

Transverse spin azimuthal asymmetries in SIDIS at COMPASS: Multidimensional analysis

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One of the important objectives of the COMPASS experiment (CERN, SPS north area) is the exploration of transverse spin structure of nucleon via study of spin (in)dependent azimuthal asymmetries with semi-inclusive deep inelastic scattering (SIDIS) processes and recently also with Drell-Yan (DY) reactions. In the past twelve years series of measurements were made in COMPASS, using 160 GeV/c longitudinally polarized muon beam and polarized ${}^6\text{LiD}$ and NH_3 targets. Drell-Yan measurements with high energy (190 GeV/c) pion beam and transversely polarized NH_3 target started in 2014 with a pilot-run have been followed by 140 days of data taking in 2015. The experimental results obtained by COMPASS for azimuthal effects in SIDIS play an important role in the general understanding of the three-dimensional nature of the nucleon and are widely used in theoretical analyses and global data fits. In addition, future first ever polarized DY-data from COMPASS compared with SIDIS results will open a new chapter probing general principles of QCD TMD-formalism. In this review main focus is given to the very recent results obtained by the COMPASS collaboration from first ever multi-dimensional extraction of SIDIS transverse spin asymmetries.

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1 Introduction

In past decades, measurements and following study of the spin dependent and *unpolarized* azimuthal effects in SIDIS has become a priority direction in experimental and theoretical high-energy physics. Using standard SIDIS notations, the differential cross-section can be written in single-photon exchange approximation as [1]–[3]:

$$\begin{aligned}
\frac{d\sigma}{dx dy dz p_T^h dp_T^h d\phi_h d\phi_S} &= 2 \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \\
&\times \left\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos(2\phi_h) + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \right. \\
&+ S_T \left[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \right. \\
&\quad \left. + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \right] \\
&+ S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \right. \\
&\quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \right] \left. \right\}, \quad (1)
\end{aligned}$$

with $\varepsilon = (1 - y - \frac{1}{4}\gamma^2 y^2)/(1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2)^*$, $\gamma = 2Mx/Q$. Target transverse polarization (S_T)[†] dependent part of this general expression contains eight azimuthal modulations in the ϕ_h and ϕ_S azimuthal angles of the produced hadron and of the nucleon spin, correspondingly. Each modulation leads to a $A_{BT}^{w_i(\phi_h, \phi_S)}$ Transverse-Spin-dependent Asymmetry (TSA) defined as a ratio of the associated structure function $F_{BT}^{w_i(\phi_h, \phi_S)}$ to the azimuth-independent one $F_{UU} = F_{UU,T} + \varepsilon F_{UU,L}$. Here the superscript of the asymmetry indicates corresponding modulation, the first and the second subscripts - respective ("U"-unpolarized, "L"-longitudinal and "T"-transverse) polarization of beam and target. Five amplitudes which depend only on S_T are the target Single-Spin Asymmetries (SSA), the other three which depend both on S_T and λ (beam longitudinal polarization) are known as Double-Spin Asymmetries (DSA).

In the QCD parton model approach four out of eight transverse spin asymmetries have Leading Order (LO) or leading "twist" interpretation and are described by the convolutions of twist-two Transverse-Momentum-Dependent (TMD) Parton Distribution Functions (PDFs) and Fragmentation Functions (FFs) [1]–[4].

The first two: $A_{UT}^{\sin(\phi_h-\phi_S)}$ "Sivers" and $A_{UT}^{\sin(\phi_h+\phi_S)}$ "Collins" effects [5, 6] are the most studied ones. These asymmetries are given as convolutions of: $f_{1T}^{\perp q}$ Sivers PDF convoluted with D_{1q}^h ordinary FF and h_1^q "transversity" PDF convoluted with the

*ratio of longitudinal and transverse photon fluxes

†in reality polarization vector has a small longitudinal component w.r.t. virtual photon direction which leads to small deviations of amplitudes (not discussed in this letter, for details see [10])

$H_{1q}^{\perp h}$ Collins FF, respectively. The other two LO terms are the $A_{UT}^{\sin(3\phi_h-\phi_S)}$ single-spin asymmetry (related to $h_{1T}^{\perp q}$ ("pretzelosity") PDF [7]–[13]) and $A_{LT}^{\cos(\phi_h-\phi_S)}$ DSA (related to g_{1T}^q ("worm-gear") distribution function [7]–[13, 14, 15]).

