Polarized Proton Elastic Scattering at very low –t region in RHIC

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Outline

- Theoretical background on proton elastic scattering process, and previously obtained experimental results

- Aspects for the proton polarimetry
  in high energy spin physics (RHIC Spin)

- Experimental techniques (setup, complex)
  - pC CNI measurements at RHIC, AGS
  - pp CNI measurements with H Jet target

- Recent results from Run-2004

- Issues and technical difficulties

Introduction for polarized proton elastic scattering

Polarized Proton-proton elastic scattering

- Measurement of helicity amplitudes at high energy
  → dynamical mechanism in asymptotic region
- 5 independent amplitudes ϕ_i (6th exists for non-identical particles scattering)

①② ③④

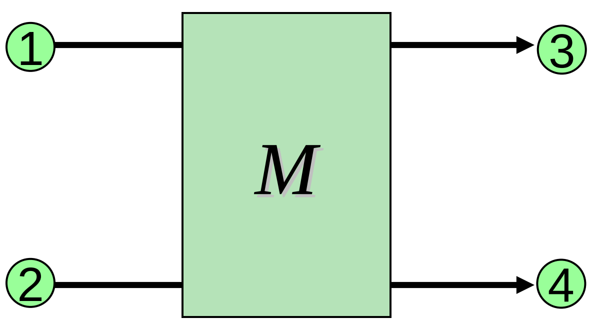
Non-flip $\phi_1(s,t)=\langle ++|M|++\rangle$

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

Non-flip $\phi_3(s,t)=\langle +-|M|+-\rangle$

double spin flip $\phi_4(s,t)=\langle +-|M|-+\rangle$

single spin flip $\phi_5(s,t)=\langle ++|M|+-\rangle$



The region at RHIC

$|t| << m << \sqrt{s}$

total cross-section (optical theorem)

$$\sigma_{\text{tot}}=\frac{4\pi}{s}\text{Im}[\phi_1(s,t)+\phi_3(s,t)]\Big|_{t=0}$$

differential cross-section

$$\frac{d\sigma}{dt}=\frac{2\pi}{s^2}\{|\phi_1|^2+|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+4|\phi_5|^2\}$$

In case of, p + Spin0
Only “Non-flip” or “Single-flip” exist

Spin dependent asymmetries

- Use initial state polarization of beams
- 7 spin independent asymmetries (AN',ALS' degenerate for identical particles)

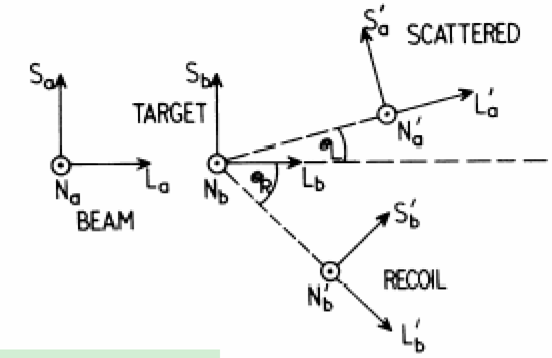
$$A_N \frac{d\sigma}{dt} = -\frac{4\pi}{s^2} \mathrm{Im}\{\phi_5^*(\phi_1+\phi_2+\phi_3-\phi_4)\}$$

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

$$A_{SS} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \mathrm{Re}\{\phi_1\phi_2^* + \phi_3\phi_4^*\},$$

$$A_{SL} \frac{d\sigma}{dt} = \frac{4\pi}{s^2} \mathrm{Re}\{\phi_5^*(\phi_1+\phi_2-\phi_3+\phi_4)\},$$

$$A_{LL} \frac{d\sigma}{dt} = \frac{2\pi}{s^2}\{|\phi_1|^2 + |\phi_2|^2 - |\phi_3|^2 - |\phi_4|^2\}.$$



Conventional shorthand

$$\phi_+ = \tfrac{1}{2}(\phi_1+\phi_3), \quad \phi_- = \tfrac{1}{2}(\phi_1-\phi_3),$$

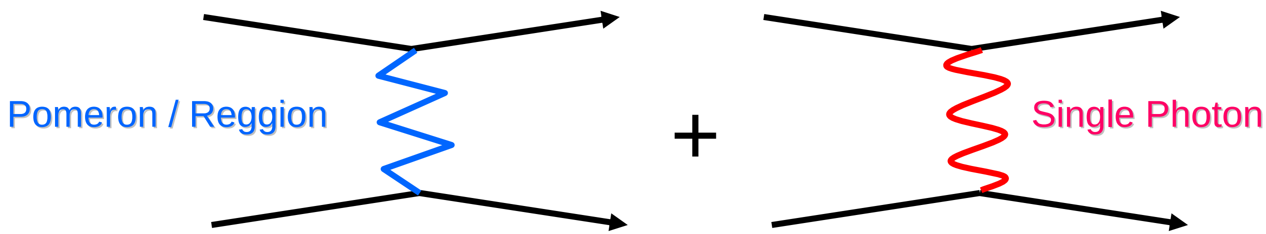
Cross section diffs. (Longitudinal/Transverse)

$$\frac{\mathrm{Im}\,\phi_-(s,0)}{\mathrm{Im}\,\phi_+(s,0)} = \frac{1}{2}\frac{\Delta\sigma_L(s)}{\sigma_{\mathrm{tot}}(s)}, \quad \Delta\sigma_L = \sigma_{\rightleftarrows} - \sigma_{\rightrightarrows},$$

$$\frac{\mathrm{Im}\,\phi_2(s,0)}{\mathrm{Im}\,\phi_+(s,0)} = -\frac{\Delta\sigma_T(s)}{\sigma_{\mathrm{tot}}(s)}, \quad \Delta\sigma_T = \sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}.$$

- Needs substantial measurements far from Experimental situation
- **Only AN (analyzing power) extensively measured**

Interference of Hadronic/Electromagnetic



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

→ Interference

CNI = Coulomb – Nuclear Interference

$$\phi_i \rightarrow \phi_i^{had} + \phi_i^{em} \exp(i\delta)$$

Single photon exchange is approximated

$$\phi_1^{\mathrm{em}} = \phi_3^{\mathrm{em}} = \frac{\alpha s}{t} F_1^2 \qquad \phi_2^{\mathrm{em}} = -\phi_4^{\mathrm{em}} = \frac{\alpha s \kappa^2}{4m^2} F_2^2$$

$$\phi_5^{\mathrm{em}} = -\frac{\alpha s \kappa}{2m\sqrt{-t}} F_1 F_2$$

QED exact calculation available

F_1,F_2 : proton em form factors

κ: anomalous magnetic moment

Hadronic amplitude

$$\phi_j \equiv \phi_j^R + \phi_j^{As} \qquad \phi_j^R / \phi_j^{As} \rightarrow 1/\sqrt{s} \ (s \rightarrow \infty)$$

simple Pomeron pole + something (one model)

$$\mathrm{Im}\, \phi_+^{As}(s) = a_P s + a_F s \ln^2 s$$

Spin flip amplitude (r_5) and $A_N(t)_{pp}$

Asymptotic behavior of non-dominant amplitudes

$$r_2 = R_2 + iI_2 = \frac{\phi_2}{2\,\mathrm{Im}\,\phi_+}$$

$$r_- = R_- + iI_- = \frac{\phi_-}{\mathrm{Im}\,\phi_+}$$

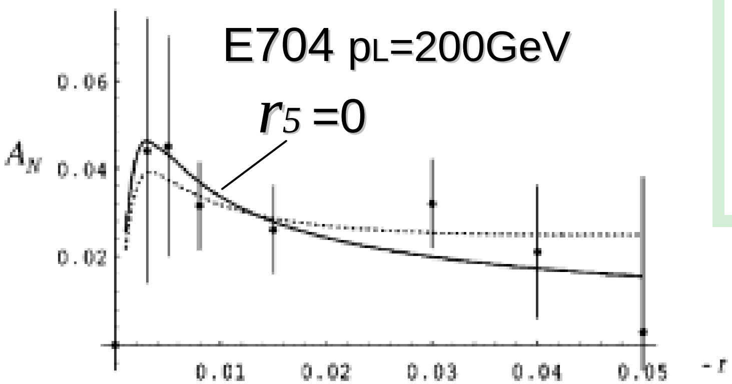
$$r_4 = R_4 + iI_4 = -\frac{m^2\phi_4}{t\,\mathrm{Im}\,\phi_+}$$

$$\boxed{r_5 = R_5 + iI_5 = \frac{m\,\phi_5}{\sqrt{-t}\,\mathrm{Im}\,\phi_+}}$$

$$A_N = \frac{\mathrm{Im}\{(2\phi_+ + 2e^{i\delta}\phi_+^{\mathrm{em}} + \phi_2)^*(\phi_5 + e^{i\delta}\phi_5^{\mathrm{em}})\}}{|\phi_+ + e^{i\delta}\phi_+^{\mathrm{em}}|^2 + |\phi_-|^2 + (1/2)|\phi_2|^2 + 2|\phi_5 + e^{i\delta}\phi_5^{\mathrm{em}}|^2}$$

$$\frac{m A_N}{\sqrt{-t}}\boxed{\frac{16\pi}{\sigma_{\mathrm{tot}}^2}\frac{d\sigma}{dt}e^{-Bt}} = [\kappa(1-\delta\rho+\mathrm{Im}\,r_2-\delta\,\mathrm{Re}\,r_2) - 2(\mathrm{Im}\,r_5-\delta\,\mathrm{Re}\,r_5)]\frac{t_c}{t} - 2(1+\mathrm{Im}\,r_2)\mathrm{Re}\,r_5 + 2(\rho+\mathrm{Re}\,r_2)\mathrm{Im}\,r_5$$

$$\boxed{\frac{16\pi}{\sigma_{\mathrm{tot}}^2}\frac{d\sigma}{dt}e^{-Bt}} = \left(\frac{t_c}{t}\right)^2 - 2(\rho+\delta)\frac{t_c}{t} + (1+\rho^2)(1+\beta^2)$$



if used for polarimetry
$\Rightarrow \Delta P/P \sim 15 - 20\%$

δ, ρ known, β=0, r_i set to 0 (except r_5)

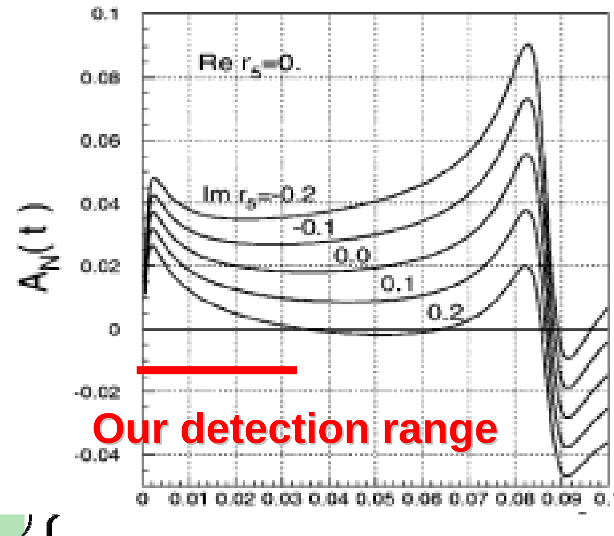
$$t_c = -8\pi\alpha/\sigma_{\mathrm{tot}}$$

r_5 is the one parameter left, A_N is function of t

Extension to *p+C* elastic scattering

based on PLD64,034004
B.Z. Kopeliovich et al (2001)

- similar form as *pp*
- substantially modified by nuclear effects
- $A_N(t)$ sensitive to r_5



-t

$$\frac{16\pi}{(\sigma_{tot}^{pC})^2}\frac{d\sigma_{pC}}{dt}A_N^{pC}(t) =$$

$$\frac{\sqrt{-t}}{m_N}F_C^h(t)\Big\{F_C^{em}(t)\frac{t_c}{t}[\kappa(1-\delta_{pC}\rho_{pC})$$

$$-2(\mathrm{Im}\, r_5^{pC} - \delta_{pC}\mathrm{Re}\, r_5^{pC})] - 2F_A^h(t)(\mathrm{Re}\, r_5^{pC} - \rho_{pC}\mathrm{Im}\, r_5^{p})\Big\}$$

$$\frac{16\pi}{(\sigma_{tot}^{pC})^2}\frac{d\sigma_{pC}}{dt} =$$

$$\left(\frac{t_c}{t}\right)^2[F_C^{em}(t)]^2 - 2(\rho_{pC}+\delta_{pC})\left(\frac{t_c}{t}\right)F_C^h(t)F_C^{em}(t) + \left(1+\rho_{pC}^2 - \frac{t}{m_p^2}|r_5^{pC}|^2\right)[F_C^h(t)]^2$$

F_c^{em}, F_c^h Form factors (Electromagnetic, Hadronic)

express pC process with r_5

$$r_5^{pC}(t) = \frac{1-i\rho_{pC}(t)}{1-i\rho_{pN}}r_5$$

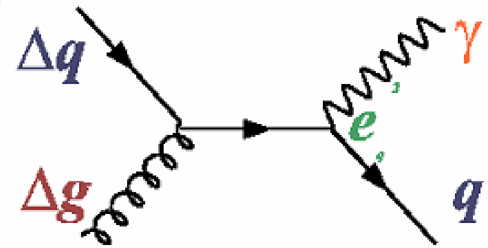
From the fit to $A_N(t)$, determination of r_5 and comparison with *pp* scattering is possible

Proton Polarimeter

Important Device for the RHIC Spin Physics

RHIC Spin Project

proton spin crisis



$$1/2=(1/2)\Delta\Sigma+\Delta g+L_Q+L_G$$

$$A_{LL}=\boxed{\frac{\Delta g(x_1)}{g(x_1)}}\otimes\frac{\sum_i e_i^2\Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)}\otimes a_{LL}(gq\to q\gamma)$$

RHIC data

pol.DIS data

pQCD

$\Delta\Sigma$: quark spin ~ 0.2-0.3 (EMC, SMC)

Δg: gluon spin $\Delta g/g=$ -0.2+/-0.3 (SMC)

L_Q,L_G : orbital angular momentum ~ ?

