Measuring proton beam polarization and analyzing power with pp and pC elastic scattering at RHIC

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September 24, 2011

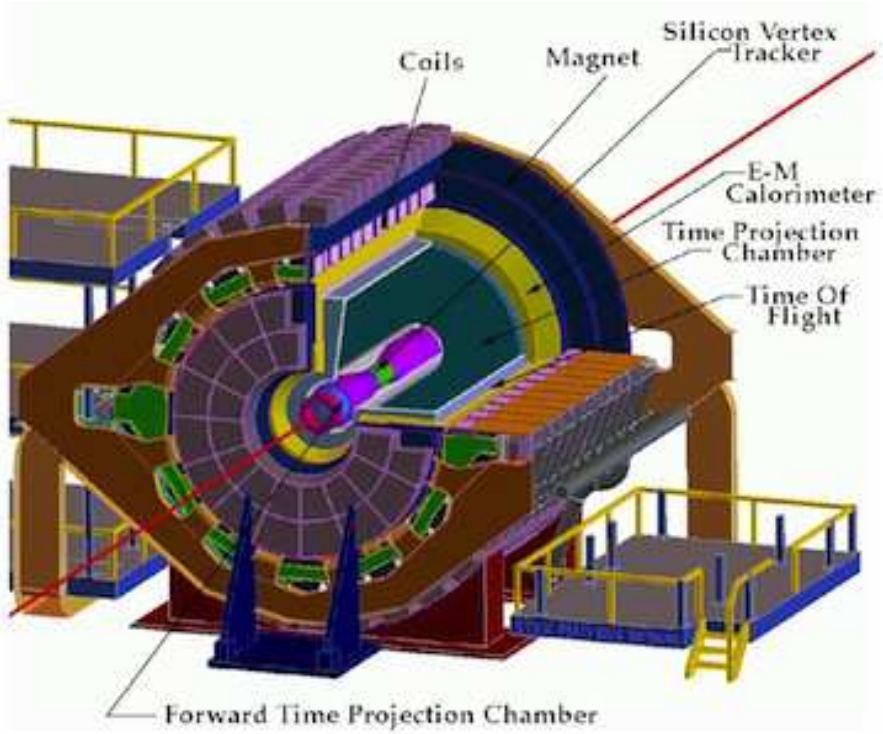
Accelerator Complex at Brookhaven Lab

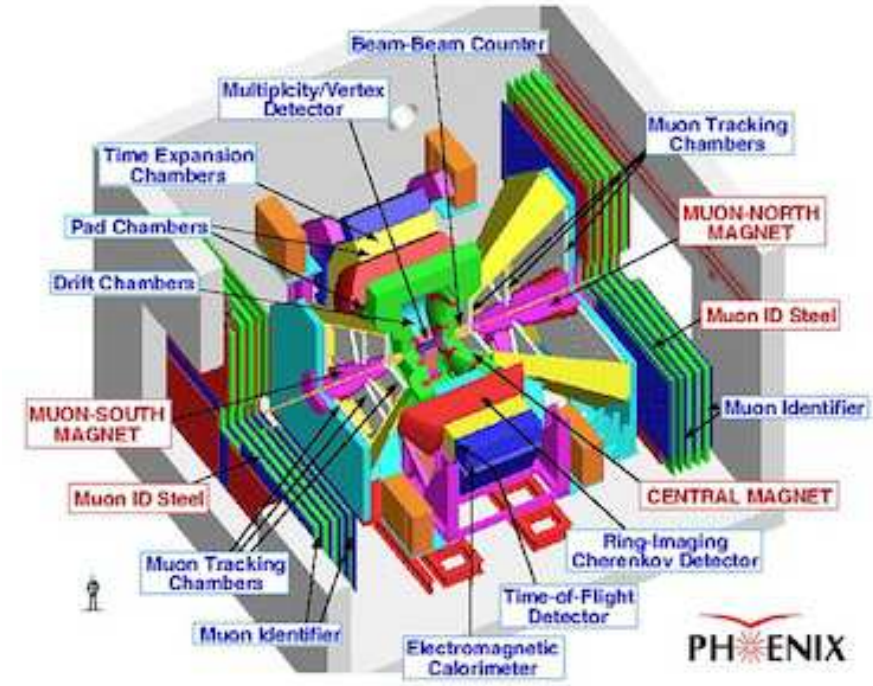
- **Relativistic Heavy Ion Collider** (RHIC) is a syperconducting synchrotron
  - In sucessful operation since 2000
  - **Provides polarized high energy proton beams**
  - **Covers wide range of energies 24 GeV to 250 GeV**
  - Also unpolarized heavy ion beams Au-Au, d-Au, Cu-Cu
- **Alternatig Gradient Synchrotron** (AGS)
  - Serves as injector for RHIC
  - Three nobel prizes since 1960

Physics Objectives and Motivation

- Two operational detectors STAR and PHENIX
  - **Measure transverse and longitudinal spin asymmetries**
  - **Aim to understand gluon polarization in the proton spin structure**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z + \Delta g$$





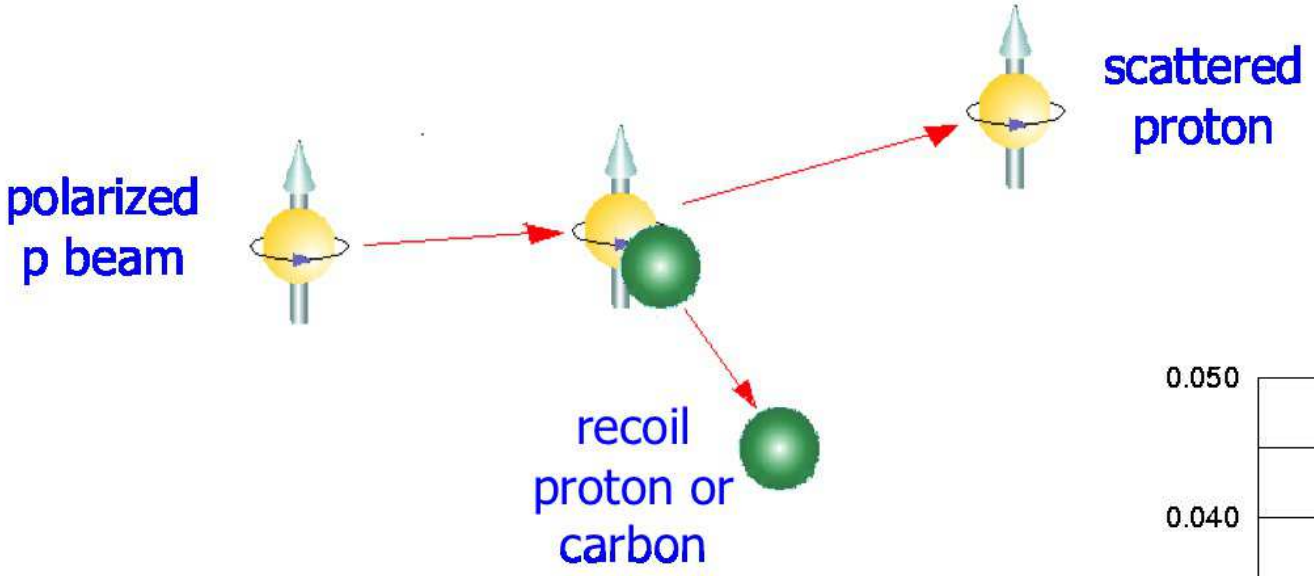
- Heavy ion program: Studies of quark-gluon plasma

Requirements on RHIC Polarimeters

- Non-destructive polarization measurement
  - Elastic scattering of a fixed target
  - Maximum asymmetry/analyzing power $\Rightarrow$
    $\Rightarrow$ Small momentum transfer $-t$ (region of Coulomb nuclear interference (CNI))
- Low energy of recoil products $\Rightarrow$
  $\Rightarrow$ the detectors are in vacuum + no material in front
- The polarimeters should operate over a wide range of beam energies from injection at 24 to 250 GeV
- Beam polarization profile
- Polarization lifetime or decay during a fill
- **The physics program requires precision polarimetry $< 5\%$**

Measuring Beam Polarization

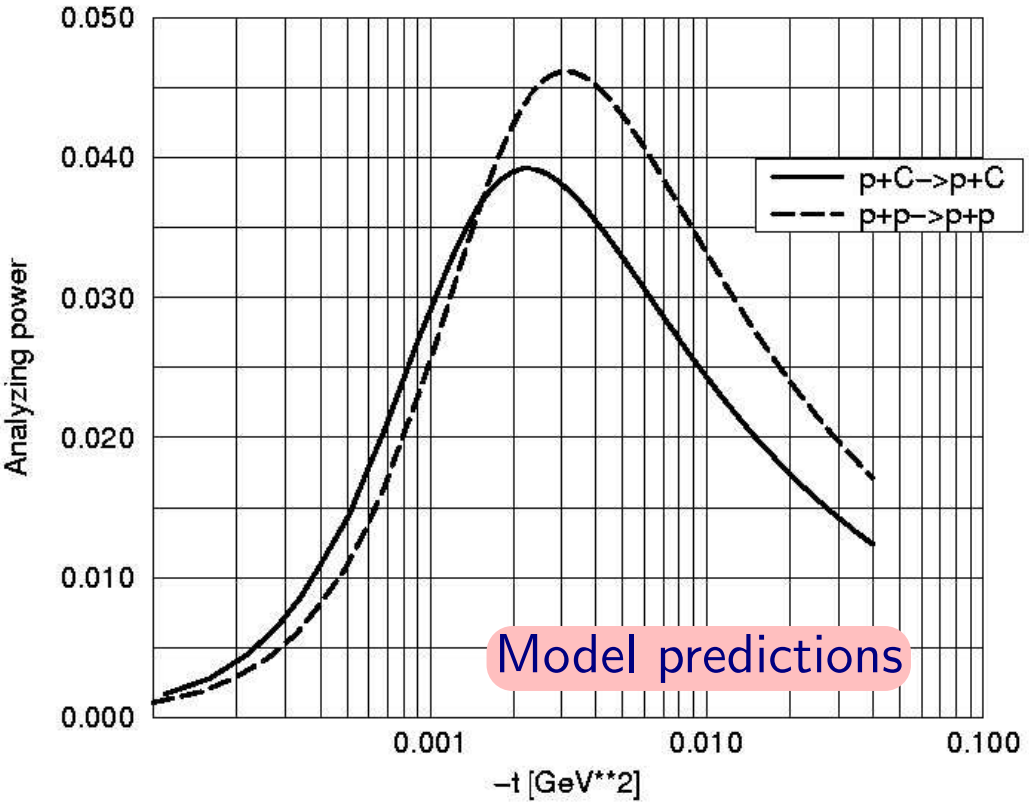
- The kinematics of elastic scattering is fully defined by the energy of recoil products
- The momentum transfer $t = (p_{\text{in}} - p_{\text{out}})^2 = -2ME_{\text{kin}}$



