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Constraining Transversity and Nucleon Transverse-polarization Structure Through Polarized-proton Collisions at STAR

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Current knowledge of nucleon transverse-polarization structure comes from measurements of transverse single-spin asymmetries (SSAs) from semi-inclusive deep inelastic scattering (SIDIS). These measurements, combined with those of e^+e^- collisions, have allowed the first extractions of transversity with limited constraints at higher values of Bjorken-x. One avenue to enrich understanding over a different kinematic range is jet+hadron and di-hadron production from polarized-proton collisions. Through these channels, the STAR detector at RHIC has for the first time observed SSAs due to the effects of transversity coupled to the Collins and interference fragmentation functions (IFFs) in polarized-proton collisions at $\sqrt{s} = 200$ and 500 GeV. In addition to transversity, the distribution of pions within jets may also provide a window into gluon linear polarization. Furthermore, the comparison of all asymmetry moments at 200 GeV and 500 GeV may yield insight into longstanding theoretical questions concerning evolution, universality, and factorization breaking in non-collinear formulations of pQCD. Preliminary results from the jet+hadron and di-hadron analyses at $\sqrt{s} = 200$ and 500 GeV will be presented, including the first observations of transversity effects in polarized-proton collisions and the first-ever measurements offering constraints on models involving gluon linear polarization.

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1. Introduction

The momentum structure of the nucleon at leading-twist can be described by three parton distribution functions (PDFs): the unpolarized parton distribution, $f(x)$; the helicity parton distribution, $\Delta f(x)$; and the transversity distribution, $h_1(x)$ [1]. Of the three, transversity, which describes the transverse polarization of quarks inside a transversely polarized nucleon, has proven the most difficult to probe, due to its chiral-odd nature. Many advances in understanding transversity have been made through the study of azimuthal transverse single-spin asymmetries, A_{UT}. Such studies in polarized-proton collisions present a challenge and an opportunity. To account for nonzero A_{UT} from high-p_T hadroproduction (e.g. Ref. [2]) one is challenged to understand pQCD beyond the collinear formulation at leading twist [3]. By so doing, one gains the opportunity for insight into the transverse polarization structure of the nucleon.

Two approaches that can generate nonzero A_{UT} in pQCD are to formulate collinear pQCD to account for higher twist multi-parton correlators (twist-3 formalism) [4, 5] or to formulate pQCD to account for intrinsic transverse momentum dependence (TMD formalism) [6]. In the twist-3 formalism one can obtain asymmetries, in principle, from both the initial state and the fragmentation functions (e.g. Ref. [7]). Similarly, in the TMD formalism one can obtain asymmetries, in principle, from both the PDFs (the so-called "Sivers effect") [6] and the fragmentation functions, e.g. the so-called "Collins effect" [8]. Furthermore, it has been shown that the intrinsic transverse momentum integrals of the TMD functions are closely related to the twist-3 functions (e.g. Ref. [9]).

Over the past decade, experiments in semi-inclusive deep-inelastic scattering (SIDIS) have provided the first measurements of TMD observables (e.g. Ref. [10]). These, combined with independent measurements of the Collins fragmentation function by e^+e^- experiments [11], have enabled the first extractions of the transversity PDF (e.g. Ref. [12]). The kinematic limitations of current datasets leave the transversity extractions relatively imprecise for $x \gtrsim 0.2$.

One avenue to enrich understanding of nucleon spin structure is through jet production from high-energy polarized-proton collisions [13]. By measuring the spin-dependent, azimuthal asymmetry in the jet production ($A_{UT}^{\sin\phi_S}$), one can access the twist-3 correlation function, related to the Sivers function. Additionally, by measuring different spin-dependent, azimuthal modulations in the distribution of hadrons within a jet ($A_{UT}^{\sin(\phi_S-\phi_H)}$ or $A_{UT}^{\sin(\phi_S-2\phi_H)}$), one can gain sensitivity to transversity or the gluon-analogue to transversity (sensitive to gluon linear polarization) coupling to spin-dependent Collins or "Collins-like" [14] fragmentation functions, respectively. Similarly to the Collins effect, one can also access transversity coupled to polarized "interference fragmentation functions" (IFF) through spin-dependent, azimuthal asymmetries in the relative orientation of two hadrons from the same parton (e.g. Refs. [15, 16]). While IFFs survive in the leading-twist, collinear formulation of pQCD with factorization expected to hold, the Collins effect depends upon TMD-factorization that is broken, in general, for high-p_T hadroproduction [17]. Thus, by studying both Collins and IFF asymmetries for overlapping kinematics, one opens the possibility to enlighten deep theoretical questions, such as TMD factorization-breaking and universality.

