

Of Pomerons, W's, and RHIC Spin

Trueman Fest

12 May 2008

G. Bunce

Thanks to: Hiromi Okada, Yousef Makdisi and Haixin Huang

Estimates of production cross sections and distributions for W bosons and hadronic jets in high-energy pp and $\bar{p}p$ collisions*

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(Received 13 April 1977)

Using the quark-parton model, with structure functions chosen to agree with electroproduction and lepton-pair-production data, the cross sections are calculated for the production of charged and neutral W mesons in high-energy pp collisions. The single- and double-particle distributions for the leptonic and hadronic decays of the W are presented along with leptonic background from electromagnetic pair production. Using the same model, the cross sections for production of single and double hadronic jets are also calculated using both colored-vector-gluon exchange and the Field-Feynman models for the elementary quark-quark scattering. It is concluded that the leptonic decay of the W should be a strong signal well above background, and that the parity violation of the weak interaction leads to characteristically different distributions for leptons and antileptons. The production in proton-antiproton collisions is also studied and found to be only slightly above the proton-proton production. The cross section does not increase rapidly with energy for $s/m_w^2 \gtrsim 10$. For hadronic jet production, the vector-gluon and Field-Feynman models lead to significantly different distributions, and if the predictions of the former are true the hadronic jet decay of the W , although plentiful, will be difficult to see above background. The effects of transverse motion of the W , neglected in the quark model, are found to be unimportant.

I. INTRODUCTION

Ever since the original theory of Yukawa, the mediating particles for weak interactions, the intermediate bosons W , have been expected to exist.¹ So far they have escaped observation. It may well be that intermediate bosons are too heavy for existing accelerators to produce. The similarities between the structure of weak interactions and electromagnetic interactions have led² to the suggestion that the appropriate scale for the mass of the W is $(\alpha/G)^{1/2} \approx 30 \text{ GeV}/c$,² where α is the fine-structure constant and G is the Fermi coupling constant. In particular, the unified gauge theory of Weinberg and Salam,³ whose successful predictions include the existence of the weak neutral current,⁴ leads to a charged W mass of about $60 \text{ GeV}/c^2$ and a neutral W mass of about $75 \text{ GeV}/c^2$.³⁻⁵ Given these masses, the intermediate bosons are energetically well within the reach of currently proposed pp and $\bar{p}p$ colliding/beam machines.

discussed here. Where they overlap with this work, we find, in general, qualitative agreement.^{9,10}

One method to estimate the W production cross sections is to rely upon the principle of conserved vector current (CVC)¹¹ (i.e., the assumption that the charged weak current and the isovector part of the electromagnetic current form an isomultiplet) and the scaling hypothesis (i.e., the hypothesis that the dimensionless cross section $m^2 d\sigma/dm$ for electromagnetic production of a lepton pair in pp collisions is a function of s/m^2 alone, where m is the dilepton invariant mass and s is the pp invariant energy squared). Using CVC, and assuming the isoscalar part of the dilepton production to be small, the cross section for producing a W with mass m is approximately given by 0.1 GeV^{-2} times the corresponding $m^3 d\sigma/dm$ for dilepton production with m in GeV units.⁶ If scaling in s/m^2 holds, the same cross sections can be used to predict cross sections for producing a heavier W at a correspond-

(W - 6)

1977: $m_W = 45-100 \text{ GeV}$?

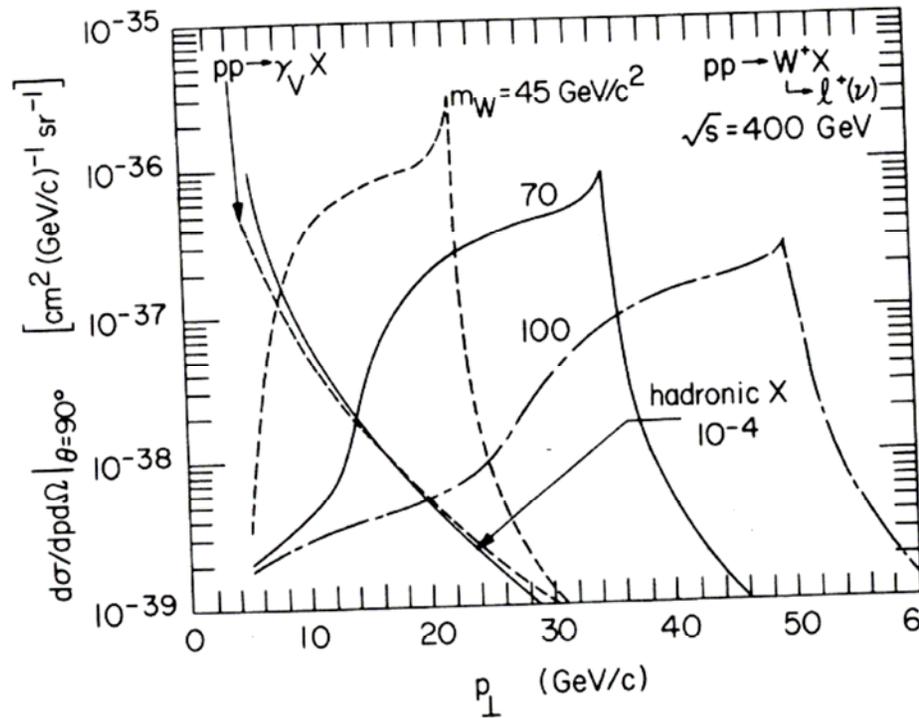


FIG. 6. $d\sigma/dp d\Omega|_{90^\circ}$ vs p_\perp for an l^+ from W^+ with mass 45, 70, 100 GeV/c^2 at $\sqrt{s} = 400 \text{ GeV}$, pp reaction. The smooth dashed curve is for l^+ from γ_V ; the smooth solid curve is obtained by multiplying the pion distribution from vector gluons discussed in Sec. IV by 10^{-4} .

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

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(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

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.,

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

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

Parity violating W Production

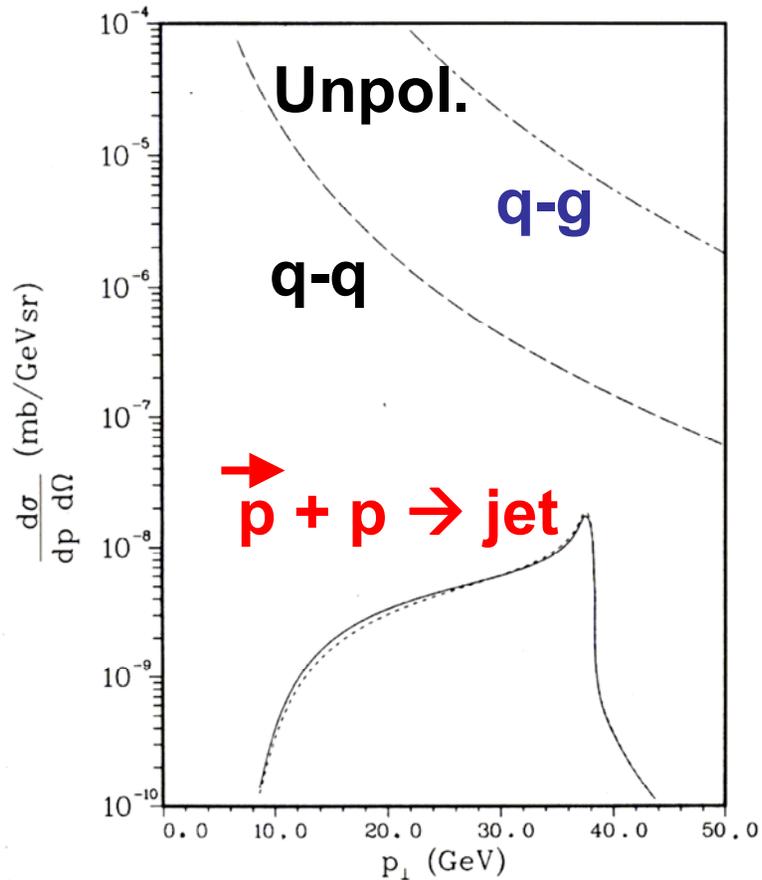


FIG. 2. Single-jet cross sections for W^\pm at $\sqrt{s} = 800$ GeV, $\theta = 90^\circ$. Solid curve: Polarization asymmetry for W^\pm . Dotted curve: Unpolarized cross section for W^\pm . Dashed curve: Unpolarized cross section for quark-quark scattering. Dot-dashed curve: Unpolarized cross section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

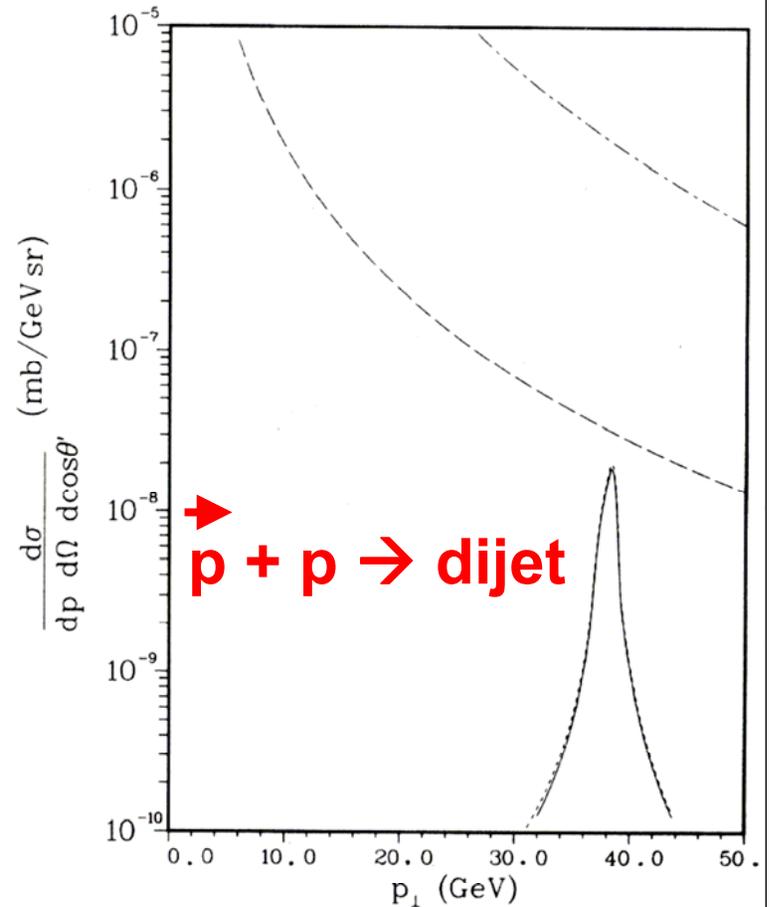


FIG. 3. Double-jet cross sections for W^\pm at $\sqrt{s} = 800$ GeV, $\theta_1 = \theta_2 = 90^\circ$. The curves have the same meanings as in Fig. 2.

ESTIMATES OF W PRODUCTION WITH POLARIZED PROTONS...

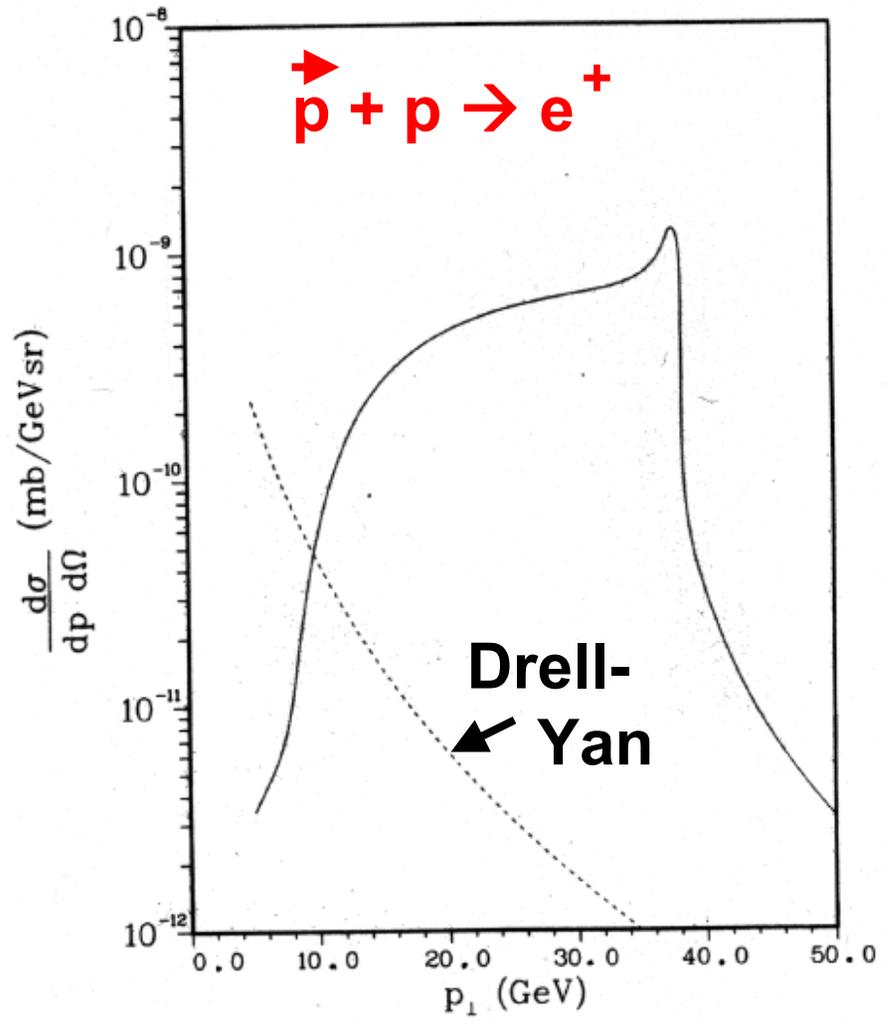


FIG. 8. Single e^+ cross section at $\sqrt{s} = 800 \text{ GeV}$, $\theta = 90^\circ$.
Solid curve: Polarization asymmetry for $W^+ \rightarrow e^+ \nu$.
Dotted curve: Unpolarized cross section for Drell-Yan process.

