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Contribution of exclusive diffractive processes to the measured azimuthal asymmetries in SIDIS

The COMPASS Collaboration

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Abstract

Hadron leptoproduction in Semi-Inclusive measurements of Deep-Inelastic Scattering (SIDIS) on unpolarised nucleons allows one to get information on the intrinsic transverse momentum of quarks in a nucleon and on the Boer-Mulders function through the measurement of azimuthal modulations in the cross section. These modulations were recently measured by the HERMES experiment at DESY on proton and deuteron targets, and by the COMPASS experiment using the CERN SPS muon beam and a ^{6}LiD target. In both cases, the amplitudes of the $\cos\phi_h$ and $\cos 2\phi_h$ modulations show strong kinematic dependences for both positive and negative hadrons. It has been known since some time that the measured final-state hadrons in those SIDIS experiments receive a contribution from exclusive diffractive production of vector mesons, particularly important at large values of z, the fraction of the virtual photon energy carried by the hadron. In previous measurements of azimuthal asymmetries this contribution was not taken into account, because it was not known that it could distort the azimuthal modulations. Presently, a method to evaluate the contribution of the exclusive reactions to the azimuthal asymmetries measured by COMPASS has been developed. The subtraction of this contribution results in a better understanding of the kinematic effects, and the remaining non-zero $\cos 2\phi_h$ modulation gives indication for a non-zero Boer-Mulders effect.

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1. Introduction

The azimuthal asymmetries in Semi-Inclusive measurements of Deep-Inelastic Scattering (SIDIS) on unpolarised nucleons are a powerful tool to access the quark intrinsic transverse momentum k_T and the Boer-Mulders [1] Transverse Momentum Dependent Parton Distribution

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Function (TMD PDF) $h_1^\perp$. The target spin-averaged differential SIDIS cross section for the production of a hadron h is given in the one-photon exchange approximation [2] by[1]

$$\frac{\mathrm{d}\sigma}{p_T^h\,\mathrm{d}p_T^h\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_h} = \sigma_0 \Big(1 + \epsilon_1 A_{\cos\phi_h}^{UU} \cos\phi_h + \\ + \epsilon_2 A_{\cos 2\phi_h}^{UU} \cos 2\phi_h + \lambda\epsilon_3 A_{\sin\phi_h}^{LU} \sin\phi_h\Big)\,, \tag{1}$$

where ϕ_h is the azimuthal angle of the hadron with respect to the lepton scattering plane, in a reference system in which the z-axis is the virtual photon direction and the x-axis is defined by the scattered lepton transverse momentum. The transverse momentum p_T^h of the hadron is the component of $\vec{p}^{\,h}$ orthogonal to the z-axis and z is the fraction of the available energy carried by the hadron. The quantity x is the Bjorken variable, y is the fractional energy of the virtual photon, σ_0 is the ϕ_h-independent part of the cross section, λ is the longitudinal polarisation of the incident lepton, and ϵ_1, ϵ_2 and ϵ_3 are kinematic factors depending on y. The amplitudes $A_{f(\phi_h)}^{XU}$ are referred to as azimuthal asymmetries in the following. The superscripts UU and LU refer to unpolarised beam and target, and to longitudinally polarised beam and unpolarised target, respectively. The possible explanation of the origin of unpolarised azimuthal asymmetries in SIDIS was given by Cahn using the simple parton model based on unpolarised TMD PDFs and FFs [4]. In this model the $A_{\cos\phi_h}^{UU}$ and $A_{\cos 2\phi_h}^{UU}$ asymmetries arise at $O(1/Q)$ and $O(1/Q^2)$, respectively, as kinematic corrections to the leading order cross-section. This approach was used, for example, in Ref. [5] to extract the value of intrinsic transverse momentum of quarks in a nucleon from existing experimental data. Within the modern pQCD approach [2], the azimuthal asymmetries in the unpolarised part of the SIDIS cross section are the $O(1)$ (leading order) $A_{\cos 2\phi_h}^{UU}$, given by a convolution of the twist-2 Boer-Mulders PDFs and the Collins FFs, and the $O(1/Q)$ $A_{\cos\phi_h}^{UU}$ asymmetry which is given by the sum of four different convolutions containing twist-3 PDFs or FFs. Notice that neglecting the quark-gluon-quark correlations in the TMD PDFs and FFs and the contributions from the T-odd distribution functions in the expression for $A_{\cos\phi_h}^{UU}$ in Ref. [2] only one contribution survives reproducing the result of the simple TMD parton model.

