Inclusive Jet Measurements in Longitudinally Polarized proton-proton Collisions at STAR

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The Proton Spin

**Proton spin sum rule:**

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

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

With fit to DIS data only, \(\Delta G = 0.46 \pm 0.43\),  
Blümelin, Böttcher, NPB 841, 205 (2010)

With fit to DIS and SIDIS data,  
\(\Delta G = 0.32 \pm 0.19\) for pos,  
\(\Delta G = -0.34 \pm 0.46\), Leader et al, PRD 82, 114018 (2010)
In longitudinally polarized $pp$ collisions, define longitudinal double-spin asymmetry $A_{LL}$ as,

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \sim \frac{\Delta f_a \Delta f_b}{f_a f_b} a_{LL} \hat{a}_{LL}(2)$$

$gg$ and $qg$ dominate jet production, making $A_{LL}$ for jets sensitive to gluon polarization.
Polarization orientation varies from RF bunches to RF bunches (9.4 MHz).
Spin rotators provide choice of polarization orientation (longitudinal or transverse).
Jet reconstruction:
- High precision tracking with Time Projection Chamber ($|\eta| < 1.3$).
- High energy resolution with Barrel and Endcap Electro-Magnetic Calorimeter (-1.0 $< \eta < 2.0$).

Global detectors for relative luminosity monitoring:
- Beam-Beam Counter, Vertex Position Detector, and Zero-Degree Calorimeter ($|\eta| > 3.4$).
Data from Longitudinally Polarized pp Collisions at STAR

STAR longitudinally polarized pp data since 2006:

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>Lum. [pb$^{-1}$]</th>
<th>Pol. [%]</th>
<th>Jet Rec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>200</td>
<td>45</td>
<td>55</td>
<td>Midpoint cone, $R = 0.7$</td>
</tr>
<tr>
<td>2009</td>
<td>200</td>
<td>54</td>
<td>56</td>
<td>Anti-$k_T$, $R = 0.6$</td>
</tr>
<tr>
<td>2009</td>
<td>500</td>
<td>53</td>
<td>35</td>
<td>Anti-$k_T$, $R = 0.6$</td>
</tr>
<tr>
<td>2012</td>
<td>510</td>
<td>144</td>
<td>52</td>
<td>Anti-$k_T$, $R = 0.5$</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>500</td>
<td>52</td>
<td>Anti-$k_T$, $R = 0.5$</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
<td>120</td>
<td>57</td>
<td>In process</td>
</tr>
</tbody>
</table>
Jet Reconstruction at STAR

- PYTHIA + GEANT + Zero-bias events as embedding sample.
- Allow to correct from detector jets to particle and parton jets.
- Determine systematic uncertainties.
STAR has measured a series of inclusive jet and di-jet cross-sections and longitudinal double-spin asymmetry $A_{LL}$s at $\sqrt{s} = 200$ GeV.

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

- **Di-jets:**
  Two jet correlation unfolds $x_1$ and $x_2$ at the leading order.

\[
x_1 = \frac{1}{\sqrt{s}} (p_T,3e^{\eta_3} + p_T,4e^{\eta_4}) \tag{3}
\]
\[
x_2 = \frac{1}{\sqrt{s}} (p_T,3e^{-\eta_3} + p_T,4e^{-\eta_4}) \tag{4}
\]
\[
M = \sqrt{x_1x_2s} \tag{5}
\]

Gluon $x_g$ sampled by inclusive and di-jets at $\sqrt{s} = 200$ GeV (PRD 95, 071103(R)).
Jet profile, fraction of the total jet transverse energy within a cone of radius ∆R centered on the reconstructed thrust axis, from STAR 2006 $\sqrt{s} = 200$ GeV data (PRD, 86, 032006).

- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction.
- Jet production is well understood at RHIC energies
Di-jet Cross-section Measurements

Di-jet cross-sections from STAR 2009 $\sqrt{s} = 200$ GeV data (PRD 95, 071103(R)).

- Di-jet cross-section is well described by the NLO pQCD calculations after hadronization and underlying event corrections.

Preliminary di-jet cross-sections from STAR 2009 $\sqrt{s} = 500$ GeV data.
Inclusive Jet Double-spin Asymmetry $A_{LL}$ Measurements

This measurement is more precise than the previous measurement from the 2006 data, (3 times at high jet $p_T$ and 4 times at low jet $p_T$).

$A_{LL}$ falls in the middle among several polarized PDF fit predictions.

$A_{LL}$ is larger than the 2008 DSSV fit, and would push the fit towards positive $\Delta g$ in the accessible $x$ region.

Inclusive jet $A_{LL}$ from STAR 2009
$\sqrt{s} = 200$ GeV data (PRL 115, 092002).
Impacts of STAR 2009 Inclusive Jet $A_{LL}$

DSSV new fit with STAR 2009 inclusive jet $A_{LL}$ data (PRL 113, 012001).

- Both groups find the STAR 2009 inclusive jet $A_{LL}$ provide significantly tighter constraints on gluon polarization than previous measurements.
  - DSSV: $\Delta G = 0.19^{+0.06}_{-0.05}$ for $x > 0.05$ at 90% C.L.
  - NNPDF: $\Delta G = 0.23 \pm 0.07$ for $0.05 < x < 0.5$.

