Techniques for Polarimetry in (ep, μp, and) pp Physics

Outline

- Some Basic Concepts
- Polarimeter Construction
- Calibrations
- Instrumental / Systematic Errors
- CNI Polarimeters - A Case Study

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10 June 2004

Some Basic Concepts

Asymmetry

For non-negative integers, N_i, measured in some process, the asymmetry is

$$\varepsilon = \frac{N_1 - N_2}{N_1 + N_2}$$

where

$$-1 \le \varepsilon \le 1.$$

The statistical uncertainty is

$$\delta\varepsilon = \sqrt{\frac{4N_1N_2}{(N_1+N_2)^3}}$$

$$\xrightarrow[N_1 \cong N_2]{} \sqrt{\frac{1}{N_1+N_2}}$$

For $\delta\varepsilon = 0.01$, $N_1 + N_2 \sim 10^4$.

Some quantities cancel in asymmetry measurements, like efficiencies, but small $\delta\varepsilon$ requires many events.

Beam Polarization

For spin-1/2 particles, like protons, the beam polarization is

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

where $\uparrow$ is parallel to the polarization direction, and $\downarrow$ is anti-parallel. The number of beam particles is N_i . Typical values of beam polarizations are:

IUCF (0.2 - 0.5 GeV)	p	0.8	AGS (~ 4 GeV/c)	p	0.7
LAMPF (0.3 - 0.8)	p	0.8	AGS (~ 24)	p	0.5
	n	0.5	FNAL (200)	p	0.4
SATURNE (0.8 - 2.8)	p	0.8	FNAL (200)	anti-p	0.4
COSY (0.4 – 2.5)	p	0.6	RHIC (100)	p	0.4

Polarized beams have also existed at other accelerators, such as the ZGS, Dubna, and KEK. There are similar polarizations at electron machines and in polarized muon beams.

Polarimeters

Hardware to measure and/or monitor the (relative) beam polarization is called a polarimeter. It may be installed in an accelerator or an external beam line dedicated to a single experiment. Polarimeters measure asymmetries for the polarized beam states:

$$\varepsilon = P\,A$$

where A is the analyzing power. The polarimeter must be calibrated in some way to determine A.

Once the beam polarization, P, is known, asymmetries measured in experiments (ε') can be turned into physically interesting parameters ($\sim \varepsilon'/P$, or $\varepsilon'/P_1 P_2$ for colliding beams of polarized particles).

Desirable Characteristics of Polarimeters

- Fast Response (large cross section)
- Large Analyzing Power (so large ε)
- Simple Design (minimize maintenance and hardware problems)
- Low Cost
- Ease of Operation
- Minimal Systematic Errors
- Ease of Calibration

Note:

$$\delta P = \delta\varepsilon / A \sim \frac{1}{A\sqrt{N_\uparrow + N_\downarrow}}$$

$$A\sqrt{N} \sim Figure\ of\ Merit$$

Therefore, large A is more important than a large count rate.

Equations for One "Detector" Polarimeters

Assume a beam polarization direction up/down, and assume the beam phase space is the same for both ↑ and ↓ polarizations. Then for a detector to the left of the beam observing the forward scattered particle,

$$N_{L\uparrow} = N_0 B_\uparrow d\Omega_L (1 + A_L P_\uparrow)$$
$$N_{L\downarrow} = N_0 B_\downarrow d\Omega_L (1 - A_L P_\downarrow)$$

where

N = detected counts

B = integrated beam

$d\Omega$ = solid angle * efficiency

A = analyzing power

P = beam polarization

N_0 = constant (cross section, target thickness, etc.)

Measure ↑ and ↓ beam at different times. However, the relative beam intensity must be monitored in some independent manner.

Equations for One "Detector" Polarimeters (cont.)

Then the asymmetry is

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

$$= A_L (P_{\uparrow} + P_{\downarrow}) / 2$$

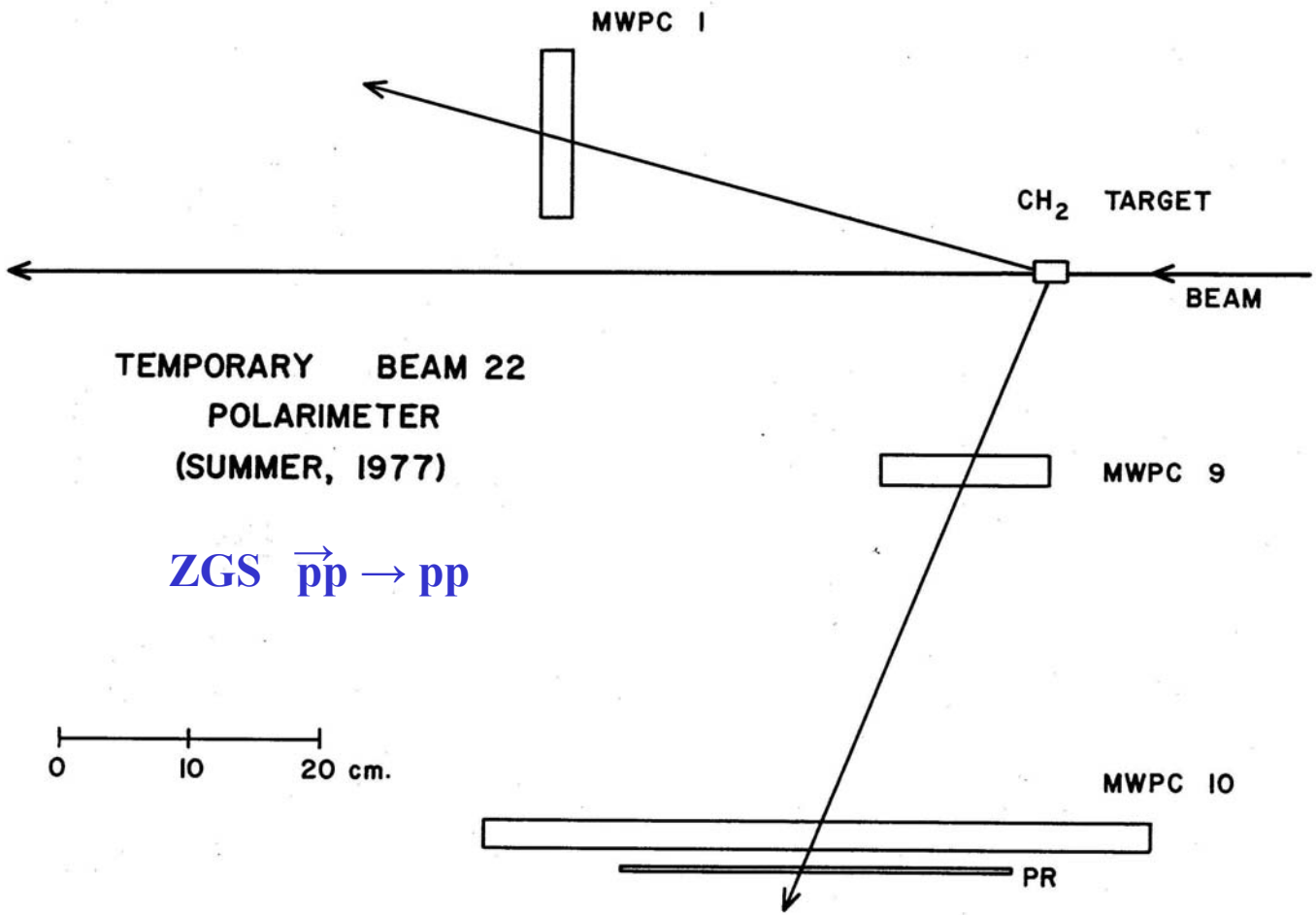
with

$$P = (P_{\uparrow} + P_{\downarrow}) / 2$$

$$= \text{average beam polarization}$$

In the asymmetry, B is the relative integrated beam intensity from independent monitors. Note, absolute intensity is not necessary.

Example of a One "Detector" Polarimeter



- Contained wire chambers and a scintillator
- Beam scintillation counters are not shown (used for trigger and measurement of beam intensity)

Equations for Two "Detector" Polarimeters

Assume a beam polarization direction up/down. Then for approximately symmetric detectors to both the left and right of the beam observing the forward scattered particles,

$$N_{L\uparrow} = N_0 B_\uparrow d\Omega_L (1 + A_L P_\uparrow)$$
$$N_{L\downarrow} = N_0 B_\downarrow d\Omega_L (1 - A_L P_\downarrow)$$
$$N_{R\uparrow} = N_0 B_\uparrow d\Omega_R (1 - A_R P_\uparrow)$$
$$N_{R\downarrow} = N_0 B_\downarrow d\Omega_R (1 + A_R P_\downarrow)$$

These yield three "square root asymmetries"

$$\varepsilon_{PHYS} = \frac{\sqrt{N_{L\uparrow} N_{R\downarrow}} - \sqrt{N_{L\downarrow} N_{R\uparrow}}}{\sqrt{N_{L\uparrow} N_{R\downarrow}} + \sqrt{N_{L\downarrow} N_{R\uparrow}}}$$

$$\cong P A + P^2 A^2 O(\delta^2)$$

(In this case, δ can be PA, ε_A, or ε_P but not ε_B or $\varepsilon_{d\Omega}$.)

Equations for Two "Detector" Polarimeters (cont.)

$$\varepsilon_{LUM} = \frac{\sqrt{N_{L\uparrow}N_{R\uparrow}} - \sqrt{N_{L\downarrow}N_{R\downarrow}}}{\sqrt{N_{L\uparrow}N_{R\uparrow}} + \sqrt{N_{L\downarrow}N_{R\downarrow}}}$$

$$\cong \varepsilon_B + PA\,\varepsilon_A + PA\,O(\delta'^2)$$

(δ' contains no contribution from $\varepsilon_{d\Omega}$.)

$$\varepsilon_{GEOM} = \frac{\sqrt{N_{L\uparrow}N_{L\downarrow}} - \sqrt{N_{R\uparrow}N_{R\downarrow}}}{\sqrt{N_{L\uparrow}N_{L\downarrow}} + \sqrt{N_{R\uparrow}N_{R\downarrow}}}$$

$$\cong \varepsilon_{d\Omega} + PA\,\varepsilon_P + PA\,O(\delta''^2)$$

(δ'' contains no contribution from ε_B .)

In the three square root asymmetries, the quantities PA, ε_A , ε_B , $\varepsilon_{d\Omega}$, ε_P are all assumed small and of about the same magnitude, δ . The physically interesting asymmetry is ε_{PHYS} . The other two describe an asymmetry in the amount of beam for the two polarization states and in the solid angle times efficiency for the two detectors.

Equations for Two "Detector" Polarimeters (cont.)

In the previous equations, the following quantities are used:

$$P = (P_\uparrow + P_\downarrow)/2 \qquad \varepsilon_P = \frac{P_\uparrow - P_\downarrow}{P_\uparrow + P_\downarrow}$$

$$A = (A_L + A_R)/2 \qquad \varepsilon_A = \frac{A_L - A_R}{A_L + A_R}$$

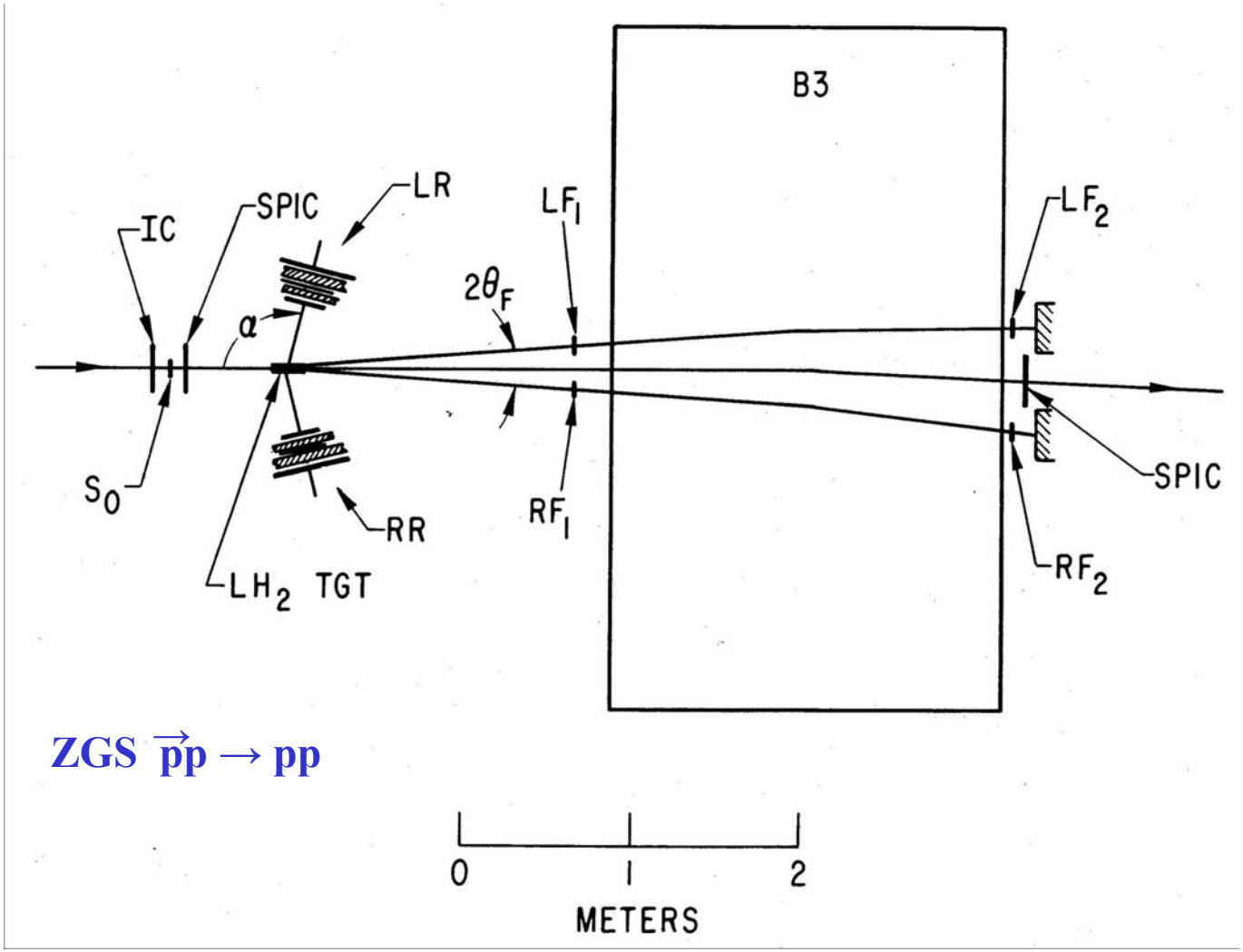
$$B = (B_\uparrow + B_\downarrow)/2 \qquad \varepsilon_B = \frac{B_\uparrow - B_\downarrow}{B_\uparrow + B_\downarrow}$$

$$d\Omega = (d\Omega_L + d\Omega_R)/2 \qquad \varepsilon_{d\Omega} = \frac{d\Omega_L - d\Omega_R}{d\Omega_L + d\Omega_R}$$

Note:

$$N_{L\uparrow} + N_{L\downarrow} + N_{R\uparrow} + N_{R\downarrow} \cong 4\, N_0\, B\, d\Omega\, [1 + O(\delta^3)]$$

Example of a Two "Detector" Polarimeter



- Contained scintillation counters and an analyzing magnet (B3)
- Position of forward counters had to be changed with beam energy

H. Spinka et al.,
NIM 211, 239 (1983)

Comments on Two "Detector" Equations

There are four derived quantities (ε_{PHYS} , ε_{LUM} , ε_{GEOM} , and $N_{L\uparrow}+N_{L\downarrow}+N_{R\uparrow}+N_{R\downarrow}$) from the four measured counts ($N_{L\uparrow}$, $N_{L\downarrow}$, $N_{R\uparrow}$, $N_{R\downarrow}$). These four quantities appear to be independent. Thus, any other formulae for physics asymmetries should be expressible in terms of them. For example,

$$\varepsilon'_{PHYS} = \frac{N_{L\uparrow}N_{R\downarrow} - N_{L\downarrow}N_{R\uparrow}}{N_{L\uparrow}N_{R\downarrow} + N_{L\downarrow}N_{R\uparrow}}$$

$$\varepsilon''_{PHYS} = \frac{N_{L\uparrow} - N_{L\downarrow}}{N_{L\uparrow} + N_{L\downarrow}} + \frac{N_{R\downarrow} - N_{R\uparrow}}{N_{R\downarrow} + N_{R\uparrow}}$$

have been used with various polarimeters, and

$$\varepsilon_{PHYS} = \frac{1}{\varepsilon'_{PHYS}} - \sqrt{\frac{1}{(\varepsilon'_{PHYS})^2} - 1}$$

The square root asymmetries will be adopted for all further discussion.

Comments on Two "Detector" Equations (cont.)

- The product PA or one of the ε_i can become sizable under some conditions, including low momentum ($P_{lab} \leq 2$ GeV/c) polarized proton accelerators. In this case, higher order terms in PA or ε_i can contribute noticeably to the previous expressions.

- A relative beam intensity monitor is required for a single "detector" polarimeter, but the beam intensity asymmetry can be found approximately from two "detector" polarimeter measurements (ε_{LUM}).

- The quantities ε_P and ε_A are difficult to obtain experimentally. With sufficient run time, and assuming $< \varepsilon_B > = 0$, then

$$\langle \varepsilon_{LUM} \rangle \rightarrow P\,A\,\varepsilon_A$$

if the beam conditions and ε_A are stable. In general, $< \varepsilon_{d\Omega} > \neq 0$, so this same trick does not work for ε_P . Sometimes unpolarized beam bunches or spills are used to help determine ε_P .

Polarimeter Construction

Polarimeter design depends on the reaction chosen and the need to reject related backgrounds. The reactions adopted often involve elastic (or quasi-elastic) scattering:

$$p + p \rightarrow p + p$$

$$p + d \rightarrow p + d$$

$$p + C \rightarrow p + C$$

$$p + C \rightarrow p + p + X$$

because it is easy to reject inelastic reactions on the basis of the outgoing particle angles.

The Primakoff effect

$$\vec{p} + Z \rightarrow \Delta / N^* + Z \rightarrow p + \pi^0 + Z$$

$$(\vec{p} + \gamma^* \rightarrow p + \pi^0)$$

Polarimeter Construction (cont.)

has been used, and inclusive particle production

$$\vec{p} + "N" \rightarrow \pi^{\pm} + X$$

$$\rightarrow \pi^{0} + X$$

has been considered for high energy polarized proton beams.

