Measurement of Proton Beam Polarization and Analyzing Power A_N with Recoil Polarimeters at RHIC

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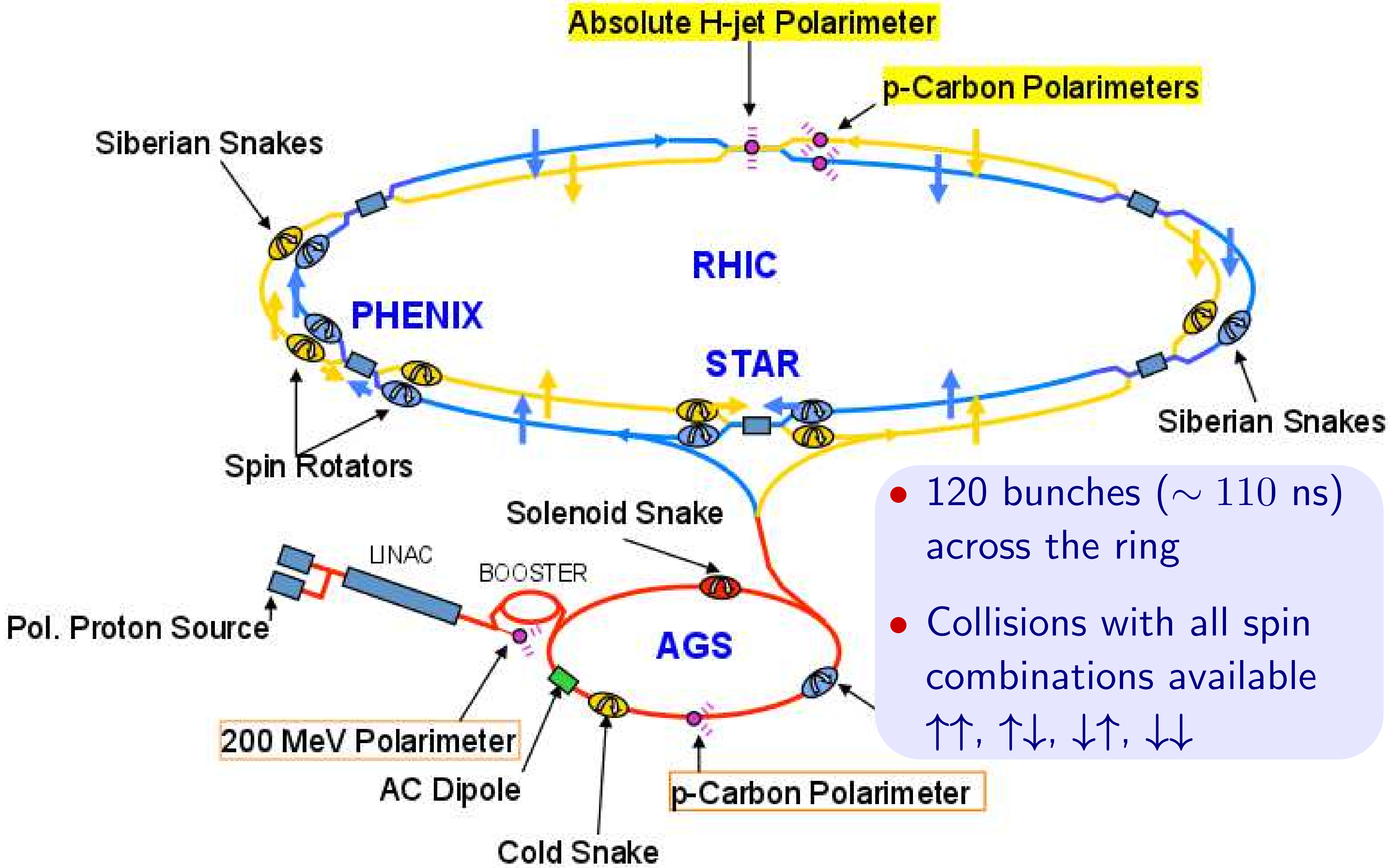
Relativistic Heavy Ion Collider
world's only polarized collider

Outline

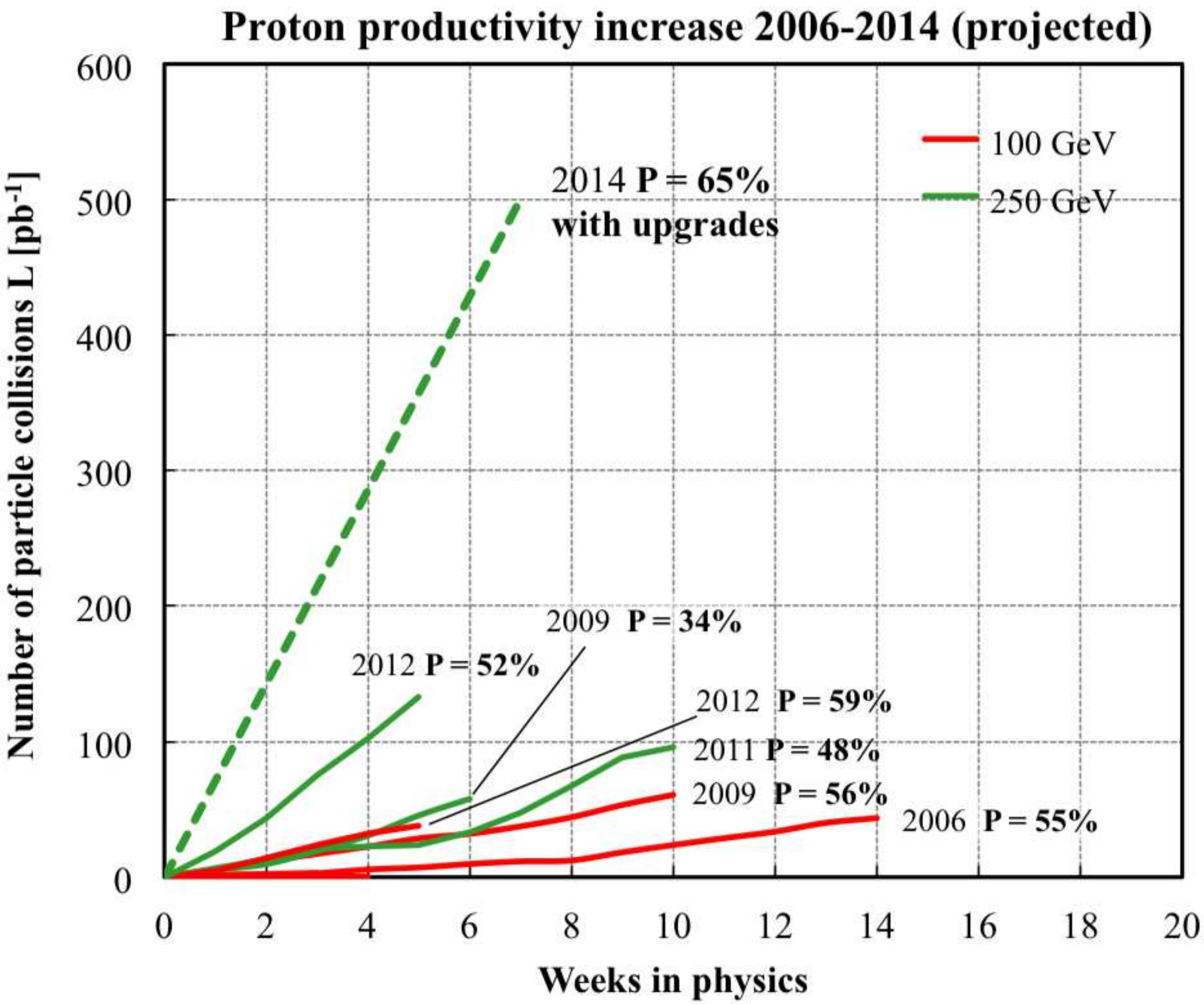
- Measuring polarization at RHIC
- Overview of RHIC polarimeters
- Polarimeter operations in 2012 run
- New results from 2012
- Single spin asymmetry A_N and spin flip in $pp \to pp$

Accelerator Complex and Polarimeters



- 120 bunches (~ 110 ns) across the ring
- Collisions with all spin combinations available $\uparrow\uparrow$, $\uparrow\downarrow$, $\downarrow\uparrow$, $\downarrow\downarrow$

RHIC Performance and Projections



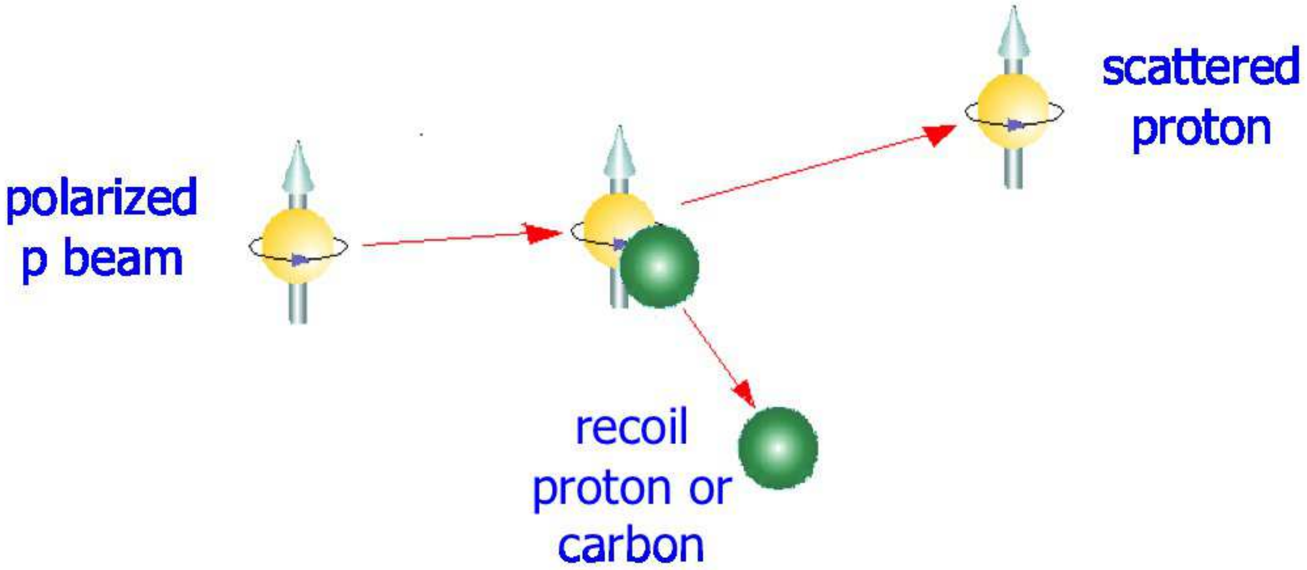
- **In 2012 pp collisions at $\sqrt{s} = 100$ and 255 GeV**
  - New record peak and fill/store average luminosities
  - Average polarization is higher than before
- **Expected next run:**
  - $\times 4$ more integrated luminosity than in 2012
  - $\sim 5\%$ increase in polarization

CNI Polarimetry at RHIC

- Particle spin in hadron interactions gives asymmetric yields w.r.t. spin direction