$$\begin{aligned} A_{UT}^{\sin(\phi_h-\phi_S)} &\propto f_{1T}^{\perp q} \otimes D_{1q}^h, & A_{UT}^{\sin(\phi_h+\phi_S)} &\propto h_1^q \otimes H_{1q}^{\perp h}, \\ A_{UT}^{\sin(3\phi_h-\phi_S)} &\propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}, & A_{LT}^{\cos(\phi_h-\phi_S)} &\propto g_{1T}^q \otimes D_{1q}^h. \end{aligned} \quad (2)$$

Remaining four asymmetries are so-called "higher-twist" effects[‡]. Corresponding structure functions enter at sub-leading order (Q^{-1}) and contain terms given as various mixtures of twist-two and twist-three (induced by quark-gluon correlations) parton distribution and fragmentation functions [2, 16, 17]. However, applying wildly adopted so-called "Wandzura-Wilczek approximation" this higher twist objects can be simplified to twist-two level (see [2, 4] for more details):

$$\begin{aligned} A_{UT}^{\sin(\phi_S)} &\propto Q^{-1}(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h), \\ A_{UT}^{\sin(2\phi_h-\phi_S)} &\propto Q^{-1}(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h), \\ A_{LT}^{\cos(\phi_S)} &\propto Q^{-1}(g_{1T}^q \otimes D_{1q}^h), & A_{LT}^{\cos(2\phi_h-\phi_S)} &\propto Q^{-1}(g_{1T}^q \otimes D_{1q}^h). \end{aligned} \quad (3)$$

In general, TSAs being convolutions of different TMD functions are known to be complex objects *a priori* dependent on the choice of kinematical ranges and multidimensional kinematical phase-space. Thus, ideally, asymmetries have to be extracted as multi-differential functions of kinematical variables in order to reveal the most complete multivariate dependence. In practice, available experimental data often is too limited for such an ambitious approach and studying dependence of the asymmetries on some specific kinematic variable one is forced to integrate over all the others sticking to one-dimensional approach. Presently, one of the hottest topics in the field of spin-physics is the study of TMD evolution of various PDFs and FFs and related asymmetries. Different models predict from small up to quite large $\sim 1/Q^2$ suppression of the QCD-evolution effects attempting to describe available experimental observations and make predictions for the future ones [18, 19, 20]. Additional experimental measurements exploring different Q^2 domains for fixed x -range are necessary to further constrain the theoretical models. The work described in this review is a unique and first ever attempt to explore behaviour of TSAs in the multivariate kinematical environment. For this purpose COMPASS experimental data was split into five different Q^2 ranges giving an opportunity to study asymmetries as a function of Q^2 at fixed bins of x . Additional variation of z and p_T cuts allows to deeper explore multi-dimensional behaviour of the TSAs and their TMD constituents.

[‡]in equation 1 the twist-2 amplitudes are marked in red and higher-twist ones in blue

2 Multidimensional analysis of TSAs

The analysis was carried out on COMPASS data collected in 2010 with transversely polarized proton data. General event selection procedure as well as asymmetry extraction and systematic uncertainty definition techniques applied for this analysis are identical to those used for recent COMPASS results on Collins, Sivers and other TSAs [5]–[13].

The eight target transverse spin dependent "raw" asymmetries are extracted simultaneously from the fit using extended unbinned maximum likelihood method and then are corrected for average depolarization factors (ε -depending factors in equation 1 standing in front of the amplitudes), dilution factor and target and beam (only DSAs) polarizations evaluated in the given kinematical bin [5]–[13].

$$\begin{aligned}
 D^{\sin(\phi_h - \phi_S)}(y) &\cong 1, \quad D^{\cos(\phi_h - \phi_S)}(y) = \sqrt{1 - \varepsilon^2} \approx \frac{y(2 - y)}{1 + (1 - y)^2}, \\
 D^{\sin(\phi_h + \phi_S)}(y) &= D^{\sin(3\phi_h - \phi_S)}(y) = \varepsilon \approx \frac{2(1 - y)}{1 + (1 - y)^2}, \\
 D^{\sin(2\phi_h - \phi_S)}(y) &= D^{\sin(\phi_S)}(y) = \sqrt{2\varepsilon(1 + \varepsilon)} \approx \frac{2(2 - y)\sqrt{1 - y}}{1 + (1 - y)^2}, \\
 D^{\cos(2\phi_h - \phi_S)}(y) &= D^{\cos(\phi_S)}(y) = \sqrt{2\varepsilon(1 - \varepsilon)} \approx \frac{2y\sqrt{1 - y}}{1 + (1 - y)^2}.
 \end{aligned} \tag{4}$$

Primary sample is defined by the following standard DIS cuts: $Q^2 > 1$ (GeV/c)², $0.003 < x < 0.7$ and $0.1 < y < 0.9$ and two more *hadronic* selections: $p_T > 0.1$ GeV/c and $z > 0.1$.

