Special Symposium on RHIC
RHIC and AGS Users Meeting
28 May 2008

RHIC Spin—Where did it come from?

--a fable with a moral

G. Bunce with help from Mike Tannenbaum, Nick Samios, Yousef Makdisi, Hiromi Okada, Haixin Huang, and more

many interweaved threads:

--accelerating and measuring polarized protons

--large spin effects at high energy

  --unexpected and expected

--the W

--the polarized DIS story and the proton spin “crisis”

--perturbative description of p-p collisions

  --and many other theoretical advances

--making the case and getting support

The 1970s…

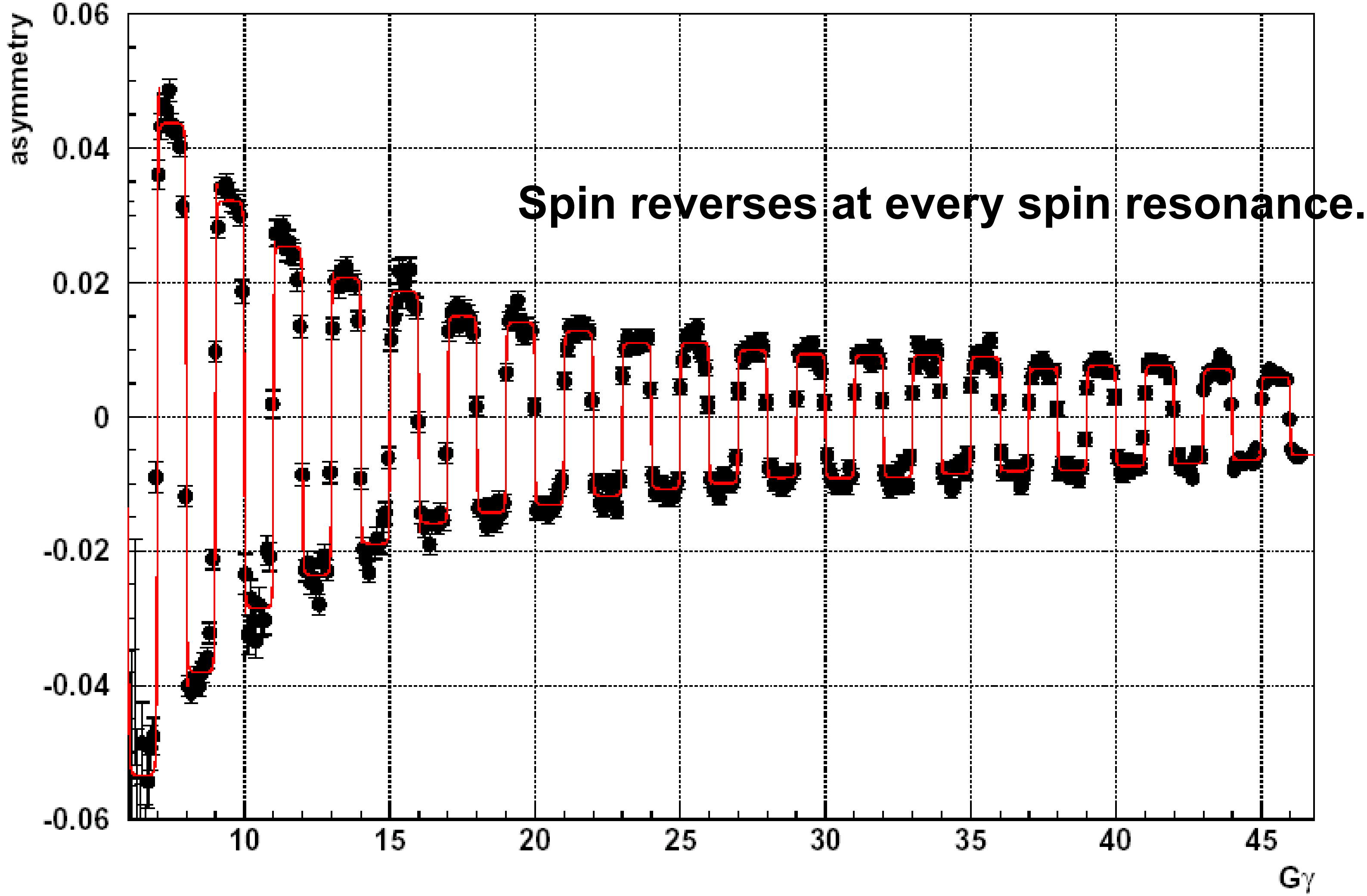
Accelerating and measuring polarized protons…

--the problem and solution is the very large anomalous magnetic moment of the proton (and the large proton anomalous magnetic moment is the basis of RHIC Spin, and RHIC polarimetry)

The problem of spin resonances:

- Spin precesses about guide field (proton: 200 precessions in one turn at RHIC, 100 GeV)
- Spin precesses about horizontal magnetic fields (for example, focusing fields)
- When the 2 precessions beat, resonance condition: every 500 MeV of acceleration!

Polarization Measurement on AGS Ramp



5 AGS 2005 16 23 GeV

(with snakes)

Solution (1973): Siberian Snakes

Polarization kinematics of particles in storage rings.
Ya.S. Derbenev, A.M. Kondratenko (Novosibirsk, IYF) . Jun 1973. 6pp.
Published in **Sov.Phys.JETP 37:968-973,1973, Zh.Eksp.Teor.Fiz.64:1918-1929,1973**.
TOPCITE = 50+ Cited 67 times

Spin resonance: spin axis is no longer vertical

Snake: precess spin 180 degrees about axis in horizontal plane.
Two orthogonal snakes: flip non-vertical component of spin each turn.
Spin unwinds away from vertical in one turn, and winds back to vertical in the next turn.
Spin resonance does not build up.

1970s: Development of polarized proton acceleration in 12 GeV ZGS --weak focusing machine

Acceleration of Polarized Protons to 8.5-GeV/c.

T. Khoe, et al. (Argonne) , A.D. Krisch, J.B. Roberts (Michigan U.) , J.R. O'Fallon (St. Louis U.) . Print-74-0985, (Received May 1974).

note: no siberian snakes

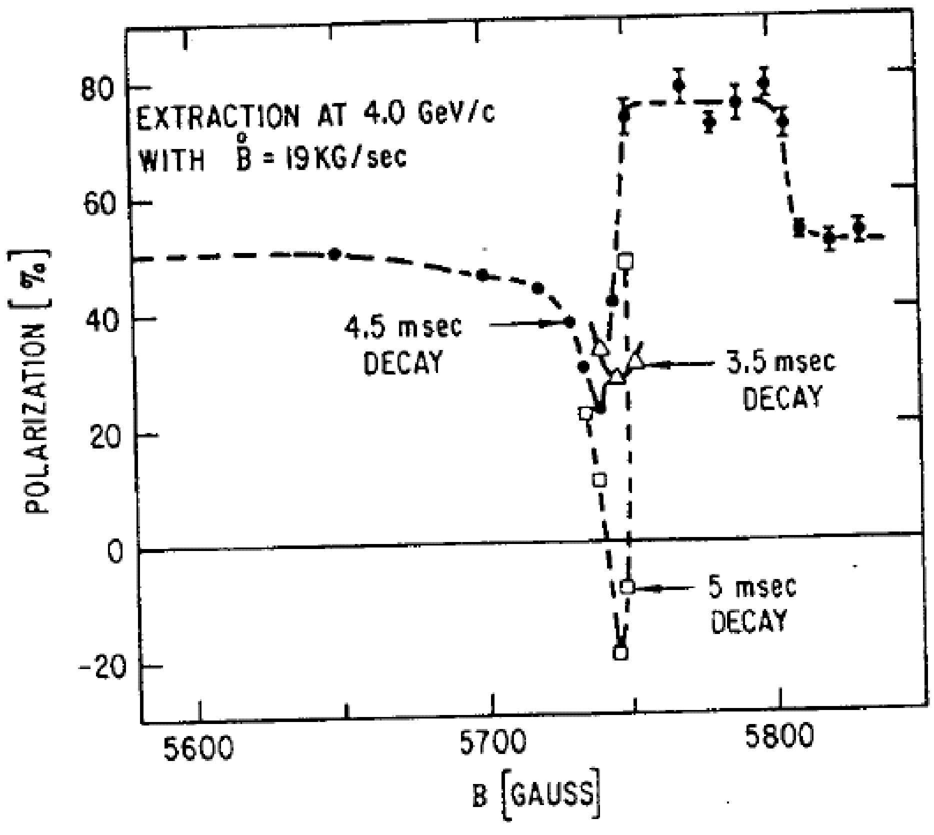


Figure 7 Polarization as a Function of Quadrupole Pulse Turn-on Time

NIM 1979: describes development of PEGGY

--started in late 1950s

A SOURCE OF HIGHLY POLARIZED ELECTRONS AT THE STANFORD LINEAR ACCELERATOR CENTER*

A polarized electron source based upon photoionization of a state-selected ^{6}Li atomic beam has been developed as an injection gun for the Stanford two-mile electron linear accelerator. The source (PEGGY) produces a pulsed beam of electrons with a maximum intensity of 2.6×10^9 electrons per pulse, a polarization of 0.85, a pulse length of 1.6 μs, and a repetition rate of 180 pulses/s. Since its installation at SLAC in July 1974, PEGGY has been used in several high energy electron–nucleon scattering experiments.

PRL 1978: first measurement of proton spin structure

$\vec{e} + \vec{p} \to e' + X$

Deep-Inelastic *e-p* Asymmetry Measurements and Comparison with the Bjorken Sum Rule and Models of Proton Spin Structure

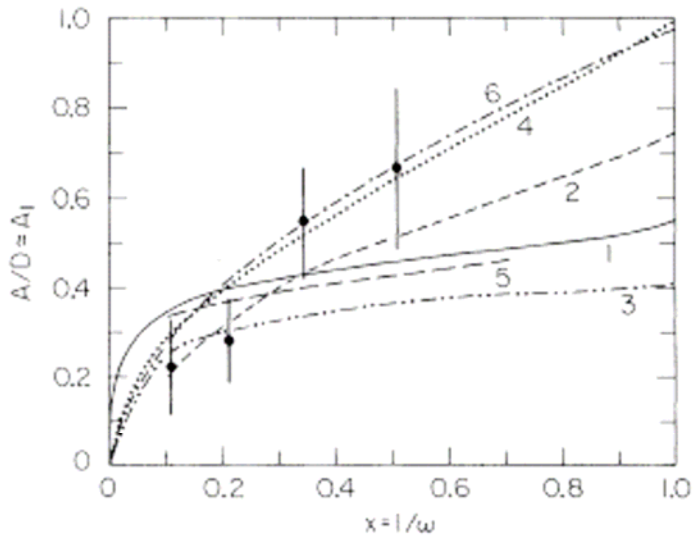


FIG. 3. Experimental values of $A/D \simeq A_1$ compared to theoretical predictions for A_1. The models are as follows: (1) a relativistic symmetric valence-quark model of the proton (Ref. 14); (2) a model incorporating the Melosh transformation which distiguishes between constituents and current quarks (Ref. 15); (3) a model introducing nonvanishing quark orbital angular momentum (Ref. 16); (4) an unsymmetrical model in which the entire spin of the nucleon is carried by a single quark in the limit of $x = 1$ (Ref. 17); (5) the MIT bag model of quark confinement (Ref. 18); (6) source theory (Ref. 19).

For hadronic scattering…

--spin effects expected to die out at high energy, and hard scattering

--but two surprises

--actually 3 surprises…

p + p → Lambda↑ + X (Fermilab)

Λ^0 Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium

PRL 1976

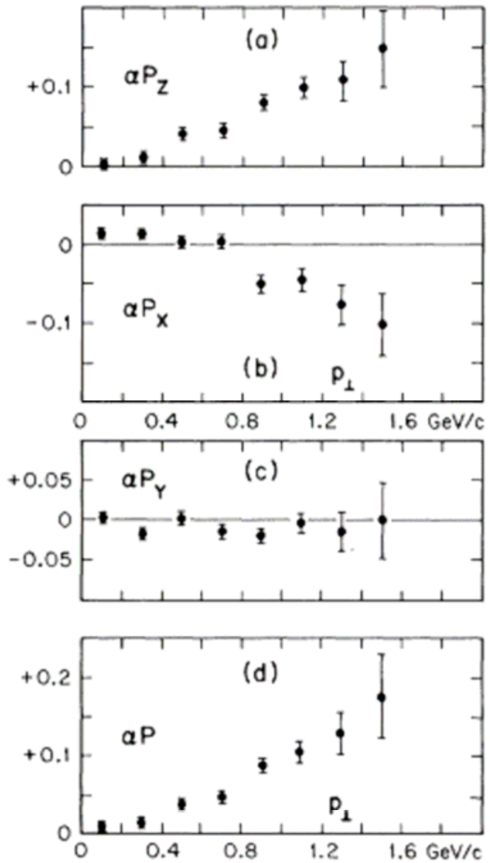


FIG. 3. Three components and magnitude of the $\Lambda^0 \to p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.

p↑ + p↑ → p + p (ZGS)

Spin Dependence of High-$P_\perp^2$ Elastic p-p Scattering

PRL 1978

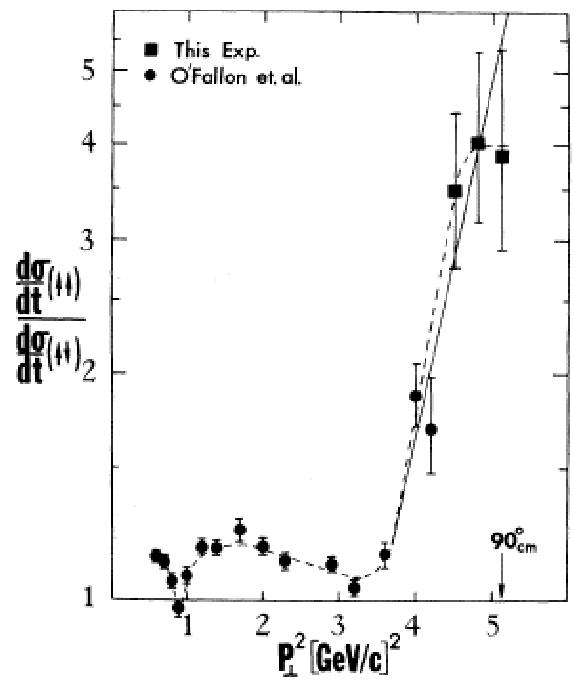
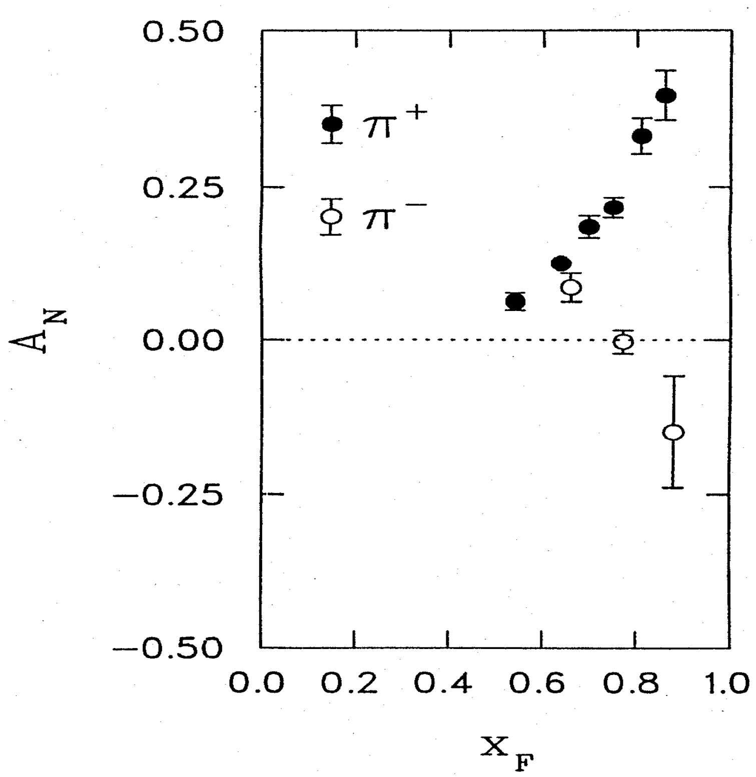


FIG. 1. Plot of the ratio of the differential elastic cross sections in pure initial-spin states for $p+p \to p+p$ at $P_{1ab}=11.75$ GeV/c. The spin-parallel cross section increases dramatically relative to the spin-antiparallel cross section at the onset of the hard-scattering component at $P_\perp^2=3.6$ (GeV/c)^2. The curves are only to guide the eye.

