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The STAR experiment reports new, high-precision measurements of the transverse single-spin asymmetries for $\pi^{\pm}$ within jets, namely the Collins asymmetries, from transversely polarized $p^{\uparrow}p$ collisions at $\sqrt{s} = 510$ GeV. The energy-scaled distribution of jet transverse momentum, $x_T = 2p_{T,\text{jet}}/\sqrt{s}$, shows a remarkable consistency for Collins asymmetries of $\pi^{\pm}$ in jets between $\sqrt{s} = 200$ GeV and 510 GeV. This indicates that the Collins asymmetries are nearly energy independent, with, at most, a very weak scale dependence in $p^{\uparrow}p$ collisions. These results extend to high-momentum scales ($Q^2 \leq 3400$ GeV^2) and enable unique tests of evolution and universality in the transverse-momentum-dependent formalism, thus providing important constraints for the Collins fragmentation functions.

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The very nature of the strong interaction obscures the mechanisms that drive the formation of the colorless hadrons from the fragmentation of high-energy quarks and gluons. A natural way to probe the process of hadronization is to study the spatial and momentum distributions of final-state hadrons and their dependence on the momentum, spin, and flavor of the parent parton. Significant correlations have been observed, for example, in the azimuthal distributions of hadrons produced in transversely polarized hadron-hadron collisions since the 1970s [1–8]. Initially, it was a challenge for collinear perturbative QCD to describe the magnitude and momentum dependence of these transverse single-spin asymmetries (TSSAs) [9]. This tension spawned the development of two QCD-based frameworks [10,11]. One is based on transverse-momentum-dependent (TMD) parton distribution functions (PDFs) [12] or fragmentation functions (FFs) [13,14], and the other is on high twist PDFs or FFs under twist-3 collinear factorization [15–17]. The high twist framework applies to measurements with a single hard scale, while the TMD framework applies to processes where there is another soft scale in addition to the hard scale, which can be as small as Λ_{QCD}. It has been shown that these approaches describe the same physics in the kinematic region where they overlap [18,19]. The high twist formalism attributes TSSA to multiparton correlation functions [15–17]. In the TMD approach, TSSAs arise from the TMD PDF or FF, most notably the Sivers [12] and Collins functions [13,14], which encapsulate initial- and final-state spin-momentum correlations within a factorized description. TMD functions play a crucial role in advancing our understanding of the three-dimensional structure of the nucleon in momentum space.

The Collins fragmentation function, one of the key TMD FFs, describes the azimuthal distribution of hadrons produced from a fragmenting transversely polarized quark. An important process to probe Collins fragmentation functions is the study of the azimuthal asymmetries of hadrons inside jets, i.e., Collins asymmetry, from transversely polarized proton-proton collisions [20], which are available only at the Relativistic Heavy Ion Collider (RHIC) [21]. The Collins asymmetry in $p^{\uparrow}p$ collisions arises from the convolution of the collinear quark transversity with the TMD Collins FF [20,22,23], $H^{\perp}_{1\pi/q}(z, j_T, Q)$. Here, Q is the TMD factorization scale, z is the hadron momentum fraction within the jet, and j_T is the hadron momentum transverse to the jet axis. The transversity distribution describes the transverse polarization of quarks in a transversely polarized proton. Study of the Collins FF provides an excellent opportunity to investigate fundamental QCD properties such as factorization, universality, and evolution of TMDs. It has been shown that the Collins FF measured for hadrons within reconstructed jets in $p^{\uparrow}p$ collisions is universal [20,22], i.e., the same as in semi-inclusive deep-inelastic scattering (SIDIS) and e^+e^- collisions. The Q dependence is generally referred to as TMD evolution. It must be inferred from experiment because it includes a contribution that cannot be calculated perturbatively [24,25]. One has to introduce a prescription for the nonperturbative part, and a moderate but visible suppression of the Collins asymmetry has been predicted with the growth of Q^2 in SIDIS and pp collisions [22,25,26]. In contrast, a significant suppression of the Sivers asymmetry in W/Z production in pp collisions has also been predicted [24,27–31].

