Longitudinal Double Spin Asymmetries of $\pi^0$ - Jet Correlations in Polarized Proton Collisions at $\sqrt{s} = 510$ GeV at STAR

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1. Introduction

Proton has a finite charge radius and consists of quarks and gluons. The proton also carries a spin of $\frac{1}{2}\hbar$, which constrains the total angular momentum of its constituents. According to the Manohar-Jaffe sum rule, the proton spin can be decomposed into all possible contributions from its constituents, as expressed by Eq. (1),

$$S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g,$$

which makes explicit the contributions from the intrinsic quark and gluon polarization ($\Delta \Sigma$ and $\Delta G$, respectively) and orbital angular momenta ($L_q$ and $L_g$, respectively).

Measurements from polarized deeply-inelastic-scattering (DIS) and semi-inclusive DIS (SIDIS) data\textsuperscript{2,3,4,5} constrain well the contribution from quarks to...
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be around 30% of the proton spin. With 2009 RHIC inclusive jet results integrated in global analyses, both DSSV\(^6\) and NNPDF\(^7\) find evidence for positive gluon polarization in the region of \(x > 0.05\). However, the uncertainties on the integral of gluon polarization \((\int_{0.05}^{0.001} dx \Delta g(x))\) over low \(x\) region are still sizable. Inclusive observables at forward rapidity or correlation observables, such as di-jets, can help to probe gluon polarization at the lower \(x\) region.

The goal of the spin physics program at RHIC is to constrain the polarized gluon distribution function, \(\Delta g(x)\), by measuring the longitudinal double-spin asymmetry \(A_{LL}\) of various final-state channels. The \(A_{LL}\) is defined as Eq. (2),

\[
A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_1, f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{a}_{f_1 f_2 \rightarrow fX} \otimes D_{f1}^\pi}{\sum_{f_1, f_2} f_1 \otimes f_2 \otimes d\hat{a}_{f_1 f_2 \rightarrow fX} \otimes D_{f2}^\pi}. \tag{2}
\]

where the \(\sigma^{++}\) and \(\sigma^{+-}\) indicate the cross-section for same helicity collisions and the cross-section for opposite helicity collisions, respectively. The \(\Delta f_i\) presents the polarized parton distribution functions, \(f_i\) is the unpolarized distribution and the \(D_{f}^\pi\) means the fragmentation functions. The partonic double spin asymmetries \(\hat{a}_{LL}\) are known from theory, then the \(A_{LL}\) measurements can directly constrain \(\Delta G\).

2. Experiments

The Relativistic Heavy Ion Collider (RHIC) is the world’s first and only polarized proton collider, and provides capability to collide many particle species at different energies. Spin rotators located around the experiments are used to provide a choice of polarization orientation of up and down, and the spin polarization of the beam can be varied from bunch to bunch. The polarized protons can be accelerated up to various center of mass energies up to 510 GeV.

The Solenoidal Tracker at RHIC (STAR) is a large-acceptance, multi-purpose detector at RHIC designed to study the Quark-Gluon Plasma (QGP) and spin physics. Enclosed in a 0.5 T solenoidal magnet are a Time Projection Chamber (TPC), a Time-Of-Flight detector (TOF), and a Barrel ElectroMagnetic Calorimeter (BEMC). The TPC is the main tracking detector for STAR. It also provides particle identification capability through measurement of the specific energy loss \((dE/dx)\). The TOF greatly improves particle identification at low transverse momenta \(p_T\). The BEMC measures the electromagnetic energy deposition of photons and electrons. These detectors cover full azimuth over a large pseudo-rapidity range \((|\eta| < 1)\). The endcap electromagnetic calorimeter (EEMC) is used to measure the energy and position of photons from \(\pi^0\) decays across the range of 1.086 < \(\eta_{det}\) < 2.0. Both the BEMC and the EEMC are segmented lead-scintillator sampling calorimeters, and two layers of Shower Maximum Detector (SMD) are assembled in the calorimeters which are used for electron identification and neutral pion analysis. At the more forward region of 2.5 < \(\eta_{det}\) < 4.0, another electromagnetic calorimeter, called Forward Meson Spectrometer (FMS), is installed to identify and analyze photon candidates for forward \(\pi^0\) and photon analysis. The above STAR sub-detectors
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Fig. 1. Left: Inclusive jet $A_{LL}$ results at $\sqrt{s}=200$ (510) GeV from STAR 2009 (2012) data. Middle: Di-jet $A_{LL}$ results at $\sqrt{s}=200$ (510) GeV from STAR 2009 (2012) data. Right: Inclusive $\pi^0$ $A_{LL}$ results in the EEMC at $\sqrt{s}=200$ GeV from STAR 2006 data.

are used for gluon polarization studies. The TPC and BEMC are used for jet reconstruction, and the EEMC and FMS are used for $\pi^0$ reconstruction.

