Proton Polarimetry at RHIC

I. Alekseev, A. Bravar, G. Bunce, S. Dhawan, R. Gill,

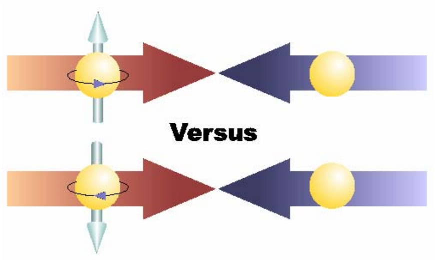
W. Haeberli, H. Huang, G. Igo, O. Jinnouchi, K. Kurita,

Y. Makdisi, A. Nass, H. Okada, N. Saito, H. Spinka, E. Stephenson,

D. Svirida, D. Underwood, C. Whitten, T. Wise, J. Wood, A. Zelenski

Polarimetry : Impact on RHIC Spin Physics

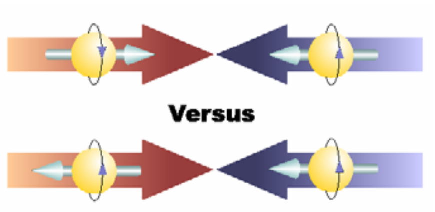
Single Spin Asymmetries



Physics Asymmetries

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

Double Spin Asymmetries

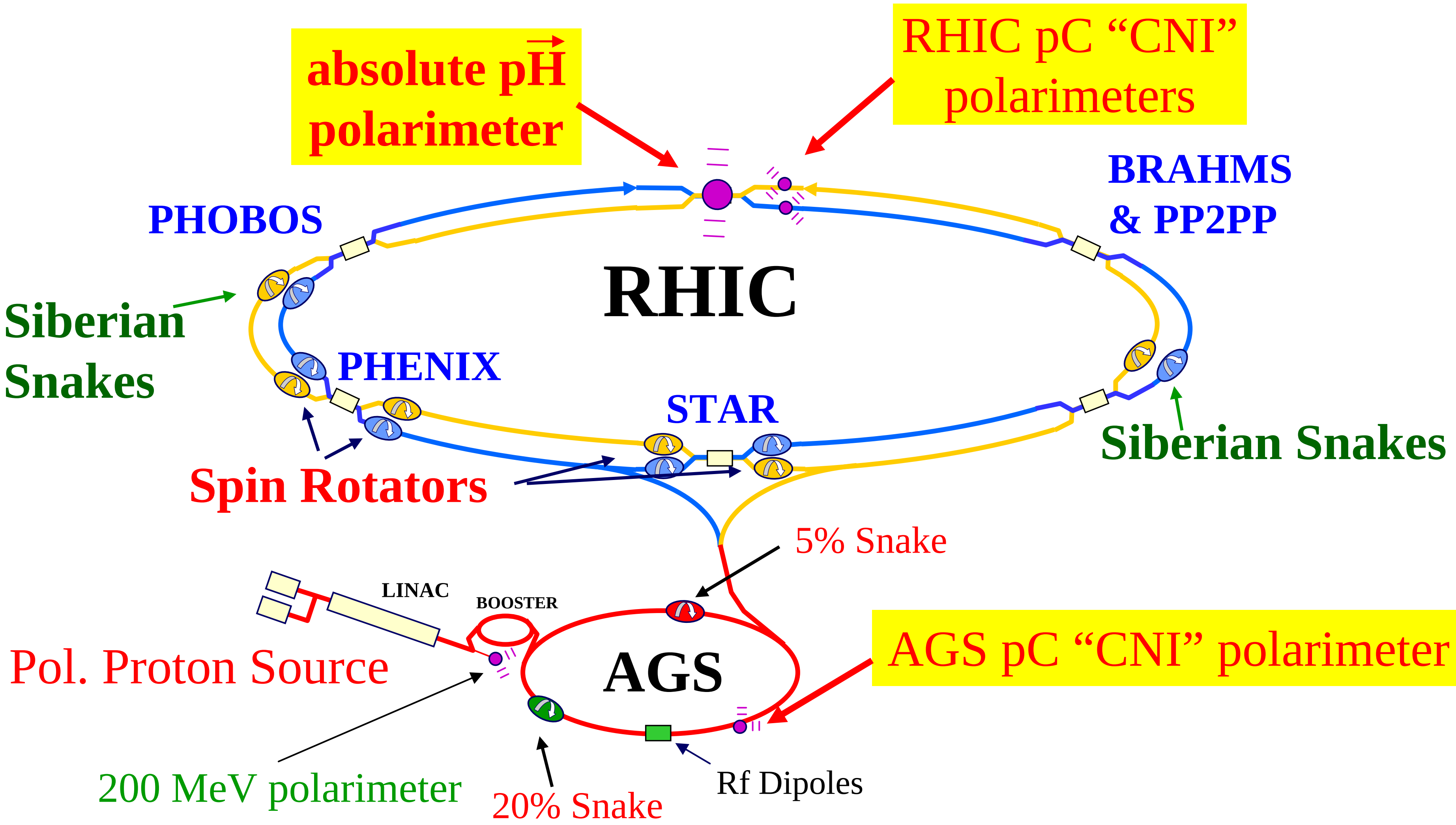


$$A_{LL} = \frac{1}{P_B^{\,2}}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right) \Rightarrow \boxed{\Delta G}$$

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 + sizable and known A_N
  - *pC* elastic scattering in CNI region, $A_N \sim 1 - 2$ % $\rightarrow$ large statistics > 10^7 events
  - (very) large $\times$ – section $\rightarrow$ fast measurements
  - requires absolute calibration $\rightarrow$ polarized gas jet target

RHIC *pp* accelerator complex



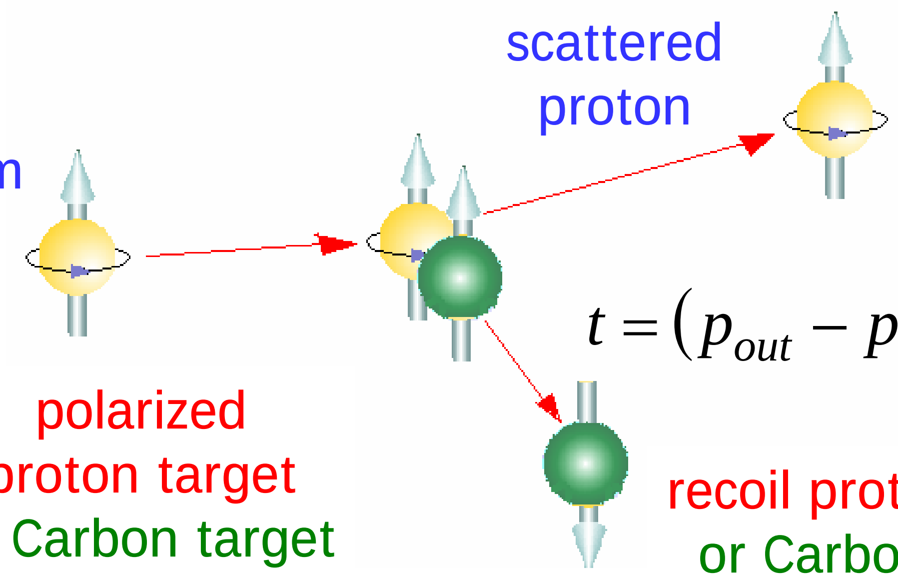
The Elastic Process

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

recoil

(polarized) proton beam

scattered proton



$$t = (p_{out} - p_{in})^2 < 0$$

polarized proton target or Carbon target

recoil proton or Carbon

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 !

⇒elastic *pp* (pC) kinematics fully constrained by recoil proton (Carbon) only !

The Very Low *t* Region

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

$\Rightarrow$ INTERFERENCE

CNI = Coulomb – Nuclear Interference

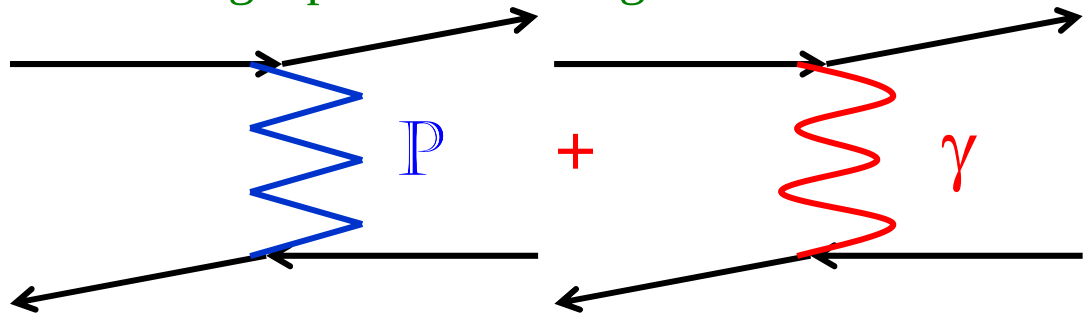
scattering amplitudes modified to include also electromagnetic contribution

