

Spin Dependence in Elastic Scattering in the CNI Region:

$$p \uparrow p \rightarrow pp \text{ \& } p \uparrow C \rightarrow pC$$

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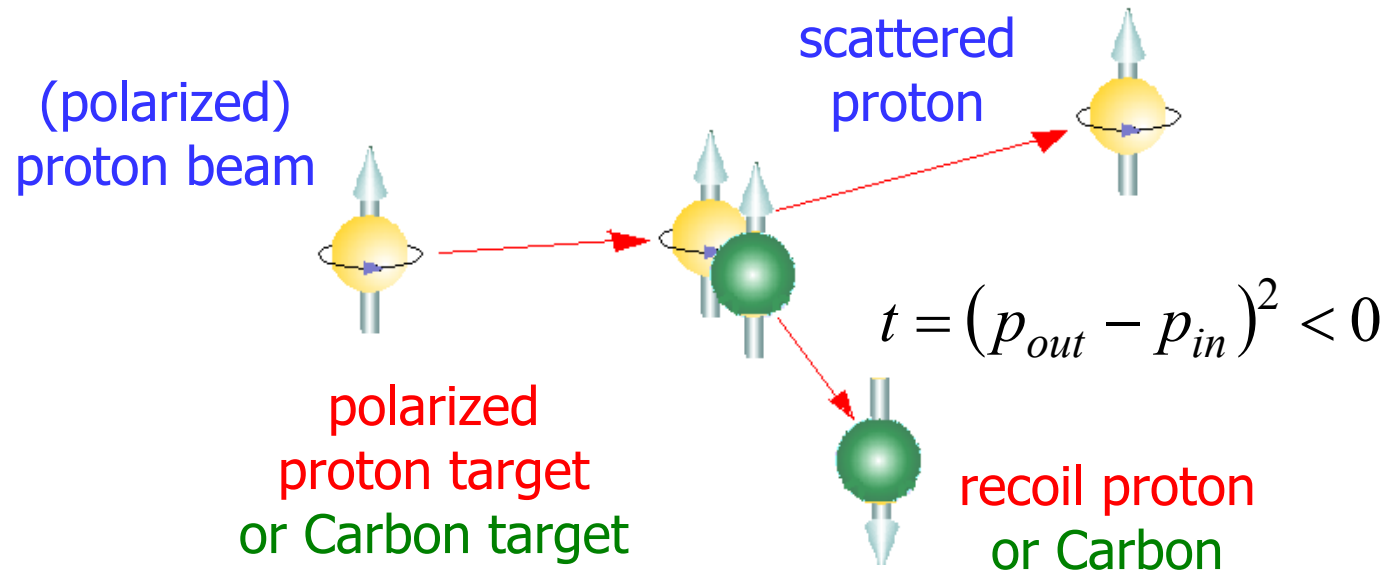
Spin 2004
Trieste
October 14, 2004

Alessandro Bravar



The Elastic Process: Kinematics

RHIC beams +
internal targets \equiv
fixed target mode
 $\sqrt{s} \sim 14 \text{ GeV}$



essentially 1 free parameter:

momentum transfer $t = (p_3 - p_1)^2 = (p_4 - p_2)^2 < 0$
 + center of mass energy $s = (p_1 + p_2)^2 = (p_3 + p_4)^2$
 + azimuthal angle ϕ if polarized !

\Rightarrow elastic pp kinematics fully constrained by recoil proton only !

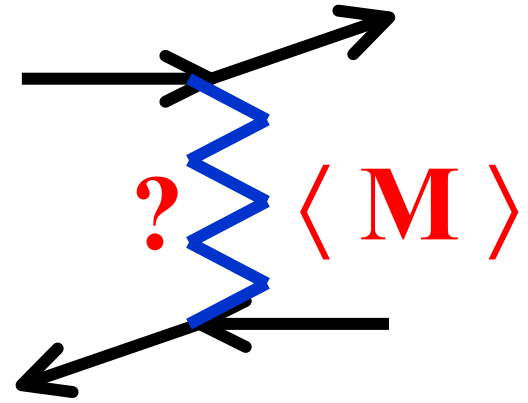
Helicity Amplitudes for spin $\frac{1}{2} \frac{1}{2} \rightarrow \frac{1}{2} \frac{1}{2}$

Scattering process described in terms of **Helicity Amplitudes** ϕ_i

All dynamics contained in the **Scattering Matrix** M

(Spin) Cross Sections expressed in terms of

- observables:
3 \times -sections
5 spin asymmetries
- spin non-flip $\phi_1(s,t) = \langle ++ | M | ++ \rangle$
 - double spin flip $\phi_2(s,t) = \langle ++ | M | -- \rangle$
 - spin non-flip $\phi_3(s,t) = \langle +- | M | +- \rangle$
 - double spin flip $\phi_4(s,t) = \langle +- | M | -+ \rangle$
 - single spin flip $\phi_5(s,t) = \langle ++ | M | + - \rangle = -\langle ++ | M | -+ \rangle$



identical spin $\frac{1}{2}$ particles

$$A_N = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\downarrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow}}$$

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

$$A_{NN} = \frac{\sigma^{\uparrow\uparrow+\downarrow\downarrow} - \sigma^{\uparrow\downarrow+\downarrow\uparrow}}{\sigma^{\uparrow\uparrow+\downarrow\downarrow} + \sigma^{\uparrow\downarrow+\downarrow\uparrow}}$$

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

formalism well developed, however not much data !
only A_N studied / measured to some extent

The Very Low t Region

around $t \sim -10^{-3} (\text{GeV}/c)^2$ $A_{\text{hadronic}} \approx A_{\text{Coulomb}}$

\Rightarrow INTERFERENCE

CNI = Coulomb – Nuclear Interference

scattering amplitudes modified to include also electromagnetic contribution

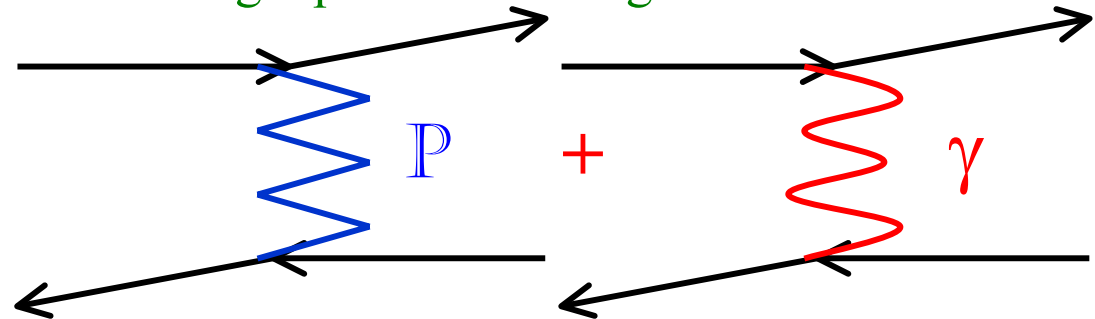
$$\phi_i^{\text{had}} \rightarrow \phi_i^{\text{had}} + \phi_i^{\text{em}} e^{i\delta}$$

hadronic interaction described in terms of Pomeron (Reggeon) exchange

electromagnetic

single photon exchange

$$\sigma = |A_{\text{hadronic}} + A_{\text{Coulomb}}|^2$$



unpolarized \Rightarrow clearly visible in the cross section $d\sigma/dt$

polarized \Rightarrow “left – right” asymmetry A_N

charge

magnetic moment

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)

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

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

in absence of hadronic spin – flip contributions A_N is exactly calculable (Kopeliovich & Lapidus):

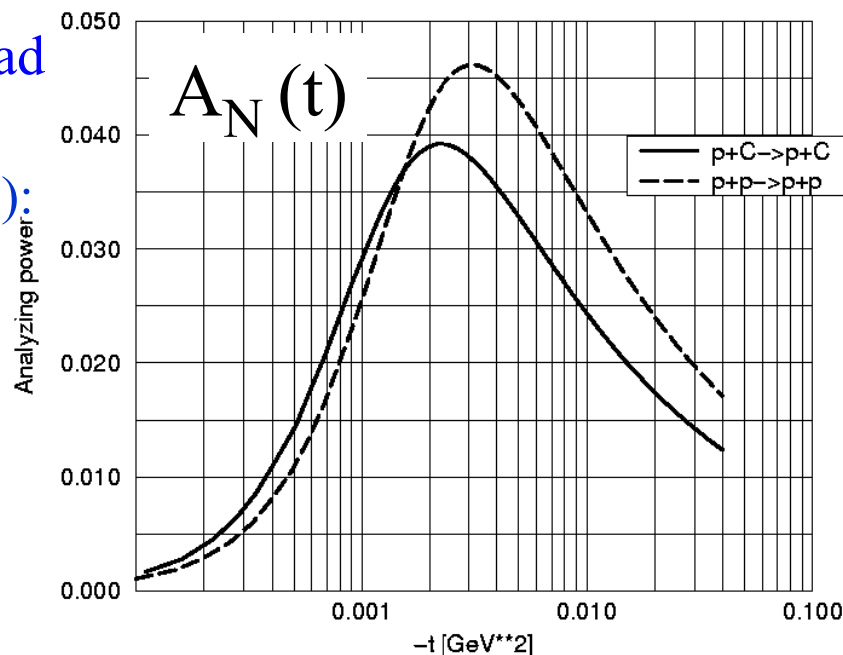
$$A_N = \sqrt{\frac{8\pi Z\alpha}{m_p^2 \sigma_{tot}^{pA}}} \frac{y^{3/2}}{1+y^2} (\mu - 1) \quad y = \frac{\sigma_{tot}^{pA} t}{8\pi Z\alpha}$$

hadronic spin- flip modifies the QED “predictions”

$$\frac{\mu_p - 1}{2} \rightarrow \frac{\mu_p - 1}{2} - I_5 + \frac{\mu_p - 1}{2} I_2$$

interpreted in terms of Pomeron spin – flip and parametrized as

$$\phi_5^{had} = \tau(s) \frac{\sqrt{-t}}{m_p} \phi_1^{had}$$



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:

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

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

$$R = 1.5 \cdot 10^{-13} A^{1/2} \text{ cm} \quad \text{and} \quad a = 0.53 \cdot 10^{-8} Z^{-1/2} \text{ cm},$$

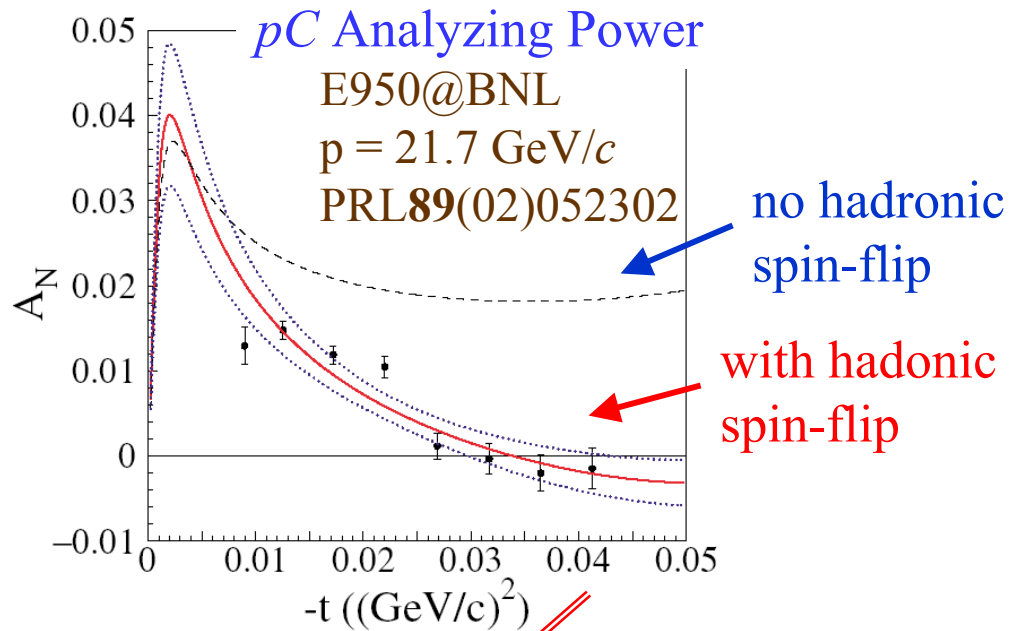
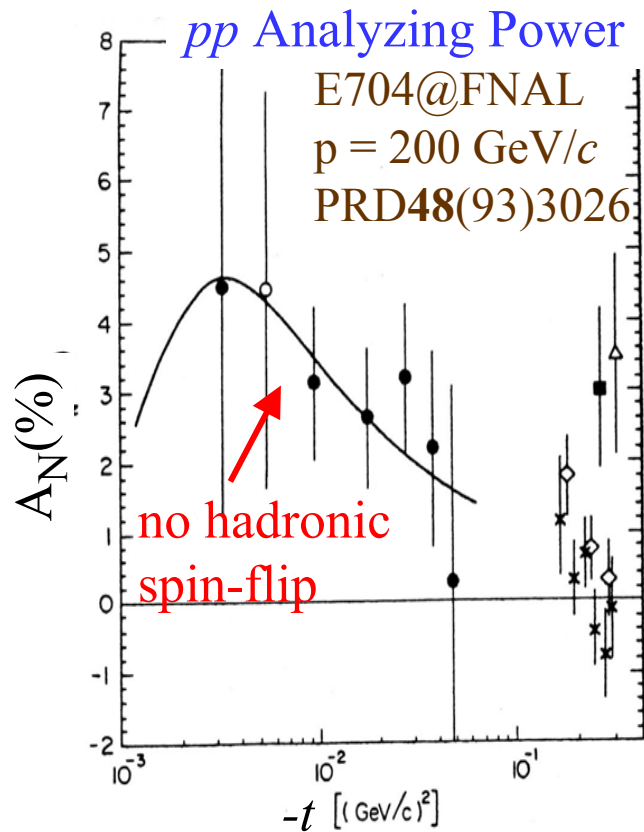
the angle restrictions for a 1-Mev neutron scattered in Pb, for example, are

