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New Measurements of Transverse Spin Asymmetries at COMPASS

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Over the past few decades, there has been enormous progress in understanding the internal structure of the nucleon, both on the experimental and theoretical sides. It has become clear that the proton's spin budget cannot be fully explained by parton spin alone, suggesting a significant role for transverse motion and orbital angular momentum within the nucleon. The COMPASS experiment at CERN, using semi-inclusive deep inelastic scattering (SIDIS) and Drell-Yan production with transversely polarized nucleons, continues to be at the forefront of this investigation. Transverse-momentum and spin dependent effects lead to azimuthal asymmetries, where the final-state particles preferentially emerge to one side relative to the nucleon's transverse spin. These asymmetries provide crucial insights into the transverse motion of partons, enabling access to transverse momentum dependent parton distribution and fragmentation functions. There has been scarcity of data, in particular, to access the d quark distributions. To address this concern, in 2022, COMPASS collected SIDIS data with a 160 GeV muon beam on a transversely polarized deuteron target, providing new insights into the transversity and Sivers distributions of u and d quarks. After the analysis of part of 2022 data, the first results for Sivers and Collins asymmetries are discussed here. Additionally, dihadron asymmetries are also shown.

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1. Experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) is a fixed target experiment located on the M2 beam line of CERN SPS in the North Area. The M2 beam line delivers both high-energy muon and hadron beams thus enabling a wide physics program at COMPASS, ranging from spectroscopy to nucleon structure. With high-energy muon beams, COMPASS conducted SIDIS on both longitudinally and transversely polarized proton and deuteron targets in addition to unpolarized targets. Using a high-energy pion beam, COMPASS explored TMD effects in Drell-Yan processes.

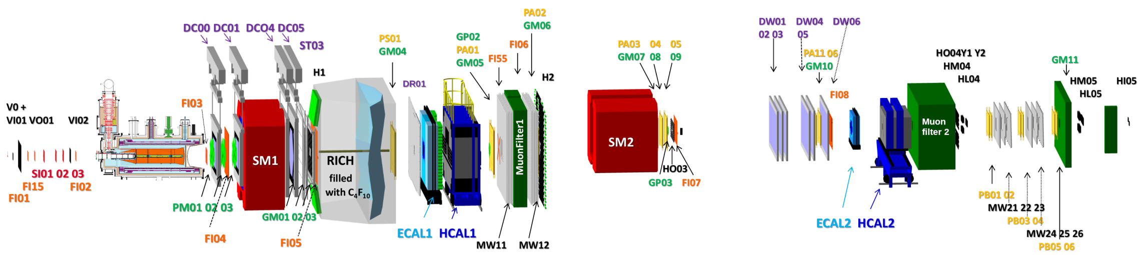

Figure 1: COMPASS setup for SIDIS run 2022

To handle the high beam intensities, the COMPASS spectrometer (see Figure 1) is structured in two stages, enabling the detection of outgoing hadrons in coincidence with the scattered beam particle across a wide range of momenta and angles. The Large Angle Spectrometer (LAS), with a wide angular acceptance of ±180 mrad, is equipped with a 1 Tm magnet, while the Small Angle Spectrometer (SAS) uses a 4 Tm magnet. Both stages feature tracking detectors, such as scintillating fibers and micromegas, for particle detection and momentum reconstruction, electromagnetic and hadronic calorimeters for energy measurement, muon walls for muon identification, and an array of hodoscopes for the trigger system. LAS is also equipped with a RICH detector for hadron identification.

The COMPASS polarized target [1] consists of a large-aperture superconducting magnet (±180 mrad since 2006), a dilution refrigerator, and target material housed in target cells. The material is polarized using the Dynamical Nuclear Polarization (DNP) method. In 2022, ^{6}LiD achieved around 40% polarization with a dilution factor of approximately 0.4, while the proton target (NH_3) reached 80-90% polarization with a dilution factor of about 0.15. The principle of COMPASS measurements, apparatus and the data analysis are detailed in Refs. [2][3].

COMPASS collected SIDIS data using a transversely polarized deuteron target from June to November 2022, with a spectrometer configuration similar to that used in the 2007 and 2010 proton measurements. Notably, the target magnet acceptance was 180 mrad, significantly larger than the 70 mrad acceptance used in the 2002-2004 deuteron measurements.