For polarized electrons, Möller and Compton scattering are often used:

$$\vec{e} + \vec{e} \rightarrow e + e$$

$$\vec{\gamma} + \vec{e} \rightarrow e + \gamma$$

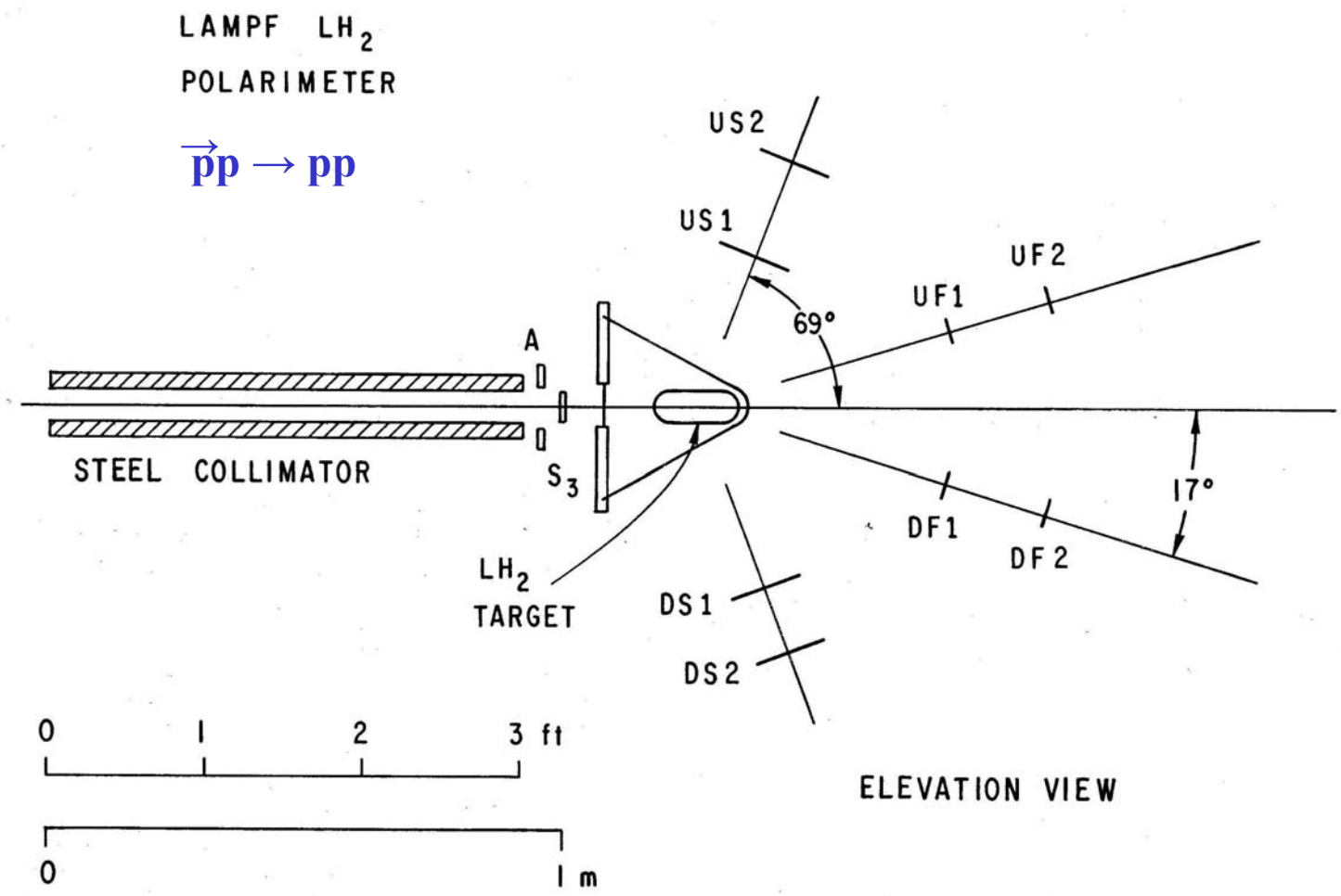
and for polarized muons, the muon decay $(\mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu})$ allows the polarization to be measured by observing the spectrum of the decay electrons.

Polarimeter Construction (cont.)

- Most polarimeters are constructed as simply as possible. Often plastic scintillation counters are a main component because of cost, good high rate capabilities, and simple and rugged construction. Wire chambers, lead glass, crystal calorimeters (CsI, NaI, etc.) or silicon solid state counters are used sometimes. Magnetic analysis of charged particles is occasionally performed.

- Polarimeter targets include liquid hydrogen, and fibers or ribbons or blocks of CH, CH_2, CD_2, nylon, and carbon. Gaseous targets are occasionally used. Radiation damage must frequently be considered, since polarimeters are often located in the accelerator. This location limits access for repairs and/or target replacement.

- Frequently, each "detector" consists of one or more counters for each outgoing particle. The coincidence of signals from these various counters rejects backgrounds and often increases the analyzing power A (and hence the figure of merit).



- Scintillation counters (up, down, left, right)
- Used to measure beam energy

H. Spinka et al.,
NIM 211, 239 (1983)

M. Hauger et al. / Nuclear Instruments and Methods in Physics Research A 462 (2001) 382–392

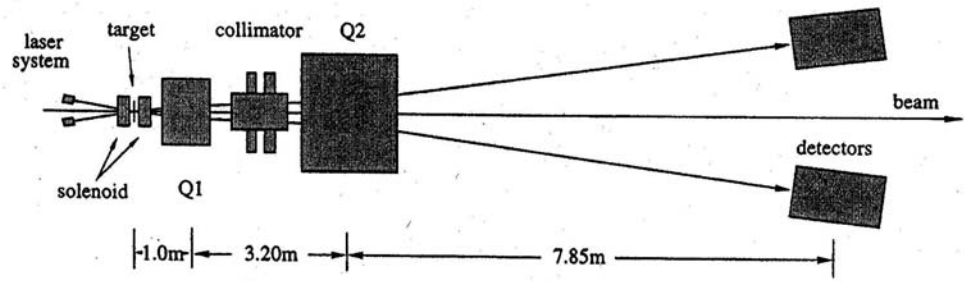


Fig. 1. Layout of the hall-C polarimeter.

JLAB $\vec{e} + \vec{e} \rightarrow e + e$

Max A_{LL} ~ -7/9 at 90° c.m.

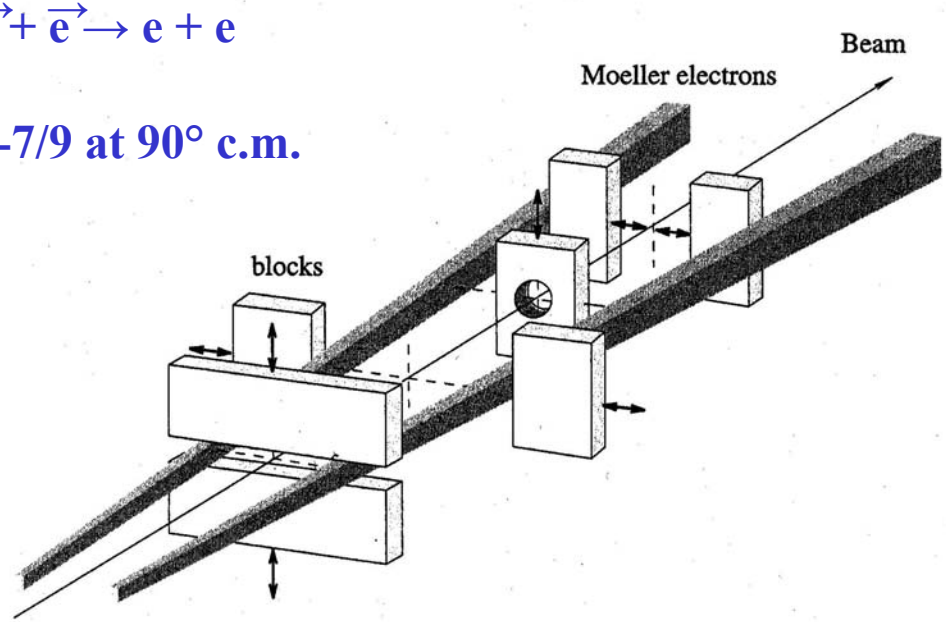


Fig. 3. Collimator system used, showing the six moveable jaws, together with the block covering the central part

- Detect the electrons in coincidence (Möller scattering)

M. Hauger et al., NIM A462, 382 (2001)

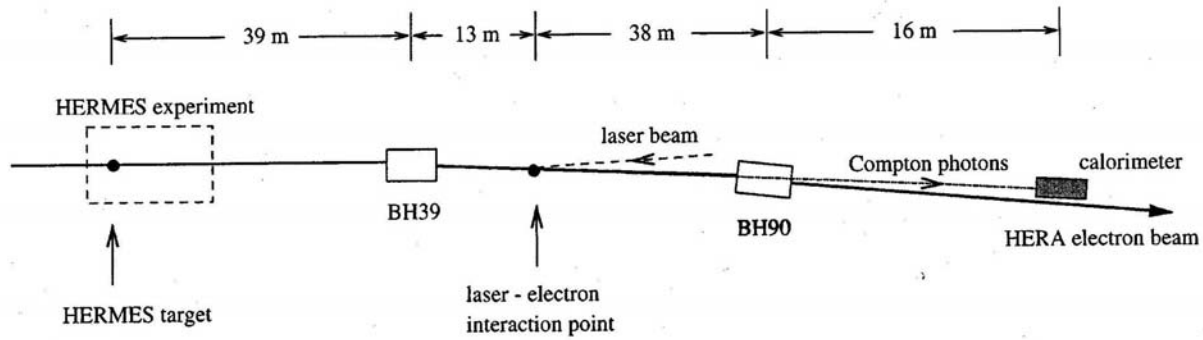


Fig. 2. Schematic overview of the Longitudinal Polarimeter in the HERA East section.

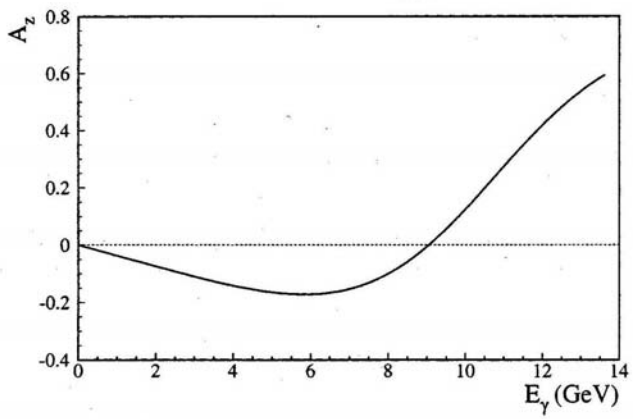


Fig. 1. The longitudinal asymmetry function A_z versus the energy E_γ of the back-scattered Compton photons for the case of a 2.33 eV photon incident on a 27.5 GeV electron.

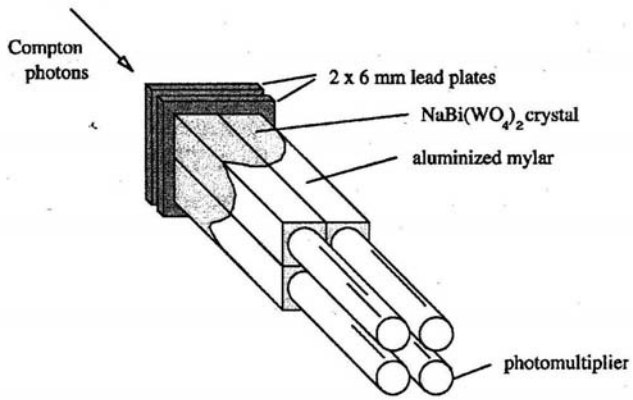


Fig. 5. Schematic layout of the $NaBi(WO_4)_2$ crystal calorimeter.

HERA $\vec{\gamma} + \vec{e} \rightarrow e + \gamma$

- Compton scattering
- Measure the energy of the backscattered photon

M. Beckmann et al.,
NIM A479, 334 (2002)

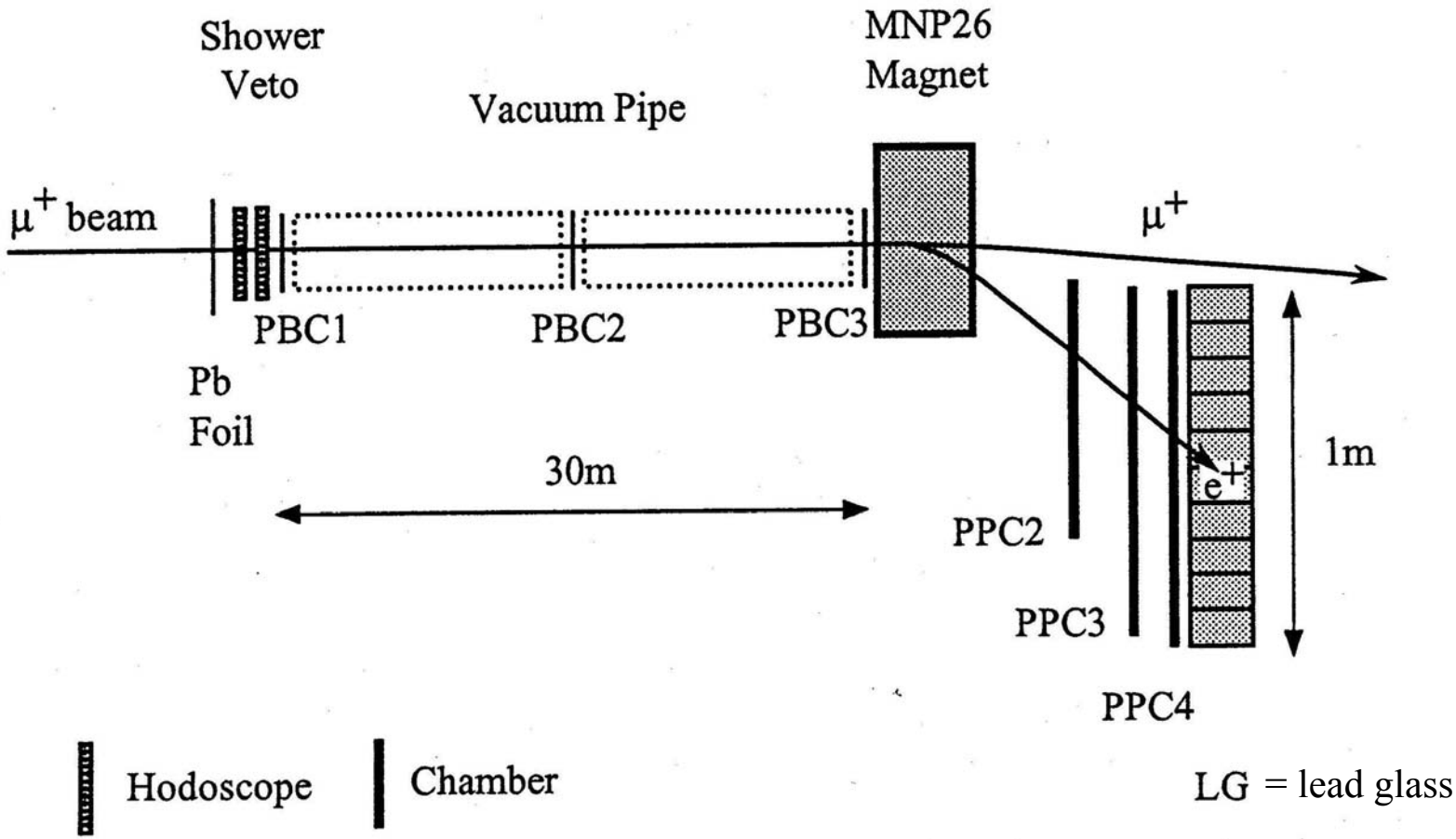


Fig. 5. The SMC muon polarimeter.

CERN $\mu^+ \rightarrow e^+ \upsilon_e \bar{\upsilon}_\mu$

- Measure the e^+ energy spectrum
- The e^+ goes preferentially along the μ^+ spin direction in the μ^+ rest frame

B. Adeva et al., NIM A343, 363 (1994)

Calibrations

- The polarimeter analyzing power can be calibrated with a beam of known polarization. However, such a beam is not normally available.

- For pp elastic scattering, identical particle and strong interaction symmetries lead to the relations:

$$
\begin{aligned}
A_N(\vec{p}\,p \to p\,p) &= A_N(p\,\vec{p} \to p\,p) \\
&= A_N(p\,p \to \vec{p}\,p) \\
&= A_N(p\,p \to p\,\vec{p})
\end{aligned}
$$

Polarized targets, with an independent means of measuring the polarization, are often used to obtain $A_N(p\,\vec{p} \to p\,p)$. Then the equations above can give the beam polarization, and consequently the polarimeter analyzing power.

Calibrations (cont.)

- For the Primakoff effect,

$$A_N(\gamma \vec{p} \rightarrow p\, \pi^0)$$

is measured at low energies. The kinematics of the reaction at high energy are chosen to match the kinematics of these low energy data.

- Asymmetries for Möller and Compton scattering are accurately calculable in QED. These calculations are used directly to give the calibrations for electron polarimeters based on these processes.

- The muon decay parameters have been well measured. Thus, the electron energy spectrum can be accurately computed as a function of muon polarization. This provides the calibration for this type polarimeter.

Calibrations (cont.)

Often a chain of studies is required to perform a calibration. Consider the previous situation at RHIC.

- A CERN polarized target experiment measured $A_N\,(p\,\vec{p} \rightarrow p\,p)$ at 24 GeV/c.
- A polarimeter consisting of scintillators and solid blocks of CH_2 and C measured the beam polarization at ~ 22 GeV/c in an external, extracted beam. (assumes knowledge of the energy dependence of A_N)
- A different polarimeter (CNI) in the AGS ring measured an asymmetry at almost the same time, and under almost the same conditions, but with the full beam. (assumes the beam polarization is the same in the highly collimated external beam as in the primary AGS beam, assumes different beam conditions don't matter, and assumes polarization is stable in time)
- Similar CNI polarimeters were constructed in the two RHIC rings, but the operating conditions are slightly different. (assumes knowledge of these detailed differences and how to correct the asymmetries in order to transfer the calibration)

CERN $p + \vec{p} \rightarrow p + p$

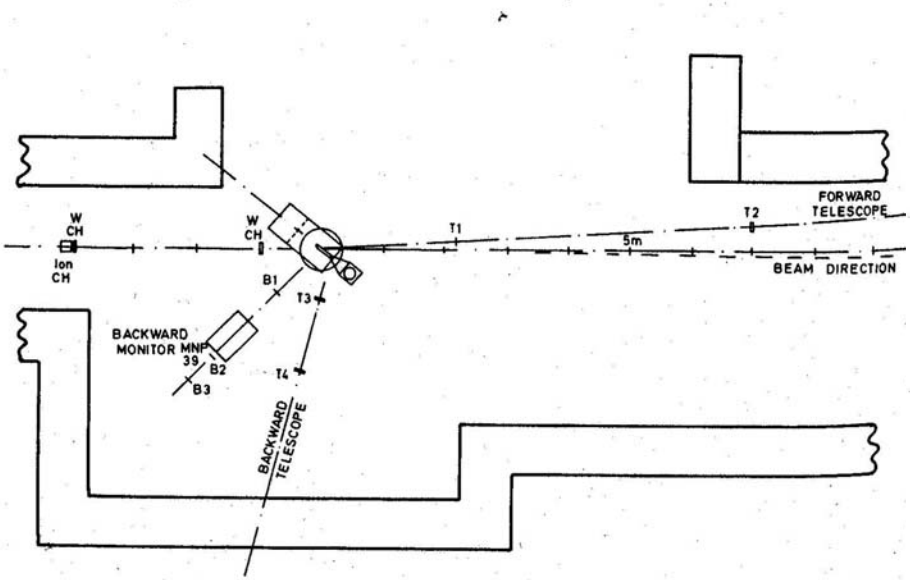


Fig. 1. Experimental lay out.

