Exploring Gluon Polarization in the Proton
with \textit{STAR}

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Outline

- Introduction
- Inclusive measurements
- Correlation measurements
Partonic origin of the proton spin?

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle \]

Polarized DIS: \( \sim 0.3 \)

Three 2006 fits of equal quality:
- \( \Delta G = 0.13 \pm 0.16 \)
- \( \Delta G \sim 0.006 \)
- \( \Delta G = -0.20 \pm 0.41 \)

all at \( Q^2 = 1 \text{ GeV}^2 \)

Leader et al, PRD 75, 074027

- Measuring the **gluon polarization distribution** is a primary goal of the RHIC spin program
Exploring gluon polarization at RHIC

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

\[ \Delta f: \text{polarized parton distribution functions} \]

\[ \frac{\Delta G}{G} \quad \frac{\Delta q}{q} \quad \frac{\Delta q}{q} \]

Partonic fractions in jet production at 200 GeV

For most RHIC kinematics, \( gg \) and \( qg \) dominate, making \( A_{LL} \) for hadrons, photons, and jets sensitive to \textbf{gluon polarization}. 

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STAR detector in two views

- High precision tracking with the TPC
- Electromagnetic calorimetry with the BEMC, EEMC, and FMS
- Additional detectors for relative luminosity, local polarimetry, and minbias triggering
Gluon polarization measurements at STAR

Inclusive measurements

– Features
  • High precision measurements
  • Average over partonic kinematics
  • Powerful for determining the scale of $\Delta G$

– Channels
  • Neutral pions
  • Direct photons
  • Jets

Correlation measurements

– Features
  • Less abundant
  • Resolve partonic kinematics on event-by-event basis
  • Provide information about the shape of $\Delta g(x)$

– Channels
  • Charged pions opposite jets
  • $\gamma+$jet
  • Di-jets

• Both types of measurements provide important information for global analyses

• Large acceptance of STAR makes jet and di-jet measurements particularly attractive
**STAR** inclusive $\pi^0 A_{LL}$ at various rapidities

- During 2006, **STAR** measured $A_{LL}$ for inclusive $\pi^0$ for three different rapidity regions
- Larger rapidity correlates to stronger dominance of $qg$ scattering with larger $x$ quarks and smaller $x$ gluons
- Expect $A_{LL}$ to decrease as $\eta$ increases

Status of '09 data analysis: See poster by W. Leight
Jet cross section from 2006 data

- 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
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**STAR** inclusive jet $A_{LL}$ from 2006

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DSSV – first global analysis with polarized jets

de Florian et al., PRL 101, 072001

- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing
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2009 upgrades

Jet specific

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

- Improvements in jet reconstruction
  - Subtract 100% of track momentum from struck tower energy (2009) instead of MIP (2006)
  - Overall jet energy resolution improved from 23% to 18%

Enhance all channels

- Increased trigger rate and reduced thresholds enabled by DAQ1000
- Sampled ~ 4 times the figure-of-merit relative to 2006
Direct photon cross section and $A_{LL}$ from 2009

- Cross section at 200 GeV is consistent with NLO pQCD calculations
- $A_{LL}$ for direct photons has very clean theoretical interpretation, but
  - Cross section is very small
  - Background is very large
  - Very difficult measurement!
- Need far more statistics

For details:
See poster by M. Betancourt
\( A_{\text{LL}} \) for inclusive jets: 2006 to 2009

- 2009 STAR inclusive jet \( A_{\text{LL}} \) measurements are a factor of 3 (high-\( p_T \)) to >4 (low-\( p_T \)) more precise than 2006
- Results fall between predictions from DSSV and GRSV-STD
- Precision sufficient to merit finer binning in pseudorapidity

\[ \sqrt{s} = 200 \text{ GeV} \quad \vec{p} + \vec{p} \rightarrow \text{jet} + X \quad |\eta| < 1 \]

\( \pm 8.8\% \) scale uncertainty from polarization not shown
2009 STAR inclusive jet $A_{LL}$

- $A_{LL}$ separated into two pseudorapidity ranges
- Forward jets involve:
  - A larger fraction of quark-gluon scattering with:
    - Higher $x$ quarks that are more polarized
    - Lower $x$ gluons that are less polarized
  - Larger $|\cos(\theta^*)|$, which reduces $\hat{A}_{LL}$
- $A_{LL}$ falls between the predictions from DSSV and GRSV-STD
Expected future inclusive jet $A_{LL}$ precision

