

Measurement of transverse single-spin asymmetries for dijet production in polarized proton-proton collisions at $\sqrt{s}=200$ GeV

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We report a new measurement of transverse single-spin asymmetries for dijet production in collisions of polarized protons at $\sqrt{s} = 200$ GeV. Correlations between the proton spin and the transverse momenta of its partons, each perpendicular to the proton momentum direction, are probed at high $Q^2 \approx 160$ GeV². Evidence for nonzero Sivers effects is measured for the first time in dijets from proton-proton collisions, but only when the jets are sorted by their net charge, which enhances the otherwise canceling opposite-sign u - or d -quark contributions to separate data samples. The resulting asymmetries are compared to recent theoretical calculations. Separately, the associated Sivers observable $\langle k_T \rangle$, the average parton transverse momentum, is extracted using a simple kinematics approach which further enables a determination of the individual partonic contributions to the observed asymmetries.

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Our understanding of the three-dimensional structure of the nucleon has progressed significantly in the past decades [1,2] and will be further advanced at the future Electron-Ion Collider [3]. In momentum space, nucleon structure is typically expressed via transverse-momentum-dependent parton distribution functions (TMD PDFs) with explicit dependence on the partonic transverse momentum ($\vec{k}_T$). One TMD PDF of particular interest is the spin-dependent Sivers function [4] $f_{1T}^\perp$ which characterizes a scalar triple-vector correlation for an unpolarized parton and its transversely polarized parent proton: $(\vec{k}_T \times \vec{S}) \cdot \vec{P}$, where $\vec{S}$ and $\vec{P}$ are the proton spin and proton momentum, respectively. In the hard scattering of transversely polarized protons, this correlation leads to a left-right asymmetry in the azimuthal distribution of produced particles. The Sivers effect was originally introduced [4] to explain the large transverse single-spin asymmetries (TSSA) observed in inclusive pion production, whose persistence to high transverse momenta p_T appeared contrary to quantum chromodynamics (QCD) expectations [5,6]. Currently, in addition to the TMD PDF

and fragmentation function framework that has expanded to describe the growing number of TMD phenomena, a collinear formalism involving twist-3 distributions (quark-gluon-quark correlations) continues its development and is more applicable for describing TSSA effects in inclusive single-hadron production. The Sivers function and its twist-3 analog, the Efremov-Teryaev-Qiu-Sterman distribution [7,8], are related quantitatively [9], providing constraints and insight from different kinematic regimes.

Experimental evidence for the Sivers effect was first obtained [10] in semi-inclusive deep inelastic scattering (SIDIS) [11–17]. Fits to these data show opposite signs and similar scale for the u - and d -quark Sivers functions [18–27], with sea quarks compatible with zero. Valence quarks nearly saturate the Burkardt sum rule [28], leaving little room for gluon Sivers contributions. Building on an unpolarized TMD foundation [29], there is also considerable recent interest in combining TMD data from SIDIS, e^+e^- annihilation and pp scattering to arrive at a unified picture including effects of the Sivers function [26,27,30–32]. While there is as yet no formal connection between the Sivers function and orbital angular momentum (OAM), the latter is a prerequisite [33] for the Sivers effect. These and other studies [22] point to an emerging nucleon 3-D structure and further understanding of possible contributions of OAM to the nucleon spin.

A distinctive feature of the Sivers function is its nonuniversality. QCD gauge invariance requires the Sivers function

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to be process dependent, a manifestation of the underlying color dynamics, resulting in opposite signs for the Sivvers asymmetries in SIDIS and the Drell-Yan process [34]. Investigations are ongoing to confirm this predicted sign change using $W^\pm/Z^0$ boson production [35], with only qualitative support so far observed [31,36,37]. Recent COMPASS Drell-Yan results obtained via virtual photons [38] indicate a consistency with the QCD sign change prediction.

