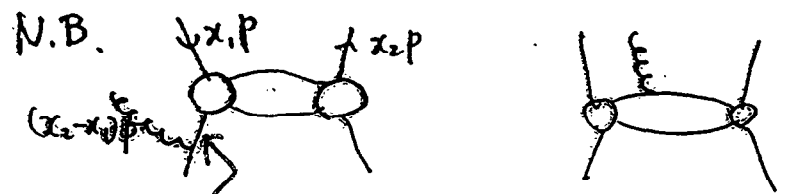
$T_F^{(i)}(x_1, x_2)$ and $T_D^{(i)}(x_1, x_2)$ are not independent.

We eventually have :

$$d\sigma = d\sigma_{ca}^0 + \underbrace{d\sigma_{ca}^1 + d\sigma_{cb} + d\sigma_{cc}}_{\text{twist-3}} + \dots$$

$$d\sigma^{\text{twist-3}} = \left\{ \begin{array}{c} T_D^{(A,S,T)}(x_1, x_2) \\ T_F^{(A,S,T)}(x_1, x_2) \end{array} \right\} \otimes \left\{ \begin{array}{c} S^\sigma(x_1, x_2, x', z) \\ \frac{\partial S^\sigma}{\partial k_i^\alpha}(x_1, x_2, x', z) \end{array} \right\}$$

$$\otimes M(x') \otimes \hat{M}(z)$$

N.B. 

$$\frac{1}{x_1 - x_2 \pm i\epsilon} = P \frac{1}{x_1 - x_2} \mp i\pi \delta(x_1 - x_2)$$

or

$$\frac{1}{x_i \pm i\epsilon} = P \frac{1}{x_i} \mp i\pi \delta(x_i - x_j)$$

real imaginary

In addition : $T_F^{(u)}(x_1, x_2)$ appears with

$$\frac{\partial S^\sigma}{\partial k_i^\alpha}(x_1, x_2, x', z) \sim \left\{ \begin{array}{c} \delta(x_1 - x_2) \delta'(\hat{s} + \hat{t} + \hat{u}) \\ \delta'(x_1 - x_2) \delta(\hat{s} + \hat{t} + \hat{u}) \\ \delta(x_1 - x_2) \delta(\hat{s} + \hat{t} + \hat{u}) \end{array} \right\} \Rightarrow x_1 = x_2 = x$$

$\delta((x'p + x'p' - \frac{1}{2}z)^2)$

$$\hat{s} + \hat{t} + \hat{u} = x'x'S - xT/z - x'U/z$$

$$\Rightarrow T_F^{(A,T)}(x, x) = 0$$

$$\frac{\partial}{\partial x} T_F^{(S,V)}(x, x) \quad \text{and} \quad T_F^{(S,V)} \quad \text{survive.}$$

At Large $x_F (\sim 1) \Rightarrow x$ large, (x' small)

$$T_F^{(v,s)}(x,x) \sim (1-x)^\beta \quad (\beta > 0) \quad \text{at } x \sim 1$$

We have $\frac{\partial}{\partial x} T_F^{(v,s)}(x,x) \gg T_F^{(v,s)}(x,x)$

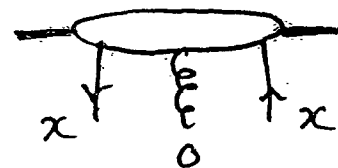
Thus we keep only terms with

$$\delta(x_1 - x_2) \delta'(\hat{s} + \hat{t} + \hat{u})$$

and

$$\delta'(x_1 - x_2) \delta(\hat{s} + \hat{t} + \hat{u})$$

"Soft gluon pole"



N.B.

$$x_F \rightarrow 1$$

$$\left\{ \begin{array}{ll} x: \text{large} & T_F^{(v)}(x,x) \text{ "Valence" contribution dominates} \\ x': \text{small} & M(x') \text{ sea and gluon contribution dominates} \end{array} \right.$$

Final result for $P^+ + p \rightarrow \pi + X$

$$F_\pi \frac{d^3\Delta\sigma}{dP_\pi^3} = \frac{\pi\alpha_s^2}{S} \sum_{a,c} \int \frac{dz}{z^3} \underline{\hat{f}_1^c(z)} \int \frac{dx}{x} \frac{1}{xS+U/z} \int \frac{dx'}{x'} \delta(x' + \frac{xT/z}{xS+U/z})$$

$$\times \epsilon_{\mu\nu\lambda\sigma} P_\pi^\mu S_1^\nu P^\lambda n^\sigma \left(\frac{1}{-\hat{u}} \right) \left[-x \frac{\partial}{\partial x} T_{Fa}^{(\nu)}(x, x) \right] \quad (\chi_F \rightarrow 1)$$

$$\times \left[\underline{G(x')} \Delta\hat{\sigma}_{ag \rightarrow c} + \sum_b \underline{f_1^b(x')} \Delta\hat{\sigma}_{ab \rightarrow c} \right] \quad \leftarrow \text{Qiu \& Sterman}$$

$$+ \frac{\pi\alpha_s M}{S} \sum_{a,b,c} \int \frac{dz}{z^3} \underline{\hat{f}_1^c(z)} \int \frac{dx'}{x'} \frac{1}{x'S+T/z} \int \frac{dx}{x} \delta(x + \frac{x'U/z}{x'S+T/z})$$

$$\times \epsilon_{\mu\nu\lambda\sigma} P_\pi^\mu S_1^\nu P^\lambda n^\sigma \left(\frac{1}{-\hat{t}} \right) \left[-x' \frac{\partial}{\partial x'} T_F^{(S)}(x', x') \right] \Delta\hat{\sigma}'_{ab \rightarrow c} \underline{h_1^a(x)}$$

$$\begin{cases} a: u, d, s, \bar{u}, \bar{d}, \bar{s} \\ b: u, d \\ c: u, d, \bar{u}, \bar{d} \end{cases}$$

dominant
at $\chi_F \rightarrow -1$

$$\Delta\hat{\sigma}'_{ab \rightarrow c} = \left\{ \frac{10}{27} + \frac{1}{27} \left(1 + \frac{\hat{t}}{\hat{u}} \right) \right\} \delta_{ab} \delta_{bc}$$

$$\Delta\hat{\sigma}'_{\bar{a}b \rightarrow c} = - \left\{ \frac{1}{9} + \frac{7}{9} \left(1 + \frac{\hat{t}}{\hat{u}} \right) \right\} \frac{\hat{t}\hat{u}}{\hat{s}^2} \delta_{\bar{a}b}$$

$$\Delta\hat{\sigma}'_{\bar{a}b \rightarrow \bar{c}} = - \left\{ \frac{1}{9} + \frac{2}{9} \left(1 + \frac{\hat{t}}{\hat{u}} \right) \right\} \frac{\hat{t}\hat{u}}{\hat{s}^2} \delta_{\bar{a}b}$$

Present
result

+ ...

The nonlocal operator expansion for Drell-Yan process

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We develop an operator formalism for studying the Drell-Yan production of lepton pair in hadron-hadron collisions. We employ the generalized Wilson operator expansion where the main ingredients are the so-called time-loop (Keldysh) technique and the gauge-invariant nonlocal operators. Compared to conventional approaches based on the collinear expansion of the relevant diagrams, our approach has an advantage of preserving explicitly Lorentz and gauge invariance, and thus provides a convenient framework for systematic treatment of the Drell-Yan processes. Utilizing the background field method, we derive the coefficient functions at tree level in the generalized operator expansion, which are relevant to the asymmetry observables through order $1/Q$ (twist-3) for the Drell-Yan processes with polarized beams. We emphasize novel role played by the “color octet terms”, which are generated by the Fierz rearrangement of the color indices for the quark fields in the electromagnetic currents. We demonstrate that at higher twist the color octet terms produce the “contact terms” due to quark-antiquark-gluon correlation, which are essential to preserving electromagnetic gauge invariance of the result.

Contents

1. Introduction

2. Factorization in Drell-Yan process (DY)

3. Previous approaches for higher twists

4. Generalized operator product expansion (OPE)

Keldysh (time-loop) technique

gauge-invariant nonlocal operator

5. Application to twist-3 chiral-even terms

in DY

twist-expansion & QCD EOM

"contact term" vs "color octet term"

6. Summary

$$d\sigma^{DY} \sim L^{\mu\nu} W_{\mu\nu}$$

$$W_{\mu\nu} = \int d^4x \bar{e}^{iq \cdot x} \langle P_A, P_B | J_\mu(x) J_\nu(0) | P_A, P_B \rangle_{in}$$

Why no OPE?

$$① W_{\mu\nu} \neq \int d^4x \bar{e}^{iq \cdot x} \langle P_A, P_B | T J_\mu(x) J_\nu(0) | P_A, P_B \rangle_{in}$$

$$② J_\mu(x) J_\nu(0) = \sum_{n=\text{dim.}} C_n(x) \underbrace{O_n(0)}_{\downarrow} \\ O_n^A(0) \otimes O_n^B(0)$$

Generalized OPE

① Operator formalism for cut diagram (Cutkosky rule)

Time-loop (Keldysh) diagram technique

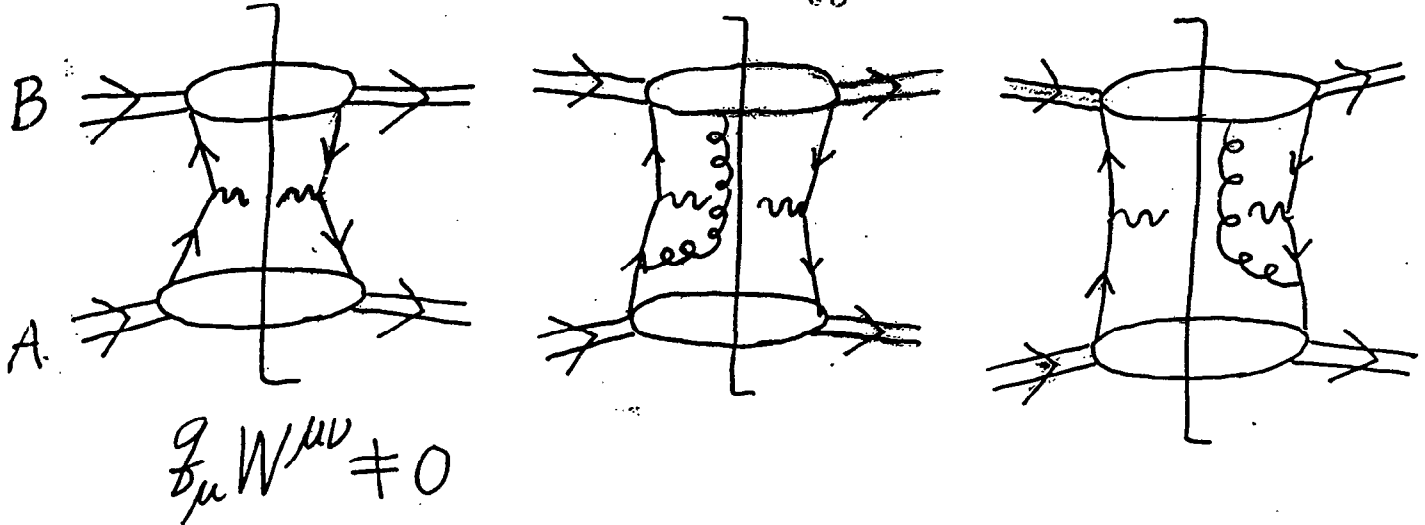
Balitsky-Braun ('91): $e^+ + e^- \rightarrow A + X$

② Nonlocal operator expansion

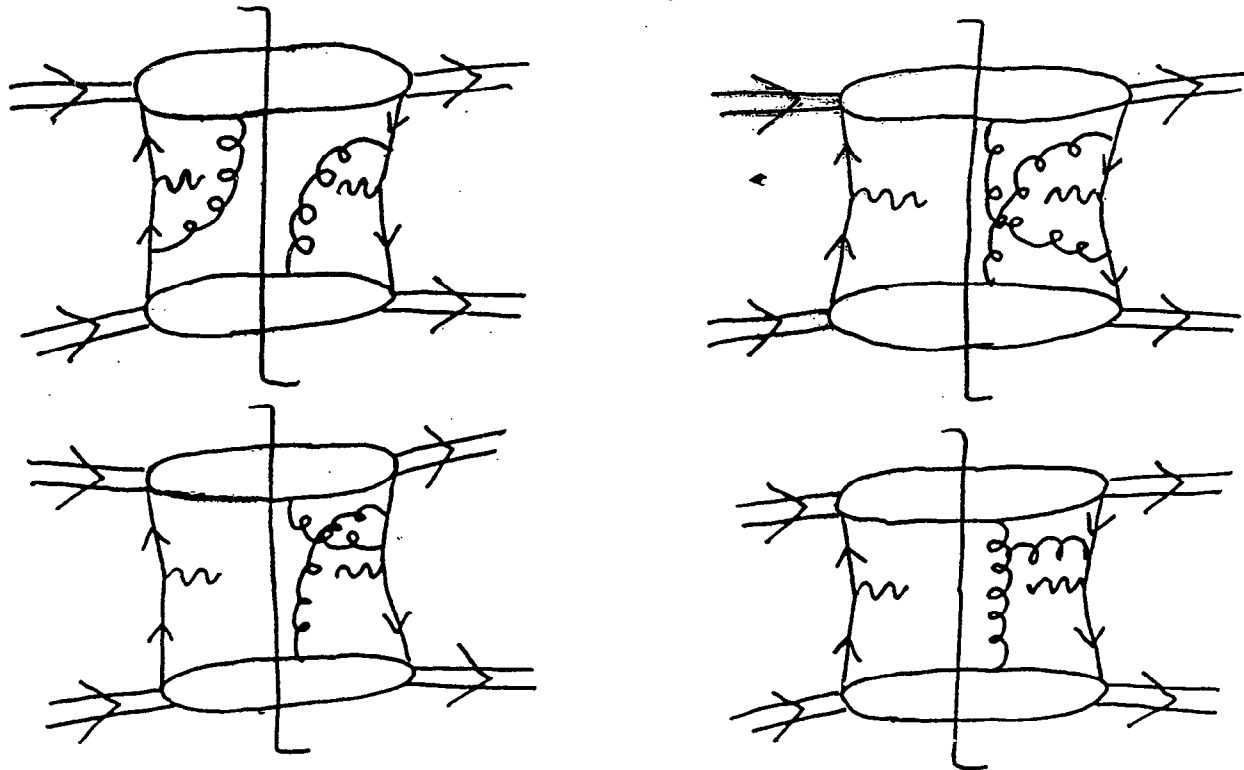
$$T J_\mu(x) J_\nu(0) = \tilde{C}(x) \underbrace{(H)(x, 0)}_{\rightarrow (H)^A(x, 0) \otimes (H)^B(x, 0)}$$

Free coefficient function for higher twist terms in DY "Diagrammatic approach"

Twist-3 in $\vec{P} + \vec{P}$: Jaffe-Ji ('92)



Twist-4 in $P + P$: Liu-Sterman ('91)

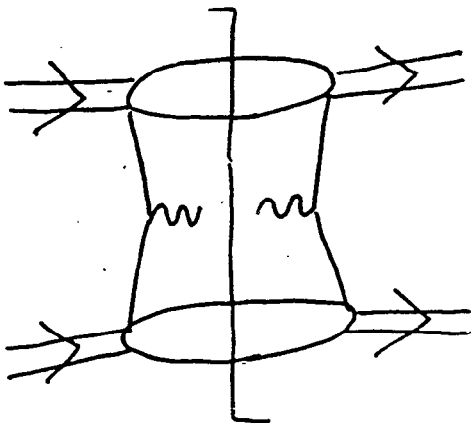


• "contact terms" added by hand

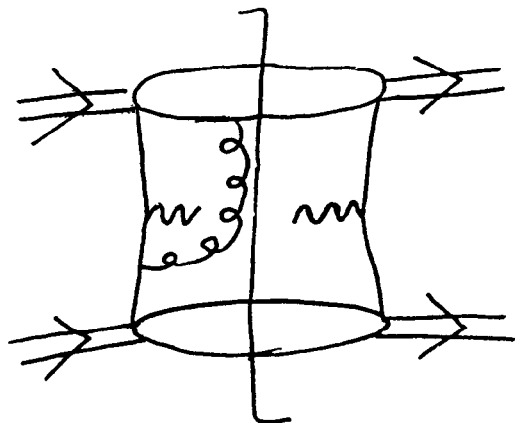
• not systematic: There might be $\Delta W^{\mu\nu}$ with $g_\mu \Delta W^{\mu\nu} = 0$

$$\begin{aligned}
 & |J_-^\mu(x) J_+^\nu(-x)|_{\chi\text{-even, spin-dep.}} \quad \left(Pe^{ig \int_{\gamma} dy_\mu A^\mu(y)} \right) \\
 &= -\frac{1}{2N_c} \left[\bar{\psi}(x) \gamma^\mu \gamma_5 \psi(-x) \bar{\psi}(-x) \gamma^\nu \gamma_5 \psi(x) \right. \\
 &\quad - \int_0^1 du u^2 \left\{ \bar{\psi}(ux) \not{x} \gamma_5 \psi(-ux) \int_{-1}^1 dv \right. \\
 &\quad \times \bar{\psi}(-x) \left(iu g \boxed{G^{\mu\lambda}(uvx)} \not{x}_\lambda \gamma^\nu \gamma_5 + g \boxed{\tilde{G}^{\mu\lambda}(uvx)} \not{x}_\lambda \gamma^\nu \right) \psi(x) \\
 &\quad \left. \left. + (x \rightarrow -x) \right\} + O(\text{twist } 4) \right]
 \end{aligned}$$

"color singlet term"



"color octet term"



• no contact terms by hand!

• keep Lorentz and gauge invariance

Summary

Generalized OPE for DY

- ① Time-loop (Keldysh) diagram technique
- ② Expansion by gauge-invariant nonlocal operators

Systematic

Lorentz covariant

Gauge-invariant

} *good news for higher twist*

Calculation of
tree level coefficient functions
for twist-3 operators

background field method

Fock-Schwinger gauge

"Color Octet term"

→ "contact quark-gluon correlation term"

Circum-Pan-Pacific RIKEN Symposium on "High Energy Spin Physics"

Structure Functions of the Nucleon based on a Relativistic Faddeev Approach to the NJL Model

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**Dept. of Physics, Faculty of Humanities and Sciences, Tokyo Woman's Christian University, Tokyo 167-8585, Japan*

(Received)

Abstract

In this work we calculate the light cone momentum distributions of valence and sea quarks in the nucleon by using the relativistic Faddeev approach to the Nambu-Jona-Lasinio (NJL) model, and compare the calculated distributions with the empirical ones extracted from the nucleon structure functions. Since the introduction of light cone variables into the relativistic 3-body equations leads to several technical difficulties, we restrict ourselves, as a first step, to the so-called 'static approximation' to the Faddeev equation, which has been shown to work reasonably well for the description of baryon masses and other observables.

Our main concern is to investigate the connection between the flavor dependence of the valence quark distributions and the strength of the quark-quark correlations in the scalar diquark ($J^P = 0^+, T = 0$) and axial vector diquark ($J^P = 1^+, T = 1$) channels. While the scalar diquark correlations give rise to a flavor dependence in qualitative agreement with the empirically observed ones, the axial vector diquark correlations tend to weaken the flavor dependence. In particular, we point out that if the strength of the axial vector diquark correlations is chosen such as to reproduce the observed delta-nucleon mass difference, the flavor dependence of the valence quark distributions is in disagreement with experiment. This seems to indicate that the description of loosely bound states like the delta in effective quark theories which do not incorporate the confinement is somewhat problematic.

We also investigate the flavor dependence of the sea quark distributions due to the effects of the (composite) pionic cloud around the constituent quarks. By making use of the familiar one-dimensional convolution formalism we find that the empirical value of the Gottfried sum is well reproduced, but the distributions themselves show that the calculated flavor dependence is too weak (except for the region of very small x .) This might indicate the necessity to go beyond the usual convolution formalism by taking properly into account the off-shellness of the 'parent' quarks in the nucleon.

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STRUCTURE FUNCTIONS OF THE NUCLEON BASED ON A RELATIVIST. FADDEEV APPROACH TO THE NJL MODEL

H. Mineo, K. Yazaki, W. Bentz

(1) Introduction: "Full" Faddeev
approach

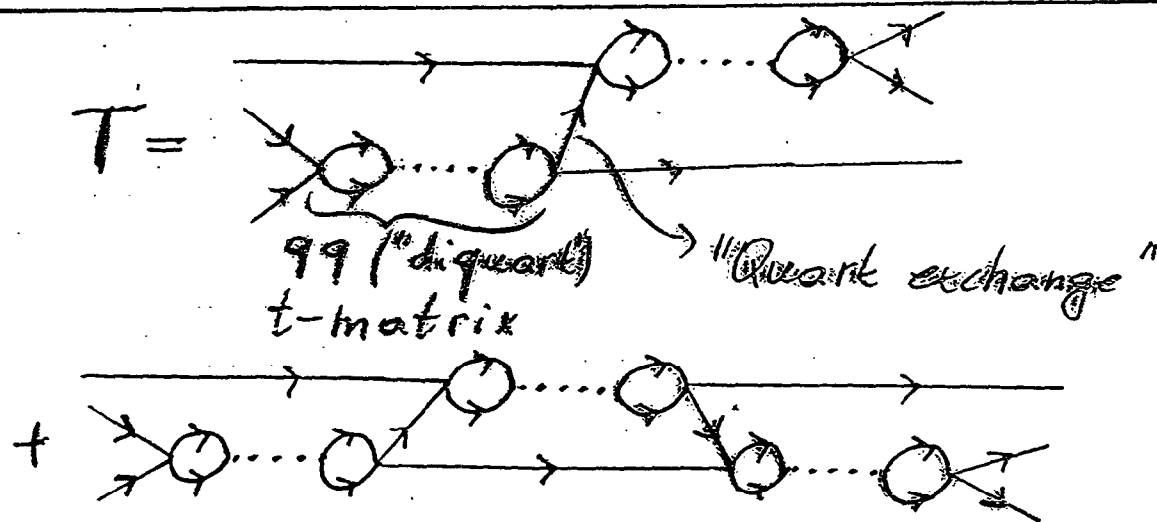
(2) Nucleon structure functions in
a simple approximation to (1);

{ Role of 1^+ qq channel
Flavor asymmetry ($u_v(x) - 2d_v(x)$)

(1) "Full" Faddeev approach to NJL

$$\mathcal{L} = (\bar{\Psi} i \not{\partial} - m) \Psi + \cancel{\mathcal{L}_I, \text{ chir. symm.}}$$

Relativistic Faddeev eq. in ladder approx



$\Rightarrow$ Effective BS equation for quark + "diquark".

"Diquark" channels: 0^+ (scalar)
 1^+ (axial vector)

Solved numerically using Wick rotation and Euclidean cut-off.

(Constit. quark mass $M = 400 \text{ MeV}$; 47

Without pion cloud: Proton = Quark + Diquark
 $(\alpha = S, A)$ q^α $D_\alpha = (qq)_\alpha$

$$q_v(x) = \text{valence} \quad \text{Diagram 1} + \text{Diagram 2}$$

$$u_v(x) = q^S(x) + \frac{1}{2} q_{D_S}(x) + \frac{1}{3} q^A(x) + \frac{5}{6} q_{D_A}(x)$$

$\bar{u} \text{ (ud)}_S + u \text{ (du)}_S + \bar{u} \text{ (ud)}_A + [u \text{ (du)}_A + d \text{ (uu)}_A]$

$$d_v(x) = \frac{1}{2} q_{D_S}(x) + \frac{2}{3} q^A(x) + \frac{1}{6} q_{D_A}(x)$$

$q^\alpha(x)$ Distrib. of q^α in proton

$q_{D_\alpha}(x)$ (Distrib. of q in D_α) $\otimes$
 (Distrib. of D_α in proton)

Normalizations (number sum rules):

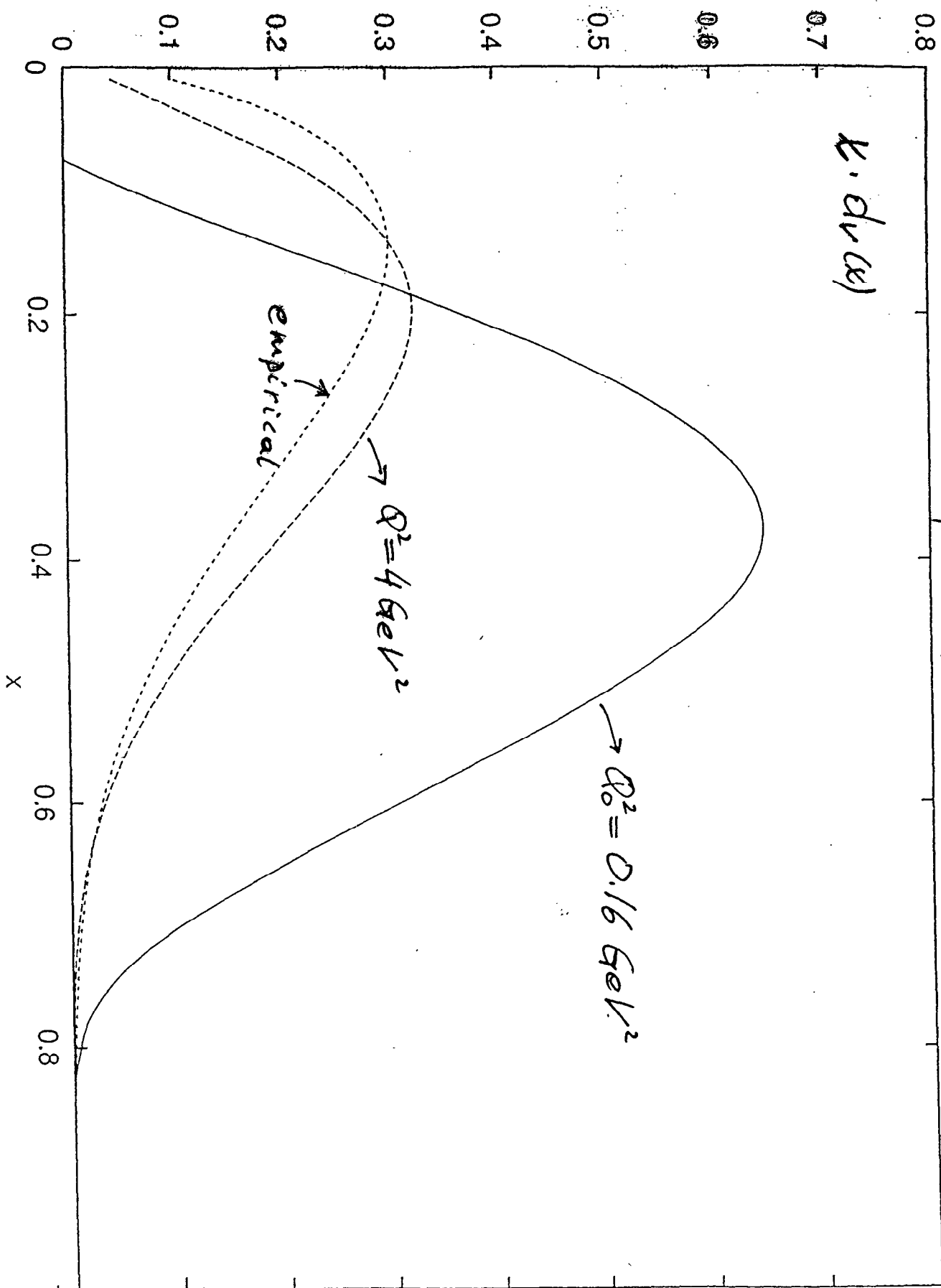
$$\int_0^1 dx q^\alpha(x) = W^\alpha; \quad \int_0^1 dx q_{D_\alpha}(x) = 2W^\alpha$$

Here W^α = "weight" of channel α

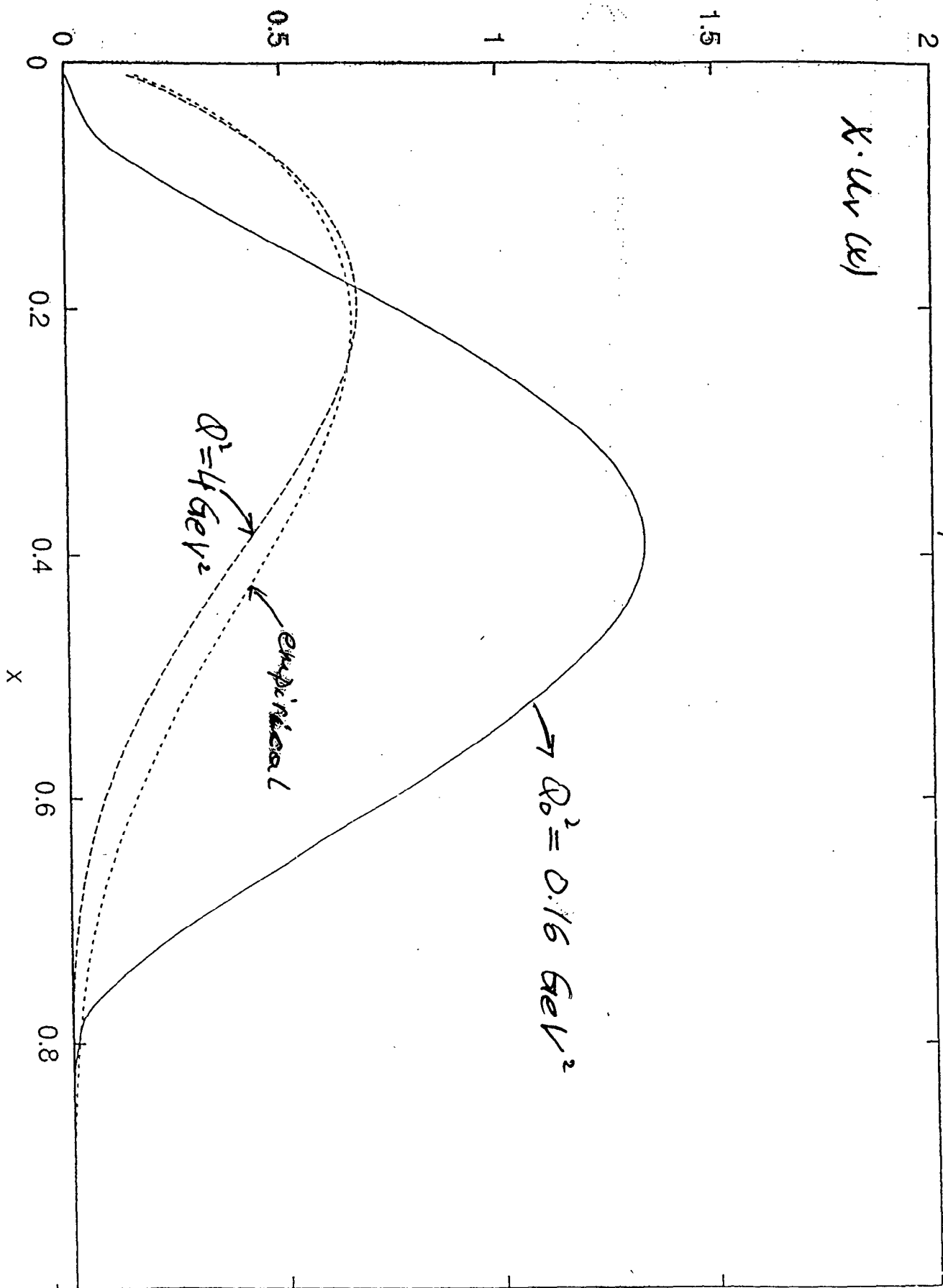
(Baryon number = $W^S + W^A = 1$.)

$$\Rightarrow \int_0^1 dx u_v(x) = 2; \quad \int_0^1 dx d_v(x) = 1.$$

Scalar + a.v. diquark, incl. π cloud effects



Scalar + a.v. diquark, incl. $\mathbb{U}$ cloud effects



Longitudinal Spin Dependence of Massive Lepton Pair Production

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Argonne, IL 60439

I show that massive lepton-pair production, the Drell-Yan process, should be a good source of independent constraints on the polarized gluon density, free from the experimental and theoretical complications of photon isolation that beset studies of prompt photon production. I provide predictions for the spin-averaged and spin-dependent differential cross sections as a function of transverse momentum Q_T at energies relevant for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven.

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SPIN DEPENDENCE IN LEPTON PAIR PRODUCTION IN HADRON COLLISIONS

Circum-Pan-Pacific RIKEN Symposium

November 3 - 6, 1999

Edmond L. Berger

with Lionel Gordon and Michael Klasen, [hep-ph/9909446](#)

also, Phys. Rev. D58, 074012 (1998)

Outline:

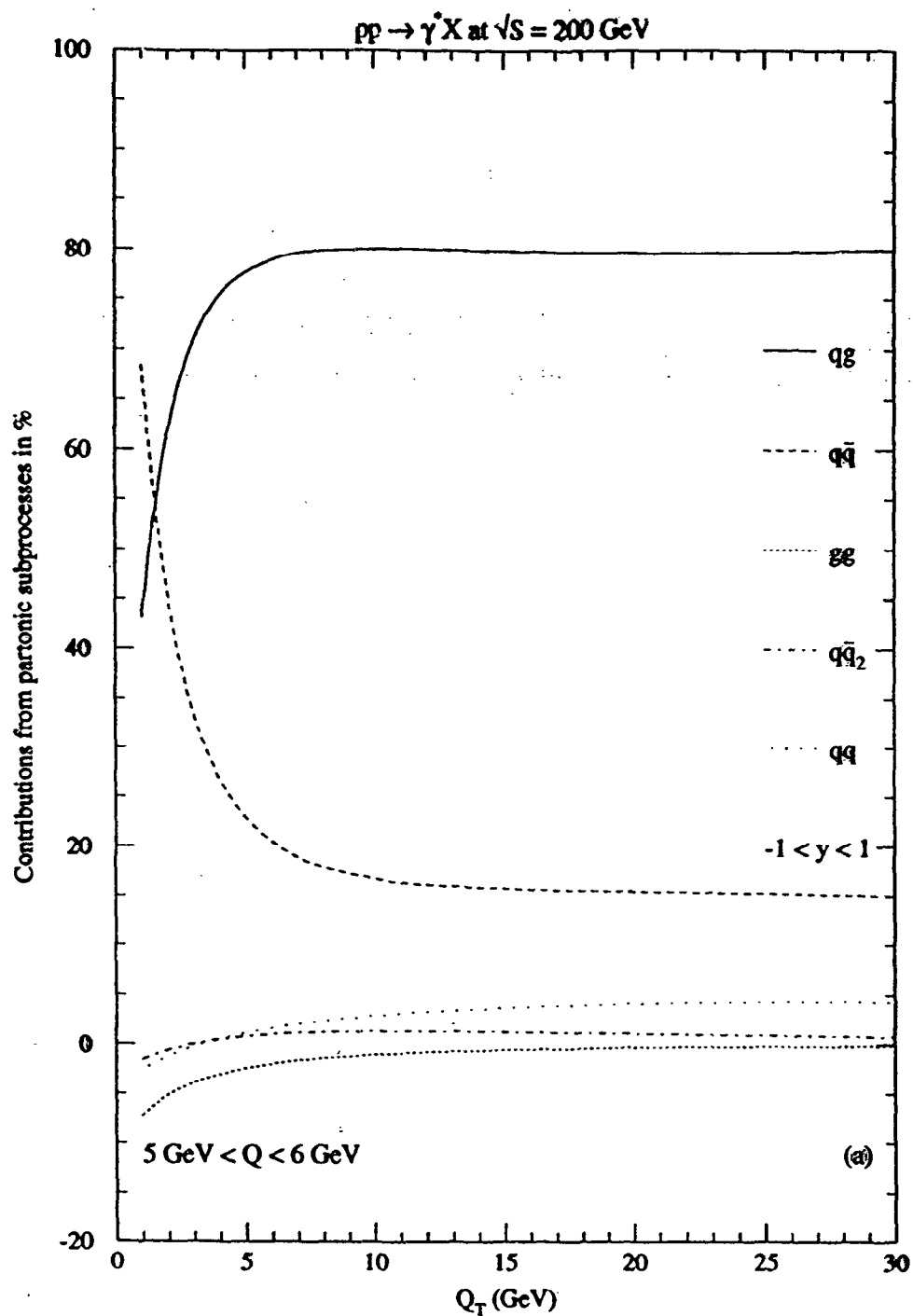
- Introduction
- Next-To-Leading Order QCD Formalism
- Transverse Momentum Distributions
- Predictions for A_{LL} at RHIC Energies
- Summary

<http://gate.hep.anl.gov/berger/seminars/RIKEN.ps>

INTRODUCTION

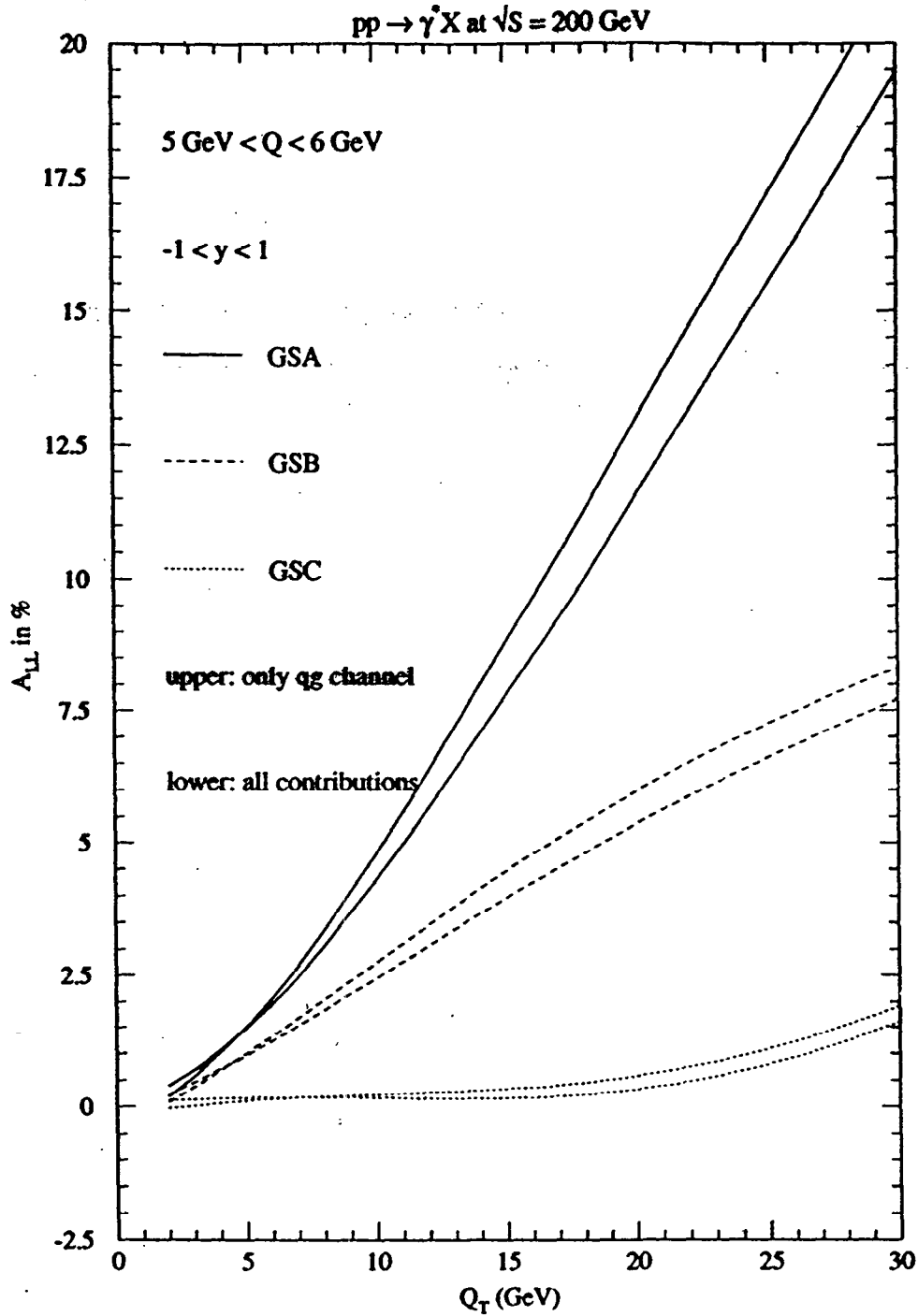
- Massive lepton pair production dominated by $q\bar{q} \rightarrow \gamma^* X$,
 “Drell-Yan process”, traditionally Q^2 large, Q_T^2 small.
 → Extract $\bar{q}(x, \mu_f^2 = Q^2)$ and $\Delta\bar{q}(x, \mu_f^2 = Q^2)$ from data
 Complementary to DIS → Extract $(q + \bar{q})(x, \mu_f^2 = Q^2)$
- Prompt photon production dominated by $qg \rightarrow \gamma X$,
 “QCD Compton process”, traditionally p_T^2 large, $Q^2 = 0$.
 → Extract $g(x, \mu_f^2 = p_T^2)$ and $\Delta G(x, \mu_f^2 = p_T^2)$ from data
- Partonic subprocesses at *finite* Q_T, p_T are identical:
 - $q\bar{q} \rightarrow \gamma^{(*)} g$
 - $qg \rightarrow \gamma^{(*)} q$
 - Higher order processes
- Focus on lepton pair production at *large transverse momentum*,
 $Q_T > Q/2$
- QCD Compton process dominant → Extract $g(x, \mu_f)$ and
 $\Delta G(x, \mu_f)$

TRANSVERSE MOMENTUM DISTRIBUTIONS



- qg accounts for about 80% of the rate at $Q_T \simeq Q$
- Subprocesses other than $q\bar{q}$ and qg are negligible

PREDICTIONS FOR A_{LL} - THREE CHOICES OF $\Delta G(x)$



- The qg channel accounts for most of A_{LL} when A_{LL} is large
- The $q\bar{q}$ subprocess, with $\hat{a}_{LL} = -1$ dilutes the effect

SUMMARY

- qg dominance is at least as strong in the Drell-Yan process for $Q_T > Q/2$ as it is in real prompt photon production
- No fragmentation function and no photon isolation required in the Drell-Yan case; no resummation needed for $Q_T > Q/2$
- Compton subprocess dominates polarized proton-proton reactions as long as $\Delta G(x, \mu_f)$ is not too small
- Extract $g(x, Q_T)$ and $\Delta G(x, Q_T)$ from data with
 - $Q > 4$ GeV at large Q_T . Establish utility
 - $Q \simeq 2$ GeV. Larger cross section
- A_{LL} should constrain the size, *sign*, and Bjorken x dependence of $\Delta G(x, \mu_f)$
- Extraction of $\Delta G(x, Q_T)$ requires several different approaches with expectation that consistent results must emerge
- Significant A_{LL} (i.e., ≥ 5 %) expected for $x_T = 2Q_T/\sqrt{S} > 0.10$ if $\Delta G(x, \mu_f)$ is as large as that in the GSA set
- For small $\Delta G(x, \mu_f)$, dominance of the qg subprocess is lost, and $\Delta G(x, \mu_f)$ is inaccessible
- Calculations of $d\sigma/dQ_T$ and of A_{LL} for $1.0 \leq y \leq 2.5$ will be available soon (PHENIX coverage)

Drell-Yan proton-deuteron asymmetry and polarized light-antiquark distributions

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ABSTRACT

We discuss proton-deuteron (p-d) asymmetry in polarized Drell-Yan processes and its relation to polarized light-antiquark flavor asymmetry. First, using the formalism of polarized proton-deuteron Drell-Yan process, which is recently completed, we explain that the p-d asymmetry R_{pd} which is defined by the ratio of pp and pd Drell-Yan cross sections ($\Delta_{(T)}\sigma^{pd}/2\Delta_{(T)}\sigma^{pp}$) is very sensitive to the polarized light-antiquark flavor asymmetry. Here, the notation $\Delta_{(T)}$ indicates Δ or Δ_T for the longitudinally polarized or transversity case, respectively. We find that the R_{pd} in the large- x_F region is particularly useful for finding the polarized flavor asymmetry.

