PROCEEDINGS OF SCIENCE

STAR Results on Transversity and TMD-Related Observables

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Constructing a three-dimensional understanding of the proton's structure has gained much interest. Theoretical frameworks, such as the transverse-momentum-dependent (TMD) framework, have been developed to describe the three-dimensional structure of the proton. In the TMD framework, the proton structure is described in terms of TMD parton distribution functions (PDFs) and fragmentation functions (FFs). Utilizing the transversely polarized proton beams accelerated and maintained by the Relativistic Heavy Ion Collider (RHIC), the Solenoidal Tracker At RHIC (STAR) experiment measures observables sensitive to transversity and TMD physics in pp collisions center-of-mass energies of 200 and 510 GeV. The transverse single-spin asymmetries (A_N) of electromagnetic jets in the forward direction provide insights into the origin of the large inclusive hadron A_N observed at forward rapidity. The Sivers effect is probed using the shift in the opening angle of dijets and A_N measurements of $W^{\pm}$ and Z^0. The convolution of collinear transversity PDF and the Interference FF is investigated via the spin-dependent di-hadron correlators. The Collins effect describing the convolution of the collinear transveristy PDF and the Collins FF is measured via the azimuthal modulations of identified hadrons in jets. Measurements of $\Lambda(\bar{\Lambda})$ hyperon transverse spin transfer offer insights into the (anti-)strange quark transversity. These proceedings discuss the recent STAR highlights and updates related to transversity and TMD physics and provide a brief overview of future STAR measurements.

7th International Workshop on "Transverse phenomena in hard processes and the transverse structure of the proton",
03-07 June 2024
University of Trieste, Trieste, Italy

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1. Introduction

Since the 1970's, a surprising large transverse single spin asymmetry (A_N) has been observed in transversely polarized pp collisions [1]. This asymmetry is characterized by certain final state hadrons being preferentially produced to the left with respect to the polarization of the proton, while others are preferentially produced to the right. However, the leading-twist collinear perturbative quantum chromodynamics predicted a small asymmetry [2], which motivated the development of the twist-3 [3–5] and Transverse-Momentum-Dependent (TMD) [6–9] theoretical frameworks to describe the large observed A_N.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the only accelerator in the world that is capable of colliding high-energy beams of polarized protons at a center-of-mass energy of up to 510 GeV. The Solenoidal Tracker at RHIC (STAR) detector [10] is located at the six o'clock position with respect to the RHIC acceleration rings and offers excellent mid-rapidity tracking, particle identification, and electromagnetic calorimetry coverage in the full azimuthal range. Figure 1 shows the kinematic coverage of STAR compared to Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments, where the x coverage is similar between STAR and SIDIS [11]. However, STAR covers up to two orders of magnitude higher Q^2 values. The proton beam polarization capabilities of RHIC, acceptance of the STAR sub-detectors, and the kinematic coverage of STAR poise STAR as an excellent experiment to probe observables related to the transversity PDF and TMD-related observables.

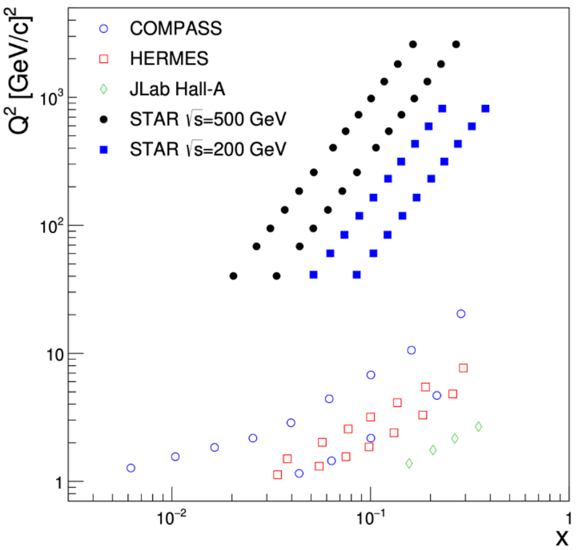

Figure 1: Kinematic coverage of STAR in Q^2 vs. x space compared to SIDIS experiments [11].

