Gluon Polarization in Longitudinally Polarized pp Collisions at STAR

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Outline

- Introduction
- Inclusive jet measurements
- $\pi^0$ measurements
- Di-jet measurements
- Conclusion
How Gluons Contribute to Proton Spin

Proton Spin:

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- \( \Delta \Sigma \): ~0.3 measured by DIS
- \( \Delta G \): poorly determined by DIS and SIDIS
- \( L_q, L_g \): undetermined yet.

- Leader et al, PRD 82, 114018 (2010) with fit to DIS and SIDIS data
- Blümlein & Böttcher, NPB 841, 205 (2010) with fit to DIS data only

\[ \Delta G = 0.32 \pm 0.19 \]

\[ \Delta G = -0.34 \pm 0.46 \]

\[ \Delta G = 0.46 \pm 0.43 \]
Exploring Gluon Contribution at RHIC

Double spin asymmetry $A_{LL}$:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

$\Delta f$: polarized parton distribution function

$\Delta G \Delta G$

$\Delta q \Delta G$

$\Delta q \Delta q$

For most RHIC kinematics, $gg$ and $qg$ dominate, making $A_{LL}$ for jets and $\pi^0$ sensitive to gluon polarization

Mukherjee and Vogelsang, PRD.86.094009

For most RHIC kinematics, $gg$ and $qg$ dominate, making $A_{LL}$ for jets and $\pi^0$ sensitive to gluon polarization
• Spin varies from rf bucket to rf bucket (9.4 MHz)
• Spin pattern changes from fill to fill
• Spin rotators provide choice of spin orientation
• Billions of spin reversals during a fill with little depolarization
• High precision tracking with Time Projection Chamber
• High energy resolution with Barrel Electro-Magnetic Calorimeter, Endcap Electro-Magnetic Calorimeter and Forward Meson Spectrometer
• Additional detectors (Beam-Beam Counter, Vertex Position Detector, and Zero Degree Calorimeter) for relative luminosity and local polarimetry
Longitudinally polarized pp collisions at 200 GeV and 510 GeV allow both cross section and double spin asymmetry $A_{LL}$ measurements on:

- **Inclusive Jet**
  $x$ down to ~ 0.05 for jets in the mid-rapidity at 200 GeV

- **Inclusive $\pi^0$**
  $x$ down to ~ 0.02 for forward $\pi^0$  
  $0.8 < |\eta| < 2.0$ at 200 GeV

- **Di-jet**
  Correlation unfolds $x_1$, $x_2$ at the leading order

Complementary to each other to achieve large $x_g$ coverage of gluon polarization
Inclusive jet measurements

$\pi^0$ measurements

Di-jet measurements
Jet Reconstruction at STAR

- For 2006 200 GeV data:
  Mid-point cone algorithm
  Adapted from Tevatron II – hep-ex/0005012
  a. Seed energy = 0.5 GeV
  b. Cone radius $R = 0.7$ in $\eta$-\phi space
  c. Split/merge fraction $f = 0.5$

- For 2009 200 GeV data
  Anti-$k_T$ algorithm
  Cacciari, Salam, and Soyez, JHEP 0804, 063
  o Cone radius $R = 0.6$

- For 2012 510 GeV data
  Anti-$k_T$ algorithm
  o Cone radius $R = 0.5$

Use Pythia + Geant to quantify detector response
Sjostrand, Mrenna, and Skands, JHEP 05, 026
• Good agreement between data and simulation
• Good agreement with NLO pQCD calculation after hadronization and underlying event correction is applied
• Jet production is well understood at RHIC energies
• STAR inclusive jet $A_{LL}$ from 2006 excluded those scenarios that had a large gluon polarization within the accessible x region
- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing
- Found relatively small gluon polarization within the region $0.05 < x < 0.2$ that was sampled by the 2006 data
Improvements for 2009

