Constraining the Gluon Helicity Distribution of the Proton with Inclusive Jet and Dijet Measurements at STAR

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Naïve picture of proton properties determined largely by three valence quarks → replaced by a highly complex, non-perturbative system in which properties “emerge” from the interactions of quarks, anti-quarks, and gluons

Decomposition not unique! For helicity distributions (collinear terms) most useful to use ‘canonical’ approach

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


Precise DIS measurements have shown quark spins contribute only ~30% (\(\Delta \Sigma\) term), but are sensitive to gluons only through scaling violations over limited \((x,Q^2)\) space → need a (colored) probe that couples directly to gluons!
What high-energy $\bar{p}p$ collisions bring to the table

Hadronic beams provide polarized QCD probes of spin-dependent partonic structure!

Assume factorization works

Interaction calculable at partonic level

H"soft" parton distribution functions

H"soft" frag. function

H"hard" $d\sigma_{QCD}$ parton-parton

Allows us to ask:
Does the gluon spin contribute significantly to that of the proton?
What about sea quarks?
Or partonic OAM?
Facilities: RHIC & STAR at BNL

- **RHIC**: provides collisions of transversely or longitudinally polarized protons at energies up to $\sqrt{s} = 510$ GeV

- **STAR**: allows for charged-particle track reconstruction for $|\eta| < 1.3$, and measures EM particle energies for $-1 < \eta < 2$, both over the full azimuthal range of $2\pi$

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Scott Wissink – DIS2022, May 2022
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### RHIC & STAR Longitudinal Data Sets

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**Solenoidal Tracker At RHIC**
Jets: a robust proxy for scattered partons

Three Simulation Levels:
- Parton level – hard-scattered partons from a 2→2 hard scattering event from Pythia
- Particle level – partons propagate, then fragment and hadronize into stable, color-neutral particles
- Detector level – simulate STAR's response to produced particles (towers and tracks), “embed” response in real zero-bias data

Anti-\(k_T\) Algorithm:
- Radius = 0.5 or 0.6
- Less sensitive to underlying event and pile-up effects
- Used in both data and simulation
Jet spin asymmetries: probe $\Delta g(x)$ directly

With longitudinally polarized beams, compare jet yields for colliding protons with same versus opposite helicities

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma}a_{LL}}{\sum f_a \otimes f_b \otimes \hat{\sigma}}$$

What we measure

What we hope to learn!

What others measure

What is calculable

$gg$ and $qg$ dominant at RHIC energies $\rightarrow$ gluons!

2009 – first large data set at $\sqrt{s} = 200$ GeV, showing positive $A_{LL}$ suggests $\Delta g(x) > 0$ in the regions of $(x, Q^2)$ probed, roughly $0.05 < x < 0.2, Q^2 \sim 10$ GeV$^2$


STAR 2009

$p+p \rightarrow$ Jet+X

$\sqrt{s} = 200$ GeV

$0.5 < |n| < 1$

$|n| < 0.5$

±6.5% scale uncertainty from polarization not shown

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2009 results: large impact on global analyses!

Great progress in determining gluon contribution to the proton spin ...

... but magnitude and shape of $\Delta g(x)$ still unconstrained for $x$ below 0.05!
Though DSSV group finds substantial gluon polarization, with small uncertainties, for $x > 0.05$, region below this is wide open – note change of scales on two axes!

STAR’s strategy for exploring low-$x$ regime:
- Increase size / integ’ed $\mathcal{L}$ of data sets
- Focus on dijets, rather than inclusive jets
- Reconstruct jets at the highest possible $\eta$
- Take data at the highest possible energy

**Ultimately, carry out all of these improvements simultaneously!**
Beyond inclusive jets: advantages of dijets

Correlation measurements, such as dijets, capture more information from the hard scattering and provide a more direct link to the initial kinematics than inclusive probes.

Dijets sample initial-state partonic $x$ values over a more limited range than inclusive jets $\rightarrow$ constraints on functional form of $\Delta g(x,Q^2)$.