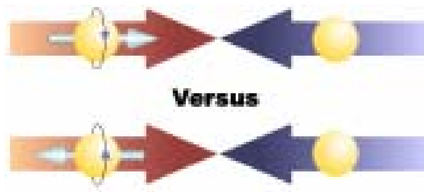
- *Δg(x) measurement*
  - Contribution of gluon polarization to the proton spin
  - The direct probe for gluon originated process using √s=200GeV, 500GeV polarized proton collisions
- Decomposition of flavor dependent contribution
- Measure Transversity

Polarimeter : Impact on the RHIC Spin project

RHIC-Spin is the first Polarized-Proton collider (E_B = 100-250GeV)

Single Spin

$N_\uparrow$



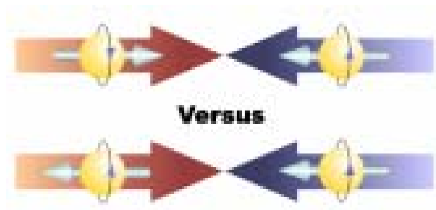
$N_\downarrow$

Physics Asymmetry

$$A_L = \frac{1}{P_B} \underbrace{\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \right)}_{= \varepsilon_L}$$

Double Spin

$N_{\uparrow\uparrow}$



$N_{\uparrow\downarrow}$

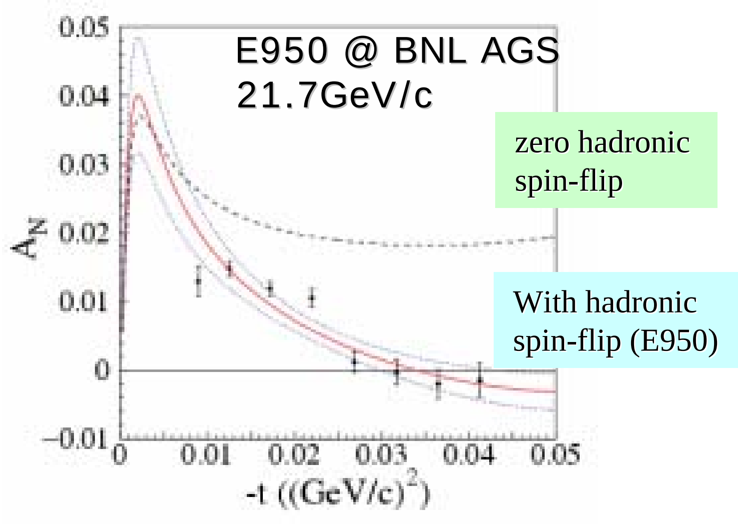
$$A_{LL} = \frac{1}{P_B^2} \underbrace{\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} \right)}_{= \varepsilon_{LL}}$$

Same for other Spin configurations (A_N, A_{TT}, etc)

- To obtain the physics quantity, the raw asymmetry (=ε) needs to be normalized by beam polarization
- Scaling correction, but generally P_B changes time to time
- Reliable and quick proton polarimeter is essential for diagnosing, monitoring the beam polarization, requires dP/P < 5%

E950 measurement at AGS

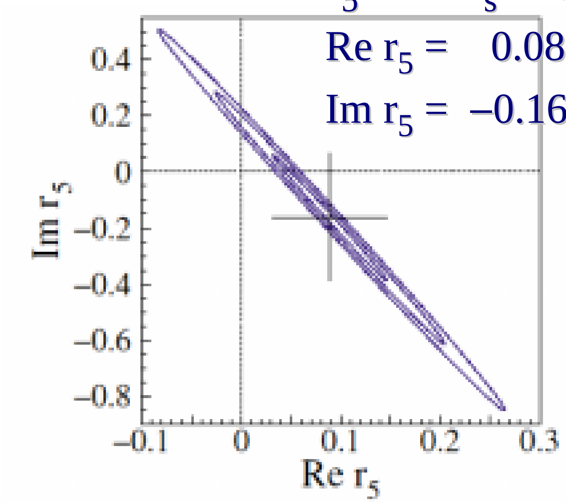
- A_N measurement for elastic $\vec{p}+C$ scattering
- 21.7 GeV/c polarized proton beam, calibrated with separate polarimeter (E925) using extracted AGS beam
- Large contribution (~15%) from hadronic spin-flip amplitude



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

$Re\, r_5 = 0.088 \pm 0.058$

$Im\, r_5 = -0.161 \pm 0.226$



- Constraint
  - Close to the RHIC injection energy (24GeV/c), but one step smaller than the last strong intrinsic resonance
  - ~30% measurement error is tied to the ambiguity of beam polarization (E925)

Pomeron spin flip amplitude

based on hep-ph/0305085
T.L.Trueman (2003)

Introduce t independent parameter $\tau(s)$

$$\phi_5(s,t) = \tau(s)\frac{\sqrt{-t}}{m}\phi_+(s,t)$$

Analogy to the non-flip scattering
(*pp* elastic, dominated by I=0 exchange)

$$\phi_5(s,t) = \frac{\sqrt{t}}{m}\{\boxed{\tau_P}\phi_P(s) + \boxed{\tau_f}\phi_f(s) + \boxed{\tau_\omega}\phi_\omega(s)\}$$

	I=0	*I=1*
pp	*P,f₁,ω*	*a₂,ρ*
pC	*P,f₁,ω*	

$\phi_P(s), \phi_f(s), \phi_\omega(s)$: form established
τ's are real numbers

$$\phi_P(s) = -Xs^\varepsilon(\cot\frac{\pi}{2}(1+\varepsilon)-i)$$
$$\phi_f(s) = -Ys^\eta(\cot\frac{\pi}{2}(1+\eta)-i)$$
$$\phi_\omega(s) = -Y's^{\eta'}(\tan\frac{\pi}{2}(1+\eta')+i)$$

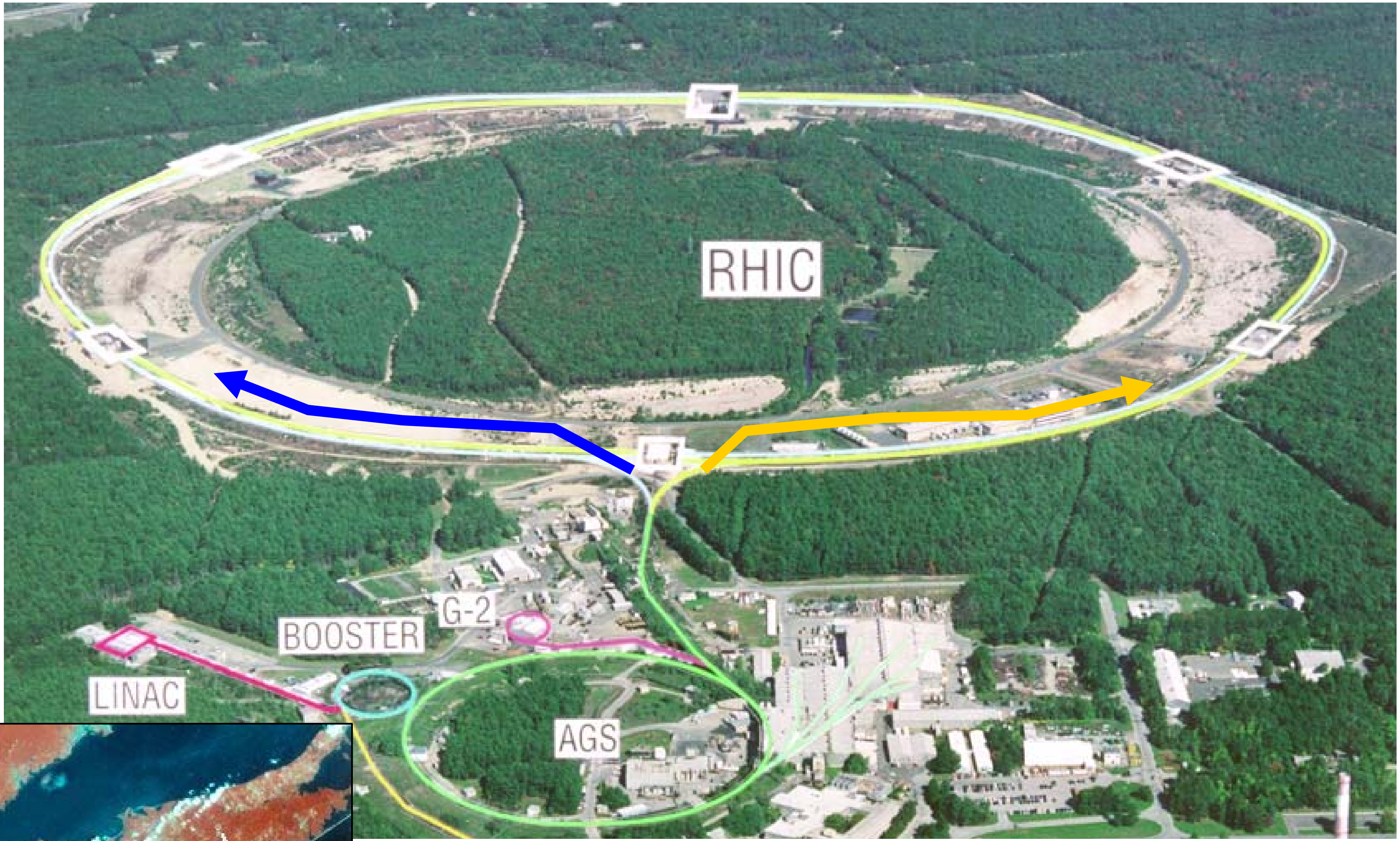
Once these parameters are determined,
$A_N(t)$ at any energy (s) can be predicted

In hep-ph/0305085
from results τ (e950) (2eq.), and
the shape of A_N at 100GeV (Run2002) (1eq.)

