Proton Polarimetry at RHIC

1. Provides polarization measurements for RHIC accelerator
2. Provides polarization measurements for experiments
3. Study polarized elastic $p^{\uparrow}p^{\uparrow} \rightarrow pp$ & $p^{\uparrow}C \rightarrow pC$ scattering

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RHIC & AGS Users' Meeting
June 21, 2005

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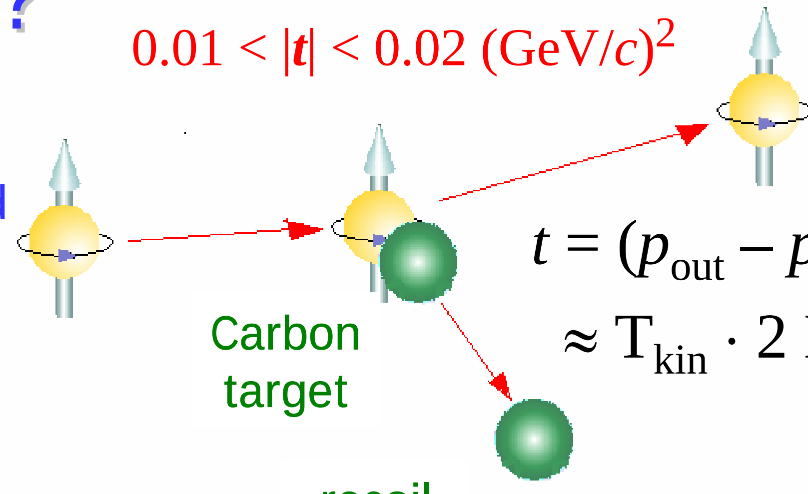
How Does It Work ?

$0.01 < |t| < 0.02\ (\mathrm{GeV}/c)^2$



$$t = (p_{out} - p_{in})^2 < 0$$
$$\approx T_{kin} \cdot 2\, M_C$$

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

Polarimetry:

requires large F.o.M: $A_N^2 \times$ *rate* for fast measurement

process with large A_N and not too large (!) σ

(not at any price however, i.e. by increasing the rates)

elastic *pC* scattering in the CNI region:

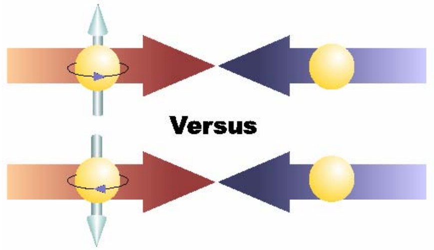
small $A_N \sim 1$ % (far from ideal !)

$\Rightarrow$ requires large statistics $> 10^7$, for $\Delta P_B \sim$ few %

$\times$–section large for *pC* $\Rightarrow$ measurement takes < 10 sec

Polarimetry : Impact on RHIC Spin Physics

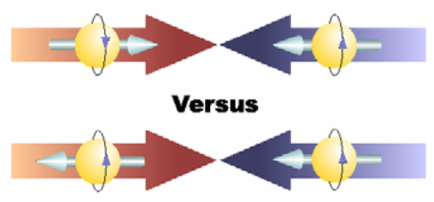
Single Spin Asymmetries



Physics Asymmetries

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

Double Spin Asymmetries



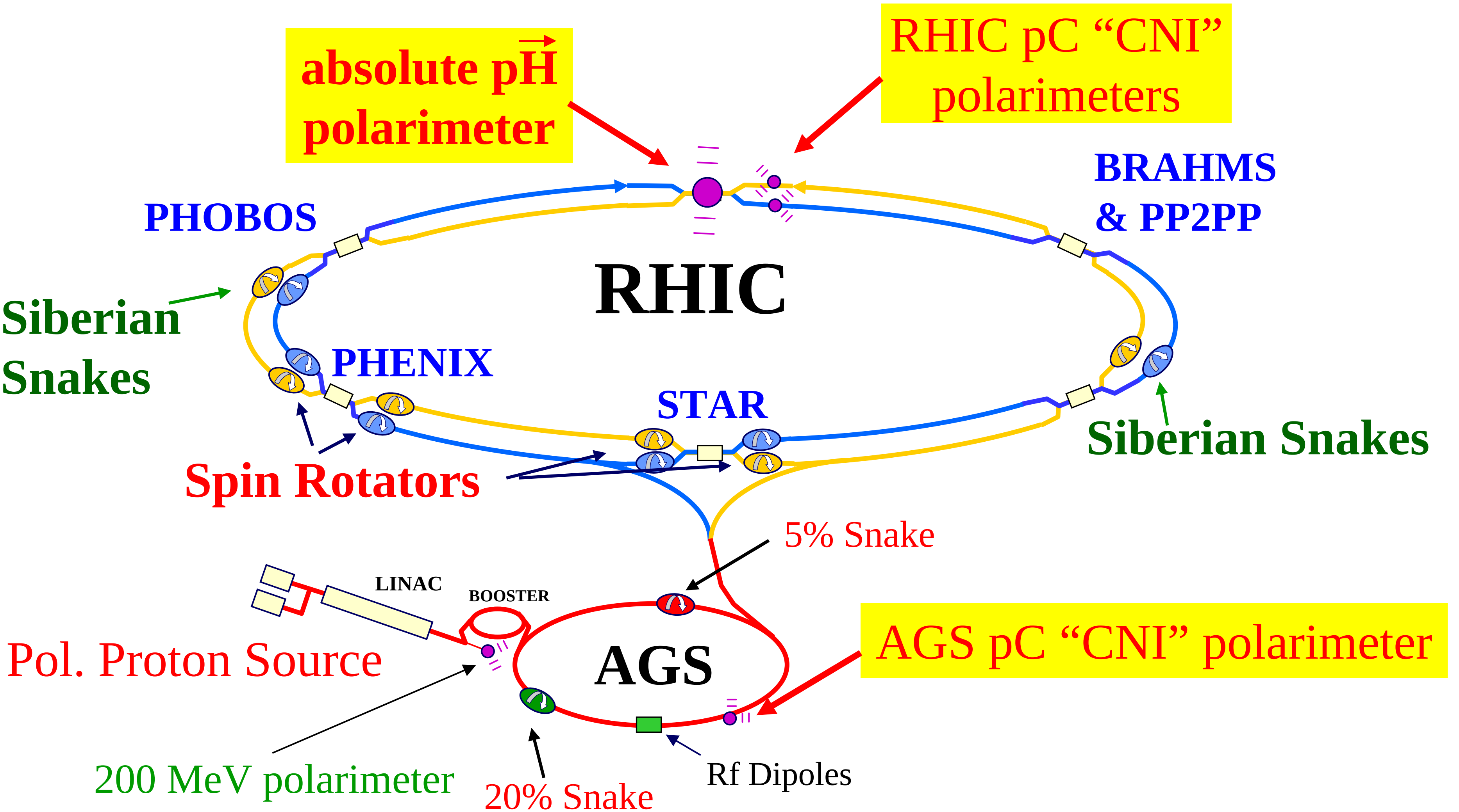
$$A_{LL} = \frac{1}{P_B^{\ 2}}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right) \Rightarrow \boxed{\Delta G}$$

measurements

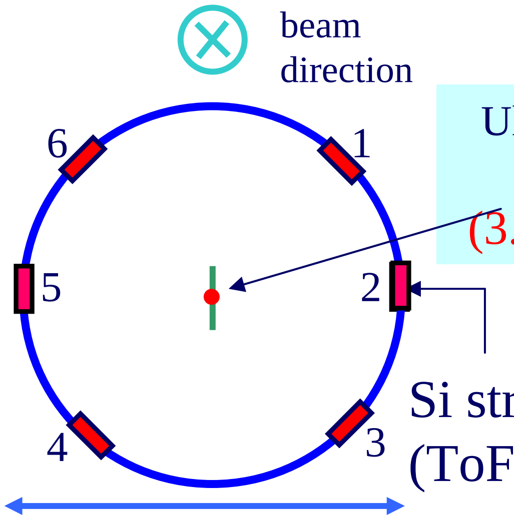
- measured spin asymmetries normalized by P_B to extract Physics Spin Observables
- RHIC Spin Program requires $\Delta P_{beam} / P_{beam} \sim 0.05$
- normalization $\Rightarrow$ scale uncertainty

RHIC *pp* accelerator complex

The polarimeters are experimental devices



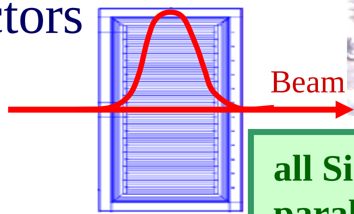
Setup for pC scattering – the RHIC polarimeters



Ultra thin Carbon ribbon Target
(3.5μg/cm², 5μm wide)

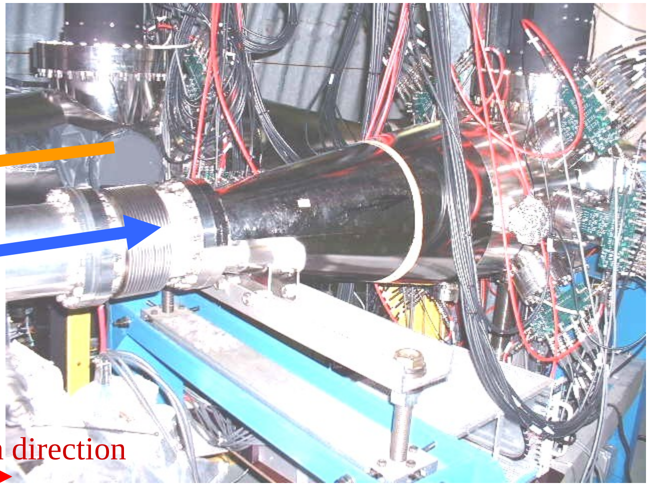
Si strip detectors
(ToF, E_C)

