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Colloquia: Transversity 2011

Interference Fragmentation in SIDIS, pp and e^+e^-

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Summary. — This review highlights some recent developments in the measurement of the transverse-spin–dependent Interference Fragmentation Functions and di-hadron correlations in semi-inclusive deep inelastic scattering and proton-proton scattering. The latter measurements can be used to extract transversity using measurements of the fragmentation function in e^+e^- annihilation. Di-hadron correlations have been measured in pp at PHENIX and lepton-proton and lepton-deuteron scattering at HERMES and COMPASS. The Interference Fragmentation Function has recently been measured at the Belle experiment. The emphasis of this article will be the Belle and PHENIX results, as these results are not presented in other contributions to this volume.

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PACS 13.66.-a – Lepton-lepton interactions.
PACS 14.65.-q – Quarks.
PACS 14.20.-c – Baryons.

1. – Introduction and motivation

In recent years the interest in transverse spin phenomena have seen a steady rise in the community. The presence of an additional degree of freedom allows the access to new aspects of the nucleon's spin structure but also creates new experimental and theoretical challenges. If one stays in a collinear picture at leading twist, transverse-spin–dependent effects in semi-inclusive deep inelastic scattering (SIDIS) off transversely polarized nucleons are connected to the fragmentation of transversely polarized quarks. The parton distribution function describing the probability to scatter off a transversely polarized quark in a transversely polarized nucleon is called transversity, h. In the picture above, in which intrinsic transverse momentum is integrated over and only leading twist is considered, the quark transversity together with the quark helicity and momentum distribution functions provide a complete picture of the spin structure of the nucleon [1]. An important test of our understanding of this structure is the ability to describe measurements by first-principle calculations. At the moment, lattice calculation [2] are coming closer to providing such a description at the relevant kinematics. However, since the lattice is using Euclidian space-time quantization and parton distribution functions are light-cone quantities, we can only compare moments of PDFs with results from lattice calculations. And because the quark transversity has been extracted so far only from a global analysis of the Collins effect in semi-inclusive deep inelastic scattering data off fixed targets, the kinematic coverage in x_{Bj}, the fractional momentum of the probed quark, is limited to x_{Bj} smaller than about 0.4 at SIDIS energy scales [3]. However, since transversity is a valence quark quantity, it takes on large values only in the valence quark region. This adds considerably to the uncertainty in the extraction of the tensor charge from experiments. It is therefore important that the experiments provide input in the high-x_{Bj} region. At the same time these measurements have to be taken in a regime where pQCD factorizationis is proven to be valid and higher twist contributions are suppressed. This usually means measurements at large scales, which are given by the four-momentum transfer squared $-Q^2$ in SIDIS or the transverse momentum p_T in proton-proton collisions.

Experiments at DESY, CERN and JLab have measured transverse-spin asymmetries in semi-inclusive deep inelastic lepton-nucleon scattering. These are fixed target experiments, accessing transversity at low to moderate x_{Bj} as described above. To access the transversity of quarks carrying a higher momentum fraction, experiments at colliders like the Relativistic Heavy Ion Collider (RHIC) or a future Electron Ion Collider (EIC) are necessary. The experiments at RHIC collected large datasets from collisions of transversely polarized protons at $\sqrt{s} = 200\,\text{GeV}$ in runs 6 and 8 (2006, 2008). This year saw the first data taken with transversely polarized protons at $\sqrt{s} = 500\,\text{GeV}$ at STAR, one of the two major RHIC experiments.

