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Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 23

HIGH ENERGY POLARIMETRY

August 18, 1999

Organizer

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

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Preface to the Series

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

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

Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form a proceedings, which can therefore be available within a short time.

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

T.D. Lee
July 4, 1997

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Introduction

Elliot Leader

The RHIC collider, in its pp mode, will be a unique machine. It will open up a new frontier in the use of spin in the study of hadronic physics. Using its polarized beams, a whole new range of tests of the Standard Model will become feasible, and much new information about the detailed partonic structure of the nucleon will emerge. It will also be possible to answer intriguing questions concerning the relationship between pp and $\bar{p}p$ total cross-sections and real parts of forward amplitudes, questions which are relevant to attempts to understand certain aspects of non-perturbative QCD.

This entire, rich program relies upon an accurate determination of the polarization of the proton beams, a matter which is far from trivial.

In the summer of 1997 Larry Trueman and I ran a six-week Working Group, the aim of which was to try to understand theoretically the accuracy with which one could predict the analyzing power of various reactions which were under consideration as high energy proton polarimeters. The results of the study [1] were somewhat negative in the sense that we concluded that analyzing powers could only be predicted to within an accuracy of $\pm 10\%$, whereas RHIC was aiming for $\pm 5\%$.

On the other hand some very positive consequences followed. The working group stimulated the study of a polarimeter based on CNI in proton-carbon scattering and this is the polarimeter that will be used in the early stages of RHIC operation. It will be regarded as a "relative" polarimeter and will have to be calibrated absolutely at some later stage, probably via use of a polarized jet hydrogen target. In addition the surprising discovery was made that proton-proton elastic scattering, at high energy and very small momentum transfer, is self-spin analyzing, in the sense that the measurement of a sufficient number of spin-dependent observables will yield not only the values of the helicity amplitudes, but also the value of the beam and target polarizations.

All methods of measuring the polarization $\mathcal{P}$ depend on measuring some asymmetry:

$$\text{Measured asymmetry} = A\mathcal{P}$$

where A is the analyzing power of the reaction.

There are two classes of reaction:

(a) Where you believe you can calculate the analyzing power e.g. CNI.

(b) Where A has been determined by experiment elsewhere e.g. $pp \to \pi X$.

For each there exist problematic questions:

Q(a): How accurately can you calculate A?

Q(b): How sure are you that A, measured at lower energies, will have the same value at RHIC?

The Working Group of the summer of 1997 mainly addressed Q(a), [at the time very little was known about Q(b)], and, as mentioned, stimulated the decision to use a proton-carbon CNI as the initial polarimeter.

The present one-day Workshop aimed to discuss:

1) the conclusions of the 1997 study (Leader, Trueman),

2) new theoretical work relating to Q(b) (Anselmino, Sterman),

3) the status of and new ideas on the experimental side (Allgower, Guryn, Huang and Stephenson).

An important conclusion from this Workshop is the realization that, besides the major spin-dependent experiments planned by STAR and PHENIX, it would also be very interesting to undertake a detailed study of spin-dependence in *pp* elastic scattering. Thereby one could test some of the QCD-based ideas about the dynamical mechanisms at work.

The Workshop, which was attended by about 30 people proved to be extremely stimulating, with a great deal of discussion and a healthy give and take between experimentalists and theorists. It is hoped that these Proceedings will be both interesting, useful and stimulating!

I am very grateful to T.D. Lee and the RIKEN/BNL Research Center for encouragement and support. My thanks to Tom Kirk for welcoming the participants, to Pam Esposito for her help in the early stages and to Fern Simes for her vital help in organizing the Workshop and preparing these Proceedings. Finally, I am grateful to the UK PPARC for a travel grant.

Reference

[1] N.H. Buttimore, B.J. Kopeliovich, E. Leader, J. Soffer and T.L. Trueman, Phys. Rev. **D59** (1999) 114010.

Outline of "The spin dependence of high energy proton scattering"

by Buttimore, Kopeliovich, Leader, Soffer, and Trueman,

Phys. Rev.D 59, 114010, (1999).

1. Introduction with background and polarimetry motivation; listing of other methods considered.

2. General formalism: amplitudes and measurables defined,some history of study of spin dependence, behaviour in small t-region and Coulomb interference, exchange symmetries, Regge terminology (pomeron, cuts vs.poles,factorization), asymptotic phases, etc..

3. State of experimental knowledge: fits to 704 data for A_N, energy dependent fit for A_N, Regge fits, old and new (Berger, Collins, πp with amplitude analysis), $\Delta\sigma_T$ and $\Delta\sigma_L$ measurements.

4. Review of various models: pert. QCD and quark models (various), pion exchange (ref. Kaidalov et al, Pumplin & Kane, Goloshkokov et al), impact picture (Soffer et al), etc.

5. Model-independent bounds on spin-dependence and energy dependence; demonstration that *logs* growth of τ allowed a la Froissart-Martin; interpretation of this using unitarity in impact parameter picture.

6. Determination of all spin dependent amplitudes independent of beam polarization. Leader will discuss this section.

7. Conclusions.

Five independent pp amplitudes

$$\phi_1(s,t) = M_{++,++}(s,t)$$

$$\phi_2 = M_{++,--}$$

$$\phi_3 = M_{+-,+-}$$

$$\phi_4 = M_{+-,-+}$$

$$\phi_5 = M_{++,+-}$$

$$\phi_\pm(s,t) = \frac{1}{2}\left(\phi_1(s,t) \pm \phi_3(s,t)\right)$$

$$\sim \left(\sin\frac{\theta}{2}\right)^{|\lambda_f - \lambda_i|}$$

$$s = E^2 \quad , \quad t = -4p^2 \sin^2\frac{\theta}{2}$$

$$\phi_i = \phi_i^h + \phi_i^e$$

$$\phi_1^c = \phi_3^c = \frac{\alpha s}{t}$$

$$s \gg m^2$$
$$|t| \ll m^2$$

$$\phi_2^c = -\phi_4^c = \frac{\alpha s}{4m^2}(\mu - 1)^2$$

$$\Longrightarrow \phi_5^c = -\frac{\alpha s}{2m\sqrt{-t}}(\mu - 1)$$

with small corrections at small t due to form factors and Bethe phase

Measurable quantities

$$\sigma_{tot} = \frac{4\pi}{s} \, \mathrm{Im}\left(\phi_1(s,0) + \phi_3(s,0) \right)$$

$$\Delta\sigma_T = -\frac{8\pi}{s} \, \mathrm{Im}\, \phi_2(s,0)$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left(|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \right)$$

$$\Rightarrow A_N \frac{d\sigma}{dt} = -\frac{4\pi}{s^2} \, \mathrm{Im}\left(\phi_5^* (\phi_1 + \phi_2 + \phi_3 - \phi_4) \right)$$

$$A_{NN} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \left\{ 2\,|\phi_5|^2 + \mathrm{Re}(\phi_1^* \phi_2 - \phi_3^* \phi_4) \right\}$$

$$A_{LL} \frac{d\sigma}{dt} = \frac{2\pi}{s^2} \left\{ |\phi_1|^2 + |\phi_2|^2 - |\phi_3|^2 - |\phi_4|^2 \right\}$$

$$= \frac{2\pi}{s^2} \left\{ 4\,\mathrm{Re}\, \phi_+^* \phi_- + |\phi_2|^2 - |\phi_4|^2 \right\}$$

$$A_{SS} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \, \mathrm{Re}\left(\phi_1^* \phi_2 + \phi_3^* \phi_4 \right)$$

$$A_{SL} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \, \mathrm{Im}\left(\phi_5^* (\phi_1 + \phi_2 - \phi_3 + \phi_4) \right)$$

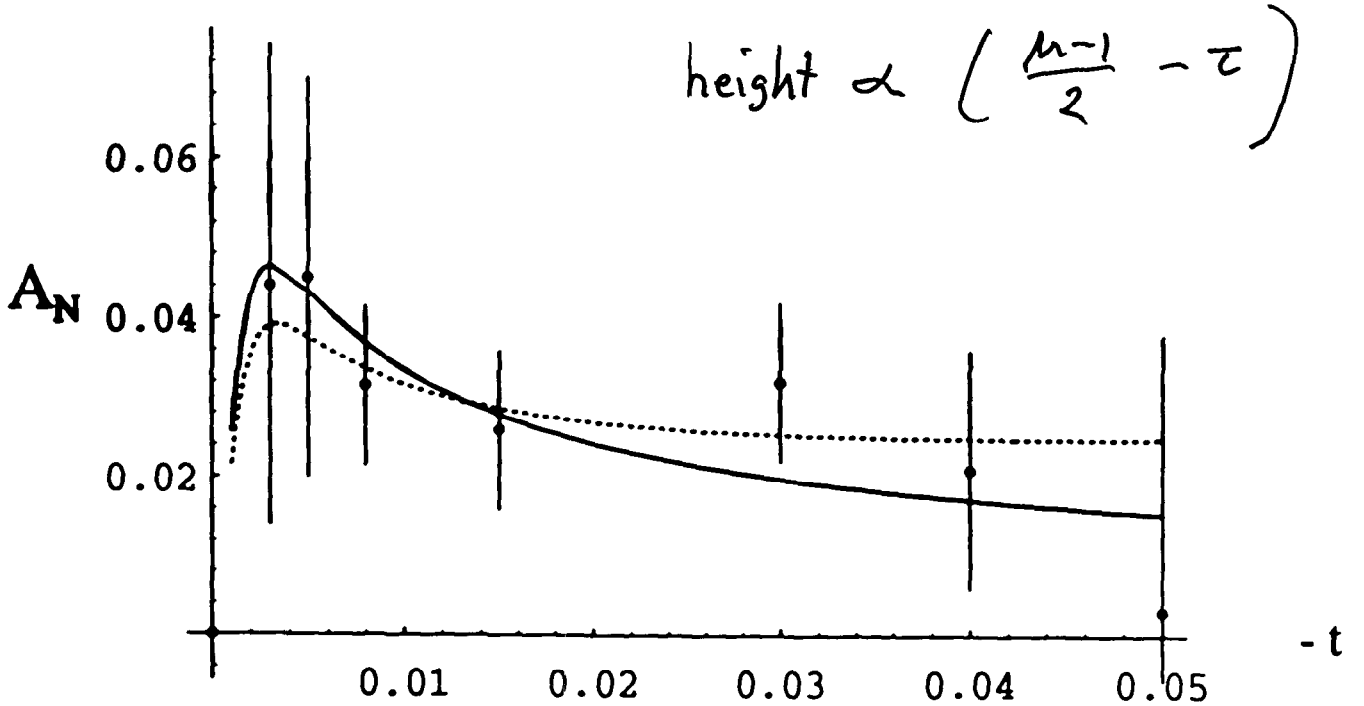
$$\Delta\sigma_L = \frac{4\pi}{s} \, \mathrm{Im}\left(\phi_1 - \phi_3 \right)$$

Buttimore, Gotsman, Leader
PRD 18, 694 (1978)

Best fits to 704 data with and without Im(τ) = 0

$$\phi_5 = \tau \frac{\sqrt{-t}}{m} \phi_+$$

height $\propto \left(\frac{\mu - 1}{2} - \tau \right)$



——— $\tau = 0.0 \pm 0.15$

····· $\tau = 0.2 + 0.03\,I \pm (0.3 + 0.01\,i)$

(Also use notation $\phi_5 = r_5 \frac{\sqrt{-t}}{m} \mathrm{Im}\,\phi_+$

so $\tau \approx \mathrm{Im}\, r_5$)

Phase of τ

(Van Hove + others)

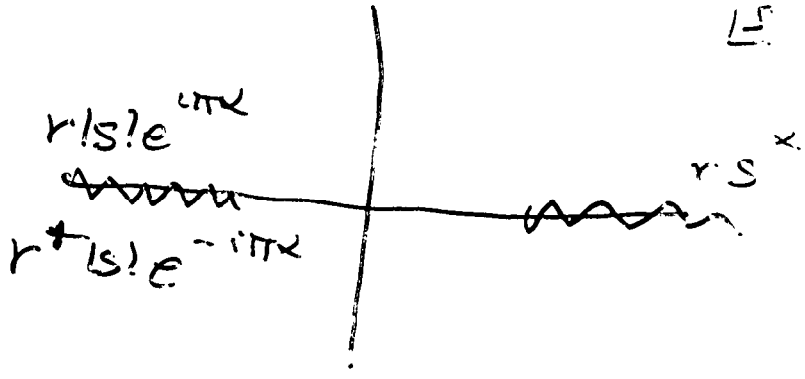
based on symmetry, polynomial boundedness & real analyticity of scattering amplitudes

$$f(s) \sim r s^{\alpha} \quad \text{as } s \to \infty$$

$$f(s^*) = f^*(s)$$

$$f(-s) = f(s) \qquad C = +1 \quad \text{exchange } (\mathbb{P})$$

$$= -f(s) \qquad C = -1 \quad \text{exchange } (\mathbb{D}, \rho, \sigma \ldots)$$



$C = +1 \qquad r^* e^{-i\pi\alpha} = r \quad$ or $\quad r = \text{real} \times e^{-\frac{i\pi\alpha}{2}}$

$C = -1 \qquad r^* e^{-i\pi\alpha} = -r \quad$ or $\quad r = \text{real} \times i \times e^{-\frac{i\pi\alpha}{2}}$

constant $\sigma \Rightarrow \alpha = 1 \Rightarrow r$ imaginary

log corrections: $f \sim s^{\alpha} \ln s^{p}$

then $f \sim i s \left(1 - \frac{i\pi p}{2 \ln s}\right)$

for $\mathbb{P}$

C: $\phi_i(s,t) = \eta_c \, \overline{\phi}_i(s,t)$

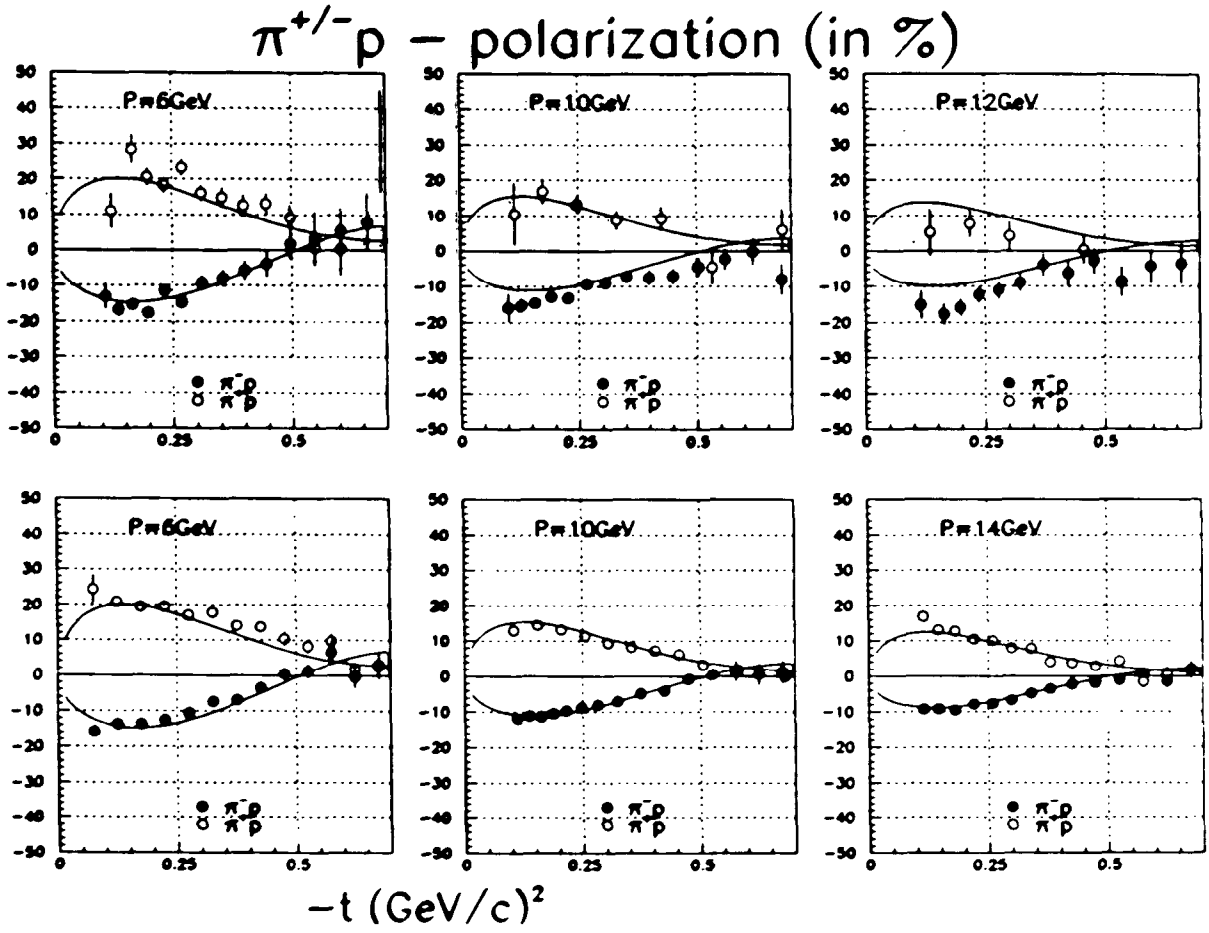
Crossing: $\overline{\phi}_1(s,t) \approx \phi_3(-s,t)$

$\overline{\phi}_5(s,t) \approx \phi_5(-s,t)$

$\overline{\phi}_2(s,t) \approx \phi_2(-s,t)$

so if $\phi_1 + \phi_3$ and ϕ_5 have same asymptotic behavior and are dominated by $C=+1$ (Pomeron) exchange τ is real: they have the same phase.

No help for CMT, but ...



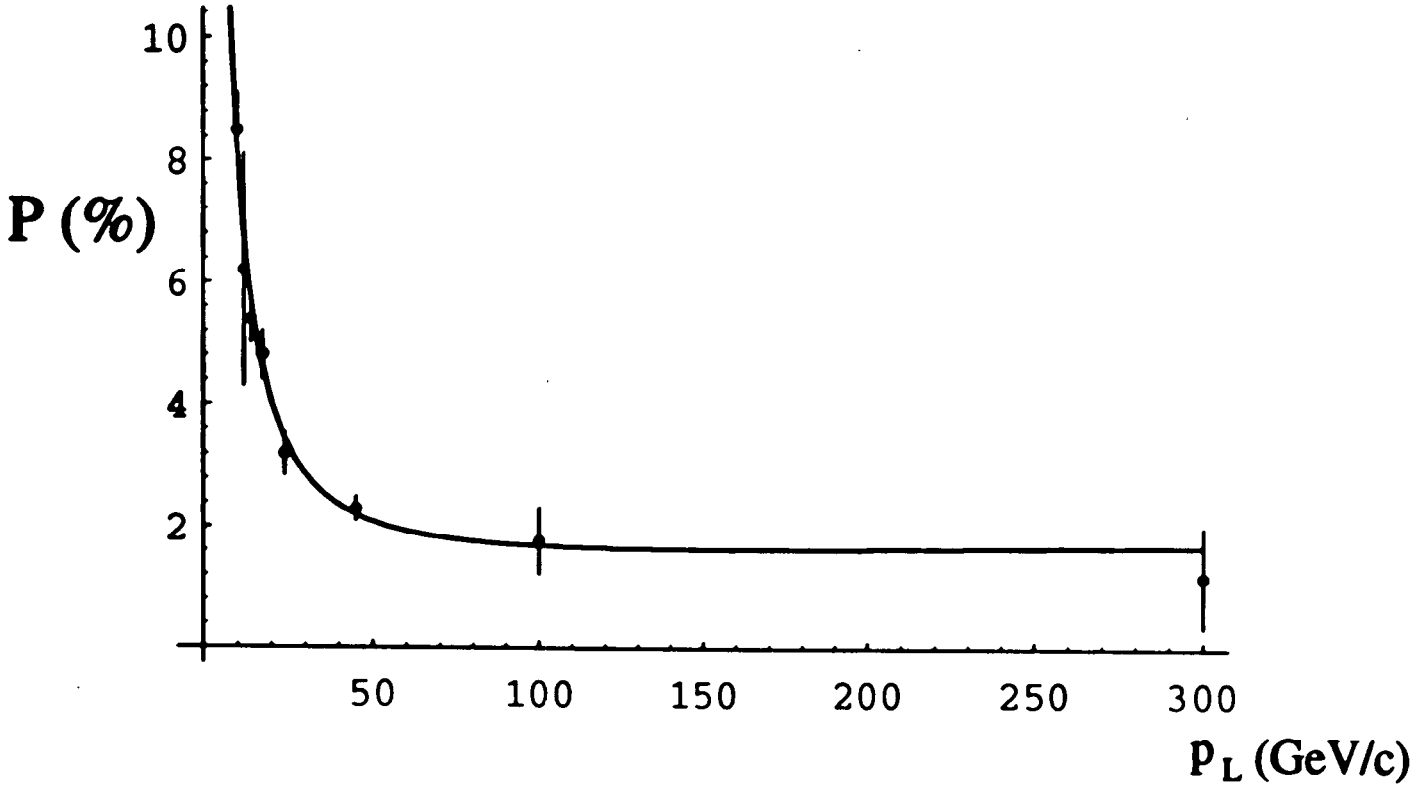
Fit $\Rightarrow$ $r_f^5(0) - r_p^5(0) = 0.06 \pm 0.01$

r_f^5 ? f - dominance ✗

f_0-ω degeneracy $r_f \approx 0.09$, $r_p = 0.23$

$f_0 = 0$ $r_f = 0$, $r_p = -0.06$

Energy dependence of P at t = -0.15 GeV^2



Best fit gives asymptotic value 2.3±1.2

Pure CNI at 300 is 1.1

10 GeV Borghini 1971
11.8 GeV Kramer 1977
14 GeV Borghini 1971
17.5 GeV Borghini 1971
24 Gev Crabb 1977
45 GeV Gaudot 1976
100 GeV Snyder 1978
300 GeV Snyder 1978

Bound on Energy Dependence of ϕ_s/ϕ_+

Model independent à la Froissart & Martin

Simplified derivation in impact parameter (b) space: ($t = -\vec{q}^{\,2}$)

$$\phi_+(s,t) = \frac{s}{2}\int \frac{d^2b}{2\pi}\, e^{i\vec{q}\cdot\vec{b}}\, \tilde{\phi}_+(b,s)$$

$$\phi_-(s,t) = \frac{s}{2}\int \frac{d^2b}{2\pi}\, e^{i\phi}\, e^{i\vec{q}\cdot\vec{b}}\, \tilde{\phi}_-(b,s)$$

Unitarity $\quad 2\,\mathrm{Im}\,\tilde{\phi}_+(b,s) \geq |\tilde{\phi}_+|^2 + |\tilde{\phi}_-|^2$

Polynomial boundedness: choose ~~[illegible]~~ $t = t_0 > 0$ in analyticity region

Then q_0 is pure imaginary and

$$\phi_+(s,t) \sim \frac{s}{2}\int \frac{d^2b}{4\pi}\int d\phi\, e^{-q_0 b\cos\phi}\, \tilde{\phi}_+(b,s)$$

$$< s\left(\frac{s}{s_0}\right)^N \text{ for some } N \text{ as } s\to\infty$$

(axiom)

$$\Rightarrow \quad e^{q_0 b} < \left(\frac{s}{s_0}\right)^N \quad \text{or}$$

$$b < R(s) = \frac{N}{q_0}\ln\frac{s}{s_0}$$

Elastic saturation of unitarity, $\mathrm{Im}\,\tilde{\phi}_+ = 2$, $b < R$ gives F-M bound

$$\phi_+(s,0) = Cs\int_0^{R(s)} b\,db = \frac{Cs}{2}R^2(s)$$

$$\sim \ln^2 s$$

Doing same for ϕ_- gives

$$\phi_- \leq \frac{Cs}{2}\int_0^{R(s)} b\,db\,qb = q\frac{Cs}{2}\frac{R^3}{3}$$

$$= \frac{1}{3}(qR)\,\phi_+ \quad \text{so}$$

$$\phi_-/q\phi_+ \sim \ln s \quad !$$

This corresponds to very different b-slope than commonly used

$$\phi_- \sim \frac{\sqrt{-t}}{m}\phi_+ \sim \frac{\sqrt{-t}}{m}Ce^{t\frac{B_+}{2}}$$

Then $\tilde{\phi}_-(b) \propto \frac{d}{db}\tilde{f}_+(b)$.

Have found slopes very different!

$$B_- = \frac{3}{5}B_+$$

Models

1. Pre-QCD Landshoff & Polkinghorne (1971)

using perceived Pomeron-photon similarity speculate that effective magnetic moment equals isoscalar e.m. moment:

$$r_5 = \frac{\mu_p - 1 + \mu_n}{2} = -0.06$$

(seen this before?)

2. QCD + quark models

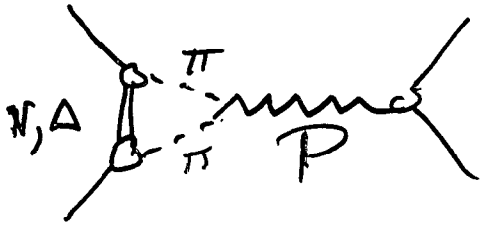
- Ryskin - uses above guess for spin-flip coupling of P to quarks; then non-rel. quark model to calculate proton spin-flip coupling

$$\mathrm{Im}\, r_5 = 0.13 \qquad (1987)$$

- Kopeliovich + Zakharov - internal transverse momentum instead of quark mag mom. Needs diquark (asymmetric) configuration. Prediction depends on diquark separation ranging from -0.15 ($r_d = .2$ f) to -0.02 (indistinguishable)

3. Non-QCD models

- Pion exchange – basic idea: small b-direct P_{pp} coupling, large b-coupling via $P_{\pi\pi}$:



uses experimental input + many detailed assumptions

earliest: Pumplin + Kane (before data) 1975 predict $\mathrm{Im}\, r_5 = -0.3$
Model then ruled out

later variant: Boreskov et al 1978 (after data) predict $\mathrm{Im}\, r_5 = +0.06$

recent variant: Gotsman + Solovyev 1997 predict $\mathrm{Im}\, r_5 = +0.035$

4. Impact picture
Bourrely and Soffer model $\tilde{f}_+(t)$ as factorizing eikonal + $\tilde{f}_5$ as $\propto \tilde{f}_+$. Fit data and predict for RHIC.
$r_5 = -0.03$ (1982)

Summary Table

Model	Im r_5	Energy Dep.	Phase ? between ϕ_5 and ϕ_+
Landhoff & Polkinghorne	**- 0.06**	**No**	*No*
Ryskin	**+ 0.13**	**No**	*No*
Kopeliovich & Zakharov	**- 0.1**	**No**	*No*
Pumplin & Kane	**- 0.3**	**Log(s)$^{3/2}$**	*Yes*
Boreskov et al	**+ 0.06**	**No**	*?*
Goloshkokov & Selyugin	**+0.035**	**No**	*Yes*
Bourrely & Soffer	**- 0.03**	**Log(s)$^{1/2}$**	*Yes*

Exchanged quantum numbers + helicity amplitudes

	$(-1)^J = P = C$	$(-1)^J = -P = -C$	$(-1)^J = -P = C$
amps	ϕ_+, ϕ_5, $\phi_2 - \phi_4$	ϕ_-	$\phi_2 + \phi_4$
es.	$\mathbb{P}$, f_2, a_2 $(C=+1)$ O, ρ, ω $(C=-1)$	a_1 $(C=+1)$	π, η, $(C=+1)$ b_1 $(C=-1)$

At RHIC, mainly Pomeron – maybe some Odderon

Goal is to understand spin dependence of $\mathbb{P}$ to proton.

Question of parity of cuts associated with $\mathbb{P} \otimes \mathbb{P}$

Factorization (true for Regge poles)

$$\frac{F_{\lambda_1\lambda_2,\lambda_3\lambda_4}}{F_{\lambda_1\lambda_2',\lambda_3\lambda_4'}} = \frac{F_{\lambda_1'\lambda_2\lambda_3'\lambda_4}}{F_{\lambda_1'\lambda_2'\lambda_3'\lambda_4'}}$$

$\{\lambda\} = (++++)$
$\{\lambda'\} = (++--)$ $\Rightarrow$ $\phi_2(t) = -\dfrac{\phi_3^2(t)}{\phi_+(t)}$ $\Rightarrow$ $\phi_2(0) = 0$

also $\phi_-(t) = 0$

$\{\lambda\} = (++--)$
$\{\lambda'\} = (-++-)$ $\Rightarrow$ $\phi_2(t)^2 = \phi_4(t)^2$ $\Rightarrow$ $\phi_2(0) = 0$

Quantum number constraint without factorization

Because $\phi_2 + \phi_4$ couples to $(-1)^J = -P = C$

$$\phi_2 \sim -\phi_4$$

unless there is such a singularity degenerate with π.

Therefore, $\phi_2(0) = 0$.

([redacted])

The Odderon

If the Odderon – the $C=-1$ partner to the Pomeron – exists and couples to the proton an arbitrary phase is possible. The Odderon coupling to $\phi_1+\phi_3$ gives non-zero $\sigma_{pp}-\sigma_{\bar{p}p}$ and makes large corrections to ρ possible. Fits (Block & co.) show that this coupling is $<2\%$ of the Pomeron. Nothing is known of its coupling to ϕ_5 and ϕ_2.

A_N is very sensitive to ratio of (Odderon coupling to ϕ_1) / (Pomeron coupling to ϕ_1). E 704 already limits this to 4% (1σ).

The unknown ϕ_2 also couples to A_N but it is not very sensitive.

Turning to A_{NN} something remarkable is seen:

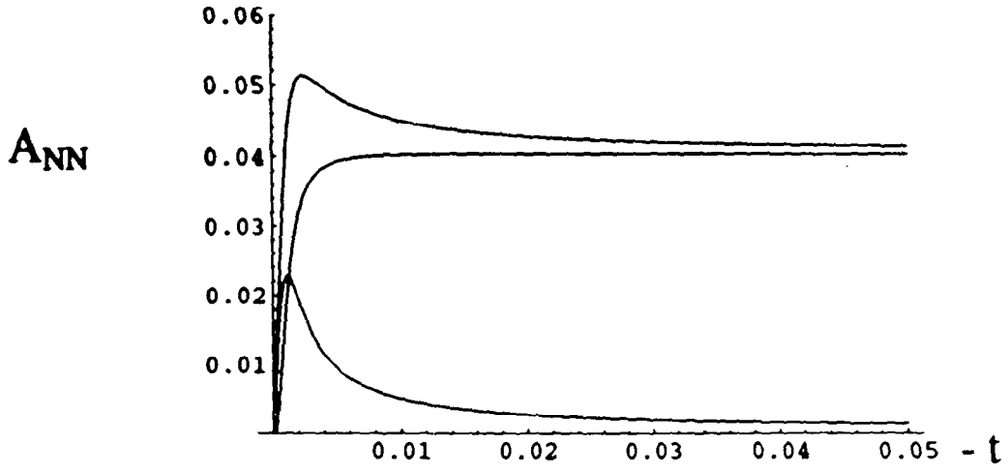
$$A_{NN} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \left\{ 2|\phi_3|^2 + \mathrm{Re}(\phi_1^* \phi_2 - \phi_3^* \phi_4) \right\}$$

The odderon contribution to ϕ_2 is (dominantly) real so it, and it alone is Coulomb enhanced (like $\phi_1 + \phi_3$ in A_N).

So it will have a reasonably large size and characteristic CNI shape.

Comparison of A_{NN} for various values of r_2:
.02 I (lower), .02 (middle), .02 + .02 I (upper).

$$\phi_2 = 2 r_2 \, \mathrm{Im}\, \phi_+$$



Conclusions for CNI polarimetry

1. Best experimental knowledge comes from E704 which gives $r_5 = 0.2 \pm 0.3$ (no theory) or $r_5 = 0.0 \pm 0.16$ (a little theory).

2. Spin-dependence falls rapidly with energy at low to moderate energy but is consistent with very large r_5 (best fit is -0.6) and leaves substantial spin-dependence at the high energy. In principle, r_5 could increase logarithmically with energy.

3. Model calculations of spin-flip coupling are varied and so are the results. All predict small r_5 (less than 10-15 %) but with different energy dependence and differing sign! Not reliable for CNI but indicates that physics can be learned by measuring A_N.

4. Spin dependence important for understanding the dynamics of high energy elastic scattering via, for example, sensitivity to the odderon.

Experimental work on the proton-Carbon CNI polarimeter

1 CNI Polarimetry

2 Experimental Setup

3 Preliminary Results

4 Plan toward RHIC

Haixin Huang
BNL

BROOKHAVEN NATIONAL LABORATORY

RHIC Polarimeter Requirement

Near Term RHIC spin program schedule

FY2000: commissioning yellow ring up to 100GeV with polarized beam(one ring polarized)

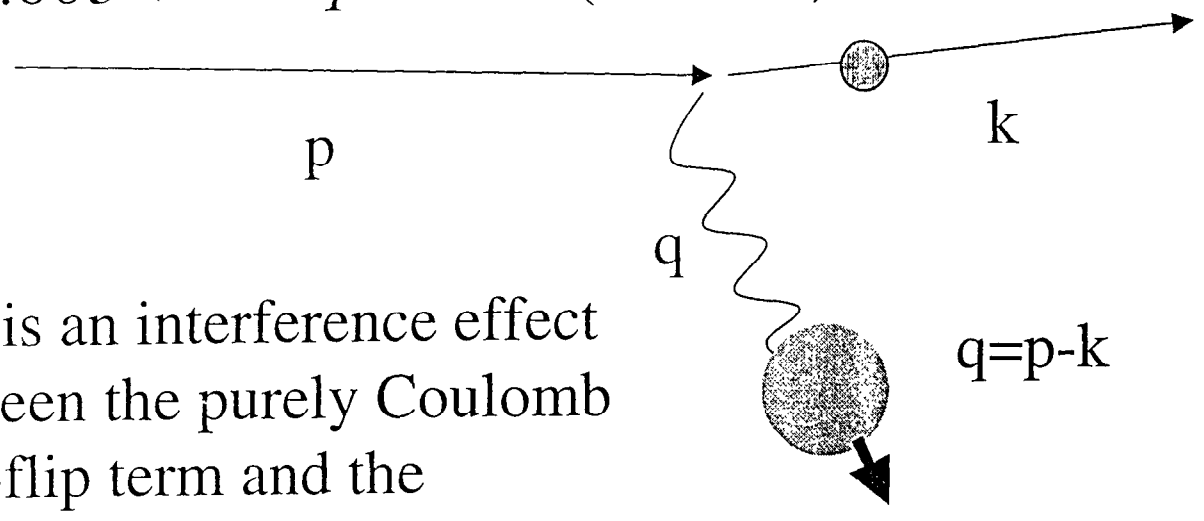
FY2001: Physics run at 100GeV(both rings polarized)

need a fast and reliable polarimeter with 10% relative error in a few minutes or seconds.

CNI Process

Coulomb Nuclear Interference Region
(very forward elastic scattering)

$$0.003 <- t = q^2 \leq 0.01 (GeV / c)^2$$



CNI is an interference effect between the purely Coulomb spin-flip term and the hadronic non spin-flip term in the scattering potential

CNI Theory

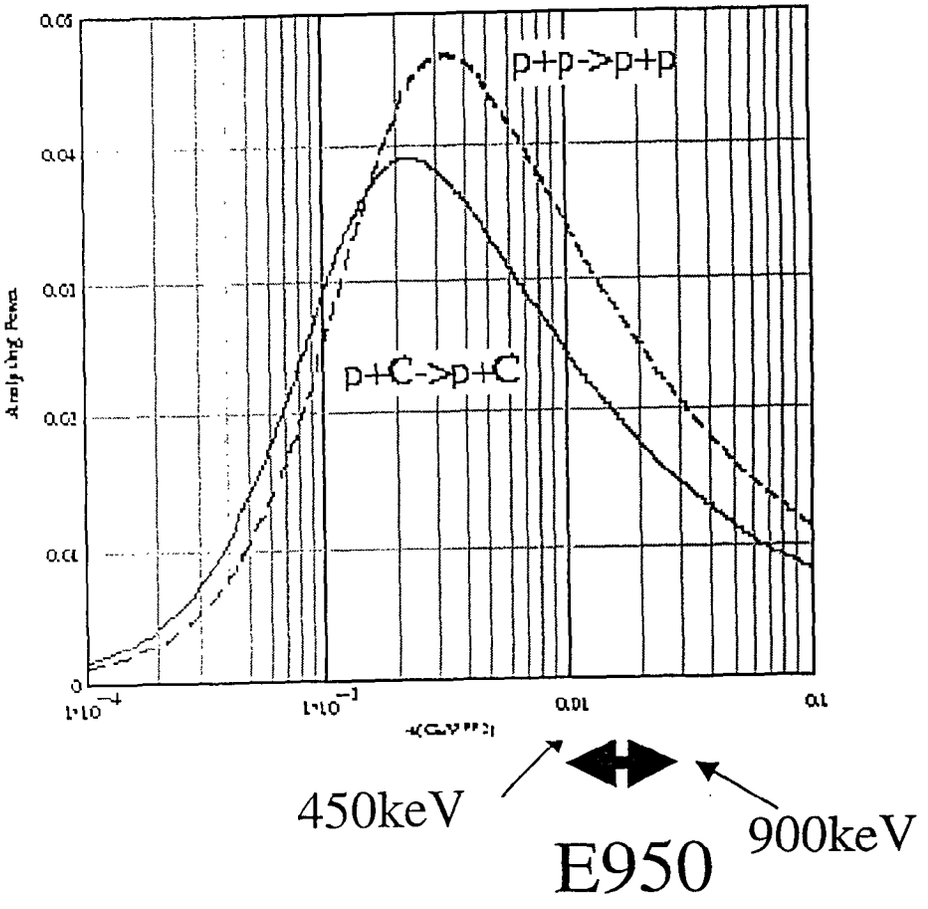
The analyzing power of CNI process is given by

$$A_N = \sqrt{\frac{8\pi Z\alpha}{m_p^2 \sigma_{tot}^{pA}}} \frac{y^{2/3}}{1+y^2}(\mu - 1 - 2\tau_A)$$

where μ is the anomalous magnetic moment of the proton (1.7928), m_p the proton mass, $y = \frac{\sigma_{tot} t}{8\pi Z\alpha}$, and $\tau_A = \frac{g}{\sqrt{\frac{-t}{m^2}(g)}}$ is the unknown contribution due to the hadronic spin-flip term g.