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

hadronic interaction described in terms of Pomeron (Reggeon) exchange

electromagnetic single photon exchange

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



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

polarized $\Rightarrow$ "left – right" asymmetry A_N **magnetic moment**

A_N & Coulomb Nuclear Interference

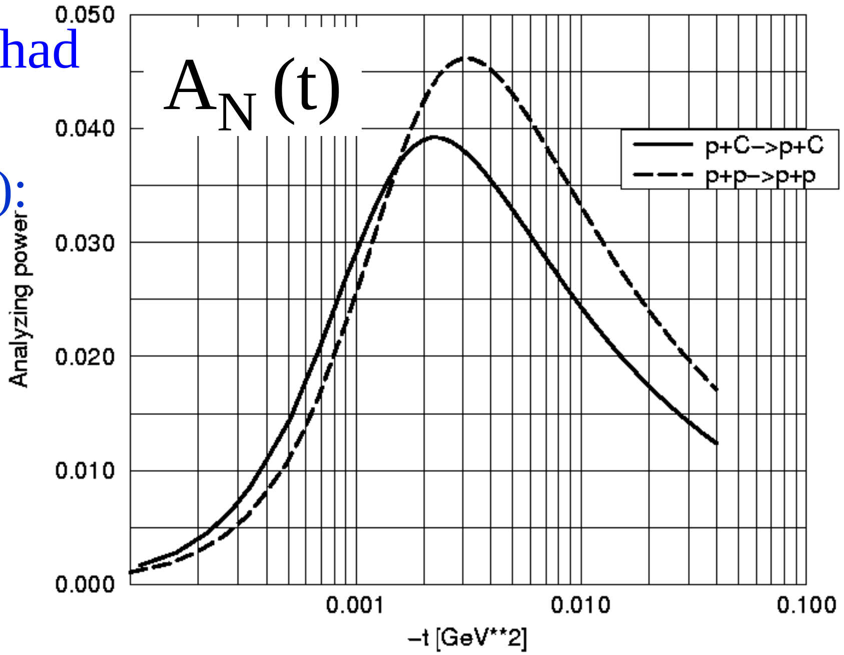
the left – right scattering asymmetry A_N arises from the interference of the spin non-flip amplitude with the spin flip amplitude (Schwinger)

$$A_N = C_1 \operatorname{Im}(\phi_{flip}^{em\,*} \phi_{non-flip}^{had}) + C_2 \operatorname{Im}(\phi_{flip}^{had\,*} \phi_{non-flip}^{had})$$

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

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

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



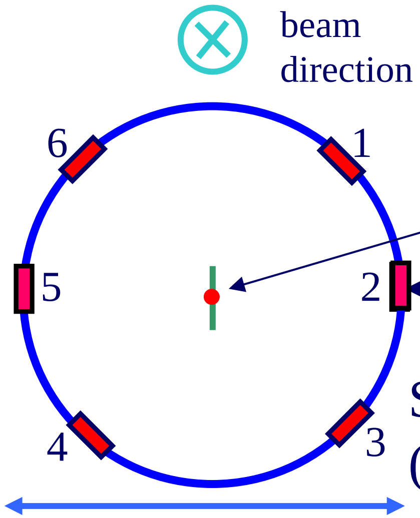
hadronic spin- flip modifies the QED "predictions"

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

interpreted in terms of Pomeron spin – flip and parametrized as

$$\phi_5^{had} = \tau(s) \frac{\sqrt{-t}}{m_p} \phi_0^{had}$$

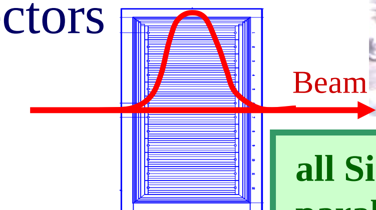
Setup for *p*C scattering – the RHIC polarimeters



RHIC × 2 rings

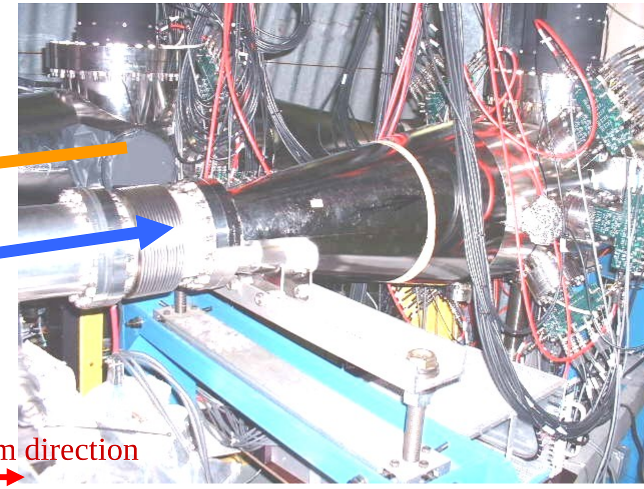
Ultra thin Carbon ribbon Target
(3.5μg/cm², 10μm wide)

Si strip detectors
(ToF, E_C)



all Si strips parallel to beam

inside RHIC ring @IP12

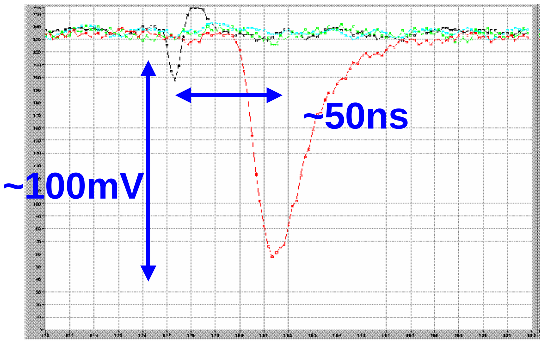


- recoil carbon ions detected with Silicon strip detectors
- 2 × 72 channels read out with WFD (increased acceptance by 2)
- very large statistics per measurement (~ 20 × 10^6 events) allows detailed analysis
  - bunch by bunch analysis
  - channel by channel (each channel is an "independent polarimeter")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

DAQ and WFD

Wave Form Digitizer = peak sensing ADC, CFD, …

common to the *pC* and JET DAQ system



→ ADC 3×140 MHz

synchronized to accelerator clocks

bunch ×-ing ⇒ "start" TDC

↓ FPGA

"online" analysis of waveform performed beteween consecutive bunch ×-ing

⇒PH, tot Q, t.o.f.;
full waveform (JET)

