Exploring nucleon structure and hadronization with dihadrons and hadrons in jets at STAR

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Abstract. Over the last decade, theoretical and experimental engagement of transverse-spin phenomena has unlocked tantalizing opportunities for new insights into nucleon structure and hadronization. Observables such as hadrons in jets and dihadron correlations from polarized proton collisions provide access to the transversity distribution function at a range of xcomplementary to existing semi-inclusive deep inelastic scattering (SIDIS) experiments but at a much higher range of Q^2 . Moreover, these two observables give access through two different factorization frameworks-transverse-momentum-dependent (TMD) and collinear-enabling a unique path to address questions concerning factorization-breaking and the universality of TMD functions. Data collected by STAR have revealed the first observations of transverse single-spin asymmetries in the azimuthal distributions of dihadron correlations and hadrons within jets from polarized proton collisions at both $\sqrt{s} = 500$ GeV and 200 GeV. The STAR 200 GeV dihadron data have recently been included in global analyses that for the first time include SIDIS, e^+e^- , and p + p data to extract the transversity distribution. The STAR hadron-in-jet data provide a unique opportunity to illuminate longstanding questions: Do factorization and universality extend to the TMD picture in proton-proton collisions, e.g. through the Collins mechanism? How do TMD functions evolve with changing kinematics? The STAR dihadron and hadron-in-jet data will be presented and discussed in context with the recent global analyses and model calculations.

1. Introduction

A complete understanding of nucleon structure requires knowledge of three leading-twist parton distribution functions (PDF): the unpolarized PDF, the helicity PDF, and transversity. The transversity distribution, $h_1(x)$, is related to the transverse polarization of quarks within a transversely polarized nucleon. Due to its chiral-odd nature, the transversity distribution has historically proven the most challenging of the three to access, requiring a second chiralodd distribution to be observed. Over the past several decades, theoretical work has shown that transversity can couple to spin-dependent fragmentation functions, such as the "Collins" fragmentation function [1] or dihadron fragmentation functions (e.g. Ref. [2; 3]), producing azimuthal transverse single spin asymmetries in the production of the fragmenting hadrons. In the Collins mechanism, the distribution of these hadrons is correlated with the transverse spin polarization of the parent quark, resulting in an azimuthal asymmetry in the distribution of hadrons around the axis of the jet. In the dihadron mechanism, the asymmetry manifests in the relative orientation of hadron pairs from the same parent quark. While the dihadron asymmetry survives in the collinear factorization, the Collins mechanism requires transverse-momentumdependent (TMD) factorization. In recent years, transversity has been successfully extracted through global analyses of data from semi-inclusive deep-inelastic scattering (SIDIS) and e^+e^- collisions using both the Collins (e.g. Refs. [4; 5]) and dihadron (e.g. Ref. [6]) channels. The precision of the extractions is limited by the kinematics of current SIDIS experiments, which reach $x \leq 0.3$ and $Q^2 \leq 20$ (GeV/c)². Furthermore, at the current SIDIS experiments, π^- production largely couples to u quarks, limiting sensitivity to d quark transversity.

One opportunity to expand upon the existing knowledge is to study Collins and dihadron asymmetries in polarized p+p collisions at the Relativistic Heavy Ion Collider (RHIC) [7]. RHIC is the only polarized p + p collider in the world, able to collide proton beams up to $\sqrt{s} = 510$ GeV, providing the possibility to enhance the kinematic reach in both x and Q^2 . Furthermore, p + p collisions eliminate the u-quark dominance of π^- production that is observed in SIDIS, enhancing sensitivity to d quark transversity. Studying the Collins mechanism at RHIC also enables important experimental tests of TMD factorization in p + p. TMD factorization is generally expected to be broken in p + p [8–10]. However, it has recently been argued [11] that for hadron-in-jet observables, such as the Collins mechanism, TMD factorization should hold in p + p. Moreover, since RHIC data probe substantially higher Q^2 than the SIDIS data, Collins measurements at RHIC provide important information on the kinematic evolution of TMDs.

2. Solenoidal Tracker at RHIC

The Solenoidal Tracker at RHIC (STAR) [12] is designed to collect data over the full azimuth and a pseudorapidity range $-1 < \eta < 4$. The STAR time projection chamber (TPC) and electromagnetic calorimeters enable full jet reconstruction over $-1 < \eta < 1.8$. The TPC and time-of-flight detectors give particle identification capability over $|\eta| < 1$, enabling measurements of identified hadron-in-jet as well as identified-dihadron correlations. Such events at STAR span a range of x similar to that of existing SIDIS experiments but at a substantially larger Q^2 [13; 14].



Figure 1. STAR dihadron asymmetries at $\sqrt{s} = 200[15]$ and 500 GeV[14] in comparison with model calculations based on SIDIS and e^+e^- [16]. The gray band represents the 68% confidence interval of the fit to SIDIS and e^+e^- data.