Dijet production TSSAs in transversely polarized proton-proton collisions are directly sensitive to the Sivvers functions of the participating partons and can be experimentally studied via the dijet opening-angle kinematic tilt (from back-to-back) that reverses under spin-flip of the proton beam [39]. Use of the dijet channel avoids spin-correlated fragmentation contributions along with suppression of some potential background effects, and at STAR probes a significantly higher Q^2 scale ($\gtrsim 160 \text{ GeV}^2$) than previous Sivvers effect studies. While the resulting asymmetries involve gauge link contributions associated with color flow to both the initial (as in Drell-Yan) and final (as in SIDIS) states [40], when compared with theory, these measurements can help probe and elucidate novel aspects of the QCD dynamics. An additional significant feature is that dijet asymmetry measurements offer a means to directly explore the underlying spin-dependent partonic $\vec{k}_T$ that characterizes the Sivvers effect, offering the potential for new insights regarding this important transverse momentum component.

An early analysis [41] with limited statistics from STAR at the Relativistic Heavy Ion Collider (RHIC) found Sivvers asymmetries consistent with zero in dijet production, presumably due to the cancellation between opposite-sign u and d quark contributions, and as suggested by then-current calculations [42]. However, deciphering results from back-to-back dijets in a theoretical framework faces nontrivial issues from TMD factorization breaking [43–45], largely due to their two-scale (jet vs dijet momentum balance) nature. Among the challenges are resummation of large logarithmic terms as well as the spin-dependent treatment of global soft functions. New Sivvers dijet measurements may enable additional insights, and there are recent theoretical approaches spurred by such interest [46,47]. We revisit the Sivvers dijet measurement at STAR with a novel jet-charge tagging method to help separate the u and d contributions, together with significantly improved statistics. Increased precision arises from inclusion of charged particle tracking in jet reconstruction.

In this analysis, we use 200 GeV transversely polarized pp data collected in 2012 and 2015 at STAR, corresponding to integrated luminosities of 22 and 52 pb^{-1} , respectively. The involved subsystems of the STAR detector [48] are the Time Projection Chamber (TPC) [49], providing charged particle tracking for pseudorapidity $|\eta^{\text{detector}}| \leq 1.3$, and the Electromagnetic Calorimeter (EMC), measuring the energy of electrons and photons while providing jet

triggering in the barrel $-1 < \eta^{\text{detector}} < 1$ [BEMC [50]] and endcap $1.1 < \eta^{\text{detector}} < 2$ [EEMC [51]] regions with full azimuthal (ϕ) coverage. The polarizations for the circulating beams are measured using Coulomb-nuclear interference proton-carbon polarimeters [52], calibrated with a polarized hydrogen gas-jet target [53]. The average beam polarization magnitudes are 56% (2012) and 57% (2015), both with a relative scale uncertainty of 3.2% [54]. The analysis treats only one beam as polarized at a time.

The data are selected using an EMC jet-patch trigger with two levels of transverse energy (E_T) threshold in a $\Delta\eta \times \Delta\phi = 1 \times 1$ (radians) region: 5.4 GeV (JP1) and 7.3 GeV (JP2). Jets are reconstructed using the anti- k_T [55] algorithm with $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.6$, employed with standard STAR selection criteria on the TPC tracks, EMC towers and proto-jet quantities [56]. To ensure the quality of the dijets, we select events with exactly two jets, one having $p_T > 6 \text{ GeV}/c$ and the other $p_T > 4 \text{ GeV}/c$, with a relative opening angle $\Delta\phi > 120^\circ$. Both jets are required to originate from a single vertex with $|Z_{\text{vertex}}| < 90 \text{ cm}$, and fall within $-0.8 < \eta < 1.8$ and $-0.7 < \eta^{\text{detector}} < 1.7$. In order to avoid false triggering effects, a trigger simulator is applied, which requires the matching of offline reconstructed jets with triggered jet patches. The resulting number of events is ~ 33 times that available in an earlier study [41].