Second, we show numerical results for the ratio $\Delta_{(T)}\sigma^{pd}/2\Delta_{(T)}\sigma^{pp}$ by using recent parametrizations for the longitudinally polarized distributions. Because there are no initial distributions for the transversity at this stage, we use the same longitudinal distributions for the initial transversity distributions at $Q^2 = 1 \text{ GeV}^2$. We simply vary $\Delta_{(T)}\bar{u}/\Delta_{(T)}\bar{d}$ by hand for investigating its effects on the R_{pd} . From this analysis, we find that the cross-section ratio R_{pd} is sensitive to the difference between $\Delta_{(T)}\bar{u}$ and $\Delta_{(T)}\bar{d}$ distributions, especially in the large- x_F region. We also investigate the dependence on the center-of-mass energy $\sqrt{s}$ and the used parametrizations. From these results, we find that the R_{pd} in the intermediate- x_F region has large dependence on the $\sqrt{s}$ and parametrizations. This fact suggests that the intermediate- x_F region is valuable to determine the detailed x dependence of the polarized antiquark distributions.

Our results are particularly important to study the flavor asymmetry in the transversity distributions because they can not be measured by the inclusive lepton scattering and W production process which is expected to provide valuable information on the flavor asymmetry in the unpolarized and longitudinally polarized distributions. At this stage, there is no proposal for the polarized pd Drell-Yan experiment. However, we think that there are possibilities at FNAL, HERA, and RHIC.

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Information on their research is available at <http://www-hs.phys.saga-u.ac.jp>.

Purpose

- ☆ Flavor asymmetry in the polarized light-antiquark distributions $\Delta_{(T)}\bar{u} - \Delta_{(T)}\bar{d}$
 - g_1 data are not enough to find the asymmetry
 - Semi-inclusive DIS $\rightarrow$ precision of the present data is not enough
 - T. Morii and T. Yamanishi, hep-ph/9905294
 - M. Wakamatsu and T. Watabe, hep-ph/9908425
 - Transversity distributions $\Delta_T \bar{q}(x)$
 - $\rightarrow$ can not be measured by inclusive DIS and W production
- $\Rightarrow$ Other processes should be studied
- $\Rightarrow$ Polarized proton-deuteron (pd)
Drell-Yan process (with pp Drell-Yan)

Proton-deuteron asymmetry

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

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

$$\Delta_{(T)} = \Delta \quad \text{or} \quad \Delta_T$$

- neglect nuclear effects in the deuteron
- assume isospin symmetry

$$\Delta_{(T)} u^d = \Delta_{(T)} u + \Delta_{(T)} d, \quad \Delta_{(T)} d^d = \Delta_{(T)} d + \Delta_{(T)} u$$

$$\Delta_{(T)} \bar{u}^d = \Delta_{(T)} \bar{u} + \Delta_{(T)} \bar{d}, \quad \Delta_{(T)} \bar{d}^d = \Delta_{(T)} \bar{d} + \Delta_{(T)} \bar{u}$$

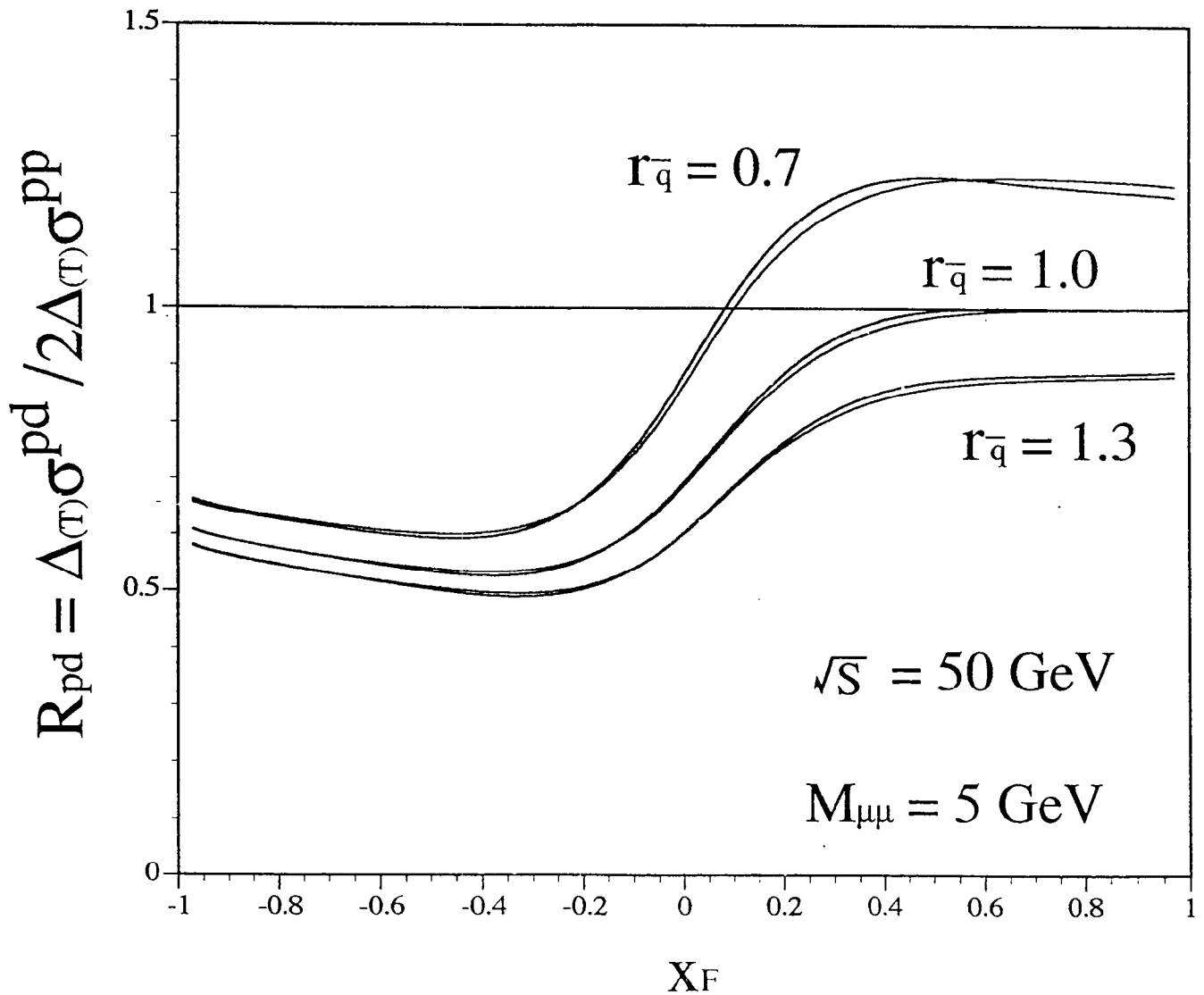
$$\Delta_{(T)} s^d = \Delta_{(T)} \bar{s}^d = 2\Delta_{(T)} s = 2\Delta_{(T)} \bar{s}$$

R_{pd} (LO evolution)

— Longitudinal

— Transverse

$$r_{\bar{q}} = \frac{\Delta_{(T)}\bar{u}}{\Delta_{(T)}\bar{d}}$$



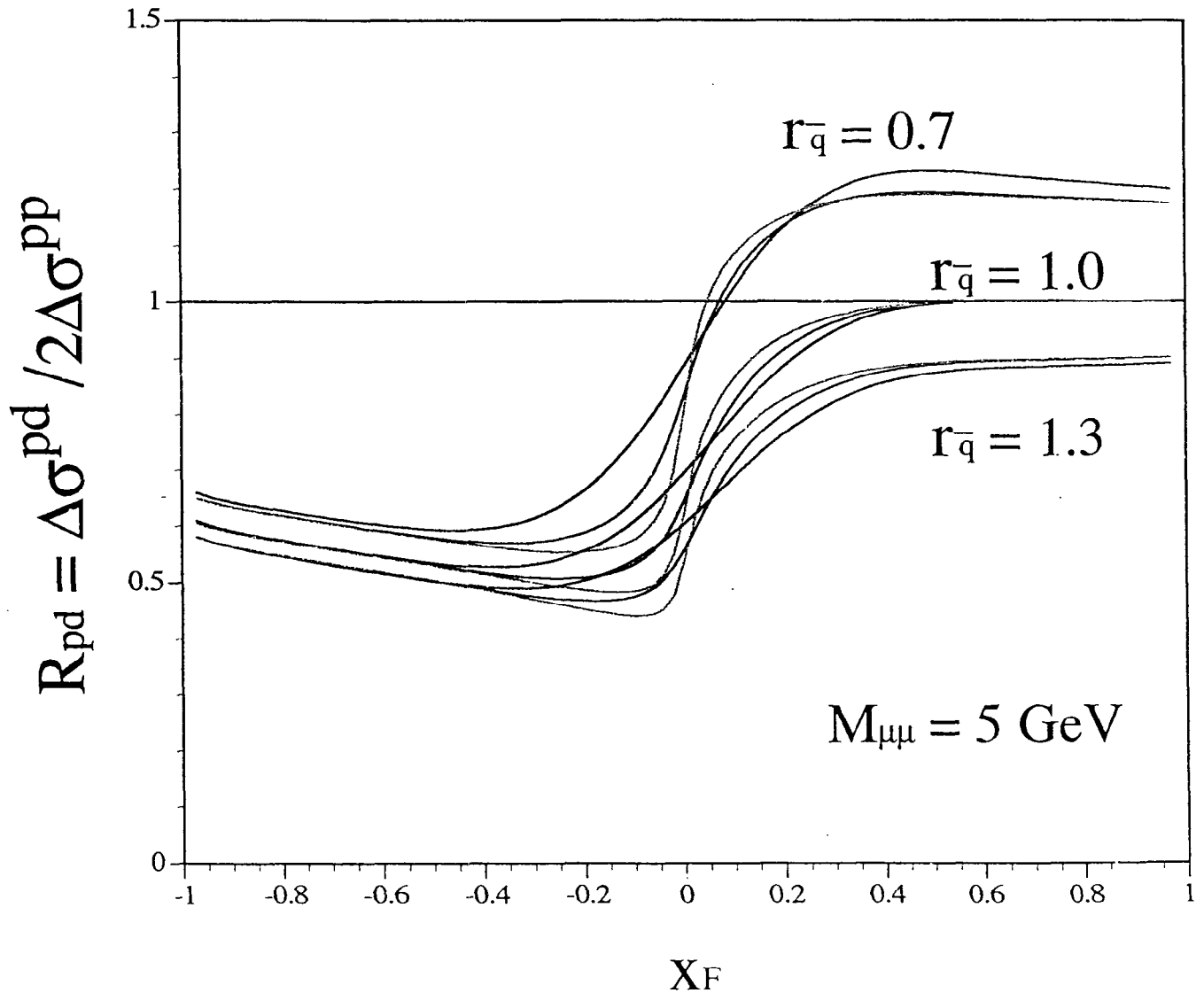
R_{pd} (c.m. energy dependence)

— $\sqrt{S} = 50$ GeV

— $\sqrt{S} = 200$ GeV

— $\sqrt{S} = 500$ GeV

$$r_{\bar{q}} = \frac{\Delta \bar{u}}{\Delta \bar{d}}$$



Summary

- $R_{pd} \equiv \frac{\Delta_{(T)}\sigma^{pd}}{2 \Delta_{(T)}\sigma^{pp}}$ has been studied.
- R_{pd} is useful for finding $\Delta_{(T)}\bar{u} / \Delta_{(T)}\bar{d}$ especially at $x_F \rightarrow 1$.
- The intermediate- x_F region
→ detailed x dependence of the $\Delta_{(T)}\bar{q}(x)$
- R_{pd} is important for the $\Delta_T q(x)$, for which W production and inclusive DIS do not provide information.
- Experimental possibility
→ FNAL , HERA , RHIC ...

Spin Dependent Structure Functions with Leading-Hadron Productions

J. C. PENG* and Guanghua XU**

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**Department of Physics, University of California,
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The feasibility of using high-mass dihadron production to probe polarized gluon distribution in the nucleon is examined. Taking into account all hard subprocesses involved in leading-order dihadron production, we obtain good agreement between calculations and the CCOR π^0 -pair production data. We predict the π^0 -pair production cross sections and double-helicity asymmetry at RHIC energies.

Spin Dependent Structure Functions with Leading-Hadron Productions

J. C. Peng

Los Alamos National Laboratory

Guanghua Xu

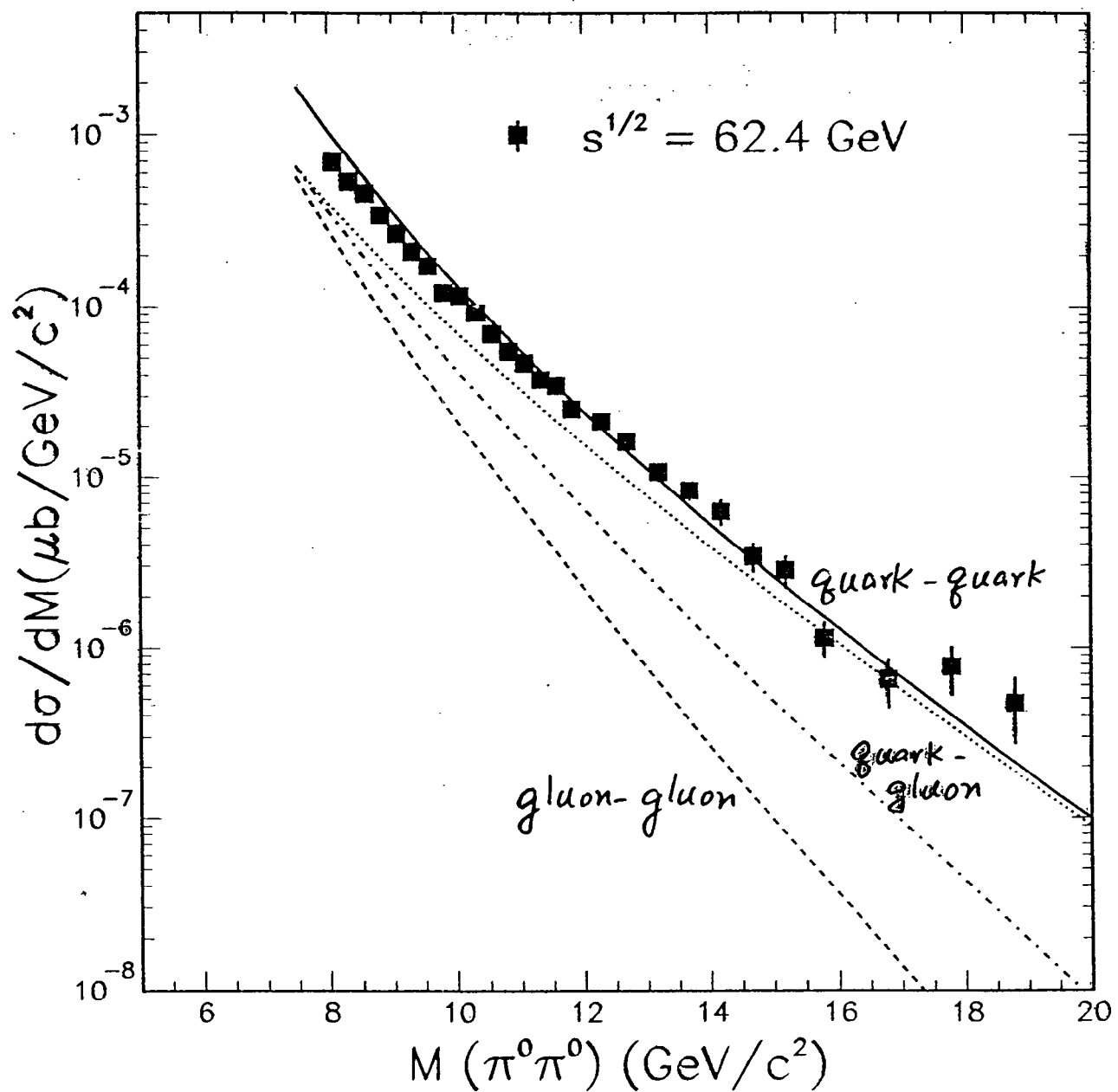
Univ. California, Riverside

RIKEN Symposium, November 4, 1999

Outline

- High-mass Dihadron Productions
- Comparison of Calculations with Existing Data
- Estimate of Sensitivities at RHIC

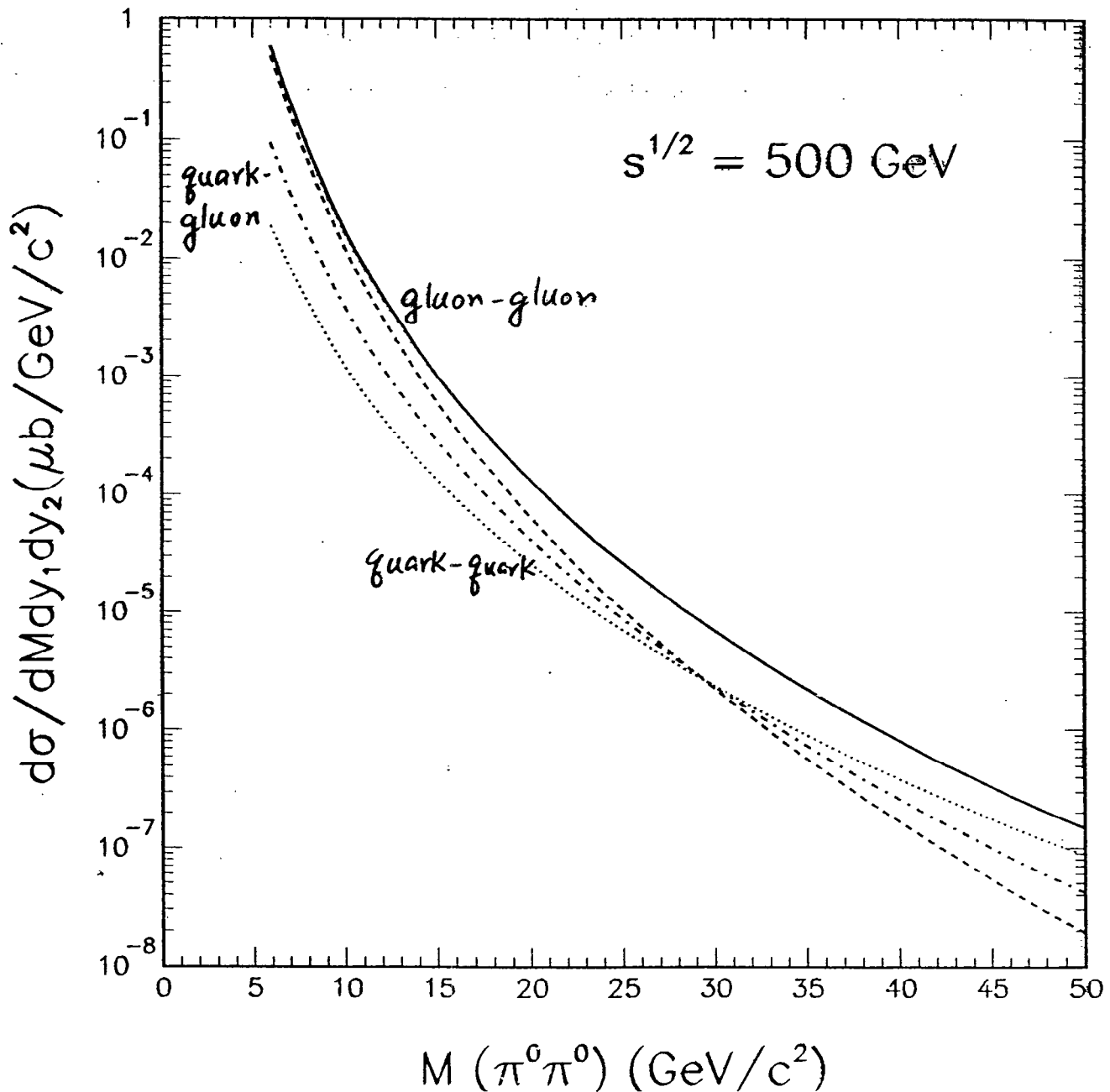
$P + P \rightarrow \pi^0 \pi^0 \chi$ data from
CCOR collaboration



$$d^3\sigma/dM dy_1 dy_2$$

$$p+p \rightarrow \pi^0 \pi^0 \pi \quad \text{at } \sqrt{s} = 500 \text{ GeV}$$

$$(y_1 = y_2 = 0, \quad P_T(\pi^0 \pi^0) < 1 \text{ GeV}/c)$$

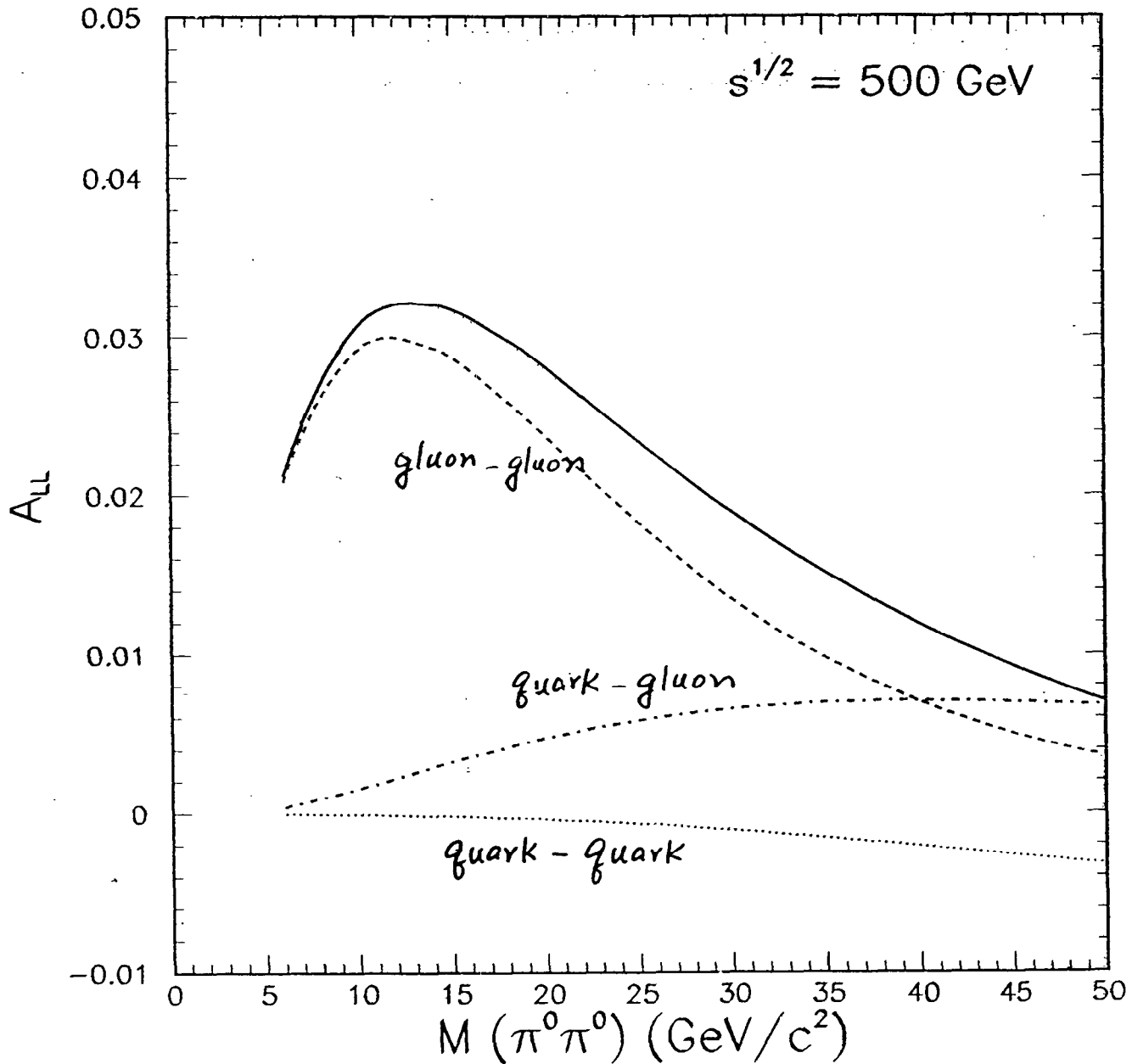


Double helicity asymmetry A_{LL}

$\vec{P} + \vec{P} \rightarrow \pi^0 \pi^0 \chi$ at $\sqrt{s} = 500 \text{ GeV}$

$(y_1 = y_2 = 0)$

$G - S(A)$



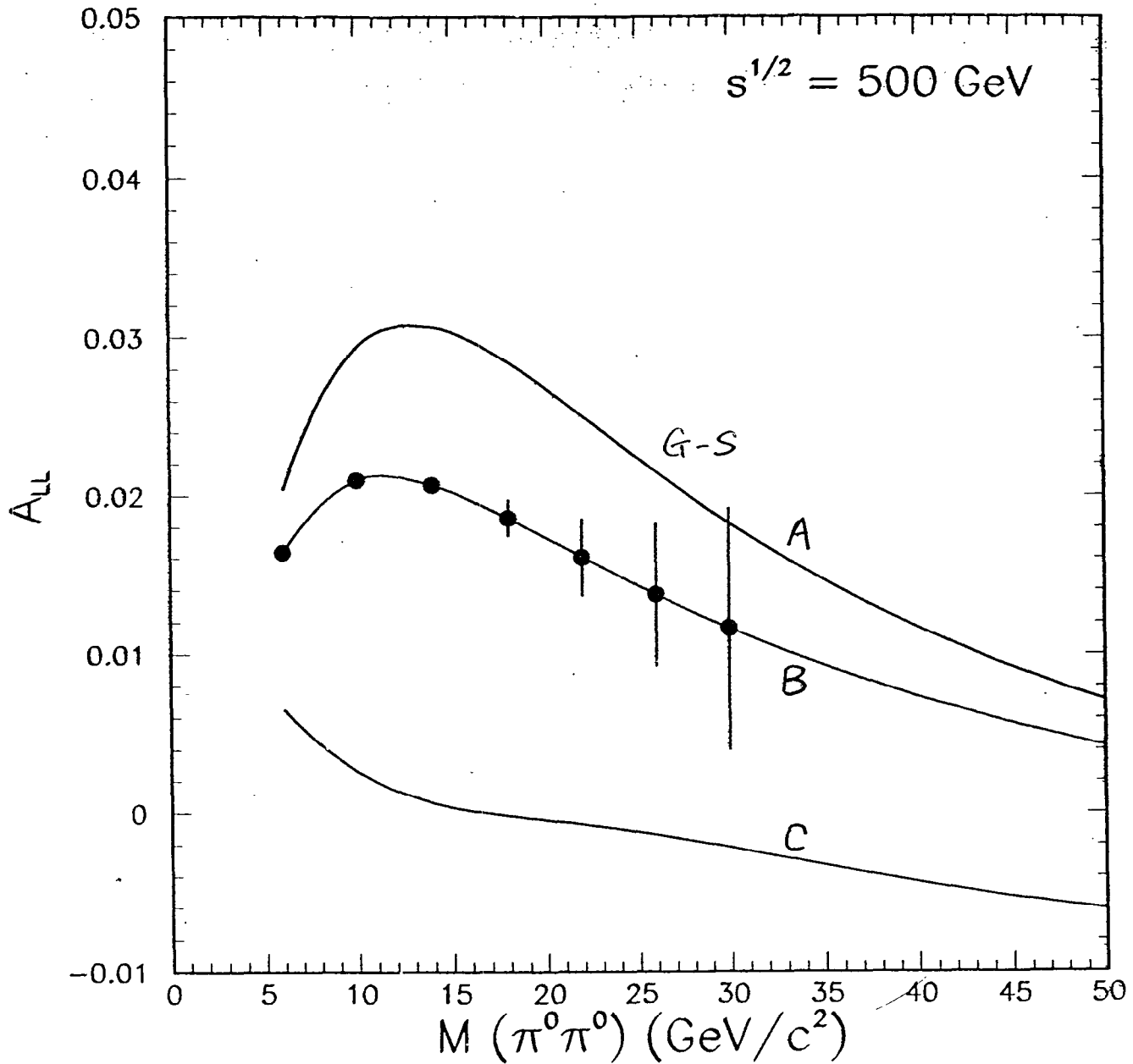
Expected statistical errors of A_{LL}

$\vec{p} + \vec{p} \rightarrow \pi^0 \pi^0 \pi$ at $\sqrt{s} = 500 \text{ GeV}$

integrated over PHENIX's acceptance

($|\eta| < 0.35$, $\Delta\phi = 2 \times 90^\circ$)

at 800 pb^{-1} luminosity



Hadron Spin Polarizations

— *The QRC Formulation, Puzzle and New Mechanism* —

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Abstract;

Spin observables in high energy hadron reactions, such as spin polarization, analyzing power and spin depolarization, are increasing interest to extract precise information of structure functions of quark partons in hadrons and even in leptons and photon. Almost two decades ago, DeGrand and Miettinen proposed a kinematical model to predict sign and to estimate order of magnitude of the spin observables produced in inclusive high energy hadron collisions.

Recently, we have proposed a general formulation for describing the spin observables of hadrons inclusively produced in high energy hadron collisions and we will show that our model, so-called microscopic quark recombination (QRC) model, is successful to reproduce the experimentally obtained spin observables. The QRC formulation can provide the spin observables as function of transverse momentum P_T and Feynman's variable x_F . This is an advantage of the model and extremely useful for extracting precise and valuable information from the observed data. I will show briefly the formulation and the results of applications.

There has been pointed out existing of so-called 'puzzles' in the hyperon spin polarizations and depolarizations observed inclusively and exclusively as well. I will discuss how it is possible to understand those 'puzzles' by extension of our QRC model with new mechanisms of hadron productions.

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Hadron Spin Polarization

*Dynamical spin-orbit interaction ,
Puzzle ,
New mechanism*

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*What kind of hadron reactions?
Motivation.*

1. The Microscopic Quark Recombination Model.
2. The Dynamical Spin-orbit Interaction.
3. Puzzle, New Mechanism.

For example, reaction $p \rightarrow \Lambda$

$$\begin{cases} q_1 = \text{valence } \underline{(ud)} \text{ diquark with spin-0} \\ q_2 = \text{sea } \underline{(s)} \text{ quark with spin-1/2} \end{cases}$$

Transition amplitude M ;

$$-iM = -i \left(\underline{M^{(2)}} + \underline{\underline{M^{(h)}}} \right)$$

$$-i \underline{M^{(2)}(p_4 s_4 p_2 s_2)} = -g^2 V(q) \bar{v}(p_4 s_4) v(p_2 s_2)$$

$$\begin{cases} v; \text{ Four-spinor with momentum } \mathbf{p}_i \\ v^{(\mu_i)}(\mathbf{p}_i s_i) = N \left(\frac{\chi^{(\mu_i)} \sigma_i \cdot \mathbf{p}_i}{E_i + m_i} \chi^{(\mu_i)} \right) \end{cases}$$

$$- \underline{\underline{M^{(h)}}} = \sqrt{(E_4 + m)(E_2 + m)} I^{(h)}$$

Spin-orbit Interaction

in the Quark Recombination Model

(1) $pp \rightarrow \Lambda X$

$$|\mathbf{M}_{\pm}|^2 \propto \mp [\mathbf{P}_s(\Lambda) \times \mathbf{P}_s(S)]_z : S(\Lambda) = \begin{cases} +1/2 \\ -1/2 \end{cases}$$

$$\langle |\mathbf{M}_{\pm}|^2 \rangle = \frac{1}{\Delta t} \int_0^{\Delta t} \langle |\mathbf{M}_{\pm}(t, \mathbf{p})|^2 \rangle_{\mathbf{p}} dt =$$

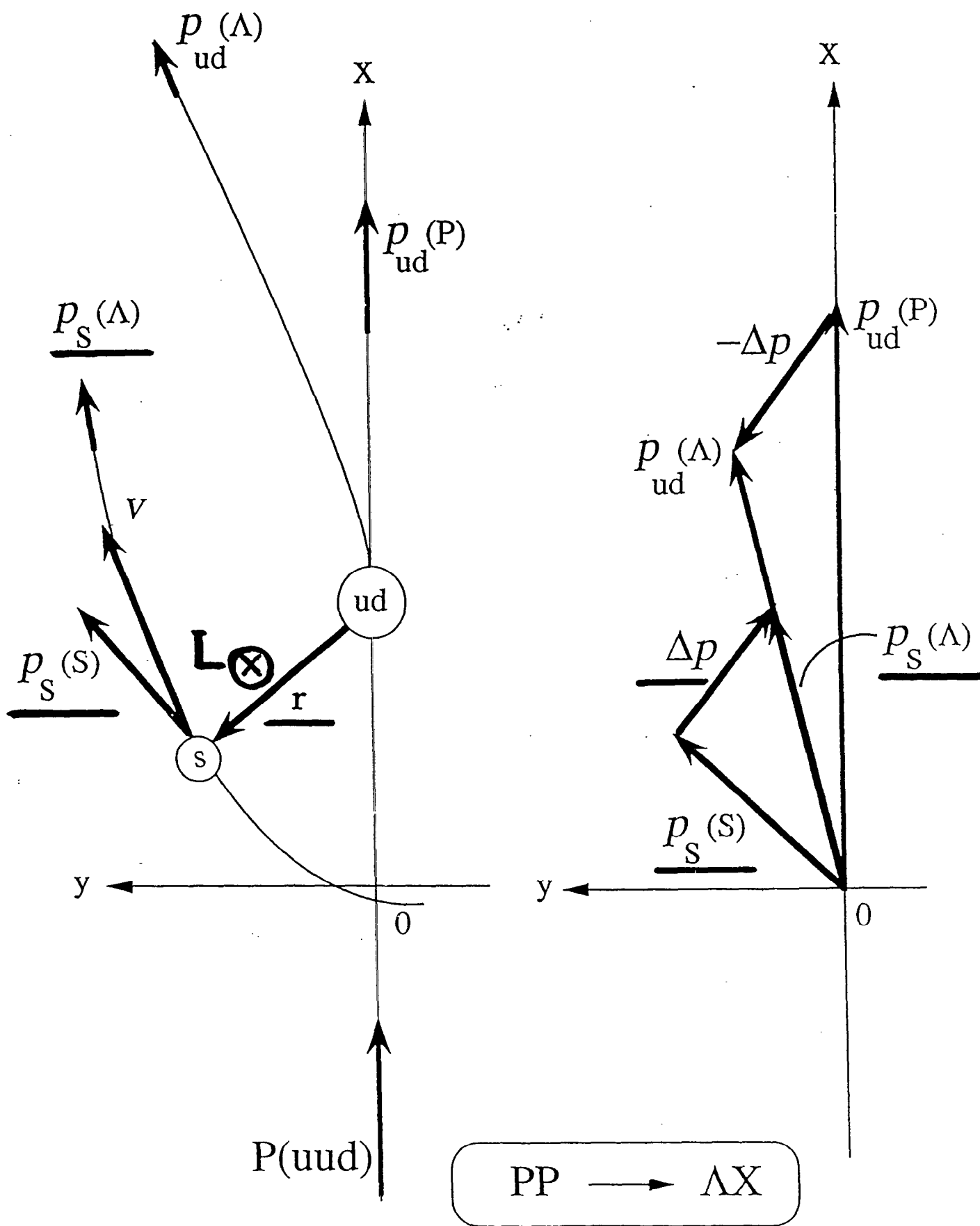
$$= \mp \frac{1}{\Delta t} \langle [\mathbf{P}_s(\Lambda) \times \mathbf{P}_s(S)]_z \rangle_{t, \mathbf{p}}$$

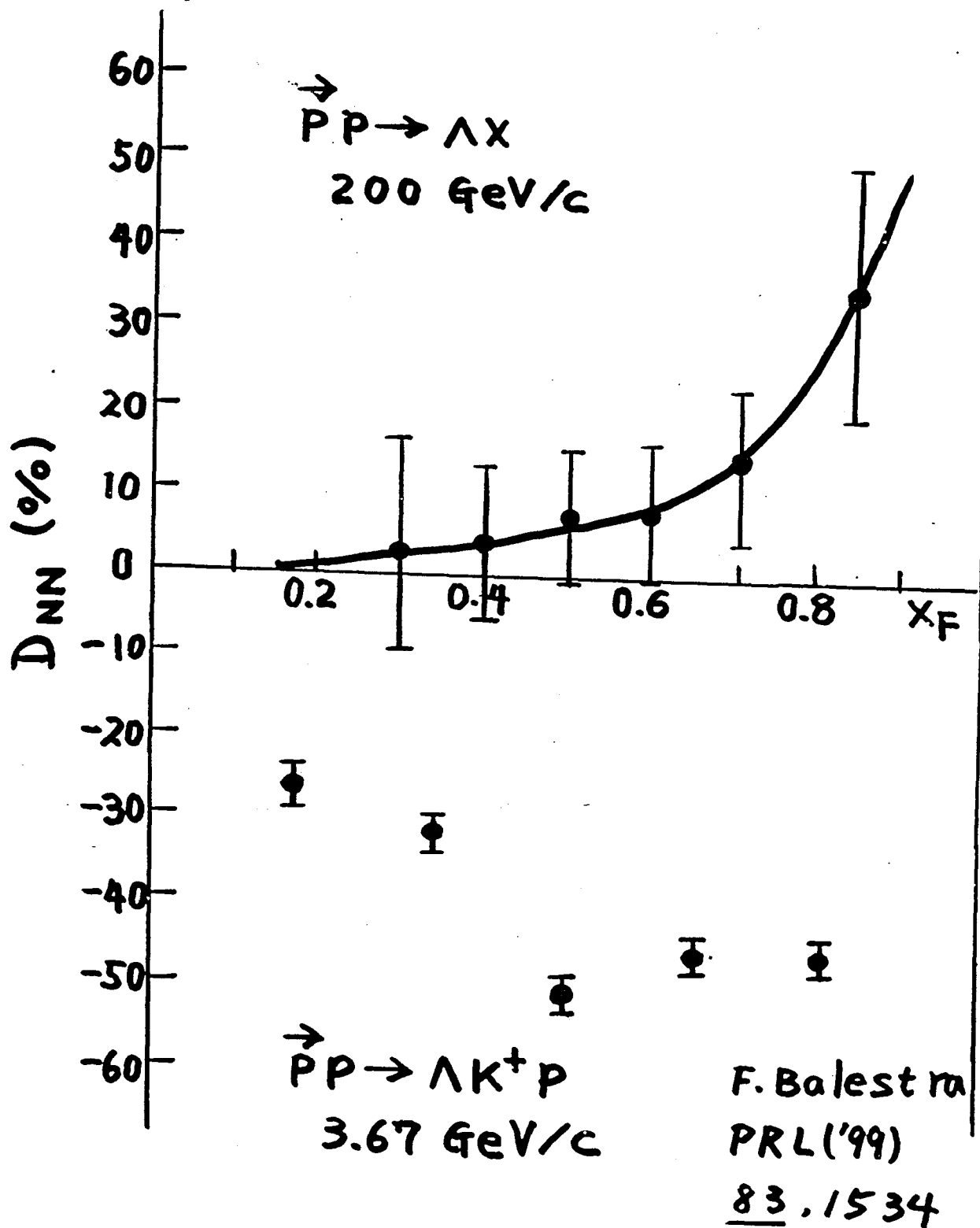
$\parallel$

$$\mathbf{P}_s(\Lambda) - \Delta \mathbf{P}$$

$$\begin{aligned} \mathbf{F} &= \frac{\Delta \mathbf{p}}{\Delta t} = \frac{\Delta \mathbf{p}}{\Delta p} \frac{\Delta p}{\Delta t} = \frac{-\mathbf{r}}{r} \frac{\Delta p}{\Delta t} \\ &= \frac{\mathbf{r}}{r} \left(-\frac{dV}{dr} \right) \leq 0 \rightarrow \underline{\left(\frac{1}{r} \frac{dV}{dr} \right) \geq 0} \end{aligned}$$

$$\langle |\mathbf{M}_{\pm}|^2 \rangle = \pm \frac{1}{2} \left(\frac{1}{r} \frac{dV}{dr} \right)_{(\mathbf{r} = \mathbf{r}_0)} - \frac{1}{2} \left(\frac{1}{r} \frac{dV}{dr} \right)_{(\mathbf{r} = \mathbf{r}_1)}$$





Flavor decomposition of the polarized quark distributions in the Nucleon by HERMES

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on behalf of the HERMES collaboration

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Spin asymmetries of semi-inclusive cross sections for the production of positively and negatively charged hadrons have been measured in deep-inelastic scattering of polarized positrons on polarized hydrogen and ^3He targets in the kinematic range $0.023 < x < 0.6$ and $1 \text{ GeV}^2 < Q^2 < 10 \text{ GeV}^2$. Polarized quark distributions are extracted as a function of x for up and down quarks. The up quark polarization is positive and the down quark polarization is negative in the measured range. The polarization of the sea is compatible with zero.