Also at ZGS: Inclusive pion production

p↑ + p → pi + X



Phys. Rev. D.18 (1978) 3939-3945

PHYSICAL REVIEW D VOLUME 19, NUMBER 3 1 FEBRUARY 1979

W - 4

Estimates of W production with polarized protons as a means of detecting its hadron jet decays

Frank E. Paige, T. L. Trueman, and Thomas N. Tudron
Brookhaven National Laboratory, Upton, New York 11973
(Received 20 September 1978)

We discuss the measurement of parity-violating asymmetries in polarized-proton-proton scattering at high energy as a method of extracting the hadronic decays of the intermediate vector boson from the high-transverse-momentum hadronic background. In particular we present predictions for these asymmetries for jet production through the charged and neutral vector bosons. The asymmetries are very large and the method looks promising.

One of the most interesting and difficult problems in the anticipated experimental studies of the W meson is how to measure its hadronic decays. Although the W is expected to be produced copiously at very high energies, as will be provided by ISABELLE,[1] and to decay most of the time into hadrons, the problem of extracting the signal from the high-$p_\perp$ hadronic background is very acute.[2,3] Some methods have been analyzed,[4] relying on the fact that the hadrons from W decay should be richer in strange or charmed particles than the background, but the outlook for these is uncertain.

Recent indications that it may be possible to store polarized protons in ISABELLE (Ref. 5) at high luminosity have led us to consider what seems to us the cleanest method of extracting the W signal from the background, viz., to measure high-$p_\perp$ jets produced with polarized protons in states of definite helicity. Because of the $V-A$ coupling to charged W's generally assumed in the theory, only left-handed quarks will produce W's. To the extent that the quarks within the proton have their helicity correlated with the proton helicity, left-handed protons should produce an appreciably larger number of W's than right-handed protons, and so the difference between the cross section for high $p_\perp$ jets produced with left-handed and right-handed protons should show a substantial W signal above a zero background from hard hadronic scattering. Many models of the spin wave function of [illegible]

nal for hadronic jets.

The calculations in this work are based on the simple model of W production and decay given in Ref. 3, supplemented by the SU(6) model for the quark-spin wave function. The model is the quark-parton model with the Drell-Yan mechanism for W production, with structure functions chosen to agree with electroproduction and lepton-pair-production data. (See Ref. 3 for a complete set of references.) We realize that there may be many corrections to this model, but we feel that for our purposes this simple approach is adequate. Thus we do not include any transverse momentum for the W. These effects are not expected to be very important.[3,9] In any case, our emphasis here is on measurements of both jets coming from the W decay and so the transverse momentum effects are controllable. There are also expected to be corrections due to violation of scaling. Fortunately, various estimates of these corrections indicate that they are not large in the region of m_W^2/s for which our calculations are done.[10]

We will assume that the quark distributions can be broken up into valence plus sea quarks and that the sea quarks are unpolarized. Thus we have, e.g.,

$$u(x) = u_v(x) + s(x),$$

$$d(x) = d_v(x) + s(x),$$

with

Parity violating W Production

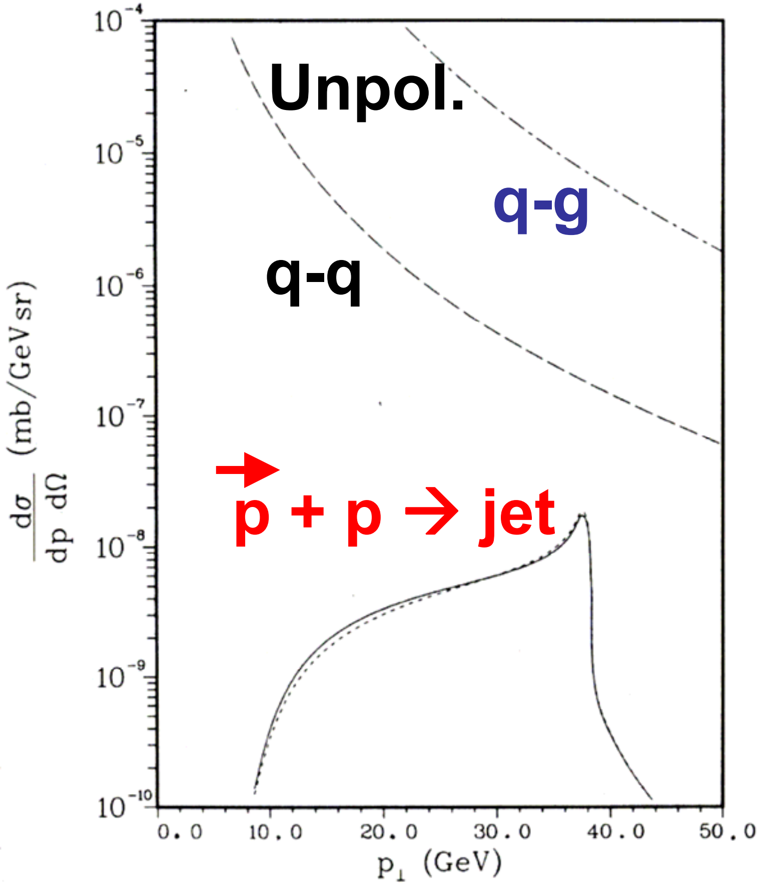


FIG. 2. Single-jet cross sections for $W^{\pm}$ at $\sqrt{s}=800$ GeV, $\theta=90°$. Solid curve: Polarization asymmetry for $W^{\pm}$. Dotted curve: Unpolarized cross section for $W^{\pm}$. Dashed curve: Unpolarized cross section for quark-quark scattering. Dot-dashed curve: Unpolarized cross section for quark and gluon scattering.

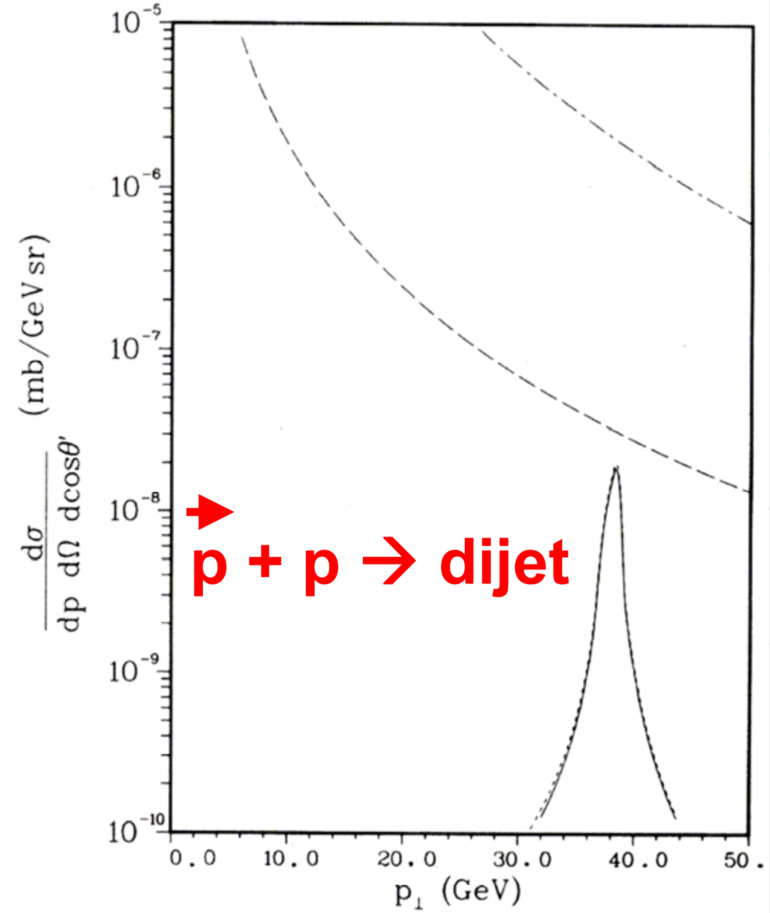


FIG. 3. Double-jet cross sections for $W^{\pm}$ at $\sqrt{s}=800$ GeV, $\theta_1=\theta_2=90°$. The curves have the same meanings as in Fig. 2.

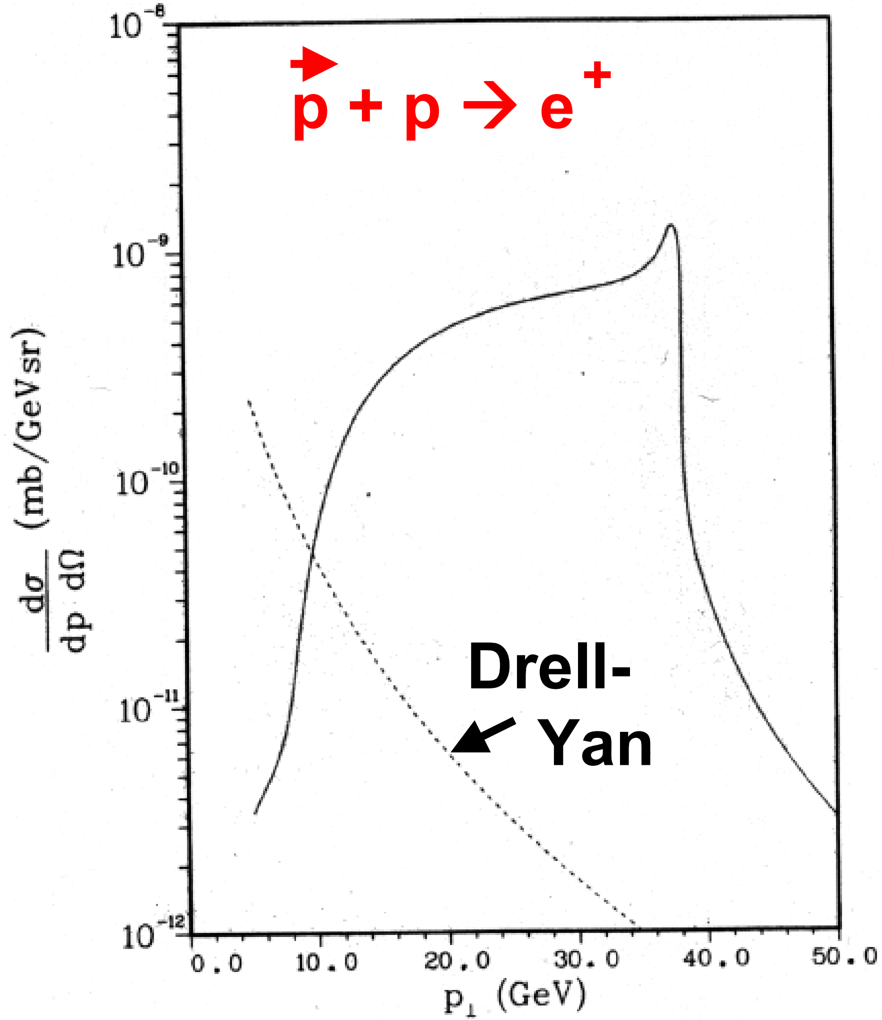


FIG. 8. Single e^+ cross section at $\sqrt{s} = 800$ GeV, $\theta = 90°$. Solid curve: Polarization asymmetry for $W^+ \to e^+\nu$. Dotted curve: Unpolarized cross section for Drell-Yan process.

1979: EMC – 9

is not due to some new hadron. Further, it provides a test of the model which is used and a measure of the quark-spin wave function. It would seem a very important experiment to perform in conjunction with the hadronic-jet-decay study. The difference in the single-lepton spectrum coming from W^+ and W^- decay between left-handed and right-handed protons is shown in Figs. 8 and 9, respectively, along with the Drell-Yan background.[3]

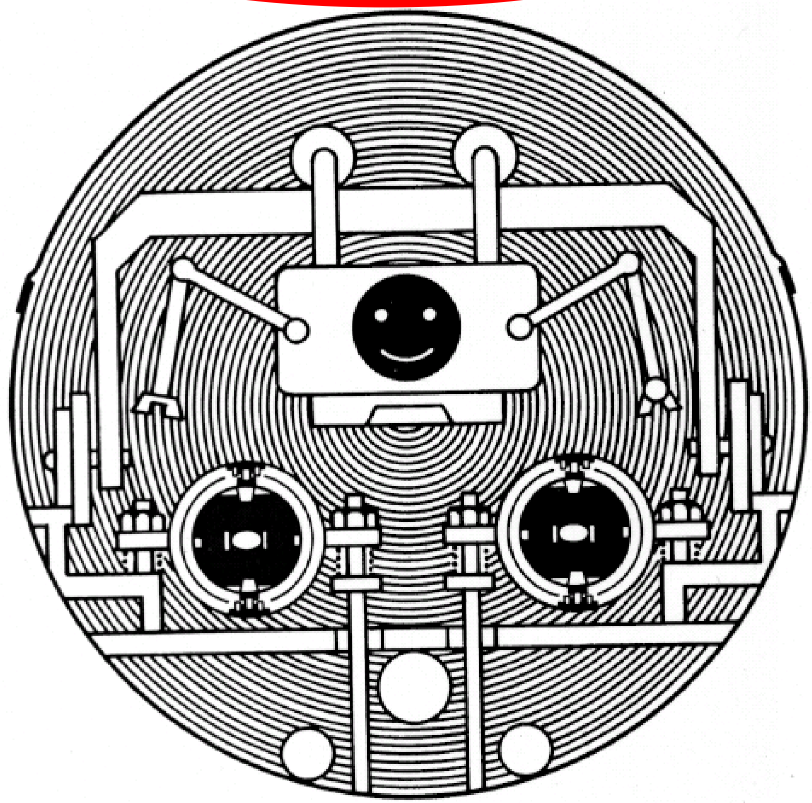
In conclusion, it seems that polarized proton beams colliding a the most practic cays of the W.

We would like t suggesting the po larized beams at I a helpful discuss authored under C with the U.S. Dep

1980s…

Proceedings Of The 1982 DPF Summer Study On Elementary Particle Physics And Future Facilities

June 28-July 16, 1982
Snowmass, Colorado



Editors
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W,Z° PRODUCTION AT A PP COLLIDER

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I. W,Z° Production at a pp Collider

Introduction

We have examined some experimental questions relating to the production of W's and Z°'s at a pp collider. To be specific we have considered a Colliding Beam Accelerator (CBA) with center of mass energy $\sqrt{s}$ = 800 GeV and luminosity $L = 10^{33}\,cm^{-2}sec^{-1}$ (the standard BNL Isabelle (ISA) operating conditions). Most experiments should accumulate 10^7 sec of beam and therefore will have an integrated luminosity $L = 10^{40}\,cm^{-2}$. This corresponds to the production of millions of conventional charged W's per interaction region and gives the potential for high statistics studies of the properties of W's and for experiments searching for higher mass objects.

