Recent STAR Measurements to Constrain the Polarized Gluon Distribution Function of the Proton

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For the STAR collaboration
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Motivation

The simplest model of proton structure (3 valence quarks only), fails to explain early results of polarized DIS.

The proton spin sum rule:

\[ < S_p > = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

Polarized DIS results \( \Delta \Sigma \approx 0.3 \)
(B. Surrow’s talk on constraining sea quarks)

What is the contribution of gluon polarization \((\Delta G)\) to the spin of the proton?

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Motivation

- Gluon polarization can be measured using longitudinally polarized double spin asymmetry ($A_{LL}$) of jets.

- For most RHIC kinematics, $gg$ and $qg$ scattering dominate.

- 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).

\[ \Delta G = \int d x \Delta g(x) \]

DSSV\(^{(1)}\): $0.19 \pm 0.06$ ($0.05 < x$)

NNPDF\(^{(2)}\): $0.23 \pm 0.07$ ($0.05 < x < 0.5$)

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

- Uncertainty of gluon polarization points to a positive value, in the high $x$ region.
- Need to increase precision in the currently sampled region to consolidate the observation of non-zero gluon polarization.
- Uncertainties in the low $x$ region are still very large.
- Need to extend sensitivity to lower $x$ to further constrain global fits in this region.
Relativistic Heavy Ion Collider

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Source

Polarimeter

RHIC

Absolute Polarimeter (H↑ jet)

RHIC pC Polarimeters

Spin Rotators
(longitudinal polarization)

Partial Snake

Siberian Snakes

AGS Polarimeter

RF dipole

AGS

Partial Snake

200 MeV Polarimeter

EBIS

LINAC

Pol. H Source

PHENIX

Siberian Snakes

Siberian Snakes

Helical Partial Siberian Snake
Polarized proton runs at RHIC

Longitudinally polarized runs

<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>200</td>
</tr>
<tr>
<td>2012</td>
<td>510</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
</tr>
</tbody>
</table>

Experimentally

\[ A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{P_1 P_2} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}} \]

\[ N = \sigma L, \quad R = \frac{L^{++}}{L^{+-}} \]

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STAR Experiment

- One of the largest experiments at the Relativistic Heavy Ion Collider (RHIC).

- The main tracking device is a Time Projection Chamber (TPC) at $|\eta| \leq 1.3$.

- Electromagnetic calorimeters ($-1 \leq \eta \leq 2$) are used to trigger high momentum particles and measure neutral component of jets.

- Forward Meson Spectrometer (FMS) is a lead-glass EM calorimeter to detect $\pi^0$ at $2.5 \leq \eta \leq 4.2$.

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Previous STAR Results
Inclusive Jets at √s=200 GeV in 2009

- Increase statistical precision compared to earlier STAR measurements in 2006.
- Results were systematically above the DSSV 2008 global fit.
- These results strongly suggest a positive gluon polarization value after inclusion in DSSV14 and NNPDF1.1 fits.
Di-jets at $\sqrt{s}=200$ GeV in 2009

- Di-jets measurements allows to probe a narrower x region.
- Results are consistent with 2014 global fits.
Forward di-jets at $\eta < 2$, allows reaching lower and narrower $x$ region.

Forward upgrades will reach $x \sim 10^{-3}$ (E. Aschenauer’s talk on STAR future program).

Publication in preparation
Inclusive and Di-jets at $\sqrt{s}=510$ GeV in 2012

- Increased center of mass energy allows probing lower $x$ values.
- Final di-jets result will be presented with finer binning in pseudorapidity.
- Details in Z. Chang’s talk on inclusive jet measurements (next talk).

Publication in preparation
Latest Measurement
Run 2013 data

- Figure of Merit relevant for double spin asymmetry: almost three times greater than the previous year.

- Average beam polarization 53%.

- STAR installed the Heavy Flavor Tracker (HFT) in the middle of the run.

- The extra material affects the reconstruction of events (e.g. average $\eta$).

![Graph showing the comparison between average JP2 Jet $\eta$ before and after HFT installation.](image)
• Jets were reconstructed using the anti-kt jet finding algorithm with R=0.5.
• Embedded simulations (in data) are used to quantify the detector response and estimate systematic uncertainties.
• Embedded simulation sample for the 2012 run agrees with data for the 2013 run (before HFT).
• Run 2009 (200 GeV), Run 2012 and the newest Run 2013 (510 GeV) $A_{LL}$ measurements show good agreement in x overlap region.

• The inclusion of the STAR Run 2009 results to the newest global fits provides better control of the systematics (e.g. trigger and reconstruction bias), allowing to improve these errors.

• The full data sample of Run 2013 (510 GeV) is already processed and simulation is being produced to finalize systematic uncertainty studies for final result.
Preliminary di-jet asymmetries results for 2009, 2012 and 2013 are in agreement.

Reduced statistical and systematic uncertainties for 2013 compared to 2012.

Preliminary results are in agreement with 2009 results in the overlap region.
Status of run 2015 (200 GeV) analyses

- Average beam polarization 55%.
- Test of tracking, jet reconstruction and triggering software: complete.
- STAR TPC and BEMC calibration: finalizing.
- QA of jet analyses: in progress.
- MC / Embedding comparison using previous sample: initial testing.
- Systematic uncertainty studies: initial testing.
- These measurements will reduce uncertainties by a factor of ~1.6, compared to 2009 results.