The observable in this analysis relies on precise knowledge of the jet directions (as compared to the magnitude of their momenta), the *signed dijet opening angle* (ζ) [39]. It is defined as $\zeta = |\Delta\phi|$ if $\cos(\phi_b) < 0$ and $\zeta = 360^\circ - |\Delta\phi|$ if $\cos(\phi_b) > 0$, where ϕ_b is the azimuthal angle of the bisector ray, which reverses direction when the beam polarization direction is flipped. The sensitivity of ζ to transverse spin effects is maximized when the two jets are parallel to the beam spin and, modulated by $|\cos(\phi_b)|$, is zero when the two jets are perpendicular.

Our method to extract an asymmetry for the spin-dependent dijet response differs, but is closely related to the single-spin analyzing power A_N . We choose the asymmetry calculated as the difference of ζ centroids $\langle \zeta \rangle$ between the spin-up and spin-down states:

$$\Delta\langle \zeta \rangle = \frac{\langle \zeta \rangle^+ - \langle \zeta \rangle^-}{P}, \quad (1)$$

where $\langle \zeta \rangle^{+/-}$ is the centroid of the Gaussian-like [41] ζ distribution in the spin-up/spin-down state, and P is the beam polarization. The asymmetry in Eq. (1) is motivated by the fact that for our jet p_T range, ζ is directly sensitive to the Sivvers function $\langle k_T \rangle$, driver of the spin-dependent shift in the dijet opening angle. This construction also sidesteps several systematic uncertainties, such as relative luminosity, asymmetric detector azimuthal acceptance and background contribution effects. $\langle \zeta \rangle$ is extracted by fitting the ζ distribution $N(\zeta)$ over a selected range with a three-

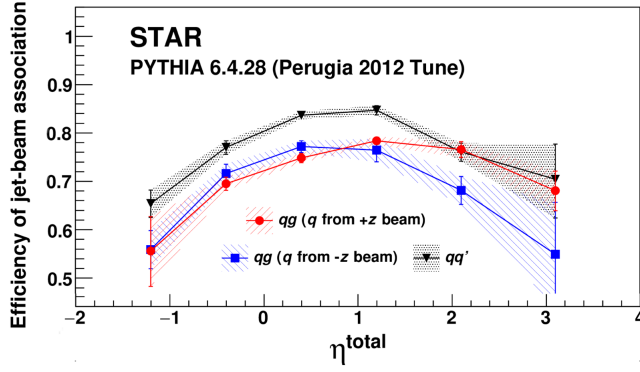


FIG. 1. Efficiency for associating beam and jet correctly in the embedding sample vs η^{total} , the summed dijet η .

Gaussian function capturing its salient features:

$$N(\zeta) = p_0 \cdot \left(e^{-\frac{(\zeta-p_1)^2}{2p_2^2}} + p_3 \cdot e^{-\frac{(\zeta-p_1)^2}{2p_4^2}} + p_5 \cdot e^{-\frac{(\zeta-p_1)^2}{2p_6^2}} \right), \quad (2)$$

where all components share the same peak position p_1 , taken as $\langle \zeta \rangle$. Values of the centroid differences $\Delta \langle \zeta \rangle$ subsequently extracted are largely insensitive to variation of this empirically driven shape [57]. Two fitting steps are performed: (1) spin-up and spin-down distributions, scaled to the same integral, are combined and fit to determine individual Gaussian parameters; (2) spin-up and spin-down ζ distributions are separately fit using Eq. (2), with only p_1 allowed to vary, making the final fit results more sensitive to the distribution centroid and improving accuracy and stability. The broad ζ distribution, driven mainly by parton-level multi-GeV intrinsic k_T and initial-state radiation effects [58], nearly fills the analyzed back-to-back dijet ζ range of $180 \pm 60^\circ$; our fit range of $180 \pm 50^\circ$ allows some room for systematic study. The resulting $\Delta \langle \zeta \rangle$ vs ϕ_b values are fit with a cosine function, whose amplitude quantifies the measured asymmetry.