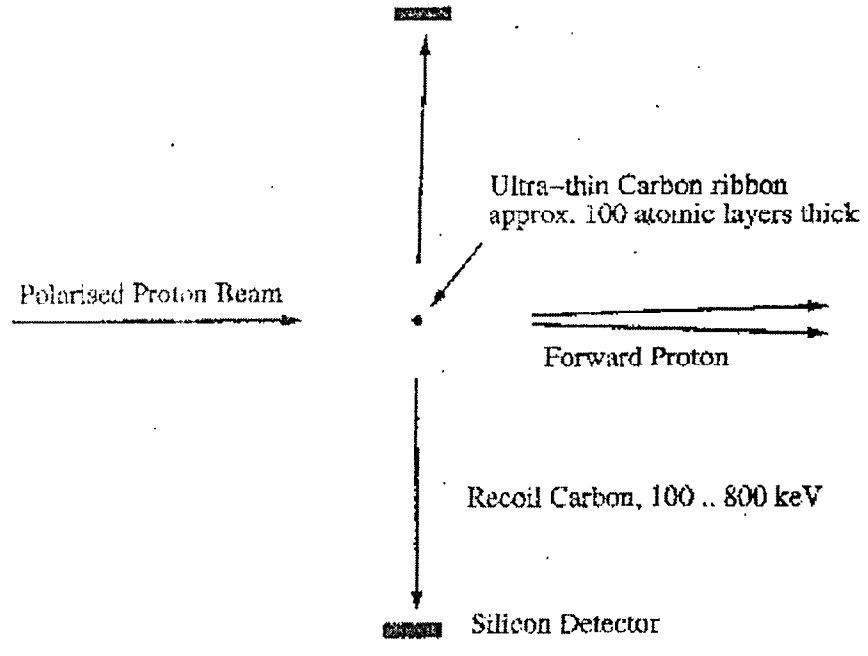
Beauty of CNI

- Calculable analyzing power of about 3~5%
- Large cross section over the whole RHIC energy range.
- Weak beam energy dependence



Principle of CNI

- Forward proton is within the beam
- Detect the carbon recoil instead(Si detector, MCP)
- Slow recoil carbon detected between bunch crossings
- Ultra thin ribbon target allows for polarization profile measurement



Challenge of CNI

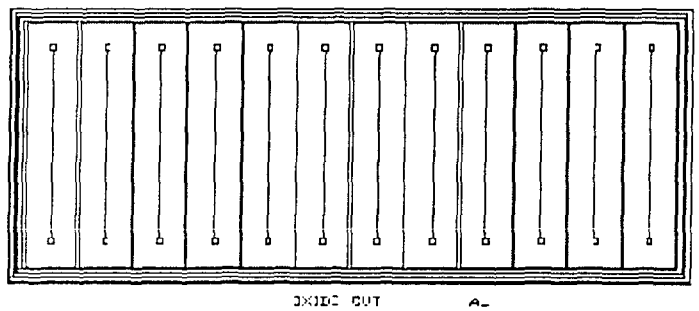
- Whether carbon nuclei have enough energy left.
  $\Rightarrow$ thin target ($4\mu g / cm^2$, $6\mu m$)
- Slow particle detection
  $\Rightarrow$ Silicon strip detector(25cm from the target)
  140-200ns from bunch crossing
  Delay trigger 50ns after the crossing to avoid the promp

- Entire CNI region for RHIC energy range is with 20 mrad w.r.t 90°
  Angular correlation not useful to restrict the kinematics
  $\Rightarrow$ Need TOF(time of flight) and energy
  can be obtained with MCP and SSD or SSD only

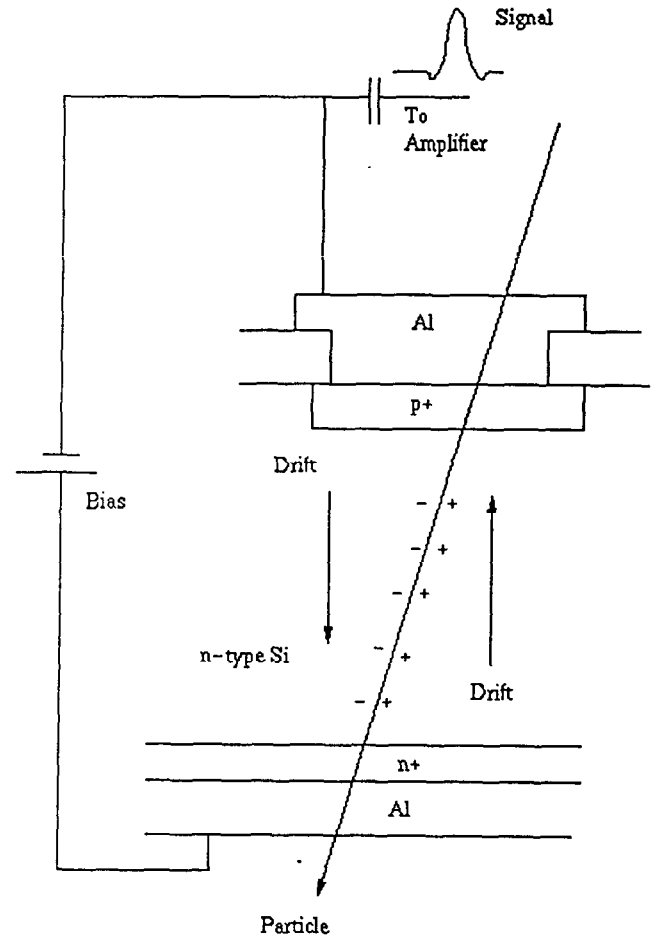
AGS E950 Goals

- Detect carbon recoils with SSD /MCP
- Determine the asymmetry and measure the analyzing power
- Check with theory the -t dependence of analyzing power
- Principle-proof experiment for RHIC CNI polarimeter

Silicon Strip Detector



12 1cmX2mm strips
Combine two strips as one channel
in the AGS Experiment
Bias voltage ~100V



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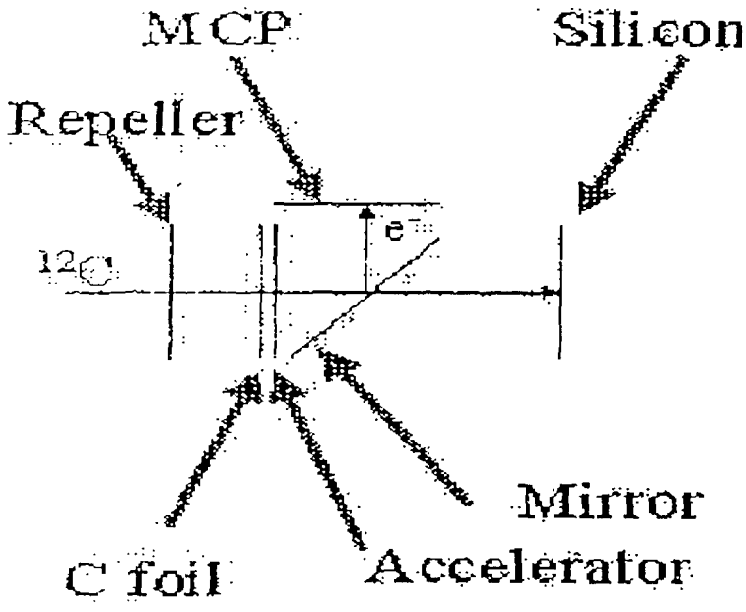
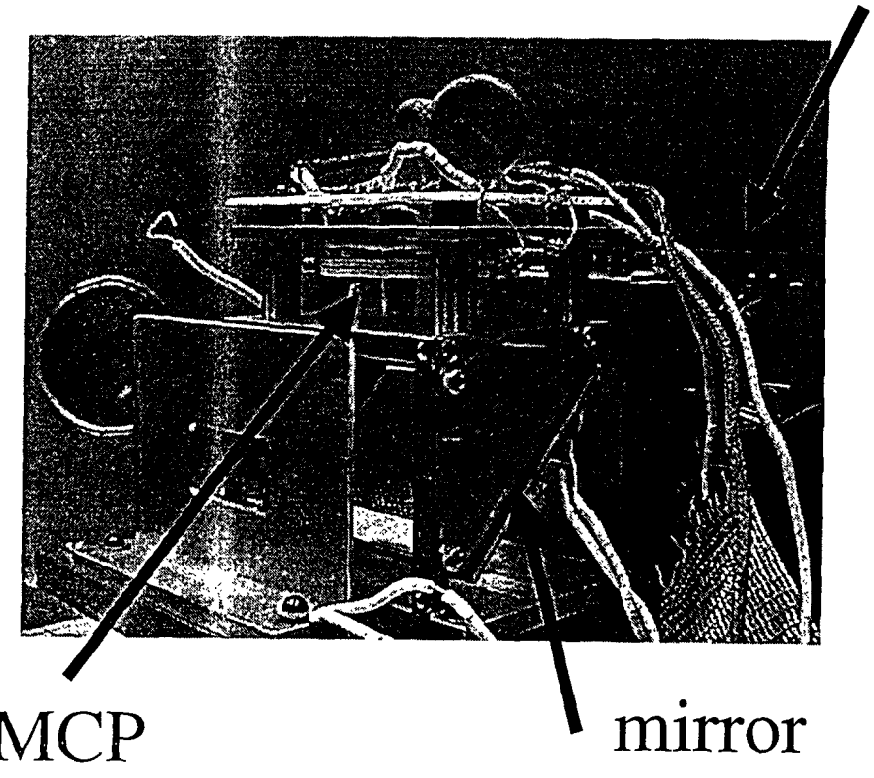
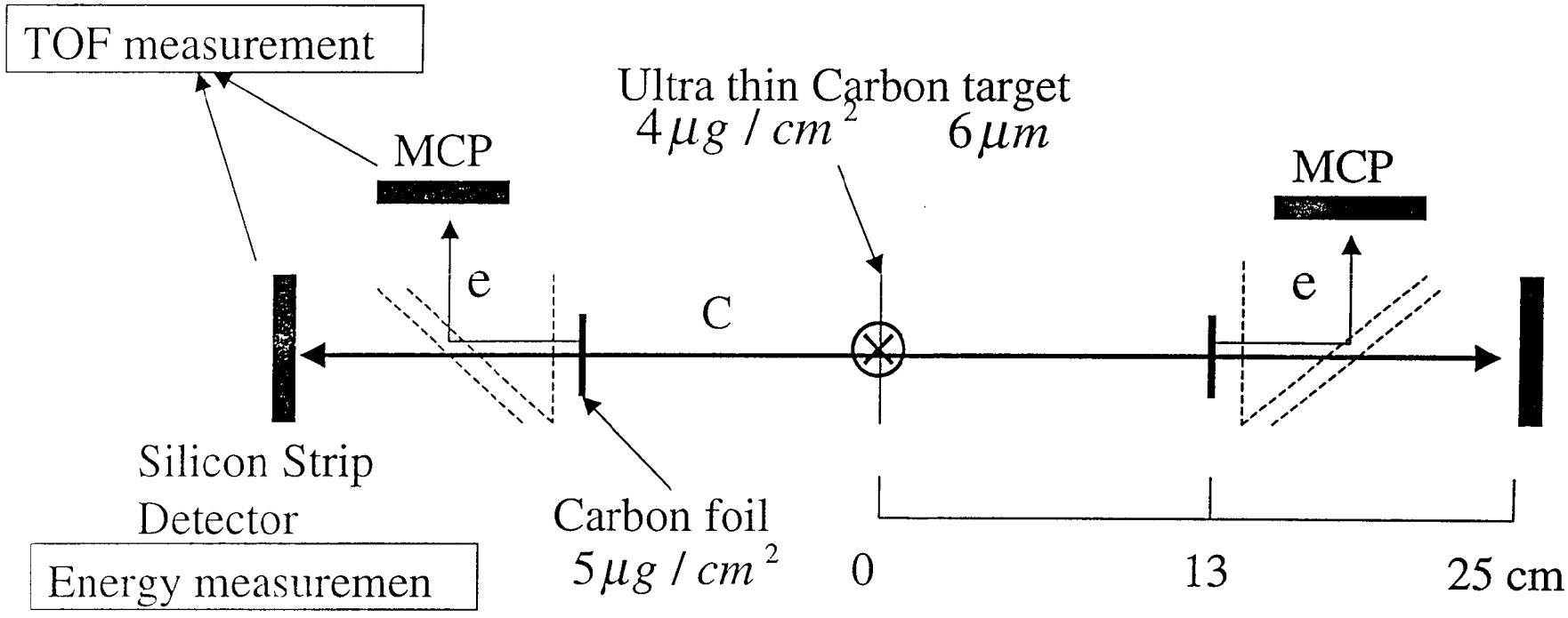
Micro-Channel-Plate Detector





Sketch of Experimental Setup



6channels,4mm/strip

E950 Detector Arrangement

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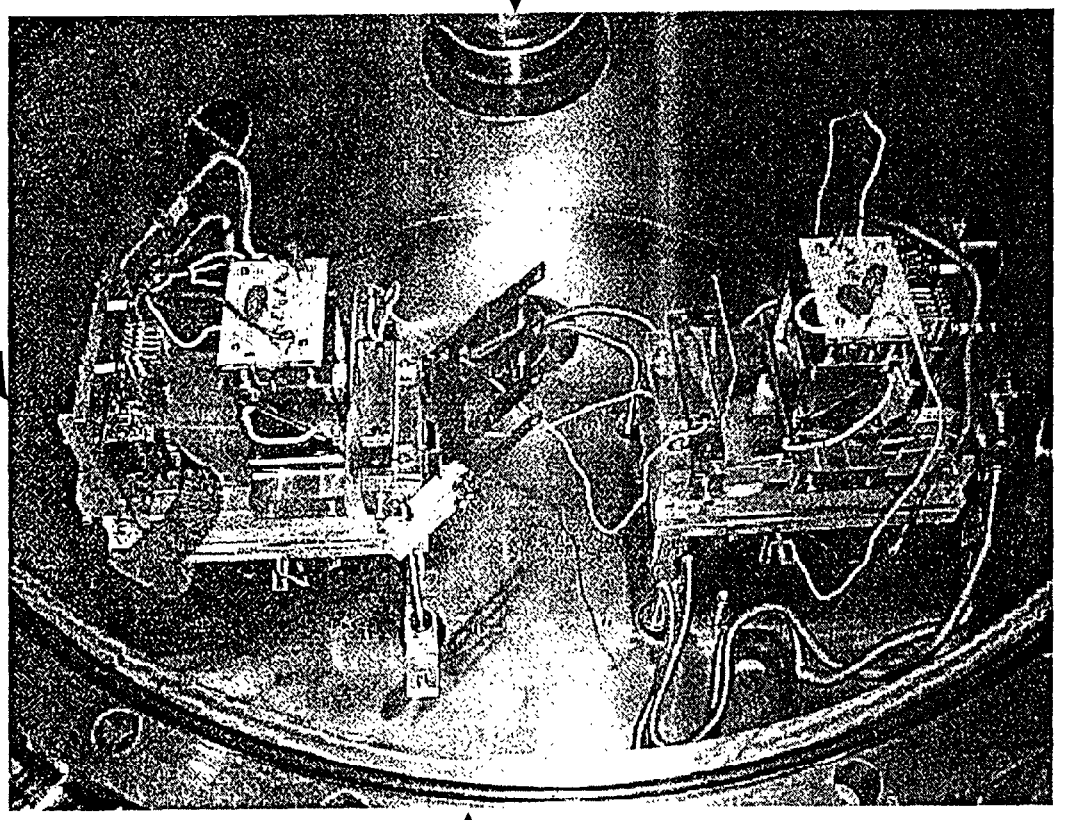
E950 Experimental Setup

Beam

Si PC board



Target holder

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AGS Experiment Running Condition

- Beam : Polarized protons

  Energy ~ 21.7 GeV/c

  Polarization ~ 40-50 % (from AGS internal polarimeter)

  Polarization : Up and down alternated every spill (+ - + - + - ...)

  1 bunch /ring, 5×10^9 protons/bunch

- Trigger

  (OR of All SSD channels) $\otimes$ RF signal

  Trigger rate ~ $2\times10^3 / spill$

- Linux based acquisition, on-line analysis capable

- Data Taking

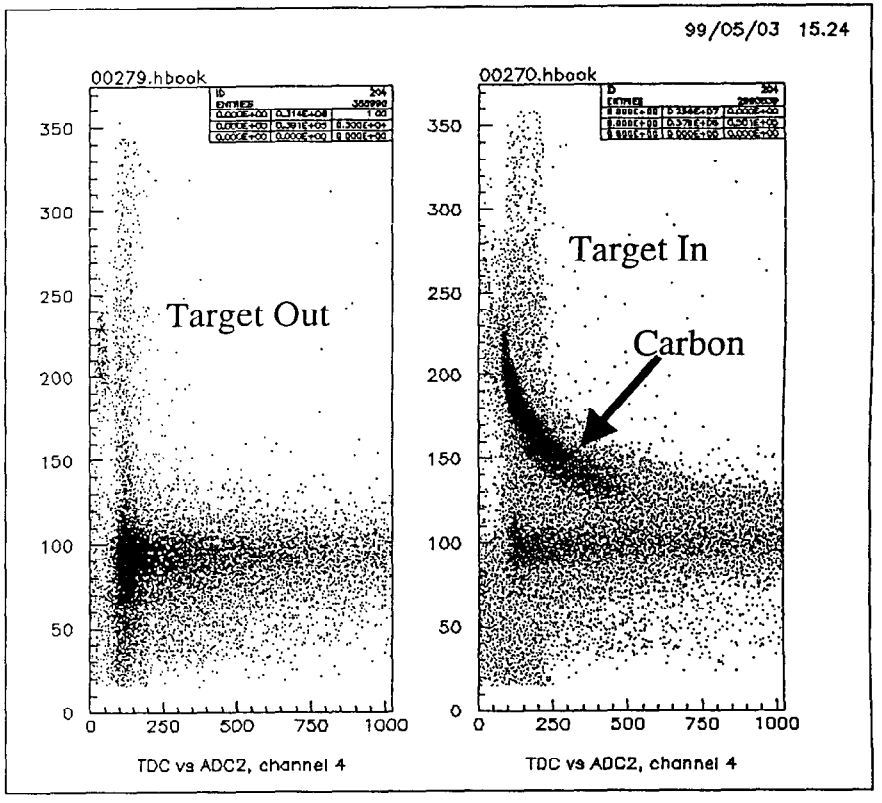
  ADC, TDC Data for All Silicon channels & MCPs

  ADC gate and TDC start are generated by RF.

Proof of Carbon events

- Comparison between target in/out runs gives the proof of Carbon detection
- Target frame may be partially in the beam even with the target out configuration
- Rate was sensitive to beam position

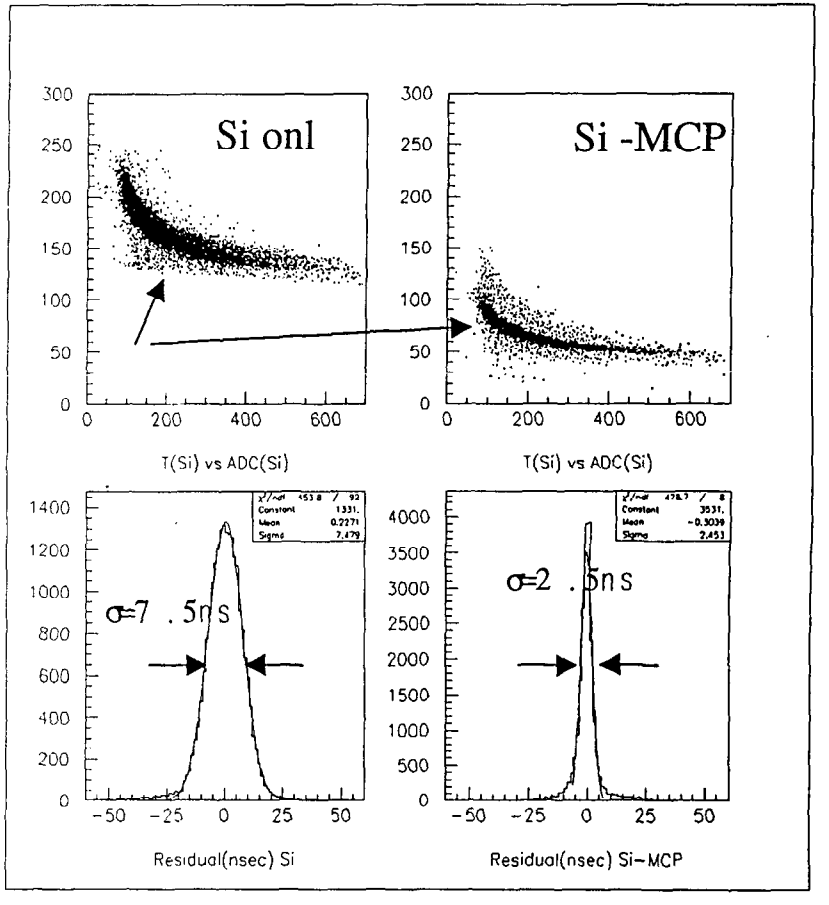
TDC distribution



ADC distribution

Resolution Improved with MCP

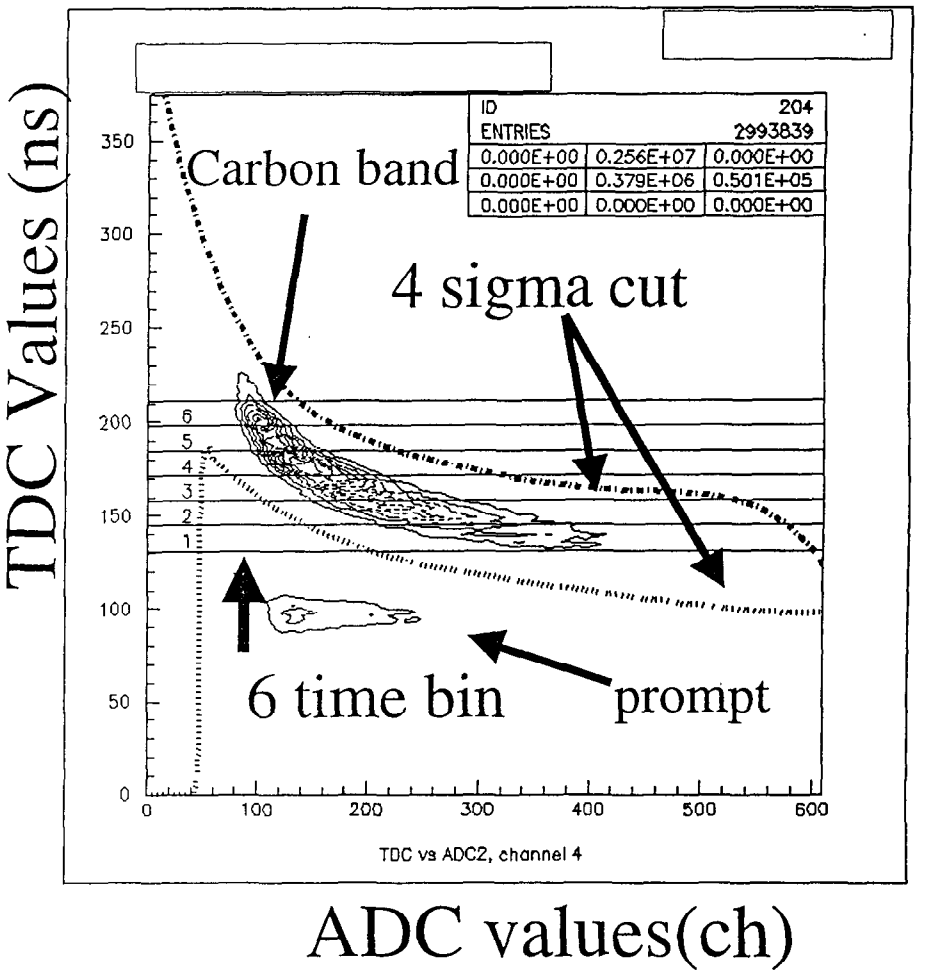
- Bunch width ~ 25 ns
  Bunch crossing freq. ~370kHz
- Trigger
  (OR of all SSD channels)⊗RF signal
- Si TDC start was beam RF
- Inherent 7.2ns width from beam bunches.
- Using Si-MCP gives inherent Si time resolution of 2.5ns.



Projection along the profile

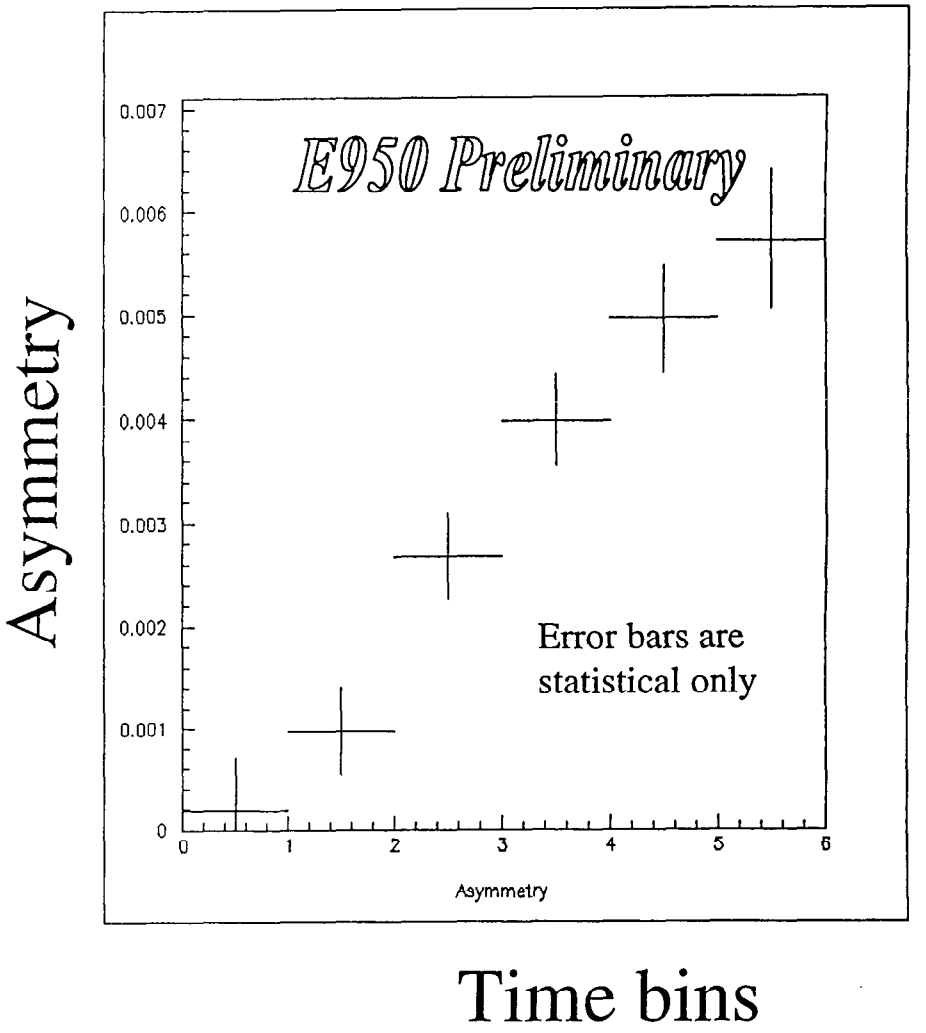
Data Analysis

- Since energy calibration is not good(yet), use time slices to get -t bins instead.
- Carbon bands were selected using 4 sigma cut from the center of the bands



Asymmetry

- Carbon asymmetry is statistically significant
- The physics asymmetry increases with arrival time => follows the general trend as expected
- Not yet absolute
- Asymmetry of prompt is less than 0.001



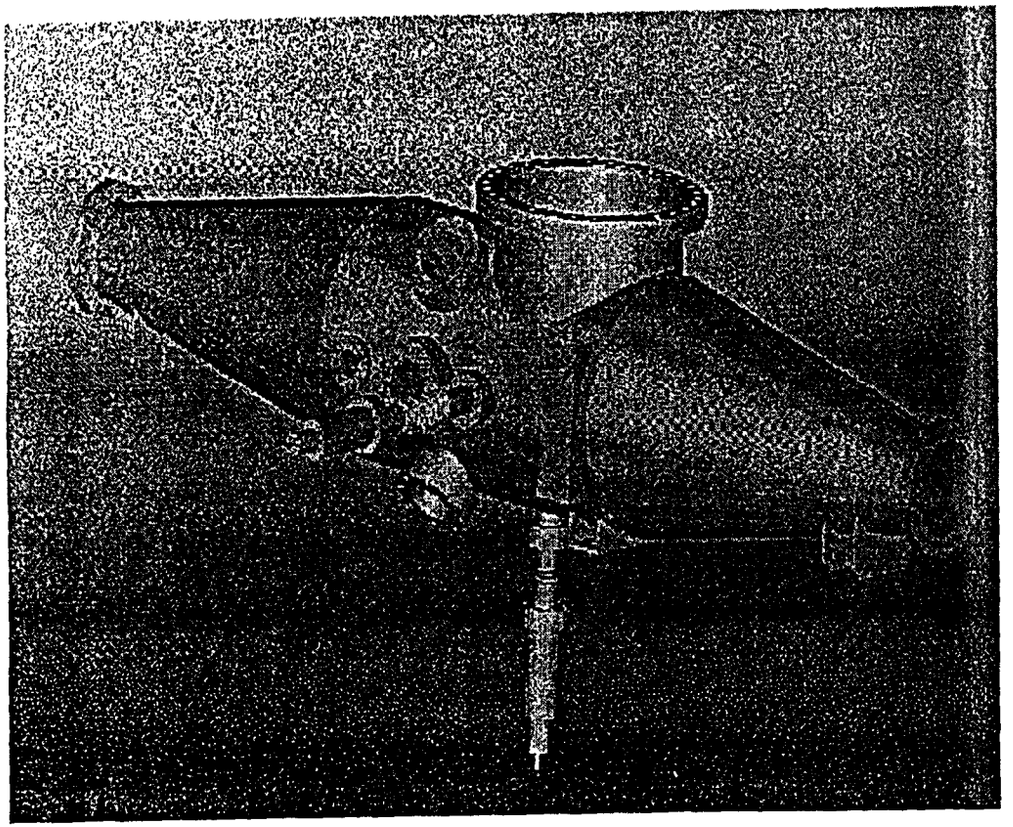
Conclusion from AGS Run

- Carbon recoils have been successfully detected in the AGS
- Seen significant asymmetry from Carbon recoils
- -t dependence seems to be qualitatively consistent with theory
- p-C CNI polarimeter should work for RHIC, too

RHIC pC CNI polarimete

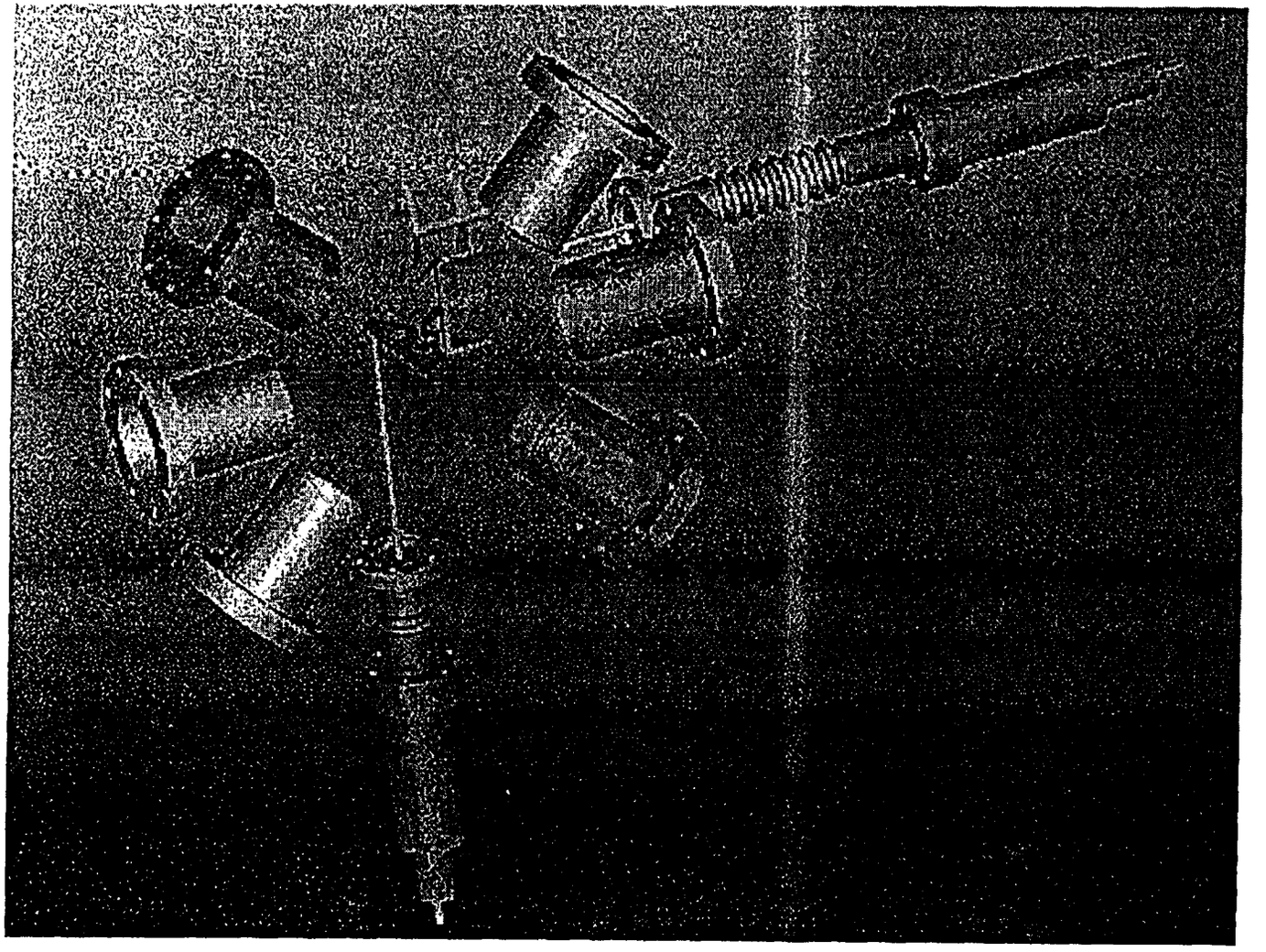
- Same statistics(20σ measurement) can be obtained in about a minute in RHIC at full luminosity
- Installation in the RHIC ring by Mar. 2000
  - Vacuum chamber design has been done
  - Target design same as the AGS one
  - Detector assembly modularized
  - Data Acquisition (remote controllable)
  - Improvement on the electrical noise reduction

pC CNI polarimeter for RHIC



- 1.6m long(5:1 tapering on both ends)
- 17cm radius
- 3 pairs of SSD detectors
- vertical and horizontal targets
- capable of measuring both vertical and horizontal beam polarization profiles

Exploded View of RHIC pC CNI Polarimeter



RHIC Polarimeter Schedule

FY2000: p+C CNI Polarimeter in yellow ring, with a possible p+C elastic scattering polarimeter for injection energy only

FY2001: p+C CNI polarimeters in both rings

p+C $\longrightarrow \pi^{\pm}$+X in one ring

p+p CNI with unpolarized gas jet target(PP2PP)

FY200n: p+p with polarized gas jet target

Polarimetry at RHIC Using pp Elastic Scattering

Wlodek Guryn

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for PP2PP (R7) collaboration

Abstract

Considering recent conceptual progress on polarimetry at RHIC we have developed a scheme to use PP2PP for the absolute measurement of beam polarization in RHIC. In addition to the equipment proper to PP2PP for detection of scattered protons, the scheme involves a jet target, both polarized and unpolarized, and a recoil detector. Measuring the scattered proton is important for background rejection. Three regions of four-momentum transfer $-t$, where the analyzing power A_N in pp elastic scattering is appreciably different from zero, are considered: the CNI region $10^{-3}<-t<2\ 10^{-2}$ $(GeV/c)^2$ and the regions of small $-t$, $0.1<-t<0.4$ $(GeV/c)^2$ and medium $-t$, $0.8<-t<1.4$ $(GeV/c)^2$. The current information about analyzing power A_N for such reactions is sufficient to give a choice of processes to be used for polarimetry at RHIC. Judicious practice recommends the use for crosscheck of at least two methods measuring the beam polarization. Two distinct goals of having a "relative" polarimeter, for a fast turn-around monitoring polarization during beam commissioning and tuning, and of an "absolute" polarimeter, necessary to determine the absolute beam polarization during the physics runs over longer times of one or more machine fills with stored beams are considered. The former needs a possibly large analyzing power, whose value however doesn't need to be very well known, but should be eventually calibrated versus the latter one, whose A_N has to be determined either from reliable theoretical calculations or from a high precision set of data at various relevant energies. The polarized jet target, of intensity $10^{12}cm^{-2}$ is sufficint to be used for the absolute calibration. An unpolarize jet of intensity $10^{14}cm^{-2}$ is proposed for online monitoring of the beam polarization. The apparatus for the measurement of recoil protons is described. Using meausred cross sections and assumed A_N, the rates and attainable precision of the absolute calibration of beam polarization are caclulated. Existing data, in the range of interest of RHIC, provide the required 5% accuracy only at few data points. Deeper scrutiny of the CNI spin asymmetry, in principle calculable on the basis of reliable QED and diffractive physics concepts indicates that the A_N is sufficiently large, of the order of 3-4%, and relatively independent on $\sqrt{s}$ to guarantee that beam polarization could be messured using pp elastic scattering process.