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

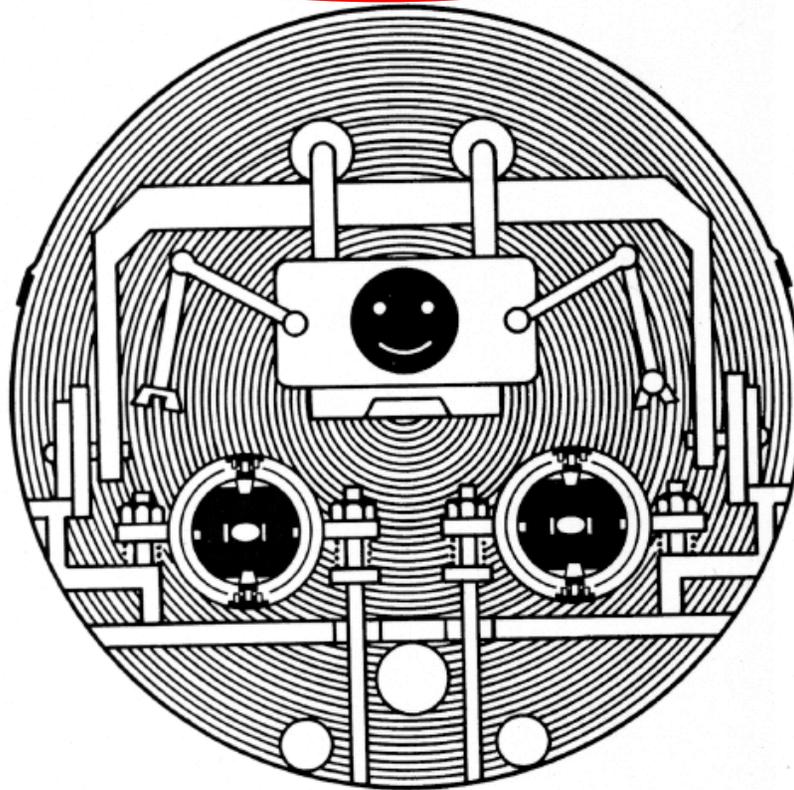
In conclusion, it seems that polarized proton

beams colliding at the most practical energies of the W .

We would like to suggest the possibility of polarized beams at a helpful discussion authored under C with the U.S. Dep

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

June 28-July 16, 1982
Snowmass, Colorado



Editors
Rene Donaldson • Richard Gustafson • Frank Paige

W,Z⁰ PRODUCTION AT A PP COLLIDER

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I. W,Z⁰ Production at a pp Collider

Introduction

We have examined some experimental questions relating to the production of W's and Z⁰'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 $L = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ (the standard BNL Isabelle (ISA) operating conditions). Most experiments should accumulate 10^7 sec of beam and therefore will have an integrated luminosity $L = 10^{40} \text{ cm}^{-2}$. 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: $pp \rightarrow W^{\pm} + X, W^{\pm} \rightarrow e^{\pm} + \nu$

The W^{\pm} cross section is $3.5 \times 10^{-33} \text{ cm}^2$ for W^+ ($1.6 \times 10^{-33} \text{ cm}^2$ for W^-) at $\sqrt{s} = 800$ GeV. Since the $W^{\pm} \rightarrow e^{\pm} \nu$ branching ratio is calculated to be 8.5%, a total of 3×10^6 W^+ (1.4×10^6 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 $L = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ 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

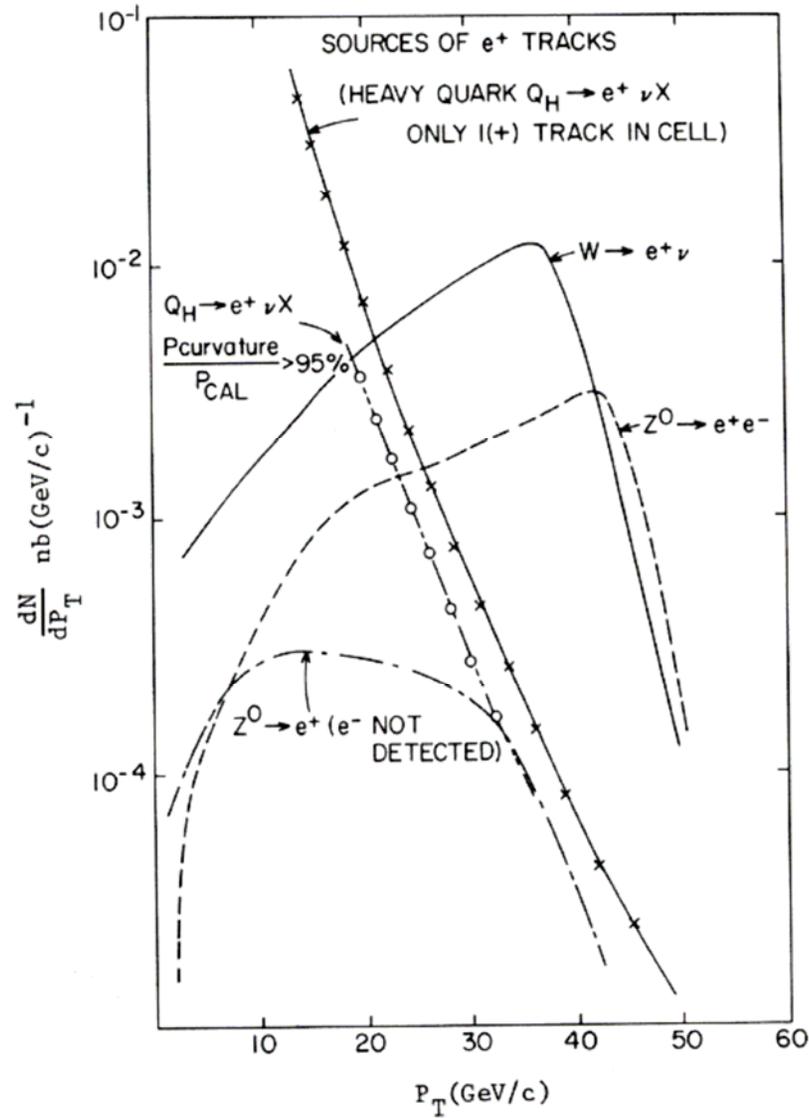


Fig. 2. Sources of high P_T positrons.

$m_W = 80 \text{ GeV?}$

1982: W - 1

Measuring Polarization and Polarization Reversal¹⁴

→ 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 Tudron¹⁵ calculated that with a 100% polarized proton beam, $\sigma_- \approx 3\sigma_+$. For a 70% polarized beam, $\sigma_- \approx 2\sigma_+$. (σ_- 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).

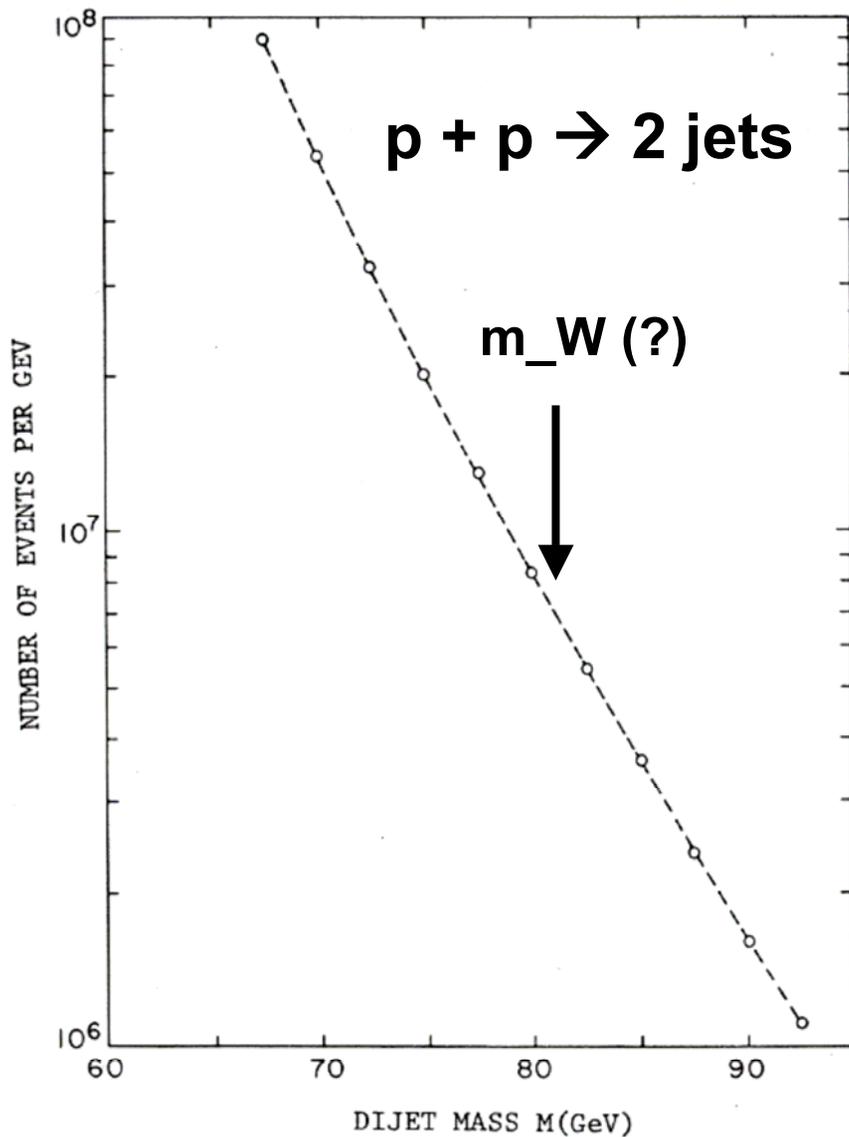


Fig. 13. Effective mass distribution for pairs of jets

\rightarrow
 $p + p \rightarrow 2 \text{ jets}$

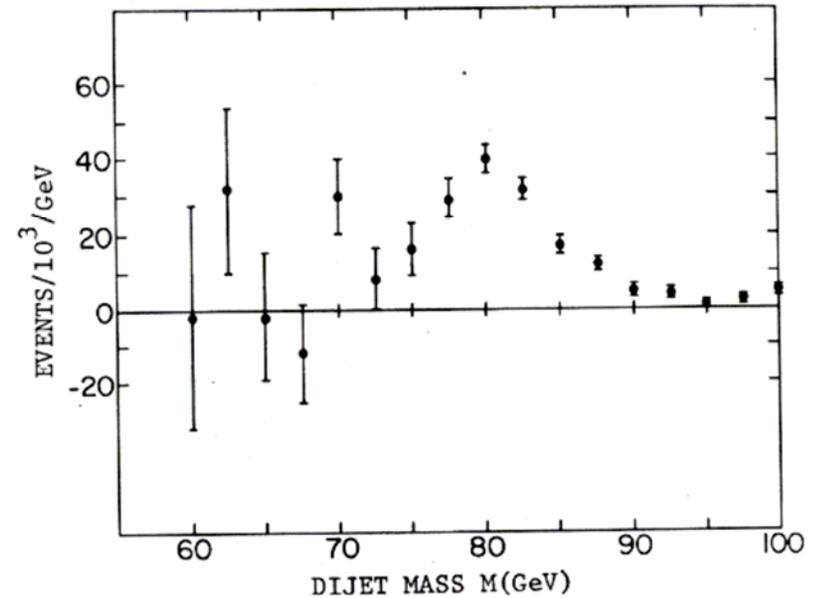


Fig. 15. Mass distribution of jet pairs obtained by subtracting bin by bin the distributions for each polarization.

**...simulation of
parity-violating subtraction**

Obviously, one can use this technique to verify and measure the magnitude of parity violation in $W \rightarrow e + \nu$ or $W \rightarrow \mu + \nu$. 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, Sivers¹⁹ has pointed out that the two-spin asymmetry in $pp \rightarrow \gamma + X$ 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 $\sqrt{s}=540$ 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- ET electrons, the other for large- ET 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 $p\bar{p} \rightarrow W^{+/-} + X$, with $W^{+/-} \rightarrow e^{+/-} + \nu$; where $W^{+/-}$ is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

Fast forward a few years...