• **STAR** will measure inclusive jet $A_{LL}$ in **500 GeV collisions** during the 2012 and 2013 RHIC runs
  – Higher beam energy provides sensitivity to smaller $x_g$
  – Expect $\sim 90$ pb$^{-1}$ during 2012; much more during 2013
Expected future inclusive jet $A_{LL}$ precision

Inclusive Jet $A_{LL}$ for $|\eta|<1$

- $STAR$ will measure inclusive jet $A_{LL}$ in **500 GeV collisions** during the 2012 and 2013 RHIC runs
  - Higher beam energy provides sensitivity to smaller $x_g$
  - Expect $\sim 90$ pb$^{-1}$ during 2012; much more during 2013

- $STAR$ also anticipates significant **future reductions** in the uncertainties for **200 GeV collisions** relative to the 2009 results
Beyond inclusive $A_{LL}$ measurements

- Inclusive $A_{LL}$ measurements at fixed $p_T$ average over a **broad $x$ range**.
- Can hide considerable structure if $\Delta g(x)$ has a node.
- **Correlation measurements can constrain the shape of $\Delta g(x)$**.
Charged pions opposite jets

- Trigger and reconstruct a jet, then look for a charged pion on the opposite side
- Events with high-z $\pi^+$ emphasize gluon scattering off highly-polarized $u$ quarks
- **Significantly increases the sensitivity of $A_{LL}(\pi^+)$**

Status of ’09 data analysis:
See poster by J. Hays-Wehle
2006 di-jet cross section

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_{T,3} e^{\eta_3} + p_{T,4} e^{\eta_4} \right) \]

\[ x_2 = \frac{1}{\sqrt{s}} \left( p_{T,3} e^{-\eta_3} + p_{T,4} e^{-\eta_4} \right) \]

\[ M = \sqrt{x_1 x_2 s} \]

\[ y = \frac{1}{2} \ln \frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2} \]

\[ |\cos\theta^*| = \tanh \left| \eta_3 - \eta_4 \right| / 2 \]

- Di-jets permit event-by-event calculations of \( x_1 \) and \( x_2 \) at LO
- Di-jet cross section is well-described by NLO pQCD with corrections for hadronization and underlying event
2006 di-jet $A_{LL}$ provides a start at constraining the shape of $\Delta g(x)$.
2009 STAR di-jet partonic coverage

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_{T,3} e^{\eta_3} + p_{T,4} e^{\eta_4} \right) \]

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For more details: See poster by M. Walker
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For more details:
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2009 STAR di-jet $A_{LL}$

- For fixed $M$, different kinematic regions sample different $x$ ranges
- $A_{LL}$ falls between DSSV and GRSV-STD

For more details:
See poster by M. Walker
Projected sensitivity for di-jets at 500 GeV

\[ x_1, x_2 = \frac{M}{\sqrt{s}} \exp \left( \pm \frac{\eta_3 + \eta_4}{2} \right) \]

- Higher energy accesses lower \( x_g \)
- Expect smaller \( A_{LL} \)
- Uncertainties shown are purely statistical
- Maybe add EEMC-EEMC di-jets to reach lowest \( x \) values after FGT is installed (?)
Conclusions

- **STAR 2006** results play a significant role in recent global analysis
- **STAR 2009** results will have a strong impact on the determination of gluon polarization
- We will reduce the uncertainties even further in the near future
- Stay tuned!

![Graphs and plots related to gluon polarization and jet production in proton-antiproton collisions.](image-url)
Jet reconstruction in **STAR**

Data jets

MC jets

Jet direction

**Midpoint cone algorithm**

(Adapted from Tevatron II - hep-ex/0005012)

- Seed energy = 0.5 GeV
- Cone radius $R = 0.7$ in $\eta$-$\phi$ space
- Split/merge fraction $f = 0.5$

Use **PYTHIA + GEANT** to quantify detector response
Jet+hadron correlations at NLO
from de Florian, PRD 79, 114014

\[ z \equiv \frac{p_T^h}{p_T^{jet}} \]

\[ x_1 \equiv (p_T^{jet} \exp(\eta_{jet}) + p_T^{jet} \exp(\eta_h)) / \sqrt{s} \]

\[ x_2 \equiv (p_T^{jet} \exp(-\eta_{jet}) + p_T^{jet} \exp(-\eta_h)) / \sqrt{s} \]

- NLO calculations show strong correlation between the real \( x \) and \( z \) values and LO estimates
Gluon polarization with gamma+jet

- Sensitivity estimates including realistic photon efficiencies and purities, benchmarked with real data
  - Maybe higher purity with future isolation cuts using FGT