Recent Results on Proton Spin Studies from STAR: Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes

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For the STAR Collaboration
Moriond QCD 2018
March 23, 2018
Contributions to the Proton’s Spin

Proton spin sum rule:
\[
\frac{1}{2} \hat{h} = \frac{1}{2} \sum_q S^z_q + S^z_g + \sum_q L^z_q + L^z_g
\]

\[
S^z_g = \Delta G = \int_0^1 dx \Delta g(x)
\]

Polarized e/µ + p: ~0.3
Puzzling for ~30 years

Relatively poorly constrained
But S\(_g\) coming into focus!

Proton momentum \(\Rightarrow\)
Proton spin \(\Rightarrow\)

\(\Delta q(x)\) \(\Rightarrow\) \(\Delta g(x)\) \(\Rightarrow\)

Longitudinal Polarization

See also Y-B Yang et al \(\chi\)QCD

A. Gibson, Valparaiso; STAR Spin; Moriond QCD
March 23, 2018
• STAR Detector
• Inclusive jets as a probe of $\Delta g(x)$
• Current Understanding of $\Delta g(x)$
• Pushing to Low $x$ with Forward $\pi^0$’s
  – In the Endcap Calorimeter
  – In the Forward Calorimeter
• Constraining $\Delta g(x)$ with Correlated Probes: Dijets
RHIC as a Polarized Proton Collider

- World’s first and only
- Average polarization 50-60%
  - “Siberian Snakes” → mitigate depolarization resonances
- Luminosity typically ~1E32 cm⁻² s⁻¹
- Spin rotators provide choice of spin orientation independent of experiment
  - Spin direction varies bunch-to-bunch (9.4 MHz)
  - Spin pattern varies fill-to-fill
- 200 and 500/510 GeV collisions (proton-proton center-of-mass energy)
Solenoidal Tracker at RHIC

Inclusive hadron (e.g. $\pi^0$) measurements:
- Barrel ElectroMagnetic Calorimeter (BEMC),
- Endcap ElectroMagnetic Calorimeter (EEMC),
- and
- Forward Meson Spectrometer (FMS)

Relative luminosity measurements:
- Beam Beam Counters (BBC) etc.

Jet and W/Z measurements:
- TPC + Barrel + Endcap EMC

η = -1

η = 0

η = 1

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Probing (Gluon) Polarized PDF’s With Jets

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

\[ A_{LL} \] for, e.g. jets, sensitive to polarized PDF’s (\( \Delta f \)) and partonic asymmetry, \( \hat{\Delta}_{LL} \)

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

Asymmetries at different values of \( p_T \) or \( \sqrt{s} \)

→ sample different mix of partonic subprocesses

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Jet Reconstruction

Jet Levels

MC Jets

STAR Detector has:
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-$K_T$ Jet Algorithm:
- Radius (e.g. 0.6 for 2009 Jet $A_{LL}$)
- Used in both data and simulation

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2009 results have factor of 3 to 4 better statistical precision than 2006 results that informed the DSSV08 fit.

Results divided into two pseudorapidity ranges which emphasize different partonic kinematics.

Results lie consistently above the 2008 DSSV fit.

DSSV = D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang

STAR 2009
\( p+p \to \text{Jet}+X \)
\( \sqrt{s}=200 \, \text{GeV} \)

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

\[ |\eta| < 0.5 \]

\[ \pm 6.5\% \text{ scale uncertainty from polarization not shown} \]
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With input from PHENIX $\pi^0$’s and STAR 2009 jets

Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.