The specific topics considered are outlined here and discussed in more detail in the following sections:

a) $W^\pm$ production: $pp \to W^\pm + X$, $W^\pm \to e^\pm + \nu$

The $W^\pm$ cross section is $3.5 \times 10^{-33}\,cm^2$ for W^+ ($1.6\times10^{-33}\,cm^2$ for W^-) at $\sqrt{s}$ = 800 GeV.[3] Since the $W^\pm \to e^\pm\,\nu$ branching ratio is calculated to be 8.5%, a total of 3×10^6 W^+ ($1.4\times10^6\,W^-$) semileptonic $W^\pm$ decays are detectable in an experiment with an integrated luminosity of $10^{40}\,cm^{-2}$. We have considered (Section II) the feasibility of doing this experiment and the mass resolution on the $W^\pm$ one might finally attain. Running at $L = 10^{33}\,cm^{-2}sec^{-1}$ is not a problem. The trigger rate for a reasonable lepton P_T cut ($P_T > 20$ GeV/c) can easily be reduced to less than 1 per second. The pile up due to event overlap

c) Polarization effects in $W^\pm$ production

The AGS at Brookhaven will soon be running with a polarized proton beam. This can be transported to the CBA to give a colliding polarized beams option. There

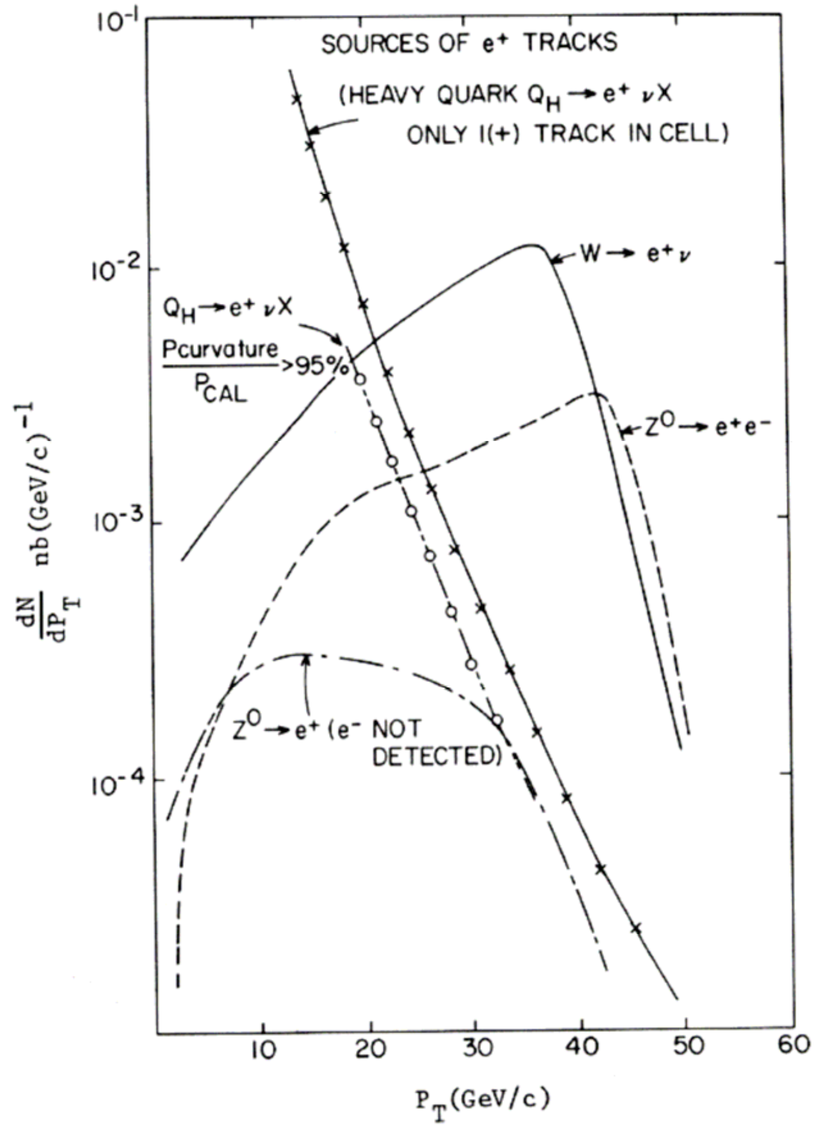


Fig. 2. Sources of high P_T positrons.

m_W = 80 GeV?

1982: W – 1

Measuring Polarization and Polarization Reversal[14]

A 5% measurement of P in 1 minute can be done using the Coulomb-nuclear interference region where the p-p analyzing power can be calculated (it is a few %). Note that the precise polarization enters most physics results only as an overall normalization, independent of P_T or dilepton masses, for example.

Polarization reversal can be done by slowly reversing the fields in the snakes and can be done hourly. If box-car stacking is used, alternate cars can have opposite polarization, effectively eliminating systematic biases.

Statistical Significance of using Polarization to Study Weak Effects

Paige, Trueman and Tudron[15] calculated that with a 100% polarized proton beam, $\sigma_- \approx 3\sigma_+$. For a 70% polarized beam, $\sigma_- \approx 2\sigma_+$. ($\sigma_-$ is the cross section with both protons left-handed, σ_+ with both right-handed.) With a polarized beam available, one can

a) add the +,− helicities together giving the unpolarized result.

b) Use the subtraction $(\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ to eliminate strong-interaction background with no assumptions about the background. One can do this bin-by-bin (say, in energy or P_T bins) to find the shape of the signal. The statistical signal is 1/1.5 smaller than the unpolarized case, but the background uncertainty is eliminated (more on this later).

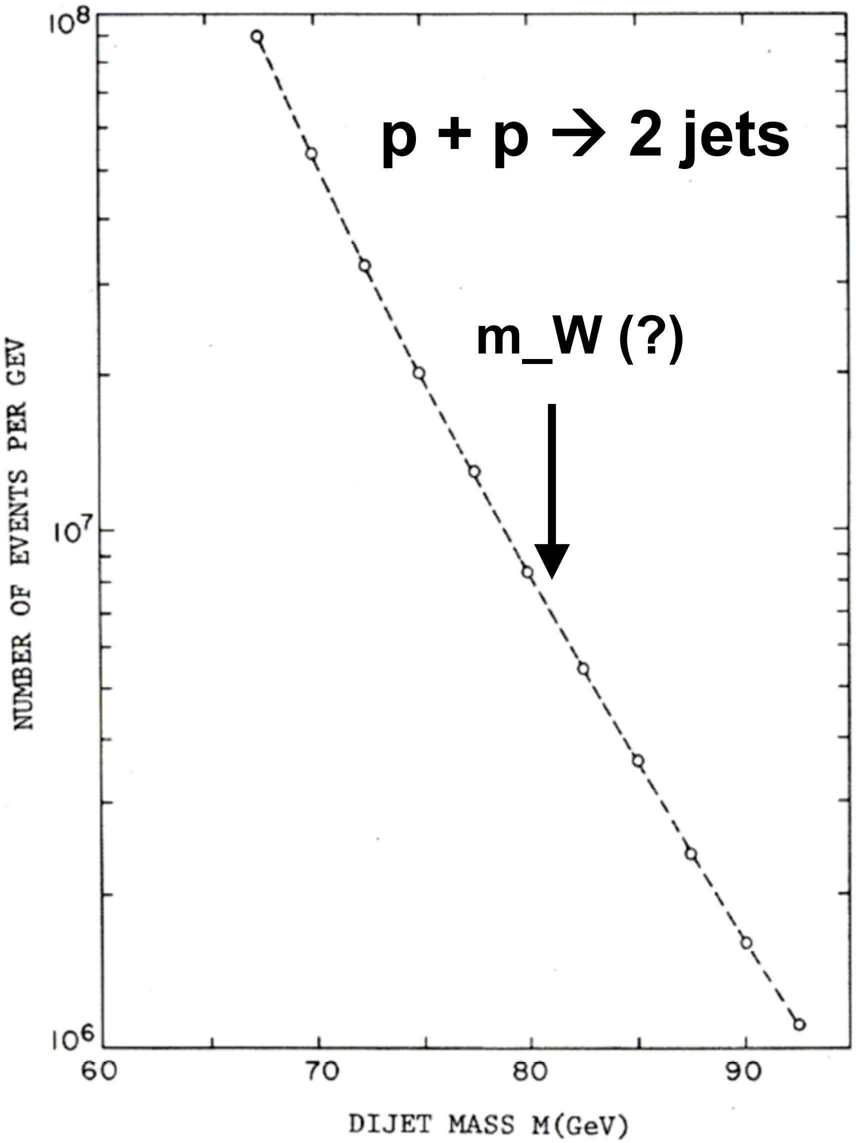


Fig. 13. Effective mass distribution for pairs of jets

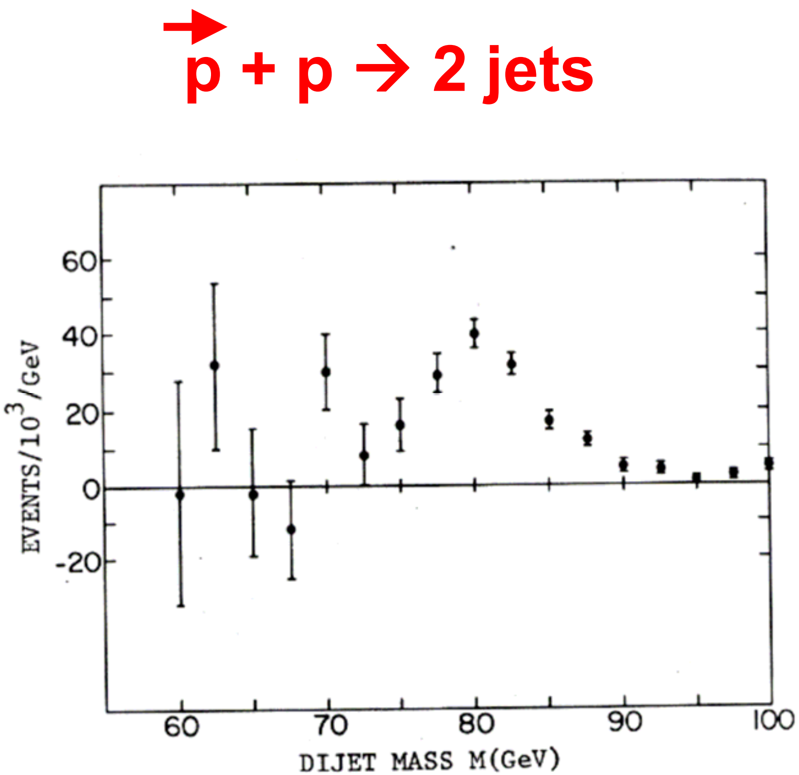


Fig. 15. Mass distribution of jet pairs obtained by subtracting bin by bin the distributions for each polarization.

…simulation of parity-violating subtraction

Obviously, one can use this technique to verify and measure the magnitude of parity violation in $W \to e + \nu$ or $W \to \mu + \nu$. This would be a very strong clear signal. If a second, higher mass W were discovered this would be especially exciting because the second W could couple either to left- or right-handed currents, and the two cases are distinctly different in this regard.

Two spin effects (the dependence of cross sections on the relative polarization states of the initial proton beams) are a valuable QCD test, as has been analyzed in detail by Babcock, Monsay and Sivers.[16] Also one would like to extend experiments of the type carried out by Krisch's group at Argonne to higher energy and P_T.[17] Single-spin asymmetries are predicted by QCD to be zero, in leading order, but in view of the large hyperon polarization seen in lower energy experiments, which is not understood,[18] it would be very interesting to carry out the analogous experiment, looking at the dependence on initial state proton polarization. Obviously, the polarization of final state hyperons is another interesting experiment. The correlation of the hyperon polarization with initial polarization is an obvious case. Finally, Sivers[19] has pointed out that the two-spin asymmetry in $pp \to \gamma + X$ is sensitive to the spin dependence of the gluon structure functions.

EMC - 6

Physics Letters B122, 24 February 1983, Pages 103-116:

Experimental observation of isolated large transverse energy electrons with associated missing energy at root(s)=540 GeV

UA1 Collaboration, CERN, G. Arnison, et al.

We report the results of two searches made on data recorded at the CERN SPS Proton-Antiproton Collider: one for isolated large-*E*T electrons, the other for large-*E*T neutrinos using the technique of missing transverse energy. Both searches converge to the same events, which have the signature of a two-body decay of a particle of mass 80 GeV/*c*. The topology as well as the number of events fits well the hypothesis that they are produced by the process pbar + p → W^+/- + X, with W^+/- →e^+/- + v; where W^+/- is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

Fast forward a few years…

- ---demise of Isabelle 1983
- ---development of RHIC proposal for heavy ion physics soon after
- ---polarized proton program at AGS mid 80s
- ---EMC: deep inelastic scattering of high energy polarized muons with a polarized proton target: (q + qbar) carry little of the proton spin!—1988/9

PRD 1989: summarized development of p↑ in AGS

Acceleration of polarized protons to 22 GeV/c and the measurement of spin-spin effects in $p_{\uparrow}+p_{\uparrow}\rightarrow p+p$

A tour de force: the AGS is a strong focusing machine.

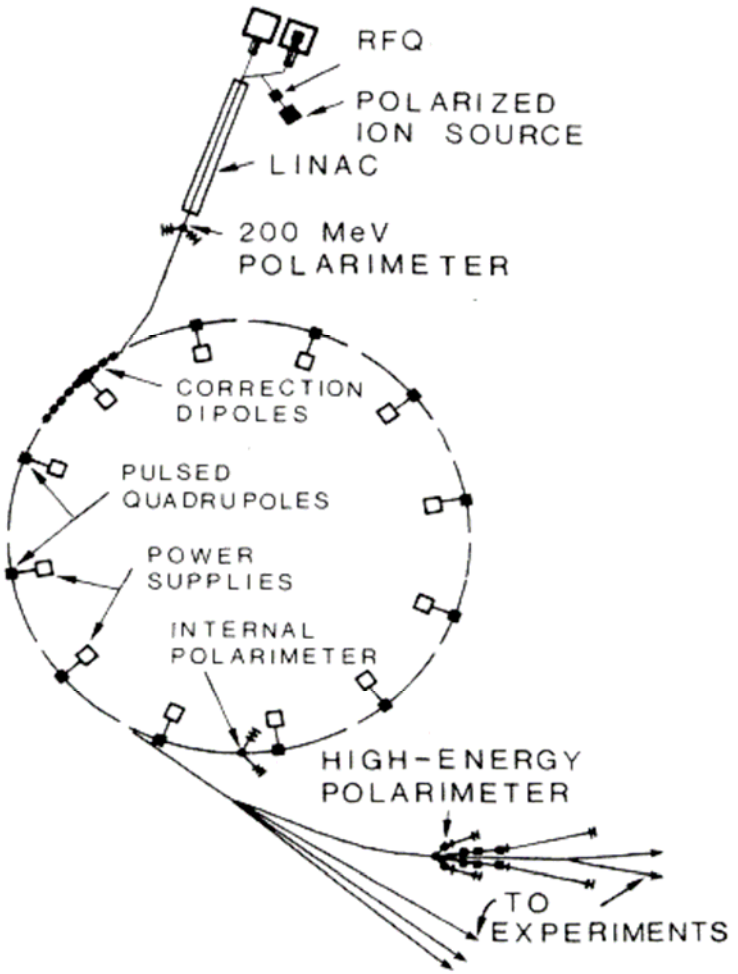


FIG. 1. AGS layout for the operation of the polarized proton beam.