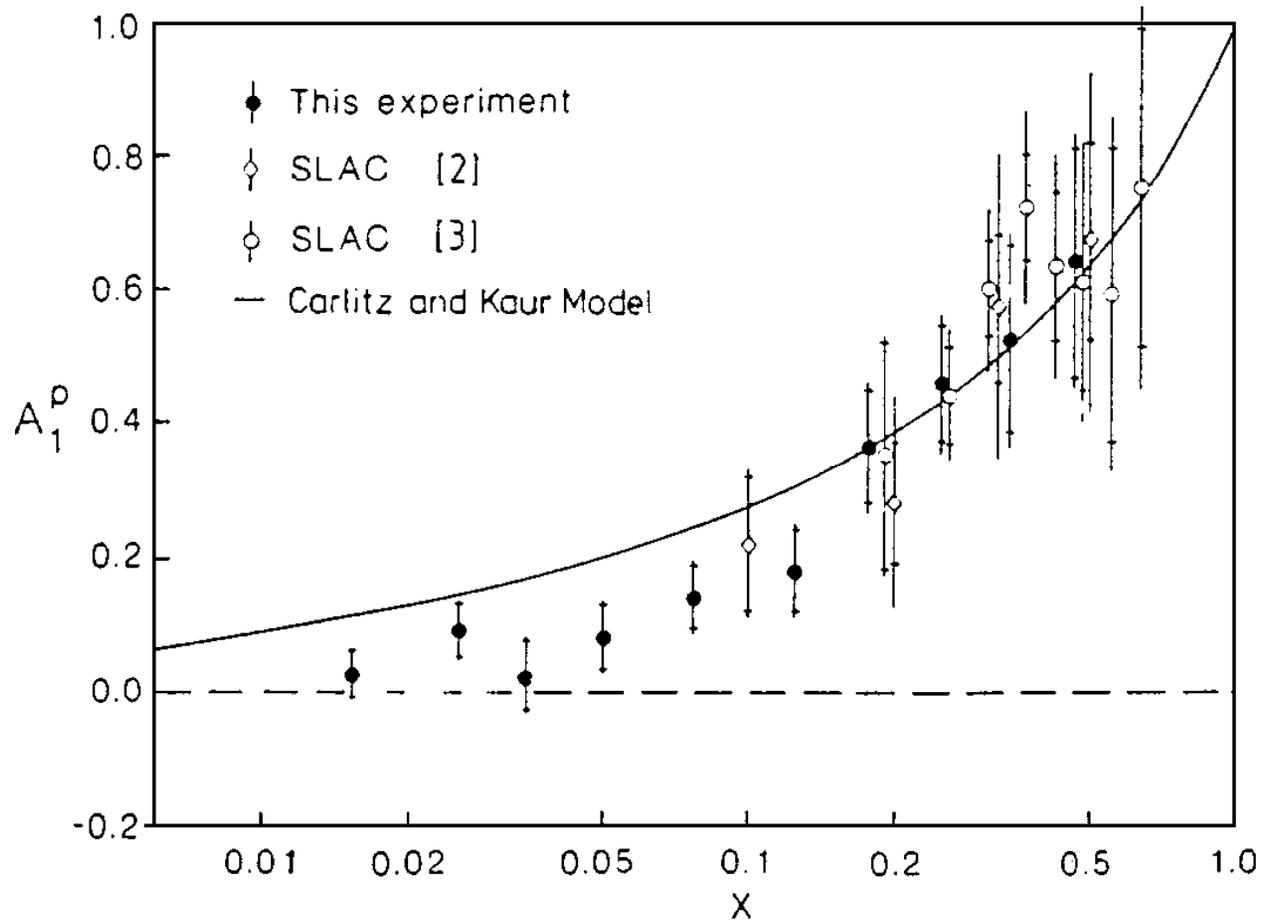
---demise of Isabelle 1983

---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

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”

1990: Polarized Collider Workshop at Penn State:

What else carries the proton spin ?

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

→ How are gluons polarized ?

→ How large are parton orbital angular mom.?

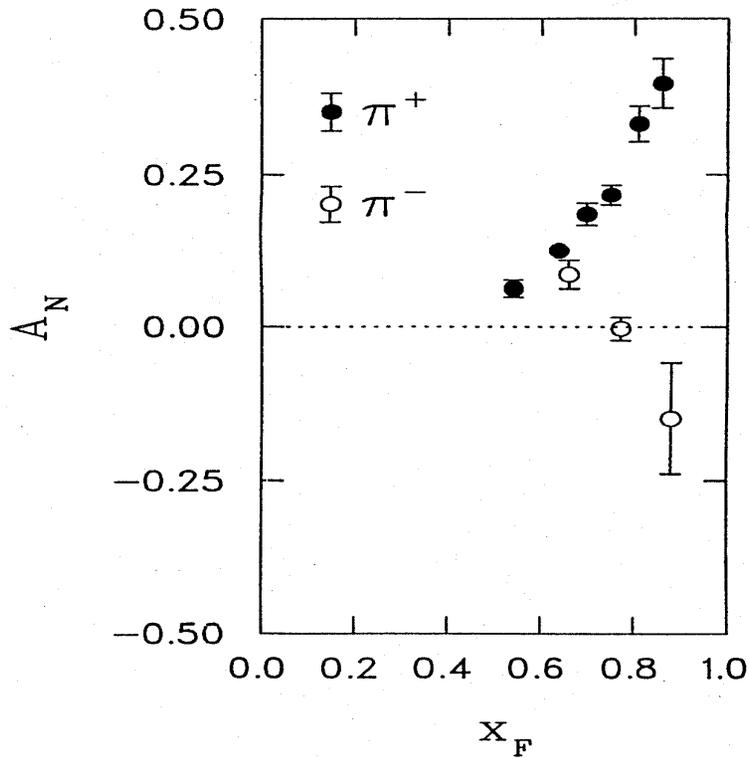
1993: proposal to collide polarized protons in RHIC

High Energy Polarimetry??

- **use inclusive pion production?**
 - 1991 result from E704 at Fermilab
- **use p-p elastic scattering at medium t?**
 - traditional, but $A_N \sim 1/p$, 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

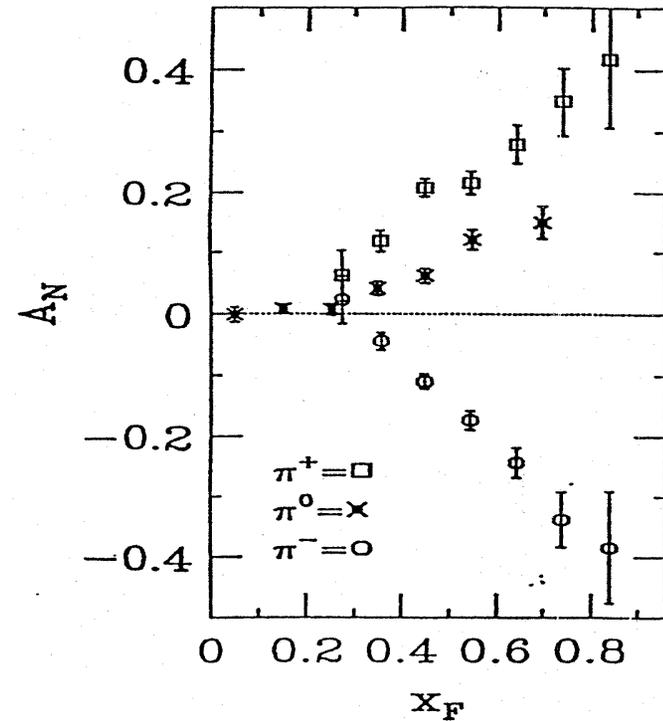
Asymmetry in inclusive pion production

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

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

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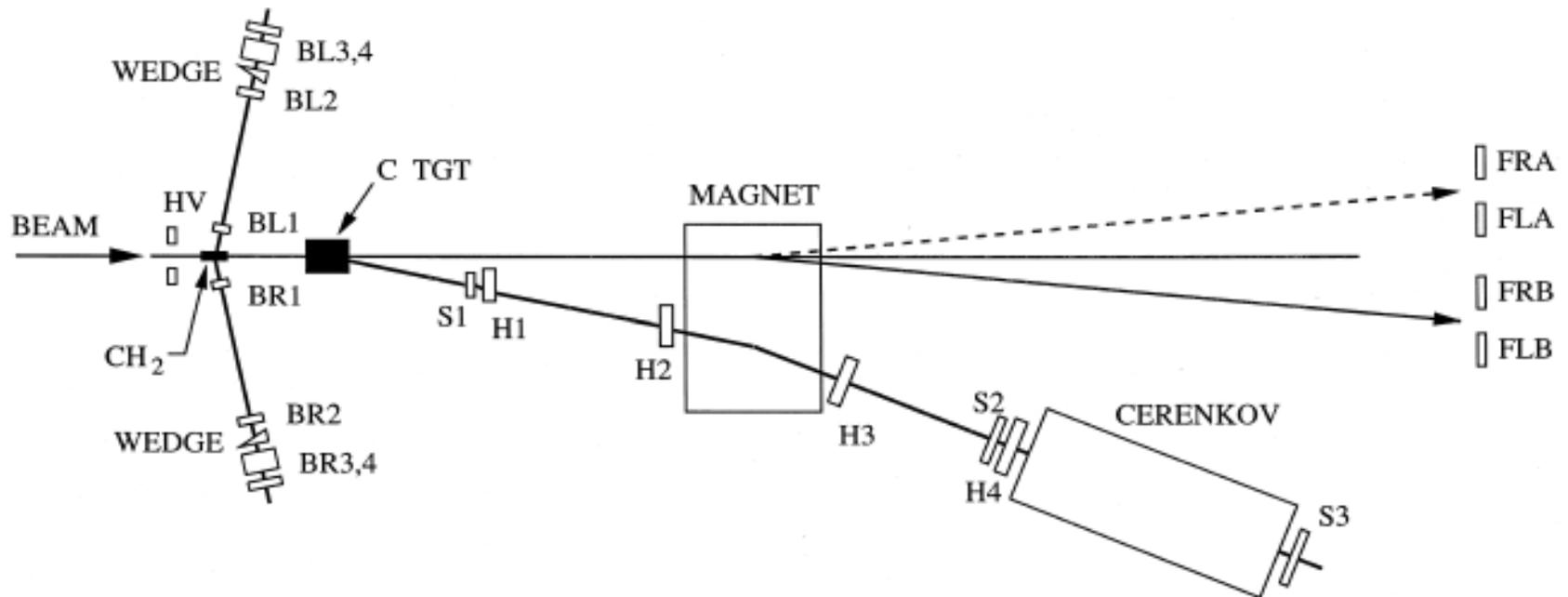
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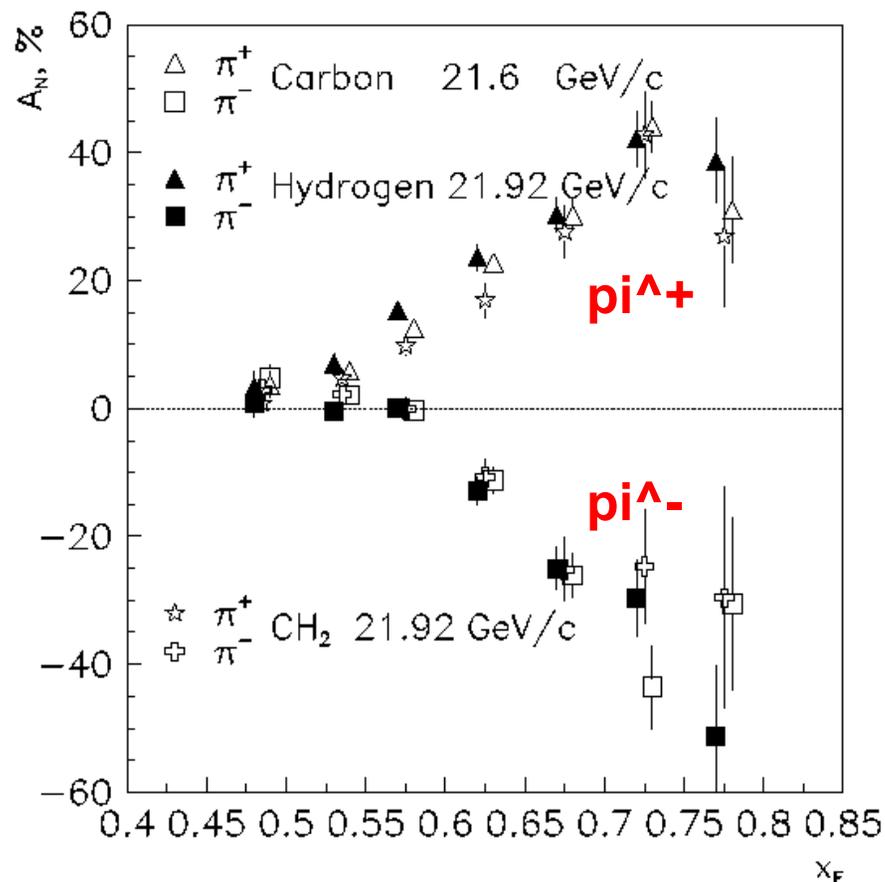
...first there was a question about pi asymmetries
and a nuclear target—multiple interactions in nucleus...