τ_P= -0.02, τ_f= -0.43, τ_ω= 0.03 with large ambiguity

Experimental Techniques (Setup, Complex)

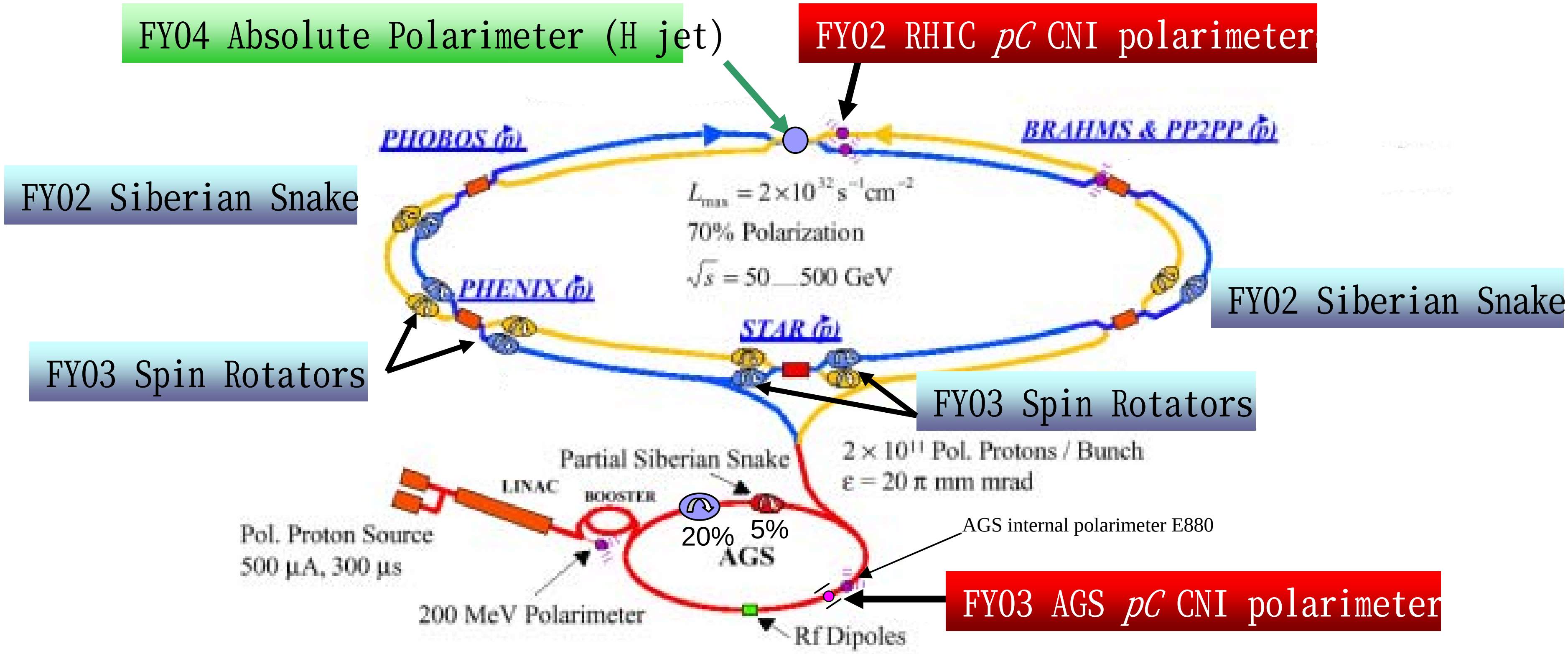
RHIC/AGS at Brookhaven National Laboratory



RHIC is visible from air-plane

4km circumference

RHIC varieties of components for pp-mode



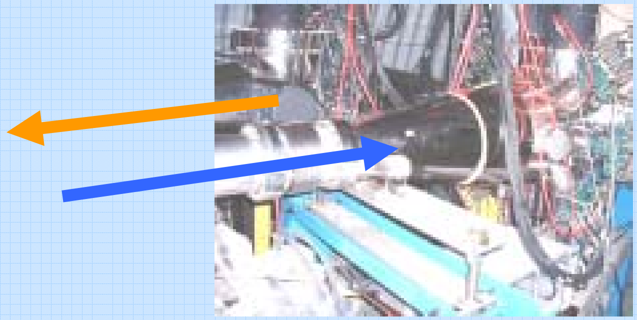
Full Siberian Snakes : Cold helical dipole magnets
Avoid all spin resonances
keep polarization at store

Spin Rotators : longitudinal spin direction at collision point

Trilogy of CNI polarimetry

RHIC – polarimeters

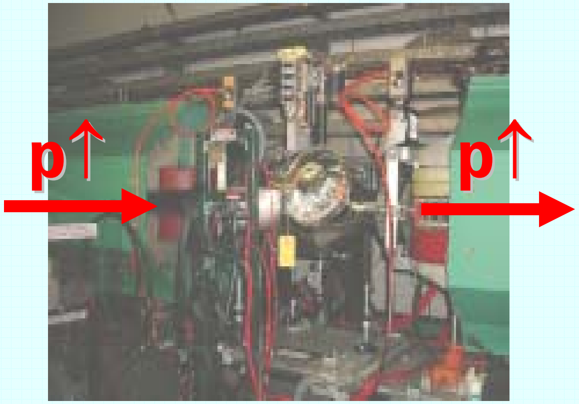
Quick and stable measurements
Provide polarization info for experiments
Goal is $\Delta p/p$=5%, needs to be calibrated



Inside the RHIC tunnel at IP12 area

AGS – polarimeter

Diagnostic device for the polarization in AGS acceleration



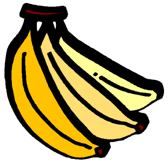
Inside the AGS tunnel at C15

Hydrogen Gas JET target polarimeter

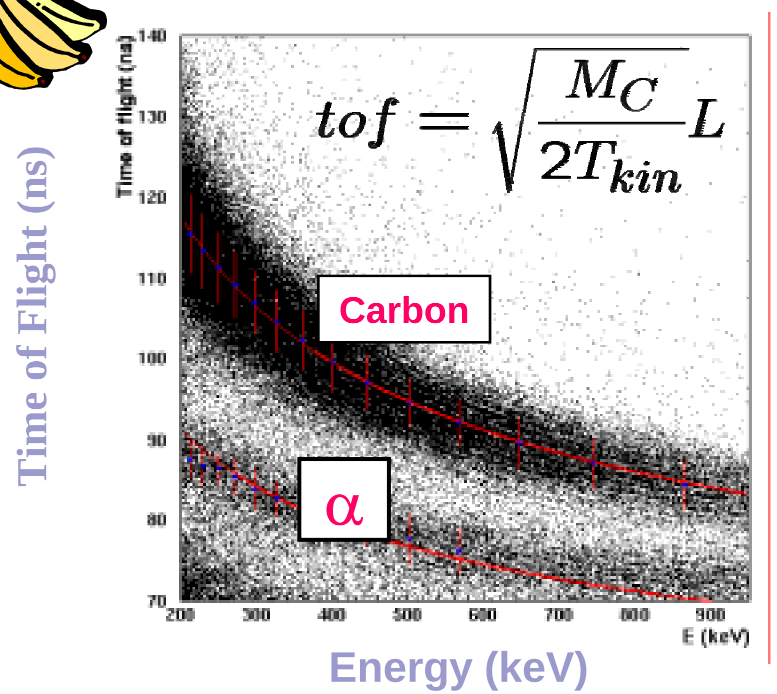
Consists of 95±1% polarized H jet target and *pp*→ *pp* elastic polarimeter
Provide beam polarization without ambiguity from theoretical model
(firstly commissioned at Run-04)

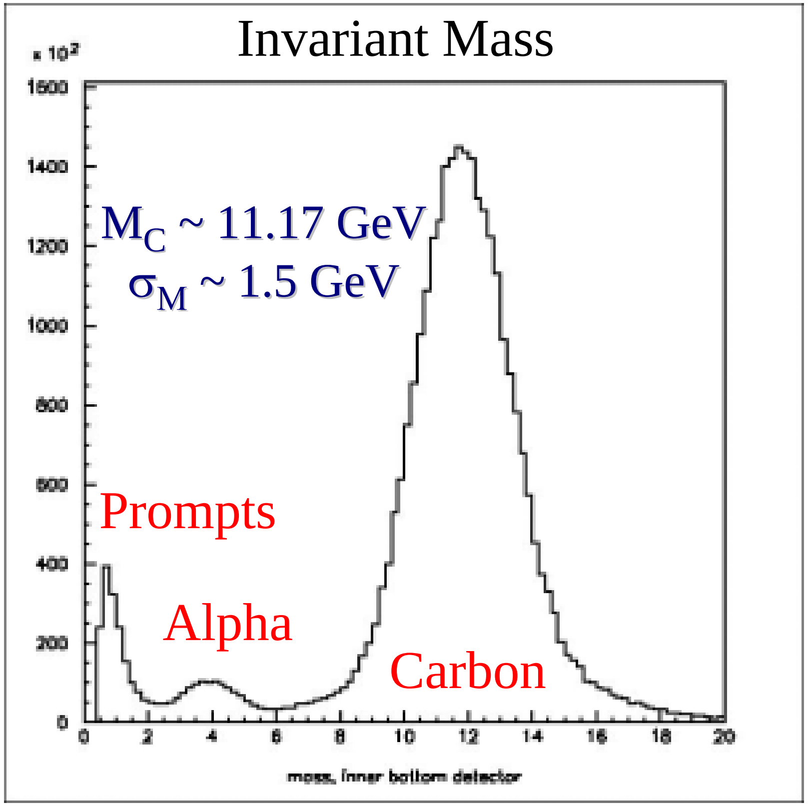
Event selection

- Strong correlation : Kinetic relation (TOF vs. Energy) of recoil particle
- Banana cut can identify the carbon (≡ mass cut)
- Back ground < a few %

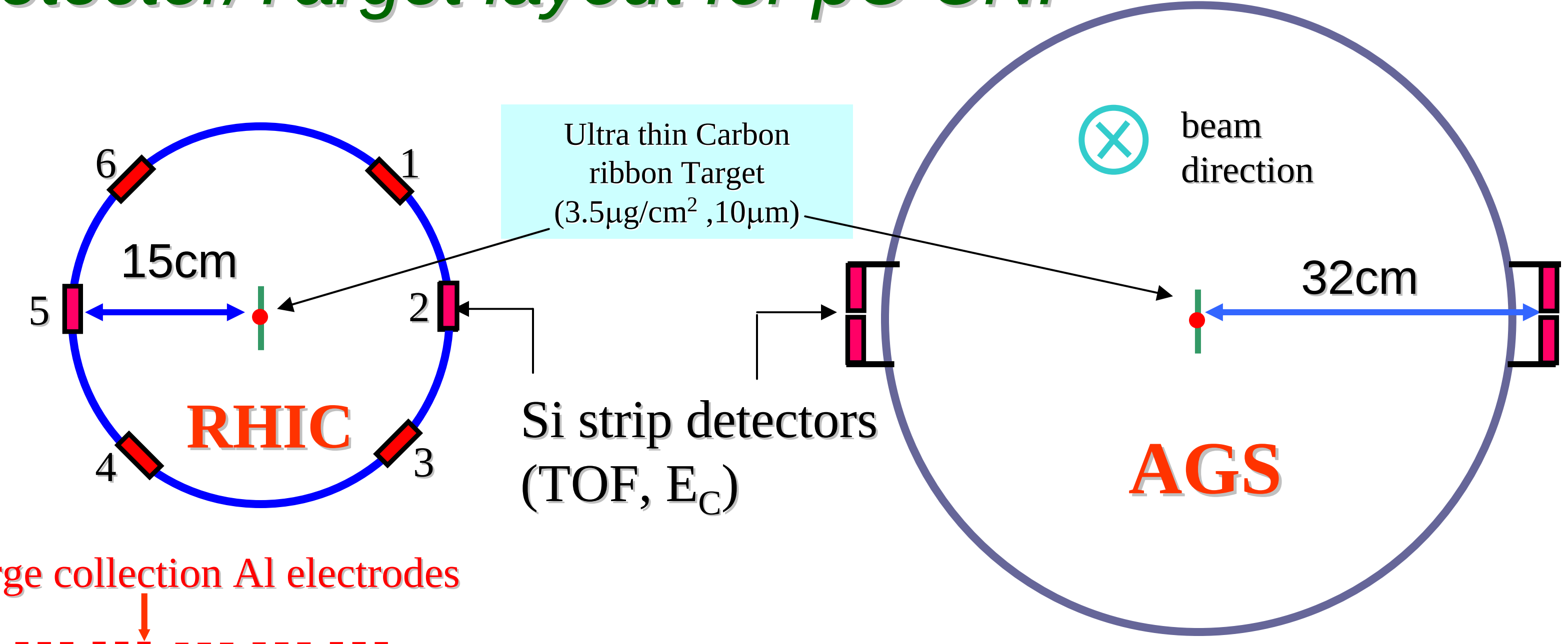


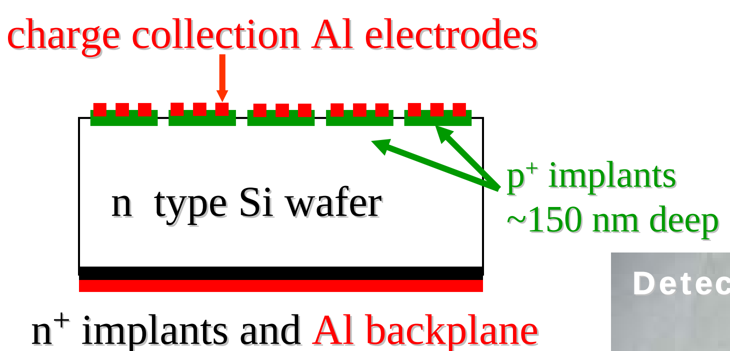
non-relativistic kinematics

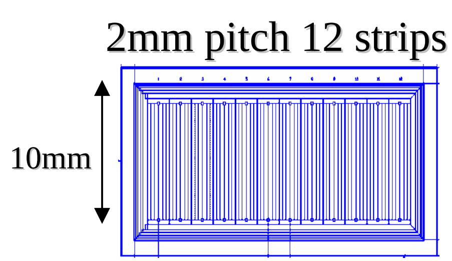


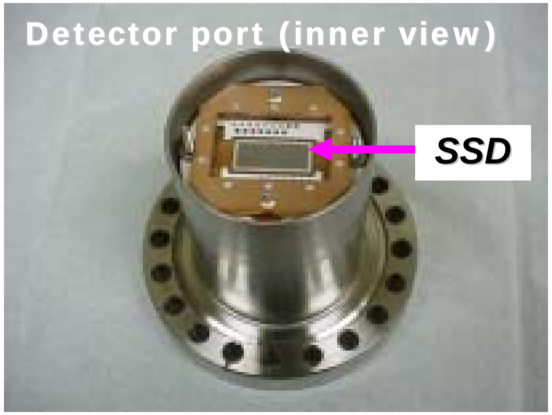


Detector/Target layout for pC CNI









- Distance: optimized for bunch crossing period
- 45 degree Si : sensitive to vertical components