To avoid possible u - d cancellation, we divide the data into multiple kinematic regions in the analysis, each with a variant parton composition, with the $\Delta \langle \zeta \rangle$ asymmetry extracted separately in each of four “jet charge” bins within the subsets of JP triggers and 2012, 2015 data. The initial selection is based on “tagging” of a jet, which must first be associated with the polarized beam. The more forward of the jets (largest detector $|\eta|$) is assumed to be likely coming from the scattered parton of the beam pointing into the same hemisphere. For instance, in a dijet event with $\eta_1 > \eta_2$, jet₁ is associated with the $+z$ beam and jet₂ with the $-z$ beam. Performance of the beam-jet association is studied with simulation based on Pythia 6.4.28 [59] [Perugia 2012 tune [58,60]] and GEANT 3 [61], and embedded into randomly selected beam bunch crossings from data to mimic real beam background, pileup and detector inefficiencies. Simulation reveals that the resulting association efficiency for qg and qq' subprocesses averages about 70%-75% (Fig. 1). This ensures good performance of

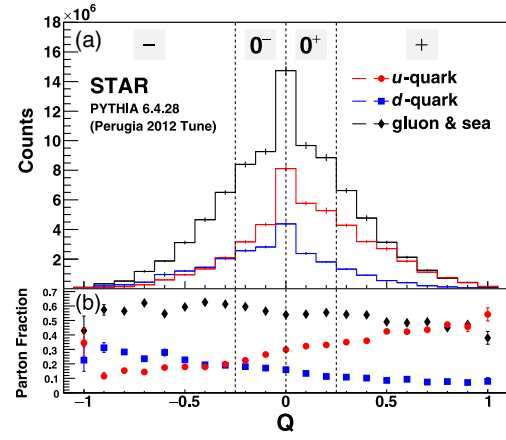


FIG. 2. (a) Distribution of Q and (b) respective parton fraction from the embedded simulation. The tagging divides the data sample into 4 bins (separated by the dashed lines).

jet tagging for the u and d quarks in the next step. (Note: for identical partons, qg and qq , the association is ambiguous.)

During hadronization, the u quarks and d quarks produce relatively more positively charged and negatively charged particles, respectively. This feature can be quantified by jet charge (Q) [62] to help in tagging jets:

$$Q = \sum_{|p^{\text{track}}| > 0.8 \text{ GeV}/c} \frac{|p^{\text{track}}|}{|p^{\text{jet}}|} \cdot q^{\text{track}}, \quad (3)$$

where q^{track} is the charge sign of each track. To reduce the influence from underlying events, only tracks with $|p| > 0.8 \text{ GeV}/c$ are selected in the calculation. The distributions of Q for different scattered partons (gluon and antiquark sea combined) are plotted using the embedding sample in Fig. 2, for which the effect of beam-jet association has also been folded in. Based on these plots, each data sample is divided into four “jet-charge” bins:

- (i) + tagging: $Q \geq 0.25$, enhancing the fraction of u .
- (ii) 0^+ tagging: $0 \leq Q < 0.25$, less enhancement of u .
- (iii) 0^- tagging: $-0.25 < Q < 0$, less enhancement of d .
- (iv) - tagging: $Q \leq -0.25$, enhancing the fraction of d .

The four binned regions are expected to show different $\Delta \langle \zeta \rangle$ asymmetries assuming opposite signs of the Sivvers function for the u and d quarks. Since the parton fraction is dependent on Bjorken x , we further divide the full data set into η^{total} bins ($\eta^{\text{total}} = \eta_1 + \eta_2 \propto \log(x_1/x_2)$) [41]. We also combine the separate $+z$ and $-z$ polarized beam results, by transforming (rotation around the y -axis) the $-z$ beam $\Delta \langle \zeta \rangle$ asymmetries into the $+z$ beam direction. The resulting $\Delta \langle \zeta \rangle$ asymmetries, now over an extended η^{total} range, for the four charge-tagged bins are shown in Fig. 3(a). We observe a 3.1σ separation between the averaged asymmetries for the + tagging and the - tagging. A correlation between $\Delta \langle \zeta \rangle$ and Q is also manifest, as the asymmetry shifts from negative to positive with increasing Q (less d