In order to study possible Q^2 -dependence the $x:Q^2$ phase-space covered by COMPASS experimental data has been divided into 5×9 two-dimensional grid (see left plot in Figure 1). Selected five Q^2 -ranges are the following ones: $Q^2/(GeV/c)^2 \in [1; 1.7], [1.7; 3], [3; 7], [7; 16], [16; 81]$ [§]. In addition, each of this samples has been divided into five z and five p_T (GeV/c) sub-ranges defined as follows:

$z > 0.1$, $z > 0.2$, $0.1 < z < 0.2$, $0.2 < z < 0.4$ and $0.4 < z < 1.0$

$p_T > 0.1$, $0.1 < p_T < 0.75$, $0.1 < p_T < 0.3$, $0.3 < p_T < 0.75$ and $p_T > 0.75$.

Using various combinations of aforementioned cuts and ranges, asymmetries have been extracted for following "3D" and "4D" configurations: 1) x -dependence in Q^2 - z and Q^2 - p_T grids. 2) Q^2 -dependence in x - z and x - p_T grids. 3) Q^2 - (or x -) dependence in x - p_T (or Q^2 - p_T) grids for different choices of z -cuts. Another approach was used to focus on z - and p_T -dependences in different x -ranges. For this study the two-dimensional $z:p_T$ phase-space has been divided into 7×6 grid as it is demonstrated in right plot in Figure 1. Selecting in addition three x -bins: $0.003 < x < 0.7$,

[§] $16 < Q^2/(GeV/c)^2 < 81$ selection repeats the definition of the so-called "high-mass" range: most promising domain for future COMPASS–Drell-Yan TSA-analyses [7, 9].

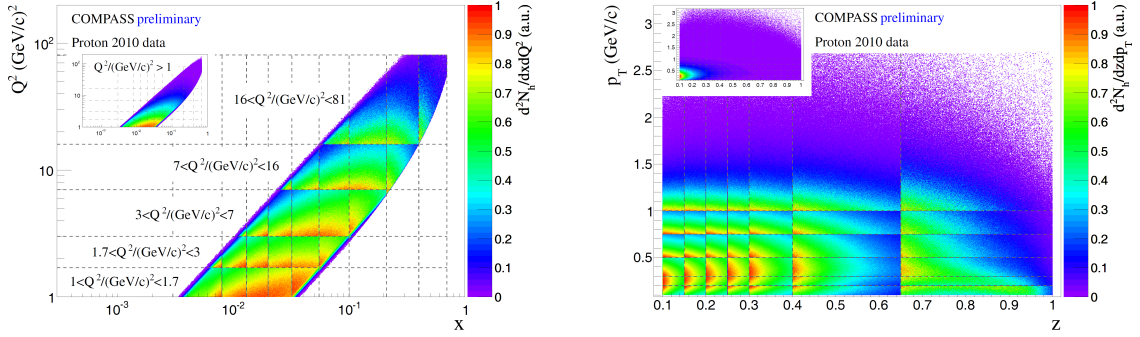


Figure 1: COMPASS $x : Q^2$ (left) and $z : p_T$ (right) phase space coverage.

$0.003 < x < 0.032$, $0.032 < x < 0.7$ asymmetries have been extracted in "3D: x - z - p_T " grid. In the next section several examples of COMPASS preliminary results obtained for multi-dimensional target transverse spin dependent azimuthal asymmetries are presented.

3 Results

¶ As an example of "3D" Sivers effect, results for the extracted x - z - Q^2 configuration are presented in the Figure 2. The results shown at the plot serve as a direct input for TMD-evolution related studies. In fact, in several x -bins there are some hints for possible decreasing Q^2 -dependence for positive hadrons which become more evident at large z . As a general observation, sizable Sivers asymmetry tending to increase with z and p_T was observed for positive hadrons, while for negative hadrons there are some indications for a positive signal at relatively large x and Q^2 and negative effect at low x .