↓ onboard memory → DAQ PC

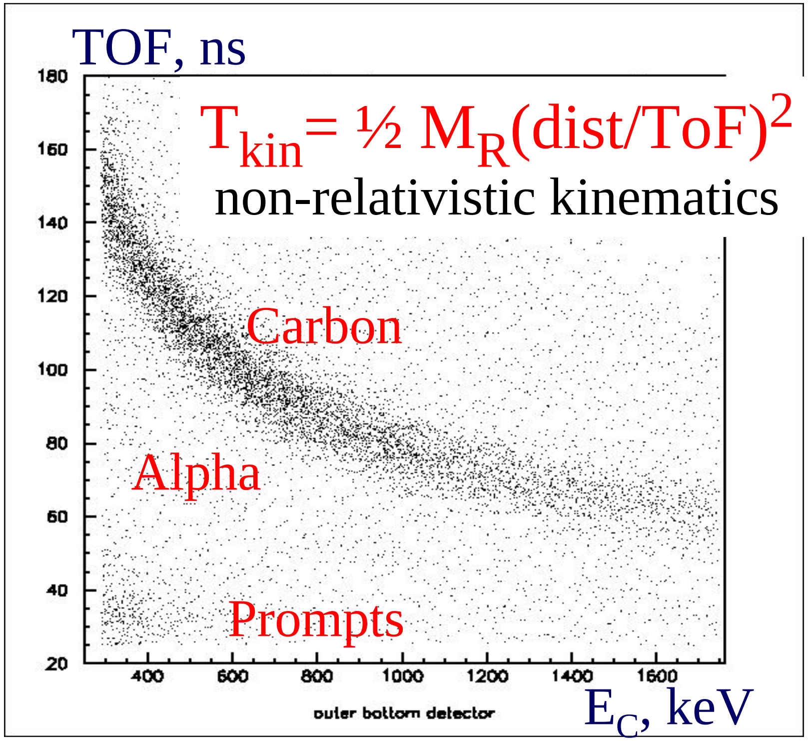
$\Delta t \sim 2$ ns

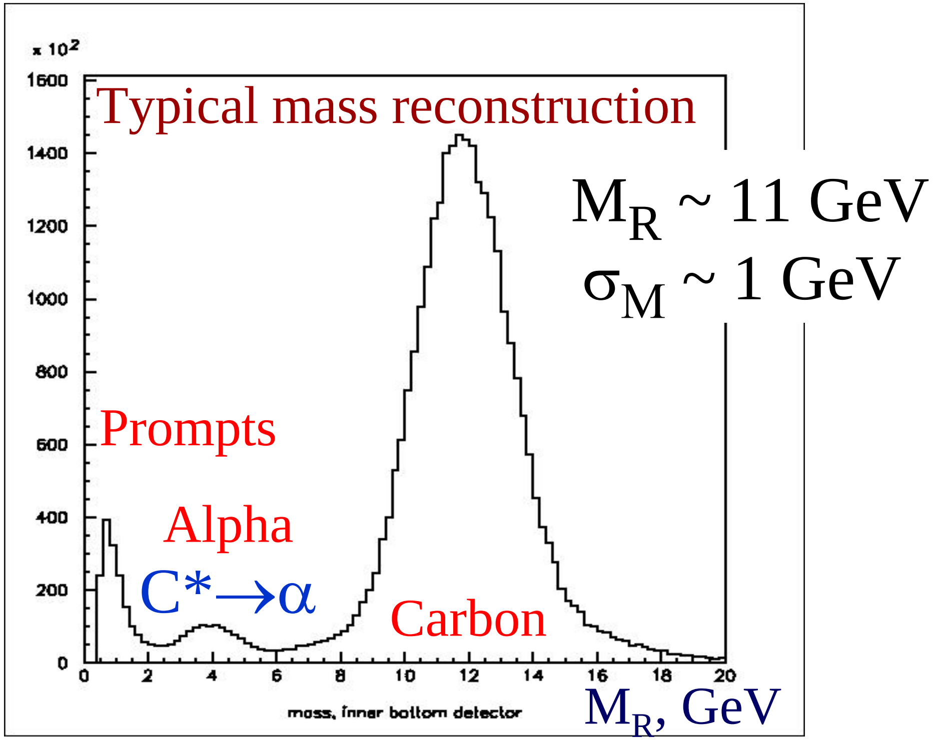
$\Delta E < 50$ keV

20×10^6 events in 20 seconds ⇒ deadtimeless DAQ system

can accept, analyze, and store 1 event / each bunch ×-ing

Event Selection & Performance



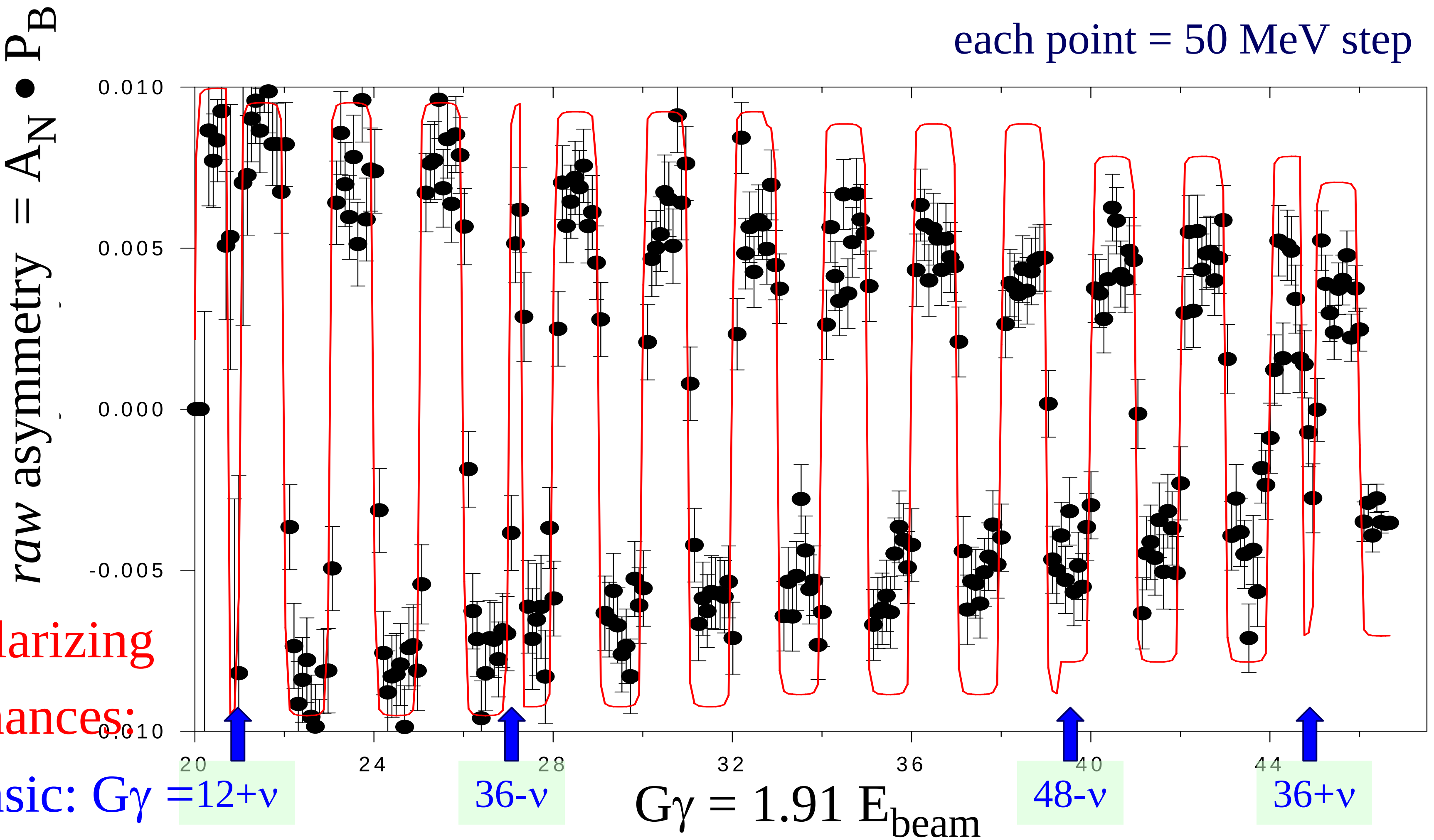


- very clean data, background < 1 % within “banana” cut
- good separation of recoil carbon from α ($C^* \rightarrow \alpha + X$) and prompts

  may allow going to very high $|t|$ values
- Δ (Tof) < $\pm$ 10 ns ($\Rightarrow \sigma_M \sim 1$ GeV)
- very high rate: 10^5 ev / ch / sec

AGS polarization during acceleration (ramp)

each point = 50 MeV step



depolarizing resonances:

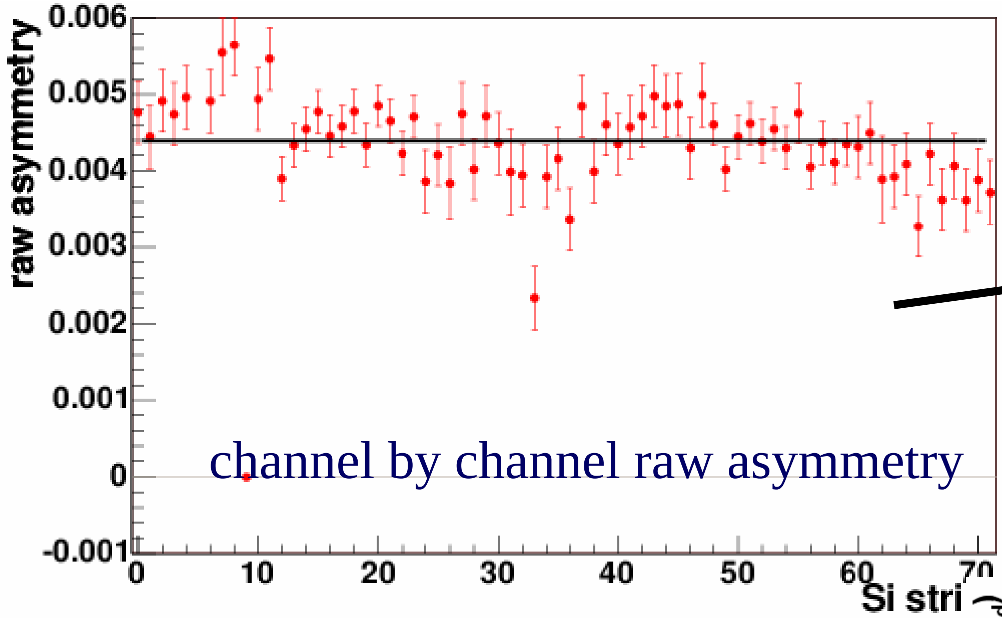
intrinsic: $G\gamma = 12+\nu$, $36-\nu$, $48-\nu$, $36+\nu$

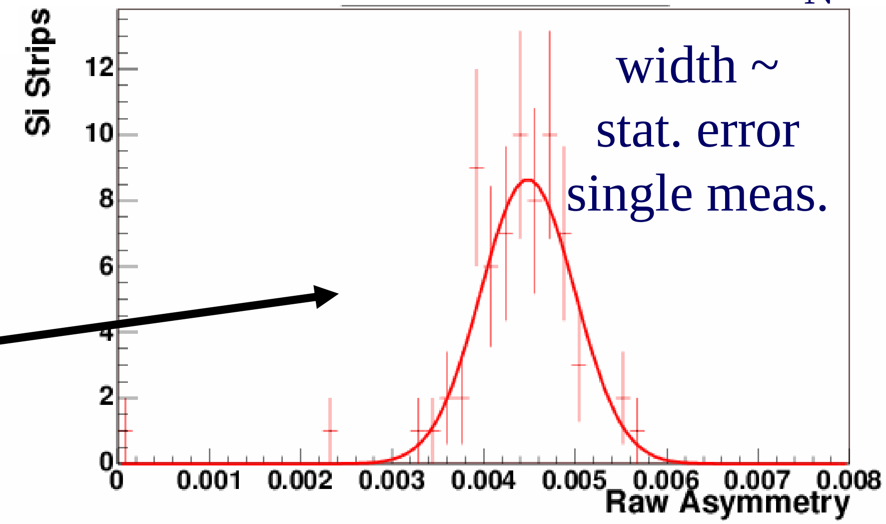
imperfection: $G\gamma = n$

red line: simulation of polarization losses assuming constant A_N

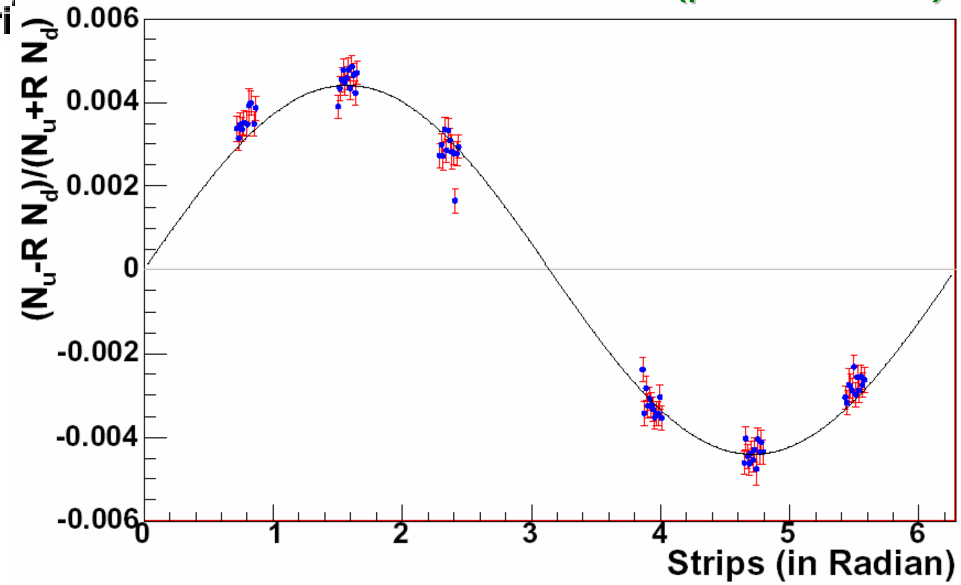
*p*C Systematics RHIC:

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





Fit with sine function (phase fixed)



sources of systematic uncertainties:

1 ΔP_{BEAM} = 8.5 % (normalization)
[$P_{BEAM} = 0.386 \pm 0.029 \pm 0.016$]