RHIC × 2 rings



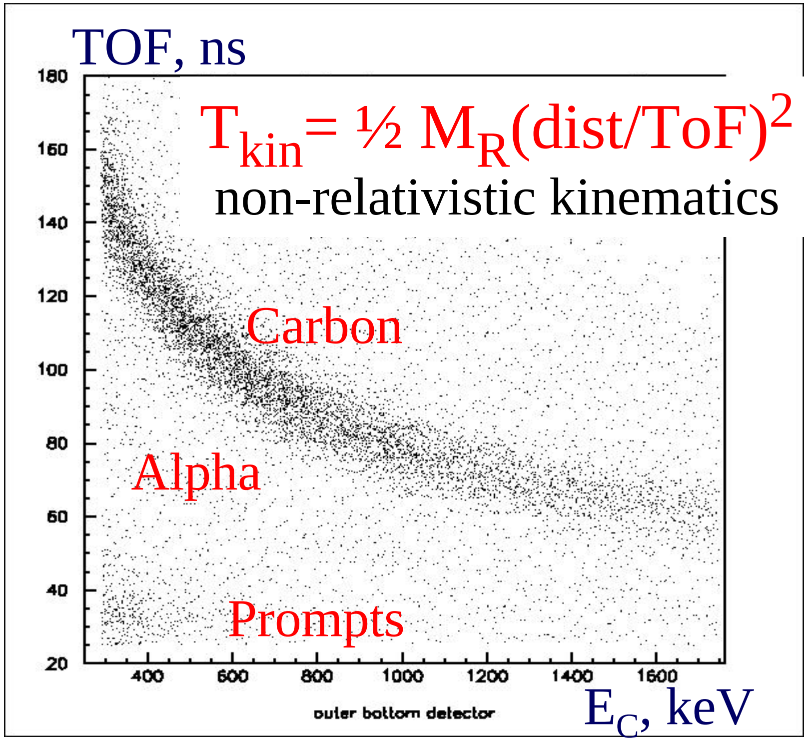
all Si strips parallel to beam

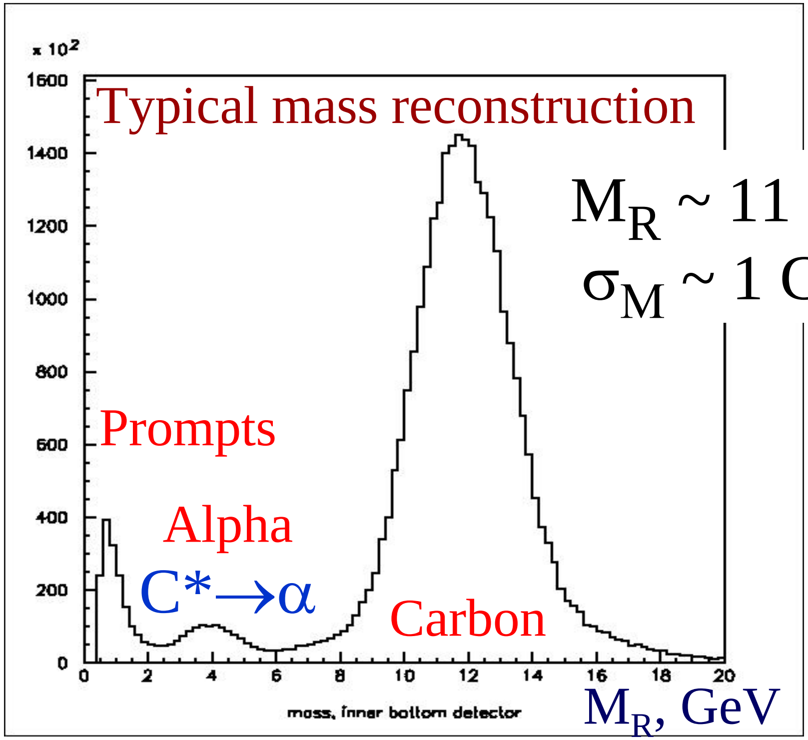
inside RHIC ring @IP12



- 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

Event Selection & Performance

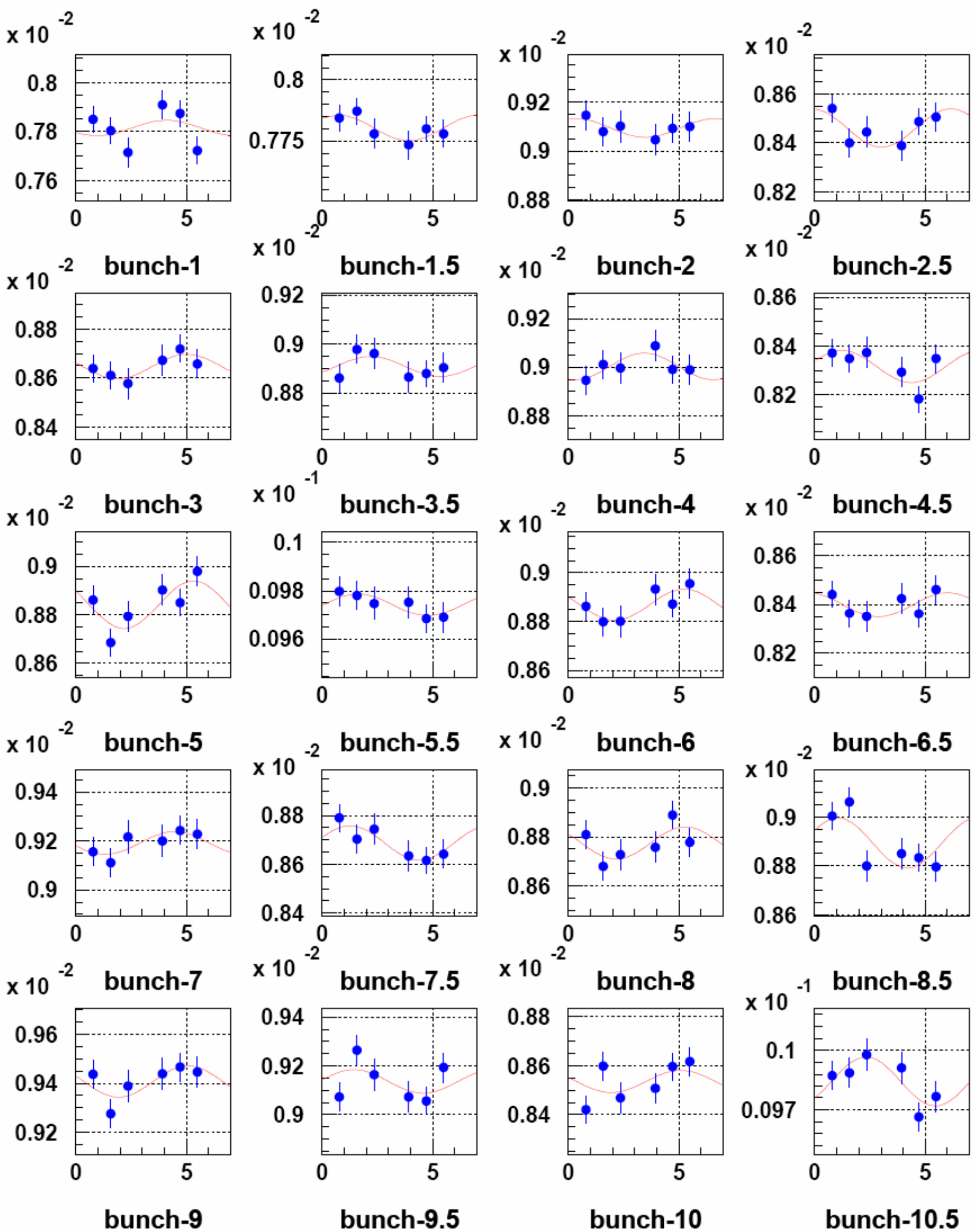


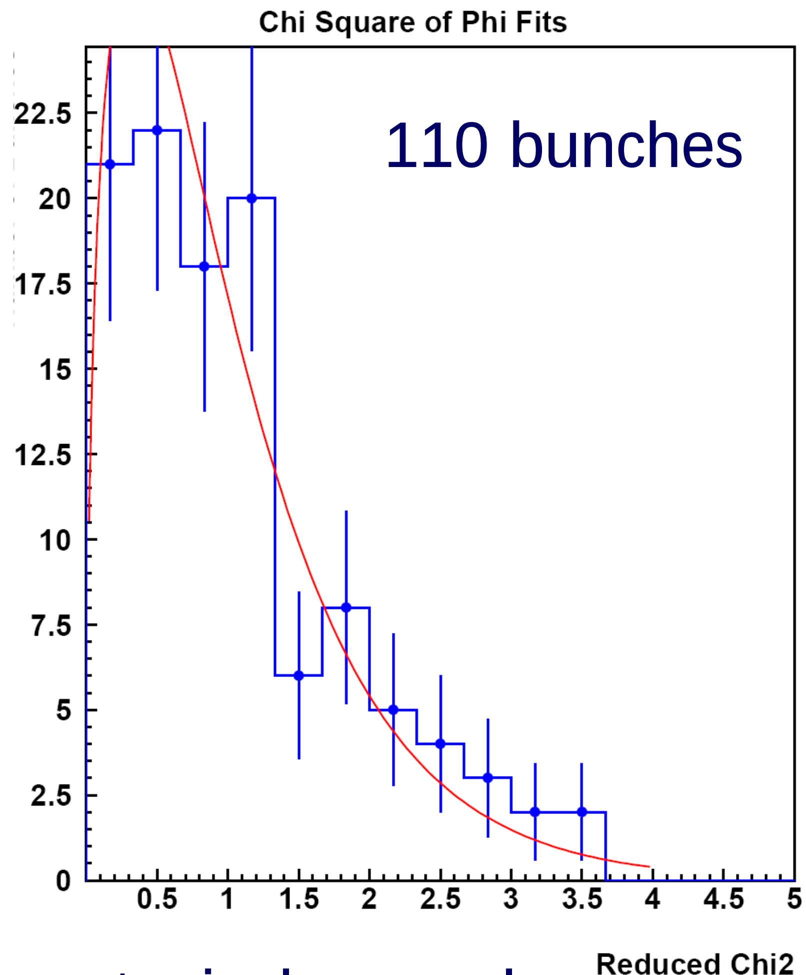


$M_R \sim 11$ GeV
$\sigma_M \sim 1$ GeV

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

Bunch by Bunch





typical example

sometime even nicer than in textbooks

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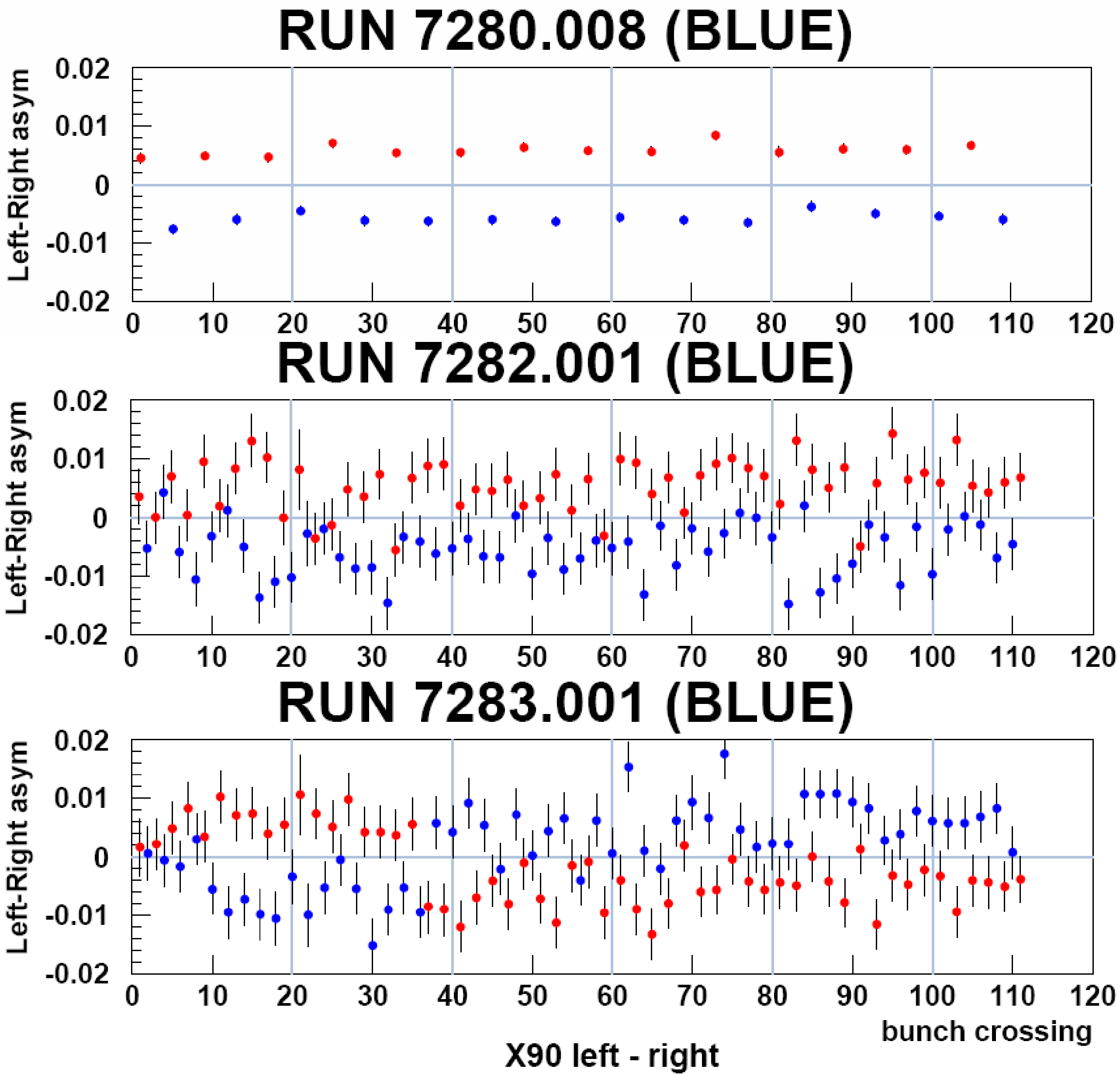
Bunch by Bunch



