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

Dmitri Smirnov
Brookhaven National Laboratory

for the RHIC Spin Group

September 17, 2012
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 $pp \rightarrow pp$
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:**
- $\times4$ more integrated luminosity than in 2012
- $\sim5\%$ 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

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

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

- Measured polarization $P = \varepsilon / A_N$

- In general, knowledge of $A_N$ is required
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.

Kopeliovich, Lapidus (1974) in absence of hadronic spin-flip amplitude analyzing power $A_N$ can be calculated exactly.

Measured polarization $P = \varepsilon / A_N$.

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
  - $\sim 4\%$ 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

SPIN2012 – September 17, 2012

Dmitri Smirnov
**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 $\times 10$ $\mu$m $\times 25$ nm
  - **Vertical** and **horizontal** targets
Detectors

- H-jet and p-Carbon polarimeters
  - Strip silicon detectors
  - Energy calibration is done with $\alpha$ particles of known energy
  - Record energy and ToF of every hit above a threshold
• **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)
Elastic events are identified with the non-relativistic relation:

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

where \( E_{\text{loss}} \) and \( t_0 \) are calibration constants extracted from the fit to the data.

**H-jet polarimeter**
- The beam and the target are both protons:
  \[ P = \frac{\varepsilon}{A_{N}^{pp}}, \quad P_{\text{beam}} = -\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \times P_{\text{target}} \]
- 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

Dmitri Smirnov
Average Polarization in 2012

100 GeV, $\langle P \rangle \approx 61\%$

255 GeV, $\langle P \rangle \approx 50\%$

100 GeV, $\langle P \rangle \approx 56\%$

255 GeV, $\langle P \rangle \approx 54\%$
Polarization Profile

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

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

\[ P_{\text{sweep}} = P \]

\[ P_{\text{coll}} = \frac{\int P(x, y)I_1(x, y)I_2(x, y)dxdy}{\int I_1(x, y)I_2(x, y)dxdy} \]
Assume gaussian profiles:

\[ P = P_{\text{max}} \exp\left(-\frac{x^2}{\sigma_P^2}\right), \quad I = I_{\text{max}} \exp\left(-\frac{x^2}{\sigma_I^2}\right) \]

Polarization profile can be described by:

- Center value \( P_{\text{max}} \)
- Profile parameter \( R = \frac{\sigma_I^2}{\sigma_P^2} \)
- \( R = 0 \) if \( \sigma_P = \infty \) i.e. no Pol. profile

\[ P = P_{\text{max}} \left(\frac{I}{I_{\text{max}}}\right)^R \]
Polarization Losses in a Fill

- Polarization is lost during beam acceleration
- 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:
  \[ \frac{dP}{dt} \sim -0.5\% \text{ or } \frac{1}{P} \frac{dP}{dt} \sim -1\% \text{ per hour} \]
  \[ \frac{dR}{dt} \sim 0.01 \text{ or } \frac{1}{R} \frac{dR}{dt} \sim 5\% \text{ per hour} \]

- Knowledge of polarization profile is critical for SSA and DSA measurements by experiments

\[
P_{SSA} = \frac{\int PI_1 I_2 dx}{\int I_1 I_2 dx},
P_{DSA} = \frac{\int P_1 P_2 I_1 I_2 dx}{\int I_1 I_2 dx}
\]

- As beam polarization $P$ both $P_{SSA}$ and $P_{SSA}$ are linear in $t$:
  \[ P_{SSA} = P_{SSA} + P'_{SSA} t \approx P(t) \left( 1 + \frac{1}{2} R(t) \right) \]

- Similarly for $P_{DSA}$
Systematic Uncertainties on Polarization

- **Overall scale uncertainty** \( \frac{\sigma(P)}{P} \approx 3\% \)
  - 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 uncertainty** \( \frac{\sigma(P)}{P} \approx 4\% \)
  - 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.

Single Spin Asymmetry $A_N$ in elastic $pp \rightarrow pp$
Five independent helicity amplitudes describe proton-proton elastic scattering:

\[
\phi_1(s, t) = \langle + + |M| + + \rangle \quad \text{spin non-flip}
\]

\[
\phi_2(s, t) = \langle + + |M| - - \rangle \quad \text{double spin flip}
\]

\[
\phi_3(s, t) = \langle + - |M| + - \rangle \quad \text{spin non-flip}
\]

\[
\phi_4(s, t) = \langle + - |M| - + \rangle \quad \text{double spin flip}
\]

\[
\phi_5(s, t) = \langle + + |M| + - \rangle \quad \text{single spin flip}
\]

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

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

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

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

\[
\phi_i(s, t) \rightarrow \phi_i^{\text{em}}(s, t) + \phi_i^{\text{had}}(s, t)
\]
Single Spin Asymmetry $A_N$

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

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

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

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

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

$$A_N(-t) = \frac{\sqrt{-t}[\kappa(1 - \rho\delta) + 2(\delta \text{Re} r_5 - \text{Im} r_5)]}{m} \frac{t_c}{t} - 2(\text{Re} r_5 - \rho \text{Im} r_5)$$

$$\left(\frac{t_c}{t}\right)^2 - 2(\rho + \delta)\frac{t_c}{t} + (1 + \rho^2)$$

- Im $r_5$ and Re $r_5$ can be extracted from a fit to the data
Previous measurements of $A_N$

$\sqrt{s} = 6.8$ GeV

H-jet [PRD79, 094014]

$|r_5| = 0$ @ 5.6$\sigma$

$\sqrt{s} = 13.7$ GeV

H-jet [PLB638, 450]

$r_5 = 0$ @ 1.6$\sigma$

No spin flip, $|r_5| = 0$

$\sqrt{s} = 7.7$ GeV

2009 H-jet, preliminary

$r_5 \neq 0$ @ 2.5$\sigma$

$\sqrt{s} = 21.7$ GeV

$r_5 = 0$ @ 1$\sigma$

$\sqrt{s} = 200$ GeV

$pp \rightarrow pp$ @ STAR, submitted to PBL
Single Spin Asymmetry $A_N$ in $pp \rightarrow pp$, 2012

2012, $\sqrt{s} = 6.8$ GeV

Preliminary

No spin flip, $|r_5| = 0$

$r_5 = 0.08 \pm 0.03$

2012, $\sqrt{s} = 13.7$ GeV

Preliminary

$r_5 = 0.03 \pm 0.02$

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

Preliminary

$\chi^2$/ndf = 16.42
Prob = 0.01
Re $r_5 = -0.00979\pm0.003$
Im $r_5 = 0.002607\pm0.01$

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

Preliminary

$\chi^2$/ndf = 4.352 / 6
Prob = 0.629
Re $r_5 = -0.01623\pm0.003217$
Im $r_5 = 0.01673\pm0.008962$

$r_5 = 0.01 \pm 0.02$

Stat. $\oplus$ Syst.

$r_5 = 0.02 \pm 0.02$
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 $pC \rightarrow pC$