Recently, the STAR experiment [32] at RHIC made the first, and, to date, only observations of the Collins asymmetry of $\pi^{\pm}$ in jets in $p^{\uparrow}p$ collisions. This was achieved at $\sqrt{s} = 200$ GeV with high statistics [8] and also at 500 GeV with a smaller data sample [4]. These measurements provide similar coverage over the range of incident parton longitudinal momentum fraction x as the current SIDIS measurements [33–39], but at much higher values of momentum transfer Q^2. This positions STAR as an ideal setting to test the evolution of TMD functions. The STAR Collins asymmetry measurements at $\sqrt{s} = 200$ and 500 GeV at mid-rapidity were compared over their common region of $x_{\mathrm{T}} = 2p_{\mathrm{T,jet}}/\sqrt{s}$, thus allowing for comparisons of measurements at similar momentum fraction regions ($x \simeq x_{\mathrm{T}} e^{\pm\eta}$). The results were statistically consistent, suggesting that the Collins effect has a weak energy dependence in hadronic collisions [8]. However, the comparatively small size of the existing 500 GeV data sample [4] limited the conclusions that could currently be drawn, thereby preventing any determination of TMD-evolution effects.

In this Letter, the STAR Collaboration presents high-precision measurements of the Collins asymmetry for $\pi^{\pm}$ in jets from transversely polarized $p^{\uparrow}p$ collisions at $\sqrt{s} = 510$ GeV, based on a dataset with 13 times the luminosity of the previously published 500 GeV results [4]. Comparing these findings with the 200 GeV results [8] places strong constraints on the TMD evolution of the Collins function. Currently, our understanding of TMD evolution is far less complete than that of collinear evolution, and experimental measurements of Collins asymmetry in pp processes at different energies have also been rather scarce. Additionally, the results are compared with theoretical predictions using quark transversity and Collins fragmentation functions derived from SIDIS and electron-positron annihilation, providing an important test of the universality of the Collins fragmentation function across different processes.

The data were collected by the STAR experiment in 2017 from transversely polarized $p^{\uparrow}p$ collisions at $\sqrt{s} = 510$ GeV. The integrated luminosity was about 320 pb^{-1} with an average beam polarization of $55.0 \pm 1.4\%$ [40]. The detector subsystems utilized for this analysis included the time projection chamber (TPC) [41], the barrel [42] and endcap (BEMC and EEMC) [43] electromagnetic calorimeters, and the time-of-flight (TOF) [44,45] detector. Events were selected using jet patch (JP) triggers, which required the transverse electromagnetic energy within a 1.0×1.0 region in pseudorapidity (η) $\times$ azimuth (ϕ) space in the BEMC and EEMC to exceed one of several predefined energy thresholds.

The analysis procedures closely followed those of the previous STAR measurements at 200 GeV [8] and 500 GeV [4]. Jets were reconstructed using the anti-k_T algorithm [46] with a resolution parameter $R = 0.5$ to reduce the contributions from soft background. Collins asymmetries were calculated for hadrons with $0.1 < z < 0.8$ within jets spanning $0 < \eta < 0.9$ relative to the polarized beam. To further limit backgrounds and minimize the underlying-event-subtraction uncertainty, an upper limit on j_{T} was enforced as in [8], which was optimized with respect to $p_{\mathrm{T,jet}}$ and hadron z to exclude hadrons within the kinematic region dominated by the underlying event. A similar requirement, $j_{\mathrm{T}} \leq j_{\mathrm{T,max}} = \min\{[(0.0093 + 0.2982 \cdot z) \cdot p_{\mathrm{T,jet}}], 2.5\ \mathrm{GeV}/c\}$, was imposed for hadrons to be included in the Collins asymmetry calculations in this analysis. A minimum distance between the hadron and the jet axis, $\Delta R_h = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, was set in the previous measurements [4,8] to ensure a robust reconstruction of the Collins angles. This cut is tightly correlated with both hadron z and j_{T} and can be approximated by $j_{\mathrm{T,min}} \approx z \times \Delta R_{\mathrm{h,min}} \times p_{\mathrm{T,jet}}$. It was set to 0.05 in the 200 GeV analysis. To align the acceptance in the current analysis at a given z and x_{T} with the 200 GeV measurement, this minimum distance was reduced to 0.02. This necessitated a finite angular resolution correction to the measured asymmetries of 25% for the lowest $p_{\mathrm{T,jet}}$ jets, dropping to 10% at $p_{\mathrm{T,jet}} = 14\ \mathrm{GeV}/c$ and $\leq 5\%$ at $p_{\mathrm{T,jet}} > 30\ \mathrm{GeV}/c$.