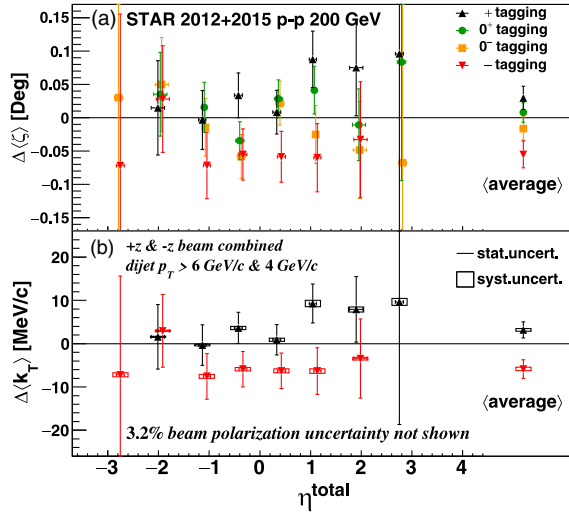


FIG. 3. (a) $\Delta\langle\zeta\rangle$ values and (b) converted $\Delta\langle k_T\rangle$ plotted as a function of η^{total} . Rightmost points represent the average over the η^{total} bins. The 0^+ and 0^- points are suppressed in the lower panel to better view the $\Delta\langle k_T\rangle$ signal and systematic errors (dominated by fitting range). Plotted points are offset in η^{total} and outsize values omitted for clarity.

and more u). This is strong evidence that the Siverts $\langle k_T\rangle$ effect for u and d are opposite in sign, as indicated in SIDIS measurements [11–13].

Our measured $\Delta\langle\zeta\rangle$ asymmetries are validated through several crosschecks. A null test made by calculating the asymmetry in the direction orthogonal to the expected Siverts $\vec{k}_T$ finds all the charge-tagged results consistent with zero, ruling out the possibility of major spin-dependent systematic effects. In the separated $+z$ beam and $-z$ beam measurements, we see overall consistency in sign and magnitude for the asymmetries within the same η^{total} bins and the same charge-tagged bins. Similar agreement is also observed for the results using only 2012 or 2015 data.

Recent theoretical calculations [46,47] of the Siverts asymmetries for 200 GeV pp dijets are expressed in terms of the analyzing power observable A_N . The connection between $\Delta\langle\zeta\rangle$ of Eq. (1) and A_N is made using the dijet opening angle ζ distribution itself, with A_N characterizing the left-right event difference arising from the tilt of nominal back-to-back jets [39], while $\Delta\langle\zeta\rangle$ is a measure of the shift of the whole distribution. Since our $\Delta\langle\zeta\rangle$ centroid analysis involves Gaussian fitting of the ζ event distribution (total events), whose spin-dependent centroid shifts are small (hence the asymmetry driving events can be simply evaluated as the peak amplitude times $\Delta\langle\zeta\rangle$), we can numerically [57] relate our $\Delta\langle\zeta\rangle$ results to those of a A_N -focused analysis: e.g., a single Gaussian of width σ gives $A_N = \frac{\text{ampl} \cdot \Delta\langle\zeta\rangle}{\text{ampl} \cdot \sigma \cdot \sqrt{2\pi}} = \frac{\Delta\langle\zeta\rangle}{\sigma \cdot \sqrt{2\pi}}$. A comparison of such extracted A_N values, for the tagged results of Fig. 3(a) with theoretical calculations is shown in Fig. 4.