In absense of hadronic spin-flip amplitude analyzing power A_N is exactly calculable from QED

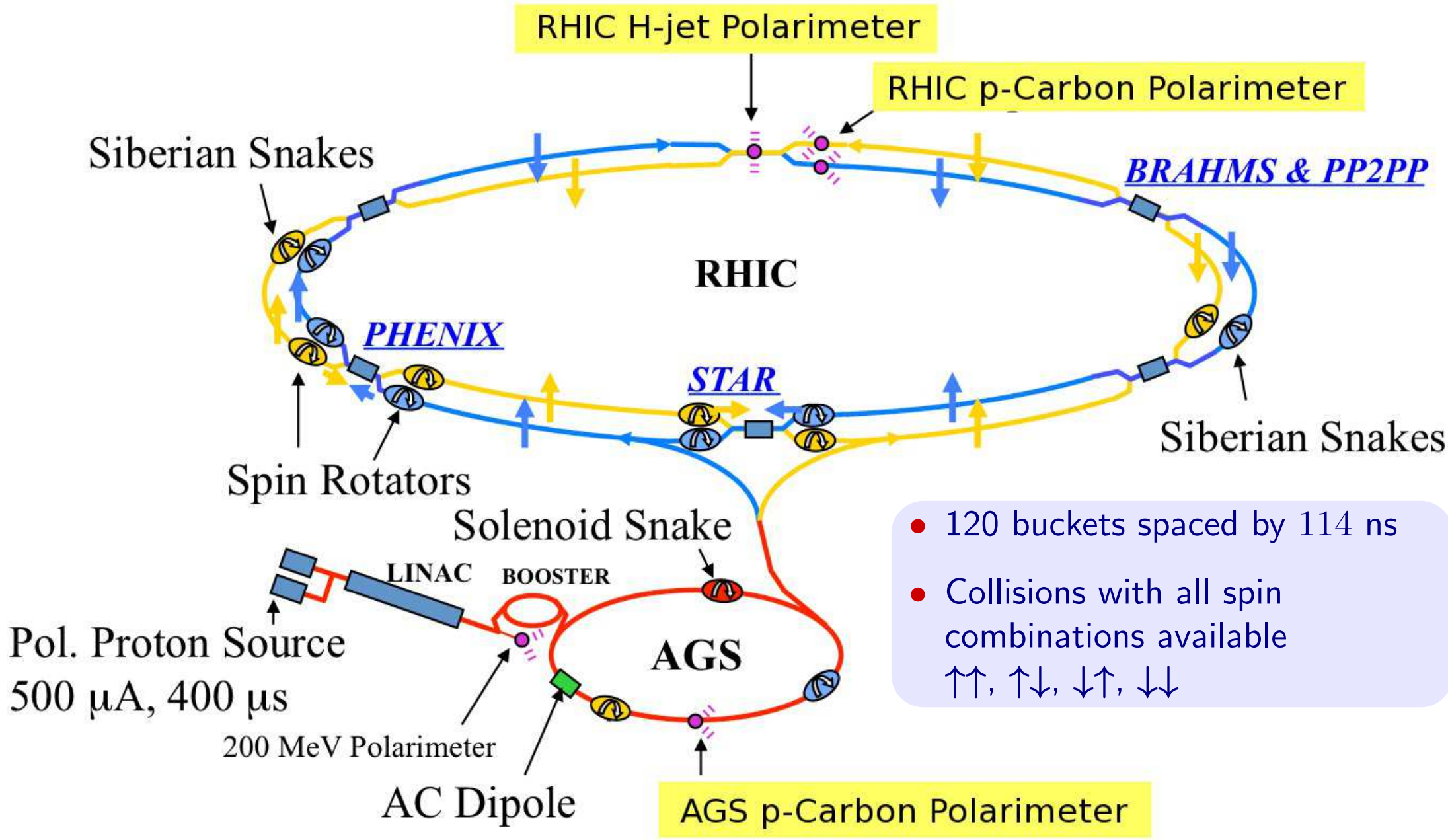
- In the experiment we measure asymmetry ε

$$\varepsilon = \frac{N_L - N_R}{N_L + N_R}, \qquad \varepsilon = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}$$



- Measured polarization $P = \varepsilon / A_N(t)$, where $A_N(t)$ is the **analyzing power**

RHIC and AGS Polarimeters



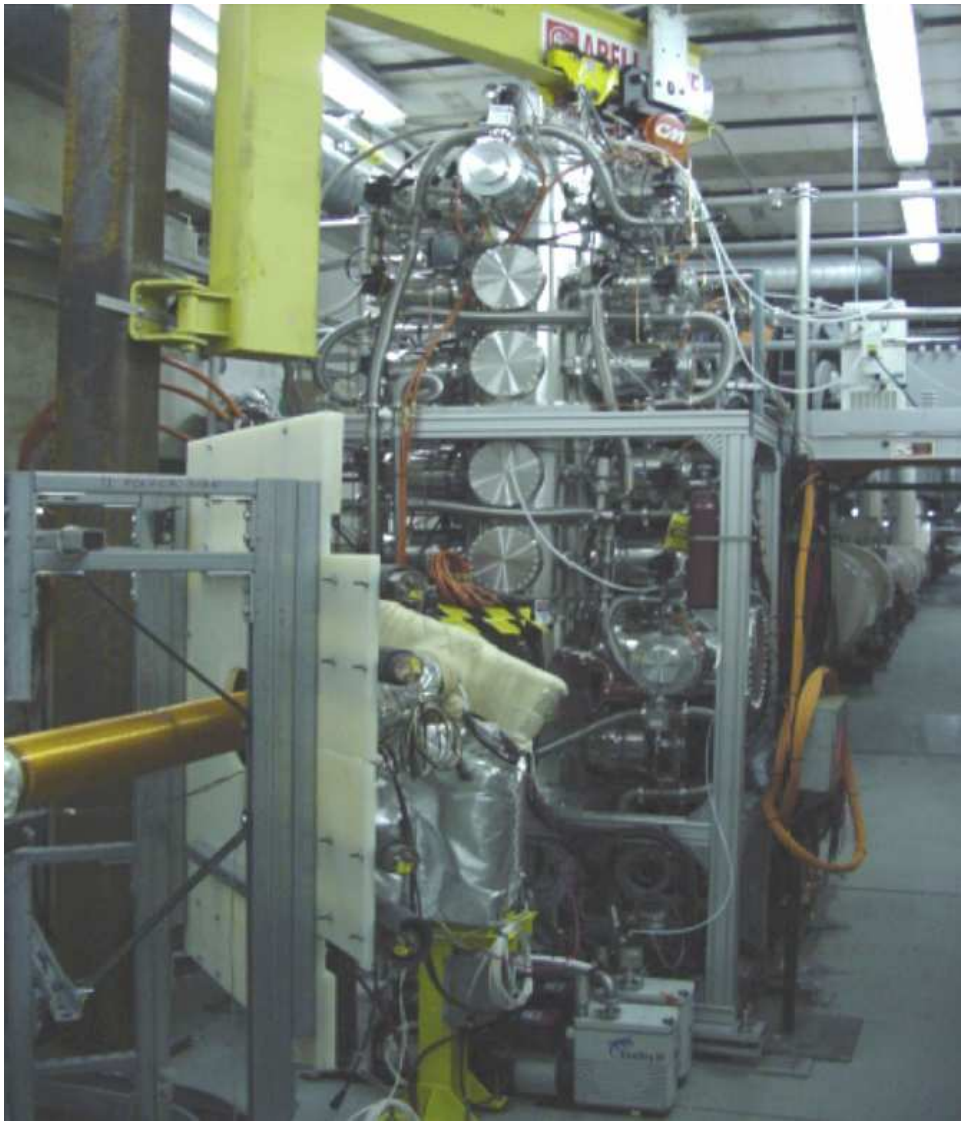
- 120 buckets spaced by 114 ns
- Collisions with all spin combinations available
  $\uparrow\uparrow$, $\uparrow\downarrow$, $\downarrow\uparrow$, $\downarrow\downarrow$

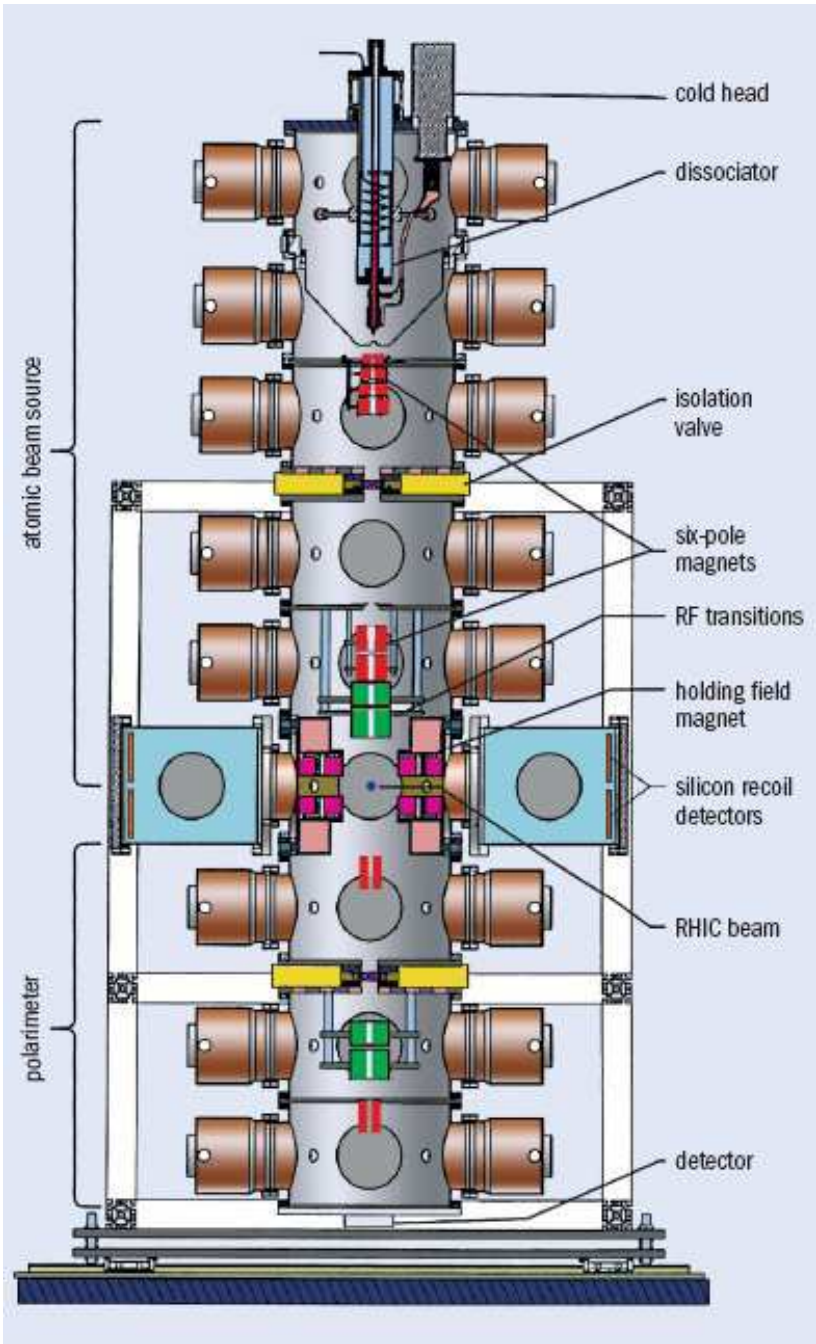
RHIC and AGS Polarimeters: Strategy and Goals