The Atomic H Beam Source

Hyperfine state
(1), (2), (3), (4)

(1), (2)

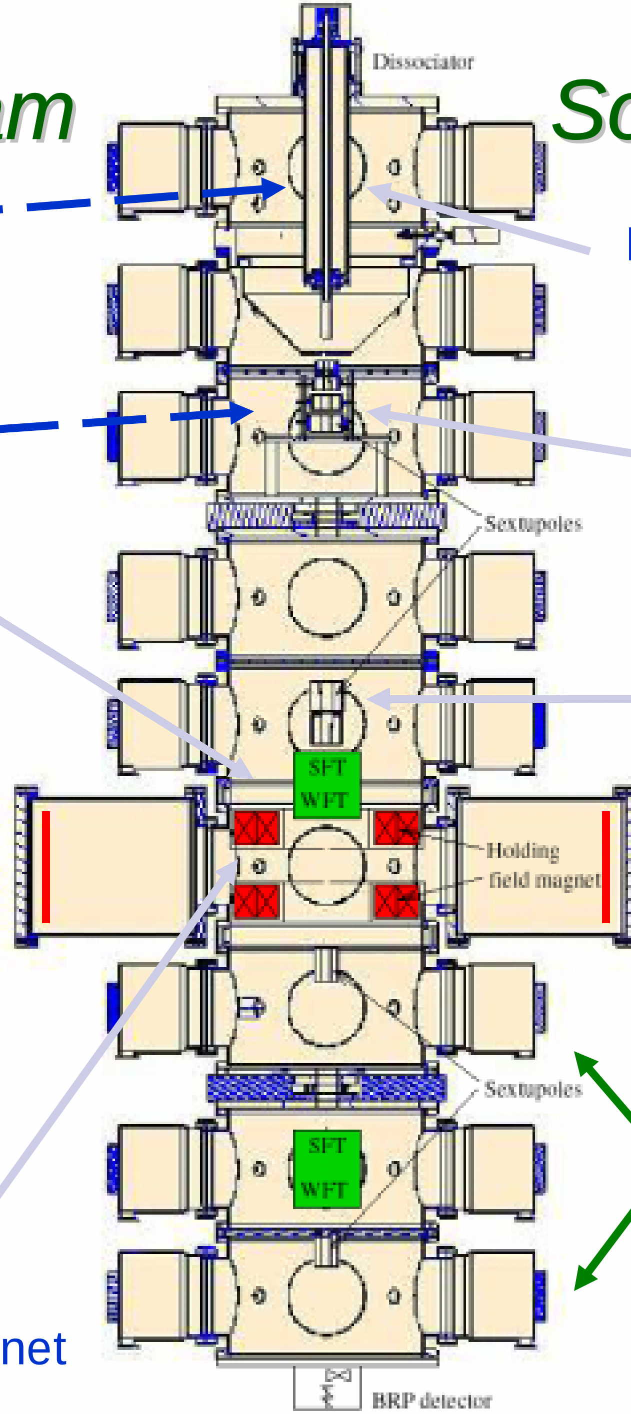
Pz+ : (1), (4) (SFT ON (2)→(4))

Pz- : (2), (3) (WFT ON (1)→(3))

Pz0: (1), (2), (3), (4)

(SFT & WFT ON)

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



H_2 dissociator

separation magnets (sextupoles)

RF transitions

focusing magnets (sextupoles)

recoil detectors

Breit-Rabi polarimeter

holding field magnet

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 blue beam

MEASURE

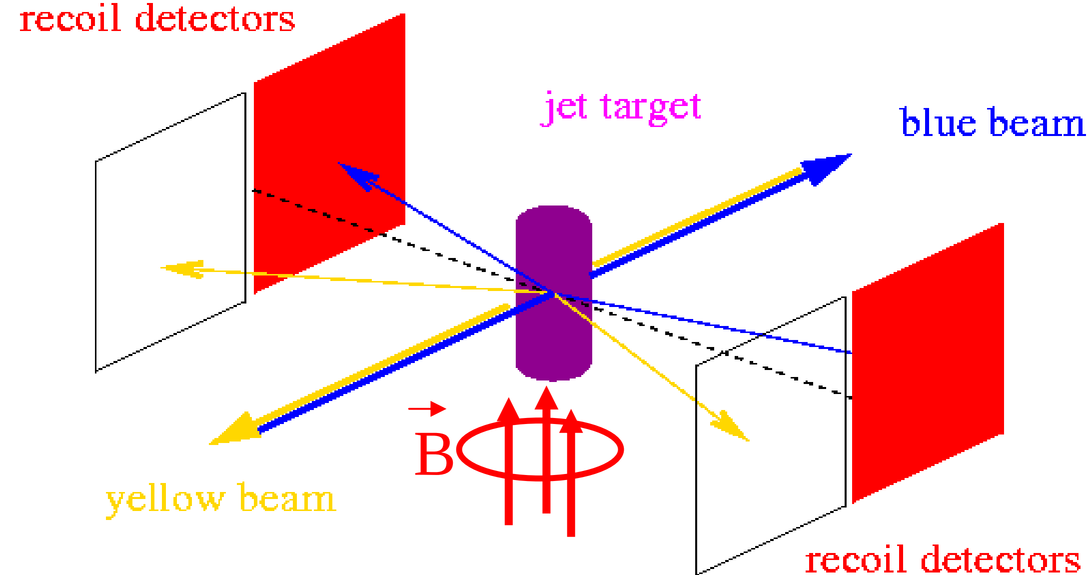
energy (res. < 50 keV)

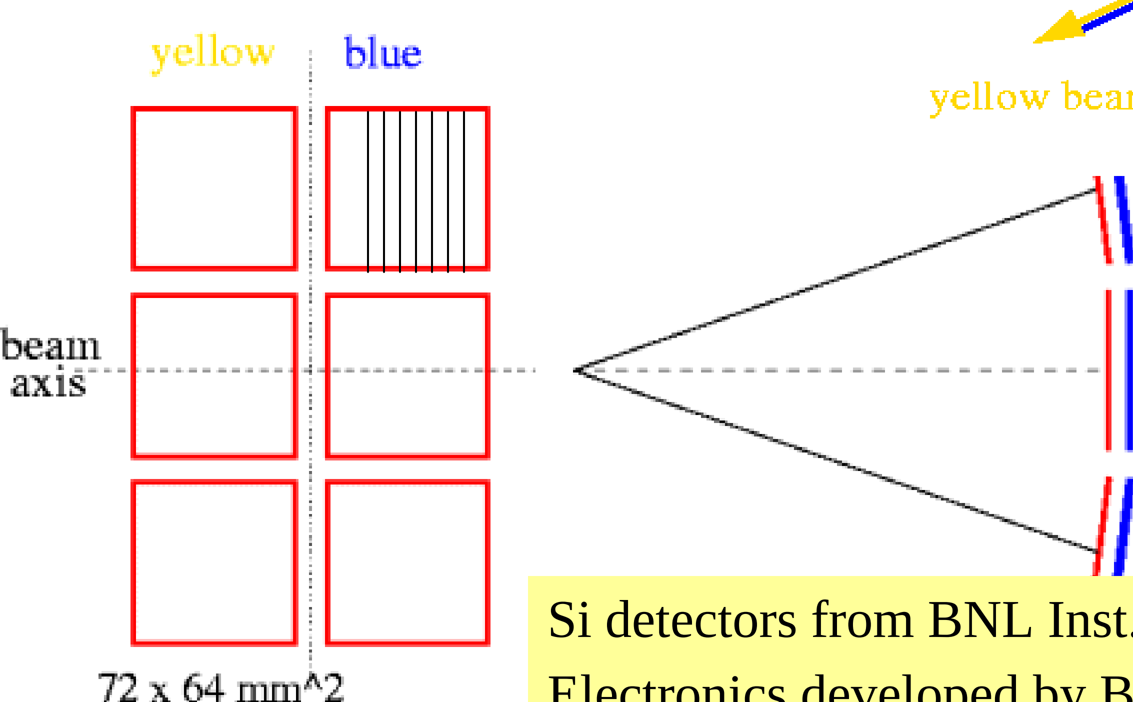
time of flight (res. < 2 ns)

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 bckgrnd rejection power

Si detectors from BNL Inst. and Hamamatsu

Electronics developed by BNL Inst. and Physics

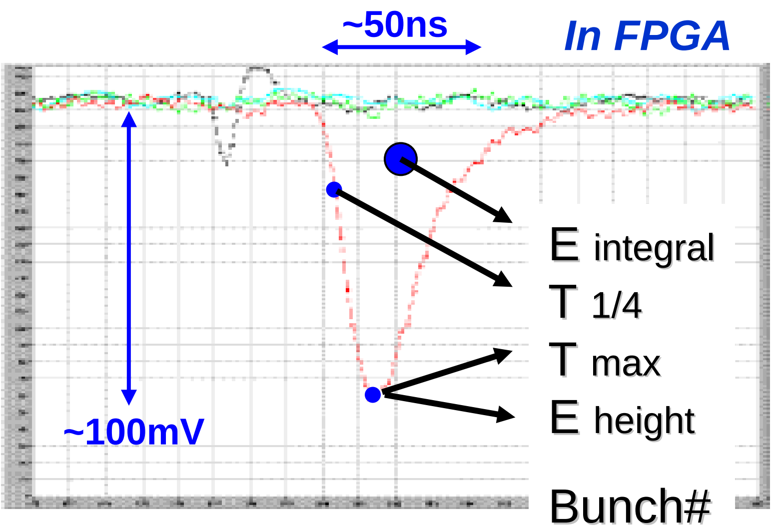
Data acquisition with WFD (Wave Form Digitizer)

CNI polarimeter is destructive for beam
Dead time free DAQ system is indispensable