Measurements of the “unpolarised” SIDIS azimuthal asymmetries were recently performed by the HERMES Collaboration for charged hadrons, pions and kaons using both proton and deuteron targets [6], and by the COMPASS Collaboration for charged hadrons using a deuteron (^{6}LiD) target [3]. They all show strong dependences on the kinematic variables. Several phenomenological analyses (for more details see Ref. [7]) did not succeed either in reproducing the data or in extracting the Boer-Mulders PDF. As a result the present knowledge of the quark intrinsic transverse momentum has very large uncertainties and a possible non-zero Boer-Mulders function in the SIDIS cross section has still to be demonstrated.

Looking at the COMPASS results [3], a few aspects for the $A_{\cos\phi_h}^{UU}$ asymmetry are particularly intriguing. Assuming that this asymmetry is mainly due to the kinematic Cahn effect, it should be negative, with absolute value increasing almost linearly with z and p_T^h and proportional to $\langle k_T^2\rangle$. The trend of the data is, however, quite different. The measured z dependence of the integrated asymmetry[2] shows a strong increase of absolute value starting at $z \simeq 0.5$. Moreover, looking at

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[1] In this paper we use the same notation as in Ref. [3].

[2] See Fig. 10 of Ref. [3].

the three-dimensional result,[3] at high z the p_T^h dependence is the opposite of the expected one, and the x dependence changes behaviour from low to high z.

These observations suggest that another mechanism, different from the TMD parton model, is at work in hadron production at large z. As a matter of fact it is known that the charged hadron SIDIS sample at large z and at small p_T^h contains a non-negligible contribution of hadrons from the decay of vector mesons (VM) produced in exclusive diffractive processes. This contribution was indeed taken into account in the measurements of hadron multiplicities [8–12]. Now, for the first time, we have investigated the effect of this VM contribution on the azimuthal asymmetries. We have measured azimuthal asymmetries for h^+ and h^- originating from the decay of exclusively produced VMs (referred to as exclusive-VM hadrons in the following), and found them to be large. Since they do not have an interpretation in the framework of the parton model TMD formalism, we have subtracted this contribution from the COMPASS asymmetries published in Ref. [3], referred to as "unsubtracted" asymmetries in the following. This correction considerably improves the agreement with the expectations for $A_{\cos\phi_h}^{UU}$ and has also a noticeable effect for $A_{\cos 2\phi_h}^{UU}$.

The paper is organized as follows: in Section 2 the measurement of the azimuthal modulations for exclusive-VM hadrons is described. In Section 3 we present the calculation of the fraction of exclusive-VM hadrons in the measured hadron sample. In Section 4 we describe the procedure used to subtract the exclusive-VM hadron contribution to the azimuthal asymmetries previously published by COMPASS [3], and give the final results.

2. Azimuthal modulations of exclusive-VM hadrons

In order to evaluate the contribution of exclusive-VM hadrons to the unsubtracted azimuthal asymmetries [3] obtained from the COMPASS data collected in 2004, we have analysed the 2006 COMPASS data, which were recently used to measure the hadron multiplicities in SIDIS [9–12], and for which all the necessary simulated data are available. The experimental conditions of the two data sets are very similar, since the same target material (^{6}LiD) was used, once limiting the spectrometer acceptance to the same restricted kinematic region investigated in Ref. [3].