• **2009 jet patch trigger upgrades**
  o Overlapping jet patches and lower $E_T$ threshold improve efficiency and reduce trigger bias
    ▪ Net increase of 37% in jet acceptance
  o Remove beam-beam counter trigger requirement
    ▪ Trigger more efficiently at high jet $p_T$
    ▪ Measure non-collision background

• **Increased trigger rate and reduced thresholds enabled by DAQ1000**

• **Sampled ~ 4 times the figure-of-merit relative to 2006**

• **Nearly 20-fold increase in event statistics**

• **Improvements in jet reconstruction**
  o Subtract 100% of track momentum from struck tower energy (2009) instead of MIP (2006)
  o Overall jet energy resolution improved from 23% to 18%
  o Switch from mid-point cone to anti-$k_T$
Inclusive Jet $A_{LL}$ from 2009 Data

- 2009 STAR inclusive jet $A_{LL}$ measurements are a factor of 3 (high-$p_T$) to >4 (low-$p_T$) more precise than 2006.
- $A_{LL}$ falls in the middle among several recent polarized PDF fit predictions.

arXiv:1405.5134

STAR 2009

$p+p \rightarrow$ Jet$+X$

$\sqrt{s}=200$ GeV

$|\eta| < 0.5$

$0.5 < |\eta| < 1$

Parton Jet $p_T$ (GeV/c)
Inclusive Jet $A_{LL}$ from 2009 Data

- $A_{LL}$ is somewhat larger than predictions from the 2008 DSSV fit
  - Points toward positive $\Delta g$ in the accessible $x$ region
Two New Polarized Distribution Fits

- Both DSSV and NNPDF have released new polarized PDF fits
- Both find 2009 STAR jet $A_{LL}$ results provide significantly tighter constraints on gluon polarization than previous measurements
- Both find evidence for positive gluon polarization in the region $x > 0.05$
  - DSSV: $0.19^{+0.06}_{-0.05}$ at 90% C.L. for $x > 0.05$
  - NNPDF: $0.23 \pm 0.07$ for $0.05 < x < 0.5$
2012 pp 510 GeV Run

- **510 GeV longitudinally polarized pp collisions**
  - average polarization 53%
  - analysis of data of integrated luminosity $50 \text{ pb}^{-1}$
- **510 GeV provides sensitivity to smaller $x_g$**
- **Same jet reconstruction method except using smaller cone radius $R = 0.5$**
  - Reduced pile-up effects
  - Better matching probability from detector jet to parton jet
- $|\eta| < 0.9$
  - Narrower vertex distribution in 2012
- **Non-collision background and transverse residual double spin asymmetry found to make negligible contributions**
2012 Inclusive Jet $A_{LL}$

- Trigger and reconstruction bias dominates the systematic uncertainties
- Relative luminosity systematic uncertainty is $4 \times 10^{-4}$
- Results agree well with latest NLO predictions
2012 Inclusive Jet $A_{\perp\perp}$ with 2009 Data

- Higher collision energy extends $x_T$ to lower region
- 510 GeV results agree well with 200 GeV data in the overlapping region
Increased Precision at 200 GeV Coming Soon

- STAR also anticipates significant future reductions in the uncertainties for 200 GeV collisions relative to the 2009 results
  - Hope to record triple the existing 200 GeV data during the 2015 RHIC run
Inclusive jet measurements

$\pi^0$ measurements

Di-jet measurements
π⁰ Measurements at STAR

- Studied π⁰ production at 0.8 < η < 2 in 200 GeV pp collisions from 2006 data
- Measure γ from π⁰ decay in electromagnetic calorimeter

STAR has measured the inclusive π⁰ cross section over a wide pseudo-rapidity range
Inclusive $\pi^0$ Double Spin Asymmetry $A_{LL}$

- **PRD.89.012001**

Graph showing $A_{LL}$ versus $p_T$ [GeV/c] with error bars.