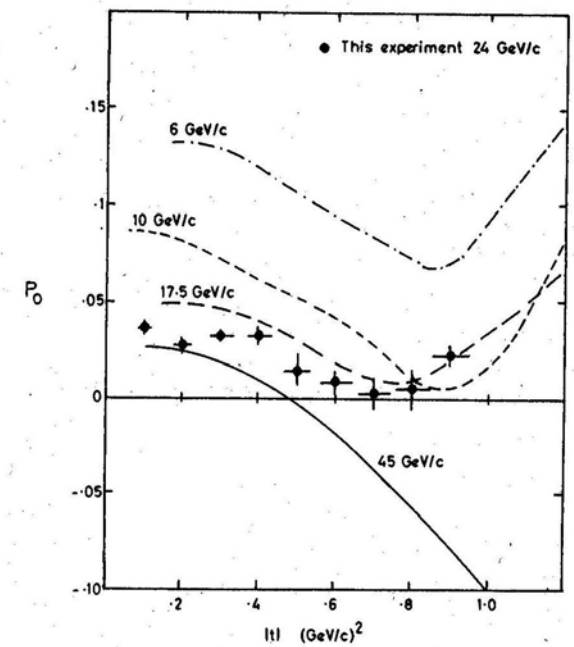
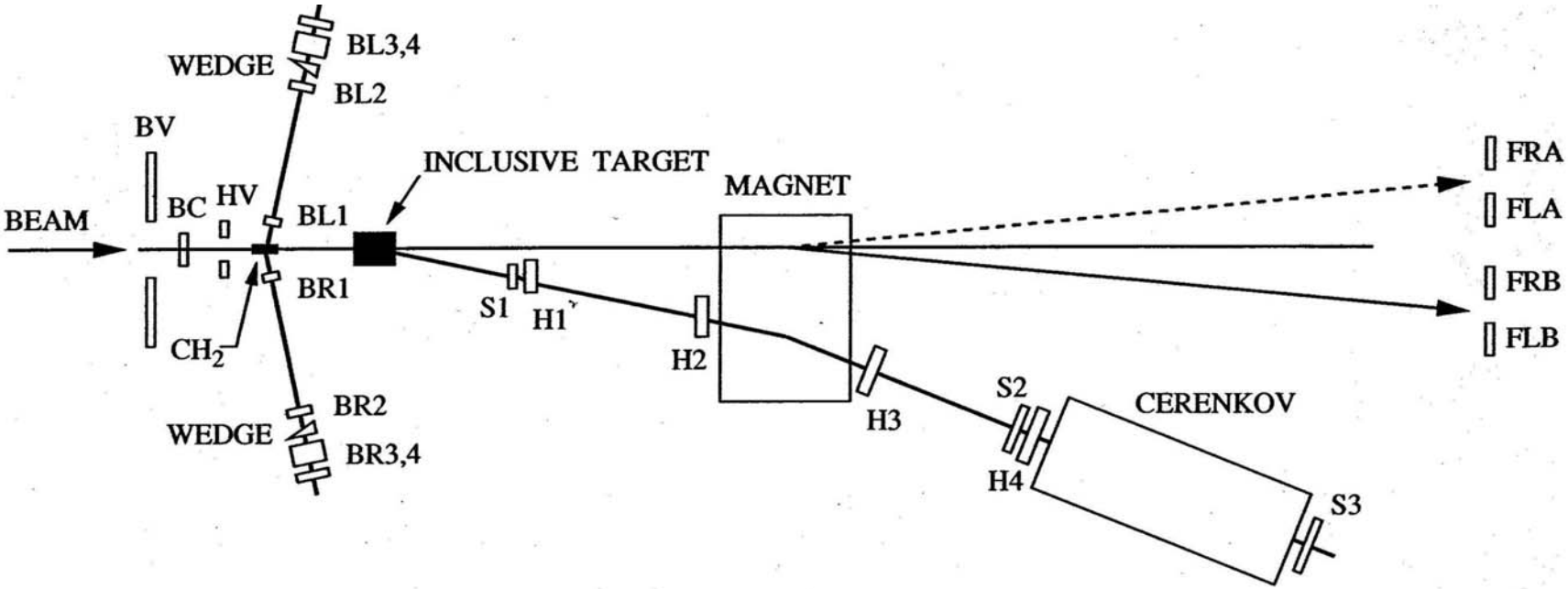


Fig. 3. Polarization in pp elastic scattering at 24 GeV/c. The curves are "visual fits" of the data at 6, 10, 17.5 and 45 GeV/c from refs. [2,3].

- Scintillation counters (T1 – T4)
- Systematic error ~ ± 5 % from absolute target polarization

D.G. Crabb et al.,
Nucl. Phys. B121, 231 (1977)

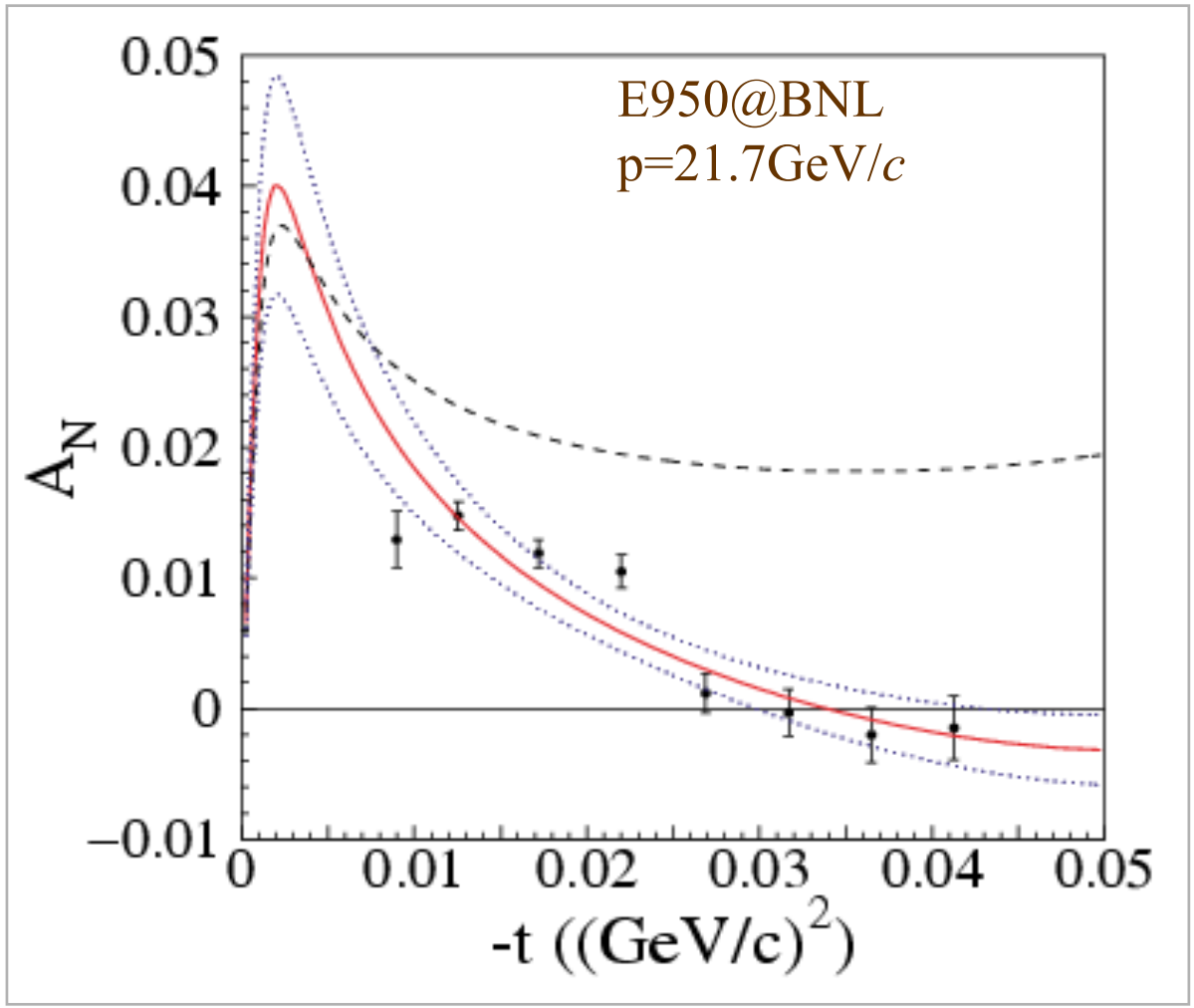


AGS E925 Experiment and Polarimeter

- Scintillation counters (BLi, BRj, FLA, FRB, …)
- Analyzing magnet
- CH_2 and C targets allow pure pp scattering to be derived

C.E. Allgower et al.,
PR D65, 092008 (2002)

pC Analyzing Power



J. Tojo et al.,
PRL 89, 052302 (2002)

Instrumental / Systematic Errors

A variety of effects can give misleading or incorrect results from polarimeters. Examples include changes in beam phase space correlated with beam spin direction (up or down) and rate effects. These correspond to non-ideal behavior of the accelerator and polarimeter, respectively.

Consider first the case where the beam is always a bit to the left for beam spin ↑ and to the right for beam spin ↓. Then

$$\begin{aligned} N_{L\uparrow} &\rightarrow N_{L\uparrow}\,(1+\xi) \\ N_{L\downarrow} &\rightarrow N_{L\downarrow}\,(1-\xi) \\ N_{R\uparrow} &\rightarrow N_{R\uparrow}\,(1-\xi) \\ N_{R\downarrow} &\rightarrow N_{R\downarrow}\,(1+\xi) \end{aligned} \quad \Longrightarrow \quad \begin{aligned} \varepsilon_{PHYS} &\rightarrow \varepsilon_{PHYS} + \xi \\ \varepsilon_{LUM} &\rightarrow \varepsilon_{LUM} \\ \varepsilon_{GEOM} &\rightarrow \varepsilon_{GEOM} \end{aligned}$$

This leads to an incorrect beam polarization by ξ/A .

Instrumental / Systematic Errors (cont.)

As another example, assume for a particular run that $B_\uparrow > B_\downarrow$. Rate problems in detectors often manifest themselves as a loss of counts because the detector or electronics cannot "keep up". Assume the right detector has this problem for the higher beam rate but not the lower rate, while the left detector has a negligible effect. Then

$$\begin{aligned} N_{L\uparrow} &\to N_{L\uparrow} \\ N_{L\downarrow} &\to N_{L\downarrow} \\ N_{R\uparrow} &\to N_{R\uparrow}(1-\kappa) \\ N_{R\downarrow} &\to N_{R\downarrow} \end{aligned} \quad \Longrightarrow \quad \begin{aligned} \varepsilon_{PHYS} &\to \varepsilon_{PHYS} + \kappa/4 \\ \varepsilon_{LUM} &\to \varepsilon_{LUM} - \kappa/4 \\ \varepsilon_{GEOM} &\to \varepsilon_{GEOM} + \kappa/4 \end{aligned}$$

Again, the wrong beam polarization is obtained.

Instrumental / Systematic Errors (cont.)

For accurate polarimetry, beam conditions must be stable from bunch to bunch and slowly varying with time. These include:

- transverse bunch dimensions and distributions
- transverse offsets from the nominal position
- longitudinal size and distribution
- longitudinal offset from the nominal position
- distributions of angles from the nominal orbit
- momentum spread
- polarization of each bunch

Some of these are well constrained by the accelerator design and operations, while others are not. The polarimeter may also limit sensitivity to certain beam conditions. For example, a very narrow, fixed polarimeter target reduces the sensitivity to transverse shifts of the beam from bunch to bunch.

CNI Polarimeters - A Case Study

- Coulomb-nuclear interference (CNI) polarimeters presently are used to determine beam polarizations in the AGS and both RHIC rings. One was also used with a polarized gas jet target to perform a calibration over the RHIC energy range.

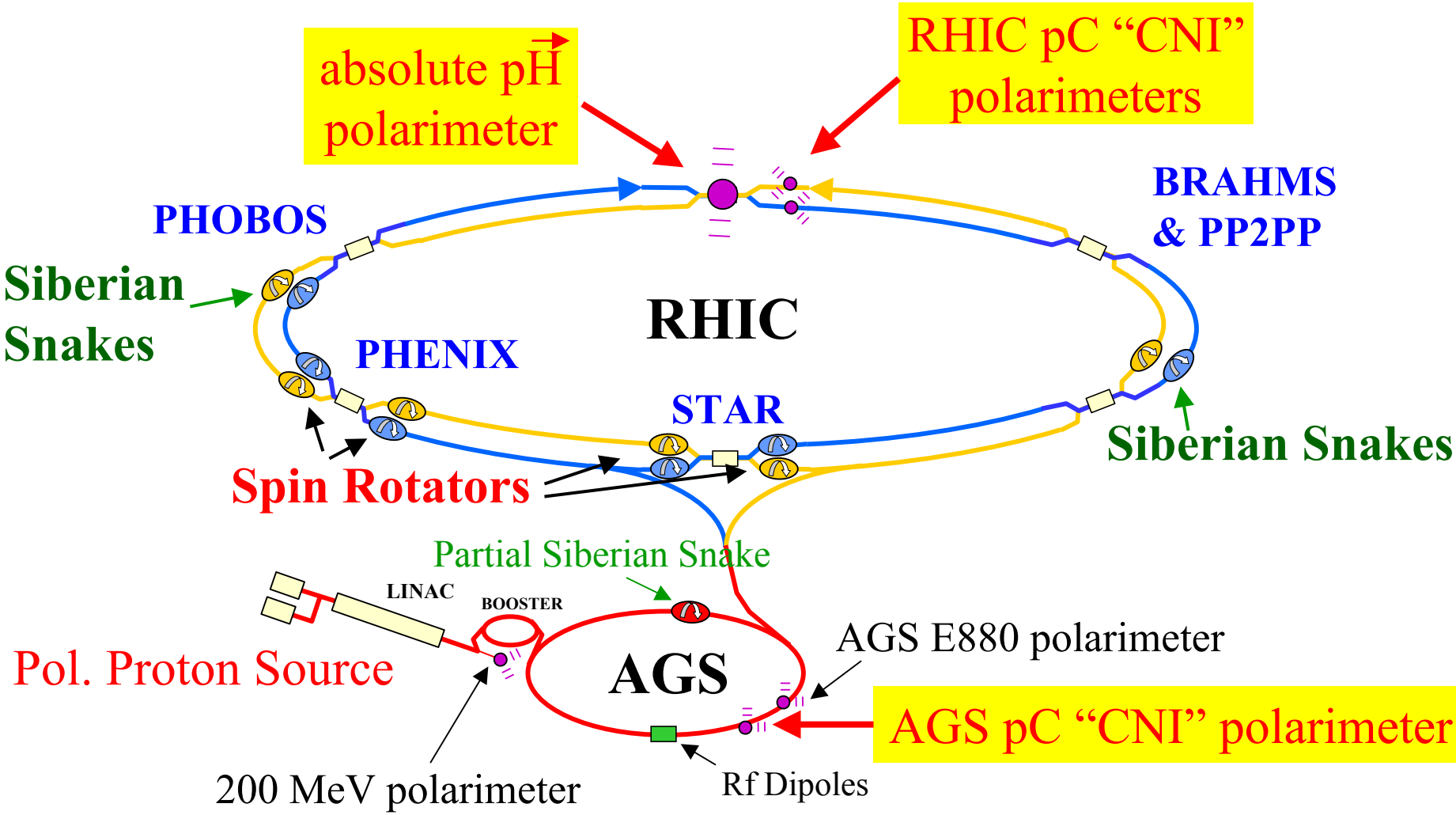
- The CNI polarimeters operate at very small 4-momentum transfer squared, *t*, for p + C or p + p elastic scattering. In this *t*-range, the scattering amplitudes for strong or nuclear and Coulomb interactions are comparable. ($t = -2\, M_{recoil}\, T_{recoil}$)

- Only the recoil C or p are measured near 90° with silicon strip detectors. They are identified by time of flight and energy loss in the silicon.

- Signals from each strip are recorded with a waveform digitizer (WFD), similar to an oscilloscope. The amplitude and timing of the signals are determined and good events selected and scaled.

RHIC: the "Polarized" Collider

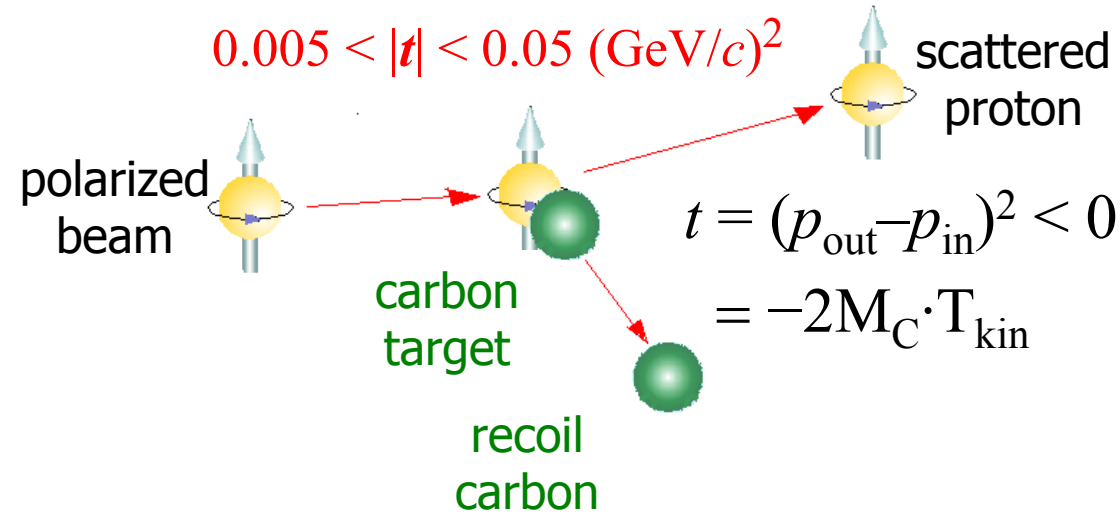
Goals: 70% Polarization, $L_{max} = 2 \times 10^{32}\ s^{-1}cm^{-2}$, $50 < \sqrt{s} < 500$ GeV



Elastic pC → pC scattering at low t

$$A_N = -\frac{1}{P_B} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

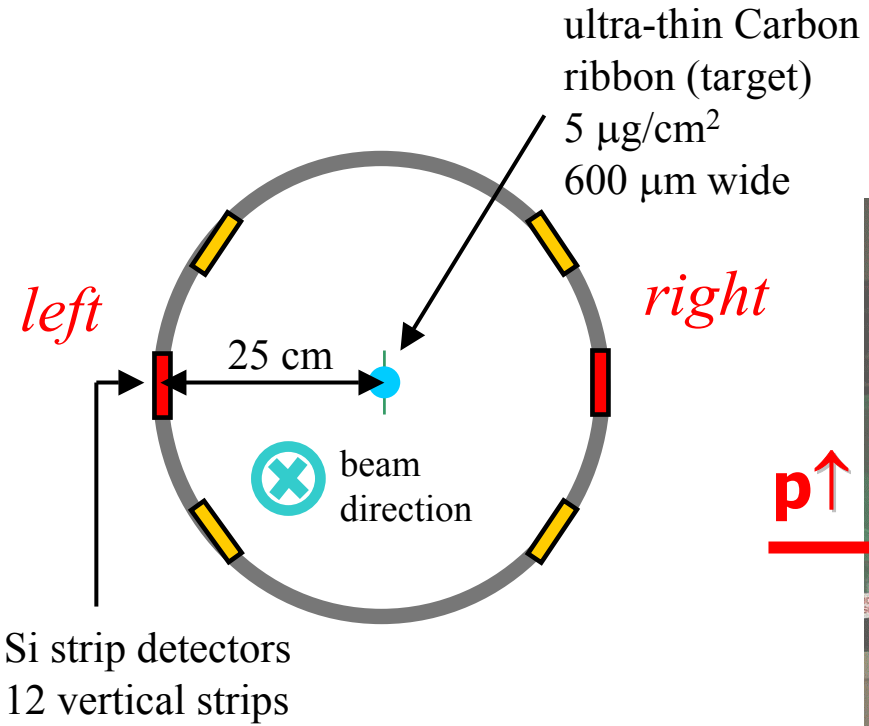
recoil



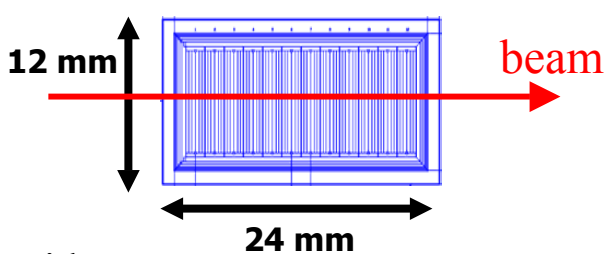
1. A_N from interference of spin non-flip and spin flip amplitudes
   ⇒ spin dependence of interaction
   ⇒ hadronic spin flip (spin-coupling of Pomeron)

2. RHIC Polarimetry
   – almost "calculable"
   – sizeable $A_N \sim 1$ % (requires large statistics, $> 10^7$)
   – large cross section
   – weak beam momentum dependence ($p > 20$ GeV/c)