AGS E925 spectrometer and polarimeter



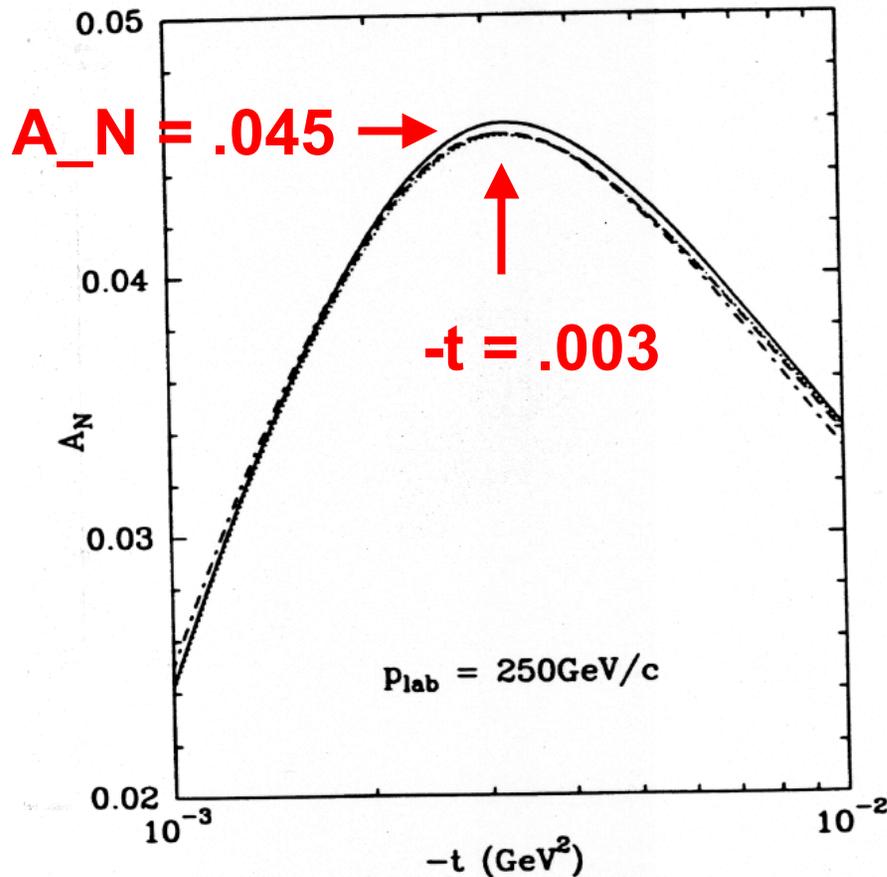
Asymmetry in Inclusive Pion Production E925 AGS

- Beam momentum
21.6 GeV/c
- First measurement with
a nuclear target
- No discernable target
dependence
- So much for the
theoretical worry



Phys. Lett. B459, 412 (1999)

p-p Elastic, Coulomb-Nuclear Interference



...from single
photon exchange
→ helicity flip

→ proton $g-2$

(original work:
Schwinger 1948;
Lapidus and
Kopeliovich
1974)

...besides p-p CNI, which would be a very slow measurement, p-A CNI!

● CNI in pA elastic scattering

If $r=0$, the CNI formulas look the same as for pp, except the replacement

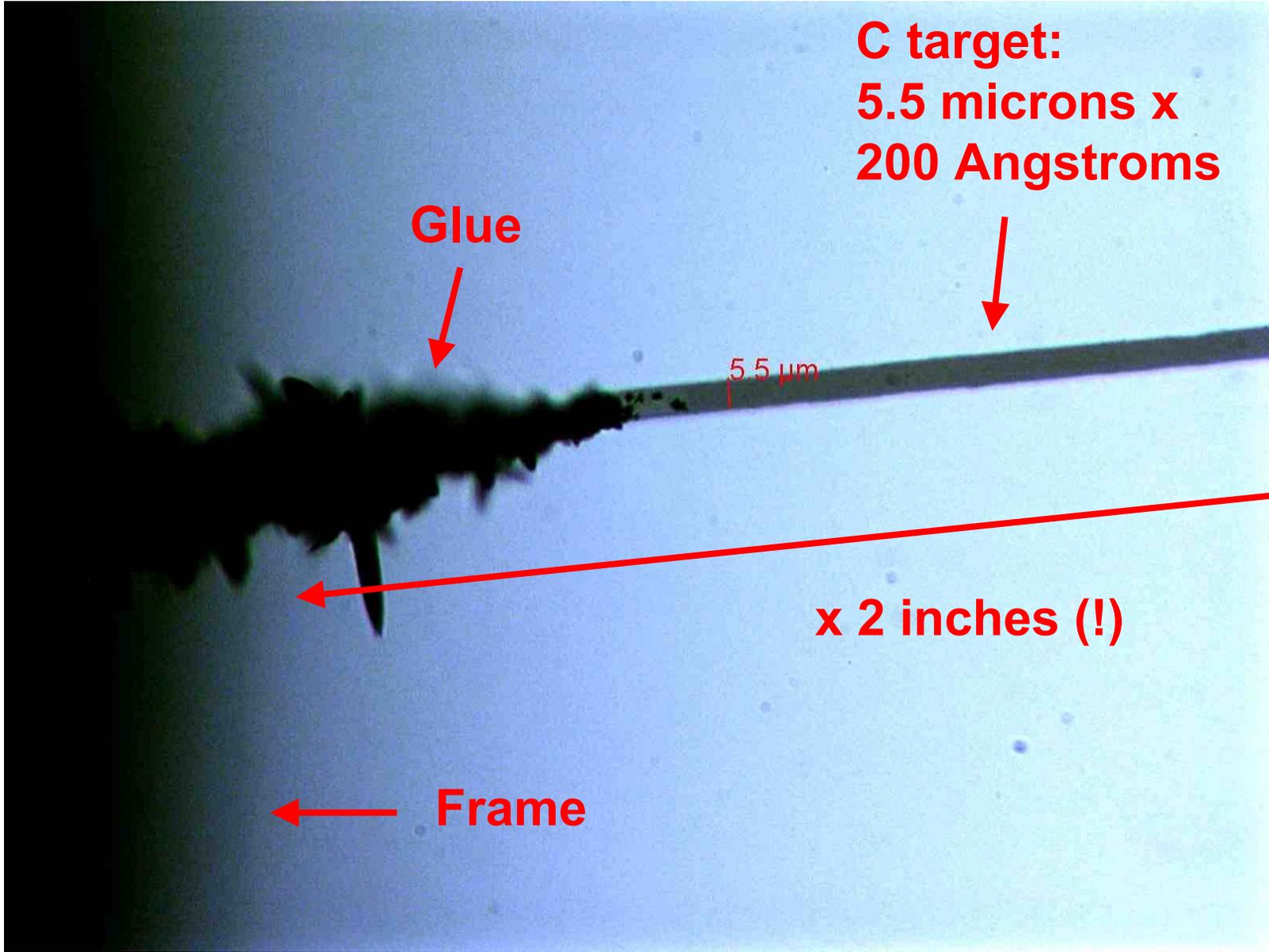
$$t_p^{PA} = t_p^{PP} \left(Z \frac{\sigma_{tot}^{PP}}{\sigma_{tot}^{PA}} \right), \text{ but } A_N^{PA}(t) \text{ changes sign at } |t| \sim 3/R_A^2$$

For pC interaction $t_p^{PC} = 2.3 \cdot 10^{-3} \text{ GeV}^{-2}$
and in the maximum

$$A_N^{PC}(t_p^{PC}) = 0.039$$

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





**C target:
5.5 microns x
200 Angstroms**

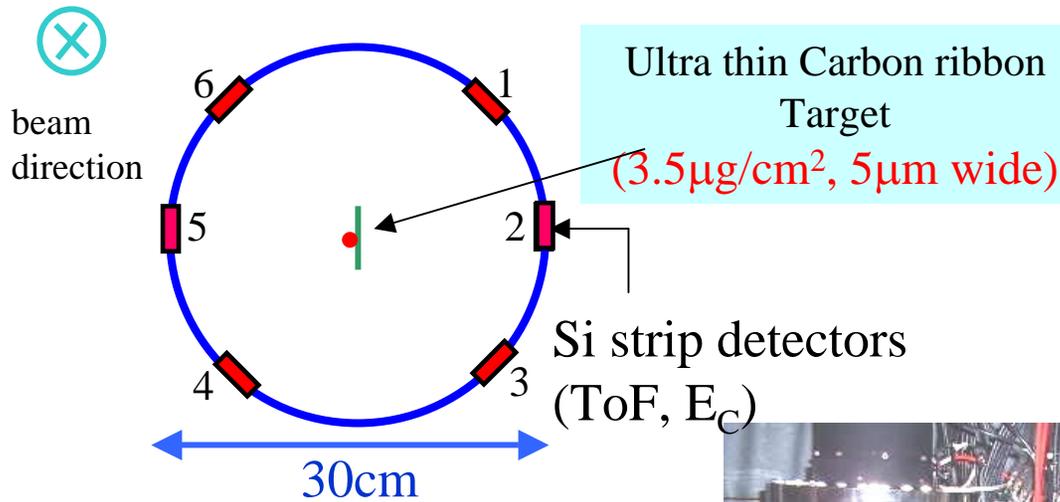
Glue

5.5 μm

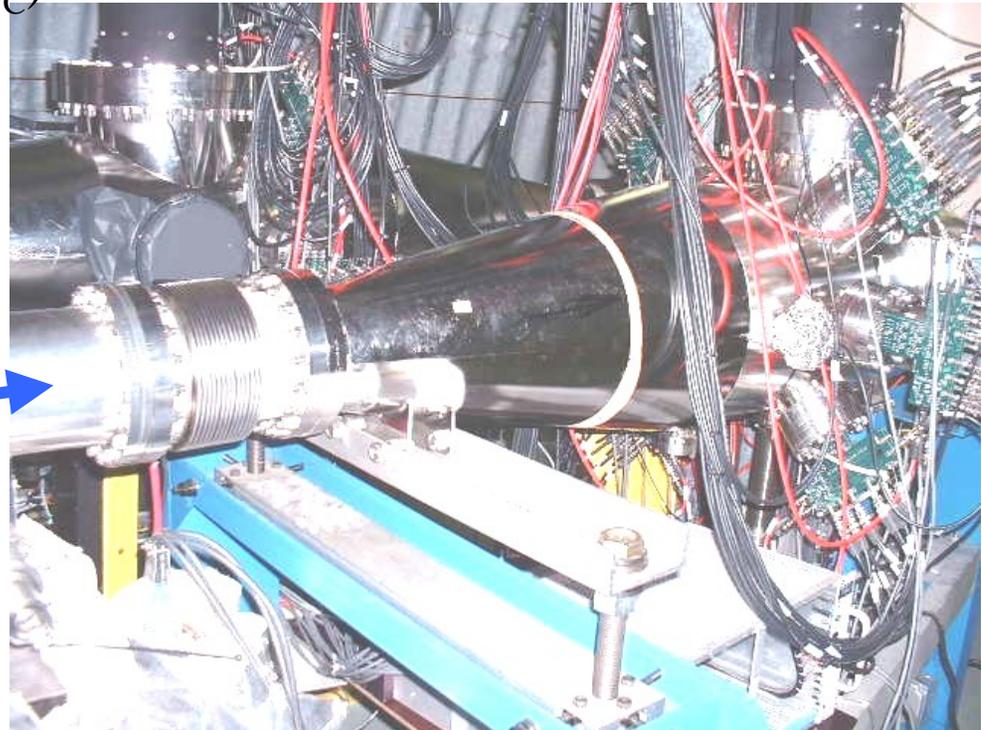
x 2 inches (!)