- In elastic scattering maximum asymmetry A_N is expected in the region of **Coulomb-Nuclear Interference** where EM and strong amplitudes are comparable in

$$\varepsilon = \frac{N_L - N_R}{N_L + N_R}$$



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

- **Measured polarization $P = \varepsilon / A_N$**

- In general, knowledge of A_N is required

CNI Polarimetry at RHIC

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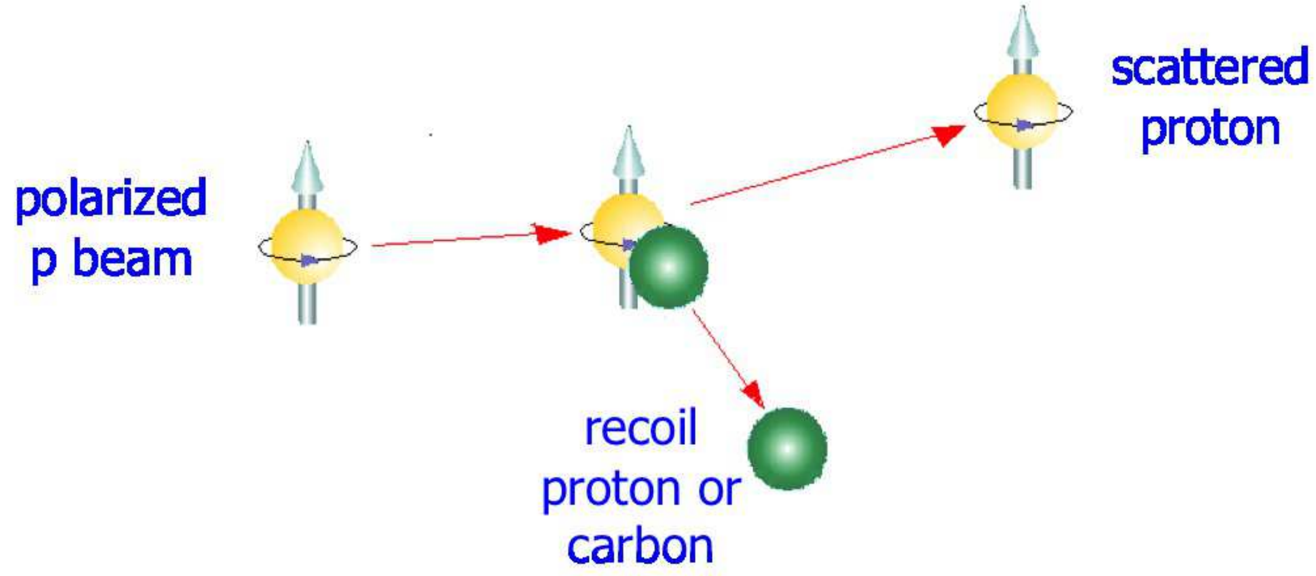
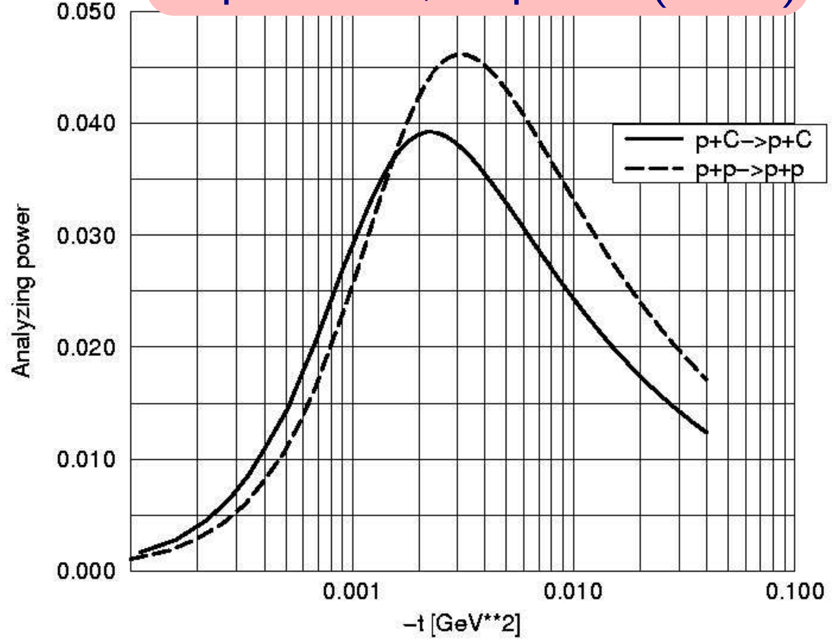


Kopeliovich, Lapidus (1974)

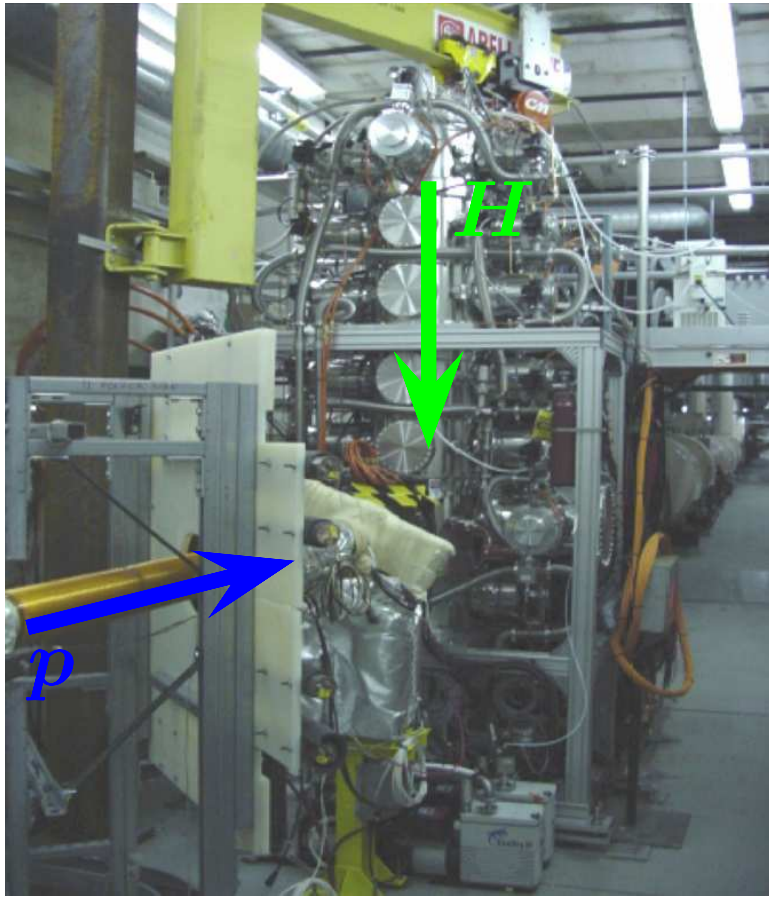


In absence of hadronic spin-flip amplitude analyzing power A_N can be calculated exactly

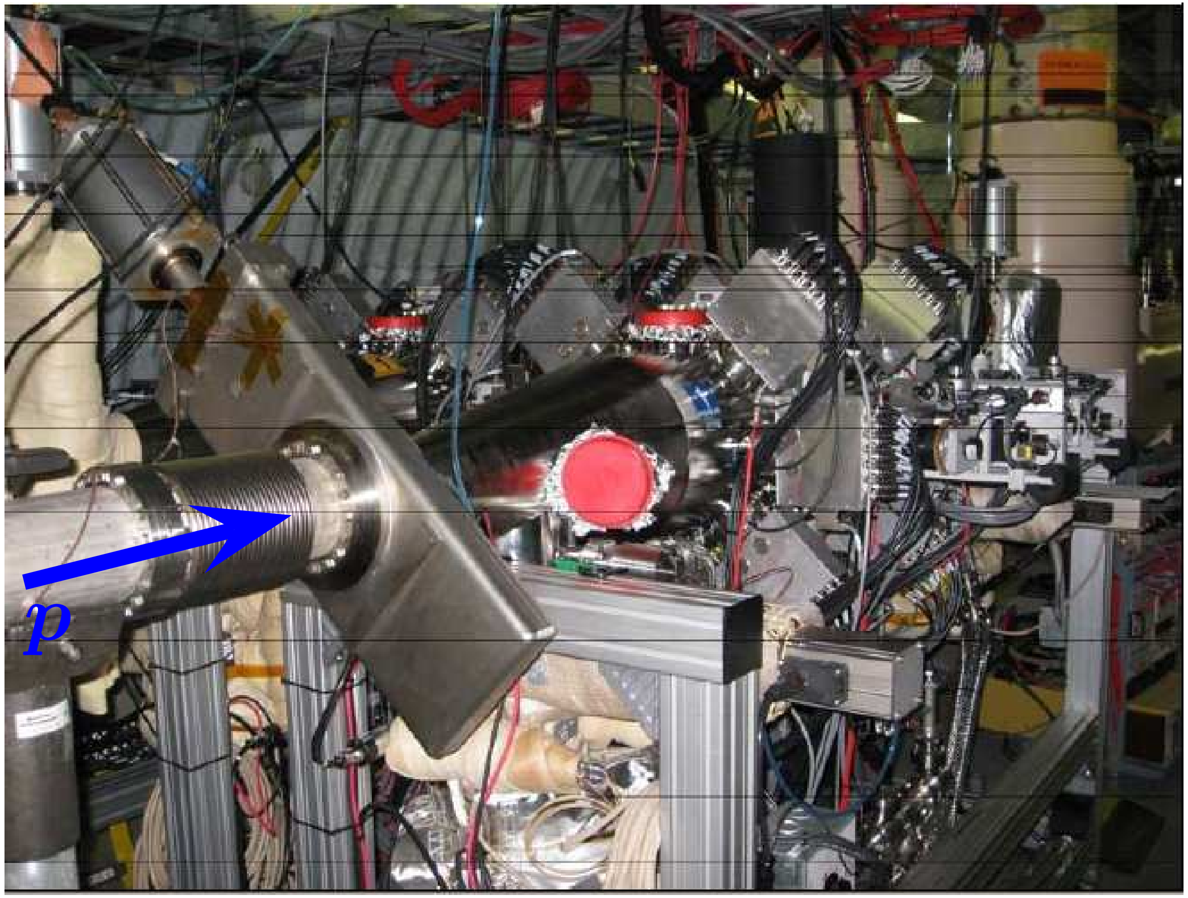
- **Measured polarization** $\boldsymbol{P = \varepsilon / A_N}$