In Figure 3 Collins asymmetry is shown in "3D: x - z - Q^2 ". Clear "mirrored" behaviour for positive and negative hadron amplitudes is being observed in most of the bins. Amplitudes tend to increase in absolute value with both z and p_T . There are no clear indications for Q^2 -dependence. Another SSA which is found to be non-zero at COMPASS is the $A_{UT}^{\sin(\phi_s)}$ term which is presented in Figure 4 (top) in "3D: x - z - p_T " configuration. Here the most interesting is the large z -range where amplitude is measured to be sizable and non zero both for positive and negative hadrons.

The bottom plot in the Figure 4 is dedicated to the $A_{LT}^{\cos(\phi_h - \phi_s)}$ DSA explored in "3D: Q^2 - z - x " grid and superimposed with the theoretical curves from [14]. This is the only DSA which appears to be non-zero at COMPASS and the last TSA for which a statistically significant signal has been detected. Remaining four asymmetries are

¶ Discussed results have been first presented at the SPIN-2014 conference [8], see also [21, 22].

found to be small or compatible with zero within available statistical accuracy which is in agreement with available predictions [16, 17, 23].

4 Conclusions

The first ever multidimensional extraction of the whole set of target transverse spin dependent azimuthal asymmetries has been done at COMPASS with proton data collected in 2010. Various multi-differential configurations has been tested exploring $x:Q^2:z:p_T$ phase-space. Particular attention was given to probes of possible Q^2 -dependence of TSAs, serving a direct input to TMD-evolution related studies. Several interesting observations have been made studying the results obtained for Sivers, Collins, $A_{LT}^{cos(\phi_h-\phi_S)}$ and $A_{UT}^{sin(\phi_S)}$ asymmetries. Other four asymmetries were found to be compatible with zero within given statistical accuracy. This highly differential data set for the eight asymmetries, combined with past and future relevant data obtained by other collaborations will give a unique opportunity to access the whole set of TMD PDFs and test their multi-differential nature and key features.

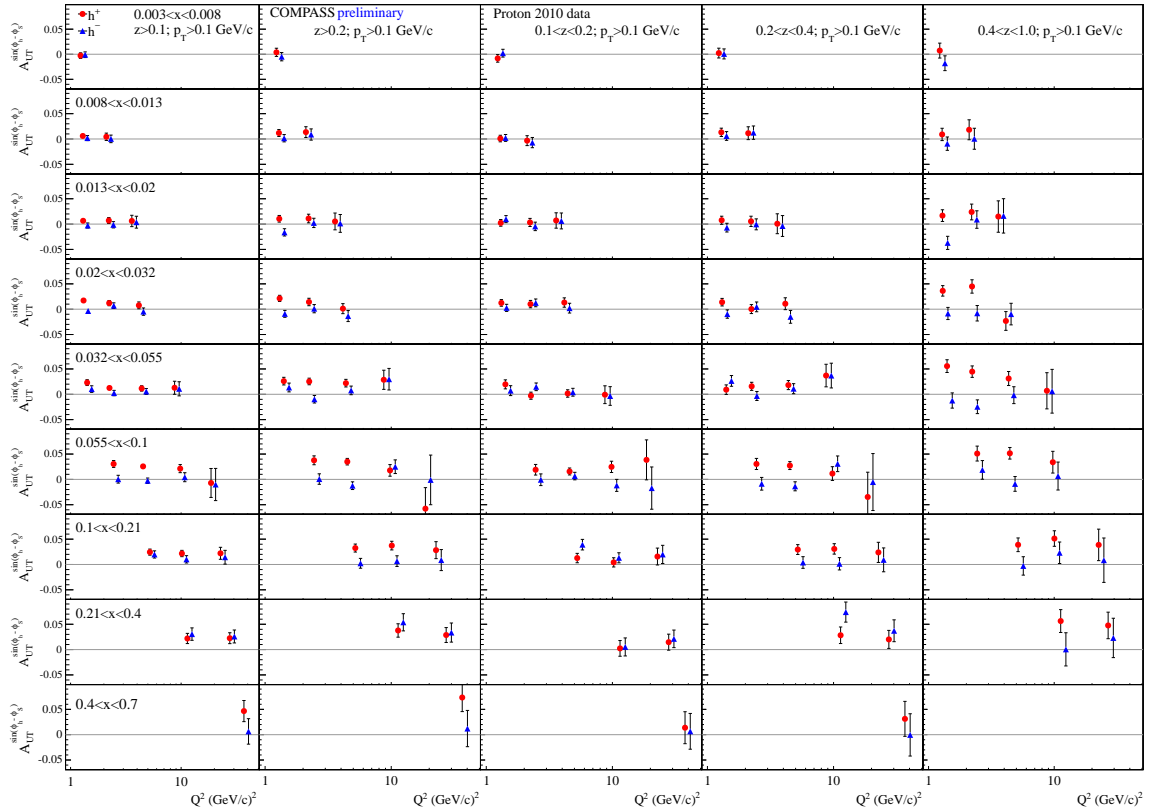


Figure 2: Sivers asymmetry in "3D": Q^2 - p_T - x (top) and x - z - Q^2 (bottom).