$$4 \cdot 10^{-4} \ll 2 \sin\vartheta/2 \ll \frac{1}{2}. \quad (4)$$

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

$$e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \quad (5)$$

Some A_N measurements in the CNI region

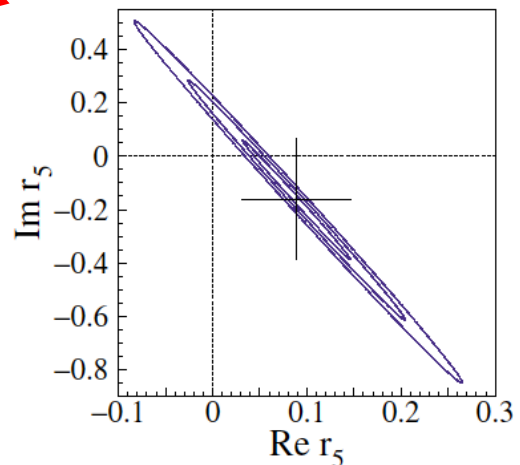


$$r_5^{pC} \propto F_s^{had} / \text{Im} F_0^{had}$$

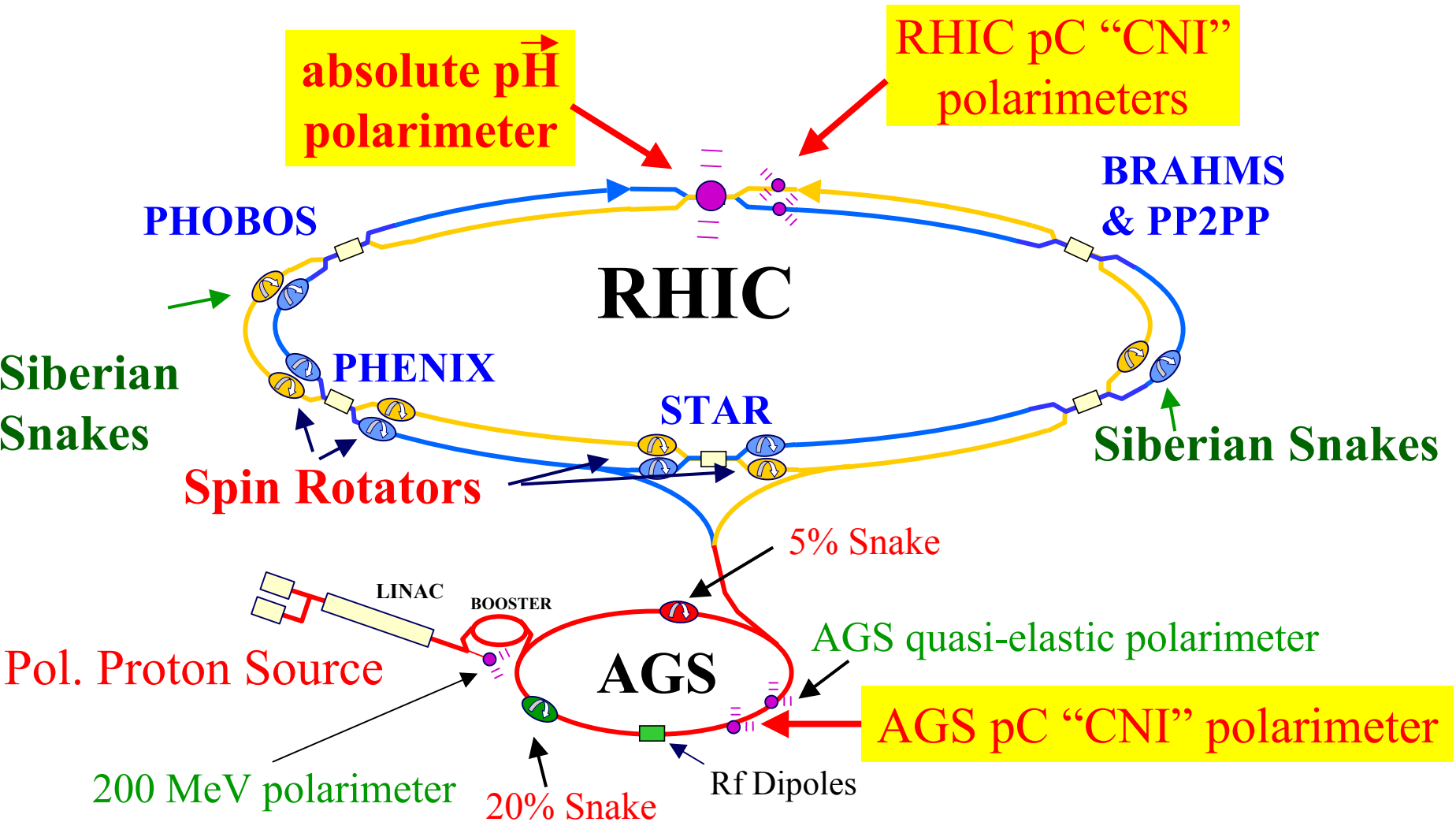
$$\text{Re } r_5 = 0.088 \pm 0.058$$

$$\text{Im } r_5 = -0.161 \pm 0.226$$

highly anti-correlated

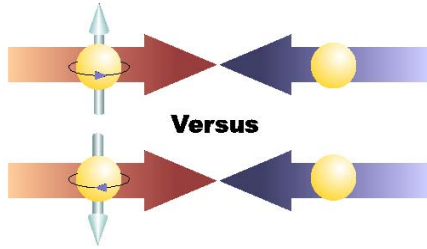


RHIC *pp* accelerator complex



Polarimetry : Impact on RHIC Spin Physics

Single Spin Asymmetries



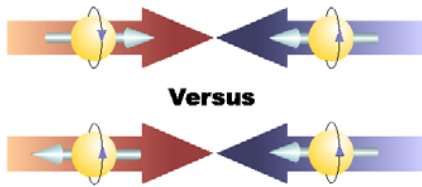
Physics Asymmetries

$$A_N = \frac{1}{P_B} \left(\frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \right)$$

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

recoil

Double Spin Asymmetries



$$A_{LL} = \frac{1}{P_B^2} \left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} \right)$$

$$\Rightarrow \boxed{\Delta G}$$

measurements

- measured spin asymmetries normalized by P_B to extract **Physics Spin Observables**
- RHIC Spin Program requires $\Delta P_{beam} / P_{beam} \sim 0.05$
- normalization \Rightarrow **scale uncertainty**
- polarimetric process with large σ and known A_N
 - pC elastic scattering in CNI region, $A_N \sim 1 - 2\%$
 - fast measurements
 - requires absolute calibration \rightarrow polarized gas jet target

The Road to P_{beam} with the JET target

Requires several independent measurements

0 JET 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 covered 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:

$$\frac{\Delta P_{beam}}{P_{beam}} = \left(\frac{\Delta P_{target}}{P_{target}} \right) \xrightarrow{\text{transfer}} \left(\frac{\Delta \varepsilon}{\varepsilon} \right)_{pp} \xrightarrow{\text{calibration}} \left(\frac{\Delta A_N}{A_N} \right)_{pC} \xrightarrow{\text{measurement}} \left(\frac{\Delta \varepsilon}{\varepsilon} \right)_{pC} \leq 6\% \quad \text{expected precision}$$

$$p \uparrow p \rightarrow p p$$

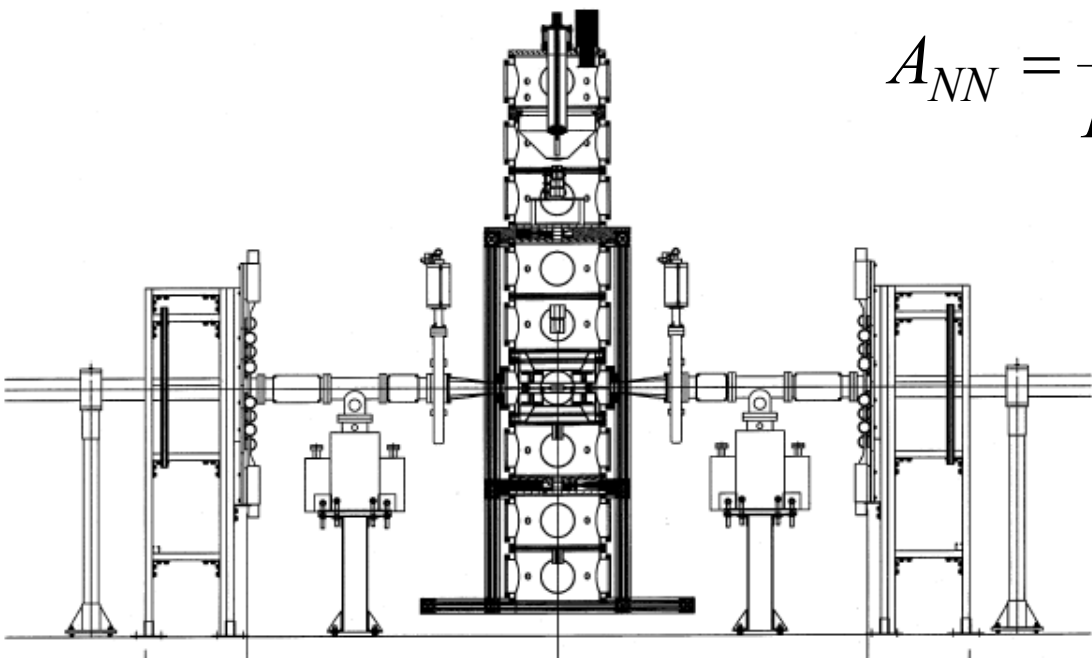
$p\uparrow p \rightarrow pp$ and $p\uparrow p\uparrow \rightarrow pp$ with a Polarized Gas Jet Target

polarized
gas JET
target



$$A_N = \frac{1}{P_T} \frac{(N_L^{\uparrow\uparrow} + N_R^{\downarrow\downarrow}) - (N_R^{\uparrow\uparrow} + N_L^{\downarrow\downarrow})}{(N_L^{\uparrow\uparrow} + N_R^{\downarrow\downarrow}) + (N_R^{\uparrow\uparrow} + N_L^{\downarrow\downarrow})}$$

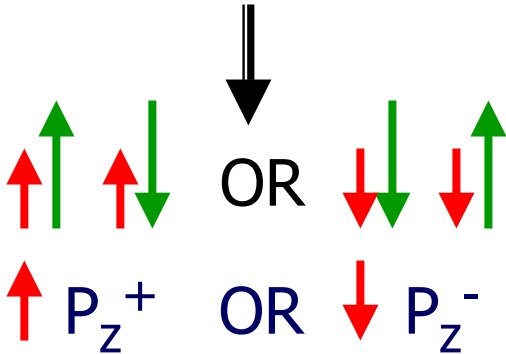
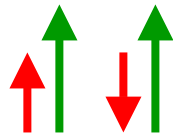
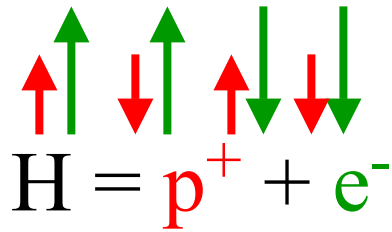
$$A_{NN} = \frac{1}{P_T P_B} \frac{N^{\uparrow\uparrow+\downarrow\downarrow} - N^{\uparrow\downarrow+\downarrow\uparrow}}{N^{\uparrow\uparrow+\downarrow\downarrow} + N^{\uparrow\downarrow+\downarrow\uparrow}}$$