about 40 of these to reach 22 GeV…

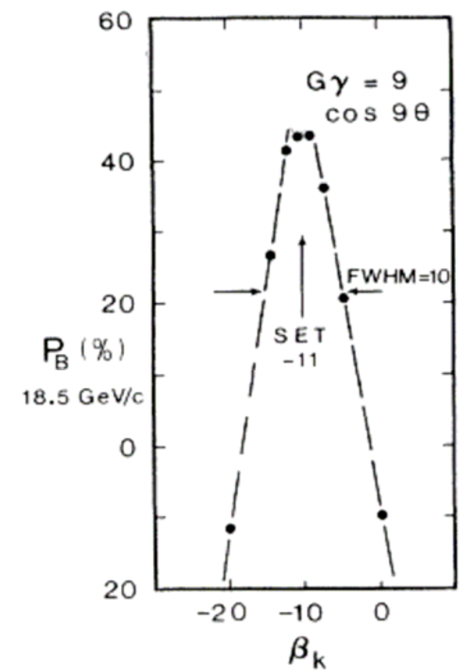
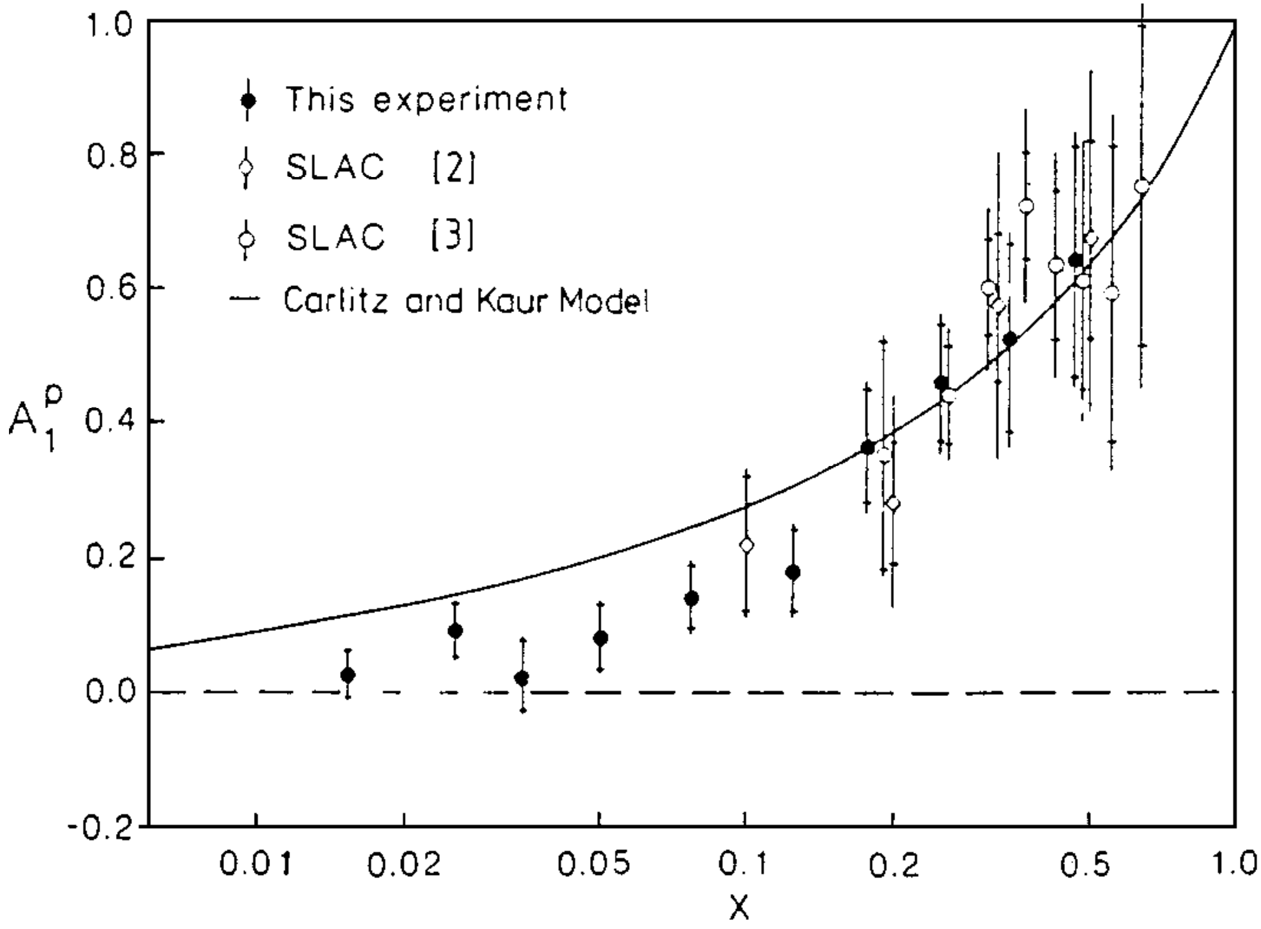


FIG. 26. The ninth harmonic cos(9θ) amplitude correction curve for the $G\gamma=9$ imperfection depolarizing resonance. The beam polarization is plotted against the dipole's ninth cosine amplitude β_9 in arbitrary units.

EMC at CERN: J. Ashman et al., NPB 328, 1 (1989):

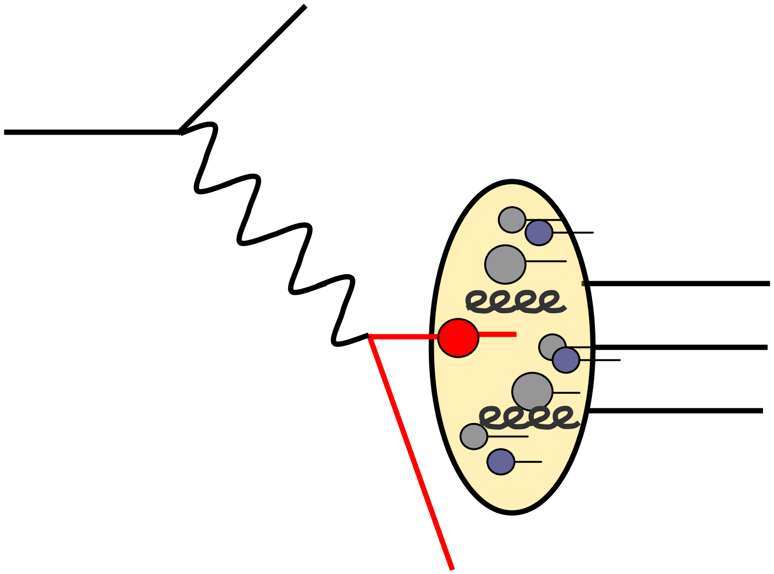
polarized muons probing polarized protons



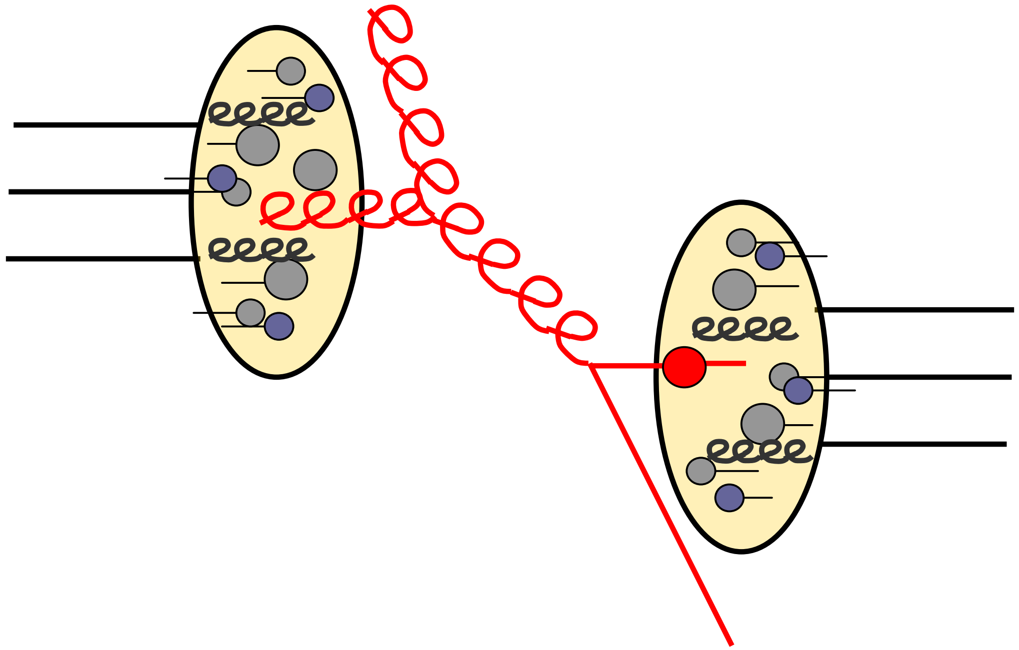
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin crisis"

DIS



pp



PRL 1989: siberian snake test at IUCF

First Test of the Siberian Snake Magnet Arrangement to Overcome Depolarizing Resonances in a Circular Accelerator

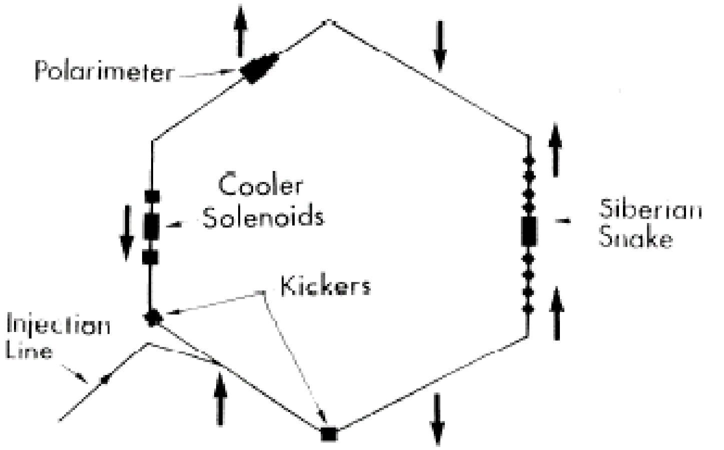


FIG. 1. Diagram of the IUCF Cooler Ring with the Siberian snake test installed. Note the kicker magnets for injection of polarized beam, the CE-01 detector used as a polarimeter, the Siberian snake, and the Cooler Ring solenoids. Each arrow indicates the stable horizontal polarization direction at 108 MeV with the snake on.

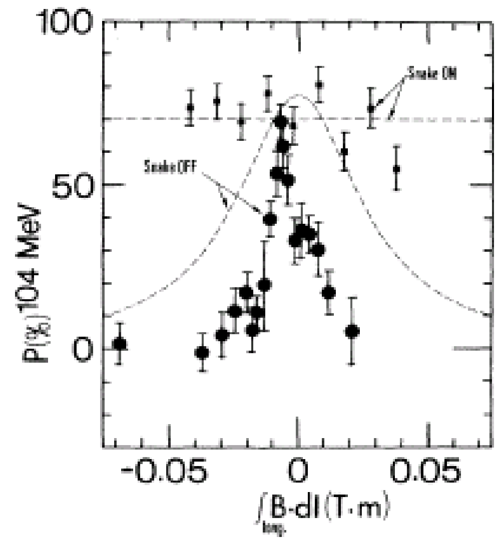


FIG. 4. The beam polarization in each stable polarization direction at 104 MeV is plotted against the longitudinal magnetic field integral in the Cooler Ring solenoids. The circles are the vertical polarization with the snake off and the injection of vertically polarized protons. The squares are the radial polarization with the snake on and the injection of horizontally polarized protons. We combined all data into bins of width 0.001 15 Tm. There is a systematic normalization uncertainty of about ±5%. The dashed curve is the predicted behavior. The straight dashed line is a fit.

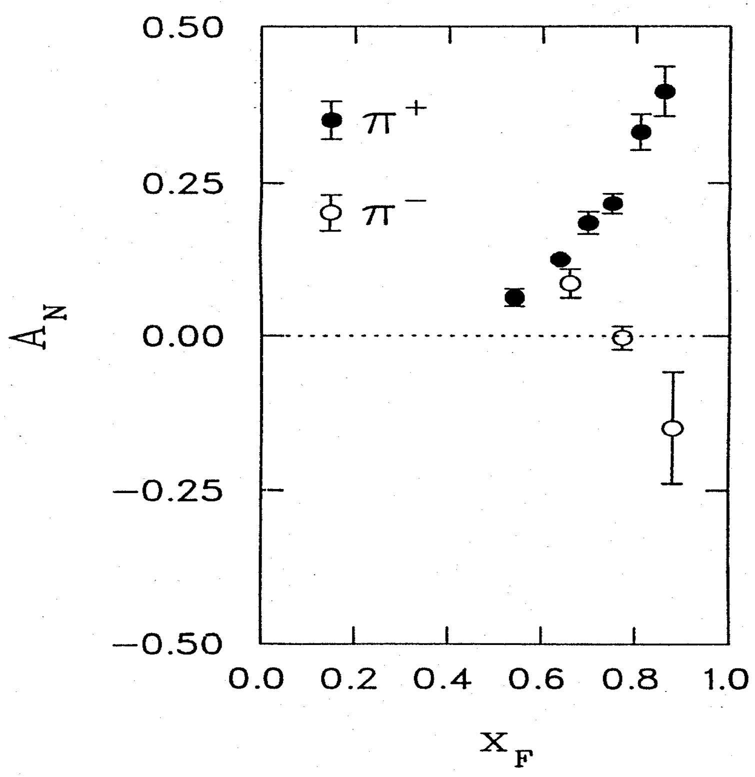
1990s…

Late 1980s-1990: Polarized protons at Fermilab

p + p → Lambda + X

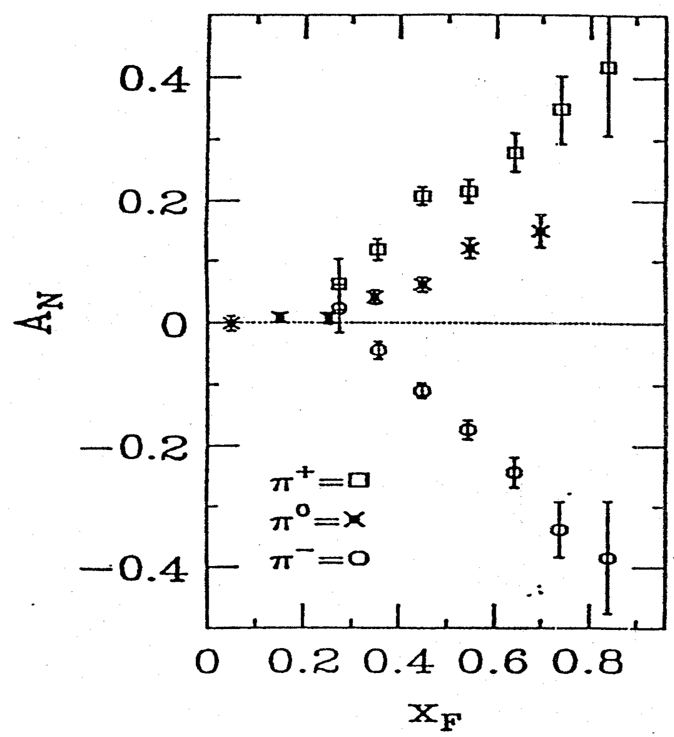
↳ p↑ + X , p↑ + p → pi + X

ZGS (12 GeV/c)



Phys. Rev. D.18 (1978) 3939-3945

Fermilab (200 GeV/c)



Phys. Lett. B261(1991)201
Phys. Lett. B264(1991)462

1990: Polarized Collider Workshop at Penn State:

What else carries the proton spin ?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\rightarrow$ **How are gluons polarized ?**
$\rightarrow$ **How large are parton orbital angular mom.?**

1993: <u>proposal to collide polarized protons in RHIC</u>

PRL 1994: partial siberian snake in AGS

Preservation of Proton Polarization by a Partial Siberian Snake

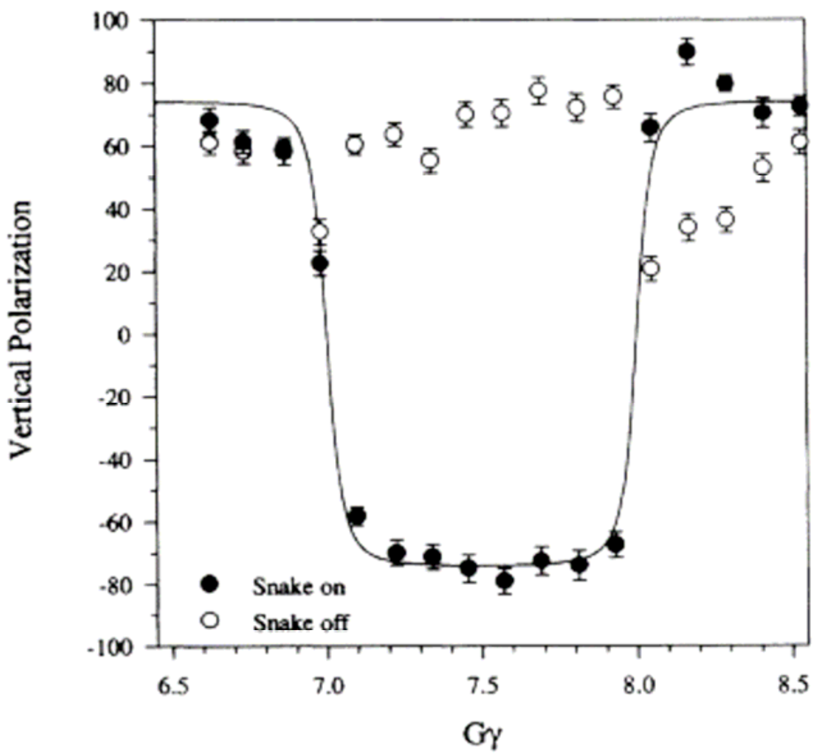


FIG. 2. The measured vertical polarization as a function of the spin tune $G\gamma$ for a 10% snake is shown with and without a snake. Note that partial depolarization at $G\gamma = 8$ is avoided by using a 10% snake. The error bars only represent the statistical errors. The solid line is the result of Eq. (5). The measurement was done at betatron tunes of $\nu_x = 8.7$ and $\nu_y = 8.8$.