2. Sivers Effect

The Sivers effect describes the relationship between the transverse momentum distribution of unpolarized partons and the transverse spin polarization of the proton [8]. STAR has recently probed this effect using dijet production [12]. A transversely polarized proton going in the longitudinal direction can have partons with a spin-dependent transverse momentum (k_T). The direction of k_T

depends on the polarization of the proton, which affects the dijet opening angle. The asymmetry in the dijet opening angle provides sensitivity to the spin-dependent k_T that characterizes the Sivers effect. Figure 2 shows the mean spin-dependent k_T as a function of the combined η of both jets in the dijet, where $\eta^{total} \propto \ln(x_1/x_2)$. Jet charge tagging combined with unfolding is used to determine the quark flavor. u quarks tend to produce more positively charged particles relative to the more negatively charged particles produced by d quarks, which is utilized to bin the data in enhanced u or d quark fractions. Parton fractions from simulation allow for measuring the individual parton spin-depended $\langle k_T \rangle$. The results show that the d-quark $\langle k_T \rangle$ is twice as large as the u-quark $\langle k_T \rangle$ and in the opposite direction, while the $\langle k_T \rangle$ for gluon and sea quarks combined is consistent with zero. This STAR result shows, for the first time, evidence of non-zero Sivers effect in dijet production from pp collisions.

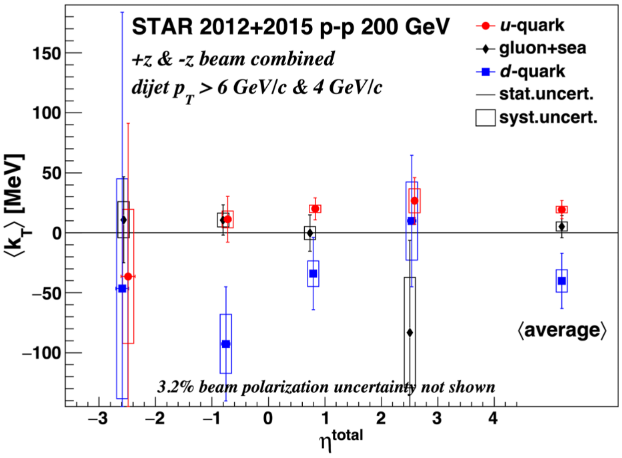

Figure 2: STAR results of the mean spin-dependent k_T vs. η^{total} from dijet production [12].

The Sivers TMD function can be accessed by studying the left and right asymmetry of $W^{\pm}$ boson production with respect to the spin of the proton. STAR performs this measurement using pp collisions at a center-of-mass energy of 510 GeV. The recoil against the $W^{\pm}$ is used to reconstruct the p_T of the bosons, which avoids having to reconstruct the elusive neutrino. The current STAR preliminary results shown in Fig. 3 are consistent with model predictions from [13] and will have the biggest impact on the high-x region of the quark TMD Sivers function. Here, $Q^2 = M_W^2 \sim$ 6500 GeV^2. STAR also measured the Z^0 A_N [14], and the result agrees with the two theoretical models [13, 15] shown in Fig. 4. However, due to the limited statistics, no conclusive statement can be drawn regarding the sign-change hypothesis of the Sivers function. This result will allow for the extraction of the Sivers TMD PDF, especially for valence quarks in the region of $x \geq 0.1$. These new $W^{\pm}/Z^0$ A_N measurements offer a significant statistical improvement compared to the first $W^{\pm}/Z^0$ A_N STAR measurements [16].

Previous STAR results investigating the large forward A_N using electromagnetic jets (EM-jets) and identified π^0 in EM-jets [17] suggested that a diffractive process could contribute to the large observed forward A_N. Figure 5 shows recent preliminary results by the STAR collaboration for the contribution of a single-diffractive process to the observed large forward A_N using EM-jets from pp collisions at 200 GeV. The rapidity gap events refer to events where no activity is detected in the pseudorapidity range of $-5 < \eta < -2$, which significantly suppresses the non-diffractive events.

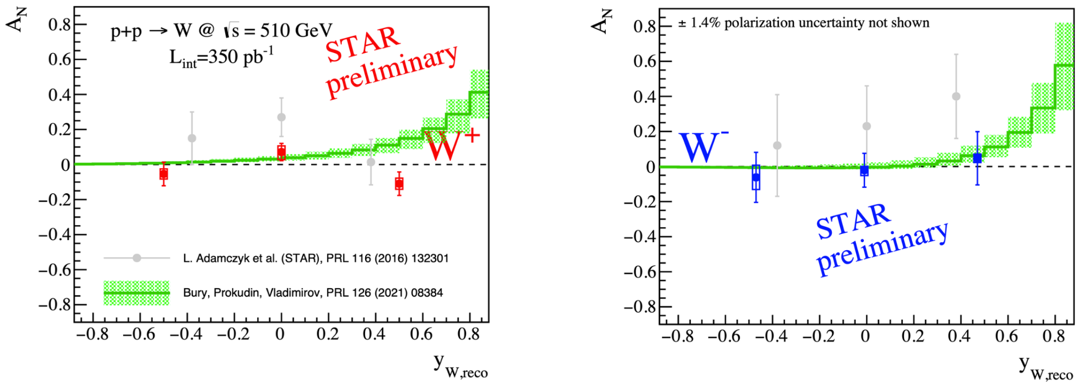

Figure 3: STAR results of $W^{\pm}$ A_N as a function of the reconstructed boson's rapidity. Left(Right) shows the asymmetry for $W^{+(-)}$