2. Theory

In the collinear picture of QCD, the transverse degrees of freedom of partons and the nucleon are neglected, thus cannot explain the contribution to nucleon spin due to partonic orbital angular momentum. In an extended approach, taking into account the partonic transverse momentum,

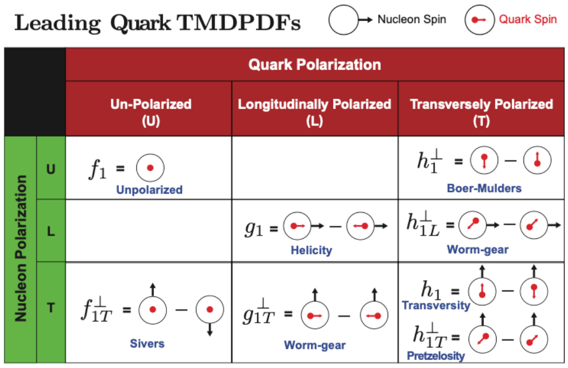

Figure 2: Leading-twist TMD-PDFs classified according to the polarizations of the quark and nucleon (U, L, T) [4]. The red dot and black circle represent the quark and nucleon, and the corresponding arrows their spin directions.

at leading twist, the nucleon structure can be described by a set of eight different Transverse Momentum Dependent Parton Distribution Functions (TMD-PDFs), see Figure 2, that depend on the longitudinal momentum fraction of the nucleon momentum (Bjorken x) and transverse momentum inside a nucleon. There are also TMD Fragmentation Functions (FFs) that describe the fragmentation of a certain (un)polarized parton into a hadron that carries a certain fraction of the parton's longitudinal momentum and a small transverse momentum relative to the parton. Out of the 8 TMD-PDFs, 3 are non-vanishing when integrating over the parton transverse momentum: the number density $f_1^q(x)$, helicity $g_1^q(x)$, and transversity $h_1^q(x)$ [4]. In a probabilistic interpretation, inside a nucleon of momentum P: $f_1^q(x)$ is the probability of finding a parton q with longitudinal momentum xP, $g_1^q(x)$ is the difference in probability that the parton q has its helicity aligned or anti-aligned with that of the nucleon, and $h_1^q(x)$ is the difference in probability that the parton q has its spin aligned or anti-aligned with that of a transversely polarized nucleon.

Despite their similar definitions, $h_1(x)$ and $g_1(x)$ are independent functions as they describe different spin structures in a relativistic framework. $h_1(x)$ is chiral-odd and appears in convolutions with a fragmentation function (FF) in processes like SIDIS, where it couples with the chiral-odd Collins FF, $H_1^\perp$, which describes the correlation between the transverse momentum of the produced hadron and the polarization of the fragmenting quark. Due to the difficulty of accessing this chiral-odd function, $h_1(x)$ is much less well-known compared to $g_1(x)$ and $f_1(x)$.

The three collinear PDFs satisfy the Soffer bound [5]: $|h_1(x)| \leq \frac{1}{2}|f_1(x) + g_1(x)|$. The transversity PDF relates to the nucleon tensor charge g_T through: $\delta q = \int_0^1 dx\,(h_1^q(x) - h_1^{\bar{q}}(x))$ and $g_T = \delta u - \delta d$, reflecting the net number of transversely polarized valence quarks in a transversely polarized nucleon and serving as a tool to constrain nucleon models [4].

Considering quark transverse momentum k_T, the remaining 5 TMD-PDFs become significant. Particularly notable is the Sivers TMD PDF, $f_{1T}^\perp(x, k_T)$, which encodes the correlation between the transverse polarization of the nucleon and the unpolarized quark's k_T.

According to the QCD factorization theorem, the total cross section of a scattering process such as SIDIS can be expressed as a convolution of the perturbatively calculable lepton-parton QCD cross section and the PDF and the FF. As the TMD effects manifest as azimuthal asymmetries in

