Recent Results in Polarized Proton-Proton Elastic Scattering at STAR

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On behalf of STAR Collaboration

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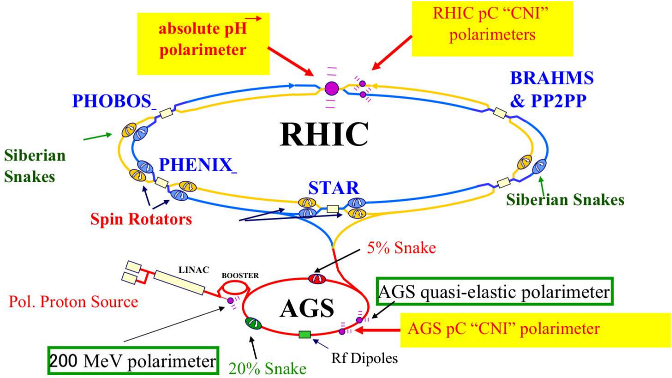
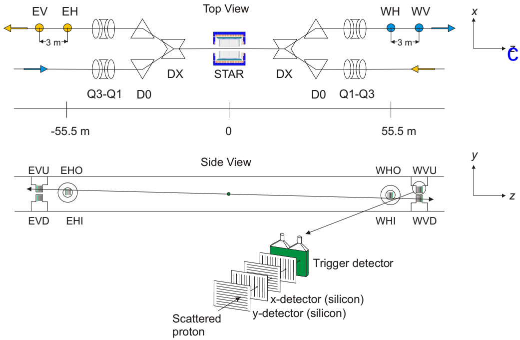
RHIC

AA: Au-Au, Cu-Cu, Cu-Au, d-Au, U-U up to $\sqrt{s_{NN}} = 200$ GeV
polarized proton-proton: up to $\sqrt{s} = 510$ GeV

this talk: $p + p \to p + p$; at $\sqrt{s} = 200$ GeV



Forward proton tagging at STAR



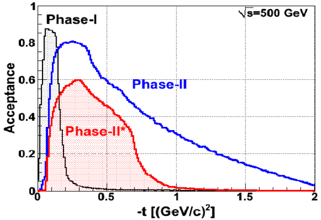
current setup(I)

- 8 Roman Pots (4 stations)
- with 4 silicon strip layers
- full angular coverage
- need special beam optics
- data at $\sqrt{s} = 200$ GeV
- $0.003 < -t < 0.035$ GeV^2

Upgrade to be installed 2014 (II*)

- 4 Roman Pots (2 stations)
- possible extension (II)
  6 Roman Pots (3 stations)
- limited angular coverage
- no special runs needed
- larger statistics
- $0.1 < -t < 1.2$ GeV^2

Acceptance for ($pp \to ppX$)



Proton-Proton Elastic Scattering

Five helicity amplitudes describe proton-proton elastic scattering

- non-flip
  $\phi_1(s,t) \propto \langle + + |M| + + \rangle$
  $\phi_3(s,t) \propto \langle + - |M| + - \rangle$
- double-flip
  $\phi_2(s,t) \propto \langle + + |M| - - \rangle$
  $\phi_4(s,t) \propto \langle + - |M| - + \rangle$
- single-flip
  $\phi_5(s,t) \propto \langle + + |M| + - \rangle$

- $\phi_i = \phi_i^{em} + \phi_i^{had}$
- $\phi_i^{had} = \phi_i^{R} + \phi_i^{I\!P}$

It is usefull to use:

- $\phi_+ = \frac{1}{2}(\phi_1 + \phi_3)$
- $\phi_- = \frac{1}{2}(\phi_1 - \phi_3)$

Some observables (cross sections and spin asymmetries)

$$\sigma_{tot}(s) = \frac{2\pi}{s} \mathrm{Im}(\phi_+)_{|t=0}$$

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

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

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

$$A_{SS}(s,t)\frac{d\sigma}{dt} = \frac{4\pi}{s^2}\mathrm{Re}\left(\phi_1\phi_2^\star + \phi_3\phi_4^\star\right)$$