2 energy scale ~ 50 keV for lowest |t| bin
(from detector dead layer)

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

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

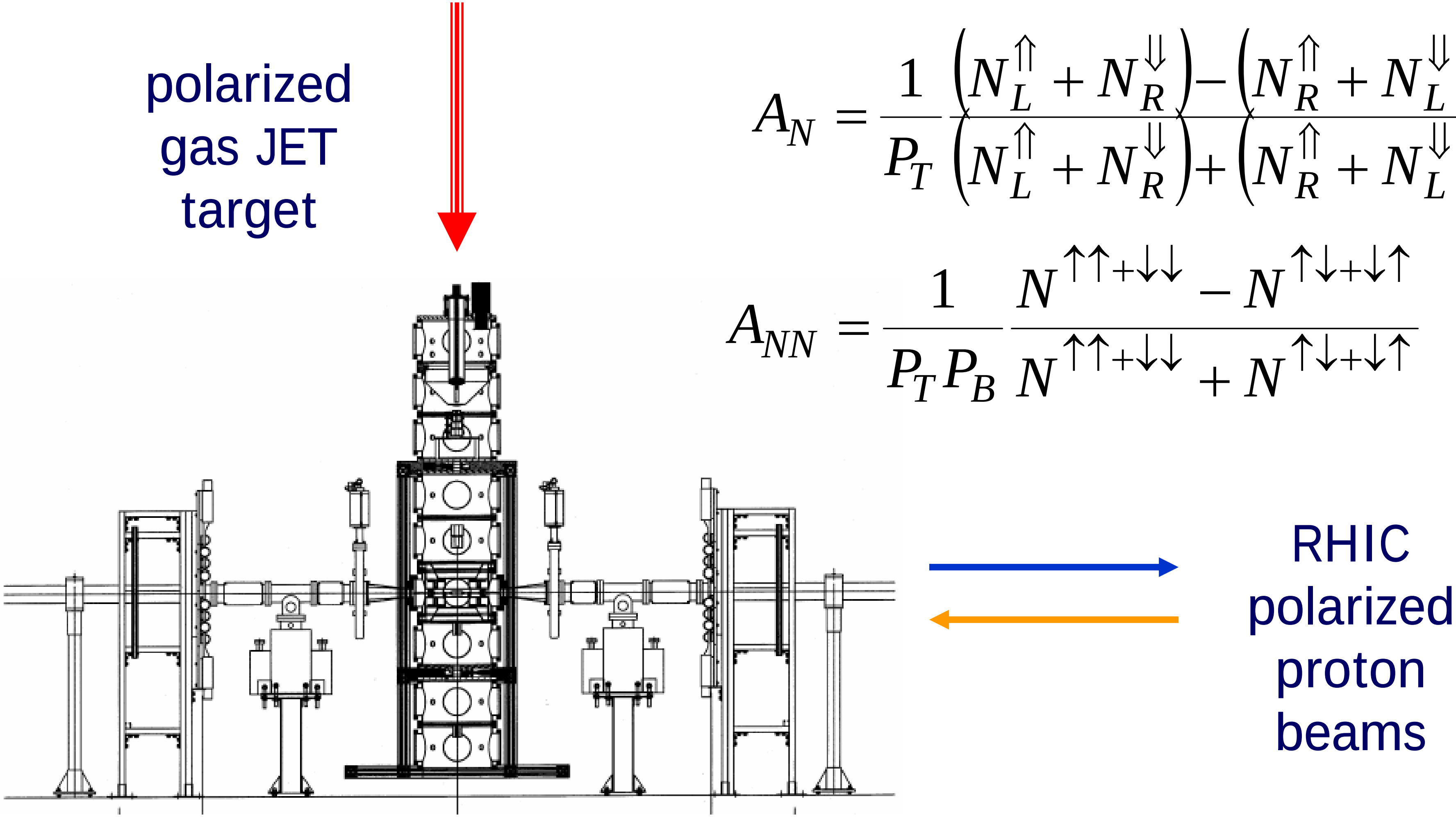
at each step pick-up some measurement errors:

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

expected precision

transfer calibration measurement

$p^{\uparrow} p \to pp$ and $p^{\uparrow} p^{\uparrow} \to pp$ with a Polarized Gas Jet Target



$$A_N = \frac{1}{P_T} \frac{\left(N_L^{\Uparrow} + N_R^{\Downarrow}\right) - \left(N_R^{\Uparrow} + N_L^{\Downarrow}\right)}{\left(N_L^{\Uparrow} + N_R^{\Downarrow}\right) + \left(N_R^{\Uparrow} + N_L^{\Downarrow}\right)}$$

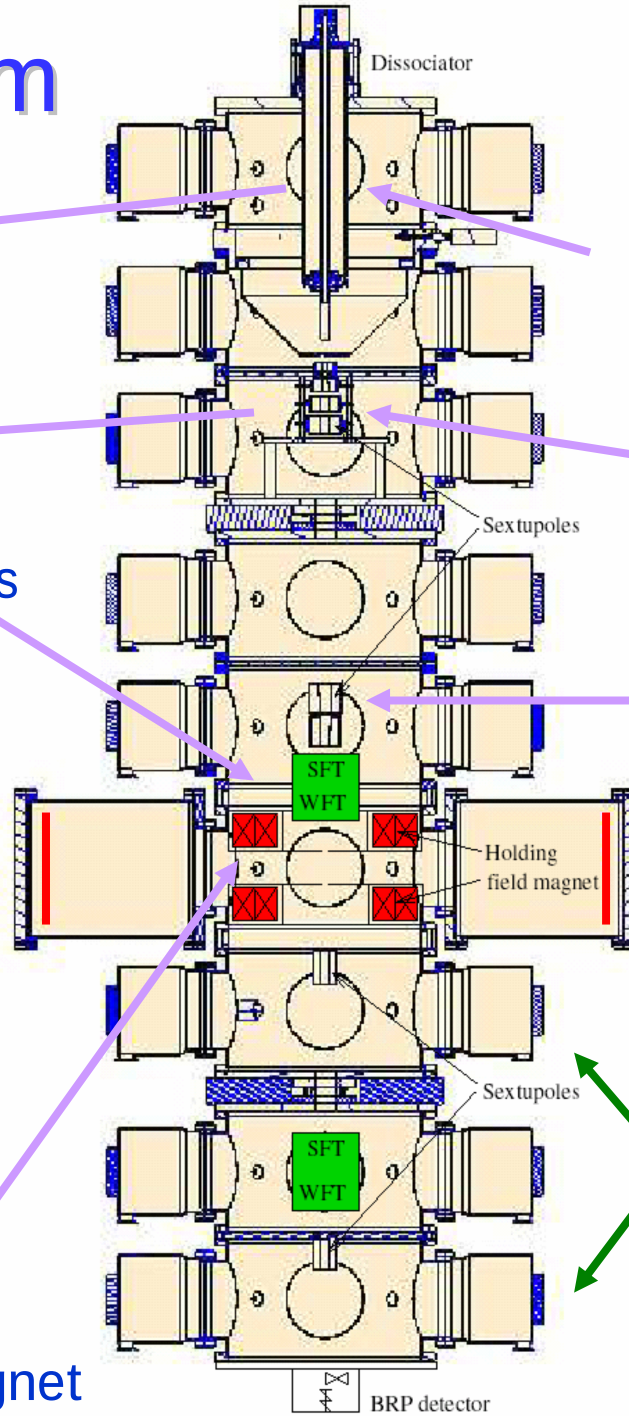
$$A_{NN} = \frac{1}{P_T P_B} \frac{N^{\uparrow\uparrow+\downarrow\downarrow} - N^{\uparrow\downarrow+\downarrow\uparrow}}{N^{\uparrow\uparrow+\downarrow\downarrow} + N^{\uparrow\downarrow+\downarrow\uparrow}}$$

The Atomic H Beam Source

$H = p^+ + e^-$

OR

P_z^+ OR P_z^-



H_2 dissociator

separation magnets (sextupoles)

RF transitions

focusing magnets (sextupoles)

recoil detectors

Breit-Rabi polarimeter

holding field magnet

- record beam intensity
- ~100% eff. RF transitions
- focusing high intensity B-R 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/cm^2 record intensity

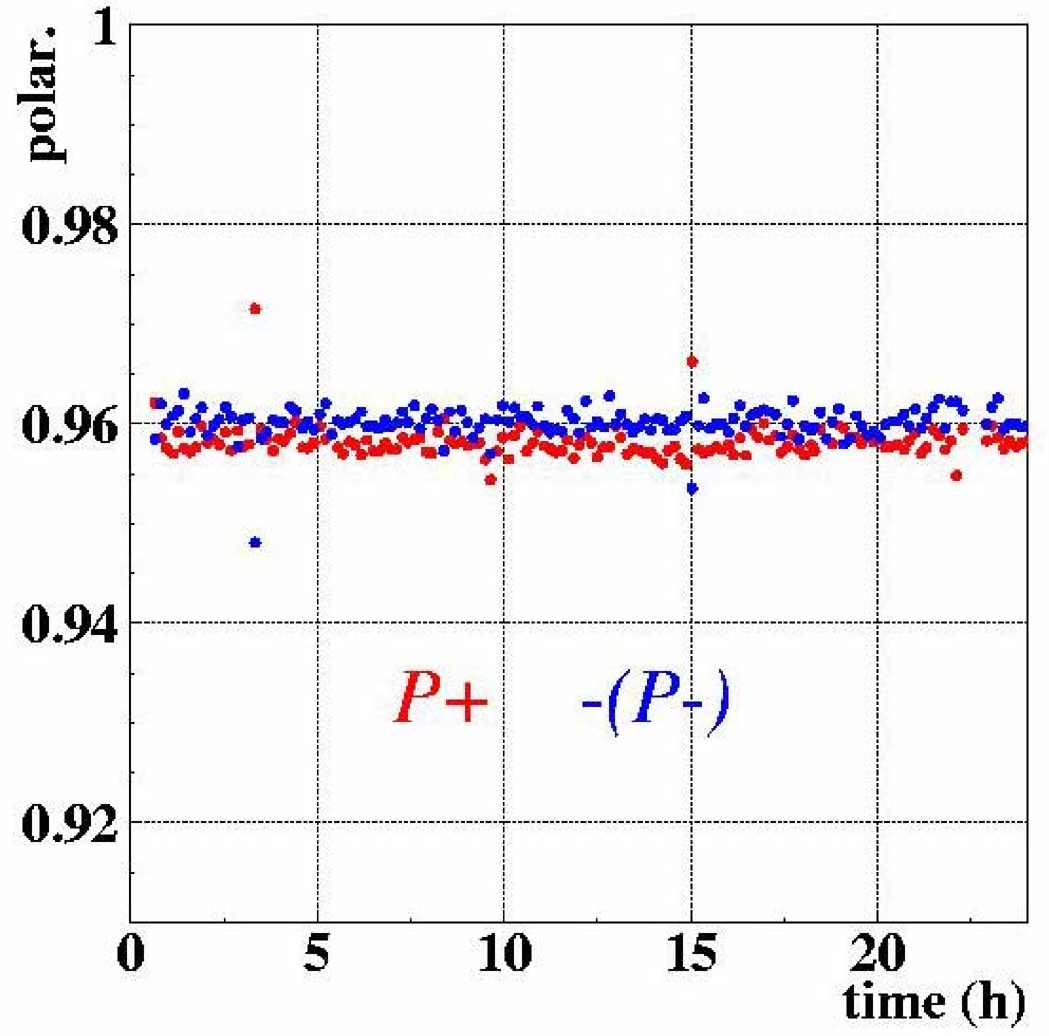
target polarization cycle +/0/- ~ 500 / 50 / 500 sec