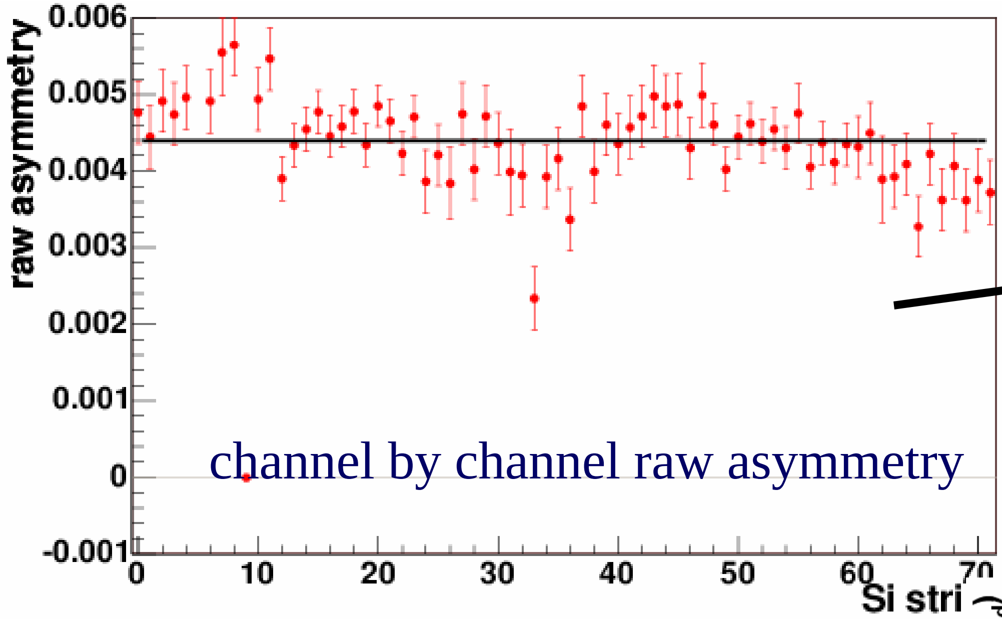
high statistics
28 bunches
@ injection

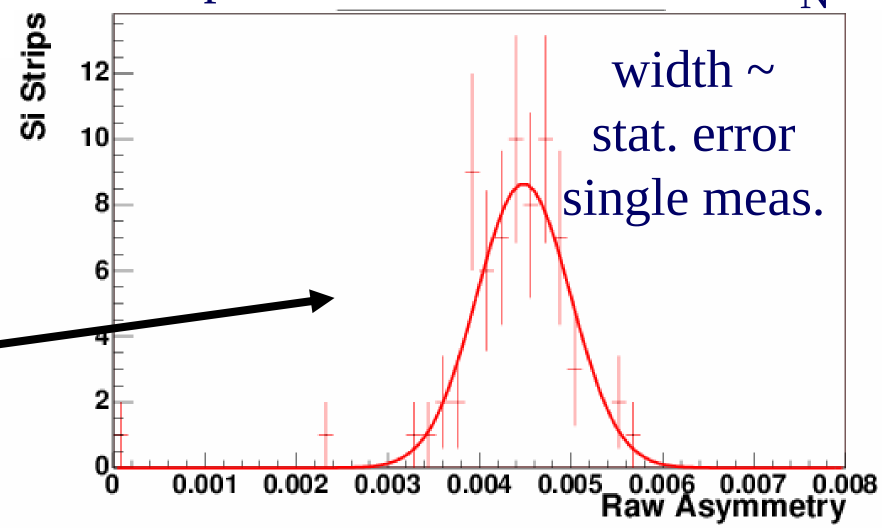
110 bunches
@ flattop
10^{11} p / bunch

110 bunches
@ flattop
with messed
spin pattern

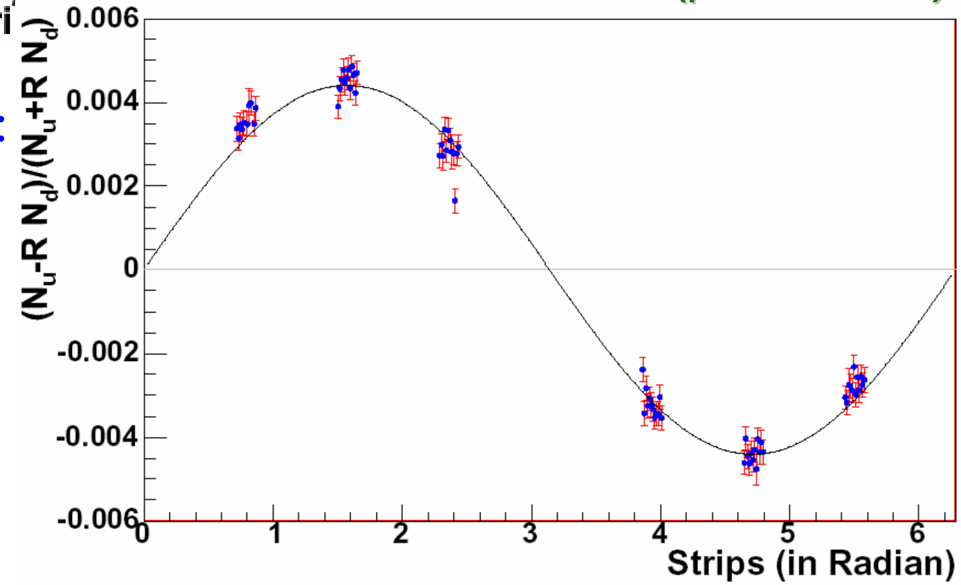
*p*C Systematics RHIC:

each detector channel covers same *t* range
→ 72 independent measurements of A_N





Fit with sine function (phase fixed)



sources of systematic uncertainties (2004):

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

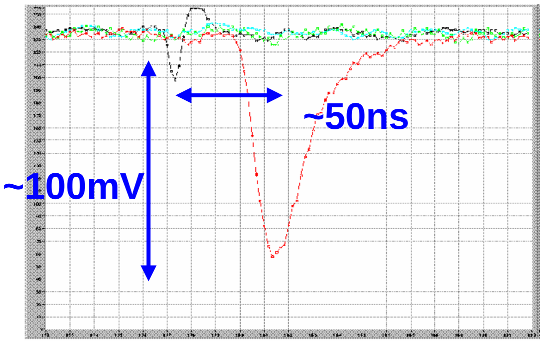
2 energy scale ~ 50 keV for lowest |*t*| bin
(from detector dead layer)

NB these are "external" factors
not "intrinsic" limitations

DAQ and WFD

Wave Form Digitizer = peak sensing ADC, CFD, …

common to the *pC* and JET DAQ system



ADC
3×140 MHz

↓

FPGA

↓

onboard memory → DAQ PC

synchronized to accelerator clocks

bunch ×-ing ⇒ "start" TDC

"online" analysis of waveform performed beteween consecutive bunch ×-ing
⇒PH, tot Q, t.o.f.;
full waveform (JET)

$\Delta t \sim 2$ ns

$\Delta E < 50$ keV

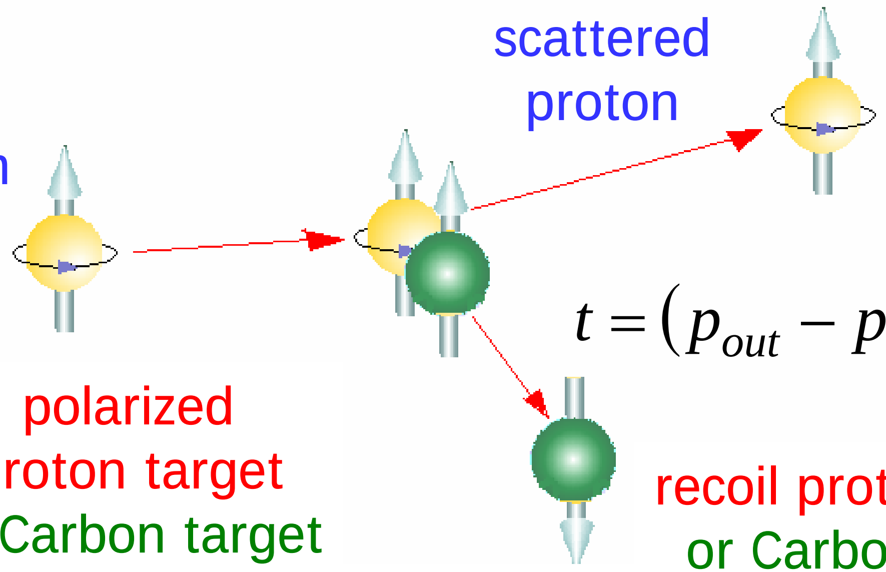
20×10^6 events in 20 seconds ⇒ deadtimeless DAQ system

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

The Elastic Process

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

recoil



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

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 !

Helicity Amplitudes for spin ½ ½ → ½ ½

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 ×-sections
5 spin asymmetries

spin non–flip $\phi_1(s,t) = \langle ++ | M | ++ \rangle$

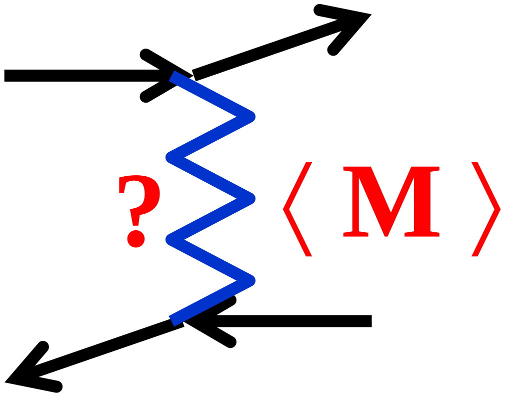
double spin flip $\phi_2(s,t) = \langle ++ | M | -- \rangle$

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 ½ particles



$$A_N = \frac{\sigma^{\Uparrow} - \sigma^{\Downarrow}}{\sigma^{\Uparrow} + \sigma^{\Downarrow}}$$

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

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

The Very Low *t* Region

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

⇒ INTERFERENCE

CNI = Coulomb – Nuclear Interference

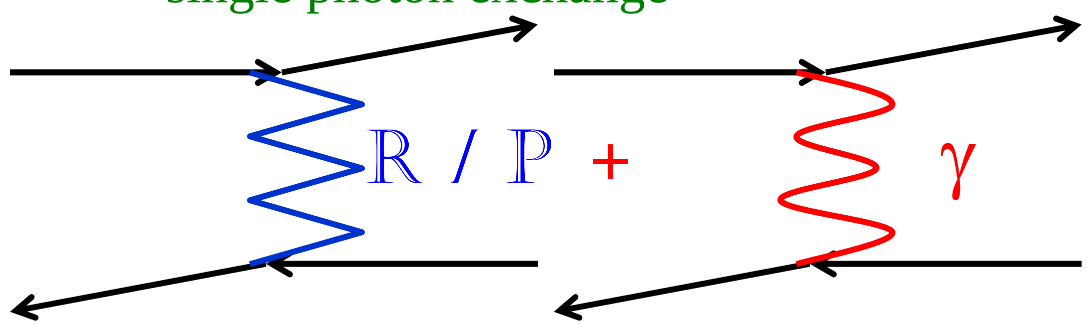
scattering amplitudes modified to include also electromagnetic contribution

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

hadronic interaction described in terms of Reggeon / Pomeron exchange

electromagnetic single photon exchange

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



unpolarized ⇒ clearly visible in the cross section dσ/dt **charge**

polarized ⇒ “left – right” asymmetry A_N **magnetic moment**

A_N & Coulomb Nuclear Interference

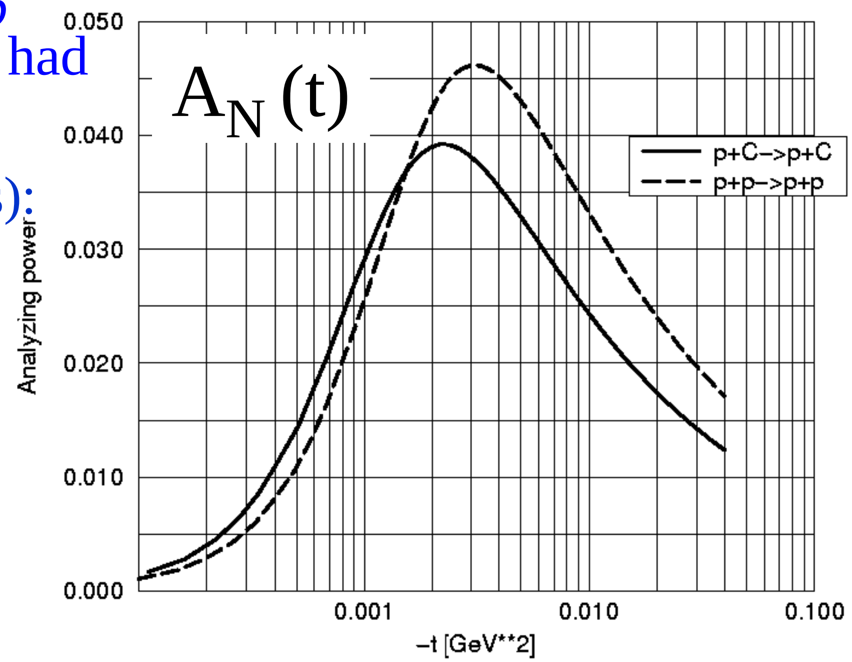
the left – right scattering asymmetry A_N arises from the interference of the spin non-flip amplitude with the spin flip amplitude (Schwinger)