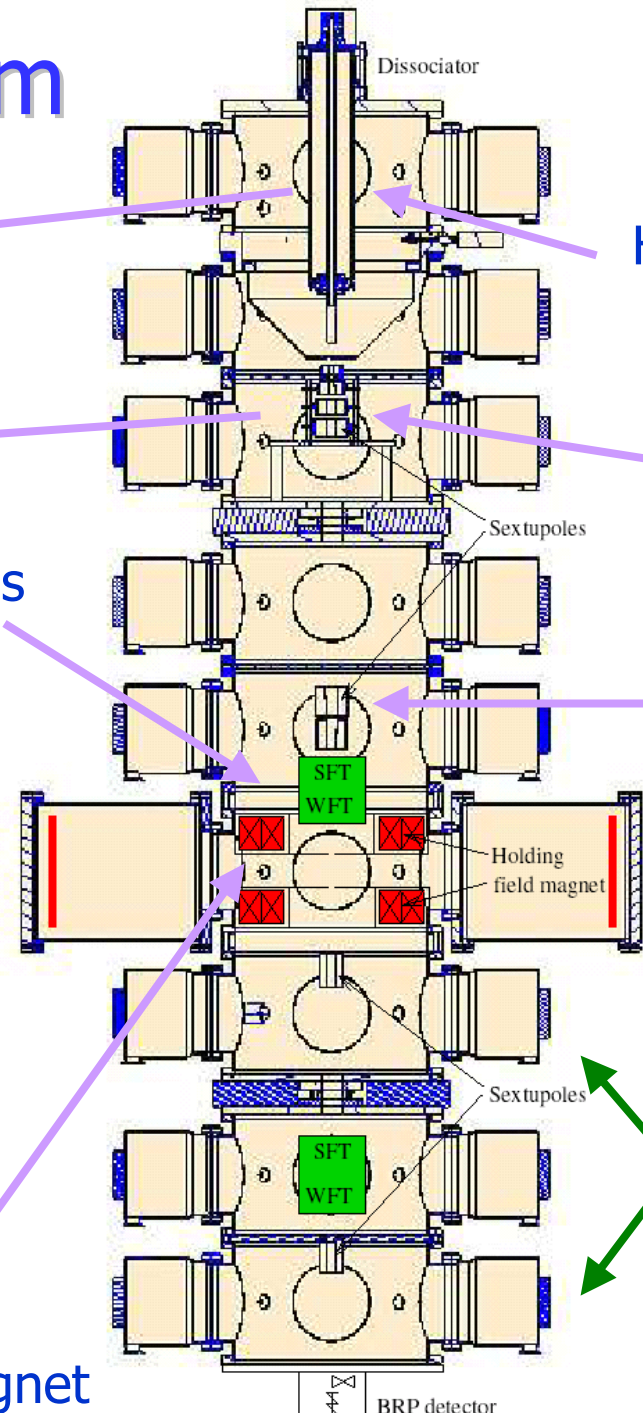
RHIC
polarized
proton
beams

The Atomic H Beam

Source



record beam intensity
 100% eff. RF transitions
 focusing high intensity
 B-R polarimeter



H₂ dissociator

separation magnets (sextupoles)

focusing magnets (sextupoles)

recoil detectors

Breit-Rabi polarimeter

JET target polarization & performance

the JET ran with an average intensity of 1×10^{17} atoms / sec

the JET thickness of 1×10^{12} atoms/cm² **record intensity**

target polarization cycle

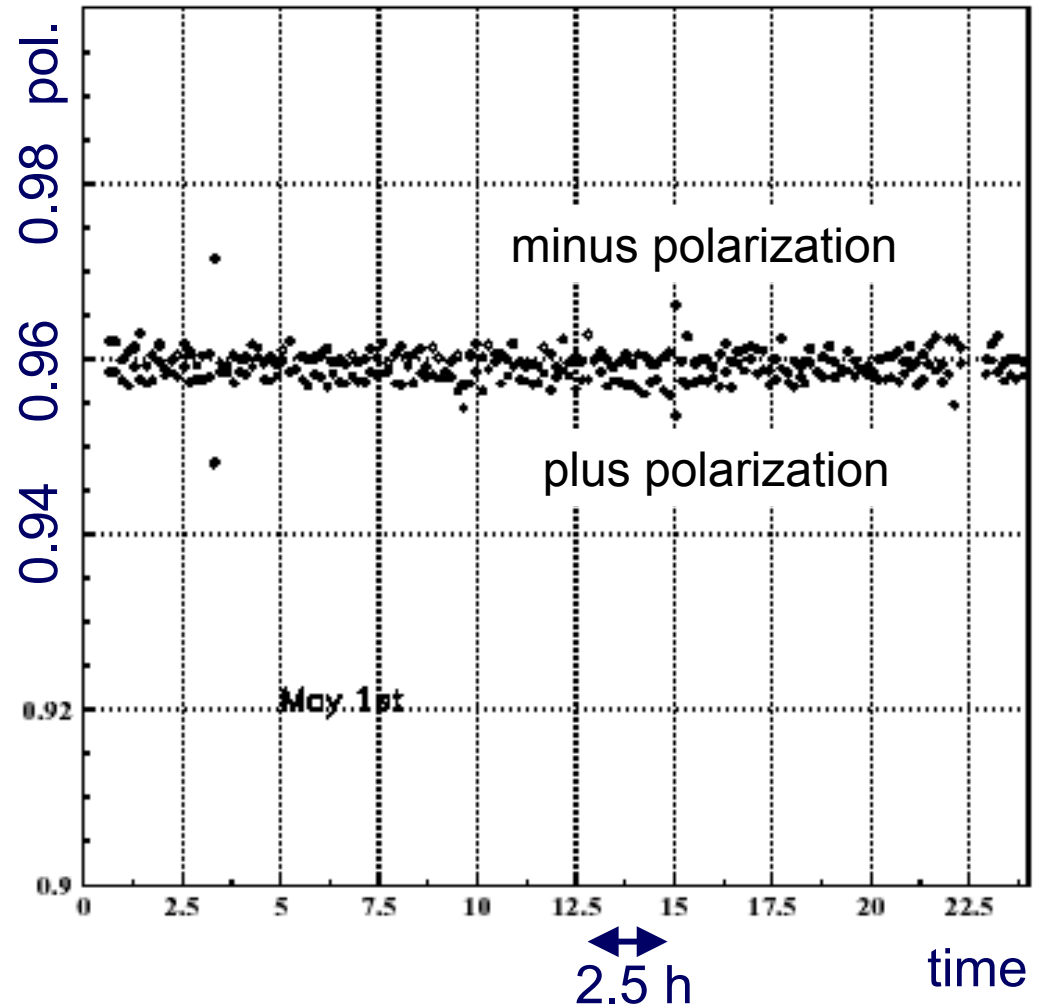
+ / 0 / - \sim 500 / 50 / 500 sec

polarization to be scaled down due to a \sim 3% H₂ background:

$$P_{\text{target}} \sim 0.924 \pm 0.018$$

(current understanding)

no depolarization from beam wake fields observed !



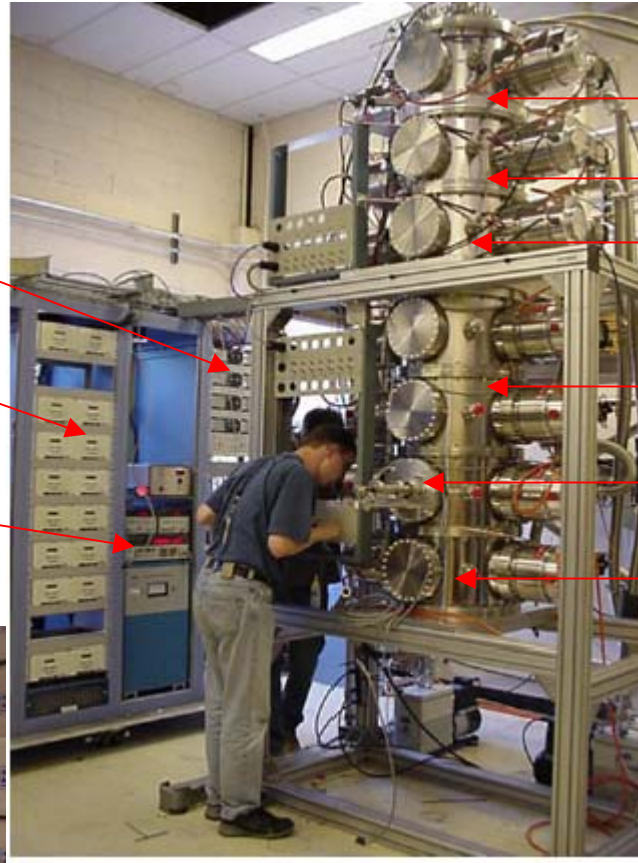
The Polarized Jet Target under development

Electronics racks

Vac. gauges monitors

Turbo pump controllers

Dissociator RF systems



Dissociator stage

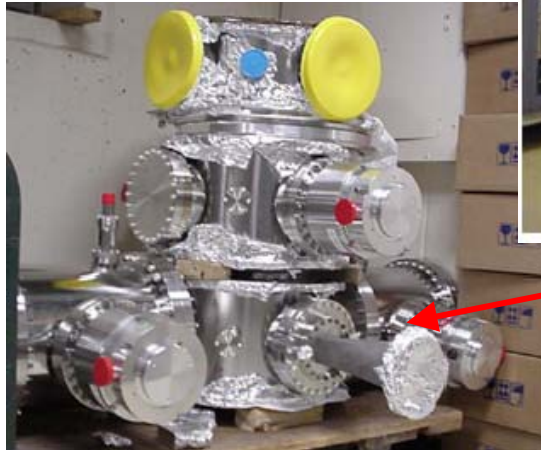
Baffle location

Sextupoles 1-4

Sextupoles 5-6

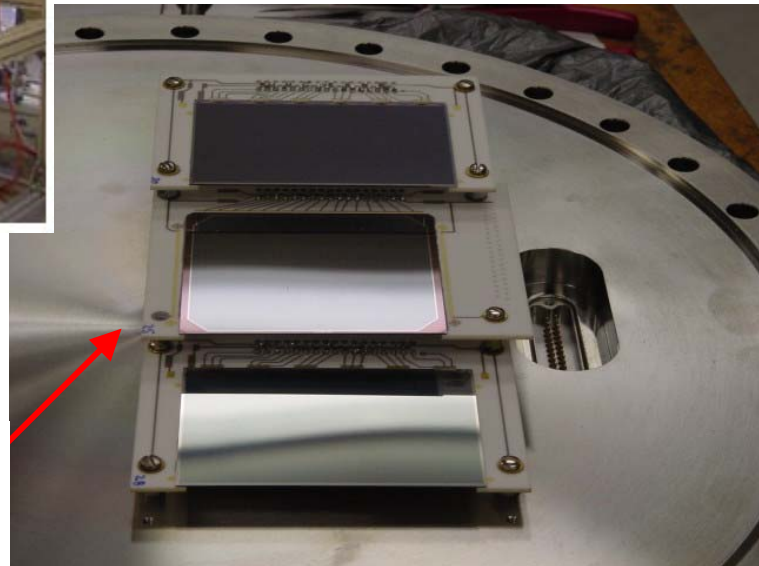
Profile measurement

BRP vacuum vessel



Target chamber &
beam pipe adapters

Recoil spectrometer
silicon detectors



Recoil Si spectrometer

6 Si detectors covering
the blue beam =>

MEASURE

energy (res. < 50 keV)

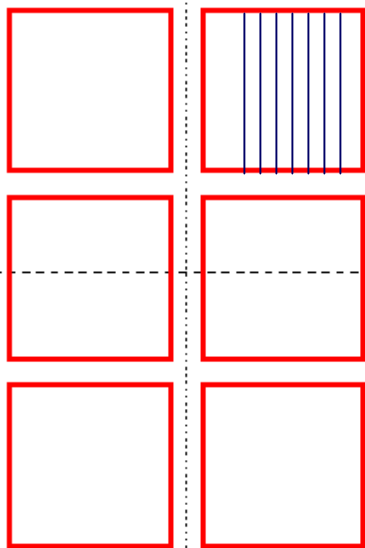
time of flight (res. < 2 ns)

scattering angle (res. ~ 5 mrad)

of recoil protons from

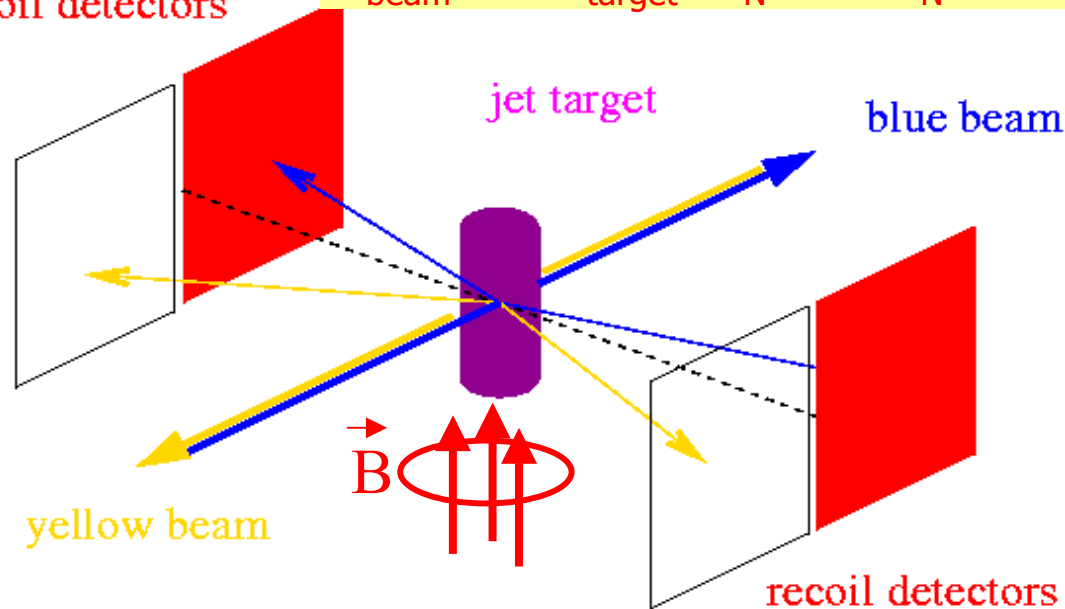
$pp \rightarrow pp$ elastic scattering

yellow blue



72 x 64 mm²

recoil detectors



$$A_N^{\text{beam}}(t) = -A_N^{\text{target}}(t)$$

for elastic scattering only!