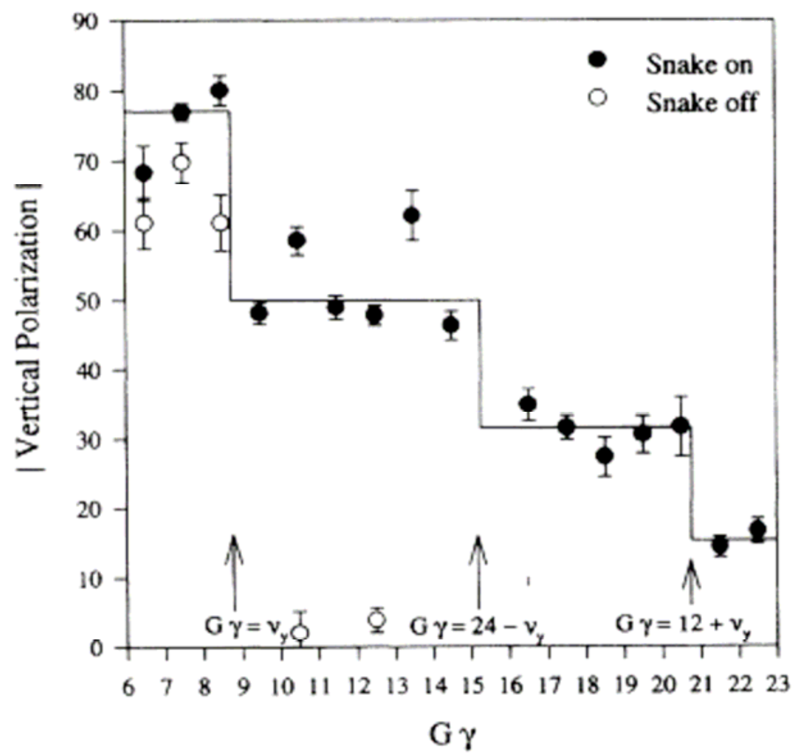
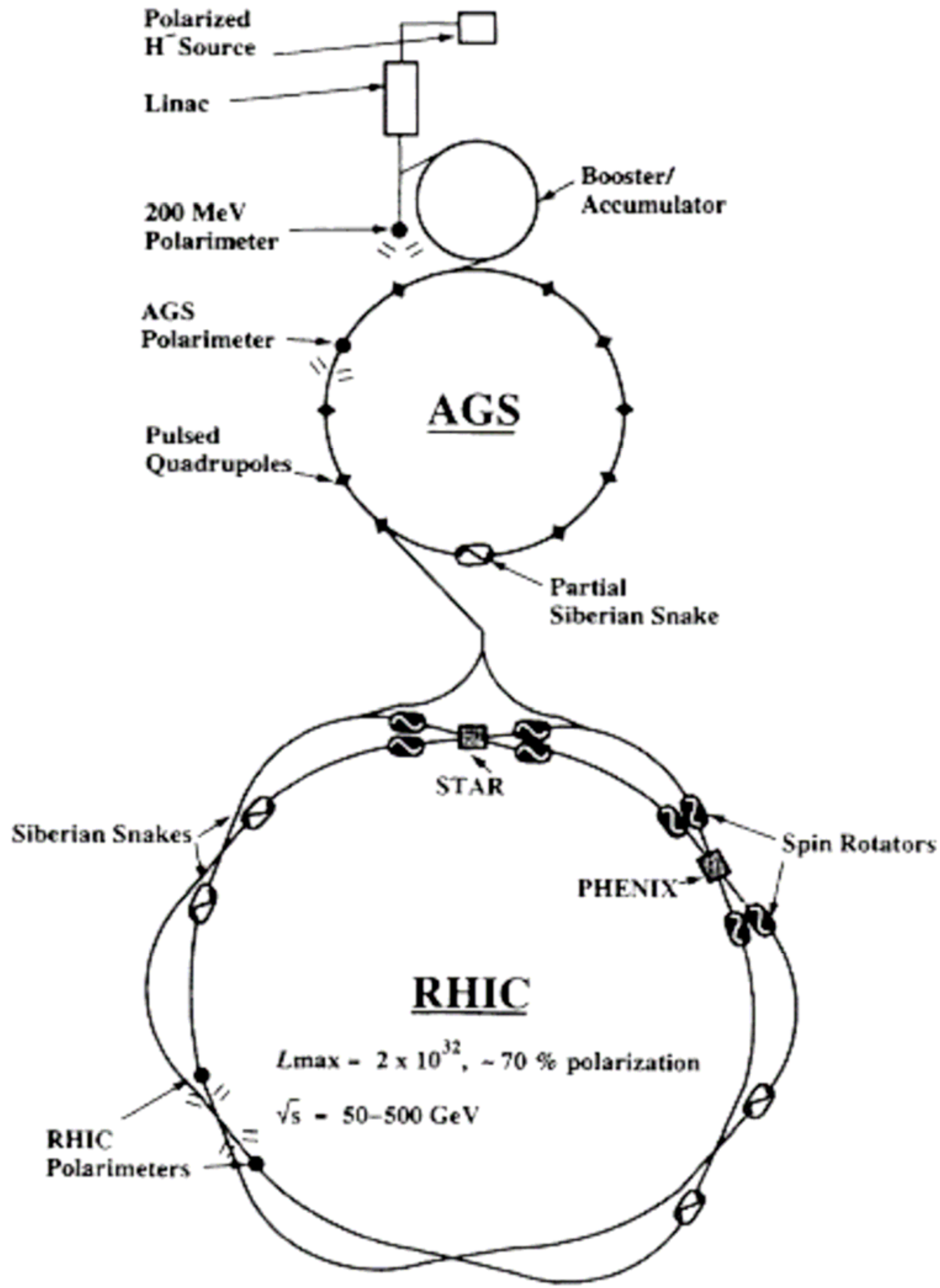


FIG. 3. The measured absolute value of the vertical polarization at $G\gamma = n + \frac{1}{2}$ up to $G\gamma = 22.5$ (solid points). Note that partial depolarization is due to intrinsic spin resonances at $G\gamma = \nu_y, 24 - \nu_y$, and $12 + \nu_y$. The error bars only represent the statistical errors. The measurement was done at betatron tunes of $\nu_x = 8.7$ and $\nu_y = 8.8$.

Also in 1994 PRL: ad for RHIC spin



Some important “politics”:

--1990: Argonne joins RHIC spin program

--Nov. 1990: Penn State workshop, RHIC Spin starts

--RHIC spin supported by PAC 1993

--1994: RIKEN/BNL collaboration toward snakes

--1995: external review supports RHIC Spin

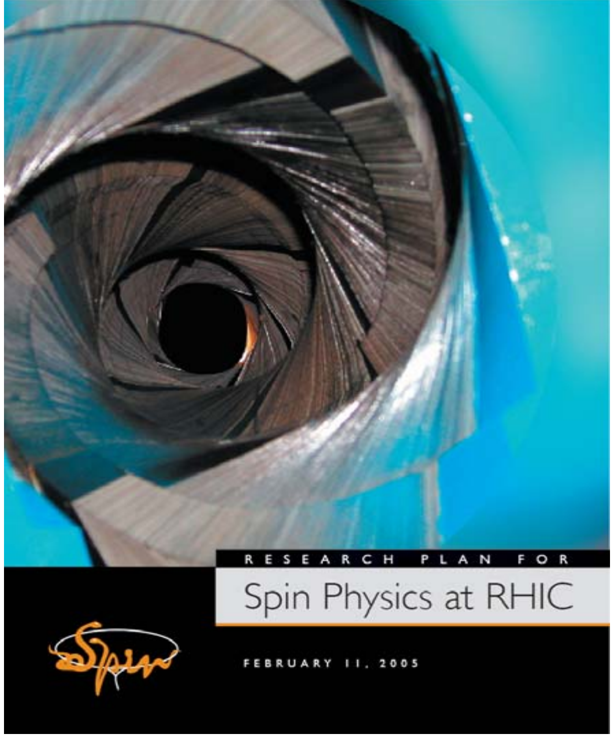
--1995: signing of BNL-RIKEN agreement

--RBRC starts in 1997

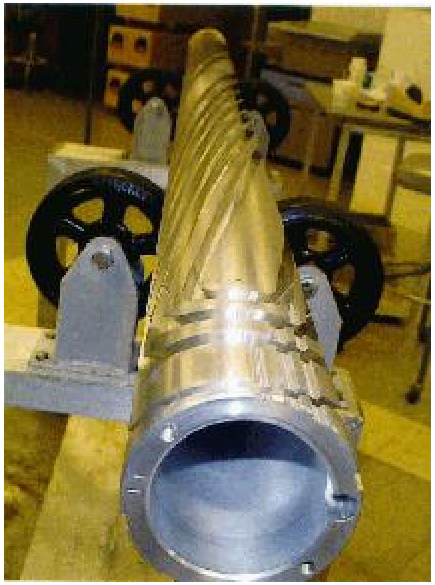
--1998: DOE Nuclear Physics includes RHIC Spin as part of the RHIC program

--DOE and NSF support—spin groups and apparatus

--2006: Renaissance Technology support of first long spin run



1996-2001: Siberian Snakes



2003-4: Warm AGS Snake

Snake: precess spin, leaving beam direction unchanged at exit of snake

Many theory advances:

Longitudinal: **($\overrightarrow{\text{DIS}}$: 1978, W: 1983, EMC: 1988)**

1966: sum rule for p, n polarized DIS <--> static properties of nucleon (beta decay parameters)

1970s-1980s: $\vec{p} + p \rightarrow \vec{W}$ --toward u,dbar, d, ubar polarizations in proton

1980s: factorization and pQCD with spin –large subprocess analyzing powers from ang. momentum conserv.

1987, 1990s: proton spin sum rule

late 1980s-2000s: NLO pQCD for all RHIC gluon probes

2008: first global description of proton using DIS and RHIC data

Theory (cont.)

Transverse spin: **(1976: Lambda↑, p↑p↑ elast., 1978, 1990: p↑ + p → pi X, 2004: p↑ + p → pi X, 2005: e + p↑ → e' pi X)**

1978: large observed spin effects not from massless q

1989/90: k_T of quarks and spin asymmetries (orbital angular momentum)

1990, 1991: quark transversity

1992, 1994: q↑ → pi (orb. ang. mom. in fragmentation)

1995: inequalities connecting longitudinal, transverse

1999: helicity flip thru q↑ --(qg) interference

2003: pQCD descriptions of transverse spin asymmetries --requires calculable initial/final state gluon interactions

2004: transverse spin sum rule

Some crucial experimental advances:

--the PHENIX, STAR, BRAHMS, and pp2pp detectors

--major spin hardware added (muon arm, barrel cal., endcap cal., trigger systems, forward cal., …)

--test detectors for local polarimetry

--local polarimeters

High Energy Polarimetry??

- **use inclusive pion production?**
  ---1991 result from E704 at Fermilab
- **use p-p elastic scattering at medium t?**
  ---traditional, but A_N ~ 1/p, 1% in RHIC energy range
- **use p-p in Coulomb-Nuclear Interference region?**
  ---unknown hadronic spin flip contribution
  ---would use H jet in RHIC--slow

Proceedings of RIKEN BNL Research Center Workshop Volume 3

HADRON SPIN-FLIP AT RHIC ENERGIES

July 21 - August 22, 1997

Organizers

Elliot Leader and T. L. Trueman

…toward RHIC polarimetry: the first RBRC Workshop

RIKEN BNL Research Center

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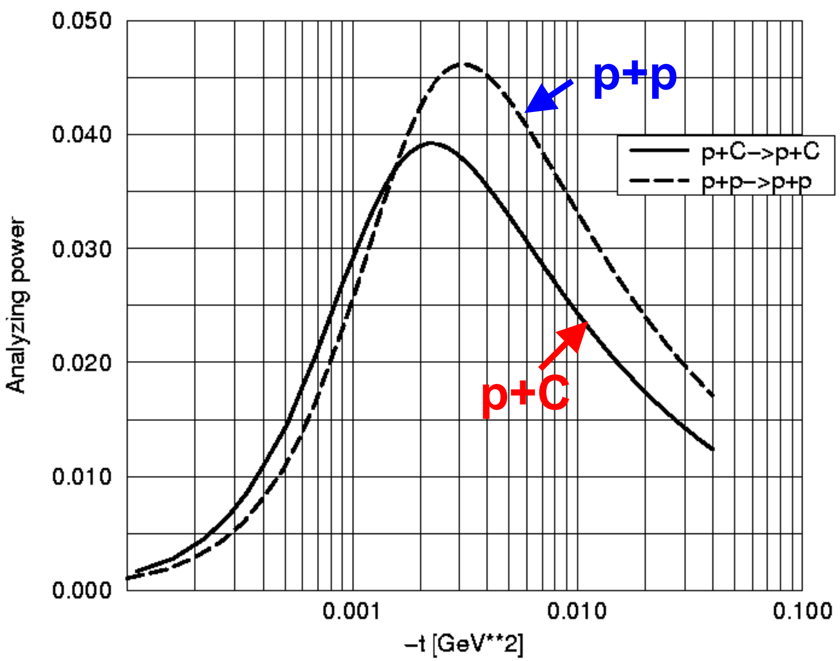
A_N & Coulomb Nuclear Interference

the left – right scattering asymmetry A_N arises from the interference of the spin non-flip amplitude with the spin flip amplitude (Schwinger)

$$A_N = C_1 \phi_{flip}^{em\ *} \phi_{non-flip}^{had} + C_2 \phi_{flip}^{had\ *} \phi_{non-flip}^{had}$$

$\propto (\mu - 1)_p$ $\propto \sigma^{pp}_{had}$ unknown

$A_N(t)$



-t (GeV/c)^2

- ---EM spin flip calculable
- ---A_N significant
- ---also over RHIC energy range
- ---for both proton and carbon targets
- ---hadronic spin flip unknown

PHYSICAL REVIEW VOLUME 73, NUMBER 4 FEBRUARY 15, 1948

On the Polarization of Fast Neutrons

can be traced back to

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts

(Received January 8, 1948)