Frame

Setup for pC scattering – the RHIC polarimeters

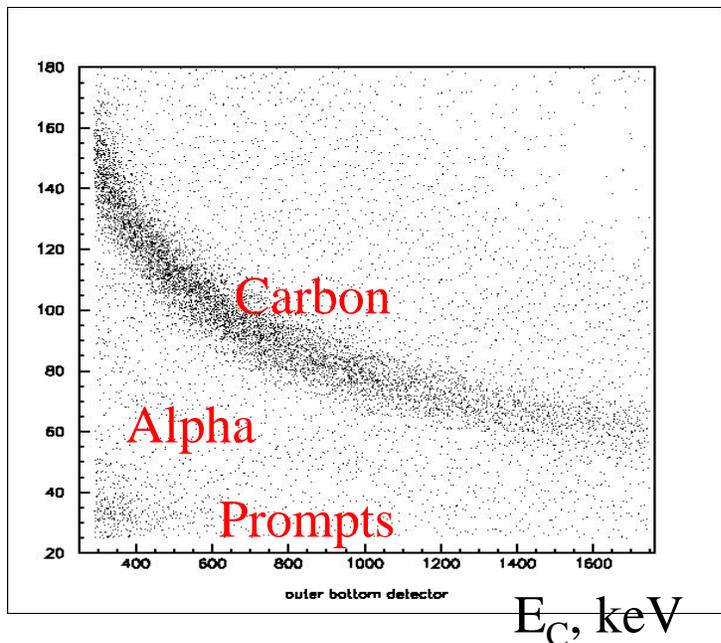


**RHIC
Beam**

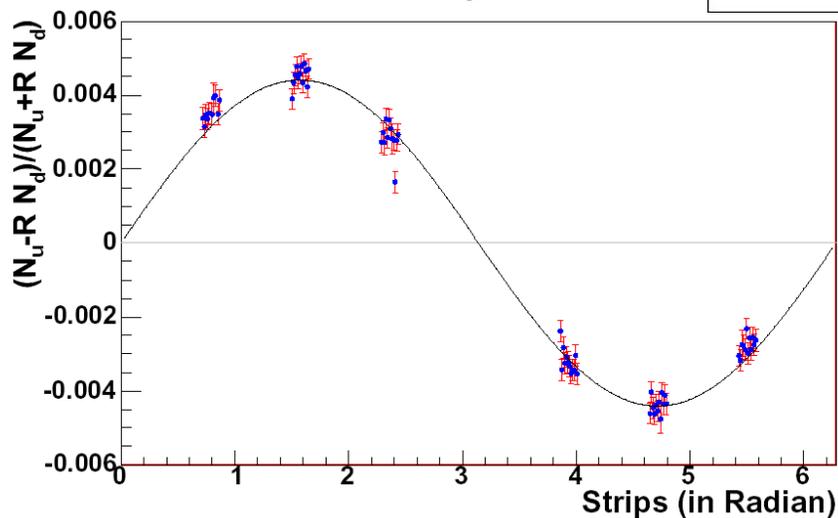
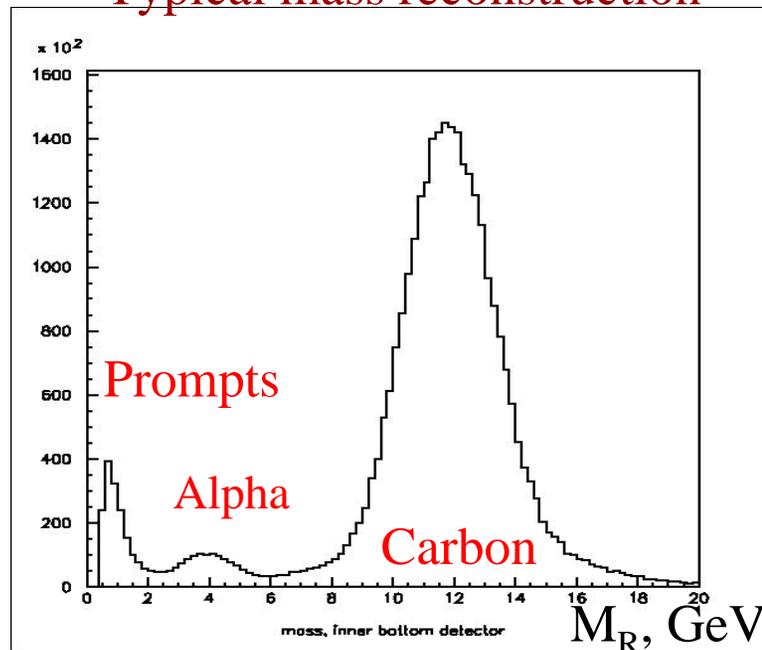


p-Carbon CNI RHIC

TOF, ns



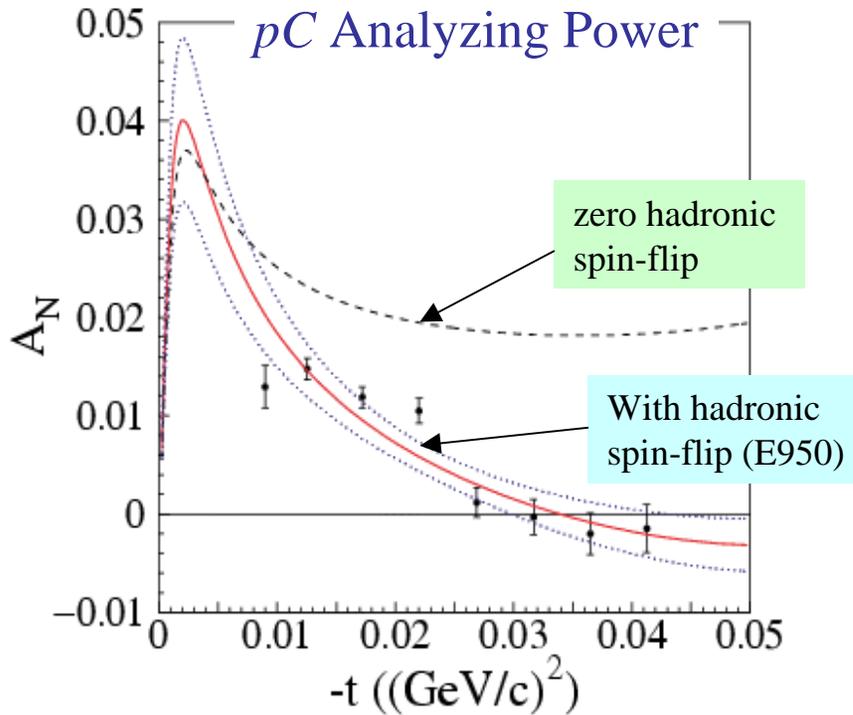
Typical mass reconstruction



← Phi dependence:
6 detectors, 72 strips

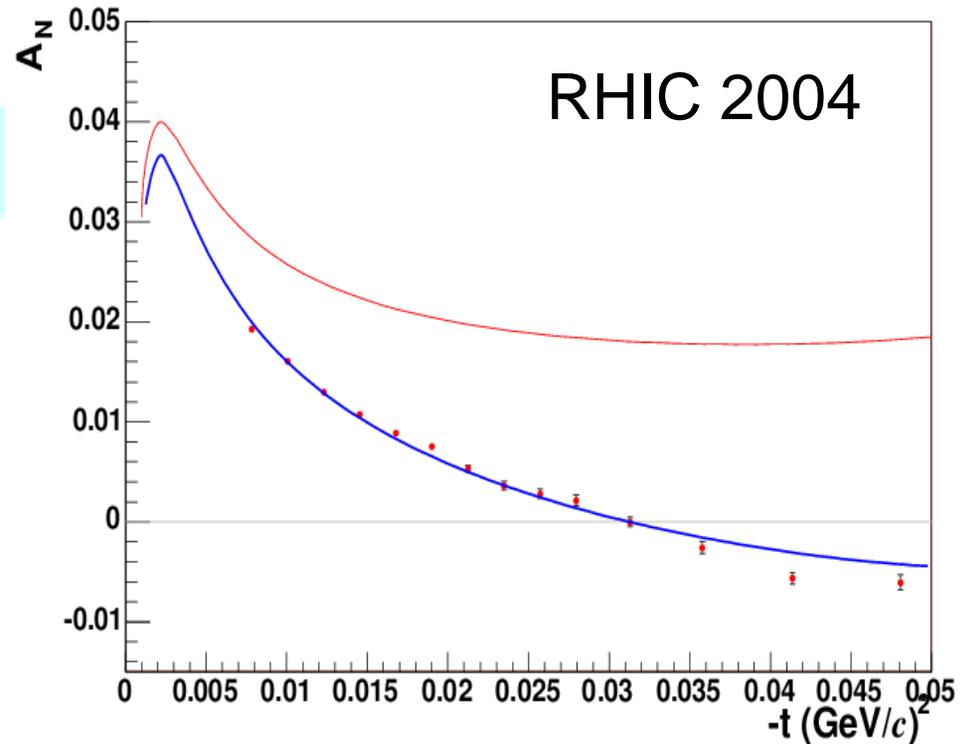
Note: Si detectors from
BNL Instrumentation

Results from p-carbon CNI



Phys.Rev.Lett.,89,052302(2002)

$E_{\text{beam}} = 21.6 \text{ GeV}$
(AGS 1999)



unpublished

$E_{\text{beam}} = 100 \text{ GeV}$

...to carry the 22 GeV measurement to 100 GeV

RHIC Spin Note

January 2002

Energy dependence of CNI analyzing power for proton-carbon scattering

T.L. Trueman *

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Abstract

We use a simple Regge model to determine the energy dependence of the analyzing power for pC scattering in the CNI region. We take the model of Cudell et al which determines the Regge couplings and intercepts for the $I = 0$, non-flip Regge exchanges (Pomeron, f_1 and ω) and extend it to the spin-flip amplitudes by allowing each of these exchanges to have independent spin-flip factors τ_P, τ_f and τ_ω . Using this we show that by making measurements at two separate energies, with polarization known at one energy, one can fix the ratios of the analyzing power at any energy. By making an additional assumption that is reasonable, but not necessarily true, namely $\tau_\omega = \tau_f$, we show that one can predict the energy dependence of the analyzing power *using the existing E950 data*. We present the corresponding predictions for beam energies of 100 GeV and 250 GeV protons on a fixed carbon target based on a fit to the Spin 2000 data. Finally, we discuss the relation of these results to the pp CNI analyzing power.

RBRC Workshop 1 became a PRD:

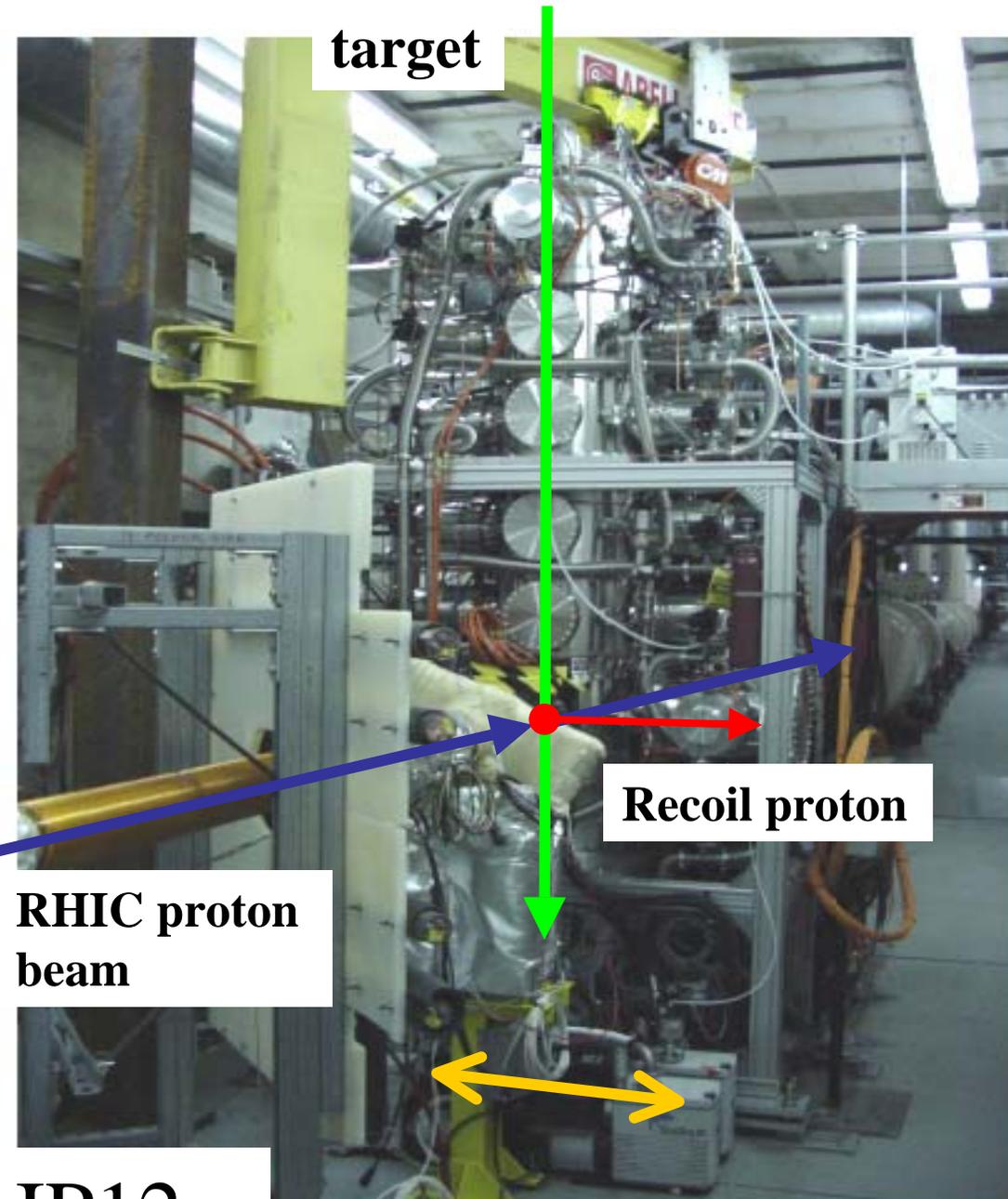
The spin dependence of high-energy proton scattering.

[Nigel H. Buttimore](#) ([Trinity Coll., Dublin](#)) , [B.Z. Kopeliovich](#)
([Heidelberg, Max Planck Inst.](#)) , [E. Leader](#) ([Birkbeck](#)
[Coll.](#)) , [Jacques Soffer](#) ([Marseille, CPT](#)) , [T.L. Trueman](#)
([Brookhaven](#)) .

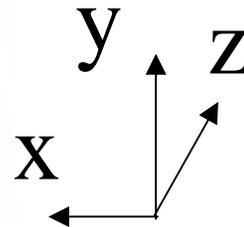
Published in **Phys.Rev.D59:114010,1999.**

And, after building proton-carbon polarimeters,
we (2002-3) built a polarized atomic
hydrogen jet target, an absolute polarimeter for
for RHIC, using p-p CNI.

