Transverse Single-Spin Asymmetries for π^0 and Electromagnetic Jets at Forward Rapidities in $p^{\uparrow}$+p Collisions at $\sqrt{s}$ = 200 GeV and 500 GeV at STAR

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(Received February 14, 2022)

There have been numerous attempts, both experimentally and theoretically, to understand the origin of the unexpectedly large transverse single-spin asymmetries (A_N) for inclusive hadron production at forward rapidity in $p^{\uparrow}$+p collisions that persist from low to high center-of-mass energies. Two potential sources are the twist-3 contributions in the collinear factorization framework and the transverse-momentum-dependent contributions from either the initial-state quark and gluon Sivers functions and/or the final-state Collins fragmentation function. To investigate the underlying physics leading to this large A_N, we study π^0 A_N with different topologies – isolated and non-isolated, and A_N for electromagnetic jets (EM-jets) of different substructures using the Forward Meson Spectrometer (FMS) at STAR. Jet A_N is sensitive to the initial-state effect and can provide access to Sivers functions. To investigate final-state effects, we measure the Collins asymmetry of π^0 inside EM-jets. We present the most recent results for these asymmetries from $p^{\uparrow}$+p collisions at 200 GeV and 500 GeV. We also present new preliminary results of A_N for EM-jets in the FMS and Endcap Electromagnetic Calorimeter (EEMC) using $p^{\uparrow}$+p collisions at 200 GeV, where we explore the dependences of A_N on photon multiplicity inside the jet, jet transverse momentum, and jet energy. These results provide rich information towards understanding the physics mechanism of large A_N in hadronic collisions.

KEYWORDS: TSSA, TMD, EM-jet

1. Introduction

Transverse Single-Spin Asymmetry (TSSA or A_N) in hadron-hadron collisions plays an important role in understanding the QCD structure of the nucleon. A_N is defined as the left-right asymmetry of particle production relative to the plane defined by the momentum and spin directions of a polarized hadron. pQCD predicts this asymmetry to be small [1], however, this turned out to be unexpectedly large for the forward hadron production in $p^{\uparrow}$+p collisions which has been verified by fixed target and collider experiments, including experiments at Fermilab and RHIC [2] - [5]. The origin of this large asymmetry is an unsolved puzzle for the last 40 years. There have been various attempts, both experimentally and theoretically, to understand the origin of large A_N for inclusive hadron production at forward rapidity in $p^{\uparrow}$+p collisions. On the theoretical side, two potential sources are the twist-3 contributions in the collinear factorization framework and the transverse-momentum-dependent (TMD) contributions from either the initial-state quark and gluon Sivers functions and/or the final-state Collins fragmentation function. Also, there are some indications from data that diffractive processes might have a non-trivial contribution to the large A_N [6]. In the TMD framework, for the Sivers mechanism, the asymmetry comes from the correlation between the proton spin and the parton transverse momentum. In analogy, the Collins effect comes from the correlation between the quark spin and the hadron transverse momentum in jets. For the twist-3 contribution, the source is the quark-gluon or gluon-gluon correlations and fragmentation functions. On the experimental side, the focus has been on measuring the signatures for the Sivers effects or Collins effects to disentangle the initial-state or final-state effects, and searching for possible other sources.

In 2011 and 2015, STAR collected data for transversely polarized $p^{\uparrow}$+p collisions at $\sqrt{s}$ = 200 and 500 GeV, which are ideal to further characterize A_N and explore its potential sources. The STAR Forward Meson Spectrometer (FMS) and Endcap Electromagnetic Calorimeter (EEMC), having full azimuthal coverages and pseudo-rapidity (η) coverages of 2.6 - 4.2 and 1.1 - 2.0 respectively, can be used to detect photons, neutral pions, and eta mesons. We present π^0 A_N with different event topologies and A_N for EM-jets using the FMS. In addition, we present the new preliminary results for A_N of EM-jets in the FMS and EEMC using $p^{\uparrow}$+p collisions at $\sqrt{s}$ = 200 GeV. For the latter analysis, we present the dependences of A_N on photon multiplicity inside the jet, jet transverse momentum (p_T), and jet energy. A jet in the context of our analysis is always an EM-jet reconstructed from photons only.