- In general, knowledge of A_N is required

Polarization Measurement Strategy

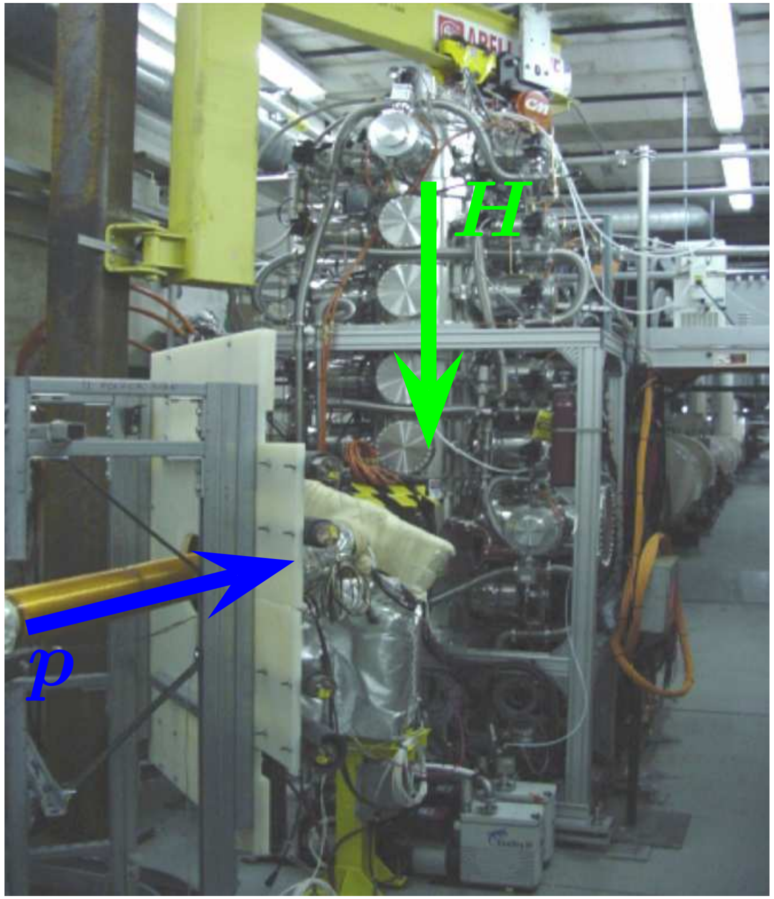


- **Hydrogen jet (H-jet) polarimeter**
  - **$\sim$ 6-8% stat. uncert. per fill**
  - Continuous operation throughout a fill
  - Provides **average** absolute polarization over the fill ($\sim 8 - 10$ hours)

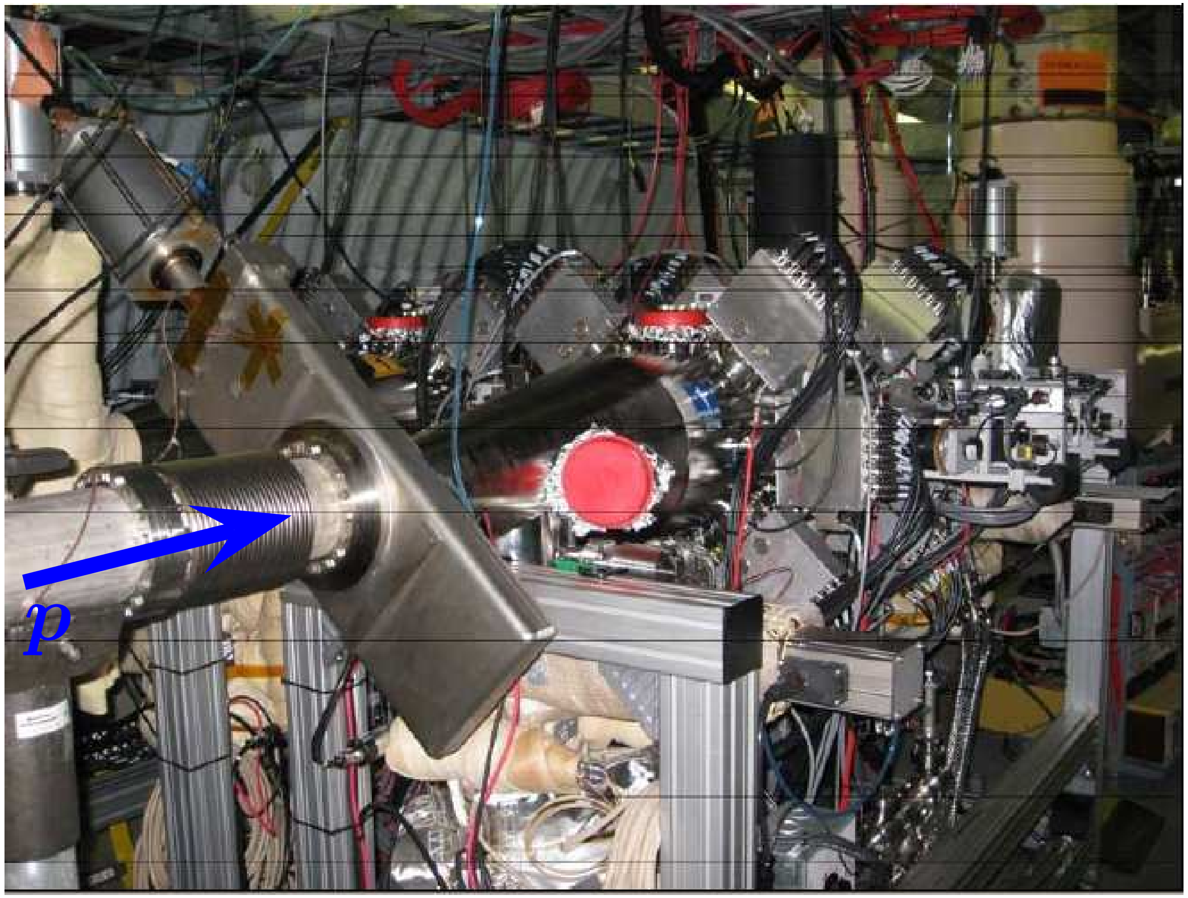


- **Two p-Carbon polarimeters in each ring**
  - **~ 4% stat. uncert. per measurement**
  - About four 2-minute measurements per fill
  - Bunch and fill polarization
  - Vertical and horizontal beam polarization profiles
  - Polarization decay in fill

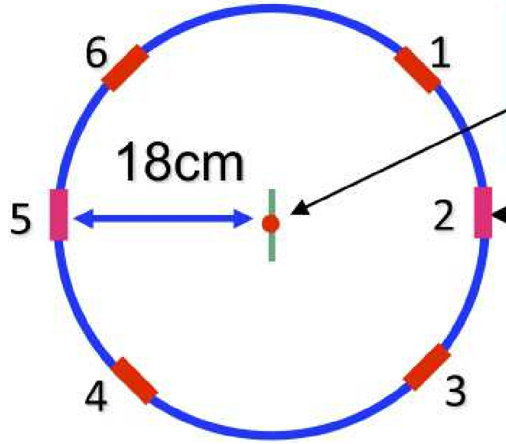
Targets



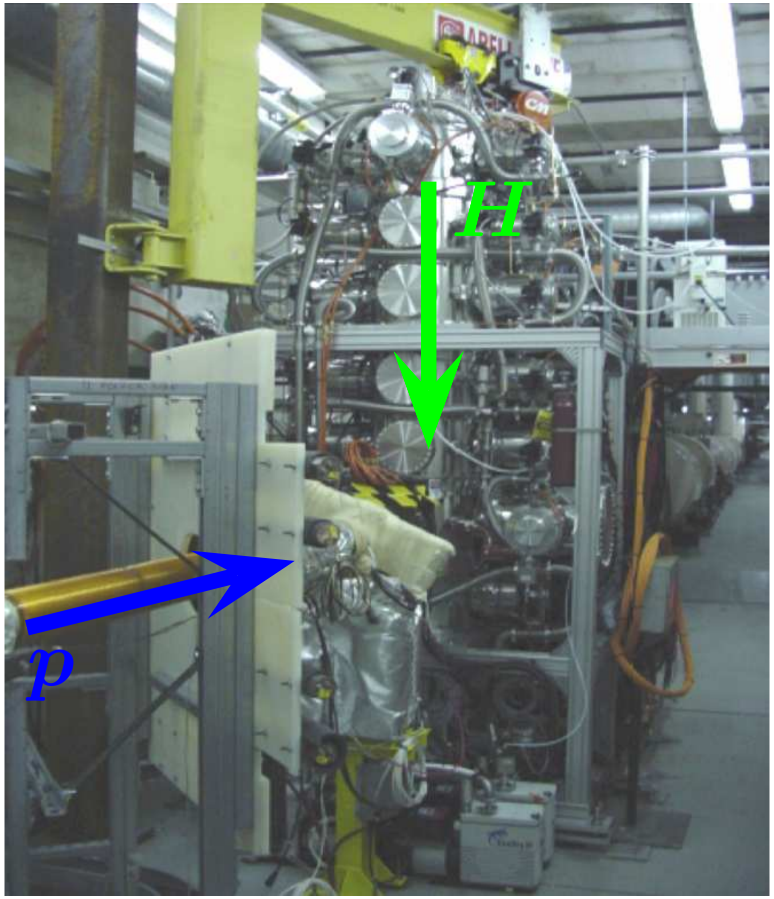
- **H-jet polarimeter**
  - Vertical polarized ($\approx 96\%$) hydrogen jet $\sim 6-7$ mm in diameter
  - Target polarization cycles $\uparrow/0/\downarrow$ every $300/30/300$ seconds

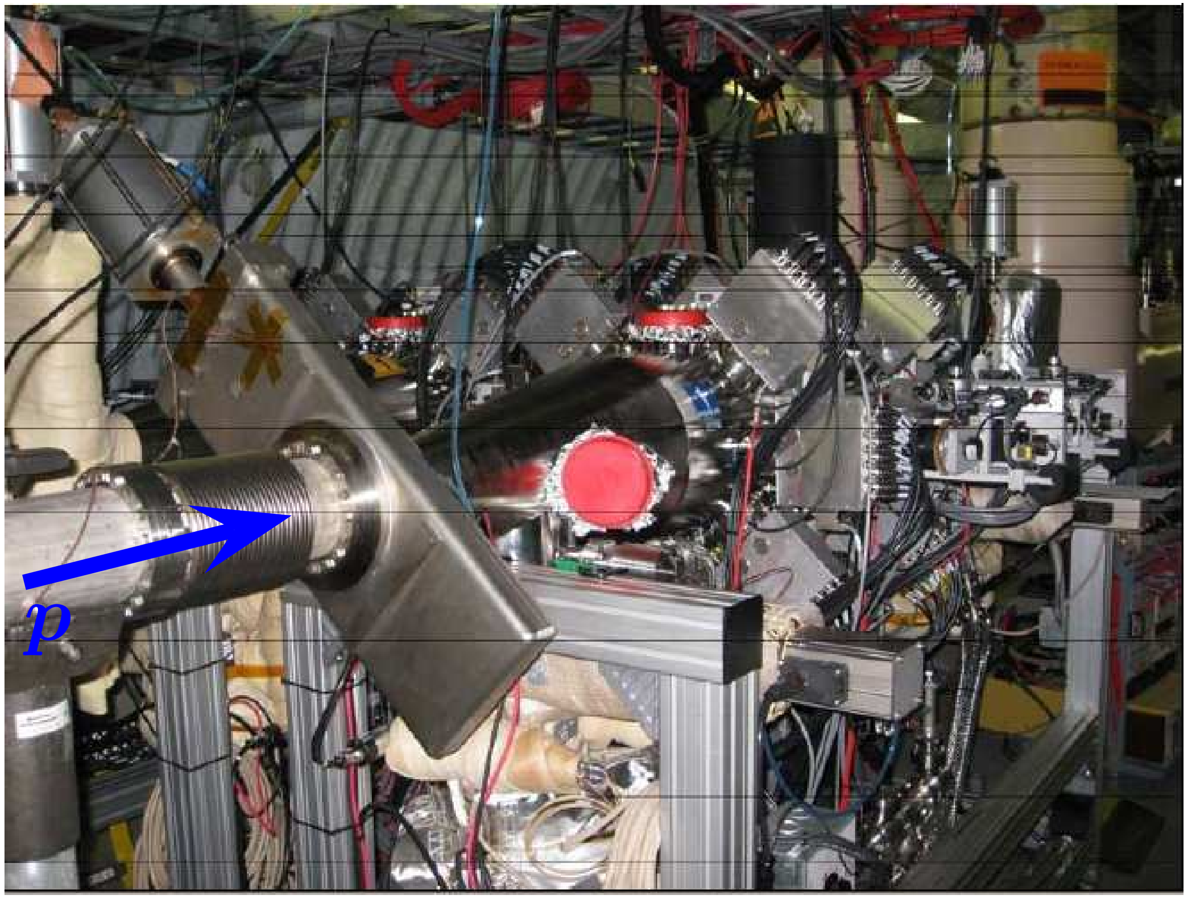


- **p-Carbon polarimeters**
  - Ultra thin carbon ribbon 2.5 cm $\times$ 10 μm $\times$ 25 nm
  - **Vertical** and **horizontal** targets