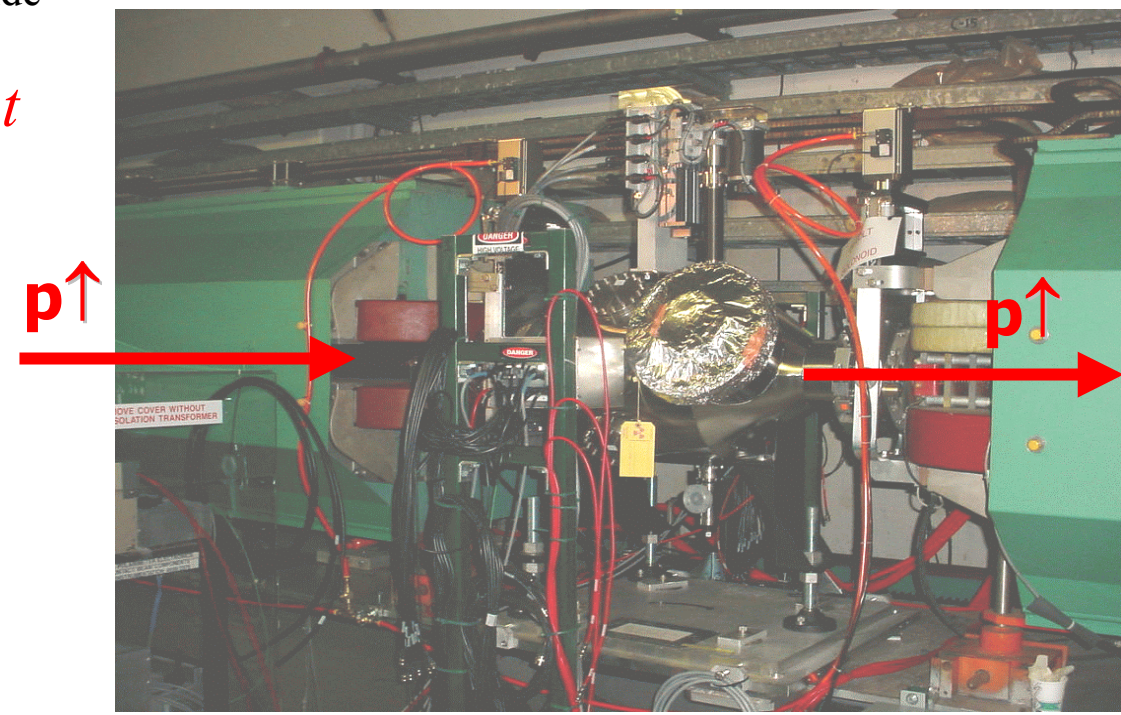
Elastic $p\uparrow$C Scattering Setup in the AGS Ring



Si strip detectors
12 vertical strips

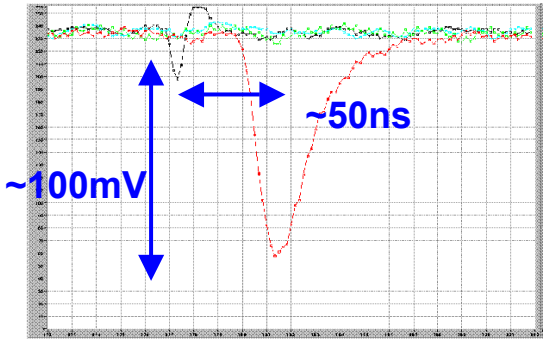


read-out with
waveform digitizers



similar setups in RHIC for each beam

DAQ and WFD



ADC
3×140 MHz

synchronized to accelerator clocks
bunch crossing ⇒ "start" TDC

FPGA

"online" analysis of waveform performed between consecutive bunch crossings
⇒ PH, tot Q, t.o.f

onboard memory

DAQ PC

$\Delta t \sim 2$ ns
$\Delta E < 50$ keV

Wave Form Digitizer = peak sensing ADC, CFD, …
"deadtimeless" DAQ system ⇒ no spin dependent dead time !
Can accept, analyze, and store 1 event for each bunch crossing
Rate: up to 10^5 events/channel/sec

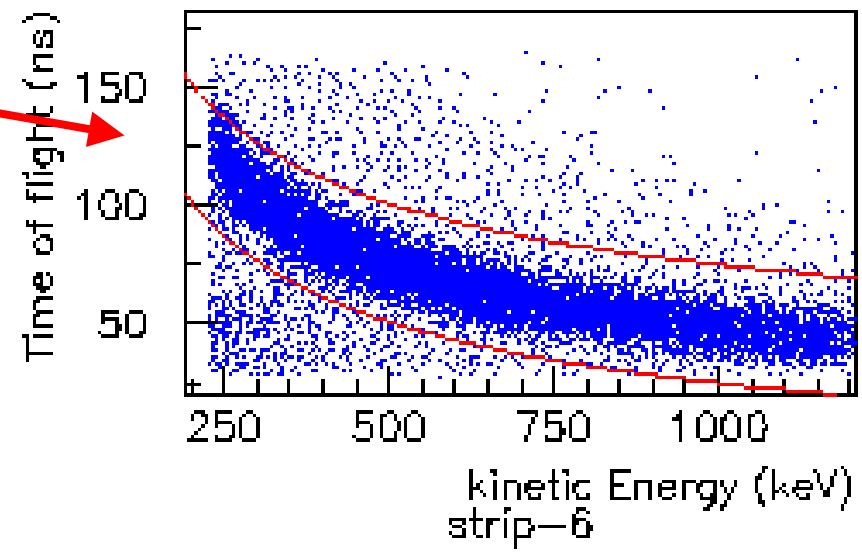
Event Selection

- recoil carbons detected with Si detectors
- "identified" via ToF vs Energy correlation

  position vs energy correlation spoiled by multiple scattering in the target

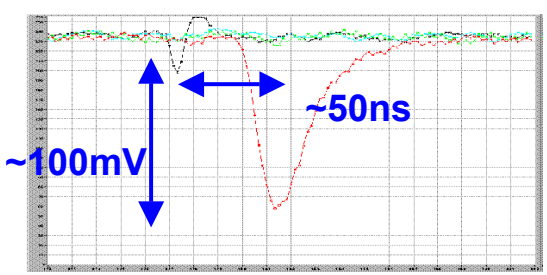
$$T_{kin} = \frac{1}{2} M_C (\text{dist} / \text{ToF})^2$$

non-relativistic kinematics



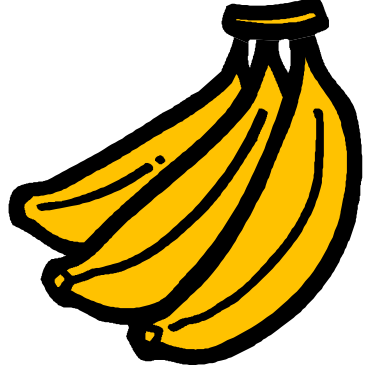
- very high event rate

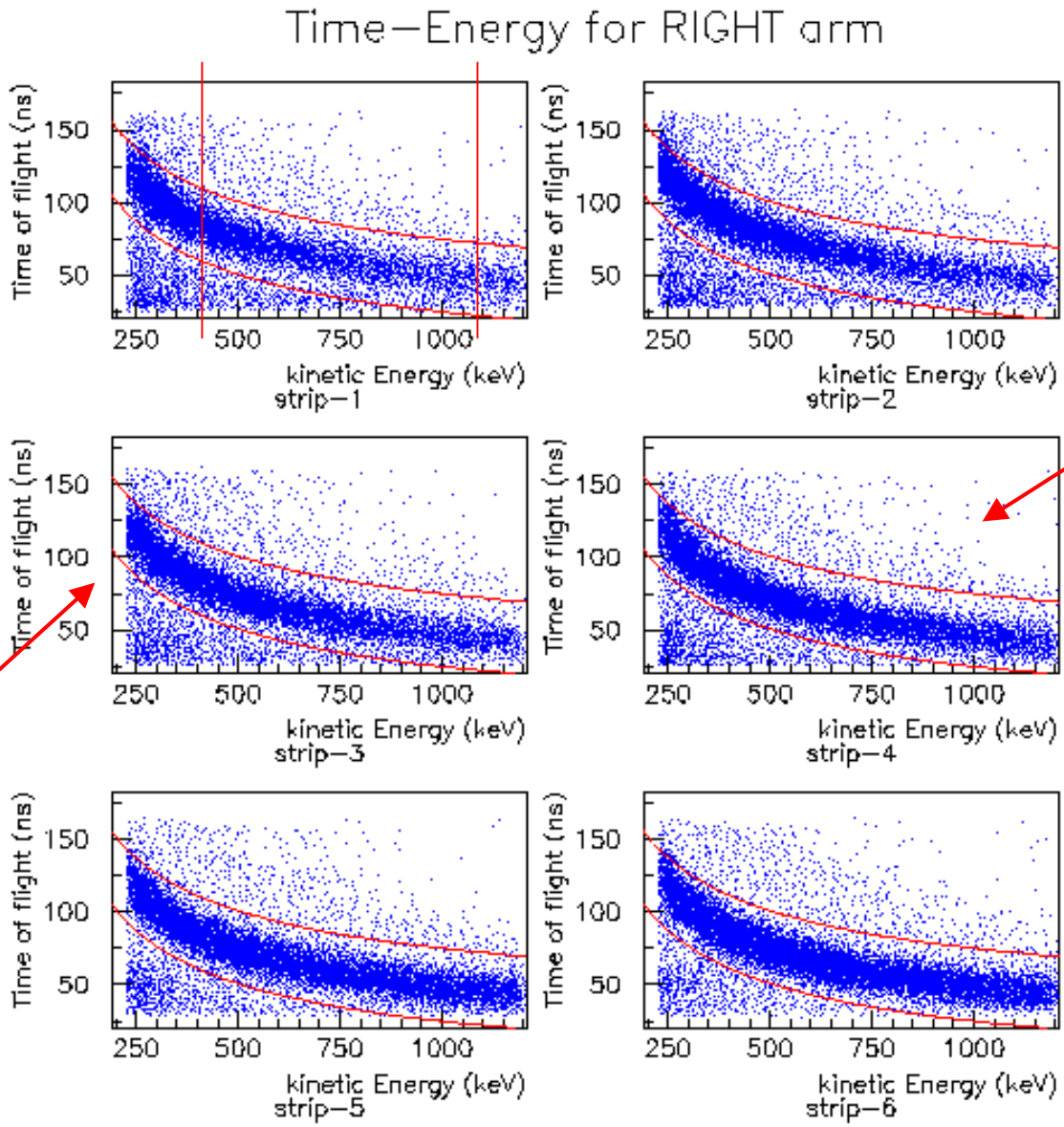
  events acquired with deadtime free wave-form digitizers



- carbon "events" found / selected in ToF vs. T_{kin} correlation band
- background events below 1% within the "banana" cut

Time of Flight vs. Energy i.e.

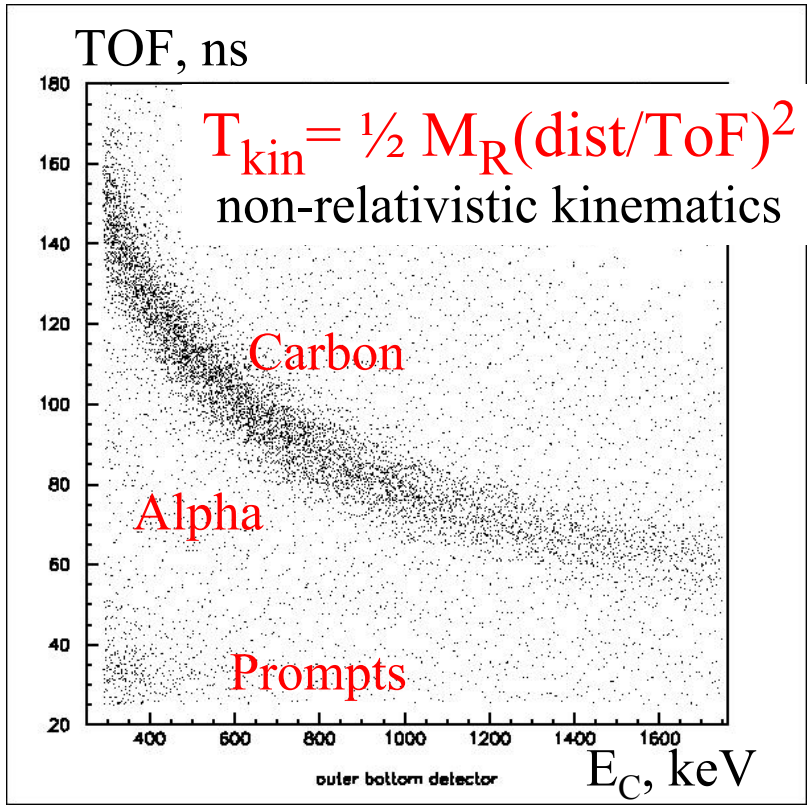


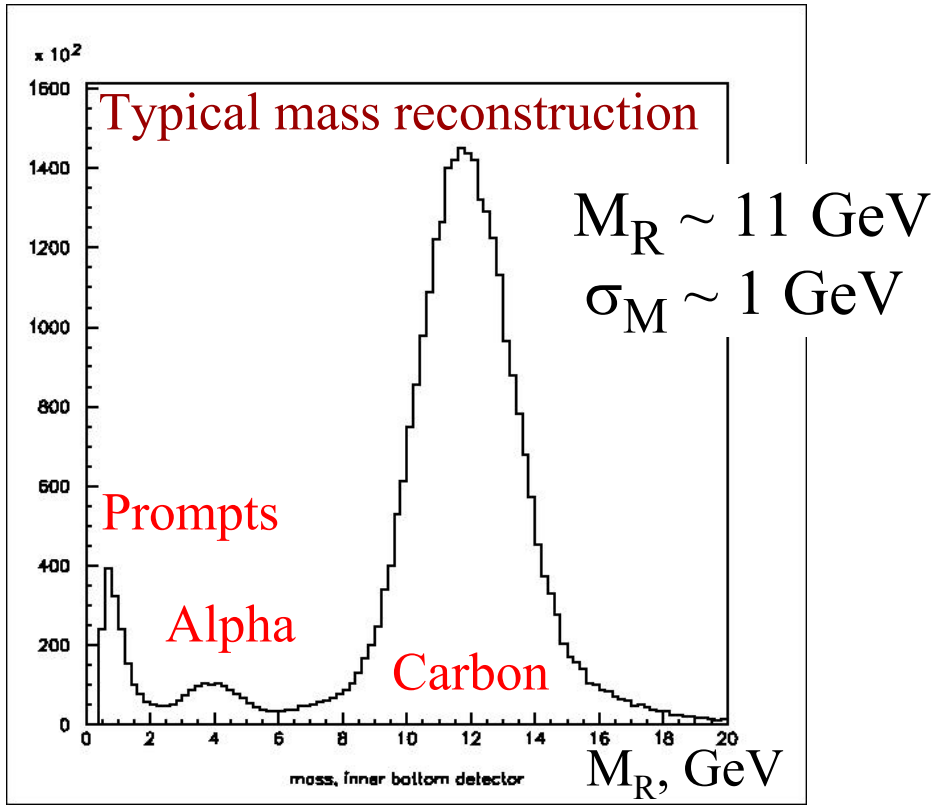


does not pass the cuts

event selection

Performance





- Very clean data
- Good separation of carbon from prompts may allow going to very high $-t$ values
- Low χ^2 of sequential measurements – stable operation

CNI Polarimetry (cont.)

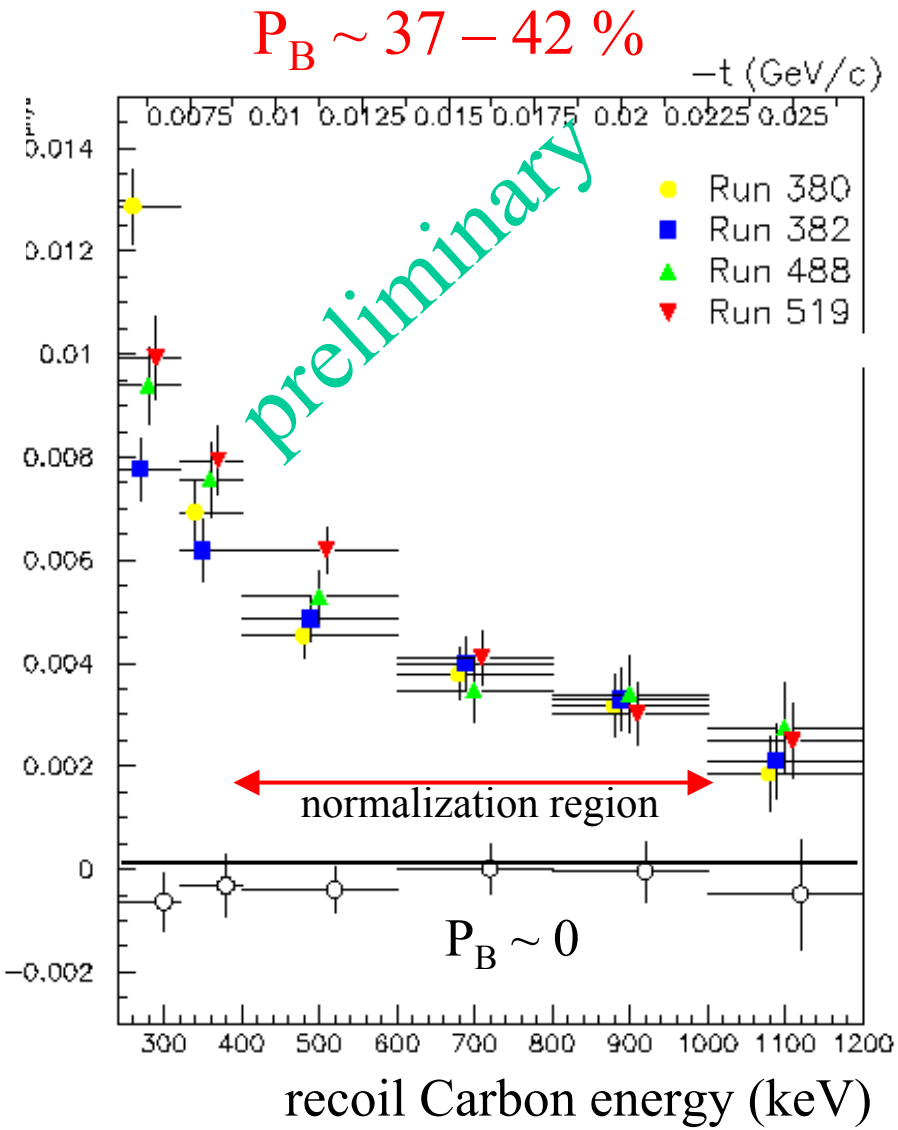
- Calibrations of the strips are performed with radioactive sources of ~ 4 – 5 MeV α's, but the energy of the carbon recoils is < 1 MeV.
- There is a "dead layer" on the surface of the silicon detectors where energy loss from particles is not recorded. A substantial fraction of the carbon energy is lost in this dead layer, which must be corrected. Uncertainties in the energy lead to uncertainties in the analyzing power.
- Radiation damage to the detectors requires their replacement every year, and sometimes more frequently. After a change, a recalibration must be performed.
- Care must be taken with the ultra-thin carbon targets. Several are usually mounted on a target holder, and breakage is not uncommon (several broke within a recent 6 week run).
- Backgrounds from electrical noise and fast ($\beta \sim 1$) particles must be carefully avoided by design and signal timing.

Desirable Characteristics of Polarimeters

- Fast Response (large cross section) ✓
- Large Analyzing Power (so large ε) ×
- Simple Design (minimize maintenance and hardware problems) —
- Low Cost —
- Ease of Operation ✓
- Minimal Systematic Errors ×
- Ease of Calibration —

All polarimeters are a compromise among various factors, as illustrated by the design of those for RHIC and the AGS. They have fast response because of the large cross section and are relatively easy to operate. However the small analyzing power increases the sensitivity to systematic errors that would be negligible for other polarimeters. Significant maintenance for the detectors and targets is required, and special electronics are used, both of which increase the cost.