$$P_{\text{beam}} = -P_{\text{target}} \cdot \epsilon_N^{\text{beam}} / \epsilon_N^{\text{target}}$$

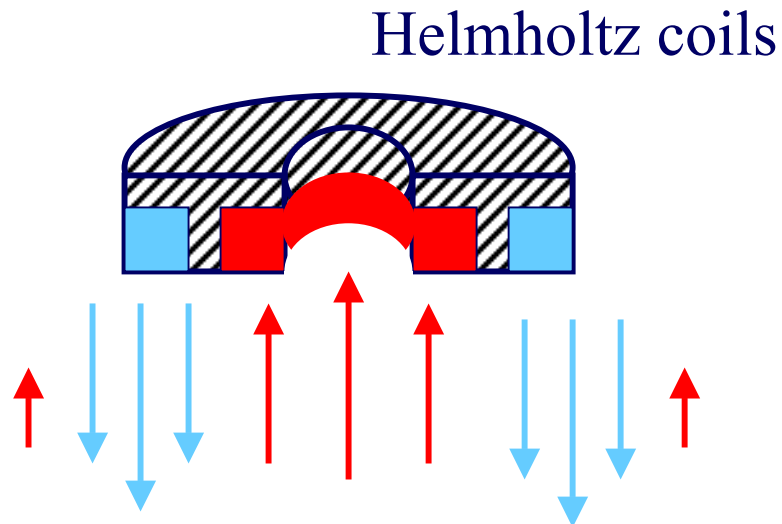
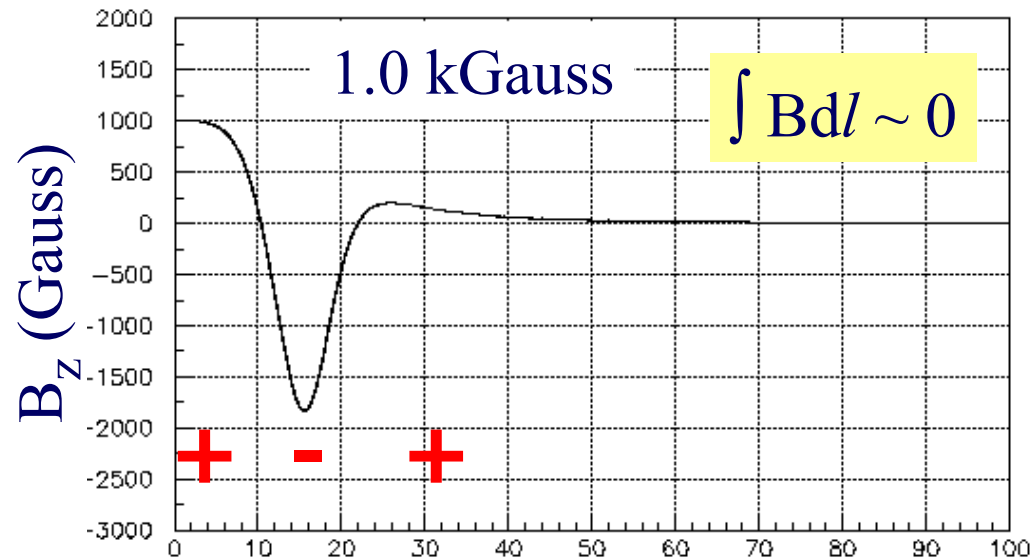
HAVE “design”
azimuthal coverage

one Si layer only

=> smaller energy range

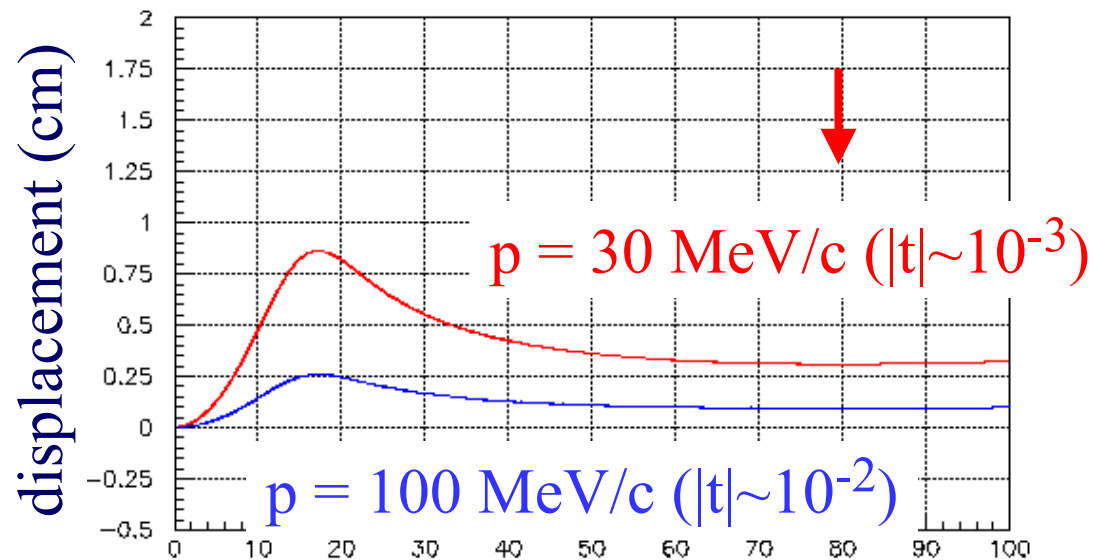
=> reduced bkg rejection power

Jet-Target Holding Magnetic Field (1.0)



almost no effect on recoil
proton trajectories:

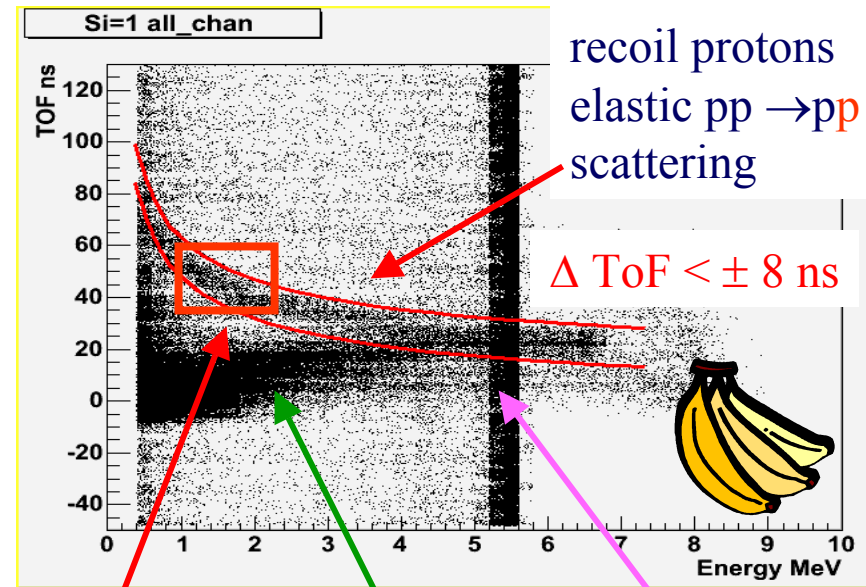
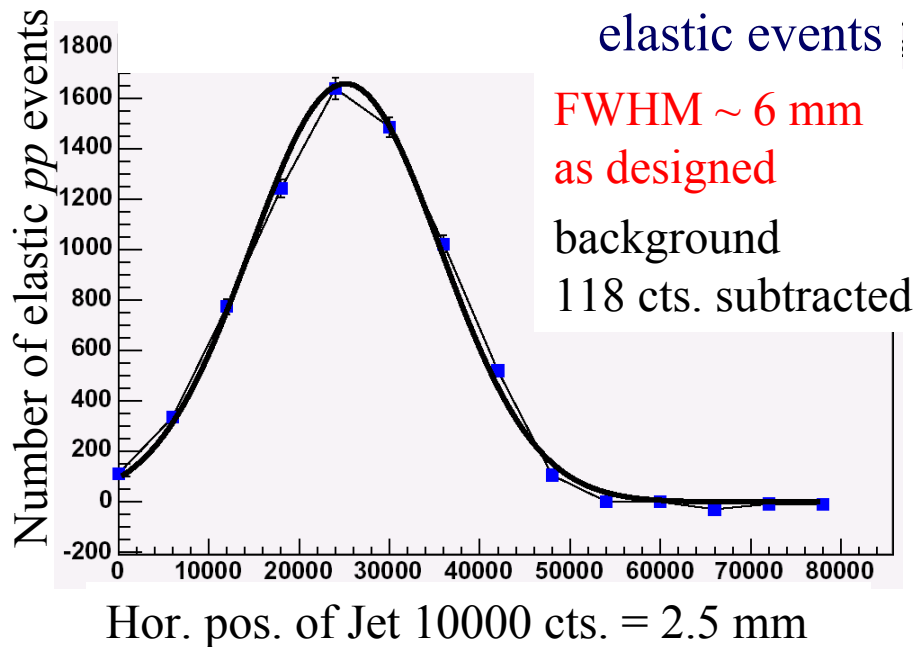
left – right hit profiles &
left – right acceptances
almost equal
(also under reversal of
holding field)



pp elastic data collected

ToF vs E_{REC} correlation
 $T_{\text{kin}} = \frac{1}{2} M_R (\text{dist}/\text{ToF})^2$

JET Profile: measured selecting pp elastic events



CNI peak A_N

$1 < E_{\text{REC}} < 2 \text{ MeV}$

prompt events and beam-gas

α source calibration

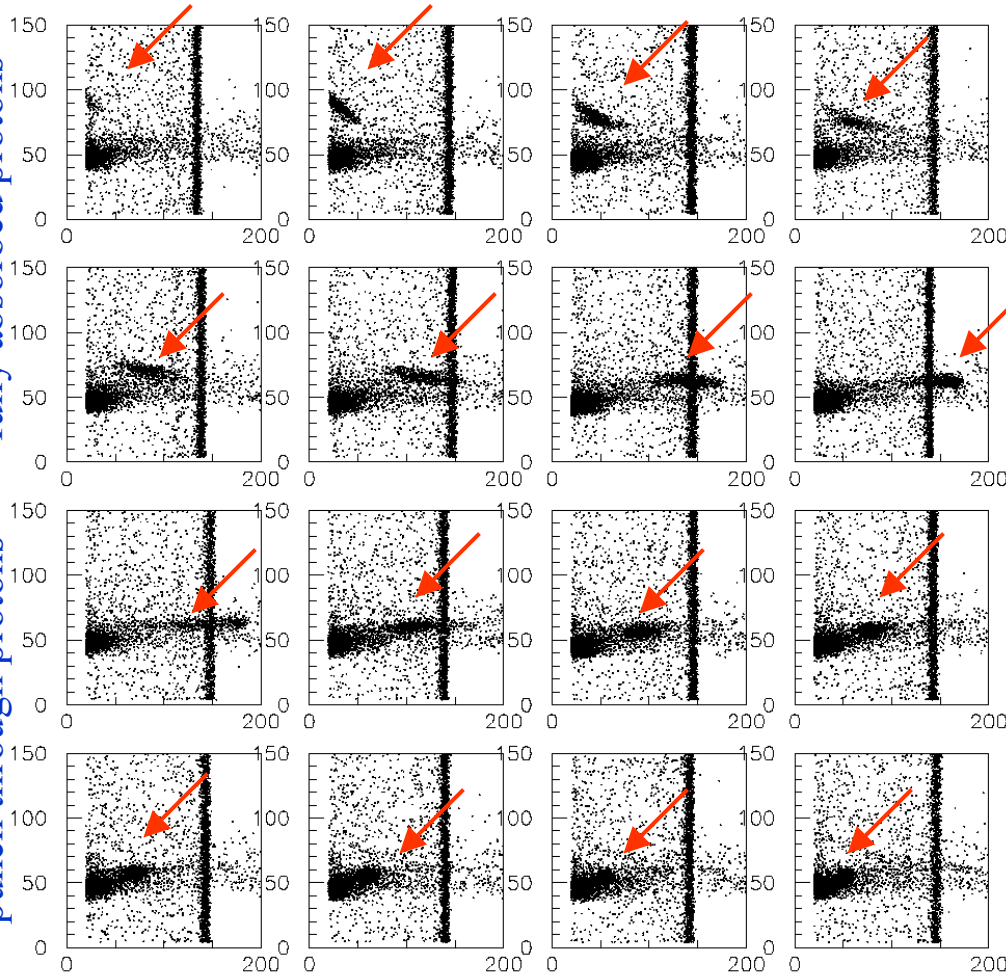
- recoil protons unambiguously identified !
- 100 GeV $\sim 1.8 \times 10^6$ events for $1.5 \times 10^{-3} < -t < 1.0 \times 10^{-2} \text{ GeV}^2$
 similar statistics for $1.0 \times 10^{-2} < -t < 3.0 \times 10^{-2} \text{ GeV}^2$
- 24 GeV $\sim 300 \text{ k}$ events