Polarized beams

With transversely polarized protons and measuring of $\Delta\sigma_{tot}$, A_N, A_{NN} we will determine helicity amplitudes $\phi_i(s,t)$:
L. Trueman et. al PRD 59, 114010 (1999)

- **the difference of σ_{tot} as function of pure initial transverse spin:**

$$\Delta\sigma_{tot} = \sigma_{tot}(\uparrow\downarrow) - \sigma_{tot}(\uparrow\uparrow)$$

- **the analyzing power, A_N:**

$$A_N = \frac{1}{P\cos\phi}\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

- **and the double-spin correlation parameter, A_{NN}:**

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

(P_i is beam polarization, ϕ is scattering azimuth)

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

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

These measurements challenge strong interaction theory, since they involve the application of QCD in a kinematical region where non perturbative effects are important.

Summary of working group on PP2PP and RHIC Polarimetry

M. Conte, W. Guryn, A. Penzo
(13-18 October 1997)

ABSTRACT

We are describing a conceptual design of a polarimeter for RHIC based on proton - proton elastic scattering. Three regions of four momentum transferred *-t*, where the analyzing power is of the order of few percent, are being considered: Coulomb Nuclear Interference (CNI) region $0.004 < |t| < 0.02$ $(GeV/c)^2$; small $|t|$: $0.1 < |t| < 0.4$ $(GeV/c)^2$; and medium $|t|$: $1.0 < |t| < 1.4$ $(GeV/c)^2$. A use of both polarized and unpolarized Hydrogen jet target is explored. A measurement of recoil proton and pp2pp apparatus to measure forward scattered proton is also considered. The measurements with pp2pp apparatus in the collider mode are also described.

Introduction.

The analyzing power A_N of proton - proton elastic scattering in various -t regions and number of incident proton momenta [1-N or a review]. They indicate that A_N is sufficiently large to provide polarization measurement using *pp* elastic scattering.

Main goals of polarimetry at RHIC.

Considering recent discussions [1] on polarimetry for RHIC we have developed a scheme to measure polarization of proton beams at RHIC using pp2pp apparatus, a jet target and a recoil detector. The goals of the RHIC polarimeter have to accomplish two fundamental tasks for the polarized collider:

1. During the commissioning of polarized beams, in the beam momentum range [25,250] GeV/c, with a (relative) polarimeter one needs to measure beam polarization P_B with 10-15% relative error, in few minutes;

2. Measure beam polarization, at top momentum 250 GeV/c, with a polarimeter with 5% absolute error.

The proposed scheme aims to satisfy the above requirements.

Single spin asymmetry A_N.

For the completeness of the discussion, we would like to discuss general issues related to any scheme used to measure the polarization. The beam polarization (normal) is measured counting left and right scatters in a polarimeter with a known analyzing power A_N (or counting scatters on one side with beam polarized up and down). Since A_N is given by:

$$A_N = \frac{1}{P_B \cos\phi} \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Where:
$N_\uparrow$ is number of events scattered into a detector when the beam polarization is "up,"
$N_\downarrow$ is number of events scattered into a detector when the beam polarization is "down,"
P_B is The beam polarization,
ϕ is the angle between the scattering plane and the beam polarization.

In order to measure polarization one needs to choose a physics process which is sensitive to the polarization of the beam, namely reaction that has an analyzing power A_N. One can then determine the beam polarization P_B through known A_N and measuring so called raw asymmetry ε:

$$\varepsilon = A_N P_B \cos\phi = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$P_B = \frac{1}{A_N} \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{\varepsilon}{A_N}$$

$$\left(\frac{\Delta P_B}{P_B}\right)^2 = \left(\frac{\Delta A_N}{A_N}\right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2$$

One can show that for $\varepsilon \ll 1$:

$$\left(\frac{\Delta \varepsilon}{\varepsilon}\right)^2 = \frac{1-\varepsilon^2}{\varepsilon^2 N_T} \approx \frac{1}{\left(A_N P_B\right)^2 N_T}$$

For a good polarimeter the contribution from the second term on the RHS in (4) will be small. This leaves the first term, the error in the analyzing power of the physics process, as the dominant contribution to the error in $\Delta P_B/P_B$.

General comments on polarimetry issues.

Better than 5% error in beam polarization measurement is required so that the error on double spin asymmetry, A_{NN} for example, is less than 10%. The polarized proton beams at RHIC will have polarization in the vertical direction, normal to the accelerator plane. Therefore we shall use notation ↑↓ do describe up and down spin orientation, or in short "N". The double-spin asymmetry, A_{NN} is given by:

$$A_{NN} = \frac{1}{P_B^{\,2}} \frac{N_{\uparrow\uparrow} - N_{\downarrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow}} = \frac{\varepsilon_{NN}}{P_B^{\,2}}$$

where ε_{NN} is the raw asymmetry, whose error is:

$$\left(\frac{\Delta A_{NN}}{A_{NN}}\right)^2 = \left(\frac{2\Delta P_B}{P_B}\right)^2 + \left(\frac{\Delta \varepsilon_{NN}}{\varepsilon_{NN}}\right)^2$$

One can show that for the total number of events N_T, the error on raw asymmetry is :

$$\Delta \varepsilon_{NN}^{\;2} = \frac{1 - \varepsilon_{NN}^{\;2}}{N}$$

and for raw asymmetry $\varepsilon_{NN} << 1$, the error is $\Delta\varepsilon_{NN} = N_T^{1/2}$ and hence:

$$\left(\frac{\Delta \varepsilon_{NN}}{\varepsilon_{NN}}\right)^2 = \left(A_{NN} P_B\right)^2 - \frac{1.}{\sqrt{N}}$$

P_B is the polarization of each beam; $N_{\uparrow\uparrow}$ ($N_{\uparrow\downarrow}$) is the normalized number of events observed with the beam polarizations parallel (anti parallel); N_T is the total number of events, $N_{\uparrow\uparrow} + N_{\uparrow\downarrow}$,. The first term on the RHS in (2) is the polarization error, the second term is the statistical error in the asymmetry.

Equation (2) shows that the fractional error in the polarization (ΔP_B/PB) contributes proportionally to the significance of the measurement (ΔA_{NN} / A_{NN}). Therefore, for a polarization error of 5% then the contribution to the two-spin asymmetry is 10%. The polarization error will be smaller than the statistical error, for measurements with less than 10 sigma statistical significance.

Wlodek Guryn
RIKEN Polarimetry Workshop
08/18/99

Polarimetry Needs

1. For physics - 5%absolute error is required, needs lots of systematic work. Doesn't have to be very fast.

2. For on-line monitoring 10% - 15% accuracy is sufficient, it has to be relatively fast to allow setting up of the machine.

3. There is a need for monitoring of the polarization at the experiments; hence -*t* region must be such that it is compatible with standard tune and available space.

4. Large figure of merit - ($P_B A_N$) for accuracy and ($P_B \sigma$) for rate are important.

We believe that analyzing power in $p^{\uparrow}p$ elastic scattering can solve the above.

Since at the moment #3 is done by pC CNI method, we will concentrate on 1, 3, and 4. (This is not to say that #3 could not be don with pp elastic also.)

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pp Elastic Scattering and Polarimetry

1. It is a simple reaction, which for the purpose of 2 and 4 can be done off line with the full power of rejecting backgrounds.

2. If used with the measured elastic cross section it can provide the luminosity monitor at each experiment.

3. Existing data in pp elastic scattering can be used as a guide to look for a suitable region in $-t$ to measure beam polarization at RHIC.

4. There is no reaction in pp (elastic scattering) in the RHIC energy domain that has been measured or been calculated to 5% accuracy.

5. A polarized jet target, or polarized Atomic Beam Source (ABS) is needed to calibrate A_N.

Guided by existing data and phenomenology, candidate regions are:

- CNI ($10^{-3} < -t < 10^{-2}$ GeV/c^2) - essentially energy independent, large figure of merit $A_N\sigma$.

- [illegible] (0.1 < $-t$ < 0.4 GeV/c^2) - large enough $A_N\sigma$, can be used with standard tune.

- [illegible] (0.8 < $-t$ < 1.4 GeV/c^2) - polarization could be higher than previous two, could be used with standard tune.

All need careful study, before application at RHIC. All have [illegible] . A survey period is an absolute necessity.

We assume as usual additivity of the hadronic and electromagnetic amplitudes ($\phi_i = \phi_i^h + e^{i\delta}\phi_i^e$, $i = 1,\ldots,5$) with δ, the Coulomb phase shift ($\delta = -\alpha \ln|bt/2 + 4t/\Lambda^2| - 0.577\alpha$) and $\Lambda^2 = 0.71\,(\mathrm{GeV}/c)^2$ the dipole Sachs form factor parameter. It is generally considered that ϕ_2, ϕ_4, and $\phi_1 - \phi_3$ are all negligible in the region of study; this is certainly true for electromagnetic amplitudes and is very likely to be true for the hadronic. Thus $\phi_1 \approx \phi_3$ and ϕ_5 are the most significant amplitudes for A_N.

The denominator of Eq. (1) with proper normalization corresponds to the pp elastic differential cross section which, at low momentum transfers, is usually parametrized by neglecting spin-dependent terms as

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{t^2} + \frac{\sigma_{\mathrm{tot}}^2}{16\pi}\left(1+\rho^2\right)e^{bt} + \frac{e^{bt/2}}{t}\alpha\sigma_{\mathrm{tot}}(\delta+\rho) \quad (2)$$

where α is the fine structure constant and b is the nuclear slope parameter. For higher values of $|t|$ we will include the contribution from the helicity single-flip amplitude as in Eq. (4). The total cross section is written in terms of the imaginary part of the hadronic nonflip helicity amplitudes according to the optical theorem as

$$\mathrm{Im}(\phi_1^h + \phi_3^h)\,|_{t=0} = \frac{1}{4\pi}[s(s-4m^2)]^{1/2}\sigma_{\mathrm{tot}} \quad (3)$$

where m is the proton mass.

The elastic pp polarization measurements performed at $|t|$ values $[0.15 \le |t| \le 2.5\,(\mathrm{GeV}/c)^2]$ at 100–300 GeV/c beam momenta [7–10] and other lower energy experiments [11,12] show the following general features.

(1) A positive analyzing power A_N at small $|t|$ values $[0.1 \le |t| \le 0.4\,(\mathrm{GeV}/c)^2]$ decreases like $\sim 1/\sqrt{s}$ up to $s \approx 50\,\mathrm{GeV}^2$, with a possible flattening around values of a few percent up to the highest energies.

(2) For $s \ge 50\,\mathrm{GeV}^2$, A_N changes sign around $|t| \approx 0.3$ to $0.4\,(\mathrm{GeV}/c)^2$ from positive to negative and reaches a negative minimum followed by a sharp zero crossing in the region where the diffractive dip in the differential cross section develops around $|t| \approx 1.2\,(\mathrm{GeV}/c)^2$ and possibly remains positive at larger $|t|$ values.

These features have stimulated a number of speculations on the existence of a hadronic helicity single-flip contribution, ϕ_5^h, that does not necessarily decrease as $s^{-1/2}$.

Recent elastic pp scattering results at very small angles from Fermilab help to advance our understanding of the hadronic single-flip helicity amplitude. By using the polarized proton beam at Fermilab and scattering on a recoil-sensitive scintillator target, it was possible for the first time to measure the analyzing power of pp scattering at very small $|t|$ values $[1.5\times10^{-3} \le |t| \le 5.0\times10^{-2}\ (\mathrm{GeV}/c)^2]$ around 200 GeV/c [13]. This momentum transfer range was not accessible in other experiments that used unpolarized beams and polarized targets at comparably high energies. The data set around 200 GeV/c that we are considering in this study spans $1.5\times10^{-3} \le |t| \le 0.6\ (\mathrm{GeV}/c)^2$. Over this region, the asymmetry can be expressed as

$$A_N = \frac{\sqrt{-t}}{m}\,\frac{(\mu-1)z - 2zI + 2(\rho I - R)(1+t/\tau)}{1+(\rho-z)^2 - \frac{t}{2m^2}\left\{[(\mu-1)z-2R]^2 + 4I^2\right\}} \quad (4)$$

where $z = t_c/|t|$, $t_c = 8\pi\alpha/\sigma_{tot} \approx 1.8\times10^{-3}\,(\mathrm{GeV}/c)^2$, and $\mu = 2.793$ is the magnetic moment of the proton [14]. The Coulomb phase may be omitted as its inclusion does not alter values of parameters significantly. I and R are the ratios of the imaginary and real parts of the reduced helicity single-flip $\tilde{\phi}_5^h = (m/\sqrt{-t})\,\phi_5^h$ to the imaginary part of the averaged nonflip amplitudes, respectively, and defined as

$$R + iI = \lim_{-t\to0}\frac{2\tilde{\phi}_5^h}{\mathrm{Im}\,(\phi_1^h + \phi_3^h)} \quad (5)$$

where the $m/\sqrt{-t}$ term originates from angular momentum conservation at $t = 0$ constraining the asymmetry to vanish at least as $\sqrt{-t}$ there.

We parametrize the asymmetry in the higher part of the $|t|$ region of interest with the factor $(1+t/\tau)$ in the last term of Eq. (4) to reflect the t dependence of the hadronic contribution. We do not attach such a t behavior to any one of ρ, I, or R in particular, but to all in combination. The parameter τ is related to the zero-crossing position of the asymmetry around -0.3 to $-0.4\,(\mathrm{GeV}/c)^2$. In the region where $|t| \ge 0.6\,(\mathrm{GeV}/c)^2$ this parametrization should be augmented to represent the second zero crossing at about $-t \approx 1.2\,(\mathrm{GeV}/c)^2$ from negative to positive after reaching a negative minimum, possibly due to a near vanishing of the spin-averaged amplitude at this value of momentum transfer [1]. However, in the region of the present analysis, $|t| \le 0.6\,(\mathrm{GeV}/c)^2$, and given current data, our linear parametrization describes the A_N behavior with sufficient precision.

Table I shows the results of fitting the expression in Eq. (4) to various combinations of available elastic pp asymmetry data (see Fig. 1). All three parameters $R, I,$

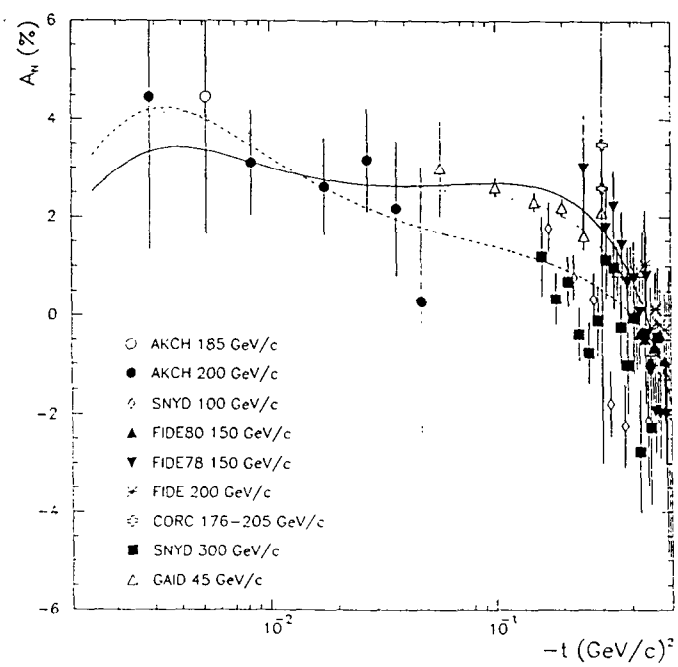
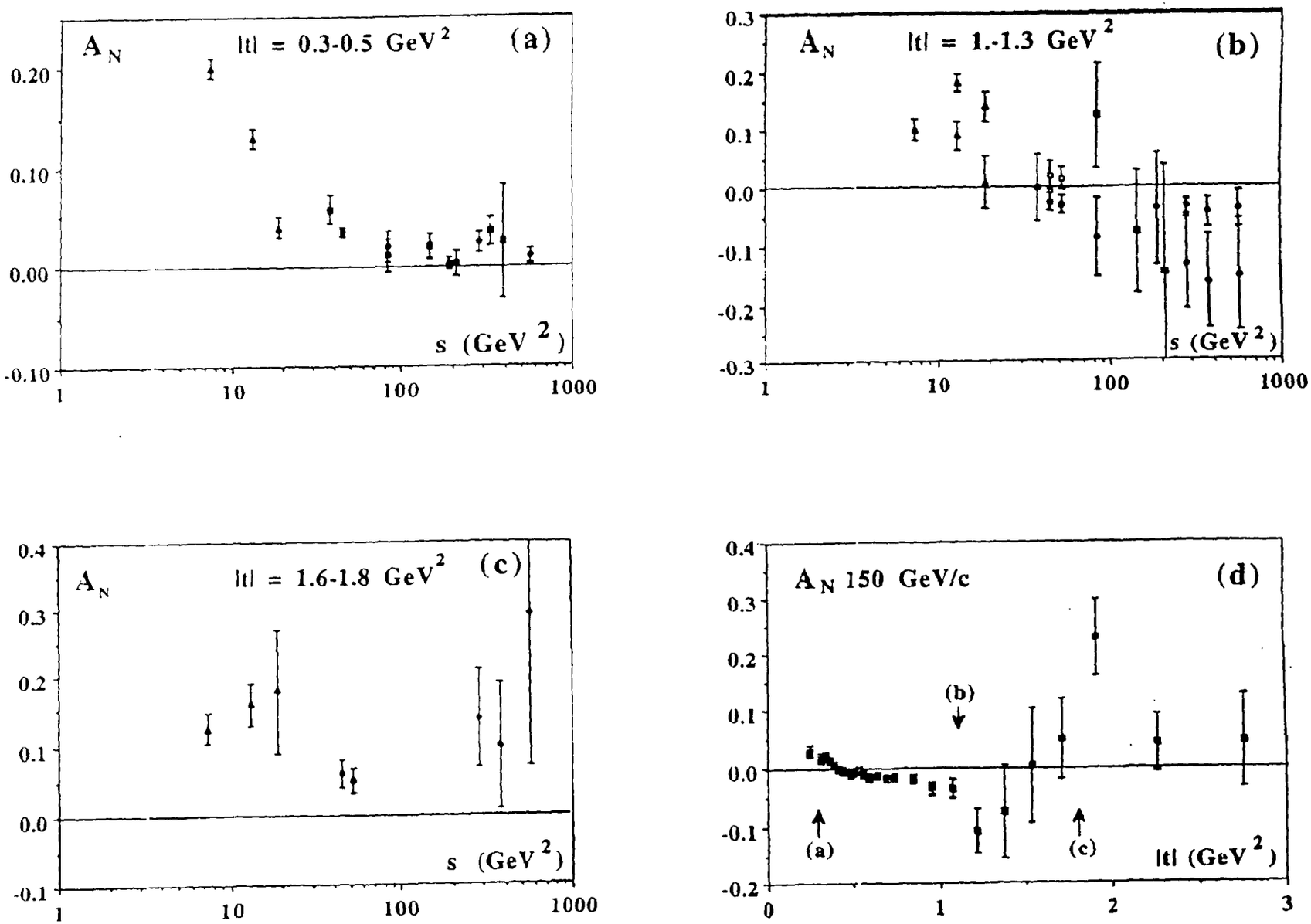


FIG. 1. The three curves represent the fits to the pp asymmetry data in the $1.5\times10^{-3} \le |t| \le 0.6\ (\mathrm{GeV}/c)^2$ range we have considered (see Table I). The solid line corresponds to 1, dashed to 2, and dotted to 3.


A N
|t| = 0.3-0.5 GeV 2
(a)
s (GeV 2)
A N
|t| = 1.-1.3 GeV 2
(b)
s (GeV 2)
A N
|t| = 1.6-1.8 GeV 2
(c)
s (GeV 2)
A N 150 GeV/c
(d)
(a)
(b)
(c)
|t| (GeV 2)

N.B., B.K, E. Leader, J.S. L. Trueman

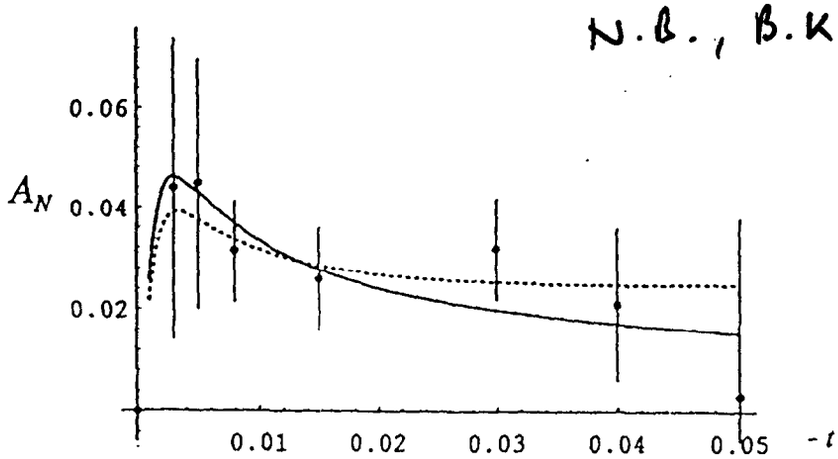


FIG. 1. The data points are from Fermilab E704 [48]. The solid curve is the best fit with the hadronic amplitude ϕ_5 constrained to be in phase with hadronic ϕ_+; the dotted curve is the best fit without this constraint.

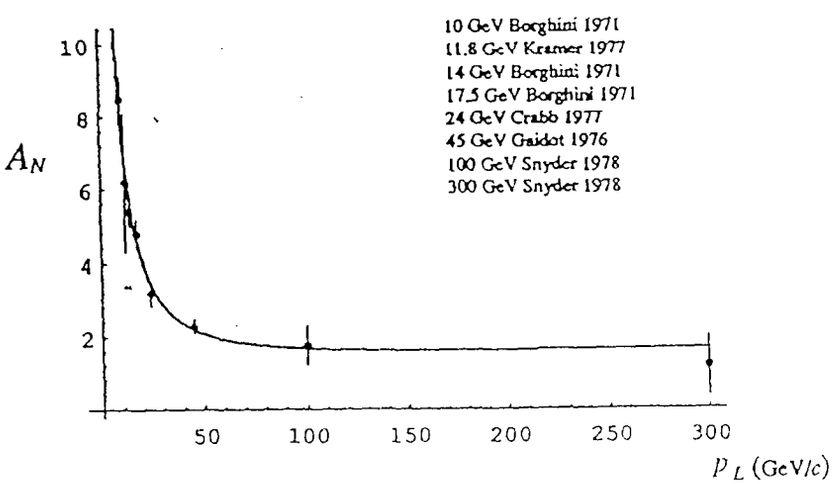


FIG. 2. $A_N = P$ in percent as a function of lab momentum p_L at $t = -0.15\ \mathrm{GeV}^2$.

a collection of data from various experiments which measure $P = A_N$ at different energies, all for $t = -0.15\ \mathrm{GeV}^2$ (or interpolated from nearby values), the smallest $|t|$ for which there is sufficient data to do this [56]. We have tried a fit suggested by Regge poles, namely, $P = a + b/\sqrt{p_L} + c/p_L$ [7]. This is shown in Fig. 2 and the relevant result is that $a = 0.023 \pm 0.012$.

Table 7 : Recoil polarimeter rate and precision estimates					
$\Delta A_N/A_N$ (*)	$\Delta A_C/A_C$ (*)	$\Delta\varepsilon_C/\varepsilon_C$	N_C	N_P	T_C(min)
0.04	0.03	0.0265	$14.2\ 10^6$	$142\ 10^6$	21
0.04	0.02	0.0346	$8.4\ 10^6$	$84\ 10^6$	13
0.08	0.03	0.0742	$1.8\ 10^6$	$18\ 10^6$	3
0.08	0.05	0.0624	$2.6\ 10^6$	$26\ 10^6$	4
0.1	0.03	0.0953	$1.1\ 10^6$	$11\ 10^6$	≈ 2
0.1	0.05	0.087	$1.3\ 10^6$	$13\ 10^6$	≈ 2

(*) Target value for $\Delta A_N/A_N$ and assumed value for $\Delta A_C/A_C$.

The rates are comfortable even taking into account the low probability for a second scattering on carbon; hardware processors to implement the second scattering process selection criteria on-line have been developed by PP2PP members [19].

5.3 Medium - |t| region

Kinematical parameters for medium-|t| [0.8< |t|< 1.4 $(GeV/c)^2$] are listed in Table 8.

Table 8 : Kinematical parameters for the large- |t| region				
|t| $(GeV/c)^2$	T_R (MeV)	p_R (GeV/c)	Θ_R (degrees)	ToF (1.5 m) (nsec)
1.	500	1.12	31	4.5
1.2	600	1.25	33	" "
1.4	700	1.37	34.5	" "

The rate is estimated : $dN/dT = L \times \langle\sigma\rangle \times \alpha = 3\ 10^{32} \times 0.3\ 10^{-30} \times 0.2 = 17$ /sec and attainable accuracies are listed in Table 9. Here the rate limitation does not come not from DAQ, but from the pp yield itself.

Table 9 : Estimates of rates and precision for the large- |t| region				
$\Delta P_B/P_B$ (*)	$\Delta A_N/A_N$ (*)	$\Delta\varepsilon/\varepsilon$	N	T(min)
0.05	0.03	0.04	$2\ 10^5$	200
0.05	0.04	0.03	$3.5\ 10^5$	340
0.1	0.04	0.1	$3.2\ 10^4$	30
0.1	0.08	0.06	$8.9\ 10^4$	90
0.15	0.04	0.14	$1.6\ 10^4$	15
0.15	0.1	0.11	$2.6\ 10^4$	25

(*) Target value for $\Delta P_B/P_B$ and assumed value for $\Delta A_N/A_N$.

In this case a polarized jet of 10^{12} atoms/cm^2 would give about 0.1 event/sec, thus taking about 300 hours for a 5% calibration at full beam intensity.

5.2 Small - |t| region

Kinematical parameters for small-|t| [$0.1 < |t| < 0.4$ (GeV/c)^2] are listed in Table 5.

Table 5 : Kinematical parameters for the small-|t| region				
|t| (GeV/c)^2	T_R (MeV)	p_R (MeV/c)	Θ_R (degrees)	ToF (1.5 m) (nsec)
0.1	50	320	9.5	15.5
0.3	150	570	16	9
0.5	250	750	21	7

Θ_R is measured from the axis perpendicular to the beam line through the jet. A dE/dx scintillation counter precedes the setup consisting of the polarimeter MWPCs and hodoscope counters for time-of-flight. The expected resolutions are:

$\Delta T_R = \pm 0.08\ T_R$ (MeV) [from dE/dx]
$\Delta\Theta_R = \pm 2$ mrad [= (σ_{MWPC} / l) ≈ 1mm/ 500 mm]
ΔToF = ± 0.5 nsec

Rates are given by $dN/dT = L \times \langle\sigma\rangle \times \alpha = 3\ 10^{32} \times 2\ 10^{-27} \times 0.2 = 1.1\ 10^5$ /sec.

Table 6: A_N precision and rates for small-|t| region				
$\Delta P_B/P_B$ (*)	$\Delta A_N/A_N$ (*)	$\Delta\varepsilon/\varepsilon$	N	T(sec)
0.05	0.04	0.03	$5.6\ 10^6$	50 (275)
0.1	0.08	0.06	$1.4\ 10^6$	13 (65)
0.15	0.1	0.11	$4.2\ 10^5$	4 (21)

(*) Target value for $\Delta P_B/P_B$ and assumed value for $\Delta A_N/A_N$.

The time required taking into account a DAQ limit of $2\ 10^4$ ev/sec is shown in parenthesis.

In this case a polarized jet of 10^{12} atoms/cm^2 would give about 730 events/sec, thus taking about 2.1 hours for a 5% calibration at full beam intensity.

5. 2.1 Recoil analysis (SKIP)

The recoil protons have (transverse) polarization $P_R = A_N$ and

$$(A_N =)\ P_R = (1/A_C)\ [(L_C - R_C)/(L_C + R_C)] = \varepsilon_C / A_C \qquad (5)$$

in the scattering of recoil protons on a carbon analyzer block, with error:

$$(\Delta A_N/A_N)^2 = (\Delta P_R/P_R)^2 = (\Delta A_C/A_C)^2 + (\Delta\varepsilon_C/\varepsilon_C)^2 \qquad (6)$$

with $(\Delta\varepsilon_C/\varepsilon_C)^2 = (1 - \varepsilon_C^2)/(\varepsilon_C^2 N_C) \approx 1/[(A_C P_R)^2 N_C]$, if $\varepsilon_C \ll 1$.

The efficiency of rescattering in the polarimeter is taken as $\langle\eta_C\rangle \approx 0.1$ and $\langle A_C\rangle = 0.5 \pm 0.01$. The statistical accuracy for this kind of calibration is shown in Table 7.

5.1 CNI region (with jet)

The kinematical parameters for the CNI region [$10^{-3} < |t| < 5\ 10^{-2}$ $(GeV/c)^2$] are listed in Table 3.

Table 3: Kinematical parameters for pp elastic CNI			
$\|t\|$ $(GeV/c)^2$	T_R (MeV)	Θ_R (mrad)	ToF (0.5 m) (nsec)
0.001	0.53	17.4	50
0.005	2.66	34.8	25
0.01	5.33	52.3	15
0.05	26.6	113.4	7

between ~~within~~ bunch

Θ_R is measured from the axis perpendicular to the beam line through the jet. The range of protons in Si is 30 μm at 1 MeV and 250 μm at 5 MeV. The estimated resolutions with Si [redacted] detectors are respectively:

$\Delta T_R = \pm [0.04 + 0.004\ T_R^2]^{1/2}$ (MeV)
$\Delta\Theta_R = \pm 6$ mrad [$= (\sigma_{jet} / l) = 3$ mm / 500 mm]
$\Delta ToF = \pm 0.8$ nsec

(MCJ)
jet 10^{14} cm^{-2}.

The rate is estimated: $dN/dT = L \times \langle\sigma\rangle \times \alpha = 3\ 10^{32} \times 3\ 10^{-27} \times 0.1 = 8\ 10^4$ /sec and attainable precisions are listed in Table 4.

Table 4: Estimates of precision and rates in the CNI region				
$\Delta P_B/P_B$ (*)	$\Delta A_N/A_N$ (*)	$\Delta\varepsilon/\varepsilon$	$N_{ev.}$	T(sec)
0.05	0.04	0.03	$2.5\ 10^6$	31 (125)
0.1	0.08	0.06	$6.3\ 10^5$	8 (32)
0.15	0.1	0.11	$1.9\ 10^5$	2.5 (10)

(*) Target value for $\Delta P_B/P_B$ and assumed value for $\Delta A_N/A_N$.

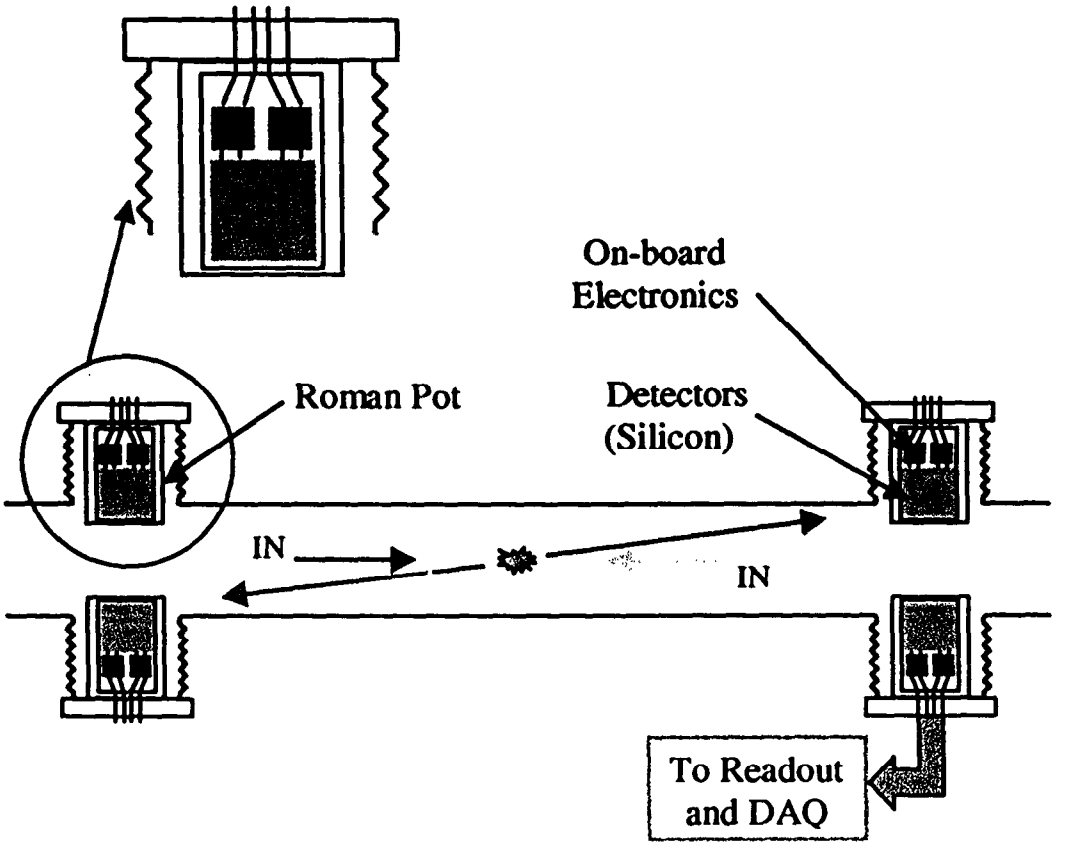
Taking into account a DAQ limit of $2\ 10^4$ events/sec the time for a measurement at the specified level of precision is shown in parenthesis. Rates are sufficiently high to meet the following conditions:

- less luminosity by a factor 10-100 (either lower beam intensity or jet density) still compatible with measurement times of few (2-5) minutes;
- smaller beam polarization $P_B = 0.4 - 0.2$;
- bunch-to-bunch polarization monitoring.

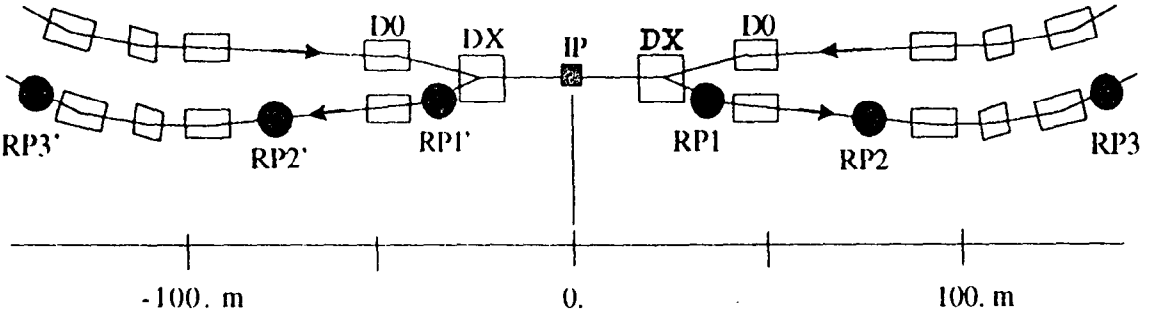
A polarized jet of 10^{12} atoms/cm^2 would give about 600 events/sec, thus taking about 1.5 hours for a 5% calibration at full beam intensity.

Experimental Method at Hadron Colliders

Roman pot location is determined by parallel to point focusing.



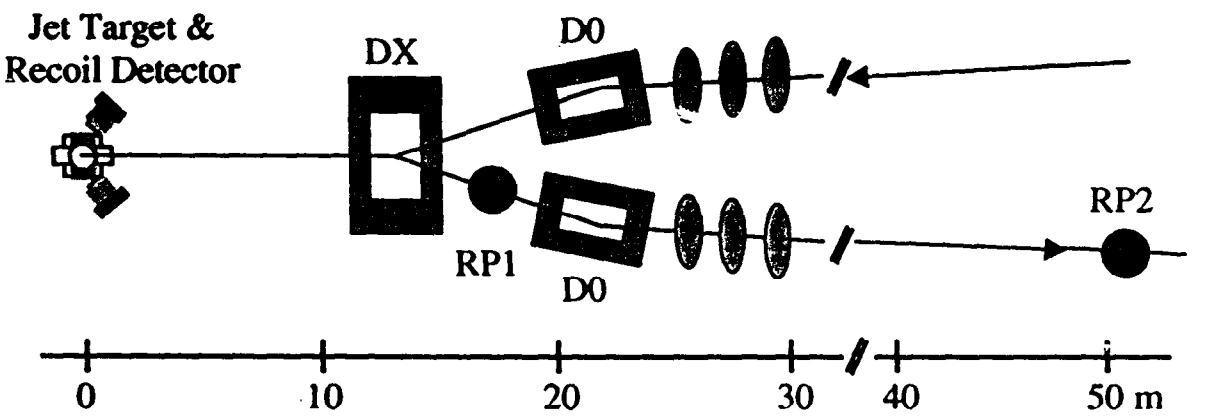
RHIC Intersection Region with PP2PP Basic CB Setup



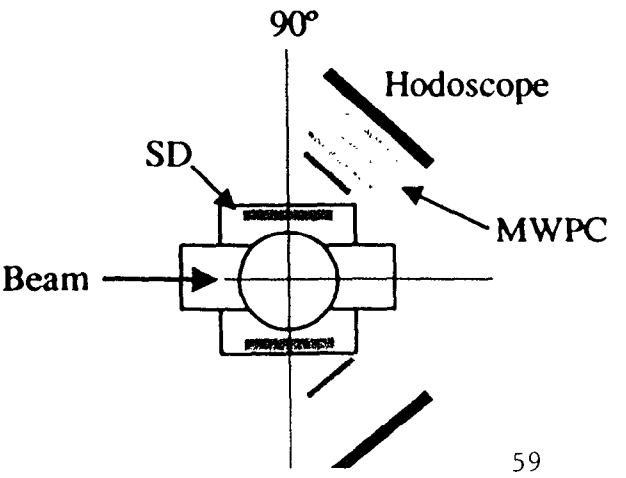
Day one PP2PP Setup with Jet Target and Recoil Detectors

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



Jet Target and Recoil Detector



Wlodek Guryn
RIKEN Polarimetry Workshop
08/18/99

Summary

1. Proton - proton elastic scattering is a very promising process that can be used for polarimetry at RHIC.

2. We plan to measure both scattered and recoil proton to reduce the background and improve $-t$ resolution. (GREAT PHYSICS.)