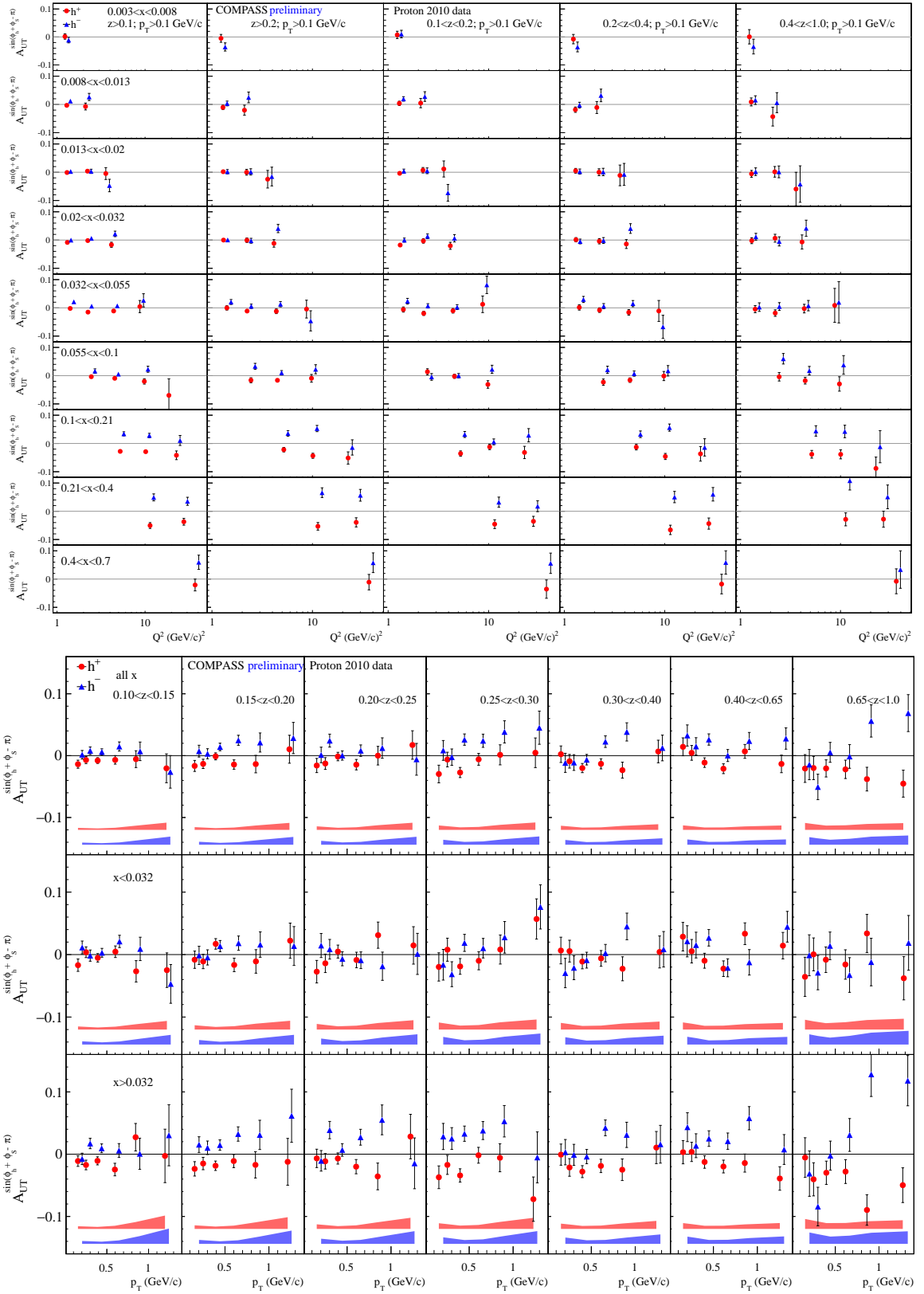


Figure 3: Collins asymmetry in "3D": $x-z-Q^2$ (top) and $x-z-p_T$ (bottom).