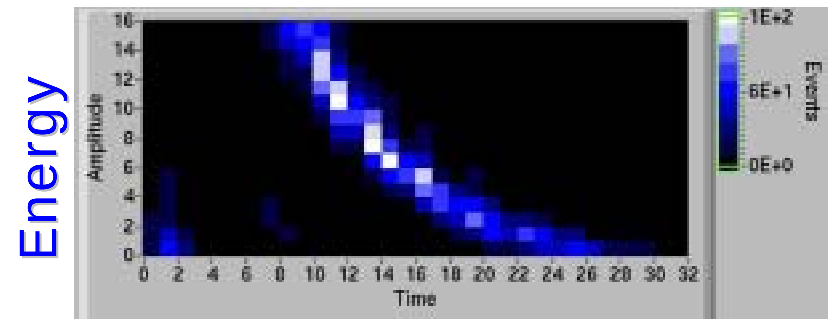
Characterize pulse with FPGA algorithm

dt ~ 1.2 nsec
dE ~ 50 keV
Sampling: 3x140MHz

In FPGA



2D Memory map in WFD



Time of Flight

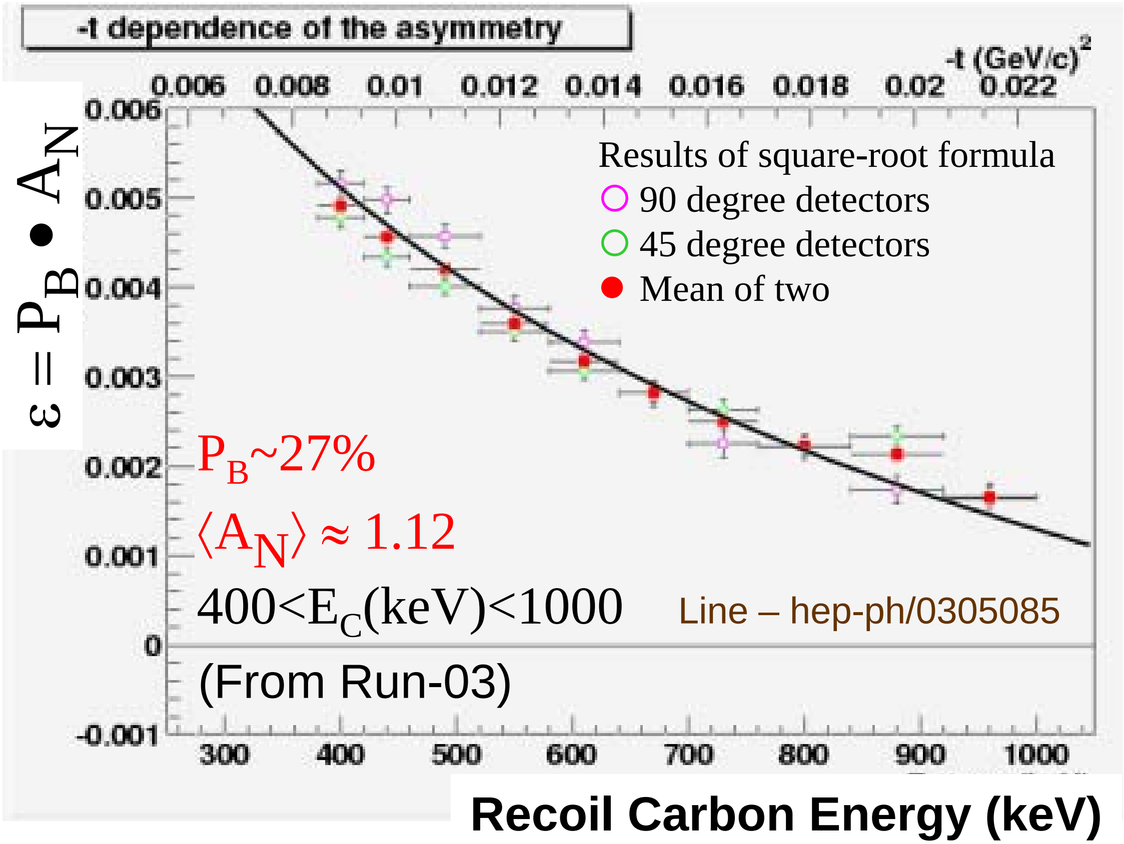
LUT → Online Results

Data stored in onboard memory
Synchronized to accelerator clock

High Statistics (20M /run)
High DAQ rate (~0.5M /sec)

Data Readout
- After Measurement (RHIC)
- Between Beam Injections (AGS)
- During Jet Polarization Flips (JET)

Raw asymmetry → Polarization



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

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

$A_N^{th}(t)$: Theoretical function fit to E950 data

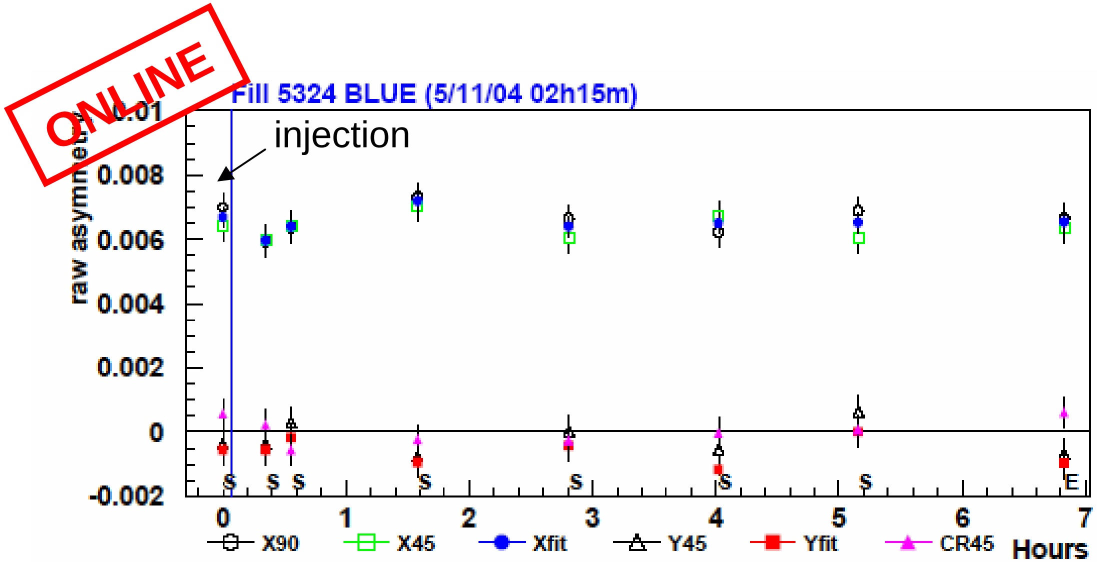
L. Trueman hep-ph/0305085

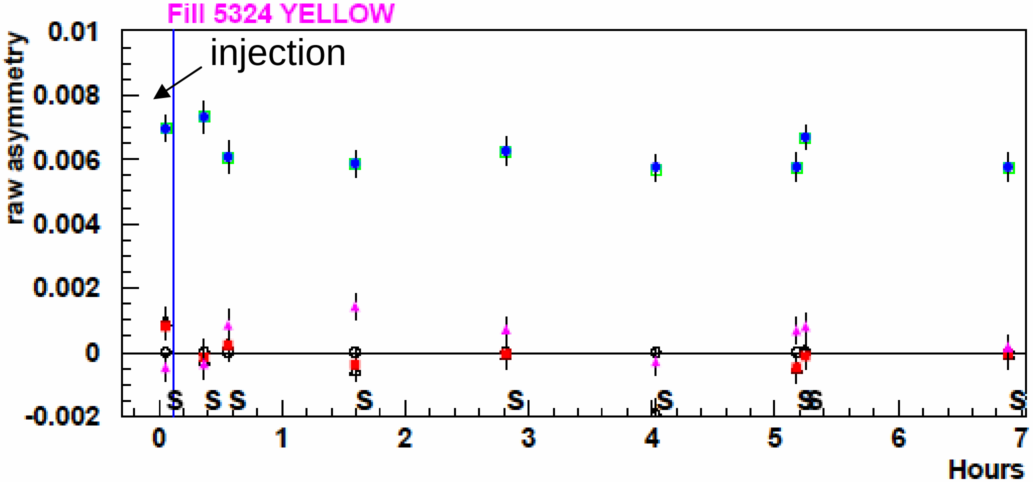
$N(t)$: Cross section curve from data

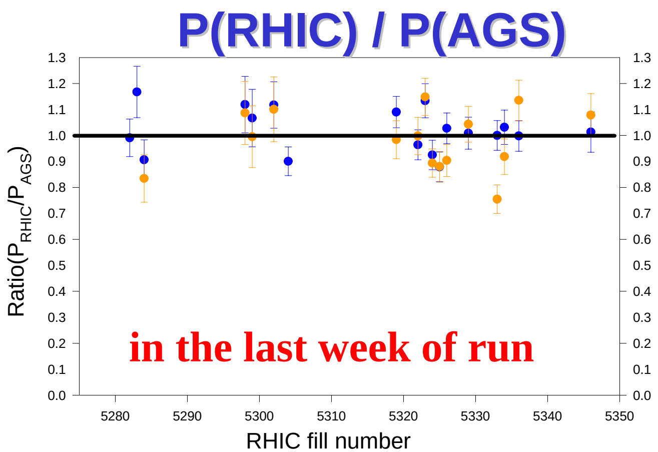
- <AN> compensates the difference in acceptance, S/N between polarimeters
- Asymmetry calculation with Square-Root Formula

Recent results from Run-04

RHIC… CNI measurements within a fill





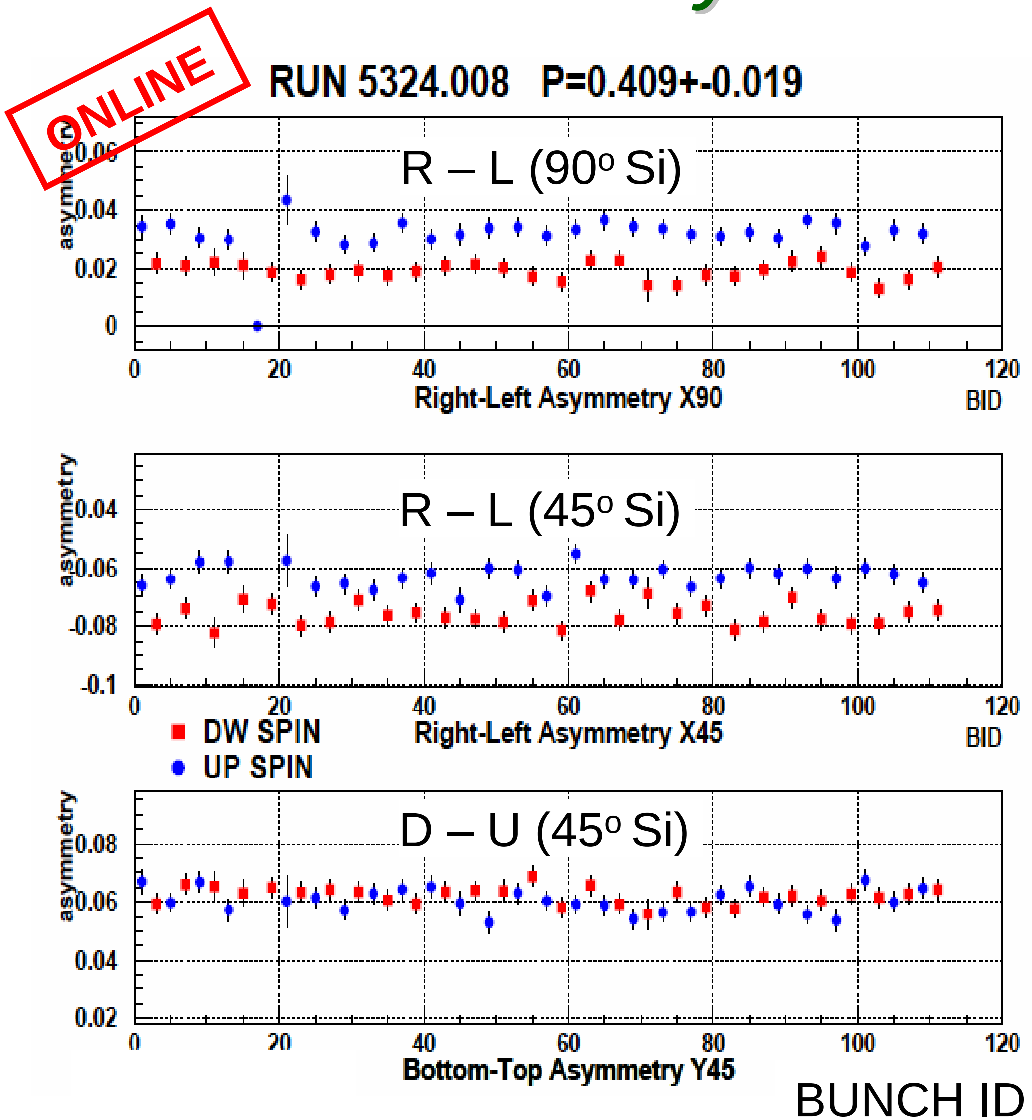


1.001+-0.016 (expect 0.974), pol.=48.7 ±0.5%

0.952+-0.019 (expect 0.993), pol.=48.6 ±0.7%

- Pol. Size is confirmed at RHIC & AGS CNI (assuming same A_N values)
- 56 bunch mode (alternating spin pattern)
- 4×10^{12} proton /ring