Leading order expressions at left show how different jet topologies (combinations of the two jet $\eta$ ranges) are sensitive to different initial-state partonic momentum fractions.

$$x_1 = \frac{1}{\sqrt{s}} \left( p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4} \right)$$

$$x_2 = \frac{1}{\sqrt{s}} \left( p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4} \right)$$

$$M = \sqrt{x_1x_2s}$$

$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$
First STAR dijet results at $\sqrt{s} = 200$ GeV

Mid-rapidity dijet $A_{LL}$ results presented for two topologies as a function of the dijet invariant mass corrected to parton level

Data are compared to expectations from DSSV14 and NNPDFpol1.1 polarized PDFs, both of which include the 2009 inclusive jet results yet show significant differences

Scale and PDF uncertainty bands shown for NNPDFpol1.1 calculation

Dijet cross section also measured
Recent results: midrapidity dijets at 200 GeV

Final longitudinal data set acquired by STAR (2015) at 200 GeV – 52 pb$^{-1}$, 2x 2009 data

Results for midrapidity inclusive jet and dijet asymmetries are seen to be consistent with those found in 2009, though with statistical errors ~1.5 times smaller

2015 data have additional corrections applied (primarily Underlying Event subtraction) to jet $p_T$, as well as greatly reduced systematic uncertainties.
Detecting jets at more forward rapidities

$2 \rightarrow 2$ scattering kinematics:

$$\eta_3 + \eta_4 = \ln(x_1 / x_2)$$

→ Shows that jet pairs found at higher pseudorapidities originate from collisions of partons with asymmetric momentum fractions

→ Jet pairs reconstructed in the STAR Endcap region, e.g., will be dominated by high-$x$ (and thus highly polarized) valence quarks interacting with the low-$x$ gluons of primary interest
Dijet $A_{LL}$ values shown for two Barrel-Endcap (East and West) and Endcap-Endcap topologies.

With one jet in Endcap, can see increased $x_1 / x_2$ asymmetry as second jet moves forward in $\eta$.

Results are again compared to DSSV14 and NNPDFpol1.1 expectations with limited statistics, no clear preference, but data tend to exceed global fits with increased asymmetry in colliding parton $x$ values.

On to $\sqrt{s} = 510$ GeV: Midrapidity inclusive jets

Why go to higher energy? Recall:

$$x_1 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta 3} + p_{T4} e^{\eta 4} \right)$$

→ For jets detected at same $p_T$ and $\eta$, higher $\sqrt{s}$ probes lower $x$

Plotted vs $x_T$, overall consistency seen among STAR data sets, with data generally above fits, with a slight preference for DSSV14

Results from 510 GeV push down to lower $x_T$, though predicted $A_{LL}$ very small in this region

Accepted in PRD, arXiv:2110.11020
On to $\sqrt{s} = 510$ GeV: Midrapidity dijets

Accepted in PRD, arXiv:2110.11020
Final longitudinal data acquired by STAR (2012, 2013) at 500 GeV, ~250 pb$^{-1}$ integrated lum.

“Pushes all the buttons” to reach lowest possible gluon $x$ values: large $\eta$, highest $\sqrt{s}$, using dijets

Preliminary results for 2012 (left) and 2013 (right) are in excellent agreement with each other, both favoring $A_{LL}$ values slightly higher than global fit expectations.

All systematic uncertainties for the two data sets are finalized, so a combined result (including their correlated uncertainties) can be published very soon.
For almost two decades, STAR has carried out precise measurements of longitudinal double-spin asymmetries for inclusive and dijet production in pp collisions.

By studying $A_{LL}$ over a wide range of kinematic regimes and at several energies, increasingly tight constraints have been placed on the gluon helicity distribution, $\Delta g(x)$, when results are included in global analyses by, e.g., the DSSV, NNPDF, and JAM groups.

Midrapidity results indicate $\sim40\%$ of the proton’s spin may be due to contributions from the spins of gluons that each carry at least 5% of the proton’s momentum.

New, higher statistics data at more forward rapidities and at higher collision energies have been recently or are soon to be published, which will provide much needed constraints in the low-$x$ region.
Backup material
Technical challenges for jets in the STAR EEMC

- Charged particle tracking efficiency falls off rapidly beyond $\eta \sim 1.3$
- Increasingly poor determination of jet $p_T$ and jet $\eta$ in endcap region

Must correct reconstructed jet properties on an event-by-event basis for biases in $p_T$, $\eta$, $R_T$

→ Highly non-linear and correlated effects!
→ Use machine learning (Multilayer Perceptron)