Gluon polarization measurements from longitudinally polarized proton-proton collisions at STAR

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The Proton Spin

Proton spin sum rule:

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_{q,g} \]

- \( \Delta \Sigma \): \( \sim 0.3 \) constrained by DIS and SIDIS
- \( \Delta G \): poorly constrained by DIS and SIDIS
- \( L_{q,g} \): unconstrained

Leader et al, PRD 82, 114018

With fit to DIS and SIDIS data,

\( \Delta G = -0.34 \pm 0.46 \)

\( \Delta G = 0.32 \pm 0.19 \) for pos

Leader et al, PRD 82, 114018
In longitudinally polarized $pp$ collisions, define longitudinal double-spin asymmetry $A_{LL}$ as:

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

$gg$ and $qg$ dominate jet production + large $\hat{A}_{LL}$ → making $A_{LL}$ for jets sensitive to gluon polarization

Experimentally, $P_B(Y)$: beam polarizations, and $R$: relative luminosity

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N^{++} - R \times N^{-+}}{N^{++} + R \times N^{-+}}$$
Impact of Recent STAR Dijet Results

- Recent STAR dijet $A_{LL}$ results at $\sqrt{s} = 200$ GeV: both jets in $|\eta| < 0.8$, or at least one jet in $0.8 < \eta < 1.8$

The DSSV study shows: $\int_{0.01}^{1} \Delta g(x, Q^2 = 10 \text{GeV}^2) = 0.296 \pm 0.108$

Florian et al., arXiv:1902.10548 [hep-ph]
STAR Detectors

- Tracking with TPC: $|\eta| < 1.3$
- EM energy and triggering with:
  - BEMC: $-1.0 < \eta < 1.0$
  - EEMC: $1.0 < \eta < 2.0$
  - FMS: $2.65 < \eta < 3.9$
Jet Reconstructions

- Dataset: $pp$ at $\sqrt{s} = 510$ GeV
- Inputs: charged tracks + electro-magnetic towers
- Algorithm: anti-$k_T$ algorithm with $R = 0.5$
- Systematics study: PYTHIA + GEANT + Zero-bias events as embedding sample
  - Data-driven modified PYTHIA Perugia Tune
  - Correct jet $p_T$ and dijet $M_{inv}$ from measured detector jets to PYTHIA parton jets
  - Trigger bias and reconstruction uncertainty
Monte Carlo Tune Study

- Tuning based on matching between PYTHIA simulation and previous STAR charged $\pi^\pm$ spectrum measurements STAR, PLB 637, 161 and STAR, PRL 108, 072302

- Default Perugia 2012 tune except a smaller $p_{T,0}$ scale parameter ($P_{90} = 0.213$ default 0.24)

\[
\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2}
\]

\[
 p_{T,0} = p_{T,\text{ref}} \times \left( \frac{\sqrt{s}}{\sqrt{s_{\text{ref}}}} \right)^{P_{90}}
\]

- Reduce multiple parton interaction contribution

- Jet spectrum comparison for three jet patch triggers, JP0, JP1 and JP2

Markers: data and lines: simulation

Two off-axis cones centered at $\pm \frac{\pi}{2}$ away in $\phi$ and the same $\eta$ relative to a given jet are used to estimate underlying event for that jet, ALICE, PRD 91, 112012

The underlying event correction on jet transverse momentum:

$$dp_T = \frac{1}{2}(\rho_{plus} + \rho_{minus}) \times A_{jet}$$

Scan $\eta$ dependence of underlying events

Allow to study the underlying event contribution to jet $A_{LL}$
Define underlying event correction $dp_T$ asymmetry:

$$A_{LL}^{dp_T} = \frac{1}{P_A P_B} \frac{<dp_T>^{++} - <dp_T>^{+-}}{<dp_T>^{++} + <dp_T>^{+-}}$$

Underlying event correction $dp_T$ asymmetries are consistent with zero, STAR, arXiv:1906.02740 [hep-ex]

Underlying event contribution to measured jet $A_{LL}$ is estimated to be $\sim 10^{-4}$, assigned as an uncertainty
**STAR 510 GeV Inclusive Jet $A_{LL}$ Measurements**

- Much reduced systematic uncertainty than the previous measurements at $\sqrt{s} = 200$ GeV, STAR, arXiv:1906.02740 [hep-ex]
- Agree with recent polarized PDF predictions
- In the overlapping $x_T = \frac{2p_T}{\sqrt{s}}$ region, both results agree well
- Allow to access $x_g$ as low as $0.015$

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Dijet $A_{LL}$ vs. invariant mass for four $\eta$ topologies, STAR, arXiv:1906.02740 [hep-ex]