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

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

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

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



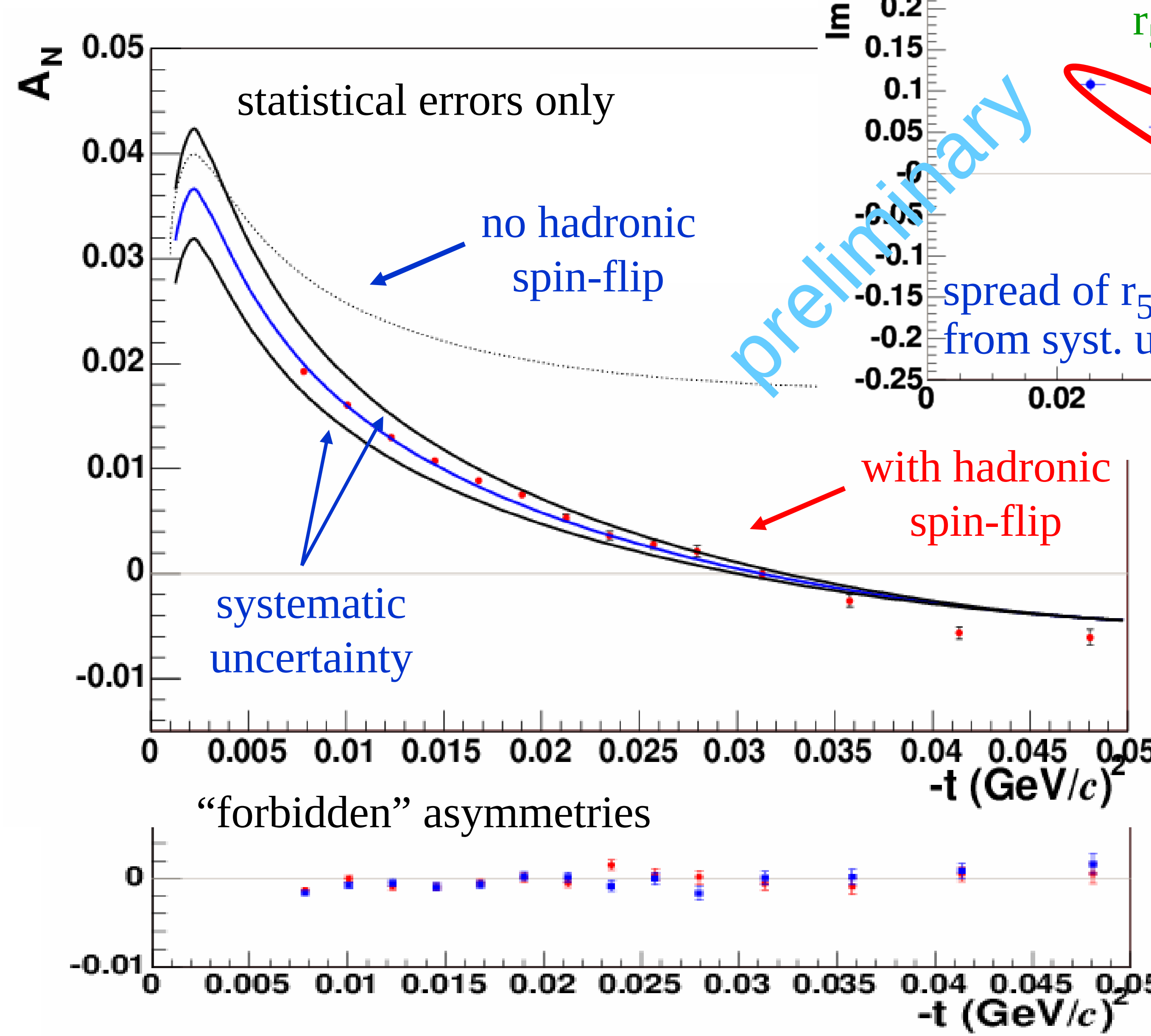
hadronic spin- flip modifies the QED "predictions"

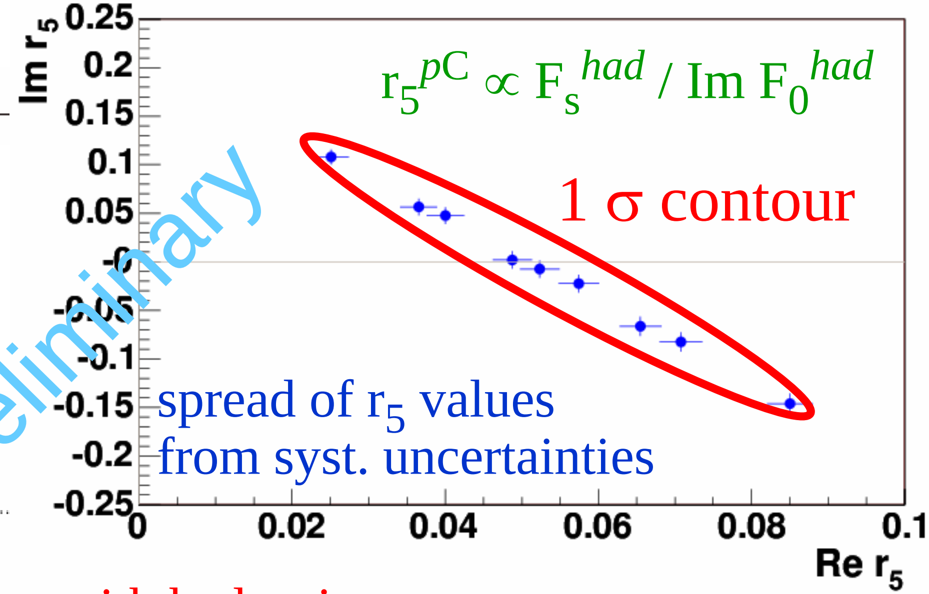
$$\frac{\mu_p - 1}{2} \rightarrow \frac{\mu_p - 1}{2} - I_5 + \left(\frac{\mu_p - 1}{2} I_2\right)$$

interpreted in terms of Pomeron spin – flip and parametrized as

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

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





best fit with
hadronic spin-flip

Kopeliovich –
Truemann model
PRD**64** (01) 034004
hep-ph/0305085

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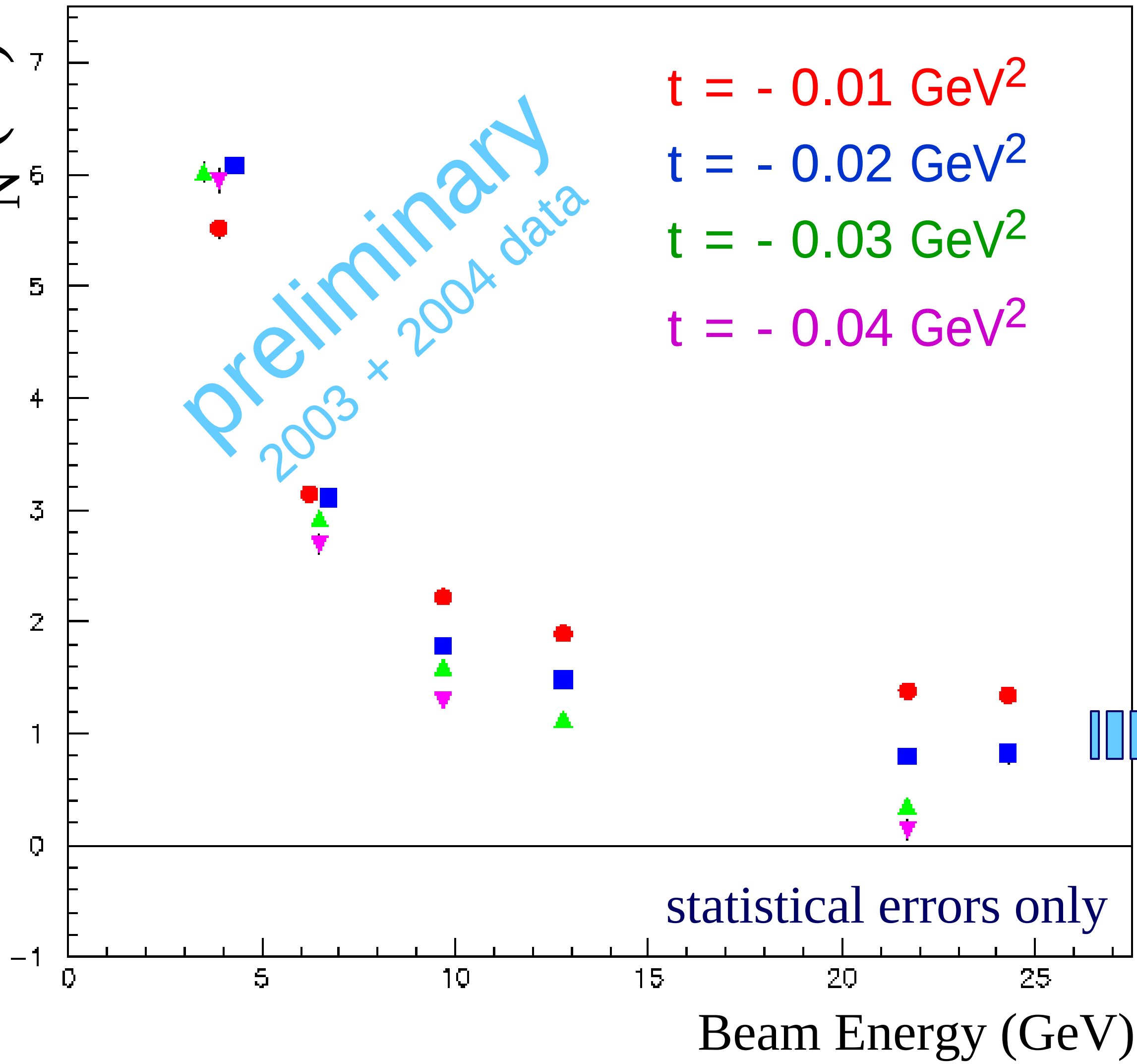
A_N $p^{\uparrow}C \rightarrow pC$: Energy Dependence



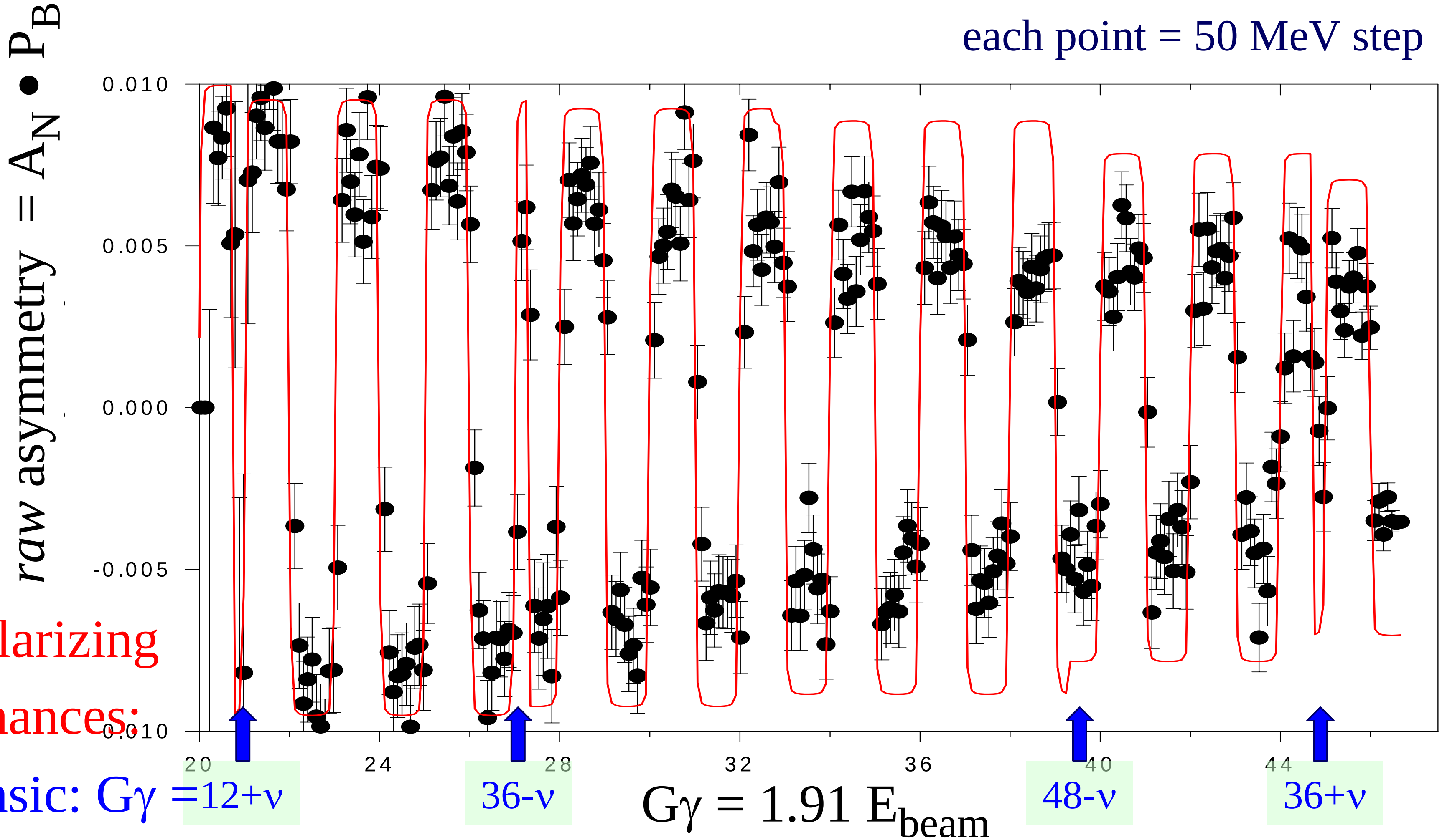
only statistical errors are shown
systematic errors as for previous slide

Asymptotic regime

E ?

No energy dependence ?