Detectors





- **H-jet and p-Carbon polarimeters**
  - Strip silicon detectors
  - Energy calibration is done with α particles of known energy
  - Record energy and ToF of every hit above a threshold

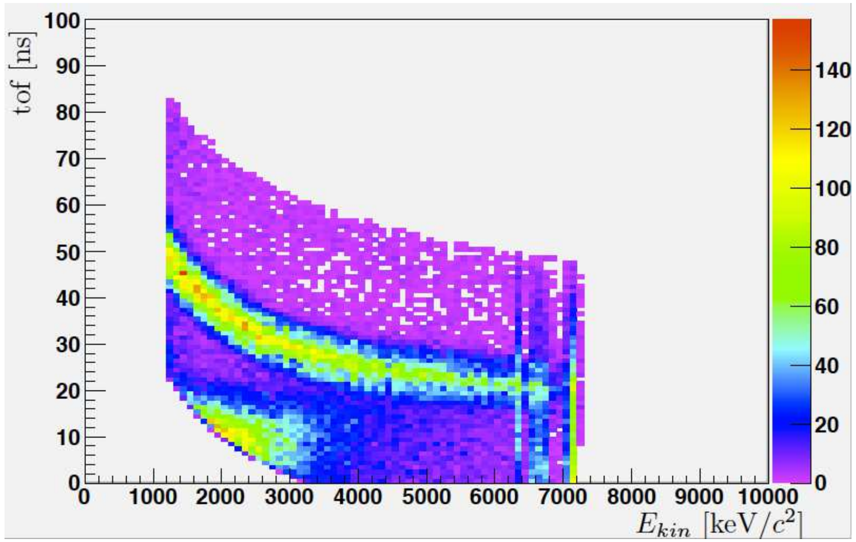
Configuration in 2012 RHIC Run

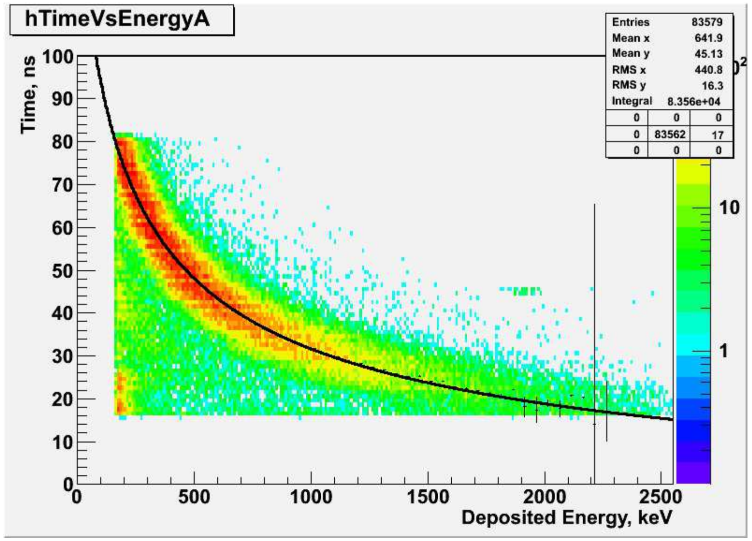
- **Detectors:** Most of the detectors were reused from Run 11
  - Observed no significant degradation due to radiation
- **Carbon targets:** Fabricated with standard technique as in previous runs
  - Few special targets and experimental detectors (different orientation, manufacturer) were placed in only one p-Carbon polarimeter
- Minimal changes to configuration aimed to ensure stable operations and also help with year-to-year systematic studies

Challenges in 2012 RHIC Run

- Beam induced **RF noise** overlapping with signal was observed in some channels/detectors
  - Added shielding
  - Found and terminated open cables close to polarimeters
  - As a result noise reduced in subsequent fills
  - Significant modifications in QA required to clean up the data
- High rate of carbon **target loss**
  - Conserved targets by reducing the number of measurements
  - All target replaced twice (required to break the vacuum)

Signal Selection





- Elastic events are identified with the non-relativistic relation:

$$E_{\text{meas}} + E_{\text{loss}} = \frac{m}{2} \times \frac{L^2}{(t_{\text{meas}} + t_0)^2}$$

where E_{loss} and t_0 are calibration constants extracted from the fit to the data

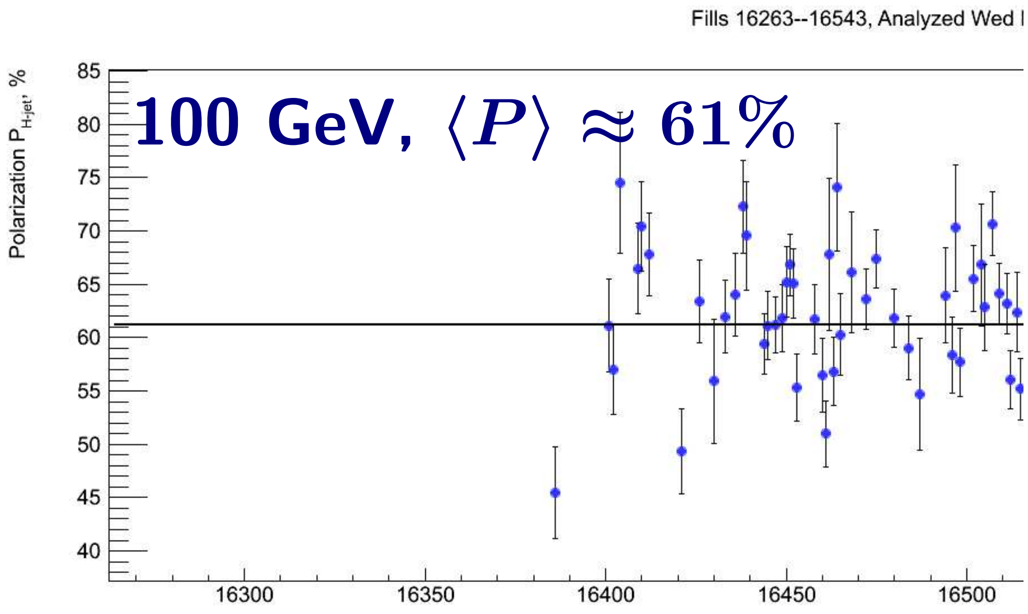
- **H-jet polarimeter**
  - The beam and the target are both protons:

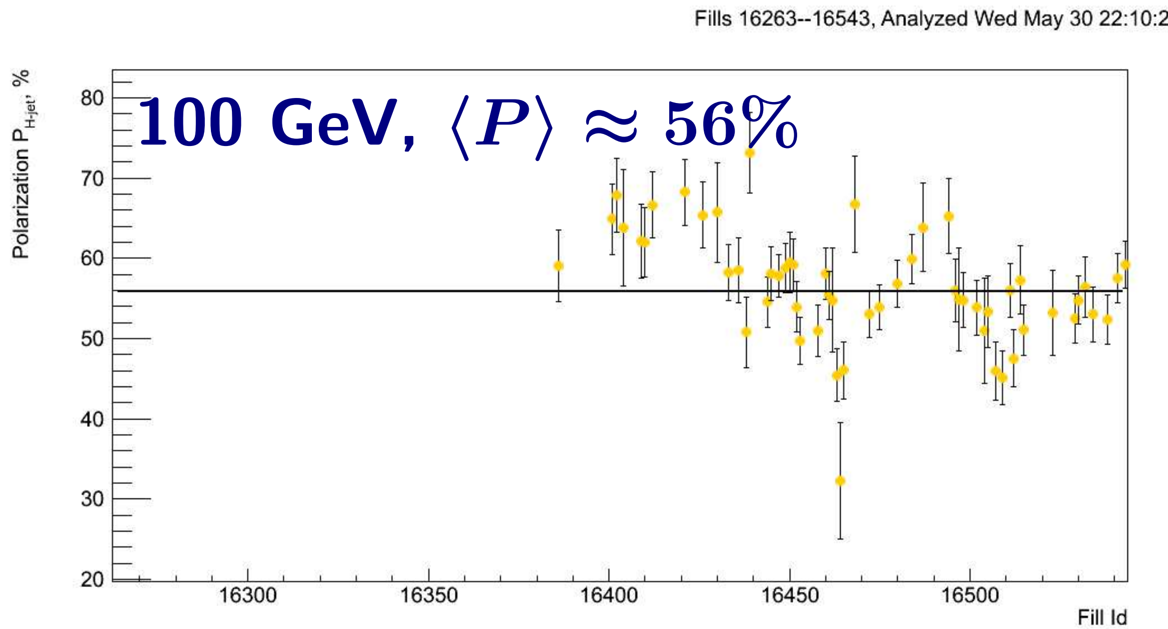
$$P = \frac{\varepsilon}{A_N^{pp}}, \qquad P_{\text{beam}} = -\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \times P_{\text{target}}$$