- **Hydrogen jet (H-jet) polarimeter**
  - Provides the **average** absolute polarization over the fill (~ 8 hours)
- **Two p-Carbon polarimeters in each ring**
  - About four 60-second measurements per fill
  - Bunch and fill polarization for the experiments
  - Vertical and horizontal beam polarization profile
  - Polarization decay in fill

- AGS polarimeter is similar to RHIC p-Carbon polarimeter
- STAR and PHENIX local polarimeters monitor spin direction at collision regions

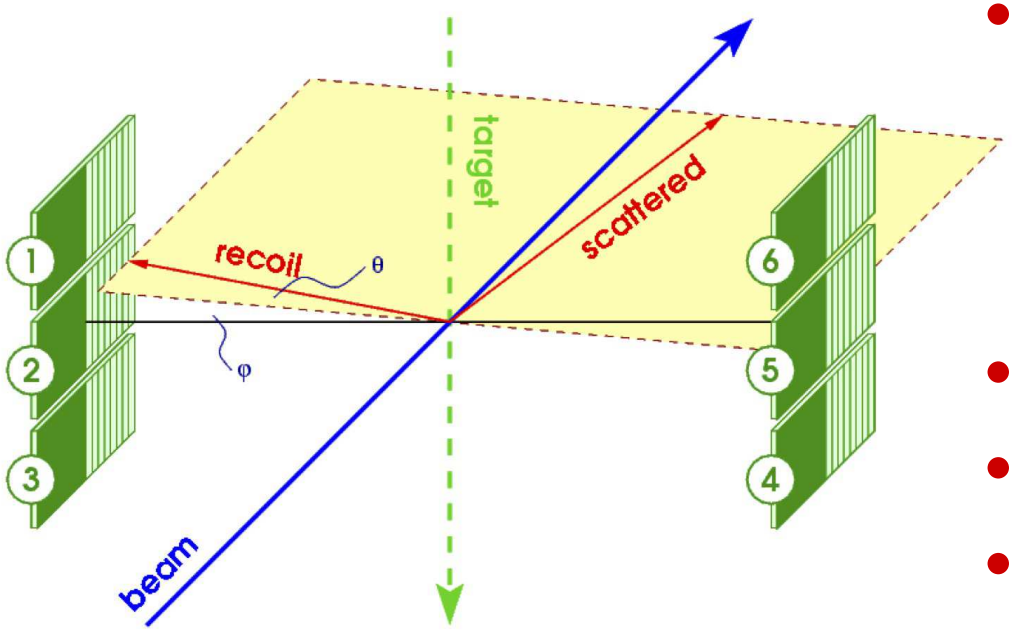
H-Jet Polarimeter





- The polarized jet target is vertical
- Target polarization cycles $\uparrow /0/ \downarrow$ every 500/50/500 seconds

H-Jet Polarimeter: Event Kinematics



- The beam and the target are both protons:

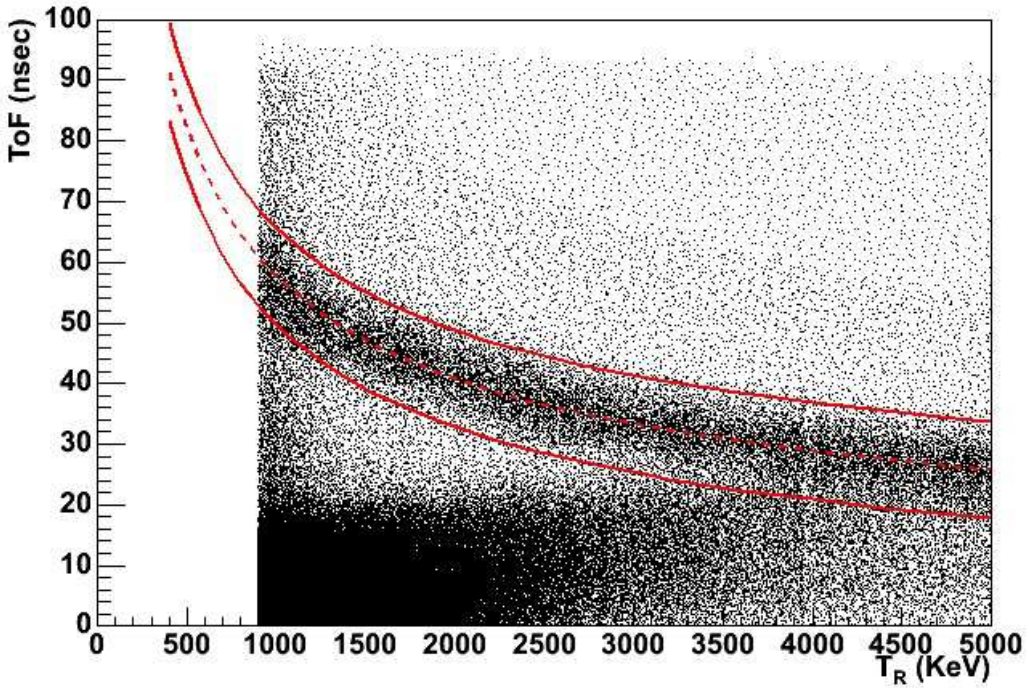
$$P = \frac{\varepsilon}{A_N(t)}, \qquad P_{\text{beam}} = -\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \times P_{\text{target}}$$

- **No need to know A_N!**
- P_{target} is measured by a Breit-Rabi polarimeter
- After correction for molecular contamination in the hydrogen jet $P_{\text{target}} \approx 92 \pm 2\%$

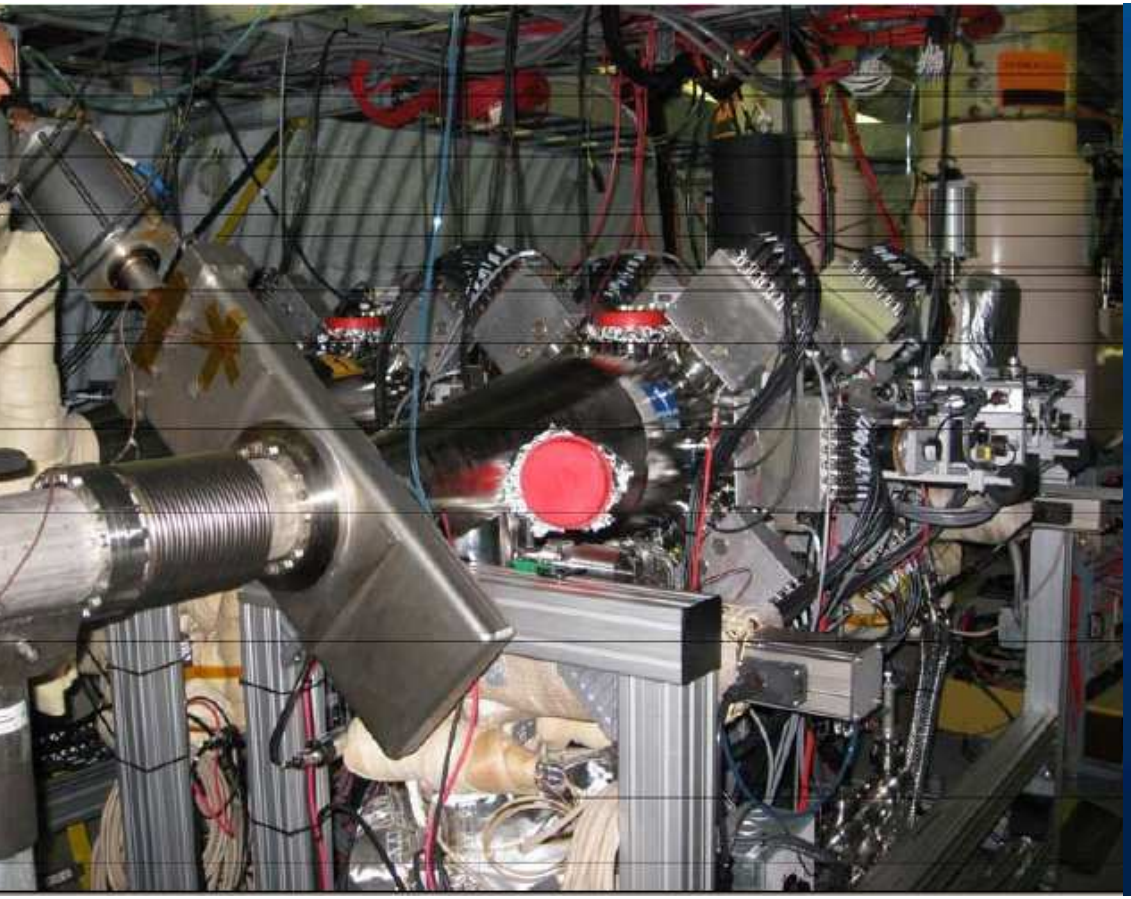
- Both beams separated by ~ 4 mm intersect the hydrogen jet target
- Elastic events are easily identified from non-relativistic equation