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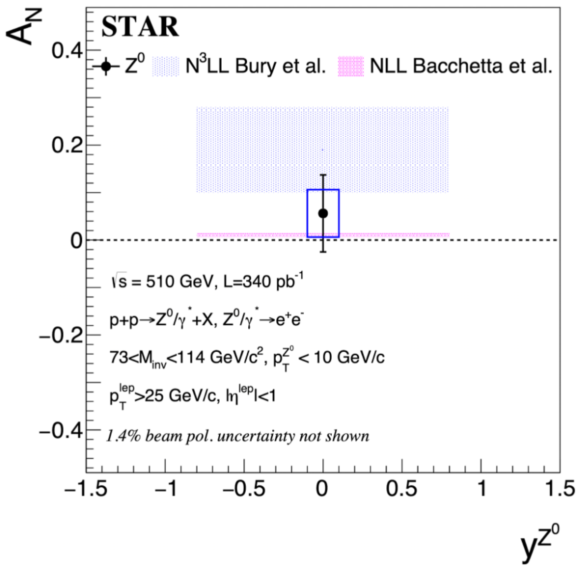

Figure 4: STAR results of the Z^0 A_N as a function of the rapidity of the Z^0 [14].

When compared to the inclusive and rapidity gap events, the single diffractive events show similar A_N values. Therefore, the current results do not provide evidence in favor of a diffractive process having a large contribution to the observed large forward A_N. STAR has also investigated the inclusive jet asymmetry at mid-rapidity, which is sensitive to the twist-3 correlators associated with the gluon Sivers function. Figure 6 shows the inclusive jet asymmetry as a function of jet x_T in two different x_F bins. This new result is compared to the published results at center-of-mass energy of 200 GeV [11], and both beam energy results are consistent with zero for the measured asymmetry. Additionally, the preliminary new results at $\sqrt{s}$ = 510 GeV extend the measurement to lower jet x_T values.

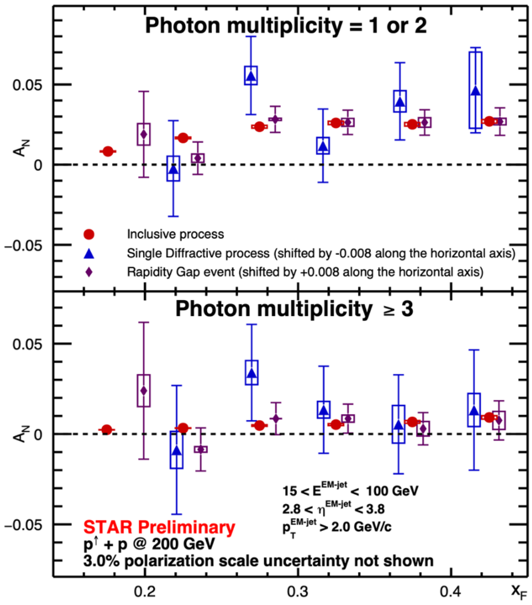

Figure 5: STAR results of the forward EM-jet A_N as a function of x_F in two photon multiplicity bins.

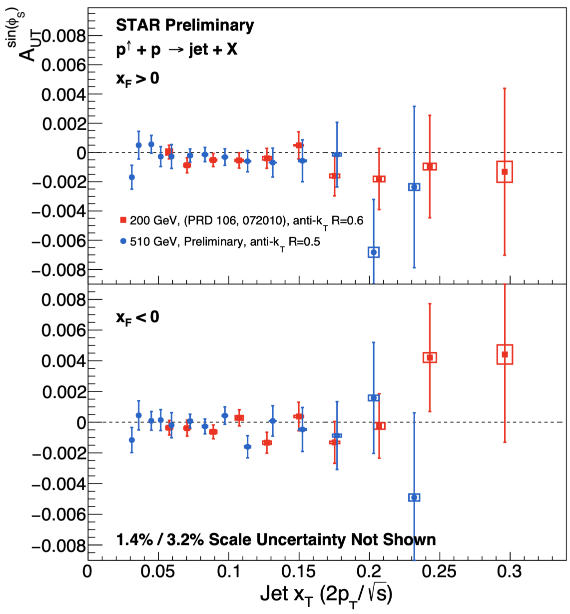

Figure 6: STAR results of the mid-rapidity jet asymmetry as a function of jet x_T in two x_F bins.