3. To be used as a polarimeter it will require a calibration run with a polarized ABS, which has been promised by NIKHEF. (Consequently two teams are involved: INFN and NIKHEF.)

4. In the CB and FT mode the range $-t > 0.006$ GeV/c^2 of CNI region can be reached with standard tune $\beta^* = 10$ m.

5. In mode with a polarized ABS of 10^{12}cm^{-2} intensity, in the CNI region short calibration runs, few hours per energy, are needed.

6. An existing, Italian molecular cluster jet has enough intensity, 10^{14}cm^{-2}, to allow quick, few minutes, beam polarization measurements.

7. Need to do careful simulation to verify the calculations and optimize setup.

8. Our progress is limited by (lack of) resources.

Single Spin Asymmetries at RHIC from Factorized Cross Sections

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Single spin asymmetries in single-particle inclusive cross sections have been observed at moderately large transverse momenta [1]. Nevertheless, they must vanish as $1/p_T$ at high enough transverse momentum, because in factorized form they require at one or more twist-3 distribution. The relevant factorization theorem in this case is [2,3]

$$\Delta\sigma_{A+B\to\pi}(\vec{s}_T) = \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}_{a+b\to c}(\vec{s}_T) \otimes D_{c\to\pi}(z)$$
$$+ \sum_{abc} \delta q_{a/A}(x, \vec{s}_T) \otimes \left\{ \phi_{b/B}(x') \otimes \hat{\sigma}'_{a+b\to c}(\vec{s}_T) \otimes D^{(3)}_{c\to\pi}(z, z') + \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}''_{a+b\to c}(\vec{s}_T) \otimes D_{c\to\pi}(z) \right\}.$$

$\phi^{(3)}_{a/A}(x'_1, x'_2, s_T)$ represents the possible twist-3 spin-dependent parton distributions, while $\delta q_{a/A}$ is the spin-dependent, chiral-odd, twist-2 transversity distribution [4], which must be paired in this case with a twist-3 chiral-odd fragmentation function $D^{(3)}$ or spin-independent parton distribution $\phi^{(3)}$, as shown.

For a number of reasons, we have suggested [3] that the dominant contribution to the asymmetry at large transverse momentum is associated with the matrix element

$$T^{(V)}_{F_a}(x_1, x_2, s_T) = \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_1 P^+ y_1^- + i(x_2 - x_1)P^+ y_2^-} \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma_+ \left[\epsilon^{s_T \sigma n \bar{n}} F_{\sigma+}(y_2^-)\right] \psi_a(y_1^-) | P, \vec{s}_T \rangle ,$$

which couples gluon and quark degrees of freedom in the nucleon. The computed spin asymmetry for pion production [5] is proportional to a derivative of $T^{(V)}_F$, which enhances the cross section in the large-x_F region, where substantial effects are seen at moderate p_T [1]. The form of the leading-order calculation suggests that the twist-3 cross section will remain observable at RHIC energies, and predicts explicit dependences on kinematic variables that can be tested, perhaps with the Brahms detector. Our analysis is complementary to that based on factorizations in transverse as well as longitudinal degrees of freedom [6].

References

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[4] J. Ralston and D.E. Soper, Nucl. Phys. B152, 109 (1979); R.L. Jaffe and X. Ji, Phys. Rev. Lett. 67, 552 (1991); Phys. Lett. B284, 137 (1992).

[5] J.W. Qiu and G. Sterman, Phys. Rev. D59, 014004 (1998).

[6] M. Anselmino, M. Boglione and F. Murgia, hep-ph/9905490; M. Anselmino, this workshop.

SINGLE-SPIN ASYMMETRIES FROM FACTORIZED CROSS SECTIONS

George Sterman
Jianwei Qiu

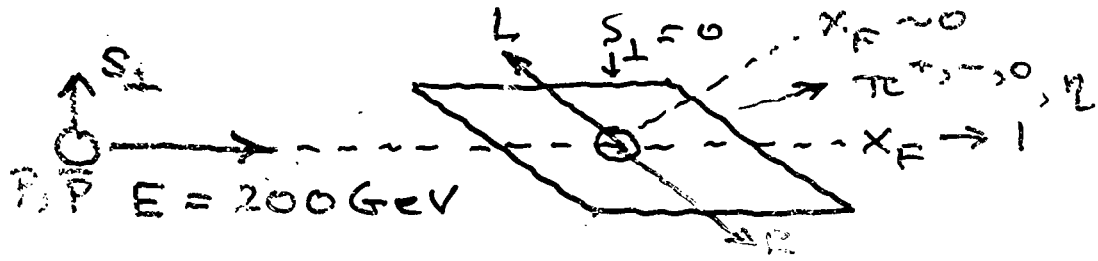
Riken-BNL Workshop
on High Energy Polarimetry
August 18, 1999

1. INTRODUCTION

The Experiments

BNL '97 + (E581/704 and predecessors: BNL, ANL, CERN, Sherpukov)

$$A_N = \left(\frac{1}{\text{Pol.}}\right)\left(\frac{\text{left} - \text{right}}{\text{left} + \text{right}}\right)(x_F, P_T)$$



(1) $x_F \to 1$ $\quad 0.7 \lesssim P_T \lesssim 2$ GeV

(2) $x_F \sim 0$ $\quad x_t \lesssim 0.4$ $\quad (P_T \lesssim 4$ GeV$)$

Chou + Yang (73, 76): 'Hadronic Matter Currents'

A Theoretical Issue: $A_N = 0$ in inclusive cross section at leading power in PQCD.

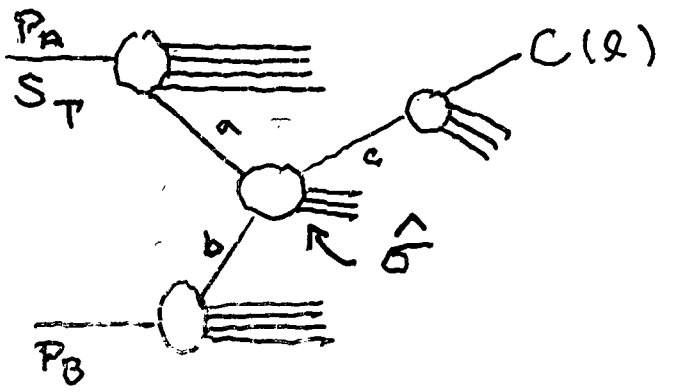
Theoretical Question: Can A_N be understood as a non-leading power in PQCD?

Another Question: If so do we learn anything?

General result: for 1PI cross sections

$$A_N \xrightarrow[p_T \to \infty]{} 0 \quad \text{at least as } 1/p_T$$

Follows from factorization at leading power:



$$\sum_{abc} f_{a/A}(x_a, S_T) \otimes f_{b/B}(x_b) \otimes \hat{\sigma}_{abc} \otimes D_{c/c}(z)$$

- Only leading-power S_T-dependent PDF is transversity (helicity flip)
- Helicity conservation in $\hat{\sigma}$ → interferen transversity matched with power suppressed (higher twist) helicity-flip $f_{b/B}$ or $D_{c/c}$.
- PT-invariance
  $\vec{p}, \vec{S} \xrightarrow[\text{parity}]{} -\vec{p}, \vec{S} \xrightarrow[\text{t-rev.}]{} \vec{p}, -\vec{S}$ (in c.m.)
  implies more than minimal number of partons (ISI or FSI)

Neglecting helicity violation in $\hat{\sigma}$ ($\mathcal{O}(m_q/p_T)$) can generalize factorization to $\mathcal{O}(1/Q)$:

$$\Delta\sigma_{A+B\to C}(S_T)$$

$$= \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, S_T) \otimes f^{(2)}_{b/B}(x') \otimes \hat{\sigma}_{abc} \otimes D^{(2)}_{C/c}(z)$$

$$+ \sum_{abc} \delta q^{(2)}(x, S_T) \otimes \left\{ f^{(2)}_{b/B}(x') \otimes \hat{\sigma}'_{abc} \otimes D^{(3)}_{C/c}(z, z') + f^{(3)}_{b/B}(x_1', x_2') \otimes \hat{\sigma}''_{abc} \otimes D^{(2)}(z) \right\}$$

chiral odd

chiral odd

T, P-invariance → at least one function has <u>two</u> x's

('initial-state' or 'final-state') interactions

Can generalize ⊗ to convolution in k_T

I.E.

J. Collins PR D43, 261 (91)

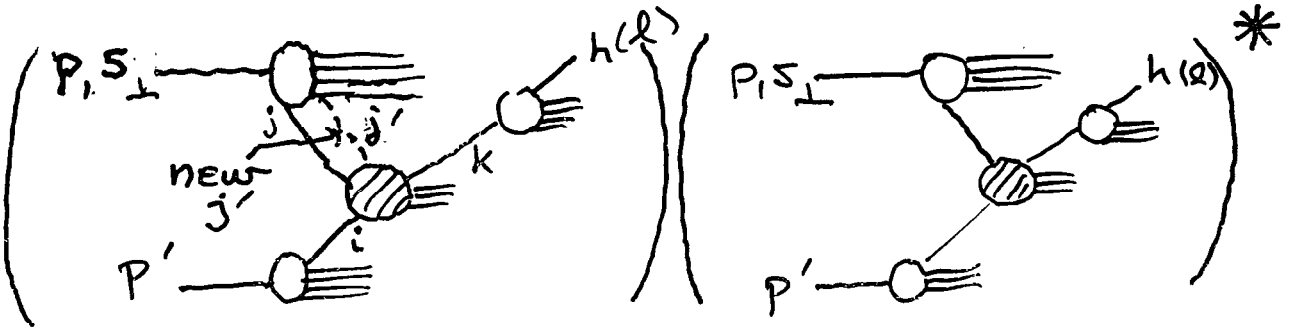
J. Collins NP B396, 161 (93)

M. Anselmino, M. Boglione, F. Murgia PL B342, 164 (95)

2. (Spin-Dependent) Factorization at $\mathcal{O}(1/Q)$ (what we need)

8

(1)



Interference $\rightarrow$ $\Delta\sigma(p, p', \ell, S_\perp)$

new j' costs $1/Q \sim 1/\ell_\perp$

(2)

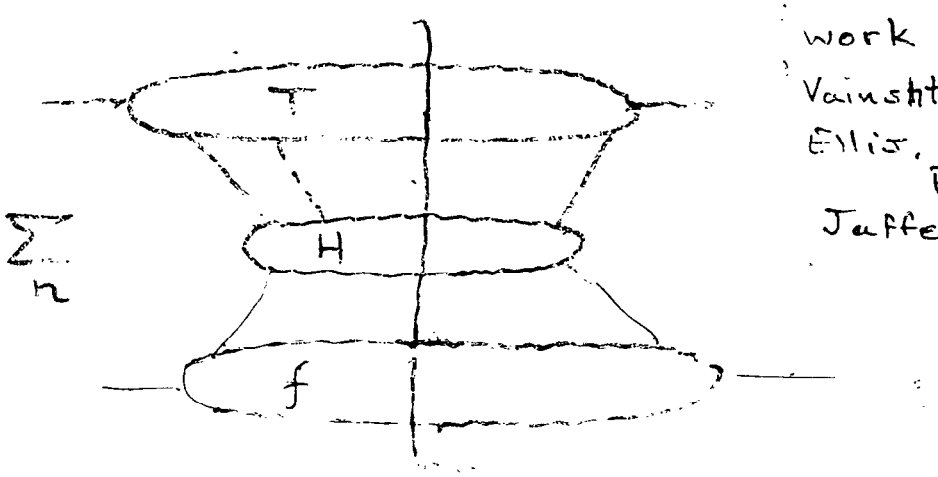
$$\omega \frac{d\Delta\sigma_\perp}{d^3p} = \sum_{i(jj')k} \int \frac{dx_i}{x_i} f_{i/p}(x_i) \int \frac{d\xi}{\xi} P_{i/k}$$

$$* \int dx_j\, dx_{j'}\, T_{(jj')/p}(x_j, x_{j'})$$

$$* H_{i(jj')k}(x_i, x_j, x_{j'}, x_L, \ell)$$

$j, j' = q, D = i(\partial + igA), F$

(3)



work in DIS:
Vainshtein, Shuryak
Ellis, Furmanski
Petronzio
Jaffe, Soldate

5

Spin-Dependent Quark-Gluon Matrix Elements

$$p^\mu \equiv P\bar{n}^\mu \qquad\qquad p'^\mu \equiv P' n^\mu$$

'projectile' $s_\perp$ $\qquad$ 'target' $\langle s \rangle$

$$T_\theta^{(i)}(x_1, x_2) = \int \frac{dy_1\, dy_2}{4\pi}\, e^{iy_2 P(x_2 - x_1) + iy_1 P x_1} * M_\theta^{(i)}(y_1, y_2)$$

$i = A, V \qquad \theta = D, F \qquad \begin{cases} D = i(\partial + igA) \\ F = \partial A - \partial A + g[AA] \end{cases}$

Four matrix elements

$$M_D^{(A)} = \langle p, s | \bar{q}(0) [\overset{i=A}{n\cdot\gamma\gamma_5}] [\overset{\theta=D}{D_\rho}(y_2)] q(y_1) | p s \rangle * s_\perp^\rho (p\cdot n)$$

$$M_D^{(V)} = \langle \ldots\ n\cdot\gamma\ D_\rho(y_2)\ \ldots \rangle * \epsilon^{\rho n \bar{n} s_\perp} (p\cdot n)$$

$$M_F^{(A)} = \langle \ldots\ n\cdot\gamma\gamma_5\ F_{\alpha\rho}(y_2)\ \ldots \rangle * n^\alpha s_\perp^\rho$$

$$M_F^{(V)} = \langle \ldots\ n\cdot\gamma\ F_{\alpha\rho}(y_2)\ \ldots \rangle * n^\alpha \epsilon^{\rho n \bar{n} s_\perp}$$

Comments on Matrix Elts:

$M_D^{(V,A)}$: Efremov, Teryaev (1985)

$M_F^{(V,A)}$: "new"

will claim: these naturally give "large" effects

Helicity-flip contributions present but kinematically suppressed (in 1PI!) where asymmetry is large. ($x_F \to 1$)

In Addition (X. Ji PL B 289, 137 (1992))

M.E.'s like

$$\langle p s | F \, D_\perp \, F | p s \rangle$$

$$\langle p s | F \, F \, F | p, s \rangle$$

as above for quarks but $\bar{\psi}\psi \to F^{+\mu} F_{\mu +}$

In following, give explicit calc's only for large 'x_F' – where expect valence quarks [illegible] to dominate [illegible] all.

Aside:

A chiral odd twist-3 distribution that contributes:

$$T_F^{(\sigma)}(x_1, x_2)$$

$$\equiv \int \frac{p^+ dy_1^-}{2\pi} \frac{dy_2^-}{2\pi} e^{i(x_2 - x_1)p^+ y_1^- + i x_1 p^+ y_2^-}$$

$$\cdot \langle p | \bar{\psi}(0) [\sigma^{-i}] F^{+i}(y_1^-) \psi(y_2^-) | p \rangle$$

unpolarized

(convoluted with $\delta q(x, \xi_T)$)

transversity

7a

What are we looking at in $T_F^{(V)}$? 11

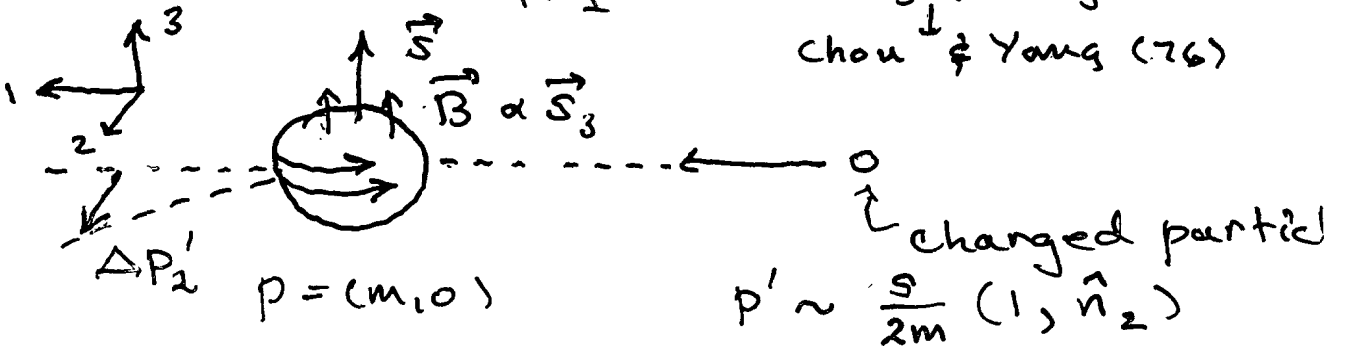
– Rotating Matter Currents?

Classical (Abelian) Analog

rest frame of $(p, s_\perp)$

Liang & Meng (90)

Chou & Yang (76)



$$\dot{p}_2' = e(\vec{v}' \times \vec{B})_2$$

$$= -e v_1 B_3$$

$$= e v_1 F_{21}$$

c.m. frame $(m, \underset{\sim}{0}) \to n$

$(1, \hat{\underset{\sim}{n}}_2) \to \bar{n}$

$$\dot{p}_2' = e n^\alpha F_{\alpha\rho} \epsilon^{\rho\nu\lambda\sigma} n_\nu \bar{n}_\lambda \delta_\sigma$$

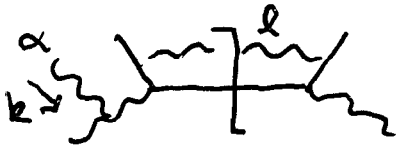
$$\Delta p_i = \int dy\, \dot{p}_i$$

But recall $T_F^{(V)}$ a quantum correlation

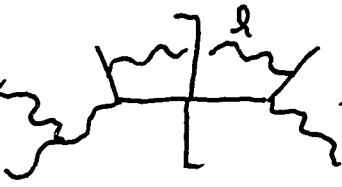
$\Rightarrow$ new information on parton/parton correlations

Calc. of an example:

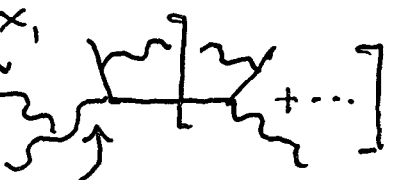
$H_F^{(v)}$ at lowest order

$\Delta\sigma_\perp^{(pert)} =$ 

$+ \cdots$

$= [-ik_\rho \bar{n}^\alpha]_\perp [n^\beta i \frac{\partial}{\partial k_\rho}$ 

$+ \cdots]$

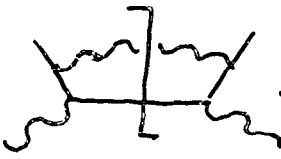
$= \langle \cdots F_\rho^\alpha \bar{n}_\alpha \cdots \rangle^{(0)}_{pert} [n^\beta i \frac{\partial}{\partial k_\rho}$ 

$+ \cdots]$

real

$i\pi\delta(x_1 - x_2) + \text{Real}$

only real contribution

$= [T_F^{(v)}]^{(0)}_{pert} [-n^\alpha \frac{\partial}{\partial k_\rho}$ 
$+ \cdots]$

$* \delta(x_1 - x_2)$

$= [T_F^{(v)}(x_1)]^{(0)}_{pert} \otimes H_F^{(v)} * \delta(x_1 - x_2)$

<u>OR</u>

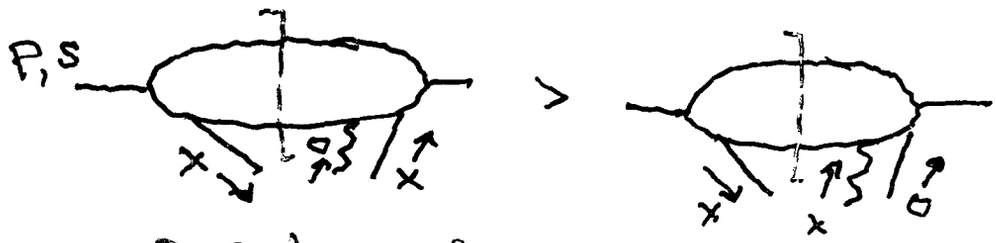
$\frac{d}{dx_1} \delta(x_1 - x_2)$

l.b.p. $\rightarrow -\frac{d T_F(x_1)}{dx_1}$

We believe $\frac{dT_F^{(V)}}{dx}$ term dominates

(1) Because we expect

$$T_F^{(V)}(x,x) > T_D^{(V,A)}(x,0)$$



overlap of states that differ by soft gluon emission > "soft quark emission"

(2) Because if

$$T_F^{(V)}(x,x) = A(1-x)^N$$

$$\frac{d}{dx} T_F^{(V)}(x,x) = AN(1-x)^{N-1} \gg T_F^{(V)}$$

So: in more complicated processes it may make sense to only look at $\frac{d}{dx}$ terms for large x_F, x_T

But: $\frac{d}{dx} \rightleftarrows \frac{d}{dk_T} \rightleftarrows \langle \bar{\psi} \overset{\text{soft}}{F} \psi \rangle$

or: $\langle FFF \rangle$

$(x_F \to 1)$

3. Results

SPIN ASYMMETRY:

$$
\begin{aligned}
E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} &= \frac{\alpha_s^2}{S} \sum_{a,c} \int_{z_{\min}}^1 \frac{dz}{z^2} D_{c\to\pi}(z) \\
&\times \int_{x_{\min}}^1 \frac{dx}{x} \frac{1}{xS + U/z} \int \frac{dx'}{x'} \delta\left(x' - \frac{-xT/z}{xS+U/z}\right) \\
&\times \sqrt{4\pi\alpha_s} \left(\frac{\epsilon^{\ell s_T n \bar{n}}}{z(-\hat{u})}\right) \\
&\times \left[-x\frac{\partial}{\partial x} T_{F_a}^{(V)}(x,x)\right] \left[\Delta\hat{\sigma}_{ag\to c}\, G(x') + \Delta\hat{\sigma}_{aq\to c} \sum_q q(x')\right]
\end{aligned}
$$

OUR FAVORITE MATRIX ELEMENT:

$$
T_{F_a}^{(V)}(x,x) = \int \frac{dy^-}{4\pi}\, e^{ixP^+y^-} \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma_+ \left[\int dy_2^-\, \epsilon^{s_T \sigma n \bar{n}}\, F_{\sigma+}(y_2^-)\right] \psi_a(y^-) | P, \vec{s}_T \rangle
$$

COMPARE TO:

$$
q_a(x) = \int \frac{dy^-}{4\pi}\, e^{ixP^+y^-} \langle P | \bar{\psi}_a(0)\gamma_+ \psi_a(y^-) | P \rangle
$$

MODEL:

$$
T_{F_a}^{(V)}(x,x) \equiv \kappa_a \lambda\, q_a(x)
$$

only for 'large' x !

$$
\kappa_u = +1 \quad \text{and} \quad \frac{\kappa_u}{\kappa_d} = -1 \quad \text{(proton)}
$$

viz A. Schafer et al PL B321, 121 (94)

11

qg SHORT DISTANCE FUNCTION:

~ BORN

note relative size

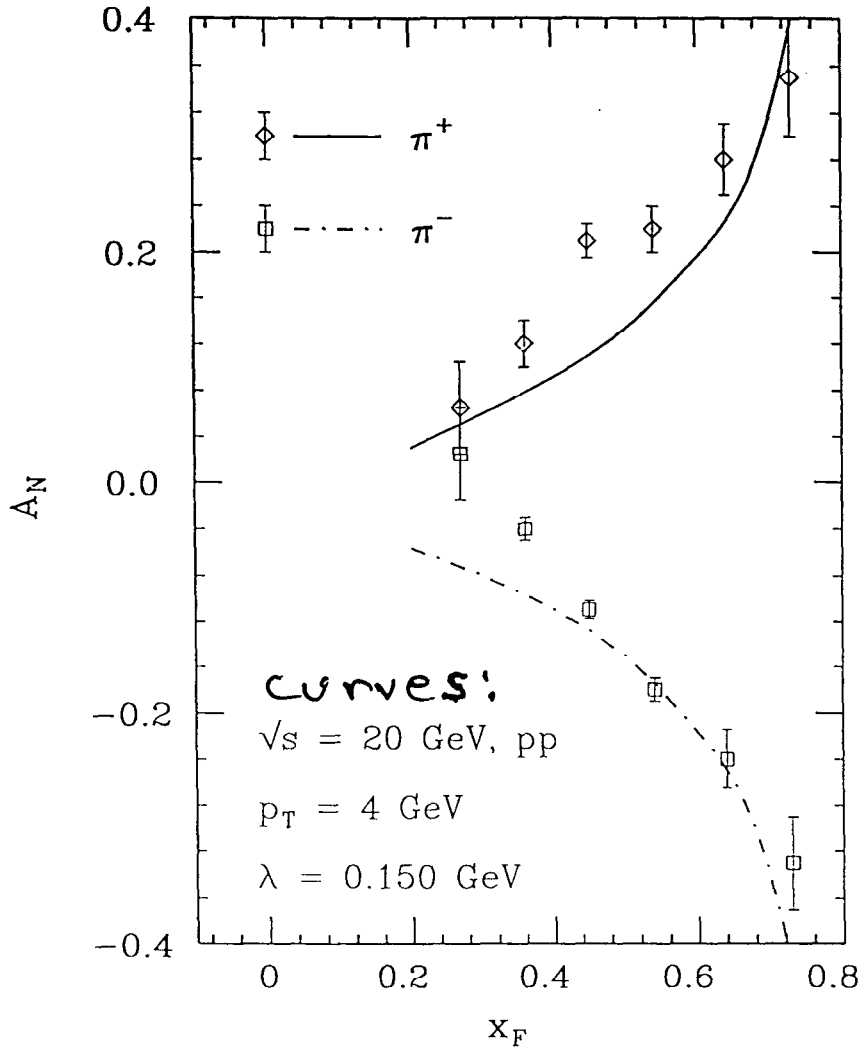
$$
\begin{aligned}
\Delta\hat{\sigma}_{ag\to c} \;=\; \delta_{ac}\Bigg\{ & 2\left(1-\frac{\hat{s}\hat{u}}{\hat{t}^2}\right)\left[\frac{9}{16}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
& +\frac{4}{9}\left(\frac{-\hat{u}}{\hat{s}}+\frac{\hat{s}}{-\hat{u}}\right)\left[\frac{63}{128}-\frac{1}{64}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
& +\left(\frac{\hat{s}}{\hat{t}}+\frac{\hat{u}}{\hat{t}}\right)\left[\frac{9}{16}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
& +\left[\frac{9}{32}\left(\frac{-\hat{u}}{\hat{s}}-\frac{\hat{s}}{-\hat{u}}\right)\right]+\left[\frac{9}{16}\left(\frac{\hat{s}}{\hat{t}}-\frac{\hat{u}}{\hat{t}}\right)\right]\Bigg\}
\end{aligned}
$$

singular for $\hat{t}\to 0$

$qq,\ q\bar{q}$ SHORT DISTANCE FUNCTIONS:

$$
\begin{aligned}
\Delta\hat{\sigma}_{ab\to c} \;=\; & \delta_{ac}\delta_{bq}\,\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)\left[\frac{21}{64}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
+\; & \delta_{ac}\delta_{b\bar{q}}\,\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)\left[-\frac{51}{64}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
+\; & \delta_{bc}\,\frac{4}{9}\left(\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)\left[\frac{21}{64}-\frac{51}{64}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
+\; & \delta_{ab}\delta_{bc}\,\frac{-8}{27}\left(\frac{\hat{s}^2}{\hat{u}\hat{t}}\right)\left[\frac{10}{8}+\frac{1}{8}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right] \\
+\; & \delta_{ab}\,\frac{4}{9}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)\left[\frac{1}{8}-\frac{51}{64}\left(1+\frac{\hat{u}}{\hat{t}}\right)\right]
\end{aligned}
$$

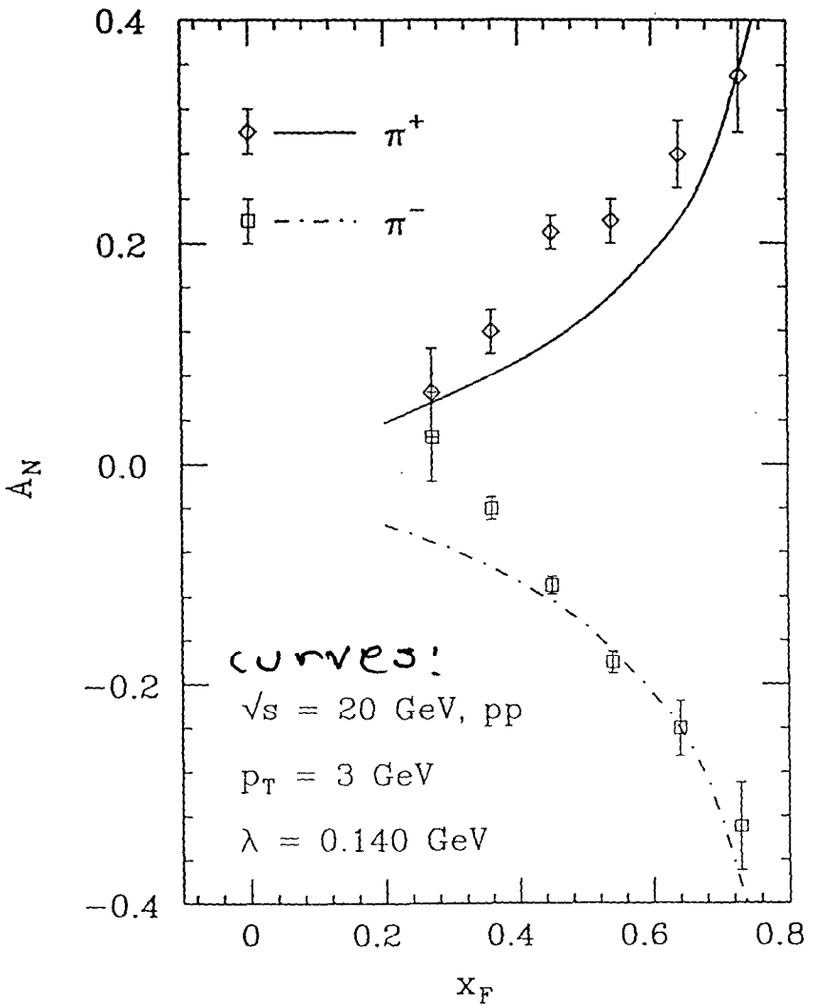
12



data at $\lesssim$ 1.5 GeV

$f_a^{(v)}(x,x') = k\, q_a(x)$

13



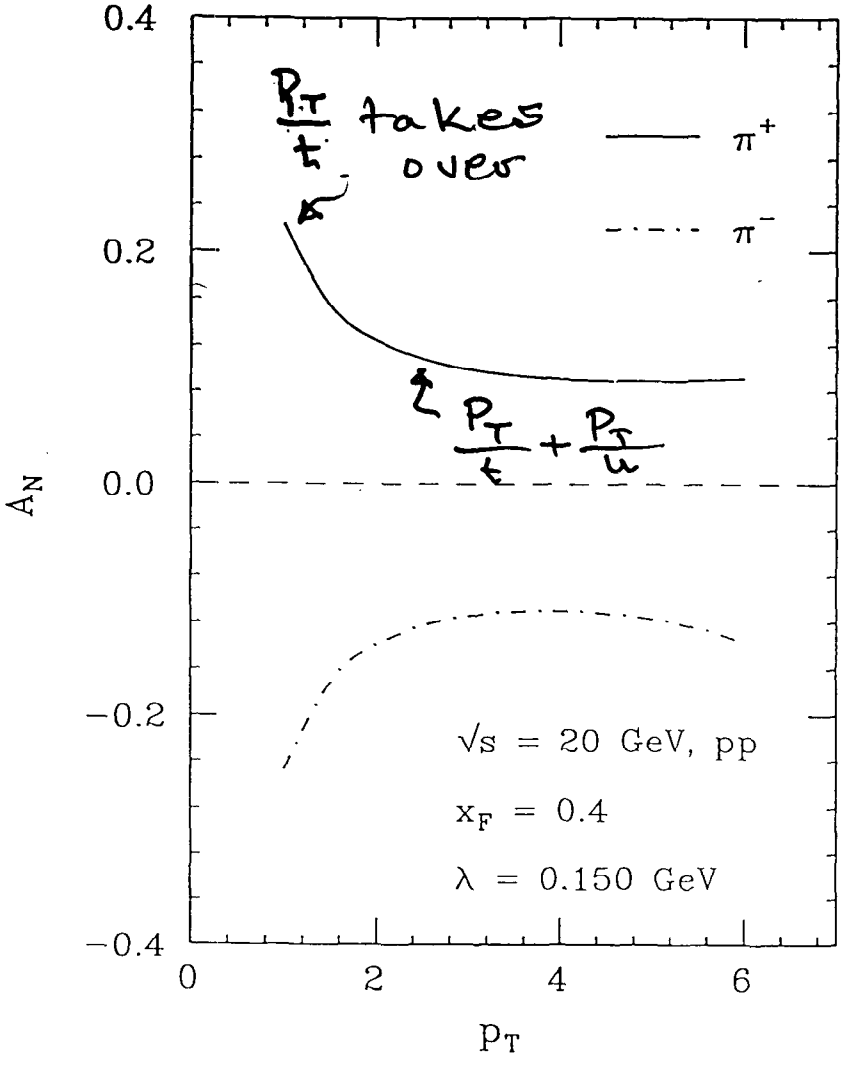
data at $\lesssim$ 1.5 GeV

14

FACT

$$\hat{\sigma} \sim \sigma_{BORN} \times \left(A \frac{p_T}{\sim \hat{u}} + B \frac{p_T}{-\hat{t}} \right) \qquad A \gg B \Rightarrow$$

$\Rightarrow A_N$ vs p_T remarkably flat! $2 < p_T < 6$



→ might not need such large p_T for 'L.C.' factorization to apply ('window' for twist-3 analysis)

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RHIC:

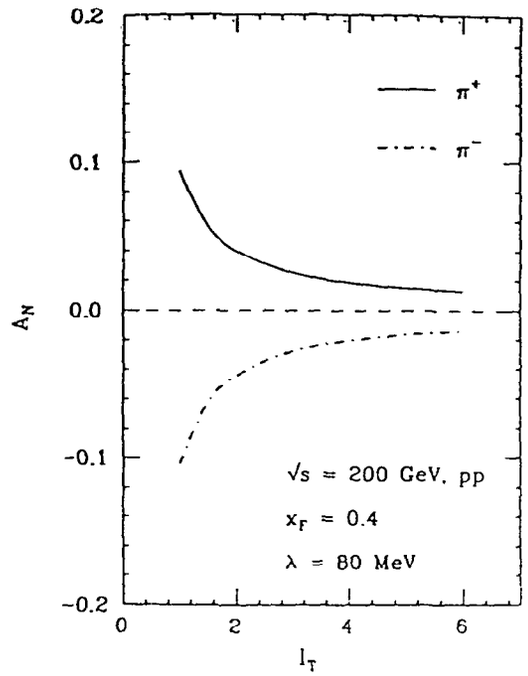

FIG. 28. Single transverse-spin asymmetry for π^+, π^- and π^0 production with a polarized proton beam, as a function of pion transverse momentum l_T. Theory curves are evaluated at $x_F = 0.4$, $\sqrt{S} = 200$ GeV and $\lambda = 0.80$ GeV.

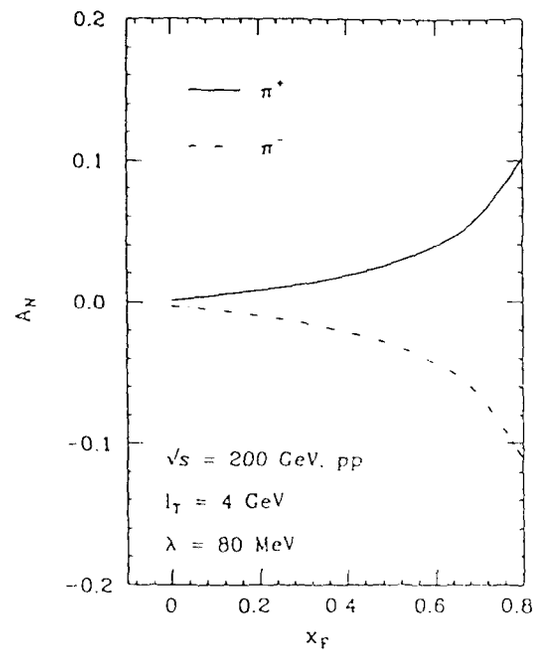

FIG. 29. Single transverse-spin asymmetry for π^+, π^- and π^0 production with a polarized proton beam, as a function of pion transverse momentum l_T. Theory curves are evaluated at $x_F = 0.4$, $\sqrt{S} = 200$ GeV and $\lambda = 0.080$ GeV.

5a

Conclusions:

- A_N appears in pQCD analysis at $\mathcal{O}(1/Q)$ for 1PI cross sections
- $T_F^{(V)}$ - model qualitatively adequate (information on qg correlations)
- Detailed kinematic predictions in $\hat{\sigma}$

  → RHIC ($\frac{p_T}{\hat{t}}$ terms scale $\frac{p_T}{\hat{u}}$ decrease)
- Eventually full treatment, including intrinsic k_T will be necessary

  Anselmino...
- Interesting to match to hadronic models at low l_T $p \to p + \pi_{virt.}$

  (C. Boros hep-ph/98...)

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Mauro Anselmino

Department of Theoretical Physics
University of Torino, Italy

A phenomenological approach, based on a straightforward generalization of the factorization theorem with the inclusion of parton intrinsic $\boldsymbol{k}_\perp$, is presented for the description of transverse single spin asymmetries in inclusive processes. New distribution and fragmentation functions, spin and $\boldsymbol{k}_\perp$ dependent, are used to fit existing data on $p^\uparrow p \to \pi X$ and to predict single spin asymmetries for other processes and other energies.

Phenomenology of transverse single-spin asymmetries in inclusive processes.

