Azimuthal Single-Spin Asymmetries of Charged Pions in Jets in $\sqrt{s} = 200$ GeV $p^\uparrow p$ Collisions at STAR

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Single spin asymmetry measurements (A_{UT}) of the azimuthal distribution of charged pions inside jets produced in transversely polarized proton collisions are sensitive to the transversity distribution and the Collins fragmentation function. The STAR Detector at the Relativistic Heavy Ion Collider is well suited for these types of measurements as it is capable of full jet reconstruction and charged pion identification in the mid-rapidity region ($|\eta| < 1$). We report here the first observation of Collins A_{UT} asymmetries in $\sqrt{s} = 200$ GeV $p^\uparrow p$ collisions.

Keywords: Transversity; Collins asymmetry; jets.

1. Introduction

A complete, fundamental understanding of the proton must include knowledge of the underlying spin structure. The transversity distribution, $h_1(x, Q^2)$, which describes the transverse spin structure of quarks inside a transversely polarized proton, is only accessible through channels that couple $h_1(x, Q^2)$ to another chiral odd distribution,¹ such as the Collins fragmentation function² ($\Delta D(z, j_T)$). Significant Collins

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asymmetries of charged pions have been observed in semi-inclusive deep inelastic scattering (SIDIS) data.^{3,4} These SIDIS asymmetries combined with measurements in e^+e^- annihilation at Belle and BABAR permit the extraction of $h_1(x, Q^2)$ and $\Delta D(z, j_T)$.^{5,6} However, the current uncertainties on $h_1(x, Q^2)$ are large compared to the corresponding quark momentum and helicity distributions^{7,8} and reflect the limited statistics and kinematic reach of the available data.

To date, transversity extractions have focused solely on data from SIDIS and e^+e^- experiments.⁹ However, asymmetry measurements of the azimuthal distribution of charged pions inside jets in polarized proton collisions provide a unique tool to constrain transversity distributions.^{10,11} In this formalism, ϕ_S represents the angle between the scattering plane and the spin polarization vector and ϕ_H describes the azimuthal distribution of charged pions in the jet as defined in Ref. 10. In the polarized cross section, the azimuthal modulation $A_{UT}^{\sin(\phi_S - \phi_H)}$ is sensitive to the Collins effect.

An exploratory measurement of the mid-pseudorapidity $A_{UT}^{\sin(\phi_S - \phi_H)}$ was made from 2.2 pb^{-1} of transversely polarized proton collisions collected in 2006.¹² These results, while statistically limited, showed hints of significant charged sign separated asymmetries and motivated the collection of an additional 20 pb^{-1} of data during the 2012 run. A significant asymmetry in this channel would provide access to $h_1(x, Q^2)$ at higher average x ranges than in SIDIS and sensitivity to the $\Delta D(z, j_T)$ at the same scales measured at Belle and BaBar.

2. Data Analysis

The STAR detector¹³ at the Relativistic Heavy Ion Collider (RHIC) is a large acceptance detector, capable of 2π azimuthal jet reconstruction. The time projection chamber (TPC) provides charged particle tracking and energy loss ($\frac{dE}{dx}$) for the pseudorapidity range $|\eta| < 1.3$, and the electromagnetic calorimeters give the energy deposition from electromagnetically interacting particles and fast triggering capabilities in the range $-1 < \eta < 2$.

Jets were reconstructed using the anti- k_T algorithm¹⁴ with a 0.6 input radius. Since gluons exhibit no transversity, it's favorable to reduce the contamination from gluon-gluon hard scatterings. Thus only jets with transverse momentum (p_T) greater than 10 GeV/c were accepted into analysis.

The Collins signal was extracted by plotting $A_{UT}^{\sin(\phi_S - \phi_H)}$, calculated using the "cross-ratio" formula,¹⁵ in bins of $\phi_C = (\phi_S - \phi_H)$ and kinematic variables j_T , z and jet p_T . Binning the data as a function of ϕ_C , $A_{UT}^{\sin(\phi_S - \phi_H)}$ is isolated as the coefficient of $\sin(\phi_C)$.¹⁰ The procedure is applied to each beam of the collider separately and the results are averaged.

Asymmetries were calculated for jets that scattered forward with respect to the polarized beam ($x_F > 0$) and backwards ($x_F < 0$). Jets in the $x_F < 0$ category sample on average a lower x distribution than jets in the $x_F > 0$ category. As a

result $A_{UT}^{\sin(\phi_S - \phi_H)}$ is expected to be smaller for $x_F < 0$ jets, due to the reduced transversity signal and the higher gluon dilution as well as reduced polarization transfer from the incident to scattered quark.