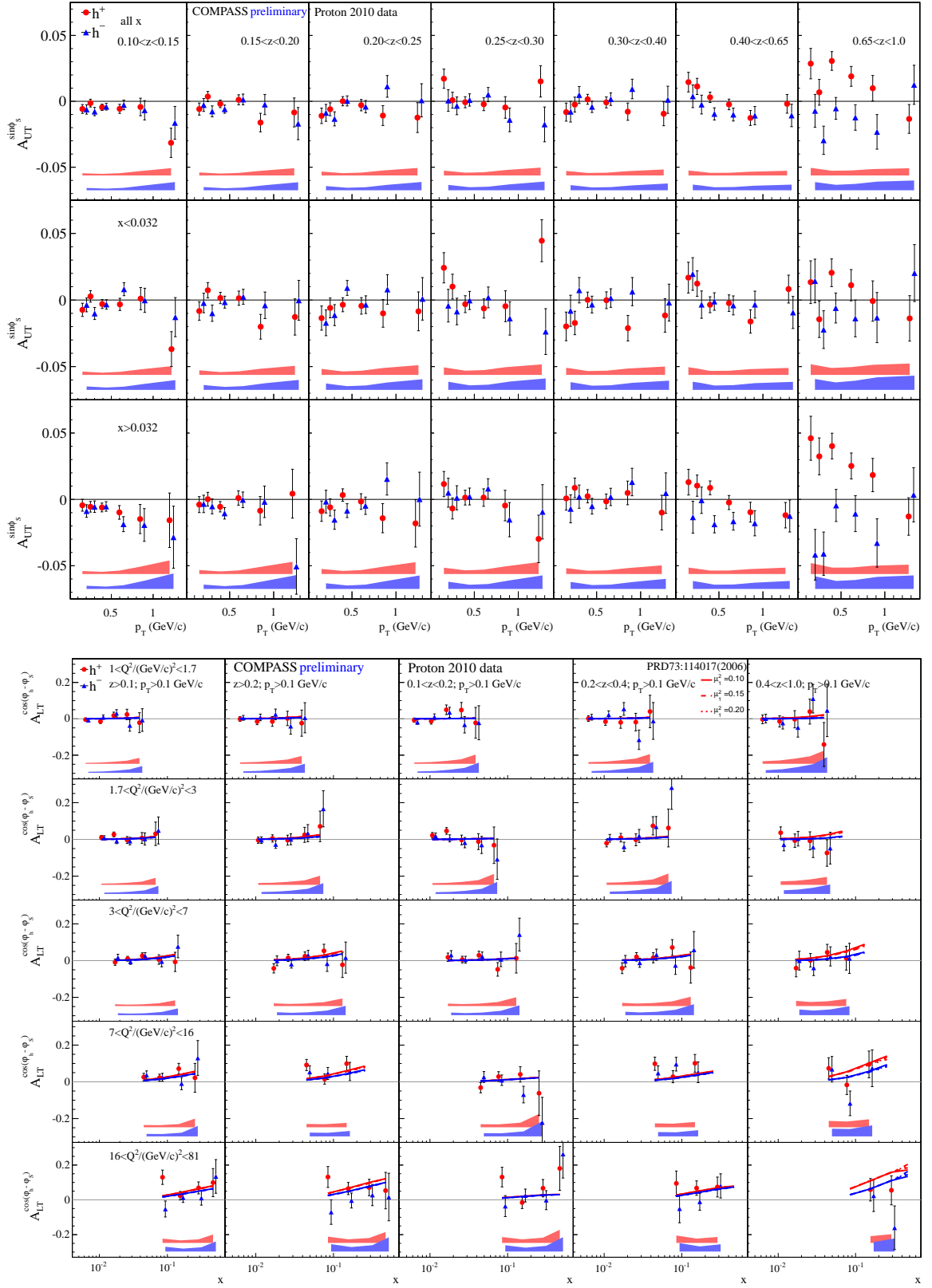


Figure 4: Top: $A_{UT}^{\sin(\phi_s)}$ asymmetry in "3D" (x - z - p_T). Bottom: $A_{LT}^{\cos(\phi_h - \phi_s)}$ in "3D" (Q^2 - z - x) superimposed with theoretical predictions from [13].

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