Since in $p + p$ collisions the initial parton kinematics are only accessible if in a 2-2 scattering event both outgoing particles are reconstructed, either in a di-jet or a photon-jet event, parton kinematics are usually described with the variable $x_F = 2p_L/\sqrt{s}$. At leading order, this variable equals the difference in the momentum fractions carried by the two partons scattering off each other: $x_F = x_1 - x_2$. In the region of large pseudorapidities η which are usually called forward, $3 < \eta < 4$, large transverse-spin asymmetries can be observed for single pions [4] because these events originate from the scattering off a parton with a high momentum fraction off one carrying a low momentum fraction. Because unpolarized PDFs peak at low x_{Bj}, x_F is correlated with x_1 in these events. For single hadrons picture 1 shows the x_{Bj} range accessible in $p+p$ with current experiments. Updated results have been shown at this workshop. Since the initial parton kinematics are unknown if only single hadrons are observed, the origin of the large A_N asymmetries is still unknown. However it is assumed that the Collins effect for transversely polarized quarks contributes at least partially. A measurement of transversity at high x_{Bj} would be important to disentangle this contribution from others, such as the Sivers effect. By now it is well known that the former interpretation in terms of Collins and Sivers effects is only valid in the kinematic region where transverse-momentum–dependent (TMD) factorization can be expected to hold, at least approximately, given the recently discussed possible breaking of TMD factorization [5]. A direct measurement of the Collins effect in $p + p$ is possible using jet reconstruction and measuring azimuthal asymmetries of pions around the jet axis. In fact, this measurement has been performed recently by the STAR experiment. However, STAR only has jet reconstruction capabilities at mid-rapidity where the effect is small. Additionally, the aforementioned problems in the interpretation of the Collins measurements and subsequent extraction of transversity in a global analysis persist:

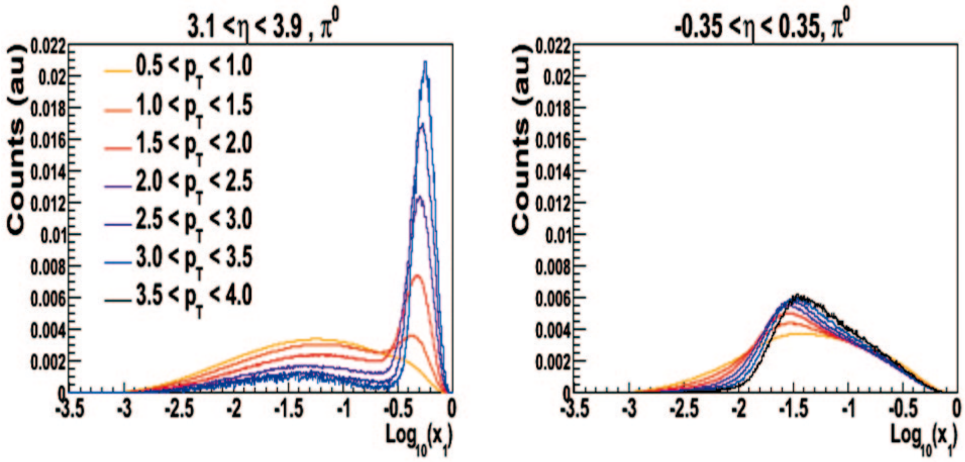

Fig. 1. – Distribution of the Bjorken scaling variable x_{Bj} of the parton fragmenting into a single hadron detected in the forward direction. Curves for different bins in p_T are shown.

– factorization in the TMD framework is not proven,

– transverse-momentum–dependent evolution equations for PDFs and fragmentation functions are not well known,

– global analysis has to assume a model for the intrinsic transverse momentum in the parton distribution function and the fragmentation function.

In order to avoid these problems, one has to integrate over intrinsic transverse momenta. However, this leads to a vanishing asymmetry. Naively this can be understood since the measured asymmetries in the fragmentation of transversely polarized quarks into unpolarized hadrons lead to left-right asymmetries due to angular-momentum conservation. To construct an observable from final state observables that carries a certain unit of orbital angular momentum, a second vector besides the hadron momentum has to be available. This naturally leads to the introduction of di-hadron correlations to measure transversity in a variety of processes. These correlations are described in terms of the product of transversity with the so-called transverse-spin–dependent Interference Fragmentation Function (IFF) $H_1^{\sphericalangle}(z, m_{\text{Inv}})$ [6]. The IFF is not dependent on the transverse momentum of the outgoing hadrons anymore, however, the second hadron introduces a second scale, the invariant mass m_{Inv} of the hadron pair. But for masses for which experimental data are available collinear factorization and evolution can be used. As is the case with the Collins Fragmentation function, the IFF is chiral-odd, and z is the fractional energy of the fragmenting quark carried by the the detected hadron pair.

High precision data showing large asymmetries are available from the fixed target SIDIS experiments HERMES [7] and COMPASS [8]. From this data transversity was extracted for the first time directly, *i.e.* not in a global analysis [9]. This extraction was made possible by our recent measurement of the Interference Fragmentation Function in e^+e^- collisisions at Belle [10] which I will discuss in the following.