Uncertainty shrinks substantially from DSSV* to new DSSV14 fit

First firm evidence of non-zero gluon polarization!
New DSSV14 Fit – Low $x$ Remains Blurry

- With input from PHENIX $\pi^0$’s and STAR 2009 jets
- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV14 fit
- Uncertainty on integral over low $x$ region is still sizable

[See also NNPDFpol1.1 fit Nucl. Phys. B887 (2014) 276-308]
• Push to lower $x_g$ w/ higher CoM energy

• RHIC had very successful, high luminosity runs in 2012 and 2013
  – 50 pb$^{-1}$ at 53% avg. polarization in 2012, and ~200 pb$^{-1}$ in 2013
  – Smaller cone, $R = 0.5$ reduces effect of pileup
  – Fits that incorporated 2009 results continue to describe the data well

• Additional 200 GeV data during 2015
  – Will reduce $A_{LL}$ uncertainties by a factor of ~1.6
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- Constraining $\Delta g(x)$ with Correlated Probes: Dijets
$A_{LL}$ in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

- Push to reasonably low $x$ by going (relatively) forward
- 2006 Dataset in the Endcap Electromagnetic Calorimeter (EEMC)
- Statistical error (bars) dominate
- Systematic error (boxes)
  - Signal fraction uncertainties from template fits
  - Uncertainty on background asymmetry
- Cross section and transverse asymmetry also measured

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot}
\caption{$\pi^0 p_T$ from 7 to 8 GeV}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph}
\caption{π$^0$ + X at STAR for 0.8 < \eta < 2.0}
\end{figure}

\begin{itemize}
\item GRSV: Older fit, without RHIC results
  PRD 63, 094005 (2001)
\item DSSV: First fit to include RHIC results
  PRL 101, 072001 (2008)
\end{itemize}

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Updated Prediction for $\pi^0 A_{LL}$, $0.8 < \eta < 2.0$

- NNPDFpol1.1 includes jet results from STAR and PHENIX, including the 2009 STAR inclusive jets
- Greater precision needed to test the fit

STAR data with NNPDF predictions

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

$\sqrt{s} = 200$ GeV

$0.8 < \eta < 2.0$

NNPDFpol1.1 from E. Nocera, R. Ball, S. Forte, G. Ridolfi, J. Rojo


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π⁰ A_{LL} Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 the 2006 luminosity) at intermediate (endcap) pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown

\[
\begin{align*}
\bar{p} + \bar{p} &\rightarrow \pi^0 + X \text{ at } \sqrt{s} = 510 \text{ GeV} \\
\end{align*}
\]

- Higher CoM energy
  - 200 \rightarrow 510 \text{ GeV}
  - Pushes to lower x gluon

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FMS

Pb Glass EM Calorimeter
pseudo-rapidity $2.7 < \eta < 4.0$
Small cells: 3.81 x 3.81 cm
Outer cells: 5.81 x 5.81 cm

Forward EM Calorimetry In STAR.
π⁰ A_{LL} Prospects in Forward Calorimeters

- Pushing even further forward, with the FMS
- Preliminary results with large 2012 and 2013 datasets at 510 GeV
  - After prescales, effectively 46 pb⁻¹ in 2012, p_T > 2.5 GeV
  - And 8 pb⁻¹ in 2013, p_T > 2.0 GeV
- Here requiring an isolation cone around π⁰
  - (Was motivated by A_N increase for isolated π⁰)
  - Inclusive analysis coming soon

![Graph showing A^2_γ for π → π^0 + X at √s = 510 GeV, 2.5 < η < 4]
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Dijet Measurements

\[
x_1 = \frac{1}{\sqrt{s}} \left( p_T^3 e^{n_3} + p_T^4 e^{n_4} \right)
\]

\[
x_2 = \frac{1}{\sqrt{s}} \left( p_T^3 e^{-n_3} + p_T^4 e^{-n_4} \right)
\]

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

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

\[|\cos \theta^*| = \tanh \left( \frac{\eta_3 - \eta_4}{2} \right)\]

- Inclusive measurements have been the workhorse of STAR Δg program to date
  - Broad \( x \) range sampled in each \( p_T \) bin
  - Dijet or other correlation measurements which reconstruct the full final state are sensitive to initial kinematics at leading order
    - Prospect of mapping out the shape of \( Δg(x) \)
  - Aside: STAR has a complementary program of unpolarized QCD e.g. the dijet cross-section along with the \( A_{LL} \) spin asymmetry

