Constraining Quark Transversity through Collins Asymmetry Measurements in Mid-Rapidity Jets in $p^+p$ Collisions at STAR

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Abstract. Quantitative insights have been obtained from past measurements of the Collins asymmetry in $e^+e^-$ collisions and deep-inelastic lepton-nucleon scattering. Further constraints can be added from measurements of the azimuthal asymmetry of leading charged pions in jets produced by transversely polarized proton collisions. This asymmetry can be expressed as a convolution of the quark transversity ($\delta q(x,Q^2)$), the Collins fragmentation function ($\Delta N D(z)$) and a hard-scattering spin-transfer coefficient. Previous measurements constrain $\Delta N D(z)$, potentially allowing an independent extraction of $\delta q(x,Q^2)$. We present progress toward asymmetry measurements from $\sqrt{s} = 200$ GeV transversely polarized ($\sim 58\%$) proton collision data collected at the Solenoidal Tracker at RHIC (STAR), with full azimuthal coverage at mid-rapidity ($|\eta| < 1$). Available data give a statistical precision of $\sigma \sim 0.01$, for average quark momentum fraction $\langle x \rangle \sim 0.2$, at each of four intervals of the hadron-jet momentum fraction $z$ over $0.1 < z < 0.6$.

1. Quark Transversity and Spin
A complete characterization of spin degrees of freedom in the nucleon at leading twist in the partonic model requires structure functions representing both longitudinal and transverse degrees of freedom, defined $\Delta q(x,Q^2)$ and $\delta q(x,Q^2)$, respectively. Along with the (unpolarized) parton distributions $q(x,Q^2)$, these provide a spin-density matrix representation of the nucleon in the parton- and nucleon- helicity basis [1].

Whereas $\Delta q(x,Q^2) \equiv q^+(x) - q^-(x)$ is the difference between the probabilities of finding partons with spin parallel and antiparallel to the proton spin when the proton is polarized parallel to the proton momentum, $\delta q(x,Q^2)$ represents the same concept with a proton polarized perpendicularly to the proton momentum (in the proton infinite momentum frame) [2].

Precise measurement of $\delta q(x,Q^2)$ requires perpendicularly polarized beams and/or targets. Transversity is a chiral-odd function correlating left- and right-handed quarks, making transversity an important tool for investigating chiral symmetry breaking [2]. Due to the non-commutativity of Lorentz boosts and rotations, $\Delta q(x,Q^2) \neq \delta q(x,Q^2)$, making transversity a probe of relativistic effects in the nucleon [2]. Compared to the helicity distributions $\Delta q(x,Q^2)$ [3], physical constraints on $\delta q(x,Q^2)$ are limited [4], asserting the need for further experimental access to transversity.
2. Measurement of the Collins Asymmetry

Existing constraints on transversity are derived from a global fit by the Belle Collaboration from KEK \(e^+e^-\rightarrow\text{hadron}\) data and SIDIS \(eN\) data from HERMES and COMPASS [5]. Because \(\delta q\) is chiral-odd, an additional universal chiral-odd Collins fragmentation function \(\Delta^N D_q\) is required, such that \(\delta q \otimes \Delta^N D_q\) is a chiral-even observable [6].

The universality of the Collins fragmentation function can also be exploited to access transversity in the reaction

\[
p(P_A, S_{\perp}) + p(P_B) \rightarrow \text{jet}(P_J) + X \rightarrow \pi^\pm + X
\]

between two protons \(P_A\) and \(P_B\), where \(P_A\) is transversely polarized. Charged pions fragment inside hadronic jets with overall momentum \(P_J\), each described by a momentum fraction \(z \equiv p_\pi/P_J\) and a momentum component \(j_T\) perpendicular to the central jet axis. The azimuthal distribution of pions within hadronic jets, relative to the polarization \(S_{\perp}\), then allows access to \(\delta q(x)\) if a parametrization of \(\Delta^N D_q(z, j_T)\) [4] is known.

If \(S_{\perp}\) and \(j_T\) make angles \(\phi_S\) and \(\phi_h\) respectively, with the collision-jet reaction plane (see Fig. 1), then the measured asymmetry over \(N\) pions

\[
A(z, j_T) \equiv \frac{\sum_N \sin(\phi_h - \phi_S)}{N}
\]

can be expressed (to leading order) as [7]

\[
A(z, j_T) \approx \sum_{u,d} \left[ \frac{\delta q(x) \Delta^N D_q(z, j_T)}{f_q(x) D^h(z, j_T)} \frac{H^\text{Collins}_{q(2)\rightarrow q(2)}}{H_{q(2)\rightarrow (3)(4)}} \right]
\]

where the three factors are ratios of polarized to (better-known) unpolarized partonic structure functions, fragmentation functions and explicitly calculable hard scattering terms, respectively (the last of these determined to be \(\sim 0.5\) in PYTHIA/GEANT simulations for this experiment). Factorization of terms should then allow access to transversity \(\delta q(x)\) [8].

![Figure 1. Kinematic quantities required to measure the Collins Asymmetry [7].](image)

3. Experimental Apparatus

This measurement employs transversely polarized proton collisions produced by the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory, New York, USA. Data was
collected by the Solenoid Tracker at RHIC (STAR) detector apparatus during the 2006 run.