2. Analysis Method

The datasets used are for transversely polarized $p^{\uparrow}$+p collisions at $\sqrt{s}$ = 500 and 200 GeV with average beam polarizations of 52% and 57% and integrated luminosities of 25 pb^{-1} and 52 pb^{-1}, respectively. Events are triggered based on the energies deposited in a cluster of towers or a jet patch sensitive to π^0s and jets in the calorimeters. A jet patch is formed by grouping calorimeter regions together. For Monte Carlo, we use PYTHIA 6.428 event generator with Perugia 2012 Tune. Events generated by PYTHIA are propagated through GEANT-based STAR detector simulation to simulate the detector response.

In the FMS, photon candidates are reconstructed by finding clusters of continuous energy depositions. Two photons are then combined to reconstruct π^0 candidates. Selected π^0s are required to have p_T > 2.0 GeV/c, $M_{\gamma\gamma}$ < 0.3 GeV/c^2 and $Z_{\gamma\gamma} = \frac{|E_1-E_2|}{E_1+E_2} < 0.7$, where E_1 and E_2 are the energies of the photon pair. Jets are reconstructed in the FMS or EEMC using the anti-k_T algorithm from the FastJet package [11] with a radius of 0.7. Reconstructed photons are used as inputs to FastJet for reconstructing EM-jets in the FMS. For EM-jets in the EEMC, towers are used as inputs. Individual photons are required to have E_γ > 1.0 GeV (FMS) or E_T > 0.2 GeV (EEMC). The jets are required to have p_T greater than 2.0 GeV/c.

The measured or raw asymmetry (ϵ) is related to A_N by the cosine modulation ($\cos\phi$) with a correction for the polarization (P) as shown in Eq. 1, where ϕ is the azimuthal angle of the π^0 or EM-jet in the lab frame. We calculate the raw asymmetry using the cross-ratio formula shown in Eq. 2, where $N^{\uparrow(\downarrow)}_{\phi(\phi+\pi)}$ is the number of π^0s or EM-jets detected at ϕ ($\phi+\pi$) for spin up (down) state. It cancels systematics coming from the relative luminosity and the detector efficiency. To extract the A_N from raw asymmetry, we fit it with a cosine function. The left plot in Fig. 1 shows one example fit for a particular jet energy, p_T, and photon multiplicity bin. The χ^2 distribution from all fits shows the overall quality of the fit for the EM-jet A_N extraction.

$$\epsilon = PA_N\cos(\phi) \tag{1}$$

$$\epsilon \approx \frac{\sqrt{N^{\uparrow}_{\phi}N^{\downarrow}_{\phi+\pi}} - \sqrt{N^{\uparrow}_{\phi+\pi}N^{\downarrow}_{\phi}}}{\sqrt{N^{\uparrow}_{\phi}N^{\downarrow}_{\phi+\pi}} + \sqrt{N^{\uparrow}_{\phi+\pi}N^{\downarrow}_{\phi}}} \tag{2}$$

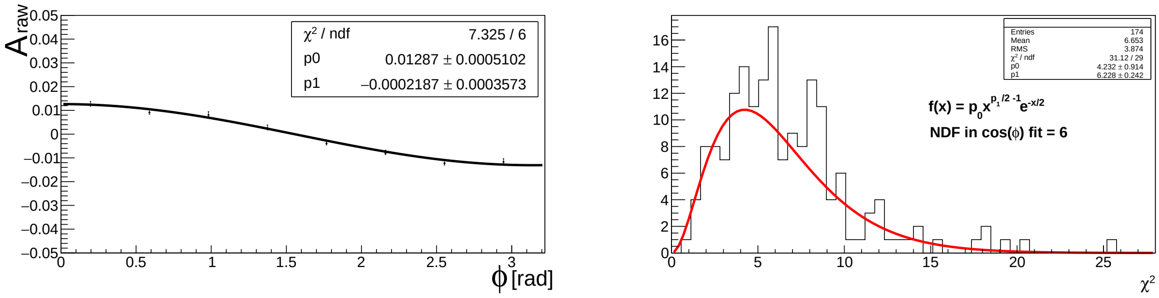

Fig. 1. (Left) Example of fitting the raw asymmetry with $p_0 \cos(\phi) + p_1$ for EM-jets with 2 photons, 20 GeV $< E^{EM}_{jet} <$ 40 GeV and 2.5 GeV/c $< p_T <$ 3.0 GeV/c. (Right) χ^2 distribution from all fits showing overall quality of the fit for EM-jet A_N extraction using 200 GeV FMS data.

