Transverse Single Spin Asymmetries of Forward π^0 and Jet-like Events in $\sqrt{s} = 500$ GeV Polarized Proton Collisions at STAR

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The large transverse single spin asymmetries (SSA) of high x_F inclusive hadrons produced in polarized proton collisions are usually explained by means of collinear twist-3 multi-parton correlations. In this picture these asymmetries can originate from initial-state twist-3 parton distributions in the polarized proton and/or through the coupling between proton transversity and twist-3 fragmentation functions. The measurement of SSA for forward inclusive hadrons produced in pp collisions out to high transverse momentum helps to examine the validity and interplay of these initial- and final-state models. These models can be further explored by investigating the dependence of the SSA on event topologies. We present our latest status on the measurement of SSA for forward inclusive π^0 detected within $2.8 < \eta < 4.0$ in $\sqrt{s} = 500$ GeV pp collisions as well as its dependence on event topologies. We will also present our analysis of Sivers and Collins asymmetries for forward jet-like events consisting of multi-photon final states. The measurements are based on the data taken in 2011 with integrated luminosity ~ 22 pb^{-1} .

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1. Introduction

The measurement of transverse single spin asymmetries (TSSA) in polarized pp collisions provides critical information on the higher-twist effects and transverse momentum dependent phenomena in parton distributions¹ and fragmentation processes.² A global analysis of TSSA in hadronic and semi-inclusive DIS processes makes it possible to examine the universality of polarized distribution³ and fragmentation functions as well as their evolutions. Therefore from an experimental point

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of view understanding the origins and relative importance of the various sources of the observed large TSSA is a prerequisite for testing proposed models.

To that end STAR has measured the transverse single spin asymmetries of forward inclusive π^0 production in terms of its dependences on x_F ($=2p_z/\sqrt{s}$), transverse momentum p_T and event topologies. The asymmetries of forward jet-like events and π^0 azimuthal asymmetry with respect to the jet axis has also been measured which provides more information on the contributions of Sivers and Collins effects. The analysis is based on data taken at STAR from RHIC 2011 running with polarized pp collisions at $\sqrt{s} = 500$ GeV. Forward π^0 within $2.8 < \eta < 4.0$ are reconstructed through the $\pi^0 \rightarrow \gamma\gamma$ channel, where the photons are recorded by STAR's Forward Meson Spectrometer (FMS).⁴

2. Analysis

2.1. π^0 signal extraction

π^0 candidates are reconstructed by forming all possible photon pairs in the FMS. By fitting the di-photon mass distribution with signal and background template shapes derived from Pythia + GEANT simulations (Fig. 1) the asymmetries of π^0 signal can be calculated using

$$A_N^{total_{sig}} = f_{sig_{sig}} * A_N^{\pi^0} + (1 - f_{sig_{sig}}) * A_N^{bkg} \quad (1)$$

$$A_N^{total_{sb}} = f_{sig_{sb}} * A_N^{\pi^0} + (1 - f_{sig_{sb}}) * A_N^{bkg} \quad (2)$$

In Eqs. (1) and (2) $A_N^{total_{sig}}$, $f_{sig_{sig}}$ denote the raw asymmetries and signal fractions in the signal region ($0.1 < M_{\gamma\gamma} < 0.2$ GeV), whereas $A_N^{total_{sb}}$, $f_{sig_{sb}}$ denote the same quantities in the sidebands ($0.0 < M_{\gamma\gamma} < 0.1$ GeV, $0.2 < M_{\gamma\gamma} < 0.3$ GeV). Note that the average background asymmetries are assumed to be the same in signal region and sideband. Solving these two equation together one can extract the asymmetries of π^0 signal and background.

Fig. 1. Distribution of di-photon mass with $38 \text{ GeV} < E_{\gamma\gamma} < 43 \text{ GeV}$, $2.8 < \eta < 4.0$ and energy sharing $Z_{\gamma\gamma} < 0.8$ ($Z_{\gamma\gamma} = |E_1 - E_2|/E_{\gamma\gamma}$). Grey area: signal region; Shaded area: sidebands.

Fig. 2. Left: inclusive π^0 transverse single spin asymmetries vs x_F . Right: compare inclusive π^0 A_N vs isolated and non-isolated π^0 A_N .

