Measurement of Transverse Single-spin Asymmetries for Dijet Production in Polarized p+p Collisions at $\sqrt{s}$ = 200 GeV at STAR

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We report a new measurement of transverse single-spin asymmetries for pair-production of jets in collisions of transversely polarized protons at $\sqrt{s}$ = 200 GeV with data taken in 2012 and 2015 at STAR. In this measurement we probe, at high Q^2, correlations between the transverse spin $(\vec{S})$ of a proton, moving in the longitudinal $(\vec{p})$ direction, and the transverse momenta of partons $(\vec{k}_T)$ within the proton. A non-zero correlation—the Sivers effect—results in a spin-dependent shift in the dijet azimuthal opening angle away from 180°. The corresponding $\langle k_T \rangle$ is then calculated based on a simple kinematic model. By using charge-tagging of the jets to enhance either *u*- or *d*-quark contributions, we see a non-zero Sivers effect for the first time in dijet production in high-energy proton-proton collisions. The individual parton contributions (*u*, *d*, gluon+sea) to the measured $\langle k_T \rangle$ are extracted through a matrix inversion of the charge-sorted $\langle k_T \rangle$ data. Preliminary results and status of the analysis will be presented.

KEYWORDS: p+p collisions, transverse spin asymmetries, dijets, Sivers effect

1. Introduction

The study of spin phenomena has a long history of yielding important and often surprising results. Attempts to understand these results have pushed the field forward, leading to the development of both new theoretical frameworks and new experimental techniques.

Results from BRAHMS, PHENIX and STAR at RHIC have shown that unexpectedly large transverse single spin asymmetries (SSA) for inclusive hadron production, A_N, first seen in p+p collisions at fixed-target energies and modest transverse momentum (p_T), extend to the highest RHIC center-of-mass energies, $\sqrt{s}$ = 510 GeV, and large p_T ([1,2] and references therein). These asymmetries, which are only weakly dependent on $\sqrt{s}$, cannot be understood within a leading-twist, collinear framework; one must either extend the theory to include twist-3 distributions due to *qgq* correlations, or allow for tranverse-momentum-dependent parton distribution and fragmentation functions (TMDs).

In this analysis, we seek a direct measurement of parton transverse motion, k_T, that is correlated with the proton spin direction—the so-called Sivers effect [3]. Formally, this involves a vector triple product within a transversely polarized proton among the proton's

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spin $\vec{S}$ and momentum $\vec{p}$ with the transverse momenta $\vec{k}_T$ of its constituent partons. If $\langle\vec{S}\cdot(\vec{k}_T\times\vec{p})\rangle\neq 0$, this will produce non-zero A_N for charged hadron production in semi-inclusive deep inelastic lepton scattering, as has been observed at COMPASS [4] and HERMES [5], and in $W^{\pm}$ and Z^0 production in p+p collisions, as measured by STAR [6]. The Sivers function is of particular interest in that it encodes the correlation between partonic orbital motion and the proton spin. It can also be related to the twist-3 Qiu-Sterman matrix element in a collinear framework [7].

2. The Sivers effect in p+p dijet production

In a 2→2 hard-scattering process, the outgoing jets might also exhibit a non-zero A_N due to the Sivers effect, though this could not be easily untangled from, *e.g.*, the Collins effect. We have adopted another approach, based only on the kinematics of the final state dijet, to seek a spin-dependent $\langle k_T\rangle$. The method is illustrated in Fig. 1, showing $\vec{k}_T$ will lead to a shift in the dijet opening angle that will reverse sign under spin-flip of the proton.

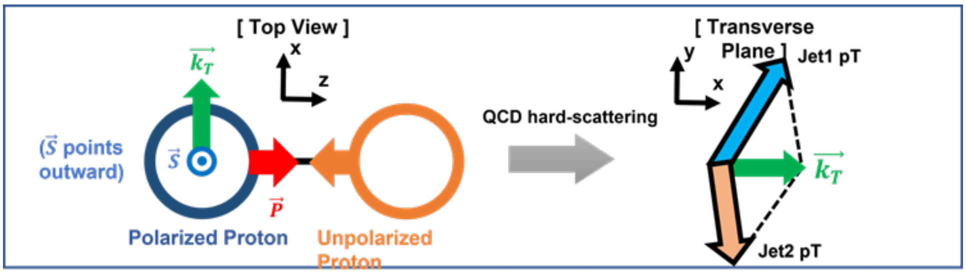

Fig. 1. Schematic illustration of the Sivers effect and the resulting 'tilt' induced in the dijet thrust axes.

Our basic technique, then, is to determine the signed dijet opening angle ζ and search for a shift in ζ associated with spin-reversal of the proton beam. This method was used in an earlier analysis at STAR [8] that found results consistent with zero, though with large statistical uncertainties. For the current analysis, we use 200 GeV transversely polarized p+p data collected in 2012 and 2015 at STAR, corresponding to integrated luminosities of 22 pb^{-1} and 52 pb^{-1}, respectively, or ~33 times that of the previous work. Both jets were reconstructed with the anti-k_T algorithm for accurate determination of the thrust axes. We used a charge-tagging method, described below, to enhance separately the *u*- and *d*-quark signals, as these are expected to be of opposite sign to keep the proton net $\langle k_T\rangle = 0$.