$p\uparrow$C *raw* asymmetry at 24.7 GeV/c



$$P_{beam} = \frac{1}{\langle A_N \rangle} \cdot \varepsilon_N$$

$$\langle A_N \rangle = \frac{\sum N(t_i) A_N^{th}(t_i)}{\sum N(t_i)}$$

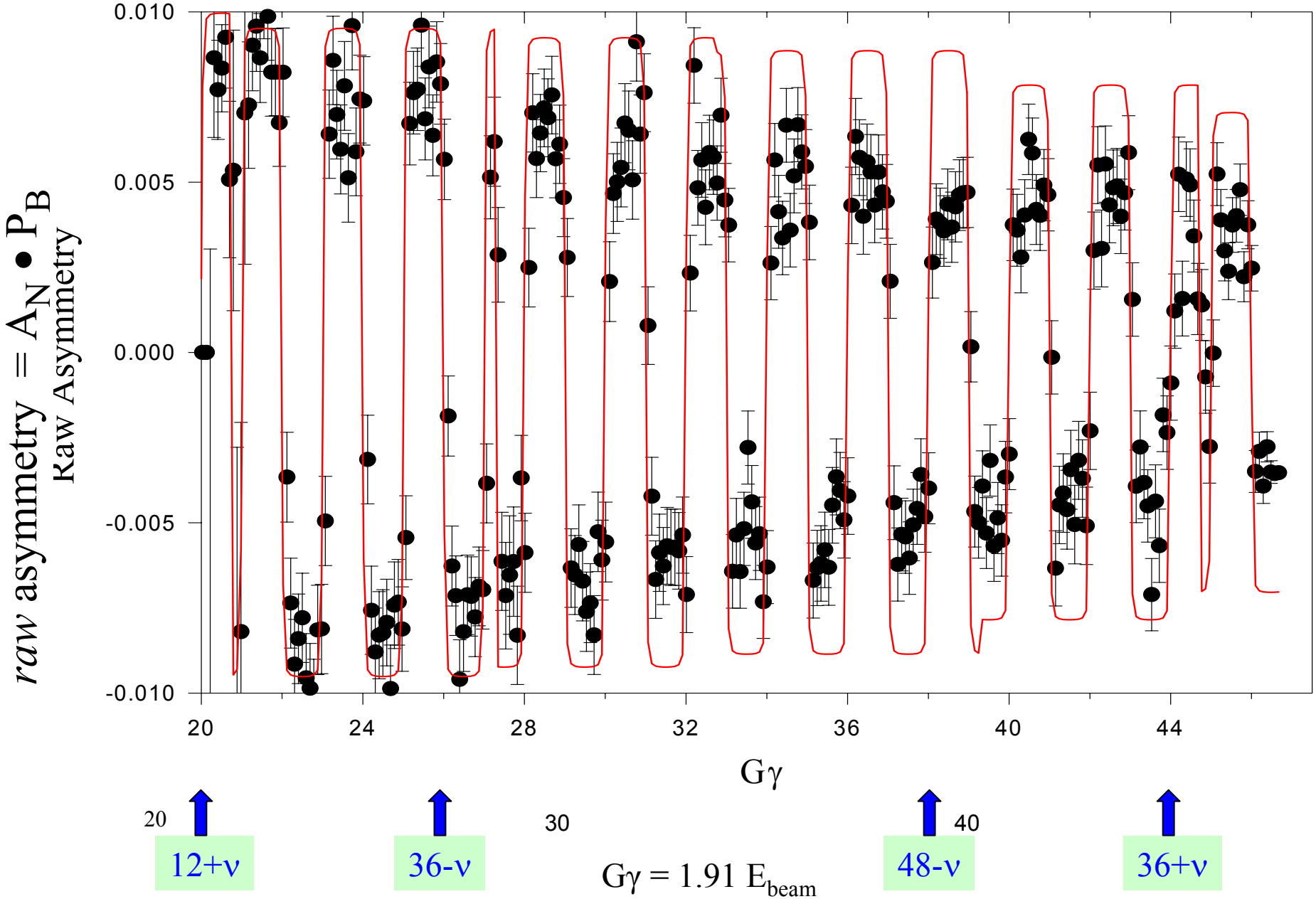
calculated over several t bins

A_N^{th} from a fit to E950 data at similar energy and $\boldsymbol{t}$ range

L. Trueman hep-ph/0305085

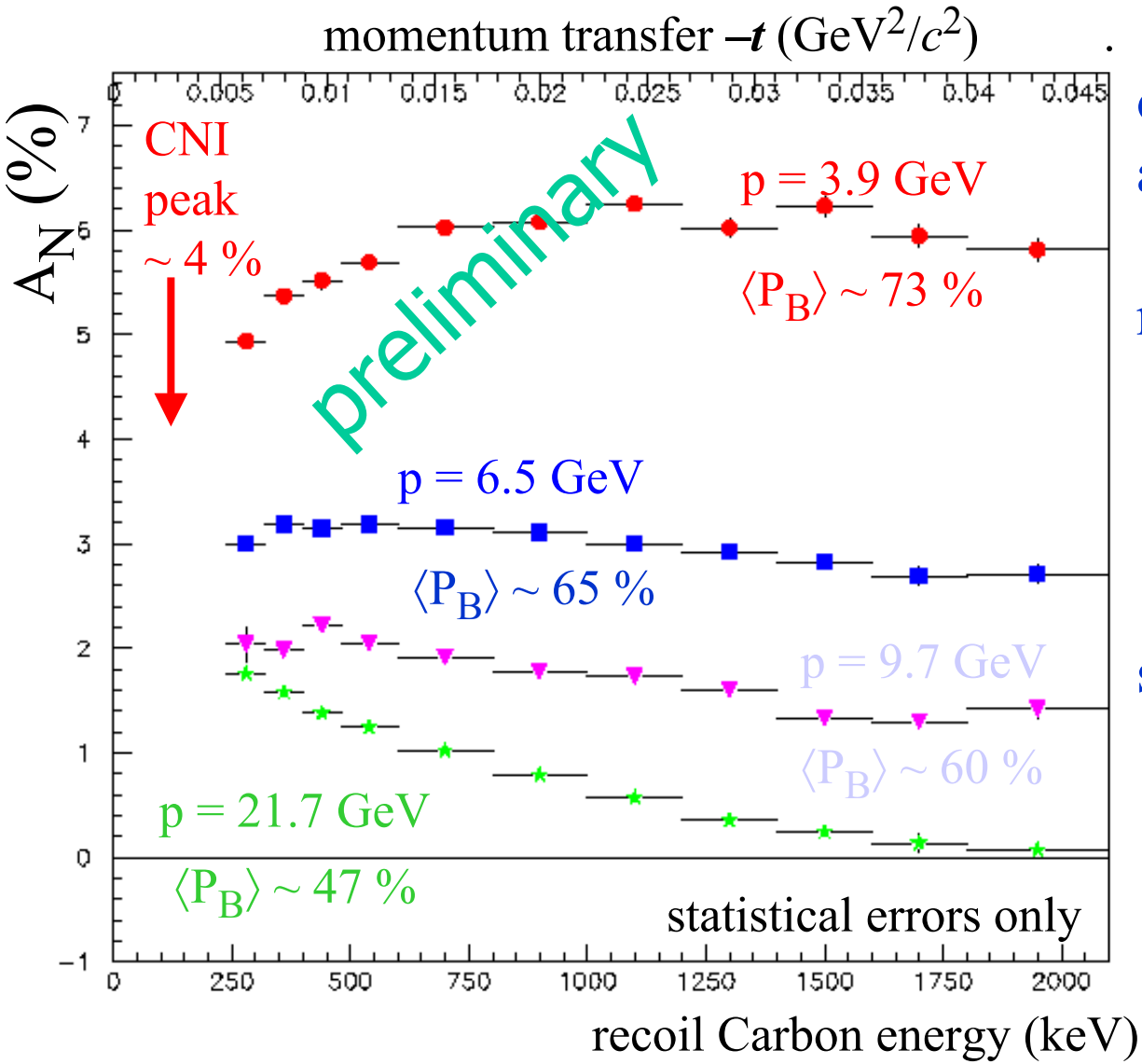
$\langle A_N \rangle \approx 0.0112$

$0.009 < |\boldsymbol{t}| < 0.022$ (GeV/c)^2



The red curve is from a simulation of depolarization effects in the AGS (assuming constant A_N).

$A_N\ p\uparrow C \rightarrow pC$ at 3.9, 6.5, 9.7 & 21.7 GeV



only statistical errors are shown

normalization errors:

~ 10 % (at 3.9)
~ 15 % (at 6.5)
~ 20 % (at 21.7)

systematic errors:

< 20 %
- backgrounds
- pileup
- RF noise

Calibration at Lower AGS Energies

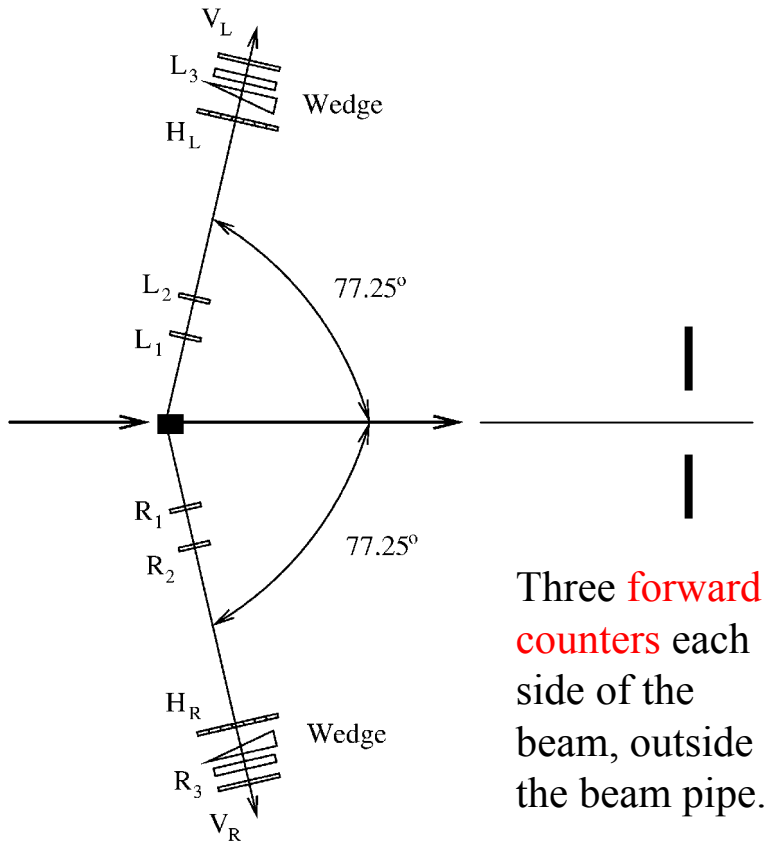
- The AGS E880 polarimeter usually consists of approximately left-right symmetric recoil telescopes of plastic scintillation counters.

- Targets are thin carbon fibers and nylon (fishline). Radiation damage limits the lifetime of the nylon.

- For absolute calibrations, forward scintillators were added. In order to avoid counters in the AGS vacuum, and to fit in the available space, the practical limit to this technique is $P < 7$ GeV/c.

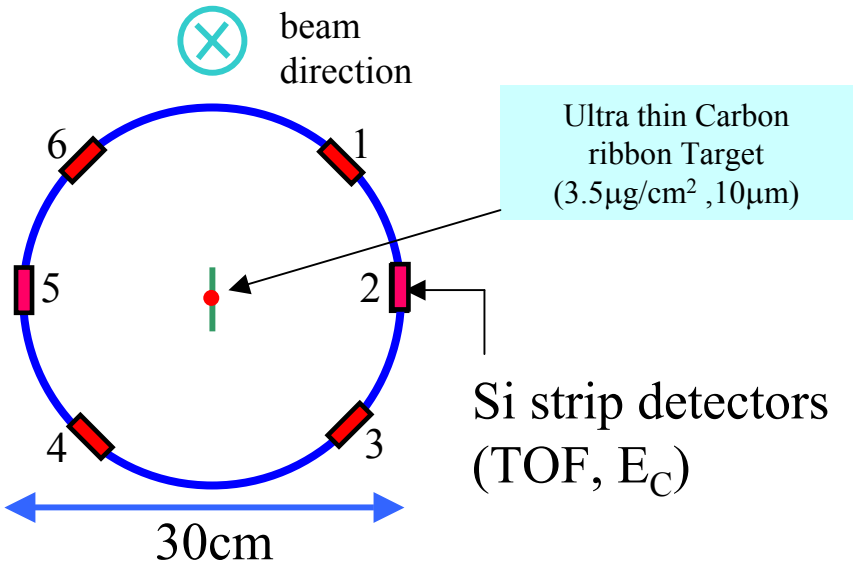
- Use a fit to pp polarization data to find A_N (pp). (NIM 211, 239 (1983))

E880 polarimeter: see C.E. Allgower et al., Phys. Rev. D65, 092008 (2002)



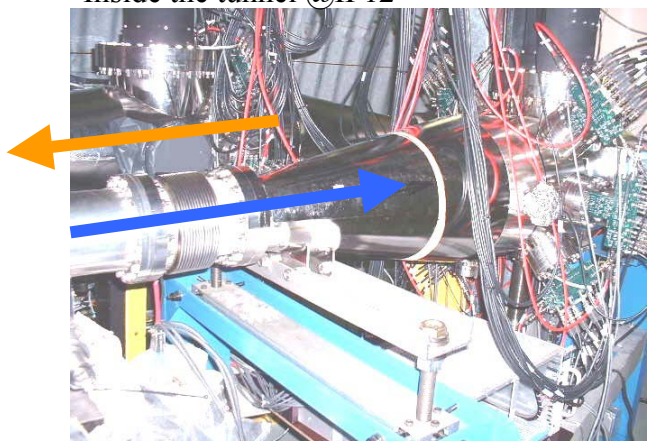
Three forward counters each side of the beam, outside the beam pipe.

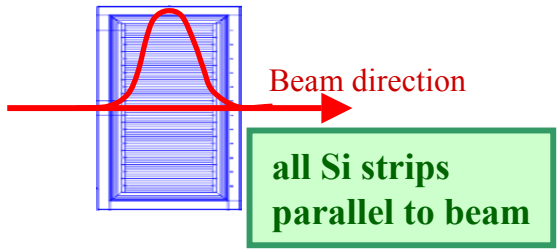
RHIC Polarimeters



RHIC x 2 rings

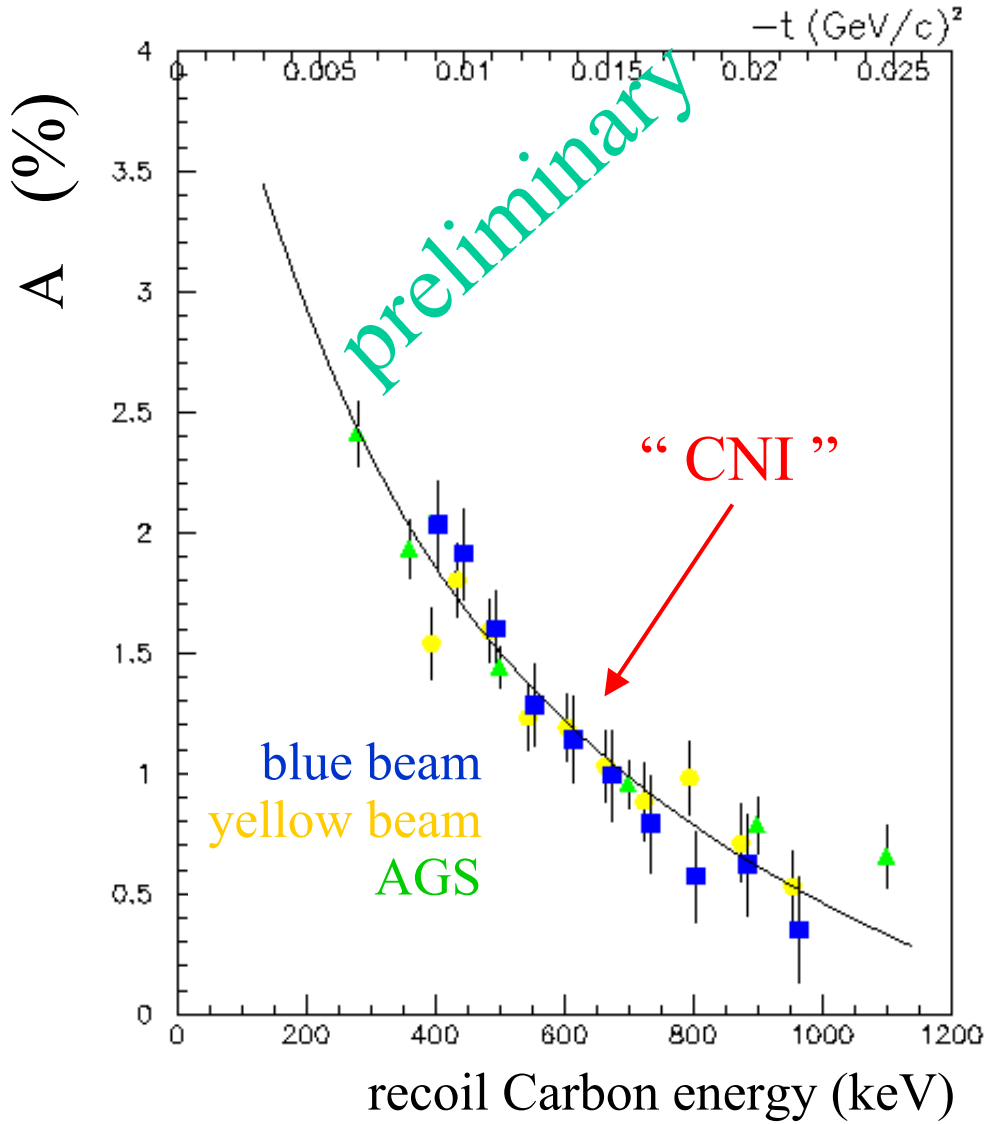
Inside the tunnel @IP12





- Detectors are ***15cm*** away from target → slowest carbons can reach Si during one bunch crossing (106 nsec = 120 bunch mode)
- 2 x 72 channels read out with WFD (increased acceptance by 2 x)
- All Si strips parallel to the beam
- Si at 45 degree : sensitive to vertical and radial components of the asymmetry

A_N: $p\uparrow C \rightarrow pC$ at RHIC energies (100 GeV/c)