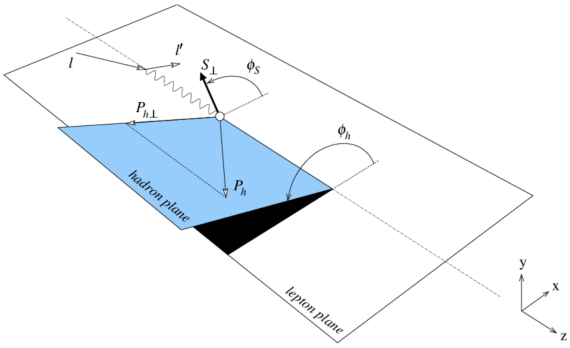

Figure 3: Definition of azimuthal angles for SIDIS in the target rest frame. $\vec{P_{h\perp}}$ (also labeled as $\vec{p_T}$) and $\vec{S_\perp}$ are the transverse parts of $\vec{P_h}$ and $\vec{S}$ with respect to the photon momentum [6].

the final state hadrons, the amplitudes of the asymmetries encode information of TMD PDFs and FFs.

The single hadron SIDIS kinematics is displayed in Figure 3. The angles ϕ_h and ϕ_s are the azimuthal angles that the hadron transverse momentum ($\vec{p_T}$) and nucleon spin ($\vec{S}$) make with the lepton scattering plane, respectively. Both angles are defined in the Gamma Nucleon System (GNS), where the virtual photon's direction is along $\hat{z}$, as shown. The most generic single hadron SIDIS cross section can be written in terms of 18 independent structure functions [6]. In the TMD formalism, these structure functions are expressed as convolutions of PDFs and FFs, offering insights into the respective functions. The cross-section is decomposed into terms that depend on the polarizations of the lepton and nucleon, with each term characterized by azimuthal modulations in the angles ϕ_h and ϕ_S. Experimentally, measuring the amplitudes of these modulations, known as azimuthal asymmetries, allows access to PDFs when independent information on FFs is available. At COMPASS, the use of longitudinally or transversely polarized protons and deuterons, along with the detection and identification of final-state hadrons, aids in accessing PDFs and achieving flavor separation.

The leading twist QCD-improved parton model interpretation of the first two Transverse Spin Asymmetries (TSAs) that appear in the cross-section can be written as:

$$\begin{aligned} A^h_{Siv} &= A^{\sin(\phi_h-\phi_s)}_{UT} \propto f^{\perp q}_{1T} \otimes D^h_{1q}, \\ A^h_{Coll} &= A^{\sin(\phi_h+\phi_s)}_{UT} \propto h^q_1 \otimes H^{\perp h}_{1q}. \end{aligned} \tag{1}$$

They are the Sivers and Collins asymmetries respectively and are measured with a transversely polarized target. The amplitude of the modulation $\sin(\phi_h - \phi_S)$ is the Sivers asymmetry and encodes information on the Sivers TMD PDF convoluted with (represented by the symbol $\otimes$) the spin averaged FF D_1, while the Collins asymmetry (amplitude of $\sin(\phi_h + \phi_S)$) contains the convolution of the transversity TMD PDF with the Collins FF.

In contrast, for dihadron production in SIDIS, a hadron pair is detected in the final state instead of a single hadron. The transverse polarisation of the fragmenting quark is correlated with the relative momentum of the two hadrons, which gives rise to an azimuthal asymmetry with respect to the virtual-photon direction and the lepton scattering plane as illustrated in Figure 4. Similar to the

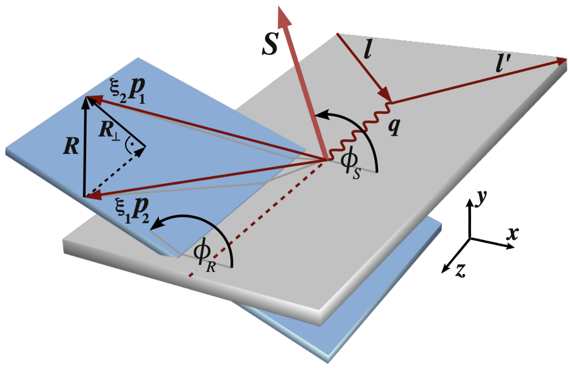

Figure 4: Definition of the azimuthal angles ϕ_R and ϕ_S for two-hadron production in SIDIS [7]

single hadron case, the cross-section of semi-inclusive dihadron leptoproduction on a transversely polarized target can be expressed as proportional to harmonic modulation in the angle ϕ_{RS}.

$$A_{UT}^{\sin(\phi_{RS})} \propto h_1^q \times H_{1,q}^{\sphericalangle} \tag{2}$$

The amplitude of this modulation, known as the dihadron asymmetry, provides information about the transversity TMD PDF and the Interference Fragmentation Function (IFF), which describes the fragmentation of a transversely polarized quark into a pair of unpolarized hadrons.