The azimuthal modulations of the exclusive-VM hadrons are measured selecting DIS events as in Ref. [3], i.e. by using:

$$Q^2 > 1\ (\mathrm{GeV/c})^2, \quad W > 5\ \mathrm{GeV/c}^2, \quad 0.2 < y < 0.9,$$

where Q^2 is the exchanged photon virtuality and W the final state hadronic mass. The events are then selected requiring in the final state, in addition to the scattered muon, only two oppositely charged hadrons with $z > 0.1$. The fraction of the final-state energy that is carried by the hadron pair, z_t, is shown in the left panel of Fig. 1. Hadron pairs originating from exclusively produced vector mesons appear as the sharp peak at $z_t \simeq 1$ and are selected by requiring $z_t > 0.95$. Contributions from other processes, which appear as background to this peak, are neglected in the present analysis.

The z distribution for the positive hadrons of the selected pairs is shown in the right panel of the same figure. Most of the hadrons come from ρ^0 decays. The broad structure at $0.4 < z < 0.6$ is due to hadrons from ϕ meson decays, whose contribution is less than 10% of that of the ρ^0.

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[3] See Fig. 12 of Ref. [3].

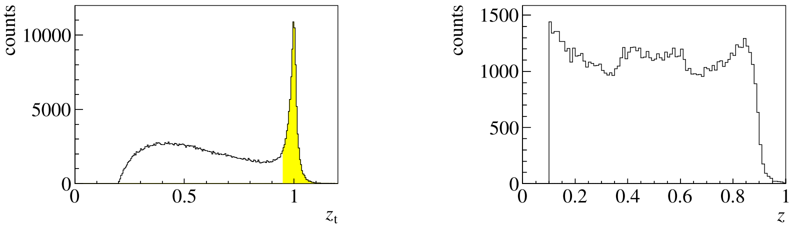

Fig. 1. Left panel: distribution of z_t for the events with only two reconstructed hadrons with opposite charge. The exclusive events are selected by the cut $z_t > 0.95$. Right panel: z distribution for the positive hadron of the selected pairs.

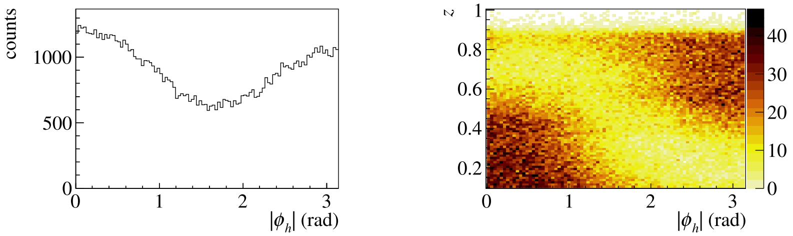

Fig. 2. Distribution of $|\phi_h|$ (left panel) and correlation between z and $|\phi_h|$ (right panel) for positive exclusive-VM hadrons.

The $|\phi_h|$ distribution of the exclusive-VM hadrons shows large modulations, as can be seen in the left panel of Fig. 2 for positive hadrons. Furthermore the $|\phi_h|$ distribution strongly depends on z, as can be seen from the right panel in Fig. 2, again for h^+. From that 2-dimensional distribution one notices that the amplitude of the $\cos\phi_h$ modulation changes sign with z. The same properties are observed also for h^-.

The acceptance-corrected azimuthal modulations of the positive and negative exclusive-VM hadrons are fitted in each x, z and p_T^h bin of Ref. [3] with the function

$$f(\phi_h) = a_0[1 + \epsilon_1 a_1 \cos\phi_h + \epsilon_2 a_2 \cos 2\phi_h], \tag{2}$$

where the amplitudes a_0, a_1 and a_2 are free parameters. The $\sin\phi_h$ modulation is not included because parallel studies on exclusive vector-meson production in COMPASS do not exhibit such a modulation [13]. Other possible orthogonal modulations are not relevant since they do not appear in the SIDIS cross section.