For the reasons discussed above, di-hadron correlations in $p^\uparrow + p^\uparrow$, first proposed by Bacchetta and Radici [11], are of special interest to expand measurements of transversity towards high momentum fractions x_{Bj} (see fig. 1). The PHENIX experiment was the first to present results [12] for this observable that will be discussed below. Additionally, the STAR experiment at RHIC, which has a larger acceptance than PHENIX, is currently analyzing data to extract di-hadron correlations at mid-rapidity and from a limited dataset taken in 2008 with a forward TPC (FTPC) [13] covering forward rapidities, making the extraction of charged-neutral pion correlations possible. Both major RHIC experiments are proposing forward upgrades which should further our understanding of transverse spin effects and our understanding of the nucleon structure. Currently both STAR and PHENIX have only electromagnetic calorimeters at forward rapidities.

In addition to the above experiments probing transversity in a regime where the subleading twist effects are suppressed, there exists a proposal at Jefferson Lab to measure di-hadron correlations with the 12 GeV upgrade of the electron beamline at CLAS12 to access the twist-3 functions e and h_L [14]. They have an interesting phenomenology of themselves and are important background contributions to other physics measurements. It is expected that the di-hadron asymmetries measured at CLAS12 will have a significant contribution from the target fragmentation region, which can be reduced by measuring π-K correlations. The measurement of the π-K IFF, needed as an input, is currently underway at Belle.

Since the theoretical foundations and recent progress in the IFF formalism was discussed at this workshop, I will restrict myself to the introduction of the measurements, present and planned, and the corresponding observables.

2. – Experimental results

Pairs of unpolarized hadrons produced in the fragmentation of transversely polarized quarks via the Interference Fragmentation Function exhibit an azimuthal dependence on the parent quark spin. This signal can be extracted by measuring the dependence of the hadron pair yield on the azimuthal angle Φ_{RS} between the difference vector $\vec{R}_T = \vec{P}_{T,1} - \vec{P}_{T,2}$ of the two hadron momenta and the nucleon spin direction $\vec{S}$. Some experiments weight by the fractional hadron energies z_i to make the measurement robust agains boosts, but these are small corrections. The azimuthal angle is measured around the momentum of the outgoing quark. In $p+p$ events and $e^+ + e^-$ annihilation, this corresponds to the jet-axis. However, as outlined above, one big advantage of the IFF is that the jet-axis does not have to be reconstructed and instead the sum vector $\vec{P}_h = \vec{P}_1 + \vec{P}_2$ can be used. Since the direction of $\vec{R}$ has to be known for the effect to survive, a unique ordering of the hadrons in the pair has to be imposed. Usually this is done by the charge. But in principle other orderings, *e.g.* by quark content would be possible. In SIDIS and $p+p$, where the spin of the protons can be flipped, the spin asymmetry A_{UT}, dependent on the azimuthal angle $\Phi_R - \Phi_S$, is then extracted:

$$A_{UT}\sin(\Phi_R - \Phi_S) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}(\Phi_R - \Phi_S). \quad (1)$$

With the relation $A_{UT} \propto h_1 \cdot H_1^{\sphericalangle}$ transversity is then directly accessed.

2·1. *Measurement of the Di-hadron Fragmentation Function in e^+e^- collsisions at Belle.* – Using unpolarized electron-positron annihilation at a center of mass energy of $\sqrt{s} = 10.58$ GeV, light quark (u,d,s) fragmentation functions can be measured with the Belle detector [15] located at the KEKB collider at KEK in Japan. Belle could sample a record setting instantaneous luminosity provided by KEKB, which reached more than $2.11 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{1}$; more than $1\,\mathrm{ab}^{-1}$ integrated luminosity were recorded. The Belle experiment has good particle ID using time of flight, $\mathrm{d}E/\mathrm{d}x$ measurements in the central drift chamber (CDC), aerogel cherenkov counters, electromagnetic calorimetry and RPCs outside a superconducting solenoid. Tracking capabilities are provided by a silicon vertex detector and the CDC in a 1.5 T magnetic field. The detector has full azimuthal coverage which is important because we cannot construct spin asymmetries to measure the fragmentation function $H_1^{\triangleleft}(z, m_{\mathrm{Inv}})$ using unpolarized beams. Instead we make use of the fact that the spins of the quarks in the process $e^+ + e^- \to \gamma^* \to q + \bar{q}$ are aligned to make up the spin of the virtual photon. Due to angular momentum conversation, the transverse projection of the spins with respect to their momentum, and therefore the jet-axis, is given by $B(\theta) = \frac{\sin^2\theta}{1+\cos^2\theta}$. The angle θ is measured between thrust axis and beam axis in the CMS. Therefore, the effect is largest in the acceptance region of the Belle barrel to which we restrict our analysis. It is not known in which direction the quarks are polarized or which jet in a two jet event originates from the quark or the antiquark. Therefore measuring the predicted asymmetry around the jet axis would average out. However, since quark and antiquark spins are correlated, one can measure the correlation of the spin-dependent effects in the two jets. The normalized yield $\mathcal{N}$ of di-hadron pairs can then be described as