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Flavor Decomposition of the Polarized Quark Distributions in the Nucleon by HERMES

Yasuhiro Sakemi

Tokyo Institute of Technology

for HERMES collaboration

Circum-Pan-Pacific RIKEN Symposium on
“High Energy Spin Physics”

Nov 3-6, 1999 at RIKEN, Wako, Saitama

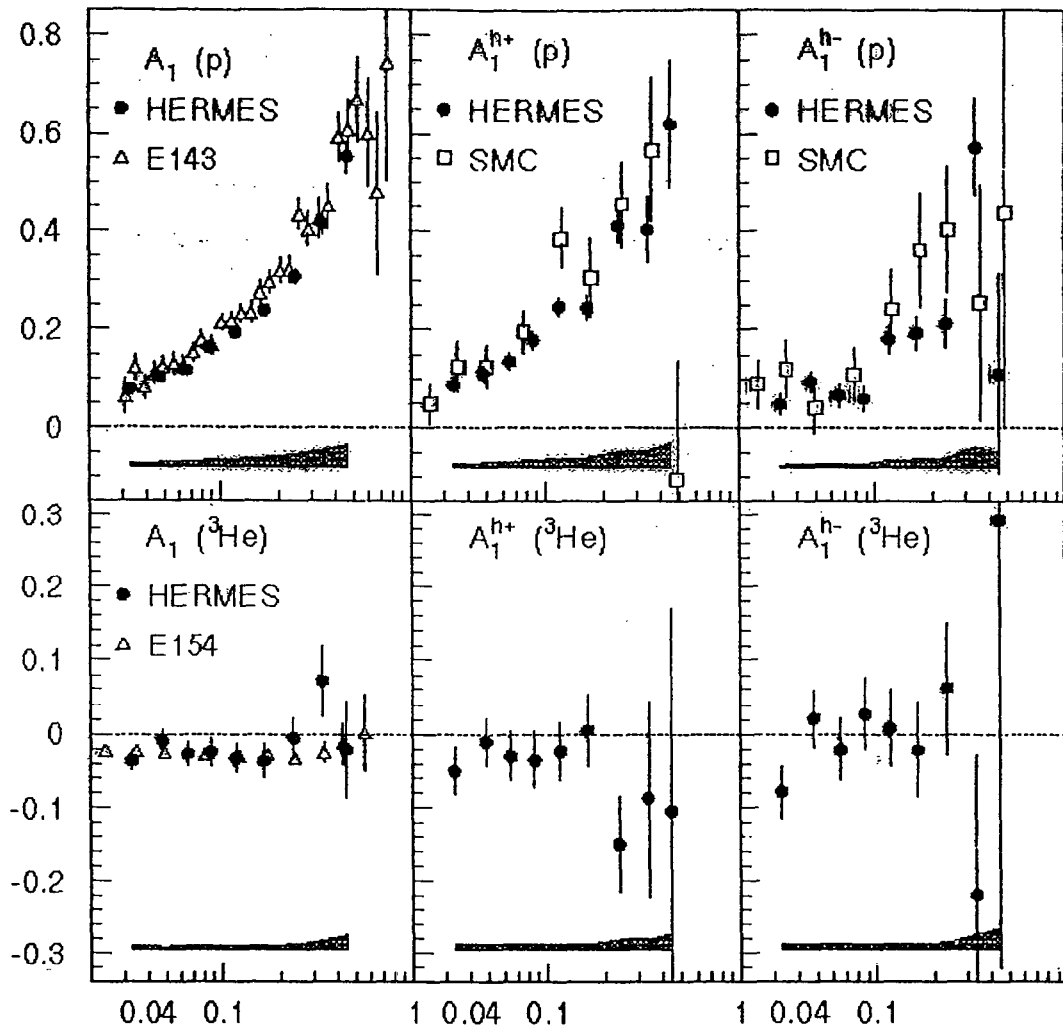


Y. Sakemi



Tokyo Tech

Hadron Asymmetries



- Statistics of proton data $\sim$ high
- Data given at mean Q^2 of each x
- Error :
 - Error bars of HERMES : statistical uncertainties
 - Bands are HERMES systematic error
 - Error bars of SLAC and SMC : total uncertainties



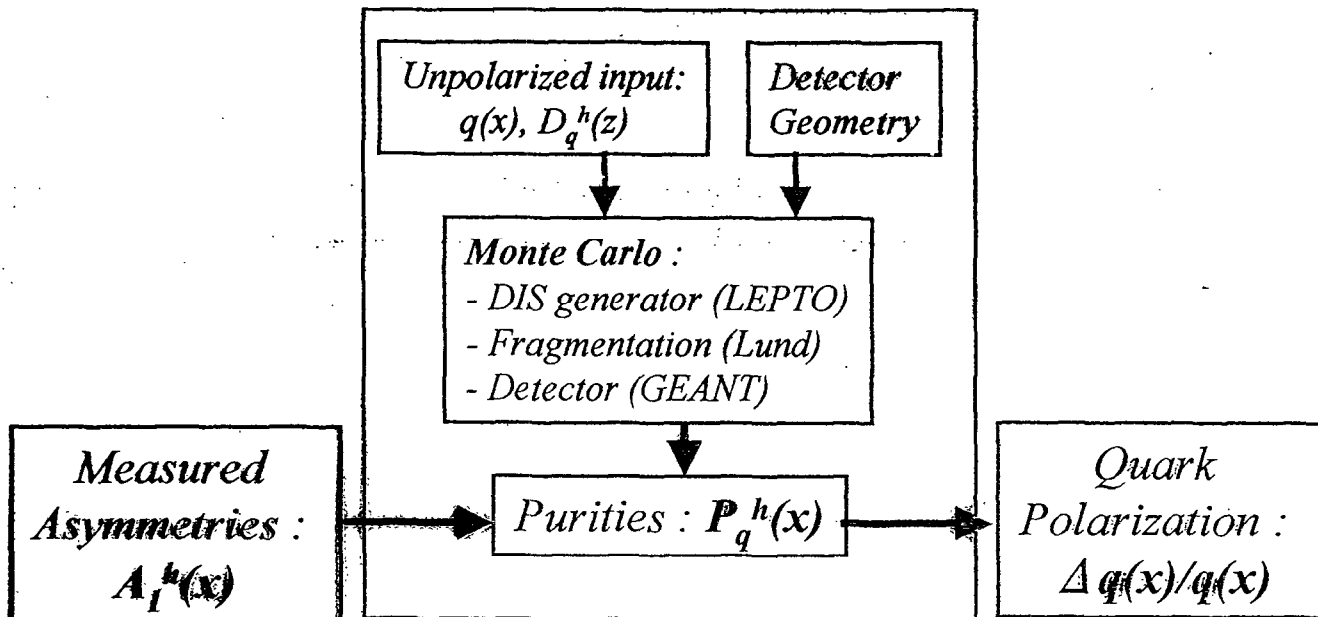
Y. Sakemi



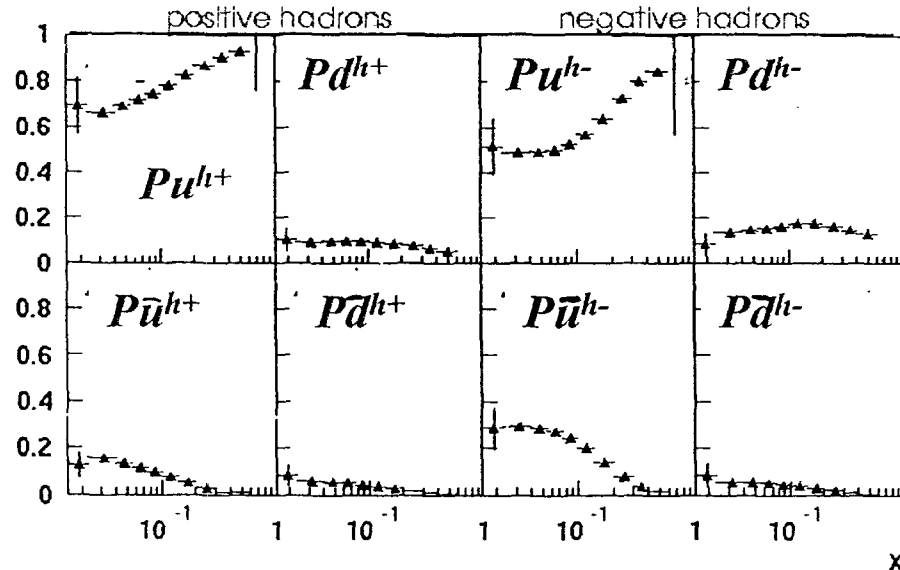
Tokyo Tech.

The purity method

- Procedure to extract quark polarization from purities

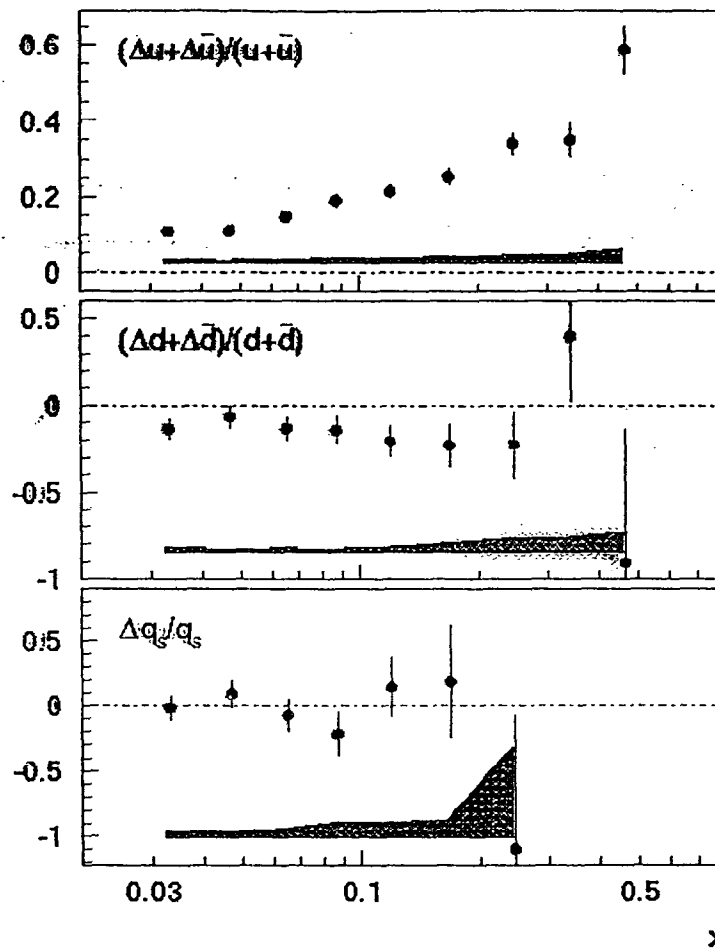


- Purities



– h^+, h^- asymmetries on the proton dominated by $\Delta u(x)$

Flavor decomposition of PDF



- Flavor decomposition of quark polarizations as a function of x at measured Q^2
- Sea assumption (flavor independent polarization) :
 - $$\frac{\Delta q_s}{q_s} \equiv \frac{\Delta u_s}{u_s} = \frac{\Delta d_s}{d_s} = \frac{\Delta s}{s} = \frac{\Delta \bar{u}}{\bar{u}} = \frac{\Delta \bar{d}}{\bar{d}} = \frac{\Delta \bar{s}}{\bar{s}}$$
- Result insensitive to sea assumption
 - *another assumption : flavor symmetric sea : checked*

Summary and Outlook

- Inclusive data:
 - *spin structure function g_1^p, g_1^n measured*
- Semi-inclusive data:
 - *A_1^h measured on H and ^3He targets*
 - *polarization of up/down/sea quarks extracted*
 - *up quark : positive polarization*
 - *down quark : negative polarization*
 - *sea quark : compatible with zero*
 - *semi-inclusive result Δq_3 agrees with Bjorken Sum Rule*
- Forthcoming results:
 - *π, K, p asymmetries and fragmentation functions from RICH*
 - *Separation of light and strange sea polarization*



Y. Sakemi



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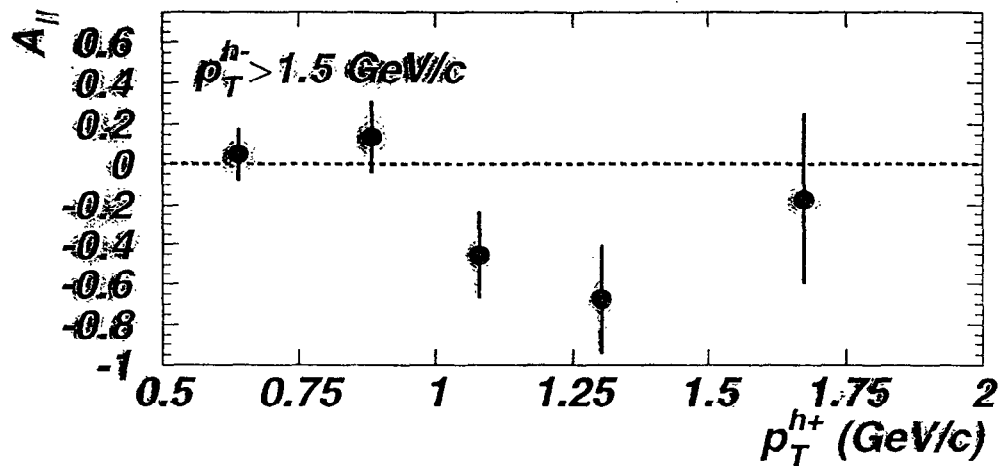
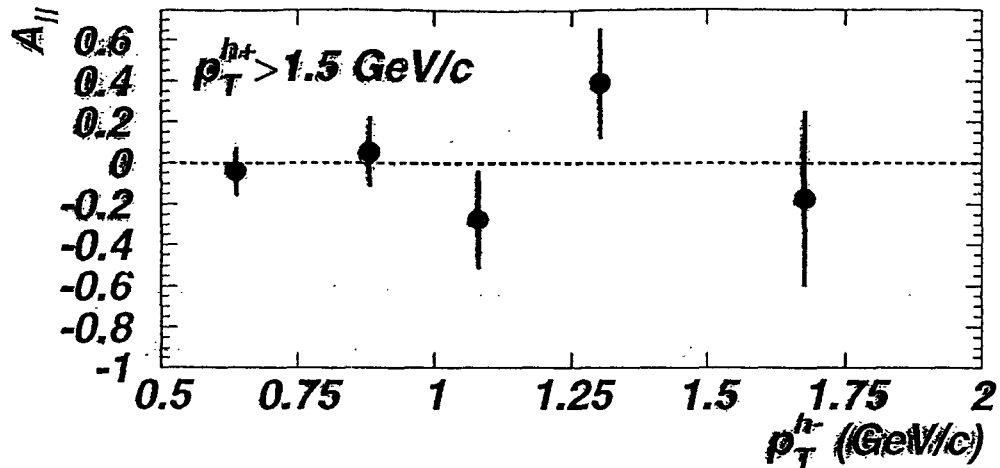
The Spin Asymmetry in the Photoproduction of Pairs of High Transverse Momentum Hadrons at HERMES

Manuella G. VINCTER*for the HERMES Collaboration
Center for Subatomic Research University of Alberta,
Edmonton, AB, Canada, T6G 2N5

Results from the HERMES experiment at the DESY Laboratory in Germany are presented on the longitudinal asymmetry in the photoproduction of pairs of oppositely charged hadrons with high transverse momentum. A negative asymmetry is determined in contrast to the positive asymmetries typically measured in deep-inelastic scattering from protons. Monte Carlo studies indicate that the photon-gluon process contributes substantially in this kinematical domain. Using this information, the negative asymmetry can then be interpreted to arise from a positive gluon polarization in the proton.

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Measured Asymmetry $A_{||}(p_T^{h^+}, p_T^{h^-})$

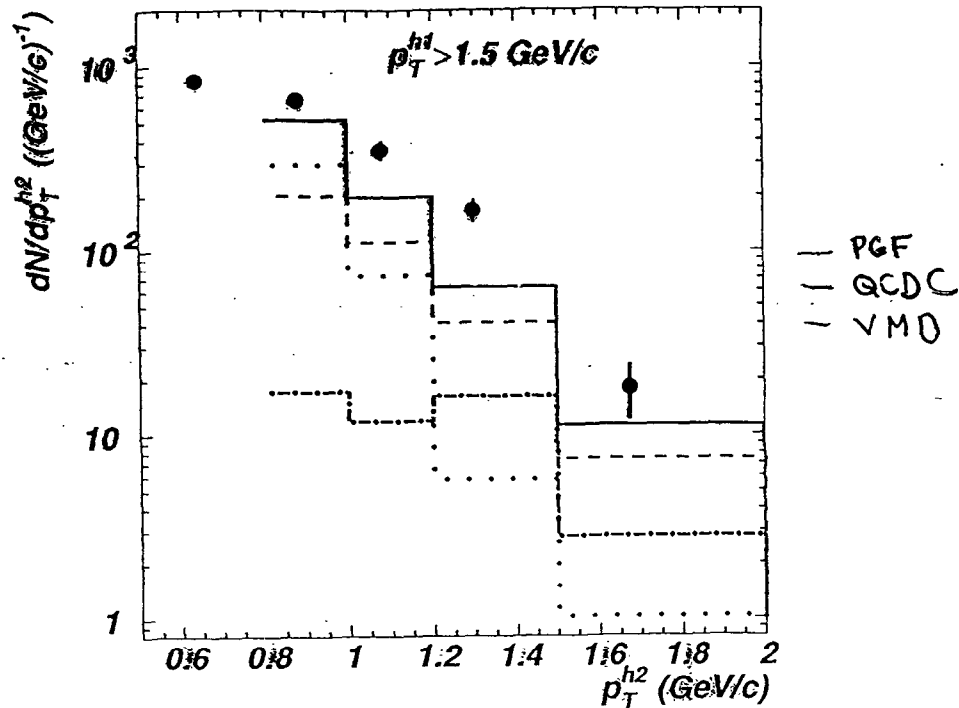


For $p_T^{h_1} > 1.5$ GeV and $p_T^{h_2} > 1.0$ GeV:

$$A_{||} = -0.28 \pm 0.12(stat) \pm 0.02(sys)$$

(Systematic error of 6% dominantly from beam and target polarization uncertainties)

Results from PYTHIA

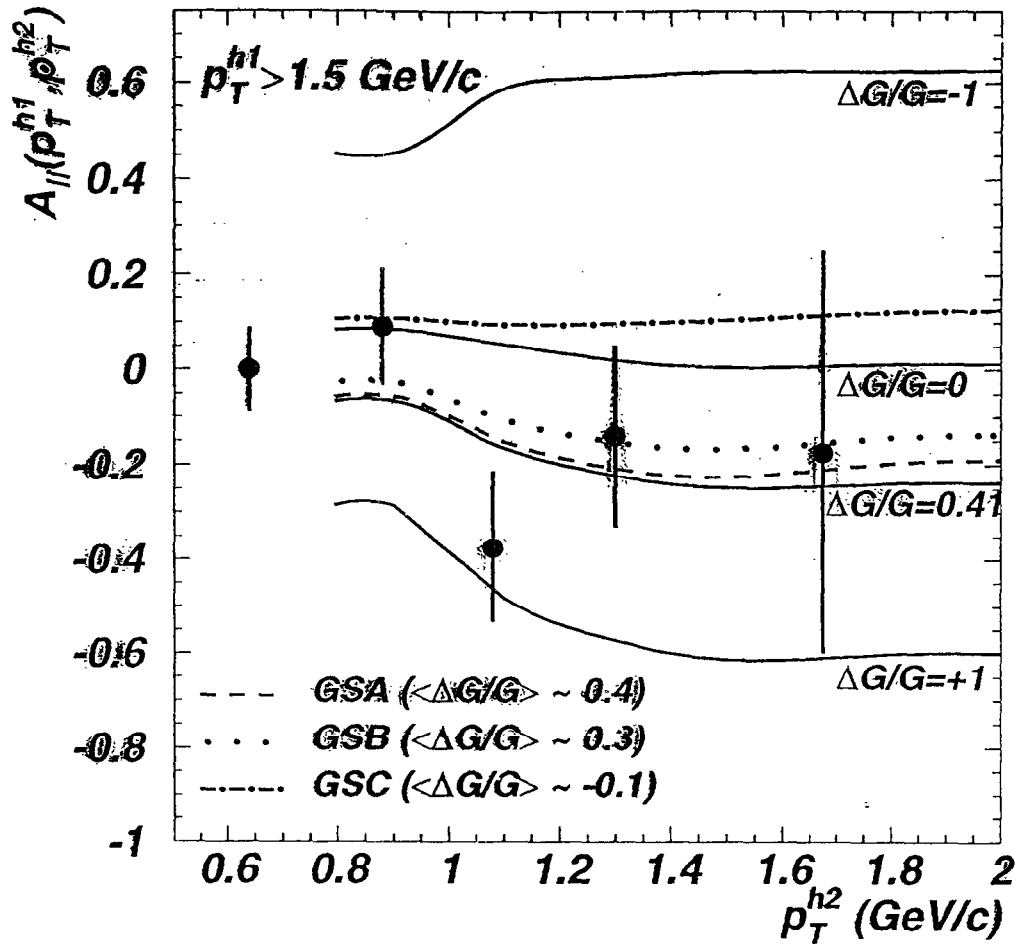


Differences could be due to

- higher order QCD processes
- hard interaction of the structure of the photon
- choice of fragmentation parameters

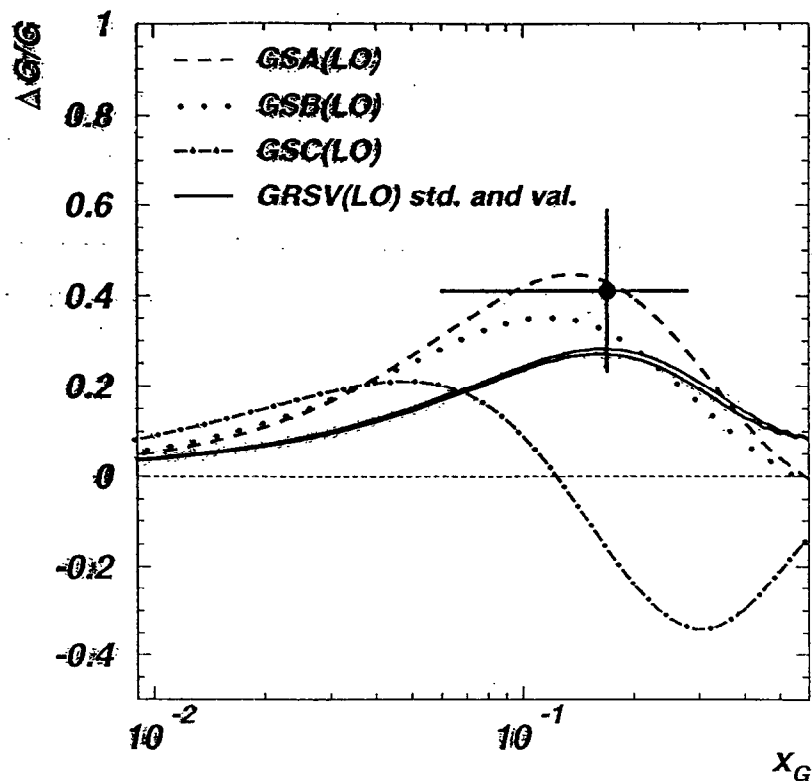
Does not significantly affect principal result on $\Delta G/G$

Results from PYTHIA



- $\langle x_G \rangle = 0.17$
- $\langle Q^2 \rangle = 0.06 \text{ GeV}^2$
- $\langle \hat{p}_T^2 \rangle = 2.1 \text{ GeV}^2$

Results from PYTHIA



$$\frac{\Delta G}{G} = 0.41 \pm 0.18(stat) \pm 0.03(sys)$$

for $p_T^{h_1} > 1.5 \text{ GeV}$ and $p_T^{h_2} > 0.8 \text{ GeV}$

$\Delta G/G$ is positive

- would need a significant contribution from neglected process with $A_{||} < 0$ to alter this conclusion

Conclusion

- HERMES observes a significant negative spin asymmetry in the quasi-real photoproduction of high p_T hadron pairs ($p_T^{h_1} > 1.5$ GeV and $p_T^{h_2} > 0.8$ GeV)
- Using PYTHIA MC generator as a model:
 - PGF dominates where $A_{||} < 0$ is seen
 - can be interpreted as $\Delta G > 0$
- HERMES also working on ΔG from charm production

Spin Structure Functions of the Nucleon Measured at SLAC

Peter Bosted, for the E155/E155x Collaboration ^{a*}

^aUniversity of Massachusetts, Amherst MA, USA

We have measured the spin structure functions g_1^p and g_1^d over the kinematic range $0.014 \leq x \leq 0.8$ and $0.6 \leq Q^2 \leq 30$ (GeV/c)² by scattering 48.2 GeV longitudinally polarized electrons from longitudinally polarized NH₃ and ⁶LiD targets. The final results for the deuteron have smaller errors than previous data, and extend the Q^2 range over which high statistics data is available. The proton results are still preliminary. The new data, combined with previous data from SLAC and other labs, allows improved determinations of the helicity-dependent parton densities, as determined from NLO QCD fits. We find the Bjorken Sum Rule to be satisfied, the net quark helicity to be small (≈ 0.2 in $\overline{MS}$ scheme), and indications that ΔG is positive.

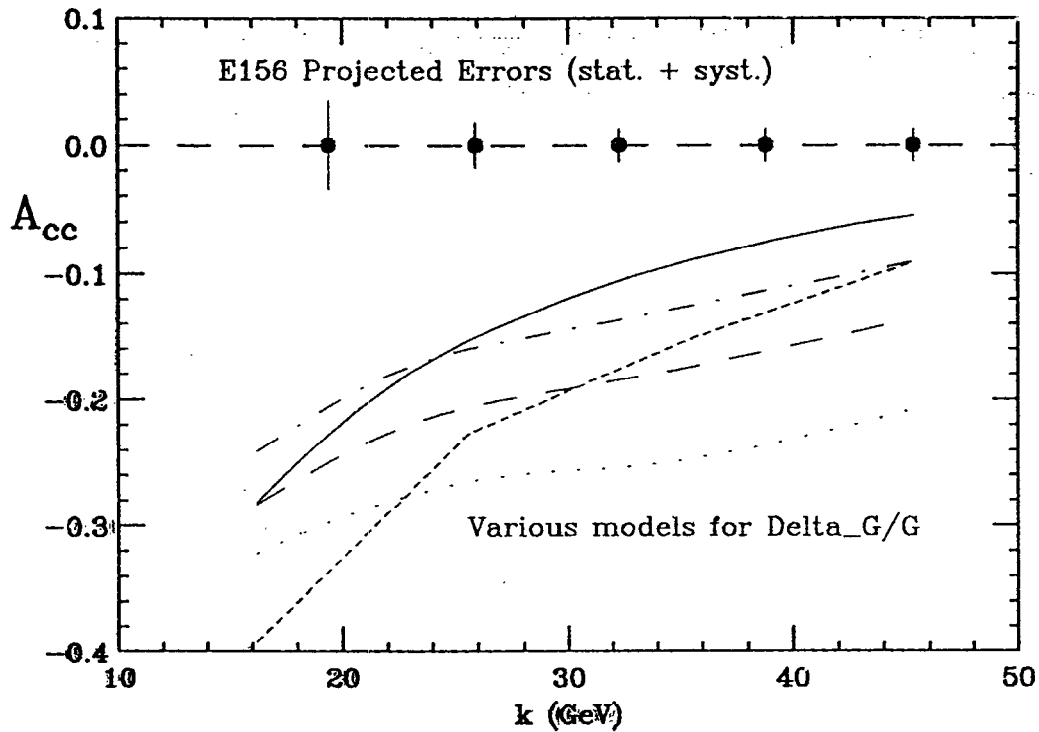
More recently, measurements were also made of the transverse spin structure functions g_2^p and g_2^d over the kinematic range $0.02 \leq x \leq 0.8$ and $0.6 \leq Q^2 \leq 20$ (GeV/c)² by scattering 29.1 and 32.3 GeV electrons from transversely polarized targets. The statistical errors are approximately three times smaller than previous measurements. Very preliminary results for xg_2 are in qualitative agreement with the twist-2 Wandzura-Wilczek calculation for the three electron scattering angles used in this experiment (2.75, 5.5, and 10.5 degrees), indicating that twist-3 contributions are not very large.

As a byproduct of these experiments, the asymmetries $A_{||}$ and $A_{\perp}$ were measured for inclusive photoproduction of hadrons (mostly pions and kaons) from the effective Bremsstrahlung photon beam created in the target. The asymmetries for the deuteron target are consistent with zero, while for the proton, positive asymmetries of order 0.01 are seen for both $A_{||}$ and $A_{\perp}$.

The talk concludes with a brief summary of future prospects at SLAC to measure the spin asymmetry in open charm photoproduction [with the goal of learning more about $\delta G()$], and the high energy contribution to the GDH sum rule.

*Work supported by the National Science Foundation and the Department of Energy contract DE-AC03-76SF00515.

POLARIZED OPEN CHARM PHOTOPRODUCTION

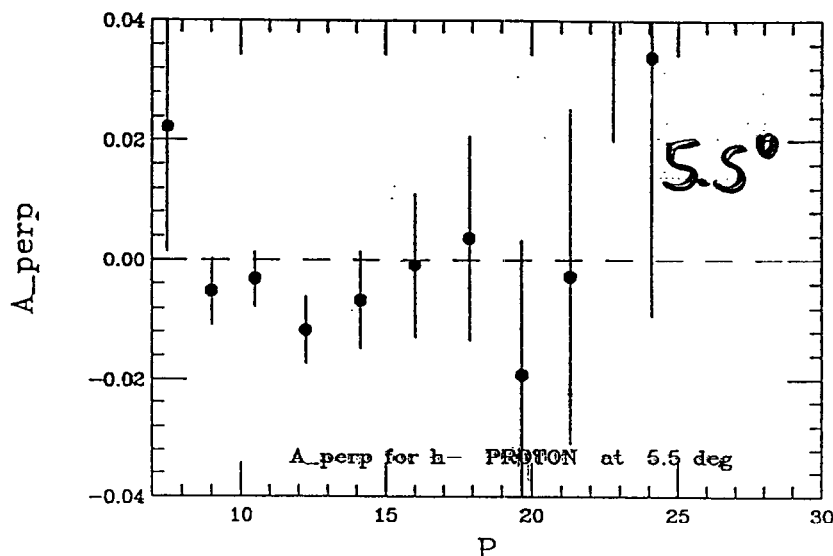


- Systematic errors dominate at high k .
- Total errors much smaller than other experiments (COMPASS, HERMES).
- Will be able to measure both shape and magnitude of $\Delta G/G$ for $x > 0.1$.

$A_{\perp}$ (or A_{LT}) FOR PROTON TARGET

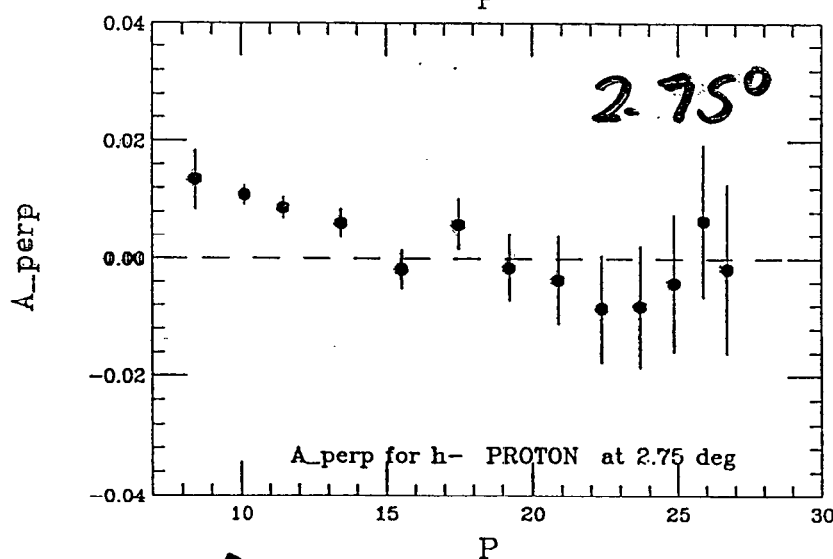
$E_{max} \sim 30 \text{ GeV}$

INCLUSIVE HADRON PHOTOPRODUCTION



VERY
PRELIMINARY

EVIDENCE OF
NON-ZERO
ASYMMETRY
AT LOW P_T ,
OF SAME
MAGNITUDE
AS $A_{||}$



↑
 $P_T \sim 0.5 \text{ GeV}$

FIRST TIME
SEEN!

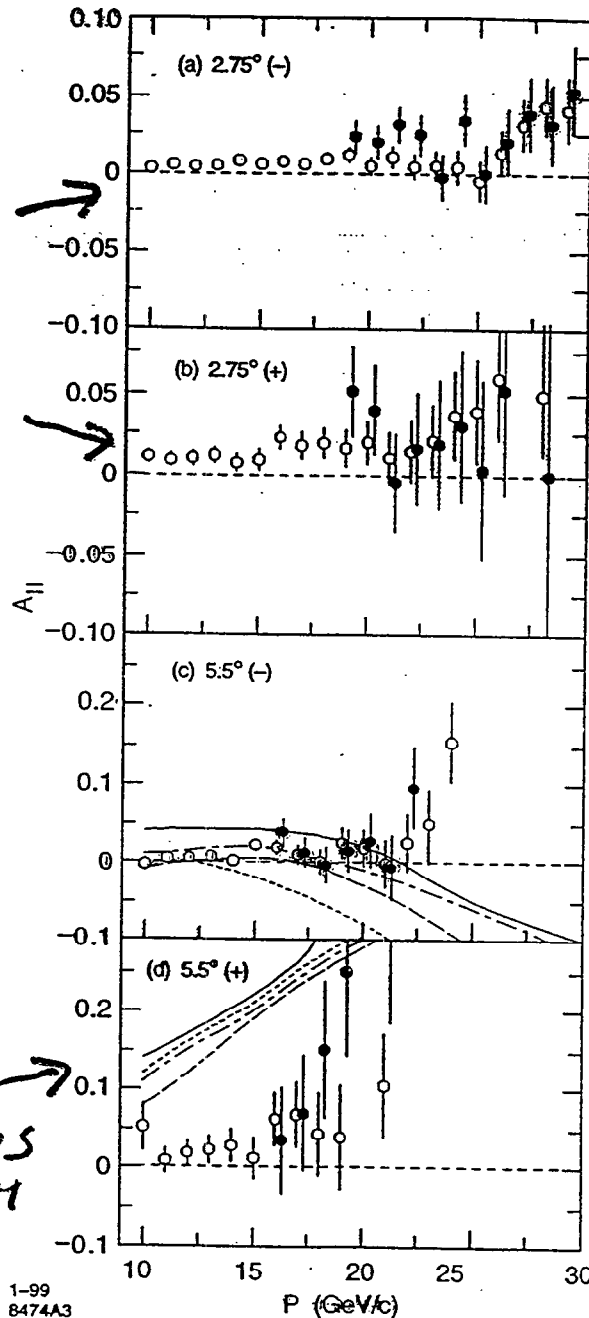
INCLUSIVE HADRONS

A_{II} FOR PROTON $E=48$

$A_{II} > 0!$
 OFT PHYSICS
 REGION
 ($P_T < 1 \text{ GeV}$)

CURVES FROM
 ARLSON et al.
 ARIOUS ΔG
 ND $\Delta U, \Delta \alpha, \Delta S$
 MODELS.

EEDED SOFT
 ONTRIBUTIONS
 O AGEE WITH
 DATA



π^-, K^- 2.75°

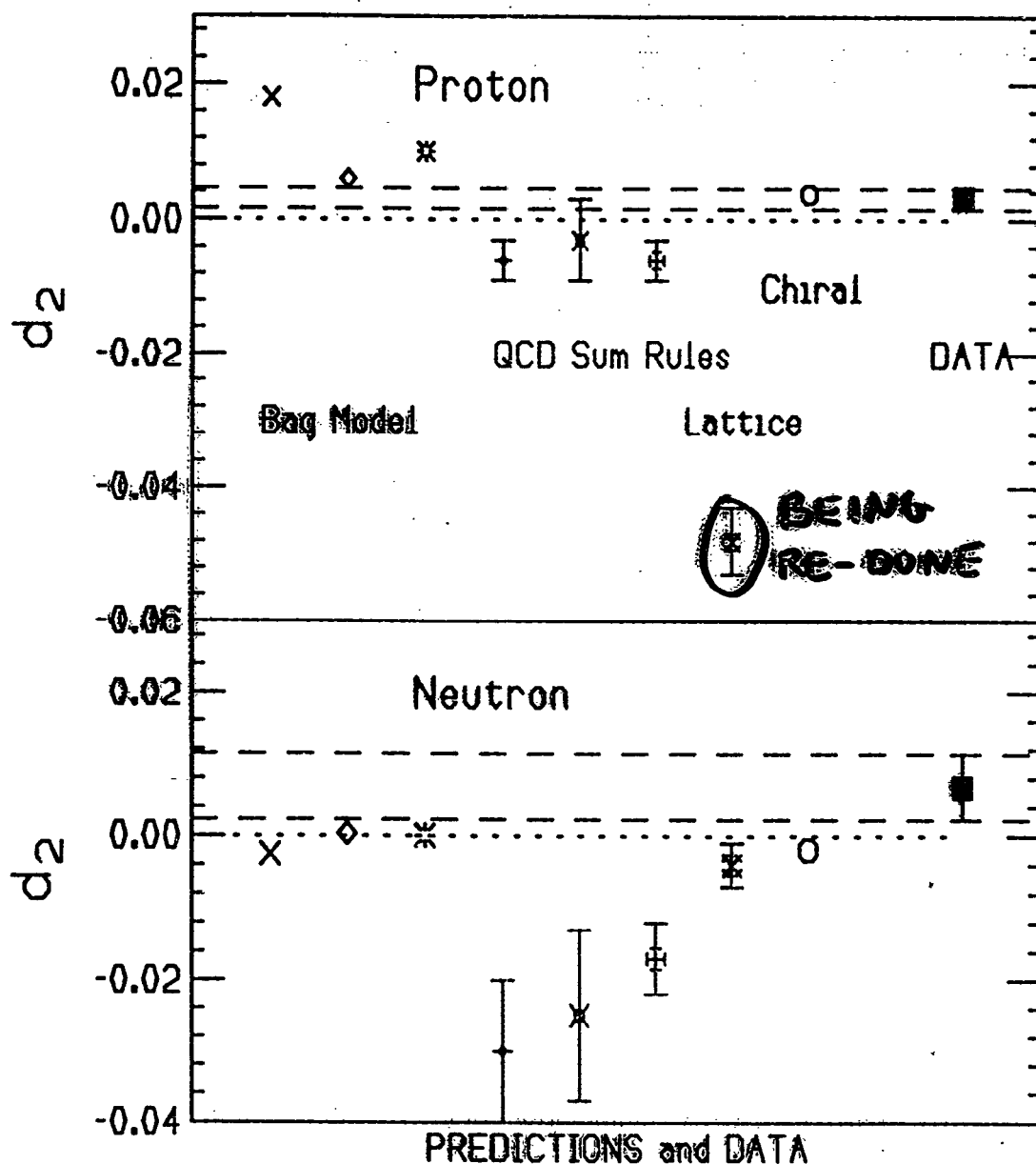
π^+, K^+, p 2.75°

π^-, K^- 5.5°

π^+, K^+, p 5.5°

DATA MAY PROVIDE CONSTRAINTS
 ON NUCLEON STRUCTURE IN
 INTERMEDIATE [SOFT/HARD] QCD

Very Preliminary Results for Twist-3 d_2 Matrix Element from E155x



WARNING: RESULTS SENSITIVE TO HIGH- x
FIT TO g_1 AND ASSUMED Q^2 -DEPENDENCE
OF g_2 .

NLO Fit Results

(Preliminary)

In the $\overline{MS}$ scheme

$$\Gamma_1^p = 0.116 \begin{matrix} +0.005 & +0.007 \\ -0.005 & -0.009 \end{matrix}$$

$$\Gamma_1^d = 0.028 \begin{matrix} +0.004 & +0.005 \\ -0.004 & -0.009 \end{matrix}$$

Bjorken sum rule

$$\Gamma_1^{p-n} = 0.172 \begin{matrix} +0.005 & +0.008 \\ -0.003 & -0.007 \end{matrix}$$

PREDICTION: 0.182 OK

Quark helicity content

$$\Delta\Sigma = 0.22 \begin{matrix} +0.04 & +0.05 \\ -0.04 & -0.07 \end{matrix}$$

SMALL COMPARED TO ELLIS JAFFE ~.6

Gluon spin contribution

$$\Delta G = 1.8 \begin{matrix} +0.7 & +1.4 \\ -0.4 & -1.2 \end{matrix}$$

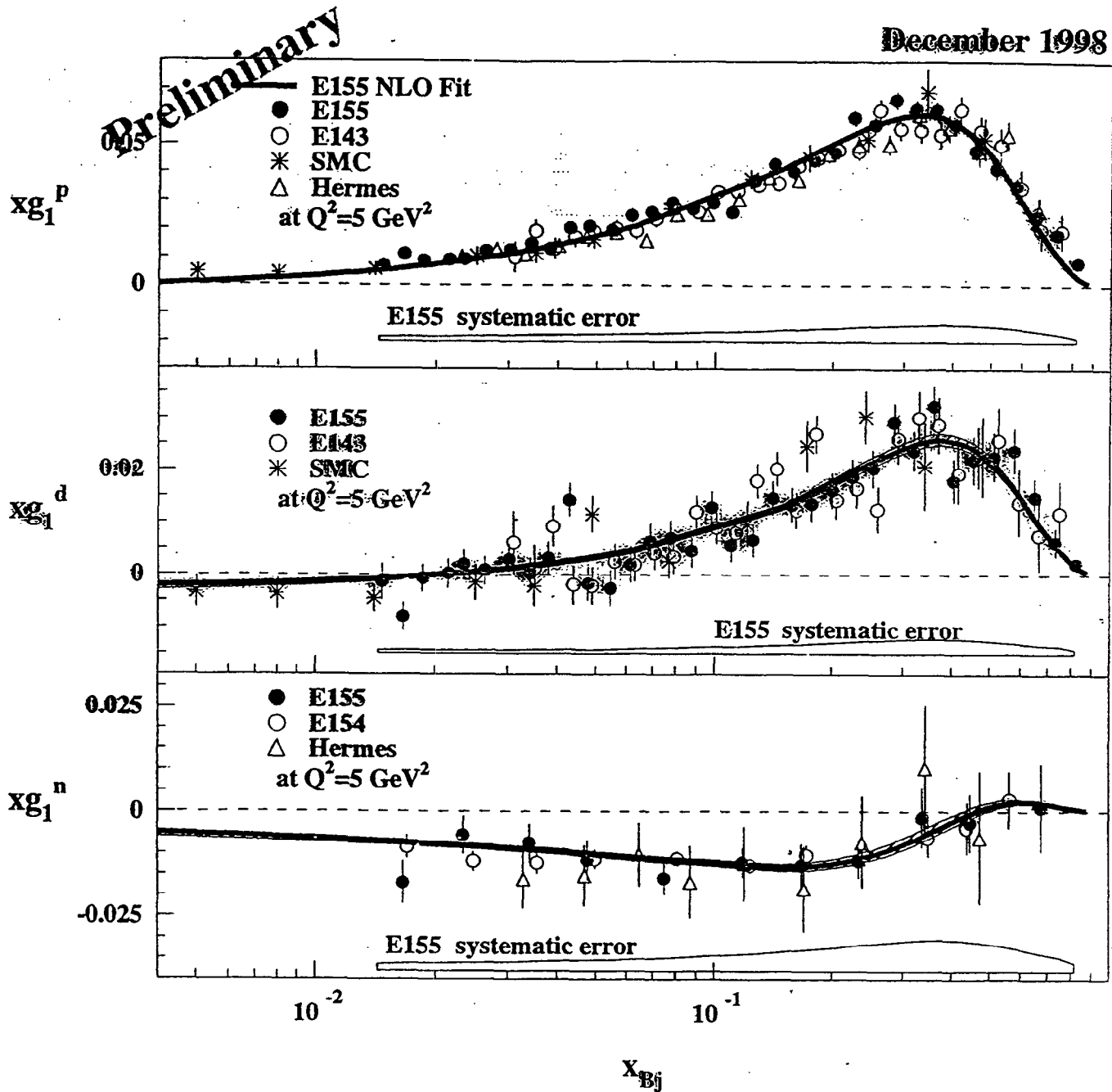
INDICATION GREATER THAN 0.

— NLO QCD FIT ($\bar{MS}$)

AREA UNDER CURVE = $\int g_1(x) dx$

IS NEUTRON COVERING AT LOW x ?