polarization to be scaled down due to a ~3% H_2 background:

P_{target} ~ 0.924 ± 0.018

(current understanding)

no depolarization from beam wake fields observed !



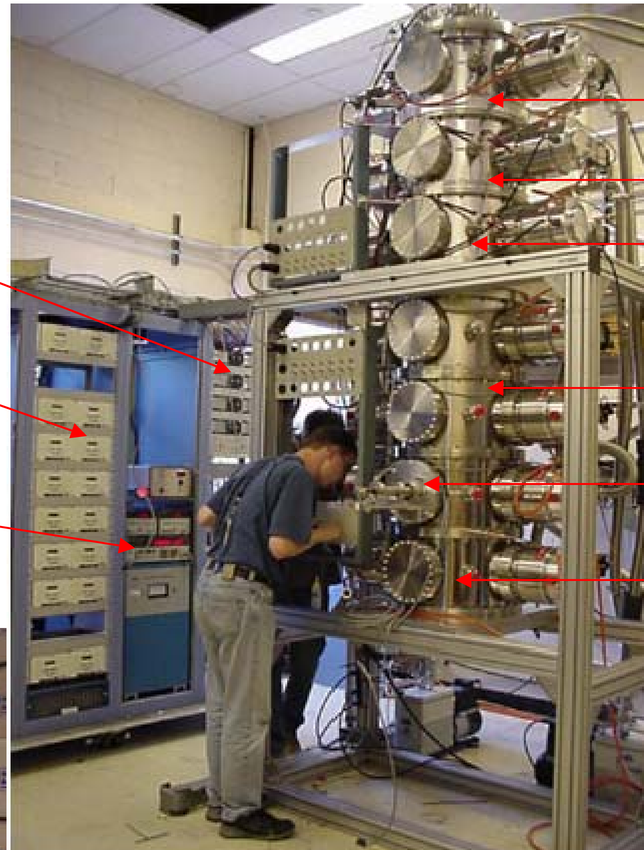
The Polarized Jet Target under development

Electronics racks

Vac. gauges monitors

Turbo pump controllers

Dissociator RF systems



Dissociator stage

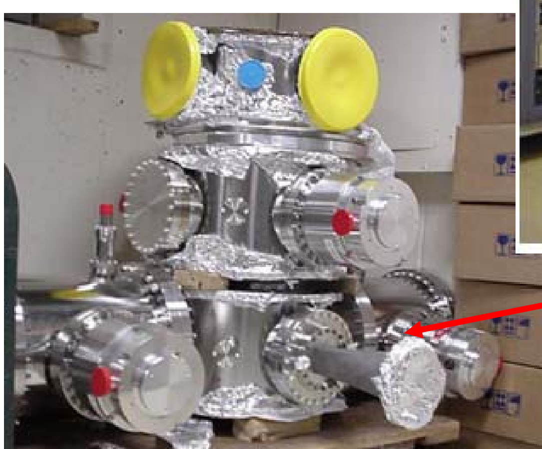
Baffle location

Sextupoles 1-4

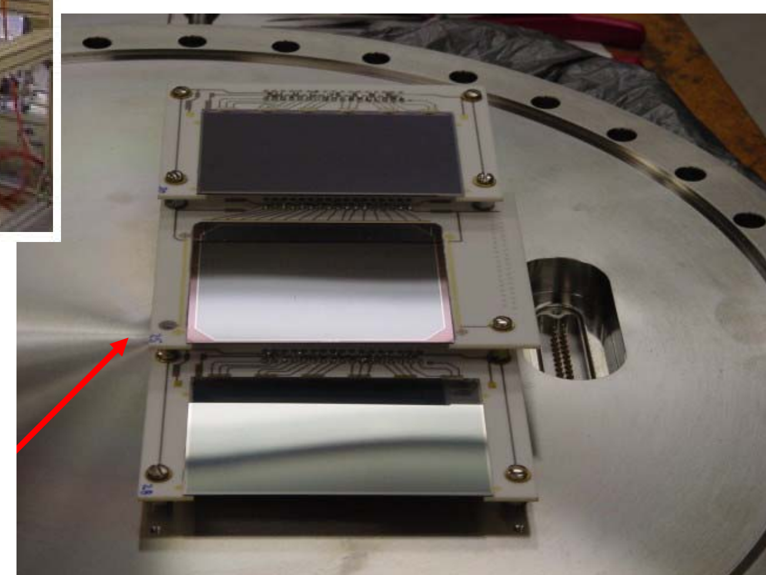
Sextupoles 5-6

Profile measurement

BRP vacuum vessel



Target chamber &
beam pipe adapters



Recoil spectrometer
silicon detectors

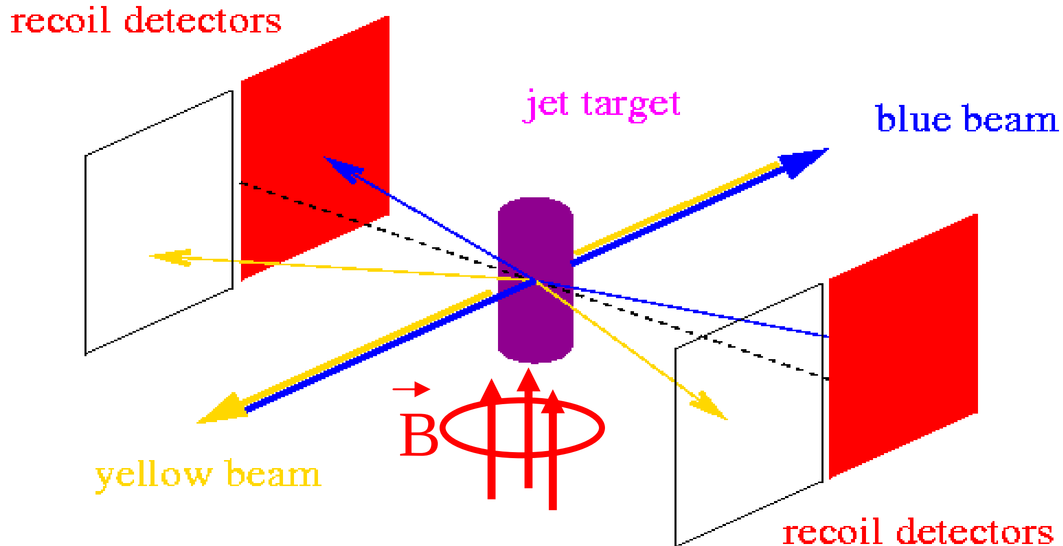
Recoil Si spectrometer

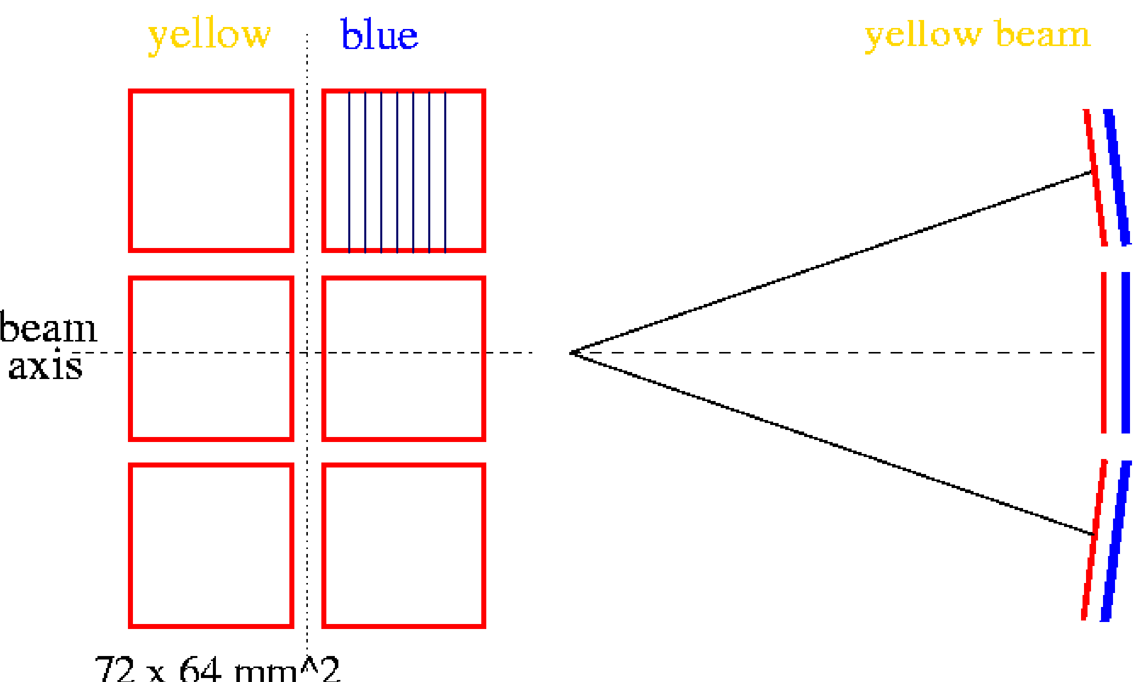
$A_N^{beam}(t) = A_N^{target}(t)$

for **elastic** scattering only!