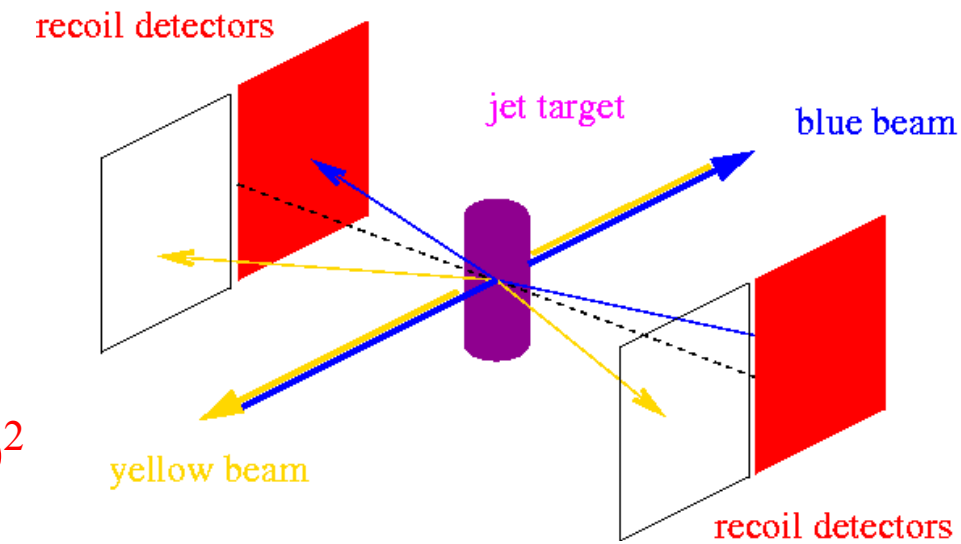
for normalization assume
A_N (24 GeV/c) = A_N (100 GeV/c)
i.e. no energy dependence
[$0.009 < |t| < 0.022$ (GeV/c)^2]

very similar shape of the t dependence at 24 and 100 GeV/c

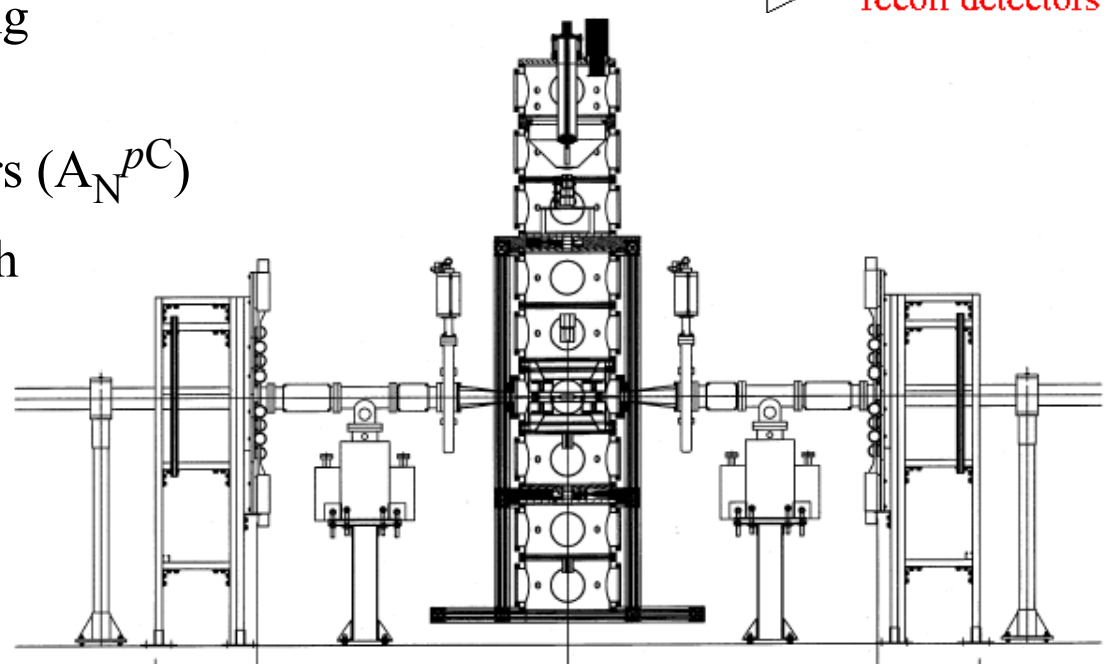
⇒ suggestive of very small energy dependence for A_N between 24 and 100 GeV/c

systematic error for RHIC data < 15%

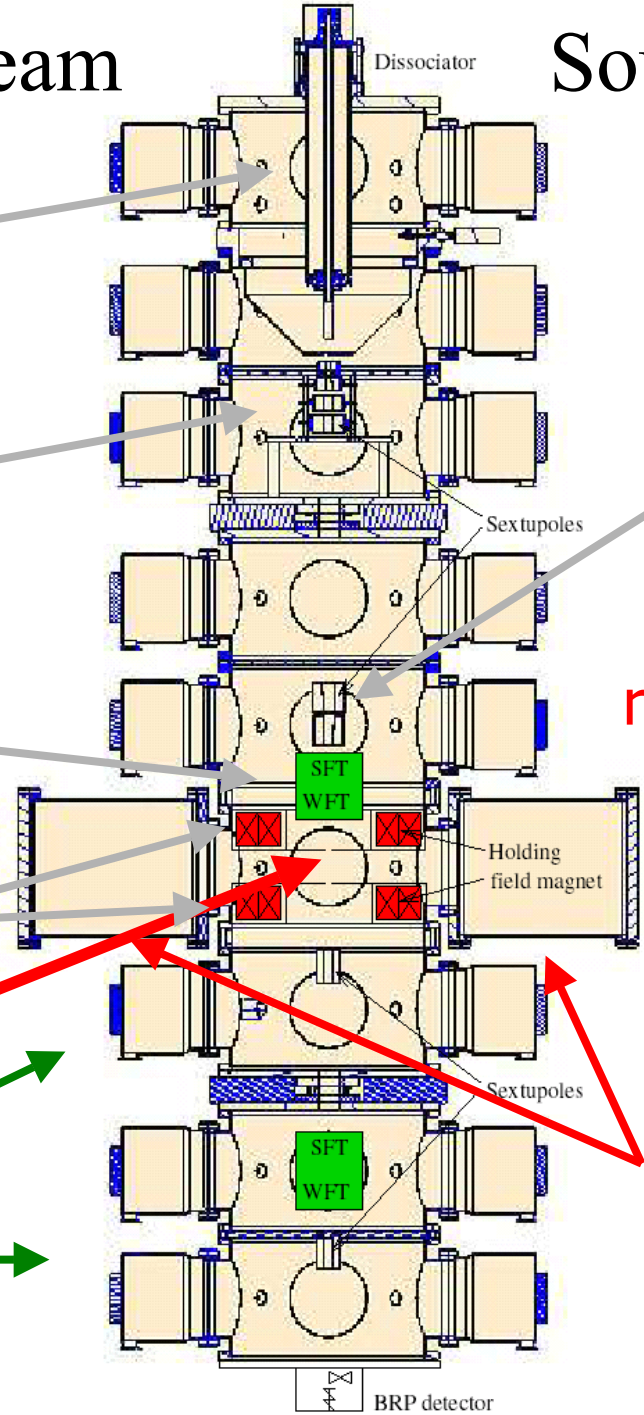
$p\uparrow p$, $pp\uparrow$ and $p\uparrow p\uparrow$ with a Polarized Gas Jet Target



- Polarized Hydrogen Gas Jet Target
  thickness of 5×10^{11} p/cm^2
  polarization > 90%
- Silicon recoil detectors
- Rate: 2 Hz for $0.002 < |t| < 0.004$ (GeV/c)^2
- Measure A_N^{pp} in pp elastic scattering in the CNI region to ~ 3% accuracy
- Transfer A_N^{pp} to the pC polarimeters (A_N^{pC})
- Expected accuracy on P_B of 6% with "calibrated" pC CNI polarimeters
- Installed/tested for the 2004 run
- Initially measure P_B to ~ 10%



The Atomic H Beam Source



H_2 dissociator

separation magnets (sextupoles)

focusing magnets (sextupoles)

RF transitions

recoil detectors

holding field magnet

RHIC beam

Breit-Rabi polarimeter

p recoil arms

The Absolute *pp* Polarimeter

JET in the IR

Polarized Hydrogen Gas Jet Target

thickness of > 10^{12} p/cm^2

polarization 93 ± 2 %

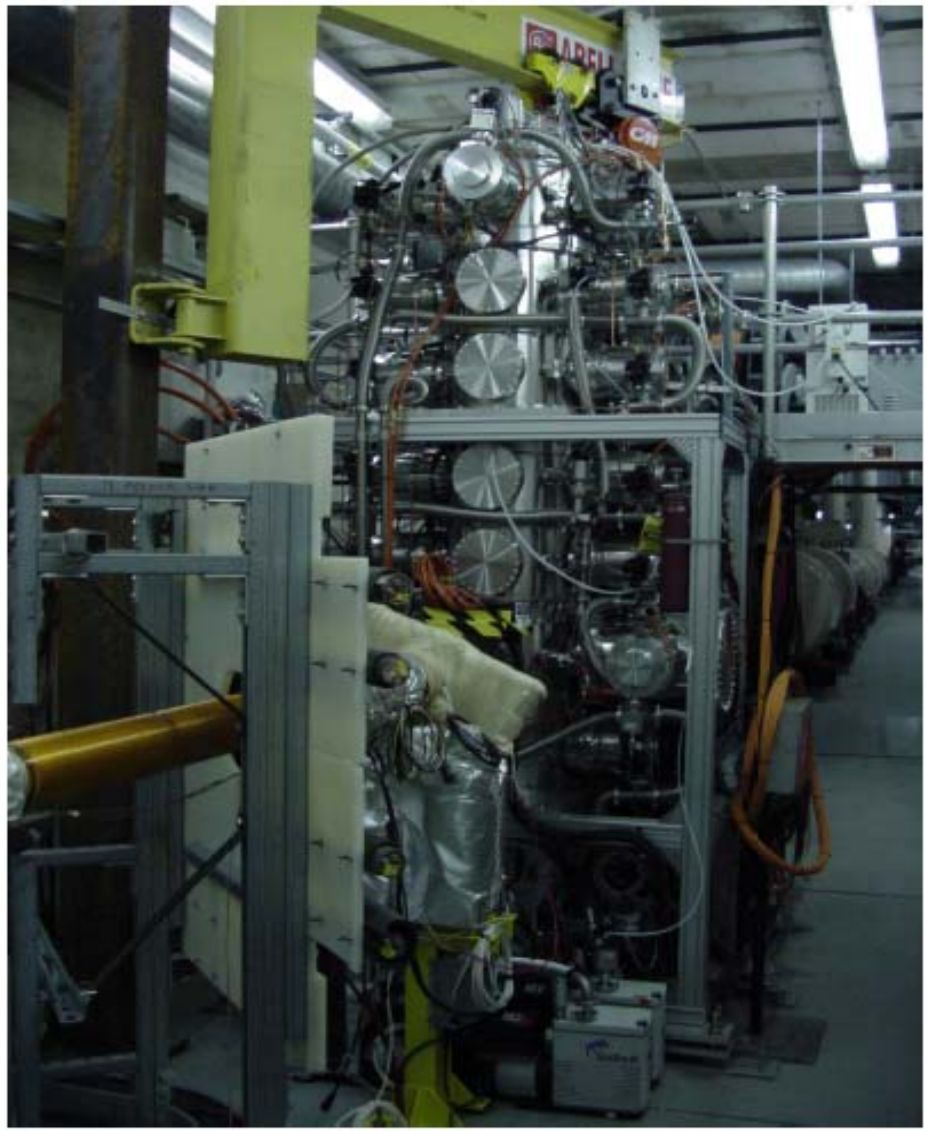
no depolarization from beam wake fields

Silicon recoil spectrometer

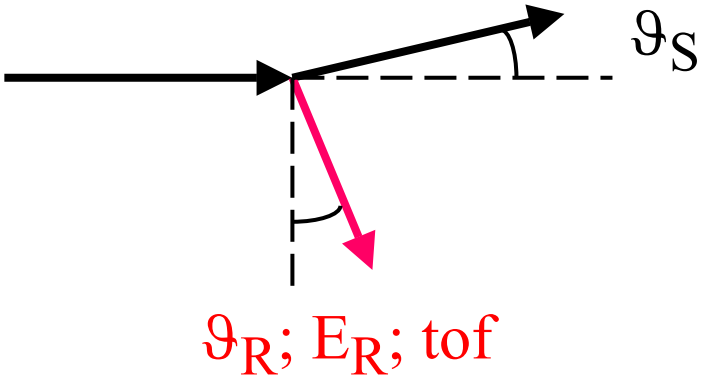
Measure A_N^{pp} in *pp* elastic scattering

in the CNI region to $\Delta A_N < 10^{-3}$ accuracy

Initially (2004) measure P_B to ~ 10%



Kinematics



$|t|$: 0.001 – 0.02 GeV^2
ϑ_R : 1 – 5 degrees
T_{kin} : 0.5 – 10 MeV
p_R : 30 – 140 MeV/c
tof : 100 – 20 nsec (@ 1m)

essentially 1 free parameter: t (+ φ) ⇒

elastic pp kinematics fully constrained by recoil proton only !

$$\sin\vartheta_R \approx \left(1+\frac{m_p}{p_{beam}}\right)\frac{\sqrt{|t|}}{2m_p}$$

$$t = -2m_p T_{kin}$$

ϑ_R & t

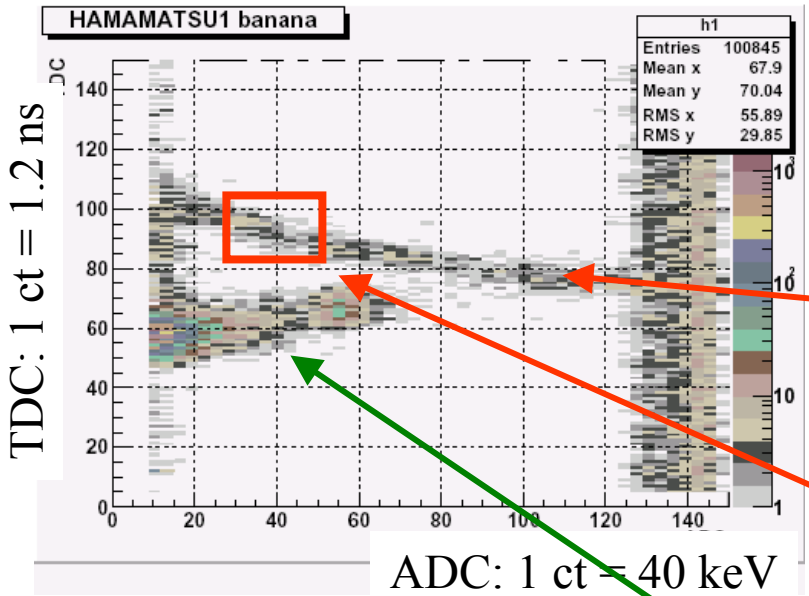
measure position and energy of recoil ⇒

$$tof \approx 1/\sqrt{2T_{kin}/m_p}\cdot D$$

⇒ additional kinematical constraint

ϑ_R & E_R ⇒ m_{beam} (M_X); tof & E_R ⇒ m_{target}

Time of Flight vs. Energy recoil protons



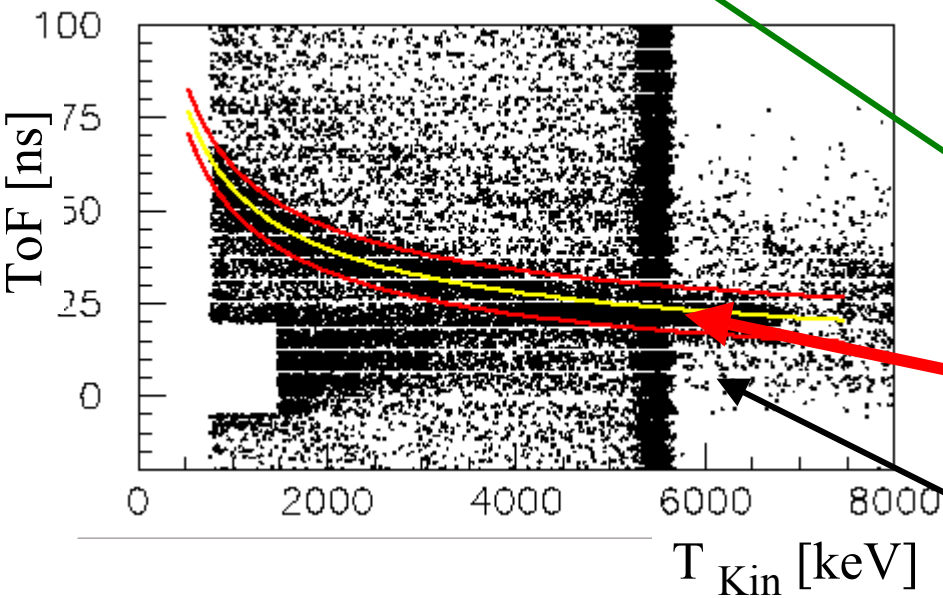
$T_{kin} = ½ M_R (dist / ToF)^2$

non-relativistic kinematics

recoil protons from elastic pp -> pp scattering

CNI peak region, i.e. A_N maximal

$1 < E_{REC} < 2$ MeV



prompt events and beam gas

Δ ToF < ± 6 ns (Full Width)

calibration α source (5.4 meV)

CNI Polarimetry (cont.)

- The p + C CNI RHIC polarimeters were in use during the 2001/2002, 2003, and 2004 runs. Systematic effects were observed in the first two – studies remain for the last period, which finished about a month ago.
- In 2001/2002, there were several independent observations suggesting the systematics effects were comparable to the statistical errors per run, or

$$\delta\varepsilon \sim \pm\, 0.0003$$

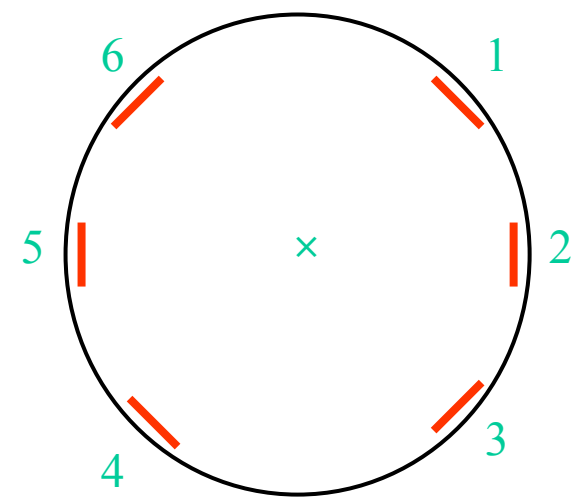
$$\delta\varepsilon / \varepsilon \sim 0.15$$

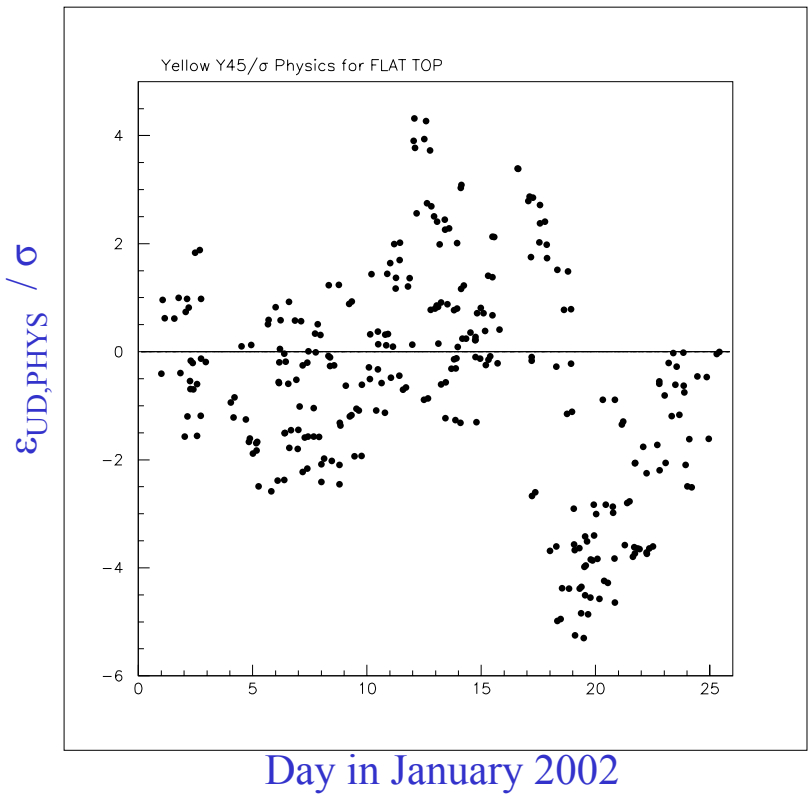
- In 2003, a systematic effect of roughly constant value was observed throughout much of the run.
- The focus of the 2004 run was on commissioning the polarized gas jet target. There were many fewer long RHIC fills than in 2001/2002.

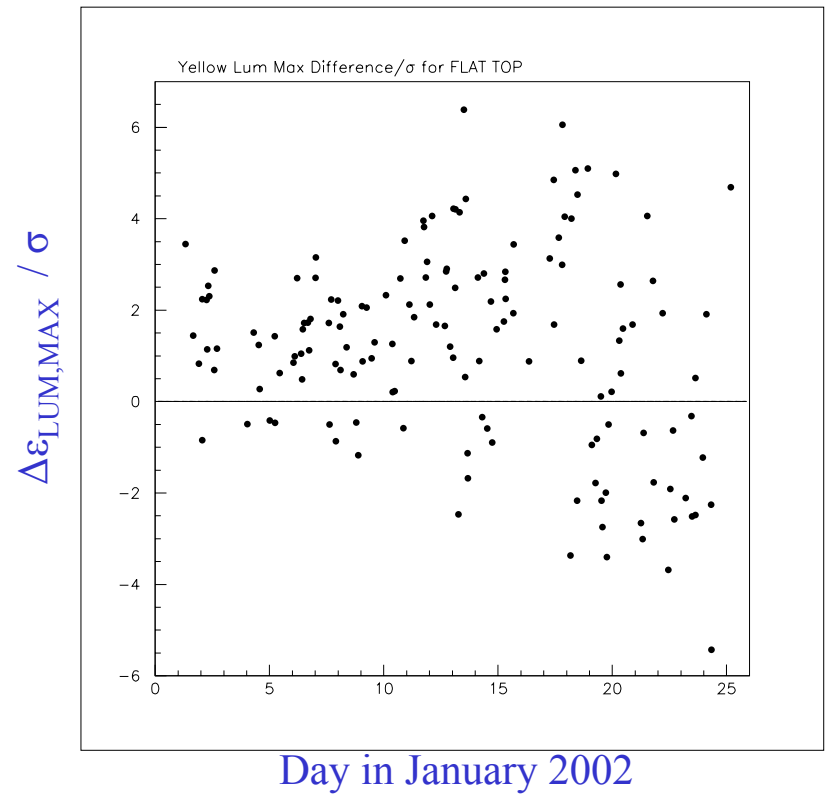
CNI Polarimetry (cont.)