3. STAR dihadron asymmetries

STAR has observed significant azimuthal transverse single-spin asymmetries in $\pi^+\pi^-$ correlations at $\sqrt{s} = 200$ GeV [15] and 500 GeV [14]. The asymmetries exhibit a strong dependence on the transverse momentum (p_T) of the dihadron pair. Figure 1 presents a selection of the 200 and 500 GeV asymmetries that sample a similar range of $x_T = 2p_T/\sqrt{s}$, showing

reasonable consistency between the two datasets. Furthermore, the asymmetries are shown in comparison to a prediction [16] for the 500 GeV data based upon fits to SIDIS and e^+e^- . The STAR data are in relative agreement with the prediction, supporting the expectation that the mechanism generating the asymmetries is universal.

Recently, the authors of Ref. [16] have included the STAR 200 GeV data into an updated global transversity analysis of dihadron data [17]. The STAR data yield an improved precision for the valence u-quark transversity over previous extractions [6]. Additionally, the STAR data qualitatively improve the valence d-quark transversity extraction, bringing it more in-line with what is observed in global analyses of Collins asymmetry data (e.g. Refs. [4; 5]).



Figure 2. STAR Collins asymmetries at $\sqrt{s} = 500$ GeV [13] in comparison with model calculations based upon SIDIS and e^+e^- [18; 19]. The DMP+2013 [18] and KPRY [19] calculations assume no TMD evolution, while the KPRY-NLL [19] calculation assumes TMD evolution up to next-to-leading-log.

4. Collins effect at STAR

STAR has made the first observations of the Collins mechanism in p + p collisions from data collected in 2011 at $\sqrt{s} = 500$ GeV [13] and in 2012 at $\sqrt{s} = 200$ GeV [20]. Figure 2 presents the 500 GeV asymmetries in comparison with model predictions [18; 19] based upon fits to SIDIS and e^+e^- data. The model calculations assume that TMD factorization holds for hadron-in-jet observables in p + p, e.g. as argued in Ref. [11]. The model calculations also make different assumptions about TMD evolution. The data are consistent at the 95% confidence interval with all model calculations, suggesting that arguments that TMD factorization holds for hadronin-jet observables in p + p are well-founded. The current data are not sufficiently precise to distinguish between the different model assumptions on TMD evolution ($\chi^2/\nu = 14/10$ without vs. $\chi^2/\nu = 17.6/10$ with TMD evolution).

Figure 3 presents the STAR 200 GeV [20] and 500 GeV [13] Collins asymmetries vs. j_T , the pion momentum transverse to the jet axis. The data are divided into three bins of z, the fraction of jet momentum carried by the pion. The range of jet p_T is selected so that the two datasets sample a similar $x_T = 2p_T/\sqrt{s}$. Presented in this way, the datasets are in complete agreement, consistent with the expectation that the observables should scale with x_T . The value of j_T where the asymmetry peaks appears to increase as the value of z increases. Until now, phenomenologists have had no data with which to constrain the transverse momentum structure



Figure 3. STAR Collins asymmetries at $\sqrt{s} = 200$ GeV [20] and 500 GeV [13], shown as a function of j_T , the pion momentum transverse to the jet axis, for three bins of z, the fraction of jet momentum carried by the pion. The datasets are selected so that the jets sample similar $x_T = 2p_T/\sqrt{s}$.

of the asymmetries. Consequently, for simplicity, calculations have assumed the asymmetry factorizes, e.g. as $A_{UT} \sim f(j_T) \times g(z)$. The STAR data for the first time provide insight that can help phenomenologists develop a more detailed model of the transverse momentum structure of the asymmetries.

5. STAR looking forward

One of the immediate needs for both dihadron and Collins global analyses is information on the unpolarized dihadron and hadron-in-jet fragmentation functions. At the moment, these are not well constrained, in particular for gluons, contributing to uncertainty in the transversity extractions. STAR analyses of these observables are currently underway. Additionally, STAR has collected high-statistics transversely polarized p + p datasets at both 200 and 500 GeV in 2015 and 2017, respectively. These datasets will provide greatly improved precision, in particular for the 500 GeV measurements. Furthermore, in 2015 STAR collected polarized p + A datasets, which will enable the first ever study of the Collins fragmentation mechanism in the presence of a nuclear environment.

In the years 2022 and following, after completion of RHIC Beam Energy Scan (BES) II, STAR has plans to carry out additional polarized p + p runs. These runs will be the first p + pruns to make use of the BES-II upgrades. For example, upgrades to the inner sectors of the TPC will extend the TPC tracking and particle-ID coverage to $|\eta| \sim 1.5$. Moreover, these runs will also be the first with the planned STAR Forward Upgrade [21]. Figure 4 presents the layout for the proposed detectors. The forward upgrade will equip STAR with a forward charged-particle tracking system (FTS), consisting of Si discs and small-strip thin gap chambers (Fig. 5), and a forward calorimeter system (FCS), consisting of both electromagnetic and hadronic calorimetry (Fig. 6), over the pseudorapidity range $2.5 < \eta < 4$. The forward upgrade will enable STAR to utilize the dihadron and hadron-in-jet measurements to probe transversity at high x, where the distribution is largely unconstrained. Significant progress has already been made on the forward upgrade, including beam tests, prototype runs, and machining of hadron calorimeter detectors.



proposed STAR forward upgrade



Figure 5. Cutaway view of the proposed STAR forward tracking system [21].



Figure 6. Proposed STAR forward calorimeter system [21].

References

Figure 4.

[21].

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