Longitudinal Double Spin Asymmetries of π^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 Institution of Particle Physics, Central China Normal University,
 Wuhan 430079, P. R. China
 wangyaping@mail.ccnu.edu.cn*

Published 3 May 2018

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 π^0 in the forward rapidity region $0.8 < \eta < 2.0$ provides a new possibility to access the $\Delta g(x)$ distribution at Bjorken- x down to 0.01. Compared to inclusive jet or inclusive π^0 measurements, this channel also allows to constrain the initial parton kinematics. In these proceedings, we will present the status of the analysis of the π^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; π^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 rule¹, 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 quark and gluon polarizations ($\Delta\Sigma$ and ΔG , respectively) and orbital angular momenta (L_q and L_g , respectively).

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 4.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

Measurements from polarized deeply-inelastic-scattering (DIS) and semi-inclusive DIS (SIDIS) data^{2,3,4,5} constrain well the contribution from the quark polarization to be around 30% of the proton spin. With 2009 RHIC mid-rapidity inclusive jet results integrated in global analyses, both DSSV⁶ and NNPDF⁷ find evidence for a positive gluon polarization in the region of $x > 0.05$. However, the uncertainty on the integral of the gluon polarization over the $x < 0.05$ region is still sizable. Inclusive or correlation observables, such as di-jets, at forward rapidity, can help to probe the gluon polarization at the low x region.

One 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 states. The A_{LL} is defined as Eq. (2),

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Sigma_{f_1, f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \rightarrow f X} \cdot \hat{a}_{LL}^{f_1 f_2 \rightarrow f X} \otimes D_f^{\pi^0}}{\Sigma_{f_1, f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \rightarrow f X} \otimes D_f^{\pi^0}}. \quad (2)$$

where the σ^{++} and σ^{+-} are the cross-section for same helicity collisions and the cross-section for opposite helicity collisions, respectively. The Δf_i represent the polarized parton distribution functions, f_i the unpolarized ones and the $D_f^{\pi^0}$ the fragmentation functions in the case of inclusive π^0 A_{LL} . The partonic double spin asymmetries $\hat{a}_{LL}$ are known from theory, and thus the A_{LL} measurements can directly constrain ΔG .

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 π^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 π^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 π^0 and photon analysis. The above STAR sub-detectors are used for gluon polarization studies. The TPC and BEMC are used for jet reconstruction, and the EEMC and FMS are used for π^0 reconstruction.

In addition, the beam-beam counters (BBCs) are used to determine luminosity and trigger on minimum bias (MB) events. 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 $\sqrt{s}=200$ GeV and 500/510 GeV allow both cross section and double spin asymmetry A_{LL} measurements at STAR for inclusive jets, inclusive π^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^{8,9}, which were compared to theoretical predictions with various parton distribution functions. The x-axis variable is x_T which is $2 \times p_T$ 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 the DSSV14⁶, NNPDF1.1⁷ and LSS10p¹⁰ polarized parton distribution functions, respectively. The red and blue lines are for the collision energy of 510 and 200 GeV, respectively. As can be seen, 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^{11,12} as a function of x_T ($= \frac{M_{\text{inv}}}{\sqrt{s}}$). 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 DSSV14⁶ and NNPDF1.1⁷ are shown in green and purple, respectively. The solid and dotted lines are for 510 GeV and 200 GeV, respectively.

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 π^0 A_{LL} results in the EEMC at $\sqrt{s}=200$ GeV from STAR 2006 data.

The right panel of Fig. 1 shows the inclusive π^0 A_{LL} results at $\sqrt{s}=200$ GeV from STAR 2006 data for $5.0 \text{ GeV}/c < p_T < 16.0 \text{ GeV}/c$ with the EEMC detector¹³. 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 GRSV¹⁴ and DSSV¹⁵, 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 π^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 algorithm¹⁶ was used for jet reconstruction in this analysis following the STAR 2009 inclusive jet analysis procedure⁸. Only tracks with $p_T > 0.2 \text{ GeV}/c$ and events with summed track $p_T > 0.5 \text{ GeV}/c$ were analyzed. The reconstructed leading jets in p_T with $p_T > 8.0 \text{ GeV}/c$ and $-0.9 < \eta < 0.9$ were considered, and a resolution parameter of $R=0.6$ was used for jet reconstruction.

The π^0 were reconstructed by invariant mass method from all possible photon pairs using their energies and opening angle between the two photons, following the procedure used in the 2006 inclusive π^0 analysis¹³. The reconstructed π^0 candidate was requested with $p_T > 4.0 \text{ GeV}/c$ and within the fiducial acceptance of $1.086 < \eta_{\text{det}} < 2.0$. The azimuthal angle difference of $|\Delta\phi| > 2.0$ was applied to the π^0 -jet pairing.

The jet-patch triggered (JP) events were used in this analysis. The jet patch triggers were provided by the BEMC detector, which was divided into 18 overlapping jet patches. Each jet patch covered 1.0×1.0 in η - ϕ coordinate system. The JP trigger required 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).

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.

Fig. 3. Comparison of leading jet p_T (Left), inclusive π^0 p_T (Middle) and $|\Delta\phi|$ of the π^0 -jet pair (Right) between the simulation and Run12 data.

