Gluon Polarization from Longitudinally Polarized Proton Collisions at STAR

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Introduction and Motivation
RHIC and STAR Detector
A_{LL} Measurements at STAR
Conclusion
Spin of the Proton

\[ S_{\text{PROTON}} = \frac{\hbar}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]


Spin of the Proton

\[ S_{\text{PROTON}} = \frac{\hbar}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]


\[ x \Delta \bar{g} \]

\[ x \Delta G \]

Q^2 = 2.5 GeV^2
How do we access $\Delta G$ at a polarized proton collider?

- **Longitudinal Double Spin Asymmetry**

$$A_{LL} = \frac{\sigma^{++} - \sigma^{--}}{\sigma^{++} + \sigma^{--}} \propto \sum_{abc} \Delta \sigma_{a\sigma b\sigma} \times \frac{\Delta f_{a} \otimes f_{b} \otimes \Delta \sigma_{a\sigma b\sigma}^{\perp}}{\sum_{abc} f_{a} \otimes f_{b} \otimes \Delta \sigma_{a\sigma b\sigma}^{\perp}}$$

- **Analyses based on final states**
  - Inclusive Jets
  - Dijets
How do we access $\Delta G$ at a polarized proton collider?

- **Longitudinal Double Spin Asymmetry**

$$A_{LL} = \frac{O^{++} - O^{-+}}{O^{++} + O^{-+}} \propto \sum_{abc} \Delta f_a \otimes \Delta f_b \otimes \hat{\Delta} O_{ab \rightarrow cx} \otimes D_\pi^c$$

- **Analyses based on final states**
  - Inclusive Jets
  - Dijets
  - Pions
\[ x \Delta g(x, Q^2 = 10 \text{ GeV}^2) \]

\[ \Delta G \]

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\[ \int_{x_{\text{min}}}^{1} dx \Delta g(x, Q^2) \]

**Phys. Rev. Lett 115.092002**

**STAR 2009**

\[ p+p \rightarrow \text{Jet+X} \]

\[ \sqrt{s} = 200 \text{ GeV} \]

\[ |\eta| < 0.5 \]

\[ 0.5 < |\eta| < 1 \]

Parton Jet \[ p_T \] (GeV/c)
How do we reduce the errors on $\Delta G$ at low $x$?

- Look at higher $\sqrt{s}$
  - 2012 Inclusive jet results

- Constrain the functional form
  - 200 GeV Dijet Results
  - 510 GeV Dijet Results

- Look at forward rapidity
  - EEMC $\pi^0$ Results
  - FMS $\pi^0$ Results
How do we reduce the errors on $\Delta G$ at low $x$?

**Note:** No experimental access to $x$ in inclusive observables in pp collisions!

$x_T = 2p_T/\sqrt{s} \sim 2\sqrt{x_1x_2}$

$y \sim \frac{1}{2} \log (x_1/x_2)$

Look at higher $\sqrt{s}$

2012 Inclusive Jet results
Constrain the functional form
200 GeV Dijet Results
510 GeV Dijet Results

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta_3} + p_{T4} e^{\eta_4} \right) \]
\[ x_2 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{-\eta_3} + p_{T4} e^{-\eta_4} \right) \]
\[ M = \sqrt{x_1 x_2 s} \]
How do we reduce the errors on $\Delta G$ at low $x$?

- **Look at forward rapidity**
  - EEMC $\pi^0$ Results
  - FMS $\pi^0$ Results

Looking at the $2.5 < \eta < 4$ region pushes the access down to $x \sim 10^{-3}$ regime for $\sqrt{s} = 510$ GeV.
- Introduction and Motivation
- RHIC and STAR Detector
- $A_{LL}$ Measurements at STAR
- Conclusion
Relativistic Heavy Ion Collider
Solenoidal Tracker At RHIC
Introduction and Motivation

RHIC and STAR Detector

$A_{LL}$ Measurements at STAR

Conclusion
Jet Reconstruction at STAR

- Anti $k_T$ algorithm
- Sequential clustering algorithm
- Infrared and collinear safe by design

- Jet and Dijet analyses
- Anti $k_T$ algorithm
- $R = 0.5 - 0.6$

- Triggers used:
  - Jet Patch Triggers: JP0, JP1, JP2

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Inclusive Jet Results

The systematics from non-collision background and residual transverse polarization are found to be negligible. The relative luminosity uncertainty is estimated as $4 \times 10^{-4}$. The left panel of Fig. 2 shows the preliminary STAR 2012 510 GeV inclusive jets $A_{LL}$ results with several of the latest polarized parton distribution function (PDF) model predictions. In the right panel of Fig. 2, the 2012 510 GeV data are plotted with the 2009 200 GeV data as a function of $x_T = 2p_T/p_s$.