The fitted amplitudes of the $\cos\phi_h$ and $\cos 2\phi_h$ modulations for exclusive-VM hadrons, $a_{\cos\phi_h}^{UU,excl}$ and $a_{\cos 2\phi_h}^{UU,excl}$, decrease with increasing p_T^h and are almost equal for h^+ and h^-, indicating that what is modulated is the direction of the parent VM. As an example, the amplitudes $a_{\cos\phi_h}^{UU,excl}$ for 0.1 GeV/c $< p_T^h <$ 0.3 GeV/c are shown in the first column of Fig. 3 for both h^+ and h^-. The $a_{\cos\phi_h}^{UU,excl}$ amplitude is very large in absolute value at large and small z, and changes sign at $z \simeq 0.5$. The $a_{\cos 2\phi_h}^{UU,excl}$ amplitudes are smaller but still non-negligible.

It should be noted that the results of the present analysis refer to a ^{6}LiD target and COMPASS kinematics. The observed azimuthal asymmetries for exclusive-VM hadrons depend on the angular distributions for ρ^0 decay and production, which are determined by Spin Density Matrix Elements (SDMEs). The SDMEs depend on ρ^0 transverse momentum [14] and on the mechanism of its production. In particular, for coherent production on the target nuclei, which

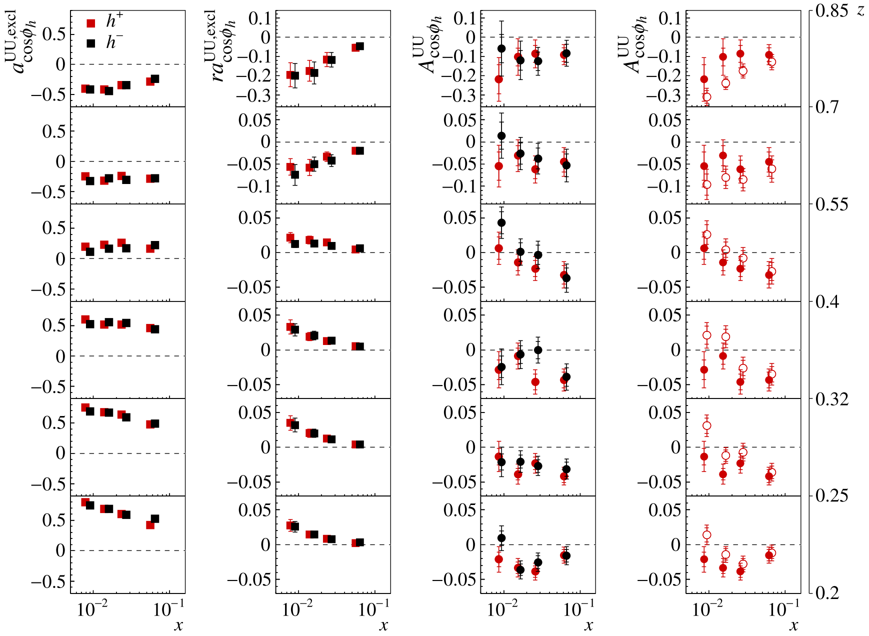

Fig. 3. First column: $a^{UU,excl}_{\cos\phi_h}$ amplitude for h^+ (red squares) and h^- (black squares). Second column: $r\,a^{UU,excl}_{\cos\phi_h}$ for h^+ (red squares) and h^- (black squares). Third column: $A^{UU}_{\cos\phi_h}$ asymmetry after the subtraction of exclusive-VM hadron contribution for h^+ (red circles) and h^- (black circles). Last column: comparison between the asymmetry for h^+ before (open circles) and after (full circles) exclusive-VM hadron subtraction. From bottom to top, results for increasing values of z are shown, as indicated on the very right of the figure. All the results refer to the first p_T^h bin (0.1 GeV/c $< p_T^h <$ 0.3 GeV/c). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

dominates at small p_T^h, one may expect different angular distributions (different SDMEs) than those for the production on a single free or quasi-free nucleon.