Charged pion candidates were selected if their ionization energy loss (dE/dx_{meas}) in the TPC was consistent with the calculated value for pions of the measured momentum ($dE/dx_{\pi,\mathrm{calc}}$). The difference was normalized with the experimental resolution ($\sigma_{dE/dx}$) [47] to obtain

$$n_{\sigma}(\pi) = \frac{1}{\sigma_{dE/dx}} \ln\left(\frac{dE/dx_{\mathrm{meas}}}{dE/dx_{\pi,\mathrm{calc}}}\right). \qquad (1)$$

Along with the TPC, TOF was used to improve the pion purity for momenta up to approximately 3 GeV/c by measuring the particles' arrival times. The TOF measurement was normalized to

$$n_{\sigma,\mathrm{TOF}}(\pi) = \frac{\mathrm{TOF}_{\mathrm{meas}} - \frac{L}{c\beta_{\pi}(p)}}{\sigma_{\mathrm{TOF}}}, \qquad (2)$$

where $\mathrm{TOF}_{\mathrm{meas}}$ is the measured flight time of the particle, L is the path length, c is the speed of light, $\beta_{\pi}(p)$ is the velocity of pions at momentum p, and σ_{TOF} represents the resolution of the TOF time measurement. To identify the pions, $n_{\sigma}(\pi)$ was constrained to lie in the range $(-1, 2)$. In regions where TOF is effective, $n_{\sigma,\mathrm{TOF}}(\pi)$ was additionally limited to $(-5, 3)$, further enhancing pion purity.

Simulated events were used to calculate corrections to the jet kinematics and to estimate the associated systematic uncertainties. They were generated using PYTHIA 6.4.28 [48] with the STAR-adjusted Perugia 2012 tune [49] [PARP(90) adjusted from 0.24 to 0.213 [50]]. PYTHIA events were processed through full detector simulations in Geant 3 [51]. These events were then embedded into randomly selected bunch crossing events collected during the 2017 510 GeV run to account for event pileup and beam background effects. The $p_{\mathrm{T,jet}}$, pion j_{T}, and pion z measured at the "detector level" were each corrected back to the "particle level." Here, the detector-level jets in simulation were reconstructed in the same way as in the data, using charged-particle tracks and calorimeter towers, while the particle-level jets were formed from the stable (as defined in [49]) final-state particles produced in the simulated collisions.

In transversely polarized $p^{\uparrow}p$ collisions, the Collins asymmetry of hadrons inside jets can be extracted through the spin-dependent azimuthal modulation of hadrons using the cross-ratio method,

$$A_{\mathrm{UT}}^{\sin\phi_C}\sin\phi_C = \frac{1}{P}\frac{\sqrt{N^{\uparrow}[\phi_S-\phi_H]N^{\downarrow}[(\phi_S+\pi)-\phi_H]}-\sqrt{N^{\downarrow}[\phi_S-\phi_H]N^{\uparrow}[(\phi_S+\pi)-\phi_H]}}{\sqrt{N^{\uparrow}[\phi_S-\phi_H]N^{\downarrow}[(\phi_S+\pi)-\phi_H]}+\sqrt{N^{\downarrow}[\phi_S-\phi_H]N^{\uparrow}[(\phi_S+\pi)-\phi_H]}}, \tag{3}$$

which accounts for detector efficiencies and spin-dependent luminosities [52]. $N^{\uparrow}$ ($N^{\downarrow}$) is the hadron yield when the beam spin is "up" ("down"), and P is the beam polarization. The azimuthal moment of the Collins asymmetry is isolated by the $\sin\phi_C = \sin(\phi_S - \phi_H)$ dependence, where ϕ_S is the angle between the proton polarization direction and the jet scattering plane, and ϕ_H is the pion's transverse azimuthal angle relative to the jet axis, as illustrated in Fig. 1. The jet scattering plane is defined by the incoming polarized proton beam and scattered jet momentum. In Eq. (3), ϕ_S spans the range $-\pi/2$ to $\pi/2$, and ϕ_H spans the full azimuth.