In addition, the beam-beam counters (BBCs) are used to determine luminosity and trigger minimum bias (MB) events. And the zero-degree calorimeters (ZDCs) are used in determination of helicity-dependent relative luminosities.

3. $A_{LL}$ Measurements at STAR

Longitudinally polarized proton+proton collisions at 200 GeV and 500/510 GeV allow both cross section and double spin asymmetry $A_{LL}$ measurements at STAR on inclusive jets, inclusive neutral pions, and di-jets, as shown in Fig. 1.

The left panel of the Fig. 1 shows the inclusive jet $A_{LL}$ results at $\sqrt{s}=200$ (510) GeV from STAR 2009 (2012) data, which were compared to theoretical curves with various parton distribution functions. The x-axis denotes $x_T$ which is $2p_T$ divided by the center of mass energy, and the asymmetries at given $x_T$ are expected to be similar. The measured $A_{LL}$ results show a good agreement between the two collision energies as expected. The solid, dotted and dashed lines are theoretical calculations with DSSV14, NNPDF1.1 and LSS10p, respectively. The red and blue lines present collision energy of 510 and 200 GeV, respectively. According to the comparison, the data at $\sqrt{s}=510$ GeV reaches a lower $x_T$ region.

The middle panel of the Fig. 1 shows the di-jet $A_{LL}$ results at $\sqrt{s}=200$ (510) GeV from STAR 2009 (2012) data as a function of $x_T$ ($=\frac{M_{jj}}{\sqrt{s}}$). In the overlapping region of $x_T>0.1$, the results from 200 GeV and 510 GeV agreed well within uncertainties. In addition, the higher collision energy clearly extends the measurements to lower $x_T$. The theoretical curves for DSSV14 and NNPDF1.1 are shown in green and purple, respectively. The solid and dotted lines are indicate 510 GeV (2012) and 200 GeV (2009), respectively.

The right panel of the Fig. 1 shows the inclusive $\pi^0$ $A_{LL}$ results at $\sqrt{s}=200$ GeV from STAR 2006 data for $5.0$ GeV/c $< p_T < 16.0$ GeV/c with the EEMC detector. Integrating over the $p_T$ range yields a value of $A_{LL} = 0.002 \pm 0.012$.

Model predictions, based on global fits by the GRSV and DSSV, are shown along with the measured $A_{LL}$ results. Systematic uncertainties shown as boxes include...
those on the signal fraction and on the estimate of the background asymmetry.
Uncertainty in the product of beam polarizations results in a 6% vertical scale uncertainty. The production of $\pi^0$ in the EEMC extends the $x$ region down to 0.01.

4. Analysis Methodology

The data used in this analysis were recorded by the STAR detectors in polarized proton+proton collisions at $\sqrt{s} = 510$ GeV with 80 pb$^{-1}$ integrated luminosity during the 2012 RHIC run.

The FastJet Anti-$k_T$ algorithm$^{16}$ was used for jet reconstruction in this analysis following the STAR 2009 inclusive jet analysis procedures$^8$. Only tracks with $p_T > 0.2$ GeV/$c$ and events with summed track $p_T > 0.5$ GeV/$c$ were analyzed. The reconstructed leading jets in $p_T$ with $p_T > 8.0$ GeV/$c$ and $-0.9 < \eta < 0.9$ were kept, and resolution parameter of $R=0.6$ was used.

The neutral pions are reconstructed by invariant mass method from all possible photon pairs using their energies and opening angle between the two photons, and follows the procedures used in 2006 inclusive $\pi^0$ analysis$^{13}$. The reconstructed $\pi^0$ candidate with $p_T > 4.0$ GeV/$c$ and within the fiducial acceptance of $1.086 < \eta_{det} < 2.0$ was requested. The azimuthal angle difference of $|\Delta \phi| > 2.0$ was applied for $\pi^0$-jet pairing.

The jet-patch triggered (JP) events were selected in this analysis. The jet patch triggers were provided by the BEMC detector, which was divided into 18 overlapping jet patches. Each jet patch covers 1.0×1.0 in $\eta$-$\phi$ coordinate system. The JP trigger requires a minimum energy deposit in a patch of calorimeter towers ($\Delta \eta \times \Delta \phi = 1 \times 1$) larger than a certain value (5.4 GeV for JP0, 7.3 GeV for JP1 and 14.4 GeV for JP2 in STAR 2012 data).