The STAR detector [18] at RHIC has seen the first signatures of transversity in polarized-proton collisions from charged-pion Collins [19] and IFF [20] asymmetries at $|\eta| < 1$ from 2.4 pb^{-1} at $\sqrt{s} = 200$ GeV collected in 2006. Motivated in large part to improve the precision of these measurements, in 2012, STAR integrated 22 pb^{-1} of luminosity from $p^{\uparrow} + p$ at $\sqrt{s} = 200$

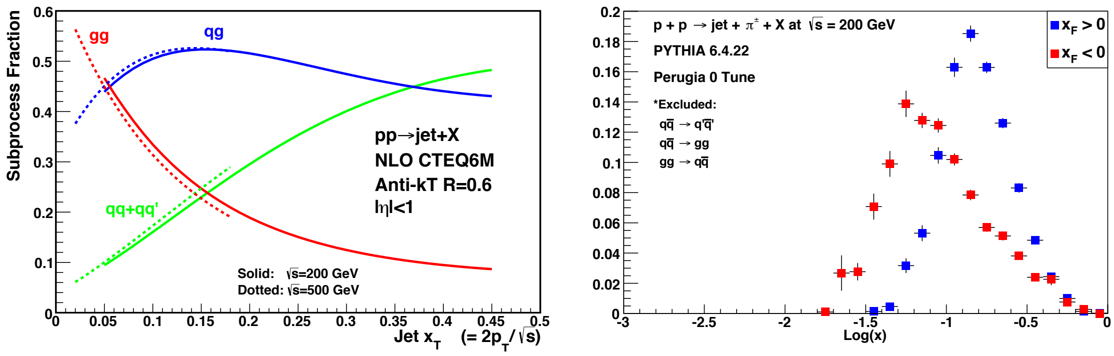

Figure 1: (left) Subprocess fractions and (right) unpolarized quark x distribution for STAR jet production. The fractions of NLO cross section [21] are shown for quark-quark, gluon-gluon, or quark-gluon interactions and presented as functions of jet x_T across a range of $5 < p_T < 45$ GeV$/c$ for collision energies of $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV. The unpolarized quark x distribution is shown for jets with $p_T > 10$ GeV$/c$ for $\sqrt{s} = 200$ GeV and separately for scattering forward ($x_F > 0$) and backward ($x_F < 0$) relative to the polarized beam.

GeV with 63% polarization. Furthermore, in 2011 STAR integrated 25 pb^{-1} of luminosity from $p^{\uparrow} + p$ at $\sqrt{s} = 500$ GeV with 53% polarization. This dataset allows the first measurements of these asymmetries at $\sqrt{s} = 500$ GeV, including the first-ever measurement of the "Collins-like" asymmetry, with sensitivity to gluonic subprocesses enhanced relative to $\sqrt{s} = 200$ GeV (Fig. 1). Comparison of all asymmetry modulations across $\sqrt{s} = 200$ and 500 GeV is expected to extend the current knowledge of these effects to broader kinematics as well as inform questions about the evolution of transversity and the TMD functions.

2. Analysis

The present data were collected with a minimum-bias trigger (VPDMB), requiring a coincidence in STAR's vertex position detector (VPD) [22], as well as with "jet-patch" triggers, requiring patches of energy in STAR's barrel (BEMC) and endcap (EEMC) electromagnetic calorimeters [18]. Jets are reconstructed using the "anti-k_T" algorithm [23] with a radius of 0.6 for $\sqrt{s} = 200$ GeV or 0.5 for $\sqrt{s} = 500$ GeV and utilize energy deposition in the BEMC and EEMC as well as charged-particle tracks from STAR's time projection chamber (TPC) [18].

Descriptions of the analysis techniques and simulation studies for the jet measurements are given in Refs. [24, 25, 26], while those for the IFF measurements are given in Refs. [20, 27, 28]. For jets, the dominant systematic uncertainties arise from jets reconstructed at the detector level that fail to match to one at the parton-jet level. Additional systematic uncertainties come from the contamination of kaons, protons, and electrons to the charged-pion signal; trigger bias; the "leak-through" of competing effects coupling to non-uniform detector acceptance; uncertainties from calorimeter gains, efficiencies, and response to charged hadrons; tracking efficiency; and Monte Carlo simulation statistics. Measured asymmetries for $\sqrt{s} = 500$ GeV are corrected for smearing due to finite azimuthal-angle resolution, while those for $\sqrt{s} = 200$ GeV account for this effect with a systematic uncertainty.