STAR measurements

- published A_N
- preliminary A_{NN} and A_{SS}
- ongoing $d\sigma/dt$ and σ_{tot}

Spin assymetries

For transversely polarized beams cross section can be expressed as:

$$\sigma = \sigma_0 \left(1 + A_N(\vec{P}_Y + \vec{P}_B)\cdot\vec{n} + A_{NN}(\vec{P}_Y\cdot\vec{n})(\vec{P}_B\cdot\vec{n}) + A_{SS}(\vec{P}_Y\cdot\vec{s})(\vec{P}_B\cdot\vec{s})\right)$$

- $\vec{n}$ - vector normal to scattering plane
- $\vec{s}$ - vector in scattering plane normal to initial momentum
- $\vec{P}_Y, \vec{P}_B$ - beam polarization vectors

For $\uparrow\uparrow$ combination of beam polarization:

$$2\pi\frac{d^2\sigma^{\uparrow\uparrow}}{dt d\phi} = \frac{d\sigma}{dt}\left(1 + A_N(P_Y^{\uparrow} + P_B^{\uparrow})\cos(\phi) + P_Y^{\uparrow}P_B^{\uparrow}[A_{NN}\cos^2(\phi) + A_{SS}\sin^2(\phi)]\right)$$

For $|P_Y^{\downarrow}| = |P_Y^{\uparrow}| = P_Y$ and $|P_B^{\downarrow}| = |P_B^{\uparrow}| = P_B$ some combinations of measurements allow extraction of spin assymetries from uncorrected for inefficiences event numbers (N)

$$\frac{\sigma^{\uparrow\uparrow} - \sigma^{\downarrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow}} = \frac{A_N(P_Y + P_B)\cos(\phi)}{1 + \delta(\phi)} = \frac{N^{\uparrow\uparrow}/L^{\uparrow\uparrow} - N^{\downarrow\downarrow}/L^{\downarrow\downarrow}}{N^{\uparrow\uparrow}/L^{\uparrow\uparrow} + N^{\downarrow\downarrow}/L^{\downarrow\downarrow}}$$

$$\frac{\sigma^{\uparrow\downarrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\downarrow\uparrow}} = \frac{A_N(P_B - P_Y)\cos(\phi)}{1 - \delta(\phi)} = \frac{N^{\uparrow\downarrow}/L^{\uparrow\downarrow} - N^{\downarrow\uparrow}/L^{\downarrow\uparrow}}{N^{\uparrow\downarrow}/L^{\uparrow\downarrow} + N^{\downarrow\uparrow}/L^{\downarrow\uparrow}}$$

$$\frac{(\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow}) - (\sigma^{\uparrow\downarrow} + \sigma^{\downarrow\uparrow})}{(\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow}) + (\sigma^{\uparrow\downarrow} + \sigma^{\downarrow\uparrow})} = \overbrace{P_Y P_B[A_{NN}\cos^2(\phi) + A_{SS}\sin^2(\phi)]}^{\delta(\phi)} = \frac{(N^{\uparrow\uparrow}/L^{\uparrow\uparrow} + N^{\downarrow\downarrow}/L^{\downarrow\downarrow}) - (N^{\uparrow\downarrow}/L^{\uparrow\downarrow} + N^{\downarrow\uparrow}/L^{\downarrow\uparrow})}{(N^{\uparrow\uparrow}/L^{\uparrow\uparrow} + N^{\downarrow\downarrow}/L^{\downarrow\downarrow}) + (N^{\uparrow\downarrow}/L^{\uparrow\downarrow} + N^{\downarrow\uparrow}/L^{\downarrow\uparrow})}$$