December 1998



Experimental Plan of COMPASS

Takahiro IWATA*

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Furoch, Chikusa-ku, Nagoya 464-8602

COMPASS is a new fixed target experiment at CERN to study the nucleon spin structure with a polarized muon beam and a polarized nucleon target. Gluon spin contribution to the nucleon spin will be studied by measuring the asymmetry of open charm production or high P_T hadron pair production in semi-inclusive deep inelastic scattering of a polarized muons on a polarized nucleon target. The COMPASS spectrometer is a two-stage spectrometer equipped with ring image Cherenkov counters and calorimeters. The run will start to take data in 2001.

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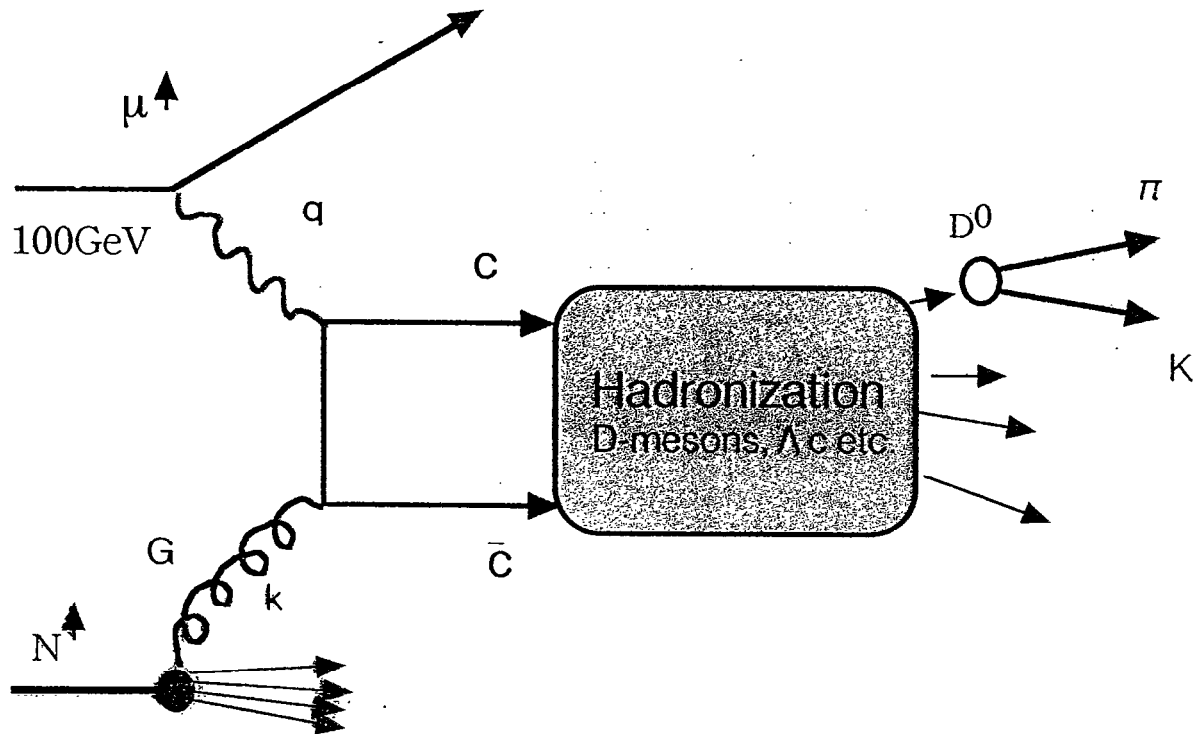
APPARATUS IN COMPASS

(MUON PROGRAM)

1. New spectrometer
2-stage spectrometer
wide aperture $\pm 180\text{mrad}$
1st stage; pions & kaons
2nd stage; muons
particle ID: 2 RICHs
calorimeters: ECALs, HCALs
trackers: high rate capability required
(ScinFi, Micromegas, GEM+MSGC)
2. Polarized target
new magnet constructed
(opening angle= $\pm 180\text{mrad}$)
target cell: $2 \times 60\text{cm}$ (twin cell), $d=3\text{cm}$
material: NH_3 ($f=0.18$) & ${}^6\text{LiD}$ ($f=0.5$)
SMC dilution cryostat reused
3. Muon beam (from SPS)
 μ^+ beam: $E_\mu=100\text{GeV}, 200\text{GeV}$
 $I_\mu=2 \times 10^8 \text{ ppp}$ (5xSMC)
 $P_\mu=80\%$

$\Delta G/G$ FROM OPEN CHARM

Photon Gluon Fusion (PGF)



Open Charm Production

large $\sigma_{c\bar{c}}$: 0.4% of σ_γ @60GeV

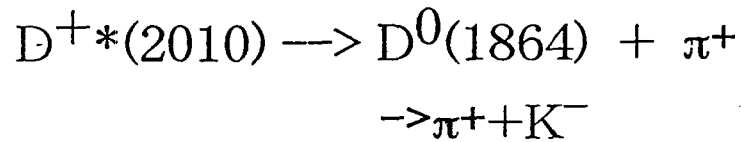
γG subprocess known

unpolarized NLO

polarized LO

FURTHER PURIFICATION

D* tagging



$$\Delta M = m(\pi^+ \pi^+ K^-) - m(\pi^+ K^-) = 145 \text{ MeV}$$

- * detect soft pion $> 1 \text{ GeV}/c$
- * cut $\Delta M \pm 5 \text{ MeV}$
- * essential BG free
- * release "z" and " $\cos\theta_K$ " cuts ($z = E_D/v$)

$$\delta A_{\gamma p}^{CC} = 0.051 \longleftrightarrow \delta \Delta G/G = 0.14$$

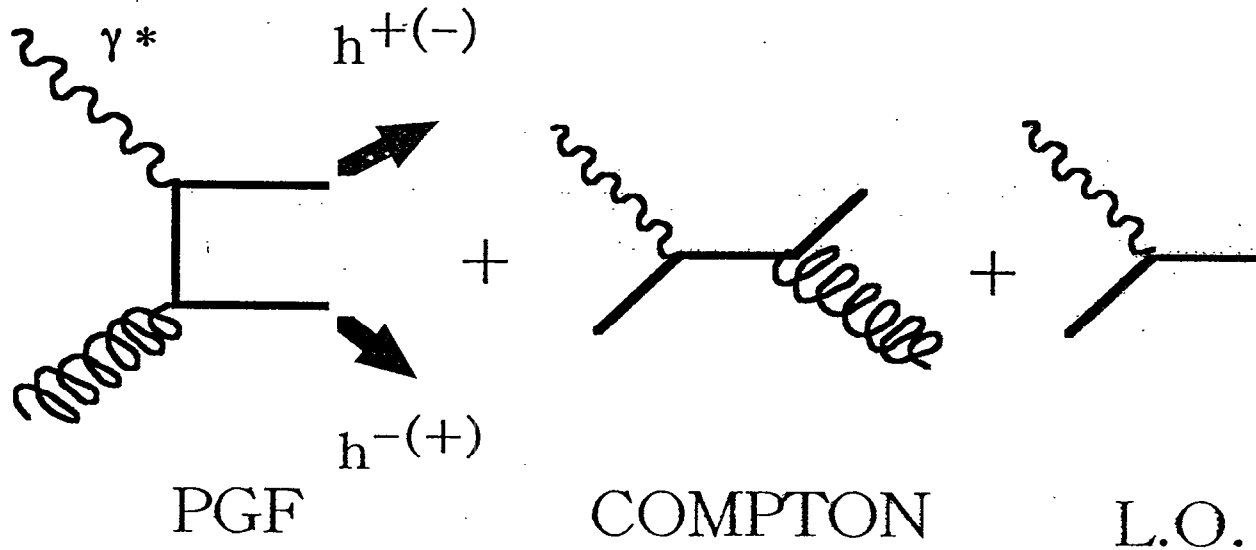
P_T cut

$$P_T(D^0) < 1.0 \text{ GeV}/c \\ \longrightarrow \text{increase analyzing power}$$

$$\delta \Delta G/G = 0.11$$

PGF BY HIGH P_T HADRON PAIR

studied for COMPASS by
A.Bravar,D.Harrach and A.Kotzinian
Phys.Lett.B421(1998)349-359



REQUIRE

- * 2 high P_T hadrons ($P_T > 1.0 \text{ GeV}/c$, $\text{mass}(1,2) > 2.5 \text{ GeV}/c^2$)
- * opposite charge, opposite azimuthal angle ($\Delta\phi = 180^\circ \pm 30^\circ$)
- * "FLAVOR TAGGING" ss (PGF) $\rightarrow K^+K^-$ likely

ESTIMATES for $E_\mu = 200 \text{ GeV}$, $0.5 < y < 0.9$, $100 < E_{\gamma^*} < 180 \text{ GeV}$,
 $W^2 > 200 \text{ GeV}^2$

	Yield ratio	S:B
no selection	1	1:6
$h^+ h^-$	$\sim 2.4 \times 10^{-3}$	1:1
$K^+ K^-$	$\sim 2.2 \times 10^{-4}$	2:1

SUMMARY

- * COMPASS is a new experiment under construction at CERN aiming at studying nucleon spin structure and hadron spectroscopy.
- * Extracting $\Delta G/G$ in detecting PGF through open charm production is the main subject of the muon program. About 10% accuracy on $\Delta G/G$ is expected in this method.
- * $\Delta G/G$ may be extracted from high PT hadron pair detection. Feasibility study gives expected accuracy to be 5% in this method.
- * COMPASS offers a rich program of physics on nucleon spin structure.
- * Physics run is expected to be started in 2001.

New parametrization of polarized parton distribution functions

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A new parametrization of polarized parton distribution functions is discussed in the leading (LO) and the next-to-leading order (NLO) of QCD. Taking account of the positivity and the counting rule of parton distributions and assuming the SU(3) flavor symmetry for the sea-quark, polarized parton distribution functions for valence u , d , sea-quark and gluons are determined from the fit to world data of spin asymmetries in polarized deep inelastic scatterings. The amount of the sum of quark spin, $\Delta\Sigma$, carrying the nucleon spin in the NLO is rather small compared with the one of other works done so far.

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New parameterization of polarized parton distribution functions

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S. Kumano ^A, M. Miyama ^A, T. Morii ^B, N. Saito ,
T. -A. Shibata ^C, E. Taniguchi ^C, and T. Yamanishi ^D

Institute of Physical and Chemical Research

^A *Saga University*

^B *Kobe University*

^C *Tokyo Institute of Technology*

^D *Fukui University of Technology*

§ 1 INTRODUCTION

§ 2 PARAMETERIZATION

§ 3 FIT AND RESULTS

§ 4 SUMMARY AND DISCUSSION

§ 2 PARAMETERIZATION AND FIT

- Parameterization

—Described with unpol-PDF for numerical analysis

$$\Delta f_i(x, Q_0^2) = h_i(x) \cdot f_i(x, Q_0^2)$$

$$h_i(x) = \eta_i N_i x^{\alpha_i} (1 + \gamma_i x^{\lambda_i}) (1 - x)^{\beta_i}$$

N_i : normalization factor

η_i : first moment factor

- Constraints on pol-PDF

—Positivity condition

$$|\Delta f_i(x, Q_0^2)| \leq f_i(x, Q_0^2)$$

—Counting rule

$$f_i^{\uparrow}(x, Q_0^2) \gg f_i^{\downarrow}(x, Q_0^2) \text{ for } x \rightarrow 1$$

$$\beta_i = 0, \quad (1 - x)^{\beta_i} = 1$$

★
 $\Rightarrow \underline{\Delta f_i(x, Q_0^2) = \eta_i N_i x^{\alpha_i} (1 + \gamma_i x^{\lambda_i}) \cdot f_i(x, Q_0^2)}$
 $i = u_V, d_V, \bar{q}, g$

Preliminary results

$$\Delta f_i(x, Q_0^2) = \eta_i N_i x^{\alpha_i} (1 + \gamma_i x^{\lambda_i}) \cdot f_i(x, Q_0^2)$$

$$i = u_v, d_v, \bar{q}, g$$

• —NLO—

$$\cdot \chi^2/\text{d.o.f} = 300.974/(374-14-1) = 0.838$$

	Δu_v	Δd_v	$\Delta \bar{q}$	Δg
η	0.926 (fixed)	-0.341 (fixed)	-0.073	0.551
α	0.095	0.000	1.462	2.155
γ	0.836	2.104	1.055	-0.994
λ	1.107	1.142	-0.962	-0.044

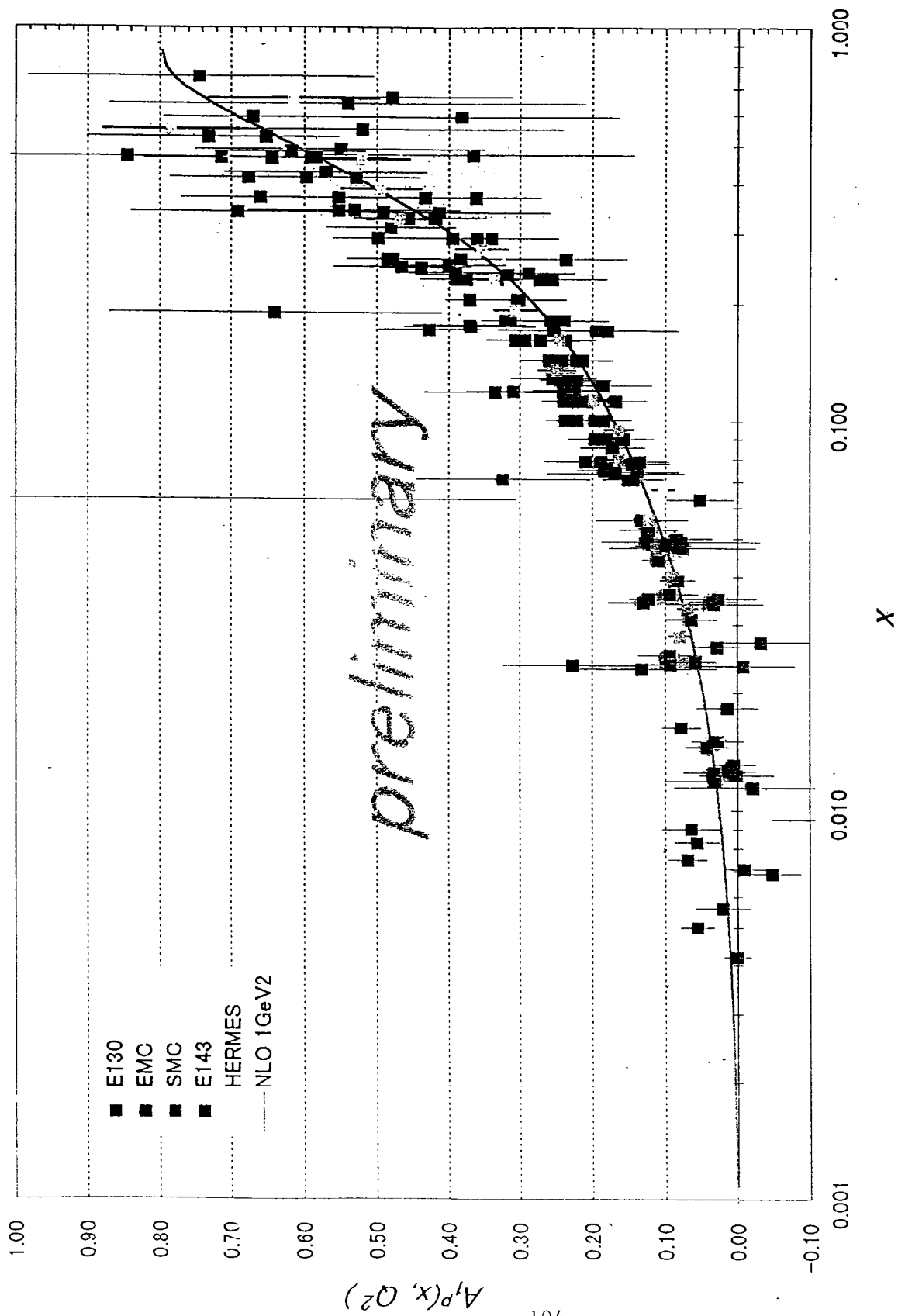
$$\cdot \Delta \Sigma = 0.147$$

• —LO—

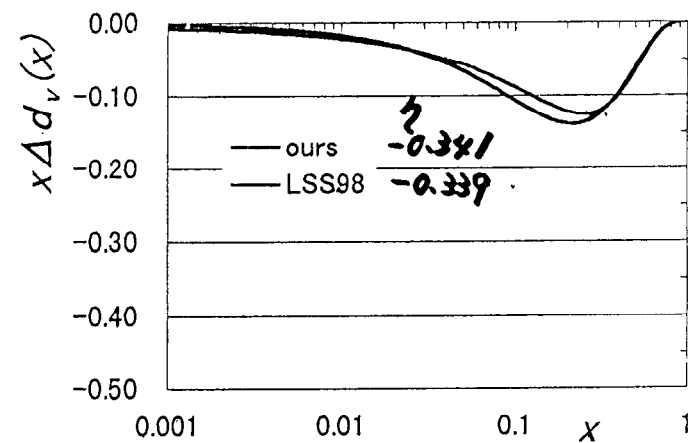
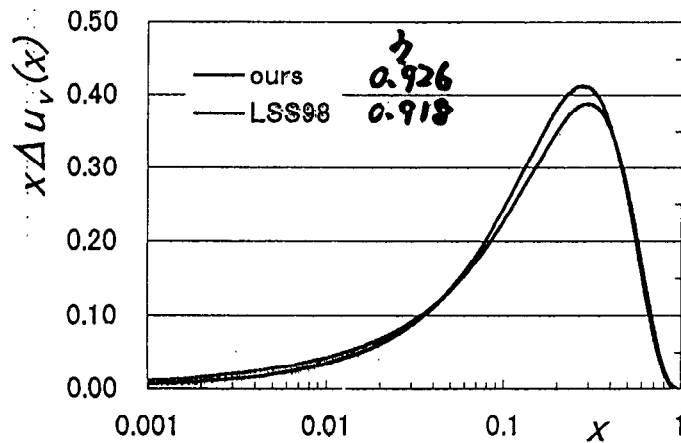
$$\cdot \chi^2/\text{d.o.f} = 322.636/(374-14-1) = 0.899$$

	Δu_v	Δd_v	$\Delta \bar{q}$	Δg
η	0.926 (fixed)	-0.341 (fixed)	-0.064	0.831
α	0.000	0.000	4.652	1.508
γ	1.475	2.653	-0.405	-1.014
λ	1.411	1.245	-4.064	-0.061

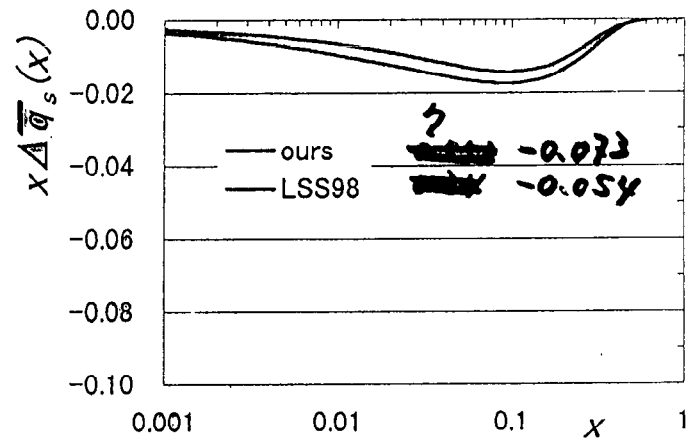
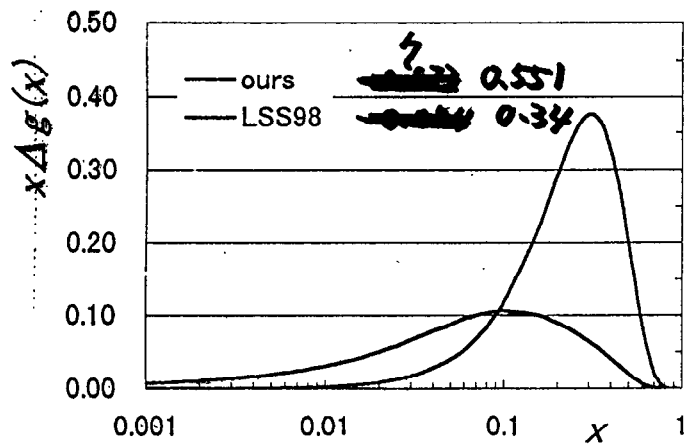
$$\cdot \Delta \Sigma = 0.201$$



polarized parton distributions for NLO at $Q_0^2=1\text{GeV}^2$



preliminary



A Comparison of Spin Observable Predictions for RHIC

Gordon P. RAMSEY*

Loyola University Physics Department, Chicago, IL, 60626 USA
and

Argonne National Lab, Argonne, IL, 60439 USA

There have been many versions of spin-dependent parton distributions in the literature. Most agree with present data, but are based upon different physical assumptions. Some physical models are discussed and the corresponding predictions for double spin asymmetries are shown. A summary of the most feasible measurements in the appropriate kinematic regions at RHIC, which should yield the most useful information about the polarized gluon distribution, is given.

*E-mail address: gpr@hep.anl.gov

x Dependent Distributions:

1. Valence Quarks: Explicit-SU(6) based
2. Gluons: 3 models - positive, zero, negative
3. Sea Model:
 - a. Define: $\eta \equiv \langle (\Delta q_s)_{exp} \rangle / \langle (x q_s)_{calc} \rangle$
 - b. Assume: $\Delta \bar{q}_i = (\Delta q_i)_s \equiv \eta_i (x q_i)$
 - c. Require: $\langle \eta_i(x) x q_i \rangle = \eta \langle x q_i \rangle$
4. Structure Functions:
 - a.
$$g_1^p = \frac{1}{18} [4\Delta u_v + \Delta d_v + 8\Delta \bar{u} + 2\Delta \bar{d} + 2\Delta s] (1 - \alpha_s^{corr})$$
 - b. Similarly for g_1^n
 - c.
$$g_1^d = \frac{1}{2} (g_1^p + g_1^n) (1 - 1.5\omega_D)$$

Observables for ΔG at RHIC

1. Polarized pp hadronic jets

Gordon and Ramsey, Phys. Rev. **D59**, 074018 (99)

Gehrmann and Stirling, Phys. Rev. **D53**, 6100 (96)

2. Direct photon production at large p_T (ibid.)

3. Polarized heavy quark production (c)

$1 \rightarrow 4\%$ at $\sqrt{s} = 200$ GeV ($p_T \geq 5$ GeV)

Berger and Gordon, Phys. Rev. **D58**, 114024 (98)

4. χ production at large p_T

$A_{\chi^0 c} \approx 8 \rightarrow 1\%$ at $\sqrt{s} = 500$ GeV (p_T : 2-30 GeV)

Morii, *et. al.*, Phys. Lett. **B372**, 165 (96)

Similarly for χ_1 (ibid.)

$A_{\chi^2 c} \approx 0 \rightarrow 4\%$ at $\sqrt{s} = 200$ GeV (p_T : 2-8 GeV)

Gehrmann and Stirling, Phys. Rev. **D53**, 6100 (96)

5. J/ψ production

$2 \rightarrow 6\%$ at $\sqrt{s} = 200$ GeV (p_T from 2-10 GeV)

Teryev and Tkabkadze, Phys. Rev. **D56**, 7331 (97)

$\sqrt{s} = 200 \text{ GeV}$

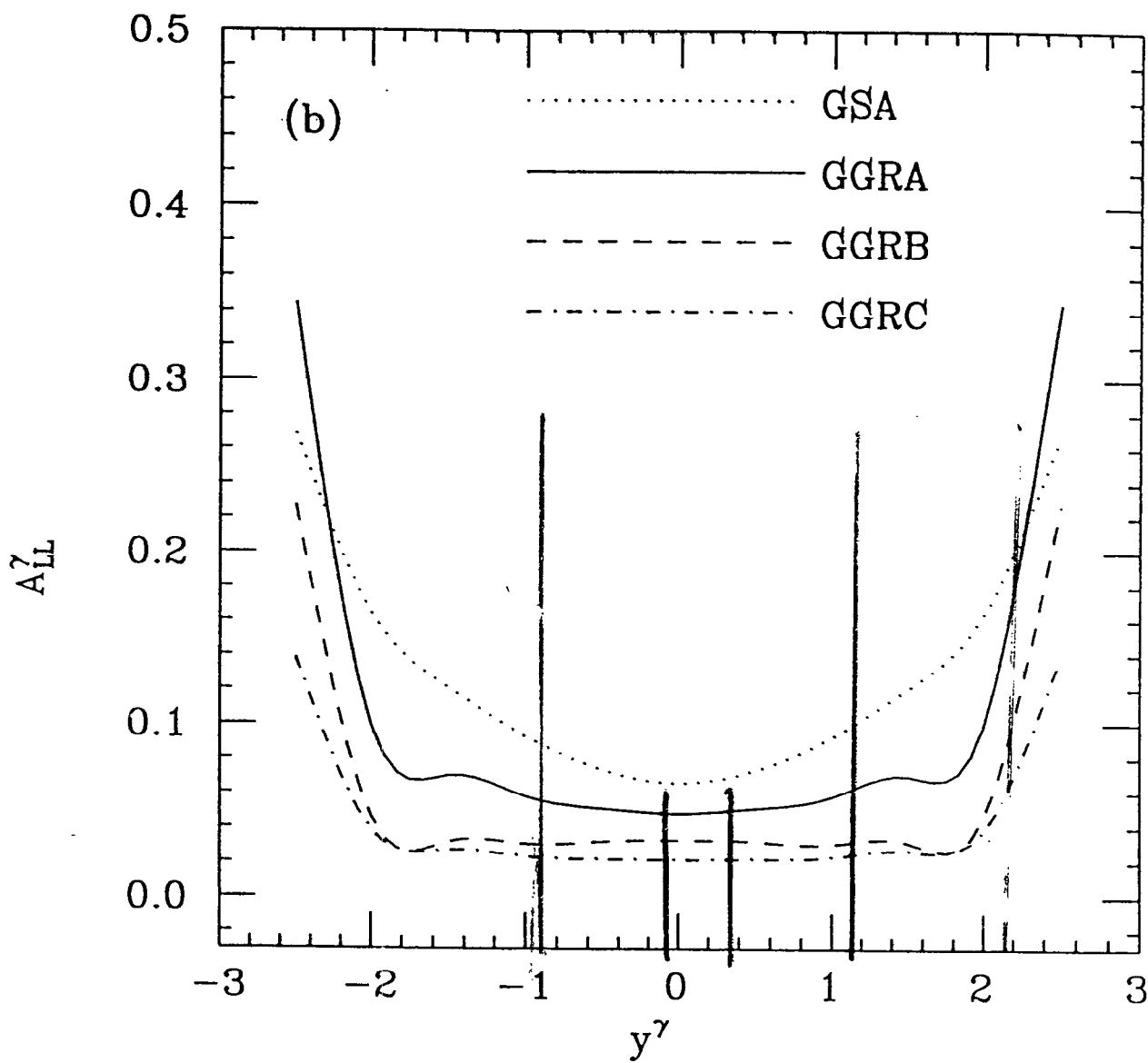


Fig. 3b

STAR DET.
W/EEPC
PHENIX

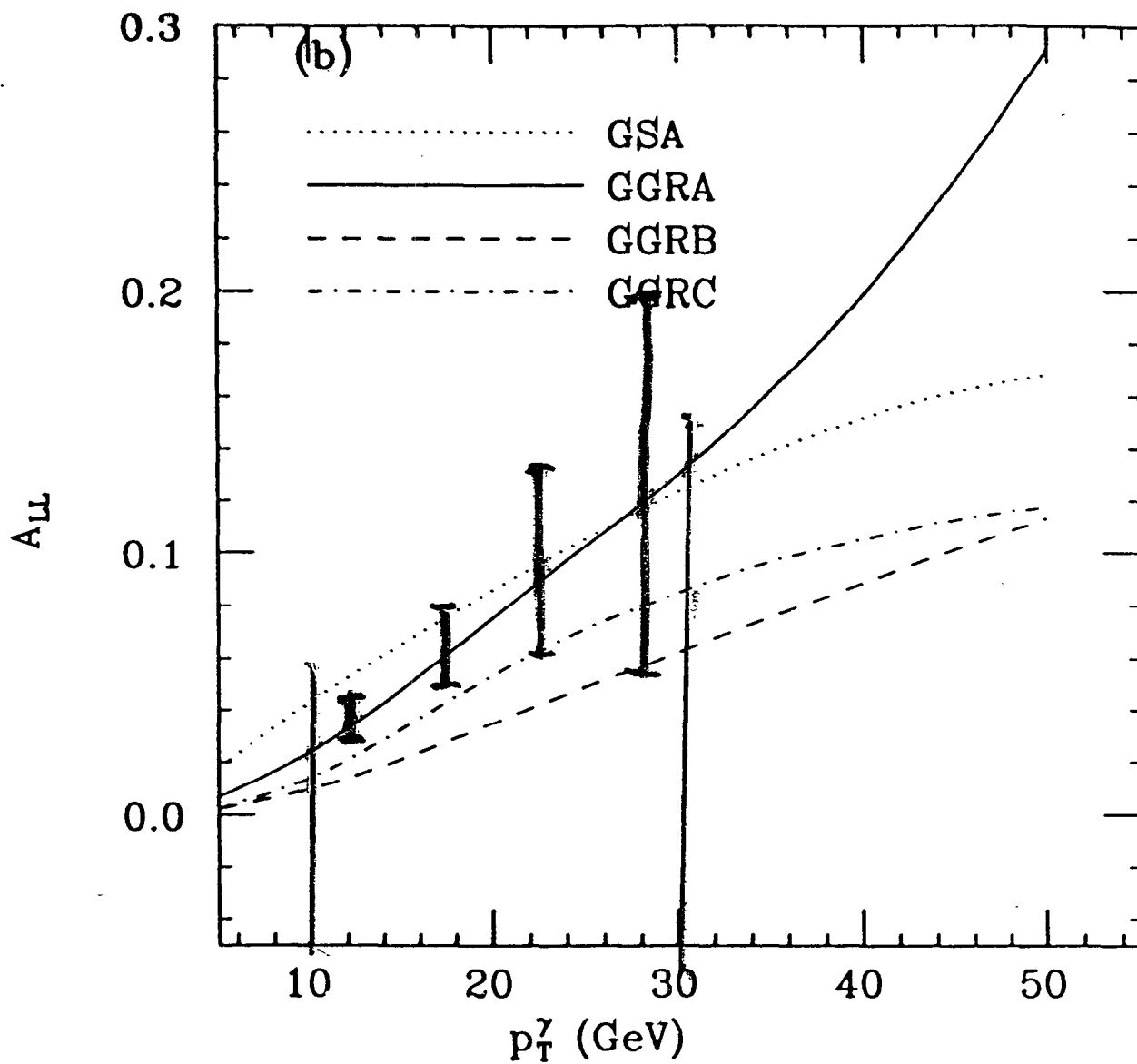


Fig. 2b

I = PROJECTED
 ERRORS - STAR
 11 = PHENIX p_T RANGE

Conclusion

1. There are differences in polarized distributions
Theoretical assumptions
Extraction of data

Size and shape of distr. flavors
2. Many large p_T observables for ΔG
Some too small for meaningful extraction of ΔG
3. Prompt photon and jet production best candidates
Differences in model predictions
Best regions to search at mid p_T and large y
4. Highly recommend endcaps (EEMC) for STAR
5. Highly recommend independent measurements
by PHENIX and STAR

Extracting nucleon spin structure functions from nuclear data

A. W. THOMAS^{a,b}, I. R. AFNAN^{a,c} and F. BISSEY^{a,b}

^aCSSM, University of Adelaide, Adelaide 5005, AUSTRALIA

^bDepartment of Physics and Mathematical Physics,
University of Adelaide, Adelaide 5005, AUSTRALIA

^cSchool of Chemistry, Physics and Earth Sciences,
Flinders University, GPO Box 2100, Adelaide 5001, AUSTRALIA

The determination of the spin-dependent structure functions of the nucleons from nuclear data requires a knowledge of the changes induced by the nuclear medium. This is especially important for the neutron because there are no free neutron targets. We present the results of a study of the accuracy with which one can extract the neutron spin structure function from data on polarized ^3He . This study is based on a three-body calculation of the wave function of the $A=3$ system, which is then used to calculate the nuclear structure functions including binding and off-shell effects.

EXTRACTING (MAINLY)

POLARIZED n - STRUCTURE

FUNCTION FROM NUCLEAR DATA

A.W. Thomas (CSSM)

with

- F. Bissey, I.R. Afnan
- W. Melnitchouk
- K. Saito, F. Steffens, K. Tsushima
(C. Boros)

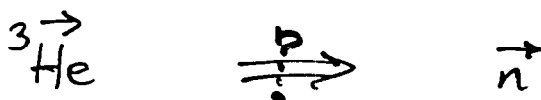
(A) Conventional binding & Fermi motion

$A=3$: Faddeev calculation results.

Inconsistency with density

extrapolation $\left(\text{e.g. } \frac{d(x)}{u(x)} \xrightarrow{x \rightarrow 1} ? \right)$

$\Rightarrow$ TEST EXPTLY!

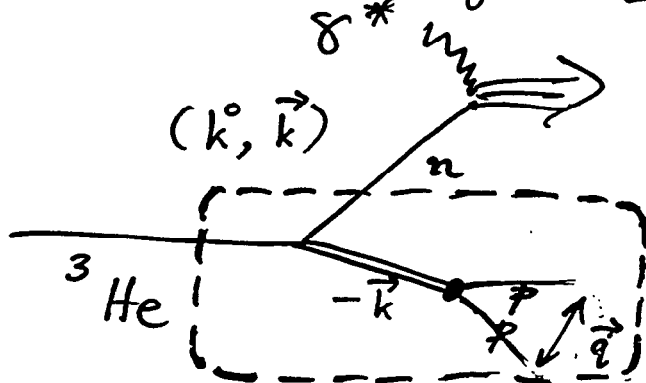


(FUTURE ${}^6\text{Li} \xrightarrow{p} \bar{D})^*$

(R)

Conventional Binding (non-relativistic)

(Eg)



DIS

Full
Faddeev
wafⁿ

(Paris
potential)

$$k^0 = m_{{}^3\text{He}} - 2m - \frac{\vec{k}^2}{4m} - \frac{\vec{q}^2}{m}$$

Convolution:

(c.g.)

$$g_{{}^3\text{He}}(\vec{x}) =$$

$$\int \frac{dy}{y} \Delta f_n(y) g_{1n}\left(\frac{x}{y}\right)$$

+ proton contributions
(D + np final states)

$$\Delta f_n(y) = y \int d^3k d^3q \left| \psi_n(\vec{k}, \vec{q}) \right|_{\uparrow \downarrow}^2 \delta\left(y - \frac{k^0 + k_z}{m}\right)$$

etc.

CAUTION:

Relativistic, including
non-convolution corrections only

made for D (& $\vec{D}$): Melnitchouk, Piller, Thomas

Melnitchouk, Bissey,
Afnan, AWT.

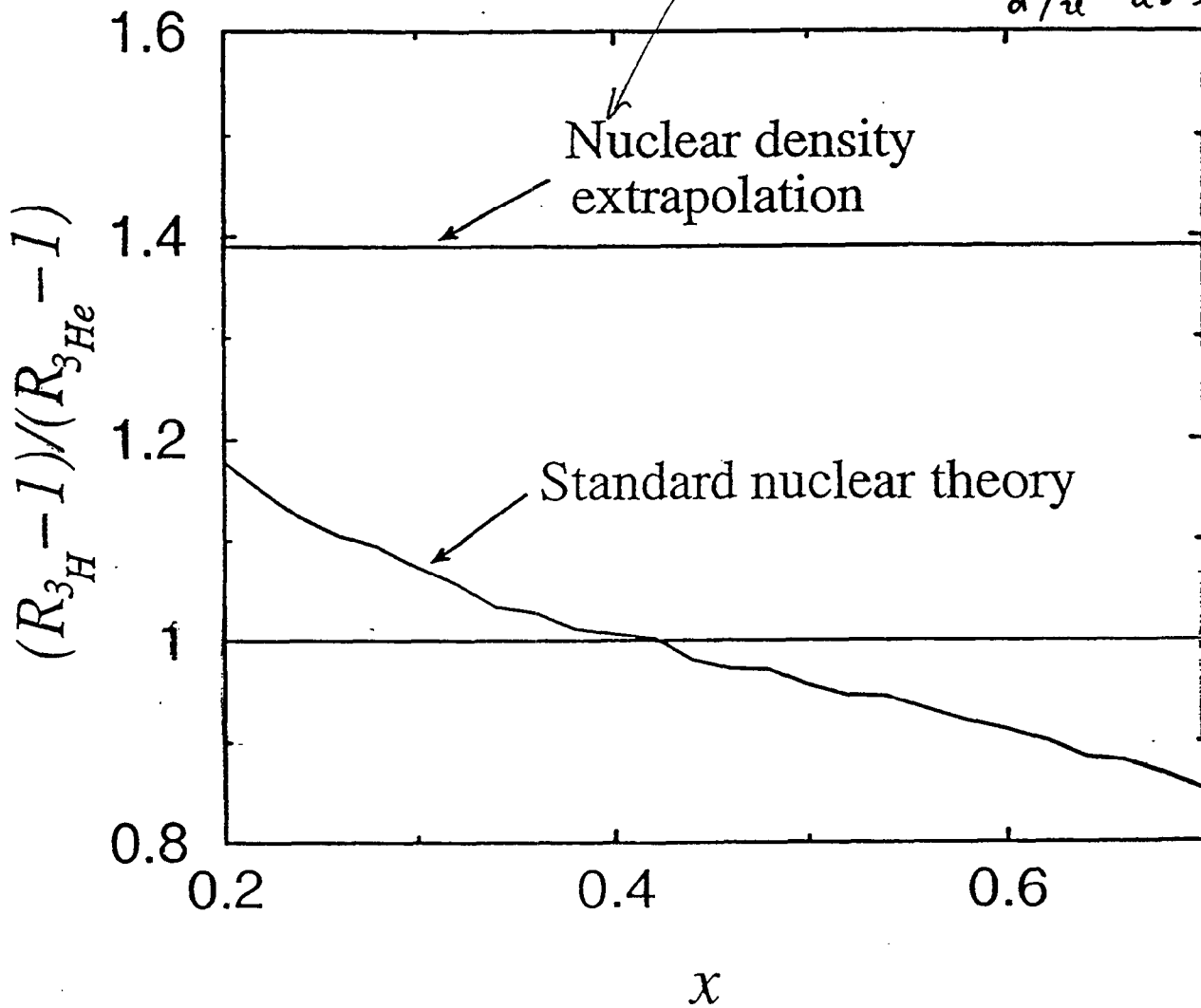
Frankfurt - Strickman

approach used to analyse
 d/u as $x \rightarrow 1$

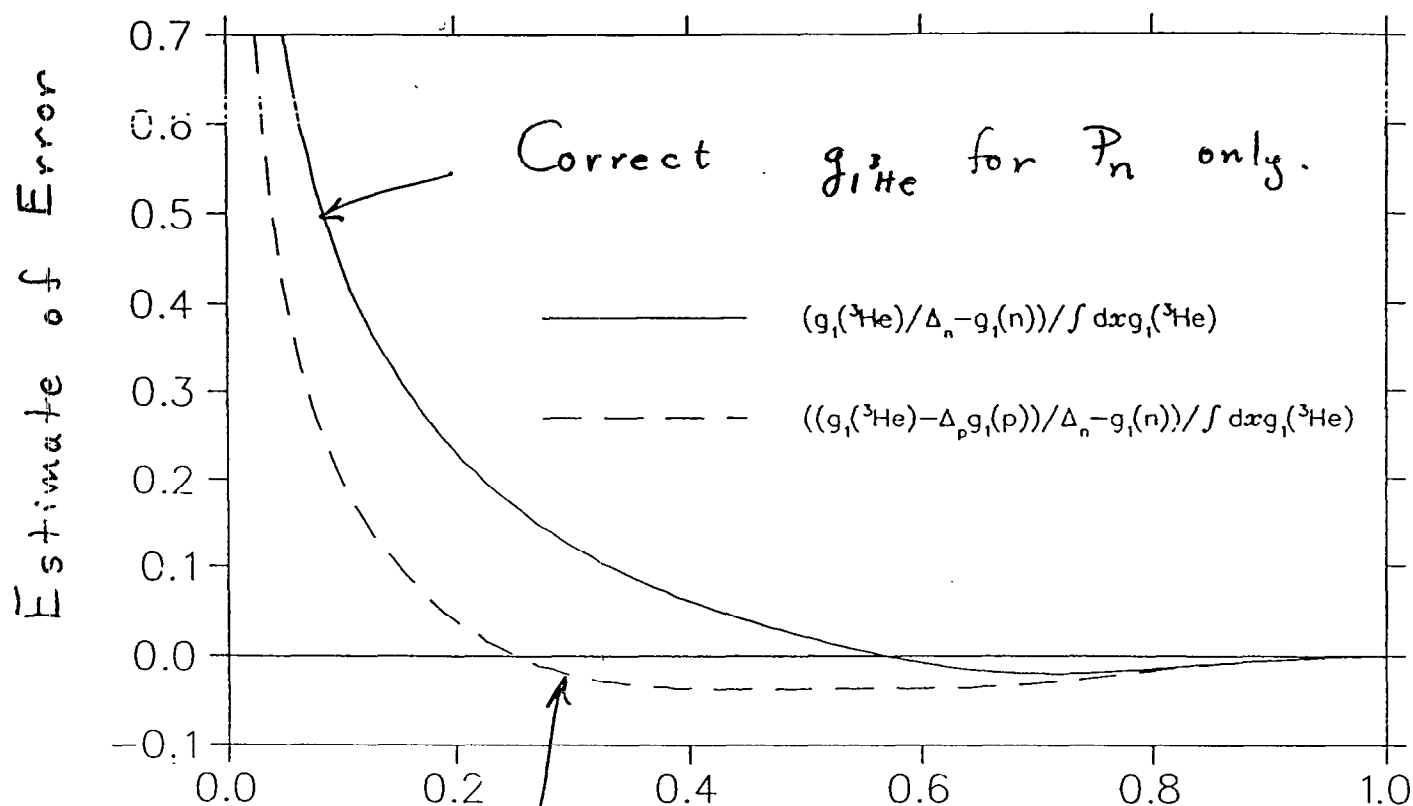
Nuclear density
extrapolation

$\Downarrow$
 $\frac{d}{u} \rightarrow 0$
 $x \rightarrow 1$

Standard nuclear theory



g_1 for ${}^3\text{He}$ including bound structure functions.



Correct $g_1^3\text{He}$ for P_n and P_p .

SUMMARY

- Unpolarized ^3H vs ^3He "EMC"
effect tests binding/Fermi
vs "average density".
- Full, Faddeev spin structure
function analysis done.
→ remains to test different
NN models (Paris, so far).
- $^6\vec{\text{Li}}$ Faddeev calculation ready
soon....
- Change in bound structure
functions[†] not large but
may be significant
→ needs extension to sea....

