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Transverse spin physics at STAR

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Summary. — The transverse spin physics program at STAR is pursuing two complementary goals. The first is to extract quark transversity, and the second is to understand the origin of large transverse single spin asymmetry (A_N) observed in the forward region. The mid-rapidity Collins and Interference Fragmentation Function (IFF) measurements at $\sqrt{s} = 200$ GeV are aimed at the extraction of transversity. In the forward region, the measurements of inclusive π^0 and η meson A_N, as functions of x_F and p_T at $\sqrt{s} = 200$ GeV and 500 GeV, allow for comparisons against theoretical models that incorporate the effects of either higher-twist, or partonic transverse momenta. The planned forward upgrade will enable the measurements of A_N for prompt photons, jets, and the Drell-Yan process.

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1. – Introduction

The recent measurements of Sivers and Collins functions at Semi-Inclusive Deep Inelastic Scattering (SIDIS) and e^+e^- experiments [1-4] have largely validated the existence of non-zero Transverse Momentum Dependent (TMD) functions. Given that the twist-3 approach has been shown to be closely related to the TMD approach [5], one may hope that the extraction of TMD functions would lead to a full description of the large A_N observed in the forward region of hadron collisions.

However, so far a number of limitations, both theoretical and experimental, have prevented us from reaching a quantitative understanding of this phenomenon. While the Collins fragmentation function is thought to be universal, a recent estimate of the Collins contribution to π^0 A_N in $p+p$ was found to be insufficient to describe the STAR data for $x_F > 0.3$ [6]. It is unclear if the Sivers function obtained in SIDIS can be directly applied to $p+p$ due to universality breaking in QCD factorization [7], and the predicted contribution from the theoretically safer twist-3 approach based on this Sivers extraction is opposite in sign relative to the measured A_N [8]. Furthermore, most of the RHIC measurements of forward A_N so far have been on inclusive hadrons, which are sensitive to both the Collins and Sivers effects.

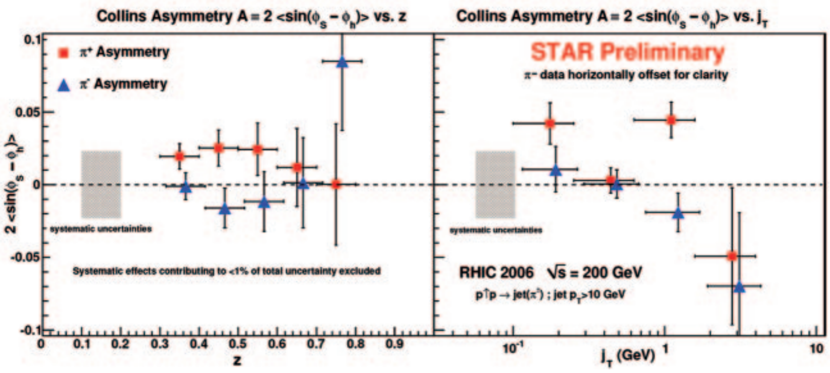

Fig. 1. – Collins asymmetry at mid-rapidity ($-1 < \eta < 1$, A_N measured for $x_F > 0$ for each beam) for the leading charged pions in jets, as a function of z (fragmentation fraction), left panel, and j_T (transverse momentum of the pion with respect to the jet axis), right panel.

STAR is pursuing two complementary measurements in transverse spin physics. First, we aim to extract quark transversity through Collins and di-hadron IFF channels, both of which are universal and can be connected directly to the SIDIS and e^+e^- results. So far, both Collins and IFF measurements have been made in the mid-rapidity region where STAR possesses jet capability. Second, we are continuing the efforts to map out the kinematic dependence of the large forward A_N in hadron collisions, and to expand the measurements beyond inclusive pions. We have measured the x_F and p_T dependence of π^0 A_N at $\sqrt{s} = 200$ and 500 GeV, and the A_N of η-mesons [9].

2. – Quark transversity

The direct measurement of the Collins fragmentation function, which is thought to be universal, at the Belle e^+e^- collider [4] allows for an extraction of transversity from Collins asymmetries in $p+p$. STAR has performed the initial measurement of the Collins asymmetries for leading charged pions in jets at mid-rapidity, based on 2.2 pb^{-1} of data taken during RHIC run 2006. The average polarization was 58%. The Collins angle is defined by the difference between ϕ_S, the angle between proton spin vector and the scattering plane of the jet, and ϕ_h, the azimuthal angle of the hadron around the jet axis.