ALTHOUGH the production of polarized thermal neutrons has long been an accomplished fact, no such success has been forthcoming with fast neutrons. Only one method for the polarization of fast neutrons has thus far been suggested,[1] of which the essential mechanism is the large, effective nuclear spin-orbit interaction present when neutrons are resonance scattered by helium and similar nuclei. It is the purpose of this note to suggest a second mechanism for polarizing fast neutrons—the spin-orbit interaction arising from the motion of the neutron magnetic moment in the nuclear Coulomb field. Despite the apparent small magnitude of this interaction, the long-range nature of the Coulomb field is such that the use of small scattering angles will produce almost complete polarization under ideal conditions. A closely related phenomenon produced by this electromagnetic interaction is an additional scattering of unpolarized neutrons which increases rapidly with decreasing

where $k=p/\hbar$ is the neutron wave number. Hence, the unscreened Coulomb field of a point nucleus will be effective for scattering in the angular range:

$$1/ka \ll 2\sin\vartheta/2 \ll 1/kR. \qquad (3)$$

If the nuclear radius and atomic screening radius are taken to be

$$R=1.5\cdot10^{-13}A^{\frac{1}{3}}\text{ cm} \quad \text{and} \quad a=0.53\cdot10^{-8}Z^{-\frac{1}{3}}\text{ cm},$$

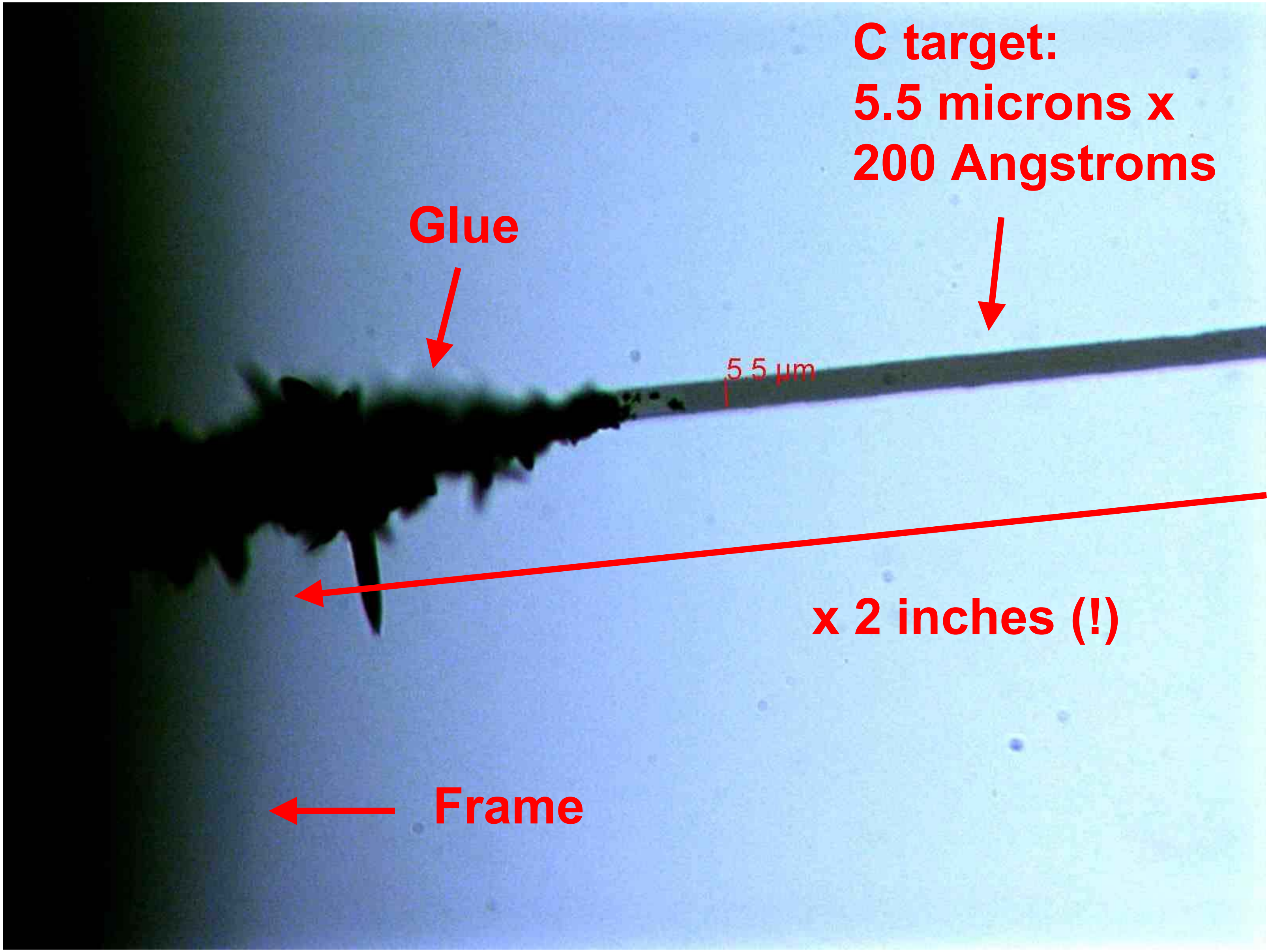
the angle restrictions for a 1-Mev neutron scattered in Pb, for example, are

$$4\cdot10^{-4} \ll 2\sin\vartheta/2 \ll \tfrac{1}{2}. \qquad (4)$$

The electromagnetic scattering of a neutron under these conditions can be calculated with the plane wave Born approximation, for the nuclear scattered wave is negligible compared with the incident wave at the significant scattering distances. We denote the incident plane wave by

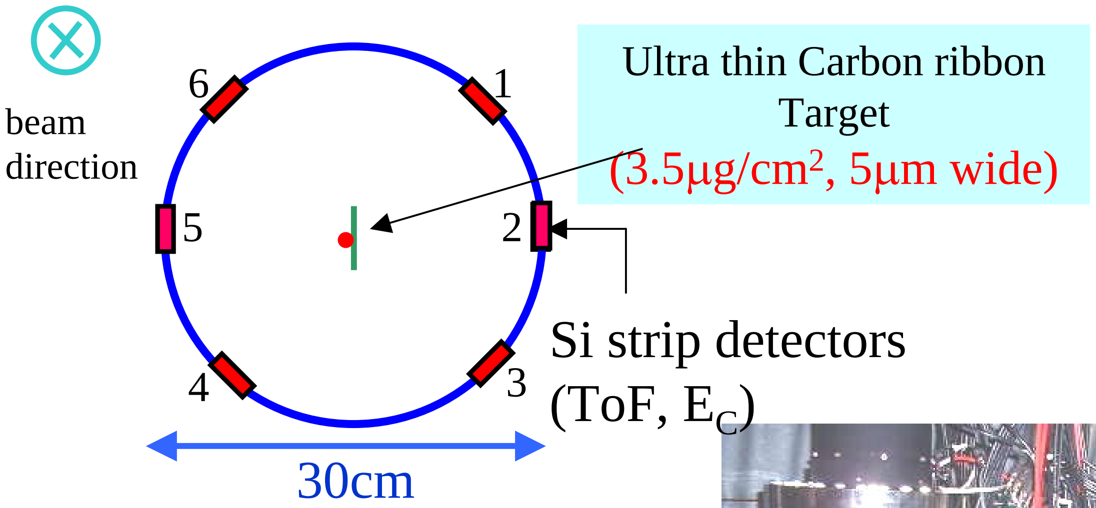
$$\psi_0 = e^{i\mathbf{k}_0\cdot\mathbf{r}}\chi, \qquad (5)$$

Bill Lozowski of IU: ultra thin C targets for stripping foils at IUCF: perfect for RHIC pC

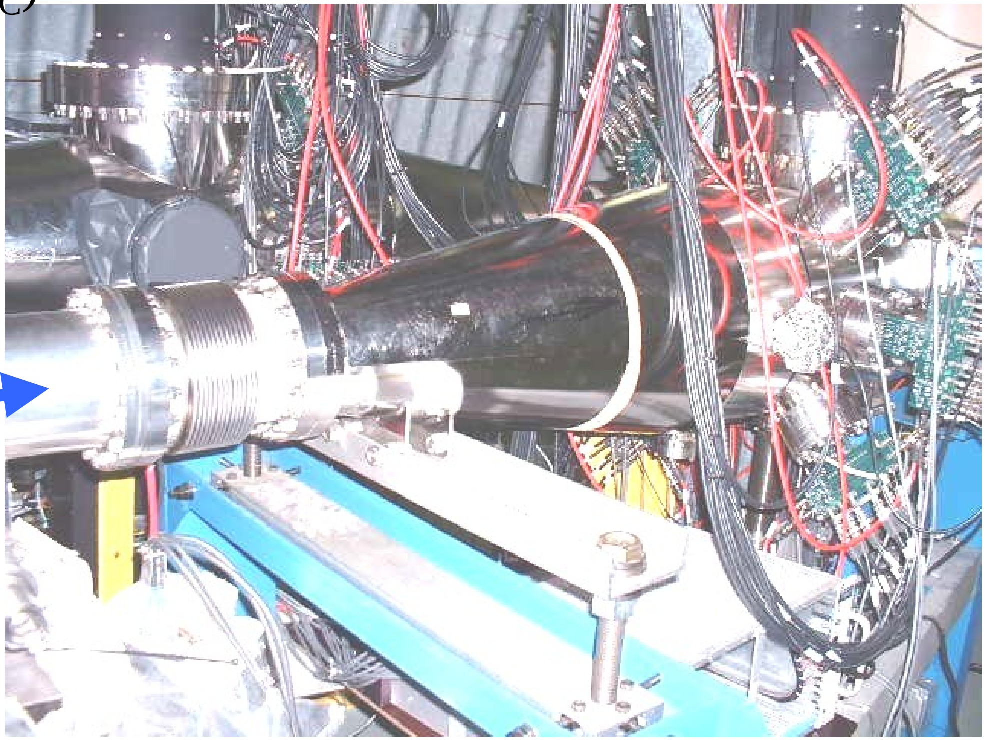

C target:
5.5 microns x
200 Angstroms
Glue
5.5 µm
x 2 inches (!)
Frame

2000s…

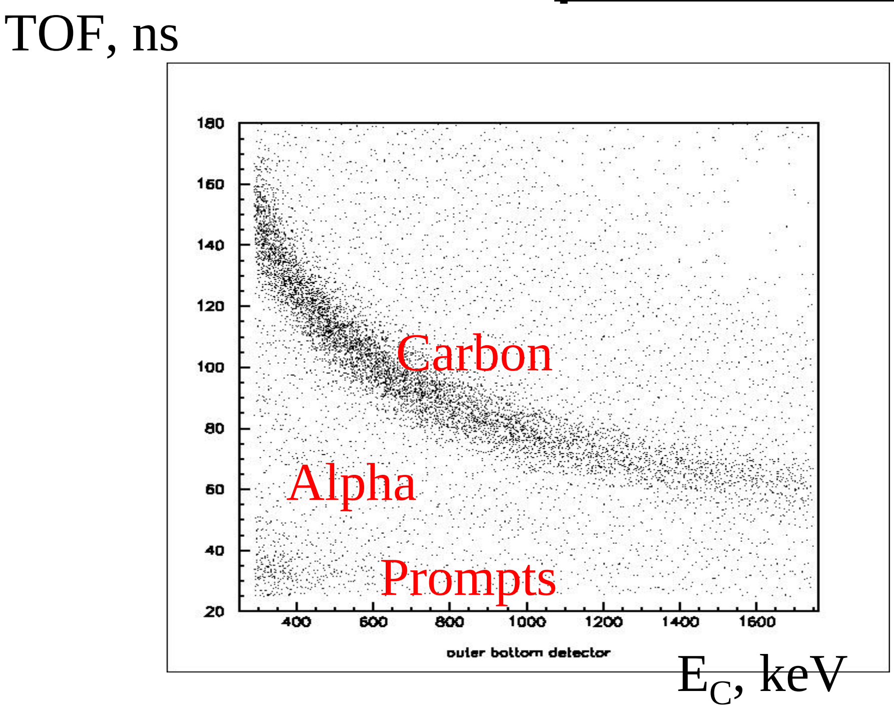
Setup for *p*C scattering – the RHIC polarimeters