3. Collins Effect

In pp collisions, the Collins effect describes the relationship between the initial state collinear transversity PDF and the final state Collins FF [9, 18, 19]. This effect manifests itself as an azimuthal modulation of final-state hadrons with respect to the parent jet axis [20, 21]. The relative difference of the spin-depended cross section for this process is given by [21]:

$$\frac{d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)}{d\sigma^{\uparrow}(\phi_S,\phi_H) + d\sigma^{\downarrow}(\phi_S,\phi_H)} \propto A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + A_{UT}^{\sin(\phi_S-\phi_H)} \sin(\phi_S - \phi_H) + A_{UT}^{\sin(\phi_S-2\phi_H)} \sin(\phi_S - 2\phi_H) + \ldots \quad (1)$$

where the $A_{UT}^{\sin(\phi_S-\phi_H)}$ asymmetry amplitude is sensitive to the transversity PDF convoluted with the Collins FF. STAR has recently made a preliminary measurement of the Collin asymmetry in polarized pp collisions at a center-of-mass energy of 510 GeV and compared it to previously published results at 200 GeV [11]. Figure 7 shows that the asymmetries from both beam energies agree well with each other and indicate little, if any, energy dependence. It is worth noting that the Q^2 values differ by a factor of 6 between the 200 and 510 GeV results.

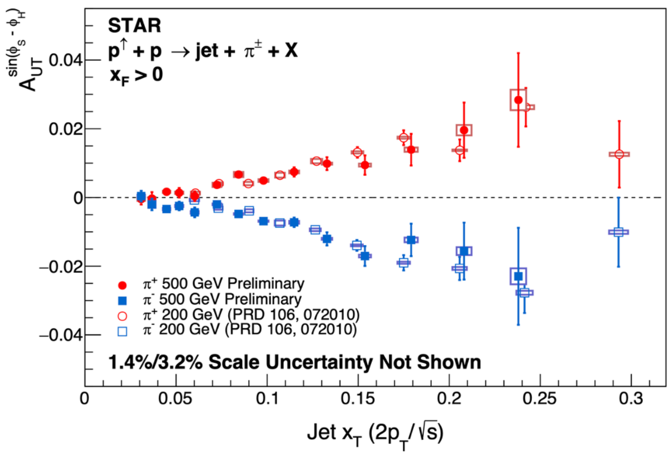

Figure 7: A comparison between recent preliminary measurement of the Collins asymmetry in pp collisions at a center-of-mass energy of 510 GeV and previously published STAR results of the Collins asymmetry in pp collisions at a center-of-mass energy of 200 GeV [11].

STAR measured the $\Lambda(\bar{\Lambda})$ hyperon transverse spin transfer (D_{TT}), which gives access to the (anti-)strange quark transversity PDF in the proton [22]. Figure 8 shows D_{TT} as a function of the hyperon transverse momentum ($p_{T,\Lambda(\bar{\Lambda})}$), where the D_{TT} values for both Λ and $\bar{\Lambda}$ are consistent with each other within uncertainties and are also consistent with zero. Measurement of the di-pion asymmetry at both 200 and 510 GeV center-of-mass energies have been performed at STAR, where the asymmetry gives access to the collinear transversity PDF. The di-pion cross section has also been measured at 200 GeV. Both the asymmetry and the cross-section measurements can pave the way to a model-independent extraction of the transversity PDF. For more details, see Ref. [23].

4. Outlook

The forward upgrade was installed and commissioned at STAR before 2022. This upgrade extends the pseudorapidity range of the forward tracking and electromagnetic and hadronic calorimetry to $2.5 < \eta < 4$, which enables new measurement capabilities at STAR, such as $h^{\pm}$, γ, π^0, jets, and hadrons in jet. It also allows sensitivity to quarks up to $x \sim 0.5$ and gluons down to $x \sim 0.001$.

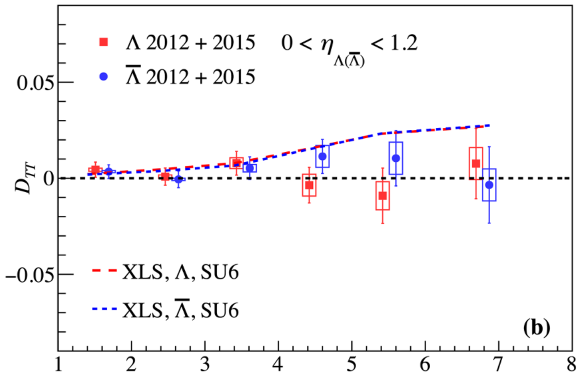

Figure 8: STAR result for the Λ and $\bar{\Lambda}$ hyperon spin transfer at 200 GeV center-of-mass energy [22].

Additionally, the forward upgrade combined with the midrapidity STAR capabilities complement the future Electron-Ion Collider kinematics. It also bridges the region between mid-rapidity STAR and Semi-Inclusive Deep Inelastic Scattering, which is beneficial for future studies, such as the Collins effect.

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