- **NPB 887.276:**
  - NNPDFpol1.1 prediction with STAR 200 GeV data ($0.8 < \eta < 2.0$)
  - Needs greater precision to constrain NLO fit
Inclusive $\pi^0$ Double Spin Asymmetry $A_{LL}$

- PRD.89.012001
  - Will achieve much greater precision with 510 GeV data that are currently being analyzed
  - Higher $\sqrt{s}$ also pushes the sensitivity to lower $x_g$
  - For new results at even further forward rapidity, see the talk by Chris Dilks

- NPB 887.276: NNPDFpol1.1 prediction with STAR 200 GeV data ($0.8 < \eta < 2.0$)
- Inclusive jet measurements
- $\pi^0$ measurements
- **Di-jet measurements**
Di-jet Measurements at STAR

- Di-jets permit event-by-event calculations of $x_1$ and $x_2$ at leading order
- Use the same technique to reconstruct di-jets as the inclusive jets

\[
x_1 = \frac{1}{\sqrt{s}} \left( p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4} \right)
\]
\[
x_2 = \frac{1}{\sqrt{s}} \left( p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4} \right)
\]
\[
M = \sqrt{x_1 x_2 s}
\]
\[
y = \frac{1}{2} \ln \frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}
\]
\[
|\cos \theta^*| = \tanh \left( \frac{|\eta_3 - \eta_4|}{2} \right)
\]
Di-jet Cross Section at 200 GeV and 500 GeV

- Di-jet cross section is well-described by NLO pQCD with corrections for hadronization and underlying event
- Will have $A_{LL}$ for 2009 di-jets at 200 GeV soon
- Also analyzing $A_{LL}$ for di-jets at 510 GeV using data from 2012 and 2013
Di-jets in Further Future

- STAR is planning to install a **Forward Calorimeter System (FCS)** in ~2020
- This will enable di-jet measurements with one or both jets in the **forward** region \((2.8 < \eta < 3.7)\)
- FCS will provide information about gluon polarization at
  a) \(x \sim 5 \times 10^{-3}\) with FCS-EEMC di-jets
  b) \(x \leq 10^{-3}\) with FCS-FCS di-jets

- \(\sqrt{s} = 500\) GeV
- Cone Algorithm, \(R = 0.7\)
- \(E_{T,3} > 5\) GeV, \(E_{T,4} > 8\) GeV
- Assumed integrated luminosity: 1000 pb\(^{-1}\)
- Assumed polarization: 60%
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- FCS will provide information about gluon polarization at:
  - $x \approx 5 \times 10^{-3}$ with FCS-EEMC di-jets
  - $x \leq 10^{-3}$ with FCS-FCS di-jets

- $\sqrt{s} = 500$ GeV
- Cone Algorithm, $R = 0.7$
- $E_{T,3} > 5$ GeV, $E_{T,4} > 8$ GeV

Forward di-jets will further constrain $\Delta g$ at $x \sim 10^{-3}$.

- Assumed integrated luminosity: 1000 pb$^{-1}$
- Assumed polarization: 60%
Conclusion

• STAR inclusive jet, $\pi^0$, and di-jet $A_{LL}$ measurements are unique to explore gluon contribution to proton spin

• STAR 2009 inclusive jet $A_{LL}$ results provide the first experimental evidence for positive gluon polarization in the RHIC range

• STAR 2012 510 GeV inclusive jet $A_{LL}$ results extend measurements at lower $x_g$ and agree well with STAR 2009 200 GeV data in the overlapping $x_T$ range

• More results coming up in the near future
  o First measurements:
    ▪ Di-jet $A_{LL}$ at 200 GeV (2009)
    ▪ Di-jet $A_{LL}$ at 510 GeV (2012 and 2013)
    ▪ Inclusive $\pi^0$ $A_{LL}$ at 510 GeV (2012)
  o Improved precision for:
    ▪ Inclusive jet $A_{LL}$ at 200 GeV (2015)

• In the further future, STAR will use forward di-jets to explore gluon polarization at very low $x_g$ ($\sim 10^{-3}$)