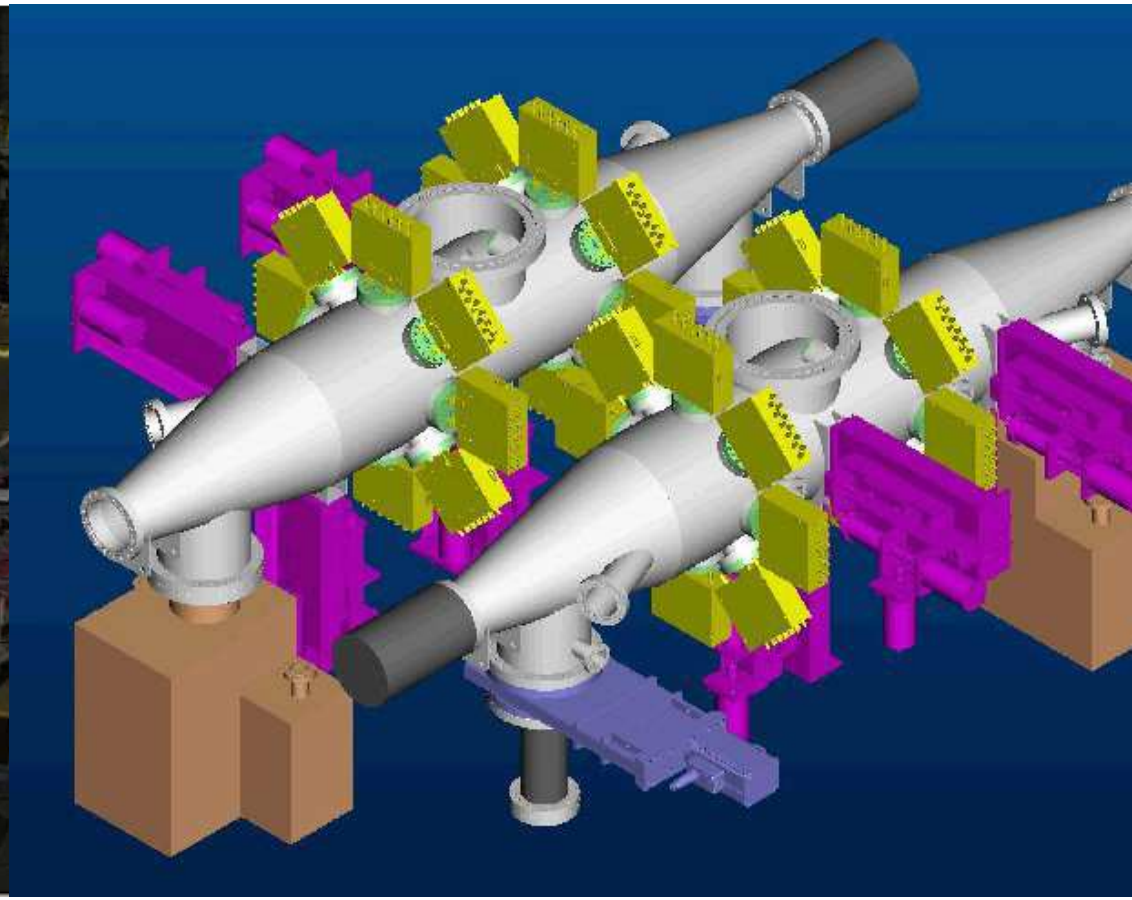
$$t_{\text{TOF}} = L\sqrt{\frac{m_p}{2E_{\text{kin}}}}$$

and recoil angle Θ

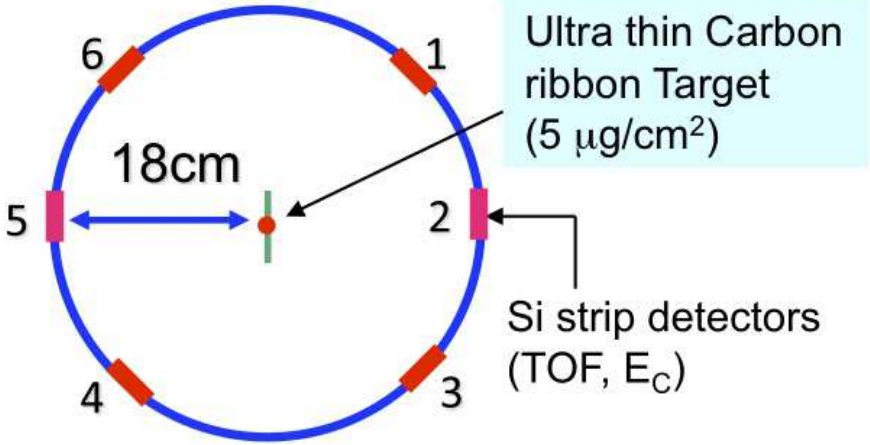


p-Carbon Polarimeters

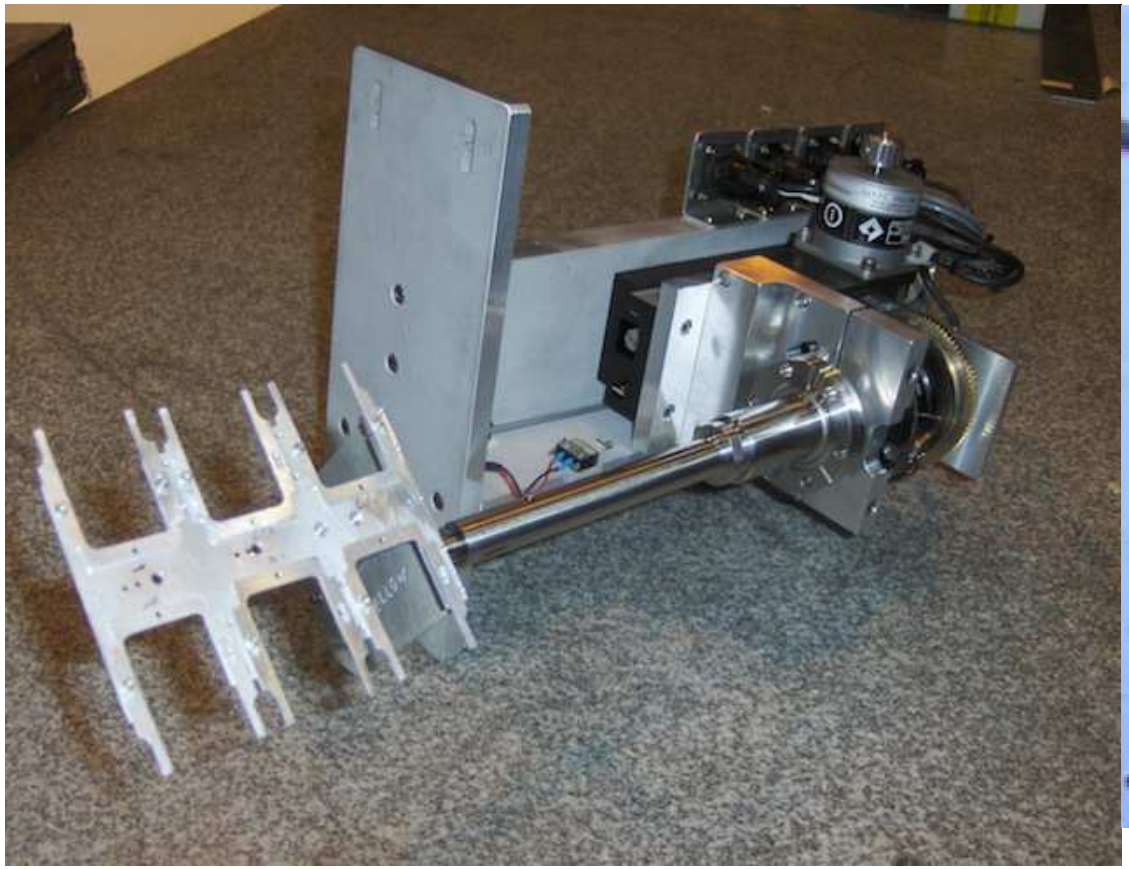


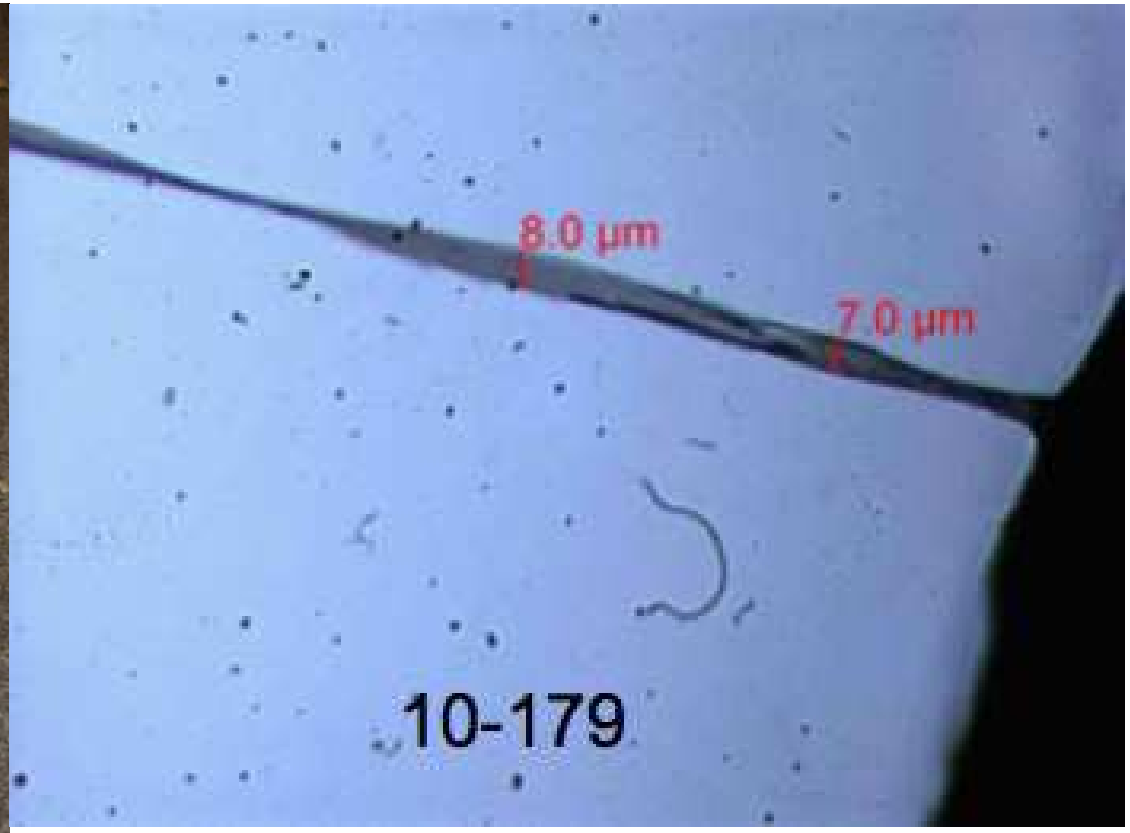


- Two polarimeters in each ring
- The readout system is multiplexed between the two pairs
- Each polarimeter employs six vertical and six horizontal ultra thin carbon targets