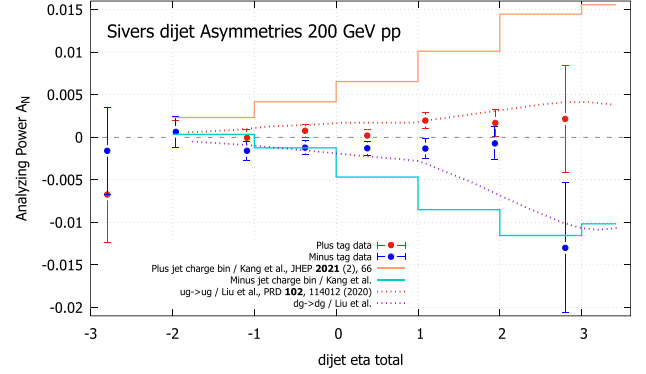


FIG. 4. Comparisons of A_N for 200 GeV pp Siverts dijet asymmetries with theoretical predictions from Kang *et al.* [47] and Liu *et al.* [46]. Measured $\Delta\langle\zeta\rangle$ asymmetries have been converted to A_N via a numerical factor as described in the text (a 10% per point RMS conversion error is not included).

Overall, one sees that both calculations and the data are comparable in magnitude, and correlate with the sign of the asymmetries for the plus (u quark)- vs minus (d quark)-tagged data, generally lending support to the scale of our experimental results. The curves from Kang *et al.* [47] are based on a QCD formalism explicitly allowing for resummation of logarithmic terms and represent a full calculation, including a sum over all contributing color line terms (e.g., both SIDIS- and DY-like contributions). While Q -charge and jet threshold selections are chosen to be similar to our experimental analysis, the predicted η^{total} dependence is not seen in our data. The calculations from Liu *et al.* [46] on the other hand, include only the use of one loop soft gluons and TMD factorization at leading order. The curves display just the behavior of the dominant $ug \rightarrow ug$ and $dg \rightarrow dg$ channels, and while they don't include tagging efficiency, they do generally describe both the magnitude and more gentle η^{total} behavior of the data reasonably well.

The nominal agreement of the single channel Liu *et al.* calculation with data, along with the similar sign and magnitude correlation of the Kang *et al.* curves, may be some indication that the pp dijet asymmetries are dominated by final-state color flow (e.g., a sign-change negative initial-state contribution appears not to dominate).

As a segue and further connection of our $\Delta\langle\zeta\rangle$ results to theoretical expressions, we note schematically that if $d\sigma^\pm(\zeta)$ denotes an element of the spin-dependent dijet opening angle distribution [e.g., cast the cross section expressions similar to Eqs. (3) and (10) of ref. [47] in a form differential in ζ], one recovers a familiar structure for A_N , and a similar expression with a ζ weighted distribution integrated over ζ for $\Delta\langle\zeta\rangle$: $\Delta\langle\zeta\rangle = (\int \zeta d\sigma^+ - \int \zeta d\sigma^-) / \int d\sigma$. That is, the difference of the distribution centroids that we measure can also be directly related to theory.

Returning now to the $\Delta\langle\zeta\rangle$ results of Fig. 3(a), we discuss the extraction of the associated average Siverts $\langle k_T\rangle$.

Formally, the difference of the individual ζ distribution-weighted averages of k_T associated with the two spin orientations is given by $\langle k_T \rangle^+ - \langle k_T \rangle^- = (\int k_T d\sigma^+ - \int k_T d\sigma^-) / \int d\sigma$. This difference is effectively the average $\text{Sivers } \langle k_T \rangle^{\text{Sivers}}$ that drives our measured $\Delta\langle\zeta\rangle$ asymmetry. We calibrate it using the dijet opening angle shift resulting from a parton level, transverse “kick” by correlating detector level $\Delta\langle\zeta\rangle$ and parton level $\langle k_T \rangle$ (notably independent of the intrinsic k_T characterization as verified by a dedicated simulation). To do the conversion, we first correct the jet p_T back to its parton level based on machine learning using the embedded simulation sample. We adopt the same algorithm, variables and training configuration as in a previous analysis [56], but now targeted toward parton p_T instead of particle jet p_T . The weights from the training are applied to the jets in the real data to determine the actual p_T distribution. Next, the $\Delta\langle\zeta\rangle$ - $\langle k_T \rangle$ correlation is constructed using kinematics alone. We independently add two opposite constant k_T vectors, $(k_T, 0, 0)$ and $(-k_T, 0, 0)$, to the corrected jet p_T to mimic dijet tilts in nominal “spin-up” and “spin-down” states, respectively. A $\Delta\langle\zeta\rangle$ asymmetry at parton level is extracted following the above analysis procedure; the results are used at detector level with a systematic described further below. By assigning 5 different k_T values in the range 1–20 MeV/c to the added vectors, an experimentally determined linear relation between $\Delta\langle\zeta\rangle$ and an effective $\langle k_T \rangle$ is observed individually for each η^{total} bin, which can be well fit with a slope: $\Delta\langle\zeta\rangle = \text{slope} \cdot \langle k_T \rangle$. Due to p_T differences in η^{total} bins, the slope ranges from $9.26^\circ \cdot c/\text{GeV}$ in the mid-rapidity region to $9.97^\circ \cdot c/\text{GeV}$ in the more forward region.