$$\mathcal{N}(z_1, z_2, m_1, m_2, \theta) \propto \cos(\Phi_1 + \Phi_2) B(\theta) \frac{\sum_q e_q^2 H_1^{\triangleleft}(z_1, m_1) \bar{H}_1^{\triangleleft}(z_2, m_2)}{\sum_q e_q^2 D_1(z_1, m_1) \bar{D}_1(z_2, m_2)}. \tag{2}$$

The angles $\Phi_{1,2}$ are the azimuthal angles between the event plane and the difference vector between the two hadron momenta in each hemisphere. The cosine modulation outlined in eq. (2) was proposed by Collins, Ladinsky and Heppelman [6] and measured by us for the first time for charged pion pairs [10]. Figure 2 shows the results for the amplitude $a_{1,2}(\theta, z_1, z_2, m_1, m_2)\cos(\Phi_1, \Phi_2) \propto \mathcal{N}$ differential in z_1, m_1 and integrated over z_2, m_2. The dependence on z is almost linear which is expected since at high z more of the spin information of the initial quark is passed on to the final state hadron. Only at low invariant masses is the z dependence flat. The dependence on the invariant mass of the hadron pair exhibits a richer structure. Around the mass of the ρ-meson the amplitude peaks. This is in line with model calculations in which an enhancement of the IFF comes from the interference of the pion pair p-wave ρ amplitude and the s-wave amplitude of non-resonant pion production.

2·2. *Di-hadron correlation measurements in SIDIS*. – Di-Hadron correlation measurements have been done in electron-proton scattering by the HERMES Collaboration and in muon-proton and muon-deuteron scattering by the COMPASS Collaboration. Both experiments have fixed targets, but use lepton beams of different energies, 27.5 GeV and 160 GeV, respectively. The higher energy at COMPASS and the resulting higher particle multiplicities, together with the higher integrated luminosity allows for a higher precision and the measurement of hadron pairs with one or more kaons. Even though the mean momentum transfer differs by a factor 2-3, the results are quite consistent, showing that the evolution has only a small effect. This is similar to the Collins asymmetry results and confirmed by theoretical calculations [9]. New results from COMPASS from unidentified charged hadrons with high precision from a dataset taken in 2010 have been shown at this conference and can be found in these proceedings. The next step will be an identification using the COMPASS RICH detector to extract asymmetries from identified