The two sets of data are consistent with each other in the overlapping $x_T$ region. The higher $p_s$ extends gluon helicity measurements to lower $x$.

Fig. 2. Left: STAR 2012 510 GeV inclusive jet $A_{LL}$ vs. jet $p_T$ in $|\eta| < 0.9$. Right: STAR 2012 inclusive jet $A_{LL}$ and 2009 inclusive jet $A_{LL}$ vs. $x_T$.

STAR is also performing $\pi^0$ measurements to explore gluon polarization in the proton. It is convenient to reconstruct $\pi^0$ by measuring from $\pi^0$ decay. The $\pi^0$s are detected by the BEMC, EEMC and FMS over a wide $\eta$ coverage. STAR has measured the inclusive $\pi^0$ cross sections over several $\eta$ ranges at 200 GeV, such as $0 < \eta < 1$, $0 < \eta < 2$, $< \eta > 3.3$, and $< \eta > 3.68$.

The STAR 200 GeV inclusive $\pi^0 A_{LL}$ at $0.8 < \eta < 2.0$ probes the gluon helicity density down to $x = 0.02$. Fig. 3 shows the 2006 inclusive $\pi^0$ results. The statistical precision of the 2006 data is not sufficient to discriminate among different models for $G_T$. The 510 GeV data recorded during 2012 will achieve significantly greater precision for inclusive $\pi^0 A_{LL}$. The projected statistical uncertainty is less than 0.015 across the entire $\pi^0 p_T$ range. The higher beam energy also will extend the sensitivity to the lower $x$ gluon helicity density. New measurements at further forward pseudo-rapidity with the FMS are discussed in another article of this journal.

arXiv:1512.05400
Dijet Results

Dijet Analysis cuts

- Asymmetric $p_T$ cut (8,6 GeV)
- Back-to-back cut
- Require one jet of the pair to point to a trigger jet patch
- $-0.8 < \eta_{\text{Physics}} < 0.8$
- Contribution from the calorimeters towards the total jet energy required to be less that 95%
Dijets at 510 GeV
Dijet $A_{LL}$ at 510 GeV

STAR Preliminary $p+p \rightarrow \text{Jet+Jet+X}$

$\sqrt{s} = 510$ GeV $R = 0.5$ $|\eta| < 0.9$

$\pm 6.5\%$ polarization scale uncertainty not shown

arXiv:1608.01332
Dijet $A_{LL}$ at 510 GeV

STAR Preliminary $p+p \rightarrow \text{Jet+Jet+X}$

- 2012 $\sqrt{s} = 510$ GeV $R = 0.5$ $|\eta| < 0.9$
- 2009 $\sqrt{s} = 200$ GeV $R = 0.6$ $|\eta| < 0.8$

Solid/dotted curves 510/200 GeV

$\pm 6.5\%$ polarization scale uncertainty not shown

arXiv:1608.01332
Pushing dijets forward into the endcap allows us to probe lower x range

<table>
<thead>
<tr>
<th>Dijet Configuration</th>
<th>Minimum X1/X2 ($\sqrt{s} = 200$ GeV)</th>
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<tbody>
<tr>
<td>Barrel-Barrel</td>
<td><img src="image1.png" alt="Histograms" /></td>
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<tr>
<td>Barrel-Endcap</td>
<td><img src="image2.png" alt="Histograms" /></td>
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<tr>
<td>Endcap-Endcap</td>
<td><img src="image3.png" alt="Histograms" /></td>
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</tbody>
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**Note:** Ting Lin will show the first fully reconstructed dijet $A_{LL}$ in the forward region with the endcap detector - see Thursday poster session!
Looking at Jets
- Tracking only extends to $\eta \sim 1.4$
- Challenge to look at jets in the forward region
- Alternative → looking at pions
\[ \pi^0 \text{ at STAR} \]

FMS

\[ \sqrt{s} = 510 \text{ GeV} \]

\[ 2.5 < \eta < 4 \]

\[ \sqrt{s} = 200 \text{ GeV} \]

\[ 0.8 < \eta < 2 \]