The RHIC accelerator is capable of producing transversely polarized proton collisions at center-of-mass collision energies of up to $\sqrt{s} = 500$ GeV \[9\]. Transverse polarizations (reaching up to $\sim 60\%$ in 2006) are measured by a Coloumb Nuclear Interference (CNI) Polarimeter, which is calibrated by polarized hydrogen jet polarimeter measurements \[10\]. STAR is one of several interaction points in the RHIC accelerator ring where collision events are detected. Beam luminosities of $\sim 10^{31}$ $s^{-1}cm^{-2}$ were achieved in the 2006 run at $\sqrt{s} = 200$ GeV; the integrated sampled luminosity of the transversely polarized experimental run was $\sim 1$ pb$^{-1}$.

STAR is a large solid angle detector ($0 < \phi < 2\pi$, $-1 < \eta < 2$) well-suited for the full reconstruction of jets \[11\] (see Figure 2). The Beam-Beam Counter (BBC) measures polarization direction, luminosity and provides a minimum bias trigger. The Time-Projection Chamber (TPC) provides charged particle identification and momentum measurement through reconstruction of their trajectories in a 0.5 T magnetic field \[12\]. The Barrel and Endcap Electromagnetic Calorimeters (BEMC, EEMC) detect neutral particles and triggering for jet reconstruction \[13\] \[14\]. TPC and EMC acceptances allow charged particle and jet detection over a pseudorapidity $|\eta| < 1$ in this analysis.

4. Analysis

Accurate reconstruction of jet momentum and direction is required to make the measurement of Eq. 2. As in past jet analyses at STAR (e.g. Refs. \[15\]), the Midpoint Cone Algorithm \[16\] is used. A TPC track or EMC tower with an energy of 0.5 GeV or greater “seeds” a jet with cone radius $R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$, incorporating tracks and towers with transverse momentum $p_T$ and energy $E_T$ (respectively) greater than 0.2 GeV.

Event triggers for results shown here required a minimum ADC sum threshold for one of 12 separate “jet patches” in $\phi$. Detector simulations incorporating this trigger response determined that a high proportion of low-$p_T$ jets originate from gluon scattering events. Therefore, a nominal cut of $p_T > 10$ GeV is imposed to optimize access to quark-scattering events, and hence the transversities $\delta u$ and $\delta d$.

Charged positive and negative pions were identified in the TPC. Cuts on the number of signal points and DCA (Distance of Closest Approach) track residual identify the presence of acceptable charged particle tracks, while a cut of fixed width in $n_\pi(\tau)$, the Gaussian distribution of $\log(dE/dx)$ about a momentum-dependent centroid \[17\], is used to separate charged pions from other charged particles. The background contamination can then be estimated from a
triple-Gaussian fit to the combined distribution of electrons, pions and heavier hadrons (see Figure 3). Only charged pions that are leading particles, that is, the highest- \( z \) particle in a particular jet, are kept for analysis. The ratio of jets with leading charged particles to jets led by higher- \( z \) neutral EMC responses is demonstrated by Figure 4.

The asymmetry of Eq. 2 is measured with respect to either \( j_T \) or \( z \), separately for the cases of \( \pi^+ \) and \( \pi^- \). Both beams in the RHIC collider (termed the “blue” and “yellow” beams, respectively) are polarized, so either beam can be used as the polarized “reference” beam \( P_A \) in Figure 1 with a suitable transformation of lab coordinates. Only jet triggers in the forward half of the detector are analyzed with respect to either “reference” beam (see Figure 5). The periodic reversal of polarizations implies a complete cancellation of detector acceptances with appropriate BBC-determined luminosity weighting.

Figure 3. Triple-Gaussian fit to the \( n_\sigma(\pi^-) \) distribution, that is, \( \log(dE/dx) \) in the TPC, for negative leading particles. A cut of \(-1 < n_\sigma(\pi^-) < 2\) is imposed, leaving less than a 4% contamination from other particles.

Figure 4. \( z \)-distributions of leading particles, separated into charged and neutral detector responses.

Figure 5. Pseudorapidity (\( \eta \))-distributions of leading \( \pi^+ \) jets in the forward hemisphere relative to either beam. Overlap occurs due to the 2 m variation in the event \( z \)-vertex position.

Figure 6. Leading \( \pi^+ \) momenta in a jet-centered (NLS) coordinate frame. The \( L \)-axis (not shown) points perpendicularly into the page and is defined by the jet momentum axis.
5. Progress Toward Preliminary Results

Checks on the veracity of the asymmetry measurement include the comparison of results calculated in both lab-based and jet-centered NLS coordinate systems [18] (see Figure 6), as well as blind calculation of artificially-generated asymmetries using PYTHIA/GEANT simulations. Further checks include the deliberate measurement of zero asymmetries by inserting implicit cancellations into either the measurement of $\phi_h$ (in the NLS frame) or $\phi_S$ (in the lab frame).

Systematic error estimation primarily centers on the study of trigger bias (the comparison of secondary jets to triggering jets) and the effects caused by detector bias on the kinematic quantities $z$ and $j_T$ (studied by applying the bias of PYTHIA/GEANT simulations to the real data). Miscellaneous systematic effects include errors on measured polarization magnitude and direction, beam luminosity error, kinematics resolution, and $\pi^\pm$ identification.

Available statistics for the asymmetry are ultimately determined by the number of triggered jets containing “leading” pions. Projected statistics for the aforementioned “jet patch” trigger, as a function of $z$, are shown in Figure 7.

![Collins Statistics vs. z: $\pi^+$](image1)

**Figure 7.** Preliminary projection of the statistical precision of the STAR measurement of the Collins Asymmetry.

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