AGS polarization during acceleration (ramp)



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

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

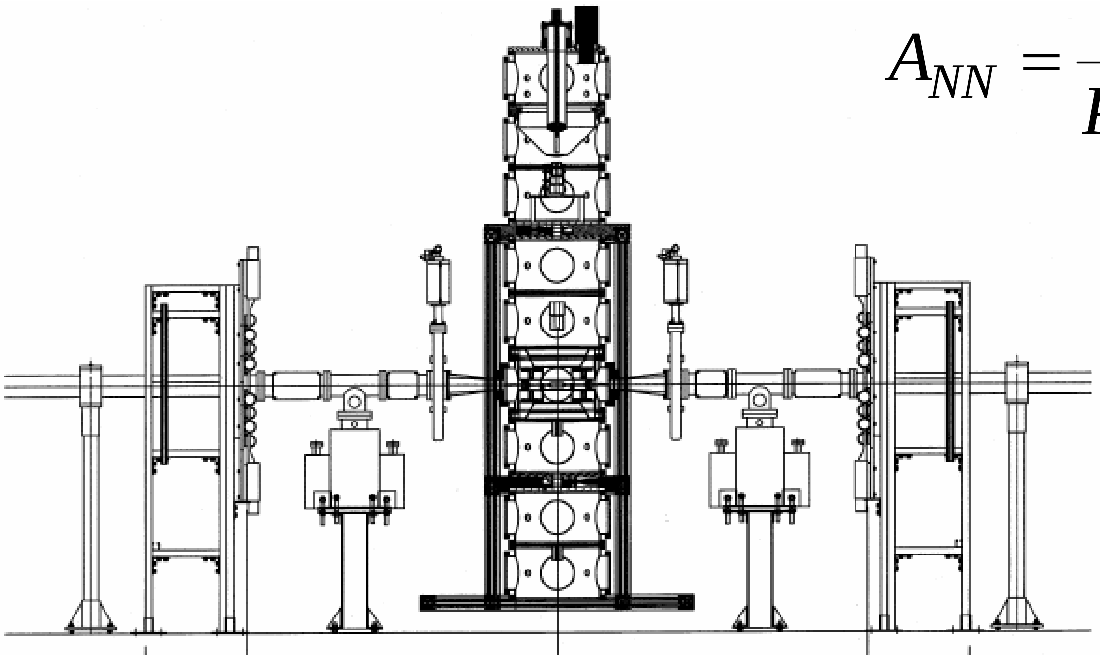
transfer calibration measurement

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

polarized gas JET target

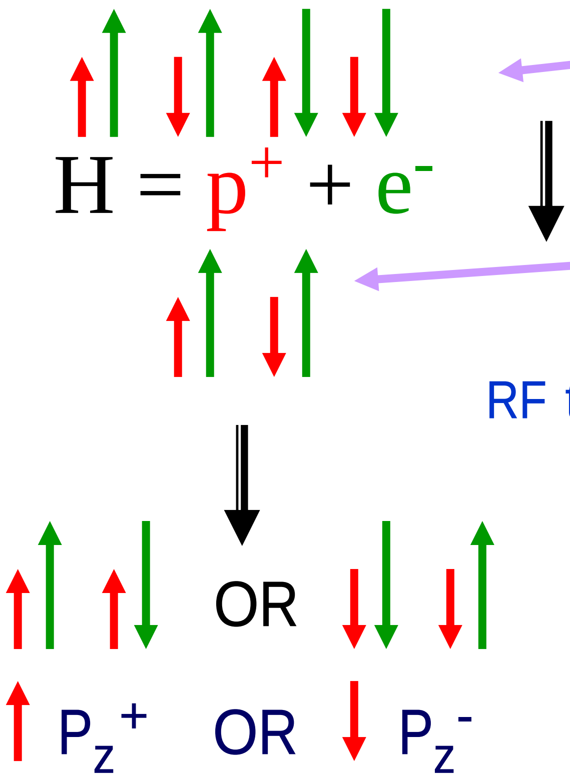
$$A_N = \frac{1}{P_T}\frac{\left(N_L^{\Uparrow} + N_R^{\Downarrow}\right) - \left(N_R^{\Uparrow} + N_L^{\Downarrow}\right)}{\left(N_L^{\Uparrow} + N_R^{\Downarrow}\right) + \left(N_R^{\Uparrow} + N_L^{\Downarrow}\right)}$$

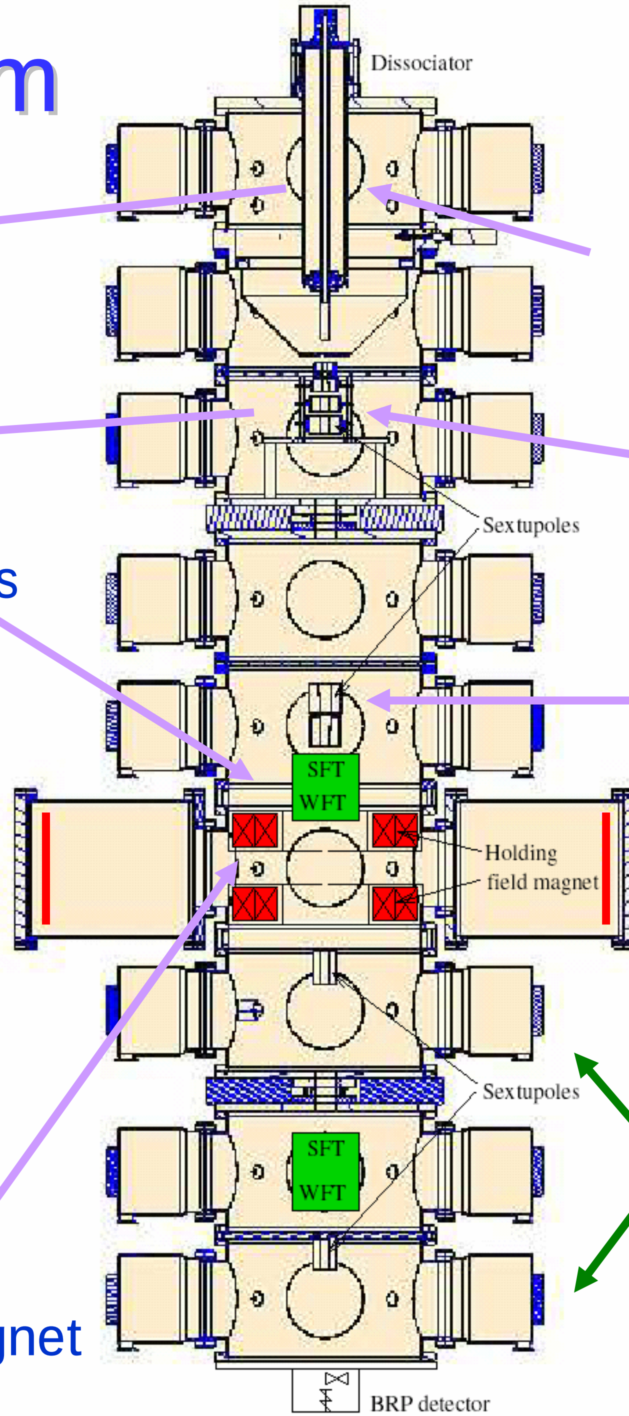
$$A_{NN} = \frac{1}{P_T P_B}\frac{N^{\uparrow\uparrow+\downarrow\downarrow} - N^{\uparrow\downarrow+\downarrow\uparrow}}{N^{\uparrow\uparrow+\downarrow\downarrow} + N^{\uparrow\downarrow+\downarrow\uparrow}}$$



RHIC polarized proton beams

The Atomic H Beam Source





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

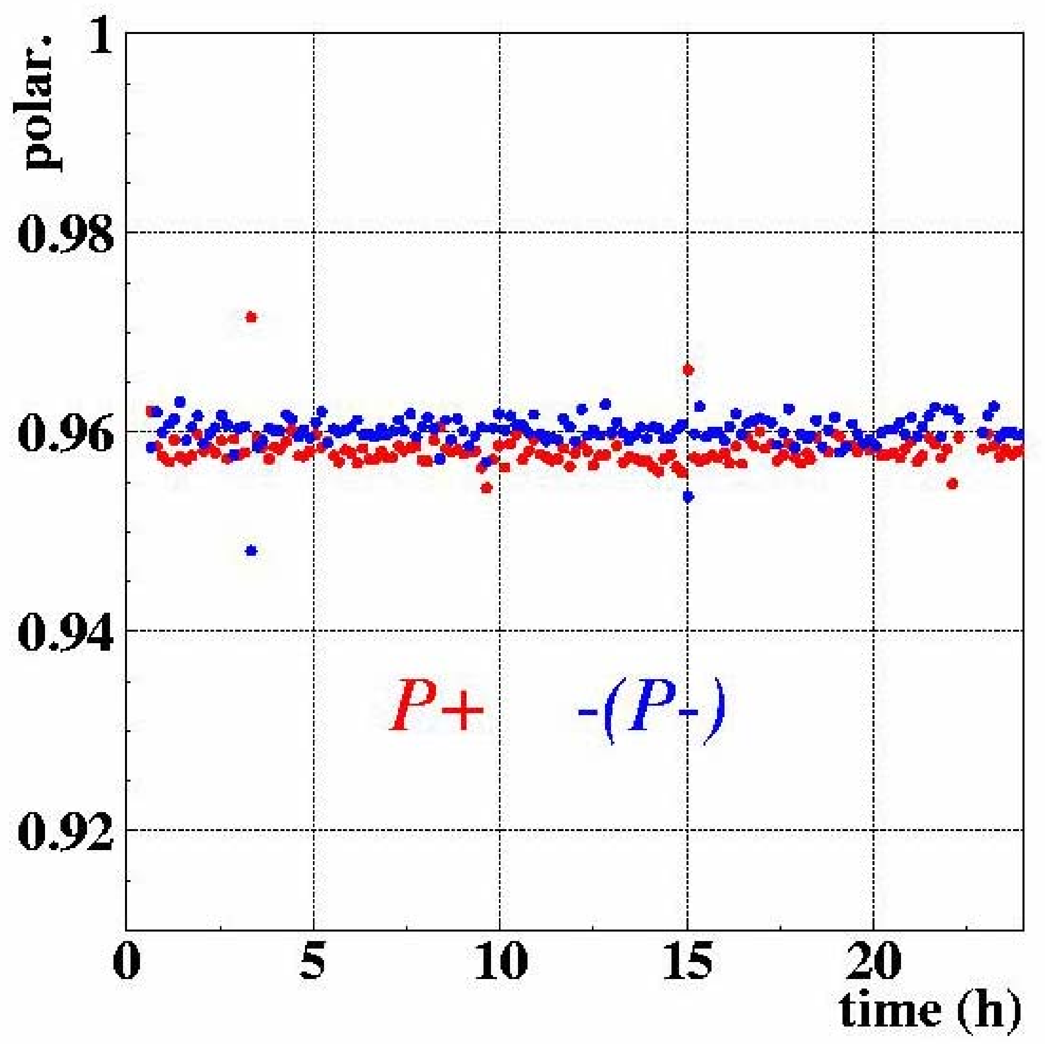
the JET thickness of 1×10^{12} atoms/cm^2 record intensity

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 !



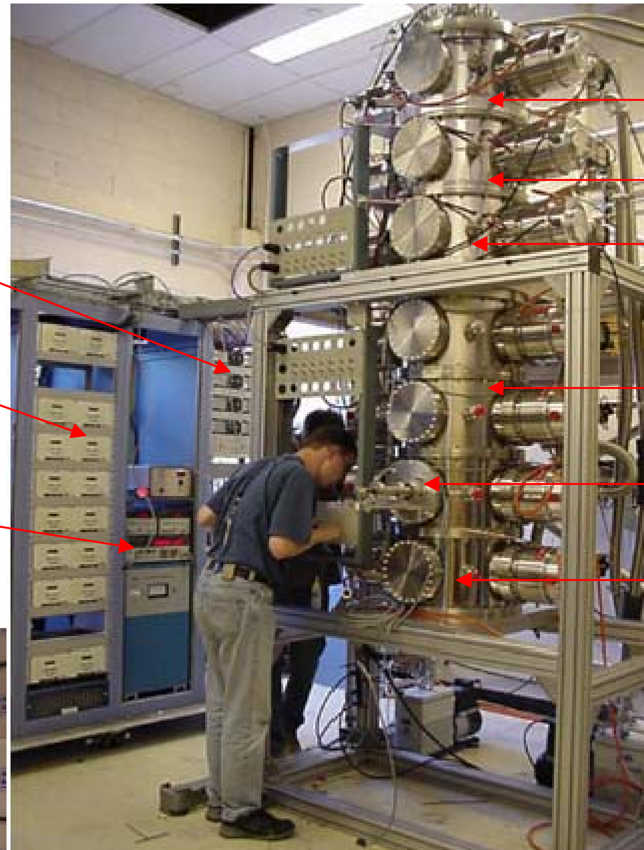
The Polarized Jet Target under development