$P_{beam} = P_{target} \cdot \varepsilon_N^{beam} / \varepsilon_N^{target}$

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





HAVE "design"
azimuthal coverage

one Si layer only
⇒ smaller energy range
⇒ reduced bkg rejection power

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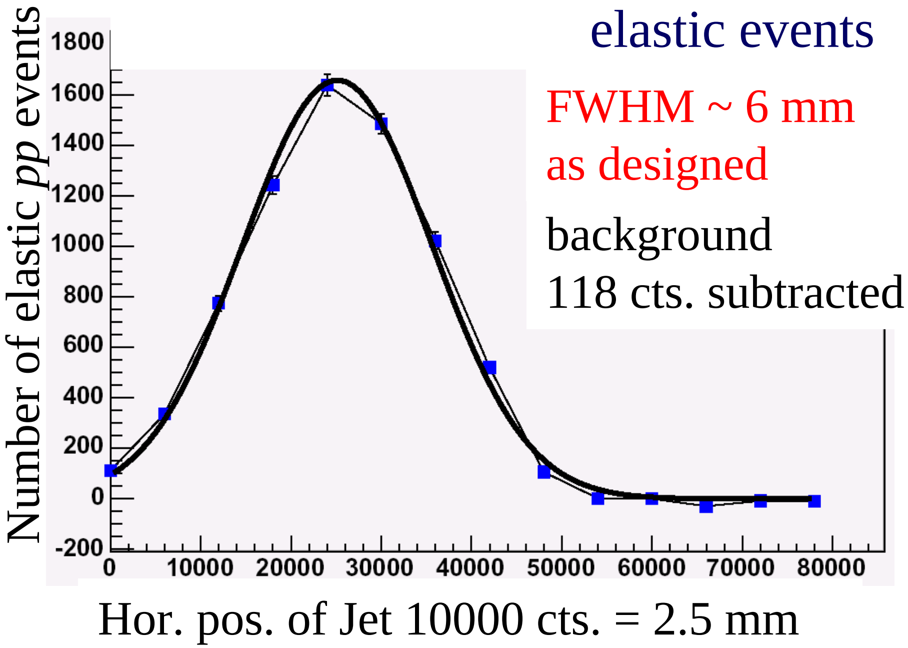
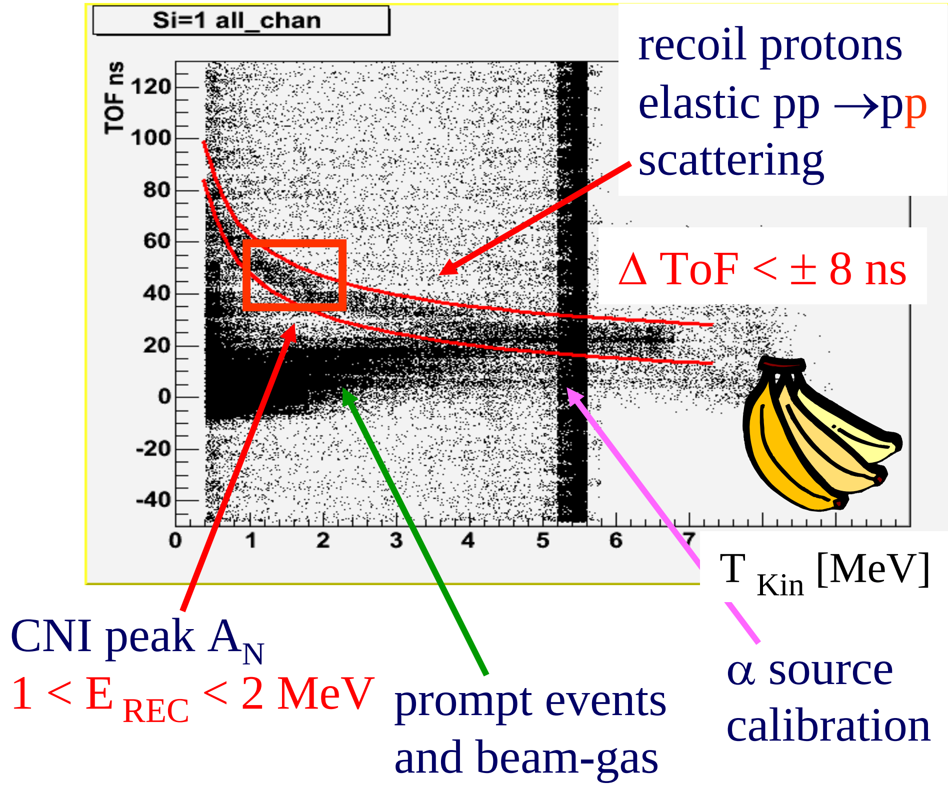
pp elastic data collected

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

JET Profile: measured selecting pp elastic events





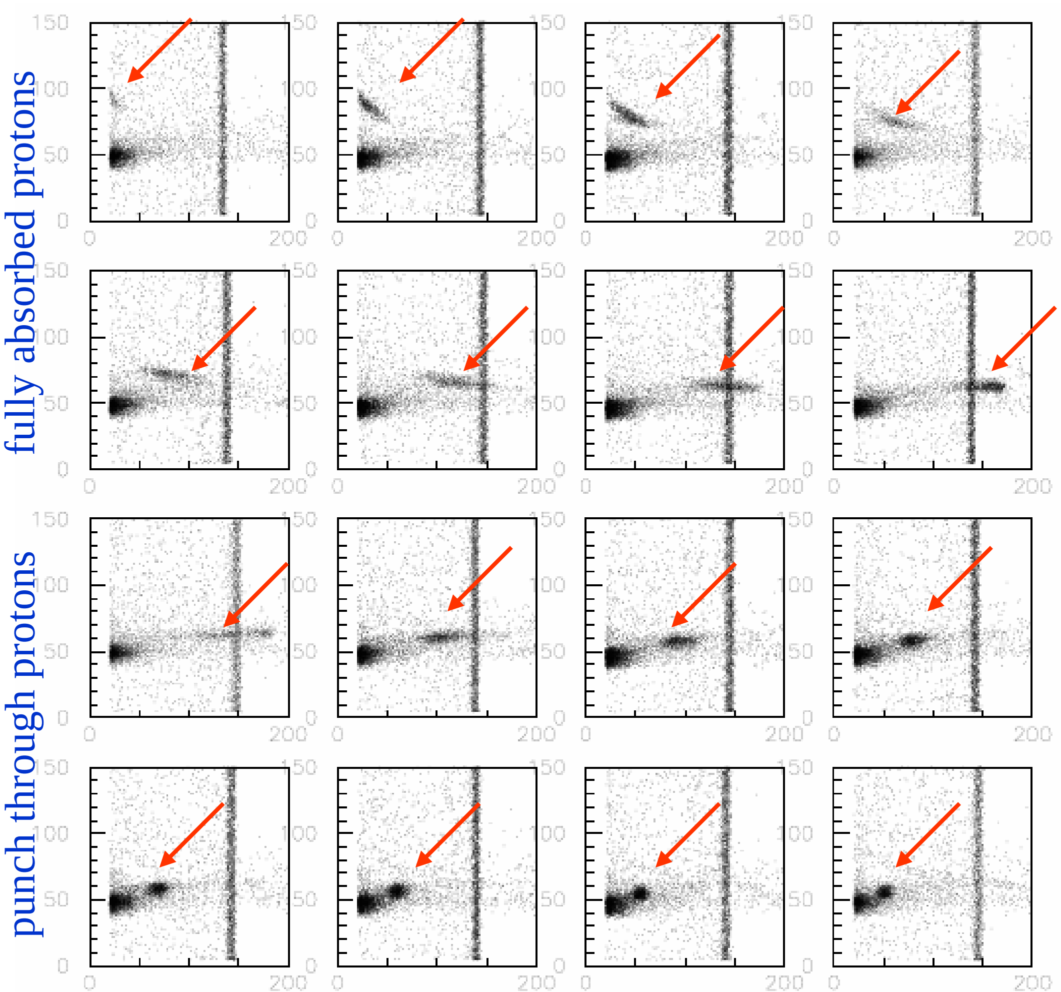
- recoil protons unambiguously identified !
- 100 GeV ~ 1.8×10^6 events for $1.5 \times 10^{-3} < -t < 1.0 \times 10^{-2}$ GeV^2
  similar statistics for $1.0 \times 10^{-2} < -t < 3.0 \times 10^{-2}$ GeV^2
- 24 GeV ~ 300 k events