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• Dijets probe a much narrower range of $x_g$ than inclusive jets
• Asymmetries consistent with predictions from global fits, albeit this is a ~subset of the dataset used to extract polarized PDF’s; some evidence dijets prefer a larger $\Delta g$?
Dijets at Forward Rapidities and $\sqrt{s} = 510$ GeV

- Probe lower $x_g$ with dijets by moving to forward rapidities and higher CoM energy
  - Reaching $x \sim 0.02$ now
  - Can push below $x = 0.01$ with additional data already recorded
  - And to $x \sim 10^{-3}$ in a few years with a forward upgrade
• Forward Calorimeter System (FCS)
  – Refurbish a portion of the PHENIX ECal, new Fe-scintillator HCal
  – Forward di-jets will extend gluon polarization to $x \lesssim 10^{-3}$
• Forward Tracking System: Silicon discs and sTGC wheels (following ATLAS design)
• An extensive suite of measurements in transverse spin and p+A collisions
• First physics planned for 2021
Constraining the Gluon Polarization Distribution with Jet, Dijet, and Neutral Pion Probes at STAR

- Inclusive Jets
  - After 30 years, **evidence of non-zero gluon polarization** in the proton
  - **Large datasets** reduce uncertainties, **higher \(\sqrt{s}\)** pushes to **lower \(x\)**
- \(\pi^0\)’s with **forward detectors probe lower \(x\)** as well
  - \(0.8 < \eta < 2.0\) in the EEMC Endcap Calorimeter
  - \(2.5 < \eta < 4.0\) in the FMS Forward Calorimeter
- Map \(\Delta g(x)\) as a function of \(x\) with correlated probes
  - Dijets and also e.g. correlated jet - forward \(\pi^0\)
- W boson \(A_L\) for flavor-separated polarized pdf’s
- Rich **transverse spin program** as well
  - Evidence, at a hadron collider, for transversity in the proton
- **Large datasets being analyzed, upgrades planned; stay tuned!**
  - New global fits expected around the time of DIS 2018, next month
RHIC Luminosity

Polarized protons

Integrals of polarized proton luminosity $L_{pb^{-1}}$

- 250/255 GeV
- 100 GeV

- 2013 $P = 53\%$
- 2017 $P = 53\%$ (L_{peak} limited)
- 2012 $P = 52\%$
- 2015 $P = 55\%$
- 2009 $P = 34\%$
- 2012 $P = 59\%$
- 2011 $P = 48\%$
- 2009 $P = 56\%$
- 2006 $P = 55\%$
- 2005 $P = 47\%$
- 2003 $P = 34\%$

Time [weeks in physics]
<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Recorded Luminosity for longitudinally / transverse polarized $p+p$ STAR</th>
<th>Recorded Luminosity for longitudinally / transverse polarized $p+p$ PHENIX</th>
<th>$\langle P \rangle$ in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>62.4</td>
<td>-- pb$^{-1}$ / 0.2 pb$^{-1}$</td>
<td>0.08 pb$^{-1}$ / 0.02 pb$^{-1}$</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>6.8 pb$^{-1}$ / 8.5 pb$^{-1}$</td>
<td>7.5 pb$^{-1}$ / 2.7 pb$^{-1}$</td>
<td>57</td>
</tr>
<tr>
<td>2008</td>
<td>200</td>
<td>-- pb$^{-1}$ / 7.8 pb$^{-1}$</td>
<td>-- pb$^{-1}$ / 5.2 pb$^{-1}$</td>
<td>45</td>
</tr>
<tr>
<td>2009</td>
<td>200</td>
<td>25 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>16 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>10 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>14 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>39</td>
</tr>
<tr>
<td>2011</td>
<td>500</td>
<td>12 pb$^{-1}$ / 25 pb$^{-1}$</td>
<td>18 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>48</td>
</tr>
<tr>
<td>2012</td>
<td>200</td>
<td>-- pb$^{-1}$ / 22 pb$^{-1}$</td>
<td>-- pb$^{-1}$ / 9.7 pb$^{-1}$</td>
<td>61/56</td>
</tr>
<tr>
<td></td>
<td>510</td>
<td>82 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>32 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>50/53</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>300 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>155 pb$^{-1}$ / -- pb$^{-1}$</td>
<td>51/52</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
<td>52 pb$^{-1}$ / 52 pb$^{-1}$</td>
<td>-- pb$^{-1}$ / 60 pb$^{-1}$</td>
<td>53/57</td>
</tr>
</tbody>
</table>

