

Dihadron Transverse-Spin Asymmetries in Muon-Deuteron Deep-Inelastic Scattering

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In 2022, the COMPASS collaboration performed semi-inclusive measurements of deep-inelastic muon-scattering on a transversely polarized deuteron (⁶LiD) target. From these data, transverse-spin-dependent dihadron asymmetries are extracted using pairs of oppositely charged hadrons. These asymmetries are directly sensitive to the quark transversity distributions and provide an independent handle on these fundamental quantities with respect to the Collins asymmetries measured in single-hadron production. The present results significantly improve upon the previous COMPASS deuteron measurements, which were the only available deuteron data worldwide, and reach a statistical precision comparable to that of the existing proton results from COMPASS. A small but nonzero asymmetry is observed at large Bjorken- x , consistent with theoretical expectations. A point-by-point extraction of the valence-quark transversity distributions yields, in particular, a substantially improved determination of the d -quark transversity. These measurements represent a major step towards a complete flavor mapping of the transverse-spin structure of the nucleon.

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Introduction—In quantum chromodynamics (QCD), a fast-moving nucleon (proton or neutron) is a composite, dynamic system of quarks and gluons (partons) exhibiting both longitudinal and transverse motion. The collinear parton distribution functions (PDFs) describe the longitudinal momentum fraction x carried by partons inside the nucleon [1,2] and form the cornerstone of QCD

phenomenology, providing the foundation for global analyses and precision predictions in high-energy processes. The transverse-momentum-dependent (TMD) PDFs extend this framework by incorporating the partonic transverse momentum $\mathbf{k}_T$, thereby offering access to the three-dimensional momentum structure of the nucleon [3–5].

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At leading twist, the full quark spin and momentum structure is described by eight TMD PDFs for each quark flavor, encompassing all possible correlations between quark spin, transverse momentum, and nucleon spin.

Among them, the spin-averaged $f_1(x, \mathbf{k}_T^2)$, the helicity $g_1(x, \mathbf{k}_T^2)$, and the transversity $h_1(x, \mathbf{k}_T^2)$ distributions have collinear counterparts: upon integration over $\mathbf{k}_T$, they reduce to $f_1(x)$, $g_1(x)$, and $h_1(x)$, respectively. The remaining five TMDs vanish upon $\mathbf{k}_T$ -integration.

The collinear transversity distribution $h_1(x)$ describes transversely polarized quarks inside a transversely polarized nucleon [2,6–9]. It represents the difference in the probability for finding a quark with spin aligned versus anti-aligned with respect to the transverse spin of the nucleon. It is directly related to the nucleon tensor charge, currently being evaluated in lattice QCD [10,11]. Being a chiral-odd function, h_1 can be measured only through its coupling to another chiral-odd partner. This property distinguishes it from chiral-even f_1 and g_1 and prevents its determination in inclusive deep-inelastic scattering (DIS).

At variance, the TMD transversity distribution $h_1(x, \mathbf{k}_T^2)$ can be accessed in single hadron production in semi-inclusive DIS (SIDIS) with transversely polarized targets through its convolution with the chiral-odd Collins fragmentation function $H_1^\perp$ [12]. In the Drell–Yan process it couples with another transversity distribution or with the chiral-odd Boer–Mulders TMD PDF [13,14]. In the TMD factorization framework the observable asymmetries involve convolutions in transverse momentum. As a consequence, the determination of the TMD PDFs and fragmentation functions FFs requires assumptions or parametrizations of their transverse-momentum shapes [2,15]. Alternatively, one can employ various weighting techniques to access transverse momentum moments of the PDFs and FFs [16–20].

In practice, SIDIS measurements [21–26] offer significantly higher statistical precision than Drell–Yan data [27,28] and enable a more direct flavor decomposition through the combined use of proton and deuteron (or neutron) targets and charge-separated hadron samples. For this reason, most of the present knowledge on the transversity distribution h_1 comes from global analyses that combine SIDIS and e^+e^- data, the latter providing essential information on the chiral-odd fragmentation functions (FFs) required for the extraction.

Despite the fact that the collinear transversity PDF $h_1(x)$ cannot be accessed in inclusive DIS, it can be measured in semi-inclusive production of oppositely charged hadron pairs, where it couples to the polarized dihadron interference fragmentation function $H_1^{\triangleleft}$ [29–31]. This approach is particularly important and unique because it allows for a direct extraction of $h_1(x)$ without requiring transverse-momentum-dependent factorization, thereby avoiding complications related to transverse-momentum convolutions and soft-factor effects. The same dihadron framework

also applies to polarized proton-proton collisions, providing an independent access to $h_1(x)$ [32].