H-jet-target system

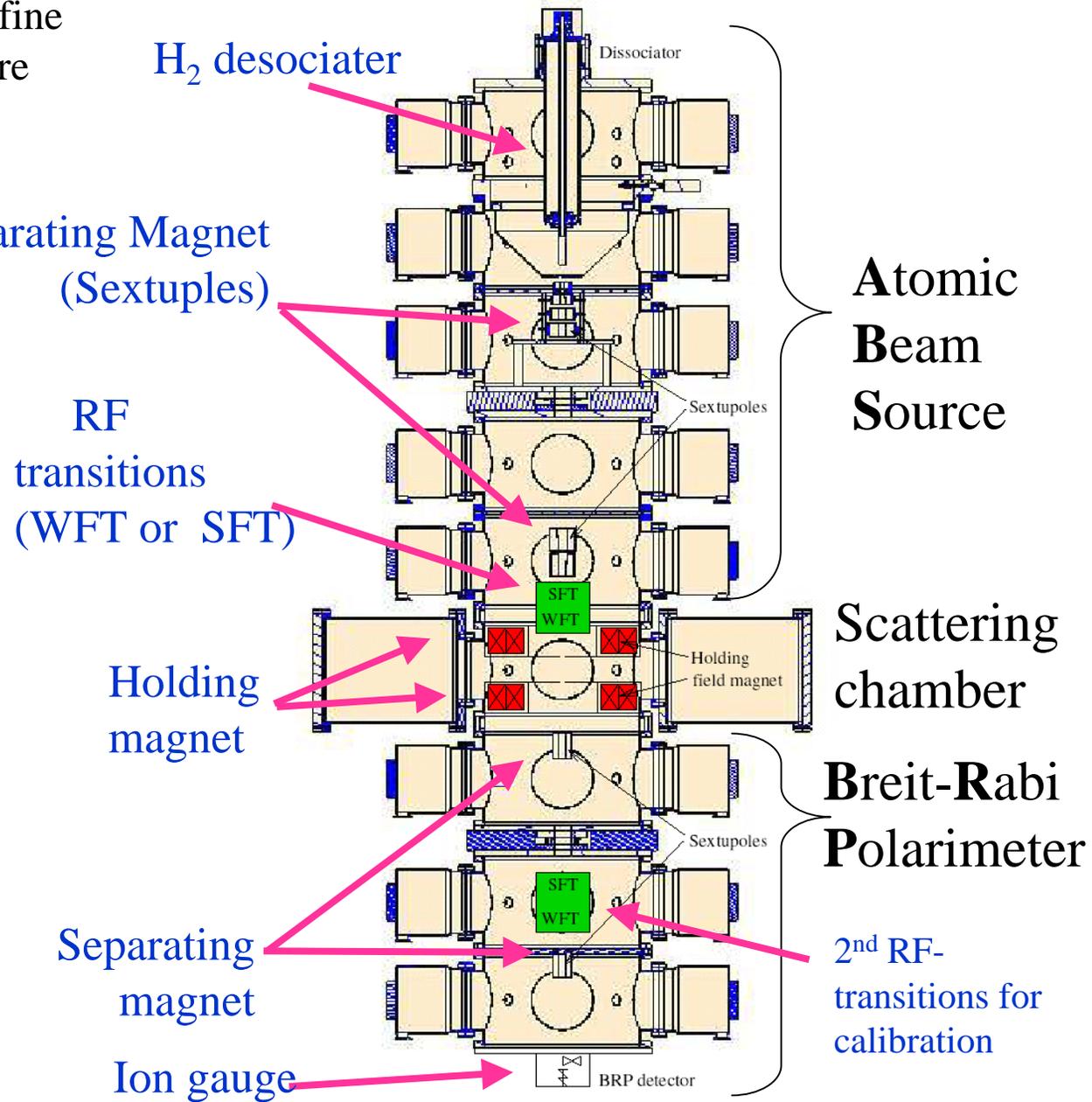
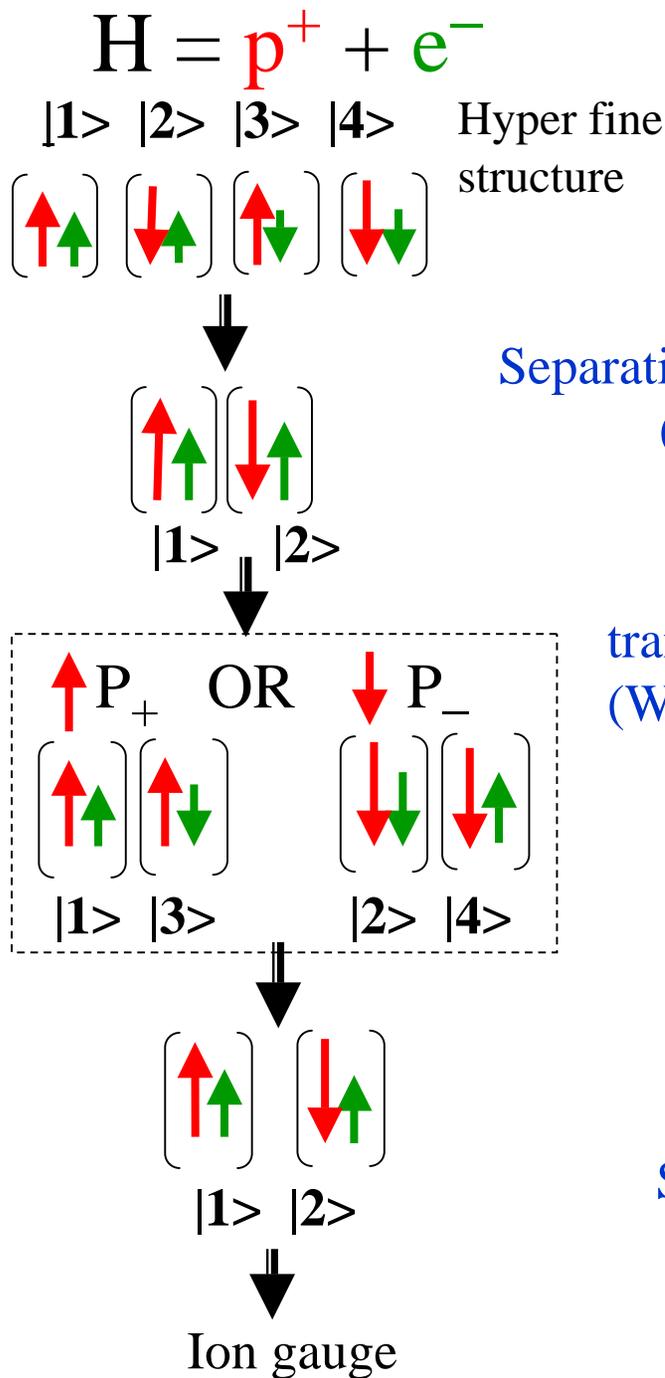


- Height: 3.5 m
- Weight: 3000 kg
- Entire system moves along x-axis $-10 \sim +10$ mm to adjust collision point with RHIC beam.

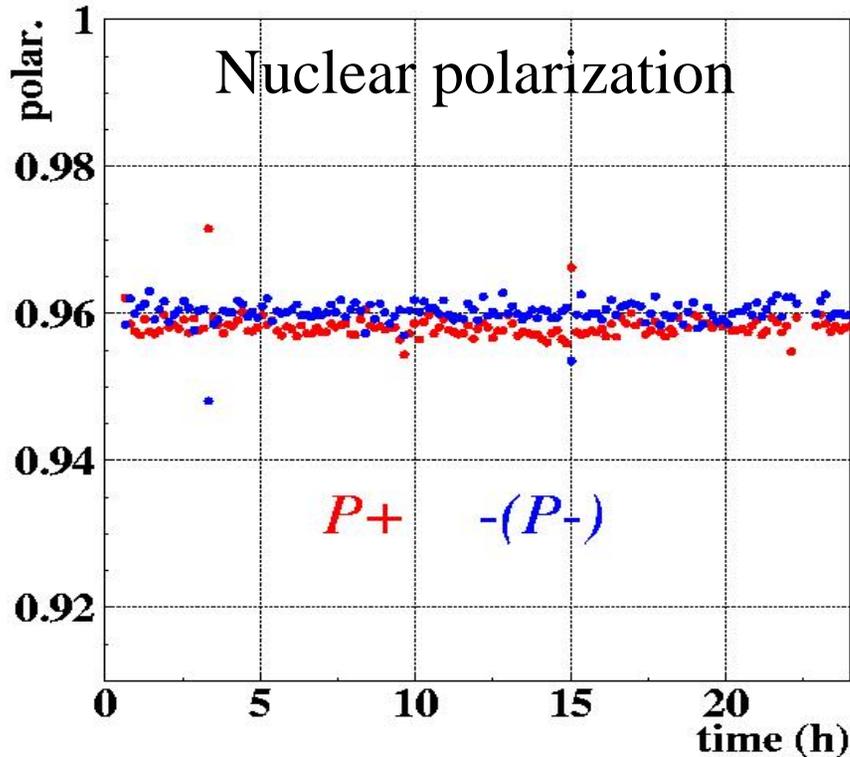


IP12

H-jet-target system



Target polarization



1 day

Polarization cycle
(+ / 0 / -) = (500/50/500) seconds

Nuclear polarization of the atoms measured by BRP:
 $95.8\% \pm 0.1\%$

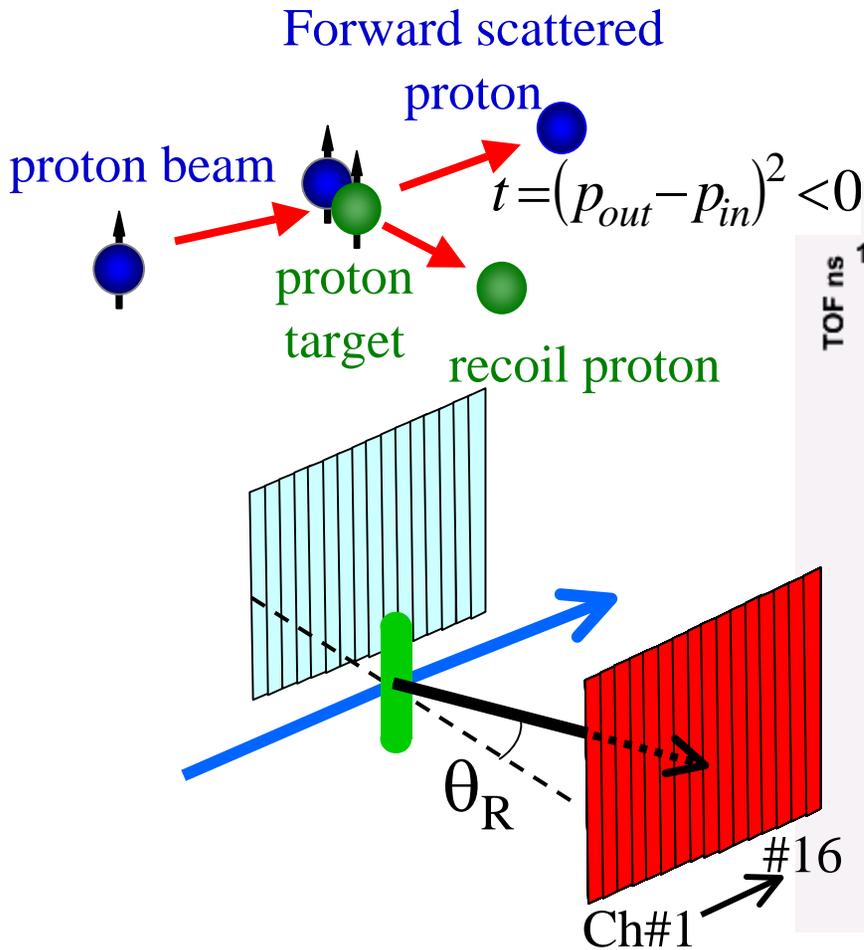
Correct H_2 , H_2O contamination.
Divided by factor 1.037

$$\mathbf{P}_{\text{target}} = 92.4\% \pm 1.8\%$$

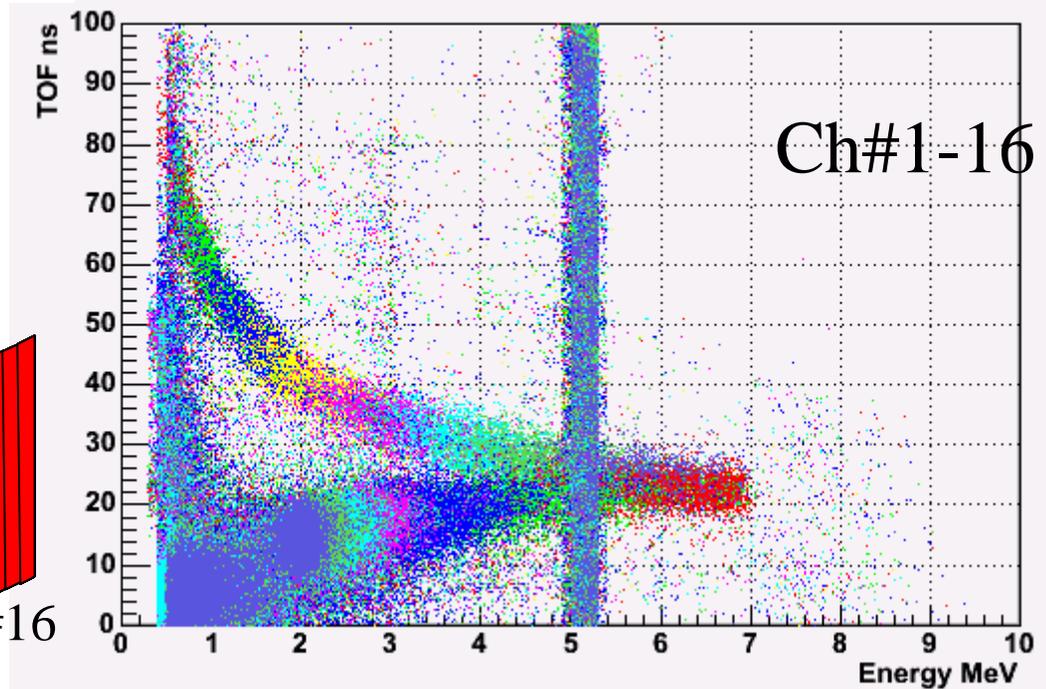
Very stable for entire run period !

$$\frac{\Delta P_{\text{target}}}{P_{\text{target}}} = 2\%$$

How to identify elastic events ?