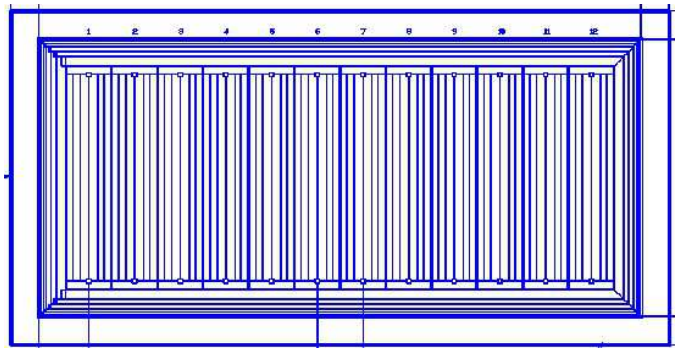
p-Carbon Polarimeters: Targets



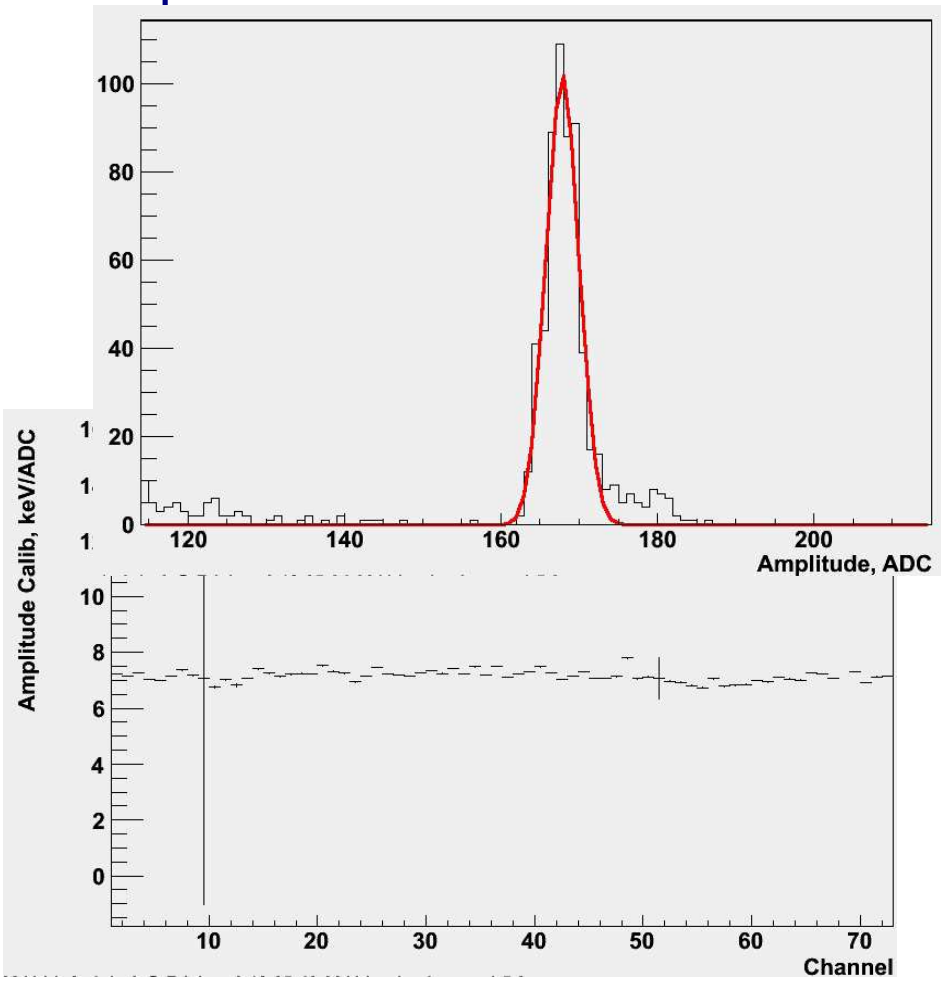


- Typical target size is 2.5 cm $\times\, 5 - 10$ μm $\times\, 25$ nm
- Targets are made by vacuum evaporation-condensation onto glass substrate
- Two stepping motors are used to move the assembly and to rotate the targets into the beam

p-Carbon Polarimeters: Detector Calibration

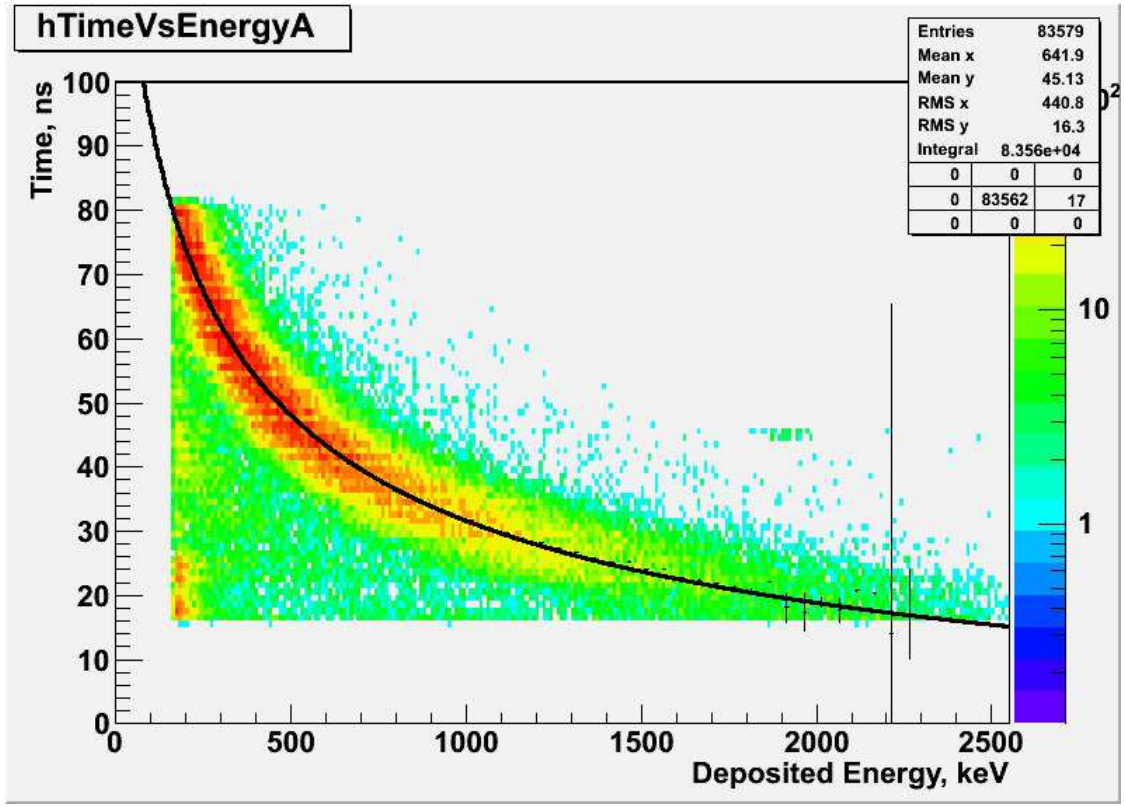


12 strips 2×10 mm



- Detectors calibrated with α source (^{241}Am, 5.5 MeV)
- The α's do not probe the surface of the detector where the carbon ions stop
  Unaccounted energy losses $\Rightarrow$
  "effective dead-layer"

p-Carbon Polarimeters: Event Kinematics



- Calibration parameters the **time offset** t_0 and the **effective dead layer thickness** x_{DL} extracted from the non-relativistic equation:

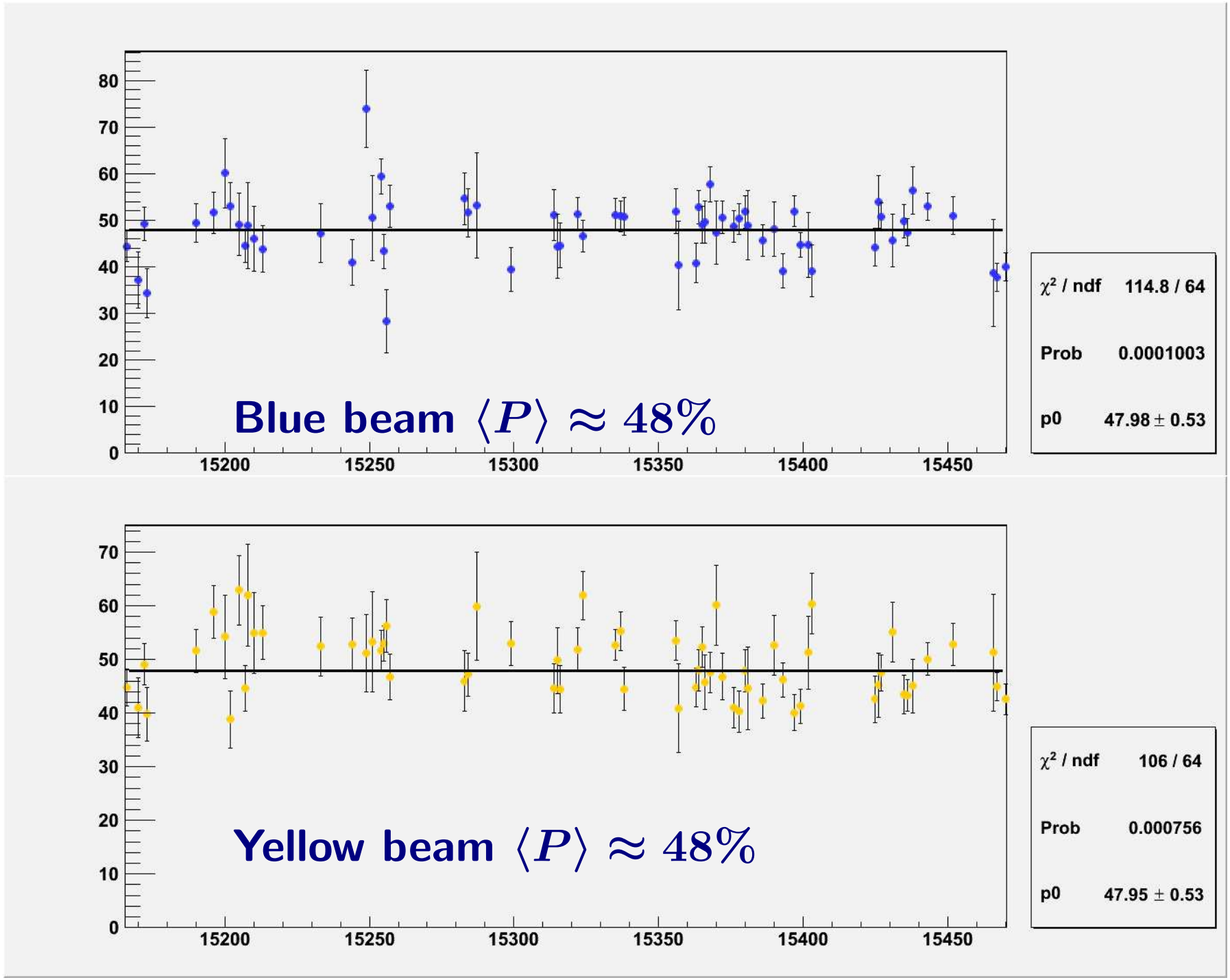
$$E_{\mathrm{meas}} + E_{\mathrm{loss}} = \frac{M_C}{2} \times \frac{L^2}{(t_{\mathrm{meas}} + t_0)^2},$$