(M.A., M. Boglione, F. Murgia, J. Hansson)

- QCD formalism for $A^{\uparrow}B \to CX$; factorization theorem at leading twist ($\vec{k}_\perp = 0$) $\Rightarrow A_N = 0$
- Intrinsic $\vec{k}_\perp$ effects in fragmentation and/or distribution functions

$\Rightarrow A_N \neq 0$ possible phenomenology of SSA

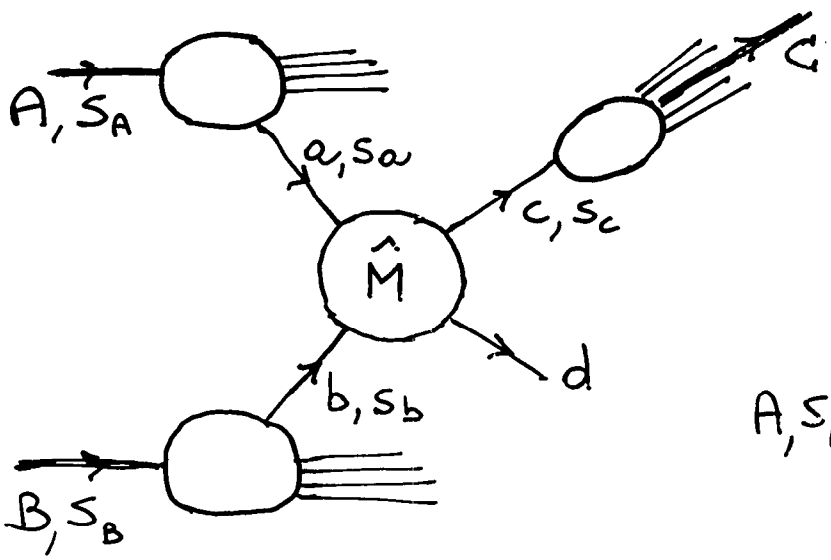
$$\hat{f}_{q|p\uparrow}(x, \vec{k}_\perp) - \hat{f}_{q|p\downarrow}(x, \vec{k}_\perp) \equiv \Delta^N f_{q|p\uparrow} \neq 0 \quad \text{(Sivers)}$$

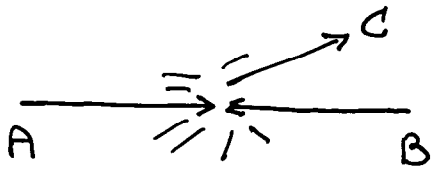
$$\hat{D}_{h/q\uparrow}(z, \vec{k}_\perp) - \hat{D}_{h/q\downarrow}(z, \vec{k}_\perp) \equiv \Delta^N D_{h/q\uparrow} \neq 0 \quad \text{(Collins)}$$

$$\left.\begin{aligned} \hat{f}_{q\uparrow/p}(x, \vec{k}_\perp) - \hat{f}_{q\downarrow/p}(x, \vec{k}_\perp) &\equiv \Delta^N f_{q\uparrow/p} \neq 0 \\ \hat{D}_{h\uparrow/q}(z, \vec{k}_\perp) - \hat{D}_{h\downarrow/q}(z, \vec{k}_\perp) &\equiv \Delta^N D_{h\uparrow/q} \neq 0 \end{aligned}\right\} \text{Boer, Mulders}$$

- Extract $\Delta^N f_{q|p\uparrow}$ and $\Delta^N D_{\pi/q\uparrow}$ from data on $pp^{\uparrow} \to \pi X$
- Use $\Delta^N D_{\pi/q\uparrow}$ for prediction in DIS

QCD factorization theorem holds with polarized particles as well [J.C. Collins NP B394 ('93) 169]





$$A, S_A + B, S_B \to C + X$$

$$\frac{E_C\, d\sigma}{d^3 p_C} = \sum_{a,b,c,d} \sum_{\substack{\lambda_a \lambda'_a;\ \lambda_b \lambda'_b;\\ \lambda_c \lambda'_c;\ \lambda_d, \lambda_C}} \int \frac{dx_a\, dx_b}{\pi z} \frac{1}{16\pi \hat{s}^2}$$

$$\rho^{a|A,S_A}_{\lambda_a \lambda'_a}\, f_{a|A}(x_a)\, \rho^{b|B,S_B}_{\lambda_b \lambda'_b}\, f_{b|B}(x_b) \qquad (1)$$

$$\hat{M}_{\lambda_c \lambda_d;\lambda_a \lambda_b}\, \hat{M}^*_{\lambda'_c \lambda_d;\lambda'_a \lambda'_b}\, D^{\lambda_c \lambda'_c}_{\lambda_C \lambda_C}(z)$$

[leading twist, collinear configurations]

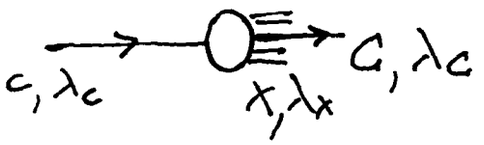
Case of a single spin $A^{\uparrow} B \to c X$

$[\ \rho_{\lambda_b \lambda'_b} = \frac{1}{2} \delta_{\lambda_b \lambda'_b}$, b is unpolarized $]$

$$\frac{E_c\, d\sigma}{d^3 p_c} = \sum_{a,b,c} \sum_{\substack{\lambda_a \lambda'_a ; \lambda_b \\ \lambda_c \lambda'_c ; \lambda_d, \lambda_c}} \frac{1}{2} \int \frac{dx_a\, dx_b}{\pi z} \frac{1}{16\pi \hat{s}^2}$$

$$\rho^{a|A^{\uparrow}}_{\lambda_a \lambda'_a}\, f_{a|A}\, f_{b|B}\, \hat{M}_{\lambda_c \lambda_d ; \lambda_a \lambda_b}\, \hat{M}^{*}_{\lambda'_c \lambda_d ; \lambda'_a \lambda_b}\, D^{\lambda_c \lambda'_c}_{\lambda_G \lambda_G}$$

- Collinear fragmentation implies



$\lambda_c = \lambda_X + \lambda_G$

$\Rightarrow \quad \lambda_c = \lambda'_c$ and (parity) $\quad \sum_{\lambda_G} D^{\lambda_c \lambda_c}_{\lambda_G \lambda_G} = D_{c/c}$

- if $\lambda_c = \lambda'_c$ helicity conservation in $ab \to cd$ implies also $\lambda_a = \lambda'_a$. Moreover, by parity,

$$\sum_{\lambda_b \lambda_c \lambda_d} |\hat{M}_{\lambda_c \lambda_d ; \lambda_a \lambda_b}|^2 = 2\,(16\pi \hat{s}^2)\, \frac{d\hat{\sigma}}{d\hat{t}}$$

and

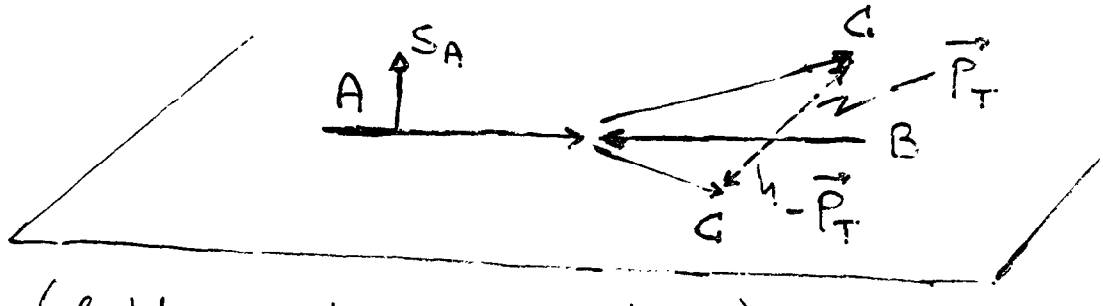
$$\sum_{\lambda_a} \rho_{\lambda_a \lambda_a} = 1$$

$$\Rightarrow \frac{E_c \, d\sigma^{A^\uparrow B \to CX}}{d^3 p_c} = \sum_{a,b,c} \int \frac{dx_a \, dx_b}{\pi z} f_{a|A}(x_a) \, f_{b|B}(x_b) \, \frac{d\hat{\sigma}}{d\hat{t}} \, D_{C|c}(z) = \frac{E_c \, d\sigma^{unp}}{d^3 p_c}$$

$\Longrightarrow$ the single spin asymmetry

$$A_N = \frac{d\sigma^{A^\uparrow B \to CX}(\vec{p}_T) - d\sigma^{A^\downarrow B \to CX}(\vec{p}_T)}{\text{"} \quad + \quad \text{"}} =$$

$$= \frac{d\sigma^{A^\uparrow B \to CX}(\vec{p}_T) - d\sigma^{A^\uparrow B \to CX}(-\vec{p}_T)}{\text{"} \quad + \quad \text{"}} = 0$$

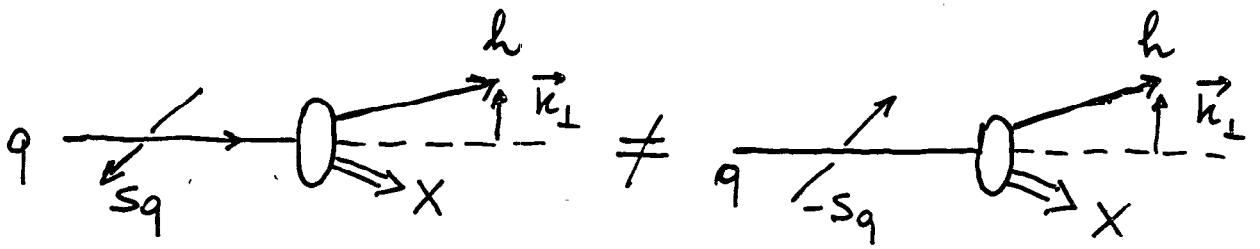


(left-right asymmetry)

$A_N = 0$ at leading twist, in pQCD factorization theorem

Allow for $\vec{k}_\perp \neq 0$ (higher twist contributions) $O(k_\perp / p_T)$

Possible spin-$\vec{k}_\perp$ effects (q-fragmentation)

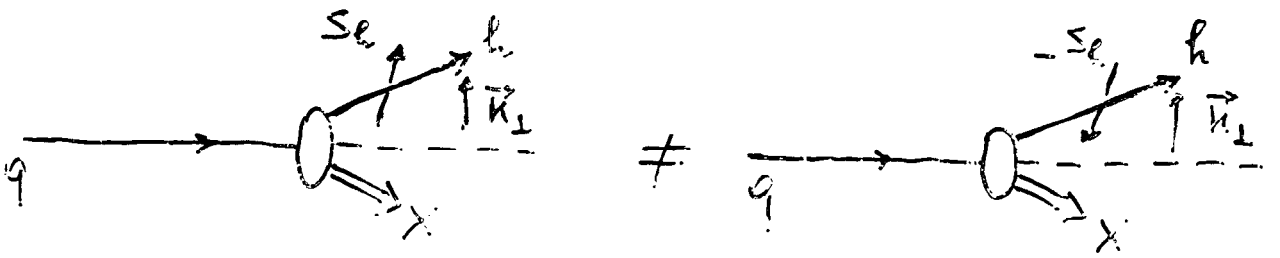


$\Delta^N D_{h/q\uparrow}$ or $H_1^\perp$ [Collins; Boer, Mulders]

Dependence of D on the relative azimuthal angle of $\vec{s}_q$ and $\vec{k}_\perp$

Time reversal: needs taking into account initial q interactions (which are present)

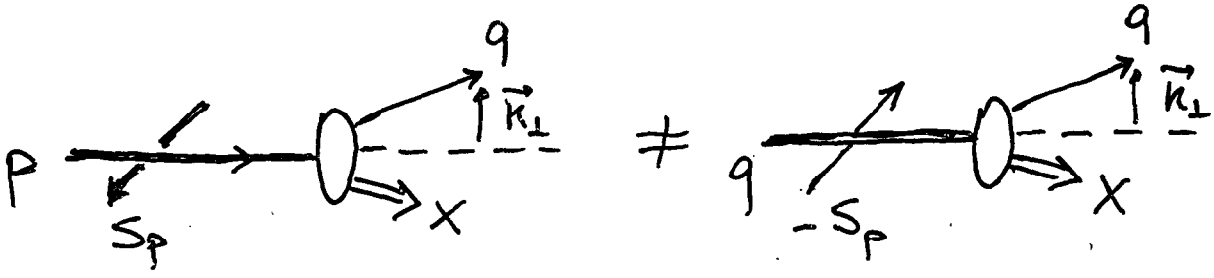
[$\vec{s}_q \cdot (\vec{q} \times \vec{k}_\perp)$ is time reversal odd.]



$\Delta^N D_{h\uparrow/p}$ or $D_{1T}^\perp$ [Boer, Mulders]

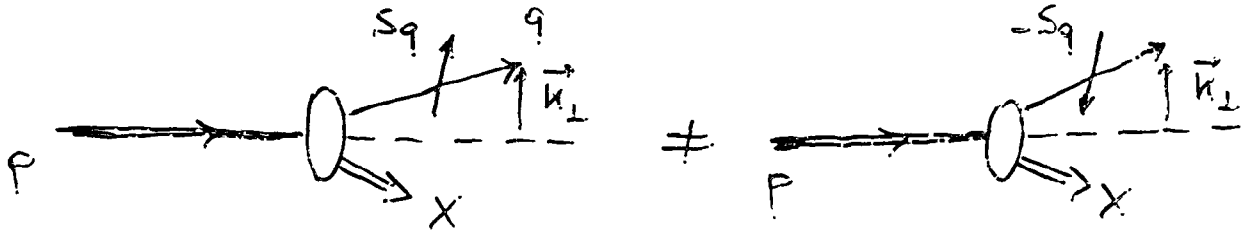
[Might be useful for understanding $pp \to \Lambda^\uparrow X$]

(q-distribution)



$\Delta^N f_{q/p^\uparrow}$ or $f_{1T}^\perp$ [Sivers; M.A., Boglione, Murgia; Boer, Mulders]

Needs initial state interactions
[Factorization? Universality?]



$\Delta^N f_{q^\uparrow/p}$ or $h_1^\perp$ [Boer, Mulders]

[might contribute to $pp \to \Lambda^\uparrow X$]

Assume one can generalize factorization theorem with intrinsic $\vec{k}_\perp$

$\Longrightarrow$

$$d\sigma^{\uparrow} - d\sigma^{\uparrow} = \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{\pi z} \times$$

$$\Big\{ \int d^2\vec{k}_\perp \underbrace{\Delta^N f_{a/p^\uparrow}(x_a, \vec{k}_\perp)}\, f_{b/p}(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(x_a, x_b; \vec{k}_\perp)\, D_{\pi/c}(z)$$

$$+ \int d^2\vec{k}'_\perp\, h_1^{a/p}(x_a)\, f_{b/p}(x_b)\, \Delta_{NN}\hat{\sigma}(x_a, x_b; \vec{k}'_\perp) \underbrace{\Delta^N_{\pi/c^\uparrow}(z, \vec{k}'_\perp)}$$

$$+ \int d^2\vec{k}''_\perp\, h_1^{a/p}(x_a) \underbrace{\Delta^N f_{b^\uparrow/p}(x_b, \vec{k}''_\perp)}\, \Delta'_{NN}\hat{\sigma}(x_a, x_b; \vec{k}''_\perp)\, D_{\pi/c^\uparrow}(z) \Big\}$$

$$h_1^{a/p} = f_{a^\uparrow/p^\uparrow} - f_{a^\downarrow/p^\uparrow}$$

$$\Delta_{NN}\hat{\sigma} \equiv \frac{d\hat{\sigma}^{a^\uparrow b \to c^\uparrow d}}{d\hat{t}} - \frac{d\hat{\sigma}^{a^\uparrow b \to c^\downarrow d}}{d\hat{t}}$$

$$\Delta'_{NN}\hat{\sigma} \equiv \frac{d\hat{\sigma}^{a^\uparrow b^\uparrow \to cd}}{d\hat{t}} - \frac{d\hat{\sigma}^{a^\uparrow b^\downarrow \to cd}}{d\hat{t}}$$

Sivers effect only –

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

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{\pi z} \int d^2\vec{k}_\perp$$

$$\Delta^N f_{a/p^{\uparrow}}(x_a, \vec{k}_\perp)\, f_{b/p}(x_b)\, \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\vec{k}_\perp)\, D_{\pi/c}(z)$$

$$\int d^2\vec{k}_\perp\, \Delta^N f_{a/p^{\uparrow}}(x_a, \vec{k}_\perp)\, \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\vec{k}_\perp) =$$

$$= \int_{k_{\perp x}>0} d^2\vec{k}_\perp\, \Delta^N f_{a/p^{\uparrow}}(x_a, \vec{k}_\perp) \underbrace{\left[\frac{d\hat{\sigma}}{d\hat{t}}(\vec{k}_\perp) - \frac{d\hat{\sigma}}{d\hat{t}}(-\vec{k}_\perp) \right]}_{O(k_\perp/p_T)}$$

$$= \underbrace{\frac{k_\perp^0}{M} N_a x_a^{\alpha_a} (1-x_a)^{\beta_a}}_{\text{parametrization of } \Delta^N f_{a/p^{\uparrow}}(x_a, \langle \vec{k}_\perp \rangle)} \left[\frac{d\hat{\sigma}}{d\hat{t}}(\vec{k}_\perp^0) - \frac{d\hat{\sigma}}{d\hat{t}}(-\vec{k}_\perp^0) \right]$$

$$\left(k_\perp^0 = \langle \vec{k}_\perp^2 \rangle^{\frac{1}{2}} \right)$$

$$\frac{k_\perp^0}{M} = 0.47\, x_a^{0.68} (1-x_a)^{0.48}$$

Fix α_a, β_a, N_a $(a = u, d)$ from best fit to data

$\Rightarrow$

$$\Delta^N f_{u/p^\uparrow} = 6.90\, x^{2.02} (1-x)^{4.06}$$

$$\Delta^N f_{d/p^\uparrow} = -2.34\, x^{1.44} (1-x)^{5.10}$$

<u>Comments</u>

- $\Delta^N f_{q/p^\uparrow}$ from best fit always $< 2 f_{q/p}$

- $\Delta^N f_{u/p^\uparrow}$ opposite in sign to $\Delta^N f_{d/p^\uparrow}$ is expected for SU(6) valence quarks if $\Delta^N f_{q/p^\uparrow} \sim \vec{P}_q \cdot (\vec{q} \times \vec{k}_\perp)$: $\vec{P}_{u_v} = -2\vec{P}_{d_v}$

- Why, at large x_F, $A_N^{\pi^+} \simeq -A_N^{\pi^-}$ but $A_N^{\pi^0} \neq \frac{1}{2}\left(A_N^{\pi^+} + A_N^{\pi^-}\right) \simeq 0$?

$P_{Lab.} = 200$ GeV/c $\quad 0.7 \leq P_T \leq 2$ GeV/c

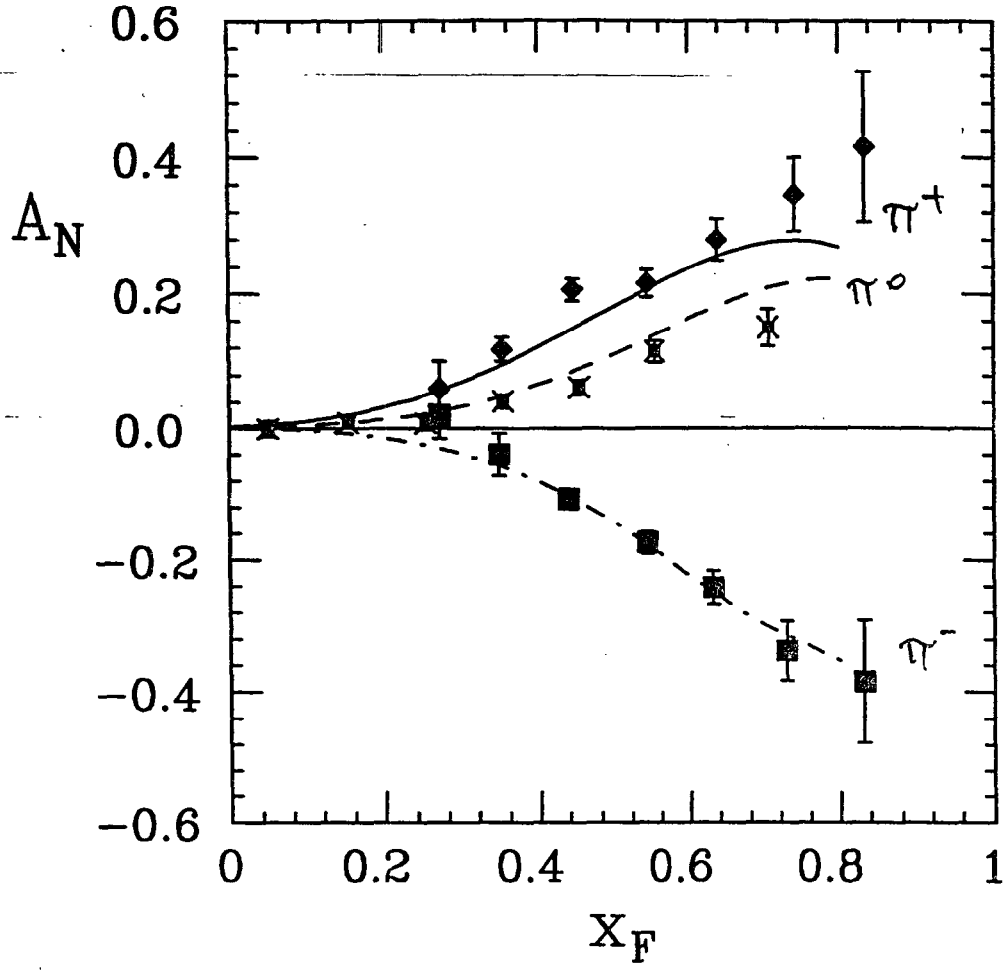


Fig. 1: Fit of the data on A_N for the process $p^\uparrow p \to \pi X$ [1], with the parameters given in Eq. (9); the upper, middle, and lower sets of data and curves refer respectively to π^+, π^0, and π^-.

$x_F = \frac{2 \cdot f_T}{\sqrt{s}}$ $\qquad f_T = 1.5$ GeV

only $\Delta^N f_{q/p^\uparrow} \neq 0$

E704 data

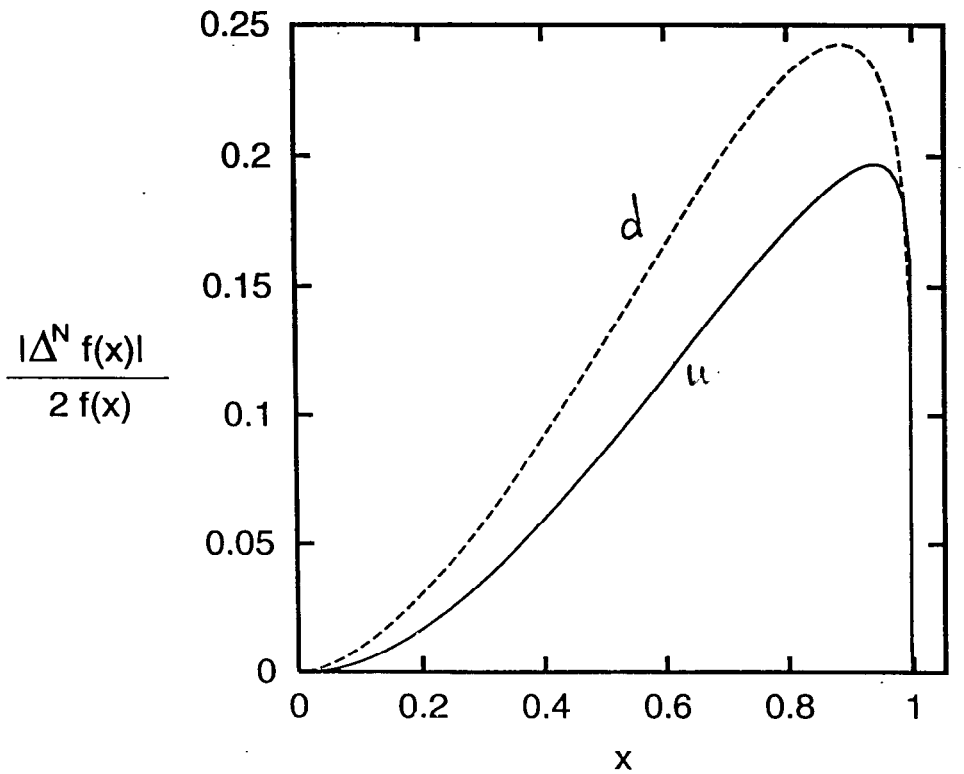


Figure 4: The ratio between $|\Delta^N f_{val}|$ and twice the valence unpolarized distribution function f, Eq. (29), as a function of x. The solid line refers to u quarks and the dashed line to d quarks. Notice that in both cases $|\Delta^N f|/2f \to 0$ for $x \to 1$.

$\frac{\Delta^N f}{2f}$ from best fit

We have, for any pion π^i $(i = 0, +, -)$

$$A_N^i = \frac{\eta^i}{\underset{\substack{\text{unpol.}\\ \text{x-section}}}{2\sigma^i}} = \frac{\sum f \, \Delta^N f_{a/p^\uparrow} \, f_b \, d\hat{\sigma} \, D_{\pi^i/c}}{2 \sum f \, f_a \, f_b \, d\hat{\sigma} \, D_{\pi^i/c}}$$

Isospin symmetry: $D_{\pi^0/c} = \frac{1}{2}\left(D_{\pi^+/c} + D_{\pi^-/c}\right)$

$\Rightarrow$

$$A_N^0 = \frac{\eta^+ + \eta^-}{2(\sigma^+ + \sigma^-)} = A_N^+ \, \frac{1 + \dfrac{A_N^- \sigma^-}{A_N^+ \sigma^+}}{1 + \dfrac{\sigma^-}{\sigma^+}}$$

$\Rightarrow$

$A_N^- \simeq -A_N^+$ (as data suggest) implies

$A_N^0 \simeq 0$ only if $\sigma^- \simeq \sigma^+$

But (at large x_F and x_a)

$$\frac{\sigma^-}{\sigma^+} \sim \frac{f_{d/p}}{f_{u/p}} \xrightarrow[x \to 1]{} 0 \Rightarrow A_N^0 \underset{x_F \to 1}{\sim} A_N^+$$

- Our $\Delta^N_{u/p^\uparrow}$ and $\Delta^N_{d/p^\uparrow}$ give good result for A_N in $\vec{p}^{\,\uparrow} p \to \pi X$ (no free parameters)

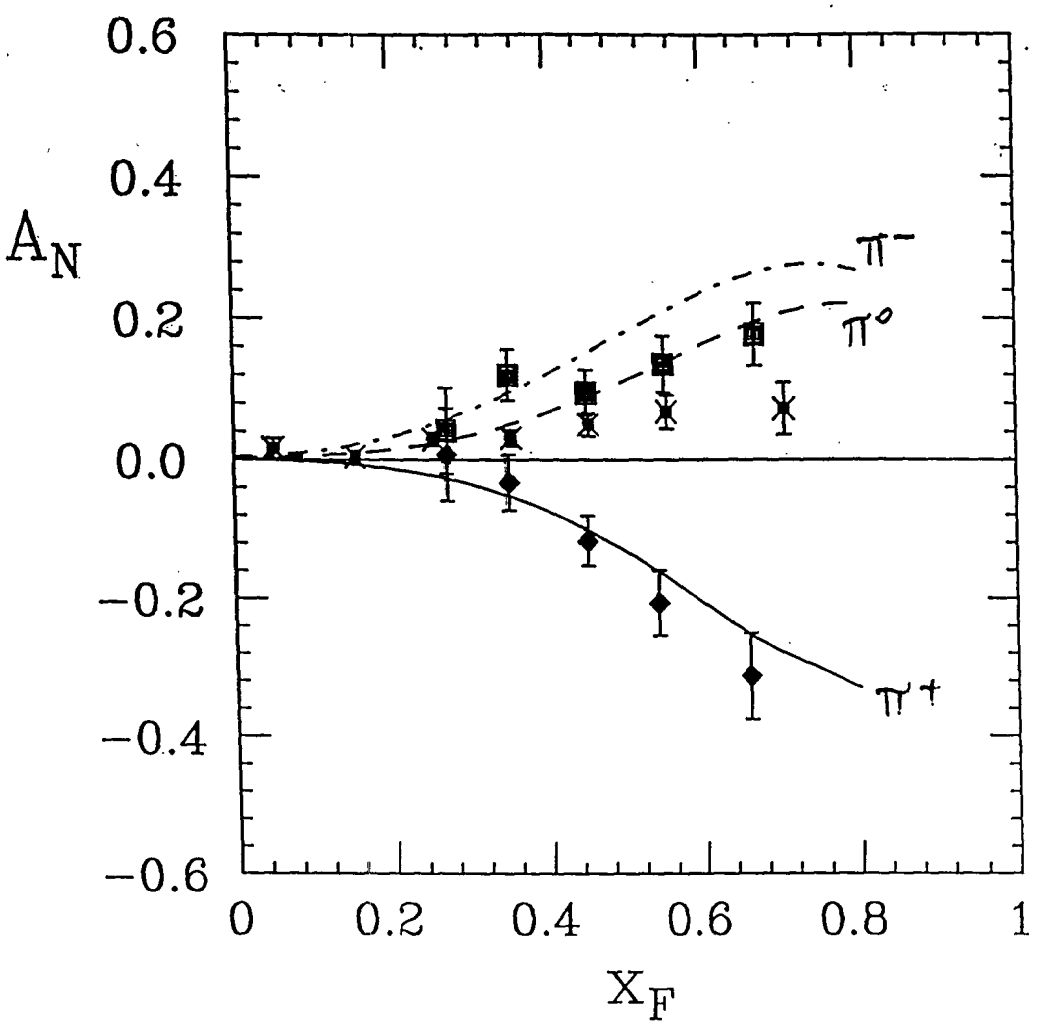


Fig. 2: Single spin asymmetries A_N for the process $\bar{p}^{\uparrow}p \to \pi X$ [2]; the lower, middle, and upper sets of data and curves refer respectively to π^+, π^0, and π^-.

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

Sivers effect only.

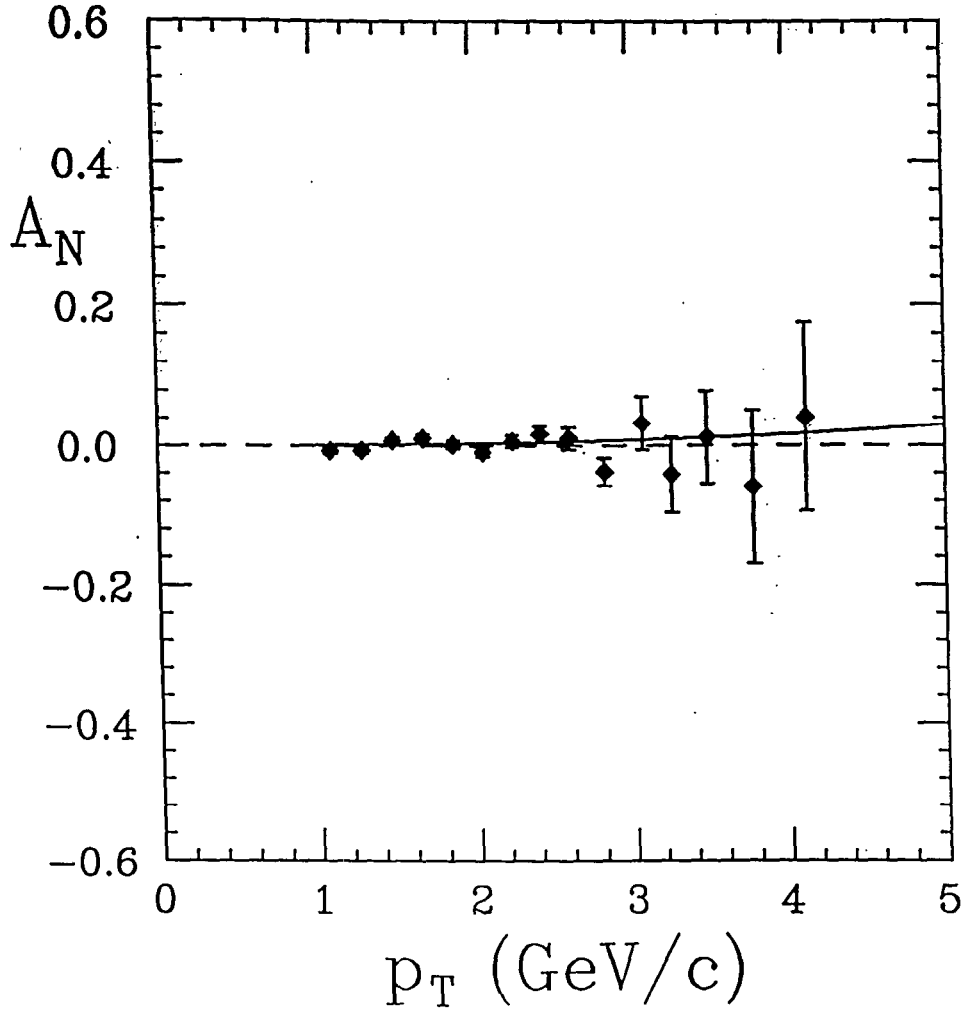


Fig. 3: Single spin asymmetry for the process $p^{\uparrow}p \to \pi^0 X$ at fixed x_F, as a function of p_T; experimental data, at $|x_F| \leq 0.15$, are from Ref. [20]; the solid curve shows our corresponding theoretical prediction at $x_F = 0$.

$|x_F| < 0.15$

Collins effect only

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{\pi z} \int d^2\vec{k}_\perp$$

$$= \overbrace{P^{a/p^\uparrow} f_{a/p}(x_a)}^{h_1^{a/p}} f_{b/p}(x_b)\, \Delta_{NN}\hat{\sigma}^{ab\to cd}(x_a, x_b; \vec{k}_\perp)\, \Delta^N_{\pi/c^\uparrow}(z, \vec{k}_\perp)$$

Parametrize (only valence quarks)

$$\Delta^N_{\pi/q^\uparrow}(z, \langle k_\perp \rangle) = \frac{\langle k_\perp \rangle}{M} N z^\alpha (1-z)^\beta$$

with

$$\frac{\langle k_\perp \rangle}{M} = 0.61\, z^{0.27} (1-z)^{0.20}$$

$$P^{u/p^\uparrow} / P^{d/p^\uparrow} \equiv P_{u/d}$$

Best fit with

$$\Delta^N D_{\pi/q^\uparrow} = -0.13\, z^{2.60} (1-z)^{0.44} \qquad z \leq 0.977$$

$$\Delta^N D_{\pi/q^\uparrow} = -2 \cdot D_{\pi/q} = -2.2.0\, z^{-1} (1-z)^{1.2} \qquad z > \text{"}$$

$$\left[\, |\Delta^N D| \leq 2D; \quad \text{at } z = 0.977 \;\; |\Delta^N D| = 2D \,\right]$$

$$P_{u/d} = -0.76 \qquad \left[\, D^{u/p^\uparrow} = \frac{2}{3} \,\right]$$

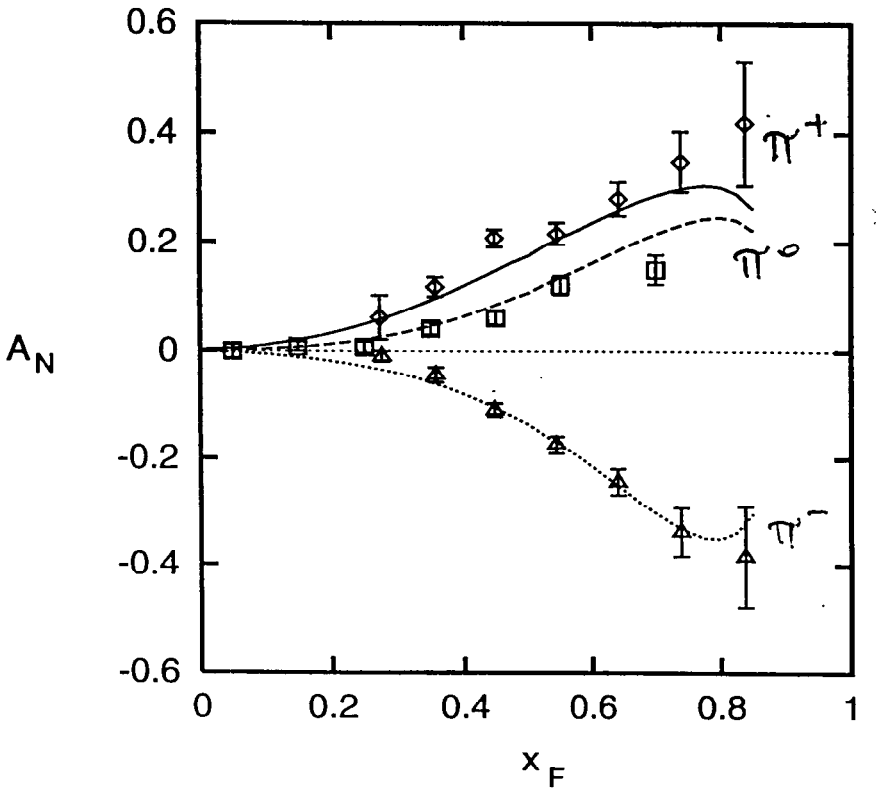


Figure 2: Single spin asymmetry for pion production, $p^\uparrow p \to \pi X$. The data points are the E704 experimental single spin asymmetry for π^+ (diamonds), π^0 (squares) and π^- (triangles) [3]. The solid line is our best fit for π^+, the dashed line for π^0 and the dotted line for π^-, obtained under the assumption of Collins effect only.

$\Delta^N D_{\pi/q^\uparrow} \neq 0$

Comments

- $\Delta^N D_{\pi/q\uparrow}$ has to saturate the positivity constrain in order to fit data:

  $|\Delta^N D_{\pi/q\uparrow}| = 2 D_{\pi/q}$ at large z (region which contributes at large x_F)

- $P_{u/d} = -0.76$

$$\Rightarrow \quad h_1^{u/p\uparrow} = \frac{2}{3} f_{u/p}$$

$$h_1^{d/p\uparrow} = -0.88 \, f_{d/p}$$

h_1^d violates Soffer's bound

$$|h_1^q| \leq \frac{1}{2}(q + \Delta q)$$

$$|h_1^{d/p\uparrow}| \leq \frac{1}{2}(f_{d/p} + \Delta d)$$

[Δd is negative $\Rightarrow$ bound for $|h_1^{d/p\uparrow}|$ is violated]

[Could Δd become positive at large x?]

