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

Yaping Wang for the STAR Collaboration

Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, P. R. China

wangyaping@mail.ccnu.edu.cn

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One of the primary goals of the spin physics program at STAR 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. Using a jet in the mid-rapidity region $|\eta| < 0.9$ correlated with an azimuthally back-to-back neutral pion in the forward rapidity region $0 < \eta < 2.0$ provides a new possibility to access the $\Delta g(x)$ distribution at Bjorken-$x$ down to 0.01. Compared to inclusive jet measurements, this channel also allows to constrain the initial parton kinematics. In these proceedings, we will present the status of the analysis of the $\pi^0$-jet $A_{LL}$ in longitudinally polarized proton+proton collisions at $\sqrt{s}=510$ GeV with 80 pb$^{-1}$ of data taken during the 2012 RHIC run. We also compare the projected $A_{LL}$ uncertainties to theoretical predictions of the $A_{LL}$ by next-to-leading order (NLO) model calculations with different polarized parton distribution functions.

Keywords: Longitudinal double spin asymmetries; $\pi^0$ - Jet Correlations; initial parton kinematics.

1. Introduction

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

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta \Sigma + \Delta G + L_q + L_g. \quad (1)$$

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$^{2,3,4,5}$ constrain well the contribution from quarks to be around 30% of the proton spin. With 2009 RHIC inclusive jet results integrated

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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),

\[
A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{a}_{f_1} f_2 \rightarrow fX \otimes D_{f_1}^{\pi^0}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{a}_{f_1} f_2 \rightarrow fX \otimes D_{f_1}^{\pi^0}},
\]

where the \(\sigma^{++}\) and \(\sigma^{+-}\) indicate the cross-section for same helicity collisions and the cross-section for opposite helicity collisions, respectively. The \(\Delta f_i\) represent the polarized parton distribution functions, \(f_i\) the unpolarized ones and the \(D_{f_i}\) the fragmentation functions in the case of inclusive \(\pi^0\) \(A_{LL}\). The partonic double spin asymmetries \(\hat{a}_{f_1} f_2\) 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 orientations, and the spin polarization of the beam can be varied from bunch to bunch. The polarized protons can be accelerated to various center of mass energies up to 510 GeV.

The Solenoidal Tracker at RHIC (STAR) is a large-acceptance, multi-purpose detector 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 \(1.086 < \eta_{\text{det}} < 2.0\). 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 \(\pi^0\) analysis. At the more forward region of \(2.5 < \eta_{\text{det}} < 4.0\), 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 are used for gluon polariza-
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3. $A_{LL}$ Measurements at STAR

Longitudinally polarized proton+proton collisions at $\sqrt{s}=200$ GeV and 500/510 GeV allow both cross section and double spin asymmetry $A_{LL}$ measurements at STAR for inclusive jets, inclusive $\pi^0$, and di-jets, as shown in Fig. 1.

The left panel of Fig. 1 shows the inclusive jet $A_{LL}$ results at $\sqrt{s}=200$ (510) GeV from STAR 2009 (2012) data\cite{8,9}, which were compared to theoretical predictions with various parton distribution functions. The $x_T$-axis denotes $x_T$ which is $2p_T/\sqrt{s}$ 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\cite{6}, NNPDF1.1\cite{7} and LSS10p\cite{10}, respectively. The red and blue lines are for the 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 Fig. 1 shows the di-jet $A_{LL}$ results at $\sqrt{s}=200$ (510) GeV from STAR 2009 (2012) data\cite{11,12} as a function of $x_T$ ($=\frac{M_{inv}}{\sqrt{s}}$). 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 predictions for DSSV14\cite{6} and NNPDF1.1\cite{7} are shown in green and purple, respectively. The solid and dotted lines are for 510 GeV (2012) and 200 GeV (2009), respectively.

The right panel of 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\cite{13}. 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\cite{14} and DSSV\cite{15}, 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 STAR 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\textsuperscript{16} was used for jet reconstruction in this analysis following the STAR 2009 inclusive jet analysis procedure\textsuperscript{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 a resolution parameter of $R=0.6$ was used for jet reconstruction.

The $\pi^0$ were reconstructed by invariant mass method from all possible photon pairs using their energies and opening angle between the two photons, and follows the procedure used in the 2006 inclusive $\pi^0$ analysis\textsuperscript{13}. The reconstructed $\pi^0$ candidate was requested with $p_T>$4.0 GeV/c and within the fiducial acceptance of $1.086<\eta_{det}<2.0$. 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 ($\Delta\eta \times \Delta\phi=1\times1$) 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-url)  

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 spectra (weighted by relative luminosities and beam polarizations) were 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 were fitted by extended likelihood formalism in RooFit, in which the signal shape was described by skewed Gaussian function, which was taken from the polarization-integrated spectrum (unpolarized). The yields for the different polarization states were then taken from the individual fits with the shape fixed. The signal (background) asymmetries, $A_{LL}^{\text{Sig}}$ ($A_{LL}^{\text{Bkg}}$), were calculated by the estimated yields according to Eq. 3,

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

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 $r = L^{++}/L^{+-}$ represents 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 $A_{LL}$...
by next-to-leading order (NLO) model calculation. Theoretical predictions by the NLO model calculations with blue (red) dotted line for DSSV2014 (NNPDF1.1) parton distribution functions are also shown in the Fig. 4.

6. Conclusion

STAR has been making significant contributions to the gluon polarization measurement via inclusive jet, inclusive $\pi^0$ and di-jets measurements. The inclusive jet and di-jets $A_{LL}$ from STAR 2009 and 2012 data are shown, and the $\pi^0$ $A_{LL}$ 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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