To exclude contamination from kaons, protons, and electrons, similar procedures as in the previous measurements were applied to extract the pure pion asymmetries [4,8]. In this approach, $\pi/K/p/e$-rich samples were first identified using the TPC and TOF information. Raw asymmetries, which represent linear mixtures of the pure asymmetries of each particle type, were calculated for each enriched sample. Using particle fractions determined from TOF and TPC data, the pure pion asymmetries were then extracted.

Particle identification and corresponding particle fractions $f_{i_{\mathrm{rich}}}^{j}$, which represent the fraction of particle type j in the i-rich sample, were obtained using the dE/dx from the TPC and the flight time from TOF when matching to available TOF hits, given detector acceptance and efficiency limitations. About half of the TPC tracks have TOF information. Raw asymmetries and particle fractions were determined separately in each particle-rich region with and without TOF data. The relationship between the raw and pure asymmetries is

$$\begin{pmatrix} f_{\pi_{\mathrm{rich}}}^{\pi_{\mathrm{TOF}}} & f_{\pi_{\mathrm{rich}}}^{K_{\mathrm{TOF}}} & f_{\pi_{\mathrm{rich}}}^{p_{\mathrm{TOF}}} \\ f_{K_{\mathrm{rich}}}^{\pi_{\mathrm{TOF}}} & f_{K_{\mathrm{rich}}}^{K_{\mathrm{TOF}}} & f_{K_{\mathrm{rich}}}^{p_{\mathrm{TOF}}} \\ f_{p_{\mathrm{rich}}}^{\pi_{\mathrm{TOF}}} & f_{p_{\mathrm{rich}}}^{K_{\mathrm{TOF}}} & f_{p_{\mathrm{rich}}}^{p_{\mathrm{TOF}}} \\ f_{\pi_{\mathrm{rich}}}^{\pi_{dE/dx}} & f_{\pi_{\mathrm{rich}}}^{K_{dE/dx}} & f_{\pi_{\mathrm{rich}}}^{p_{dE/dx}} \\ f_{K_{\mathrm{rich}}}^{\pi_{dE/dx}} & f_{K_{\mathrm{rich}}}^{K_{dE/dx}} & f_{K_{\mathrm{rich}}}^{p_{dE/dx}} \\ f_{p_{\mathrm{rich}}}^{\pi_{dE/dx}} & f_{p_{\mathrm{rich}}}^{K_{dE/dx}} & f_{p_{\mathrm{rich}}}^{p_{dE/dx}} \end{pmatrix} \begin{pmatrix} A_{\mathrm{UT},\pi}^{\mathrm{pure}} \\ A_{\mathrm{UT},K}^{\mathrm{pure}} \\ A_{\mathrm{UT},p}^{\mathrm{pure}} \end{pmatrix} = \begin{pmatrix} A_{\mathrm{UT},\pi_{\mathrm{rich}}}^{\mathrm{TOF}} \\ A_{\mathrm{UT},K_{\mathrm{rich}}}^{\mathrm{TOF}} \\ A_{\mathrm{UT},p_{\mathrm{rich}}}^{\mathrm{TOF}} \\ A_{\mathrm{UT},\pi_{\mathrm{rich}}}^{dE/dx} \\ A_{\mathrm{UT},K_{\mathrm{rich}}}^{dE/dx} \\ A_{\mathrm{UT},p_{\mathrm{rich}}}^{dE/dx} \end{pmatrix} \tag{4}$$

Electron fractions do not appear because $A_{\mathrm{UT},e}$ is expected [8]—and was found—to be zero. The pure asymmetries were then extracted by χ^2 minimization of Eq. (4) utilizing Moore-Penrose pseudoinversion [53,54].