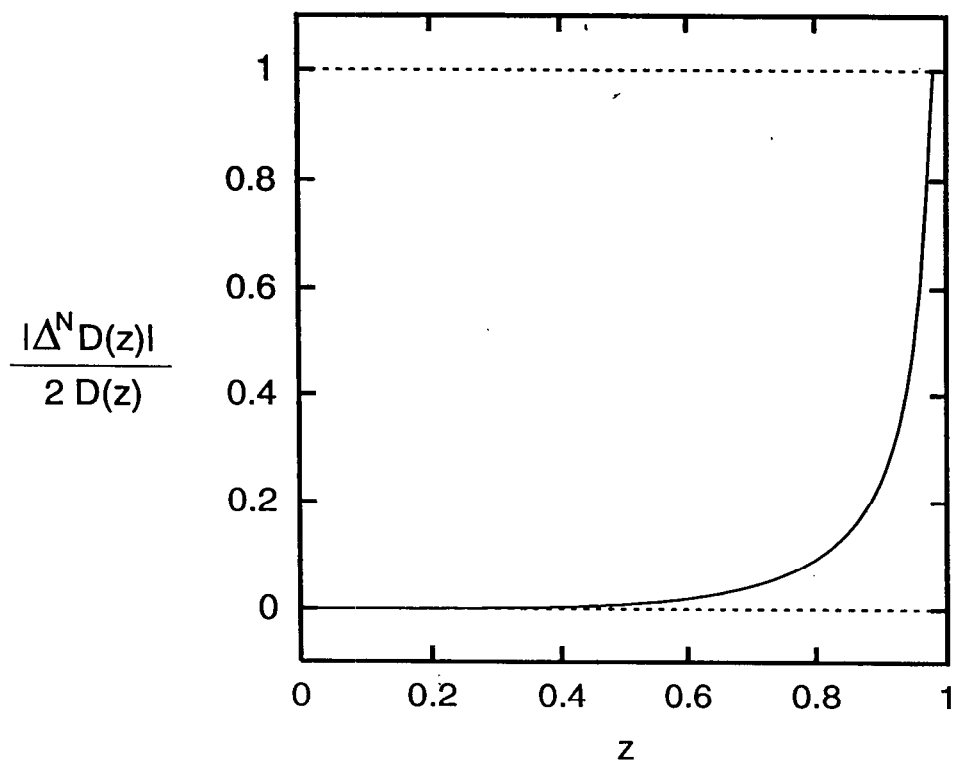
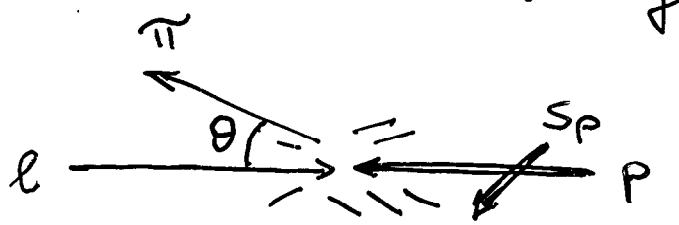


Figure 3: The ratio between $|\Delta^N D_{val}|$ and twice the valence unpolarized fragmentation function D, Eq. (28), as a function of z. Notice that $|\Delta^N D|/2D = 1$ for $z \geq 0.97742$.

$\frac{\Delta^N D}{2D}$ from best fit

Single spin asymmetries in $\ell p^\uparrow \to \pi X$

(only Collins effect)



$$\frac{E_\pi d^3\sigma^\uparrow}{d^3p_\pi} - \frac{E_\pi d^3\sigma^\downarrow}{d^3p_\pi} = \sum_q \int \frac{dx}{\pi z} \int d^2\vec{k}_\perp$$

$$h_1^{q/p}(x)\, \Delta_{NN}\hat{\sigma}^q(x,\vec{k}_\perp)\, \Delta^N_{\pi/q^\uparrow}(z,\vec{k}_\perp)$$

with

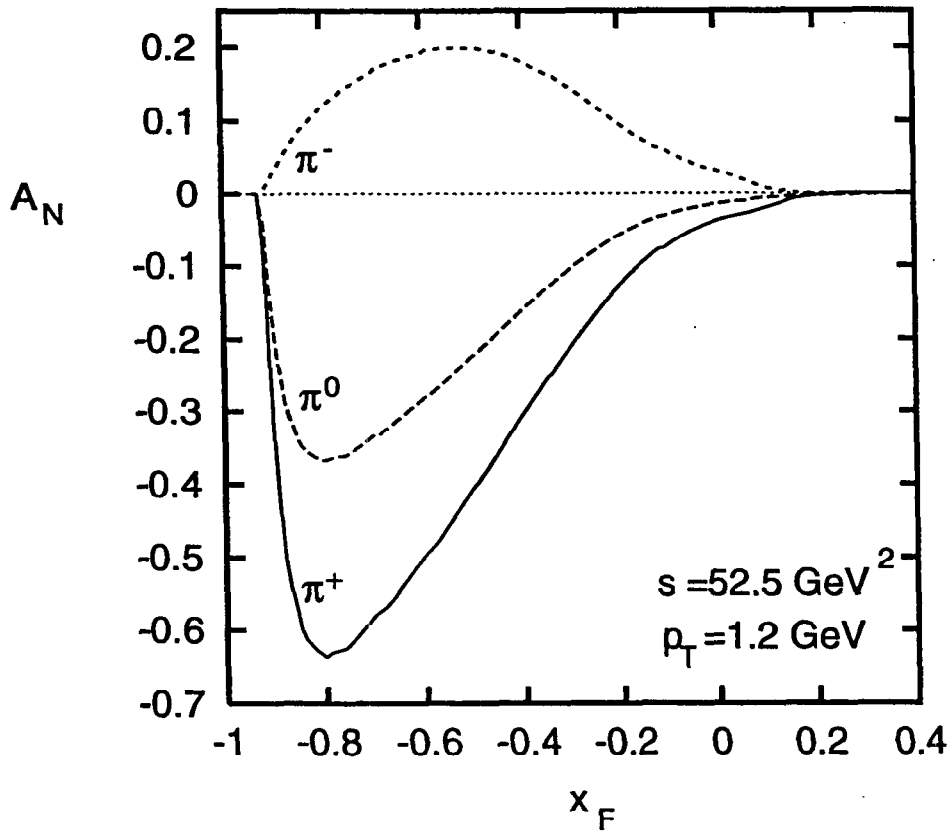
$$\Delta_{NN}\hat{\sigma}^q = \frac{d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\uparrow}}{d\hat{t}} - \frac{d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\downarrow}}{d\hat{t}}$$

Large x_F pions come from valence q

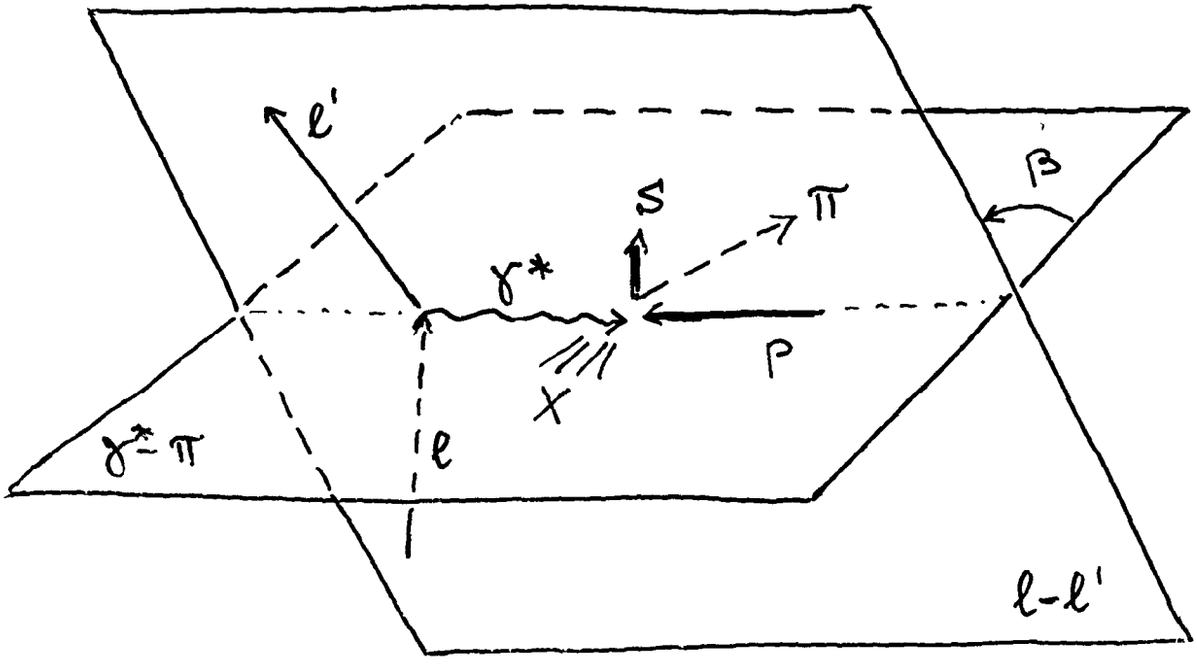
$$h_1^{q/p}(x) = P^{q/p^\uparrow} f_{q/p}(x)$$

$P^{q/p^\uparrow}$ = polariz. of q in $p^\uparrow$ (constant)

$\Delta^N_{\pi/q}$ is taken from fit to data on $p^\uparrow p \to \pi X$ (with only Collins effect)


0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
A_N
π^-
π^0
π^+
s =52.5 GeV^2
p_T=1.2 GeV
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
x_F

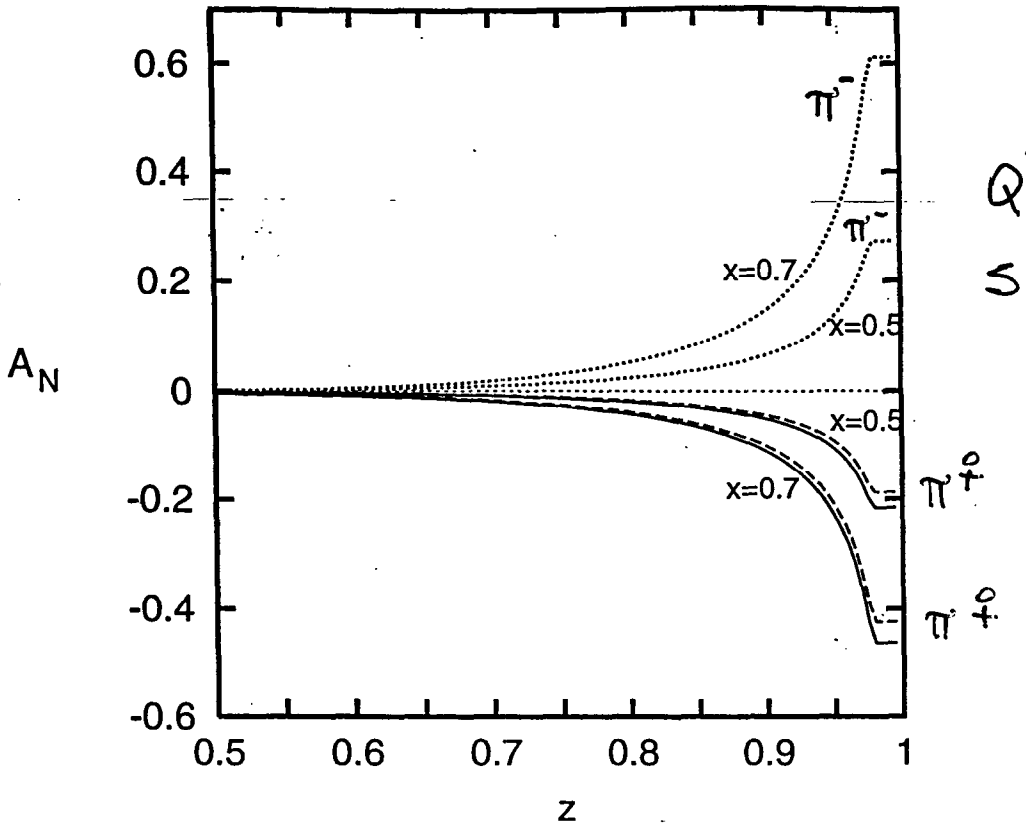
Single spin asymmetries in $\gamma^* p^\uparrow \to \pi X$



$$A_N^{\gamma^* p^\uparrow \to \pi X}(x, Q^2, z, \langle k_\perp \rangle) = \frac{(1-y)\cos 2\beta}{[1+(1-y)^2]}$$

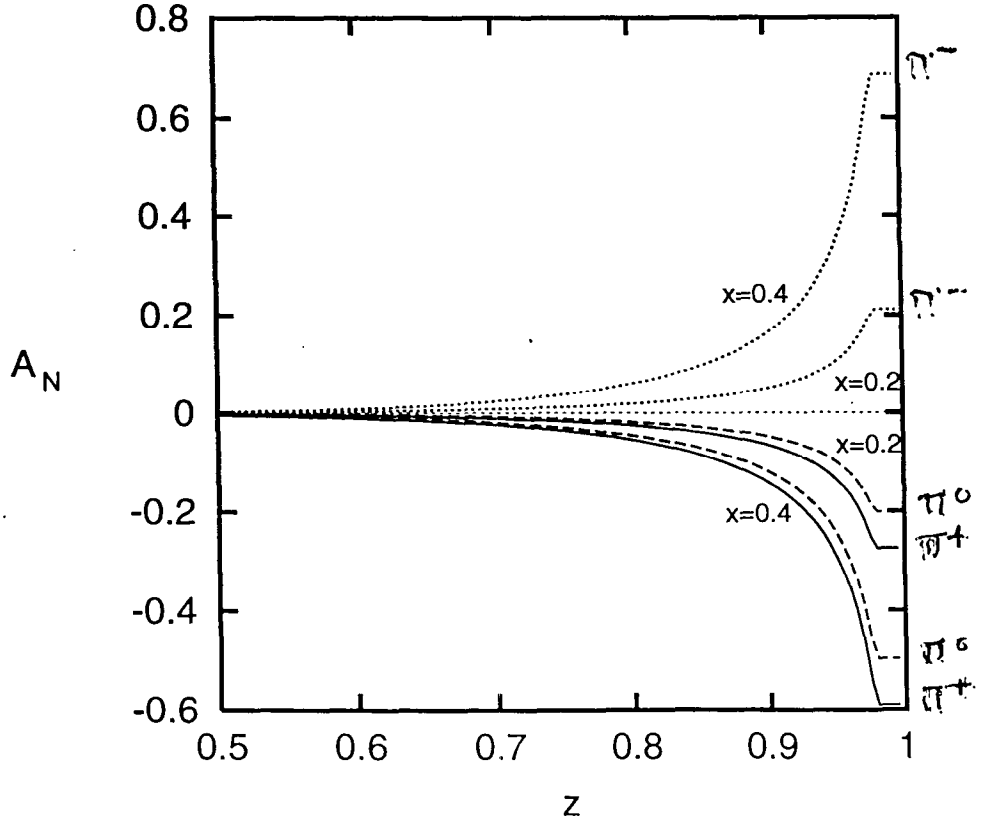
$$\times \frac{\sum_q e_q^2 \, P^{q|p^\uparrow}(x) \, f_{q/p}(x) \, \Delta^N D_{\pi/q}(z, \langle k_\perp \rangle)}{\sum_q e_q^2 \, f_{q/p}(x) \, D_{\pi/q}(z)}$$

$$y = \frac{Q^2}{x \cdot s}$$



$Q^2 = 5\ GeV^2$

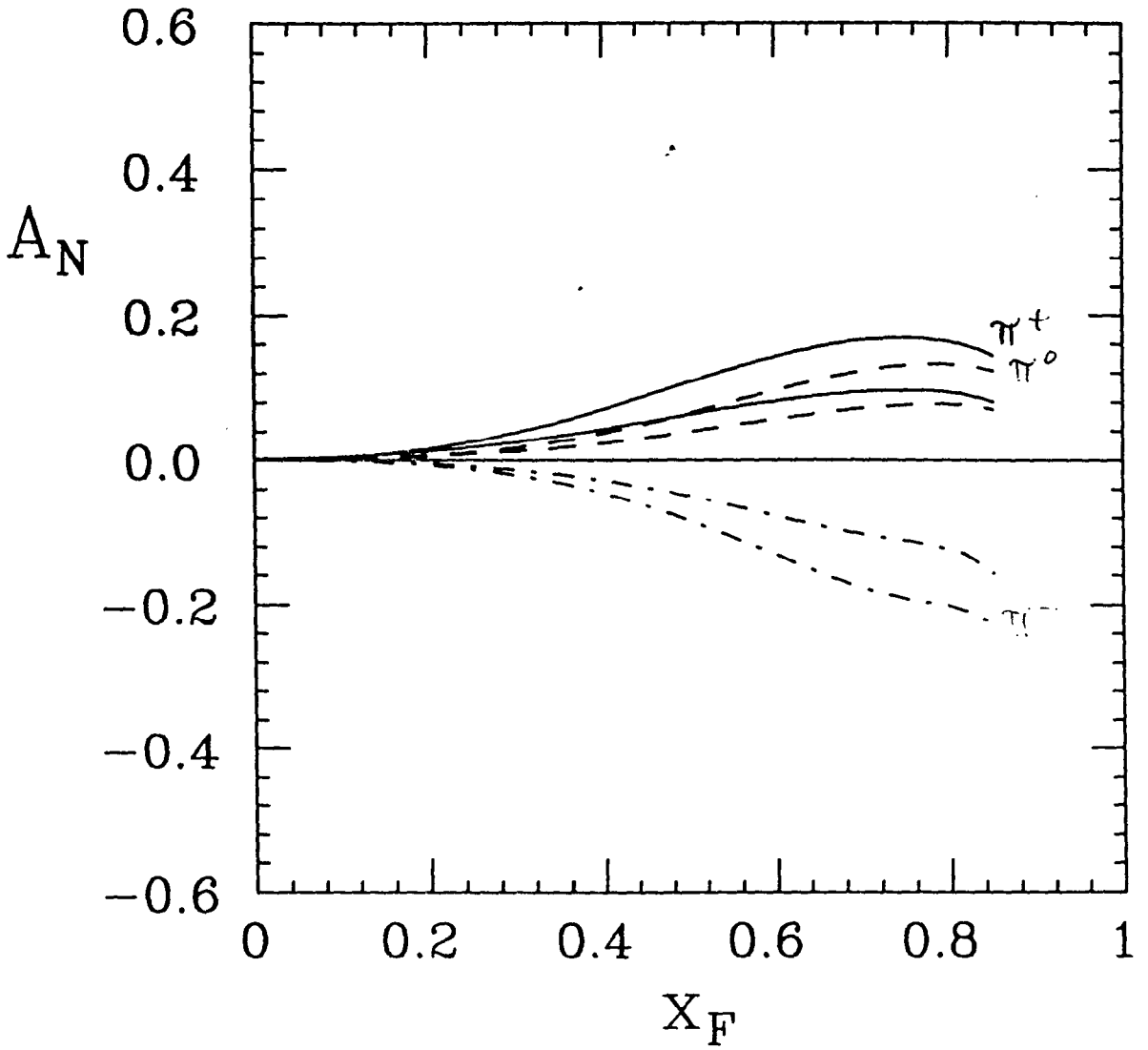
$s = 12\ GeV^2$



$Q^2 = 8\ GeV^2$

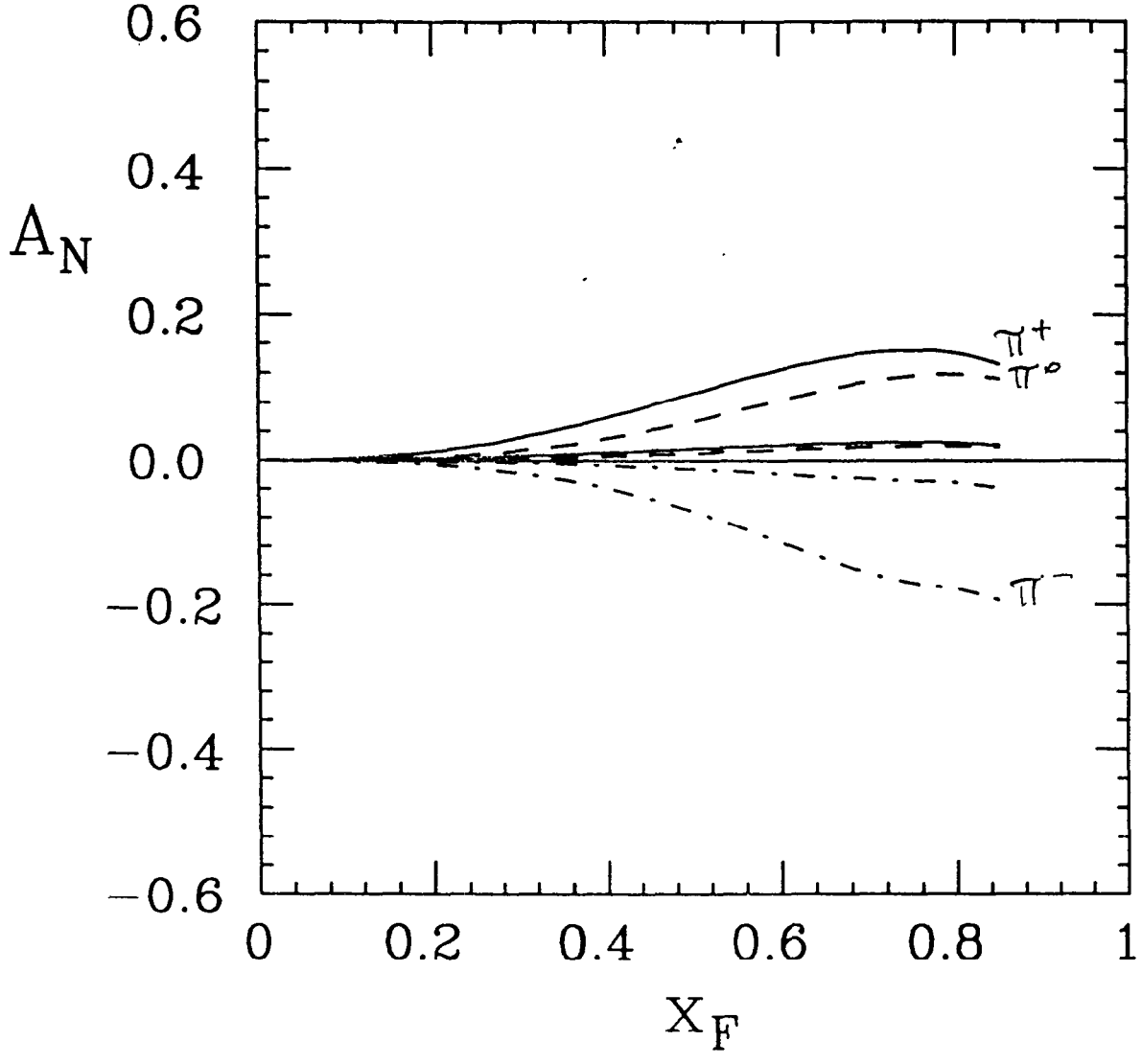
$s = 52.4\ GeV^2$

- Phenomenological model based on generalization of factorization theorem with inclusion of $\vec{k}_\perp$
- New partonic - spin and $\vec{k}_\perp$ dependent - functions [universality, Q^2 evolution? ...]
- Sivers effect can describe $p^\uparrow p \to \pi X$ data and gives good results for $\bar{p}^\uparrow p \to \pi X$
- Collins effect (seen in DIS?) has more problems, at least with a simple parametrization of $\Delta^N D_{\pi/q^\uparrow}$
- Prediction for A_N in DIS, where Collins effect only should be active
- Predictions for A_N in $p^\uparrow p \to \pi X$ at RHIC energies, with Sivers effect only



$\sqrt{s}$ = 50 GeV, p_T = 2/4 GeV

Sivers effect only; $\Delta^N f_{u,d/p^\uparrow}$ from fit to E704 data



$\sqrt{s}$ = 200 GeV, p_T = 2/15 GeV

Asymmetries in Inclusive Pion Production from Polarized Protons on Carbon and Hydrogen Targets for the RHIC Polarimeter

Chris Allgower[1]

[1] High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439

Talk for Polarimetery Workshop, August 18, 1999

Why Inclusive Pions?

Analyzing powers seem to be relatively energy-independent over RHIC energies, with no sign changes.

Relatively easy to measure, although it requires a magentic spectrometer (i.e. $ $ $.)

Pions are copiously produced at high energies, allowing measurements to be done quickly. (Important consideration for accelerator spin tuning.)

E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

E925 measured $\pi^{\pm}$ and proton inclusive analyzing powers at 21.6 GeV/c, and verified that they are large and have the same signs and general appearance as do the 200 GeV data.

Verification of large carbon analyzing powers at RHIC injection energy was a main goal of E925, since carbon targets are envisioned for RHIC Polarimetry.

There were two running periods:

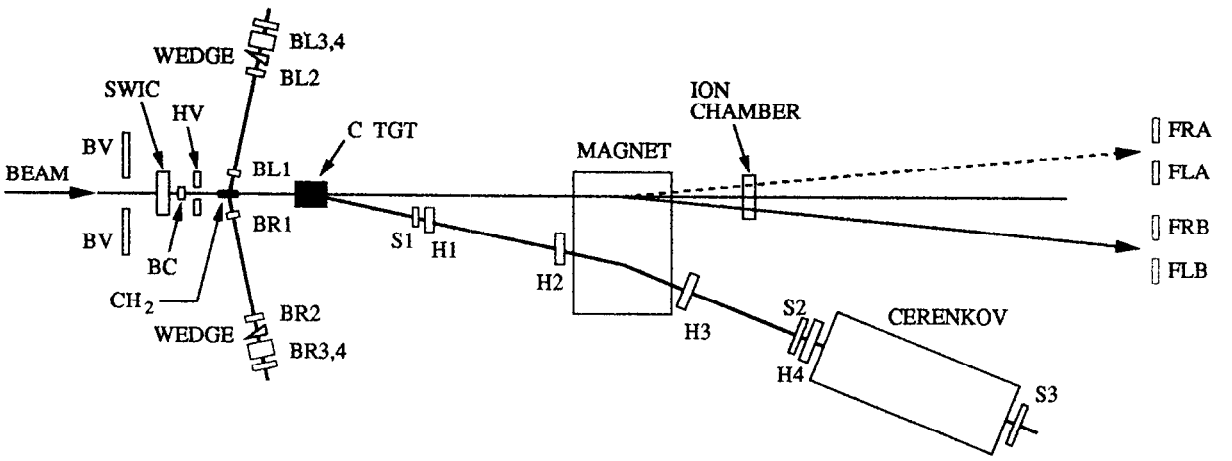
November 1997 - Carbon Target

March 1999 - Hydrogen Target

Hydrogen target run was done to allow direct comparisons with other data, and to see dilution effects from carbon.

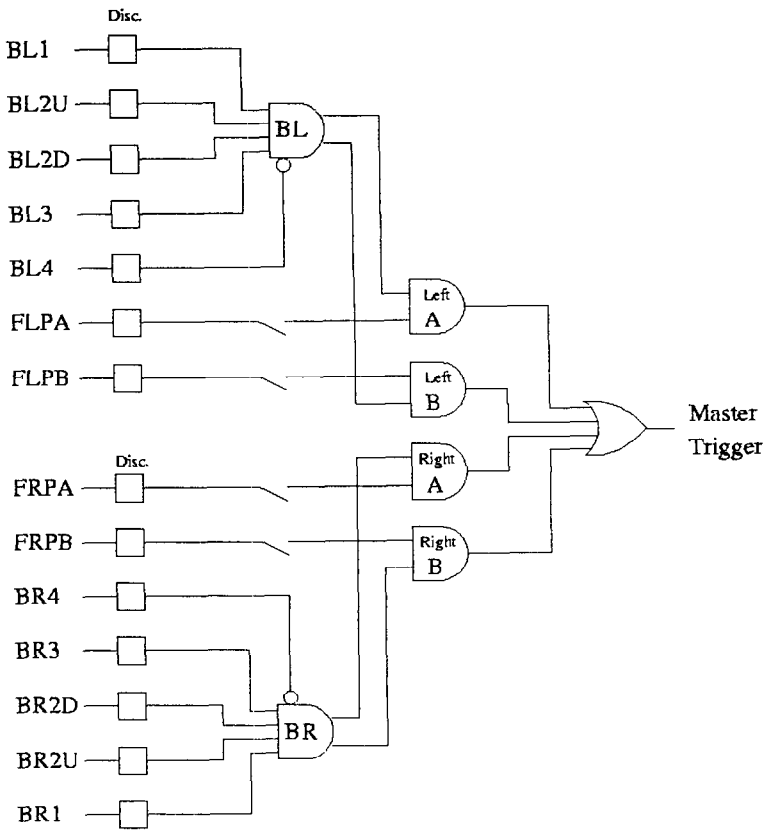
E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

Experimental Layout:



The Experiment was done in the B1 line at the AGS.

Absolute P_{beam} was measured via pp elastic asymmetry, and known A_N.



Trigger selected forward-backward coincidence. Recoil protons were stopped in thick B3 counters, pions went through B4.

The elastic target was a small piece of CH_2, so there was an estimated 3-5% background from the Carbon.

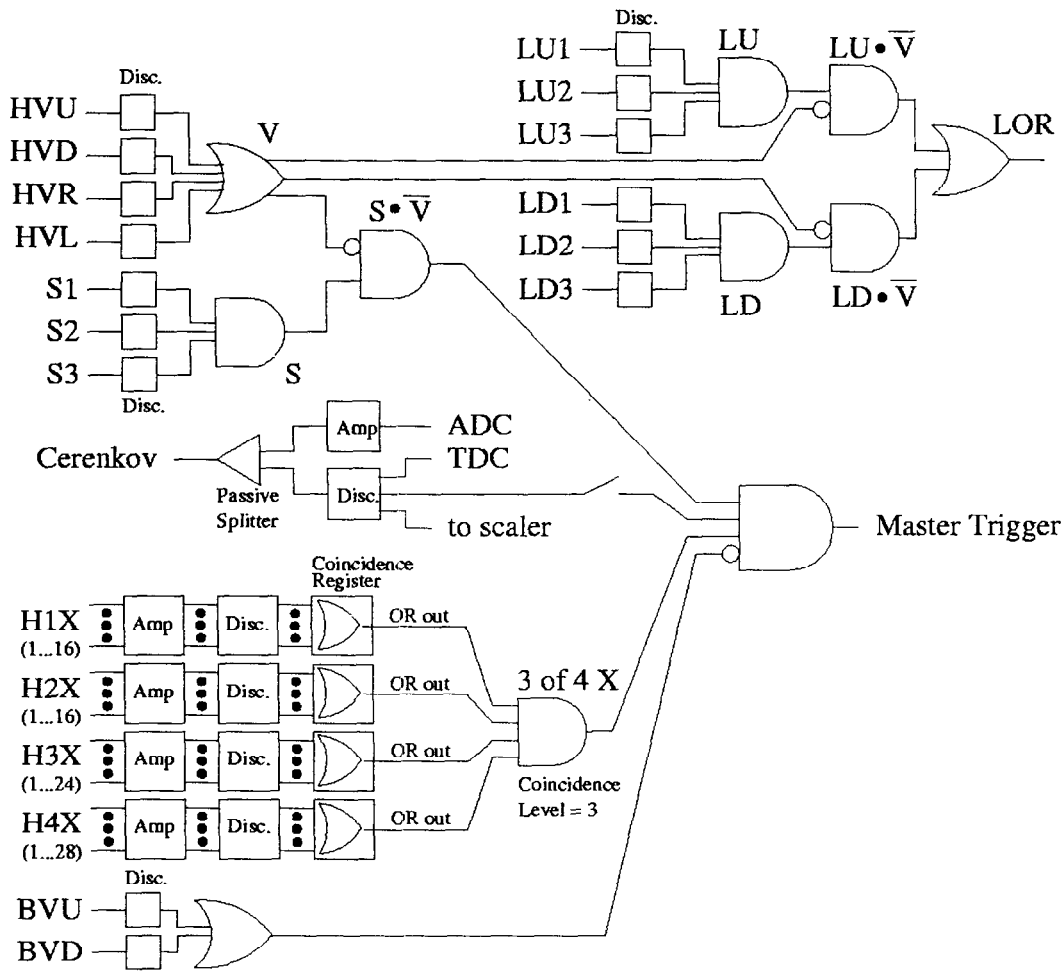
After correction for this, the P_{beam} values at 21.6 GeV/c for the two running periods were

$$(1997) : P_{beam} = 0.271 \pm 0.059 \pm 0.028$$

$$(1999) : P_{beam} = 0.405 \pm 0.\cancel{??} \pm 0.\cancel{??}.$$

0.030 0.040

Inclusive Trigger Logic

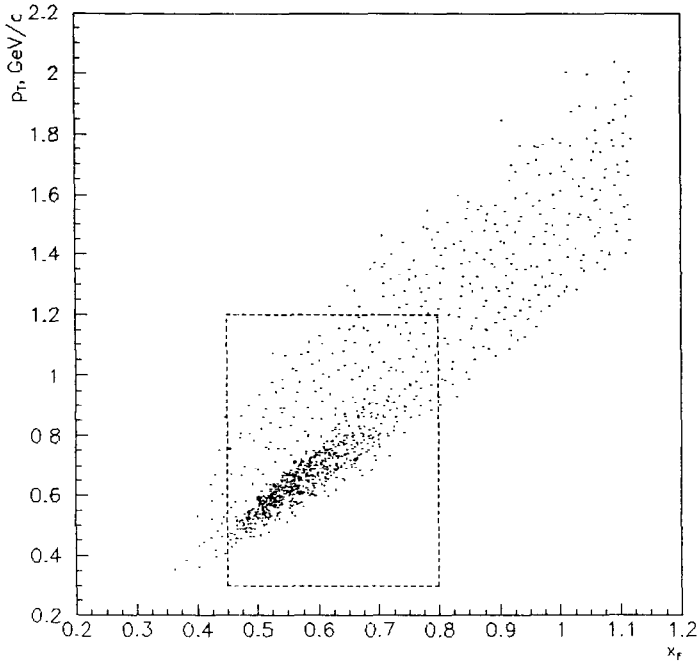


DAQ was a PC running simple acquisition code that handled rates up to 200 events/spill, reading out from a single CAMAC crate.

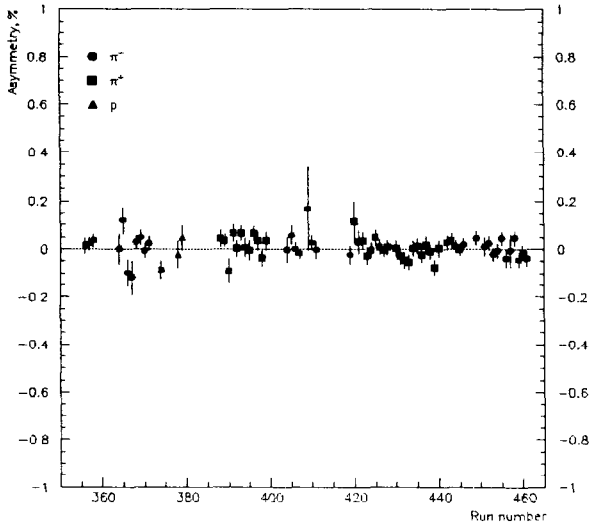
Beam intensity was $2 - 6 \times 10^7$ protons / spill.

E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

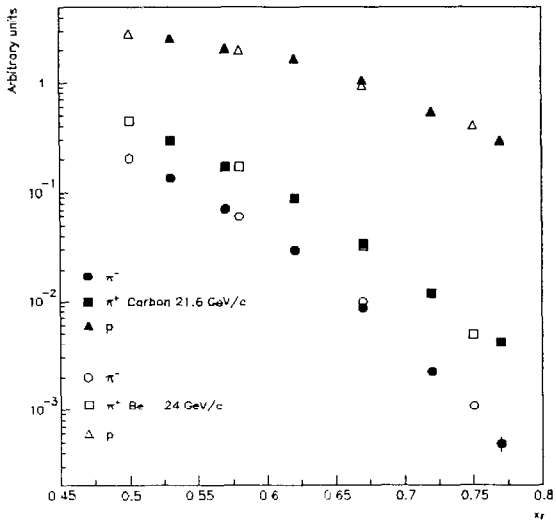
Acceptance Cut in X_F and P_T:



Luminosity Asymm.