Once a valid dijet event has been identified, our first step is to follow the "parton flow" during the scattering and decide which of the reconstructed jets arises from fragmentation of a parton contained initially in the polarized proton beam. To do so, we assume the more forward of the two jets (larger |η|) is associated with a fragmenting parton from the beam moving in that direction. Simulations indicate this method yields the correct beam→jet association about 70-80% of the time for *qq* and *qg* scattering (and 50% for *gg*).

As noted above, we next evaluate the net charge of each jet, to yield samples enhanced to different extents from fragmenting *u*-quarks and *d*-quarks. Rather than using the charge of the leading hadron, we calculate a momentum-weighted charge sum for the jet, adding the charges for each track with p_T above 0.8 GeV/*c* (to suppress underlying event contributions), weighted by the fraction of the jet p_T carried by the track. Jets are then sorted into four bins depending on this charge sum Q: plus-tagging (Q > 0.25); zero+ (0 < Q < 0.25); zero- (-0.25 < Q < 0); and minus-tagging (Q < -0.25). Simulations of PYTHIA [9] events run through GEANT [10], shown in Fig. 2, confirm that the probability of a u-initiated jet falls as Q varies from +1→-1, with the opposite trend for d quarks.

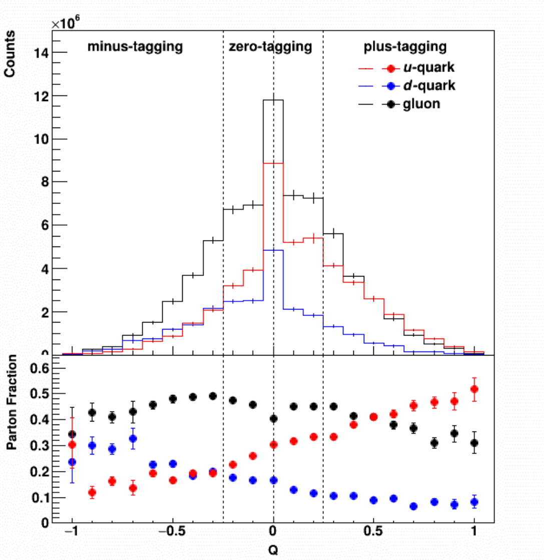

Fig. 2. Simulated jet yields, sorted by their net charge Q. Fractional yields are shown below.

The spin-dependent dijet opening angle, $\Delta\zeta$, can now be extracted for each of the four charge-tagged bins, sorting the ζ values by the polarization direction (up / down) of the proton beam associated with the jet. Results for the two RHIC beams were determined independently and found to be consistent after 'flipping' the signs of both η and $\Delta\zeta$ for one beam. The two were then combined to increase the statistical accuracy of the data.

The four $\Delta\zeta$ asymmetries are shown in Fig. 3. Results have been plotted as a function of the sum of the pseudorapidities of the two jets, $\eta^{total} \equiv \eta_3 + \eta_4$, which is related to the ratio of the momentum fractions, x_1/x_2, of the colliding partons at leading order.

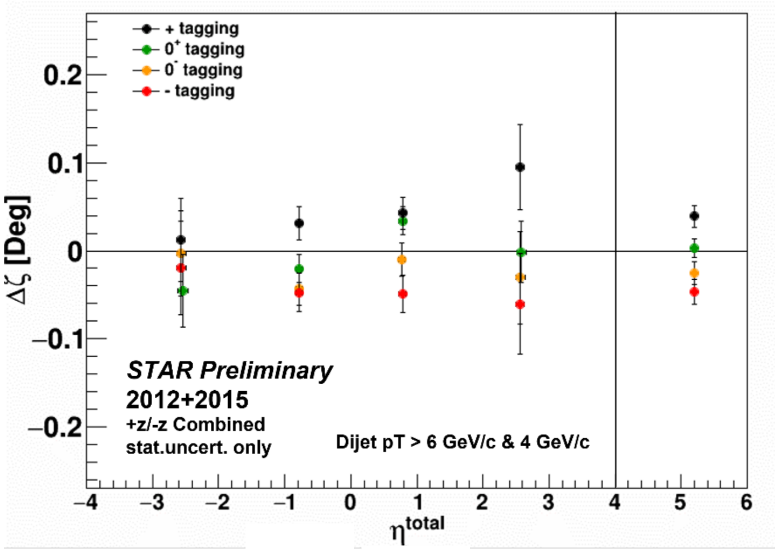

Fig. 3. Extracted centroid shifts of the spin-sorted ζ distributions for each of the four charge tagged bins. Results are plotted as a function of the sum of the jet pseudorapidities. Average values are at far right.

One can see that the average asymmetries, shown on the right, systematically shift from positive to negative values as the sample moves from u-quark to d-quark dominated, with ~5σ separation between plus-tagging and minus-tagging. These two bins also show an increase with η^{total}, as the sampled data become more enriched in qg scattering events. Finally, we note that the asymmetries are consistent with zero if averaged over the four charge bins, which confirms the conclusions of the earlier STAR measurement, albeit with higher statistics.