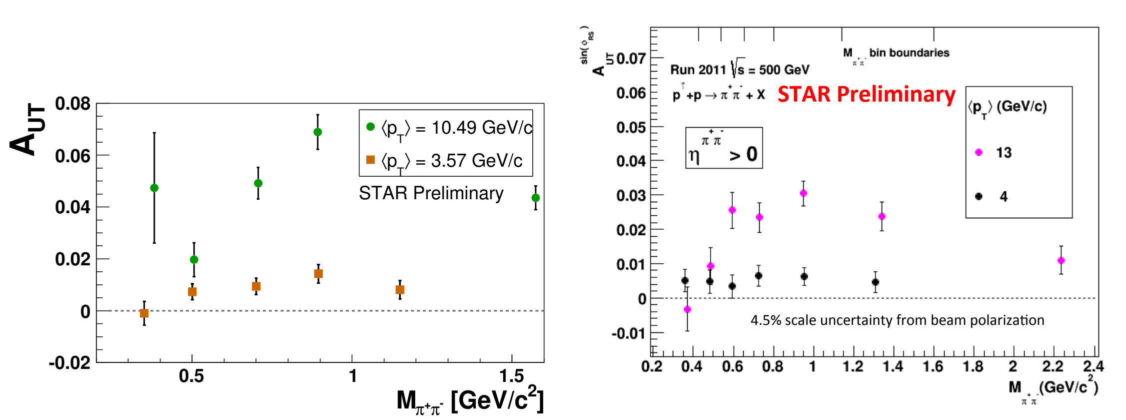

Figure 2: STAR preliminary charged-pion IFF asymmetries for (left) $\sqrt{s} = 200$ GeV [28] and (right) $\sqrt{s} = 500$ GeV [27]. Asymmetries are shown as functions of two-pion invariant mass for two bins of two-pion p_T. For both $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV, the asymmetries show qualitatively similar behavior with a strong dependence upon p_T.

3. Results

Figure 2 shows STAR preliminary charged-pion IFF asymmetries for $\sqrt{s} = 200$ GeV [28] (collected in 2012) and $\sqrt{s} = 500$ GeV [27] (collected in 2011) as functions of two-pion invariant mass, $M_{\pi^+\pi^-}$. The asymmetries are each presented for $\eta_{\pi^+\pi^-} > 0$ (relative to the polarized beam) in two bins of two-pion p_T. For both $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV, the asymmetries show qualitatively similar behavior, though the data have not yet been robustly examined for a quantitative comparison. The asymmetries show a strong dependence upon p_T and a slower dependence upon invariant mass.

Figure 3 shows STAR preliminary charged-pion Collins asymmetries for $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV as functions of $z = p_\pi / p_{\text{jet}}$. The asymmetries are each presented for $\eta_{\text{jet}} > 0$ (relative to the polarized beam). Selection criteria for the $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV datasets are chosen so that the two sets have roughly the same x_T. For the $\sqrt{s} = 200$ GeV data, jets are required to have $p_T > 10$ GeV$/c$ with $\langle p_T \rangle = 12.9$ GeV$/c$; while for the $\sqrt{s} = 500$ GeV data, jets are required to have $22.7 < p_T < 55$ GeV$/c$ with $\langle p_T \rangle = 31.0$ GeV$/c$. It is expected that the datasets will have sensitivity across a range of $0.1 \lesssim x \lesssim 0.3$ (Fig. 1 and Ref. [26]). In order to ensure further that the two datasets span the same kinematic phase space, the data are compared for two different sets of restrictions on the minimum hadron radius, $\Delta R = \sqrt{(\eta_{\text{jet}} - \eta_\pi)^2 + (\phi_{\text{jet}} - \phi_\pi)^2}$. To ensure robust determination of the azimuthal orientation of the pion about the jet axis, ΔR is required to be above a minimum threshold. However, such a cut also restricts the sampled kinematic phase space, since

$$j_{T,\min} \approx z \times \Delta R_{\min} \times \langle p_{T,\text{jet}} \rangle, \tag{3.1}$$

where j_T is the pion transverse momentum measured relative to the jet axis. Thus, in Fig. 3, the data are presented for two sets of ΔR cuts: (top) $\Delta R > 0.1$ for $\sqrt{s} = 200$ GeV and $\Delta R > 0.04$ for $\sqrt{s} = 500$ GeV and (bottom) $\Delta R > 0.25$ for $\sqrt{s} = 200$ GeV and $\Delta R > 0.1$ for $\sqrt{s} = 500$ GeV. For the more restrictive ΔR threshold shown in the bottom panel, the asymmetries are consistent with