Electronics racks

Vac. gauges monitors

Turbo pump controllers

Dissociator RF systems



Dissociator stage

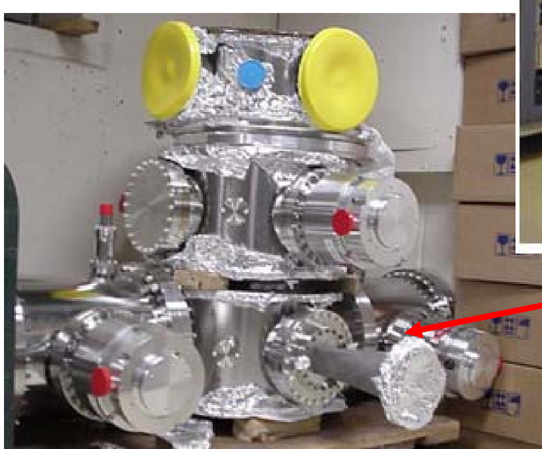
Baffle location

Sextupoles 1-4

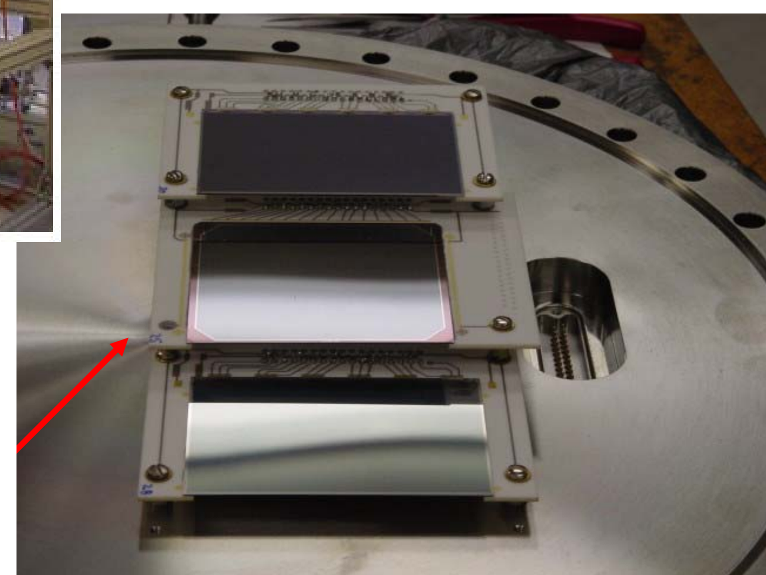
Sextupoles 5-6

Profile measurement

BRP vacuum vessel



Target chamber & beam pipe adapters



Recoil spectrometer silicon detectors

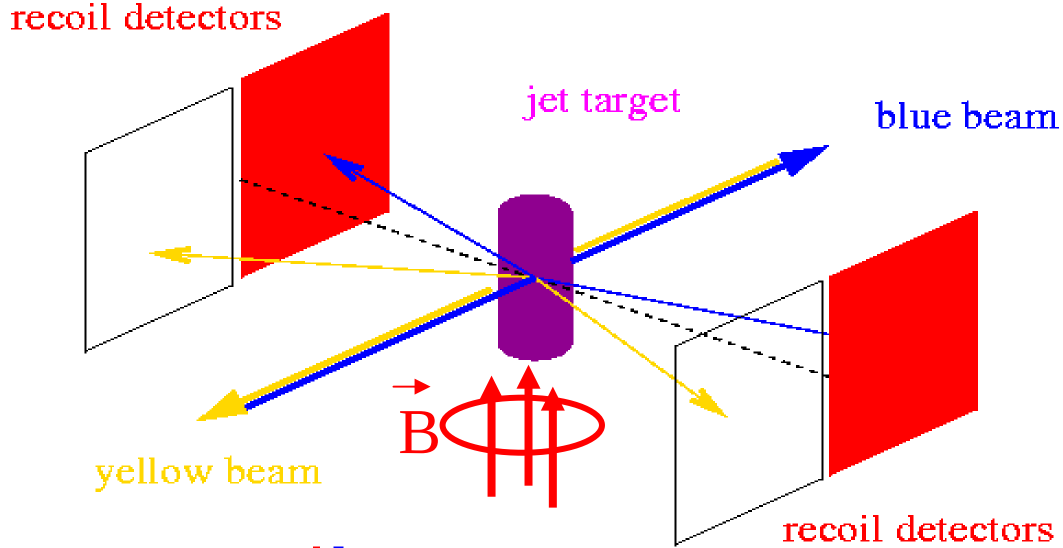
Recoil Si spectrometer

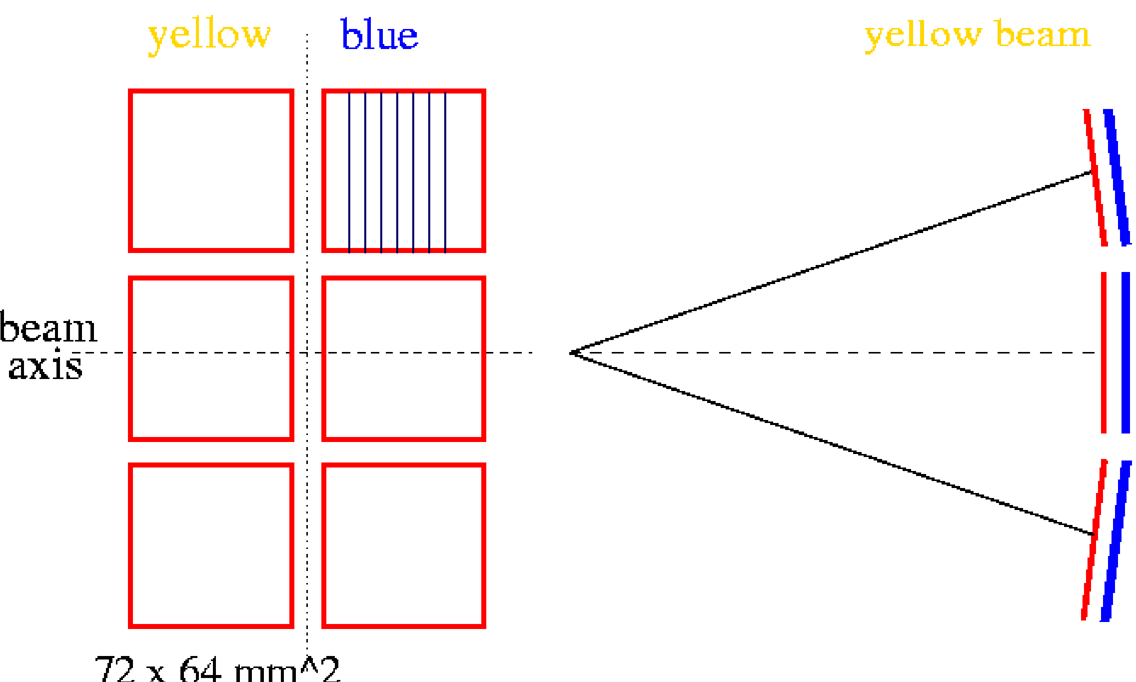
$A_N^{beam}(t) = A_N^{target}(t)$

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 → *pp* elastic scattering





HAVE “design”
azimuthal coverage

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

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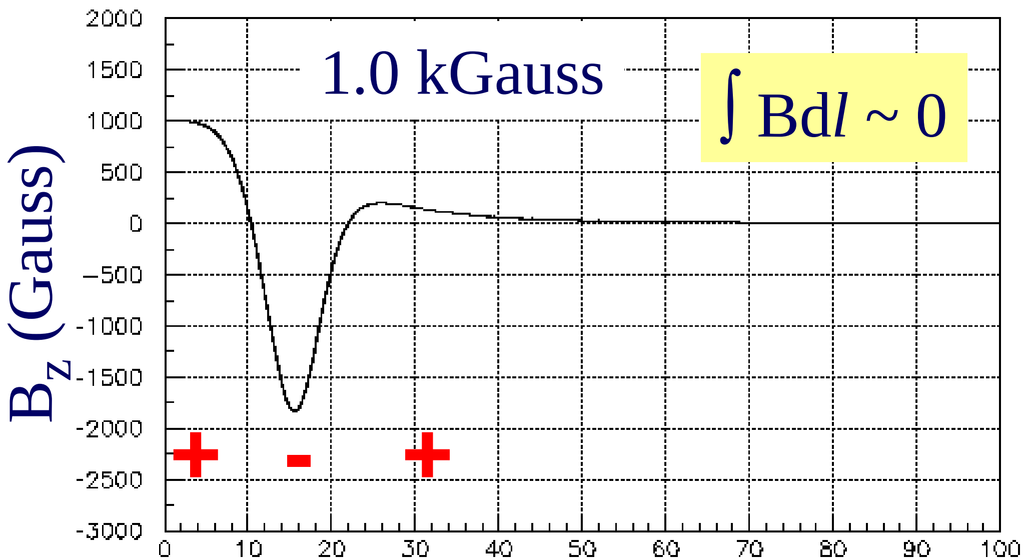
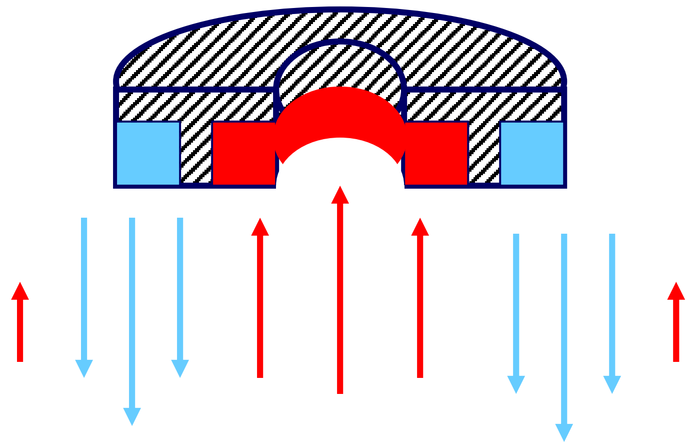
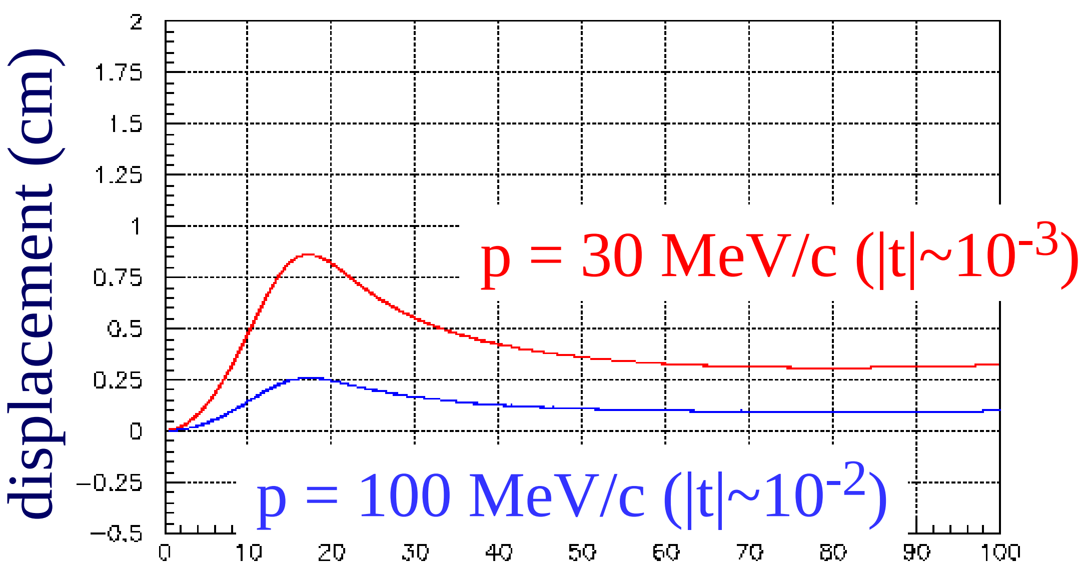
Jet-Target Holding Magnetic Field (1.0)



Helmholtz coils





almost no effect on recoil proton trajectories:

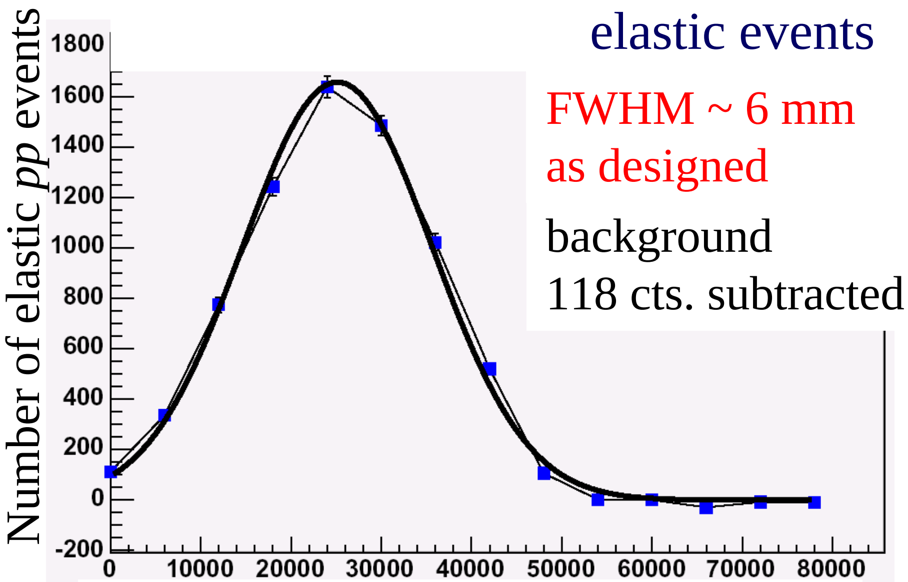
left – right hit profiles & left – right acceptances almost equal (also under reversal of holding field)

pp elastic data collected

ToF vs E_{REC} correlation

$T_{kin} = ½ M_R(dist/ToF)^2$

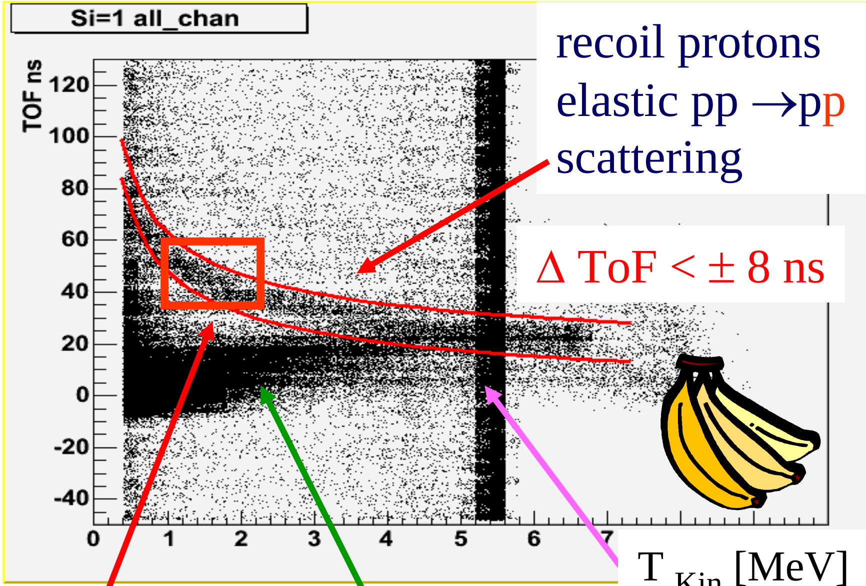
JET Profile: measured selecting pp elastic events