Spin and Flavor Dependent Parton Distribution and Fragmentation Functions for Octet Baryons

C. Boros, J.T. Londergan¹ and A.W. Thomas

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¹ *Department of Physics and Nuclear Theory Center, Indiana University, Bloomington, IN
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Abstract

We discuss the quark parton structure of octet baryons and the fragmentation of quarks into baryons in a spectator diquark model. The hyperfine interaction, responsible for the Δ - N and Σ^0 - Λ mass splittings, leads not only to sizable $SU(3)$ and $SU(6)$ symmetry breaking in the quark distributions among the octet baryons but also to significant polarized non-strange quark distributions for the Λ . The same arguments suggest flavor asymmetric quark fragmentation functions for the octet baryons and non-zero polarized non-strange quark fragmentation functions for Λ . The calculated fragmentation functions give a good description of all measured observables in lambda production. We predict significant positive longitudinal Λ polarization in inclusive lambda production both in DIS and in proton-proton collisions while models based on $SU(3)$ flavor symmetry predict zero or negative Λ polarization. Our predictions can be tested at RHIC.

Spin and Flavor Dependent

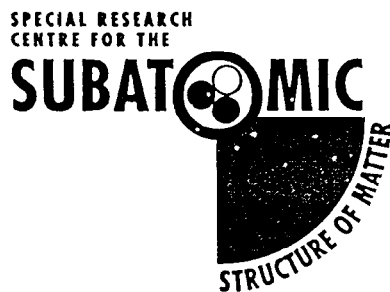
Parton Distribution

Fragmentation Functions

for Octet Baryons

C. Boros

CSSM and Department of Physics, Mathematical
Physics, University of Adelaide Australia

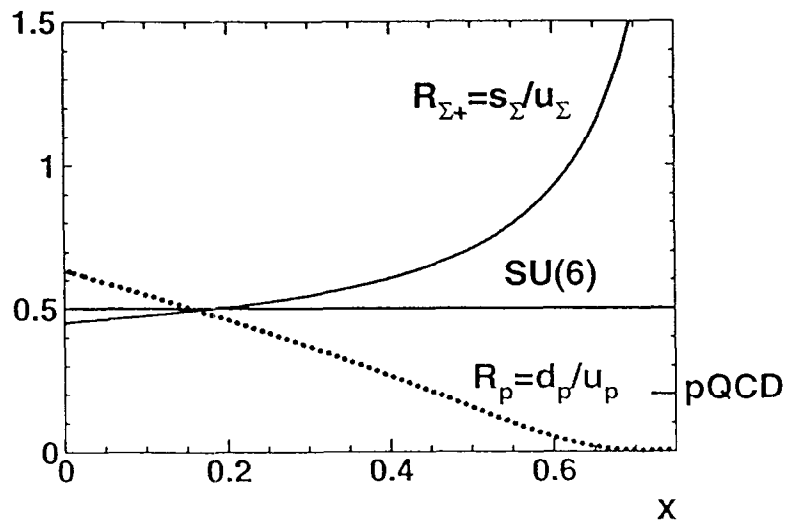
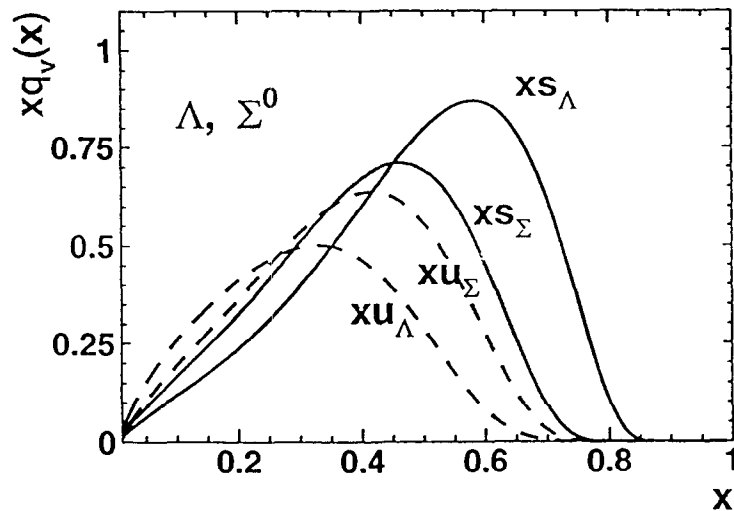


C.B. and A.W.Thomas, Phys.Rev. D60 (1999) 074017;

C.B., J.T. Londergan and A.W. Thomas, hep-ph/9908260

● BARYON OCTET

- $s_\Lambda(x) [(ud)_s]$ harder than $s_{\Sigma^0}(x) [(ud)_v]$
- $s_\Lambda(x) [(ud)_s]$ harder than $u_\Lambda(x) [(us)_v]$
-



Fragmentation Functions

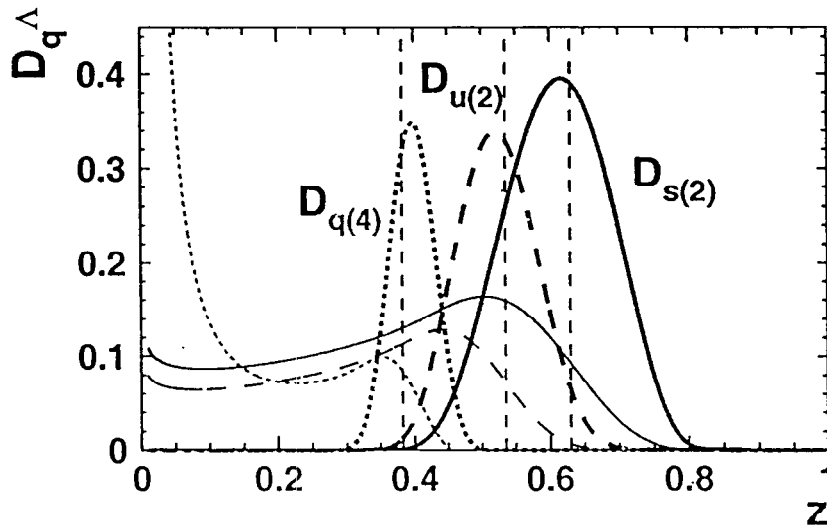
$$\frac{D_{q\Lambda}^\Gamma(z)}{z} = \frac{P^+}{2\sqrt{2}} \sum_n \int \frac{d\xi^-}{2\pi} e^{-iP^+\xi^-/z} \times \text{Tr}\{\Gamma \langle 0|\psi(0)|PS;p_n\rangle \langle PS;p_n|\bar{\psi}(\xi^-)|0\rangle\}$$

Translation invariance, leading twist, helicity proj... ^a

$$\frac{D_{q\Lambda}^{\uparrow\downarrow}(z)}{z} = \frac{P^+}{2} \sum_n |\langle 0|\psi_+^{\uparrow\downarrow}(0)|PS_{\parallel};p_n\rangle|^2 \delta\left[\frac{P^+}{z} - P^+ - p_n^+\right]$$

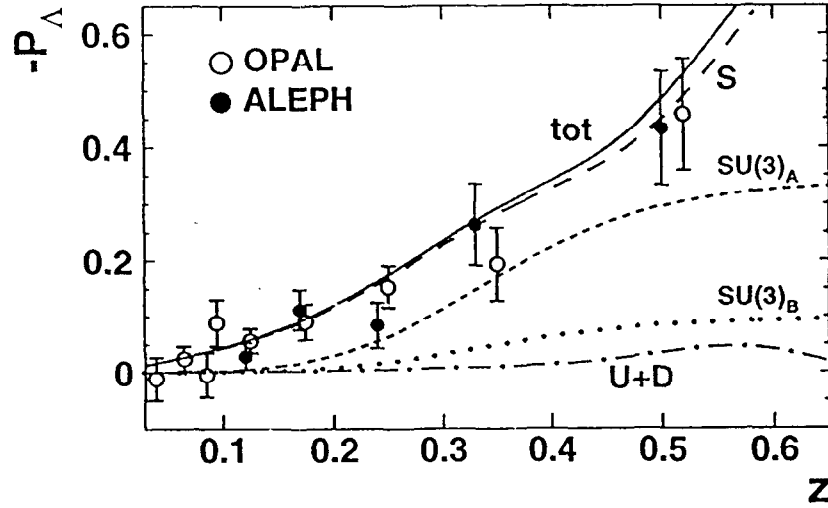
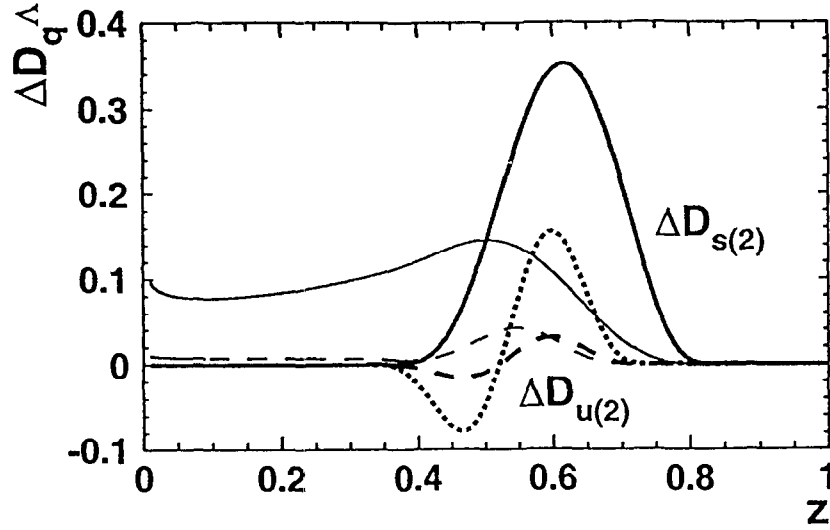
$$\Rightarrow \boxed{z_{max} \sim \frac{M_\Lambda}{M_\Lambda + M_n}}$$

Bag model calculation:



^aCollins/Soper ('82), Jaffe/Xi ('93)

● P_Λ IN e^+e^- ANNIHILATION AT Z -POLE

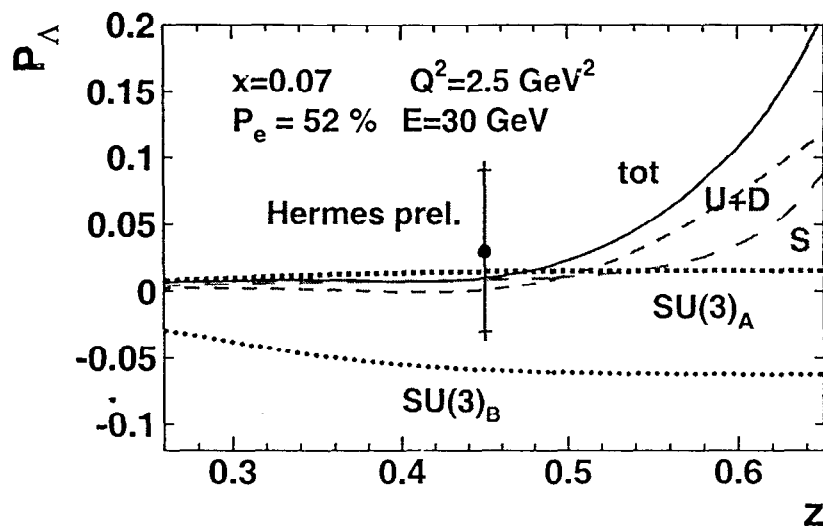


$$SU(3) : D_{u\Lambda} = D_{d\Lambda} = D_{s\Lambda};$$

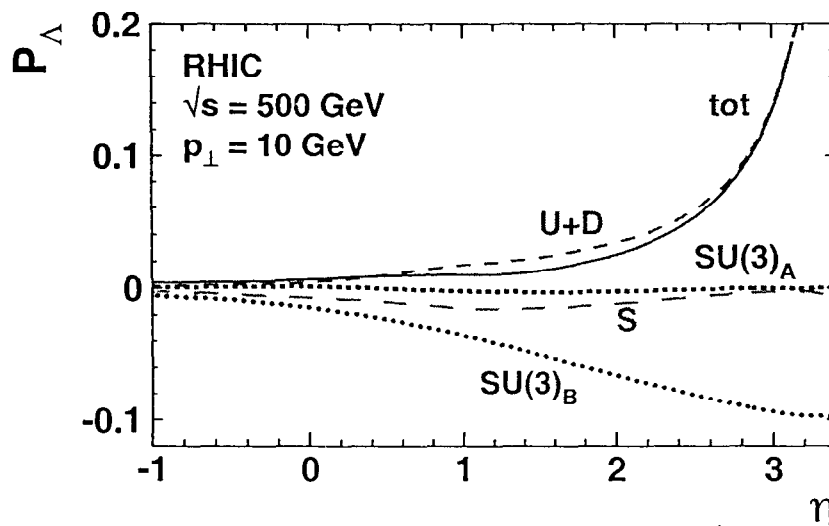
$$SU(3)_A : \Delta D_{u\Lambda} = \Delta D_{d\Lambda} = 0 \text{ and } \Delta D_{s\Lambda} = D_{s\Lambda}$$

$$SU(3)_B : \Delta D_{u\Lambda} = \Delta D_{d\Lambda} = -0.2D_{u\Lambda} \text{ and } \Delta D_{s\Lambda} = 0.6D_{s\Lambda}. \text{ Burkardt/Jaffe ('93)}$$

- Semi-inclusive DIS $e^-(\uparrow) + p \rightarrow \Lambda(\uparrow) + X$
 $u \rightarrow \Lambda$ and $d \rightarrow \Lambda$ dominate for large x ; Jaffe('96)



- $p(\uparrow) + p \rightarrow \Lambda(\uparrow) + X$ ^a



^adeFlorian *et al.*('98), C.B./Londergan/Thomas('99)

Substructure of the Nucleon in the Chiral Quark Model*

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Abstract

Quark spin, flavor content and quark orbital angular momentum in the nucleon are studied nonperturbatively in the chiral quark model with SU(3) symmetry-breaking [1]. The structure of the nucleon is determined by the valence quark content and all possible chiral fluctuations up to first order. The model explains most flavor and spin observables of the nucleon, and predicts the orbital angular momentum carried by quarks and antiquarks [2]. Generalizing to other octet and decuplet baryons, the quark spin and orbital angular momentum are given, and the magnetic moments of those baryons are calculated [3]. The model is further extended to the SU(4) case. The intrinsic charm quark content and charm quark polarization are predicted [4].

[1] X. Song, Phys. Rev. D **57**, 4114 (1998)

[2] X. Song, hep-ph/9801332, hep-ph/9802206

[3] X. Song, hep-ph/9804461

[4] X. Song, ICTP Report, 1998

* Talk given in the Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics, November 3-6, 1999, RIKEN, Wako, Japan.

Quark Orbital Angular Momentum

$$u_{\uparrow} \rightarrow d_{\downarrow} + \pi^+ (u, \bar{d})$$

$$u_{\uparrow} \rightarrow s_{\downarrow} + K^+ (u, \bar{s})$$

$$u_{\uparrow} \rightarrow u_{\downarrow} + (GB)_+^0$$

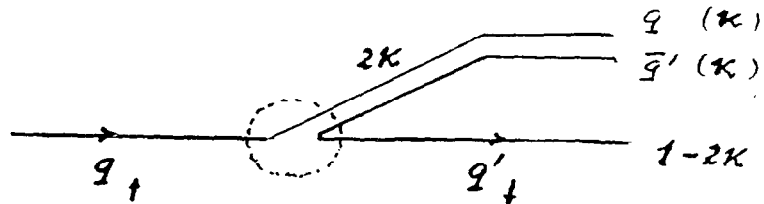
$$\underline{\Delta s_z = -1}, \quad \underline{\Delta L_z = +1}$$

$$u_{\uparrow} \rightarrow d_{\uparrow}$$

$$\underline{\Delta s_z = 0}, \quad \underline{\Delta L_z = 0}$$

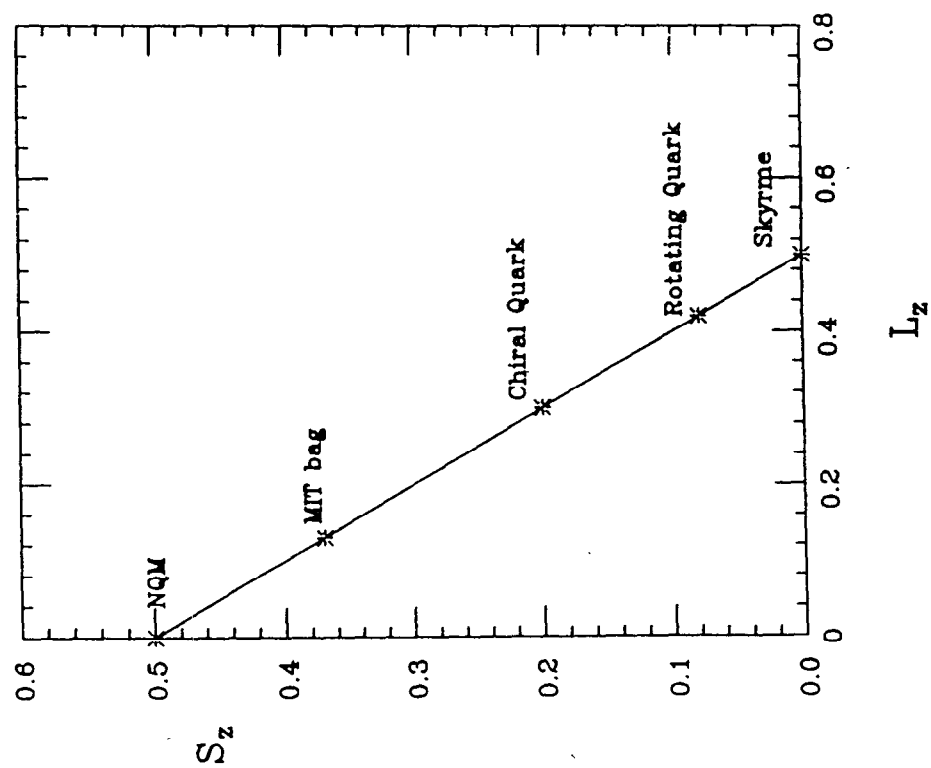
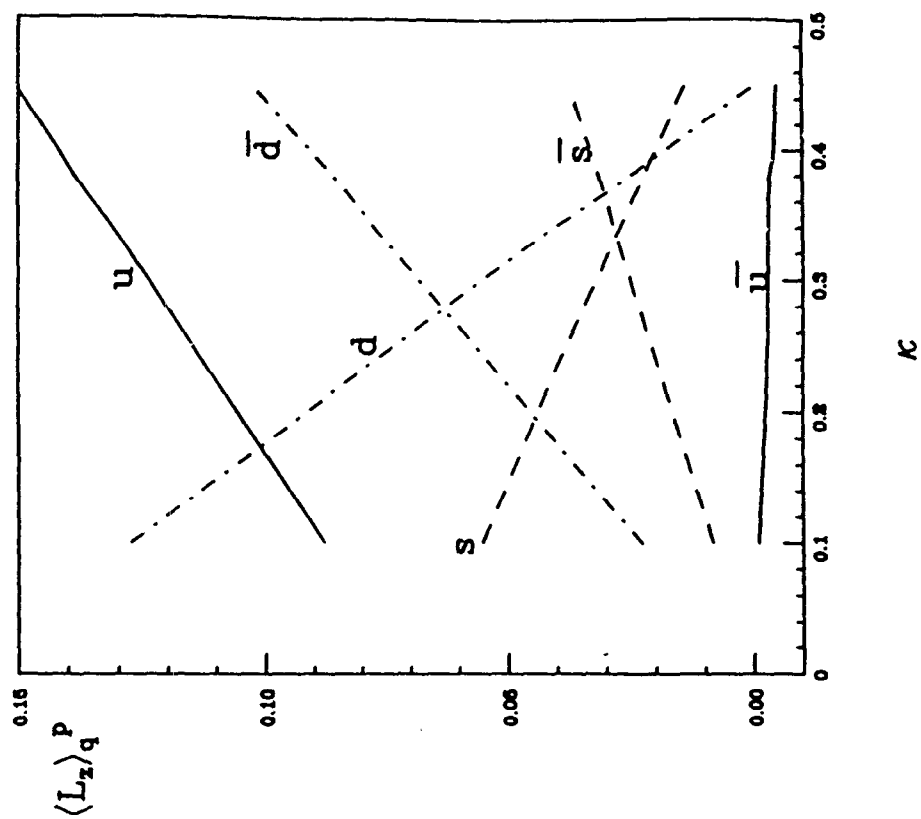
Partition factor κ :

$$0 < \kappa < \frac{1}{2}$$



$$\langle L_z \rangle_{u/q_{\downarrow}} = - \langle L_z \rangle_{u/q_{\uparrow}}$$

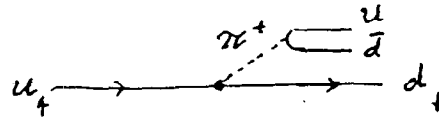
$$\langle L_z \rangle_u^p = \sum_{q=u,d} [n_p^{(0)}(q_{\uparrow}) - n_p^{(0)}(q_{\downarrow})] \langle L_z \rangle_{u/q_{\uparrow}}$$



SU(4) Symmetry Breaking χ QM

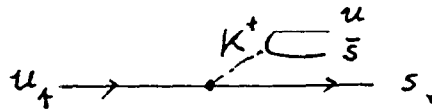
$$L_I = g_{15} \bar{q} \begin{pmatrix} G_u^0 & \pi^+ & \sqrt{\epsilon} K & \sqrt{\epsilon_c} \bar{D}^0 \\ \pi^- & G_d^0 & \sqrt{\epsilon} K^0 & \sqrt{\epsilon_c} D^- \\ \sqrt{\epsilon} K^- & \sqrt{\epsilon} \bar{K}^0 & G_s^0 & \sqrt{\epsilon_c} D_s^- \\ \sqrt{\epsilon_c} D^0 & \sqrt{\epsilon_c} D^+ & \sqrt{\epsilon_c} D_s^+ & G_c^0 \end{pmatrix} q$$

$\odot u_{\uparrow} \rightarrow d_{\downarrow} + \pi^+$



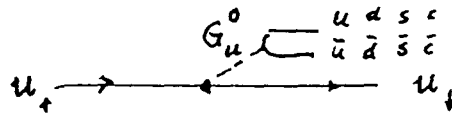
$\sim a \sim |g_{15}|^2$

$\odot u_{\uparrow} \rightarrow s_{\downarrow} + K^+$



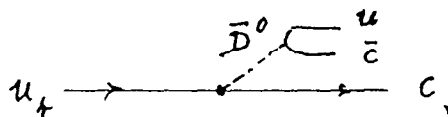
$\sim \epsilon a$

$\odot u_{\uparrow} \rightarrow u_{\downarrow} + G_u^0$



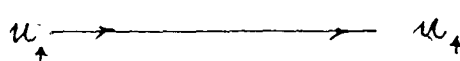
$\sim f \cdot a$

$\odot u_{\uparrow} \rightarrow c_{\downarrow} + \bar{D}^0$



$\sim \epsilon_c a$

$\odot u_{\uparrow} \rightarrow u_{\uparrow}$



$\sim 1 - (1 + \epsilon + \epsilon_c + f) a$

TABLE III. Quark spin observables

Quantity	Data	SU(3)	SU(4)
Δu	0.85 ± 0.04	0.86	0.83
Δd	-0.41 ± 0.04	-0.40	-0.39
Δs	-0.07 ± 0.04	-0.07	-0.07
Δc	-0.020 ± 0.004 [17] $-5 \cdot 10^{-4}$ [18]	0	-0.029 ± 0.015
$\Delta \bar{u}, \Delta \bar{d}$	-0.02 ± 0.11	0	0
$\Delta \bar{s}, \Delta \bar{c}$	-	0	0
$\Delta c / \Delta \Sigma$	-0.08 ± 0.01 [15] -0.033 [17]	0	-0.08 ± 0.05
$\Delta c / c$	-	-	-0.314
Γ_1^p	0.136 ± 0.016	0.133	0.133
Γ_1^n	-0.036 ± 0.007	-0.037	-0.034
Δ_3	1.2573 ± 0.0028	1.26	1.259
Δ_8	0.579 ± 0.025	0.60	0.578

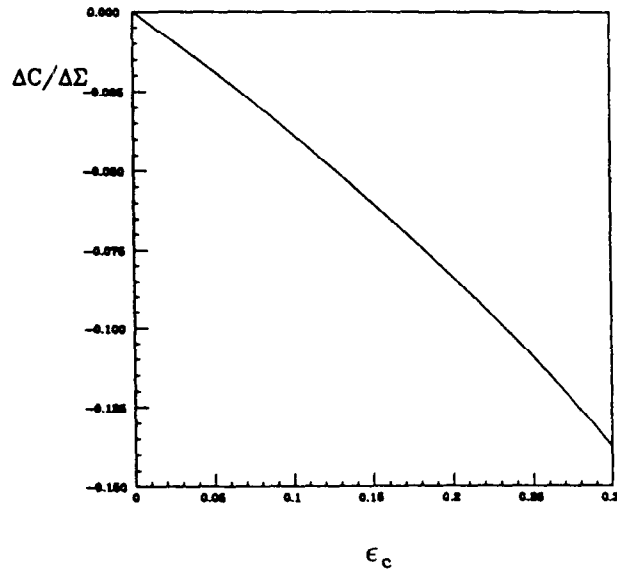
FIG. 1. Intrinsic charm quark polarization in the proton as function of ϵ_c .

TABLE II. Quark flavor observables

Quantity	Data	SU(3)	SU(4)
$\bar{d} - \bar{u}$	0.147 ± 0.039 0.110 ± 0.018	0.147	0.120
$\bar{u}/\bar{d}$	$[\frac{\bar{u}(x)}{\bar{d}(x)}]_{0.1 < x < 0.2} = 0.67 \pm 0.06$ $[\frac{\bar{u}(x)}{\bar{d}(x)}]_{x=0.18} = 0.51 \pm 0.06$	0.65	0.69
$2\bar{s}/(\bar{u} + \bar{d})$	$\frac{\langle 2x\bar{s}(x) \rangle}{\langle x(\bar{u}(x) + \bar{d}(x)) \rangle} = 0.477 \pm 0.051$	0.69	0.69
$2\bar{c}/(\bar{u} + \bar{d})$	—	0	0.28 ± 0.14
$2\bar{s}/(u + d)$	$\frac{\langle 2x\bar{s}(x) \rangle}{\langle x(u(x) + d(x)) \rangle} = 0.099 \pm 0.009$	0.128	0.120
$2\bar{c}/(u + d)$	—	0	0.05 ± 0.02
$f_s \equiv 2\bar{s}/\sum(q + \bar{q})$	0.10 ± 0.06 0.15 ± 0.03 $\frac{\langle 2x\bar{s}(x) \rangle}{\sum \langle x(q(x) + \bar{q}(x)) \rangle} = 0.076 \pm 0.022$	0.10	0.09
$f_c \equiv 2\bar{c}/\sum(q + \bar{q})$	0.03 [7] 0.02 [1] 0.005 [8]	0	0.03 ± 0.01
$\sum \bar{q}/\sum q$	$\frac{\sum \langle x\bar{q}(x) \rangle}{\sum \langle xq(x) \rangle} = 0.245 \pm 0.005$	0.235	0.246
f_3/f_8	0.23 ± 0.05	0.21	0.22

T-odd Effects in QCD

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Bogoliubov Theoretical Laboratory,
Joint Institute for Nuclear Research,
141980 Dubna, Russia

The sources of T-odd spin effects in QCD are analyzed. While T-odd distribution may appear only effectively, T-odd fragmentation and fracture functions are compatible with QCD factorization. The zero sum rules for T-odd fragmentation functions and their possible relation to Burkhardt-Cottingham sum rule are discussed.

*E-mail address: teryaev@thsun1.jinr.ru

The way to probe

$$p \uparrow p \rightarrow \gamma X \quad A \sim \frac{M}{P_L} (T - x \frac{dT}{dx}) S^{\text{Giu Sterman}}_{\text{thermal}}$$

↑ source of growth for $x_F \rightarrow 1$

$$p \uparrow p \rightarrow e^+ e^- X$$

Hammon
Schäfer
Q.T.

Low p_T -

lepton plane should
be fixed

RHIC

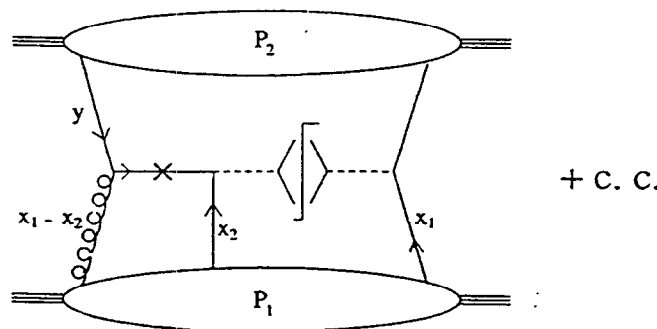


Fig. 2. Twist 3 diagramm for the process $P + P(\uparrow) \rightarrow l \bar{l} + X$. The quark propagator generates the imaginary part when it is put on-shell, therefore the gluon has vanishing four-momentum $(x_1 - x_2) \approx 0$.

leads to the following expression for the polarized part of the asymmetry

$$\sigma_{\text{pol.}} = \frac{g}{\pi} \int dx_2 \frac{T(x_1, x_2)}{(x_1 - x_2)} q(y) \cdot \text{Tr} \left[P_2 \gamma^\mu \frac{(x_1 - x_2)}{(x_1 - x_2) y s + i\epsilon} P_1 + y P_2 \Delta \not{V} \gamma^\rho \Delta \not{V} \right] \epsilon^{\rho\mu S P_1} \quad (8)$$

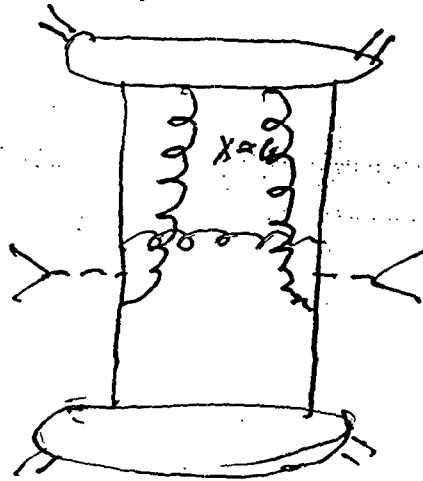
where $\Delta l^\mu = l_1^\mu - l_2^\mu$ and $l^\mu = l_1^\mu + l_2^\mu$. The last factor in the bracket follows from $\not{V}_1 \gamma^\rho \not{V}_2 + \not{V}_2 \gamma^\rho \not{V}_1 = (\not{V} \gamma^\rho \not{V} - \Delta \not{V} \gamma^\rho \Delta \not{V})/2$ and the fact that the vector Δl^μ is needed for the contraction with the epsilon tensor, such that only the last term contributes.

$$A \sin 2\theta \cos \theta (T(x_1, x_2) \frac{dT}{dx} (x_1, x_2))$$

Similar effect

twist-4 nuclear
enhancement

Qia;
Stermann



$$pp \rightarrow \gamma^*(p_T) X$$

$$\int dx dy dz e^{ip+z} \langle \bar{\psi}(0) F(x) F(y) \psi(z) \rangle$$

$$\sim \int d(x-y) d\left(\frac{x+y}{2}\right) \langle F(x) F(y) \rangle \Big|_{\text{singlet}}$$

} $R_{\text{nucleus}} - A^{1/3}$

May be studied also for
dilepton tensor polarization
and

R. Fries
B. Müller
E. Stein
A. Schäfer

single spin Asymmetries

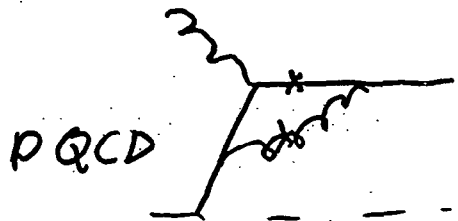
$$RMIC: \vec{p} A \rightarrow \ell^+ \ell^- X$$

R. Fries
Schäfer,
Stein
S.T.
in progr.

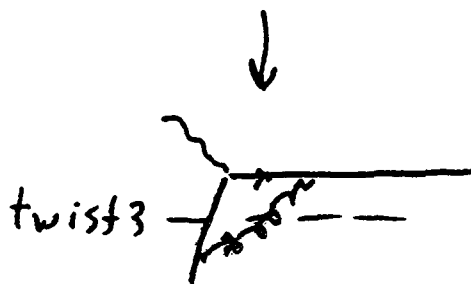
Can phases

arise entirely

from large distances?

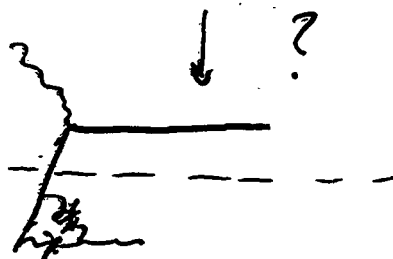


Hard



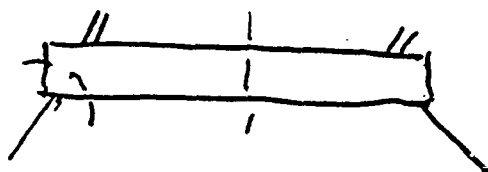
Hard

Soft

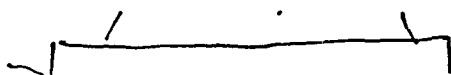


Soft

Yes - for Fragmentation functions



No - for distributions

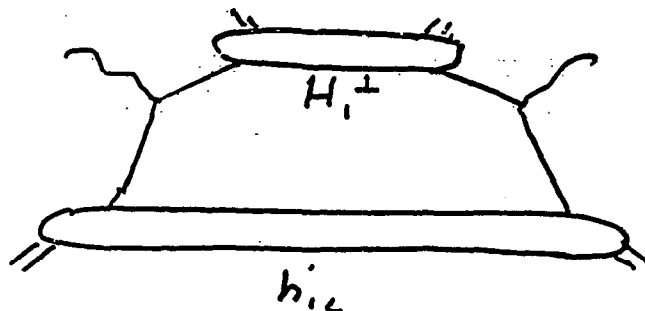


Efremov
Mankiewicz
Tongvald
Collins
Haldane
Tongvald
Takahashi
G.T.
Jaffe
Silver

QCD Mechanisms (inclusive)

- T-odd fragmentation function

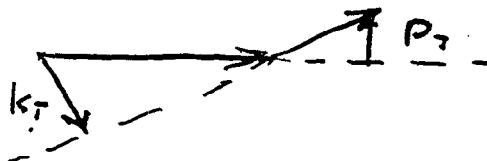
Mulders
Tangenz



$$\langle 0 | \bar{\Psi} \epsilon_{\mu\nu} | \bar{u} X \rangle \langle X | \psi | 0 \rangle$$

$$\sim H_1^\perp p^\mu \frac{k_T^\nu}{M}$$

Collins



$$p^+ = z k^+$$

$$p_\perp = -z k_\perp$$

Longitudinal momentum conservation

$$\sum_h \int_0^1 dz z^2 \underbrace{\int D(z, k_T) d^2 k_T}_{D(z)} = 1$$

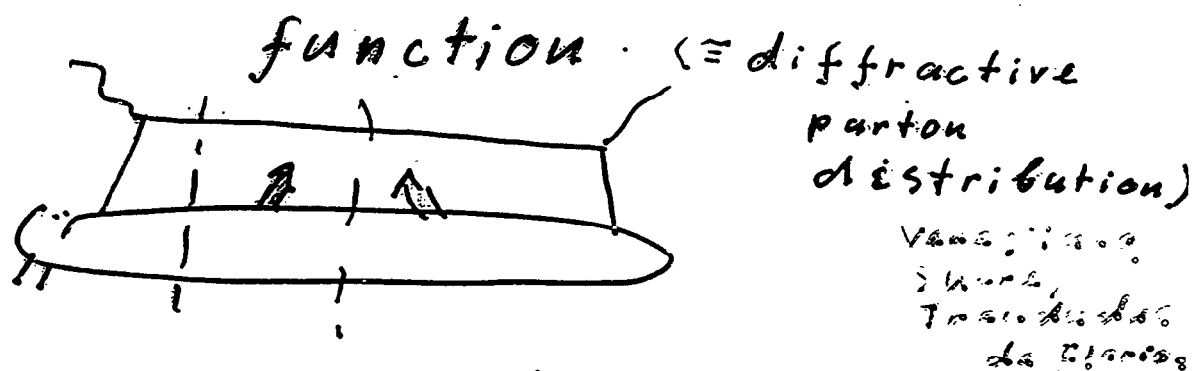
Transverse

$$\sum_h \int_0^1 dz z^2 \int \underbrace{H_1^\perp(z, k_T) \frac{k_T^2}{M^2}}_{\text{}} d^2 k_T = 0$$

Modest momentum
transfer from target
to meson - fracture
function



... T-odd fracture (extended)



Naturally explain also the growth of the
hadronic SSA.

for $x_F \rightarrow 1$

& Mass parameter from spin-independent fragmentation
function

Source for SSA / T-odd
correlations of diffractive
mesons at HERA

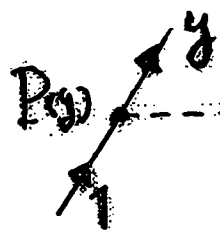
T-odd quark fragmentation function and transverse spin asymmetries in the pion production

Katsuhiko SUZUKI

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We study the time-reversal odd quark fragmentation function and its consequences on the hard processes. T-odd quark fragmentation function may arise, although QCD is T-invariant, from the non-perturbative dynamics in the fragmentation process. Assuming the factorization, we extract the T-odd fragmentation function from the inclusive pion production in the transversely polarized proton-proton collision. We then estimate the single spin asymmetry A_{OT} of the semi-inclusive deep inelastic scattering with unpolarized lepton and the transversely polarized proton. We also discuss the meson cloud effects on the transversity distribution $h_1(x)$ of the nucleon. Asymmetry for the π^- production is found to be much smaller than the naive expectation, since the d -quark transversity is considerably suppressed by the pion cloud effects.