COMPASS published Collins and Sivers asymmetries for a transversely polarized deuteron target in 2005 [8], while around the same time, the HERMES collaboration published the first results for a proton target [9]. A striking difference between the two was observed: the proton data showed clear signals for both Collins and Sivers asymmetries, whereas the deuteron asymmetries were small or consistent with zero. This suggested a cancellation between the u- and d-quark Sivers and transversity distributions, as the equal number of u and d valence quarks in a deuteron neutralized each other's effects. In 2007 and 2010, COMPASS collected data using a transversely polarized proton target, confirming the HERMES findings [2, 3].

Meanwhile, global fits for the transversity and Sivers functions, incorporating all existing experimental data, suggested opposite behavior between the u- and d-quarks, particularly in the valence region [10, 11]. However, the limited statistical precision on the d-quark distributions remained a concern. This motivated the COMPASS collaboration to request an additional SPS year for data collection to complete the nucleon 3D structure exploration program.

This talk presents the first results from COMPASS for Sivers, Collins, and dihadron asymmetries, as well as a point-by-point extraction of the transversity and Sivers distributions in a model-independent way.

3. Results and discussion

The analysis presented here is based on two-thirds of the total 2022 data, for which data processing, quality checks, and systematic studies have been completed, and published in Ref. [12]. SIDIS events are selected using kinematic cuts requiring a photon virtuality $Q^2 > 1\,\text{GeV}^2$, inelasticity $0.1 < y < 0.9$, and hadronic final state mass $W > 5\,\text{GeV}$. Final state hadrons must also have a transverse momentum $p_T > 0.1$ GeV and a fraction of the available energy, $z > 0.2$ for single hadron and $z > 0.1$ each for dihadron final state.

The results for Sivers asymmetries are shown in Figure 5, A_{Siv}, measured as functions of x, z, and p_T. The closed points represent the 2022 data, while the open points correspond to deuteron data from 2002-2004 (left) and proton data (right). Results are shown separately for positive (top) and negative (bottom) hadrons.

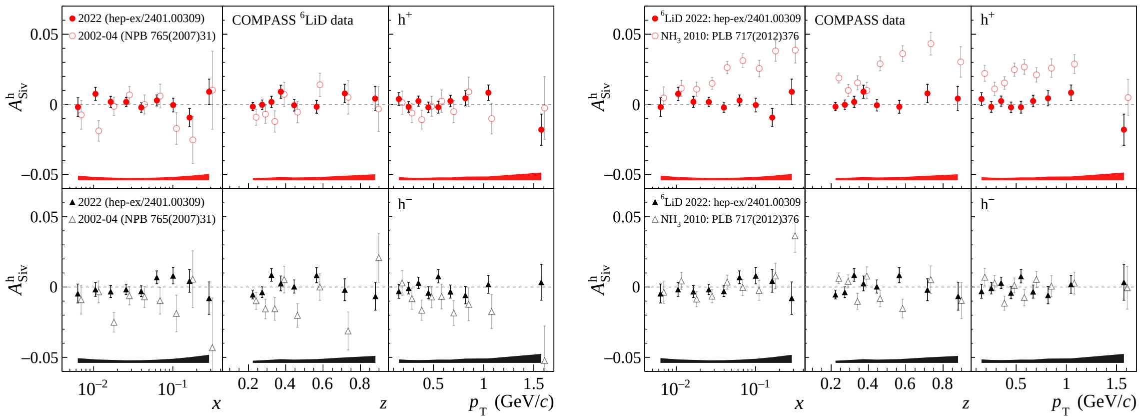

Figure 5: Sivers asymmetries for positive (top) and negative (bottom) hadrons and comparison with the old deuteron data (left) and proton data (right)

The 2022 data show significant improvements in statistical uncertainties compared to the older deuteron data, and now match the precision of the proton data. The deuteron asymmetries remain consistent with zero, strongly suggesting the cancellation of u- and d-quark Sivers distributions.