Energy - Position correlations

$$T_{\text{kin}} \propto \theta^2 \text{ (i.e. position}^2\text{)}$$

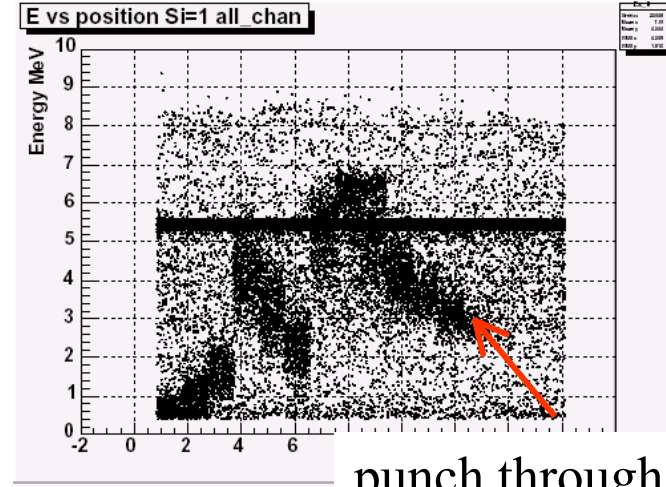
fully absorbed protons

punch through protons

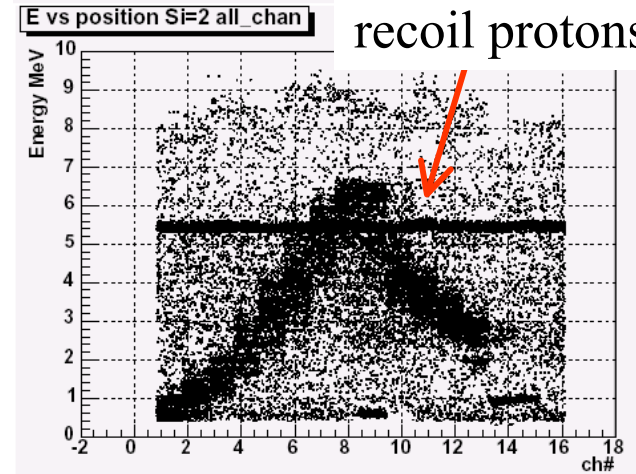


TDC vs ADC individual channels

recoil energy



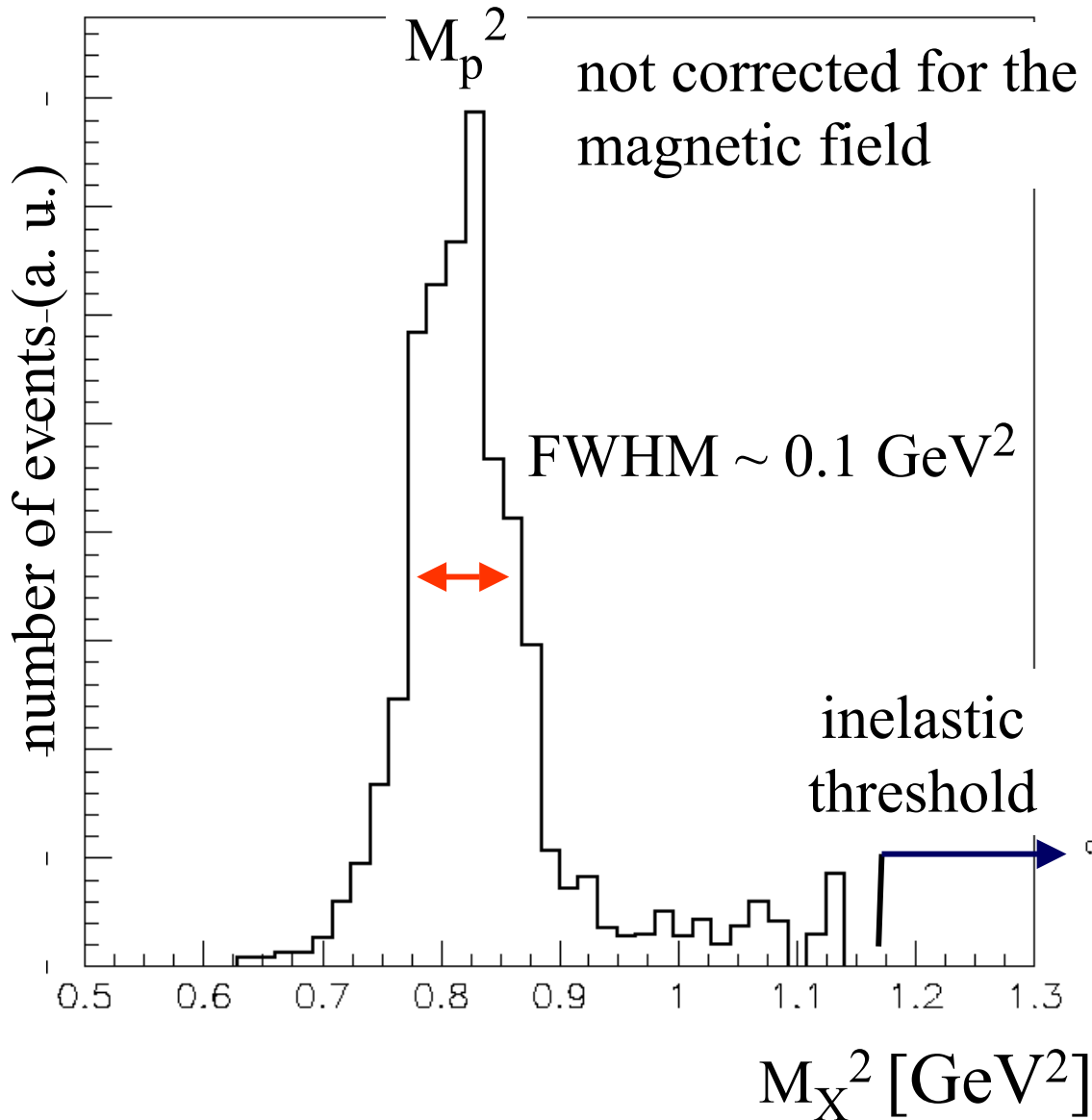
punch through
recoil protons



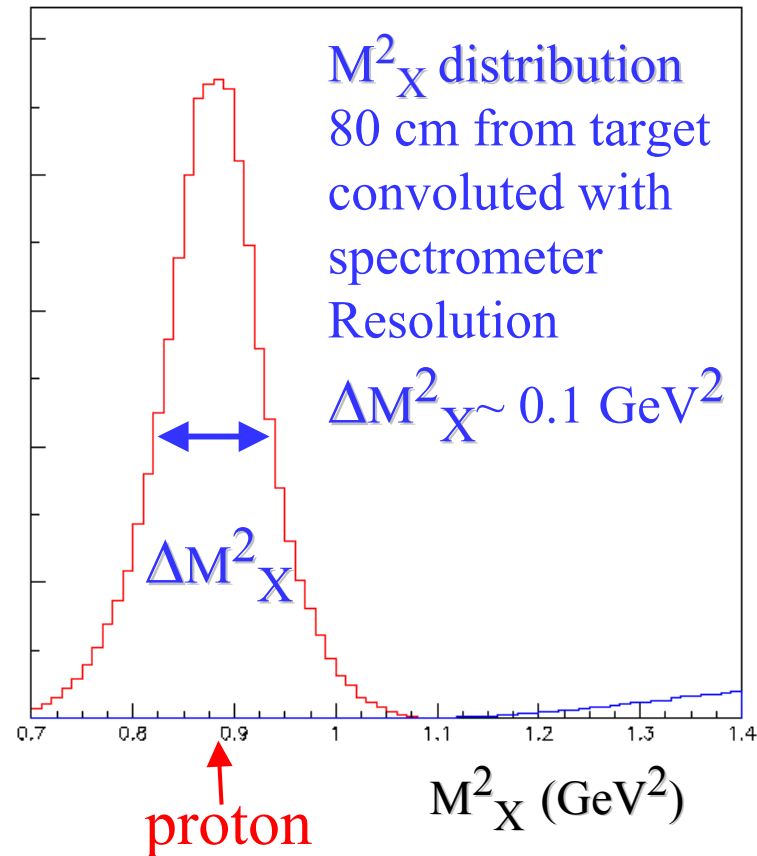
position

pp elastic events
clearly identified !

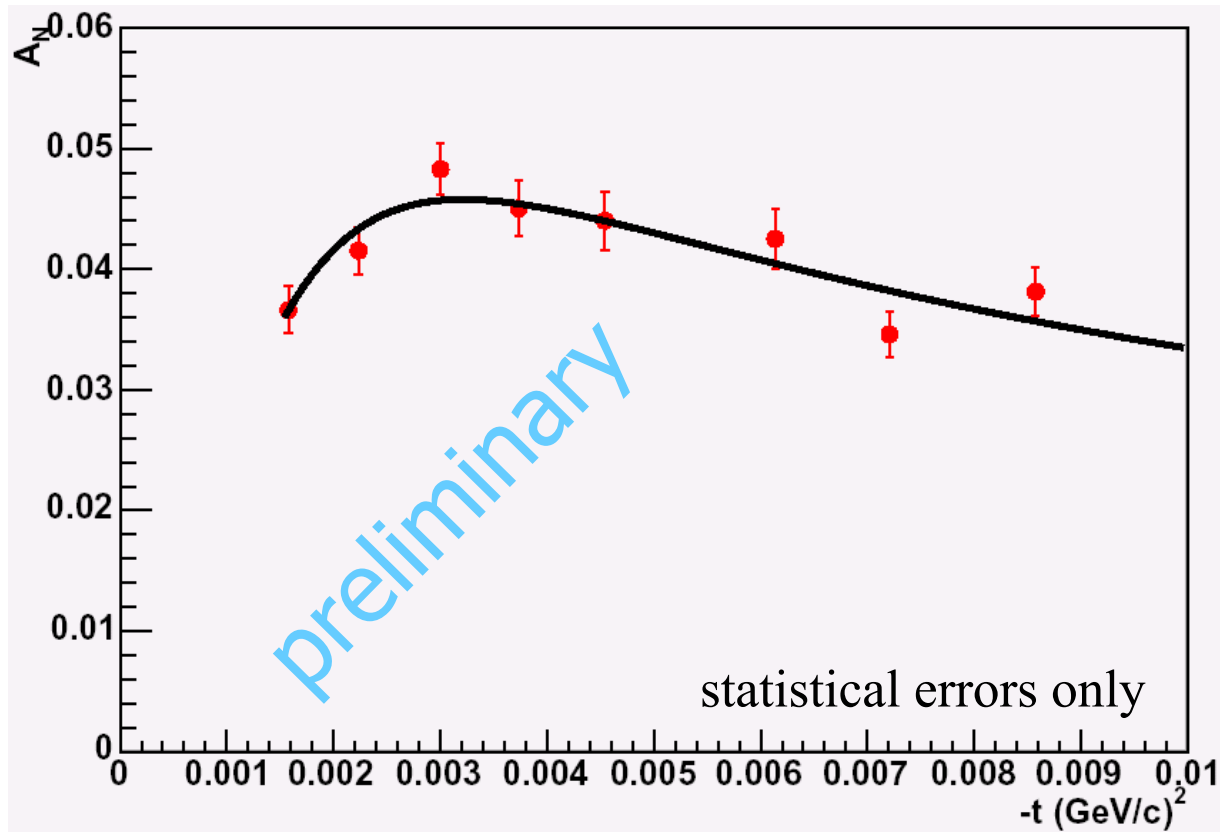
Missing Mass M_X^2 @ 100 GeV



simulations



A_N for $p \uparrow p \rightarrow pp$ @ 100 GeV



source of systematic errors:

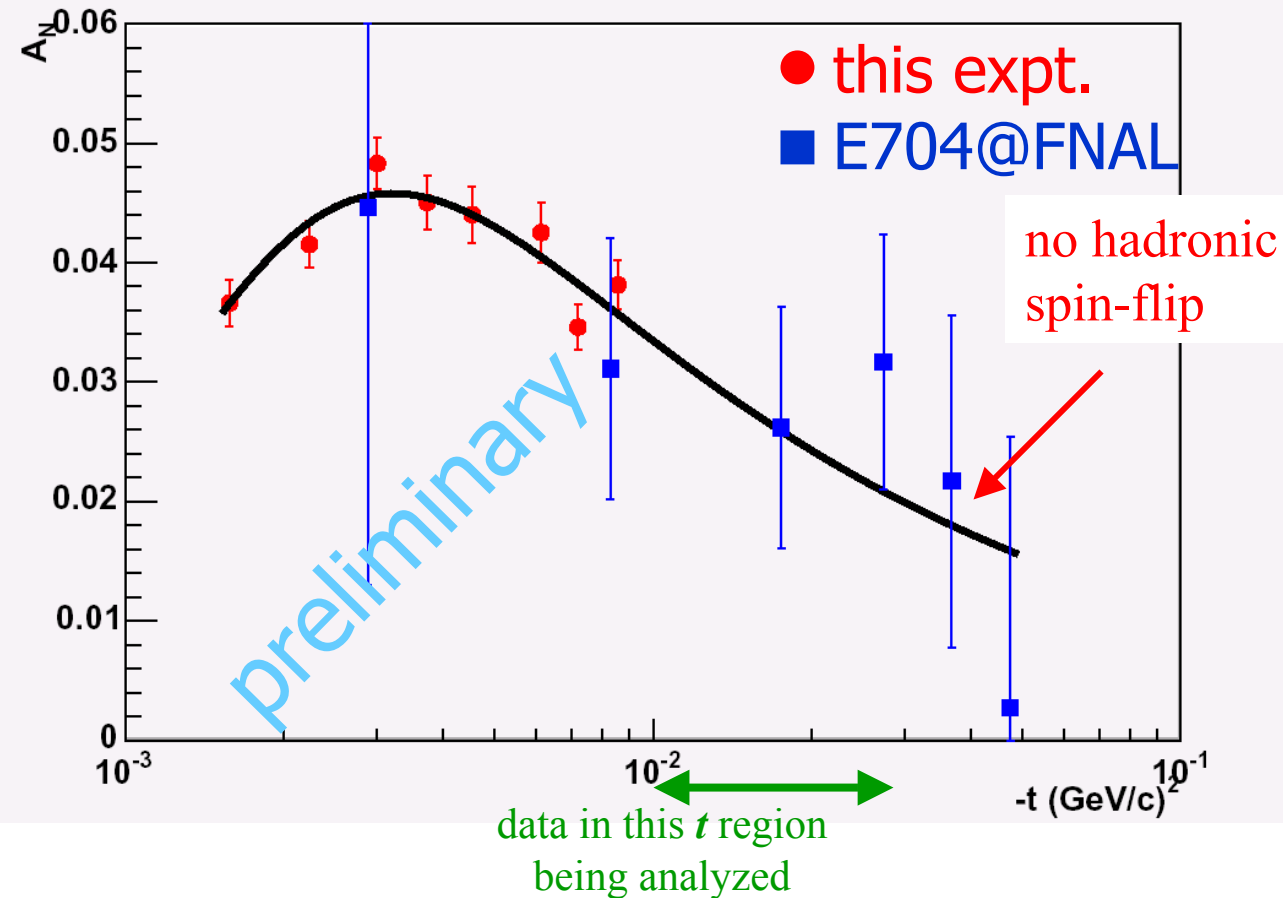
- 1 $\Delta P_{\text{TARGET}} = 2\%$ (normalization error)
- 2 from backgrounds $< \pm 0.0015$
- 3 false asymmetries: small

A_N for $p \uparrow p \rightarrow pp$ @ 100 GeV

data (from this expt. only)
fitted with CNI prediction
[$\sigma_{TOT} = 38.5$ mbarn,
 $\rho = 0, \delta = 0$]

fitted with:
 $\mathcal{N} \times f_{CNI}$
 $\mathcal{N} =$
“normalization factor”
 $\mathcal{N} = 0.98 \pm 0.03$
 $\chi^2 \sim 5 / 7$ d.o.f.

the errors shown are
statistical only
(see previous slide)



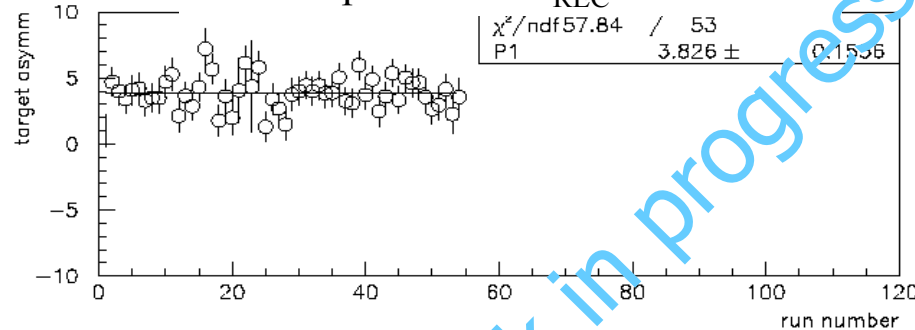
no need of a hadronic spin – flip contribution to describe these data
however, sensitivity on ϕ_5^{had} in this t range low

"ONLINE" measured asymmetries & Results

ONLINE \equiv statistical errors only
 no background corrections
 no dead layer corrections
 no systematic studies
 no false asymmetries studies
 no run selection

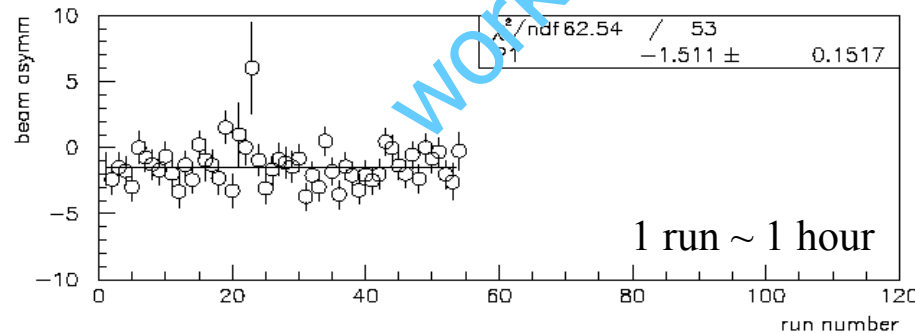
data divided into 3 p energy bins

an example: $750 < E_{REC} < 1750$ keV



"Target":
 average over
 beam
 polarization

blue beam with alternating bunch
 polarizations: $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\dots$



"Beam":
 average over
 target
 polarization

good uniformity from run to run
 (stable JET polarization)
 JET polarization reversed
 each ~ 5 min.

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

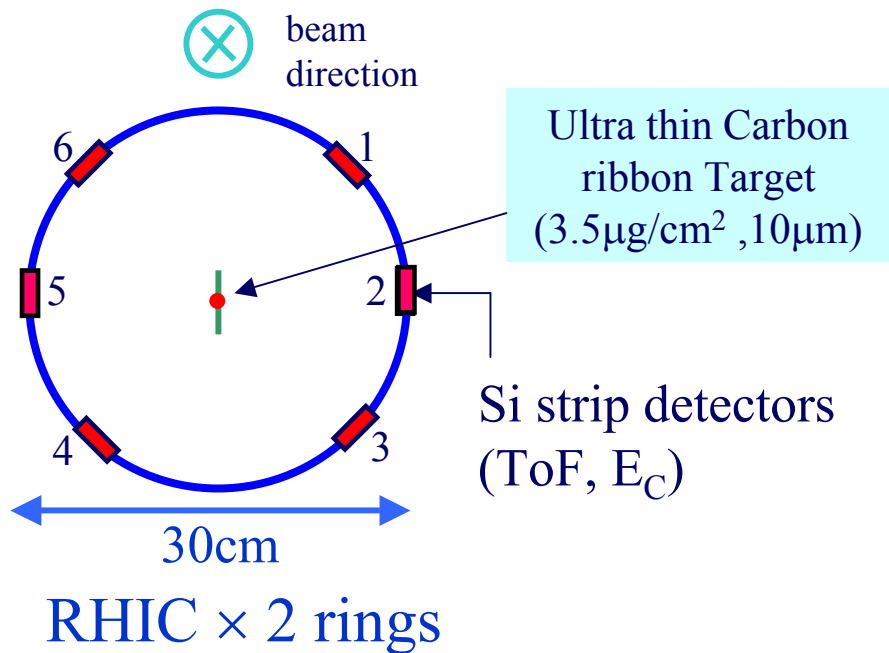
$$\langle P_{beam} \rangle = 37 \% \pm 2 \%$$

$$\langle P_{beam} (pC\ CNI) \rangle = 38 \%$$

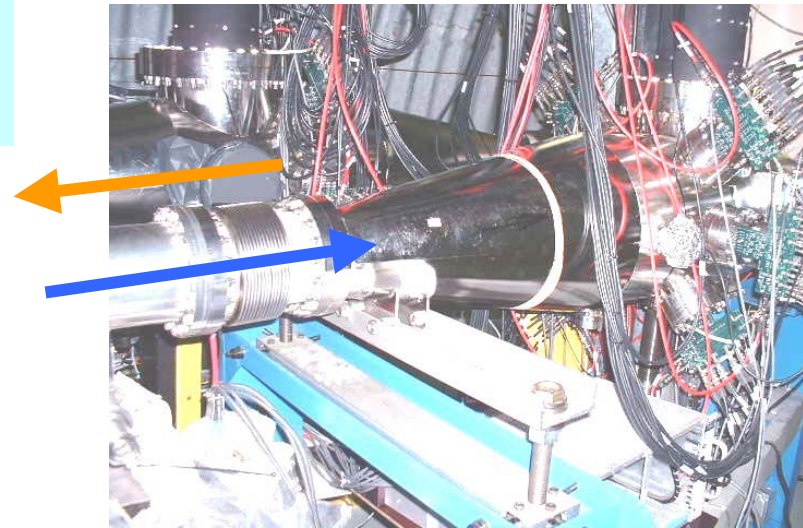
No major surprises ?
 (statistical errors only !)

$$p \uparrow C \rightarrow p C$$

Setup for pC scattering – the RHIC polarimeters

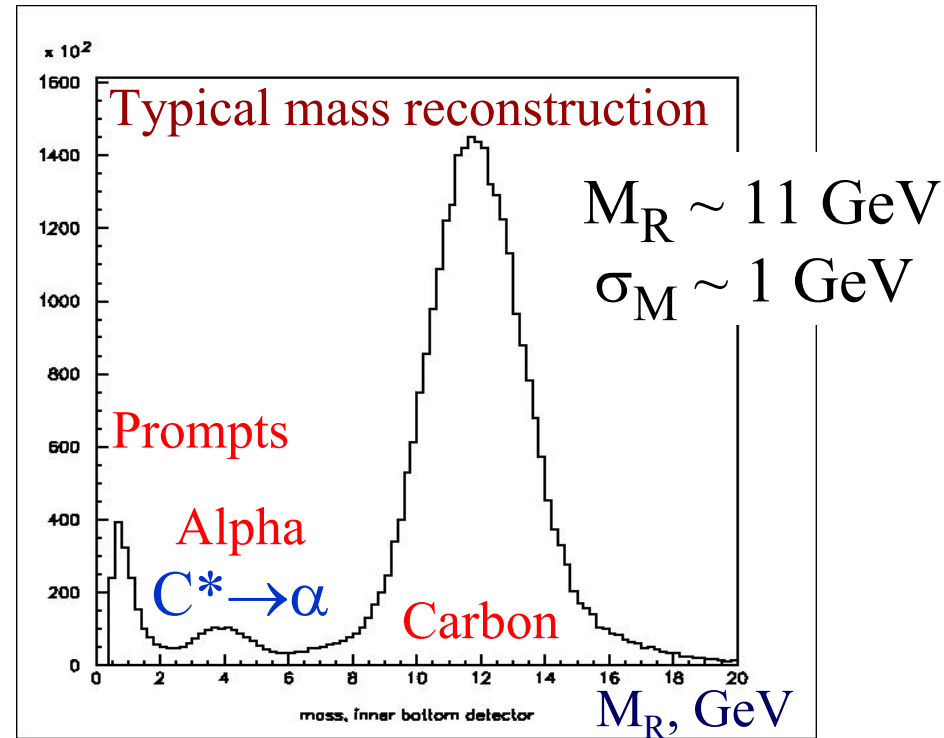
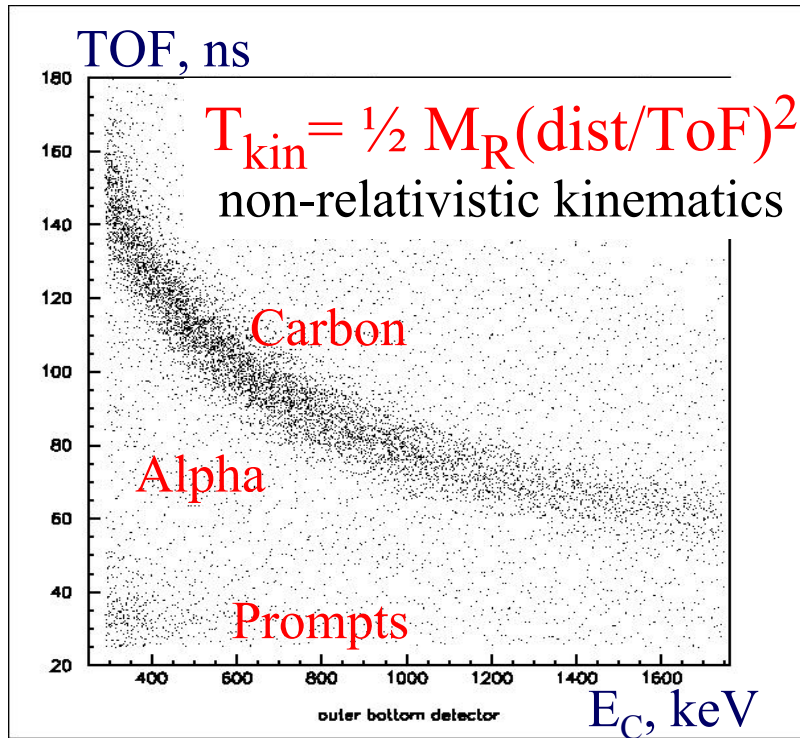