RHIC… Bunch by bunch Asymmetry



Simple Left-Right asymmetry

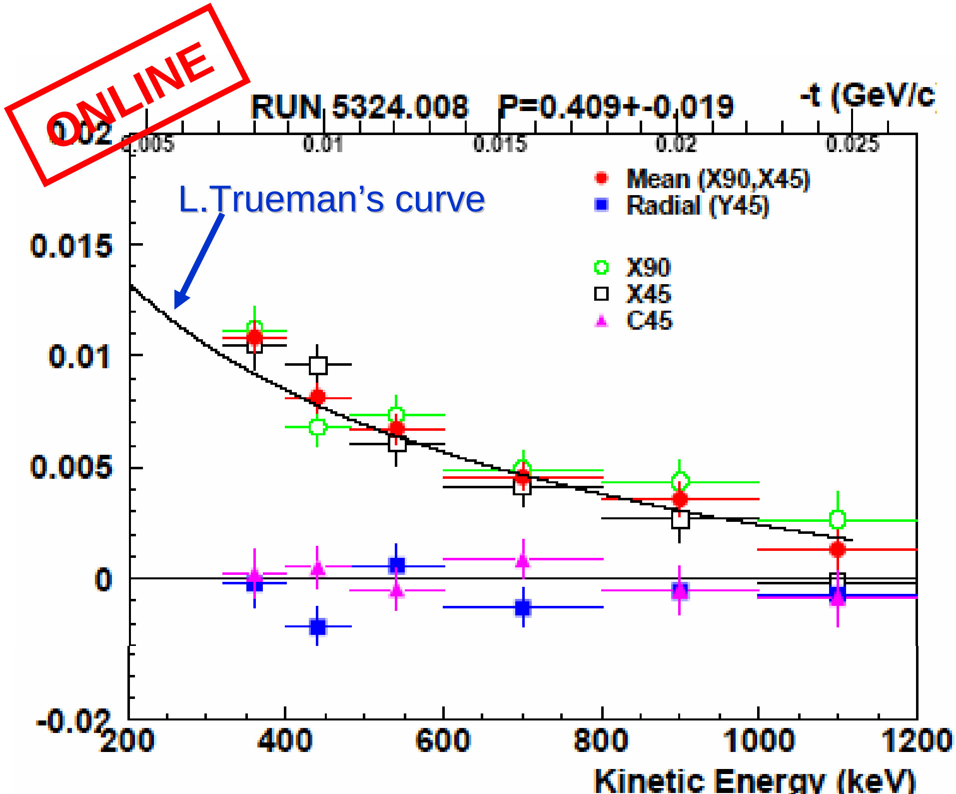
$$\varepsilon^{(i)} = -\frac{N_L^{(i)} - N_R^{(i)}}{N_L^{(i)} + N_R^{(i)}}$$

recoil detection

- + / – bunches clear separation
- Luminosity / Acceptance asymmetry stable

typical run (not best)

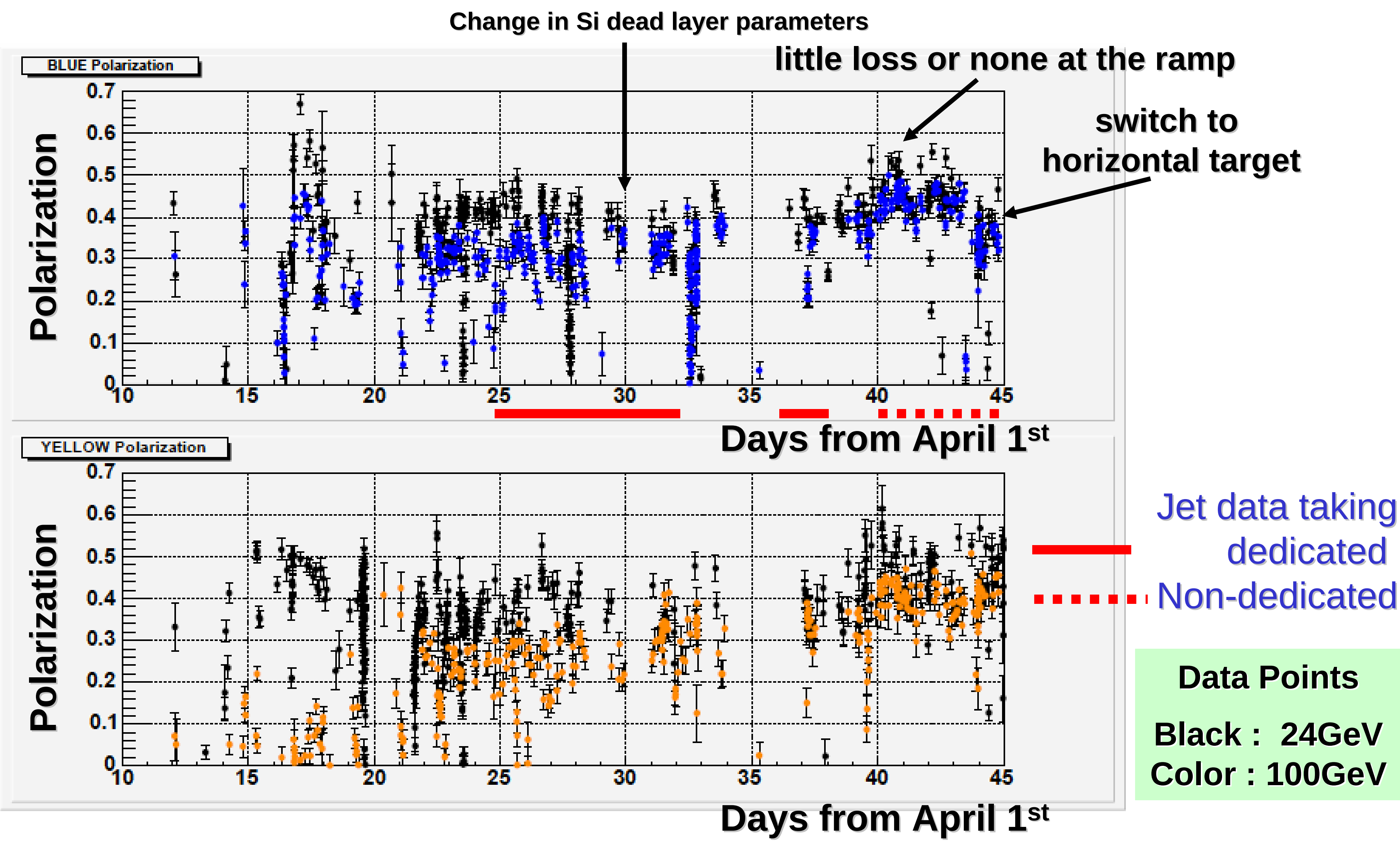
RHIC… -t dependence



typical run (not best)

- *-t* dependence follows theoretical model
- False asymmetries (Cross, Radial) are clean
- Physics asymmetries 90^o, 45^o agree

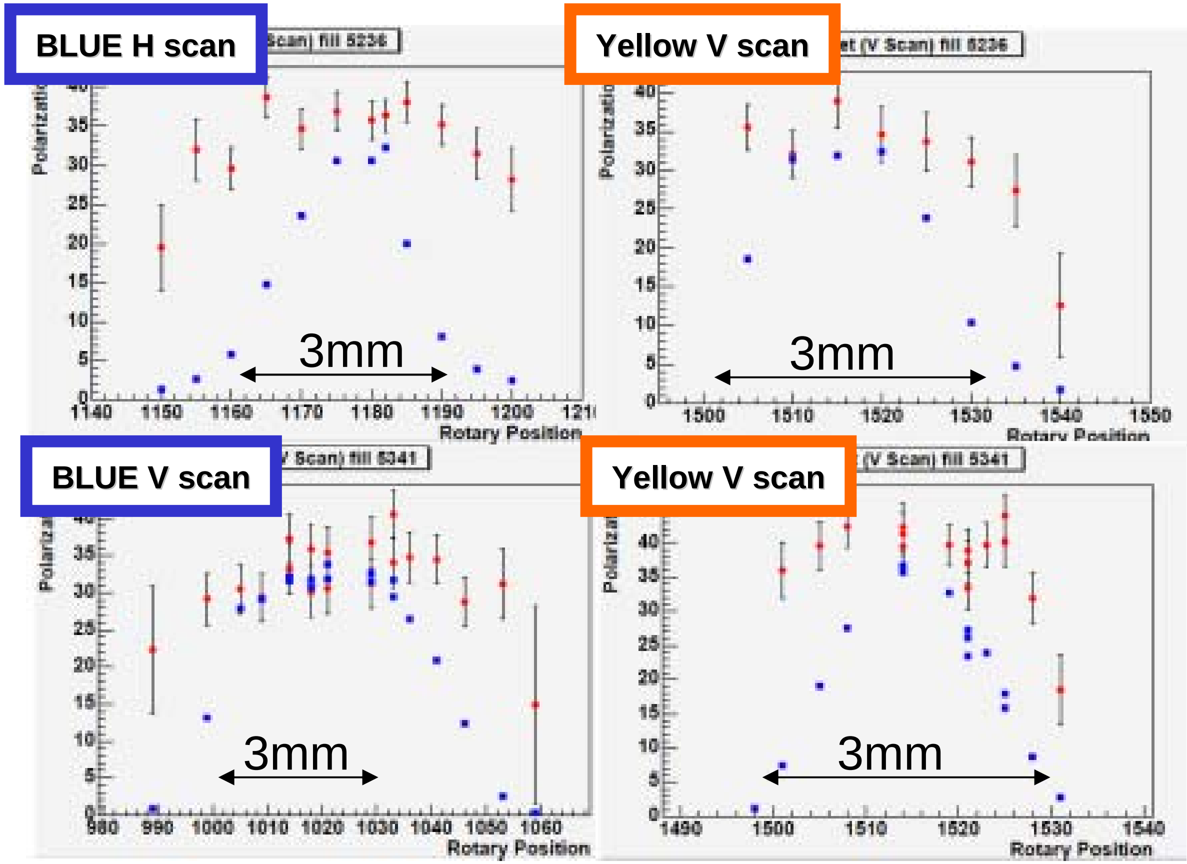
RHIC… Polarization history in pp run-04



Data Points

Black : 24GeV
Color : 100GeV

RHIC… Issues on polarization profile



● Polarization
■ Beam Intensity

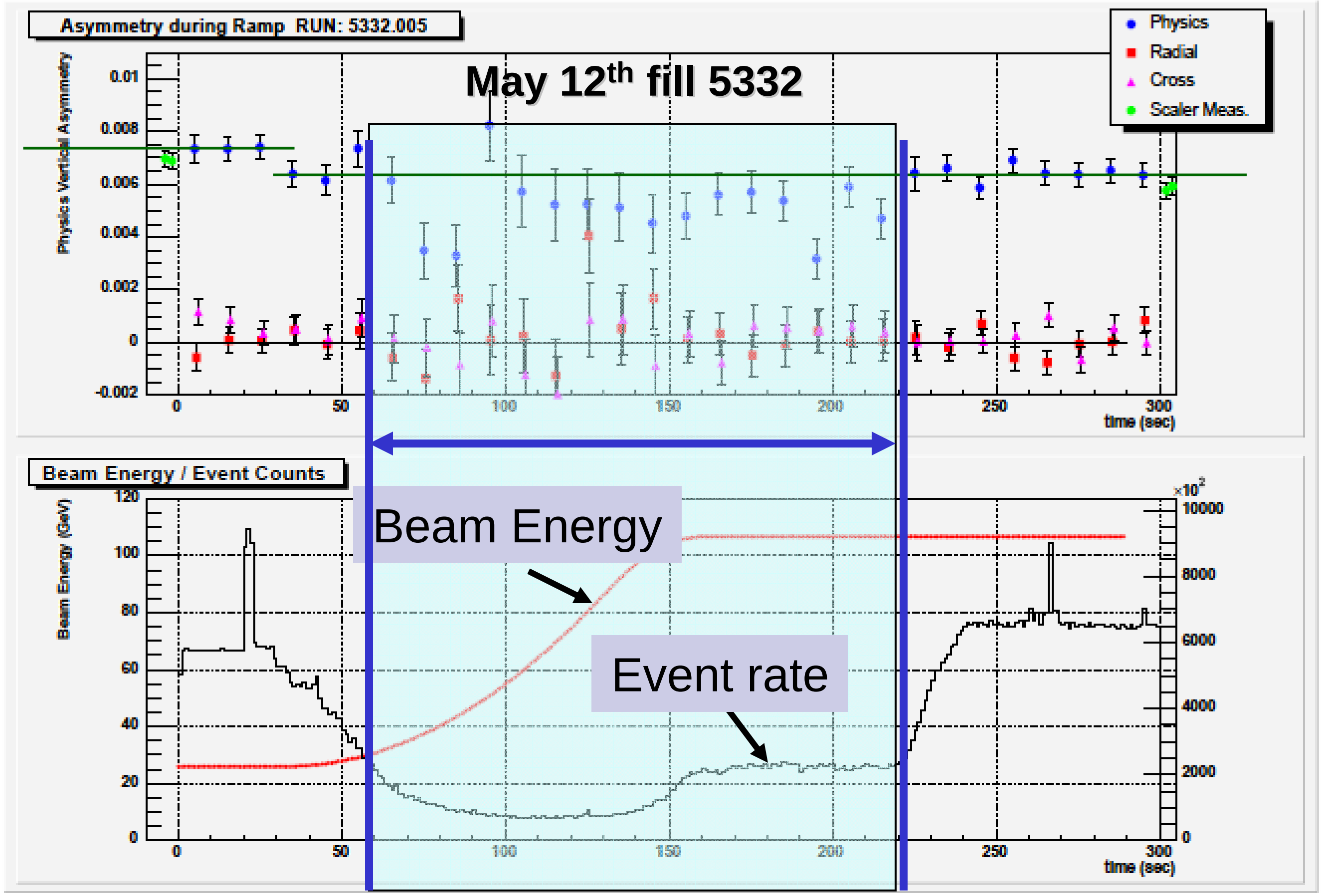
H Scan --horizontal scan with vertical target