The dihadron fragmentation function $H_1^{\triangleleft}$, which couples to transversity in collinear factorization, can originate from different mechanisms. One arises from the interference between quantum amplitudes associated with two competing channels for hadron-pair production, such as the direct production of the pair versus its production through a resonance decay [29,33] or the production of the pair from the decays of two different resonances [30]. Another mechanism is provided by the string + $^3P_0$ model, in which the string connecting, e.g., the scattered quark and the target remnant in a DIS event, breaks via the tunneling of quark-antiquark pairs with correlated spins and transverse momenta in the relative $^3P_0$ state [34,35]. As in the case of the Collins FF, the $H_1^{\triangleleft}$ has been extracted in global analyses combining e^+e^- annihilation data from the Belle Collaboration [36] with SIDIS data, where it is determined simultaneously with the transversity distribution [37–39]. A Monte Carlo model based on the Nambu–Jona-Lasinio approach has also been developed [40].

The dihadron transverse-spin asymmetries TSAs have been measured to be nonzero by HERMES [41] and COMPASS [42–44] on transversely polarized proton targets. For flavor separation, measurements with neutron or deuteron targets are required. Prior to this work, the only such result was the COMPASS measurement with a transversely polarized deuteron target from the 2002–2004 dataset [42], where the asymmetries were found to be compatible with zero within uncertainties.

This Letter presents new COMPASS results on dihadron TSAs, extracted from the 2022 dataset collected with a transversely polarized deuteron target. It constitutes a natural continuation of the single-hadron transverse spin asymmetry analysis recently published in Ref. [26], now extended to the dihadron channel.

Formalism—The coordinate frame for dihadron production in SIDIS and the definitions of the relevant angles are provided in Fig. 1. The relevant momenta are the incoming lepton momentum $\mathbf{l}$, the virtual-photon momentum $\mathbf{q}$, and the relative hadron momentum $\mathbf{R} = \xi_2 \mathbf{p}_1 - \xi_1 \mathbf{p}_2$, where

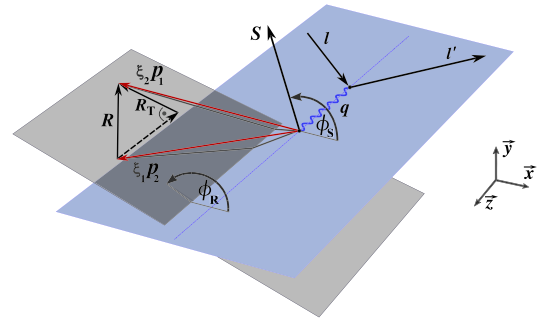


FIG. 1. Dihadron production coordinate frame and definition of the relevant vectors and azimuthal angles.

$\mathbf{p}_1$ and $\mathbf{p}_2$ are the momenta of the two selected final-state hadrons, and $\xi_i = z_i/(z_1 + z_2)$, with z_1 and z_2 being the fractions of the virtual-photon energy carried by hadron 1 (positive) and hadron 2 (negative), respectively. The azimuthal angle ϕ_S of the spin of the nucleon is defined between the lepton scattering plane (spanned by $\mathbf{l}$ and $\mathbf{l}'$) and the transverse-spin component $\mathbf{S}_T$, while ϕ_R denotes the angle between the lepton scattering plane and the plane containing $\mathbf{q}$ and the transverse component of the relative momentum $\mathbf{R}_T$.

At leading twist and after integration over the total transverse momentum of the hadron pair, the differential cross section for dihadron production on a transversely polarized nucleon can then be written as [33,42]

$$\begin{aligned} & \frac{d^7\sigma}{d\cos\theta dM_{\text{hh}} d\phi_R dz dx dy d\phi_S} \\ &= \frac{\alpha^2}{2\pi Q^2 y} \left(\left(1 - y + \frac{y^2}{2}\right) F_{\text{UU}} \right. \\ & \quad \left. + S_T(1 - y) \sin\theta F_{\text{UT}}^{\sin\phi_{\text{RS}}} \sin\phi_{\text{RS}} \right). \end{aligned} \quad (1)$$

Here, α is the fine-structure constant. The variable y denotes the fraction of the lepton energy (in the laboratory frame) transferred to the virtual photon, and Q^2 is the negative squared four-momentum transfer. The variables $z = z_1 + z_2$, M_{hh} , and θ correspond to the fraction of virtual-photon energy carried by the hadron pair, its invariant mass, and the polar angle of the positive hadron with respect to the two-hadron boost axis in the pair rest frame. Here, $\phi_{\text{RS}} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi$, where $\phi_{S'}$ is the azimuthal angle of the spin vector of the fragmenting quark [22].