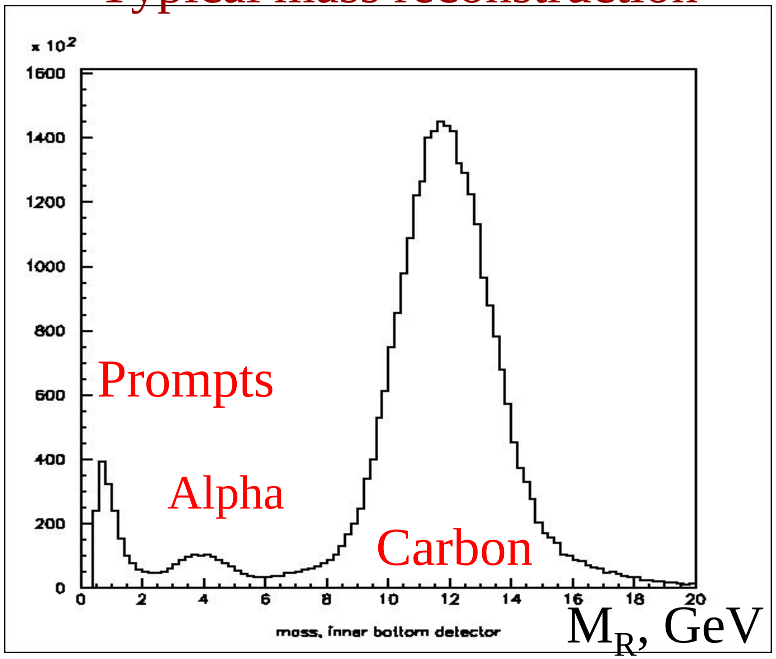
RHIC Beam

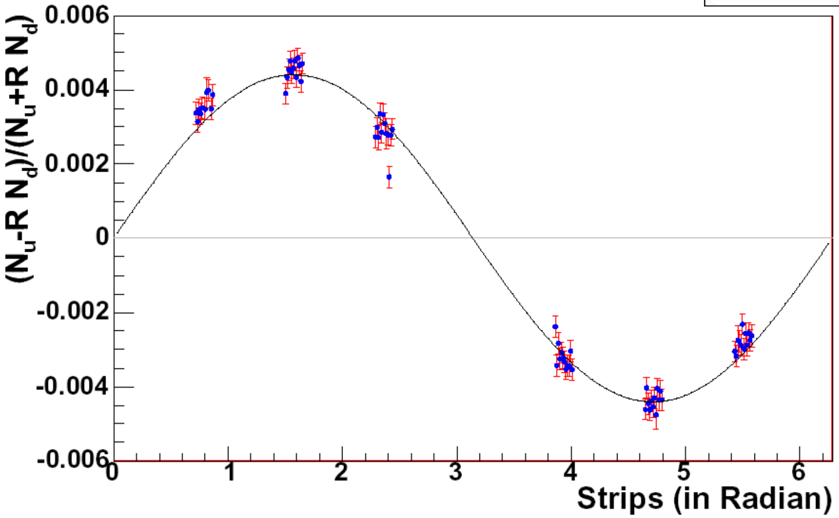


p-Carbon CNI RHIC



Typical mass reconstruction

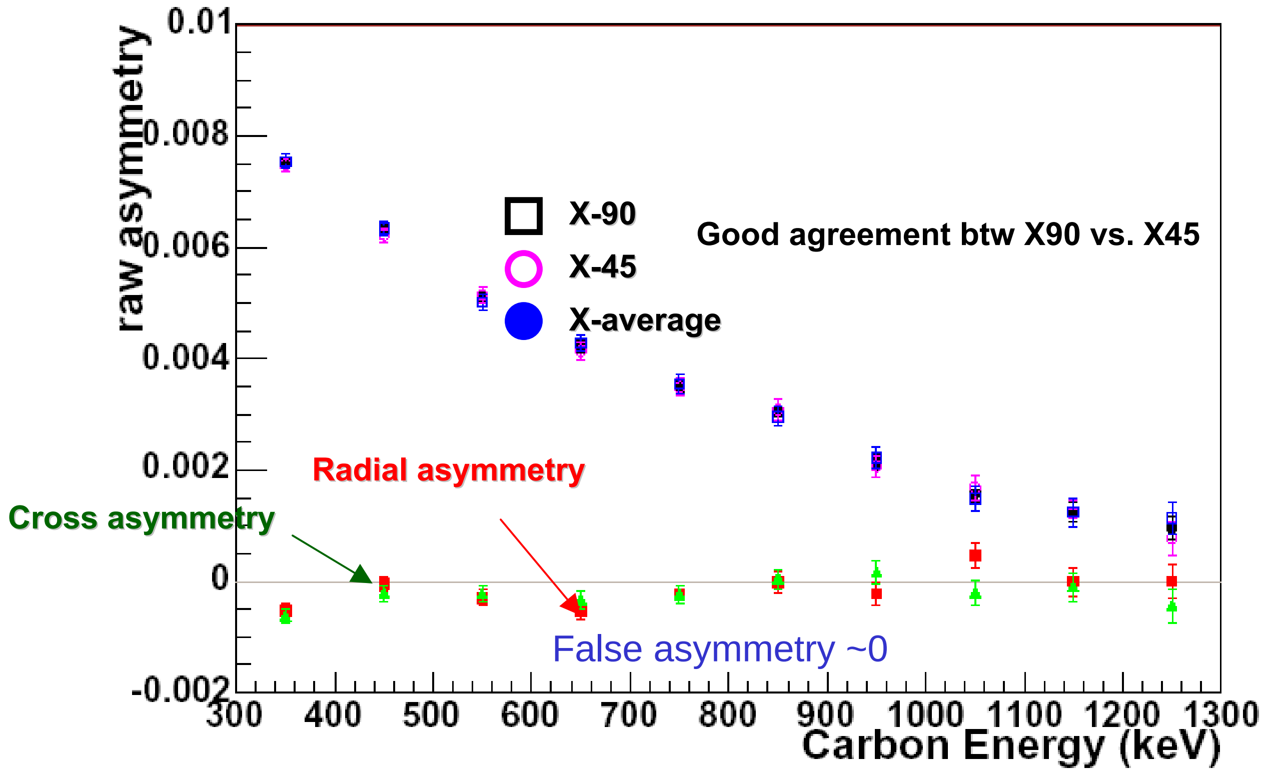




Phi dependence:
6 detectors, 72 strips

Note: Si detectors from
BNL Instrumentation

Raw asymmetry @ 100 GeV



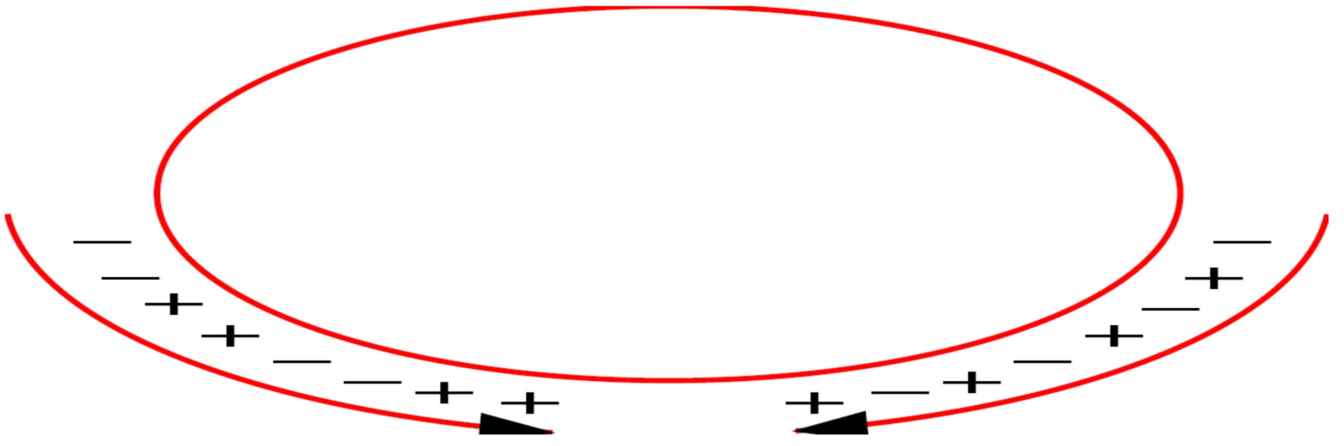
Regular polarimeter runs (every 2 hours)

--measurements taken simultaneously with Jet -target

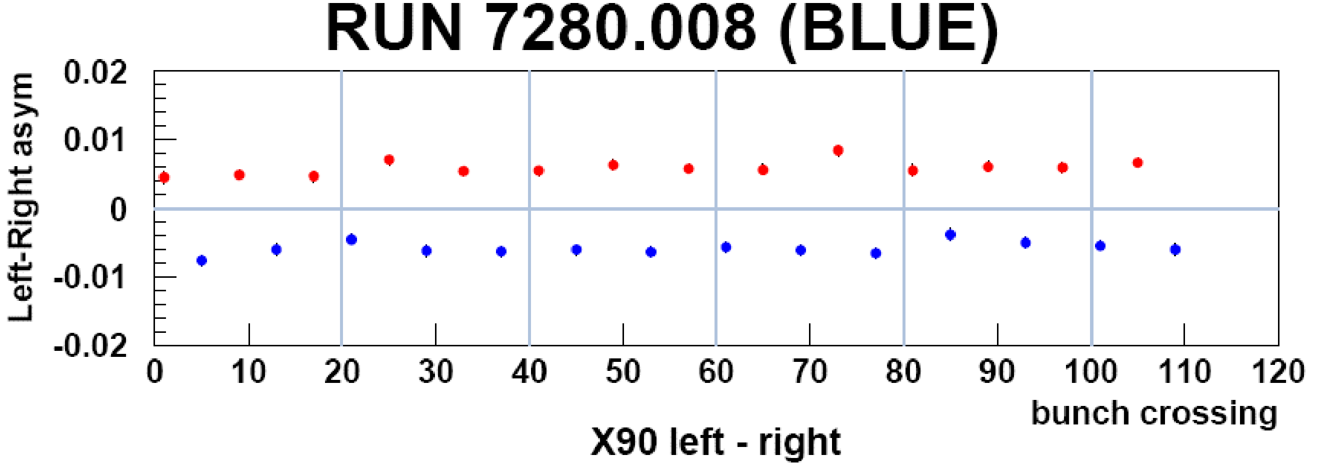
--very stable behavior of measured asymmetries

--ΔP = 3% per measurement (20 M events, 30 s)

Exquisite Control of Systematics



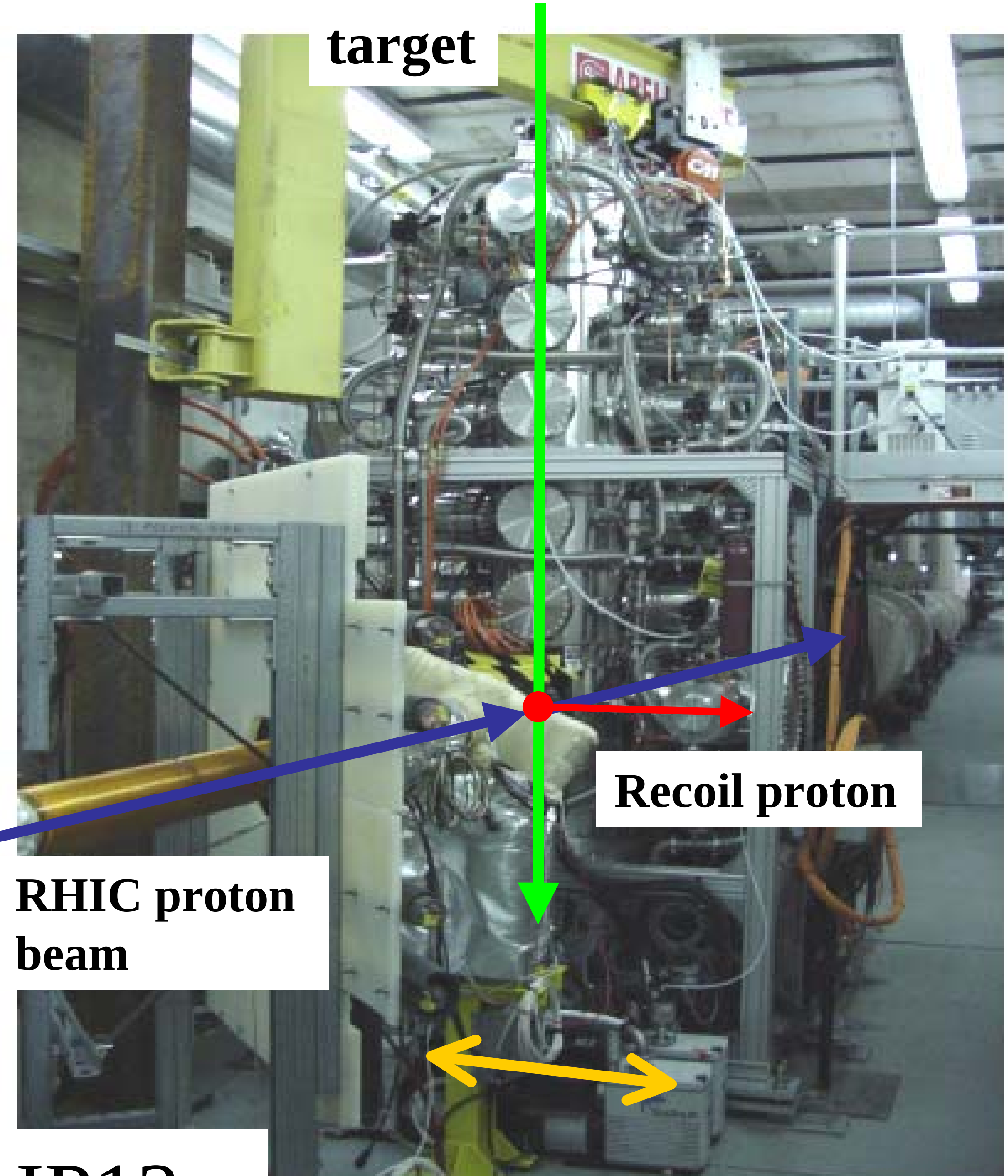
Raw asymmetries from carbon polarimeter by bunch:



In 2003-4, we built a polarized atomic hydrogen jet polarimeter for RHIC, to calibrate the pC polarimeters.

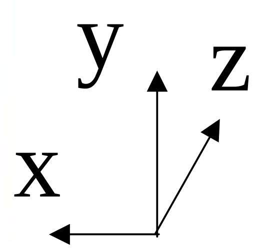
Goal: RHIC beam polarization to DP/P = +/-5%

H-jet-target system

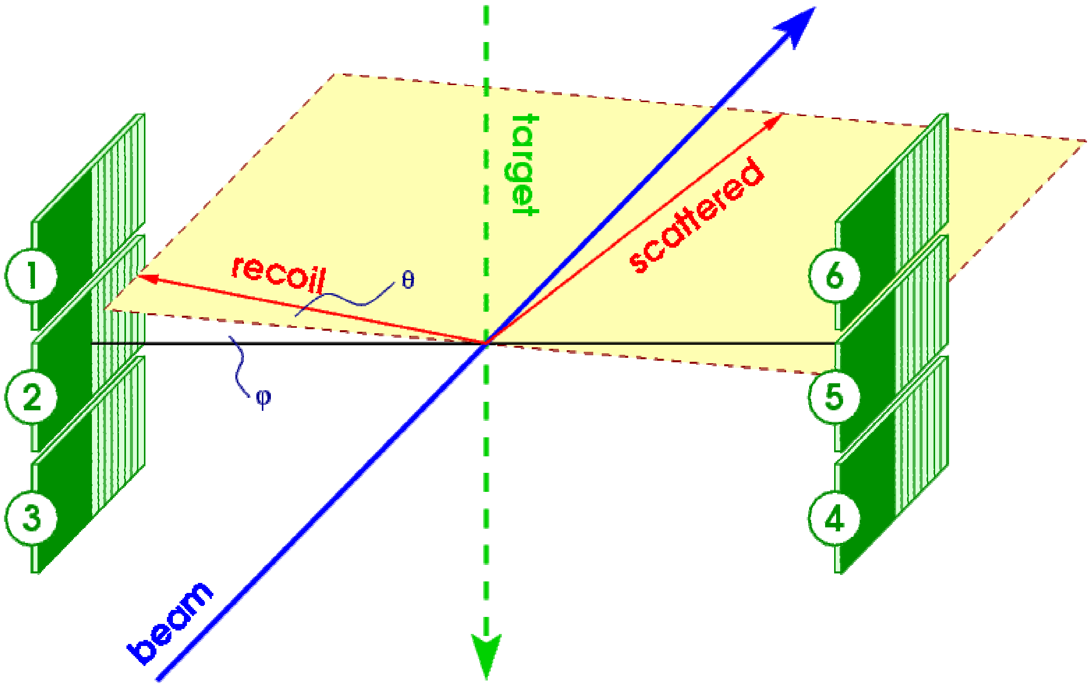


IP12

- Height: 3.5 m
- Weight: 3000 kg
- Entire system moves along x-axis –10 ~ +10 mm to adjust collision point with RHIC beam.



Recoil Silicon Strip Spectrometer



For p-p elastic scattering only:

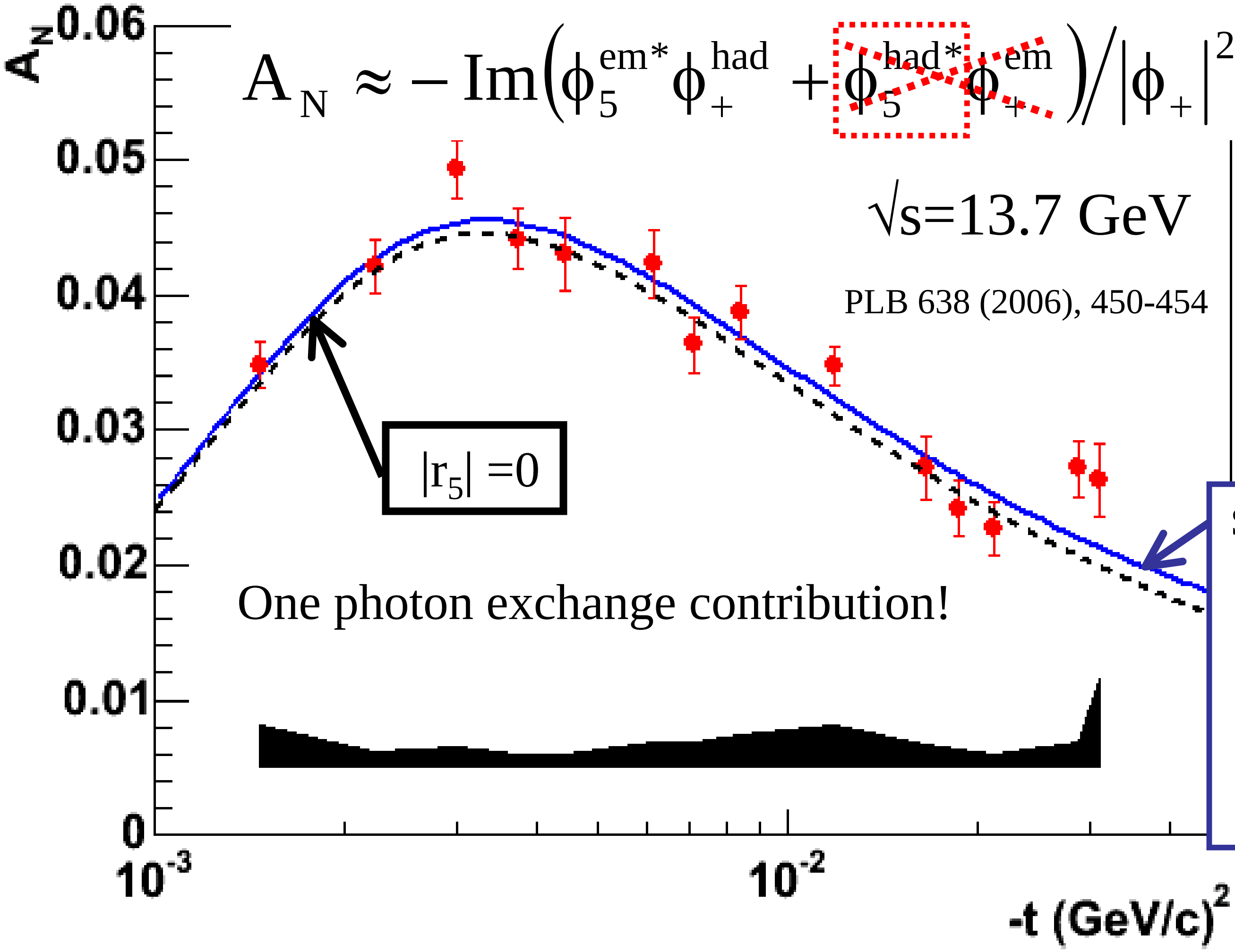
$$\varepsilon = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

$$\varepsilon_{beam} = A_N \cdot P_{beam}$$

$$\varepsilon_{target} = -A_N \cdot P_{target}$$

$$P_{beam} = -\frac{\varepsilon_{beam}}{\varepsilon_{target}} \cdot P_{target}$$

Results of A_N in the CNI region @ √s=13.7 GeV



$$r_5 = \frac{m_p \phi_5^{had}}{\sqrt{-t}\,\mathrm{Im}\,\phi_+^{had}}$$

Set r_5 as free parameter:

→ $\chi^2/ndf = 11.1/12$

→ $\mathrm{Im}\, r_5 = -0.015 \pm 0.029$

→ $\mathrm{Re}\, r_5 = -0.0008 \pm 0.0091$

→ $|r_5|$ is consistent with zero!