where $E_{\mathrm{loss}} = E_{\mathrm{loss}}(E_{\mathrm{meas}}, x_{\mathrm{DL}})$ is an energy loss parameterization for carbon

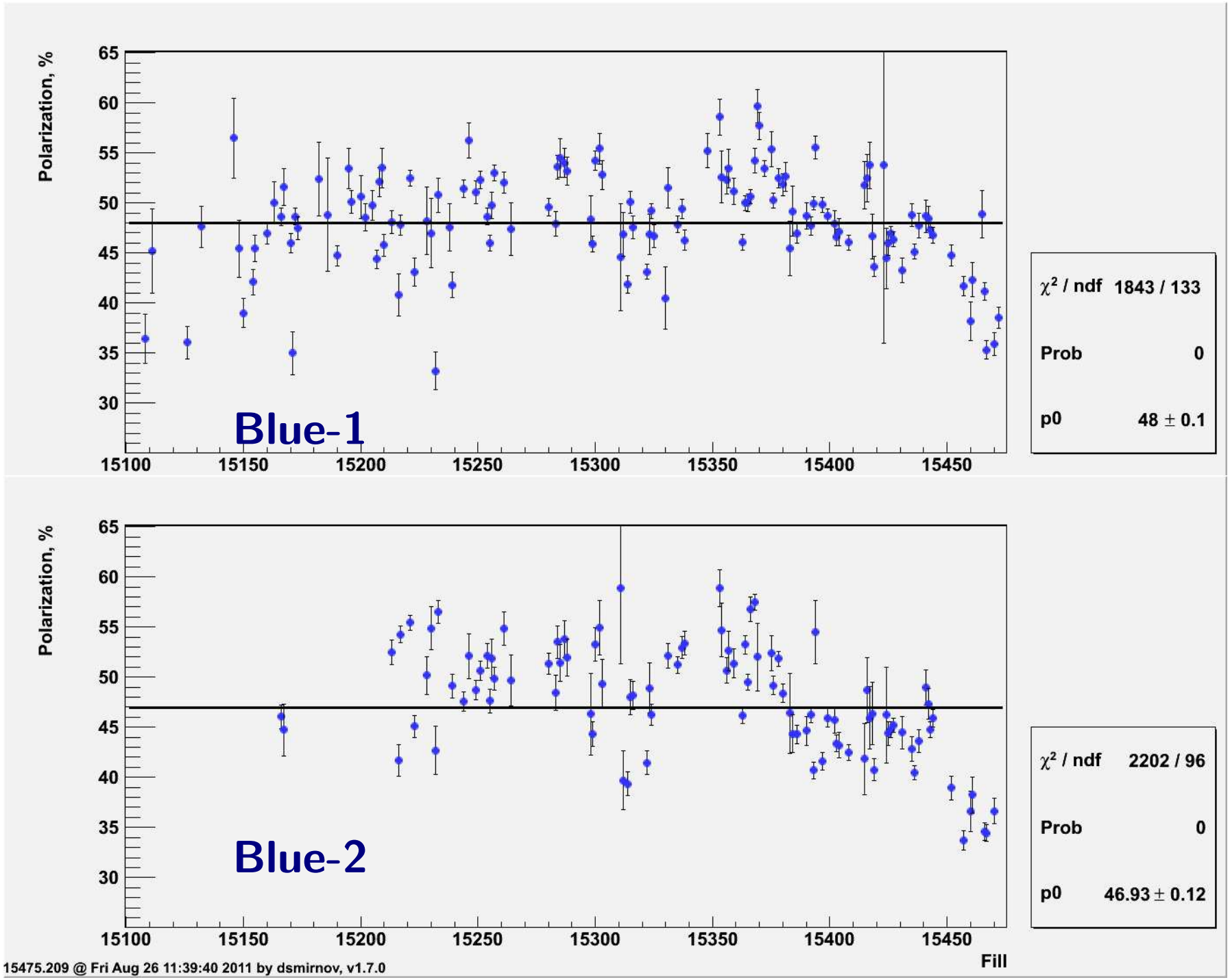
Overview of RHIC Polarimeters

	H-jet Polarimeter	p-Carbon Polarimeters
Target	Polarized atomic hydrogen gas jet target	Ultra thin carbon ribbon
Calibration	Self-calibrating due to known target polarization	Normalized to the H-jet due to unknown A_N
Event Rate	~ 20 Hz Stat. uncertainty $\sim 8\%$ in 6–8 hour fill	~ 2 MHz Stat. uncertainty $\sim 2\%$ per measurement
Operation	Continuous throughout a fill	Few minutes every few hours
Role	• Average beam polarization • Absolute normalization for p-Carbon polarimeters	• Fast online feedback • Beam polarization profiles • Bunch by bunch polarization • Fill by fill polarization for the experiments