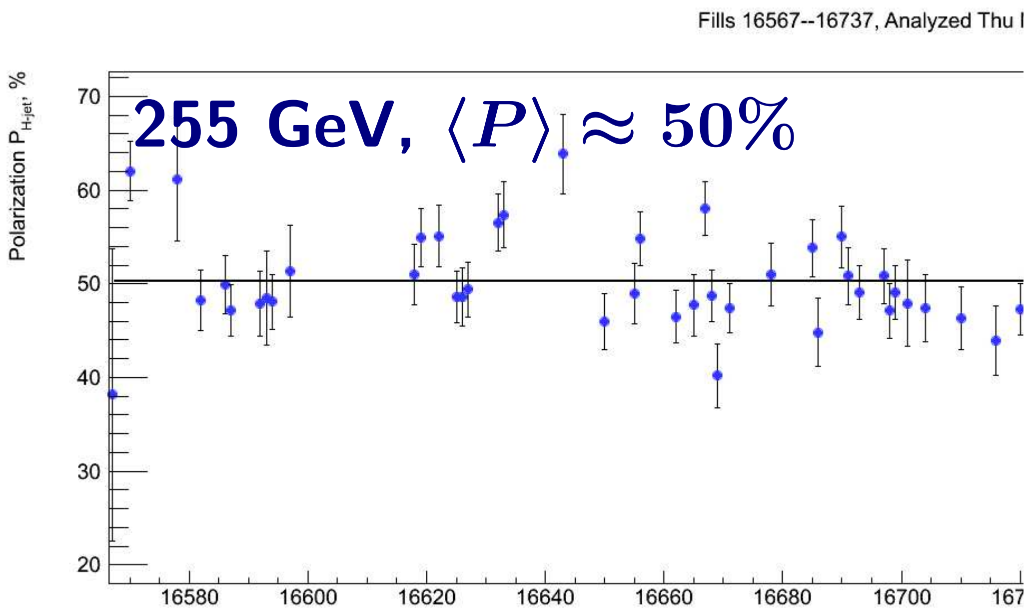
  - **No need to know A_N^{pp}!**

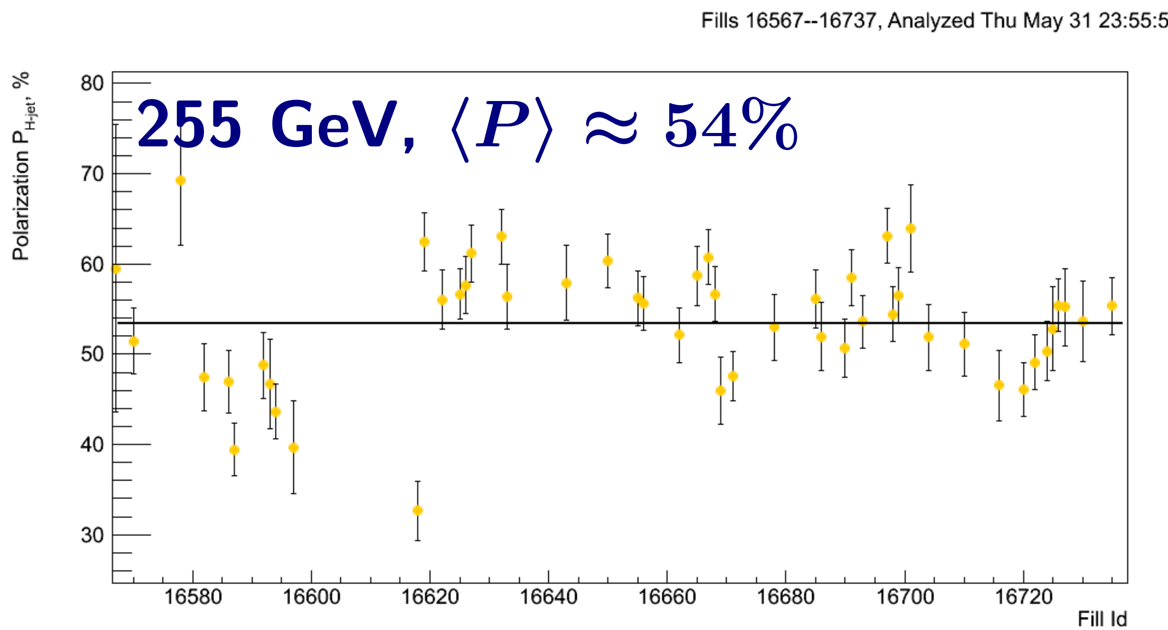
- **p-Carbon polarimeter**
  - (either) A_N^{pC} is known from previous measurements
  - (or) Polarization from p-Carbon normalized to H-jet value over many fills

Average Polarization in 2012





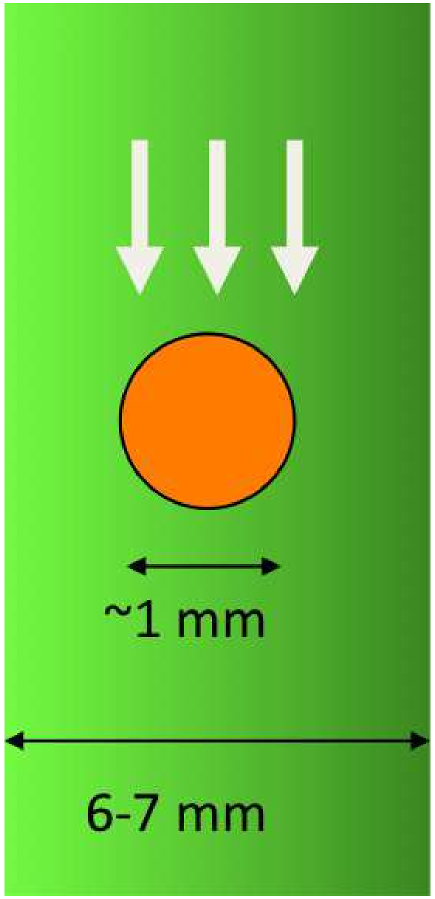




Polarization Profile

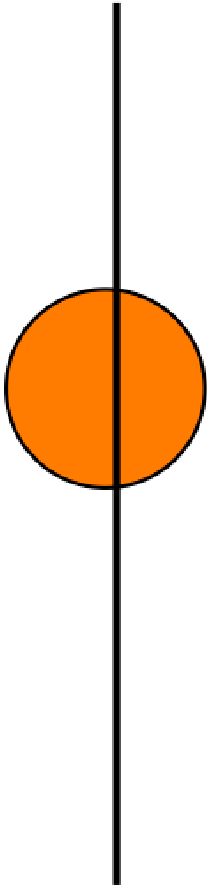
- If polarization varies across the beam the average polarization seen by polarimeters and experiments is different

H-Jet



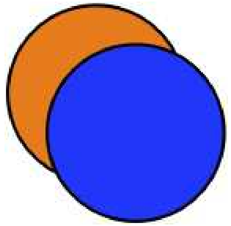
$$P = \frac{\int P(x,y)I(x,y)dxdy}{\int I(x,y)dxdy}$$

p-Carbon



$$P_{\text{sweep}} = P$$

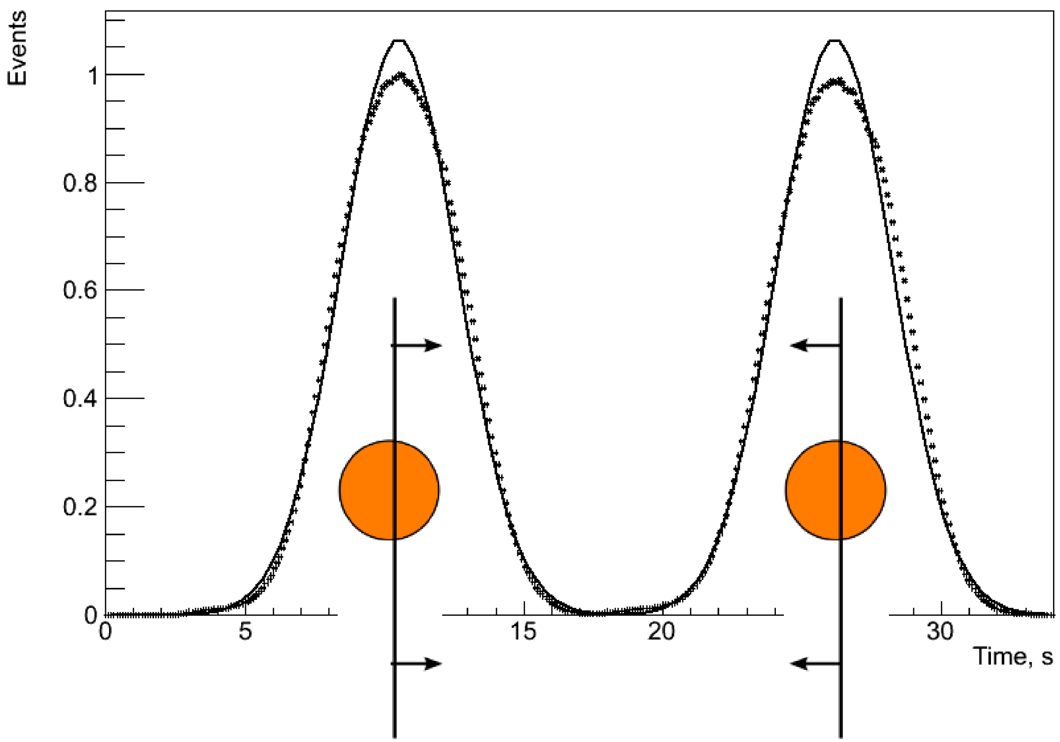
Beam collisions

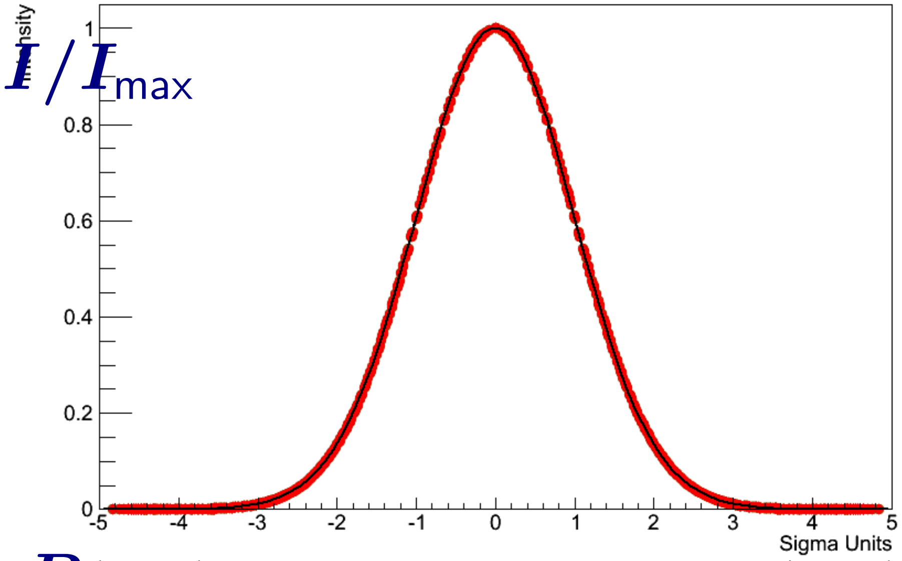


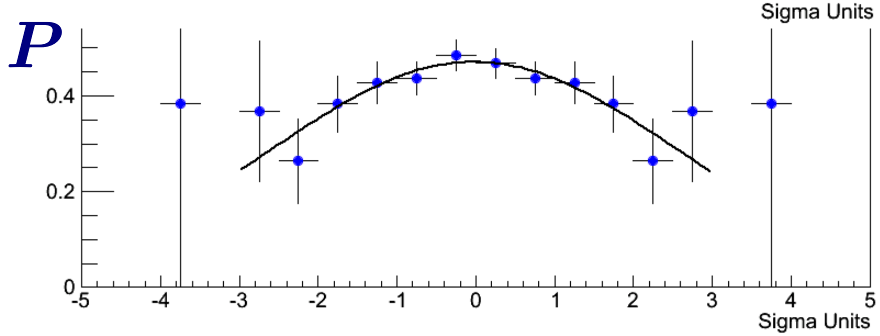
$$P_{\text{coll}} = \frac{\int P(x,y)I_1(x,y)I_2(x,y)dxdy}{\int I_1(x,y)I_2(x,y)dxdy}$$

Polarization Profile

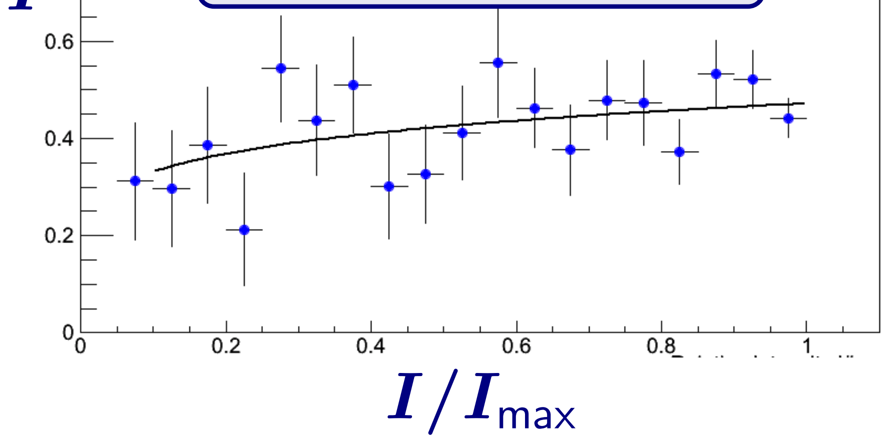
- Assume gaussian profiles: $P = P_{\text{max}} \exp(-\frac{\vec{x}^2}{\sigma_P^2})$, $I = I_{\text{max}} \exp(-\frac{\vec{x}^2}{\sigma_I^2})$
- Polarization profile can be described by
  - Center value P_{max}
  - Profile parameter $R = \frac{\sigma_I^2}{\sigma_P^2}$
  - $R = 0$ if $\sigma_P = \infty$ *i.e.* no Pol. profile