3. Fraction of exclusive-VM hadrons in the SIDIS sample

For a quantitative estimate of the exclusive-VM hadron contribution to the unpolarised azimuthal asymmetries, it is necessary to determine the number N_h^{excl} of exclusive-VM hadrons relative to the total number of hadrons N_h^{tot}, i.e. the ratio $r = N_h^{excl}/N_h^{tot}$. Here we use a parameterisation obtained from previous works [9–11], which was based on a combined use of HEPGEN [15] and LEPTO [16] Monte Carlo generators. The former one is used to model differential cross sections of various hard processes of exclusive leptoproduction of single mesons or photons at COMPASS kinematics. For the determination of r, only exclusive ρ^0 production, which gives the main contribution to the exclusive-VM hadrons, is taken into account in the present study. By doing this, we might underestimate r, but only in the bins at lowest p_T^h and $z \simeq 0.5$, where it could be larger by at most a factor 1.2.

Since the binning in Ref. [9–11] is different from that in Ref. [3], we had to parameterise r as a function of x, z and p_T^h. The estimated values of r in all the kinematic bins are shown in Fig. 4 and are assumed to be the same for positive and negative hadrons. As one can see, the fraction of

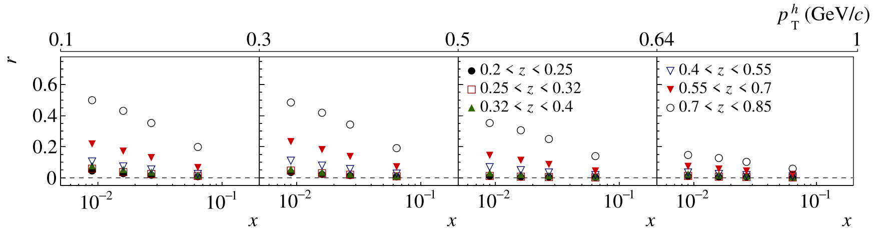

Fig. 4. Fraction r of exclusive-VM hadrons evaluated as function of x in the different z and p_T^h bins.

pions coming from the decay of exclusively produced ρ^0 is very large at large z and small p_T^h, where it reaches 50%, and diminishes for decreasing z and increasing p_T^h. The overall systematic uncertainty on r is estimated to be approximately 30% and is mainly due to the uncertainty on the knowledge of the diffractive cross section [9–11].

4. Results for the unpolarised SIDIS azimuthal asymmetries

The exclusive-VM hadron contributions to the unsubtracted azimuthal asymmetries $r\,a_{\cos\phi_h}^{UU,excl}$ and $r\,a_{\cos 2\phi_h}^{UU,excl}$ are calculated in each x, z and p_T^h bin of Ref. [3]. The results for the smallest p_T^h bin, i.e. 0.1 GeV/c $< p_T^h <$ 0.3 GeV/c, are shown for h^+ and h^- in the second column of Fig. 3. As can be seen, the contribution of exclusive-VM hadrons is clearly different from zero and reaches values up to 20% at large z in this low p_T^h range. The contribution to the $\cos 2\phi_h$ modulation is smaller but still non-negligible, in particular if compared to the measured values of the asymmetries.

The asymmetries $A_{\cos\phi_h}^{UU}$, corrected for the contribution of exclusive-VM hadrons, are obtained using

$$A_{\cos\phi_h}^{UU} = \frac{1}{1-r}\left(A_{\cos\phi_h}^{UU,uns} - r\,a_{\cos\phi_h}^{UU,excl}\right), \tag{3}$$

where $A_{\cos\phi_h}^{UU,uns}$ are the unsubtracted values. A similar expression is used to obtain $A_{\cos 2\phi_h}^{UU}$.