3. Results

The results for A_N of π^0 at 200 GeV and 500 GeV using the FMS are presented in Fig. 2 (left). We find that A_N for isolated π^0 is significantly larger than A_N of non-isolated π^0. An isolated π^0 is a π^0 without any energy deposited around it. The theoretical calculations, shown in solid curves, are based on the latest global fit [8]. Figure 2 (right) shows EM-jet A_N results at 200 GeV and 500 GeV using

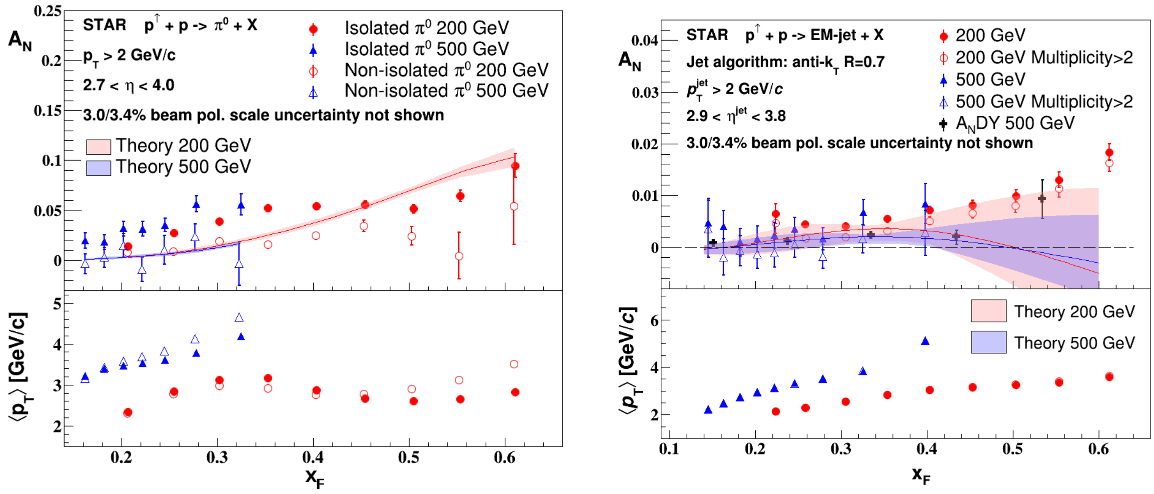

Fig. 2. (Left) A_N as a function of longitudinal momentum fraction, Feynman-x (x_F), for the isolated and non-isolated π^0 in transversely polarized p$^\uparrow$+p collisions at 200 and 500 GeV [6]. The average p_T of the π^0 for each x_F bin is plotted in the lower panel. (Right) EM-jet A_N as a function of x_F in polarized p$^\uparrow$+p collisions at 200 and 500 GeV [6]. Results with at least three photons inside an EM-jet are shown as open circles. Previous results by the $A_N DY$ Collaboration are also plotted in black solid points. The theory curves shown are for TSSA of the full jets at $< y > = 3.25$ for 200 GeV and$< y > = 3.57$ for 500 GeV. The average p_T of the EM-jet for each x_F bin is shown in the lower panel.

the FMS. We find that EM-jet A_N is small compared to π^0 A_N. EM-jets with more than 2 photons have smaller asymmetries than EM-jets consisting of 1 or 2 photons. The impact of this forward EM-jet A_N result on up and down quark Sivers functions has been recently presented in [7]. Figure 3 shows the Collins asymmetry for π^0 in a jet at 200 GeV and 500 GeV. In the figure, z_{em} is given by $z_{em} = \frac{E_\pi}{E_{jet}}$. The Collins asymmetries are found to be very small at both energies. We also find weak j_T dependence, where j_T is the π^0 transverse momentum relative to the jet axis. Details on the results in Figs. 2 and 3 and related discussions can be found in Ref. [6].