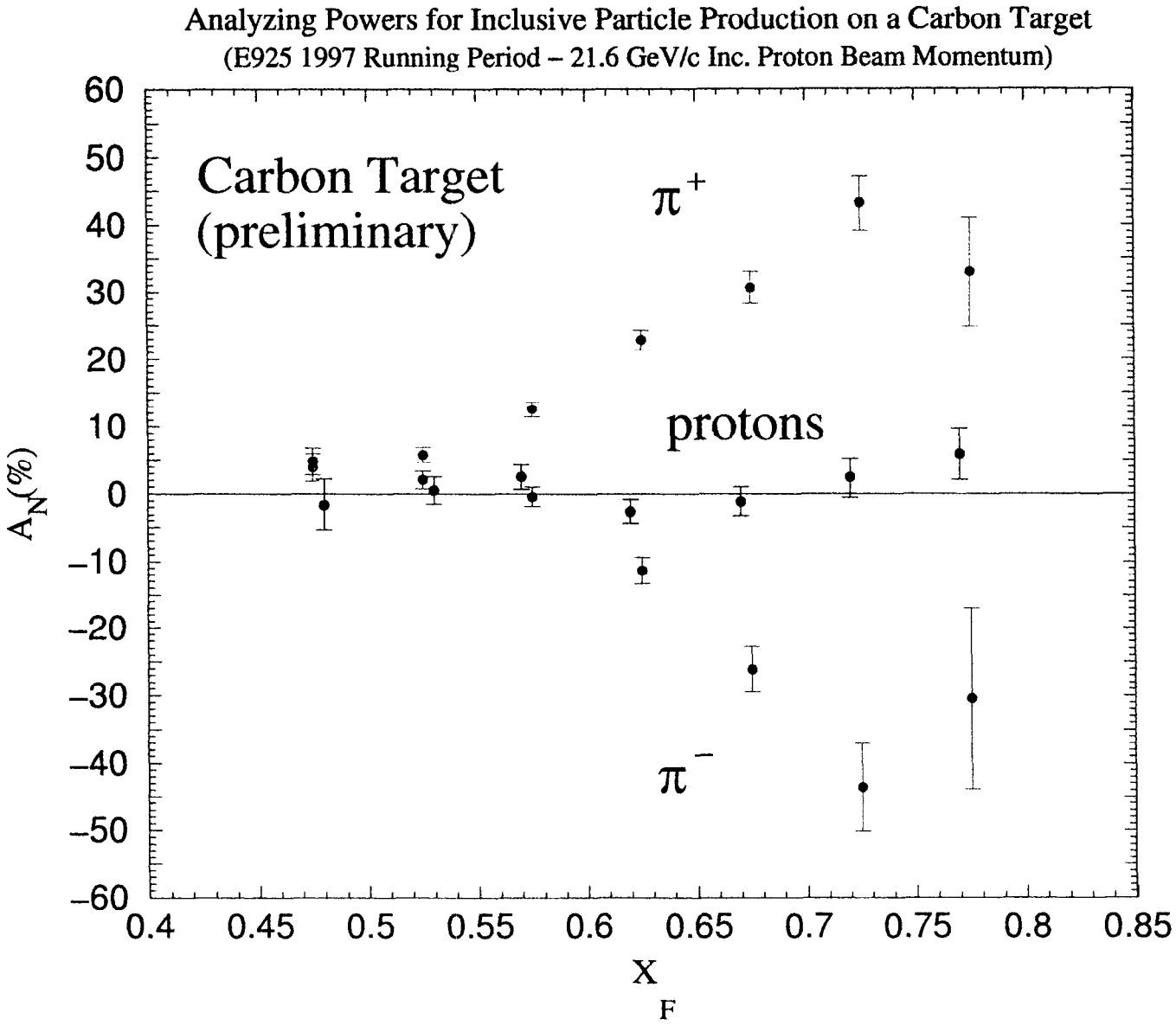


Rel. Cross Sections



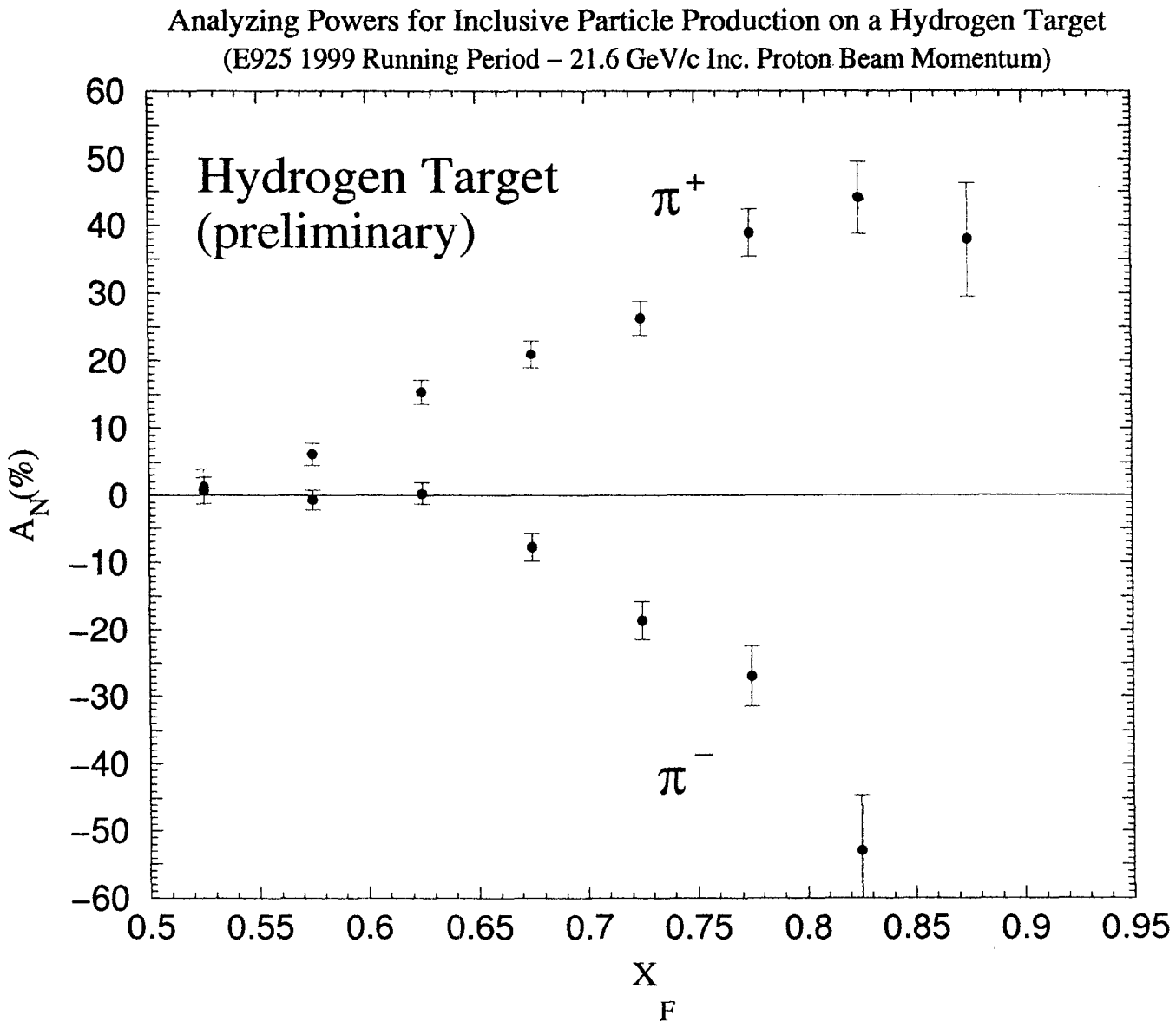
E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

Preliminary A_N Results on Carbon Target (1997 Running Period)



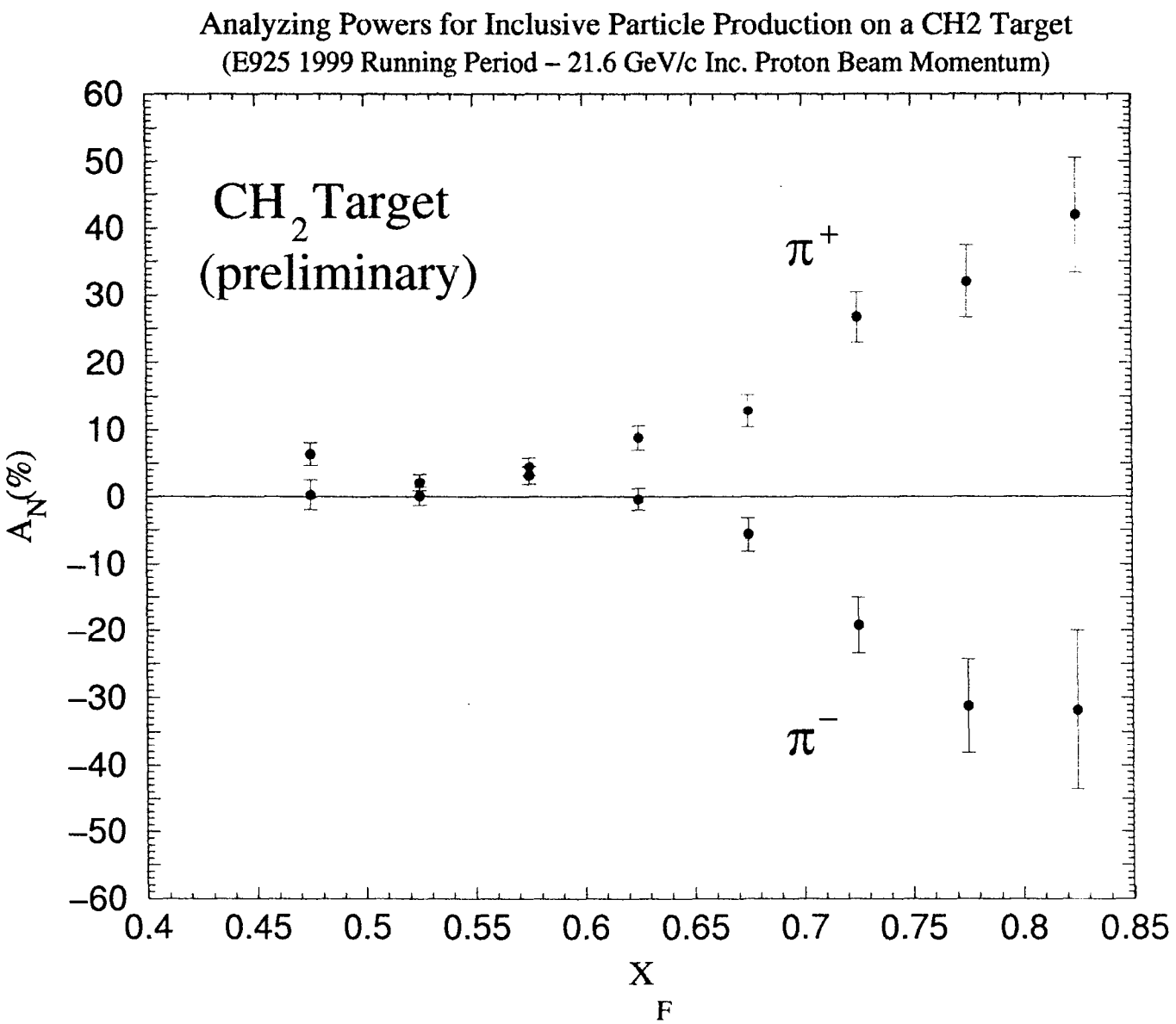
E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

Preliminary A_N Results on Hydrogen Target (1999 Running Period)



E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

Preliminary A_N Results on CH_2 Target (1999 Running Period)



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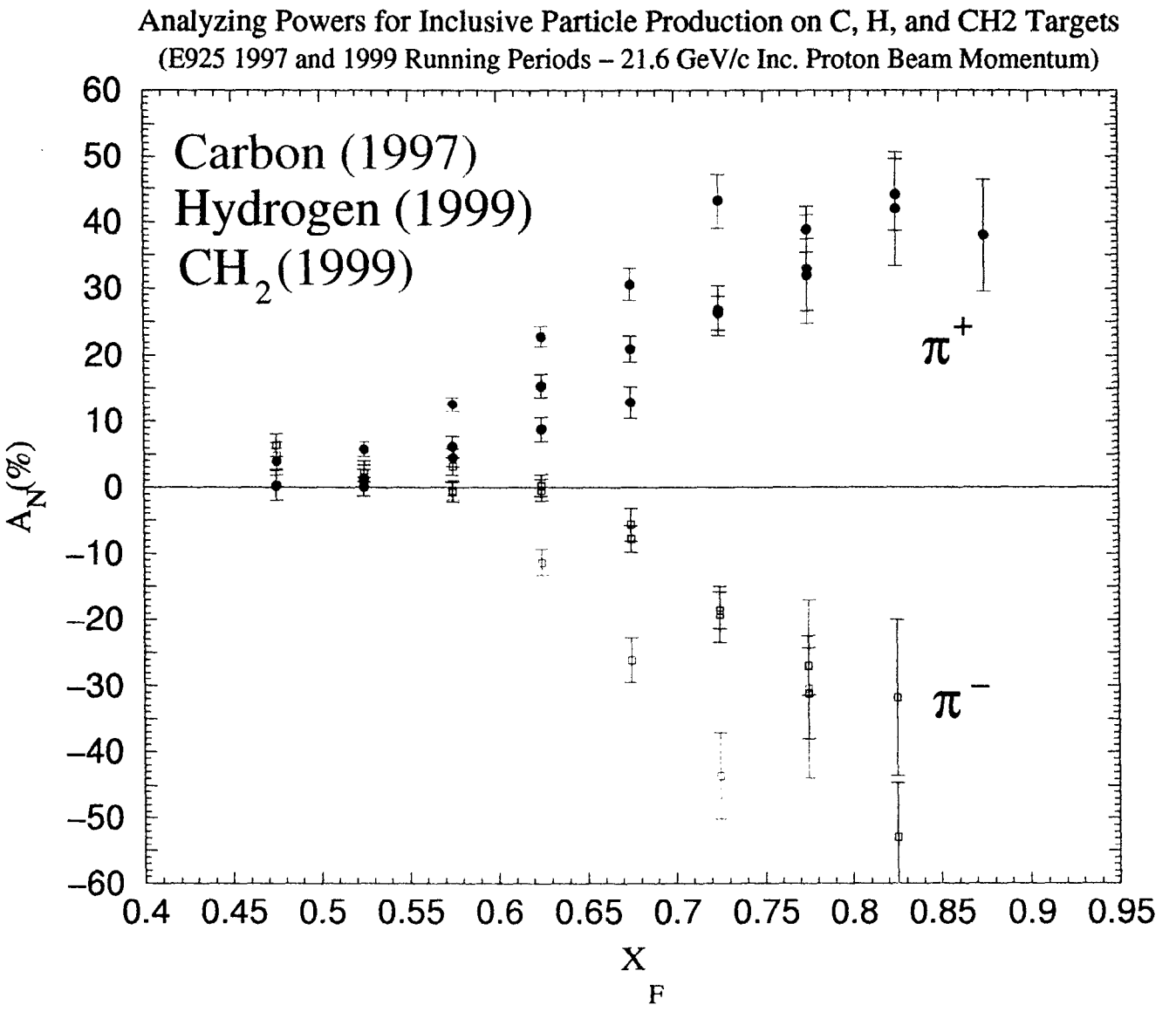
E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

Comparisons on Different Targets (1997 and 1999 Running Periods)

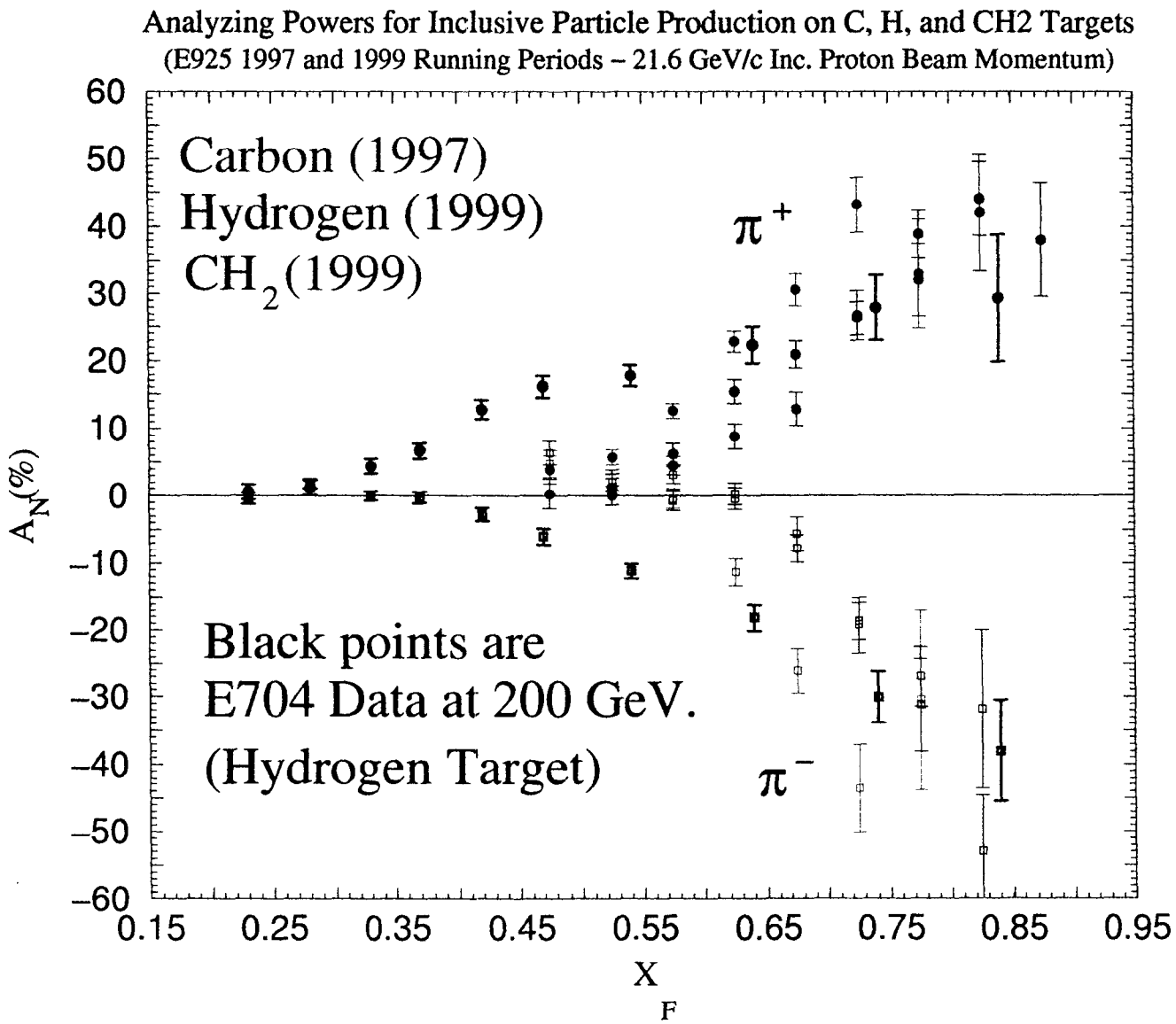
(All data are preliminary)



E925 - Measurement of Pion-Inclusive A_N at 21.6 GeV/c

Comparison with 200 GeV Data from Fermilab E704

(Note - E704 had larger P_T acceptance than E925.)



RHIC Implementation

At this time, implementation is uncertain due to lack of funding.

A Carbon CNI polarimeter will be tried first, at least for commisioning.

Only certainty is that polarimeters will be at 12 o'clock in RHIC.

We have confirmed and feel confident that a pion inclusive polarimeter with a carbon target will work in RHIC.

Requirements for RHIC Polarimtery are Different from E925 at AGS:

1. Large energy range (20-250 GeV) poses challenges for selecting large P_T and X_F - need strong magnets in a limited space.

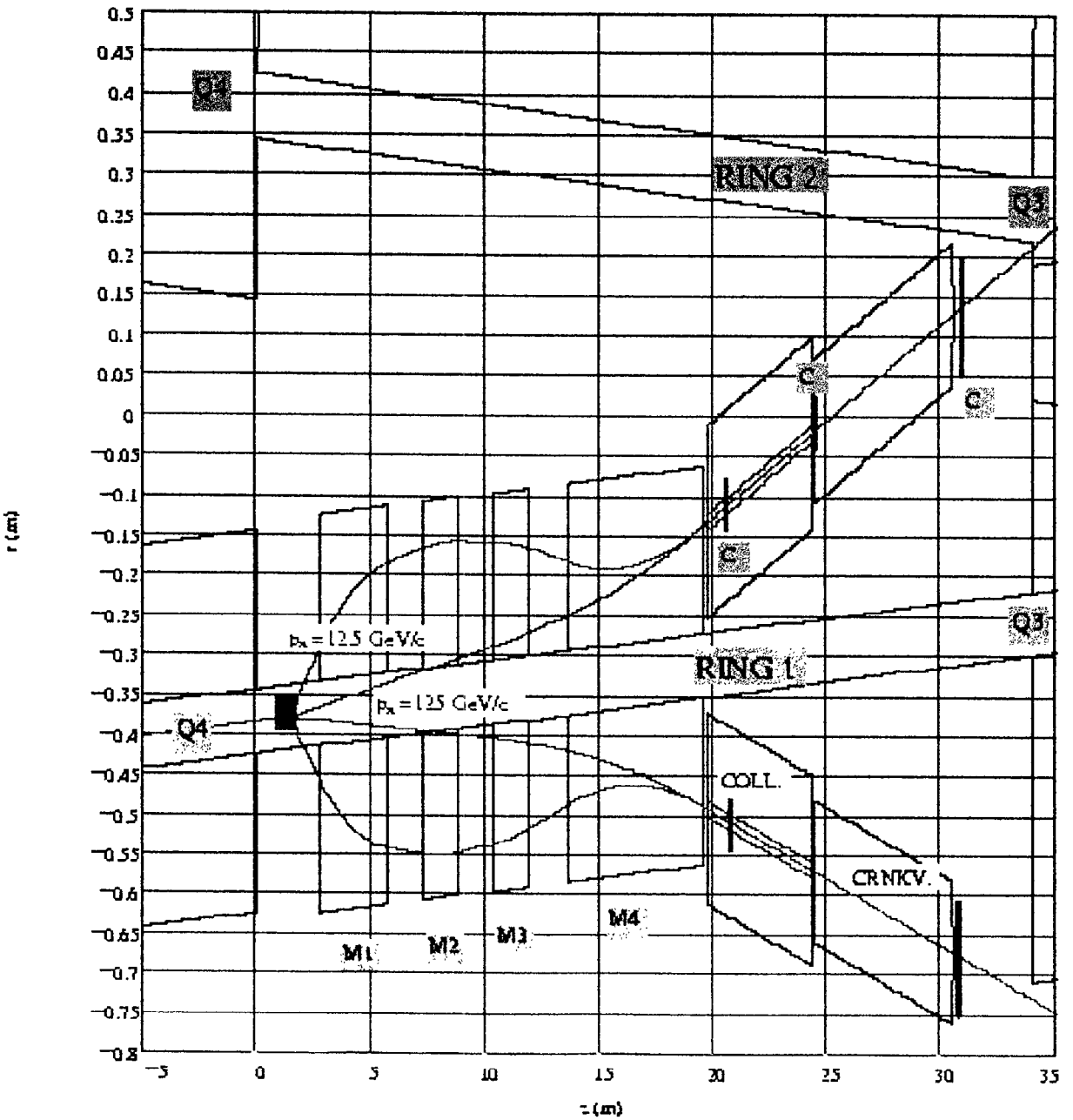
2. Thin carbon ribbon target is required to get rate down to manageable level and not kill RHIC beam. Target may have limited life in RHIC beam, but tests with the CNI setup will tell. (Ribbons worked fine in the AGS.)

3. DAQ has to be completely different because of RHIC ring environment instead of extracted beam of E925. DAQ must handle high rates and keep track of bunch timing, etc.

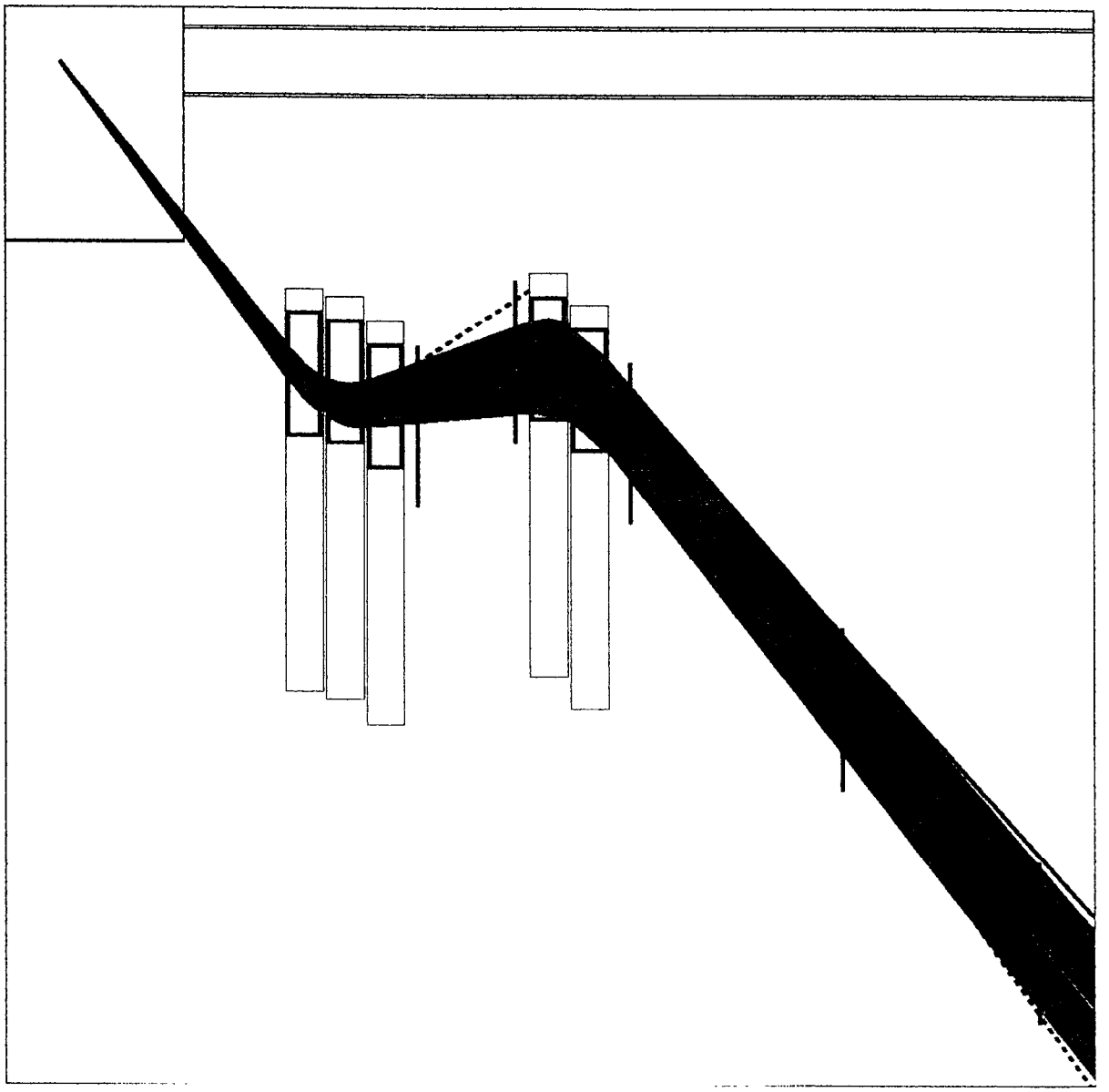
4. Analysis must be semi-automated to get results out within 5-10 minutes for machine people to do beam tuning.

5. Data have to be shipped to experiments at some level in case they want to do independent analysis.

Past Design I - Toroid Magnet ($ 1.7M for 2 double-armed polarimeters)



Past Design II - "No Frills" Design ($ 0.7M, One Arm Only)



Tracks shown are for 25 GeV. Scale is greatly exaggerated - vertical scale is ~3m and horizontal scale is ~100 m.

Asymmetry in Charge-Exchange Reactions (BNL E948)

E.J. Stephenson
Indiana University Cyclotron Facility, Bloomington, IN 47408

The full list of collaborators is found on transparency (1).

Based on the large analyzing powers observed for p+n charge exchange scattering at energies below 12 GeV/c (2), we began an investigation of whether such processes could be the basis of a beam-line polarimeter for the circulating proton beams in RHIC. From the known p+n charge-exchange cross section and analyzing power, the figure of merit (3) would suggest that we operate between −0.2 and −0.4 $(\mathrm{GeV/c})^2$.

As test assembly was made to mock up a polarimeter (4) for use in the 22-GeV/c AGS polarized proton beam. In making a simple setup with scintillators rather than a more elaborate charge-exchange experiment, we lost tight geometry constraints (since the neutrons would be bound in nuclei and subject to Fermi motion) and a good measurement of the energy of the forward neutral hadron. Charged particle (mostly p+p elastic) data were also taken. The targets (5) of C, CH_2, and CD_2 were used to test charge exchange on carbon, the first RHIC polarimeter target, as well as to investigate scattering from protons and nearly-free neutrons. The p+p elastic channel tests the system and provides a template for the calorimeter response. Deuterium checks whether the charge-exchange analyzing power remains high, and the comparison to carbon investigates nuclear attenuation. A diagram of the setup (6) shows the recoil scintillators for scattered protons detection, and the forward calorimeter bars. The bars were preceeded by two scintillators separated with lead that sorted charged from neutral particles, and taged those showers that were likely to be electromagnetic.

In the data analysis (7), recoil protons were separated from minimum-ionizing particles. The calorimeter bars showed a ridge associated with little signal in the two upstream scintillators (8). These events were interpreted as "hadronic." Cuts on charged or neutral, and hadronic or electromagnetic, are shown in transparency (9). The calorimeter energy of these four classes of events is shown in transparency (10).

Those events that are "charged, hadronic" match the cross section for p+p elastic scattering. There is the expected dependence of the cross section on $-t$. The analyzing power (11) matches earlier elastic data. The "neutral, hadronic" spectrum (12) is much too large to be just p+n charge exchange. In addition, the asymmetry appears to depend on calorimeter energy. Using preliminary values of the beam polarization, the analyzing power in each bin is shown for C, CD_2, and D by subtraction. The higher calorimeter energies show a substantial spin dependence [the same sign as shown earlier (2)]. The analyzing power is noticably attenuated for the carbon target. Figures of merit (13) for various cuts are all within a factor of a few of each other.

For commissioning, CNI polarimetry is being implemented at RHIC (14), but this still leave open longer term issues relating to additional polarimeters, systematic error handling, reproducibility, and calibration. For E948 (15), it would be good to have better energy resolution for the neutral particles, and some information on the reactioin channels contributing to the neutral spectrum. Without measurements at higher energies, it is important to have theoretical guidance for how best to optimize this polarimeter design and extrapolate to higher energies.

Testing Charge-exchange Scattering as a Possible Polarimeter for RHIC

(Brookhaven Exp. 948)

IUCF:
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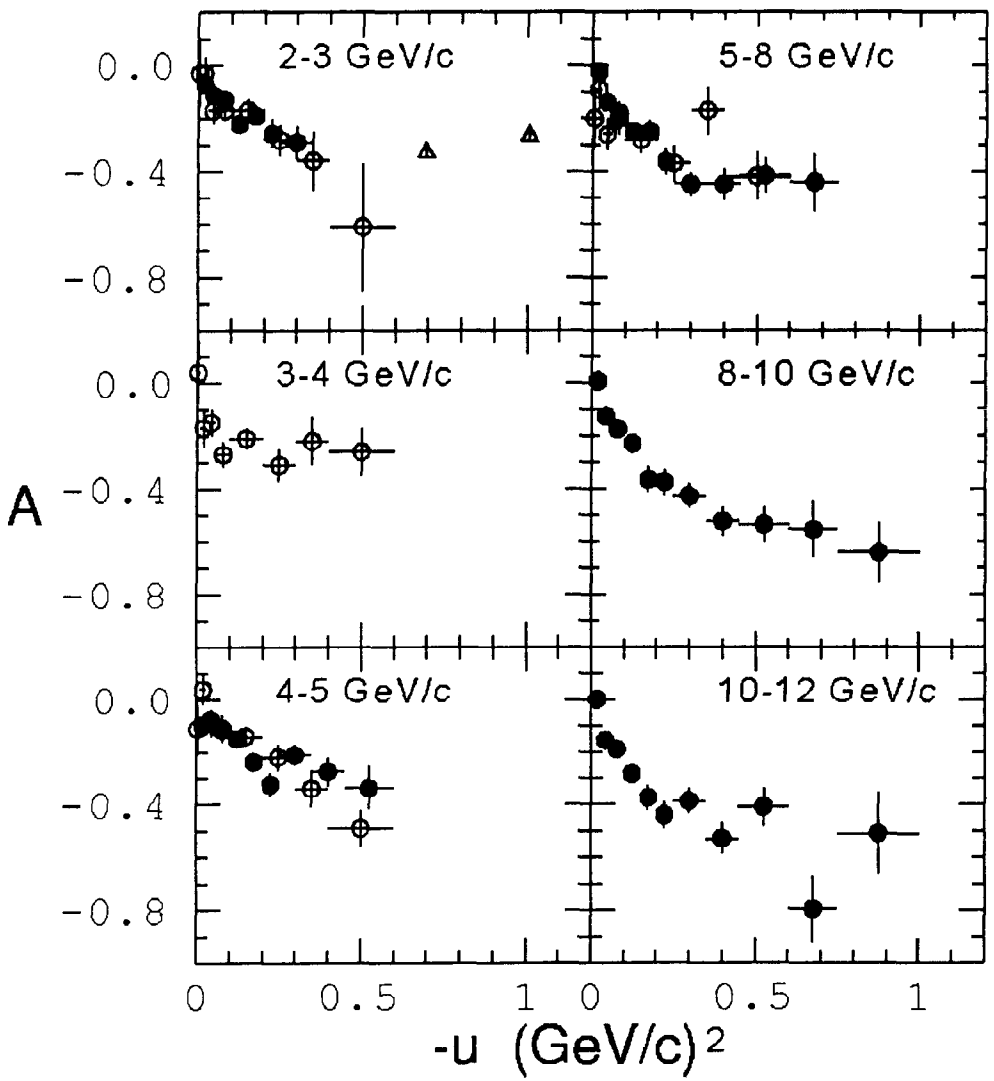
W.W. Jacobs
T. Rinckel
J. Sowinski
E.J. Stephenson*
J. Vanderwerp
S.W. Wissink
*spokesman

Kent State U.
B.D. Anderson
J.W. Watson
W.-M. Zhang

This experiment used forward calorimeters and side recoil scintillators in a quasi-elastic geometry to test a potential polarimeter configuration based on charge exchange scattering. Data was taken in March, 1999, running parasitically with E925.



Analyzing power data for charge-exchange scattering from lower energies

References:

Abolins... PRL **30**, 1183
Robrish... PL **31B**, 617
Makdisi... PRL **45**, 1529

Large spin dependence reflects absence of Pomeron exchange amplitude.

cross section data from
Kreisler... NP **B84**, 3

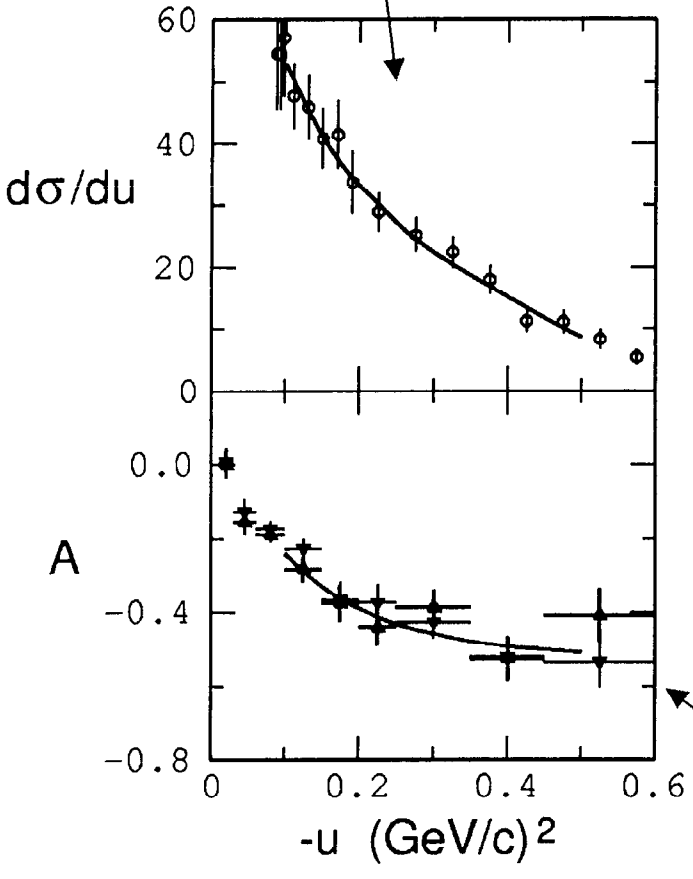
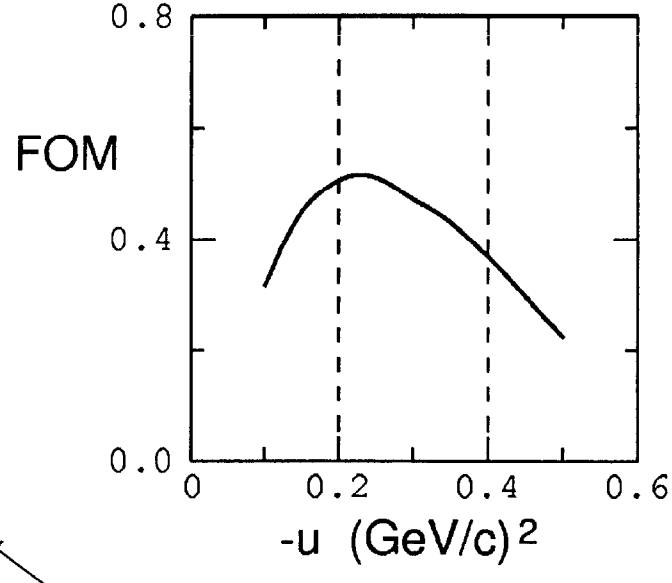


Figure of merit:
$(d\sigma/du)\times A^2$

(arbitrary units)



9 and 11 GeV/c data from
Abolins... PRL **30**, 1183

Charge-exchange experiment or polarimeter design test?

A good n+p scattering experiment might involve a secondary neutron beam and polarized proton target.

By choosing to emphasize a polarimeter test, we lost and gained some features:

- The neutrons are bound, final geometry is not tightly constrained.
- The energetic forward particle is neutral. Its energy is not well measured in a calorimeter. Other channels may add to signal. At small momentum transfers, calorimeters must be close to beam, adding background and losing some of shower signal.
+ Scintillation detector setup is simple and rugged, and capable of high rates. Detector costs are modest.

During tests, also take data on forward charged particles. This ought to be mostly p+p and can give representative spectra and check results.

Any polarimeter must be reproducible. Watch for landmarks in data and other helpful processes. It is not necessary that it be highly selective for charge-exchange if background is also spin dependent.