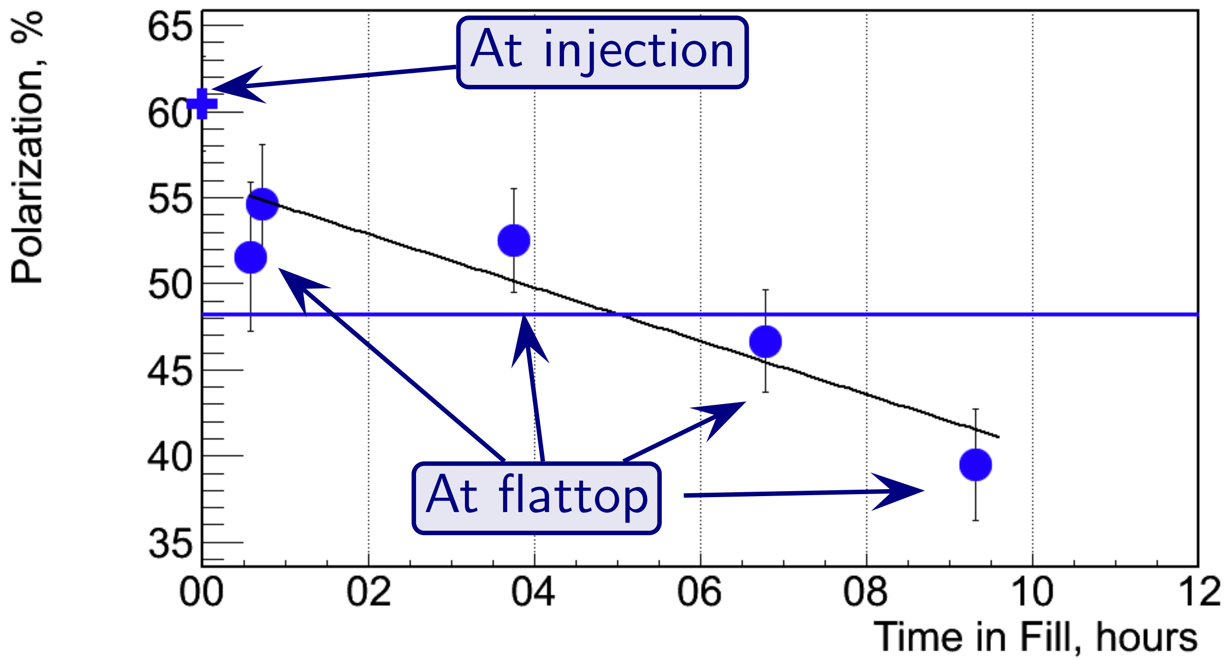


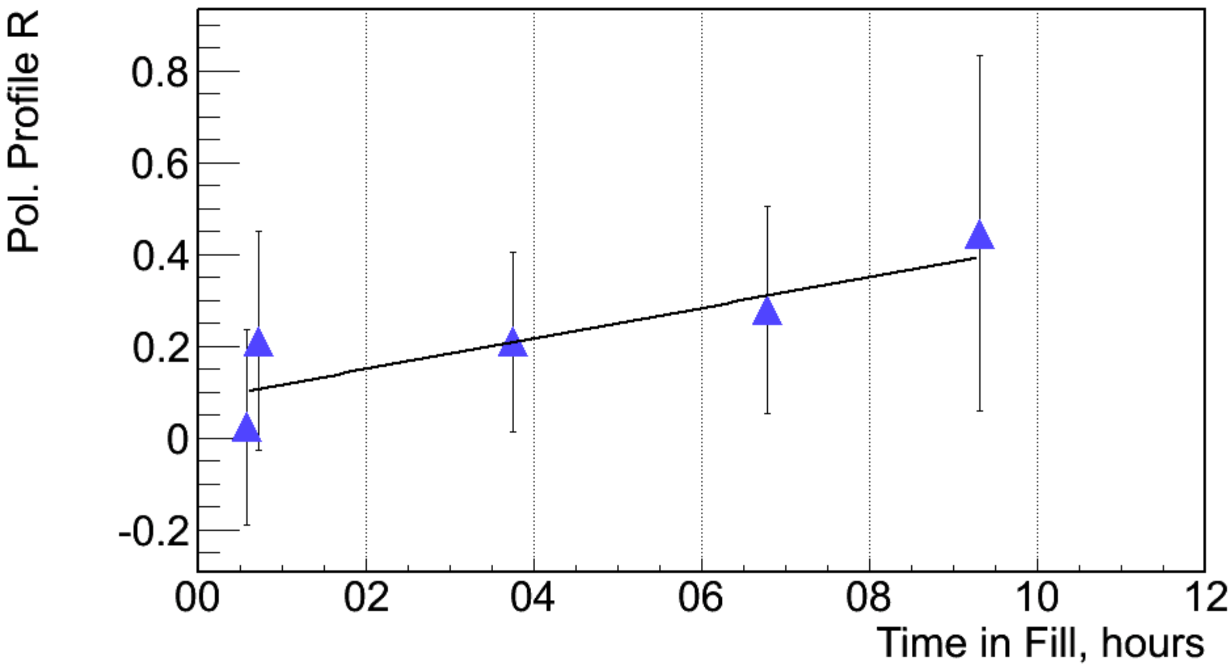


$$P = P_{\text{max}} (I/I_{\text{max}})^R$$



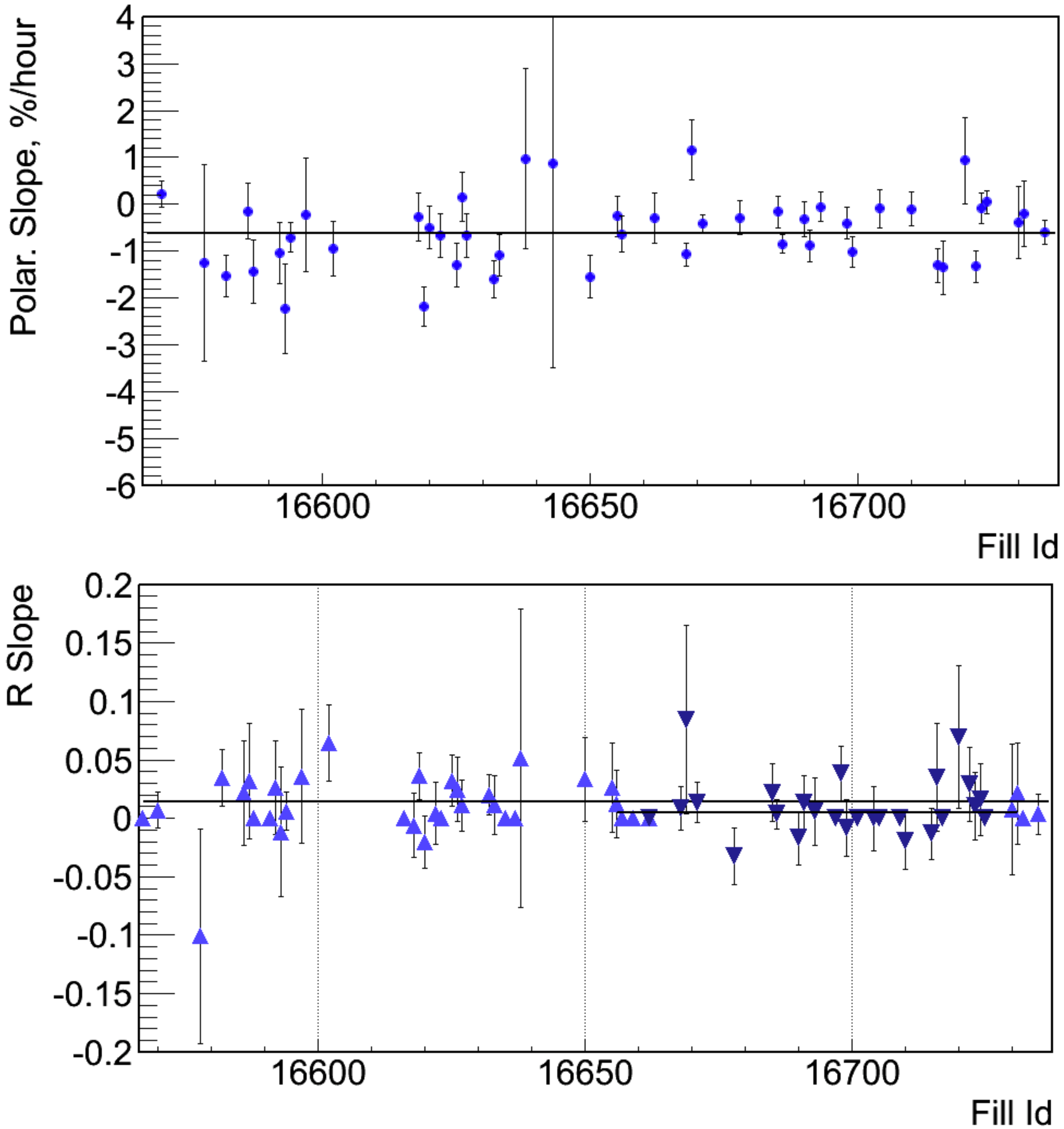
Polarization Losses in a Fill





- Polarization is lost during beam accelleration
- Polarization decreases during the fill while R increases
  - $R_v \sim R_h \approx 0.20$ for accelerated beam
- In addition to the average fill P we provide $P_0|_{t=0}$ and $\frac{dP}{dt}$
  - STAR and PHENIX experiments can reweight individual fills according to their recorded luminosity

Polarization for Experiments



- Average change in P and R are:
  $\frac{dP}{dt} \sim -0.5\%$ or $\frac{1}{P}\frac{dP}{dt} \sim -1\%$ per hour
  $\frac{dR}{dt} \sim 0.01$ or $\frac{1}{R}\frac{dR}{dt} \sim 5\%$ per hour
- Knowledge of polarization profile is critical for SSA and DSA measurements by experiments

$$P_{\text{SSA}} = \frac{\int P I_1 I_2 dx}{\int I_1 I_2 dx}, P_{\text{DSA}} = \frac{\int P_1 P_2 I_1 I_2 dx}{\int I_1 I_2 dx}$$

- As beam polarization P both P_{SSA} and P_{SSA} are linear in t:

$$P_{\text{SSA}} = P_{\text{SSA}} + P'_{\text{SSA}} t \approx P(t) \left(1 + \frac{1}{2} R(t)\right)$$