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Pion Analysis
Forward $\pi^0$ analysis

- The $A_{LL}$ measurement of $\pi^0$ at $\sqrt{s} = 510$ GeV allows reaching the lowest $x$ values at STAR (2012 and 2013).
- Requiring 2-photon isolation cones: 35 mr and 100 mr around $\pi^0$.

- Control of the systematics is critical for this precision measurement.
- Preliminary results are consistent with zero.
- Final results will be using a modified cone method for pion identification.

Publication in preparation
Summary and Projections

- The STAR spin program provided evidence of non-zero gluon polarization.

- Results of $A_{LL}$ for inclusive jet, di-jets and $\pi^0$ are consistent and agree with the global fits DSSV14 and NNPDFpol1.1.

- Run 2013 embedding studies are ongoing. The path to final results is well established after completion of MC sample.

- STAR took additional 200 GeV pp data during 2015, to consolidate previous measurements in 2009.

- These high precision measurements motivate the natural step forward to the STAR forward upgrade program and an Electron Ion Collider.
Runs QA

Procedure:
1.- Divide Period 1 in four sub-periods A, B, C, D.
2.- Calculate the average of each quantity per run per period.
3.- Plot versus ZDC rate.
4.- Fit a 2nd order polynomial per quantity.
5.- Calculate RMS of sample respect to the pol2 fit.
6.- Runs outside 3*RMS per quantity, are removed.

All quantities studied (34):
• Vertex Z
• Bunch Crossing
• Asymmetry
• Each False Asymmetry (4)  
  (for Asymmetries took the ->Integral(3,15), not mean)
• Each Relative Luminosity (6)
• Each Polarization (2)
• Jets per Event, Pt, Rt, Eta, Phi, Det Eta, Underlying event
• Tracks per jet, Pt, DcaXY, Eta, Phi, DcaZ
• Tower multiplicity, Et, Energy, Eta, Phi, Adc

Showing all period 1. The RMS lines match each sub-period.
Comparison of data and simulation (run 13)

Jets per event

Jets Transverse Momentum

Jets Neutral Energy ($R_\eta$)

Jets $\eta$

Jets $\phi$

Jets detector $\eta$

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False asymmetries

Longitudinal Single Spin Asymmetry Blue beam

Longitudinal Single Spin Asymmetry Yellow beam

Longitudinal Double Spin Asymmetry like sign

Longitudinal Double Spin Asymmetry unlike sign

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Jet Energy Scale systematic

1. $P_T$ shift: is the statistical error of each bin obtained for the ProfileX of the $p_T$ shift (appendix).

2. BEMC track:

$$p_{T,\text{avg}} \sqrt{((1-R_T) \times \text{trk}_p)^2 + ((1-R_T) \times (NH - \text{trk}_{\text{eff}} \times \text{trk}_{\text{dep}}) \times \text{BEMC}_{\text{trk}} \times \text{BEMC}_{\text{unc}} / \text{trk}_{\text{eff}})^2}$$

$\text{Trk}_p$ = Track momentum uncertainty as 1%
$\text{NH}$ = Scale up for neutral hadrons 1.1628
$\text{Trk}_{\text{eff}}$ = Track efficiency 55%
$\text{Trk}_{\text{dep}}$ = Track deposition in projected tower 50%
$\text{BEMC}_{\text{trk}}$ = BEMC resp to track 30%
$\text{BEMC}_{\text{unc}}$ = BEMC resp to track uncertainty 9%

3. BEMC neutral:

$$p_{T,\text{avg}} \times R_T \sqrt{(\text{gain})^2 + (\text{eff}_{\text{unc}})^2}$$

gain = 8% (5% run 13 + 3% Run12 emb) and Eff_{unc} = 1%

4. 7% track loss: $\sqrt{(pt-\text{pt7})^2 + 0.01^2}$

5. UE shift: difference between Profile of UE in data and UE in simulation.

6. $P_T$ tune: extrapolate Zilong results to my $p_T$ bins. Tune13 = ($P_{T13}/P_{T12}$) * Tune12
$A_{LL}$ systematic uncertainty

1.- Relative luminosity systematic: $5.6 \times 10^{-4}$.

2.- UE systematic: $1 \times 10^{-4}$.

3.- Trigger Bias:
  - Use NNPDF1.1 100 replicas.
  - Take the diff Detector – Parton for each replica.
  - The Mean is the $A_{LL}$ correction.
  - The RMS is the systematic.

4.- The RMS of NNPDF1.1 best fit Detector – Parton is the systematics.

5.- Track 7% loss:
  - Take the average of 100 rep. nominal and 7% loss.
  - The difference of Detector Nominal – Detector 7% loss is the systematic.

**Final systematic, add everything in quadrature**
Correlation Measurements

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta_3} + p_{T4} e^{\eta_4} \right) \]
\[ x_2 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{-\eta_3} + p_{T4} e^{-\eta_4} \right) \]
\[ M = \sqrt{x_1 x_2 s} \]
\[ \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \]
\[ |\cos \theta^*| = \tanh \left| \frac{\eta_3 - \eta_4}{2} \right| \]