Square root formula for single spin asymmetry

Symmetry properties: $\sigma^{\uparrow\uparrow}(\phi) = \sigma^{\downarrow\downarrow}(\pi - \phi)$ and $\sigma^{\uparrow\downarrow}(\phi) = \sigma^{\downarrow\uparrow}(\pi - \phi)$ allow extraction of A_N using non-normalized event numbers only

$$\frac{\sigma^{\uparrow\uparrow}(\phi) - \sigma^{\downarrow\downarrow}(\phi)}{\sigma^{\uparrow\uparrow}(\phi) + \sigma^{\downarrow\downarrow}(\phi)} = \frac{\sqrt{\sigma^{\uparrow\uparrow}(\phi)\sigma^{\downarrow\downarrow}(\pi - \phi)} - \sqrt{\sigma^{\downarrow\downarrow}(\phi)\sigma^{\uparrow\uparrow}(\pi - \phi)}}{\sqrt{\sigma^{\uparrow\uparrow}(\phi)\sigma^{\downarrow\downarrow}(\pi - \phi)} + \sqrt{\sigma^{\downarrow\downarrow}(\phi)\sigma^{\uparrow\uparrow}(\pi - \phi)}}$$

$$\frac{A_N (P_Y + P_B)\cos(\phi)}{1 + \delta(\phi)} = \frac{\sqrt{N^{\uparrow\uparrow}(\phi)N^{\downarrow\downarrow}(\pi - \phi)} - \sqrt{N^{\downarrow\downarrow}(\phi)N^{\uparrow\uparrow}(\pi - \phi)}}{\sqrt{N^{\uparrow\uparrow}(\phi)N^{\downarrow\downarrow}(\pi - \phi)} + \sqrt{N^{\downarrow\downarrow}(\phi)N^{\uparrow\uparrow}(\pi - \phi)}} = \epsilon_N(\phi)$$

Similary

$$\frac{A_N (P_B - P_Y)\cos(\phi)}{1 - \delta(\phi)} = \frac{\sqrt{N^{\uparrow\downarrow}(\phi)N^{\downarrow\uparrow}(\pi - \phi)} - \sqrt{N^{\downarrow\uparrow}(\phi)N^{\uparrow\downarrow}(\pi - \phi)}}{\sqrt{N^{\uparrow\downarrow}(\phi)N^{\downarrow\uparrow}(\pi - \phi)} + \sqrt{N^{\downarrow\uparrow}(\phi)N^{\uparrow\downarrow}(\pi - \phi)}} = \epsilon'_N(\phi)$$

In our measurement

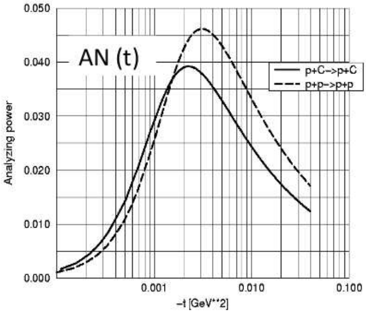
- $\delta(\phi) << 1$
- $P_B = 0.604 \pm 0.026 \quad P_Y = 0.618 \pm 0.028$
- $\epsilon_N \approx A_N (P_Y + P_B)\cos(\phi)$
- $\epsilon'_N \approx 0$ (consistency check)

A_N and hadronic single-flip contribution

- Double-flip spin contributions are small

$$\Rightarrow A_N \frac{d\sigma}{dt} \approx \frac{-8\pi}{s^2} \mathrm{Im}\left(\phi_5^{em\star}\phi_+^{had} + \phi_5^{had\star}\phi_+^{em}\right)$$

- ϕ_+^{had} constrained by $\sigma_{tot}, \rho, \ldots$
- *em* amplitudes fully calculable in QED.
- presize prediction of A_N for $\phi_5^{had} = 0$



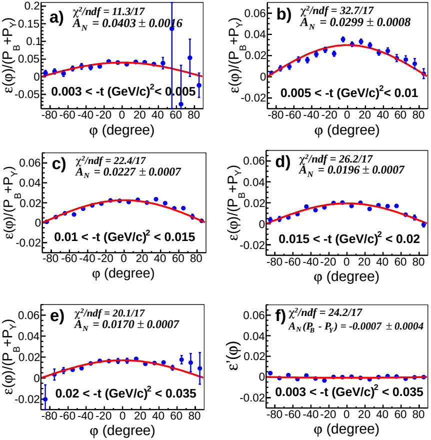
- Any difference from the above indicates contribution from hadronic spin-flip process caused by Regeon or Pomeron exchange.
- Usually hadronic spin-flip amplitude is parameterised using non-flip amplitude