- The RHIC p + C CNI polarimeters consist of three pairs of detectors, one pair in the horizontal plane, and one pair each at ± 45°. Values of ε_{LUM} from each pair should agree within statistics. Many more sizable differences were observed than expected.
- The beam polarization direction at the polarimeters is expected to be vertical. However, an up-down asymmetry was observed more frequently than expected based on statistics.

$$N_{U\uparrow} = N_{1\uparrow} + N_{6\uparrow}$$
$$N_{D\uparrow} = N_{3\uparrow} + N_{4\uparrow}$$
$$N_{U\downarrow} = N_{1\downarrow} + N_{6\downarrow}$$
$$N_{D\downarrow} = N_{3\downarrow} + N_{4\downarrow}$$
$$\varepsilon_{UD,PHYS} = \frac{\sqrt{N_{U\uparrow}N_{D\downarrow}} - \sqrt{N_{U\downarrow}N_{D\uparrow}}}{\sqrt{N_{U\uparrow}N_{D\downarrow}} + \sqrt{N_{U\downarrow}N_{D\uparrow}}}$$







- The up-down physics asymmetry and the maximum difference in luminosity asymmetries among the three pairs of detectors, each divided by the statistical uncertainty, are plotted. Many more runs than expected deviate by large amounts from the expected value, 0.

J. Wood

CNI Polarimetry (cont.)

- A typical fill in 2001/2002 consisted of 26 ↑ and 26 ↓ bunches spaced about 213 ns apart around the RHIC ring in an alternating pattern (↑↓↑↓↑↓… or ↑↑↓↓↑↑↓↓…). The polarization direction can be artificially reassigned so "↑" corresponds to an equal number of true ↑ and ↓ bunches, and similarly for "↓". The distribution of $\varepsilon_{\text{"PHYS"}}$ for many reassignments should have mean 0 and width calculable from statistics. However, the observed width is larger.
- A cross asymmetry can also be formed from the 45° detector counts, and should be zero for any polarization direction, but is not!

$$N_{\alpha\uparrow} = N_{1\uparrow} + N_{4\uparrow}$$

$$N_{\beta\uparrow} = N_{3\uparrow} + N_{6\uparrow}$$

$$N_{\alpha\downarrow} = N_{1\downarrow} + N_{4\downarrow}$$

$$N_{\beta\downarrow} = N_{3\downarrow} + N_{6\downarrow}$$

$$\varepsilon_{CR,PHYS} = \frac{\sqrt{N_{\alpha\uparrow}N_{\beta\downarrow}} - \sqrt{N_{\alpha\downarrow}N_{\beta\uparrow}}}{\sqrt{N_{\alpha\uparrow}N_{\beta\downarrow}} + \sqrt{N_{\alpha\downarrow}N_{\beta\uparrow}}}$$

Randomized spin bit pattern

Basic idea is to see the distribution of physics asymmetries with forced un-polarized spin bit patterns

Procedure:

from the spin bit pattern

BLUE: 0++--++-- …

For + sign (26bunch)
2nd,3rd,6th,7th …

For – sign (26bunch)
4th,5th,8th,9th …

half → group1

Half-flip → group2

half → group3

Half-flip → group4

Randomly dividing into two groups, and assign the flipped spin bit for group2 and group4 to force un-polarization

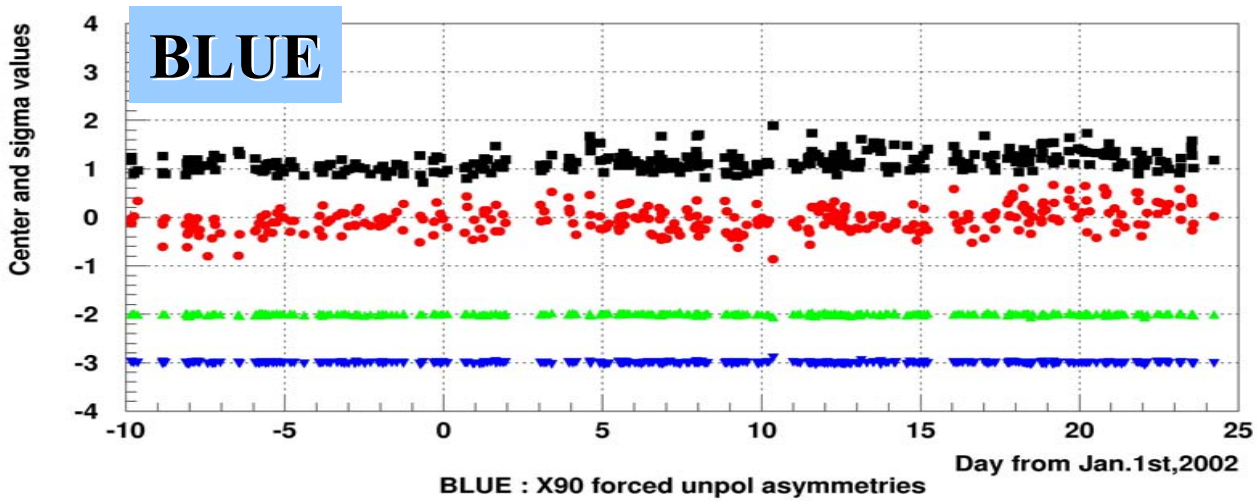
Possible combinations are

$${}_{26}C_{13} * {}_{26}C_{13} = (26!/13!/13!)^2 \sim 1.1*10^{14} \text{combinations}$$

O. Jinnouchi

Day plots for significance value (=asymmetry/σ_{stat})

10^3 random spin patterns are applied for every run



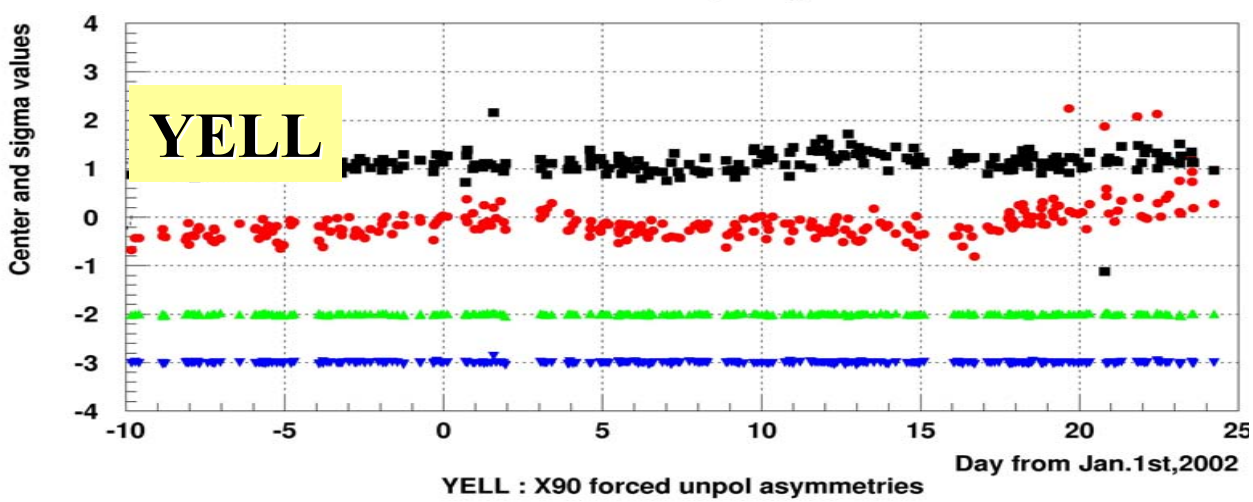
←Sigma(from fit)

←Mean(from fit)

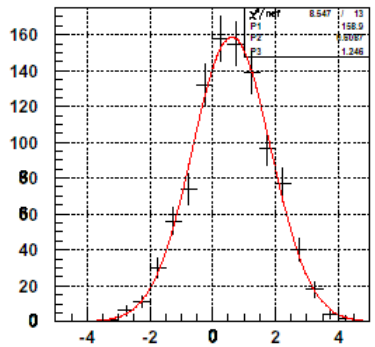
For Consistency check

←(Fit mean – Average mean) -2

←(Sigma – RMS) -3



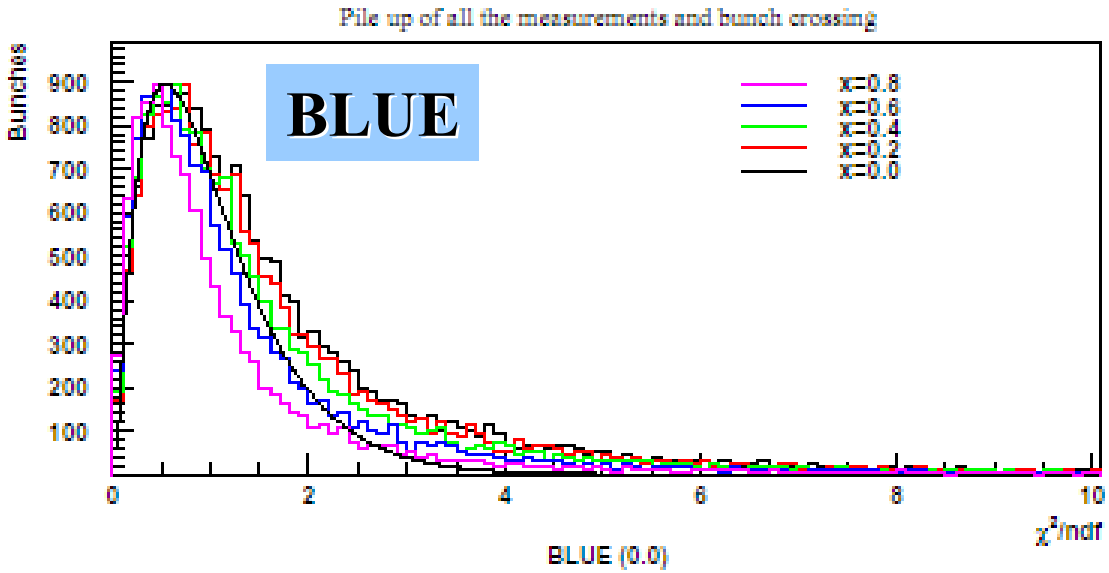
Fit sample run789

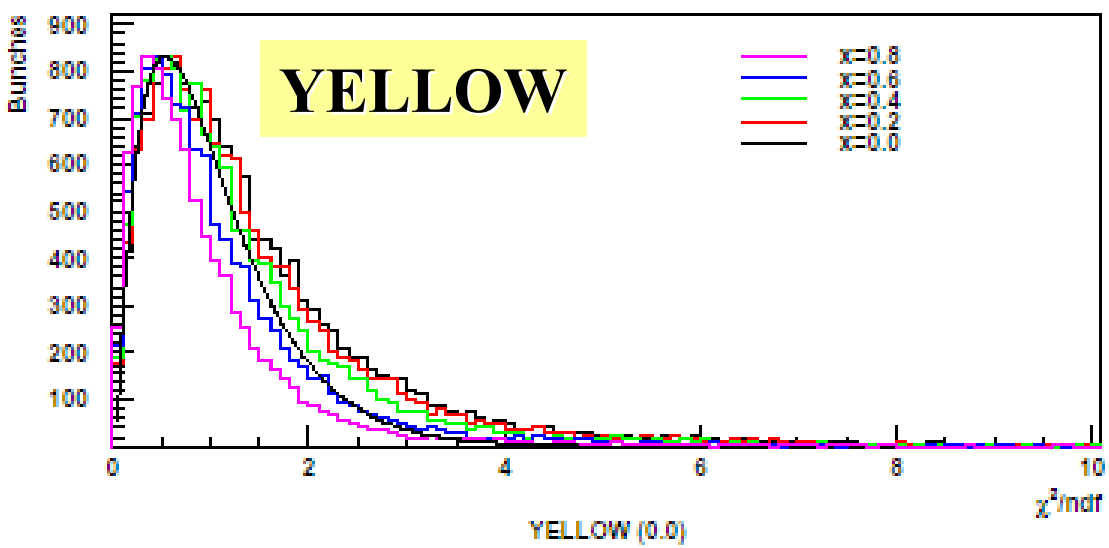


X90/sigma

O. Jinnouchi

Scaled χ^2/ndf distributions





$$\chi^2 = \sum_{\text{detector}} \left(\frac{(x_i - \bar{x}_i)^2}{\sigma_{stat}^2 + \sigma_{sys}^2} \right)$$

$$= \frac{1}{(1+f^2)} \sum_{\text{detector}} \left(\frac{(x_i - \bar{x}_i)^2}{\sigma_{stat}^2} \right)$$

"f" looks to be between 0.4 and 0.6

- Distributions are normalized with the maximum contents

O. Jinnouchi

CNI Polarimetry (cont.)

- These four bits of information all suggest systematic errors comparable to statistical uncertainties in the 2001/2002 data.

- Consider the effect of the loss of counts due to backgrounds or multiple good events from the same bunch. It is assumed that both cases would lead to the loss of a good event. The basic equations would then be

$$N_{L\uparrow} = N_0 B_\uparrow d\Omega_L (1 + A_L P_\uparrow)(1 - f_{BL\uparrow} - f_{L\uparrow})$$
$$N_{L\downarrow} = N_0 B_\downarrow d\Omega_L (1 - A_L P_\downarrow)(1 - f_{BL\downarrow} - f_{L\downarrow})$$
$$N_{R\uparrow} = N_0 B_\uparrow d\Omega_R (1 - A_R P_\uparrow)(1 - f_{BR\uparrow} - f_{R\uparrow})$$
$$N_{R\downarrow} = N_0 B_\downarrow d\Omega_R (1 + A_R P_\downarrow)(1 - f_{BR\downarrow} - f_{R\downarrow})$$

where f_{Bi} is the fraction of events lost due to background and f_j is the fraction lost due to multiple good events from the same bunch. These fractions were on the order of a percent, and the effects initially believed to be negligible.

CNI Polarimetry (cont.)

- Assuming the f_j are proportional to the observed counts N_j, and the f_{Bi} are proportional only to the integrated beam and solid angle,

$$f_{L\uparrow} = f_T (B_\uparrow / B)(d\Omega_L / d\Omega)(1 + A_L P_\uparrow)$$

$$f_{BR\downarrow} = f_B (B_\downarrow / B)(d\Omega_R / d\Omega)$$

then

spin independent!!

$$\varepsilon_{PHYS} \cong PA(1 - f_T) - (f_B + f_T)\varepsilon_B \varepsilon_{d\Omega} + h.o.t.$$

$$\varepsilon_{LUM} \cong \varepsilon_B (1 - f_B - f_T) + PA\,\varepsilon_A + h.o.t.$$

- For the 2001/2002 run, typical values were $PA \sim 0.002$, $|\varepsilon_B| \sim 0.04$, $|\varepsilon_{d\Omega}| \sim 0.1$, $f_T \sim 0.009$, $f_B \sim 0.03$, and thus

$$\delta\varepsilon_{PHYS} \sim 0.00016$$

$$\delta\varepsilon_{LUM} \sim 0.0016$$

These multiples rates are only a few percent, yet lead to sizable effects on the physics and luminosity asymmetries! It is concluded that such rate effects may have contributed to the observed systematic errors.

CNI Polarimetry (cont.)

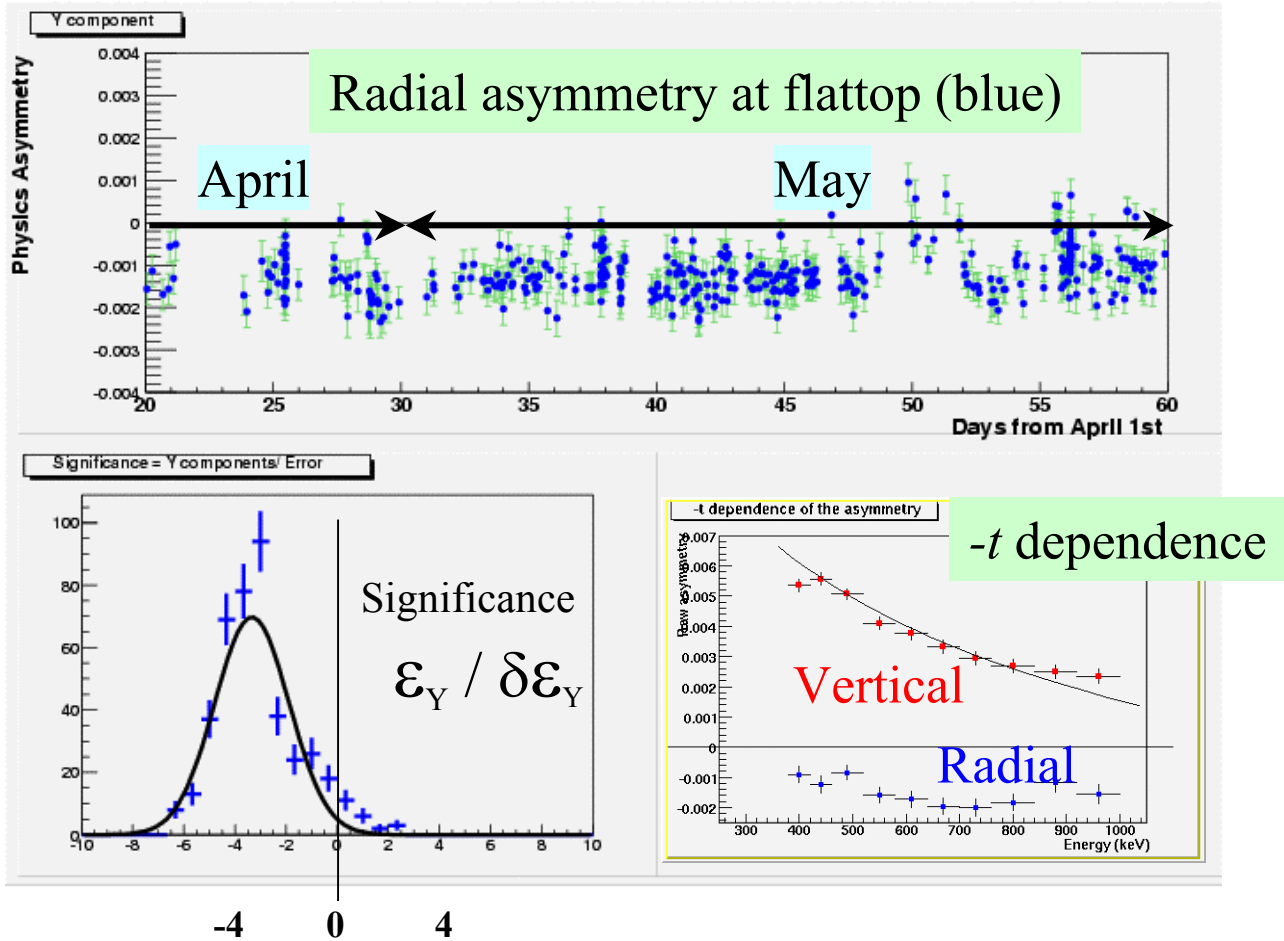
- The 2003 RHIC polarimeter data had unexpected up-down and cross-ratio asymmetries, $\varepsilon_{UD,PHYS}$ and $\varepsilon_{CR,PHYS}$, in the blue ring over much of the run. These observations are indicative of systematic errors.

- However, it was pointed out that a significant difference in analyzing power for one of the four polarimeter detectors might lead to the observed results. Note, each detector actually consists of a number of silicon strips, and dead layers can differ from strip to strip and detector to detector. Improper dead layers can lead to incorrect energy calibration and analyzing power.

- Sizable differences in analyzing power can also impact

$$\varepsilon_{LUM} \sim \varepsilon_B + PA\, \varepsilon_A + PA\, O(\delta^2).$$

- This problem should actually be evaluated through a four "detector" set of equations. The expressions become more complicated. Calculations can reproduce the left-right and up-down physics asymmetries.