The Collins asymmetries, A_{Coll}, from the 2022 data are shown in Figure 6 as closed points for positive (top) and negative (bottom) hadrons. While the previous data (2002-2004) did not exhibit

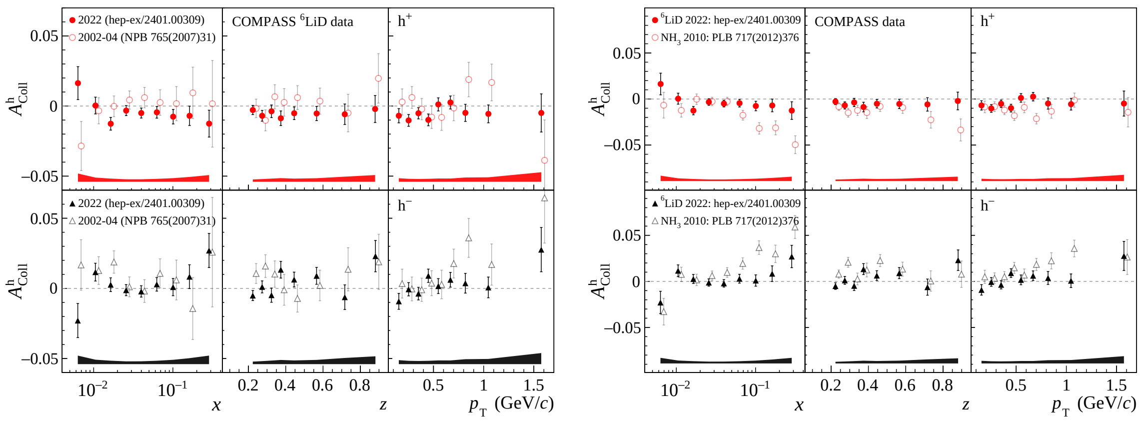

Figure 6: Collins asymmetries for positive (top) and negative (bottom) hadrons and comparison with the old deuteron data (left) and proton data (right)

any clear trends, and the points were compatible with zero within statistical uncertainties, the current results show indications of negative (positive) values at large x for positive (negative) hadrons. The x-dependence is also similar to that observed in A_{Coll} for protons, as shown in Figure 6, where the new deuteron results are compared with COMPASS proton data. The statistical uncertainties for both proton and deuteron are now comparable, showing significant improvement.

The current results, combined with the previously published proton and deuteron data from COMPASS and Belle e^+e^- data, enable a point-by-point extraction of the transversity distributions for u and d valence quarks. The results, shown as closed points in Figure 7 left, are obtained following the procedure used in Ref. [13] assuming that all the charged hadrons are pions. The open points show the values obtained without the present 2022 results [13]. Opposite sign behavior is observed for u and d quarks, with significantly improved uncertainties—up to a factor of 4 in the large x bins. This improvement in precision is evident for both quark flavors. Using these transversity distributions, the truncated nucleon tensor charge is extracted, found to be about 20% smaller now with a factor of two improvement in statistical precision as described in Ref. [12]. Additionally, the first k_T^2 moments of the Sivers functions are extracted using the same procedure as in Ref. [14] but assuming that all the charged hadrons are pions. The results obtained using the present measurement of the Sivers asymmetry are the closed points in Figure 7 right compared with the results from Ref. [14]. The gain in precision due to the addition of 2022 data is strikingly remarkable.

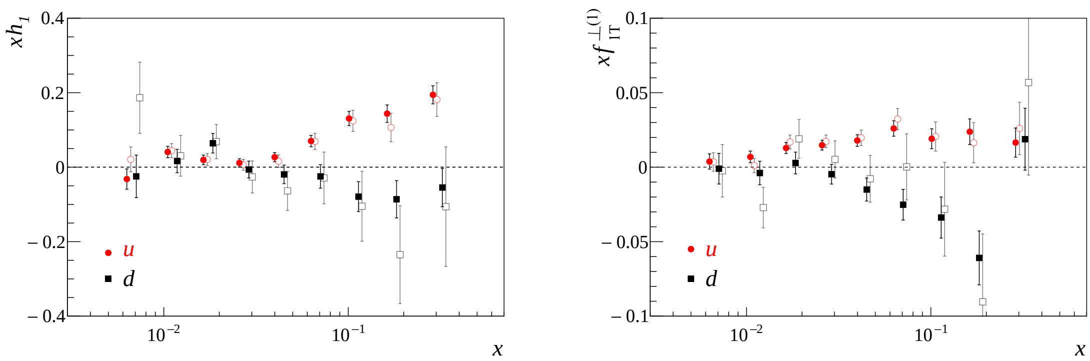

Figure 7: First moments of transversity (left) and Sivers (right) functions. The closed (open) points correspond to including (excluding) the new COMPASS data from 2022.