V Scan – vertical scan with horizontal target

- Large polarization profile in vertical (small profile in horizontal)
- Observed position dependent fluctuation in pol measurements

RHIC… Ramp measurements

the last and the best one

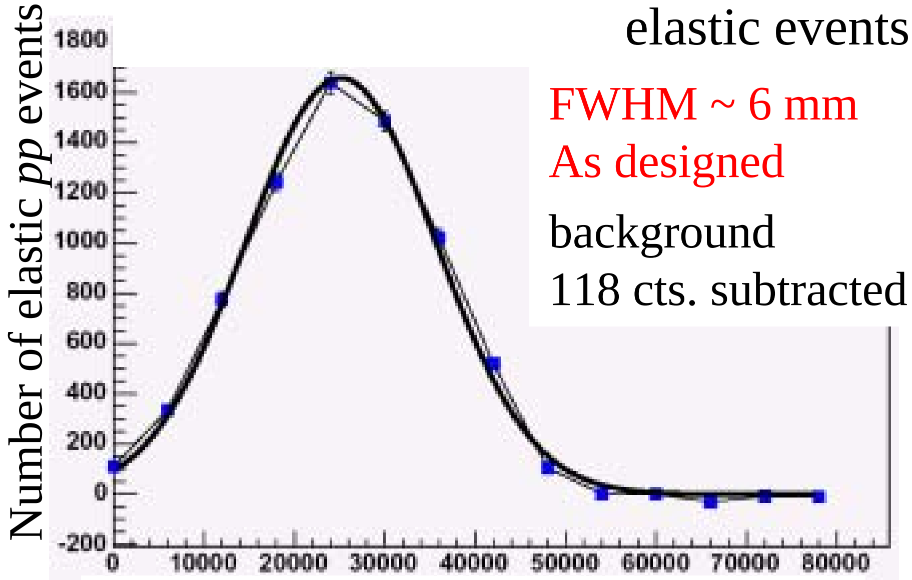


- 5 ramp measurements taken in Run-04 (Fill: *5159,5169,5170,5199,5332*)
- Larger on-board memory, larger statistics
- All of them suffered large profile effects due to the beam motion along the ramp
- Found the depolarization point prior to the energy ramp (200MHz RF cavity magnet ramp)

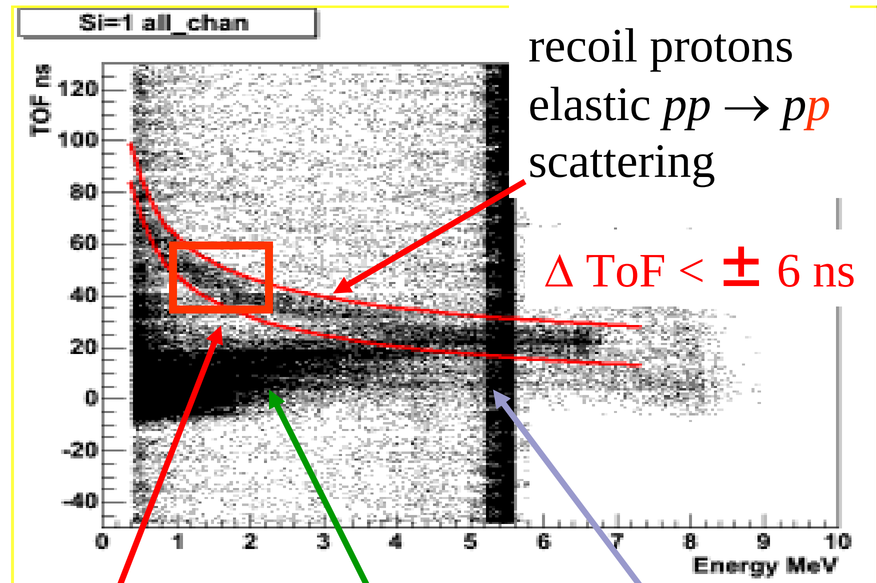
JET… pp elastic data collected

ToF vs E_{REC} correlation
$T_{kin} = ½ M_R(\text{dist}/\text{ToF})^2$

JET Profile: measured selecting *pp* elastic events



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

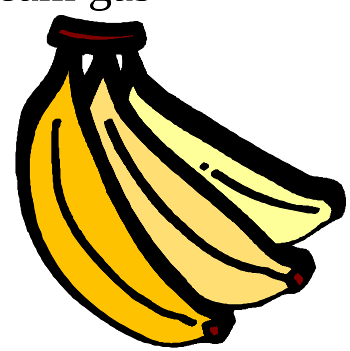


CNI peak A_N
$1 < E_{REC} < 2$ MeV

prompt events and beam gas

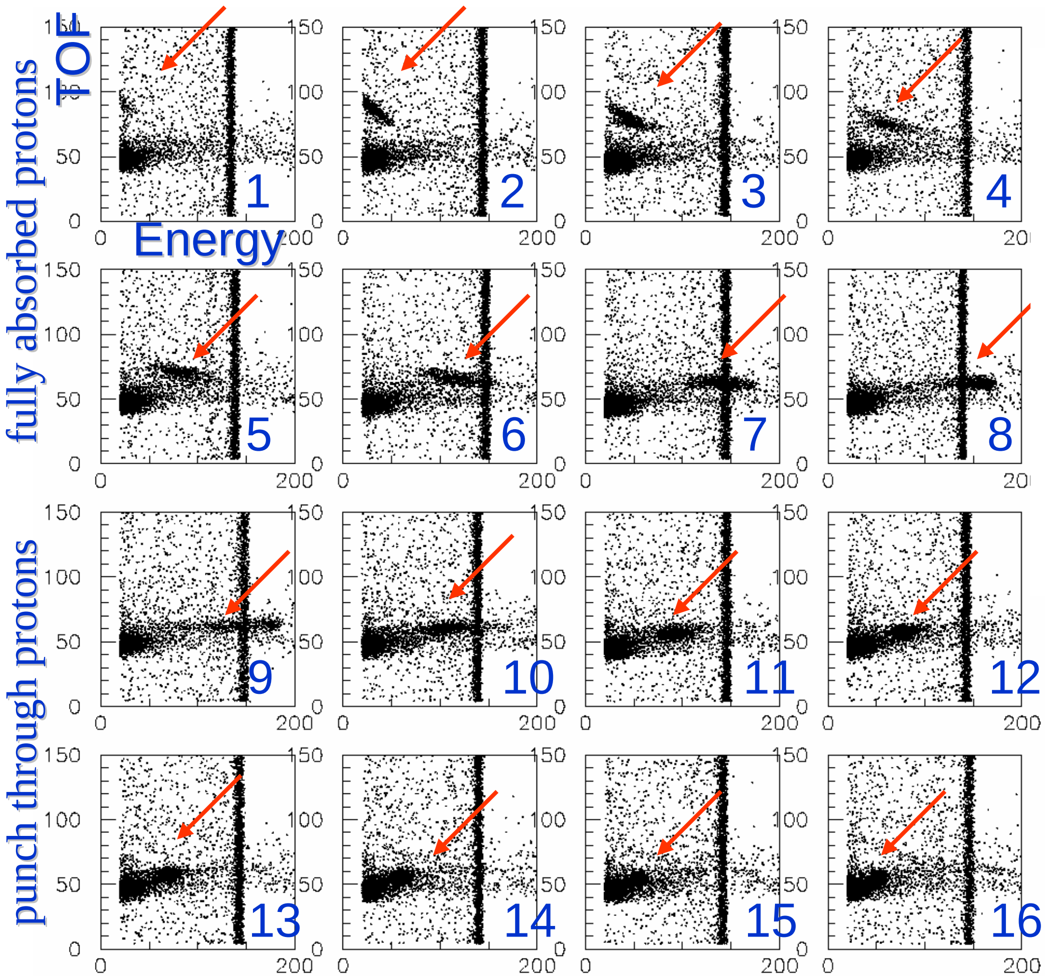
α source calibration

- recoil protons unambiguously identified !
- 100 GeV ~ 700,000 events at the peak of A_N ~ 100 hours
  (~ 2 x 10^6 total useful *pp* elastic events)
- 24 GeV ~ 120,000 events at the peak of A_N ~ 17 hours
  (~ 4 x 10^5 total useful *pp* elastic events)



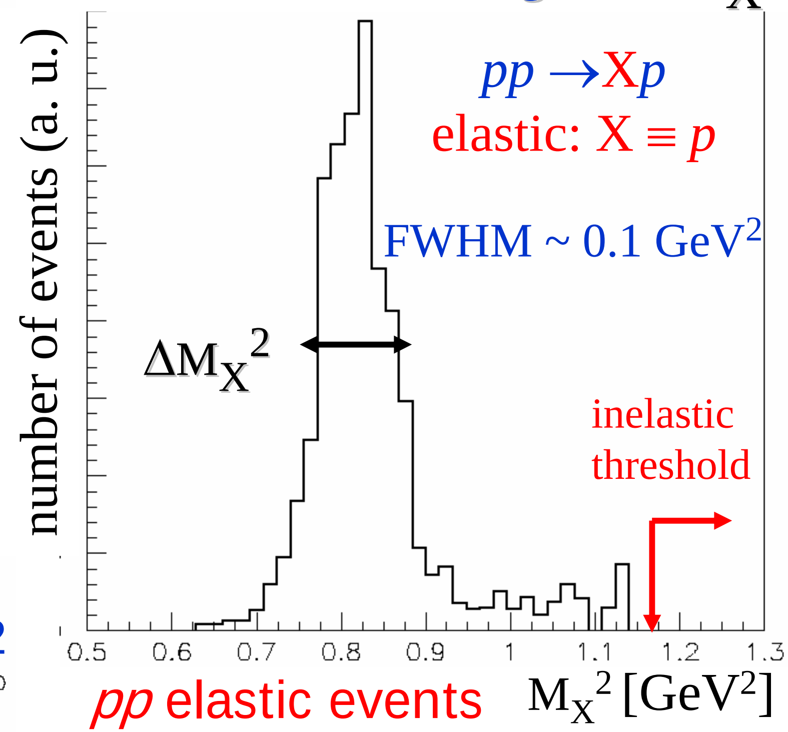
JET… Energy - Position correlations

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



TDC vs ADC individual channels

reconstructed missing mass M_X^2



$$M_X^2 = \frac{(\sin\theta_{Xp} - \sin\theta_{el})}{2P_{beam}\sqrt{|t|}} + m_p^2$$