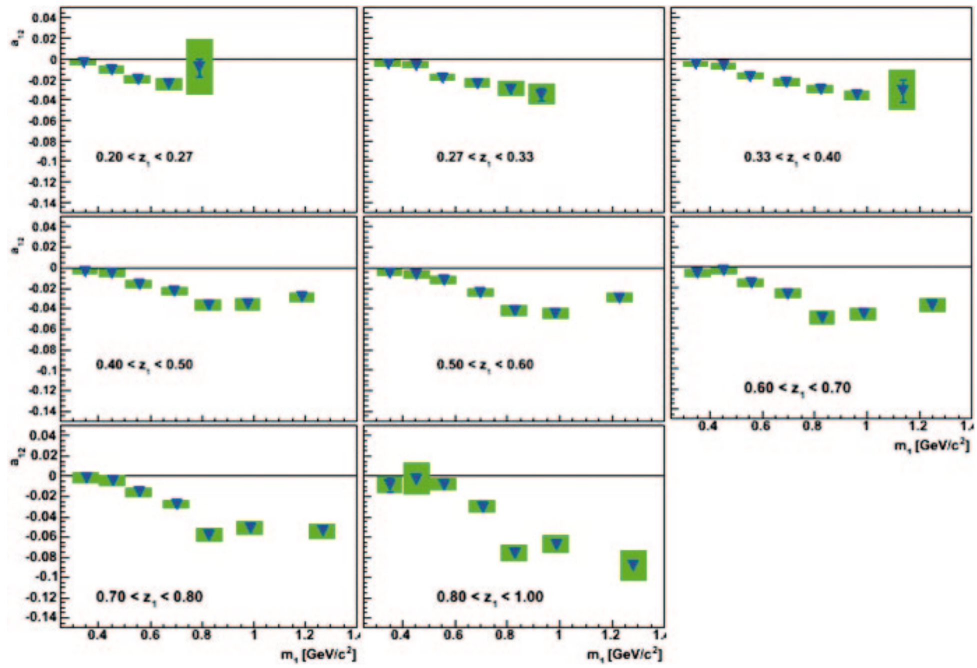

Fig. 2. – Results for di-hadron pair correlations in $e^+ + e^-$ annihilation at Belle.

pions and kaons. Both experiments see large asymmetries, up to 10% with the proton target [16]. Using the isospin symmetric deuterium target, COMPASS sees only very small asymmetries which can be explained by the opposite signs of the effect for u- and d-quarks.

2·3. *Di-hadron correlation measurements in* $p+p$. – Both major experiments at RHIC, PHENIX and STAR, have an extensive transverse-spin physics program that includes the measurement of di-hadron correlations. The PHENIX detector is described in detail in [17]. The data used for the di-hadron correlation masurement presented here were taken in the years 2006 and 2008. In 2006, PHENIX sampled a delivered luminosity of $0.7\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 200\,\mathrm{GeV}$ with 54% polarization. In 2008 a delivered integrated luminosity of $1.1\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 200\,\mathrm{GeV}$ could be sampled but at a lower transverse polarization of 46%. Since di-hadron correlations can only be measured for particle pairs for which an unambigous ordering can be imposed, the analysis is restricted to the central region, $-0.35 < \eta < 0.35$, where charged particle tracking and neutral particle detection is available. Here PHENIX is intrumented by two arms each covering $\pi/2$ of the azimuth. Unidentified charged tracks can be reconstructed in each arm with the pad- and wire-chambers and neutral pions with the electromagnetic calorimeters. For these particles a minimum p_T of $1\,\mathrm{GeV}/c$ is required. In order to select tracks from the same jet, we use pairs in the same arm. Figures 3 and 4 show the results in bins of the invariant mass m_{Inv} of the hadron pair and the combined transverse momentum, respectively. We choose this binning because the results from the Belle Collaboration shown in fig. 2 for the IFF of (π^+/π^-) pairs show a strong dependence on the invariant mass of the hadron. Since the

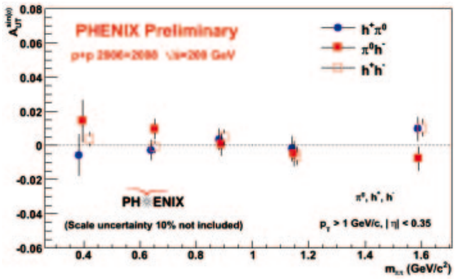

Fig. 3. – Results for the di-hadron asymmetry A_{RS} in $m_{\rm Inv}$ binning of the produced hadron pair.

measured asymmetry is a product of transversity and IFF $A_{RS} \propto h_1(x) \cdot H_1^{<}(z, m_{\rm Inv})$ we can expect a strong dependence on x_{Bj}, $m_{\rm Inv}$ and the fractional momentum of the fragmenting parton z the produced hadron pair carries. However, x_{Bj} and z are not accessible. The fractional momentum x_{Bj} is correlated to p_T, but, as seen in fig. 1 at small rapidities it is not possible to select valence quarks with a p_T cut. The measured asymmetries are small, however they exhibit the linear behavior expected in this range for $m_{\rm Inv}$. The slope for π^0/h^- is opposite to h^+/π^0. SIDIS results have shown large asymmetries for π^+/π^- pairs [16], which is not observed in $p+p$. This can be explained by u-quark dominance in SIDIS and the opposite sign for u- and d-quark transversity. This might also cause the sign difference in the slopes for π^0 combinations with positive and negative hadrons. But since the fragmentation function has not been measured yet and there are no SIDIS results available for these combinations, this interpretation is speculative.