2.2. Inclusive π^0 single spin asymmetries

The left panel of Fig. 2 shows the inclusive π^0 transverse single spin asymmetries vs x_F for both positive and negative x_F . The right panel of Fig. 2 shows the same inclusive asymmetries at forward x_F and breaks it down to the contributions of isolated and non-isolated π^0 asymmetries. Isolated π^0 are found by applying anti- k_T jet algorithm with $R = 0.7$ on FMS photons and require the jet contains only two photons. For the non-isolated case π^0 candidates are reconstructed from the photons within the same jet, with an additional requirement that the fraction of jet energy taken by the π^0 candidate Z_{EM} to be less than 0.9. This condition essentially selects those π^0 produced in a less exclusive environment. As shown in Fig. 2, A_N from isolated π^0 makes dominant contribution to the inclusive π^0 asymmetries, whereas A_N for non-isolated π^0 is close to zero. The particular selection of $Z_{EM} < 0.9$ makes the equivalent Z -dependence of A_N more dramatic since isolated π^0 essentially corresponds to $Z_{EM} = 1.0$. Therefore unless such a dramatic Z -dependence is supported by QCD theory in which π^0 emerges as a result of $2 \rightarrow 2$ partonic hard-scattering there must be other potential sources that generate the observed isolated π^0 with large asymmetries. But it should be pointed out that here the reconstructed jet is only the electromagnetic component of the full jet. In the future with forward detector upgrades at STAR a full jet reconstruction will be possible.

The p_T dependence of inclusive π^0 A_N can also be used to test theory predictions, e.g. from twist-3 expectations A_N will always decrease with increasing p_T due to the nature of higher twist terms. Figure 3 shows A_N vs p_T for inclusive and isolated π^0 from two x_F bins.

2.3. Sivers/Collins asymmetries of jet-like events and π^0 in jets

In the transverse momentum dependent framework the observed asymmetries are generated through the Sivers⁵ and Collins⁶ mechanism. These theories describe processes which involve two scales such as di-jet asymmetries⁷ and azimuthal asymmetries of hadrons within jet.⁸ It has been shown that the Sivers function is related

Fig. 3. Inclusive π^0 A_N vs p_T . Left: $0.24 < x_F < 0.32$, Right: $0.32 < x_F < 0.40$.

Fig. 4. A_N of EMjets containing different number of photons.

to twist-3 parton distribution function via an integral relation,³ and there exists a similar relation between Collins function and twist-3 fragmentation functions.² With the same dataset STAR has measured asymmetries of forward EMjets and π^0 azimuthal asymmetries within the EMjet.

Figure 4 shows A_N of EMjet constructed by applying anti- k_T algorithm with $R = 0.7$ on FMS photons. The asymmetries are plotted for jets having only two photons (π^0 -Jets) and the ones having more than two photons (EM-Jets). For jets having only two photons a cut on the pair invariant mass $M_{\gamma\gamma} < 0.3$ GeV makes isolated π^0 the main source for this of event topology. It can be seen that isolated π^0 has larger asymmetries than other EMjet with higher multiplicities. Figure 5 shows EMjet asymmetries vs p_T for jets containing different number of photons. The size of the asymmetry is the greatest when the jets contain exactly two photons, which have high probabilities of coming from the decay of π^0 . Both Fig. 4 and Fig. 5 indicate that jet-like events have much smaller asymmetries than isolated π^0 at the same energy, which points to the similar trend as the previous analysis of A_N of π^0 within a jet (Fig. 2).

Fig. 5. A_N of EMjets vs p_T . Fig. 6. A_{UT} of π^0 Left: vs energy fraction Z_{EM} , Right: vs jet x_F .

With the reconstructed jet and π^0 one can look at the azimuthal asymmetries $A_{UT}^{Collins}$ of π^0 relative to the jet axis, which represents the Collins asymmetry of π^0 . It has been shown in theory that this type of asymmetry is generated by the coupling of transversity distribution of the proton and Collins fragmentation function.⁸ Figure 6 shows π^0 Collins asymmetry A_{UT} vs the fraction of EMjet energy (Z_{EM}) taken by the π^0 and jet x_F .

The band on top of data points represents systematic errors due to detector resolution of Collins angle $\phi_s - \phi_h$, which reduces the amplitude of the measured Collins asymmetries. The Z_{EM} dependence of Collins asymmetry shows the expected shape of rising at low Z_{EM} and falling towards high Z_{EM} . Both panels in Fig. 6 indicate non-zero asymmetries, but the size of the asymmetries are much smaller compared to inclusive π^0 asymmetries.

3. Summary and Outlook

STAR has measured the transverse single spin asymmetries of forward inclusive π^0 which can be readily compared with theory predictions. To investigate the origins of $\pi^0 A_N$ the event topology dependence of π^0 asymmetries has been studied and analysis showed that isolated π^0 tend to have significantly larger asymmetries than π^0 associated with jet activities in the vicinity. On the other hand the total of Sivers and Collins asymmetries of EMjet and π^0 relative to jet axis are found to be insufficient to account for the observed inclusive π^0 single spin asymmetries.

Equipped with a new pre-shower detector in the upcoming run the FMS will make new contributions to the understanding of transverse spin asymmetries in the forward direction. A measurement of the A_N of prompt photons will provide clean information on the initial distribution functions.⁹ The additional hadron rejection capabilities will help separating isolated vs non-isolated π^0 so that a better event topology dependence study will become possible. In the near future a full instrumentation covering the forward region $2.5 < \eta < 4.5$ with a hadronic calorimeter and a compact EM calorimeter will enable a series of new measurements with jets, photons and Drell-Yan e^+e^- pairs.

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