inside RHIC ring @IP12



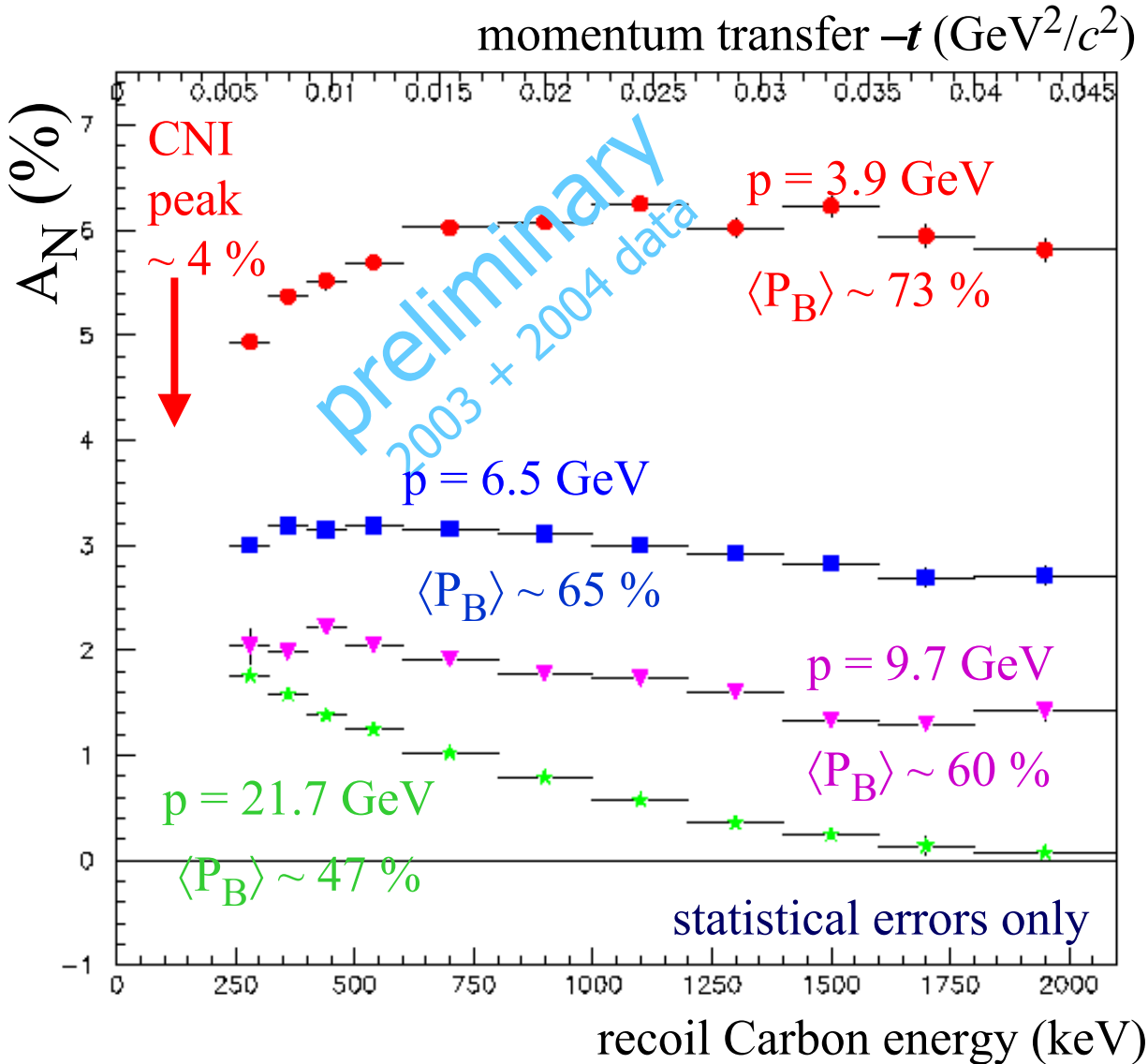
- recoil carbon ions detected with Silicon strip detectors
- 2×72 channels read out with WFD (increased acceptance by 2)
- very large statistics per measurement ($\sim 20 \times 10^6$ events) allows detailed analysis
 - bunch by bunch analysis
 - channel by channel (each channel is an “independent polarimeter”)
 - 45° detectors: sensitive to vertical and radial components of \vec{P}_{beam}
 - unphysical asymmetries

Event Selection & Performance



- very clean data, background $< 1 \%$ within “banana” cut
- good separation of recoil carbon from α ($C^* \rightarrow \alpha + X$) and prompts
 - may allow going to very high $|t|$ values
- $\Delta(\text{Tof}) < \pm 10 \text{ ns}$ ($\Rightarrow \sigma_M \sim 1 \text{ GeV}$)
- very high rate: $10^5 \text{ ev / ch / sec}$

$A_N p \uparrow C \rightarrow p C$ at 3.9, 6.5, 9.7 & 21.7 GeV (AGS)



only statistical errors are shown

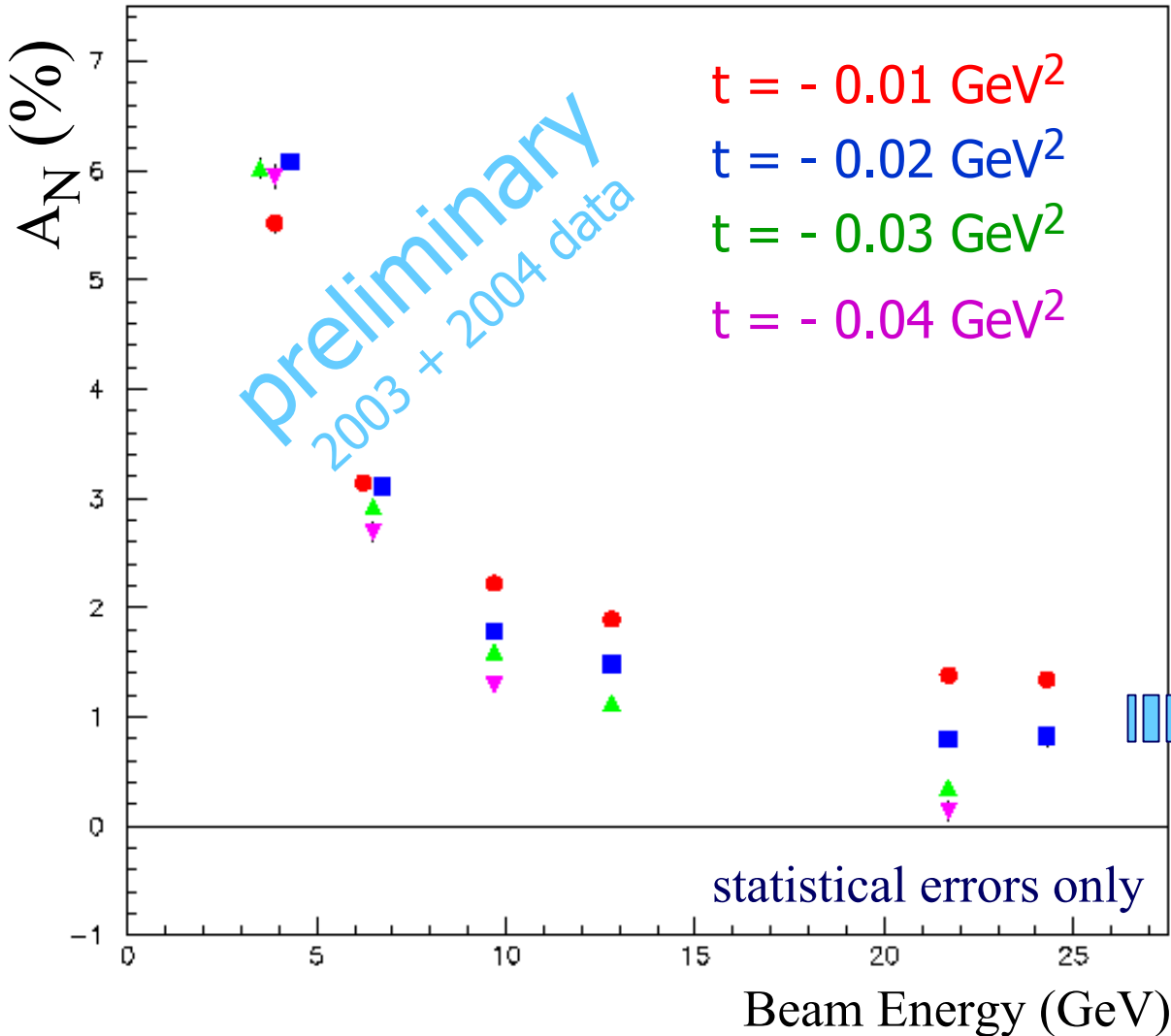
normalization errors:

- $\sim 10\%$ (at 3.9)
- $\sim 15\%$ (at 6.5)
- $\sim 20\%$ (at 21.7)

systematic errors:

- $< 20\%$
- backgrounds
- pileup
- RF noise

$A_N p \uparrow C \rightarrow pC$: Energy Dependence



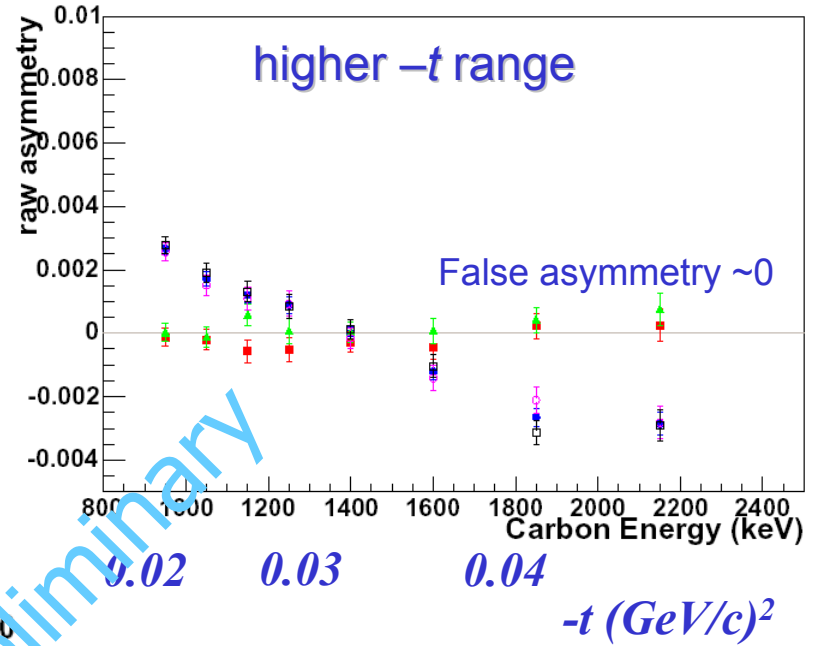
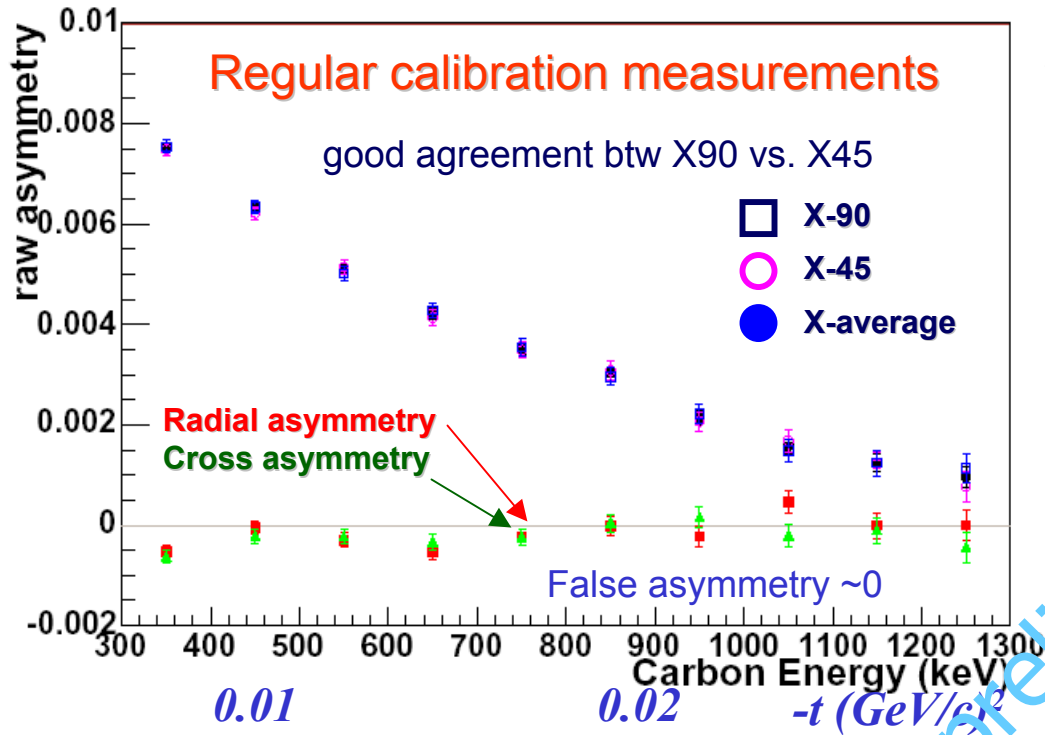
only statistical errors
are shown
systematic errors
as for previous slide

Asymptotic regime

E ?