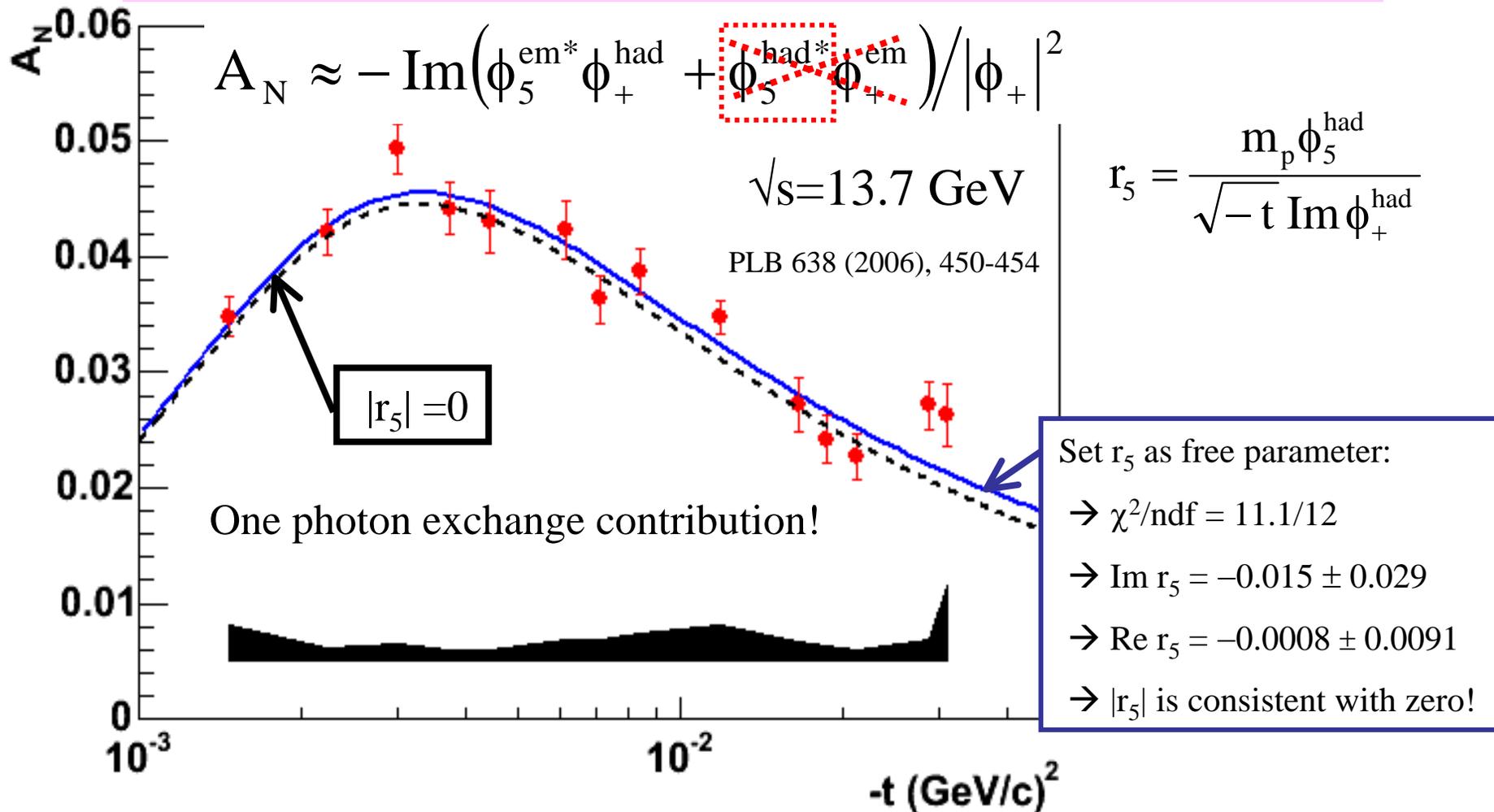


$\text{Ch\#} \propto \theta_R$, θ_R big $\Rightarrow T_R$ big
 \Rightarrow fast protons



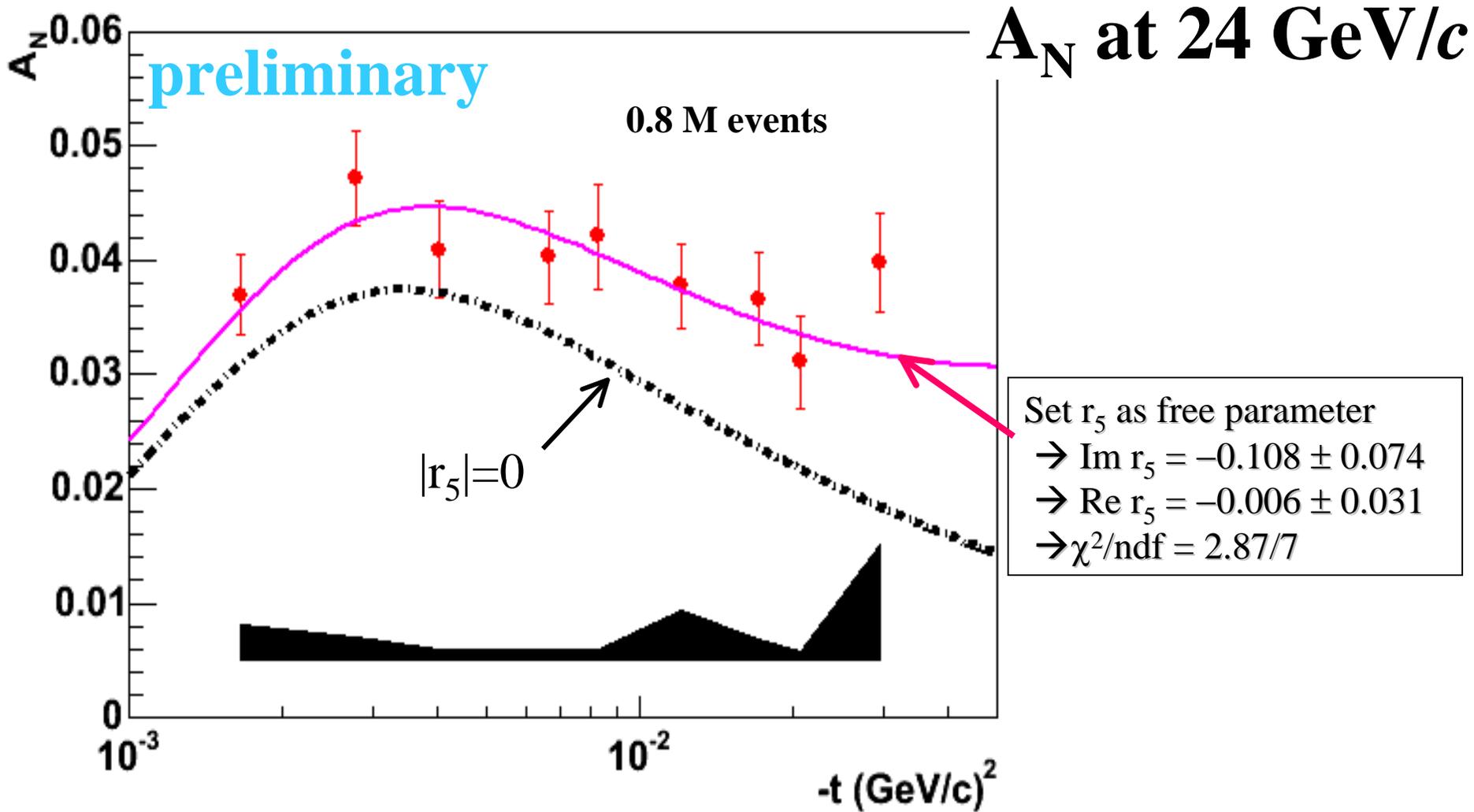
Array of Si detectors measures T_R & ToF of recoil particles.
Channel # corresponds to recoil angle θ_R .
2 correlations (T_R & ToF) and (T_R & θ_R) \rightarrow the elastic process

Results of A_N in the CNI region @ $\sqrt{s}=13.7$ GeV



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

ϕ_5^{had} is consistent with zero at $\sqrt{s} = 13.7$ GeV.

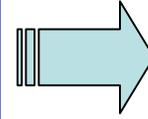


- ◆ Compare measured A_N and expected curve with $|r_5|=0$
→ $\chi^2/\text{ndf} = 35.5/9$.
- ◆ r_5 has \sqrt{s} dependence ? → Not improbable in theory.

Contribution to theoretical understanding of A_N

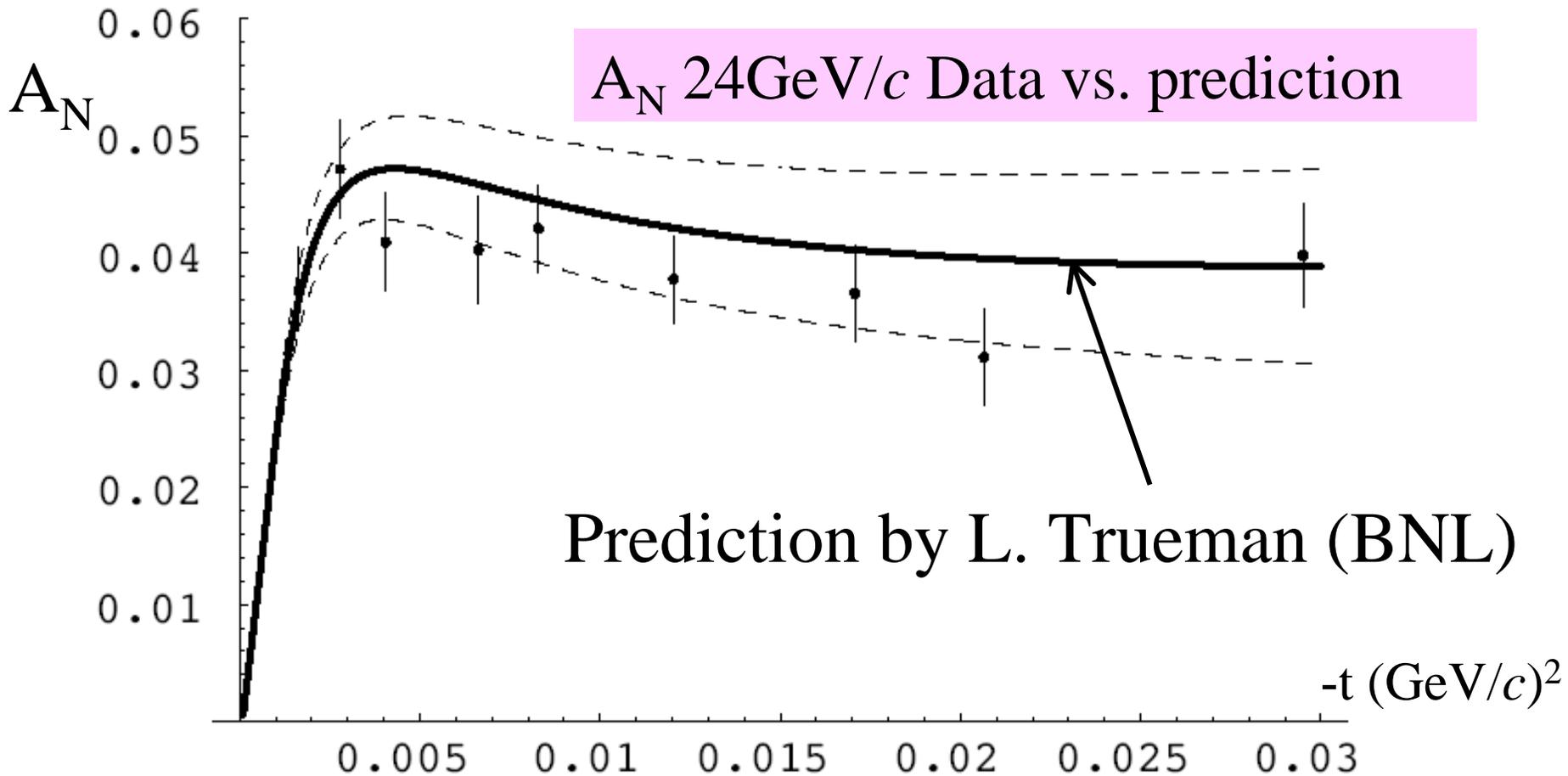
Input: A_N^{pC} at 24GeV/c, 100GeV/c

A_N^{pp} at 100GeV/c



Prediction:

A_N at 24GeV/c



Spin asymmetries for elastic proton scattering and the spin dependent couplings of the Pomeron.

[T.L. Trueman](#) ([Brookhaven](#)) . BNL-HET-07-14,
Nov 2007.