< Modifications of $h_1(x)$ >



Meson emission is calculated in Infinite Momentum Frame

- Unpolarized $P_{\pi}(y) = g^2 \int \frac{dk_T^2}{(16\pi^2)} \frac{1}{y(1-y)} \frac{(1-y)^2 m^2 + k_T^2}{y[m^2 - M^2]^2}$
- Helicity $\Delta P_{\pi}(y) = g^2 \int \frac{dk_T^2}{(16\pi^2)} \frac{1}{y(1-y)} \frac{(1-y)^2 m^2 - k_T^2}{y[m^2 - M^2]^2}$ Small
- Transversity $\delta P_{\pi}(y) = g^2 \int \frac{dk_T^2}{(16\pi^2)} \frac{1}{y(1-y)} \frac{(1-y)^2 m^2}{y[m^2 - M^2]^2}$

m : Nucleon mass

$$M^2 = \frac{m^2 + k_T^2}{y} + \frac{m^2 + k_T^2}{1-y}$$

Drell, Levy, Yan (70)
Speiser, Thomas (96)

- Modified distribution • ($Z = 1 - \frac{3}{2} P_{\pi} - \dots$)

$$\delta u(x) = Z \delta u_0(x) + P_{\pi} \otimes \delta d_0 + \frac{1}{2} P_{\pi} \otimes \delta u_0 + \dots$$

$$\delta d(x) = Z \delta d_0(x) + \delta P_{\pi} \otimes \delta u_0 + \frac{1}{2} \delta P_{\pi} \otimes \delta d_0 + \dots$$

Negative Positive

Cancellation $\Rightarrow h_1^d$ is suppressed

- Example: Tensor charge -

$SU(6)$ symmetry for u_0, d_0

Helicity	Transversity
$\Delta u_0 = \frac{4}{3}$ $\Delta u = 0.86$	$\delta u_0 = \frac{4}{3}$ $\delta u = 0.91$

* Transverse single spin asymmetry in pp collision provides a chance to observe (?)

$$\underline{h_1(x) \text{ at large } x}$$

$$\begin{cases} h_1^u / f_1^u \rightarrow 1 \\ h_1^d / f_1^d \rightarrow -1 \end{cases} \text{ at } x \sim 1$$

while

* Pion production in semi-inclusive DIS possible to extract

$$\underline{h_1(x) \text{ at middle or small } x}$$

INTERESTING TOPICS =

" Q^2 evolution

" unique small- x behavior

Kirschner et al. Z-Phys. C74 501

" effects of meson cloud

physical nucleon is surrounded by Virtual Mesons

Fock state expansion

$$|p\rangle = \sum |p_0\rangle + c_1 |n \pi^+\rangle + c_2 |p \pi^0\rangle + c_3 |\Delta^+ \pi^0\rangle + \dots (\text{Vector meson}) + \dots$$

$$Z \sim 0.5 \sim 0.7$$

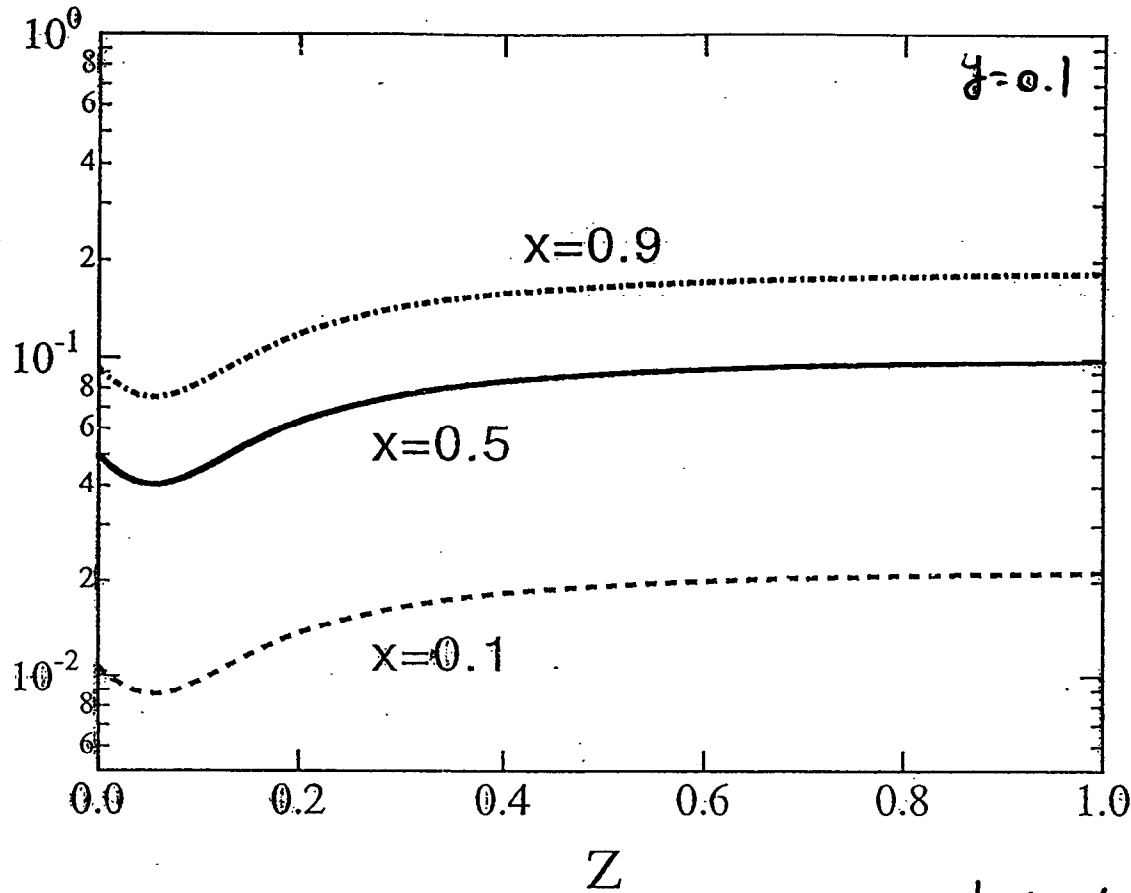
⇒ Reasonable explanation for $\bar{u}, \bar{d}$ asymmetry
HERA experiment $e+p \rightarrow e+n+X$

- Correction to $h_1(x)$

• down quark transversity is suppressed h_1^d

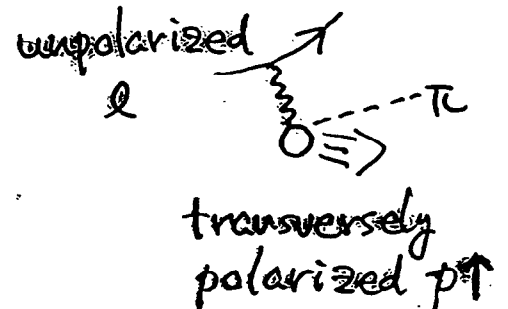
Estimates of the asymmetry A_T for semi-inclusive DIS

Angle weighted asymmetry



$$A_{OT} = \frac{\int d\varphi \, d^2p_{T\perp} \frac{p_{T\perp}}{zM_{T\perp}} \sin\varphi (d\sigma\uparrow - d\sigma\downarrow)}{\int d\varphi \, d^2p_{T\perp} (d\sigma\uparrow + d\sigma\downarrow)}$$

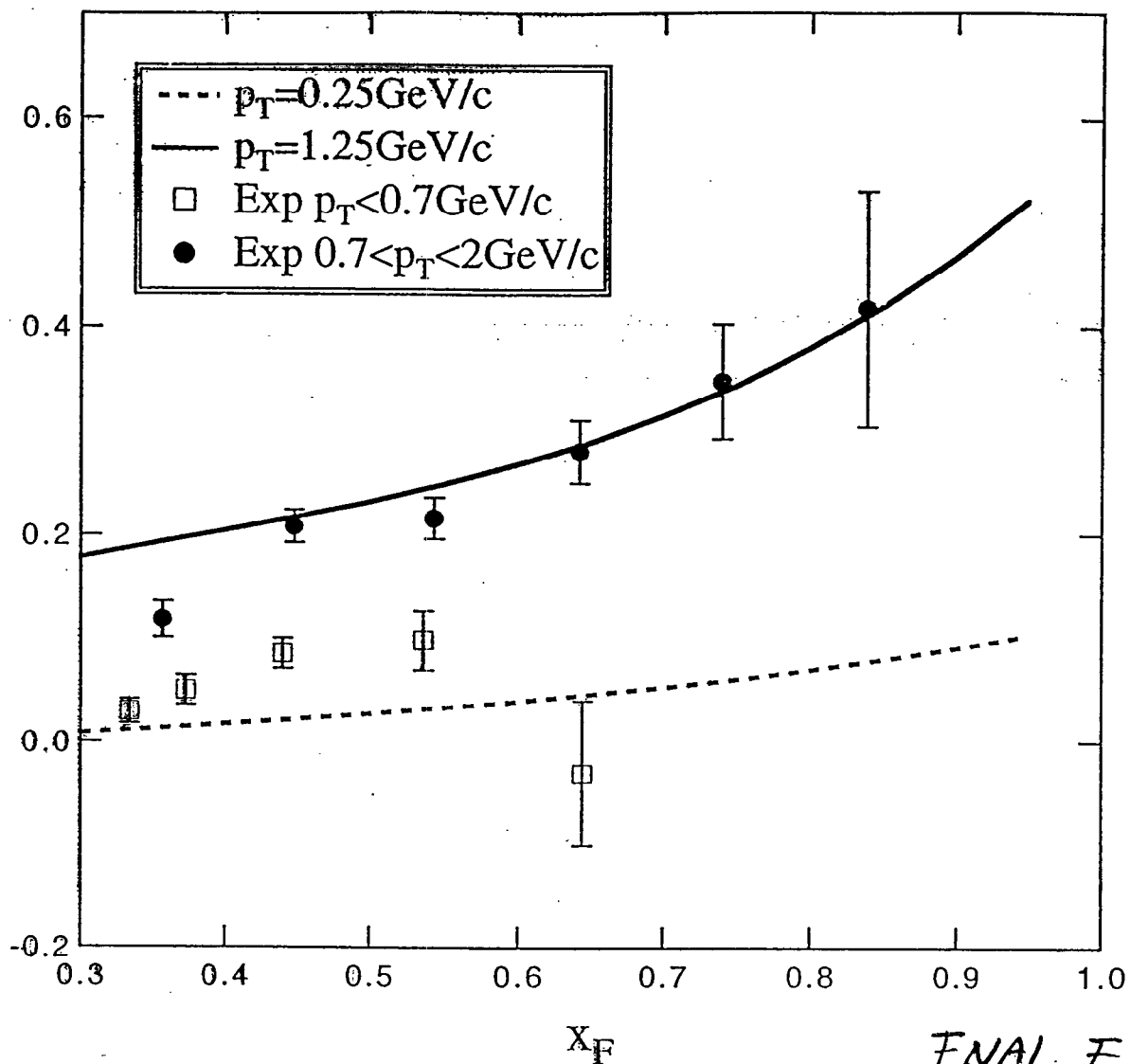
$$= -|S_T| \frac{2(1-y)}{1+(1-y)^2} \cdot \frac{h_1^a(x) H_{1\perp}^a(z)}{f_1^a(x) D_1^a(z)} \leftarrow T\text{-odd}$$



〃 A_T の π^+ , π^- の場合を比較すると.

h_1^d と h_1^u の区別がわかる。 139 $A_T(\pi^+) \quad h_1^u \quad f_1^d$

Single Spin Asymmetry π^+



! $x_F \sim x_B \cdot z$

Asymmetry at large x_F provides
 "large x_B behavior of quark distribution"

$$p \rightarrow q(x_B) \rightarrow D(z) \rightarrow \pi(x_F)$$

Phenomenological Analysis

Try to estimate T-odd fragmentation function using existing data

$$A_N \text{ in } p \uparrow + p \rightarrow \pi^a(K, \eta) + X \text{ at large } x_F$$

- Procedure -

1. Assume the function from for T-odd quark fragmentation function

2. Determine parameters to reproduce the single spin asymmetry in pp collision

$$p \uparrow + p \rightarrow \pi^a + X$$

3. Estimate the asymmetry for semi-inclusive DIS off transversely polarized nucleon

$$e + p \uparrow \rightarrow e' + \pi^a + X$$

Assume

$$\Delta D = C \frac{z}{1-z} \frac{k^2}{(k^2 - m^2)} (\mathbf{k}_\perp \times \mathbf{s}_\perp)_z$$

C is fixed by π^+ data

$\sin \phi$
dependence!

We neglect un-favored process

$$u \rightarrow \pi^-, d \rightarrow \pi^+$$

The Spin Structure of the Proton

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It is shown that the proton “spin crisis” or “spin puzzle” can be understood by the relativistic effect of quark transversal motions due to the Melosh-Wigner rotation. The quark helicity Δq measured in polarized deep inelastic scattering is actually the quark spin in the infinite momentum frame or in the light-cone formalism, and it is different from the quark spin in the nucleon rest frame or in the quark model. The flavor asymmetry of the Melosh-Wigner effect for the valence u and d quarks and the intrinsic sea $q\bar{q}$ pairs are also the important ingredients in a $SU(6)$ quark-spectator-diquark model framework to understand the “spin puzzle”. Such a picture of the spin structure can be tested by use of several simple relations to measure the quark spin distributions in the quark model.

*E-mail address: mabq@hptc5.ihep.ac.cn

The spin structure of the proton

Bo-Qiang Ma (IHEP, Beijing)

馬伯強

- The proton "spin crisis"
- The Melosh-Wigner Rotation
- The $SU(6)$ quark-spectator-diquark model
- How to test the picture
- Conclusion

• Wigner Rotation

$$\vec{S}, p_\mu \longrightarrow \vec{S}', p'_\mu \quad (\vec{S}, p_\mu) \quad (\vec{S}', p'_\mu)$$

$$\vec{S}' = R_W(\Lambda, p) \vec{S}, \quad p' = \Lambda p$$

$$R_W(\Lambda, p) = L(p') \Lambda L^{-1}(p) \quad \text{a pure rotation}$$

Wigner Rotation

• Melosh Rotation

H.J. Melosh, Phys. Rev. D 9(12):1291, 1974

$$q_F^S = \sum_{S'} M_{S'S}(R) q_T^{S'}$$

$$R = \frac{m + k_0 + k_3 + i \epsilon_{ij3} \sigma_i k_j}{[2(k_0 + k_3)(m + k_0)]^{1/2}}$$

$$\begin{cases} q_T^\uparrow = w[(k^+ + m) q_F^\uparrow - k^R q_F^\downarrow] \\ q_T^\downarrow = w[(k^+ + m) q_F^\downarrow + k^L q_F^\uparrow] \end{cases}$$

$$w = [2k^+(m + k_0)]^{-1/2}, \quad k^{R,L} = k_1 \pm i k_2, \quad k^+ = k_0 + k_3, \quad k_0 = (m^2 + \vec{k}^2)^{1/2}$$

$$\Delta q_F = M_q \Delta q_T$$

$$M_q = \frac{[(k^+ + m)^2 - \vec{k}_\perp^2]}{2k^+(m + k_0)}$$

Light-cone spinors
an instant-form spinors

• What is Δq

Δq is defined by

$$\Delta q_{S_M} = \langle p, s | \bar{\psi} \gamma_M \gamma_5 \psi | p, s \rangle$$

$$\Delta q = \langle p, s | \bar{\psi} \gamma^+ \gamma_5 \psi | p, s \rangle \quad t = 0+3$$

① using light-cone Dirac Spinors

$$\Delta q = \int_0^1 dx (q^\uparrow(x) - q^\downarrow(x))$$

W. P. Schleich, S. J. Brodsky

Phys. Rev. D 22 (1980) 2317

W. Kerner, H. J. Witten

Phys. Rev. D 11 (1975) 1770

② using conventional Dirac Spinors

$$\Delta q = \int d^3 \vec{p} M_q (q^\uparrow(p) - q^\downarrow(p))$$

$$u^s = \begin{pmatrix} \chi^s \\ \frac{\vec{\sigma} \cdot \vec{p}}{E+m} \chi^s \end{pmatrix}$$

$$= \langle M_q \rangle \Delta q_T$$

$$M_q = \frac{(p_0 + p_3 + m)^2 - \vec{p}_\perp^2}{2(p_0 + p_3)(m + p_0)}$$

$$\Delta q_T = \int (q^\uparrow(p) - q^\downarrow(p)) d^3 \vec{p}$$

Thus Δq is Δq_F , not Δq_T

a possible picture:

$$J_p = \frac{1}{2} \Delta \Sigma + L_g + J_g$$

$$\Delta \Sigma \sim 30\%$$

$$L_g \sim 50-70\%$$

$$J_g \sim 0-30\%$$

$$\begin{matrix} \swarrow & \searrow \\ \Delta g & L_g \\ ? & ? \end{matrix}$$

$$J_g = \Delta g + L_g$$

However, It is interesting how the spin of the Proton
is distributed among $\Delta \Sigma$, L_g , Δg , and L_g
and how to measure these quantities

Experimentally !!

The Conclusions

- The spin "puzzle" or "crisis" is due to the neglect of quark transversal motions
 - relativistic effect
 - The Melosh-Wigner rotation
 - Small-component of the Dirac spinors
- The experimental results do not in conflict with the $SU(6)$ quark model, by taking into account the Wigner rotation, the flavor asymmetry of the valence quarks, and the intrinsic $q\bar{q}$ pairs.

- The Ellis-Jaffe sum rule violation is closely related to the Gottfried sum rule violation, and the strange conflict et al. by the non-perturbative $q\bar{q}$ pairs.
- The spin picture can be tested by future experiments by use of several simple relations :

$$\Delta \bar{q}_{\text{RF}}(x) + \Delta q(x) = 2 \delta q(x) \quad \text{MSS}$$

$$\frac{1}{2} \Delta q(x) + L q(x) = \frac{1}{2} \Delta \bar{q}_{\text{RF}}(x) \quad \text{MS}$$

$$\Delta q(x) + L q(x) = \delta q(x) \quad \text{MS}$$

The modified Gottfried sum rule [1] has explained the NMC deficit in the Gottfried sum [2] almost model independently. It has shown that the deficit is the reflection of the hadronic vacuum originating from the spontaneous chiral symmetry breakings. In this sense the physics underlining this algebraic approach has a common feature with that of the mesonic models reviewed in [3]. However, in the algebraic approach, importance of the high energy region not only in the theoretical meaning but also in the numerical analysis has been made clear. Further the numerical prediction based on this sum rule exactly agrees with the recent experimental value from E866/NuSea collaboration [4]. This experiment also gives us the light antiquark difference ($\bar{d}(x) - \bar{u}(x)$) and the ratio $\bar{d}(x)/\bar{u}(x)$ in the range $0.02 \leq x \leq 0.345$. An unexpected behavior is that the asymmetry seems to disappear at large x . On the other hand, a typical calculation in the mesonic models based on the πNN and the $\pi N\Delta$ processes account for about a half of the NMC deficit [3]. According to the E866 experiment, an explanation of the remaining half of the NMC deficit should be given by contributions in the medium or the small x region. Unfortunately, the approach from the mesonic models can not account for the magnitude from these regions definitely. In fact, the $\pi N\Delta$ process partly cancels the positive contribution to the ($\bar{d}(x) - \bar{u}(x)$) from the πNN process. The contributions from the higher resonances or from the multiparticle states are obscure. Hence the best we can say is that the mesonic models explain the flavor asymmetry of the light sea quarks qualitatively. These facts suggest that there may exist a dynamical mechanism so far overlooked to produce the flavor asymmetry at medium and high energy, and that it may compensate the above flaw of the mesonic models. In this talk, it is shown that the soft pion theorem in the inclusive reaction at high energy [5] can explain the magnitude about $-0.04 \sim -0.02$ in the NMC deficit. The theoretical prediction depends heavily on the spin dependent structure function $g_1^{ep} - g_1^{en}$, and the main contribution to the NMC defect in this theorem comes from the small x region. This type of the contribution may become the background of the mesonic model. However, further study is needed to say something about this. An interesting point of the soft pion at high energy is that in some cases it gives us a good reason that a seeming charge violating phenomena is not the violation of the isospin symmetry but the reflection of the asymmetry in the soft pion limit.

References

- [1] S.Koretune, Phys.Rev.D**47**(1993),2690;and early references cited therein.
- [2] P.Amaudruz *et al.*, Phys. Rev. Lett.**66**(1991),2712.
- [3] S.Kumano, Phys.Rept.**303**(1998),183.
- [4] E866Collaboration, E.A.Hawker *et al.*, Phys. Rev. Lett.**80** (1998),3715;
J.C.Peng *et al.*, Phys.Rev.D**58**(1998),092004.
- [5] N.Sakai and M.Yamada, Phys.Lett.**37B**(1971),505;
N.Sakai, Nucl.Phys.**B39**(1972),119.

Soft pions at high energy and the flavor asymmetry of the
light sea quarks
Susumu Koretune
Department of Physics, Shimane Medical University

★ The modified Gottfried sum rule(Koretune , Phys.Rev.D47,2690(1993))takes the form

$$\int_0^1 \frac{dx}{x} \{F_2^{ep}(x, Q^2) - F_2^{en}(x, Q^2)\} \\ = \frac{1}{3} \left(1 - \frac{4f_K^2}{\pi} \int_{m_K m_N}^{\infty} \frac{d\nu}{\nu^2} \sqrt{\nu^2 - (m_K m_N)^2} \{ \sigma^{K^+n}(\nu) - \sigma^{K^+p}(\nu) \} \right),$$

and based on this sum rule the Gottfried sum is predicted to be 0.26 ± 0.03 . This sum rule suggests an importance of the contributions from high energy regions.

★ The experimental value of E866/NuSea(E.A.Hawker et al,Phys.Rev.Lett.80,3715(1998) J.C.Peng et al, Phys.Rev.D58,092004(1998)) is about 0.26.

The Gottfried sum S_G can be expressed by the parton model as

$$S_G = \frac{1}{3} - \frac{2}{3} \int_0^1 (\bar{d}(x) - \bar{u}(x)) dx \\ NMC : \int_0^1 (\bar{d}(x) - \bar{u}(x)) dx = 0.148 \pm 0.04 \\ E866 : \int_0^1 (\bar{d}(x) - \bar{u}(x)) dx = 0.100 \pm 0.018$$

A typical calculation by meson cloud model(Kumano ,Phys.Rep.303,183(1998)) gives us $S_G \sim 0.29$. This model explains E866 experiments fairly well, but we need to explain extra contribution to the Gottfried sum about the magnitude -0.03 .

★ Algebraic Symmetry (S.Weinberg, “*dynamic and algebraic symmetries*” in *Lectures on Elementary Particles and Quantum Field Theory*(1970 Brandais Univ. Summer Institute in Theoretical Physics, V.1)p.283-p.394)

The low energy is closely related to the high energy through the spontaneous chiral symmetry breakings.

★ The method by Sakai and Yamada(Phys.Lett.37B,505(1971))

Using the high energy phenomenology it makes it possible to calculate the soft pion’s contribution at high energy.

Let us take the semi-inclusive reaction $\pi + p \rightarrow \pi_s(k) + \text{anything}$.

The differential cross section is defined as

$$f(k^3, \vec{k}^\perp, p^0) = k^0 \frac{d\sigma}{d^3k},$$

where p^0 is the energy in the CM frame. Let us assume that at high energy Feynman scaling is satisfied as

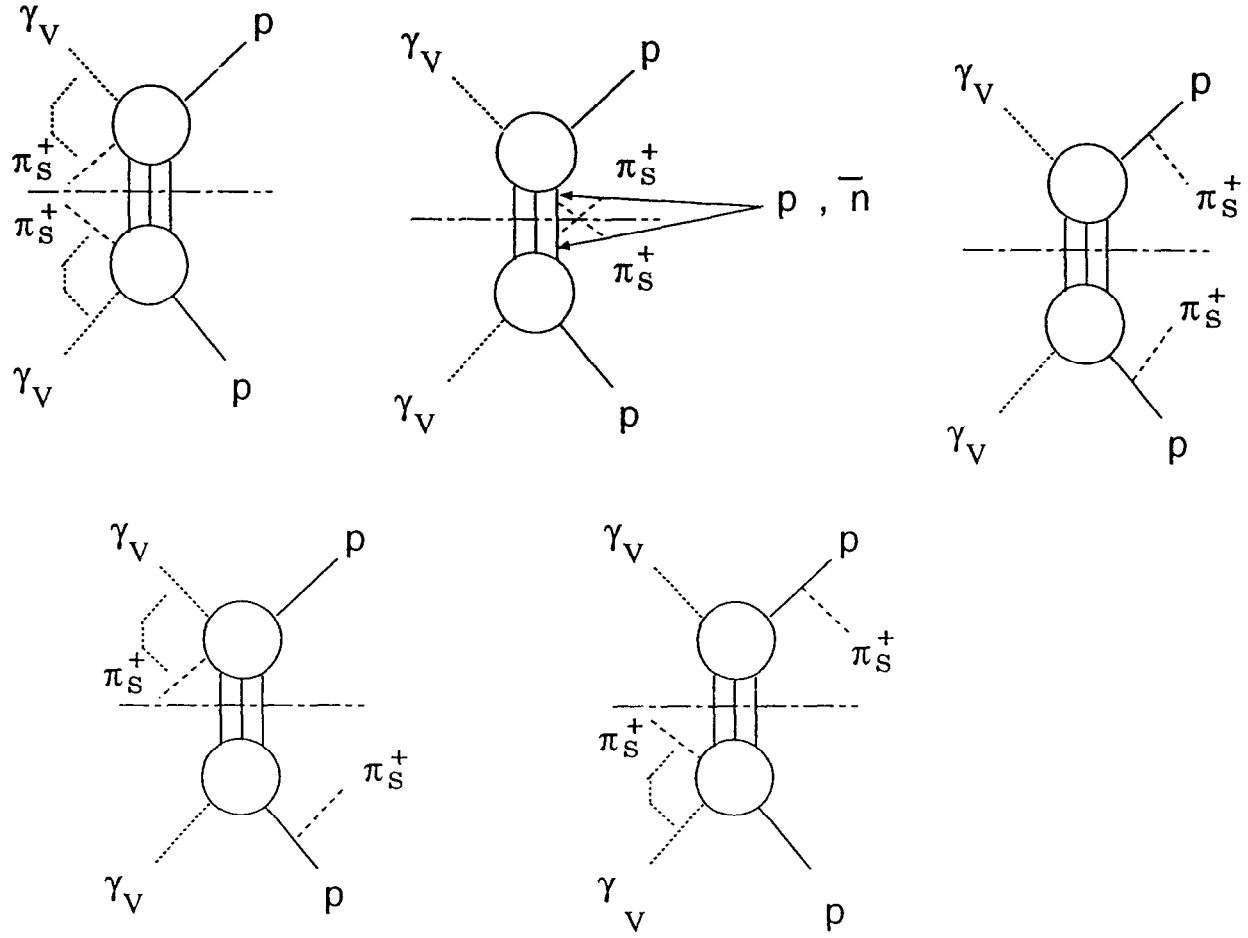
$$f \sim f^F\left(\frac{k^3}{p^0}, \vec{k}^\perp\right) + \frac{g(k^3, \vec{k}^\perp)}{p^0}.$$

Then we obtain

$$\lim_{p^0 \rightarrow \infty} f^F\left(\frac{k^3}{p^0}, \vec{k}^\perp = 0\right) = f^F(0, 0) = \lim_{p^0 \rightarrow \infty} f(0, 0, p^0).$$

In the CM frame, we can regard the pion with its momentum $k^3 < O(p^0)$ and $\vec{k}^\perp = 0$ as the soft pion.

★ Charge Asymmetry (Koretune, Phys.Lett.115B,261(1982))



By assuming symmetric sea polarization

$$F_2^+ - F_2^- = \frac{1}{4f_\pi^2} [F_2^{\bar{\nu}p} - F_2^{\nu p} + 2g_A^2(0)F_2^{en} - 8xg_A(0)(g_1^{ep} - g_1^{en}) \\ + 2g_A^2(0)(\langle n \rangle_p + \langle n \rangle_{\bar{n}} - \langle n \rangle_{\bar{p}} - \langle n \rangle_n)F_2^{ep}]$$

$$F^+ - F^- = \frac{1}{64\pi^3 f_\pi^2} \left[\frac{F_2^{\bar{\nu}p} - F_2^{\nu p}}{F_2^{ep}} + 2g_A^2(0) \frac{F_2^{en}}{F_2^{ep}} - 8xg_A(0) \frac{(g_1^{ep} - g_1^{en})}{F_2^{ep}} \right. \\ \left. + 2g_A^2(0)(\langle n \rangle_p + \langle n \rangle_{\bar{n}} - \langle n \rangle_{\bar{p}} - \langle n \rangle_n) \right]$$

★ Soft pion contribution to the Gottfried sum

$$\begin{aligned}
& (F_2^{ep} - F_2^{en})|_{soft} \\
&= \frac{I_\pi}{4f_\pi^2} [g_A^2(0)(F_2^{ep} - F_2^{en})(3 \langle n \rangle - 1) - 24xg_A(0)(g_1^{ep} - g_1^{en}) \\
&\quad + \frac{4}{3}xg_A(0)(g_1^{\bar{\nu}p} - g_1^{\nu p})]
\end{aligned}$$

$$\langle n \rangle = \langle n \rangle_p + \langle n \rangle_n + \langle n \rangle_{\bar{p}} + \langle n \rangle_{\bar{n}}$$

$$\langle n \rangle = a \log_e s + 1 \quad s = (p + q)^2$$

$$I_\pi = \int \frac{d^2 \vec{k}^\perp dk^+}{(2\pi)^3 2k^+}$$

(1) The transverse momentum satisfies $|\vec{k}^\perp| \leq bm_\pi$.

(2) Feynman scaling variable $x_F = 2k^3/\sqrt{s}$ satisfies $|x_F| \leq c$.

we take $b = 1$ and $c = 0.1$.

$$J(\alpha, \beta) = \int_\alpha^\beta \frac{dx}{x} (F_2^{ep} - F_2^{en})|_{soft}$$

$$a = 0.20, b = 1, c = 0.1$$

$$J(10^{-4}, 0.2) = -0.018, J(10^{-5}, 0.2) = -0.021,$$

$$J(10^{-6}, 0.2) = -0.023. \quad J(0.2, 1) = -0.005.$$

★ Soft pion contribution to the Ellis-Jaffe sum rule

$$\begin{aligned}
& xg_1^{ep}|_{soft} \\
&= \frac{I_\pi}{4f_\pi^2} [-(xg_1^{\nu p} + xg_1^{\bar{\nu}p}) + g_A^2(0)(xg_1^{ep} + 2xg_1^{en}) + 3g_A^2(0) \langle n \rangle xg_1^{ep} \\
&\quad - 3g_A(0)(F_2^{ep} - F_2^{en}) - \frac{g_A(0)}{6}(F_2^{\nu p} - F_2^{\bar{\nu}p})]
\end{aligned}$$

The contribution above $x = 0.0001$ is very small, but we see that the contribution from small x region may become large.

★ Summary

We have calculated the soft pions' contribution to the Gottfried sum and find that its magnitude is about $-0.04 \sim -0.02$. This magnitude is about the same order required by the meson cloud model.

The same soft pion contribution to the Ellis-Jaffe sum rule in the region above $x = 0.0001$ is calculated, and find that it is very small, but we find that soft pions' contribution to xg_1^p below $x = 0.001$ becomes positive.

Is the polarized light flavor sea-quark asymmetric?

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We propose new formulas for extracting a difference of the polarized light sea-quark density, $\Delta\bar{d}(x) - \Delta\bar{u}(x)$, from polarized deep-inelastic semi-inclusive data[1]. By using these formulas, we have estimated the value of it from the present experimental data measured by SMC and HERMES groups. We have parametrized the result with the formula, $\Delta\bar{d}(x) - \Delta\bar{u}(x) = Cx^\alpha(\bar{d}(x) - \bar{u}(x))$, with 2 parameters C and α . The χ^2 fitting lead to $C = -3.40$ and $\alpha = 0.567$ for the GRV98(LO)[2] unpolarized parton distributions. $C < 0 (\neq 0)$ is a remarkable result, suggesting an asymmetry of $\Delta\bar{d}(x)$ and $\Delta\bar{u}(x)$ as shown in Fig. 1, though the precision of the present data is not enough for confirming it.

References

- [1] T. Morii and T. Yamanishi, hep-ph/9905294.
- [2] M. Glück, E. Reya, and A. Vogt, Eur. Phys. J. C5 461 (1998).

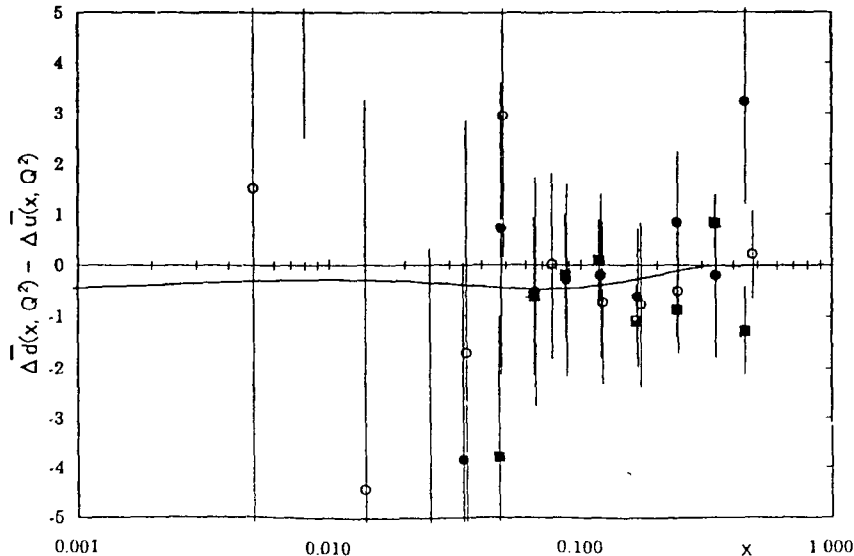


Fig. 1

Is the polarized light flavor sea-quark asymmetric ?

T.Morii (Kobe Univ.)

T.Yamanishi (Fukui Univ. of Tech.)

1. Introduction
2. Simple formula for $\Delta\bar{d}(x) - \Delta\bar{u}(x)$
3. Extraction of $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ from
semi-inclusive data
4. Discussion and conclusion

Ref. hep-ph/9905294

4. Simple formula for $\Delta \bar{d}(x) - \Delta \bar{u}(x)$

The asymmetries for semi-inclusive processes :

$$A_p(x, Q^2) = \frac{\sum_{i,j} c_i^2 [A_{ij}(x, Q^2) D_i^H(Q^2) + \Delta A_{ij}(x, Q^2) D_j^H(Q^2)]}{\sum_{i,j} c_i^2 [B_{ij}(x, Q^2) D_i^H(Q^2) + \Delta B_{ij}(x, Q^2) D_j^H(Q^2)]} \times \{1 + R(x, Q^2)\},$$

from which one can define

$$\begin{aligned} \Delta N_p^h(x, Q^2) &= \frac{A_p^h(x, Q^2) [\sum_{i,j} c_i^2 \{B_{ij}(x, Q^2) D_i^H(Q^2) + \Delta B_{ij}(x, Q^2) D_j^H(Q^2)\}]}{\{1 + R(x, Q^2)\}} \\ &= \Delta N_p^h(x, Q^2). \end{aligned}$$

By combining various ΔN_p^h , we can get $\Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2) =$

- From semi-inclusive charge hadron productions,

$$\begin{aligned} \Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2) &= \frac{\Delta N_p^{h+}(x, Q^2) - \Delta N_n^{h+}(x, Q^2) - \Delta N_p^{h-}(x, Q^2) + \Delta N_n^{h-}(x, Q^2)}{2 I_1(Q^2)} \\ &\quad - \frac{\Delta N_p^{h+}(x, Q^2) - \Delta N_n^{h+}(x, Q^2) + \Delta N_p^{h-}(x, Q^2) - \Delta N_n^{h-}(x, Q^2)}{2 I_2(Q^2)} \end{aligned}$$

where

$$I_1(Q^2) = 5D(Q^2) + 4D^K(Q^2) + 3D^p(Q^2) - 5\bar{D}(Q^2) - 4\bar{D}^K(Q^2) - 3\bar{D}^p(Q^2),$$

$$I_2(Q^2) = 3D(Q^2) + 4D^K(Q^2) + 3D^p(Q^2) + 3\bar{D}(Q^2) + 2\bar{D}^K(Q^2) + 3\bar{D}^p(Q^2).$$

- From charged pion productions,

$$\begin{aligned} \Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2) &= \frac{1}{6(D(Q^2) + \bar{D}(Q^2))} \\ &\quad \times \{J(Q^2) - 1\} \{\Delta N_p^{\pi+}(x, Q^2) - \Delta N_n^{\pi+}(x, Q^2)\} - \{J(Q^2) + 1\} \{\Delta N_p^{\pi-}(x, Q^2) - \Delta N_n^{\pi-}(x, Q^2)\}, \end{aligned}$$

where

$$J(Q^2) = \frac{3(D(Q^2) + \bar{D}(Q^2))}{5(D(Q^2) - \bar{D}(Q^2))}.$$

Fitting to the results:

Parametrization

$$\Delta \bar{d}(x, Q^2) - \Delta \bar{u}(x, Q^2) = C x^\alpha (\bar{d}(x, Q^2) - \bar{u}(x, Q^2))$$

From χ^2 -fitting by using GRV98(LO) for the unpolarized distributions,

$$C = -3.40, \alpha = 0.60, \quad \text{at } Q^2 = 1 \text{ GeV}^2$$
$$\chi^2/\text{d.o.f.} = 24.30/27 = 0.90$$

$$C = -3.40, \alpha = 0.57, \quad \text{at } Q^2 = 4 \text{ GeV}^2$$
$$\chi^2/\text{d.o.f.} = 24.57/27 = 0.91$$

$$\left(\begin{array}{l} \text{In case of MRST98(LO) for } \bar{d}(x), \bar{u}(x), \text{ we have} \\ C = -3.87, \alpha = 0.525, \quad \text{at } Q^2 = 4 \text{ GeV}^2 \\ \chi^2/\text{d.o.f.} = 0.90 \end{array} \right)$$

Theoretical model :

$$\text{Instanton} \rightarrow \Delta \bar{d}(x) - \Delta \bar{u}(x) < 0$$

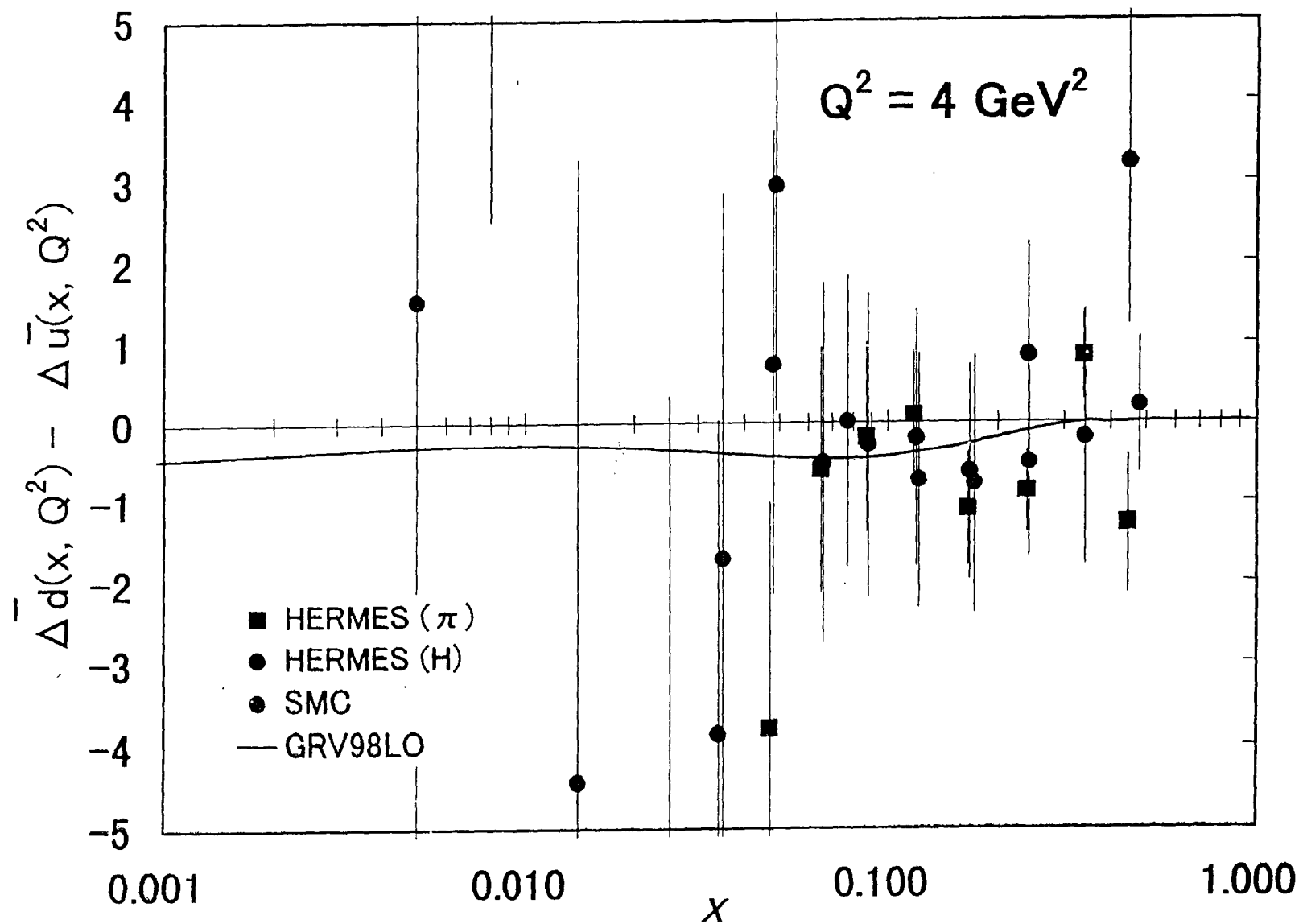
Kochenev et al., P.L.B304 167(1993)

$$\text{chiral quark soliton model} \rightarrow \Delta \bar{d}(x) - \Delta \bar{u}(x) < 0$$

Wakamatsu et al., hep-ph/9908425

$1/N_c$ -expansion of QCD

B.Dressler et al., hep-ph/9909541



4. Discussion and conclusion

- We presented new formulas for extracting $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ from semi-inclusive data.
 - These formulas depend on $q_i(x, Q^2)$ and $D_i^h(Q^2)$; unfortunately, some of them are poorly known at present. In addition, $\Delta N_{p(n)}^h$ depends on $A_{1p(n)}^h$ with some experimental errors. Therefore, we need more precise data.
 - If the polarized cross sections are presented, then the formulas make more sense by replacing $A_{1p(n)}^h$ by the polarized cross section themselves, where $q_i(x, Q^2)$ and R do not come in.
- We extracted $\Delta\bar{d}(x) - \Delta\bar{u}(x)$ from the present semi-inclusive data, which might suggest to be negative.
- However, the precision of the present data is not enough for extracting the exact value of $\Delta\bar{d}(x) - \Delta\bar{u}(x)$, and unambiguously testing the polarized light sea-quark asymmetry.
- Other processes should be studied:

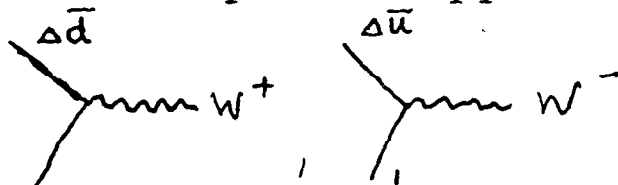
– polarized Drell - Yan processes, $\vec{p}\vec{p}, \vec{p}\vec{d}$

S.Hino, S.Kumano, P.R.D59 094026 (1999)

P.R.D60 054018 (1999)

S.Kumano, M.Niyama, hep-ph/9909432

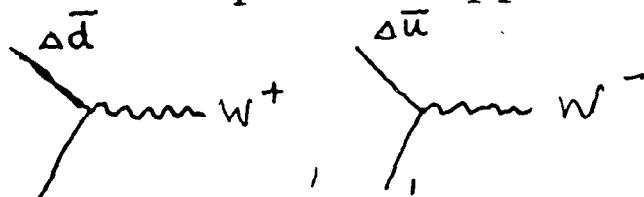
– $W^\pm$ productions in polarized pp collisions, $\vec{p}\vec{p}$.



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 - $W^\pm$ productions in polarized pp collisions, $\vec{p}\vec{p}$.



Compound states of the reggeized gluons in QCD

L.N. Lipatov[†]

Petersburg Nuclear Physics Institute,
Gatchina, 188350, St.Petersburg, Russia

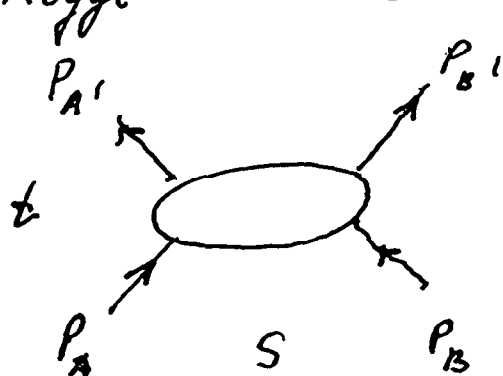
Next-to-leading corrections to the BFKL equation are investigated in the framework of the BLM renormalization scheme. The dependence of the pomeron intercept from the conformal spin is discussed in QCD and in the supersymmetric gauge theories. The duality symmetry of reggeon interactions is used to construct the wave functions of three-gluon states. The intercept and other properties of the new pomeron and odderon solutions are discussed.

[†] *Supported by the INTAS grant 97-31696*

Pomeron and other reggeon singularities in perturbative QCD

L. Lipatov (St. Petersburg, Russia)

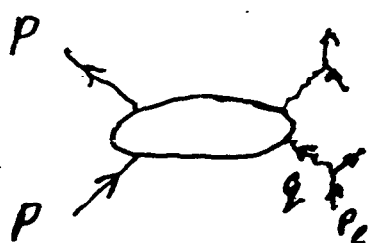
Regge kinematics for hadron scattering:



$$s = 4E^2 \gg -t = \vec{q}^2 \simeq E^2 \vartheta^2$$

$$\text{or } \vartheta \ll 1$$

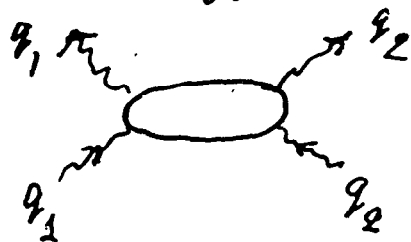
Quasi-Regge kinematics for DIS:



$$x = \frac{Q^2}{2pq} \ll 1, \quad Q^2 \gg m^2$$

$$Q^2 = -q^2$$

Quasi-Regge kinematics for $\gamma^* \gamma^* \rightarrow \text{hadrons}$ (L3)



$$s = 2q_1 q_2 \gg -q_1^2 \sim -q_2^2 \gg m^2$$

Quasi-Regge kinematics for jet production (A. Miller)

$$\gamma^* + p \rightarrow \text{jet} + X, \quad \text{jet has } |k_\perp| \sim Q \text{ and a frequency } \omega$$

Quasi-Regge kinematics for the hadron production

$$\gamma^* + p \rightarrow V(P_S) + X, \quad \text{hadron flies along } \gamma^*$$

T... N Ph o R

Locality in the rapidity space, numerical constraints.

Reggeized quarks and gluons are responsible for the interaction of particles with a big difference in their rapidities $y = \frac{1}{2} \ln \frac{k_0 + k_3}{k_0 - k_3}$

$\Delta y \gg \eta \gg 1$, where η is a parameter.

The interaction of particles with close rapidities leads to the regge trajectories $j_g(-\vec{q}^2)$, $j_q(-\vec{q}^2)$ and reggeon couplings

$$\boxed{\Delta y < \eta} \rightarrow \text{diagram}$$

The physical results do not depend on η .

It is similar to the independence from μ for DIS.

Let us consider for simplicity the description of the reggeized gluons.