The structure function F_{UU} represents the spin-averaged contribution to the dihadron production cross section, corresponding to the case of an unpolarized beam and an unpolarized target. At leading twist, it is given by

$$F_{\text{UU}} = \sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{\text{hh}}^2, \cos\theta). \quad (2)$$

The sum runs over the quark and antiquark flavors q with charge e_q , and $D_{1,q}(z, M_{\text{hh}}^2, \cos\theta)$ denotes the unpolarized quark dihadron fragmentation function (FF).

The spin-dependent term $F_{\text{UT}}^{\sin\phi_{\text{RS}}}$ is proportional to the product of the transversity PDF $h_1^q(x)$ and the dihadron FF of transversely polarized quarks $H_{1,q}^{\leftarrow}(z, M_{\text{hh}}^2, \cos\theta)$:

$$F_{\text{UT}}^{\sin\phi_{\text{RS}}} = \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{\text{hh}}} \sum_q e_q^2 h_1^q(x) H_{1,q}^{\leftarrow}(z, M_{\text{hh}}^2, \cos\theta). \quad (3)$$

The dihadron TSA $A_{\text{UT}}^{\sin\phi_{\text{RS}}}$ is given by the ratio of the two structure functions:

$$A_{\text{UT}}^{\sin\phi_{\text{RS}}} = \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{\text{hh}}} \frac{\sum_q e_q^2 h_1^q(x) H_{1,q}^{\leftarrow}(z, M_{\text{hh}}^2, \cos\theta)}{\sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{\text{hh}}^2, \cos\theta)}. \quad (4)$$

The dihadron TSA is extracted from the number of hadron pairs integrated over θ (see Ref. [42]):

$$\begin{aligned} & N_{\text{hh}}(x, y, z, M_{\text{hh}}^2, \phi_{\text{RS}}) \\ & \propto \sigma_{\text{UU}} [1 + f(x, y) P_T D_{\text{nn}}(y) \langle A_{\text{UT}}^{\sin\phi_{\text{RS}}} \sin\theta \rangle \sin\phi_{\text{RS}}], \end{aligned} \quad (5)$$

where $f(x, y)$ is the target-polarization dilution factor accounting for the fraction of polarizable nucleons in the target material, P_T is the transverse target polarization, and $D_{\text{nn}}(y)$ is the transverse-spin transfer coefficient.

Experimental data and event selection—The present analysis closely follows the procedures established in previous COMPASS dihadron studies [42,43], including event selection criteria, kinematic cuts, and the extraction method for azimuthal asymmetries. The data analyzed in this work are the same as those used for the Collins and Sivers asymmetry measurements reported in Ref. [26], where the experimental apparatus, data taking, and event selection are described. The data were collected by the COMPASS experiment [45] at CERN during the 2022 run, using a 160 GeV/ c naturally polarized μ^+ beam scattering off a transversely polarized deuteron (^6LiD) target. The experimental setup included a two-stage spectrometer equipped with tracking detectors, calorimetry, and particle identification systems to ensure precise reconstruction of the scattered muon and produced hadrons.

The analysis is based on events that fulfill deep-inelastic scattering conditions: $Q^2 > 1$ (GeV/ c)², $0.1 < y < 0.9$, and hadronic invariant mass $W > 5$ GeV/ c^2 . For dihadron studies, at least two oppositely charged hadrons originating from the interaction vertex are required. These hadrons must have $z_{1,2} > 0.1$ and $z = z_1 + z_2 < 0.9$ to suppress exclusive contributions. The selection $M_{\text{hh}} > 0.3$ GeV/ c^2 is adopted to avoid the low-mass threshold region.

The target consisted of three cylindrical cells, 30, 60, and 30 cm in length and 1.5 cm in radius, which were polarized in alternating directions to minimize acceptance effects. The target polarization was reversed in the middle of each of the ten data-taking periods of the 2022 run to minimize systematic effects. Data from the two polarization orientations were then combined to extract the transverse-spin asymmetries.