Figure 2 shows the Collins asymmetries for $\pi^{\pm}$ in jets at $\sqrt{s} = 510$ GeV (solid points) as a function of the jet x_{T} compared with previously published results at 200 GeV (open points) [8]. The primary source of systematic uncertainty in A_{UT}, shown by the height of the uncertainty boxes, is trigger bias, which can reach up to 20% in certain kinematic regions. This uncertainty was estimated based on simulations, as the STAR JP trigger system may have different efficiencies for quark- and gluon-initiated jets, thereby distorting the measured asymmetries. An overall systematic uncertainty of 3.2% for the 200 GeV data and 1.4% for the 510 GeV data, arising from beam polarization, is not displayed. Systematic uncertainties are discussed further in Supplemental Material [55]. The dominant uncertainty in x_{T}, shown by the width of the uncertainty boxes, arises from jet-energy-scale uncertainties, primarily

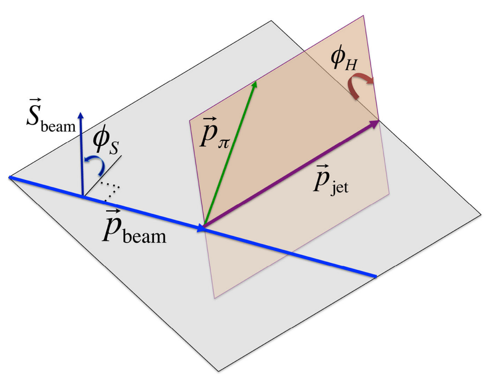

FIG. 1. Representation of the jet scattering plane along with the definitions of the azimuthal angles ϕ_S and ϕ_H [4].

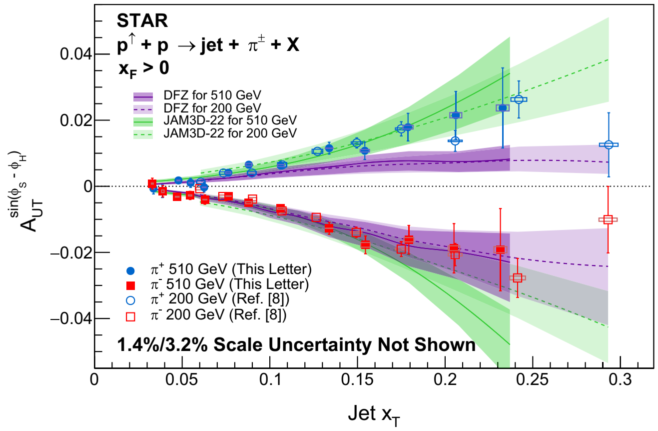

FIG. 2. Collins asymmetries, $A_{\mathrm{UT}}^{\sin(\phi_S-\phi_H)}$, as a function of jet x_{T} ($\equiv(2p_{\mathrm{T,jet}}/\sqrt{s})$) for $\pi^{\pm}$ in $p^{\uparrow}p$ collisions at $\sqrt{s}=510$ GeV (solid points) compared with previous results at $\sqrt{s}=200$ GeV (open points). Vertical bars show the statistical uncertainties; boxes show the systematic uncertainties in x_{T} and A_{UT}.

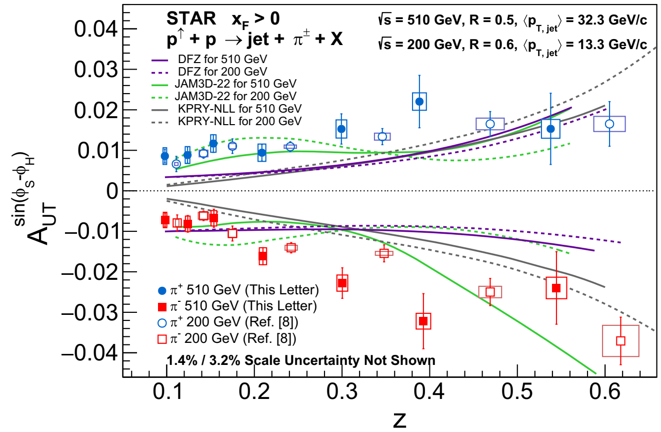

FIG. 3. Collins asymmetries, $A_{\mathrm{UT}}^{\sin(\phi_S-\phi_H)}$ as a function of $\pi^{\pm}$ longitudinal momentum fraction z in $p^{\uparrow}p$ collisions at $\sqrt{s}=$ 510 GeV and 200 GeV. Vertical bars show the statistical uncertainties; boxes show the systematic uncertainties. Model uncertainties can be found in [55].

due to the efficiency and resolution of the electromagnetic calorimeters.