$A_+(x)$ is the reggeon field describing emission of the reggeized gluon: $\text{emission} = A_+(x)$

$A_-(x)$ describes its absorption $\text{absorption} = A_-(x)$

Kinematical constraints: $x_{\pm} = x_0 \pm x_3$

$$\boxed{\partial_- A_+(x) = \partial_+ A_-(x) = 0} \quad \text{consequence of } \Delta y \gg \eta$$

Gauge transformations: $\delta v_\mu = [D_\mu, \chi]$, $\delta \psi = -g \chi \psi$

$$1) \delta A_{\pm} = 0 \quad \text{for } \chi|_{x_{\pm} \rightarrow \infty} \rightarrow 0$$

$$2) \delta A_{\pm} = g[A_{\pm}, \chi] \quad \text{for } \chi = \text{const}$$

The effective action for reggeon-particle interactions

$$\mathcal{L}(\psi, \psi^\dagger, \psi, \psi^\dagger) = \mathcal{L}_{\text{QCD}}(\psi, \psi^\dagger) + t_2 \left[j_- (\psi) A_+ + j_+ (\psi) A_- \right]$$

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$x^- \backslash \nearrow x^+$ A_+ depends

BLM approach (S. Brodsky, V. Fadin, V. Kim, L. Lipatov, G. Pivovarov)

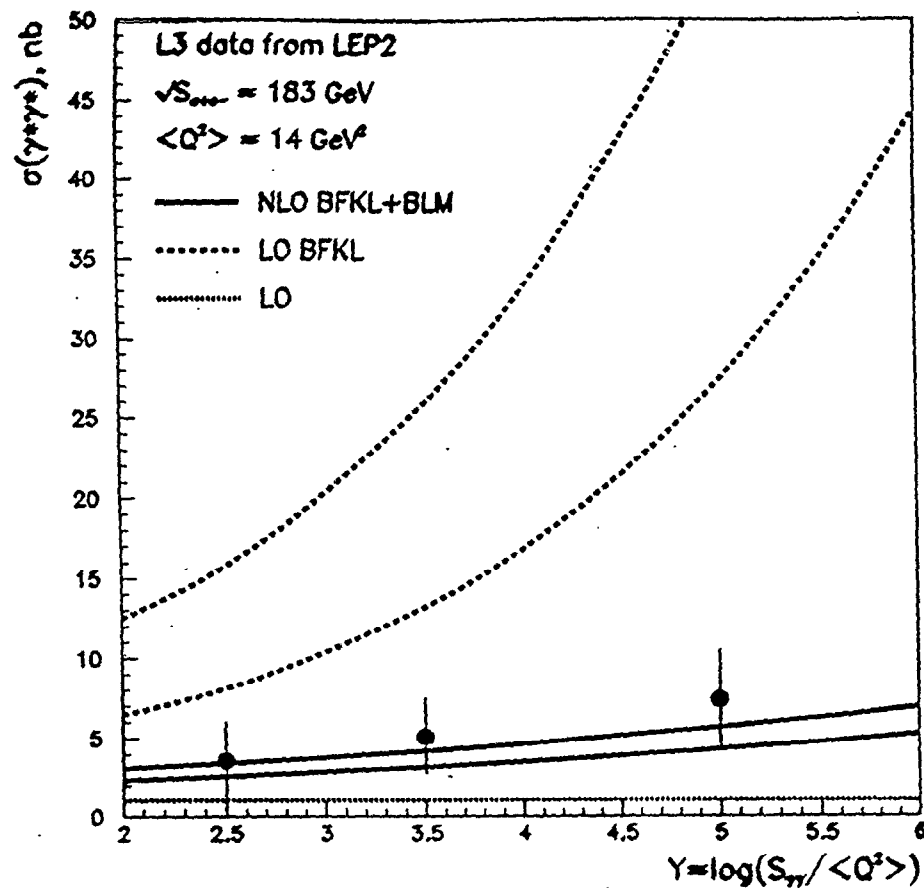


Figure 1. Virtual gamma-gamma total cross section by the NLO BFKL Pomeron within BLM approach vs L3 Collaboration data at energy 183 GeV of e^+e^- collisions. Solid curves correspond to NLO BFKL in BLM; dashed: LO BFKL and dotted: LO contribution. Two different curves are for two different choices of the Regge scale: $s_0 = Q^2/2$, $s_0 = 2Q^2$

In LLA $\omega_0 = \frac{g^2}{\pi^2} 3 \ln 2$, $b_0 \sim \left(\frac{s}{s_0}\right)^{\omega_0}$, $s_0 = c Q^2$
for $n = \tilde{n} = \frac{1}{2}$

In NLLA

$$\omega = \frac{g^2(c\vec{k}_\perp^2)}{\pi^2} 3 \ln 2 - \frac{g^4/c\vec{k}_\perp^2}{\pi^4} a$$

a is big and does not depend essentially on the renormalization scheme.

In BLM approach c is chosen to cancel p_0 -contribution in a .

In the non-abelian physical schemes (MOM and $\overline{V}$)

Duality symmetry of the reggeon interactions



$$\left. \begin{aligned} \vec{p}_1 &\leftrightarrow \vec{p}_{23} \\ \vec{p}_2 &\leftrightarrow \vec{p}_{31} \\ \vec{p}_3 &\leftrightarrow \vec{p}_{12} \end{aligned} \right\} \begin{array}{l} \text{Canonical transformation} \\ \text{under which } H \text{ and} \\ \text{integrals of motion are} \\ \text{invariant} \end{array}$$

Duality operator in the $\vec{x}$ -representation (L.L. 1999)

$$Q_{m, \tilde{m}} = |x(1-x)|^2 (i\partial)^{1+m} (i\partial^*)^{1+\tilde{m}}$$

Duality transformation:

$$Q_{m, \tilde{m}} \psi_{m, \tilde{m}}(x, x^*) = |\lambda| \psi_{1-m, 1-\tilde{m}}(x, x^*)$$

Application to the small- x behaviour of $G_2(x)$ and to the Odderon problem is given below.

There is the solution of the Schrödinger equation and of the integrals of motion:

$$\psi_{m, \tilde{m}}^{(0)}(x, x^*) = 1 + (-x)^m (-x^*)^{\tilde{m}} + (x-1)^m (x^*-1)^{\tilde{m}}$$

This function is normalized only for

$$n = m - \tilde{m} \text{ odd} = 1, 3, 5 \dots$$

It corresponds to the completely anti-symmetric wave function $\psi(\vec{p}_1, \vec{p}_2, \vec{p}_3)$. Due to the Bose symmetry the colour wave function should be also anti-symmetric. Therefore physically it corresponds to f -coupling and

$[C = +1]$. It can give singular contribution to $G_2(x)$.

The reggeon intercept is $[J = 1]$ and therefore $[G_2(x) \sim \frac{1}{x}]$.

On the other hand by solving the duality equation

$$Q_{1-m, 1-\tilde{m}} \psi_{1-m, 1-\tilde{m}}^{(1)} = |\lambda| \psi_{m, \tilde{m}}^{(0)}, \text{ we obtain } \psi_{1-m, 1-\tilde{m}}^{(1)}$$

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which is symmetric under $p_i \leftrightarrow p_j$. Therefore

On the Relations Between Polarized Structure Functions

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The status of the twist-2 and the twist-3 integral relations between polarized structure functions in deep inelastic scattering for electromagnetic and electroweak interactions is reviewed. One novel integral relation for the twist-3 contributions can be tested in the upcoming high statistics measurements of the structure function $g_2(x, Q^2)$ in the range $Q^2 \gtrsim M_p^2$.

INTEGRAL RELATIONS BETWEEN POLARIZED STRUCTURE FUNCTIONS

J. BLÜMUEIN, DESY

- 1) INTRODUCTION
- 2) LIGHT CONE EXPANSION
- 3) STRUCTURE FUNCTION RELATIONS: TWIST 2
 - WHY ARE THE CG & WW RELATIONS STRUCTURALLY DIFFERENT?
- 4) STRUCTURE FUNCTION RELATIONS: TWIST 3
 - A REMARK ON ELT
- 5) CONCLUSIONS

3 RELATIONS @ TWIST 2

(JB, N. KOCHIELEV

1996)

$$g_4^i(x, Q^2) = 2 \times g_5^i(x, Q^2) \quad \text{DICUS '72}$$

$$g_2^i(x, Q^2) = -g_1^i(x, Q^2) + \int_x^1 \frac{dy}{y} g_1^i(y, Q^2)$$

WANDZURA

- WILCZEK '77

$$\begin{aligned} g_3^i(x, Q^2) &= 2 \times \int_x^1 \frac{dy}{y^2} g_4^i(x, Q^2) \\ &= 4x^2 \int_x^1 \frac{dy}{y^2} g_5^i(x, Q^2) \end{aligned}$$

JB, KOCHIELEV '96

→ STABLE, NON-DESTRUCTIVE $M \rightarrow 0$ LIMIT
(NUCLEON MASS)

BASIS : $g_1^i(x, Q^2)$, $g_5^i(x, Q^2)$

$M^2/Q^2 \ll 1$: JB, A. TKABLADZE DESY 98-181
NPB IN PR.

→ • CORRECTION TERM TO DICUS RELATION

→ • COMMUTATION OF TARGET MASS RESUMMATION
& WW-RELATION, BK-RELATION RESP.

↑

THE NEW RELATIONS :

$$g_{1,\tau=3}^i(x, Q^2) = \frac{4M^2 x^2}{Q^2} \left[g_{2,\tau=3}^i(x, Q^2) - 2 \int_x^1 \frac{dy}{y} g_{2,\tau=3}^i(x, Q^2) \right]$$

$$\frac{4M^2 x^2}{Q^2} g_{3,\tau=3}^i(x, Q^2) = g_{4,\tau=3}^i(x, Q^2) \left(1 + \frac{4M^2 x^2}{Q^2} \right) + 3 \int_x^1 \frac{dy}{y} g_{4,\tau=3}^i(y, Q^2)$$

$$2x g_{5,\tau=3}^i(x, Q^2) = - \int_x^1 \frac{dy}{y} g_{4,\tau=3}^i(y, Q^2)$$

TWIST 2:

$$g_{1,\tau=2}, g_{4,\tau=2}$$

DETERMINES : $g_{2,3,5;\tau=2}$

TWIST 3:

$$g_{2,4;\tau=3}$$

DETERMINES : $g_{1,3,5;\tau=3}$

$M^2/Q^2 \rightarrow 0$ BREAK DOWN OF THE ABOVE RELATIONS.

TWIST 3 LIVES IN THE DOMAIN $M^2/Q^2 \nless 1$,
HOWEVER!

CRUCIAL POINT:

- $\frac{M^2}{Q^2}$ CANNOT BE NEGLECTED !
- IF SO, THEY HAVE TO ^{BETO} RESUMMED TO ALL ORDERS TO AVOID UNPHYSICAL (NON-EXISTENT) SINGULARITIES FOR $x \rightarrow 1$

(JB, A. TKABADZE '98)

↘ LCE WITH TARGET MASSES. NPB '99
hep-ph/9812478

→ ALL POLARIZED STRUCTURE FUNCTIONS RECEIVE TWIST 3 TERMS !

EARLIER TREATMENT ($S_{\perp}$, JB, KOCHIEV
 $S_{\parallel}$ VARIOUS AUTHORS)

→ HAD TO BE EXTENDED.

WHAT HAS TO BE DONE IN THE SLAC g_2 EXPERIMENTS?

$$\begin{aligned} \frac{d^2\sigma(\pm S_L)}{dx dy} &= \mp 4\pi \frac{\alpha^2}{Q^2} \left\{ \left(2-y - \frac{2xyM^2}{S}\right) \left[\underline{g_1^{(2)}} + g_1^{(3)}\right] \right. \\ &\quad \left. + \frac{4xM^2}{S} \left[g_2^{(2)} + \underline{g_2^{(3)}}\right] \right\} \\ &\equiv \mathcal{L}_L(g_1^{(2)}, g_2^{(3)}) \end{aligned}$$

$$\begin{aligned} \frac{d^3\sigma(\pm S_T)}{dx dy d\phi} &= \mp 4 \frac{\alpha^2}{Q^2} \sqrt{\frac{M^2}{S}} \sqrt{xy \left[1-y - \frac{xyM^2}{S}\right]} \cos(\alpha-\phi) \\ &\quad \left\{ \left[\underline{g_1^{(2)}} + g_1^{(3)}\right] - \frac{2}{y} \left[g_2^{(2)} + \underline{g_2^{(3)}}\right] \right\} \\ &\equiv \mathcal{L}_T(g_1^{(2)}, g_2^{(3)}) \end{aligned}$$

WITH:

$$g_2^{(2)}(x) = -g_1^{(2)}(x) + \int_x^1 \frac{dz}{z} g_1^{(2)}(z)$$

$$g_1^{(3)}(x) = \frac{4M^2 x^2}{Q^2} \left[g_2^{(3)}(x) - 2 \int_x^1 \frac{dz}{z} g_2^{(3)}(z) \right]$$

MEASURE: $g_1^{(2)}(x, Q^2, M^2)$

$g_2^{(3)}(x, Q^2, M^2)$

(DETERMINED ITERATIVELY)

Factorization Scheme Dependence of Parton Distributions in the Polarized Virtual Photon^{*}

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Spin-dependent parton distributions in the polarized virtual photon are investigated in QCD up to the next-to-leading order (NLO). In the case $\Lambda^2 \ll P^2 \ll Q^2$, where $-Q^2$ ($-P^2$) is the mass squared of the probe (target) photon, parton distributions can be predicted completely up to the NLO, but they are factorization-scheme-dependent. Parton distributions are analyzed in four different factorization schemes. The scheme dependence is clearly seen in the first moments and the large- x behaviors of quark parton distributions.

^{*}Presented by K. Sasaki

§4 The $n=1$ moments of p.d.f.

* Quark d.f.

• $a = \overline{CI}, \overline{AB}, \overline{OS}$ schemes

$$\begin{cases} w(n=1, a) = 0 \\ z(n=1, a) = N_f \end{cases} \quad A_{q,a}^{n=1} = A_{NS,a}^{n=1} = 0$$

$\Downarrow$

$$\Delta g_s^\gamma(n=1, Q^2, P^2) \Big|_a = \Delta g_{NS}^\gamma(n=1, Q^2, P^2) \Big|_a = 0$$

• $\overline{MS}$

$$\begin{aligned} \Delta g_s^\gamma(n=1, Q^2, P^2) \Big|_{\overline{MS}} &= \left[-\frac{\alpha}{\pi} \overset{\text{QED a.a.}}{\downarrow} 3 \langle e^2 \rangle N_f \right] \left\{ 1 - \frac{2}{\beta_0} \overset{\text{QCD a.a.}}{\downarrow} \frac{\alpha_s(P^2) - \alpha_s(Q^2)}{\pi} N_f \right\} \\ \Delta g_{NS}^\gamma(n=1, Q^2, P^2) \Big|_{\overline{MS}} &= \left[-\frac{\alpha}{\pi} \overset{\text{QED a.a.}}{\uparrow} 3 (\langle e^4 \rangle - \langle e^2 \rangle^2) N_f \right] \times \{ 1 + O(\alpha_s^2) \} \end{aligned}$$

$\delta_{q4, \overline{MS}}^{(1), n=1} \neq 0$

* Gluon d.f. scheme-indep. up to NLO

$$\Delta G^\gamma(n=1, Q^2, P^2) = \frac{12\alpha}{\pi\beta_0} \langle e^2 \rangle N_f \frac{\alpha_s(Q^2) - \alpha_s(P^2)}{\alpha_s(Q^2)}$$

* The sum rule for $g_1^\gamma(x, Q^2, P^2)$

$$\int_0^1 dx g_1^\gamma(x, Q^2, P^2) = -\frac{3\alpha}{\pi} \langle e^4 \rangle N_f \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)$$

$$+ \frac{6\alpha}{\pi \beta_0} [\langle e^2 \rangle N_f]^2 \frac{\alpha_s(P^2) - \alpha_s(Q^2)}{\pi} + O(\alpha_s^2)$$

Narison, Shore & Veneziano

Kematsu & Sasaki

• $a = CI, AB, OS$

$$\Delta g_S^\gamma(n=1) = \Delta g_{NS}^\gamma(n=1) = 0$$

Contributions coming from gluon and photon d.f.

$$\Delta C_{G,a}^{\gamma,n=1} = -\langle e^2 \rangle \frac{\alpha_s(Q^2)}{2\pi} N_f \quad \text{QCD a.a.}$$

$$\Delta C_{\gamma,a}^{\gamma,n=1} = -\frac{3\alpha}{\pi} \langle e^4 \rangle N_f \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) \quad \text{QED a.a.}$$

$$\underbrace{\Delta C_{G,a}^{\gamma,n=1} \Delta G^\gamma(n=1, Q^2, P^2)}_{\text{2nd term}} \Big|_a + \underbrace{\Delta C_{\gamma,a}^{\gamma,n=1}}_{\text{1st term}} \Rightarrow \text{the sum rule for } g_1^\gamma$$

• $\overline{MS}$

$$\Delta C_{G,\overline{MS}}^{\gamma,n=1} = \Delta C_{\gamma,\overline{MS}}^{\gamma,n=1} = 0$$

Contributions coming from quark d.f.

$$\Delta C_{S,\overline{MS}}^{\gamma,n=1} = \langle e^2 \rangle \Delta C_{NS,\overline{MS}}^{\gamma,n=1} = \langle e^2 \rangle \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)$$

$$\Delta C_{S,\overline{MS}}^{\gamma,n=1} \Delta g_S^\gamma(n=1, Q^2, P^2) \Big|_{\overline{MS}} + \Delta C_{NS,\overline{MS}}^{\gamma,n=1} \Delta g_{NS}^\gamma(n=1, Q^2, P^2)$$

$\Rightarrow$ the sum rule for g_1^γ

§5 Behaviors of p.d.f. near $x=1$

Behavior near $x=1 \iff$ large n limit

LO

$$\Delta g_s^\gamma(n, Q^2, P^2) \Big|_{(NS)}^{LO} \sim \frac{1}{n \ln n}$$

$$\Delta G^\gamma(n, Q^2, P^2) \Big|^{LO} \sim \frac{1}{(n \ln n)^2}$$

$$\Delta g_s^\gamma(x, Q^2, P^2) \Big|_{(NS)}^{LO} \sim \frac{\alpha}{4\pi} \frac{4\pi}{d_s(Q^2)} N_f \langle e^2 \rangle \frac{9}{4} \frac{-1}{\ln(1-x)} \quad \text{vanishes}$$

$(\langle e^4 \rangle - \langle e^2 \rangle^2)$

$$\Delta G^\gamma(x, Q^2, P^2) \Big|^{LO} \sim \frac{d}{4\pi} \frac{4\pi}{d_s(Q^2)} N_f \langle e^2 \rangle \frac{1}{2} \frac{-\ln x}{\ln^2(1-x)} \quad \text{vanishes}$$

NLO

$$\Delta G^\gamma(n, Q^2, P^2) \Big|^{NLO} \sim \frac{1}{n^2}$$

$$\Delta G^\gamma(x, Q^2, P^2) \Big|^{NLO} \sim \frac{\alpha}{4\pi} N_f \langle e^2 \rangle 3 [-\ln x] \quad \text{vanishes}$$

• $\overline{MS}$, CI, AB

$$\Delta g_s^\gamma(n, Q^2, P^2) \Big|_{NS}^{NLO} \sim \frac{\ln n}{n}$$

$\implies$ quark d.f. diverge as $x \rightarrow 1$

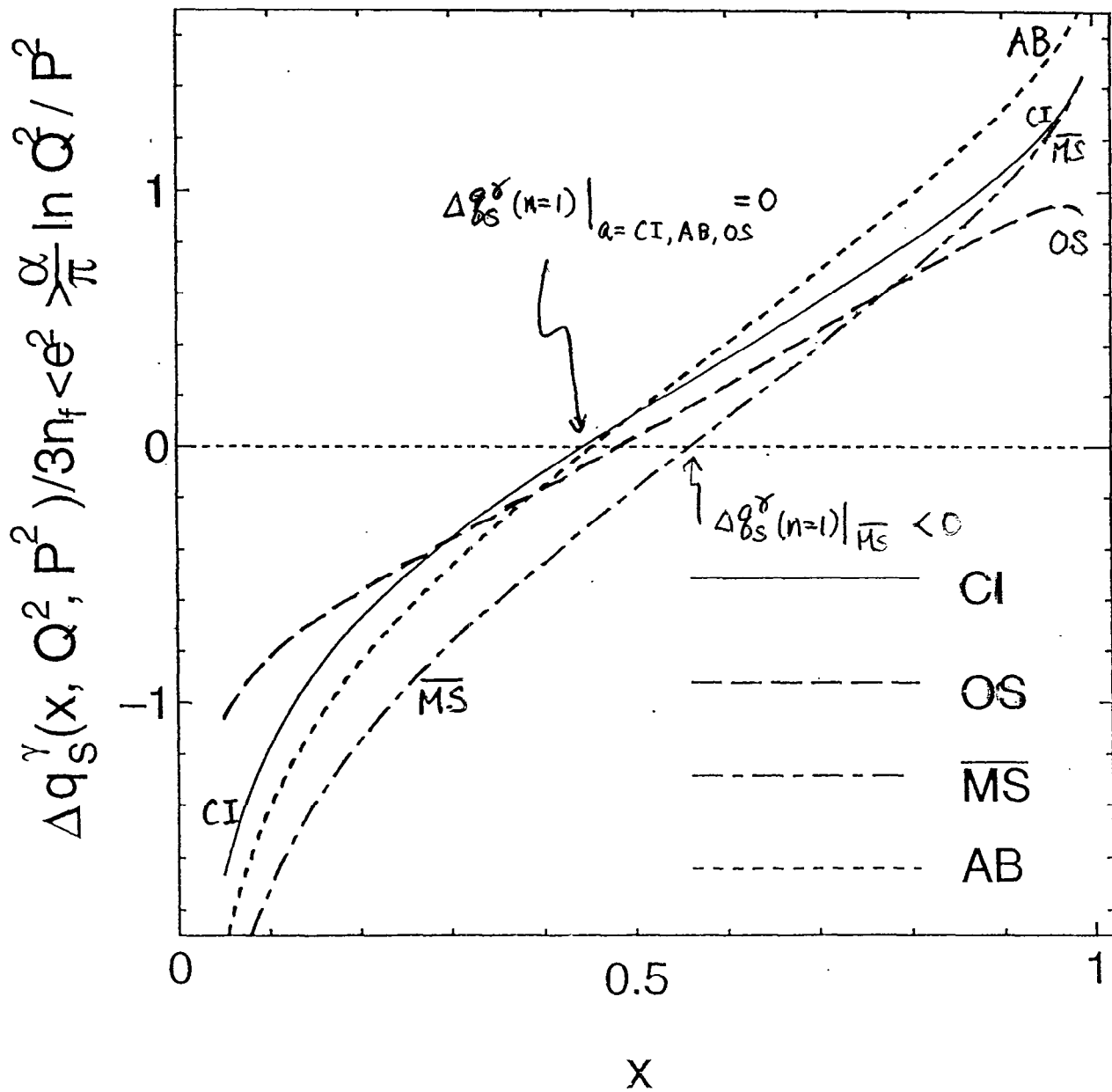
$$\Delta g_s^\gamma(x, Q^2, P^2) \Big|_{\overline{MS}, CI}^{NLO} \sim \frac{\alpha}{4\pi} N_f \langle e^2 \rangle \frac{6}{1} [-\ln(1-x)]$$

$(\langle e^4 \rangle - \langle e^2 \rangle^2)$

$$\Delta g_c^\gamma(x, Q^2, P^2) \Big|^{NLO} \sim \frac{\alpha}{n} N_f \langle e^2 \rangle 6 [-\ln(1-x) + 2]$$

Factorization Scheme Dependence of Normalized Quark Distributions

$$Q^2 = 30 \text{ GeV}^2 \quad P^2 = 1 \text{ GeV}^2 \quad n_f = 3$$



§7 Summary and Conclusion

- Polarized p.d.f. in photon is perturbatively calculable up to NLO
- Factorization scheme dependence of p.d.f. studied

$\overline{MS}$, CI , AB , OS

- The $n=1$ moments of p.d.f. studied
They are connected closely to the QED and QCD anomalies
- Behaviors of p.d.f. near $x=1$ are analytically evaluated and compared with numerical results
- The scheme dependence is clearly seen in the $n=1$ moments and the behaviors near $x=1$ of the quark d.f.
- Our preference is OS scheme.

Hadronic Light-Cone Wavefunctions and the Unification of QCD Bound-State Phenomena

Stanley J. Brodsky

Stanford University, Stanford, California 94309

the bound-state quark and gluon properties of hadrons, including their helicity and flavor correlations, in terms of universal process-independent and frame-independent wavefunctions. It also provides a physical factorization scheme for separating hard and soft contributions in both exclusive and inclusive hard processes. A new type of jet production reaction, “self-resolving diffractive interactions” can provide direct information on the light-cone wavefunctions of hadrons in terms of their QCD degrees of freedom as well as the composition of nuclei in terms of their nucleon and mesonic degrees of freedom.

Circum-Pacific RIKEN Symposium

High Energy Spin Physics

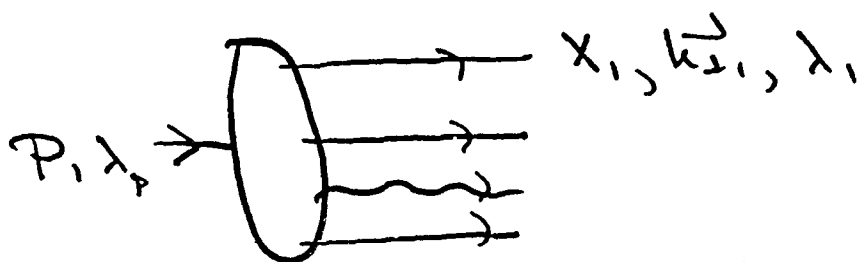
Nov. 3-6, 1998

Spin Physics and Hadronic

Light-Cone Wavefunctions in QCD

S. Brodsky

SLAC



$$\{ \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \}$$

This conference : Copious data on polarization corr.

New Expts : HERMES, RHIC, COMPASS
SLAC E84, BABAR, BELLE ...

How to organize at fundamental level?

- * Quantum Mechanics $\Rightarrow$ Amplitudes not Probabilities
- * Relativity $\Rightarrow$ Frame-independent description
- * Quantum Field Theory $\Rightarrow$ Fluctuations in pert. $\neq$
- * QCD : Non-perturbative $\Leftrightarrow$ Perturbative
Unification

$\Rightarrow$ Light-Cone Quantization

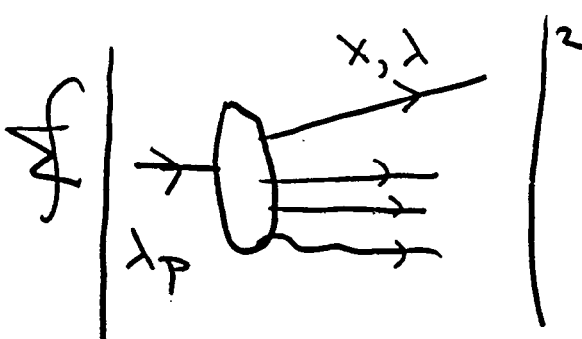
$$H_{LC}^{QCD} |\Psi_p\rangle = M_p^2 |\Psi_p\rangle$$

$$\text{fixed } \tau = t + z/c$$

G.P. Vignani
SJB

Light-Cone Wavefunctions

encode all helicity, transversity
distributions

$$Q_{\lambda/\lambda_P} = \left| \int \left[\begin{array}{c} x, \lambda \\ \lambda_P \end{array} \right] \right|^2$$


$$Q_{\lambda/\lambda_P}(x, \Lambda) \left\{ \begin{array}{l} \text{transversity: density} \\ \text{matrix} \\ \text{light-cone helicity} \end{array} \right.$$

$$= \sum_{n, \lambda} \int \left| \Psi_{n, \lambda_P}^{(\Lambda)}(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2 \prod_{j=1} \tilde{\pi} dx_j \prod_{j=1} \tilde{\pi} d^2 k_j$$

$$\delta(\sum_i x_i - 1) \delta(\sum_i \vec{k}_{\perp i})$$

$$\delta(x - x_0) \delta_{\lambda, \lambda_0}$$

$$\Theta(\Lambda^2 - m^2)$$

Program:

Construct $\{\psi_n^P(x_i, \vec{k}_{\perp i}, \lambda_i)\}$

Constraints:

- * 1. Rigorous limits $x \rightarrow 1$, high $\vec{k}_{\perp}$, high M_n^2
- * 2. "Ladder relations" at $x \rightarrow 0$ from Eqn.
- * 3. Guides from "Reduced" QCD(1+1), QED $(M \rightarrow 0)$
- * 4. Sum rules, LGTH moments, DLCC
- * 5. Empirical constraints!

$$M_P, g_A^P, R_P^2$$

$$F_i(q^2), \phi_P(x_i, Q), F_i(x, Q)$$

- * 6. QCD-based models

bqg, chiral theories ...

- * 7. Non-rel. matching $\psi_{LC} \Leftrightarrow \psi_{Schr}^{non-rel}$

Light-Cone Formalism:

- Consistent with

* OPE, Current Conservation

* DGLAP Evolution, ERBL Evolution

- Covariant Regularization

* Pauli Villars, Broken Supersymmetry

$$* M_n^2 = \sum_{i=1}^n \left(\frac{k_{\perp i}^2 + m^2}{x} \right)_i < \Lambda^2 \quad \text{on Fock Space}$$

$$* \Delta M_n^2 < \Lambda^2 \quad \text{on h.f.}$$

- Factorization Scheme $q(x, Q^2)$

$$\psi = \psi(m_n^2 < Q^2) + \psi(m_n^2 > Q^2)$$

- Explicit anomaly 

- Renormalization scheme $\alpha_V(Q^2)$, CSB, BLM

- Gauge choices $A^+ = 0$, Cov. gauge

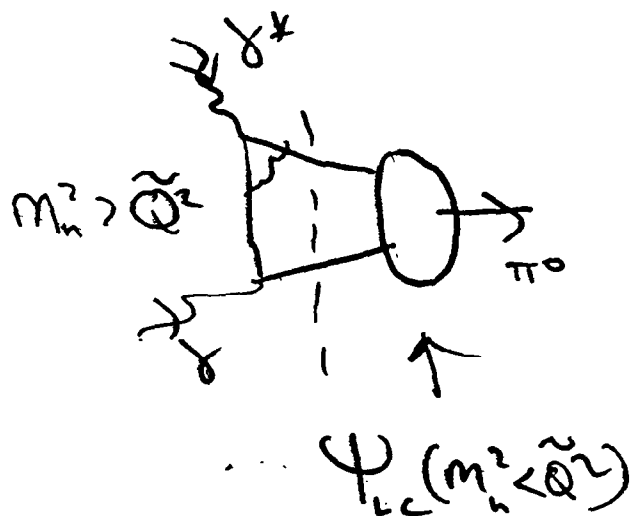
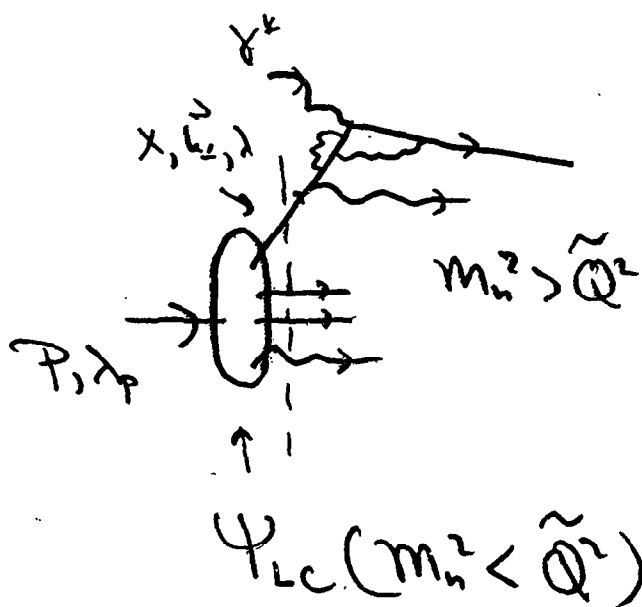
* Light-Cone Formalism ($A^+ = 0$ gauge)

Direct Proofs of Factorization

Lepage
SJB

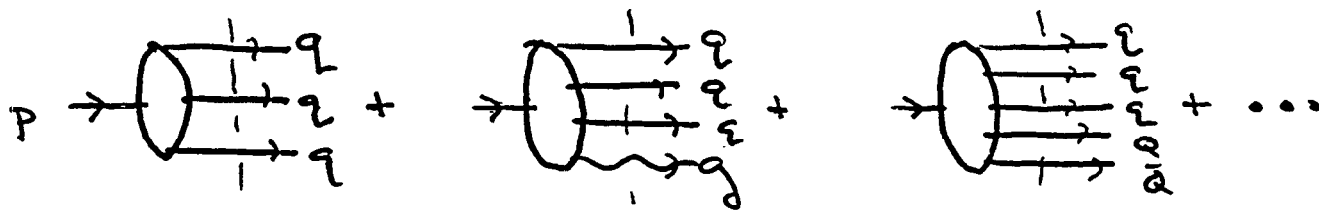
* Inclusive and Exclusive Reactions

* Evolution Equations



- * Evolution starting point $Q_0^2 = f(x)!$
- * $k_\perp$ "smearing"
- * all helicity correlations
- * No scale ambiguities
- * Extrinsic vs. Intrinsic Contr.

Light-Cone Fock Representation of Hadrons



$$|P\rangle = \sum_n |n\rangle \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$\sum x_i = 1, \sum \vec{k}_{\perp i} = 0$$

* Explicit solutions
using "DLCQ"

QCD(1+1), "collinear" QCD

SJB, Pauli, Hornbostel
Antonuccio, Delley

* Calculate structure
Functions

$q(x), \bar{q}(x), Q(x)$
Spin-dependence

* Calculate Regge behavior
using "ladder relations"

$x \rightarrow 0$, BFKL

Spin-dependence

Mueller, SJB, Antonuccio, Delley

* $x \rightarrow 1$ constraints

Lepage, SJB, Burkhardt, Schi

* Properties of heavy quark sea: $S(x) \neq \bar{S}(x)$

Extrinsic vs intrinsic

Koyan

Ma

Schmidt

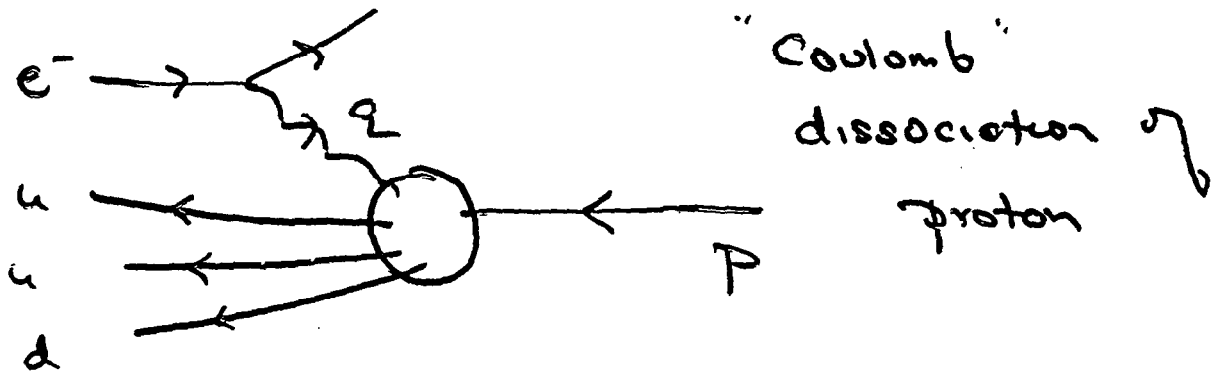
physics of $\Delta\Sigma$, anomaly

Bell

SJB

Schlumpf

"Self-Resolving" e-p Interaction HERA, ERM



Hoyer
Peigne
SJB

Observe 3 jets $\langle q_{\perp}^2 \rangle \ll \langle k_{\perp}^2 \rangle$
at large $k_{\perp}^2$ low $q_{\perp}^2$

$$\frac{dN}{d \ln q_{\perp}^2 dx_1 dx_2 d^2 k_{\perp 1} d^2 k_{\perp 2}} \sim \left| \sum_i e_i \frac{\partial \psi(\vec{k}_{\perp 1}, x)}{\partial \vec{k}_{\perp 2} \partial q_{\perp}^2} \right|$$

$$\frac{d\sigma}{d \ln q_{\perp}^2 dx_1 dx_2} (k_{\perp 1}^2 > k_{\perp \text{min}}^2) \sim \frac{\alpha F_N^2 g(k_i)}{(k_{\perp \text{min}}^2)^4}$$

$$[F_N] = [M^2]$$

Measure proton distribution ampl.
 $\phi(x_i)$

Outstanding Spin Problems

* 1. ANN in $\frac{d\sigma}{dt}(pp \rightarrow pp) \big|_{90^\circ}$

$$\sqrt{s} = 5 \text{ GeV}$$

ANL, BM

* 2. $J/\psi \rightarrow p\pi$, $\psi' \not\rightarrow p\pi$
e+e-

* 3. $pp \rightarrow \psi' X$ at high p_T
Longitudinal Pol.
CDF

* 4. $\pi N \rightarrow \mu^+ \mu^- X$ Angle corr.
CP, NA10

* 5. $F_2(Q^2)/F_1(Q^2) \neq \frac{C}{Q^2}$
 $1) Q^2 > 3 \text{ GeV}^2$ Jefferson

Polarized structure functions from the lattice

T. BLUM^{*} and S. SASAKI[†]
RIKEN BNL Research Center
Brookhaven National Lab
Upton, NY 11973-5000, USA

We give a brief sketch of lattice structure function calculations and review previous results for the axial coupling g_A . We outline a new technique for treating fermions on the lattice that preserves chiral symmetry, domain wall fermions. Finally, we give preliminary results for the nucleon spectrum using this new technique. Remarkably, a large mass splitting between the N and N^* , roughly consistent with experiment, is produced in the calculation. These results are encouraging for proposed calculations of nucleon structure functions.

^{*}Talk given by T. Blum

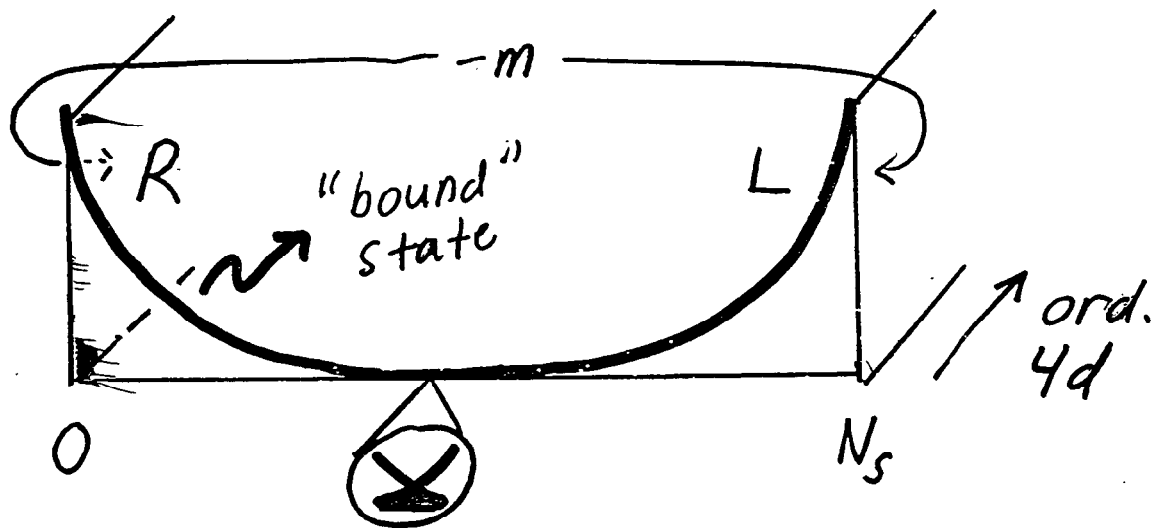
[†]email: tblum@bnl.gov

[‡]email: ssasaki@bnl.gov

Domain Wall Fermions

(Kaplan, Shamir, Narayanan and Neuberger)

- Remove doublers, maintain χ Symm at $a \neq 0$
- Simulations much more continuum-like (m_u/m_p , B_k , E' , NPR...)
- DWF work by adding xtra 5th dim



- χ Symm Manifest
- $\Psi_{R,L}(x,s) \sim \psi(s) \phi_{R,L}(x)$

$$m_g \propto m$$

- Gauge fields are 4d

Previous Lattice Results

- $\Delta q,$
 g_A
1. Y. Kuramashi (Nucl. Phys. A 1998) δq
 2. K.F. Liu, et.al. (hep-lat/9908052) L_q
 3. G. Schierholz (DIS 97, hep-ph/9706502)
 4. M. Göckeler, et.al. (Phys. Rev. D 1996)
 5. F. Fukugita, et.al. (Phys. Rev. Lett. 1995)
 6. K.F. Liu, et.al., (Phys. Rev. D 1994)

...

$\langle X^n \rangle,$
 $a_2, d_2,$
 PDF'S

hep-ph/9909253, 3., .4

— Higher Twist contributions

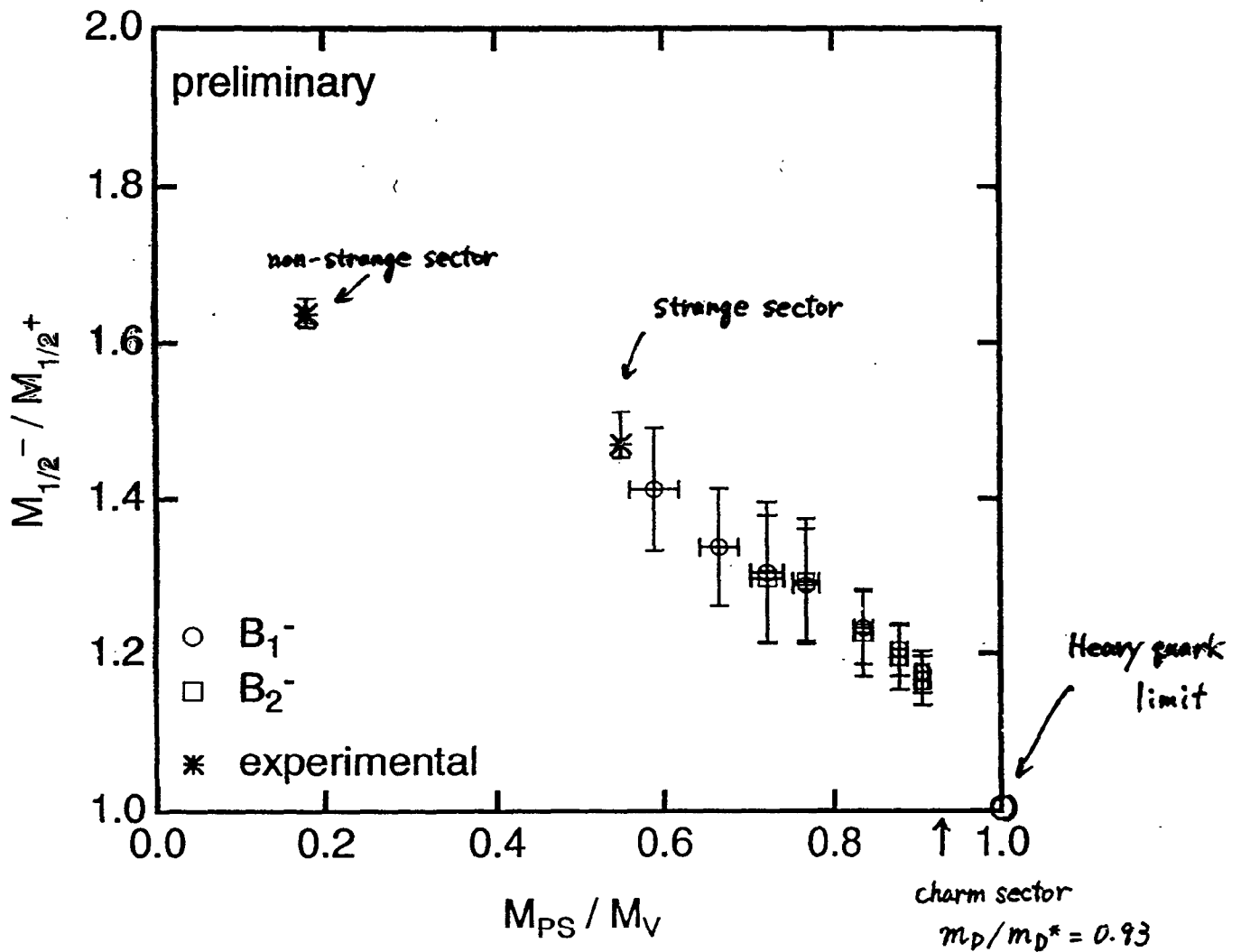
S. Capitani, et.al. (hep-lat/9908038)
 (hep-lat/9906320)

(4 fermion ops, Wilson coef. on the lattice)
 $\chi^2 \neq 0$, so many ops.