- Similarly for P_{DSA}

Systematic Uncertainties on Polarization

- **Overall scale uncertatinty** $\boldsymbol{\frac{\sigma(P)}{P} \approx 3\%}$
  - Due to normalization to the H-jet measurements
  - Includes:
    $\sim 2\%$ on H-jet target polarization,
    $\sim 1\%$ due to background dilution, and
    $\sim 1 - 2\%$ on the p-Carbon normalization
- **Fill-to-fill uncorrelated uncertatinty** $\boldsymbol{\frac{\sigma(P)}{P} \approx 4\%}$
  - Scales down as $1/\sqrt{N}$ when fills combined
  - Includes:
    $\sim 2.2\%$ due to possible profile missmeasurement,
    $\lesssim 3\%$ on energy scale due to recoil energy losses in target, dead layer, etc.
- More details available at

  `http://www.phy.bnl.gov/cnipol/fills/`

Single Spin Asymmetry A_N in elastic $pp \to pp$

Proton-proton Elastic Scattering Amplitudes

- Five independent helicity amplitudes describe proton-proton elastic scattering:

$$\phi_1(s,t) = \langle ++|M|++\rangle \qquad \text{spin non-flip}$$
$$\phi_2(s,t) = \langle ++|M|--\rangle \qquad \text{double spin flip}$$
$$\phi_3(s,t) = \langle +-|M|+-\rangle \qquad \text{spin non-flip}$$
$$\phi_4(s,t) = \langle +-|M|-+\rangle \qquad \text{double spin flip}$$
$$\phi_5(s,t) = \langle ++|M|+-\rangle \qquad \text{single spin flip}$$

- Assuming $|t| \ll m \ll \sqrt{s}$ some observables [Buttimore *et. al.*, PRD59, 114010] are:

$$\sigma_{\text{tot}} = \frac{4\pi}{s}\,\text{Im}(\phi_1+\phi_3), \qquad \frac{d\sigma}{dt} = \frac{2\pi}{s^2}(|\phi_1|^2+|\phi_2|^2+|\phi_3|^2+|\phi_4|^2+4|\phi_5|^2)$$

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

- Interference of electromagnetic and hadronic amplitudes is taken into account by replacing:

$$\phi_i(s,t) \to \phi_i^{\text{em}}(s,t) + \phi_i^{\text{had}}(s,t)$$

Single Spin Asymmetry A_N

- Neglecting double spin flip contribution the left-right asymmetry A_N is:

$$A_N \approx \mathrm{Im}\left(\phi_{\text{flip}}^{\text{em}*}\phi_{\text{non-flip}}^{\text{had}} + \phi_{\text{flip}}^{\text{had}*}\phi_{\text{non-flip}}^{\text{em}}\right)$$

  with $\phi_{\text{flip}} \equiv \phi_5$ and $\phi_{\text{non-flip}} \equiv \frac{\phi_1+\phi_3}{2}$

- Hadronic spin flip contribution is described by

$$r_5 = \frac{m}{\sqrt{-t}}\frac{\phi_{\text{flip}}^{\text{had}}}{\mathrm{Im}\,\phi_{\text{non-flip}}^{\text{had}}}$$

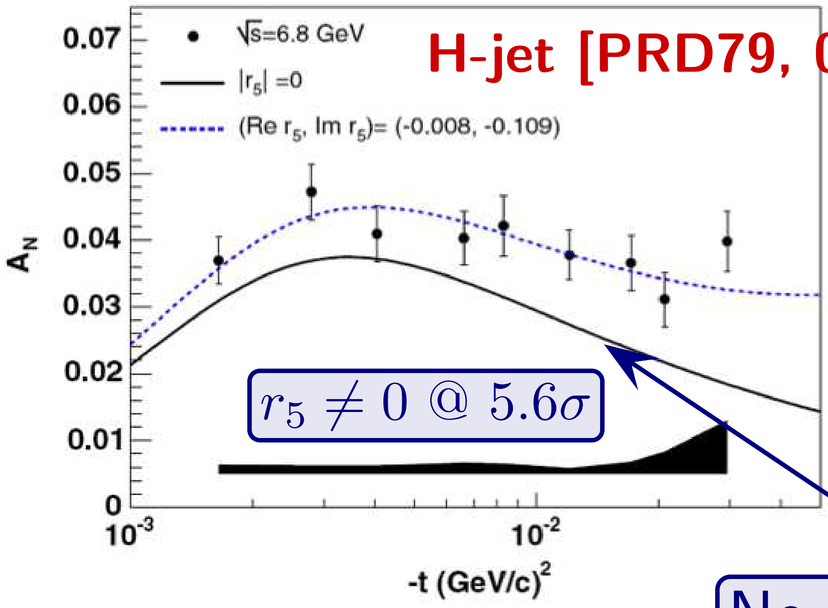
- With phenomenological input ($t_c = \frac{-8\pi\alpha}{\sigma_{\text{tot}}}$, ρ, $\delta = \delta(B)$) A_N is parameterized as

$$A_N(-t) = \frac{\sqrt{-t}}{m}\frac{\left[\kappa(1-\rho\delta) + 2(\delta\mathbf{Re}\,\boldsymbol{r_5} - \mathbf{Im}\,\boldsymbol{r_5})\right]\frac{t_c}{t} - 2(\mathbf{Re}\,\boldsymbol{r_5} - \rho\mathbf{Im}\,\boldsymbol{r_5})}{\left(\frac{t_c}{t}\right)^2 - 2(\rho+\delta)\frac{t_c}{t} + (1+\rho^2)}$$

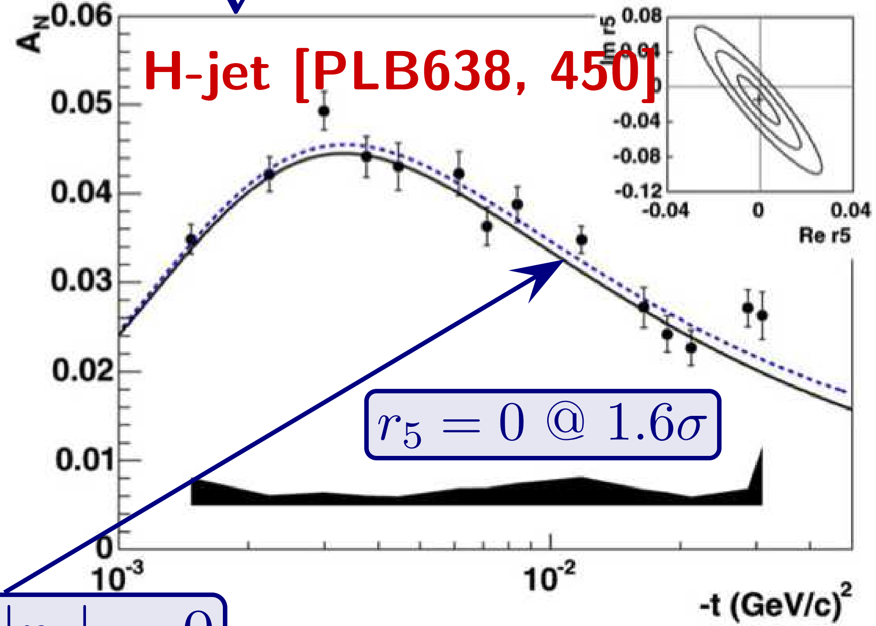
- $\mathrm{Im}\,r_5$ and $\mathrm{Re}\,r_5$ can be extracted from a fit to the data