EEMC $\pi^0$ Results

$p + p \rightarrow \pi^0 + X$

$\sqrt{s} = 200$ GeV
$0.8 < \eta < 2.0$

Data/\text{pQCD}

$p_T$ [GeV/c]

$A_{LL}$

$\vec{p} + \vec{p} \rightarrow \pi^0 + X$

$\sqrt{s} = 200$ GeV
$0.8 < \eta < 2.0$

$pp \rightarrow \pi^0 + X$

$\sqrt{s} = 510$ GeV

$2.5 < \eta < 4$

STAR PRELIMINARY

$A_L$

$p_T [\text{GeV/c}]$
RHIC's highly polarized proton beams have facilitated a robust spin program at STAR. STAR utilizes its wide acceptance at mid-rapidity for jet reconstruction and dedicated calorimeters at forward rapidities for pion reconstruction.

STAR inclusive jet measurements at $\sqrt{s} = 200$ GeV have provided the first evidence of a significant polarized gluon distribution for $x > 0.05$.

By extending these measurements to higher $\sqrt{s}$ and more forward regions it is possible to constrain the $x < 0.05$ region. Dijet observables allow for reconstruction of the partonic kinematics at leading order.

In 2013 STAR collected 3 times more data, of longitudinally polarized proton collisions at $\sqrt{s} = 510$ GeV.
Stay Tuned!

Thank You
Backup
The systematic error on the reconstructed dijet $M_{\text{INV}}$ is due to the jet energy scale uncertainty. This includes contributions from BEMC calibration and tracking efficiency uncertainty.
Trigger Bias Studies

- Detector resolutions and inefficiencies distort our measured jet distributions from the true jet distributions.

- The bias of the jet patch triggers towards a quark jet vs. a gluon jet.
  - Sub-process fractions in the events are affected, and the “expected” asymmetry changes.

- We use different theoretical parameterizations, and create $A_{LL}$ predictions at the detector and parton levels.

- The uncertainty is calculated as the difference between the parton & detector $A_{LL}$.

- Process repeated for different models, and the uncertainty is taken from the model with the largest difference.
π⁰ at STAR (EEMC)

- 2006 Run

- Towers in EEMC measure the photon energy by summing up the energy deposited

- Cuts imposed
  - Minimum energy 2 GeV in the towers
  - 0.8 <η<2
  - $p_T$ (π⁰ candidate) >5 GeV
  - TPC vertex within 120 cm of nominal vertex

- Signal fraction – fitting a combination of template functions to the 2 photon mass distribution (0,0.3).

- Three template functions were determined by fitting MC data to represent- π⁰ signal, conversion background, all other backgrounds.

- Signal – Matching momentum direction of reconstructed pairs to that of generated π⁰’s in the eta-phi space

- Conversion background - Matching momentum direction of reconstructed pairs to that of decay photons in the eta-phi space

- Other backgrounds – Non matched reconstructed pairs
\( \pi^0 \) at STAR (FMS)

- Relative Luminosity calculated using Vertex Position Detector \((4.2 < |\eta| < 5.1)\) and Zero Degree Calorimeter \((6.5 < |\eta| < 7.5)\)

- Invariant mass distribution for the 2-photon clusters which pass the analysis cuts
  - \( p_T \geq 2.5 \text{ GeV} \) (2012), \( p_T \geq 2 \text{ GeV} \) (2013)
  - \( p_T < 10 \text{ GeV} \)
  - \( 30 \leq E_{\gamma \gamma} < 100 \text{ GeV} \)
  - \( |E_1 - E_2|/E_{\gamma \gamma} < 0.8 \)
  - \( E_{\gamma \gamma} \) dependent \( M_{\gamma \gamma} \) cut
  - Isolation cone cut (both 35 mrad and 100 mrad analyzed)
    - The use of isolation cones – motivated by the dependence of transverse single spin asymmetry \( A_N \) on \( \pi^0 \) isolation, more isolated \( \pi^0 \)'s exhibited higher asymmetries
    - Goal of the study was to verify that \( A_{LL} \) is independent of \( \pi^0 \) isolation

- Widths of the pion mass peaks determined by –
  - The cluster position resolution for the two closely spaced photons
  - The width of the vertex distribution \((60\text{-}80 \text{ cms})\).

- The dominant systematic error for this measurement is from the relative luminosity and beam polarization measurements (vertical shading in the plot).