Charged pions were identified by the characteristic energy loss $(\frac{dE}{dx})$ curve in the TPC, and accepted for analysis if they passed a $\Delta R > 0.1$ radius cut where $\Delta R = \sqrt{(\eta_{jet} - \eta_\pi)^2 + (\phi_{jet} - \phi_\pi)^2}$. A cut of $-1 < n_\sigma(\pi^\pm) < 2.5$, where $n_\sigma(\pi)$ is the $\log(\frac{dE}{dx})$ distribution divided by the expected mean and $\frac{dE}{dx}$ resolution for pions,¹⁶ was implemented to minimize the contamination from kaons, protons and electrons. These contaminations are independent of the jet p_T and contribute less than 3% of the total systematic error.

Corrections and systematic errors due to detector effects are estimated using simulated QCD events generated by PYTHIA¹⁷ tuned to Perugia 0.¹⁸ Effects due to pile-up are incorporated by embedding the simulated events into real zero-bias STAR data. The detector response is simulated with GEANT,¹⁹ allowing for jet reconstruction at the particle level (no detector effects) and at the detector level.

Events were analyzed if they satisfied the jet patch (JP) trigger condition which requires an $\eta \times \phi = 1 \times 1$ patch of the calorimeter to register energies above 5.4 GeV or 7.3 GeV. The JP trigger enhances the high- p_T jet sample and therefore increases the extracted $A_{UT}^{\sin(\phi_S - \phi_H)}$ by reducing the gluon dilution and enhancing the quark contribution. Comparisons of the fraction of events originating from quarks at the detector and particle levels reveals that there is a 5% enhancement of quark events in jet patch triggered events relative to unbiased events.

The largest systematic error arises from the angular resolution of pions around the jet axis. The effect on $A_{UT}^{\sin(\phi_S - \phi_H)}$ was estimated by weighting asymmetries into the simulation events. The weights were tuned so that the reconstructed asymmetries matched those observed in the data. The comparison of $A_{UT}^{\sin(\phi_S - \phi_H)}$ at the particle and detector level in the simulation determines the bin-by-bin systematic error due to angular resolution effects.

3. Results and Conclusions

The asymmetries in Figures 1-3 represent the first observation of Collins asymmetries in transversely polarized proton collisions at $\sqrt{s} = 200$ GeV. Averaged across the entire kinematic range for $x_F > 0$ there is a $7\sigma(6\sigma)$ separation from zero for $\pi^+(\pi^-)$, and a 9.5σ separation between the π^+ and π^- asymmetries. As expected, for the backwards scattered jets the asymmetry is much smaller with a 2σ separation for π^+ , and consistent with zero for π^- .

Figure 1 shows that the asymmetry increases as the component of the pion momentum transverse to the jet axis (j_T) decreases. The bottom two panels show the average pion momentum fraction (z), and the average jet p_T for each j_T bin. These panels make it clear that z and j_T are correlated due to the ΔR cut. The asymmetry increases for $z < 0.3$ (Fig. 2), but starts to decrease above this mark,

Fig. 1. Collins asymmetry as a function of the pion transverse momentum in the jet (j_T).

Fig. 2. Collins asymmetry as a function of the jet momentum fraction (z) carried by the pion.

Fig. 3. Collins asymmetry as a function of the jet transverse momentum (p_T).

with the correlation between z and j_T seeming to drive this behavior of the z asymmetry. Figure 3 makes it clear that p_T is independent of z and j_T , and thus the shape is independent of the other two asymmetries. Within the scope of these statistics, the asymmetry seems to increase with increasing jet p_T .

A complementary analysis of the same channel has been performed at STAR in the $\sqrt{s} = 500$ GeV data and shows excellent agreement when compared with the $\sqrt{s} = 200$ GeV data in Fig. 4. The $\langle p_{T,jet} \rangle$ of the 500 GeV data is higher to facilitate comparisons at similarly sampled quark momentum fractions (x) and gluon dilutions. The two panels illustrate the significant j_T dependence in the data. The top panel shows large asymmetries for cuts of $\Delta R > 0.1(0.04)$ and then vanishing asymmetries for $\Delta R > 0.25(0.1)$ in the 200(500) GeV data. The ability to measure the j_T dependence of this channel over a wide range of Q^2 and $\sqrt{s}$ highlights the unique contributions STAR can make in the worldwide effort to constrain the transversity and Collins distributions.

Collins asymmetries in transversely polarized proton collisions are a unique channel to probe transversity. These measurements provide the opportunity to test the universality of both the Collins and transversity distributions and to study factorization breaking effects in hadronic collisions.²⁰ A longer run with transverse protons coming in 2015 will allow for an expansive, multidimensional analysis of the Collins channel.

Fig. 4. Data from $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV show excellent agreement when compared in similar kinematic regions.

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