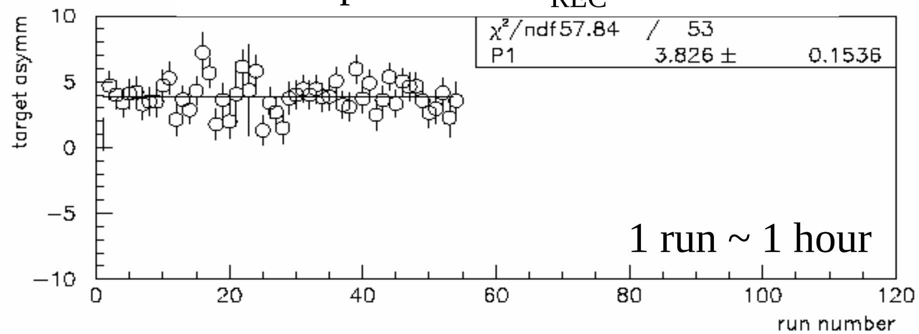
JET… "ONLINE" measured asymmetries & Results

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

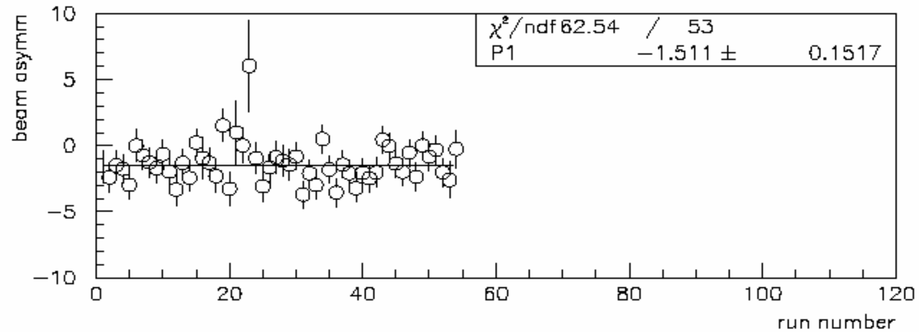
data divided into 3 recoil energy bins

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

"Target": average over beam polarization



"Beam": average over target polarization



blue beam with alternating bunch polarizations: ↑↓ ↑↓ ↑↓ …

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

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

P_{beam} = 36.9 % ± 1.9 %

$\langle P_{beam}$ (pC CNI) $\rangle$ = 38.1 %

No major surprises ?

(statistical errors only !)

Issues and technical difficulties

Important issue for the systematic (-t determination)

- *-t* is estimated from recoil Carbon energy

$$-t = 2M_C E_{elastic}$$

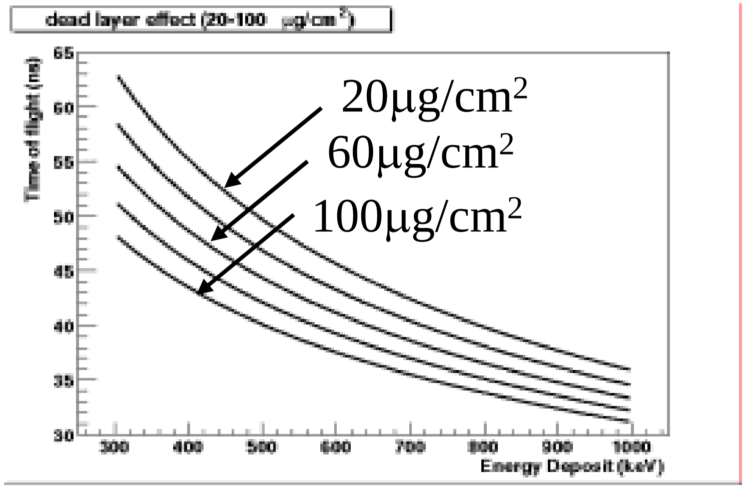
$$E_{elastic} = E_{deposit} + \Delta E_{target} + \Delta E_{deadlayer}$$

$$(\Delta E_{target} \sim 0.1 \times \Delta E_{deadlayer})$$

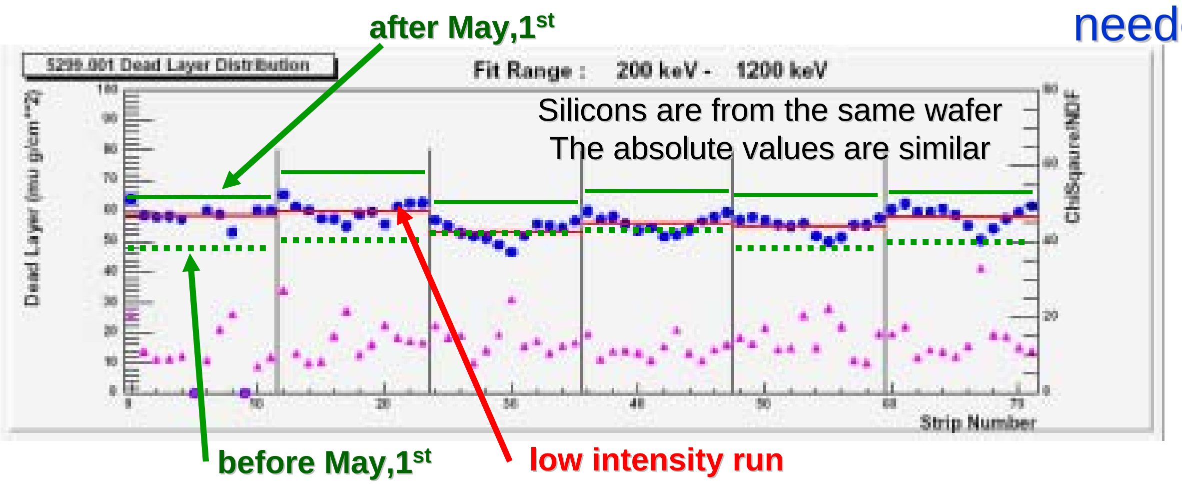
- Estimation with kinetic fit to banana

$$Tof(ns) = \sqrt{\frac{M_C}{2}} \frac{Distance}{\sqrt{E_{elastic}}} + t_0$$

$$E_{elastic} = f(E_{deposit}, D_{width})$$

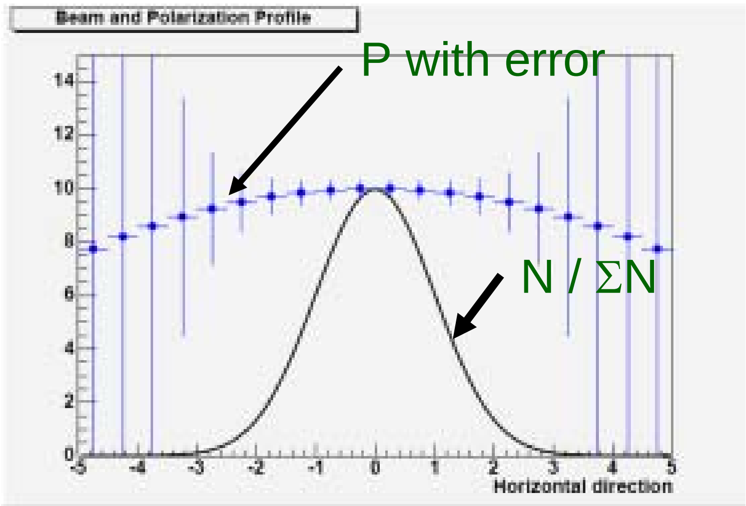


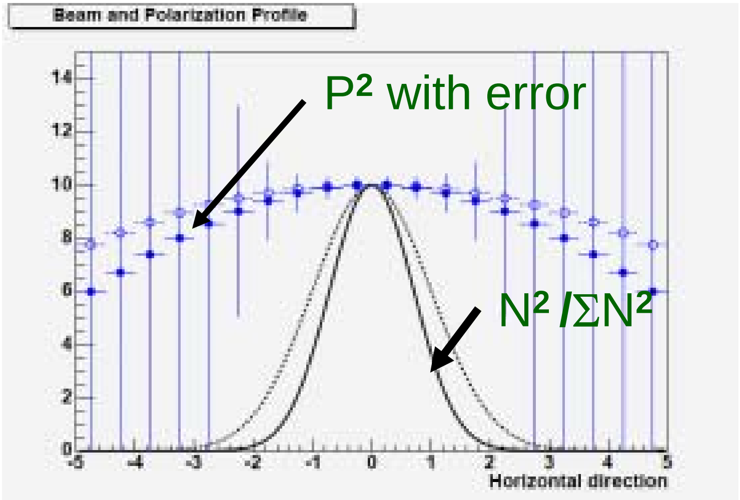
Once the dead layer issue solved, the jet-measurements will not be needed anymore ….



IF NOT, calibration needed every year

In order to be Insensitive to Polarization Profile (For stable and robust CNI measurements)





- Definition of *P* differs in measurements

1) *pC* CNI samples one point
2) *pp*-Jet target covers whole beam profile

$$\overline{P} = \sum_x N(x)P(x) / \sum_x N(x)$$

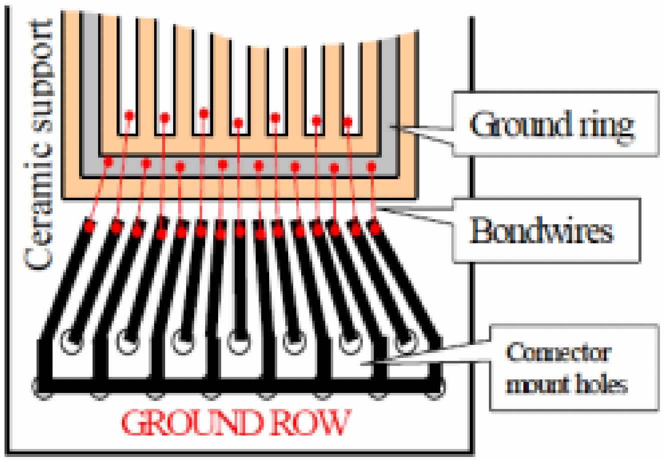
3) Experiments head-on collisions

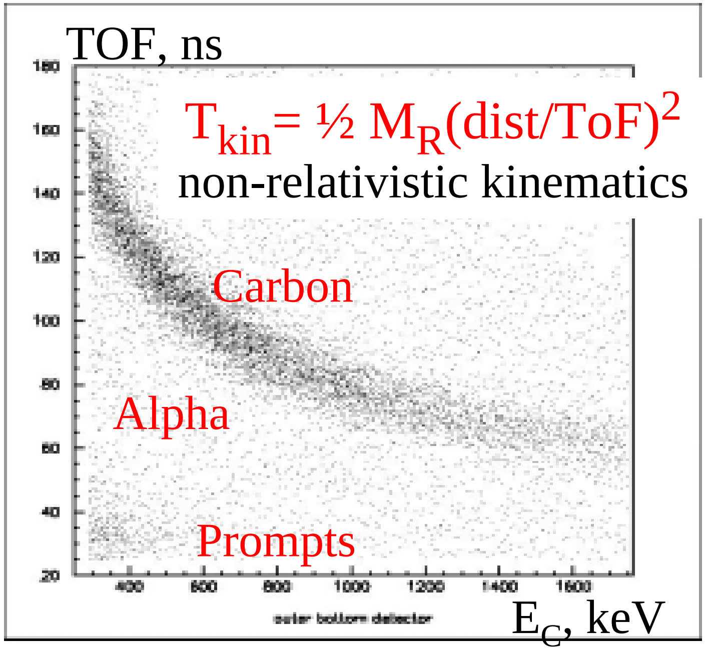
$$\overline{P} = \sqrt{\sum_x (N(x)P(x))^2 / \sum_x (N(x))^2}$$

- The idea is to move the target across the beam in steps during regular runs
  - Online results → 2)
  - Offline results → 1),2),3)

Induced current free silicon design

No More Beam Induced Pickups…





NO BEAM CHARGE INDUCED SIGNAL !!!

(Up to $2{\cdot}10^{11}$ p/bunch)

- New improvement in AGS CNI
  - every second wire is ground line, from edge to edge.
  - wide range of $-t$ is available
  - able to open the time window to very close to the beam crossing

- To apply for RHIC CNI
  - new vacuum ports
  - new detector mounts (ceramics)
  - R&D on the glue for the vacuum
  - new RF shields
  - add coolers

Plan of RHIC Spin

- On Polarimetry
  - *pp*, *pC* calibration → determine r_5
  - more precise calibration at 2005 (100GeV)
  - 250GeV calibration (2008)
- RHIC Spin General
  - Long physics run at 2005
  - W→ flavor decomposition (2008)

Summary

- Successful Jet-target commissioning done
- Calibration from online result looks consistent with calibration by E950
- Efforts of extracting *pp, pC* A_N are in progress

- Final goal $\Delta P/P = 5\%$ will be obtained in run-05