5. Simulation and Analysis Status

In this analysis, using a jet in the mid-rapidity region $|\eta| < 0.9$ correlated with an azimuthally back-to-back π^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. Compared to inclusive jet measurements, this channel also allows to constrain the initial parton kinematics, such as x_1 , x_2 and invariant mass $\sqrt{\hat{s}}$.

Simulated events were generated from PYTHIA 6.426¹⁷ with the Perugia 0 tune¹⁸. As shown in Fig. 2, the reconstructed x_1 and x_2 of matched π^0 -jet pair show an approximately linear correlation with Monte Carlo generated values.

STAR jet reconstruction efficiency was used to reweight for the reconstructed spectra (solid black line as shown in Fig. 3) in simulation. As indicated in Fig. 3, the p_T spectrum of the π^0 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 photon-pair invariant mass spectra (weighted by relative luminosities and beam polarizations) were fitted to estimate π^0 yield for each kinematic variable bin ($p_T^{\pi^0}$, p_T^{jet} , x_1 , x_2 and $\sqrt{\hat{s}}$, respectively). In this analysis, we considered the same of signal and background sources of the STAR 2006 inclusive π^0 analysis¹³. The signal was defined as a reconstructed photon pair that is associated with the π^0 signal, the conversion background was a reconstructed photon pair that is associated with the conversion background, and the other background was the photon pairs that were not identified as signal or conversion background.

The raw yields of π^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 (unpolarized) invariant mass spectrum. The yields for the different polarization states were then taken from the individual fits with the shape fixed. The signal (background) asymmetries, A_{LL}^{sig} (A_{LL}^{bkg}), were calculated by the estimated yields according to Eq. 3,

$$A_{LL} = \frac{\sum P_Y P_B (N^{++} - rN^{+-})}{\sum P_Y^2 P_B^2 (N^{++} + rN^{+-})}, \quad (3)$$

where P_Y and P_B are the polarizations of the yellow and blue beams, respectively. N^{++} and N^{+-} are the π^0 -jet yields from beam bunches with the same and opposite

Y. Wang

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^{jet} (Top-Middle), $\sqrt{s}$ (Top-Right), x_1 (Bottom-Left) and x_2 (Bottom-Right).

helicity configurations, respectively. The $r = \mathcal{L}^{++}/\mathcal{L}^{+-}$ represents relative integrated luminosity of these helicity configurations.

Statistical uncertainty projections of the π^0 -jet A_{LL} in STAR Run12 proton+proton data at $\sqrt{s}=510$ GeV as functions of $p_T^{\pi^0}$, p_T^{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 calculation¹⁹. The predictions with the DSSV2014 (NNPDF1.1) parton distribution functions are also shown in the Fig. 4 as blue (red) dotted curves.

6. Conclusion

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

This work was supported in part by the National Natural Science Foundation of China (Grant No.11475069), and the Programme of Introducing Talents of Discipline to Universities of SAFEA of China (Grant No. B08033).

References

1. R. L. Jaffe and A. Manohar, *Nucl. Phys. B* **337**, 509 (1990).

2. B. Adeva et al. (Spin Muon Collaboration), *Phys. Rev. D* **58**, 112002 (1998).
3. K. Abe et al. (E143 Collaboration), *Phys. Rev. D* **58**, 112003 (1998).
4. M. G. Alekseev et al. (COMPASS Collaboration), *Phys. Lett. B* **693**, 227 (2010).
5. A. Airapetian et al. (HERMES Collaboration), *Phys. Lett. B* **666**, 446 (2008).
6. D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, *Phys. Rev. Lett.* **113**, 012001 (2014).
7. E. R. Nocera, R. D. Ball, S. Forte, G. Ridol, and J. Rojo (NNPDF), *Nucl. Phys. B* **887**, 276 (2014).
8. L. Adamczyk et al. (STAR Collaboration), *Phys. Rev. Lett.* **115**, 092002 (2015).
9. Z. Chang for STAR Collaboration, *Int. J. Mod. Phys. Conf. Ser.* **40**, 1660021 (2016).
10. E. Leader, A.V. Sidorov, and D.B. Stamenov, *Phys. Rev. D* **82**, 114018 (2010) .
11. L. Adamczyk et al. (STAR Collaboration), *Phys. Rev. D* **95**, 71103 (2017).
12. S. Ramachandran for STAR Collaboration, *PoS DIS2016* **231** (2016), arXiv:1608.01332 [hep-ex].
13. L. Adamczyk et al. (STAR Collaboration), *Phys. Rev. D* **89**, 012001 (2014).
14. M. Glück et al., *Phys. Rev. D* **63**, 094005 (2001).
15. D. de Florian et al., *Phys. Rev. Lett.* **101**, 072001 (2008).
16. M. Cacciari, G. P. Salam, and G. Soyez, *JHEP* **04**, 063 (2008).
17. T. Sjöstrand, S. Mrenna, and P. Skands, *JHEP* **0605**, 026 (2006).
18. P. Skands, arXiv: 0703039 [Physics].
19. D. de Florian, *Phys. Rev. D* **79**, 114014 (2009).