The main detector of the STAR experiment [18] is a Time Projection Chamber (TPC) in a 0.5 T magnetic field. The TPC provides tracking between $-1.4 < \eta < 1.4$ and dE/dx measurements for PID of low momentum tracks. Electromagnetic calorimetry (EMC) exists continuous in azimuth between $-1 < \eta < 1$ (barrel EMC), $1 < \eta < 2$ (Endcap EMC) and $2 < \eta < 4$ (forward meson spectrometer, FMS). In the year 2008 data from collisions of transversely polarized protons at $\sqrt{s} = 200\,\text{GeV}$ were taken with a forward TPC installed. This detector provided charged particle tracking for $2.5 < \eta < 4$. For the measurement of di-hadron correlations, data taken in the barrel region, where both tracking and calorimetry is available, is currently being ana-

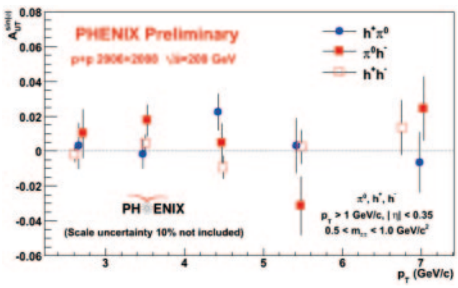

Fig. 4. – Results for the di-hadron asymmetry A_{RS} in p_T binning of the produced hadron pair.

lyzed and it is expected that the next run will provide a transverse spin dataset at $\sqrt{s} = 200\,\text{GeV}$ with much higher statistics. Compared to the measurements at PHENIX, STAR profits from the coverage of the full azimuth, which is favorable when measuring azimuthal asymmetries. Furthermore slightly more forward rapidities can be reached even in the barrel, leading to larger expected amplitudes of the asymmetry. At forward rapidities, data from run 8 from the FTPC and the forward electromagnetic calorimeter FMS is currently being analyzed, however statistics is limited to this one run and the slow readout of the FTPC has an impact on the expected precision of the measurement.

3. – Planned measurements

The Interference Fragmentation Functions and di-hadron correlations are a very active area of research. With the measurements of the fragmentation function at Belle and the subsequent direct extraction of transversity from SIDIS data this trend intensified as shown at this workshop. Currently several interesting measurements are underway: Charged and neutral pion correlations at STAR and the extraction of $\pi^{\pm}/\pi^{0}$ IFF at Belle which is needed to extract transversity from the $p+p$ measurements. At Belle it is also planned to extract charged pion-kaon combinations, as well as the unpolarized di-hadron fragmentation functions, which are needed as a normalization factor in the extraction of transversity from the measured asymmetries. Furthermore both PHENIX and STAR plan major upgrades for the next decade as documented in the respective decadal plans of the experiments [19]. A central piece of these forward upgrades would be PID, tracking and electromagnetic calorimetry in the forward direction, covering at least $3 < \eta < 4$, enabling identified hadron correlation measurements in the valence quark region. On the theory side, the near future will hopefully see the full di-hadron cross-section for $e^{+}+e^{-}$ and $p+p$, giving experimentalists the foundation to access other transverse spin effects in di-hadron correlations, such as the Boer-Mulders function, as well.

4. – Summary and outlook

The importance of the measurements presented above is maybe best illustrated by the fact, that they made the first ever direct extraction of transversity possible [9]. Contrary to the global analysis of Collins asymmetries this is a point-by-point extraction of transversity from the HERMES and Belle data. The results are consistent with the global analysis of the Collins asymmetries. Inclusion of COMPASS results and $p+p$ results with the corresponding fragmentation functions measured at Belle will increase the precision considerably. Other than the unpolarized di-hadron fragmentation function used for normalization of the asymmetries, this extraction is not model dependent. This function is currently taken from Pythia [20] Monte Carlo simulations, but in the future it will be extracted from Belle data. Cross-section expressions for $p+p$ and $e^{+}+e^{-}$ will give experimentalists the tools to measure other aspects of the nucleon structure, such as the Boer-Mulders function. Using results from the planned measurements in $p+p$ at mid and forward rapidities, together with the corresponding transverse-spin–dependent and spin-integrated fragmentation functions, a measurement of the tensor charge will be possible that has much lower uncertainties from model dependencies. At the same time, high-precision data from identified mesons at COMPASS will allow access to the flavor structure of transversity. At JLab it is planned to study higher-twist correlation functions in di-hadron correlations.

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