Energy - Position correlations

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

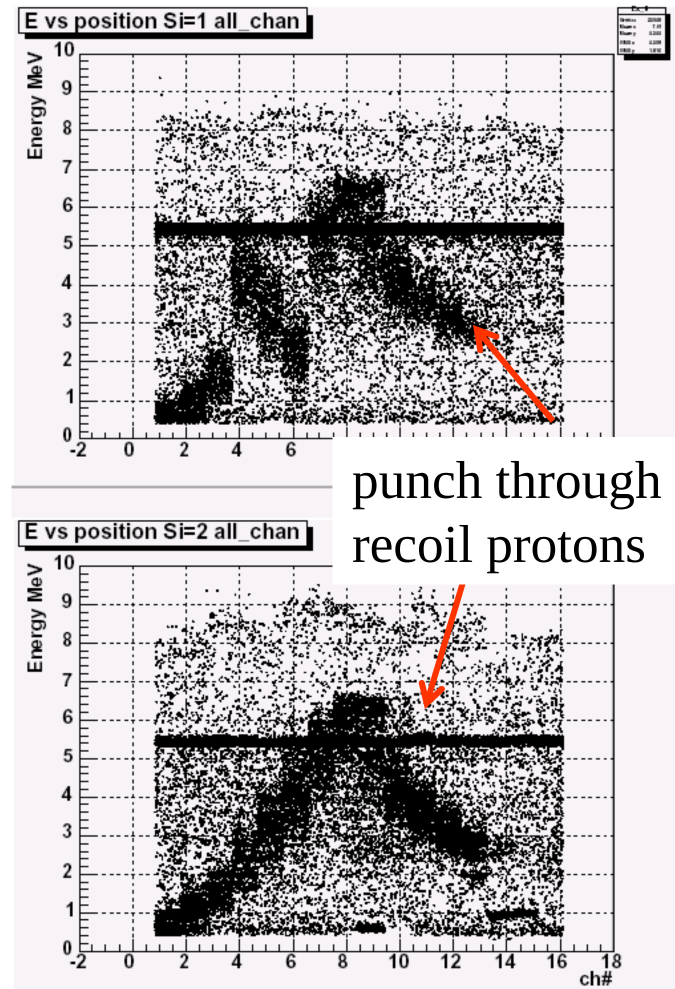
fully absorbed protons

punch through protons



TDC vs ADC individual channels

recoil energy

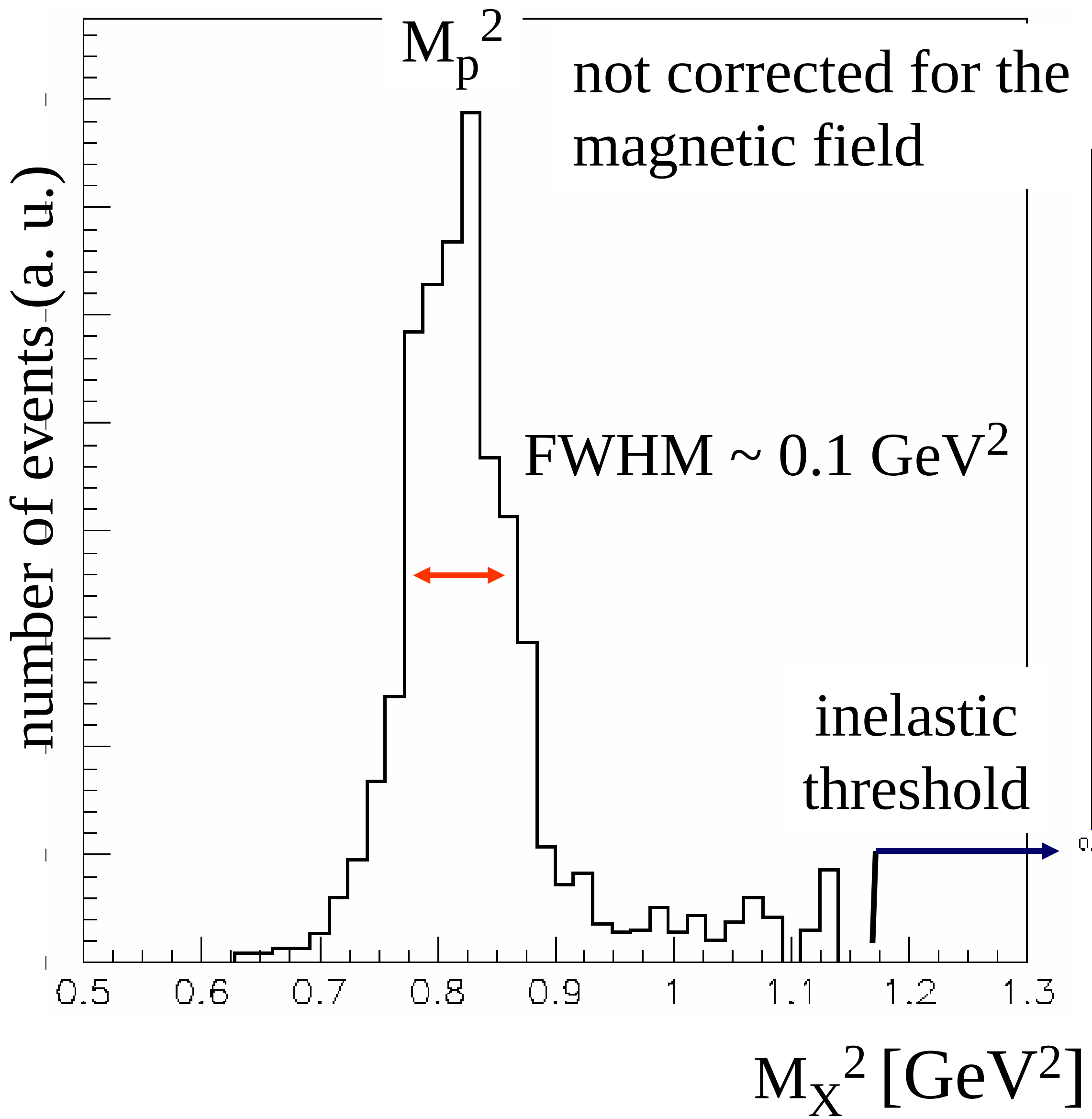


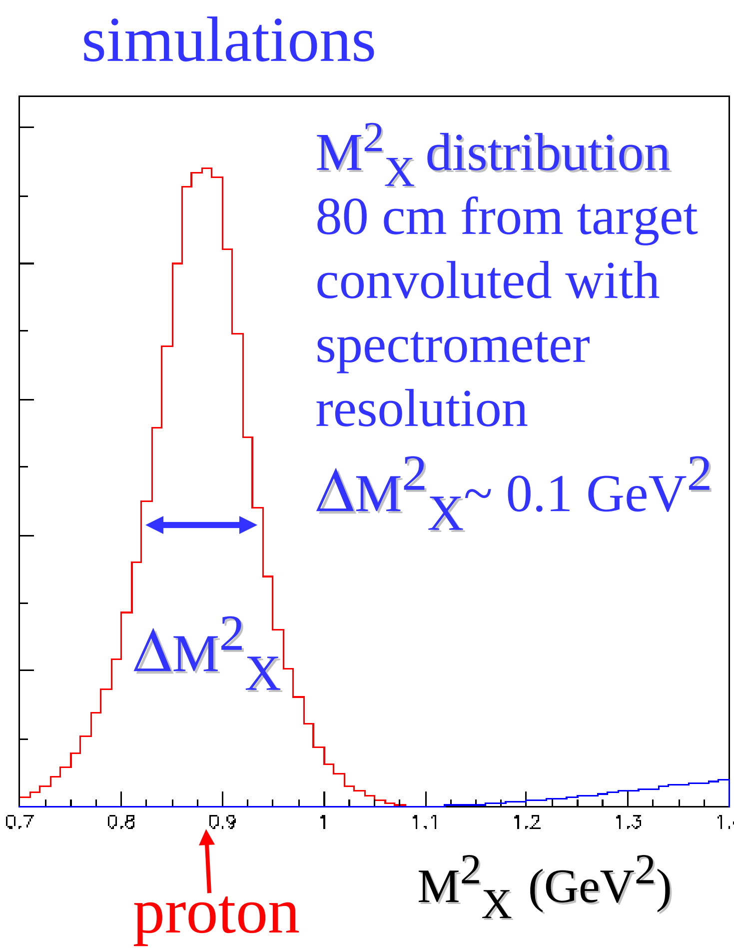
punch through recoil protons

position

pp elastic events clearly identified !

Missing Mass M_X^2 @ 100 GeV





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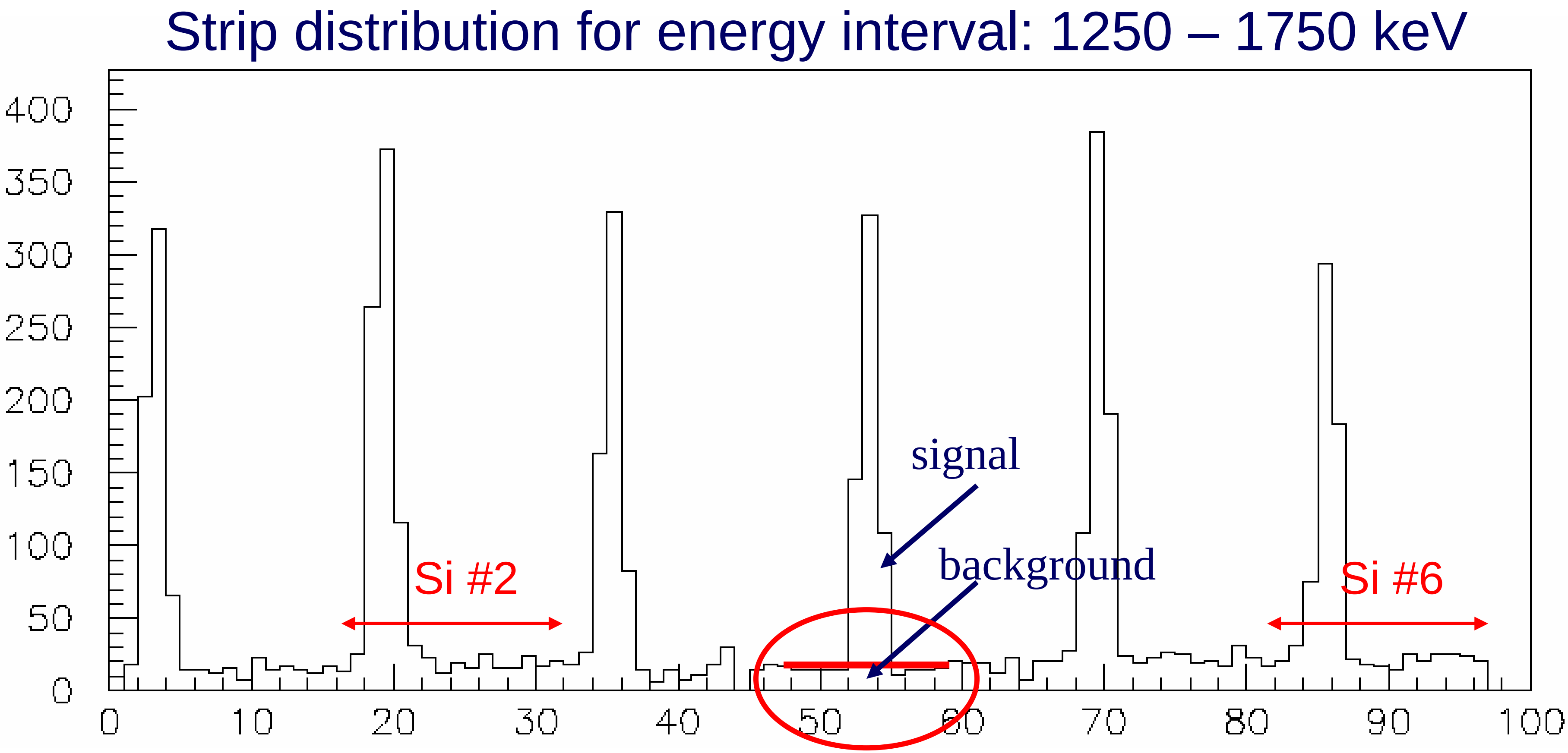
Event selections & Backgrounds