The $\Delta\langle\zeta\rangle$ results are converted to $\Delta\langle k_T \rangle$ results, Fig. 3(b), by applying the reverse of the above calculated slope, $\Delta\langle k_T \rangle = \Delta\langle\zeta\rangle / \text{slope}$. The η^{total} -averaged $\Delta\langle k_T \rangle$ is found to be 3.2 ± 1.9 MeV/c for the + tagging bin, and -5.8 ± 2.1 MeV/c for the - tagging bin. The untagged asymmetry, -0.4 ± 0.9 MeV/c, obtained from the error-weighted mean of the four charge-tagged bins, is consistent with zero. We observe an $\sim 2\sigma$ level linear η^{total} -dependency in the + tagging $\langle k_T \rangle$ results. This is likely due mainly to the x -dependence of the parton fractions.

The tagged $\Delta\langle k_T \rangle$ results provide sufficient constraints to solve for the $\text{Sivers } \langle k_T \rangle$ of individual partons if we know the parton fractions in each charge-tagged bin, which can be estimated from simulation. The inversion method used is based on fundamental concepts; we assume simple $2 \rightarrow 2$ scattering kinematics in the simulation sample which then guides the analysis to determine the magnitude and sign of the $\text{Sivers } \langle k_T \rangle$ for individual partons. Combining the gluon and sea quark contributions, there are four constraints from charge tagging vs three unknown variables: $\langle k_T^u \rangle$, $\langle k_T^d \rangle$ and $\langle k_T^{g+\text{sea}} \rangle$. To increase the stability of the inversion process, data from adjacent bins in η^{total} are combined, leading to the eight constraints:

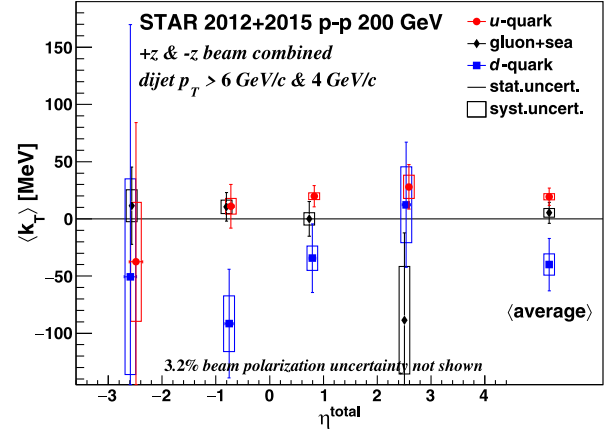


FIG. 5. $\langle k_T \rangle$ for individual partons, inverted using parton fractions from simulation and tagged $\langle k_T \rangle$, plotted as a function of η^{total} , with rightmost points the η^{total} average. Plotted points are offset in η^{total} for clarity, and systematic uncertainties in η^{total} are set nonzero to improve visibility.

$$f_{i,j}^u \langle k_T^u \rangle + f_{i,j}^d \langle k_T^d \rangle + f_{i,j}^{g+\text{sea}} \langle k_T^{g+\text{sea}} \rangle = \langle k_T \rangle_{i,j}, \quad (4)$$

where f represents the parton fraction from simulation [57], the right-hand side $\langle k_T \rangle$ is the tagged measurement in data, i runs over all the charge tagging bins, and j runs over the two adjacent η^{total} bins. The over-constrained system is solved through Moore-Penrose inversion, yielding values for the individual parton $\langle k_T \rangle$, displayed in Fig. 5 and discussed further below.