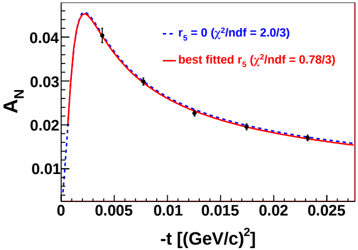
$$\phi_5^{had}(s,t) = r_5(s)\frac{\sqrt{-t}}{m}\mathrm{Im}\phi_+^{had}$$

- $\mathrm{Im} r_5$ and $\mathrm{Re} r_5$ can be obtained from the t-dependence of A_N
- Measurement of r_5 constrains models predicting hadronic spin-flip contribution.

Results on A_N and r_5

A_N from fits to ϵ_N in 5 t-bins





From fit to ϵ'_N

$A_N(P_B - P_Y) = 0.0007 \pm 0.0004$

$\text{Re}r_5 = 0.0017 \pm 0.0017(\text{stat.}) \pm 0.0061(\text{syst.})$

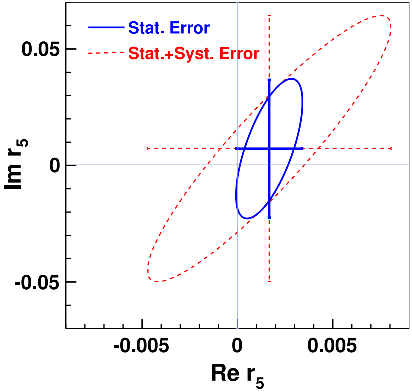
$\text{Im}r_5 = 0.007 \pm 0.030(\text{stat.}) \pm 0.049(\text{syst.})$

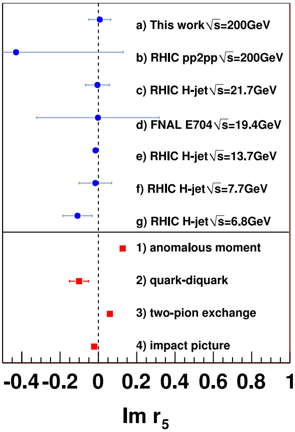
systematic uncertainty dominated by polarization error

Result on r_5

$$\mathrm{Re}r_5 = 0.0017 \pm 0.0017(\mathrm{stat.}) \pm 0.0061(\mathrm{syst.})$$

$$\mathrm{Im}r_5 = 0.007 \pm 0.030(\mathrm{stat.}) \pm 0.049(\mathrm{syst.})$$





Precise measurement of r_5 at high energy

spin-flip contribution at high energy consistent with zero

A_{NN}, A_{SS} and double-flip contributions and Odderon

- Spin-flip contribution is small $\Rightarrow$

$$A_{NN}(s,t)\frac{d\sigma}{dt} \approx \frac{4\pi}{s^2}\mathrm{Re}\left(\phi_1^\star\phi_2 - \phi_3^\star\phi_4\right)$$

$$A_{SS}(s,t)\frac{d\sigma}{dt} = \frac{4\pi}{s^2}\mathrm{Re}\left(\phi_1\phi_2^\star + \phi_3\phi_4^\star\right)$$

- or

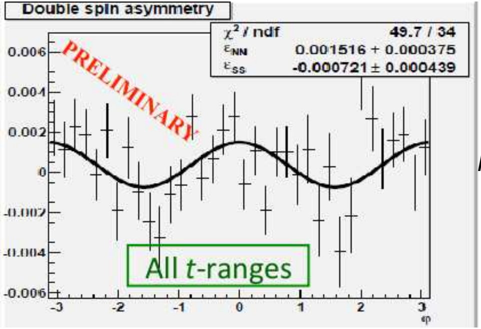
$$\frac{A_{NN}+A_{SS}}{2}\frac{d\sigma}{dt} \approx \frac{4\pi}{s^2}\mathrm{Re}(\phi_1\phi_2{}^\star)$$

$$\frac{A_{NN}-A_{SS}}{2}\frac{d\sigma}{dt} \approx -\frac{4\pi}{s^2}\mathrm{Re}(\phi_3\phi_4{}^\star)$$