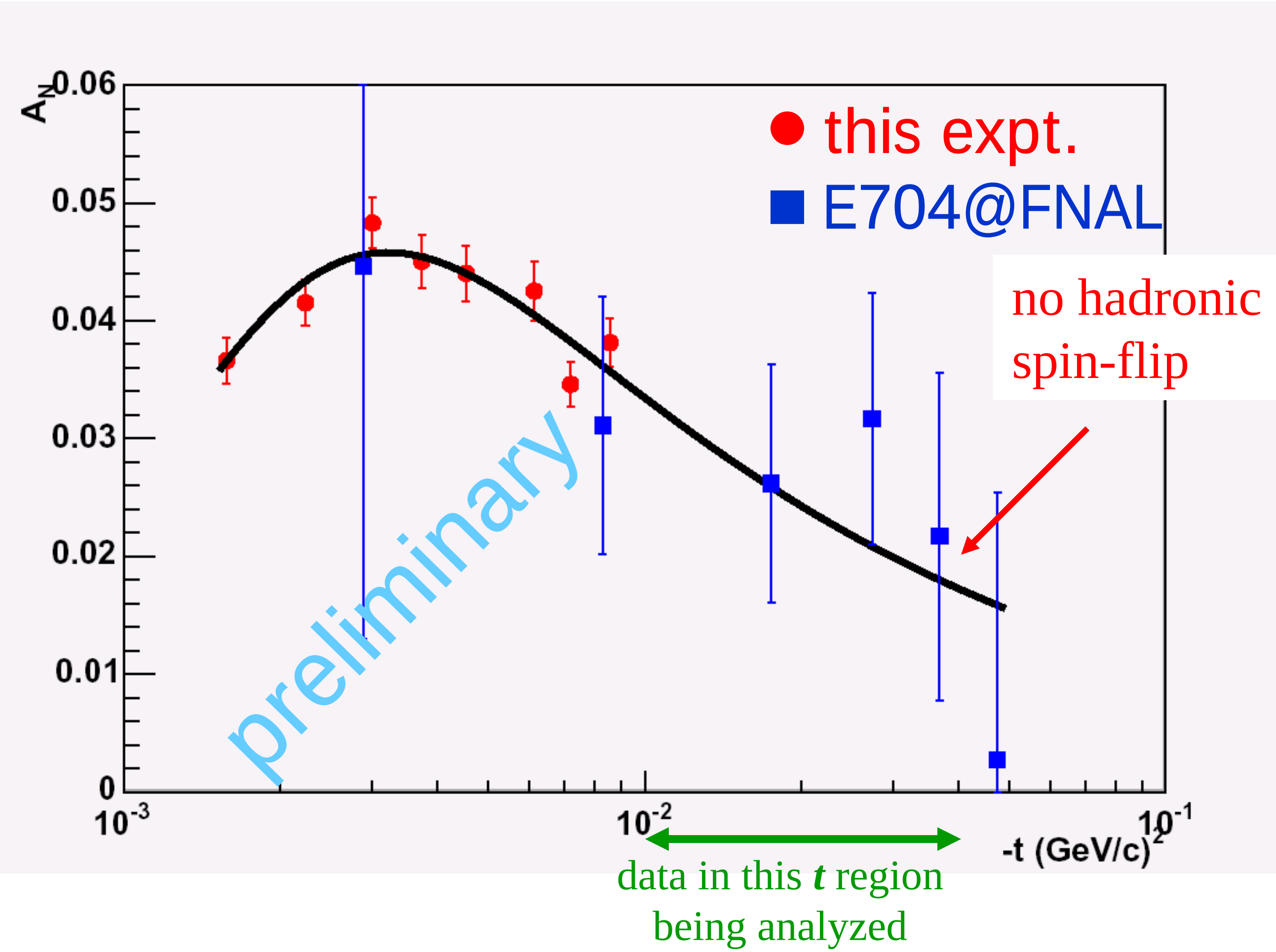
implement the energy / angle correlation in selecting elastic *pp* events

typically, for each energy bin, select 3 to 4 strips per detector

Background only from selected channels not from whole detector (4 – 5 × smaller !)

Total Backgrounds < 8 %: α source < 4%, "interaction" backgrounds < 4 %

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



data (from this expt. only) fitted with CNI prediction [σ_{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.

source of sys. errors:

1 D PTARGET = 2 %

2 from bckgrnd < ± 0.0015

3 false asymmetries: small

no need of a hadronic spin – flip contribution to describe these data

however, sensitivity on ϕ_5^{had} in this *t* range low

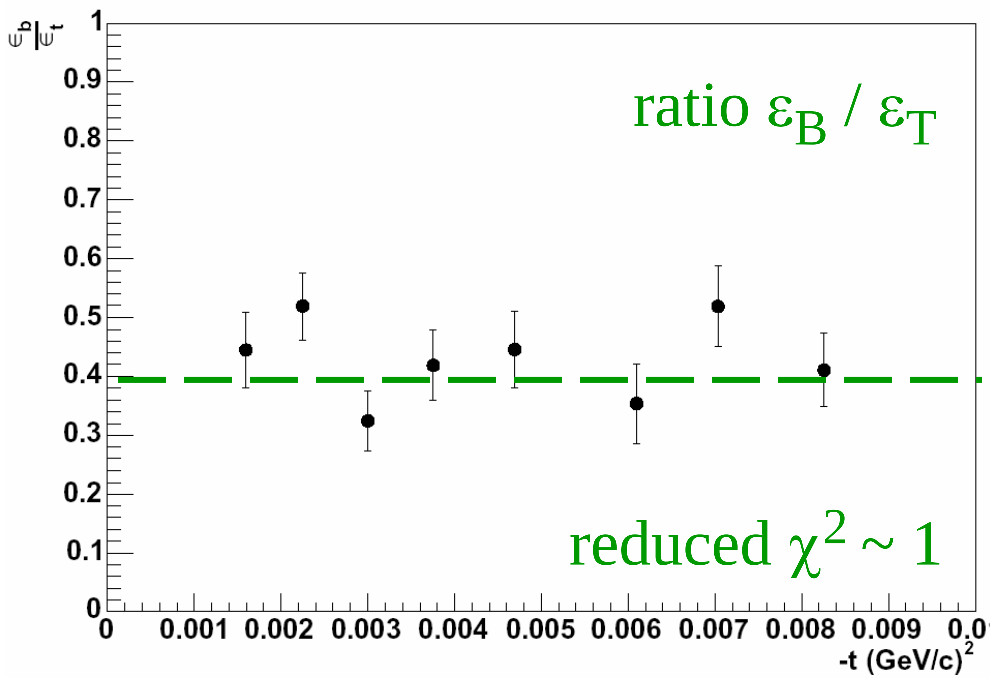
P_{BEAM} …

"self calibrating"

"Target": ε_T – target asymmetry average over beam polarization

"Beam": ε_B – beam asymmetry average over target polarization

$$P_{Beam} = P_{Target} \cdot \frac{\varepsilon_{Beam}}{\varepsilon_{Target}}$$



tot sys = 0.016

$P_{BEAM} = 0.392 \pm 0.021\ (stat) \pm 0.008\ (\Delta P_{TARGET}) \pm 0.014\ (sys) = 0.392 \pm 0.026$

2004 ERROR: $\Delta P_{BEAM} / P_{BEAM} = 6.6\ \%$

Summary

- the polarimeters work reliably
- steady progress in understanding and addressing systematic issues
- fast measurements of P_{beam} in few min. (AGS) / 30 sec. (RHIC)
- polarized gas JET target workes beautifully

  (target, recoil spectrometer, …)
- During 2004 run with Jet target precision on beam polarization

  $\Delta P_{BEAM} / P_{BEAM} = 6.6\ \%$
- based on present understanding and developments in 2005 expect

  ~ 5 % “calibration” of *pC* polarimeters

Summary

- measured A_N^{pp} for elastic $pp \rightarrow pp$ scattering at 100 GeV with very high accuracy (statistical and systematic)
  - $|t|$ range: $0.0015 < |t| < 0.010$ $(\text{GeV}/c)^2$
  - soon A_N in $|t|$ range of $0.010 < |t| < 0.030$ $(\text{GeV/c})^2$
  - soon A_{NN} in same $|t|$ range (stat. err. × 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 $|t| \sim 0.03$ $(\text{GeV/c})^2$

- 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