The asymmetry clearly increases with jet x_{T}, consistent with the expectation that the magnitude of quark transversity grows with parton momentum fraction x. As the asymmetries here are expected to originate from the convolution of quark transversity with the Collins function, the comparison of Collins asymmetries from two energies at a fixed x_{T} (corresponding to a similar x) reflects the effect of TMD evolution. With high statistics of this analysis, a detailed comparison across different collision energies is now possible. As shown in the figure, the high-precision Collins asymmetry results at 510 GeV and 200 GeV align well within the overlap region $0.06<x_{\mathrm{T}}<0.25$, despite the corresponding Q^2 values differing by a factor of about 6. To quantify the consistency of the Collins asymmetries between the two energies, a t-test was conducted that showed no statistically significant evidence of a difference in the asymmetries [55]. This strongly suggests a surprisingly weak TMD evolution for the Collins function in hadronic interactions. Our measurements were compared with two theoretical calculations, JAM3D-22 [56] and DFZ [57]. The JAM3D-22 analysis simultaneously includes TMD and collinear twist-3 observables without TMD evolution based on global analysis of e^+e^-, SIDIS, and $p^{\uparrow}p$ data [56]. The DFZ calculation [57] employs a simplified TMD approach at leading order and a collinear configuration for the initial state based on global fit of e^+e^- and SIDIS data without TMD evolution [58]. Neither of the two models includes the previous STAR Collins results in Refs. [4,8]; the data agree well with both models with x_{T} up to ~0.2, consistent with theoretical models defined by weak energy dependence. The agreement with DFZ calculation supports the universality of the Collins function and TMD factorization.

Figure 3 shows the Collins asymmetries as a function of pion z. For the 510 GeV data, the $p_{\mathrm{T,jet}}$ range is integrated over $24.5<p_{\mathrm{T,jet}}<62.8$ GeV/c to achieve comparable jet x_{T} values to the 200 GeV measurement with $p_{\mathrm{T,jet}}>9.9$ GeV/c. The asymmetries increase slowly with z, and again, the results at the two energies are in good agreement under t-tests [55]. The data are compared with three theoretical calculations: KPRY [22], JAM3D-22, and DFZ. The KPRY calculation uses a framework combining collinear and TMD factorization. KPRY includes TMD evolution, extending to next-to-leading logarithmic accuracy, and is based on a global analysis of e^+e^- and SIDIS data [25]. All three models follow the trend of our data in general, with weak energy dependence. Again, the comparison of our $p^{\uparrow}p$ data with the KPRY and DFZ calculation provides a test of the universality of the Collins function and TMD factorization in this process, since they fit only SIDIS and e^+e^- data.

Figure 4 shows the Collins asymmetries as a function of pion j_{T} in four hadron-z bins, with the same $p_{\mathrm{T,jet}}$ ranges as Fig. 3. The (j_{T},z) dependence of the Collins asymmetries at the same x_{T} is consistent at the two beam energies, again indicating a very weak energy dependence of the Collins effect in hadronic collisions. These results are also compared with theoretical models, JAM3D-22 and DFZ. Both models generally follow the experimental data trend, yet significant discrepancies remain, in particular when j_{T} and z are both large. Thus, these data offer crucial constraints on Collins fragmentation functions.