$x\Delta g$ from NNPDF with STAR 2009 inclusive jet $A_{LL}$ data (NPB 887.276).
Higher $\sqrt{s} = 510 \text{ GeV}$ provides sensitivity to smaller $x_g$. $x_g$ sampled by two jet $p_T$ bins with mean $p_T = 7.7$ and 34.4 GeV/c:

Smaller $R = 0.5$ for anti-$k_T$ algorithm reduces pile-up effects and is less sensitive to background.

By comparing with various detectors, relative luminosity is estimated more precisely than previous measurements $\sim 10^{-4}$.

Using replicas from the polarized NNPDF PDF set to estimate trigger bias and reconstruction uncertainties.
Choose default Perugia 2012 tune with a smaller $p_{T,0}$ scale parameter ($P_{90}$ from 0.24 to 0.213)

\[
\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2} \quad (6)
\]

\[
p_{T,0} = p_{T,ref} \times \left( \frac{\sqrt{s}}{\sqrt{s_{ref}}} \right)^{P_{90}} \quad (7)
\]

- Reduce multiple parton interaction contribution
- Lead to better matching between PYTHIA simulation and previous STAR charged $\pi^\pm$ spectrum measurements (PLB 637, 161,2006 and PRL 108, 072302, 2012).
Two off-axis cones are used to estimate underlying event for a given jet (ALICE, PRD 91, 112012).

The underlying event correction: \( dp_T = \frac{1}{2}(\rho_{\text{plus}} + \rho_{\text{minus}}) \times A_{\text{jet}} \)

Sample \( \eta \) dependence of the underlying event.

Other applications: jet analysis in \( pA \) collisions.
Underlying event $dp_T$ vs. jet $p_T$ for three jet patch triggers JP0, JP1 and JP2. The difference in $dp_T$ between data and simulation used as a systematics as underlying event correction on jet $p_T$. 

Underlying event $dp_T$ vs. jet $p_T$ for three jet patch triggers JP0, JP1 and JP2. The difference in $dp_T$ between data and simulation used as a systematics as underlying event correction on jet $p_T$.
Define underlying event correction $dp_T$ asymmetry:

$$A_{LL}^{dp_T} = \frac{1}{P_A P_B} \left( \frac{1}{2} \left( \langle dp_T \rangle^{++} + \langle dp_T \rangle^{--} \right) - \left( \langle dp_T \rangle^{+-} + \langle dp_T \rangle^{-+} \right) \right)$$

Underlying event correction $dp_T$ asymmetries. Little asymmetries for the underlying event correction.

Underlying event contribution to jet $A_{LL}$ is estimated $\sim 10^{-4}$, assigned as an uncertainty. More detail in backup slides.
Preliminary STAR 2012 and 2013 $\sqrt{s} = 510$ GeV inclusive jet $A_{LL}$ results compared with the STAR 200 GeV data from 2009. Both preliminary results agree well with:

- The STAR 200 GeV data in the overlapping $x_T$ region.
- Recent polarized PDF predictions.
- Final 2012 results will have much smaller systematic uncertainties.
The combined 2015 data with the existing STAR 200 GeV data will significantly reduce the uncertainties for the 200 GeV inclusive jet $A_{LL}$, by a factor of two relative to the 2009 results.
STAR is proposing to install a Forward Calorimeter System (FCS), including an electromagnetic calorimeter and a hadron calorimeter, and a Forwarding Tracking System (FTS) in 2020s.

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

FCS will provide gluon polarization at very low $x$
- $x \sim 5 \times 10^{-3}$ with FCS-EEMC di-jets
- $x \leq 10^{-3}$ with FCS-FCS di-jets

See Elke’s talk:
The STAR Cold QCD Physics Program after 2020.
STAR inclusive jet and di-jet cross-section measurements provide valuable information to constrain unpolarized gluon distribution in the proton. The results are consistent with NLO pQCD calculations.

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

1. The 200 GeV results provided the first experimental evidence for positive gluon polarization over RHIC kinematic range.
2. The 510 GeV results extend gluon polarization measurement at lower $x$.

Publication preparation:

1. 510 GeV inclusive jet and di-jet $A_{LL}$,
2. 200 GeV forward di-jet $A_{LL}$,
3. 510 GeV inclusive jet cross-sections.

The STAR forward upgrade will provide new opportunities to probe low $x \sim 10^{-3}$ gluon polarization where the current polarized PDF studies show large uncertainties.
Underlying event systematic uncertainty on inclusive jet $A_{LL}$ for 2012 510 GeV data compared with systematic uncertainty due to relative luminosity.
Backup: STAR 200 GeV Di-jet $A_{LL}$ Measurements

STAR 2009 $\sqrt{s} = 200$ GeV di-jet $A_{LL}$ measured with jets at $|\eta| < 0.8$ (PRD 95, 071103(R)).

Preliminary STAR 2009 $\sqrt{s} = 200$ GeV di-jet $A_{LL}$ with one jet at $|\eta| < 0.8$ and the other at $0.8 < \eta < 1.8$.

Preliminary STAR 2009 $\sqrt{s} = 200$ GeV di-jet $A_{LL}$ measured with jets at $0.8 < \eta < 1.8$. 

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DIS2018, Kobe, Japan
Preliminary STAR 2012 $\sqrt{s} = 510$ GeV di-jet $A_{LL}$
measured with jets at $|\eta| < 0.9$ compared with STAR 2009 data.

Preliminary STAR 2013 $\sqrt{s} = 510$ GeV di-jet $A_{LL}$
compared with STAR 2009 data.
STAR charged $\pi^\pm$ yields. PRL 108, 072302, 2012