FWHM ~ 6 mm
as designed

background
118 cts. subtracted

Hor. pos. of Jet 10000 cts. = 2.5 mm



recoil protons
elastic pp →pp
scattering

Δ ToF < ± 8 ns

T_{Kin} [MeV]

CNI peak A_N
$1 < E_{REC} < 2$ MeV

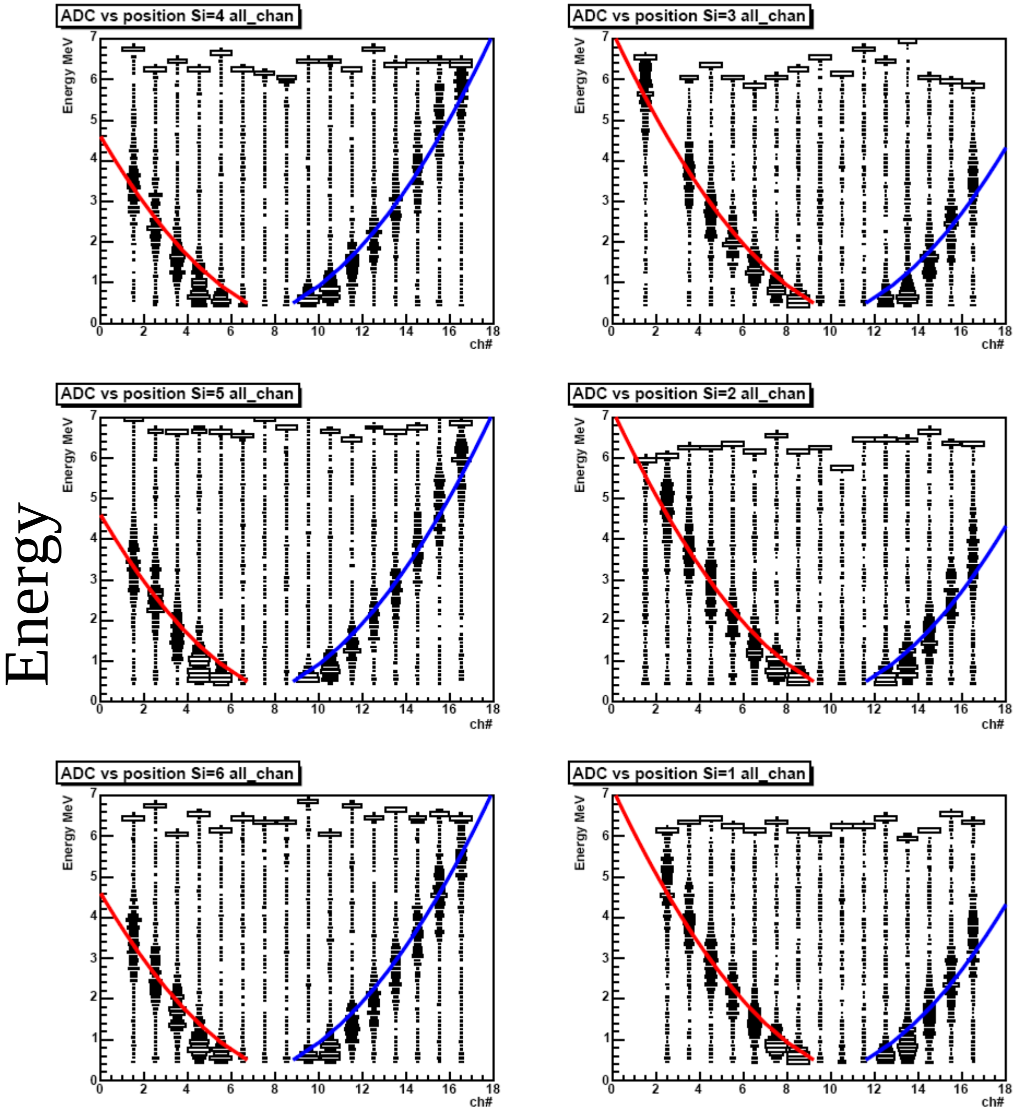
prompt events
and beam-gas

α source
calibration

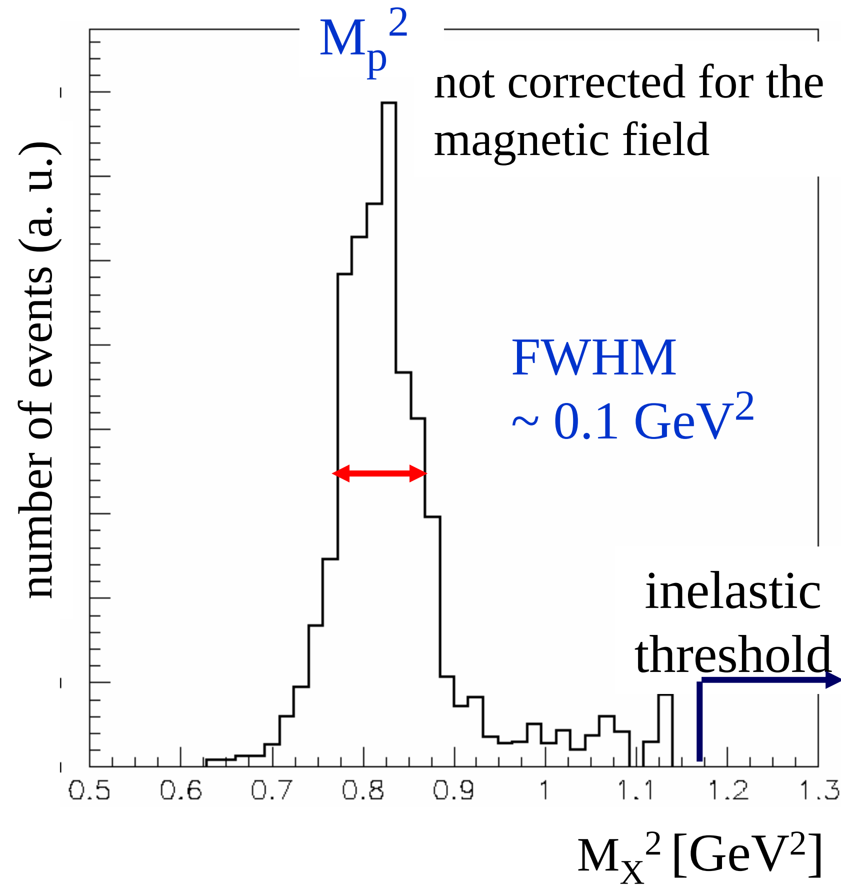
- recoil protons unambiguously identified !

Energy - Position correlations

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

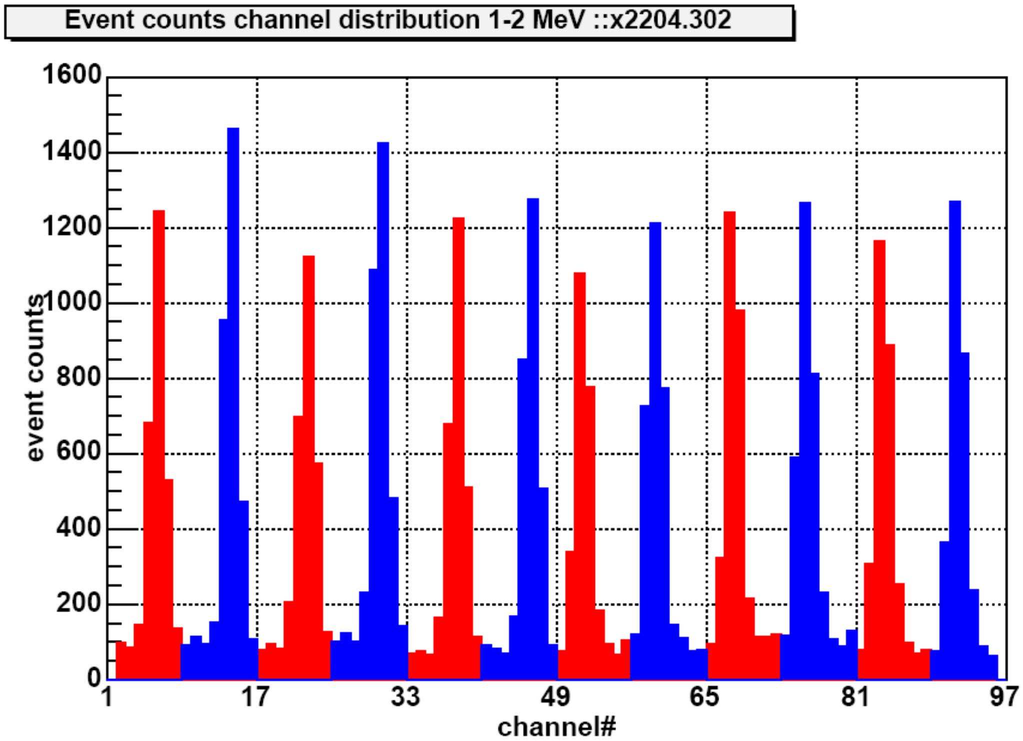


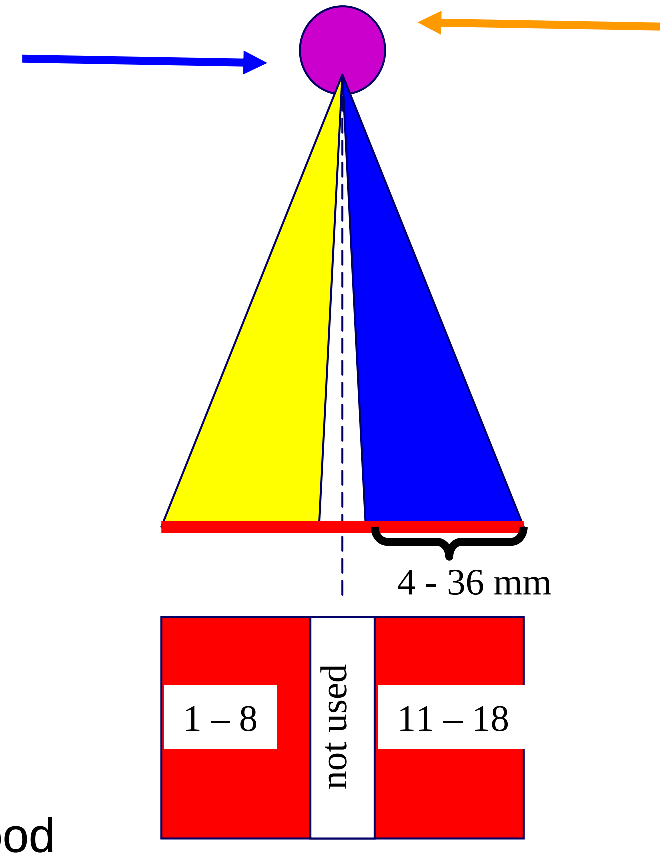
Position



pp elastic events clearly identified !