No energy dependence ?

Raw asymmetry (t) @ 100 GeV (RHIC)



Regular polarimeter runs

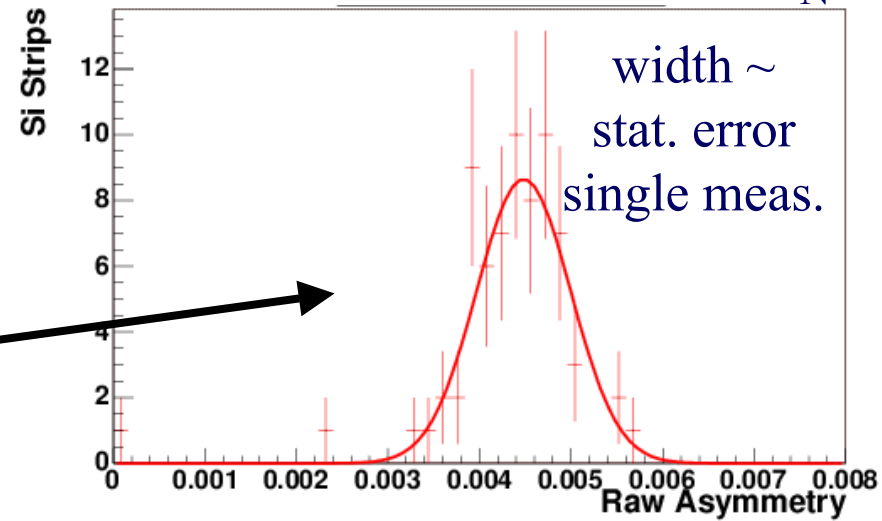
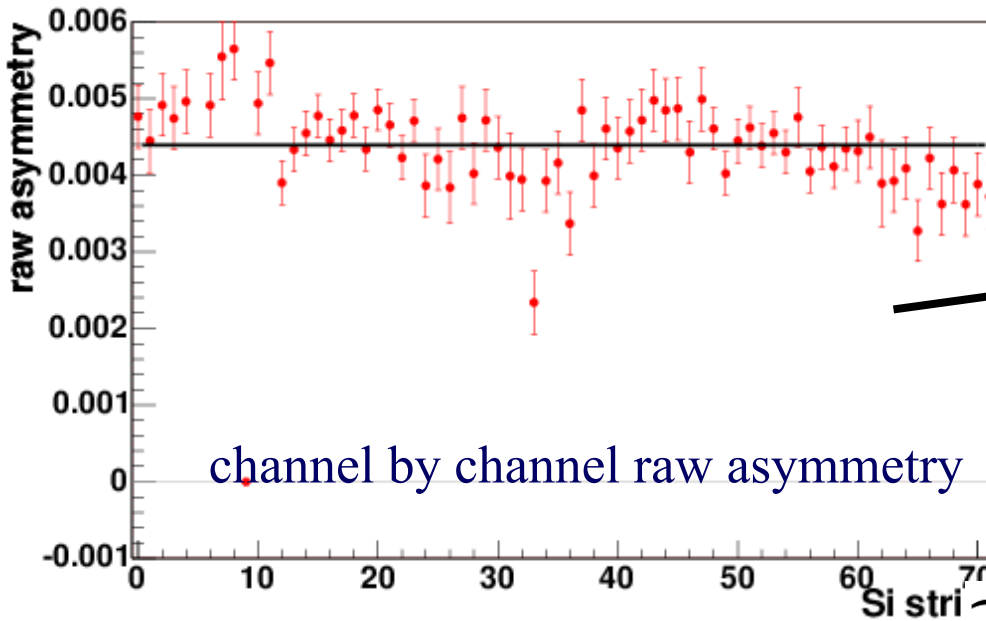
measurements taken simultaneously with Jet -target
 very stable behavior of measured asymmetries

Polarimeter dedicated runs (high $-t$)

Signal attenuation (x1/2) to reach higher $-t$
 Normalized at overlap region to regular runs
Zero crossing measured with large significance

ρC Systematics:

each detector channel covers same t range
 \rightarrow 72 independent measurements of A_N

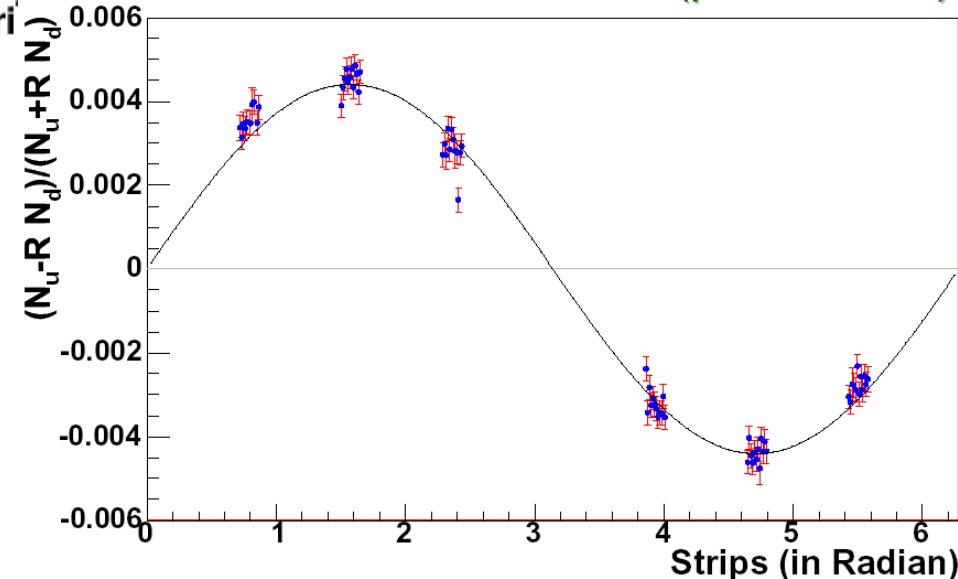


sources of systematic uncertainties:

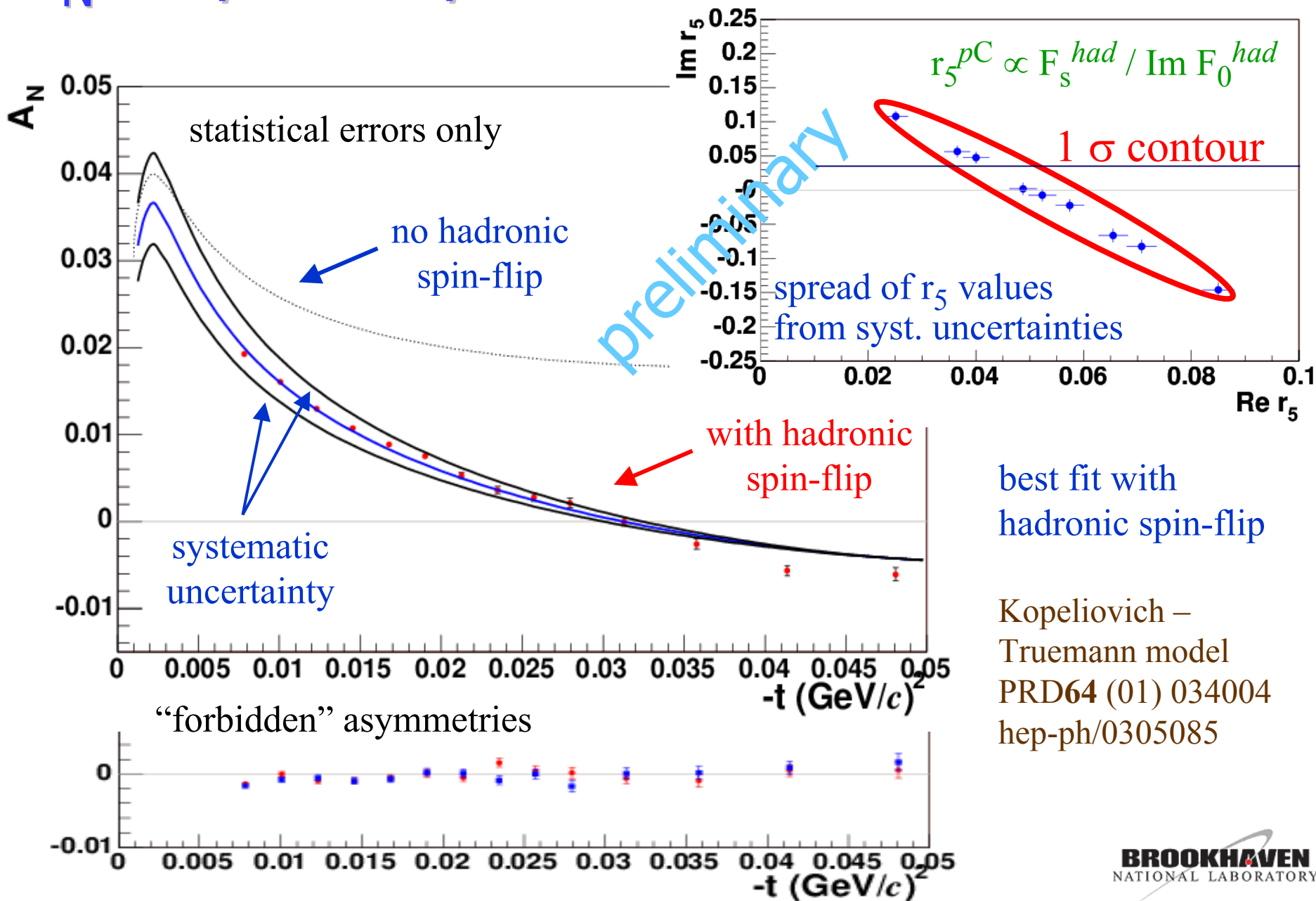
- 1 $\Delta P_{\text{BEAM}} = 7.8 \%$ (normalization)
 $[P_{\text{BEAM}} = 0.386 \pm 0.030, \text{stat. error}]$
- 2 energy scale ~ 50 keV for lowest $|t|$ bin
 (from detector dead layer)

NB these are “external” factors
 not “intrinsic” limitations

Fit with sine function (phase fixed)



A_N for $p \uparrow C \rightarrow p C$ @ 100 GeV



Summary

- measured A_N^{pp} for elastic $pp \rightarrow pp$ scattering at 100 GeV with very high accuracy (statistical and systematic)
 - $|t|$ range: $0.0015 < |t| < 0.010$ (GeV/c)²
 - soon A_N in $|t|$ range of $0.010 < |t| < 0.030$ (GeV/c)²
 - soon A_{NN} in same $|t|$ range (stat. err. $\times 2.5$ larger)
- pp data well described by CNI – QED predictions (“S – LK”)
no need for a hadronic spin-flip term
- measured A_N^{pC} for elastic $pC \rightarrow pC$ scattering at 100 GeV (RHIC)
 - zero crossing around $|t| \sim 0.03$ (GeV/c)²
- pC data require substantial hadronic spin-flip !
- measured A_N^{pC} for $pC \rightarrow pC$ scattering over $3.5 < E_b < 24$ GeV (AGS)
 - $E_b < 10$ GeV/c: almost no t dependence & departure from “CNI” shape