- A_{NN} and A_{SS} sensitive to the Odderon contribution
  for example arXiv:hep-ph/0604153v1 (2006)

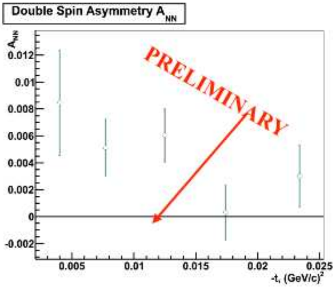
Preliminary results on A_{NN}, A_{SS}

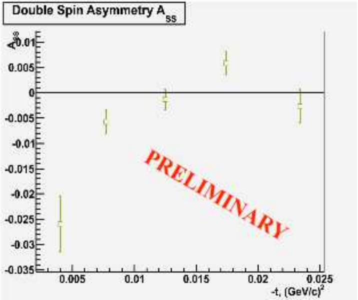
$$
\begin{aligned}
\delta(\phi) &= \frac{(N^{\uparrow\uparrow}/L^{\uparrow\uparrow} + N^{\downarrow\downarrow}/L^{\downarrow\downarrow}) - (N^{\uparrow\downarrow}/L^{\uparrow\downarrow} + N^{\downarrow\uparrow}/L^{\downarrow\uparrow})}{(N^{\uparrow\uparrow}/L^{\uparrow\uparrow} + N^{\downarrow\downarrow}/L^{\downarrow\downarrow}) + (N^{\uparrow\downarrow}/L^{\uparrow\downarrow} + N^{\downarrow\uparrow}/L^{\downarrow\uparrow})} \\
&= P_Y P_B [A_{NN} \cos^2(\phi) + A_{SS} \sin^2(\phi)] \\
&= P_Y P_B \left[\frac{A_{NN} + A_{SS}}{2} + \frac{A_{NN} - A_{SS}}{2} \cos(2\phi) \right]
\end{aligned}
$$



$P_B P_Y = 0.372 \pm 0.023$

Preliminary results on A_{NN}, A_{SS}

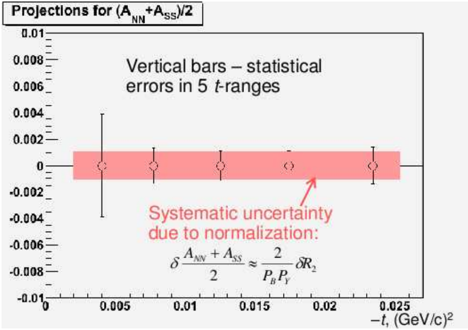




- Both A_{NN} and A_{SS} are very small
- Need much better analysis of the normalization (uncertainties of standard method is of the order of effect)

Projection for $\frac{A_{NN}+A_{SS}}{2}$

Further normalization studies use independent ratios instead of luminosity and we have considered using STAR detectors such as beam-beam counters (BBC), vertex position detector(VPD), zero degree calorimeter(ZDC) for external normalization .



Achieved uncertainty on $\frac{A_{NN}+A_{SS}}{2}$ of the order of 8×10^{-4}

Summary and outlook

- We have collected 20 million good elastic events in polarized pp scattering at $\sqrt{s} = 200$ GeV, highest $\sqrt{s}$ to date in $-t$ range $0.003 - 0.035$ GeV^2
- We published high precision measurements of A_N indicating spin-flip contribution at high energy consistent with zero
- Preliminary results on A_{NN}, A_{SS} have been obtained. Measurement indicates that transverse double spin asymmetries are small but non-zero. Results planned to be submitted for publication in near future.
- Program of elastic scattering measurements will continue. Planning a Phase II which allows to collect more data at $\sqrt{s} = 200(500)$ GeV