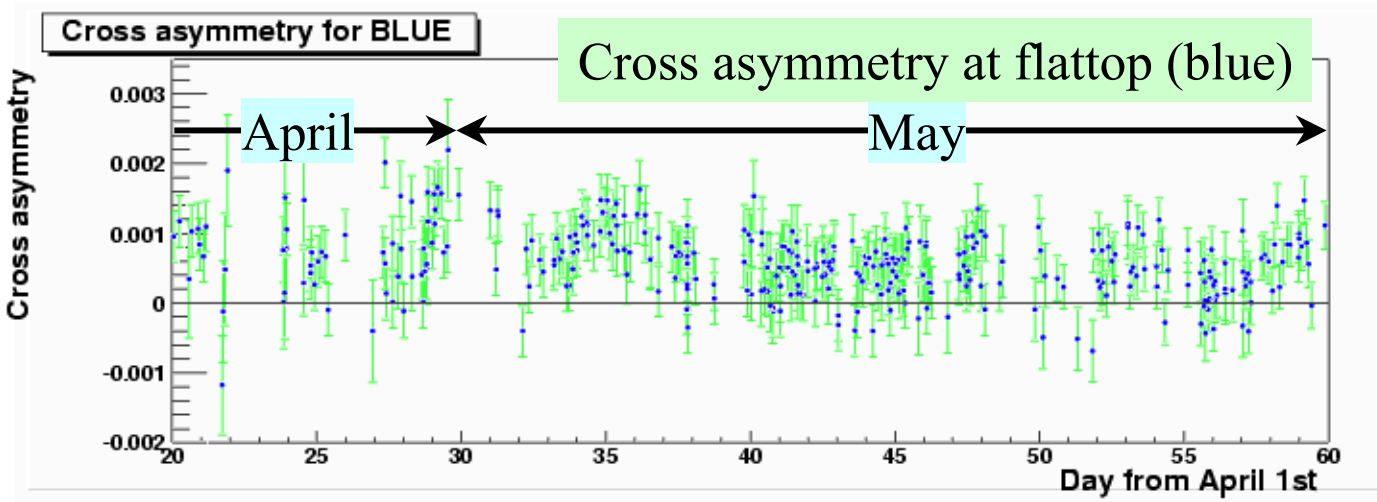


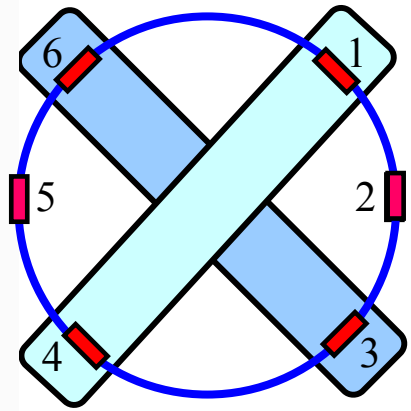
- False asymmetry (radial component) was consistently observed throughout the 2003 run
- *-t* dependence for the radial component is not the usual CNI shape and is considered to be a systematic error

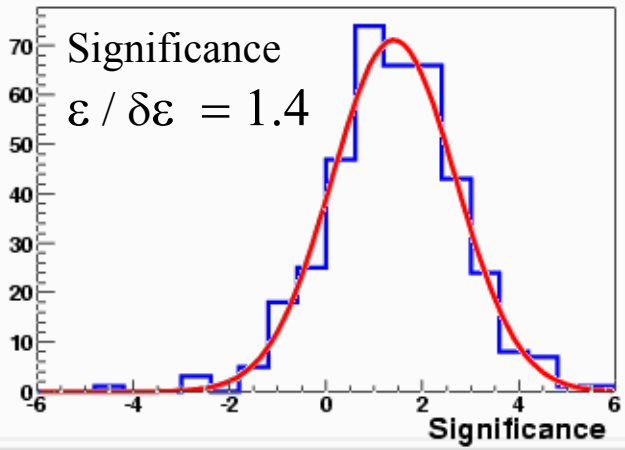
O. Jinnouchi

Systematic errors

Cross = (1+4) vs. (3+6)







- In Blue flattop, a false cross-ratio asymmetry was consistently observed throughout the run
- Other checks with the radial component showed a similar systematic error
- The size and mechanism are being studied

O. Jinnouchi

CNI Polarimetry (cont.)

- The physics asymmetries, $\varepsilon_{UD,PHYS}$ and $\varepsilon_{CR,PHYS}$, and the corresponding value for $\varepsilon_{LR,PHYS}$ can be expanded in terms of analyzing powers, solid angle asymmetries, and the average beam polarization as follows:

$$\varepsilon_{LR,PHYS} \cong P[A_1 + A_3 + A_4 + A_6]/4 + P^2 A^2 O(\delta^2)$$
$$+ P[(A_1 - A_3)\varepsilon_{\Omega 13} + (A_6 - A_4)\varepsilon_{\Omega 64}]/4$$
$$\varepsilon_{UD,PHYS} \cong P[A_3 - A_1 - A_4 + A_6]/4 + P^2 A^2 O(\delta^2)$$
$$+ P[(A_3 - A_4)\varepsilon_{\Omega 43} + (A_6 - A_1)\varepsilon_{\Omega 16}]/4$$
$$\varepsilon_{CR,PHYS} \cong P[A_1 - A_3 - A_4 + A_6]/4 + P^2 A^2 O(\delta^2)$$
$$+ P[(A_1 - A_4)\varepsilon_{\Omega 14} + (A_6 - A_3)\varepsilon_{\Omega 36}]/4$$

- Note the signs are reversed for $\varepsilon_{UD,PHYS}$ and $\varepsilon_{CR,PHYS}$ in the formulas and the figures.

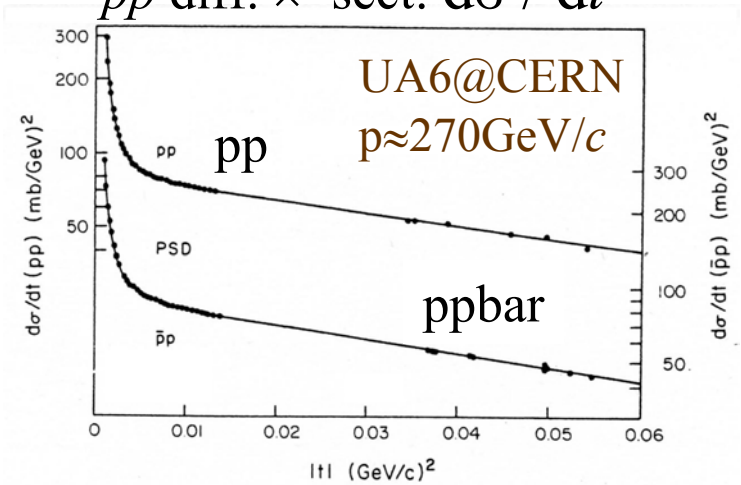
- It is not obvious the expressions for $\varepsilon_{UD,PHYS}$ etc. are optimum, given the complicated form illustrated above.

Summary

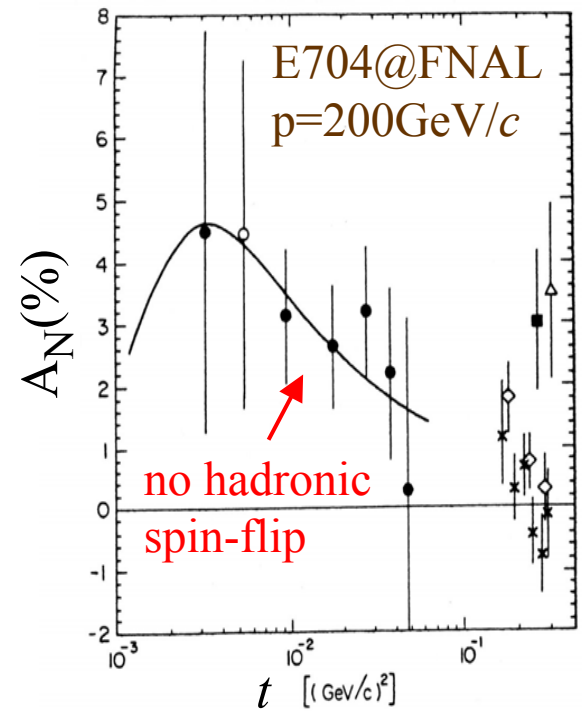
- Beam polarimeters are often essential for spin experiments.
- Symmetric pairs of "detectors" allow significant advantages. Square root asymmetries are frequently used to find PA.
- Construction techniques are dependent on many factors, including energy, the reaction chosen, backgrounds, etc.
- Calibrations of electron polarimeters are based on QED calculations, of muon polarimeters on muon decay parameter data, and of proton polarimeters on proton scattering measurements (often energy dependent).
- Instrumental/systematic effects can cause errors in beam polarization determinations, and must be studied carefully.

Elastic *pp* & *p*C: $d\sigma / dt$ and A_N

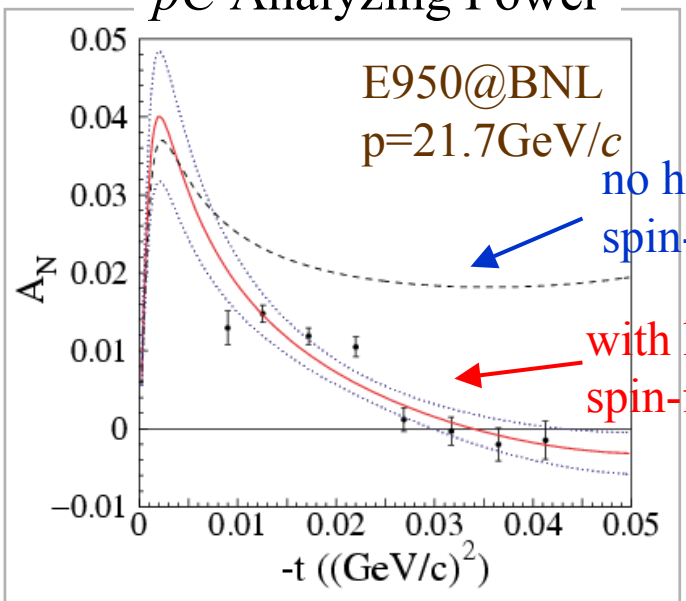
pp diff. ×–sect: $d\sigma / dt$



pp Analyzing Power A_N



pC Analyzing Power



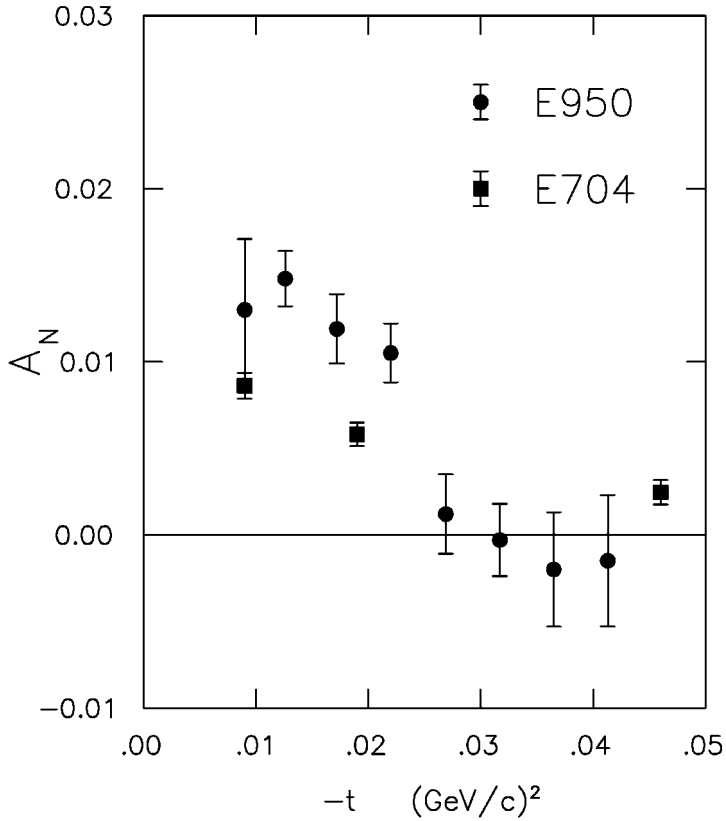
$$r_5^{pC} = (0.088 \pm 0.058) - i\,(0.161 \pm 0.226)$$

$$\propto F_s^{had} / Im\, F_0^{had}$$

A_N: $p\uparrow C \rightarrow pC$ at RHIC Energies (cont.)

- A second, "CNI-like" measurement was made at FNAL E704 (200 GeV/c).
- The beam trajectory was measured with hodoscopes on a particle by particle basis.
- The scattered particle position downstream of the target was measured. The angle was calculated assuming scattering in the target.
- A polarized target was used ($C_5H_{12}O$).
- No particle identification was used for the scattered particles. No background subtraction was performed.
- The results at 200 GeV/c are not very different from those at 22 GeV/c!

E950: J. Tojo et al., PRL 89, 052302 (2002)
E704: D. Grosnick et al., Phys. Rev. D55, 1159 (1997)



The Road to P_{beam}

Requires several independent measurements

0 target polarization P_{target} (Breit-Rabi polarimeter)

1 A_N for elastic *pp* in CNI region: $A_N = 1 / P_{target}\, \varepsilon_N'$

2 $P_{beam} = 1 / A_N\, \varepsilon_N''$

1 & 2 can be combined in a single measurement: $P_{beam} / P_{target} = - \varepsilon_N' / \varepsilon_N''$

"self calibration" works for elastic scattering only

3 CALIBRATION: A_N^{pC} for *pC* CNI polarimeter in detector kinematical range:

$A_N^{pC} = 1 / P_{beam}\, \varepsilon_N'''$

(1 +) 2 + 3 measured simultaneously with several insertions of carbon target

4 BEAM POLARIZATION: $P_{beam} = 1 / A_N^{pC}\, \varepsilon_N''''$ to experiments

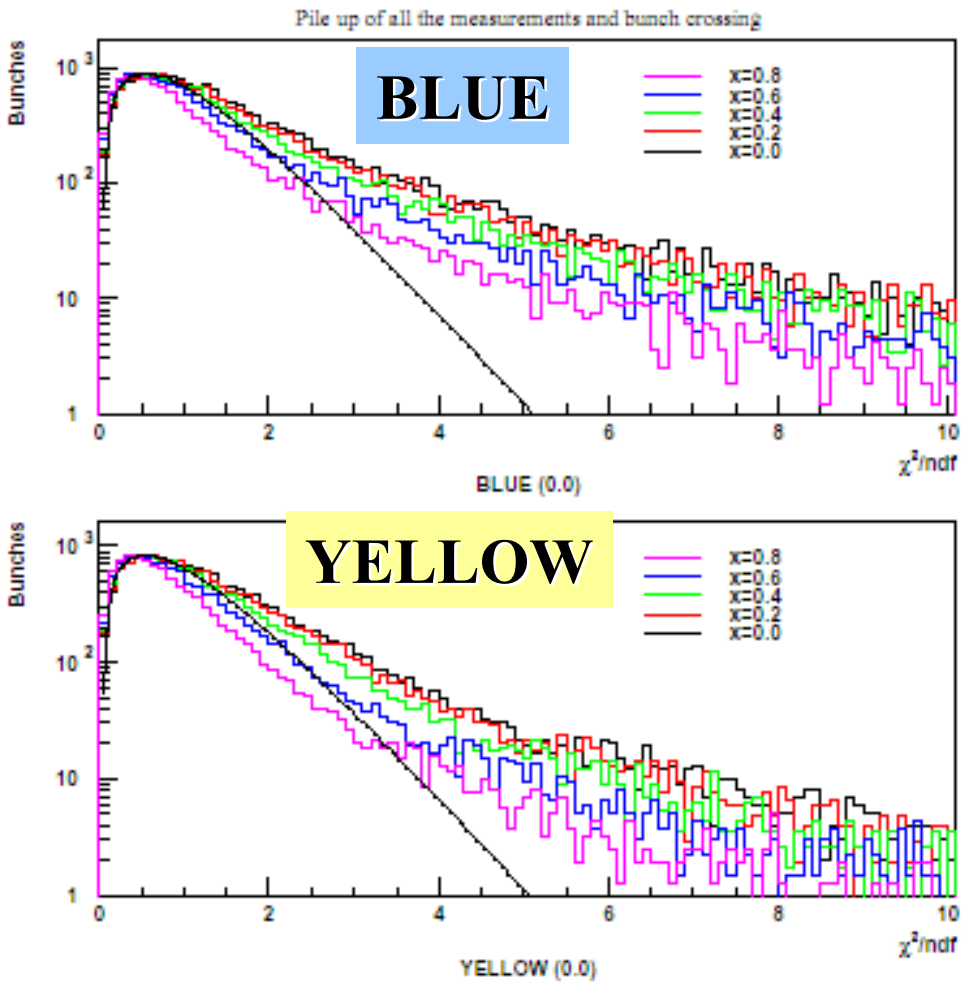
at each step pick-up some measurement errors:

$$\frac{\Delta P_{beam}}{P_{beam}} = \left(\frac{\Delta P_{target}}{P_{target}}\right) \oplus \left(\frac{\Delta \varepsilon}{\varepsilon}\right)_{pp} \oplus \left(\frac{\Delta A_N}{A_N}\right)_{pC} \oplus \left(\frac{\Delta \varepsilon}{\varepsilon}\right)_{pC} \leq 6\%$$

expected precision

transfer calibration measurement

Scaled χ^2/ndf distributions (in log scale)

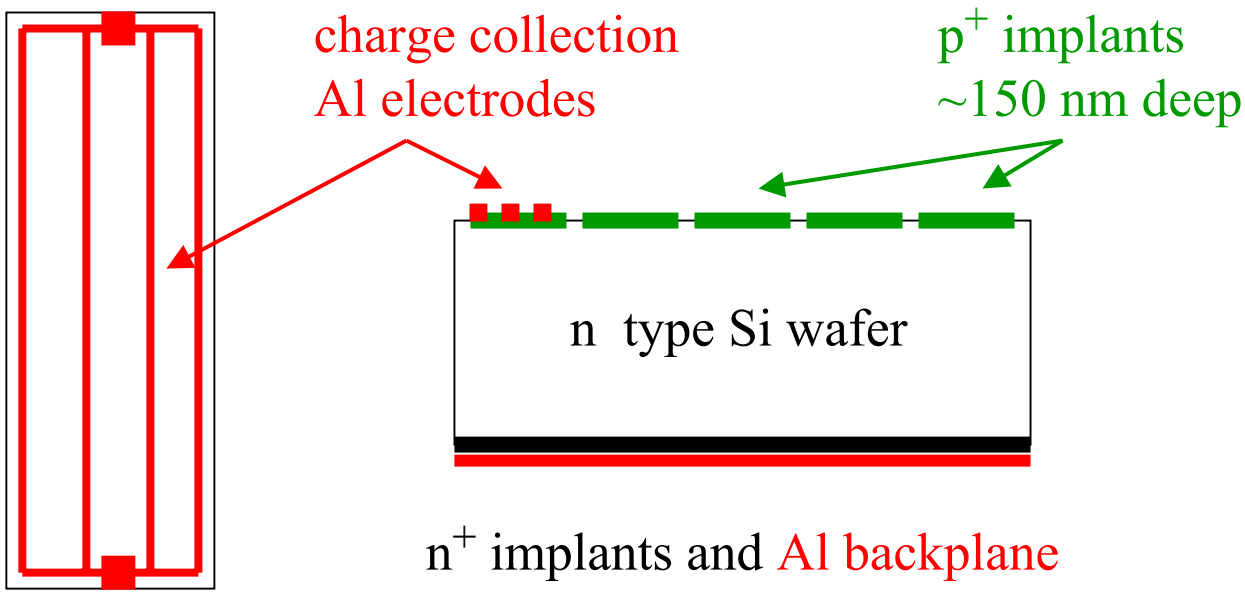


Si Detector and Energy Loss

at $t \sim -0.01\ (\mathrm{GeV}/c)^2$, Energy of recoil Carbon $E_{kin} \sim$ few 100 keV
($E_{kin} = -t / 2M_C$)

range in Silicon, only fraction of micrometer
substantial fraction of Carbon energy lost in dead layer (entrance window)
correct E_{kin} for energy loss → energy scale error

important to minimize energy losses in dead layer of detector



top view of Si strip

active area
24 x 12 mm^2

thickness
400 μ

12 2 mm wide
DC coupled strips