5. Simulation and Analysis Status

In this analysis, using a jet in the mid-rapidity region $|\eta| < 0.9$ correlated with a back-to-back $\pi^0$ in the forward rapidity region $0.8 < \eta < 2.0$ in the STAR endcap provides a new tool to access the $\Delta g(x)$ distribution at Bjorken-$x$ down to 0.01.

![Figure 2](image.png)  
Fig. 2. Comparison of $x_1$ (Left) and $x_2$ (Right) between reconstructed (in y-axis) and generated (in x-axis) values in the simulated events.
Compared to inclusive jet measurements, this channel also allows to constrain the initial parton kinematics, such as $x_1$, $x_2$ and invariant mass $\sqrt{s}$.

Simulated events were generated from PYTHIA 6.426\textsuperscript{17} with the Perugia 0 tune\textsuperscript{18}. As shown in Fig. 2, the reconstructed $x_1$ and $x_2$ of matched $\pi^0$-jet pair show a good linearity with Monte Carlo generated values.

STAR jet reconstruction efficiency was applied for the reconstructed spectrum (solid black line as shown in Fig. 3) in simulation. As indicated in Fig. 3, the $p_T$ spectrum of the neutral pions and leading jets, and $|\Delta\phi|$ distribution from simulation are consistent with data (red dotted line in Fig. 3) after weighting by the jet reconstruction efficiency.

The invariant mass spectrum (weighted by relative luminosities and beam polarizations) are fitted to estimate signal yield for each kinematic variable bin ($p_T^{\pi^0}$, $p_T^{\text{jet}}$, $x_1$, $x_2$ and $\sqrt{s}$, respectively). In this analysis, we followed the definition of signal and background sources of the STAR 2006 inclusive $\pi^0$ analysis\textsuperscript{13}. The signal is defined as a reconstructed photon pair that is associated with the $\pi^0$ signal, the conversion background is a reconstructed photon pair that is associated with the conversion background, and the other background is the photon pairs that are not identified as signal or conversion background.

The raw yields of $\pi^0$-jet are fitted by extended likelihood formalism in RooFit, in which the signal shape was described by skewed Gaussian function. The shape is taken from the integrated spectrum (unpolarized). The yields for the different polarization states are then taken from the individual fits with the shape fixed. The signal (background) asymmetries, $A_{LL}^{\text{sig}}$ ($A_{LL}^{\text{bg}}$), are calculated by the estimated yields according to Eq. 3,

$$A_{LL} = \frac{\sum P_Y P_B (N^{++} - rN^{+-})}{\sum P_Y^2 P_B^2 (N^{++} + rN^{+-})},$$

where $P_Y$ and $P_B$ are the polarizations of the yellow and blue beams, respectively.

$N^{++}$ and $N^{+-}$ are the $\pi^0$-jet yields from beam bunches with the same and opposite helicity configurations, respectively. The $r = \mathcal{L}^{++}/\mathcal{L}^{+-}$ presents relative integrated luminosity of these helicity configurations.

Statistical uncertainty projections of the $\pi^0$-jet $A_{LL}$ in STAR Run12 proton+proton data at $\sqrt{s}=510$ GeV as functions of $p_T^{\pi^0}$, $p_T^{\text{jet}}$, $x_1$, $x_2$ and $\sqrt{s}$ are shown in Fig. 4. Daniel de Florian presented a theoretical description of hadron-jet $A_{LL}$.
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Fig. 4. Uncertainty projections of the π^0-jet A_{LL} in STAR Run12 proton+proton data at \( \sqrt{s} = 510 \) GeV as functions of p_T^\pi^0 (Top-Left), p_T^\pi^- (Top-Middle), \( \sqrt{s} \) (Top-Right), x_1 (Bottom-Left) and x_2 (Bottom-Right).

by next-to-leading order (NLO) model calculation\(^{19}\). Theoretical predictions by the NLO model calculations with blue (red) dotted line for DSSV2014 (NNPDF1.1) parton distribution function were shown in the Fig. 4.

6. Conclusion

STAR has been making significant contributions to the gluon polarization measurement via inclusive jets, inclusive neutral pions and di-jets measurements. The inclusive jets and di-jets A_{LL} from STAR 2009 and 2012 data are shown, and the neutral pion A_{LL} from STAR 2006 data with EEMC is also presented. The status of the analysis of the \( \pi^0 \)-jet A_{LL} in longitudinally polarized proton-proton collisions at \( \sqrt{s} = 510 \) GeV in 2012 is reported.

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References

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