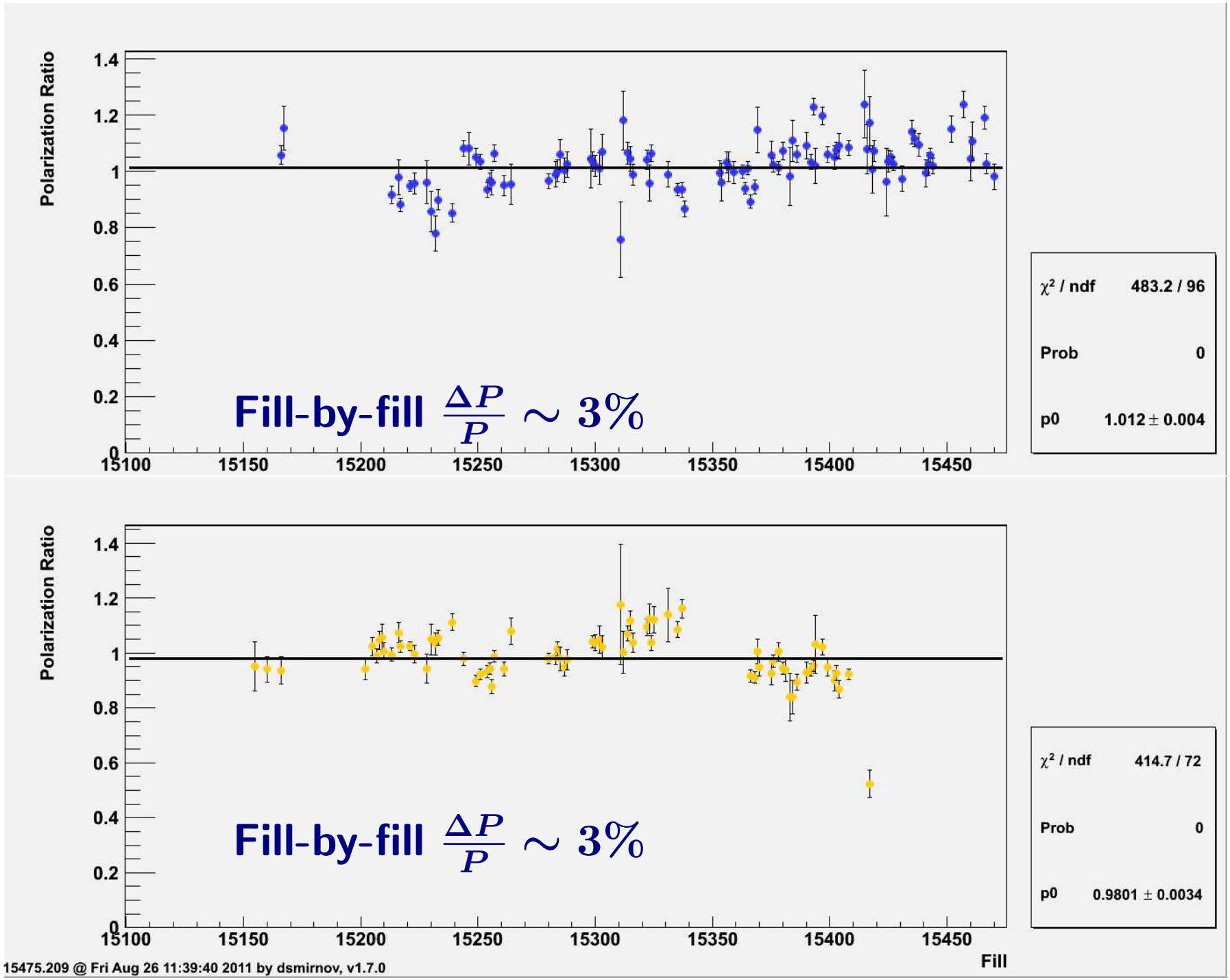
Fill Polarization: H-Jet Polarimeter



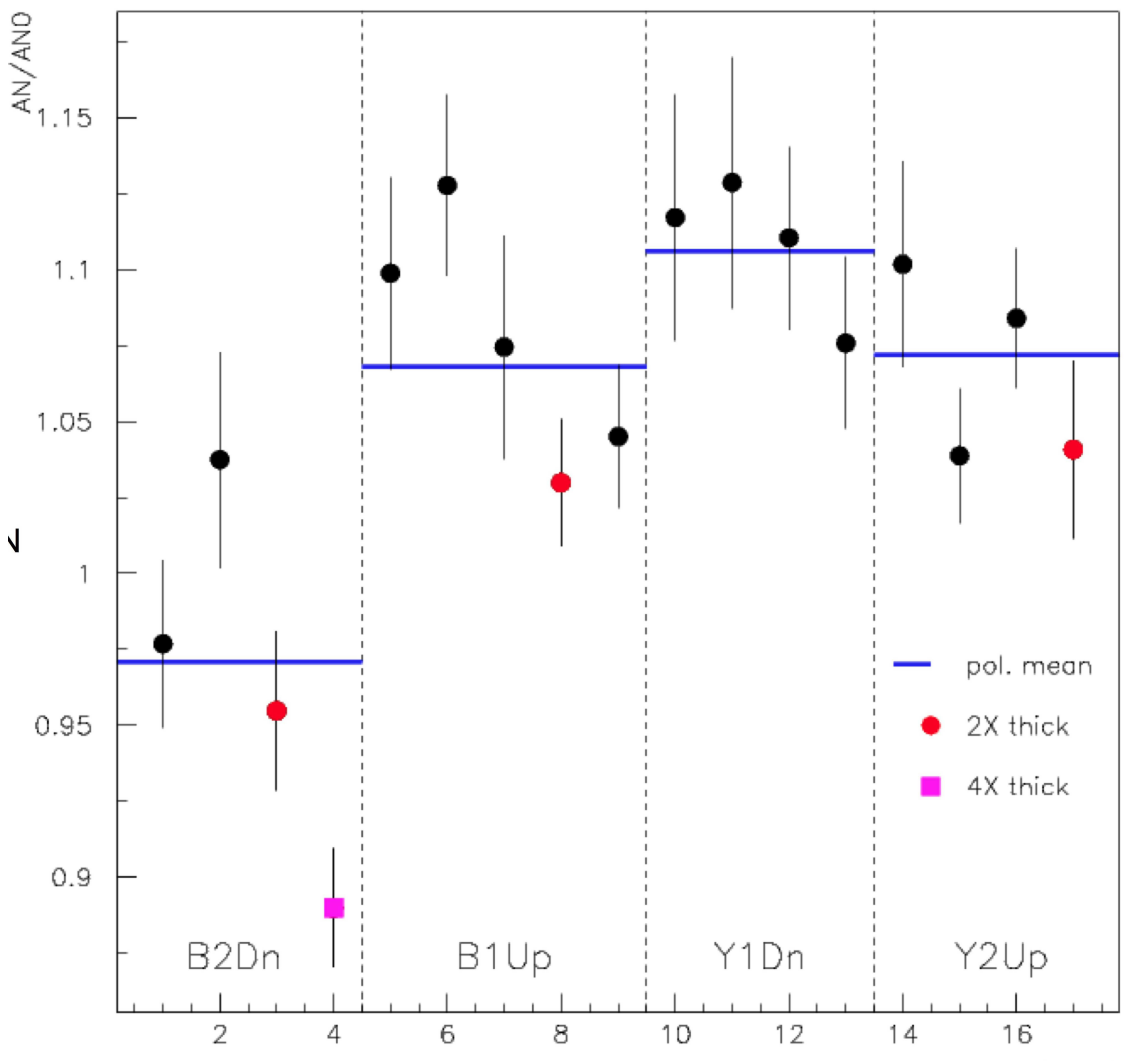
Fill Polarization: p-Carbon Polarimeters



Systematics: Polarimeter-1 vs Polarimeter-2



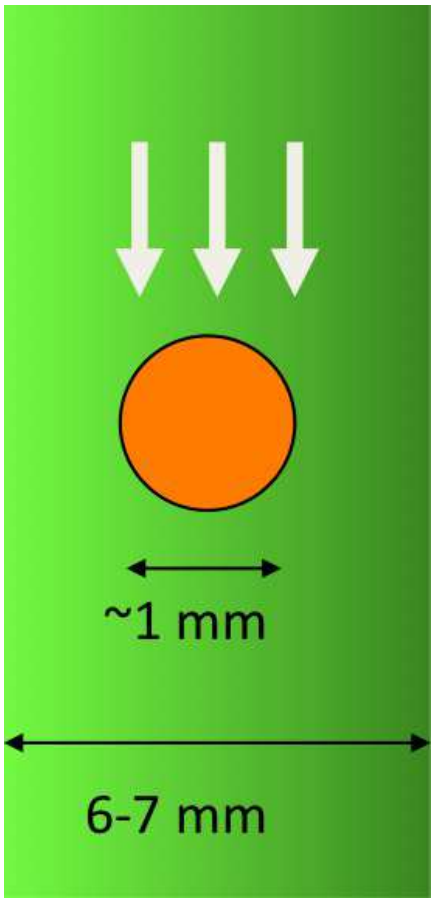
Systematics: Energy Losses in Target



- We check normalization factors to a fixed A_N for different targets
- Thicker targets are more susceptible to orientation
- Normalization for thicker targets is consistent with larger energy losses

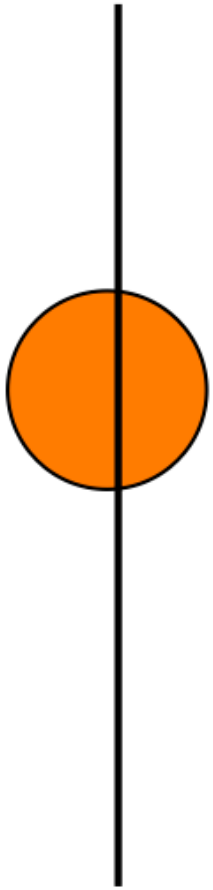
Polarization in Beam Collisions

H-Jet



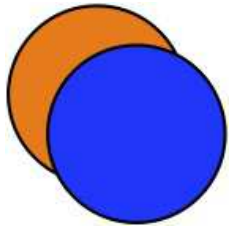
$$\langle P \rangle = \frac{\int P(x,y) I(x,y) dxdy}{\int I(x,y) dxdy}$$

p-Carbon



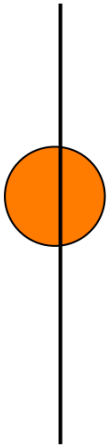
$$\langle P \rangle_{\text{sweep}} = \langle P \rangle$$

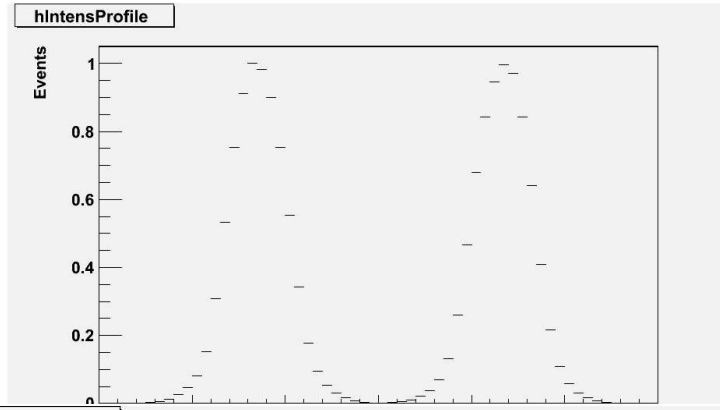
Beam collisions

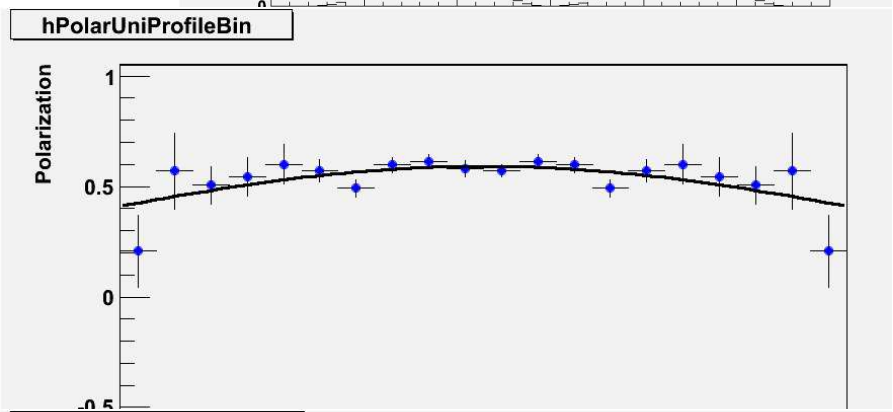


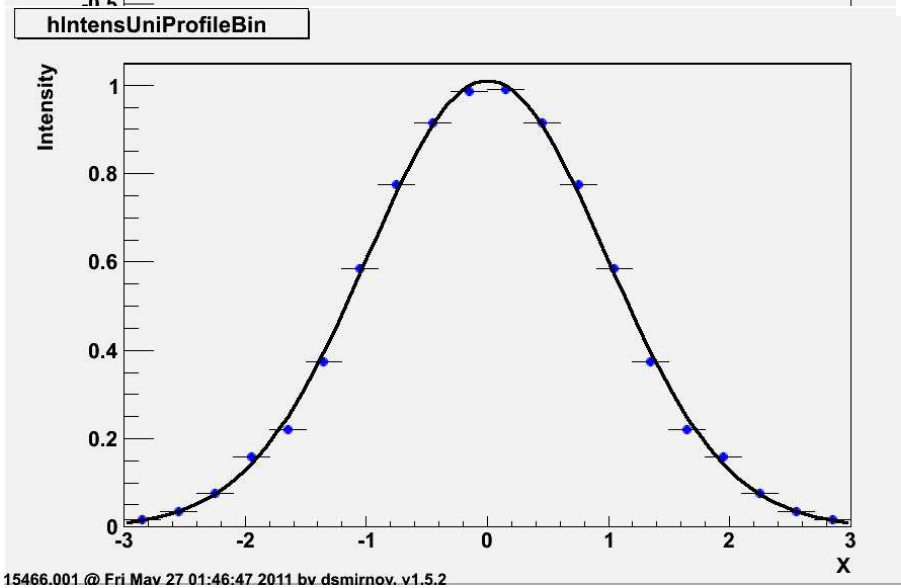
$$\langle P \rangle_{\text{coll}} = \frac{\int P(x,y) I^{(\text{B})}(x,y) I^{(\text{Y})}(x,y) dxdy}{\int I^{(\text{B})}(x,y) I^{(\text{Y})}(x,y) dxdy}$$