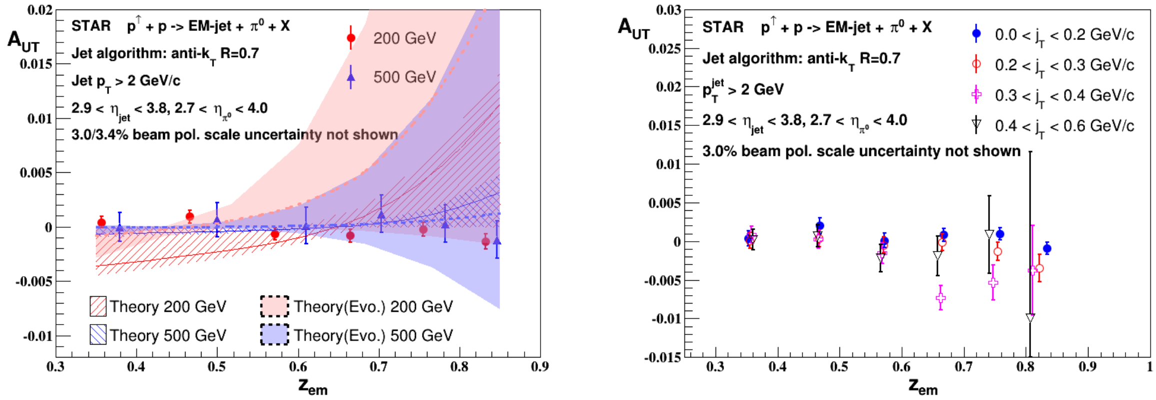

Fig. 3. (Left) The Collins asymmetry for π^0s in an EM-jet for transversely polarized p$^\uparrow$+p collisions at 200 GeV and 500 GeV [6]. The theory curves shown are for the Collins asymmetry of π^0s in a full jet with or without the TMD evolution [9]. (Right) The j_T dependence of the Collins asymmetry in transversely polarized p$^\uparrow$+p collisions at 200 GeV.

To investigate the substructure dependence of A_N, we carry out a detailed analysis of photon-multiplicity dependence of EM-jet A_N at forward rapidity using the FMS in p$^\uparrow$+p collisions at $\sqrt{s}$ =200 GeV. Figure 4 shows EM-jet A_N at the forward rapidity (FMS) for the cases: n_γ <= 2 (red), n_γ = 3 (black) and n_γ >= 4 (open circle). We find that A_N increases with increasing x_F. EM-jet A_N is the strongest for EM-jets consisting of 1 or 2 photons. EM-jets with 3 photons have a non-zero A_N but lower than that of 1-photon or 2-photon EM-jets. EM-jets with higher photon multiplicities have significantly smaller asymmetries.

Next, we perform a multi-dimensional analysis to demonstrate the dependences of A_N on photon multiplicity inside the jet, jet transverse momentum, and jet energy. The results obtained using p$^\uparrow$+p collisions at $\sqrt{s}$ = 200 GeV are presented in Fig. 5. The left plot shows the results at forward rapidity using the FMS. For $x_F > 0$, we observe that EM-jet A_N decreases with increasing photon multiplicity ("jettiness"), i.e A_N is the strongest for EM-jets consisting of 1 or 2 photons and significantly smaller for EM-jets with 4 or 5 photons. A_N at $x_F < 0$ is found to be consistent with zero regardless of the photon multiplicity. These results are consistent with our previous measurement at 500 GeV [10]. The right plot shows the results at the intermediate rapidity measured using the EEMC. A_N is zero at low p_T and positive at higher p_T for $x_F > 0$. A_N is significantly smaller for EM-jets at the intermediate rapidity, probing a much lower x_F range, compared to forward rapidity. The trend of EM-jet A_N decreasing with increasing photon multiplicity ("jettiness") seems to hold. A_N at $x_F < 0$ is consistent with zero. Here, the systematic uncertainties (rectangular boxes

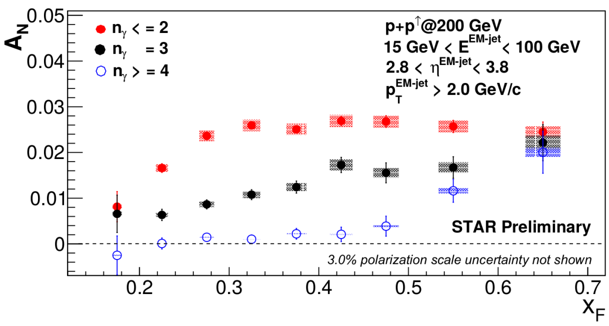

Fig. 4. EM-jet A_N at the forward rapidity (FMS) for the cases: n_γ <= 2 (red), n_γ = 3 (black) and n_γ >= 4 (open circle). The systematic uncertainties (rectangular) come from possible misidentification of the event category.