To make connections with theoretical predictions, the Δζ values need to be converted to their associated partonic transverse momenta, $\langle k_T \rangle$. This is done using non-spin-sorted data by first correcting detector-level jet p_T to parton-level p_T using machine learning. We then assume a given k_T for all events, calculate Δζ for the corrected jet p_T distribution in each η^{total} bin and extract the resulting Δζ - $\langle k_T \rangle$ correlation, which is found to be linear. This allows us to convert Δζ to $\langle k_T \rangle$ in each η^{total} bin. Very roughly, a measured Δζ of 0.1° corresponds to a $\langle k_T \rangle$ of about 15 MeV/*c*. In our preliminary analysis, we find that $\langle k_T \rangle$ for plus-tagged events is +6.1 MeV/*c*, while for minus-tagging it is -7.3 MeV/*c*.

The final step is to convert our $\langle k_T \rangle$ values for the charge-tagged bins to values for the various parton channels. Up to this point, the analysis was only weakly dependent on simulation results; for this last piece, however, we rely on the information summarized in Fig. 2 for our matrix inversion from tagged results, representing different parton mixtures, to the $\langle k_T \rangle$ of individual partons (*u*, *d*, gluon+sea). The system is over-constrained, and was solved using standard matrix inversion techniques, which were stable.

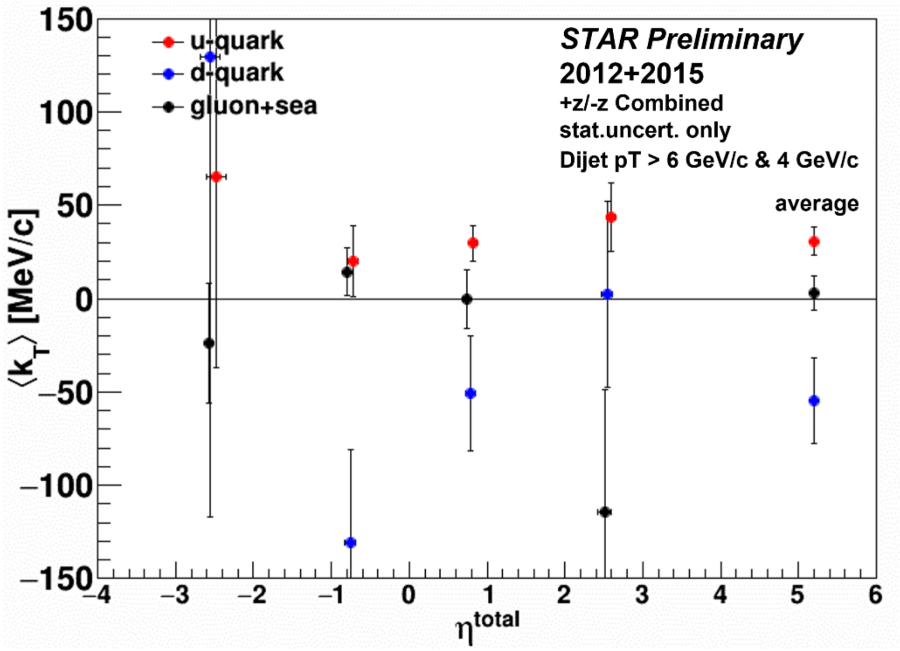

Fig. 4. Preliminary values for the spin-dependent $\langle k_T \rangle$ for *u*, *d*, and gluon+sea as a function of the summed pseudorapidities of the two jets. Only statistical uncertainties are shown, including those of the inversion process. Values averaged over all η^{total} are shown on the far right.

Our preliminary results are summarized in Fig. 4. The data represent the first direct evidence for a non-zero Sivers effect in dijet production, or any purely hadronic channel. Averaged over η^{total}, the partonic results follow general expectations, indicating a positive $\langle k_T \rangle$ for *u* quarks and negative for *d* quarks, while $\langle k_T \rangle$ for gluons and sea quarks is consistent with zero. We note that the $\langle k_T \rangle$ ratio for *d*:*u* is close to -2, which would be expected in a valence quark picture to keep the proton net $\langle k_T \rangle$ zero. Unfortunately, with the given statistics it is difficult to extract solid information on the η^{total} dependence, though there are hints that $\langle k_T \rangle$ increases in magnitude for both *u* and *d* quarks for events in which the parton from the polarized proton is scattered at high η.

3. Conclusions

We have presented preliminary results for the Sivers asymmetries from dijet production in high-energy p+p collisions at STAR, based on the 2012 and 2015 data sets. These data are the first observations of non-zero Sivers asymmetries in a purely hadronic reaction channel. Using simulations, average spin-dependent transverse momenta have been extracted for individual partons, yielding $k_T^u \approx 30$ MeV/c, $k_T^d \approx$ -55 MeV/c, and an average $\langle k_T \rangle$ for gluons and sea quarks that is statistically consistent with zero. No strong dependence on η^{total} is observed, which would suggest a fairly weak *x* dependence in the Sivers function $f_{1T}^{\perp}(x, k_T)$.

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