Figure 1 shows the preliminary results of $A_N = \langle \sin(\phi_S - \phi_h) \rangle$ for charged pions as a function of z, the fragmentation fraction, and j_T, the transverse momentum of the pion with respect to the jet axis. The systematic uncertainties are dominated by the non-uniformity of the detector acceptance. A much larger data set of 24 pb^{-1} has been recorded during RHIC run 2012, with average polarization of 60%. The analysis of the new data set is ongoing, and the systematic uncertainty will be reduced substantially by adopting the cross-ratio technique that is insensitive to moderate detector non-uniformities.

In addition, STAR has reported the initial measurement of di-pion transverse single spin asymmetries (A_{UT}) at mid-rapidity. The di-pion A_{UT} is sensitive to transversity and IFF, the latter of which has also been measured by the Belle Collaboration [10]. Because the transverse momentum relevant to the IFF asymmetry is confined within the di-pion system, collinear factorization is preserved [11]. If $\overrightarrow{P_1}$ and $\overrightarrow{P_2}$ are the charge

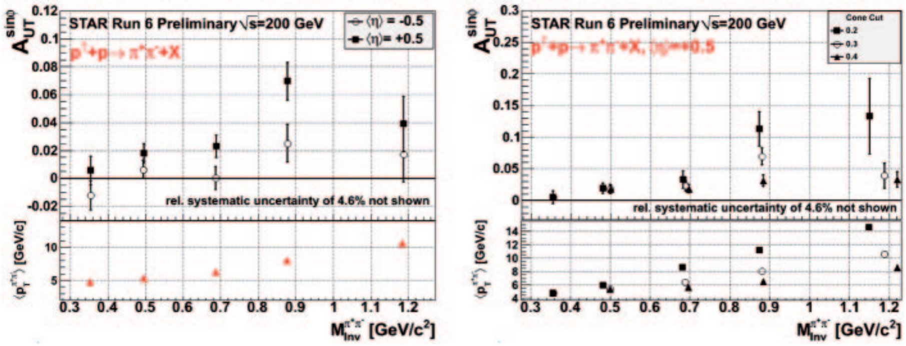

Fig. 2. – IFF asymmetry at mid-rapidity ($-1 < \eta < 1$) for charged pion pairs, as a function of di-pion invariant mass. For two pseudo-rapidity bins, left panel. For three cone cut radii in η-ϕ space, right panel.

ordered momentum vectors of the two pions, the asymmetry is described by the IFF angle, defined as the difference between Φ_S, the angle between proton spin vector and the scattering plane of $\overrightarrow{P_1} + \overrightarrow{P_2}$, and Φ_R, the azimuthal angle of $\overrightarrow{P_1} - \overrightarrow{P_2}$ around $\overrightarrow{P_1} + \overrightarrow{P_2}$.

Figure 2 shows preliminary results for the IFF asymmetry as a function of the di-pion invariant mass for two pseudo-rapidity bins, and also for three cone cut radii in η-ϕ space. The largest asymmetry is found with the smallest cone cut at high invariant mass / high di-pion transverse momentum. The predictions [11] are in qualitative agreement with the observations. The analysis of the ten times larger data sample obtained in 2012 is ongoing.

3. – Large forward transverse single-spin asymmetry

Figure 3 shows the measurements of the x_F dependence of the η-meson A_N at $\sqrt{s} = 200\,\text{GeV}$ [9], and π^0 A_N at $\sqrt{s} = 500\,\text{GeV}$. The η-meson A_N was found to be larger than that of the π^0, but additional statistics are needed to conclusively establish the difference. The magnitude of π^0 A_N does not show a strong dependence in $\sqrt{s}$, but the point in x_F at which the asymmetry starts to rise was found to be lower than it was at $\sqrt{s} = 200\,\text{GeV}$.