The COMPASS 2002-2004 deuteron data showed no significant dihadron asymmetries [15]. In contrast, the same analysis on a proton target revealed signal-like behavior, particularly in the valence region, indicating a non-zero transversity PDF and interference fragmentation function [15]. The dihadron asymmetries for positive hadrons on the proton target were very close to their corresponding Collins asymmetries, suggesting a similar mechanism behind both single hadron and dihadron transverse spin-dependent effects [16]. The newly extracted asymmetries from the 2022 deuteron data are shown in Figure 8, comparing the new results with the older deuteron data (top) and proton data (bottom) as a function of x, z, and the invariant mass of the hadron pair $M_{h^+h^-}$. The improved statistical uncertainties are evident, alongside a clear similarity in trends in the large x region for both proton and deuteron targets.

In summary, the COMPASS Collaboration's 2022 SIDIS data with a deuteron target has provided high-precision measurements of Collins, Sivers, and dihadron asymmetries. These new measurements showcase a remarkable improvement in precision and provide crucial input for

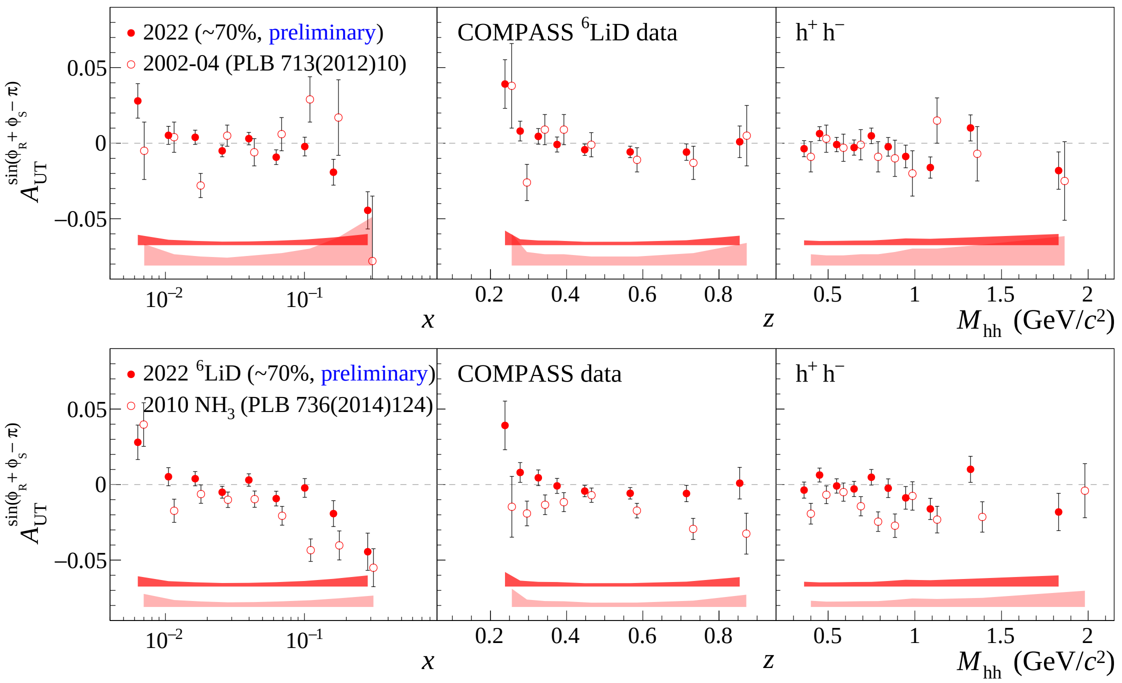

Figure 8: Dihadron asymmetries from the 2022 data shown in closed points compared with old deuteron data (top) and proton data (bottom).

phenomenological analyses. In particular, they allow for transverse spin asymmetry analyses that were previously limited by the lower statistics of deuteron data. The 2022 results complete COMPASS's transverse spin studies in SIDIS and will remain a key reference until future data from the Electron-Ion Collider or Jefferson Lab become available.

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