A/Forward-Forward:
$0.3 < |\eta_{3,4}| < 0.9$
$\eta_3 \cdot \eta_4 > 0$

B/Forward-Central:
$|\eta_{3,4}| < 0.3,$
$0.3 < |\eta_{3,4}| < 0.9$

C/Central-Central:
$|\eta_{3,4}| < 0.3$

D/Forward-Backward:
$0.3 < |\eta_{3,4}| < 0.9$
$\eta_3 \cdot \eta_4 < 0$

- Topology binning narrows the sampled $x_g$ and the $\cos\theta^*$ ranges
- Sampled $x_g$ distributions much narrower than those from inclusive jets
Inclusive and Dijet $A_{LL}$ from STAR 2013 510 GeV Data

- Preliminary inclusive jet (left) and dijet (right) $A_{LL}$ from STAR 2013 510 GeV data, Quintero, arXiv:1809.00923 [nucl-ex]

- Same procedure being applied as in 2012 $\sqrt{s} = 510$ GeV data
- The 2012 and 2013 results agree well
- Two $\eta$ topologies for dijet $A_{LL}$
- The study of the systematic uncertainty is underway for the final results

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STAR 510 GeV Forward $\pi^0 A_{LL}$

- $\pi^0$ reconstructed in STAR FMS
- Measured $A_{LL}$ is small, less than $5 \times 10^{-3}$
- Allow to access $x_g \sim 10^{-3}$
STAR is planning to install a Forward Calorimeter System (FCS), including an EMCal and a HCal, and a Forwarding Tracking System (FTS) in time for polarized 510 GeV run in 2022.

Dijet measurements with one or both jets in the forward region (2.8 < $\eta$ < 3.7) will be one of the highlights of this upgrade.

With both jets in the FCS, it will provide gluon polarization at $x_g \sim 10^{-3}$

STAR inclusive jet and dijet double-spin asymmetry measurements are unique to explore gluon polarization in the proton

- The 510 GeV results extend gluon polarization over $x \sim 0.015$ to $x \sim 0.2$, STAR, arXiv:1906.02740 [hep-ex]
  1. Inclusive jets will constrain the magnitude of the gluon polarization
  2. Dijets will constrain the shape of $\Delta g(x)$

Inclusive jet and dijet $A_{LL}$ are being studied with the 2013 $pp$ data at $\sqrt{s} = 510$ GeV

- The forward upgrade will provide new opportunities to probe low $x \sim 10^{-3}$ gluon polarization where the current polarized PDF studies show large uncertainties
Selected longitudinally polarized $pp$ datasets at $\sqrt{s} = 200$ and 510 GeV:

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Recorded Luminosity (pb$^{-1}$)</th>
<th>B/Y polarization $\langle P \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>200</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td>2012</td>
<td>510</td>
<td>82</td>
<td>50/53</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>300</td>
<td>51/52</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
<td>52</td>
<td>53/57</td>
</tr>
</tbody>
</table>

- **2009** and **2012** data are in publication
- **2013** and **2015** data are under analysis
STAR has measured a series of inclusive jet and dijet cross-sections and longitudinal double-spin asymmetry $A_{LL}$s at $\sqrt{s} = 200$ GeV

- **Inclusive jets:**
  $x_g$ as low as $\sim 0.05$ at $\sqrt{s} = 200$ GeV

- **Dijets:**
  two jet correlation unfolds $x_1$ and $x_2$ at the leading order

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

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

  $$M = \sqrt{x_1 x_2 s}$$

- Sampled $x_g$ distributions by inclusive and dijets at $\sqrt{s} = 200$ GeV

  [Graph showing normalized yield for different $x_g$ distributions]

  [Graph showing normalized yield for different $x_g$ distributions]
Underlying Event Systematics on Jet $A_{LL}$

$$\delta A_{LL} = \frac{p_{T, \text{max}} - <dp_T> \times A_{LL}^{dp_T} \int \frac{d\sigma}{dp_T} dp_T - p_{T, \text{min}} - <dp_T> \times A_{LL}^{dp_T} \int \frac{d\sigma}{dp_T} dp_T}{p_{T, \text{max}} - <dp_T> \times A_{LL}^{dp_T} \int \frac{d\sigma}{dp_T} dp_T + p_{T, \text{min}} + <dp_T> \times A_{LL}^{dp_T} \int \frac{d\sigma}{dp_T} dp_T}$$

Figure: Underlying event systematic uncertainty on inclusive jet $A_{LL}$ for 2012 510 GeV data compared with systematic uncertainty due to relative luminosity.
Figure: STAR charged $\pi^{\pm}$ yields. STAR, PRL 108, 072302, 2012