JET: Elastic pp Events



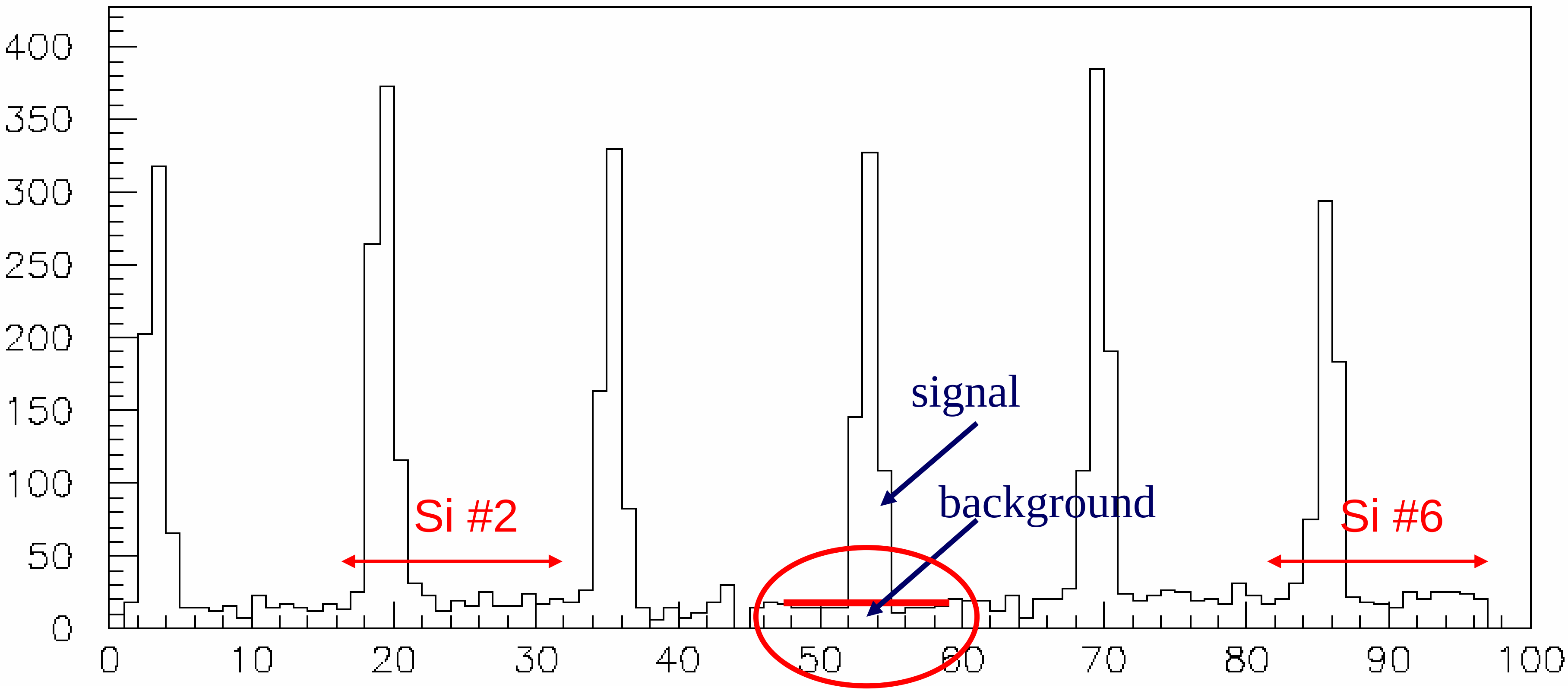


Backgrounds 2 x larger than in 2004; not fully understood
In principle could run with both beams at the same time, however decided to run with one beam at the time

Statistics: (04/20 – 06/07) 1,500 k events in Yellow 1 – 2 MeV region
900 k events in Blue
10 % empty target runs (background studies)

Event selections & Backgrounds (2004)

Strip distribution for energy interval: 1250 – 1750 keV



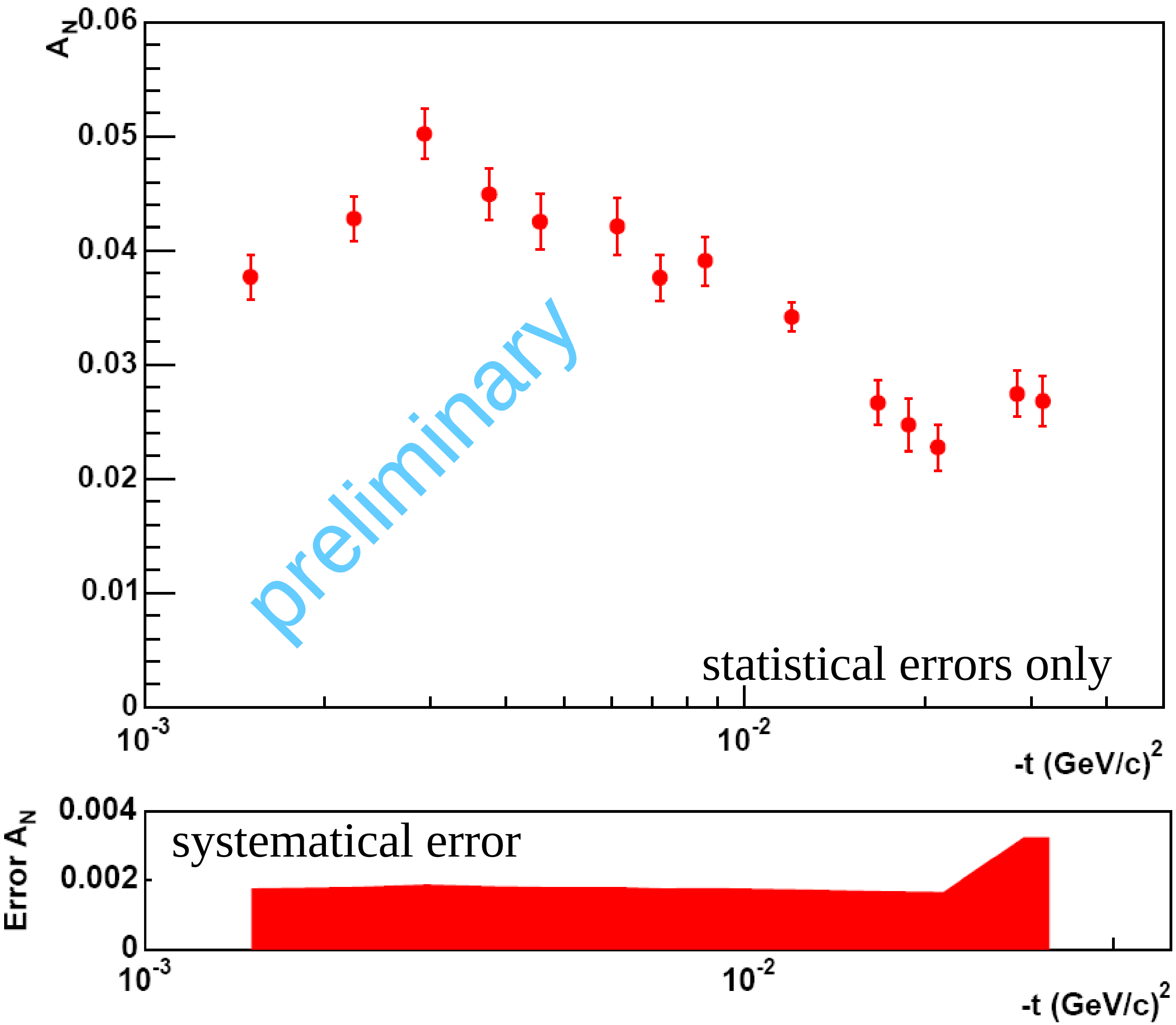
implement the energy / angle correlation in selecting elastic *pp* events

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 $p^{\uparrow}p \to pp$ @ 100 GeV

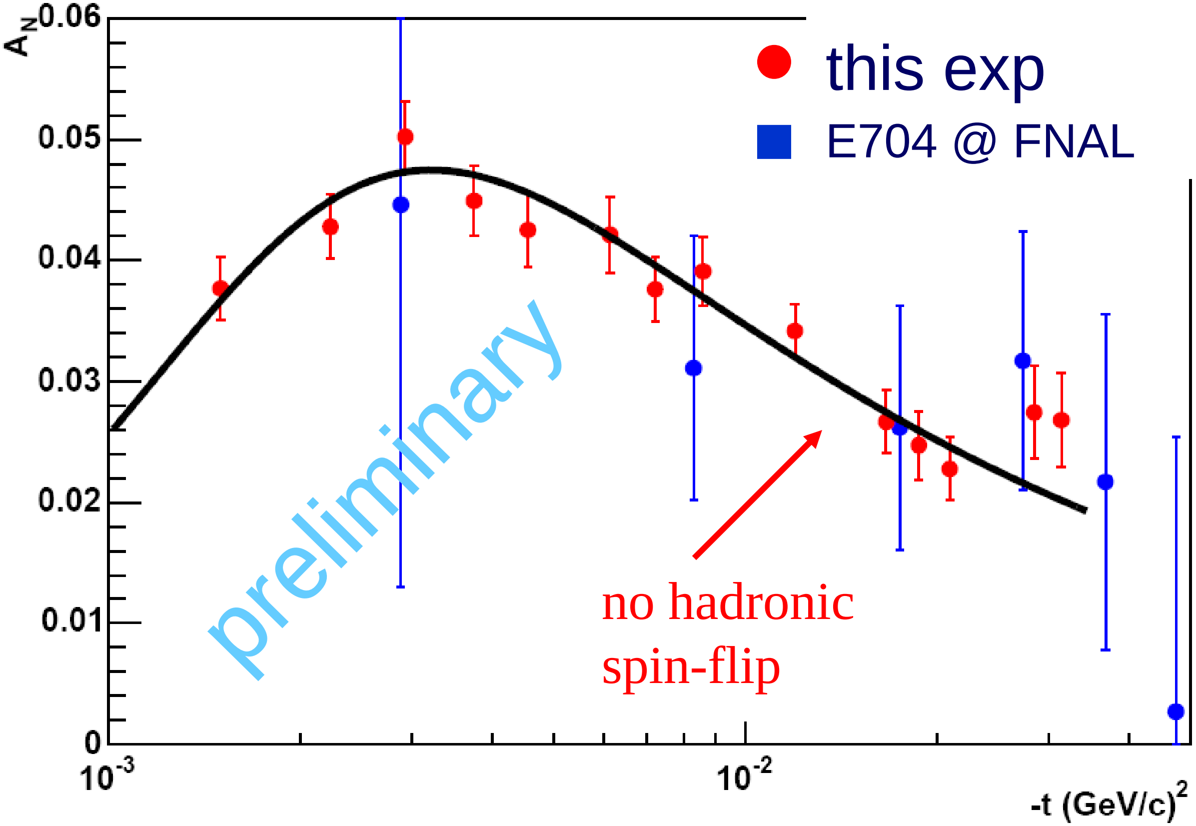


$$A_N = \frac{1}{P_T} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

source of systematic errors:

1. $\Delta P_{TARGET} = 2\ \%$
2. from backgrounds $< \pm 0.0016$
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"
$\mathcal{N} = 1.01 \pm 0.02$
$\chi^2 \sim 12 / 13$ d.o.f.

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

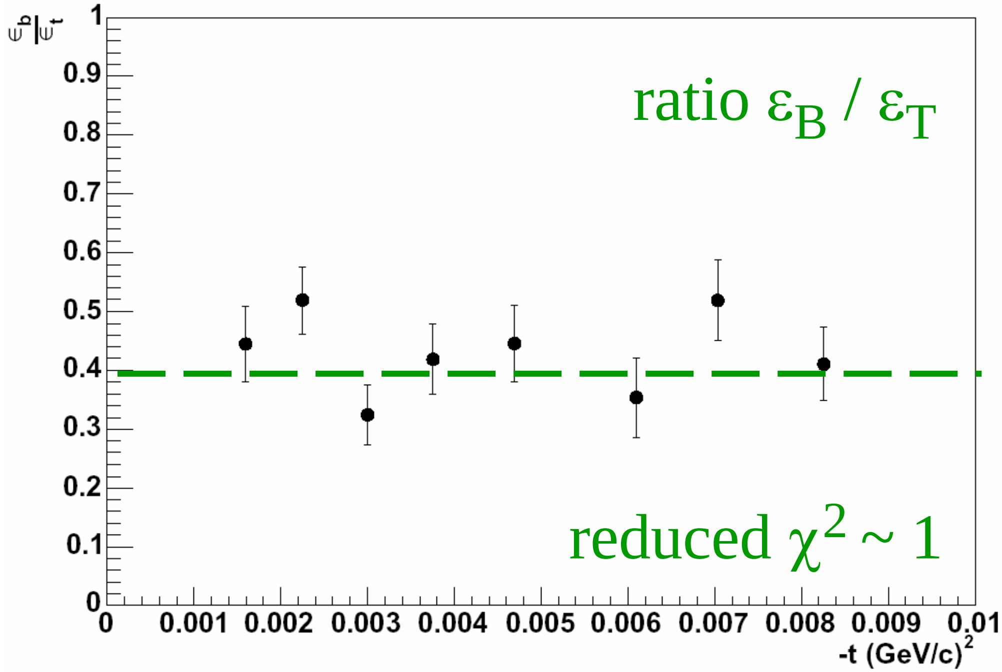
however, sensitivity on ϕ_5^{had} in this $\boldsymbol{t}$ range low

P_{BEAM} …

"self calibrating"

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

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



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

2004:

tot sys = 0.016

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

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

$\langle P_{Beam} \rangle$ during the 2005 run ~ 0.5 (~10% error, mainly from backgrounds)

Summary

- the polarimeters work reliably
- steady progress in understanding and addressing systematic issues
- fast measurements of P_{beam} in few min. (AGS) / 10 sec. (RHIC)
- polarized gas JET target works 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

  ~ 6 – 8 % “calibration” of *pC* polarimeters