Beam Polarization Profile









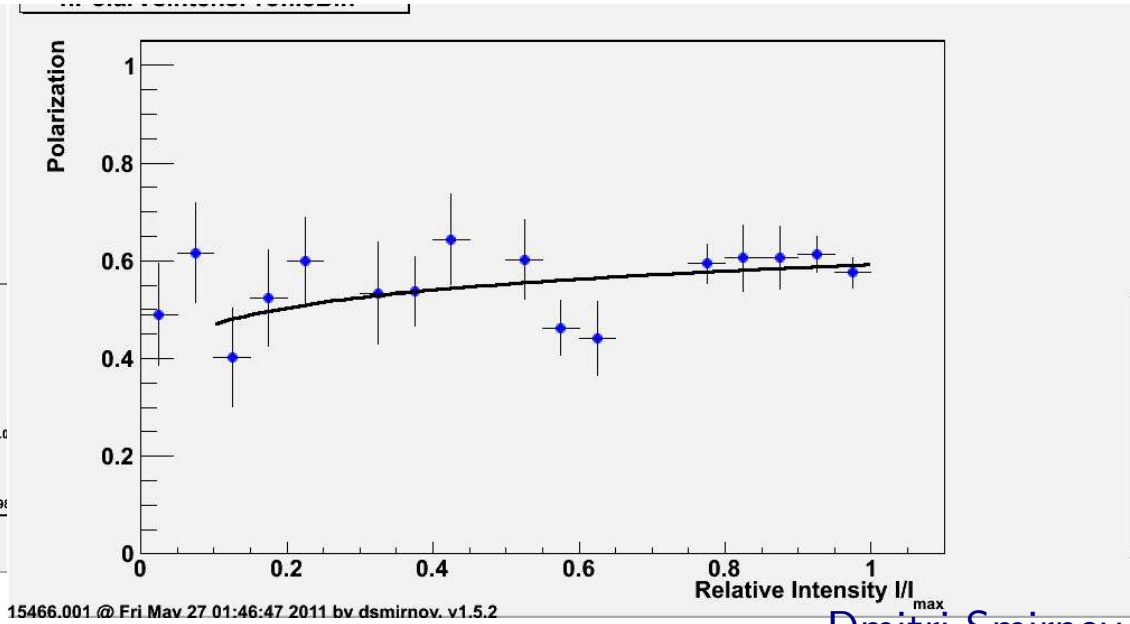
- Precise target position is not necessary if the beam is assumed to have a gaussian profile

$$I(x) = I_{\max} e^{-\frac{x^2}{2\sigma_I^2}}, \qquad P(x) = P_{\max} e^{-\frac{x^2}{2\sigma_P^2}}$$

x can be either time or distance

- The intensity and polarization can be related as

$$\frac{P}{P_{\max}} = \left(\frac{I}{I_{\max}}\right)^R \quad \text{with} \quad R = \frac{\sigma_I^2}{\sigma_P^2}$$



Beam Polarization Profile

- Average polarization can be defined as:

$$\langle P \rangle = \frac{P_{\text{max}}}{\sqrt{1+R}}$$

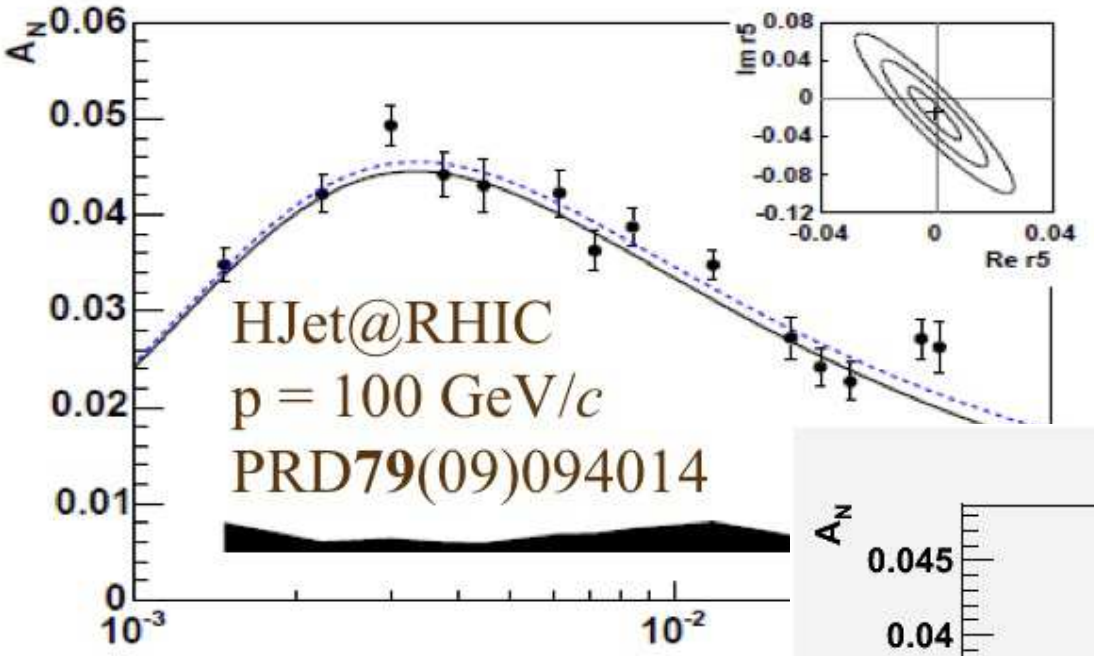
  - Another source of systematic uncertainty comes from the profile measurments $\langle P \rangle$ vs $\langle P \rangle_{\text{sweep}}$
  - Fill-by-fill $\frac{\Delta P}{P} \sim 3\%$

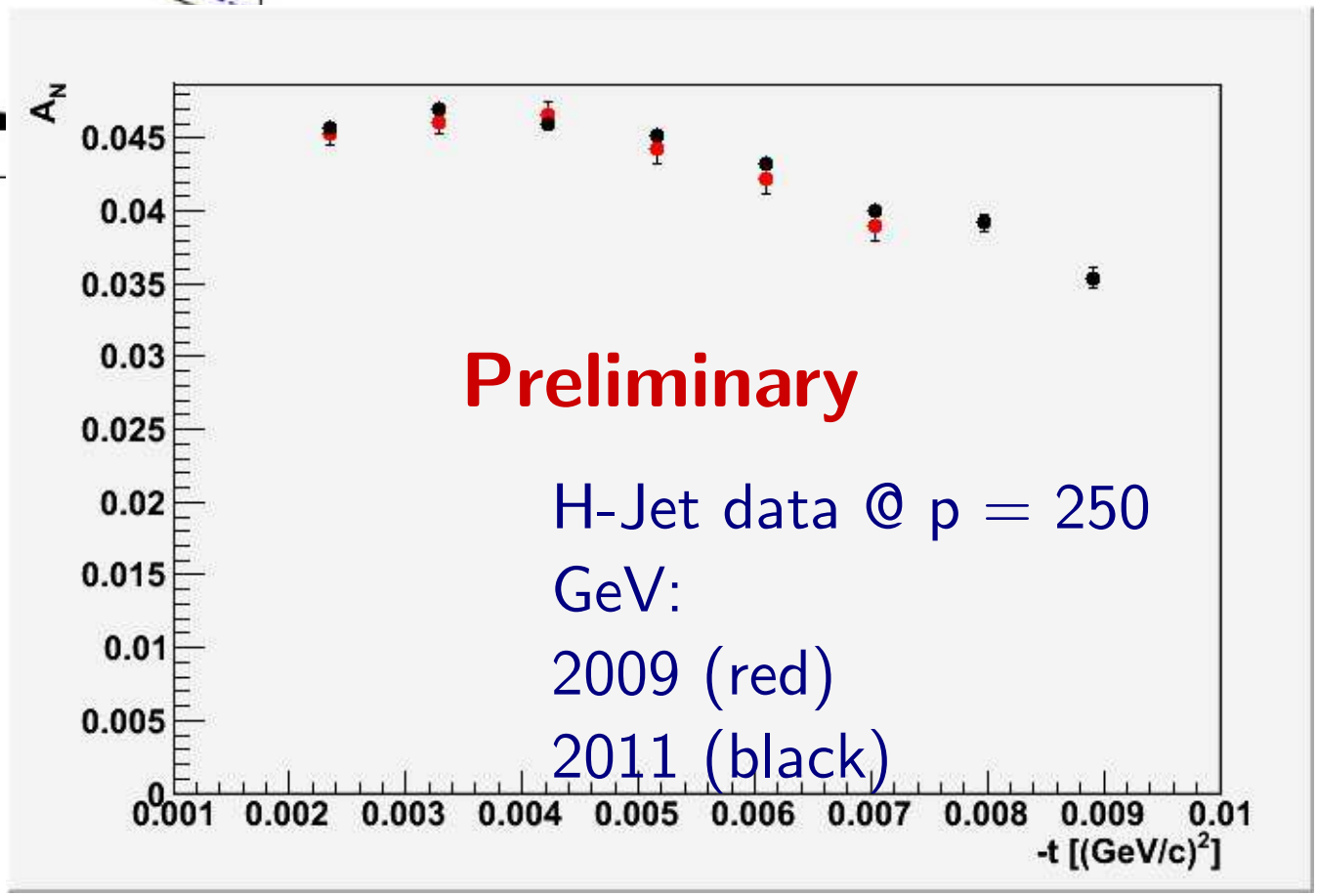
- Assuming gaussian profiles polarization in collisions is:

$$\langle P \rangle_{\text{coll}} = \langle P \rangle \frac{\sqrt{1+R_h}\sqrt{1+R_v}}{\sqrt{1+\frac{1}{2}R_h}\sqrt{1+\frac{1}{2}R_v}}$$

  - Results published online at https://www.phy.bnl.gov/cnipol/rundb/fills/

pp Analyzing Power A_N





- Good agreement between this and previous year!

Summary

- **The pp and pC elastic scattering in CNI region is well suit for polarimetry in wide beam energy range**
- RHIC polarimeters are non-destructive, unique, and compliment each other

- **Polarimeters performed well in 2011 run**
  - Measured beam polarization
  - Measured polarization profiles and beam polarization for the experiments
  - Estimated fill-by-fill systematic uncertainties

- **Future plans and outlook:**
  - Finallize global systematic uncertainties
  - Consider a different geometry for carbon targets as an alternative to ribbon
  - Calculate the analyzing power A_N for pC

RHIC Spin (+Polarimetry) Group in 2010/2011

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RHIC Spin Group web page