The systematic uncertainty of the parton $\langle k_T \rangle$ has major contributions from two sources: the fitting range of ζ and the more dominant error associated with the estimation of parton fractions. The fit range uncertainty is estimated by varying the range from $180 \pm 40^\circ$ to $180 \pm 60^\circ$ and extracting $\langle\zeta\rangle$ as a deviation from nominal; the resulting uncertainty is less than 15% for + tagging/- tagging as indicated in Fig. 3(b). Parton fractions are estimated with leading-order PYTHIA simulations, which come with their own set of contributing systematics, dominated by the choice of PDF and ISR/FSR [see Ref. [57]]. These uncertainties vary with parton purity in the charge bins and as a function of $-3.6 < \eta^{\text{total}} < 3.6$, ranging from 18 to 7–12% for u and d , and 3–21% for $g + \text{sea}$. There is also a systematic associated with the parton to detector level $\Delta\zeta$ mapping. A comparison of values for a wide range of simulated $\langle k_T \rangle$, gives an uncertainty of $\sim 5.6\%$, due largely to average momentum differences in the various bins.

The inverted results and average over all the η^{total} bins are shown in Fig. 5. The average $\langle k_T^u \rangle$ is estimated to be $+19.3 \pm 7.6$ (stat.) ± 2.6 (syst.) MeV/c, in which the positive sign means the u quarks are correlated with the proton spin and proton momentum following the right-hand rule: $\vec{k}_T^u \cdot (\vec{S} \times \vec{P}) > 0$. In contrast, the average $\langle k_T^d \rangle$ is estimated to be $-40.0 \pm 22.9 \pm 9.3$ MeV/c, showing an

opposite sign and a similar magnitude compared to $\langle k_T^u \rangle$. While these results are likely somewhat specific to their extraction in pp dijets with possible contributions from different color flow and an average over kinematic bins rather than global extraction, they are roughly comparable to the u - d correlation in SIDIS measurements at a much lower scale extracted as 96_{-28}^{+60} and -113_{-51}^{+45} MeV for u and d , respectively [21]. We also find that the gluon and sea quarks are consistent with zero, $\langle k_T^{g+\text{sea}} \rangle = 5.3 \pm 9.2 \pm 3.8$ MeV/ c . Our measurement probes a range $0.03 < x < 0.6$ (u and d quarks), and $0.01 < x < 0.5$ (gluons); bin-by-bin parton x and $\langle k_T \rangle$ values are listed in Supplemental Material [57].

In summary, transverse single-spin asymmetries for dijet production in pp collisions are measured in jet-charge bins using $\sqrt{s} = 200$ GeV data at STAR. This is the first time that evidence for nonzero Sivers signals in pp -induced dijet production is measured. Comparison of our results with further theoretical developments may help to probe interesting aspects of the QCD dynamics. Through $\Delta\langle\zeta\rangle$ -to- $\langle k_T \rangle$ conversion and pseudoinversion, the Sivers $\langle k_T \rangle$ for individual partons are unfolded in a kinematic approach. The u - and d -quark $\langle k_T \rangle$ are found to have opposite signs and similar magnitudes, while $\langle k_T \rangle$ for gluon and sea quarks combined is consistent with zero within still large uncertainties. Inclusion of these data in global analyses can enhance a consistent extraction of Sivers observables and perhaps impact the understanding of evolution effects,

process dependence and other important issues relating to the Sivers TMD function.

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