The TSAs are extracted by fitting the distribution of hadron-pair yields [Eq. (5)] as a function of ϕ_{RS} using an unbinned maximum-likelihood method [42]. The extracted observable is $\langle A_{\text{UT}}^{\sin\phi_{\text{RS}}} \sin\theta \rangle$, integrated over θ . In the COMPASS acceptance, θ peaks near $\pi/2$ with $\langle \sin\theta \rangle = 0.94$, and the $\cos\theta$ distribution is symmetric about zero. The fit function includes the $\sin\phi_{\text{RS}}$ modulation, and the extracted fitted amplitudes are normalized by $P_T f(x, y) D_{\text{nn}}(y)$. The average target polarization during

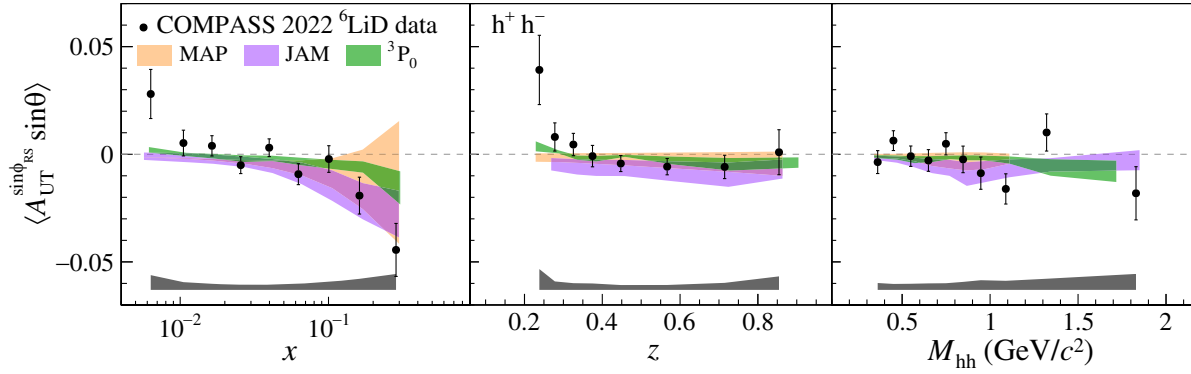


FIG. 2. Measured dihadron TSA as a function of x , z , and M_{hh} . The gray bands illustrate the associated systematic uncertainties. For comparison, the calculations from different models based on Refs. [46] (JAM), [39] (MAP), and [47] ($^3P_0$) are also shown.

the 2022 data-taking was approximately 0.50 with a relative uncertainty of about 3%, estimated from regular NMR calibrations. The dilution factor varies between 0.35 and 0.45 depending on kinematics. Its uncertainty is estimated to be 2%. Systematic uncertainties are assessed by varying the event selection criteria, testing alternative binning and fit ranges, and evaluating the stability of the results over the different data-taking periods. In addition, so-called false asymmetries are extracted by reassigning the target polarization orientation in cells and found to be consistent with zero within statistical uncertainties. All of these studies confirm the robustness of the extraction method. Further details of the analysis technique can be found in Refs. [42,43].

Results—The extracted dihadron TSAs are presented in Fig. 2 as a function of x , z , and M_{hh} . The statistical uncertainties on the extracted asymmetries range from 0.5% to 2% depending on the kinematic bin, while the total uncorrelated point-to-point systematic uncertainties, shown by the gray bands, are below 60% of the statistical ones. Tables with all numerical values are available in HEPdata.

The uncertainties are reduced by a factor of about 2 to 3 compared to the previous COMPASS deuteron measurement [42]. No significant signal is observed over the full kinematic range. The measured asymmetries remain small, typically below the percent level, and are statistically compatible with zero in most bins. This behavior is qualitatively consistent with expectations for a deuteron target, where cancellations between u - and d -quark contributions suppress the net asymmetry. A hint of a nonzero asymmetry is observed at large x , where the transversity distribution is expected to be sizable and the u -quark contribution dominates. No significant signal is observed in the ρ^0 resonance region.

The overall trend of the asymmetries agrees with the JAM (orange band) and MAP (purple band) global fit predictions [39,46], which are based on e^+e^- , SIDIS, and pp two-hadron data TSA, including, in particular, previous COMPASS deuteron and proton results [42,43]. The

dihadron FFs and h_1^u and h_1^d are extracted simultaneously in the global QCD fits. The difference between the two models and the size of the shown statistical uncertainty bands is driven by the differences in the approaches, the datasets used, and various constraints and assumptions adopted by the groups.