In summary, the STAR Collaboration presents high-precision measurements of the Collins asymmetries for $\pi^{\pm}$ inside jets from transversely polarized $p^{\uparrow}p$ collisions at $\sqrt{s}=510$ GeV. These new results reveal an excellent consistency with previous measurements at 200 GeV over

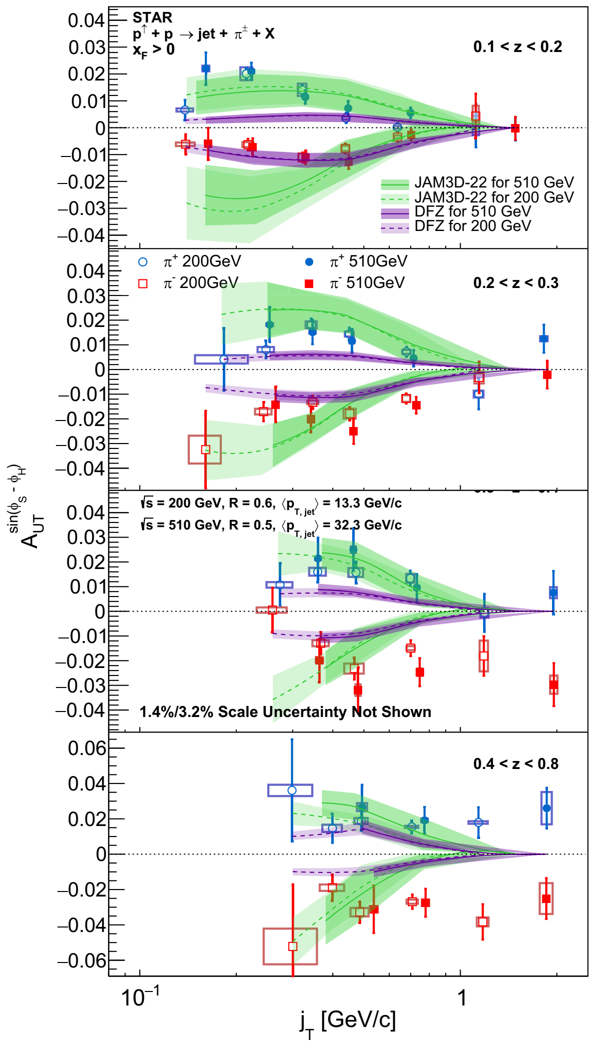

FIG. 4. Collins asymmetries, $A_{\mathrm{UT}}^{\sin(\phi_S-\phi_H)}$, as a function of the $\pi^{\pm}$ momentum transverse to the jet axis, j_{T}, in four longitudinal momentum fraction z bins. The solid points show the results from this analysis of $\sqrt{s}=510$ GeV $p^{\uparrow}p$ collisions with an average $\langle p_{\mathrm{T,jet}}\rangle = 32.3$ GeV/c, while the open points show the results from $\sqrt{s}=200$ GeV $p^{\uparrow}p$ collisions with an average $\langle p_{\mathrm{T,jet}}\rangle =$ 13.3 GeV/c [8]. Vertical bars show the statistical uncertainties, and boxes show the systematic uncertainties in j_{T} and A_{UT}.

the common x_{T} region, providing evidence for no significant energy evolution of the Collins asymmetry in hadronic interactions. The results are in good agreement with theoretical models that do not implement TMD evolution. This apparent energy independence is in striking contrast to predictions that TMD evolution of the Sivers function leads to a substantial suppression of TSSA for $W^{\pm}$ production [24,27–30].

A good agreement between our pp data and theoretical models (KPRY and DFZ) that include only $e^{+}e^{-}$ and SIDIS data supports the universality of the Collins function and TMD factorization in this process. Discrepancies are still observed in the results versus j_{T}, indicating the need for an improved theoretical understanding of the physics in this region. These results provide essential information on transverse spin-dependent effects, especially regarding quark transversity and Collins fragmentation functions. With upgraded detectors at forward rapidities, STAR collected additional datasets at both 200 GeV and 510 GeV, which represent the final opportunity in the near term to explore the factorization, universality, and evolution of the Collins asymmetry. In the long term, these pp data will provide the baseline for the ultimate universality test when compared to similar measurements in ep collisions at the future Electron-Ion Collider (EIC).

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Data availability—The data that support the findings of this Letter are openly available [59].

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