Table 1-3: Recorded luminosities for collisions of longitudinally and transverse polarized proton beams at the indicated center-of-mass energies for past RHIC runs since 2006. The PHENIX numbers are for $|vtx| < 30$ cm. The average beam polarization as measured by the Hydrogen-jet polarimeter, if two polarization numbers are given if the average polarization for the two beams was different.
2012 Inclusive Jet $A_{LL}$ at 510 GeV

- Push to lower $x_g$ w/ higher CoM energy
- 50 pb$^{-1}$ at 53% avg. polarization
- Smaller cone, $R = 0.5$ reduces effect of pileup
- Agrees well with latest predictions

Z. Chang SPIN 2014
arXiv:1512.05400
2012 Inclusive Jet $A_{LL}$ at 510 GeV

- Push to lower $x_g$ w/ higher CoM energy
- 50 pb$^{-1}$ at 53% avg. polarization
- Smaller cone, $R = 0.5$ reduces effect of pileup
- Agrees well with latest predictions
- Higher CoM pushes to lower $x_T$
  - Results agree in overlap region

Z. Chang SPIN 2014
arXiv:1512.05400
What is the contribution of gluon polarization ($\Delta G$) to the spin of the proton?

$$<S_p> = \frac{1}{2}(\upsilon_L + \nu_L + \nu_g - \Delta g)$$

Gluon polarization can be measured using $A_{LL}$ of jets, within RHIC kinematic range.

- STAR A$_{LL}$ inclusive jet results (2009) at 200 GeV, provide the first evidence of non-zero gluon polarization at $x > 0.05$ (Phys. Rev. Lett. 115, 092002).

- DSSV (1): $0.19 \pm 0.06$ ($0.05 < x$)
- NNPDF (2): $0.23 \pm 0.07$ ($0.05 < x < 0.5$)

(1) DSSV (2014), PRL 113, 012001
(2) NNPDF (2014), NPB 887, 276
2009 Dijet Cross Section Results

Green box includes quadrature sum of systematic errors on the data

Blue box is theory + UEH correction and width is theory error (pdf uncert, renormalization and factorization scales x0.5, x2, UEH uncert)

Red box is syst errors on the UEH (underlying event and hadronization effects) correction, shown separately

Phys. Rev. D 95, 071103(R) (2017)
π⁰ - Jet $A_{LL}$ measurements at STAR

Channel: Using a jet in the mid-rapidity region correlated with an opposite-side neutral pion in the forward rapidity region $1.08 < \eta < 2.0$ in the STAR EEMC provides a new tool to access the $\Delta G(x)$ distribution at Bjorken-$x$ down to 0.01.

\[
x_1 = \frac{p_T^{jet}}{\sqrt{s}}(e^{\eta_{jet}} + e^{\eta_{\pi^0}}),
\]
\[
x_2 = \frac{p_T^{jet}}{\sqrt{s}}(e^{-\eta_{jet}} + e^{-\eta_{\pi^0}}),
\]
\[
\sqrt{s} = \sqrt{x_1x_2s}.
\]

- Compared to inclusive jet measurements, this $\pi^0$ - jet channel also allows to constrain the initial parton kinematics, such as $x_1$, $x_2$ and $\sqrt{s}$.
La Bataille de Reines; Col du Petit St. Bernard; August 2010