- Compare measured A_N and expected curve with $|r_5| = 0$
  → $\chi^2/ndf = 13.4/14$, $|r_5|$ is consistent with zero!

ϕ_5^{had} is consistent with zero at √s = 13.7 GeV.

RUN5 Absolute beam polarization at 100GeV/*c*

P(target) = 92.4% ± 1.8%

		stat.	sys.
P(blue beam)	**= 49.3%**	**± 1.5%**	**± 1.4%**
P(yellow beam)	**= 44.3%**	**± 1.3%**	**± 1.3%**

Achieved goal.

$$\frac{\Delta P(\mathrm{beam})}{P(\mathrm{beam})} = 4.2\%$$

- How:

---collide beams of protons in the world’s only polarized proton collider

---polarized H^- : 1 mA, 85% polarized

---”Siberian Snakes” to maintain the spin directions of the protons as we accelerate

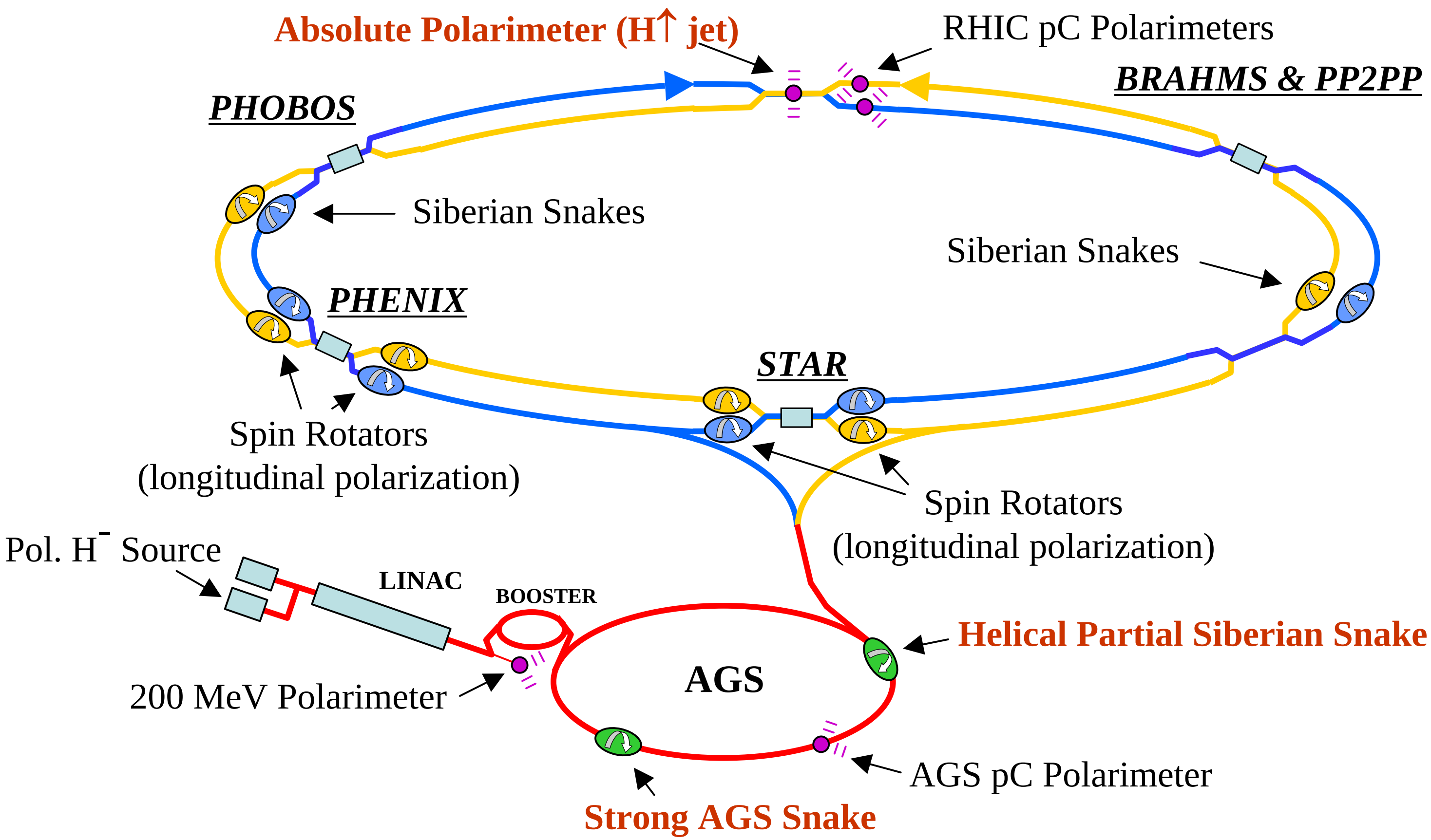
---polarized H ABS in RHIC to obtain absolute RHIC beam polarization

---STAR, PHENIX, and BRAHMS (transverse spin only) experiments

RHIC Spin Runs

	P	L(pb^-1)	Results
2002	15%	0.15	first pol. pp collisions!
2003	30%	1.6	pi^0, photon cross section, A_LL(pi^0)
2004	40%	3.0	absolute beam polarization with polarized H jet
2005	50% (P^4 x L = 0.8)	13	large gluon pol. ruled out
2006	60% (P^4 x L = 6)	46	first long spin run
2007			no spin running
2008	50%		(short) run

RHIC Polarized Collider

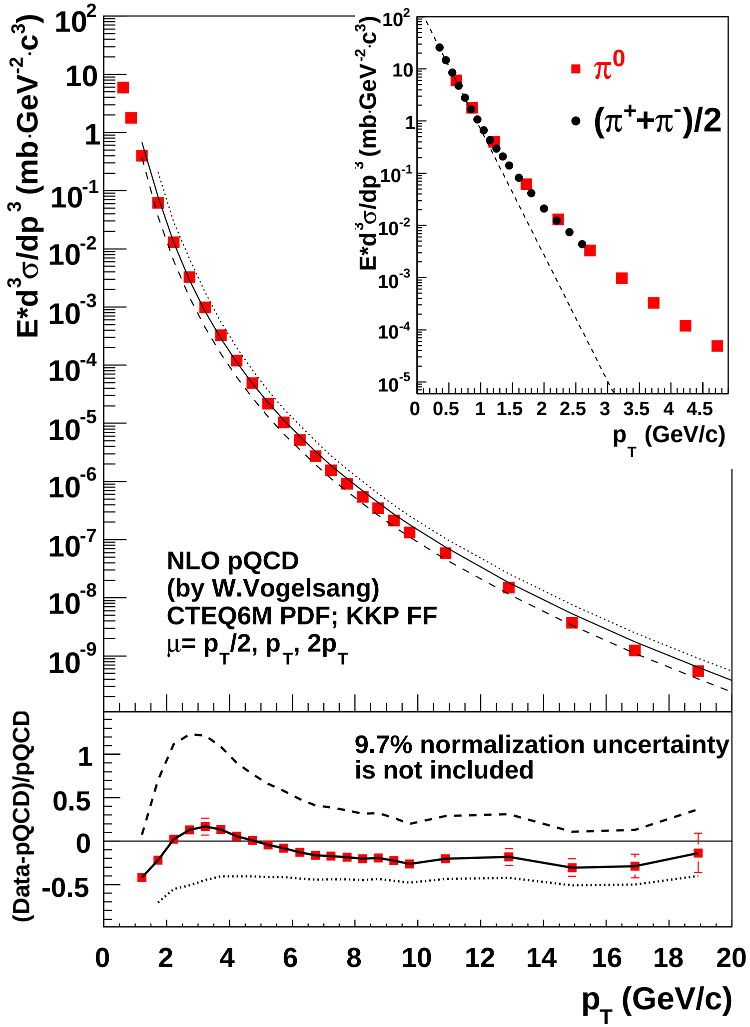


2006: 1 MHz collision rate; P=0.6

Cornerstones to the RHIC Spin program

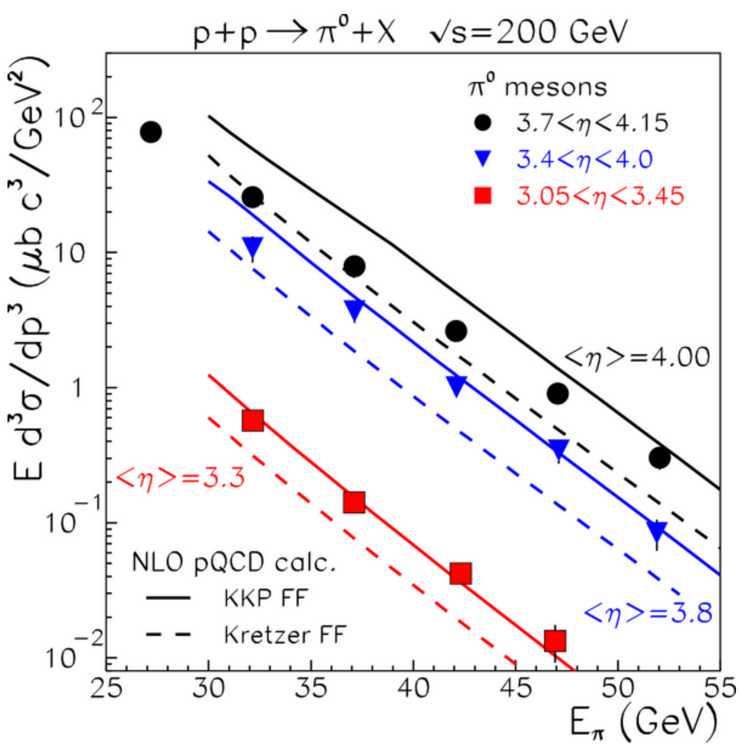
$pp \rightarrow \pi^0 X$

Mid-rapidity: PHENIX



PR **D76**, 051106 (2007)

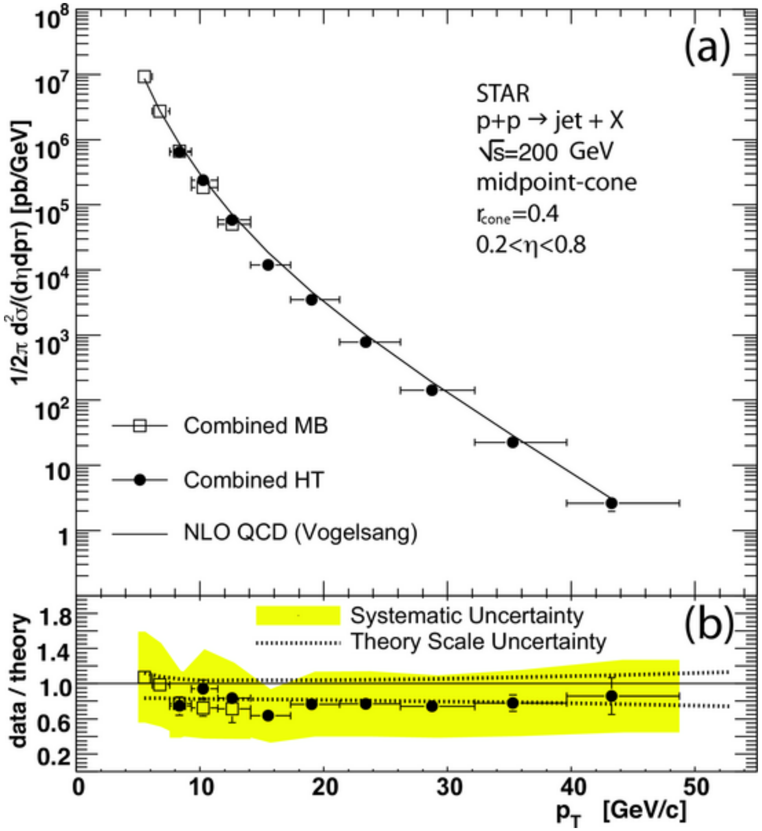
Forward: STAR



PRL **97**, 152302 (2006)

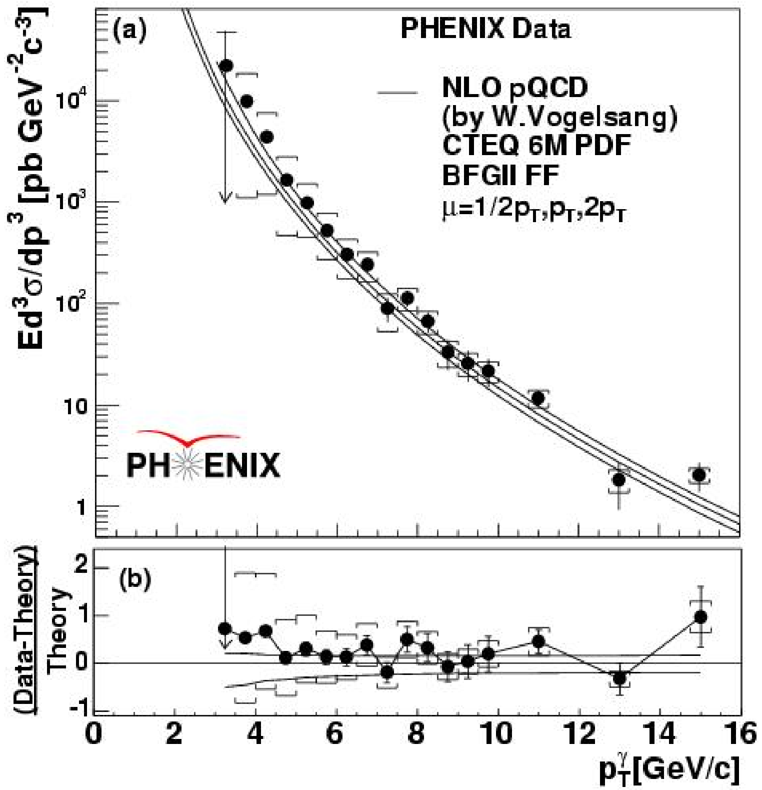
And Jets and Direct γ

pp $\rightarrow$ jet X : STAR



PRL 97, 252001 (2006)

pp $\rightarrow \gamma$ X : PHENIX



PRL 98, 012002 (2007)

And what is the moral?

- investments made well before the "proton spin puzzle" were crucial
- ideas from well before their application were crucial
- theory <--> experiment
- running is crucial

If we knew where we were (are) going, it wouldn't be science.