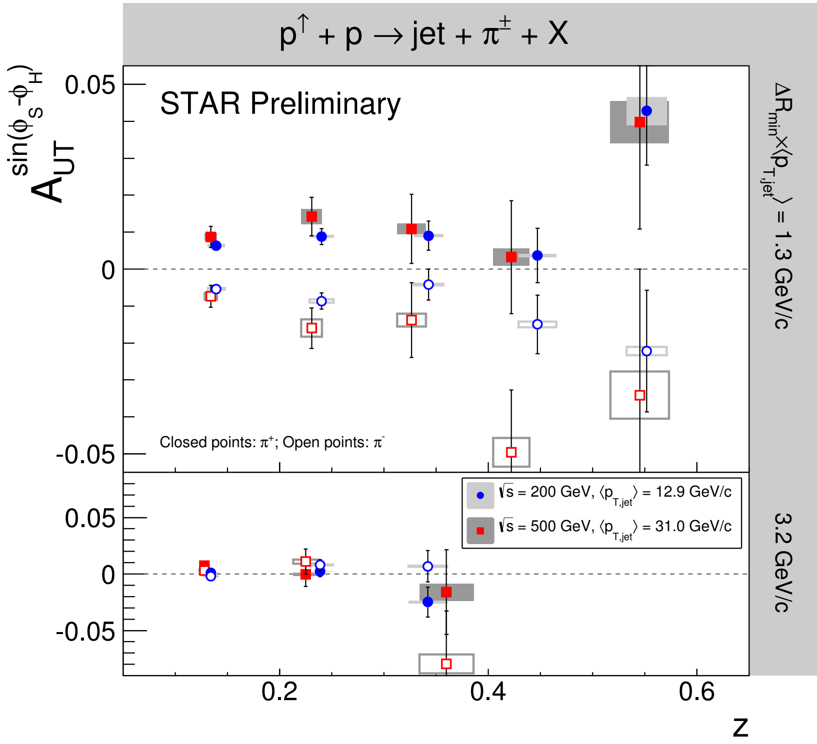

Figure 3: STAR preliminary charged-pion Collins asymmetries for $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV [25, 29, 26]. Asymmetries are shown as functions of pion z for two bins of $\Delta R_{\text{min}} \times \langle p_{T,\text{jet}} \rangle$. Within the current precision, STAR Collins asymmetries are consistent with x_T scaling.

zero. In contrast, when the ΔR threshold is relaxed, as shown in the top panel, the asymmetries for both $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV are nonzero with positive asymmetries for π^+ and negative asymmetries for π^-. This dependence on ΔR_{min} demonstrates a strong dependence upon pion j_T that can be seen explicitly for the $\sqrt{s} = 200$ GeV data in Ref. [26]. Furthermore, within the current precision, the preliminary asymmetries are consistent with x_T scaling between $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV.

As can be seen in Refs. [24, 25], at $\sqrt{s} = 500$ GeV the inclusive jet asymmetry, $A_{UT}^{\sin\phi_S}$, sensitive to the twist-3 correlation function [4, 5] (related to the Sivers function [6]), is consistent with zero across the range of $6 < p_{T,\text{jet}} < 55$ GeV$/c$. This is consistent with previous measurements at $\sqrt{s} = 200$ GeV [30] but with improved limits and enhanced sensitivity to gluonic subprocesses (Fig. 1). In addition, the Collins-like asymmetry, $A_{UT}^{\sin(\phi_S - 2\phi_H)}$, sensitive to linearly polarized gluons is measured for the first time and found to be consistent with zero, well below the maximally allowed projections of $\approx 2\%$ [13]. These data should enable the first experimental constraints on gluon linear polarization.

4. Conclusions

For the first time, the effects of transversity in polarized-proton collisions are observed in charged-pion IFF and Collins asymmetries at both $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV. At the current precision, the preliminary Collins asymmetries are consistent with x_T scaling. The STAR data are expected to probe an x-range complementary to existing data from SIDIS at higher values of Q^2. Thus, in addition to expanding the current experimental kinematic sensitivity, the STAR data should provide the opportunity to probe theoretical questions such as TMD factorization-breaking, universality, and evolution.

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