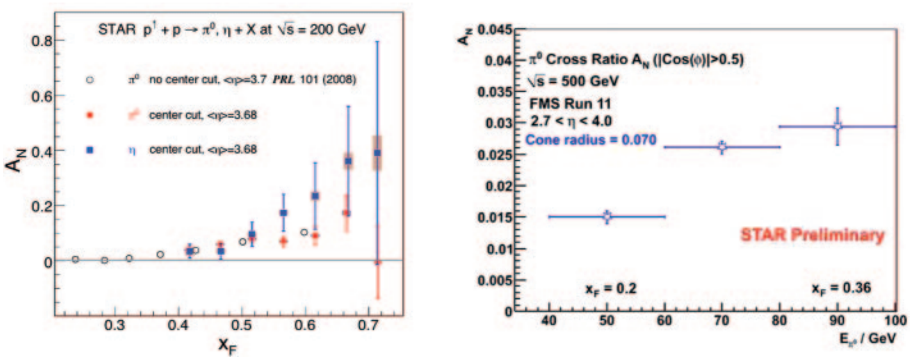

Fig. 3. – A_N of π^0 and η-mesons *vs.* Feynman-x (x_F) at $\sqrt{s} = 200\,\text{GeV}$ [9], left panel. A_N of π^0 *vs.* pion energy ($250\,\text{GeV} \times x_F$) at $\sqrt{s} = 500\,\text{GeV}$, right panel.

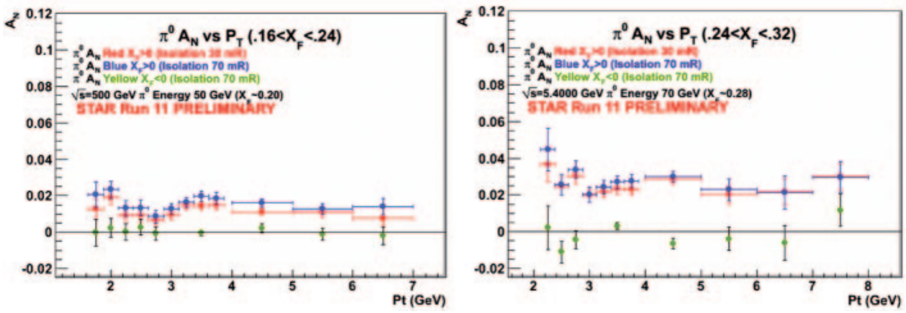

Fig. 4. – π^0 A_N *vs.* p_T at $\sqrt{s} = 500\,\text{GeV}$ in two x_F bins. $\langle x_F \rangle \sim 0.20$, left panel. $\langle x_F \rangle \sim 0.28$, right panel.

As shown in fig. 4, STAR has also reported preliminary results for the p_T dependence of π^0 A_N at $\sqrt{s} = 500\,\text{GeV}$, which significantly extends the p_T reach of the previous measurement. Consistent with the trend seen in the previous result [13], A_N shows little dependence in p_T even out to p_T as high as 8 GeV. The measurements were made with two isolation cuts on all EM clusters around the π^0. We found a surprising result that A_N was consistently higher for the larger isolation cut.

Even with the reasonable agreement between RHIC forward cross-sections and pQCD calculations, it is conceivable that A_N receives diffractive or soft contributions. In fixed target experiments, such as FNAL E704, pQCD predictions on production cross-sections were significantly below the measured values, and at the same time the A_N was found to be very large. However, we also know from the recent SIDIS and e^+e^- results that the well known pQCD based models are capable of generating asymmetries that are at least qualitatively similar to what is observed at RHIC energies. This suggests that the forward region of $p + p$ may be a regime in which the observed spin asymmetry receives contributions from both perturbative and non-perturbative processes. In such a case, understanding the dynamical origins of the large A_N in $p+p$ would require going beyond disentangling the Sivers and Collins effects.

4. – Conclusions

STAR transverse physics program has demonstrated the persistence of sizable transverse spin effects at RHIC energy [12], and subsequently measured the x_F and p_T dependence of π^0 A_N [13], and the x_F dependence of η-meson A_N [9]. We are now planning the next phase of measurements that aims to extract quark transversity, and to understand the origins of large asymmetries observed in the forward region. The planned forward upgrade at STAR focuses on the gluon saturation physics in $p + A$ collisions and forward transverse spin physics. It includes improved calorimetry (EMCal + HCal), tracking, and potentially particle identification for the forward region of STAR [14]. These new capabilities will enable the extraction of transversity in the large Bjorken-x (x_B) region, as well as the measurements of jets and prompt photons that are crucial not only in separating the Collins and Sivers contributions, but also in understanding the nature of processes involved in the forward region of $p + p$. The most significant challenge will be the detection of the Drell-Yan process through the di-electron channel, which will provide a crucial test of universality in QCD factorization through the comparison of its A_N to the Sivers asymmetry in SIDIS [15].

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