TARGETS

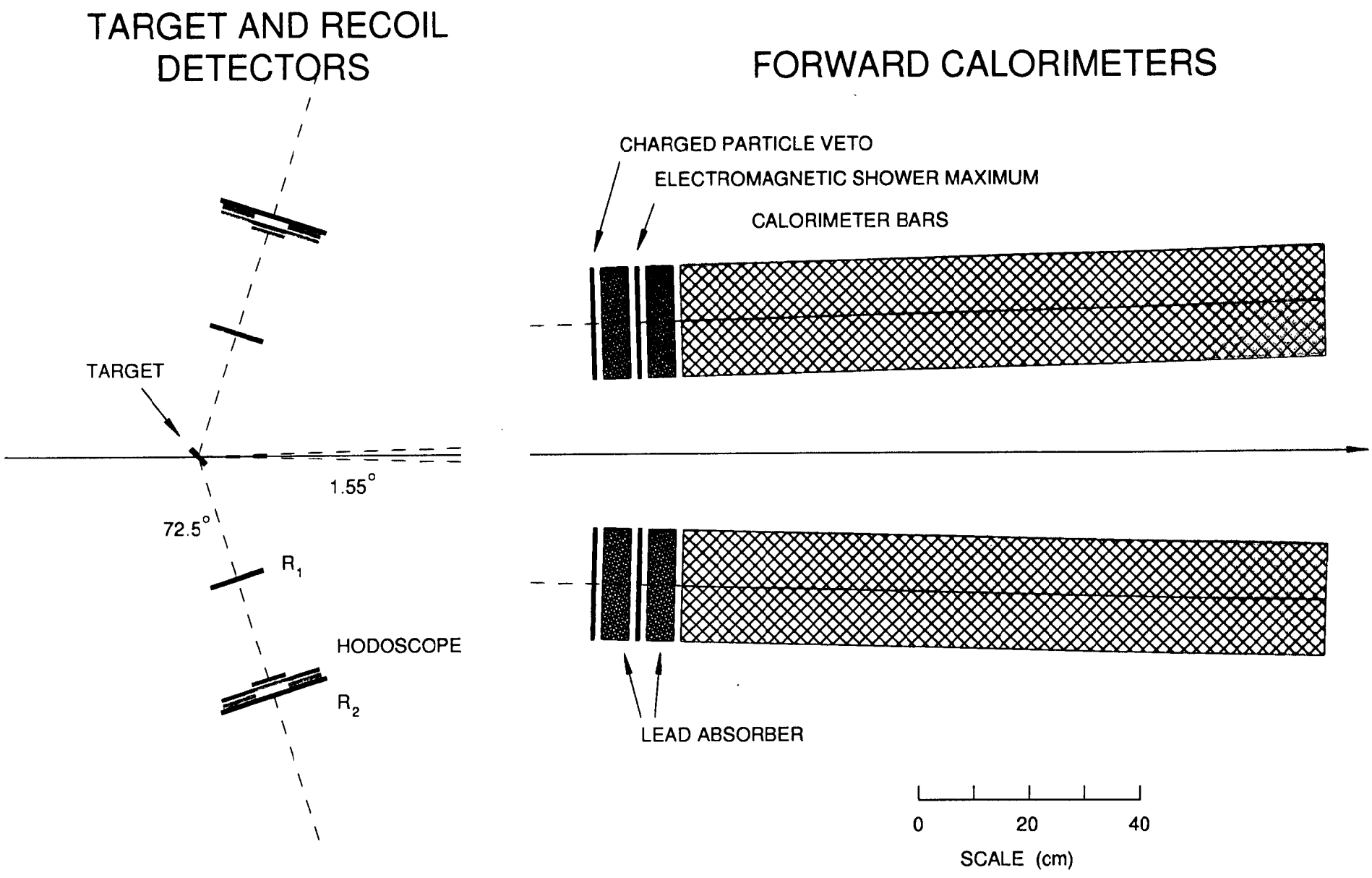
C needed since RHIC will use fiber targets

CH_2 provides p+p scattering from hydrogen as a reference

CD_2 provides a nearly free neutron to test charge exchange

By comparing the spin dependence among these targets, we hoped to learn:

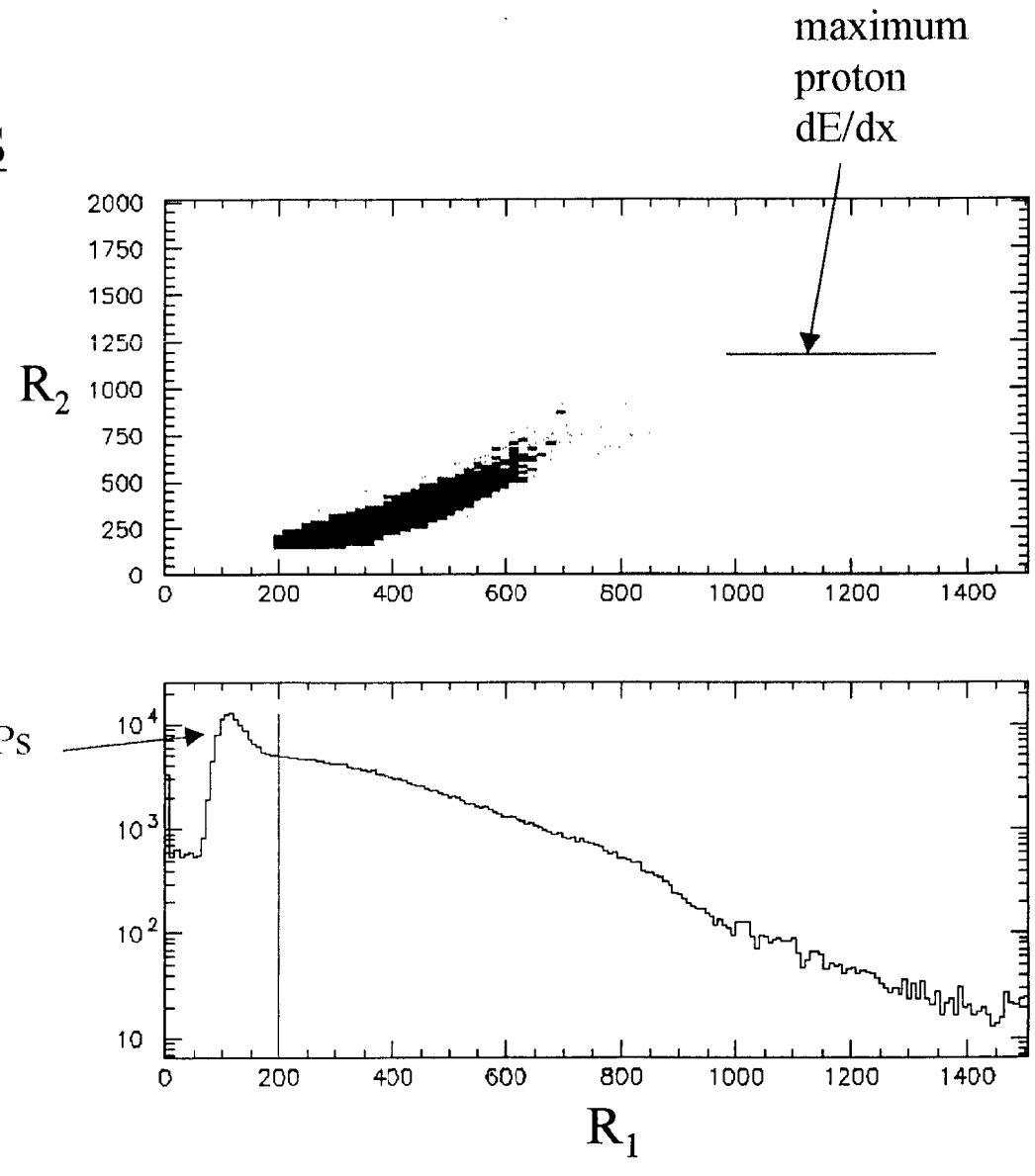
1. whether the setup was able to reproduce known values for p+p.
2. whether the analyzing power for charge exchange remains large at 22 GeV/c by observing scattering from a nearly free neutron.
3. whether any large charge exchange spin dependence remains for neutrons bound in a carbon nucleus.


TARGET AND RECOIL DETECTORS
TARGET
1.55°
72.5°
R1
HODOSCOPE
R2
FORWARD CALORIMETERS
CHARGED PARTICLE VETO
ELECTROMAGNETIC SHOWER MAXIMUM
CALORIMETER BARS
LEAD ABSORBER
0
20
40
SCALE (cm)

SELECTION OF EVENTS FOR ANALYSIS

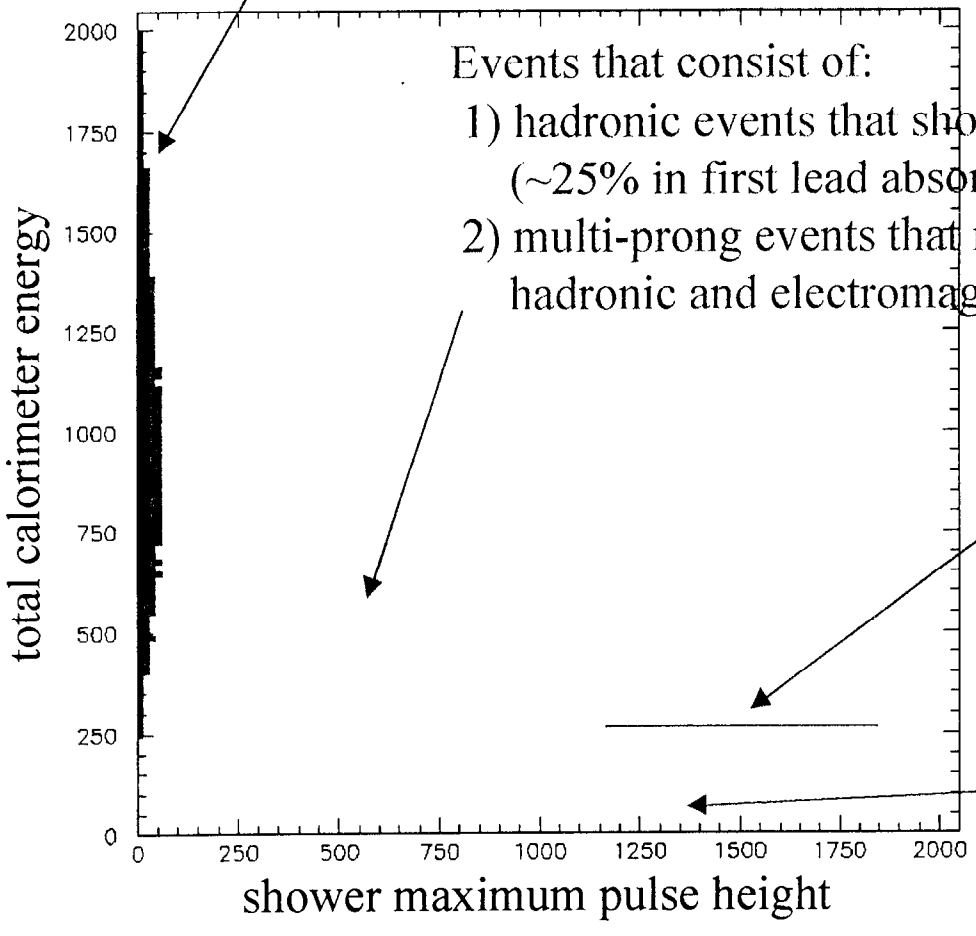
RECOIL DETECTORS

Simulations of Fermi motion show all recoils lie at 75<E<500 MeV. Their scintillator pulse height is above minimum ionizing.



SEPARATING EVENTS WITH CALORIMETER AND SHOWER MAX

"Hadronic" events that shower in the second lead absorber or the calorimeters

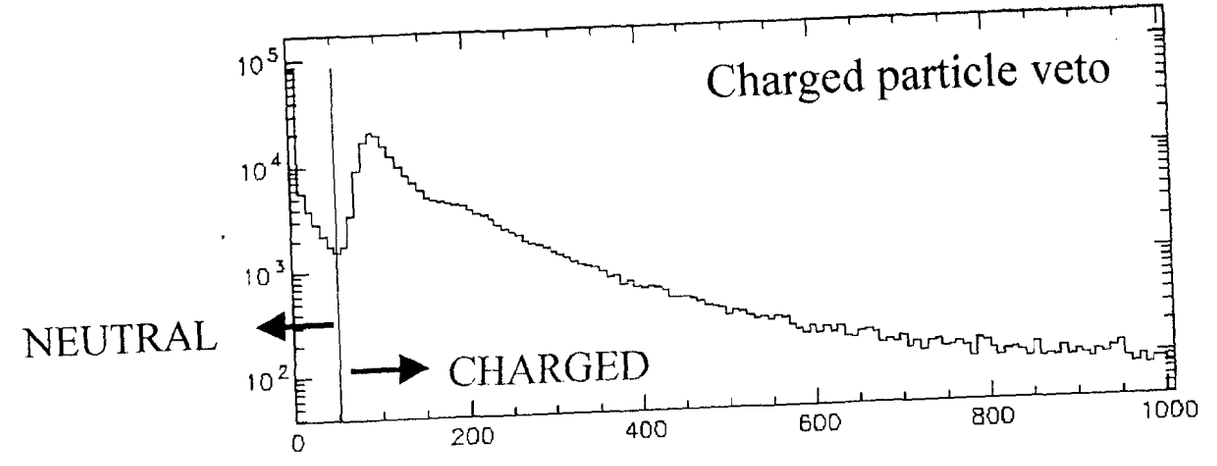


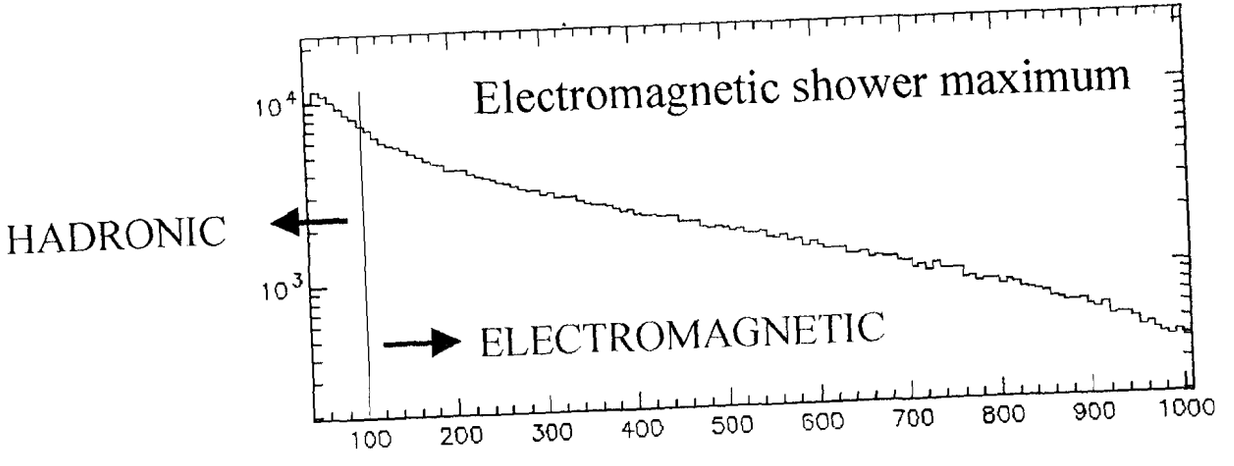
Events that consist of:
1) hadronic events that shower early (~25% in first lead absorber)
2) multi-prong events that mix hadronic and electromagnetic

Soft cutoff resulting from requirement that <u>all</u> calorimeter bars receive some energy, excluding some multi-prong and in-flow background

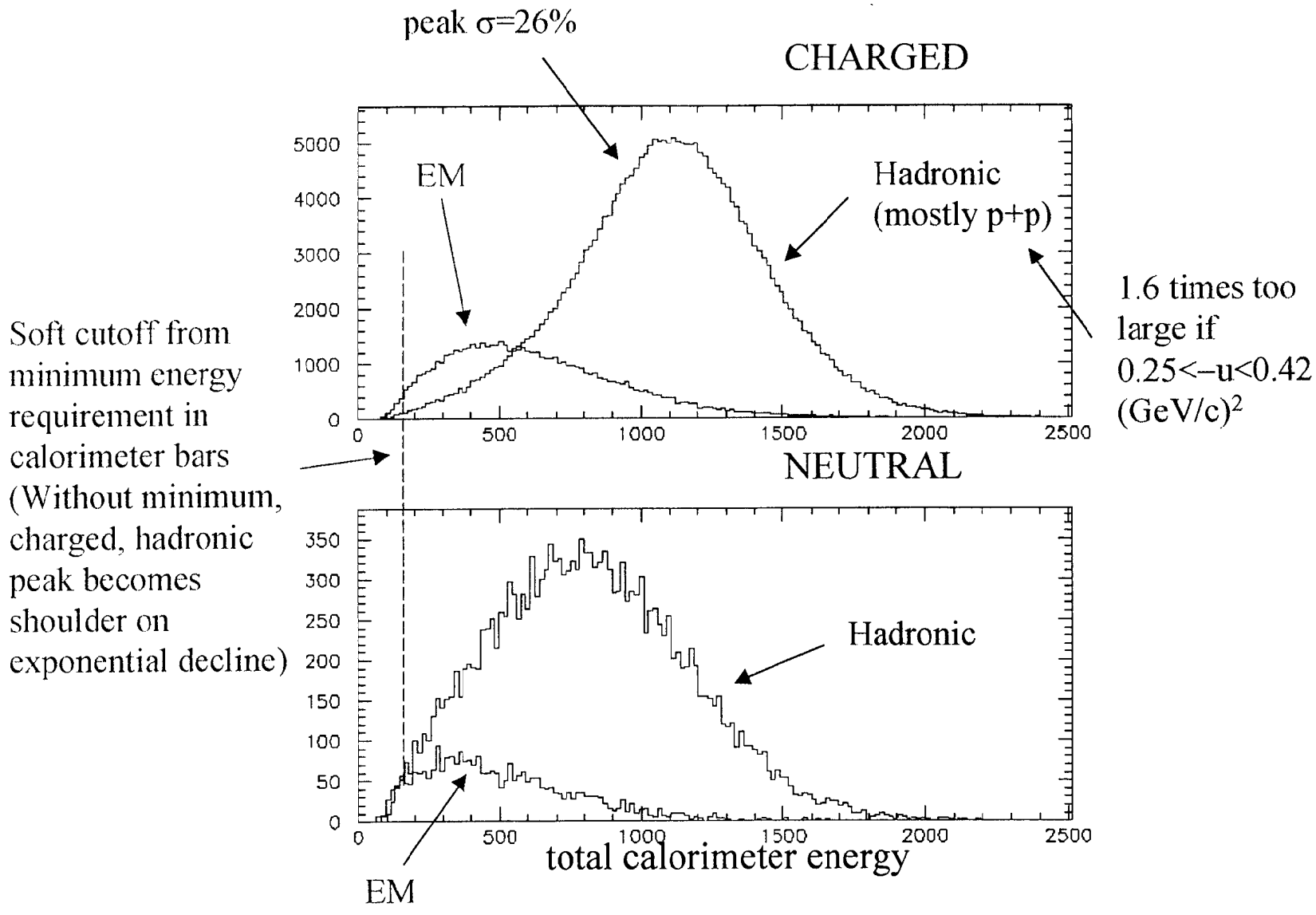
Most likely location of purely electromagnetic events

SEPARATING EVENT CLASSES



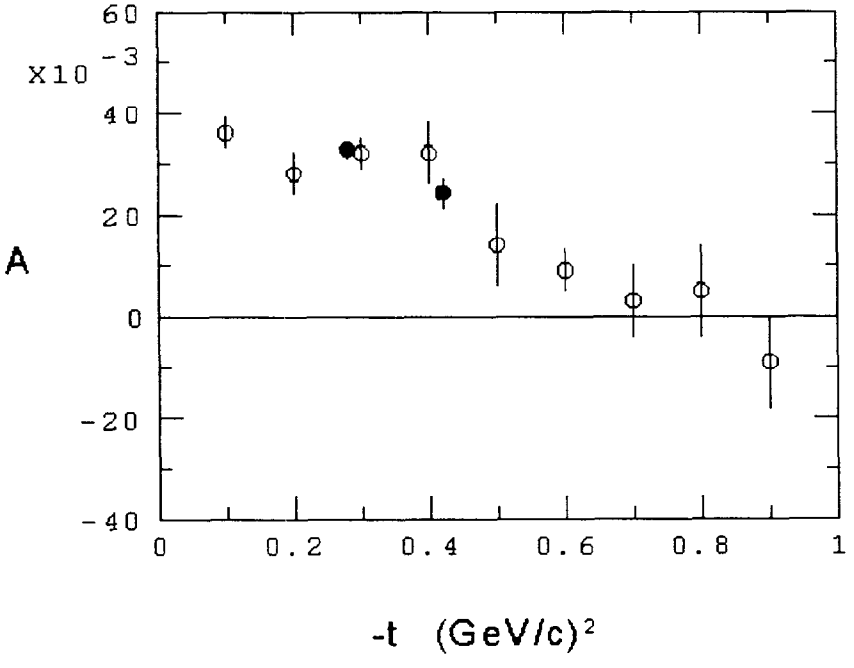


FOUR EVENT CLASSES FOR CD_2 TARGET



COMPARISON TO ELASTIC SCATTERING ANALYZING POWER

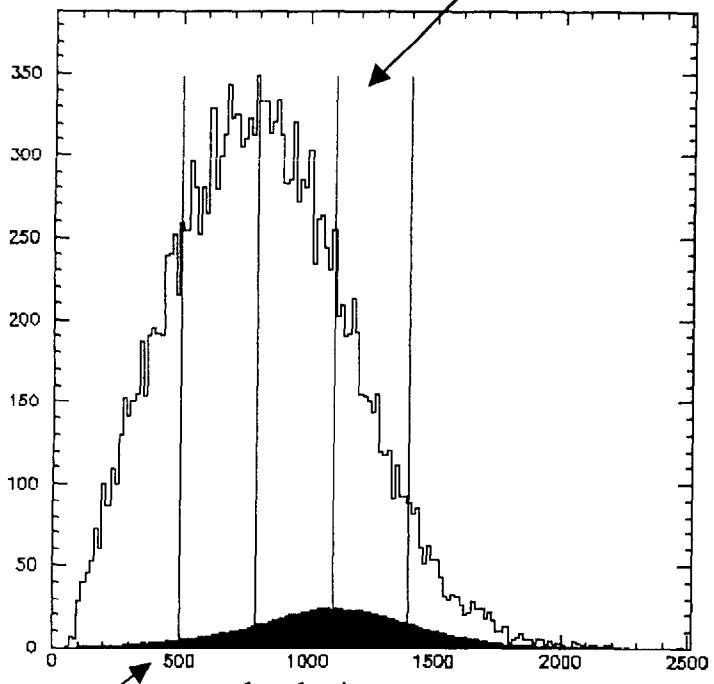
Open circles = data from Crabb at 24 GeV/c



Average beam polarization = 0.425 ∓ 0.055
(preliminary)

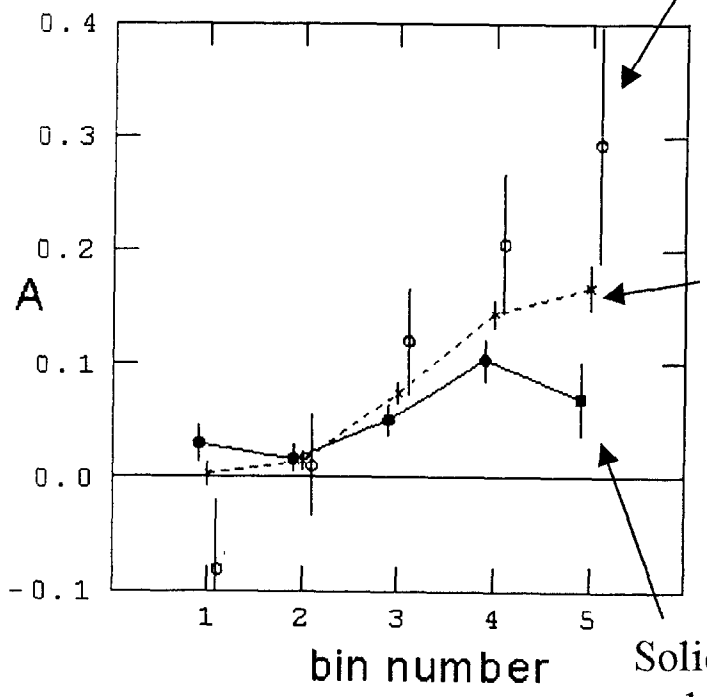
"NEUTRAL, HADRONIC" SPECTRUM

The spin dependence changes with calorimeter energy. Results are shown for 5 bins.



This is the "charged, hadronic" spectrum scaled by the ratio of the charge-exchange to the elastic cross section. It is always less than the measured spectrum.

Open circles = deuterium alone



x = CD_2 target

Solid dots = carbon target

FIGURES OF MERIT
(hadronic)

	σ (μb)	A	F. O. M.
charged:			
C	1340	0.0271 ∓ 0.0024	0.98
CH_2	4030	0.0273 ∓ 0.0025	3.00
CD_2	3445	0.0341 ∓ 0.0019	4.01
neutral, full peak:			
C	167	0.0400 ∓ 0.0069	0.27
CD_2	245	0.0564 ∓ 0.0054	0.78
neutral, upper half of calorimeter energy:			
C	87	0.0610 ∓ 0.0096	0.33
CD_2	136	0.1015 ∓ 0.0074	1.40
deuterium only:			
charged	1051	0.0387 ∓ 0.0079	1.57
neut., all	39	0.0915 ∓ 0.0268	0.33
neut., top-E	24	0.1753 ∓ 0.0351	0.75
charge-exchange (anticipated):			
	6.2	0.4	0.99

Polarimeter design issues

(Early) design constraints:

carbon fiber target

known analyzing power over RHIC energy range

modest cost

→ CNI polarimeter for commissioning

Longer term issues:

- Where (how many) polarimeters do we need? What must we know about off-axis components, and rotator performance?
- Systematic error suppression (favors larger A).
- Calibration:
  - Polarized proton target needs large A if p+p is used. Other reactions need careful balance.
  - Ramping up and down
  - Absolute schemes?
- Checking longitudinal polarization in experiment

E948 ISSUES

Experimental:

How do we improve resolution for neutrals? (This helps to separate large A processes.)

- Calorimeter size is restricted by proximity to beam. This problem gets worse with energy.
- It is important to maintain efficiency.

Analysis:

What processes make up neutrals spectrum? (Simulations with phase space distribution can include known total cross sections for nucleon excitation, particle production, multi-prong events. They must have "low energy" charged recoil and forward neutral without hitting veto.)

Theory (guidance in the absence of date):

- What is np→pn mechanism? With ρ or A_2, it may be possible to explain cross section? What is source of large imaginary amplitude needed for analyzing power?
- What is evolution with energy?
- Are other channels similar? (Deuterium A is consistent with CEx A=1 and other A=0.)

An Absolute Polarimeter for Protons

Elliot Leader (Birkbeck College, London)

Larry Trueman has summarized the bulk of the conclusions from the Workshop on High Energy Polarimetry held at the RIKEN/BNL Center during the summer of 1997. In my talk I shall focus on just one result, in many ways a most surprising one, that emerged from that study. Namely that at high energies and very small momentum transfer *pp* elastic scattering is "self-analyzing", in the sense that the measurement of a sufficient number of observables, using a polarized beam and target, allows a determination of both the helicity amplitudes of the reaction *and* the degree of polarization of beam and target. This is, in a way, quite different from the traditional methodology, where, knowing the polarization of beam and target, one measures enough observables to determine the amplitudes. The reason one obtains the extra information i.e. the polarization of beam and target, is very simple. One is in the region of momentum transfer where interference between unknown hadronic and known electromagnetic amplitudes is important. This, somehow, provides the extra input needed.

The results we get have essentially zero theoretical error. More precisely, if the measurement of the observables had zero error the result for the analyzing power of the *pp* reaction would be correct up to tiny errors of order $\alpha(QED)$. What we do not know is how the effect of experimental errors will influence this.

These results add one more important reason why a detailed study of spin-dependence in *pp* elastic scattering should be carried out, as it uniquely can be, at RHIC.

AN ABSOLUTE POLARIMETER FOR PROTONS.

N.H. BUTTIMORE, B.Z. KOPELIOVICH, E. LEADER,
J. SOFFER, T.L. TRUEMAN

PHYS. REV. D59 (1999) 114010

1) BACKGROUND TO THE PROBLEM : CNI

2) A SURPRISING DISCOVERY :

"PROTON - PROTON SCATTERING

IS SELF - ANALYZING"

* CAN MAKE A COMPLETE DETERMINATION *
OF ALL THE pp HELICITY AMPLITUDES
AT SMALL t

1) BACKGROUND

WORKSHOP BNL-RHIKEN TO STUDY ACCURACY OF COULOMB-NUCLEAR INTERFERENCE POLARIMETER FOR RHIC. (1997)

RHIC REQUIREMENT $\pm 5\%$ on P.

* STIMULATED DEVELOPMENT OF CARBON POLM. *

CNI ANALYZING POWER: $pp \to pp$

$$A_N \frac{d\sigma}{dt} = -\frac{4\pi}{s^2} \, \mathrm{Im} \left\{ \phi_5^* \left(\phi_1 + \phi_2 + \phi_3 - \phi_4 \right) \right\}$$

$$\phi_j = \phi_j^N + \phi_j^{EM} e^{i\delta}$$

Hadronic Amp.

1 Photon exchange; REAL

Coulomb Phase

[illegible] m^2 can [illegible]

ϕ_2 AND ϕ_4

$$A_N \frac{d\sigma}{dt} \propto \mathrm{Im}\left\{ \left(\phi_+^N + e^{i\delta}\phi_+^{EM}\right)\left(\phi_5^N + e^{i\delta}\phi_5^{EM}\right)\right\}$$

TO SEE MAIN STRUCTURE, IGNORE δ :

$$\phi_+ \equiv \frac{1}{2}\left(\phi_1 + \phi_3\right)$$

$$A_N \frac{d\sigma}{dt} \propto \underbrace{\left(\mathrm{Im}\,\phi_+^N\right)}_{\sigma_{TOT}} \phi_5^{EM} - \phi_+^{EM}\left(\mathrm{Im}\,\phi_5^N\right)$$

VERY ACCURATELY KNOWN

?

NEED

$$\phi_5^N = \langle ++ | M | +- \rangle \text{ AT RHIC}$$

FOLKLORE : $r_5 \equiv \dfrac{m\,\phi_5^N/\sqrt{-t}}{\mathrm{Im}\,\phi_+^N} \approx 0$

EXTRAPOLATION OF DATA : $r_5 \lesssim 10\%$

MODELS : $-6\% \leq \mathrm{Im}\, r_5 \leq +13\%$

RIGOROUS THEORY : $|r_5| \lesssim \ln s$!!!

2) SELF-SPIN-ANALZING PROPERTY OF $pp \to pp$.

- CONVENTIONAL WISDOM:

  KNOWING POLARIZATION OF BEAM AND TARGET, WITH ENOUGH EXPERIMENTS, CAN MEASURE THE AMPLITUDES ϕ_j.

- NEW:

  a) KNOWING BEAM AND TARGET ARE POLARIZED, BUT NOT KNOWING MAGNITUDE $\mathcal{P}$ OF POLARIZATION,

  b) KNOWING THAT ROTATION OF SPIN FROM TRANSVERSE TO LONGITUDINAL DOES NOT ALTER $\mathcal{P}$,

CAN MEASURE ALL ϕ_j AT VERY SMALL t

$\therefore$ WILL KNOW A_N

$\therefore$ CAN MEASURE $\mathcal{P}$!

EXPRESSIONS FOR OBSERVABLES AT SMALL $|t|$: –

$$\frac{m\sqrt{-t}}{\sigma_{\rm tot}} P A_N \frac{d\sigma}{dt} = -\alpha\, a_N + \frac{\sigma_{\rm tot}}{8\pi} b_N\, t + \ldots,$$

$$\frac{t}{\sigma_{\rm tot}} P^2 A_{LL} \frac{d\sigma}{dt} = \alpha\, a_{LL} + \frac{\sigma_{\rm tot}}{8\pi} b_{LL}\, t + \ldots,$$

$$\frac{t}{\sigma_{\rm tot}} P^2 A_{NN} \frac{d\sigma}{dt} = \alpha\, a_{NN} + \frac{\sigma_{\rm tot}}{8\pi} b_{NN}\, t + \ldots,$$

$$\frac{t}{\sigma_{\rm tot}} P^2 A_{SS} \frac{d\sigma}{dt} = \alpha\, a_{SS} + \frac{\sigma_{\rm tot}}{8\pi} b_{SS}\, t + \ldots.$$

$$-\frac{m\sqrt{-t}}{\sigma_{\rm tot}} P^2 A_{SL} \frac{d\sigma}{dt} = \alpha\, a_{SL} + \frac{\sigma_{\rm tot}}{8\pi} b_{SL}\, t + \ldots.$$

5

Expressions for coefficients :-

asymmetry	a_i	b_i
A_N	$P\{\frac{\kappa}{2}(1+I_2)-I_5\}$	$PI_5\{(\rho-\rho_5)+I_2(\rho_2-\rho_5)\}$
A_{NN}	P^2R_2	$P^2R_2\{\rho+\frac{1}{\rho_2}+I_-(\rho_-+\frac{1}{\rho_2})\}$
A_{LL}	P^2R_-	$P^2\{R_-(\frac{1}{\rho_-}+\rho)+R_2I_2(\frac{1}{\rho_2}+\rho_2)\}$
A_{SL}	$P^2\{\frac{\kappa}{2}(R_-+R_2)\}$	$P^2I_5\{(I_-+I_2)+\rho_5(R_-+R_2)\}$

Also have:

$$P^2\Delta\sigma_T = -2I_2\,\sigma_{TOT}P^2$$

$$P^2\Delta\sigma_L = -2I_-\,\sigma_{TOT}P^2$$

Notation: $\phi_\pm^N = \frac{1}{2}(\phi_1^N \pm \phi_3^N)$

$$\rho = \frac{\mathrm{Re}\,\phi_+^N}{\mathrm{Im}\,\phi_+^N} \qquad \rho_j = \frac{\mathrm{Re}\,\phi_j^N}{\mathrm{Im}\,\phi_j^N} \quad j=2,4,5$$

$$R_2 + iI_2 = \frac{\phi_2^N}{2\,\mathrm{Im}\,\phi_+^N} \qquad R_- + iI_- = \frac{\phi_-^N}{\mathrm{Im}\,\phi_+^N}$$

[illegible] ϕ_4^N $\qquad R_5 + iI_5$ [illegible]

[illegible] t [illegible] ϕ^N $\qquad \sqrt{-t}\ \mathrm{Im}\,\phi_+$

BY TAKING SUITABLE RATIOS AND COMBINATIONS OF THE MEASURED PARAMETERS CAN SOLVE FOR ALL THE AMPLITUDES. (see paper)

EXAMPLE:

$$\mathcal{P}^2 = \frac{a_{NN}^2 + \left[\mathcal{P}^2 \Delta\sigma_T / 2\sigma_{TOT}\right]^2}{b_{LL} - \left[\mathcal{P}^2 \Delta\sigma_L / 2\sigma_{TOT}\right] - \rho\, a_{LL}}$$

SOLVE for $\mathcal{P}^2$. Then --

CAN USE THIS TO CALCULATE A_N

THEREAFTER USE CNI MEASUREMENT OF $\mathcal{P} A_N$ TO MEASURE $\mathcal{P}$.

THIS IS, IN PRINCIPLE,

AN ABSOLUTE

POLARIMETER

[illegible] $\approx \alpha$ (QED)

EXPERIMENTAL ERROR ??

Conclusion

1) RHIC will carry out a unique program, using its polarized beams, to test the Standard Model in a totally new regime. Knowledge of the beam polarization is crucial for the level of accuracy envisaged. An absolute polarimeter, to calibrate the on-line relative polarimeters is thus very important.

2) Quite aside from this RHIC offers a unique opportunity to study all sorts of fascinating questions about $pp \to pp$, linked to fundamental aspects of QCD. Aside from the question of spin-dependence, even an accurate measurement

8

of the pp total cross-section, and comparison of it with the $\bar{p}p$ cross-section measured at the CERN $Sp\bar{p}S$, might have extraordinary consequences!

9

Workshop on High Energy Polarimetry

August 18, 1999

Organizer: Elliot Leader

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Workshop on High Energy Polarimetry
August 18, 1999
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Workshop on High Energy Polarimetry
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RIKEN/BNL Workshop on High Energy Polarimetry

Wednesday 18th August, 1999
Physics Department
Room 2-160
Brookhaven National Laboratory
Organizer: Elliot Leader

9:15		**Coffee**
9:30	T. Kirk	(BNL) *Welcome*
9:35	T.L. Trueman	(BNL) *Spin dependence of high energy proton scattering*
10:35		**Coffee**
10:50	H. Huang	(BNL) *Experimental work on the proton-Carbon CNI polarimeter*
11:25	W. Guryn	(BNL) *Polarimetery using proton-proton CNI*
12:00		**Lunch**
13:30	G. Sterman	(SUNY, Stony Brook) *Single-spin production asymmetries at RHIC from factorized cross-sections*
14:30	M. Anselmino	(Istituto di Fisica Teorica, Turin) *Phenomenology of transverse single-spin asymmetries in inclusive processes*
15:30		**Tea**
15:45	C. Allgowar	(ANL) *Measurements of pion asymmetries from a 22 GeV/c polarized proton beam in preparation for RHIC*
16:15	E. Stephenson	(IUCF) *Asymmetry in pn charge exchange reactions*
15:45	E. Leader	(Birkbeck College, London) *An absolute polarimeter for high energy protons*
17:15		**End**

Forthcoming RIKEN BNL Center Workshops

Title:	**RHIC Spin**
Organizer:	G. Bunce
Dates:	Oct. 6–8, 1999

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

HIGH ENERGY POLARIMETRY

AUGUST 18, 1999

Li Keran

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Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T. D. Lee

Speakers:

C. Allgowar
H. Huang
G. Sterman
M. Anselmino
E. Leader
T.L. Trueman
W. Guryn
E. Stephenson

Organizer: Elliot Leader