— Almost all are quenched, small vol,
 $a \neq 0$, Wilson fermions

DWF result

S. Sasaki



{ non-Strange sector : m_{N^*} / m_N vs. m_π / m_ρ
 { strange sector : $m_{\Sigma(1750)} / m_{\Sigma^+}$ vs. m_K / m_{K^*}

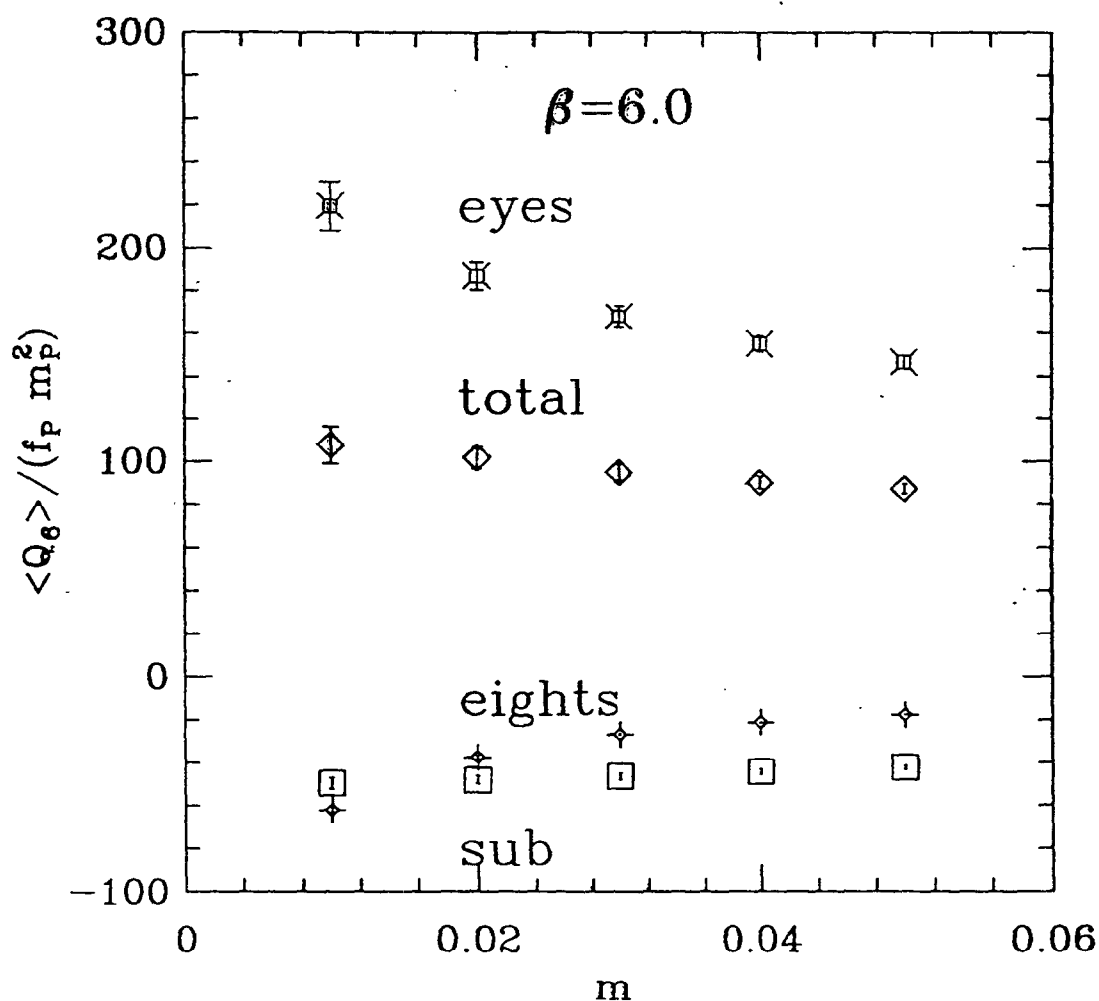
Dominant cont. to ϵ' gives Sign

Calculation of CP violation in the Standard Model (cont.)

QCD penguin Q_6 (unrenormalized)

$$K \rightarrow \pi\pi$$

Total dominated by eye $\rightarrow$ **sign is positive**, eights consistent with phenom. calculations (factorization).

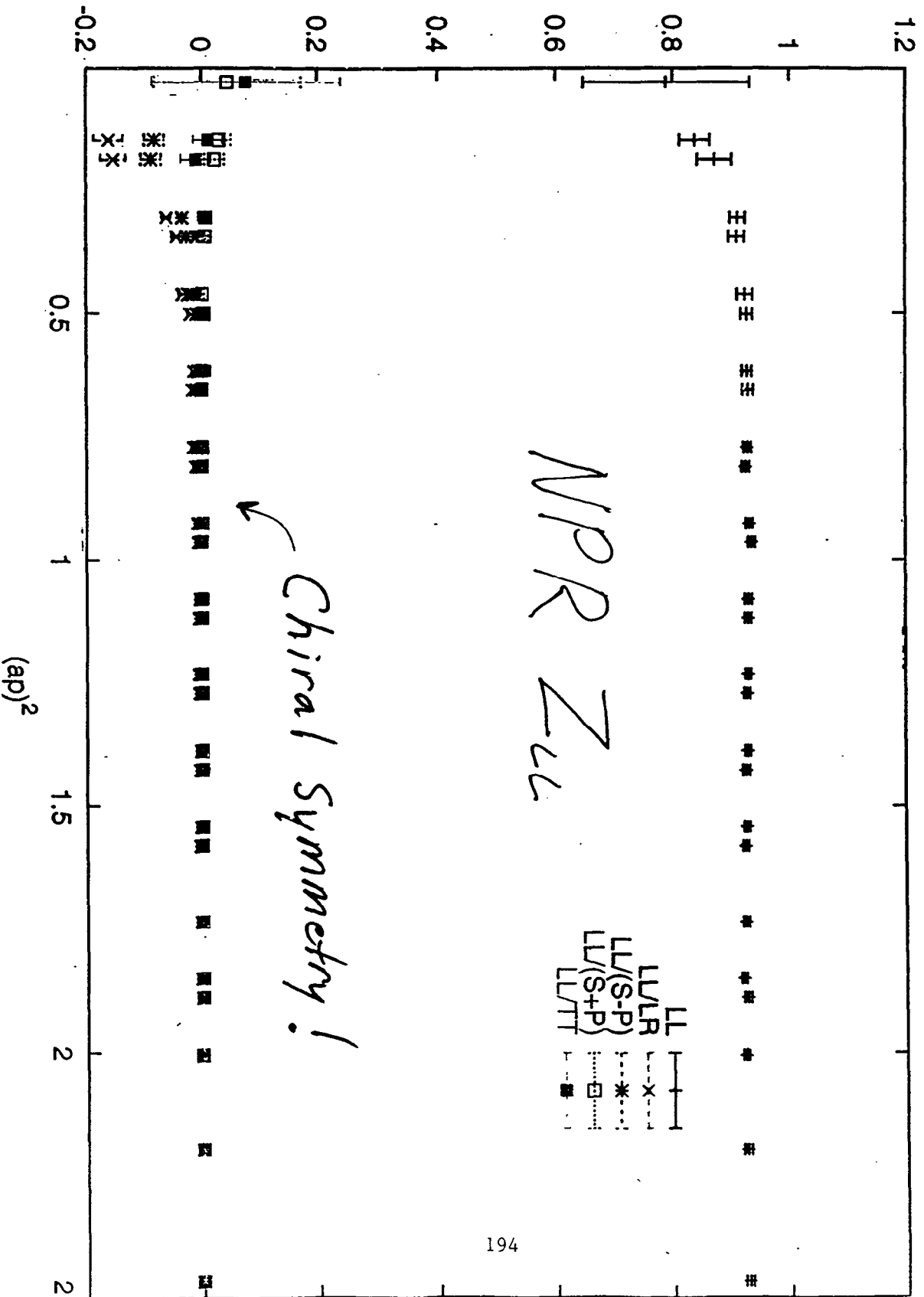


37

Ren. Const. for O_L (needed for B_k, ϵ)

C. Dawson et al (RBC Collab.)

Z_L/Z_A : Beta=6.0; Ns=16; Configs=52



Q^2 dependence of the generalized GDH sum rule in a quark model

Yu-bing DONG*

Institute of High Energy Physics,
The Chinese Academy of Sciences
P. O. Box 918, Beijing 100039, P.R. China

The study of the Gerasimov-Drell-Hearn (GDH) sum rule is reported. Based on a simple constituent quark model, the generalized GDH sum rule, the nucleon spin structure function g_1 , the photoabsorption cross sections and the higher-twist QCD effect in the low- Q^2 range are discussed. It is shown that the measurement of the generalized GDH sum rule in the resonance region is crucial for understanding the nucleon spin structure function and the QCD higher-twist effect in the low energy region.

*E-mail address: dongyb@alpha02.ihep.ac.cn

Q^2 dependence of the generalized GDH sum rule in a quark model

Y. B. Dong*

Institute of High Energy Physics, Academia Sinica, Beijing 100039, P. R. China

1. Introduction
2. Calculations based on quark model
3. Results of quark model
4. Higher-twist effect
5. Conclusions

*Talk given in the Circum-Pan-Pacific RIKEN symposium on 'High Energy Spin Physics'

1 Introduction

GDH sum rule

S. B. Gerasimov, Sov. J. Nucl. Phys. **2**, (1966), 430.

S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16**, (1966), 908.

In the real photons limits, GDH sum rule is

$$-\frac{\kappa^2}{4} = \frac{M_N^2}{8\pi^2\alpha} \int_{\omega_{th}}^{\infty} \frac{\sigma_{1/2}(\omega) - \sigma_{3/2}(\omega)}{\omega} d\omega \quad (1)$$

ω_{th} is the photoproduction threshold lab energy, and κ is anomalous magnetic moment of the nucleon.

1) Based on general principles of physics (Lorentz and gauge invariance, cross symmetry, causality and unitarity), Therefore, it is model-independent result.

2) Mainly affected by the low-lying resonances ($\Delta(1232)$, $N^*(1440)$, $S_{11}(1535)$, and $D_{13}(1520)$). Because of $1/\omega$ -dependence, - - - - -

3) It connects between the nucleon ground state ($\kappa_{p,n}$) and its resonance state properties (such as, helicity amplitudes, photoabsorption cross sections $\sigma_{1/2}(\omega)$ and $\sigma_{3/2}(\omega)$ and total photon absorption cross section).

4) The understanding of the generalized GDH sum rule (In the real photons limited and in the small momentum transfer Q^2 , namely, in nonperturbative QCD region) can give information about how to connect GDH sum rule to the Bjorken sum rule or Ellis-Jaffe sum rule in perturbative QCD region.

5) The evolution of the generalized GDH sum rule to the sum rules in the DIS region indicates that $\Gamma_1 = \int_0^1 g_1(x) dx$ should rapidly change sign in the region $0 < Q^2 < 1 \text{ GeV}^2$, (EMC data: at $Q^2 = 10 \text{ GeV}^2$, $\Gamma_1^p = 0.126 \pm 0.010 \pm 0.015$).

$$\Gamma_1^p(Q^2=0) < 0$$

3 Results of quark model

- 1) Zero-cross point of the $g_1(Q^2)$.
- 2) Resonance contribution to the total photoabsorption cross sections.
- 3) Resonance contribution to the integral of the spin structure function.
- 4) Nonresonance contributions.

4 Higher-twist effect

Because of the GDH sum rule and the Ellis-Jaffe sum rule, the integral of the spin-structure function g_1 changes rapidly from the physics of resonance-driven coherent processes to incoherent scattering off the constituents.

In the quark model, only the inelastic contribution is included in the low energy physics region. Ji and Melnitchouk argued that there is a duality between the two regions: Nonperturbative resonance region and perturbative region in DIS region.

★ The Duality:

In the region around the resonance region, both the resonance physics and deep inelastic physics languages are applicable to explain the spin structure functions. Therefore, from resonance physics, one can get information about

Higher-twist effect and strong coupling constant $\alpha_s(Q^2)$.

Summary Talk of the Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics

Tsuneo UEMATSU*
Department of Fundamental Sciences, FIHS,
Kyoto University, Kyoto 606-8501

Summary of the symposium and some remarks are given

*E-mail address: uematsu@phys.h.kyoto-u.ac.jp

Summary Talk

— Concluding Remarks —

T. Uematsu

1. Summary of the Symposium

2. Some Remarks

1. Summary of the Symposium

9 experimental talks

23 theory talks

3+1 extra talks in the
discussion session

	3	4	5	6
Exp.	Ozaki En'yo Bland Bazilevsky Guryn	Sakemi Vinter Bosted Iwata		
Theory	Boer Koike Tanaka ----- Bentz	Berger Miyama Peng Kubo Yamanishi Ramsey Thomas Boros Song ----- Ma	Teryaev Suzuki Ma Koretune Morii ----- Peng	Lipatov Blümlein Sasaki Brodsky Blum Dong ----- Boros

Experiments

Present Status & Future Plan / Recent Data

9 talks

- RHIC

project (Ozaki)

Spin physics @ PHENIX (En'yo)

Prompt photon reconstruction (Bazilevsky)

" @ STAR (Bland)

$\bar{p}p$ elastic $pp \rightarrow pp$ (Guryan)

- HERMES

Flavor Decomposition

from Semi-inclusive DIS (Sakemi)

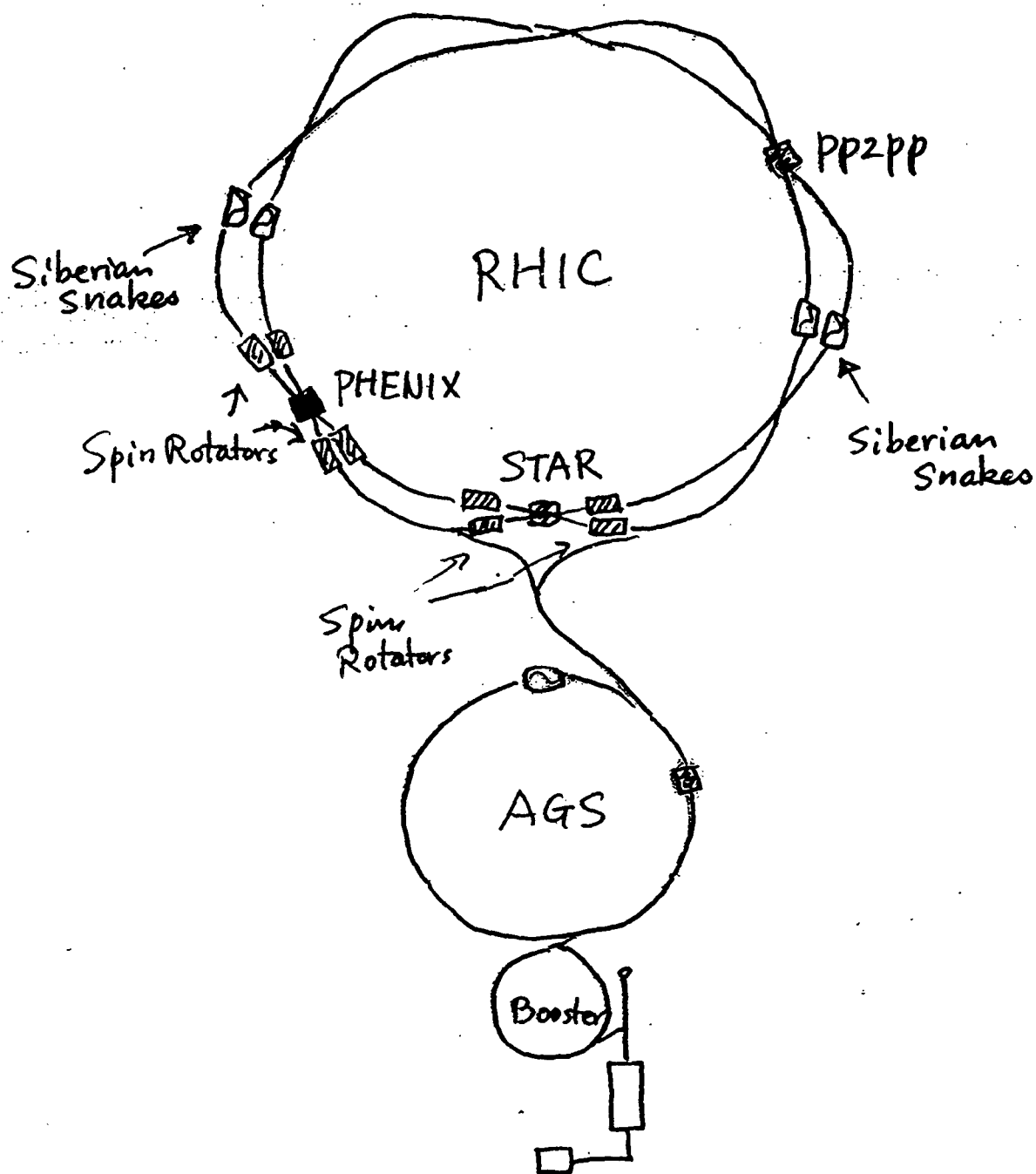
$\Delta G(x)$ from photoproduction
of high P_T pairs (Vincter)

- E155/E155X

Spin structure fns (Bosted)

- COMPASS

Exp. plan (Iwata)



4 Siberian Snakes

8 Spin Rotators

1 Siberian Snake completed

BNL RHIC Spin Program (Ozaki)

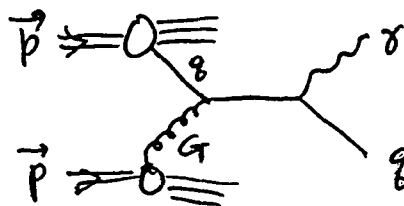
- RHIC is now commissioning phase
- Beam test $\Rightarrow$ sound in its design and construction
- Detectors PHENIX & STAR ... Large
PHOBOS & BRAHMS ... Small
made good progress in construction

PHENIX (En'yo)

- physics to be studied
 - ΔG gluon polarization
 - $\Delta \bar{q}$ anti-quark polarization
 - h_1 transversity
 - $\vdots$ Test of pQCD, W, Z @ 500 GeV, ...

Measuring of ΔG

Prompt photon via Gluon Compton $g+g \rightarrow \gamma+X$



$$A_{LL}(p_T) \sim \frac{\Delta G(x_g, Q^2)}{G(x_g, Q^2)} A_L(x_g, Q^2) A_{LL}(x_q, Q^2)$$

Background reduction for $\pi^0 \rightarrow 2\gamma$

Construction on going.

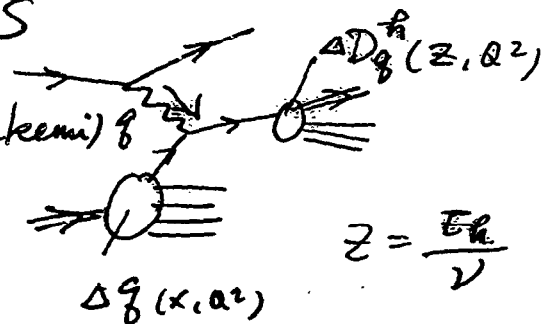
STAR (Bland)

- gluon pol.
- anti-quark vs. quark
- $W^\pm$ production
- SM test via parity violation
- Polarized fragmentation fns. in hyperon productions

HERMES (DESY)

- Semi-inclusive DIS

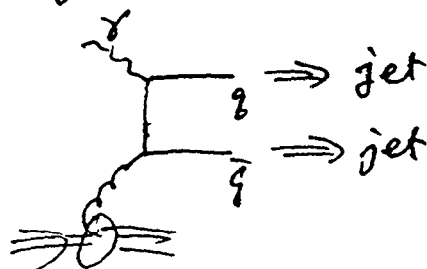
flavor decomposition (Sakemi)
of polarized quark
distribution



u: positive $\Delta u + \Delta \bar{u}$
d: negative $\Delta d + \Delta \bar{d}$
sea: compatible with zero $\Delta s + \Delta \bar{s}$

$$A_1^h(x, Q^2) = \frac{\int dz \sum_j e_j^2 \Delta q_j(x, Q^2) D_j^h(z, Q^2)}{\sum_j q_j}$$

- Spin asymmetry in the photoproduction of pairs of high P_T hadrons (Vincter)



negative asymmetry $A_{||}$

dominant PGF

$$\Rightarrow \Delta G$$

E155/E155X (SLAC) (Bosted)

Latest results on Spin structure functions

g_1

Bj. sum rule satisfied

$$\Delta \Sigma = 0.22$$

$$\Delta G = 1.8^{+0.7}_{-0.4} \quad +1.4_{-1.2}$$

• proton data is still preliminary

g_2

$$g_2^{tw.3} \text{ small} \quad g_2 \approx g_2^{ww} = -g_1 + \int_x^1 \frac{dy}{y} g_1(y, Q^2)$$

g_2 definitely non-zero close to g_2^{ww}

• Inclusive Hadron photoproduction has small non-zero asymmetries

Future open charm $\rightarrow \Delta G(x)$ for $x > 0.1$

COMPASS (CERN) (Iwata)

Exp. plan of COMPASS

1. $\Delta G/G$ through open charm high p_T hadrons (D-tagging)

2. Flavor and Valence-Sea decomposition in semi-inclusive DIS

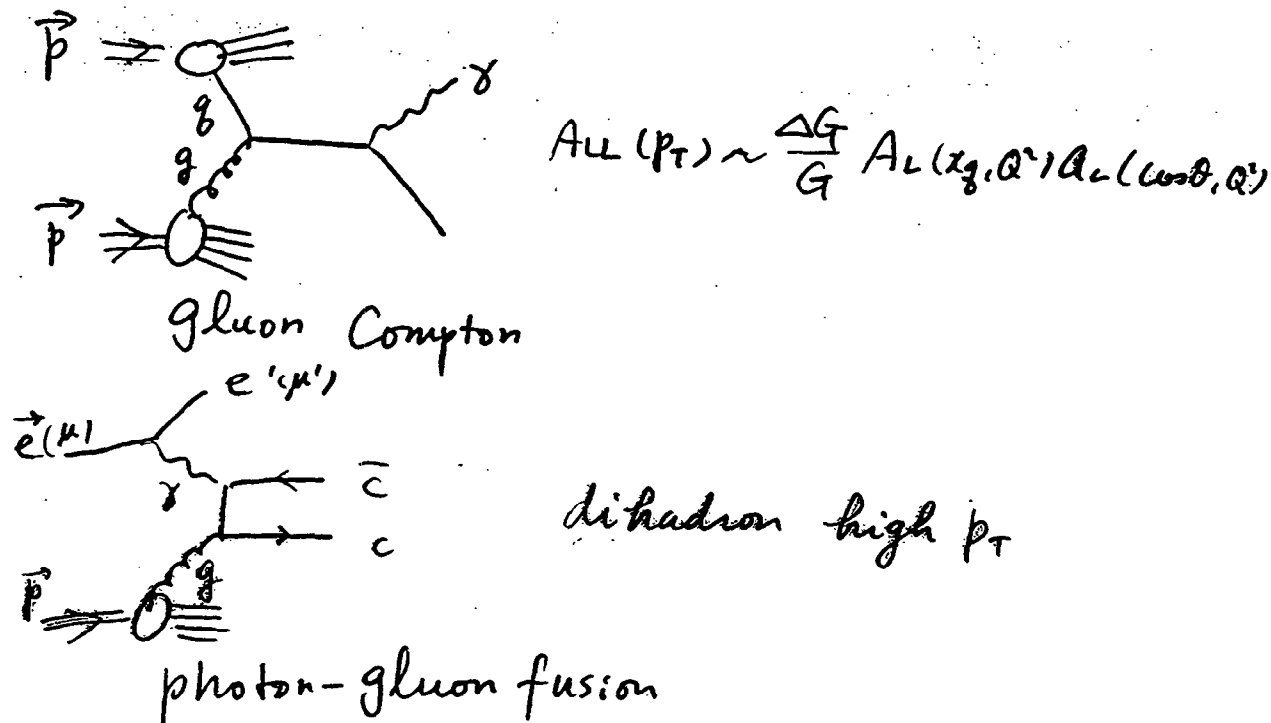
3. Transverse spin dist. h_1

4. Λ pol.

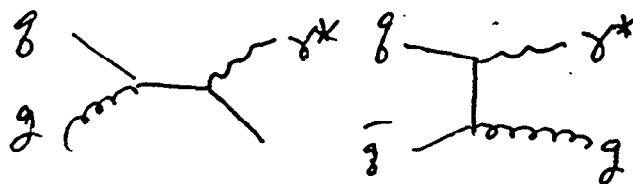
Physics issues

- $\Delta G(x, Q^2)$ gluon polarization

Presently poorly constrained experimentally.
How to measure?



- ΔG from $\bar{p} p \rightarrow \gamma^* X$
massive lepton pair collisions (Berger)

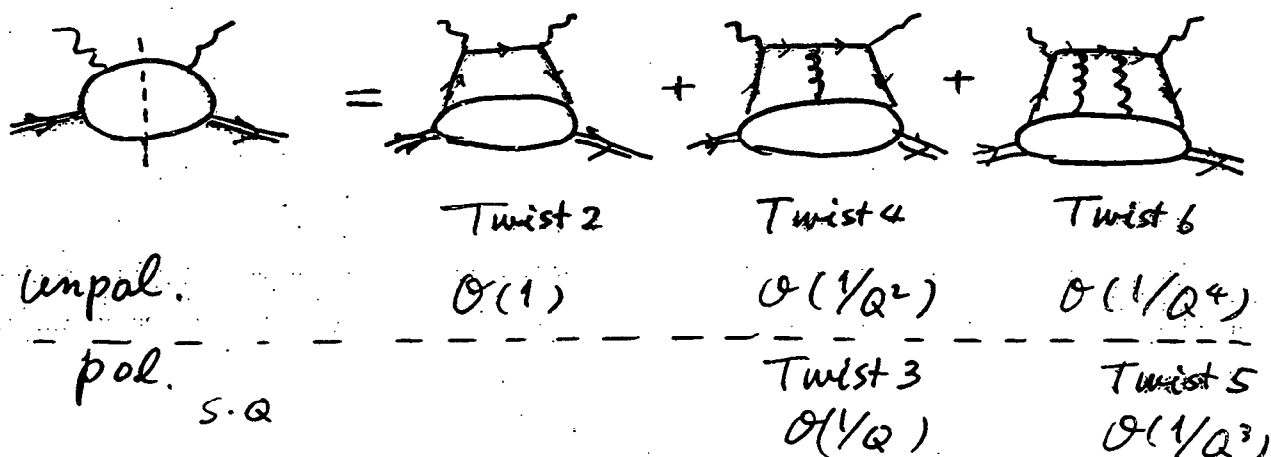


$q \bar{q}$ dominates over $g \bar{g}$ for $Q_T > \frac{Q}{2}$

no fragmentation fn.
no prompt photon isolation } needed

$\sqrt{s} = 150 \sim 200 \text{ GeV}$ seems best

• Higher-twist



twist-3 Contribution to $g_2(x, Q^2)$

experimentally very small

E155/E155X (Bosted)

$$g_2 \approx g_2^{WW}$$

↑
twist-2

How about h_L ?

Semi-inclusive DIS $ep \rightarrow e\pi X$

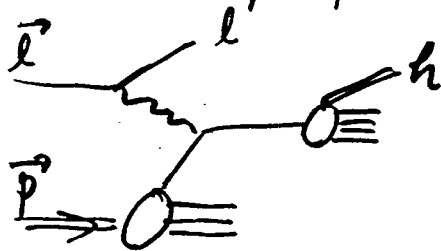
High-mass dihadron production
(Peng)

$$\vec{p}\vec{p} \rightarrow \pi^0\pi^0 X$$

All vs $M(\pi^0\pi^0)$ at RHIC

→ studying ΔG

• Flavor Decomposition



$$\sigma \sim \Delta f \otimes \hat{\sigma} \otimes D_f^h(z)$$

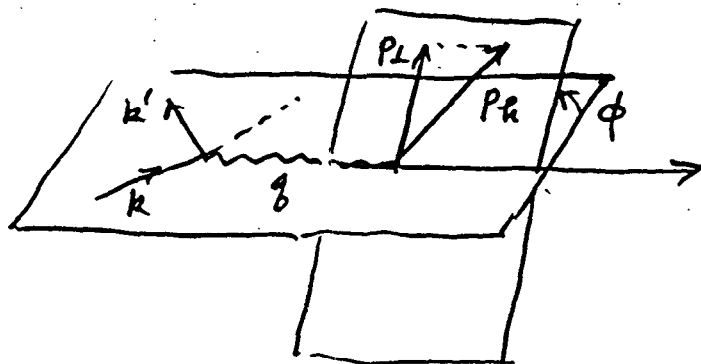
Semi-inclusive DIS

$$\Delta f + \Delta \bar{f}$$

SMC, HERMES, COMPASS

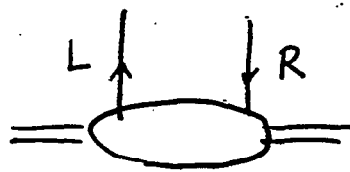
Azimuthal Single-Spin Asymmetry in Semi-inclusive DIS from HERMES

Significant $\sin\phi$ asymmetry
of the order 2%



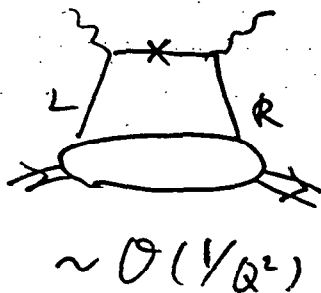
• Transverse Spin

chiral odd

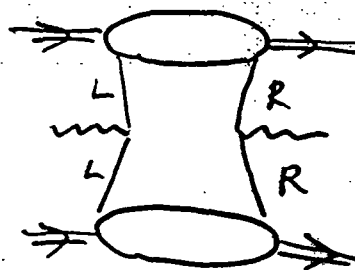


$$\delta g(x) (\equiv h_1(x))$$

DIS



Drell-Yan



Measuring Transversity

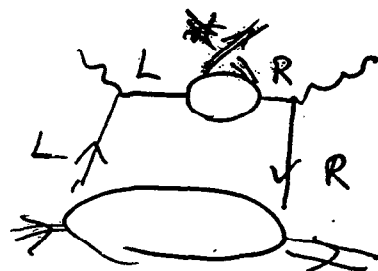
$$DY(pp \rightarrow \mu\mu X)$$

$$\sigma \sim \delta g(x_1) \delta \bar{g}(x_2)$$

Semi-inclusive DIS

Fragmentation Function

(Jaffe)



$\hat{h}_1(z)$ transverse spin dep. fragmentation function ($\vec{\Lambda}$ in final state)

$\delta g_I(z, m^2)$ two pion interference frag. fu.

$C(z) (\equiv H_1^{\perp(1)}(z))$ Single particle azimuthal asymmetry frag. function (Collins)

2. Some Remarks

① Factorization Scheme Dep. of Parton distribution / fragmentation fns.

$$\sigma \sim (\text{Short Distance}) \otimes (\text{Large Distance})$$

Coefficient fn. Parton dist. fn.

$$= Z(\quad) \otimes Z^{-1}(\quad)$$

↙ ↘
renormalization const.

In the analysis of parton distribution/fragm. functions, one should note which scheme is being used.

Cf. Singlet quark 1st moment.

$$\Delta g_s|_{\overline{MS}} = \Delta g_s|_{AB} - \frac{\alpha_s}{2\pi} n_f \Delta G|_{AB}$$

Conversion from one scheme to another is known.

② Some relationships between the QCD corrections to different processes

Bjorken Sum Rule

$$\int_0^1 [g_1^p(x, Q^2) - g_1^n(x, Q^2)] dx = \frac{1}{6} \frac{g_A}{g_V} \left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2) \right)$$

Kodaira-Matsuda-Muta-Sasaki-U.

Phys. Rev. D 20 (1979) 629

Crewther's relation

$$S = K R$$

where S : the anomalous const for $\pi^0 \rightarrow 2\gamma$

R : e^+e^- R-ratio (Drell-ratio)

K : Bj. sum rule.

Product of three currents

$$T(A_\lambda^3(x) J_\mu(0) J_\nu(y))$$

$$T(J_\mu(0) J_\nu(y)) \underset{y \rightarrow 0}{\sim} i \epsilon_{\mu\nu\rho\sigma} \frac{y^\rho}{(y^2 - i\epsilon)^2} \sum E_i (y^2 - i\epsilon, y) A_\sigma^i(0)$$

$$T(A_\lambda^3(x) J_\mu(0) J_\nu(y)) \underset{x \gg y}{\sim} \sum_i T(A_\lambda^3(x) A_\sigma^i(0))$$

In the limit $x \rightarrow 0$ ($x \gg y$),

$$T(A_\lambda^3(x) A_0^i(0)) \underset{x \rightarrow 0}{\sim} \frac{x^2 g_{\lambda 0} - 2x_\lambda x_0}{\pi^4 (x^2 - i\epsilon)^4} F(x^2 - i\epsilon, g) \delta^i I$$

We finally obtain

$$\begin{aligned} T(A_\lambda^3(x) J_\mu(0) J_\nu(y)) \\ \underset{x \gg y}{\sim} \frac{x^2 g_{\lambda 0} - 2x_\lambda x_0}{\pi^4 (x^2 - i\epsilon)^4} \cdot \frac{i \epsilon_{\mu\nu}^{\rho\sigma} y_\rho}{(y^2 - i\epsilon)^2} \\ \times E_3(y^2 - i\epsilon, g) F(x^2 - i\epsilon, g) I \end{aligned}$$

On the other hand, the short distance behavior of the product (2) is completely determined by the singularity $G_{\lambda\mu\nu}(x, y)$

$$T(A_\lambda^3(x) J_\mu(0) J_\nu(y)) = G_{\lambda\mu\nu}(x, y) I$$

Which is further restricted by scale

inv. as

$$G_{\lambda\mu\nu}(x, y) = \frac{5}{\pi^2} \Delta_{\lambda\mu\nu}(x, y)$$

$$\Delta_{\lambda\mu\nu}(x, y) \underset{x, y \rightarrow 0}{\sim} \frac{\text{Tr} \{ \gamma_5 \gamma_\lambda \gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma \gamma_\rho \gamma_\sigma \delta(x-y) \}}{(x^2 - i\epsilon)^2 (y^2 - i\epsilon)^2 ((x-y)^2 - i\epsilon)^2}$$

Anomalous constant S is known to be free from higher-order radiation correction

Crewther relation holds up to the violation of scale invariance in terms of β -function

Apart from the scale inv. violation we have

$$S = KR$$

Since the left-hand side is

$$S = KR = K_0 \left(1 - \frac{\alpha_s}{\pi}\right) R = K_0 R_0$$

$$\therefore R = \left(1 + \frac{\alpha_s}{\pi}\right) R_0 = \left(1 + \frac{\alpha_s}{\pi}\right) \sum_i e_i^2$$

Note if the conformal inv. violation considered the

Conclusion

- Many interesting talks have been presented in the Symposium.
- Future Experimental Project will open a new era of high-energy spin physics.
- There still remain many interesting questions unanswered.

⇒ we need
more ideas !

Organization

International Advisory Committee

G. M. Bunce, I. T. Cheon, N. Horikawa, K. Imai, M. Ishihara,
R. L. Jaffe, F. C. Khanna, J. Kodaira, T. Morii, S. N. Mukherjee,
G. P. Ramsey, Z.-X. Sun, A. W. Thomas, A. I. Titov, S. N. Yang

Local Organizing Committee

chair K. Yazaki, co-chair T.-A. Shibata, S. Kumano
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Circum-Pan-Pacific RIKEN Symposium on
 "High Energy Spin Physics"
 November 3-6, 1999
 RIKEN, Wako, Japan

 Schedule

40 (30) min = 35 (25) min talk + 5 min discussion

Nov. 3 =====

8:30 - 9:00 Registration

Chair: K. Imai

9:00 - 9:10	S. Kobayashi	Welcome to RIKEN
9:10 - 9:20	M. Ishihara	Opening address
9:20 - 9:30	K. Yazaki	Greeting from the organizers
9:30 - 10:10	S. Ozaki	RHIC project

10:10 - 10:40 coffee (additional registration, lunch ticket)

Chair: G. M. Bunce

10:40 - 11:20	H. En'yo	The PHENIX experiment for the first spin collider RHIC
11:20 - 12:00	L. Bland	Spin physics with the STAR detector
12:00 - 12:10		Announcement

12:10 - 14:00 Welcome lunch at the 2nd cafeteria (Hirosawa club)

Chair: N. Saito

14:00 - 14:30	A. V. Bazilevsky	Prompt photon reconstruction in PHENIX
14:30 - 15:00	W. Guryn	Polarized proton proton elastic scattering at RHIC
15:00 - 15:30	D. Boer	Transverse polarization distribution and fragmentation functions

15:30 - 15:50 coffee

Chair: J. Kodaira

15:50 - 16:20	Y. Koike	Probing the hadron spin structure in hard processes
16:20 - 16:50	K. Tanaka	The nonlocal operator expansion for Drell-Yan process
16:50 - 17:20	discussion (W. Bentz, Structure function in the NJL model)	

17:20 Meeting of the international advisory committee

18:00 Bus to Daiichi hotel

Nov. 4

Chair:	B.-Q. Ma	
9:00 - 9:30	E. L. Berger	Spin dependence of massive lepton pair production in proton-proton collisions
9:30 - 10:00	M. Miyama	Drell-Yan proton-deuteron asymmetry and polarized light-antiquark distributions
10:00 - 10:30	J. C. Peng	Spin-dependent structure functions with leading-hadron productions
10:30 - 10:50 coffee		
Chair:	P. Bosted	
10:50 - 11:20	K. Kubo	New mechanisms for the anomalous spin observables in high energy hyperon productions
11:20 - 11:50	Y. Sakemi	Flavor decomposition of the polarized quark distributions in the nucleon by HERMES
11:50 - 12:20	M. G. Vinciter	The spin asymmetry in the photoproduction of pairs of high transverse momentum hadrons at HERMES
12:20 - 13:40 lunch at the 2nd cafeteria		
Chair:	A. Masaike	
13:40 - 14:20	P. Bosted	Spin structure functions of the nucleon measured at SLAC
14:20 - 14:50	T. Iwata	Experimental plan of COMPASS
14:50 - 15:20	T. Yamanishi	New parametrization of polarized parton distribution functions
15:20 - 15:50	G. P. Ramsey	A comparison of spin observable predictions
15:50 - 16:10 coffee		
Chair:	K. Saito	
16:10 - 16:40	A. W. Thomas	Extracting nucleon spin structure functions from nuclear data
16:40 - 17:10	C. Boros	Spin and flavor dependent parton distribution and fragmentation functions of octet baryons
17:10 - 17:40	X. Song	Substructure of the nucleon in the chiral quark model
17:40 - 18:10 discussion		
18:30 Bus to Daiichi hotel		

Nov. 5

Chair: E. L. Berger

9:00 - 9:30 O. V. Teryaev

T-odd effects in QCD

9:30 - 9:50 K. Suzuki

T-odd quark fragmentation function and transverse spin asymmetries in the pion production

9:50 - 10:20 B.-Q. Ma

The spin and flavor structure of baryons

10:20 - 10:40 coffee

Chair: F. C. Khanna

10:40 - 11:10 S. Koretune

Soft pions at high energy and the flavor asymmetry of the light sea quarks

11:10 - 11:40 T. Morii

Is the polarized light flavor sea-quark asymmetric?

11:40 - 12:10 discussion (J. C. Peng, Fermilab-E866 Drell-Yan results)

12:10 - 13:20 lunch at the 2nd cafeteria

13:20 - 17:00 excursion

Bus in front of the 2nd cafeteria

17:00 - 19:00 banquet

Yamaya restaurant

Nov. 6

Chair:	S. J. Brodsky	
9:00 - 9:40	L. Lipatov	Pomeron and other reggeon singularities in perturbative QCD
9:40 - 10:10	J. Bluemlein	Integral relations of structure functions in polarized DIS
10:10 - 10:40	K. Sasaki	Factorization scheme dependence of parton distributions in the polarized virtual photon
10:40 - 11:00 coffee		
Chair:	L. Lipatov	
11:00 - 11:40	S. J. Brodsky	Spin physics and hadronic light-cone wavefunctions in QCD
11:40 - 12:20	T. Blum	Polarized structure functions from the lattice
12:20 - 13:30 lunch at the 2nd cafeteria		
Chair:	A. W. Thomas	
13:30 - 14:00	Y. B. Dong	Q ² dependence of the generalized GDH sum in a quark model
14:00 - 14:30	discussion	
14:30 - 14:50	T. Uematsu	Summary
15:30 Bus to Daiichi hotel		

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

Title: Equilibrium and Non-Equilibrium Aspects of Hot, Dense QCD

Organizers: H. de Vega, D. Boyanovsky, and D. Rischke

Dates: July 17-30, 2000

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RIKEN BNL RESEARCH CENTER

CIRCUM-PAN-PACIFIC RIKEN SYMPOSIUM ON
“HIGH ENERGY SPIN PHYSICS”

NOVEMBER 3–6, 1999

RIKEN, WAKO, JAPAN



Li Keran

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*Nuclei as heavy as bulls
Through collision
Generate new states of matter.*
T. D. Lee

Speakers:

A.V. Bazilevsky	W. Bentz	E.L. Berger	L. Bland	J. Bluemlein	T. Blum
D. Boer	C. Boros	P. Bosted	J. Brodsky	Y.B. Dong	H. En'yo
W. Guryn	M. Ishihara	T. Iwata	S. Kobayashi	Y. Koike	S. Koretune
K. Kubo	L. Lipatov	B.-Q. Ma	M. Miyama	T. Morii	S. Ozaki
J.C. Peng	G.P. Ramsey	Y. Sakemi	X. Song	K. Sasaki	K. Suzuki
K. Tanaka	O.V. Teryaev	A.W. Thomas	T. Uematsu	G. Vinciter	T. Yamanishi
K. Yazaki					

Organizers: Shunzo Kumano, Toshi-Aki Shibata and Koichi Yazaki