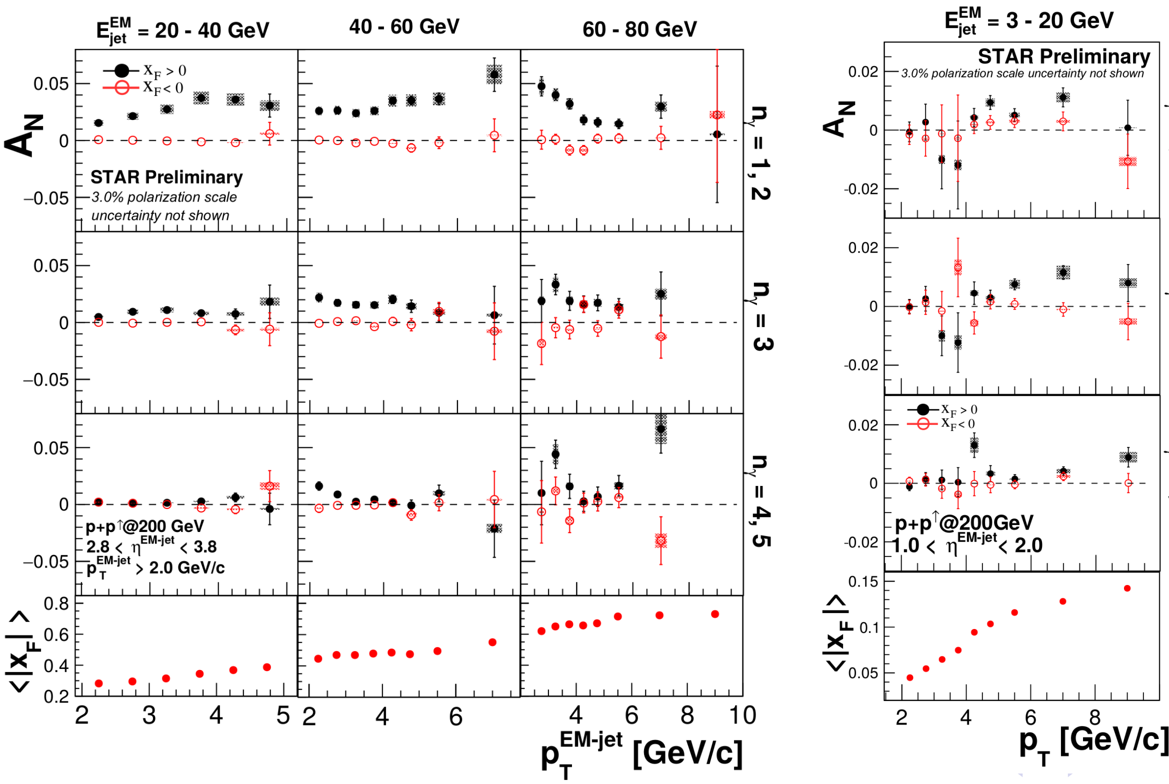

Fig. 5. (Left) A_N for EM-jets at the forward rapidity (FMS) sorted by photon multiplicity inside the jet and different p_T and energy bins. (Right) EM-jet A_N at the intermediate rapidity (EEMC) as a function of p_T sorted by EM-jet photon multiplicity. The lowermost panels show average x_F for each p_T bin.

around data points) arise from possible misidentification of the event category.

4. Conclusion

We present π^0 A_N with different topologies and A_N for EM-jets using the FMS at STAR in p$^\uparrow$+p collisions at $\sqrt{s}$ = 200 GeV and 500 GeV. A_N for isolated π^0 is significantly larger than A_N of non-isolated π^0. The Collins asymmetry is found to be small. We also study A_N for EM-jets of different substructures using the FMS and EEMC at STAR in 200 GeV p$^\uparrow$+p collisions. EM-jet A_N decreases with increasing photon multiplicity ("jettiness"). These results provide rich information towards understanding the physics mechanism of large A_N in hadronic collisions.

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