Published in **Phys.Rev.D77:054005,2008.**

e-Print: **arXiv:0711.4593** [hep-ph]

...however, let's look at the 1999 paper again

PHYSICAL REVIEW D, VOLUME 59, 114010

Spin dependence of high energy proton scattering

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(Received 19 January 1999; published 21 April 1999)

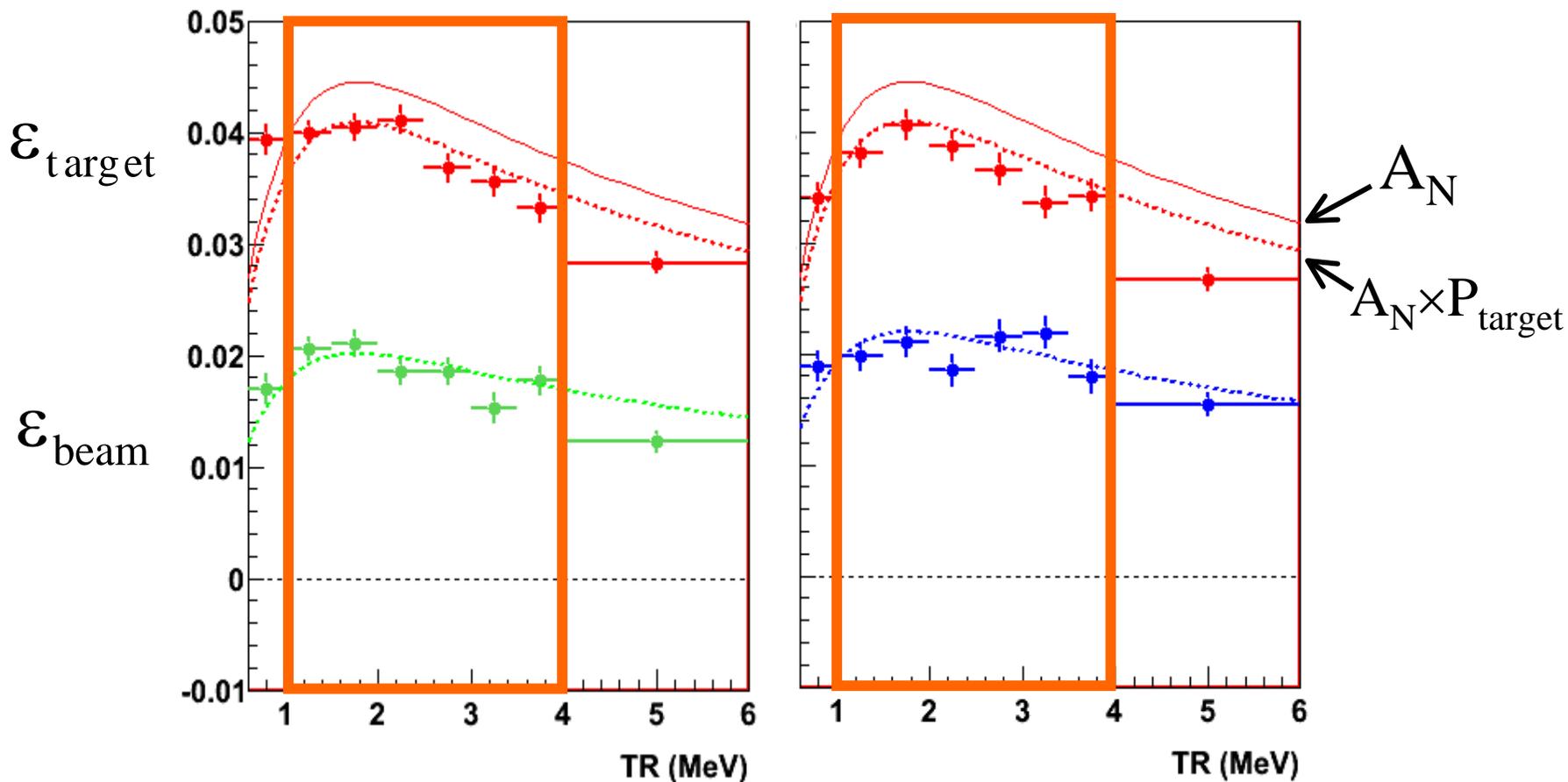
Motivated by the need for an absolute polarimeter to determine the beam polarization for the forthcoming BNL RHIC spin program, we study the spin dependence of the proton-proton elastic scattering amplitudes at high energy and small momentum transfer. In particular, we examine experimental evidence for the existence

In summary while the various approaches give results which differ in sign and magnitude, and while it is not clear to what extent perturbative and nonperturbative approaches overlap, it seems reasonable to assert that $|r_5| < 10\%$ at RHIC energies. This level of accuracy is unfortunately inadequate for the needs of an absolute polarimeter. We have

Raw asymmetries from RUN5

Yellow beam 3.7M events

Blue beam 2.9M events



$$P_{\text{beam}} = \frac{\epsilon_{\text{beam}}}{\epsilon_{\text{target}}} P_{\text{target}}$$

Run5 statistics Yellow: 5.3 M events

Blue: 4.2 M events

RUN5 Absolute beam polarization at 100GeV/c

$$P(\text{target}) = 92.4\% \pm 1.8\%$$

	stat.	sys.
$P(\text{blue beam})$	$= 49.3\% \pm 1.5\%$	$\pm 1.4\%$
$P(\text{yellow beam})$	$= 44.3\% \pm 1.3\%$	$\pm 1.3\%$

Achieve goal !!

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

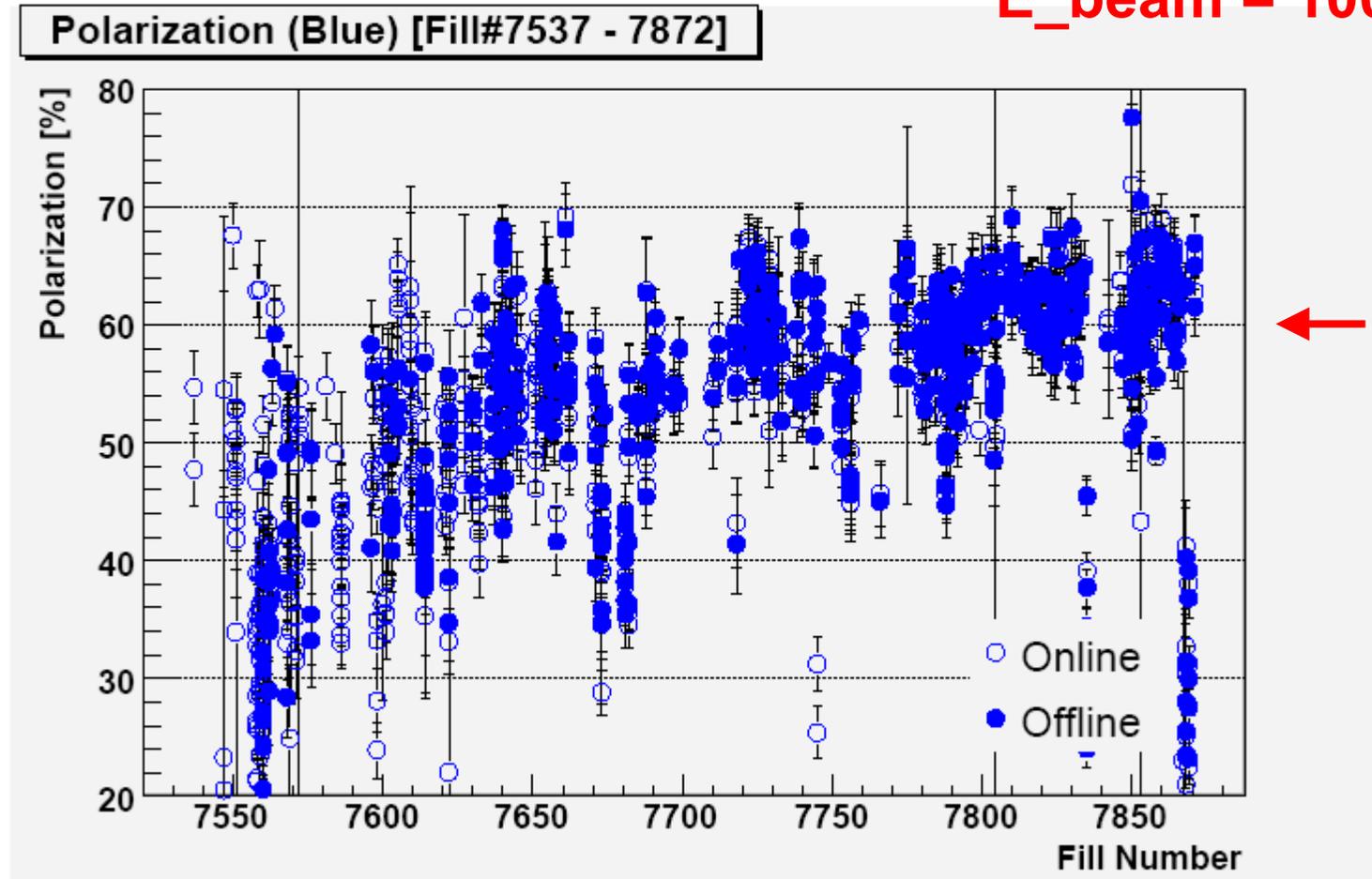
Measurement of the Analyzing Power A_N in pp elastic scattering in the CNI region with a Polarized Atomic Hydrogen Gas Jet Target

Hiromi Okada from RIKEN

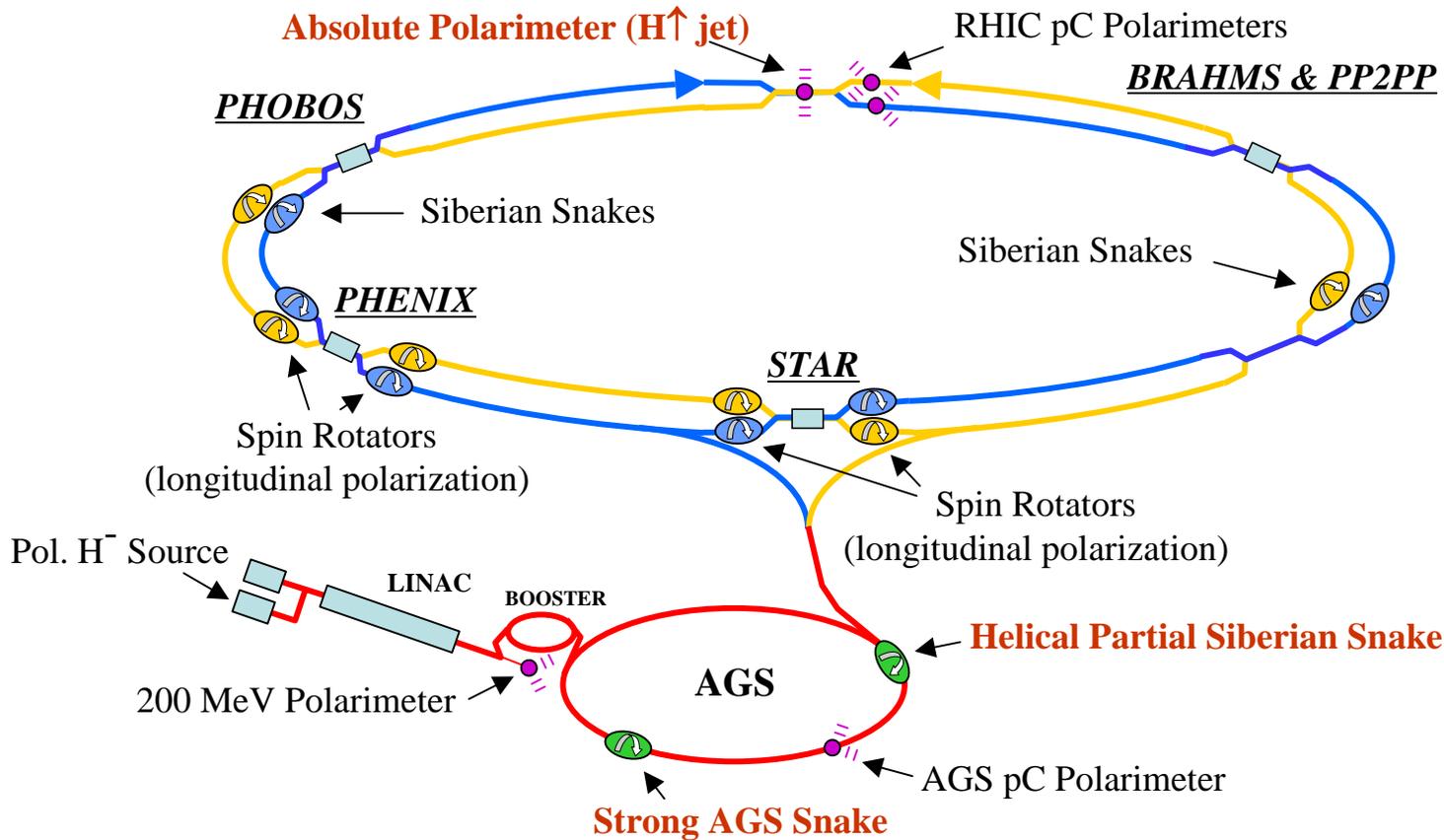
**I. Alekseev, A. Bravar, G. Bunce,
S. Dhawan, O. Eyser, R. Gill, W. Haeberli,
O. Jinnouchi, A. Khodinov,
K. Kurita, Z. Li, Y. Makdisi,
I. Nakagawa, A. Nass, S. Rescia, N. Saito,
H. Spinka, E. Stephenson, D. Svirida,
T. Wise, A. Zelenski**

Polarization Measurements 2006 Run

E_beam = 100 GeV



RHIC Polarized Collider



2006: 1 MHz collision rate; P=0.6