In Fig. 2, the measured asymmetries are also compared with results from simulations of DIS events on a transversely polarized deuteron target using the string + $^3P_0$ model (green band) [35,48]. In this approach, the color field between the scattered quark and the target remnant is modeled by a relativistic string. The breaking of the string into smaller segments describes the hadronization process. It occurs through tunneling of quark-antiquark pairs in the relative $^3P_0$ state, thus correlating the spin and transverse momentum of the quarks [34]. Such a mechanism gives rise to a nonzero Collins FF and $H_1^{\perp}$ if the fragmenting quark is transversely polarized [35]. The simulations were performed with the Pythia generator [49] using the StringSpinner package [47]. The latter enables spin effects via the string + $^3P_0$ model. The polarization of the fragmenting quark is parameterized using the point-by-point extractions of $h_1^{u_v}(x)$ and $h_1^{d_v}(x)$ obtained in Ref. [26]. As seen in the figure, the simulated asymmetries agree with the data within the uncertainties across all kinematic variables. The error bands reflect the statistical uncertainties of the parameterised transversity PDFs, while statistical uncertainties of the simulations are negligible.

To illustrate the expected improvement in the knowledge of the transversity distributions provided by the present measurement, $h_1^{u_v}(x)$ and $h_1^{d_v}(x)$ are extracted from the dihadron TSAs following the leading-order procedure of Ref. [50]. This extraction method requires parameterizations of neither transversity nor the fragmentation functions, and it does not rely on Monte Carlo simulations for the fragmentation functions. As in the case of the Collins asymmetries [26], the essential inputs are the measurements of the TSAs in SIDIS off proton and deuteron targets in the same kinematic range and the corresponding asymmetries measured in e^+e^- annihilation.

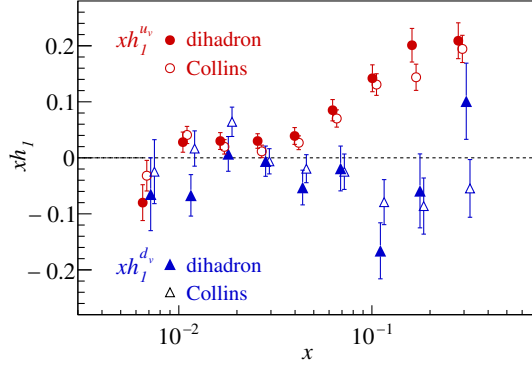


FIG. 3. The u_v (red circle) and d_v (blue triangles) valence-quark transversity in the different x bins, extracted from the full set of COMPASS measurements of the dihadron TSAs (closed points) and the Collins asymmetries (open points) [26]. Error bars represent statistical uncertainties.

Both $h_1^{u_v}$ and $h_1^{d_v}$ have been extracted from the dihadron TSAs using, first, only the previously published COMPASS results [42,43] and, subsequently, the full dataset including the present high-statistics deuteron measurement. With the complete set of COMPASS results, the statistical uncertainties are reduced by about a factor of two for both $h_1^{u_v}$ and $h_1^{d_v}$, clearly illustrating the impact of the new measurement. The results obtained using the full COMPASS data are shown in Fig. 3 as closed red circles and blue triangles. The u -quark transversity is well determined and clearly positive in the valence region, while $h_1^{d_v}$ is predominantly negative and lies within the Soffer bound [51], which is not imposed in the extraction. For comparison, the open points in Fig. 3 show the transversity values obtained from the point-by-point extraction [26] using the measured Collins asymmetries. The agreement between the valence transversities extracted from the Collins TSAs, based on transverse-momentum-dependent factorization of single-hadron production, and from the dihadron TSAs, based on collinear factorization of dihadron production, is quite good. This consistency supports the validity of both frameworks, in line with the conclusion drawn from the COMPASS study of the transverse-momentum-weighted Sivers asymmetries [20].

Conclusions—Transverse-spin-dependent dihadron asymmetries have been measured using the 2022 COMPASS data collected with a transversely polarized deuteron target. The statistical precision of the present results is comparable with that of the existing proton data and represents a substantial improvement over the previous measurement from the 2002–2004 deuteron data. This enables a more detailed investigation of the transverse spin structure of the nucleon within the collinear framework. The results show a nonzero trend at large x , consistent with expectations for the transversity distribution, while no significant signal is observed across the rest of the kinematic range. A comparison with recent

theoretical predictions based on global fits reveals good agreement. The new data has an important potential to reduce the systematic and statistical uncertainties and constrain the parameterizations for the transversity PDFs. A bin-by-bin extraction of the transversity PDFs demonstrates that the deuteron data provide crucial sensitivity, especially to the d -quark transversity distribution, complementing existing measurements on proton targets and contributing to a more balanced flavor separation [52].

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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