Previous measurements of A_N

$\sqrt{s} = 6.8$ GeV



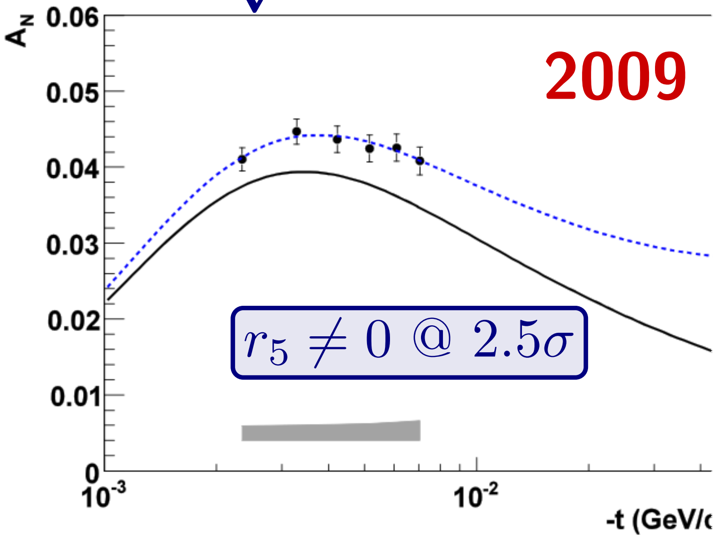
$\sqrt{s} = 13.7$ GeV



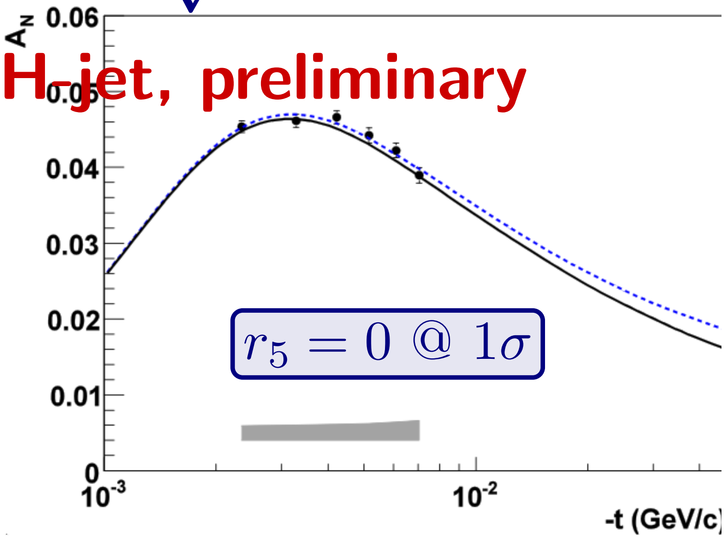
No spin flip, $|r_5| = 0$

$\sqrt{s} = 7.7$ GeV

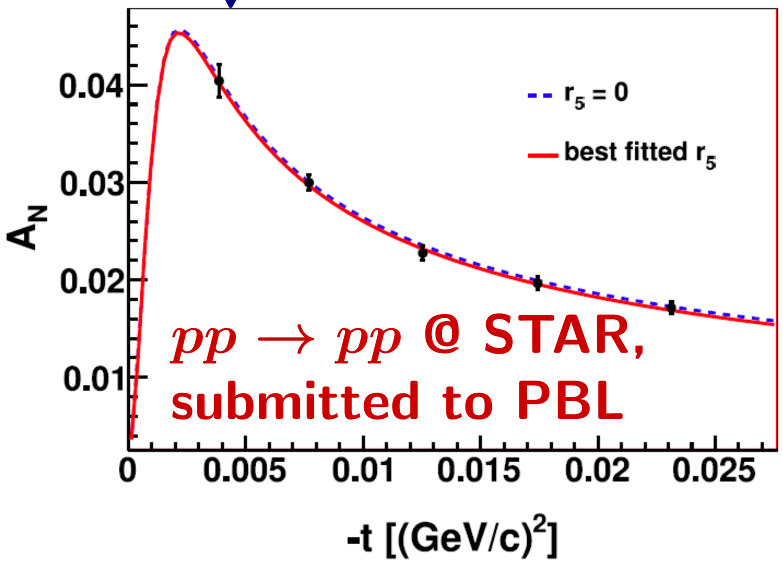
2009 H-jet, preliminary



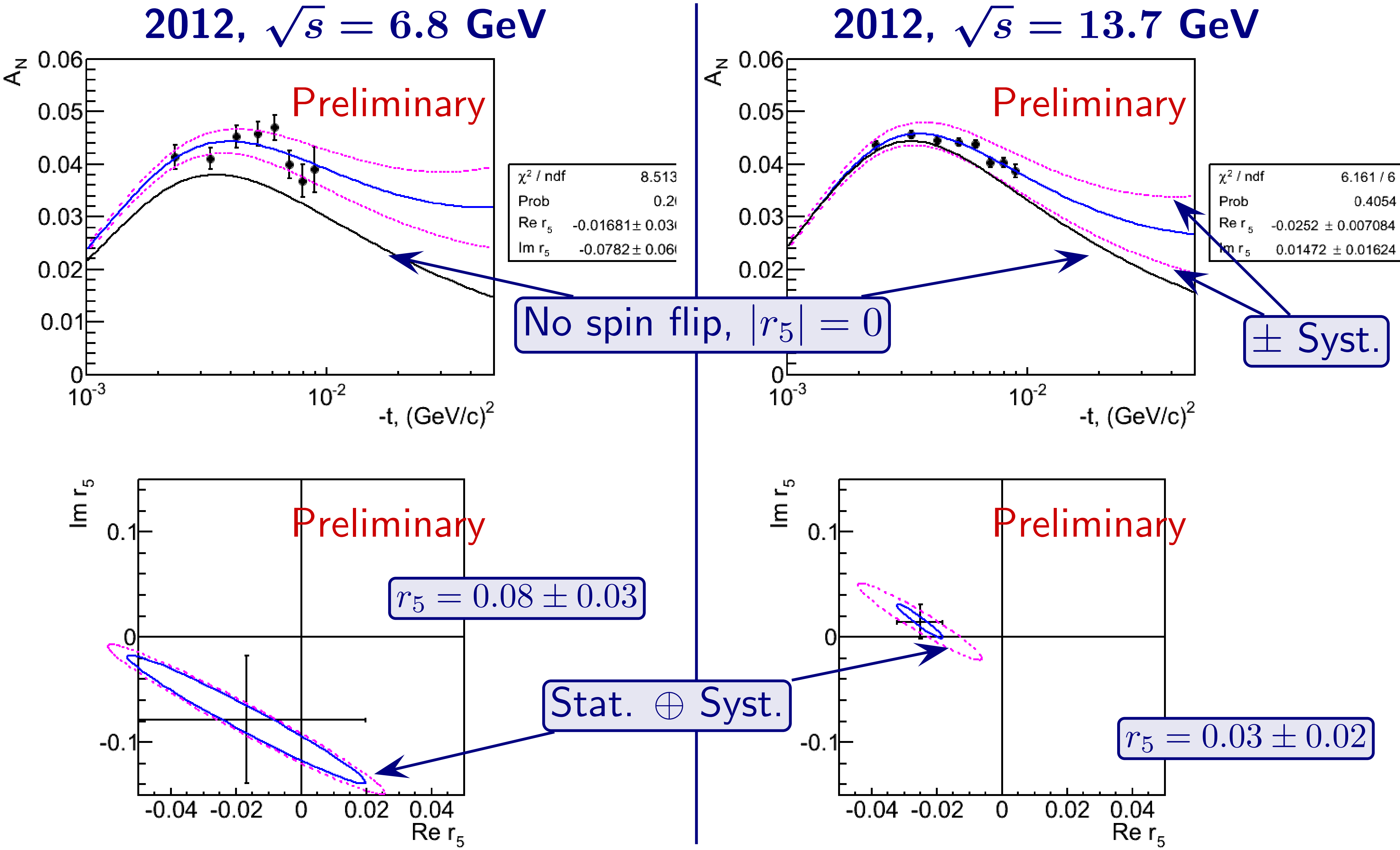
$\sqrt{s} = 21.7$ GeV



$\sqrt{s} = 200$ GeV

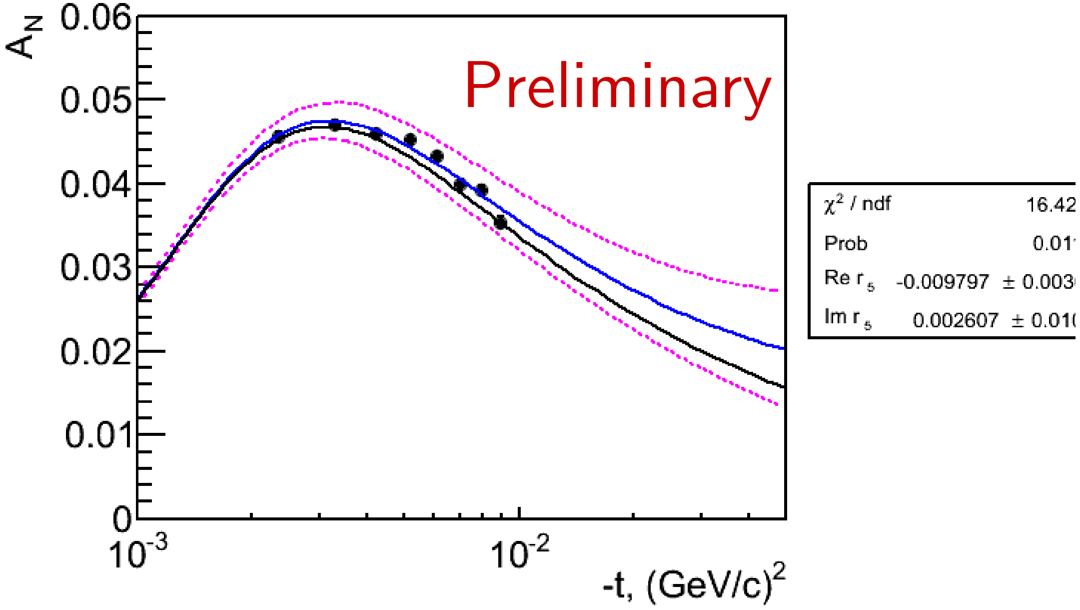


Single Spin Asymmetry A_N in $pp \to pp$, 2012

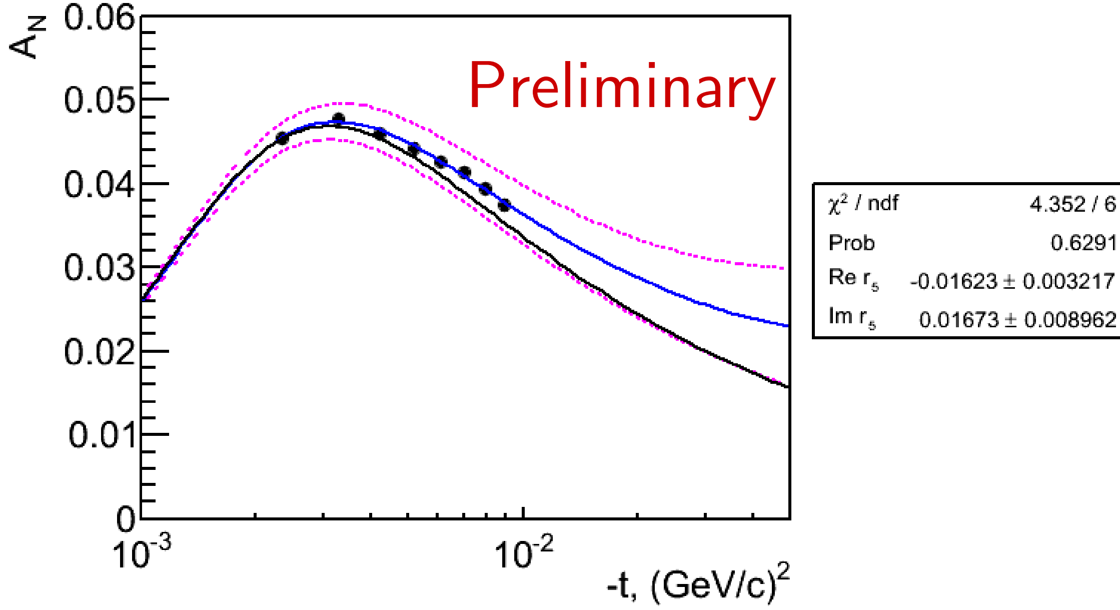


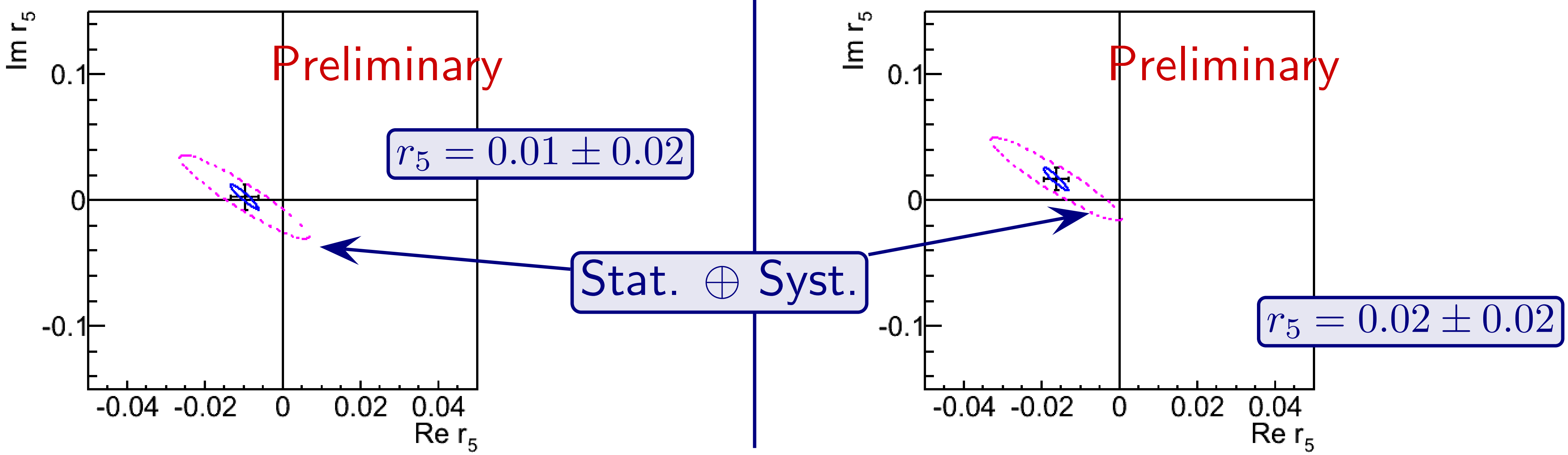
Single Spin Asymmetry A_N in $pp \to pp$, 2011 2012

2011, $\sqrt{s} = 21.7$ GeV



2012, $\sqrt{s} = 21.9$ GeV





Summary

- **Polarimeters performed well in 2012 RHIC run**
- Results available for 2011 and 2012 runs
  - Calculated beam polarization and profiles
  - Introduced time dependent polarization for RHIC experiments
  - Estimated systematic uncertainties
- **Single spin asymmetry was measured with H-jet**
  - The result is limited by systematics
  - Extracted hadronic spin flip contribution is consistent with previously reported values at $\sqrt{s} = 6.8, 13.7, 21.7$ GeV
- **Next run outlook:**
  - Expect much more data and $\sim +5\%$ polarization
  - Further background studies in H-jet may help to improve systematics
  - Calculate A_N for elastic $pC \to pC$