The resulting $A_{\cos\phi_h}^{UU}$ azimuthal asymmetries are shown in the third column of Fig. 3, again for the smallest p_T^h bin. After subtraction, the x dependence of the asymmetry becomes weaker, and in particular only a few positive values remain. The last column of the figure shows the comparison between the asymmetries as published in Ref. [3] and after subtracting the contribution of exclusive VMs for h^+. One can also see that the contribution of exclusive-VM hadrons is sizable at all z.

The results for $A_{\cos\phi_h}^{UU}$ for positive and negative hadrons in all x, z and p_T^h bins are shown as closed points in Fig. 5 and 6, respectively. For comparison, the open points show the unsubtracted asymmetries. The results for $A_{\cos 2\phi_h}^{UU}$ for positive and negative hadrons are compared to the unsubtracted asymmetries in Fig. 7 and 8. The inner error bars correspond to the statistical uncertainties only, while the outer bars represent the total uncertainties. The increase in the statistical uncertainties is due to the low statistics of the exclusive-VM hadrons. The systematic uncertainties have been evaluated by adding in quadrature the uncertainties of the unsubtracted asymmetries (estimated to be of the same order of the statistical ones) and those due to the subtraction procedure. For the last ones the dominant contribution is that of the poor knowledge of r, which can cause an uncertainty at most as large as the statistical one, apart from a few bins

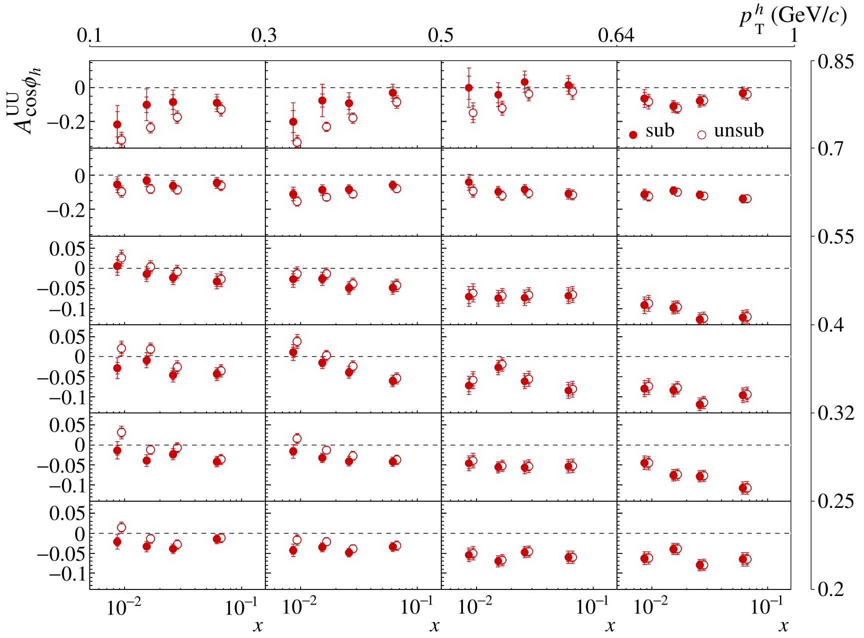

Fig. 5. $A^{UU}_{\cos\phi_h}$ asymmetry on ^{6}LiD for h^+ after subtracting from the asymmetry published in Ref. [3] the contribution of exclusive-VM hadrons, as function of x, in z and p_T^h bins (closed circles). Inner (outer) error bars denote statistical (total) uncertainties. The open circles show the unsubtracted asymmetry.

at the highest z- and lowest x-values. The total uncertainties are evaluated by adding in quadrature the statistical and the systematic uncertainties. The numerical values of the asymmetries are available on HepData [17].

In spite of the large uncertainties we consider this work as a major step forward in understanding the 3D structure of the nucleon. To give an idea of the impact, in Fig. 9 we compare $A^{UU}_{\cos\phi_h}$ with a simple Monte Carlo simulation for the Cahn effect. We have used the Monte Carlo code of Refs. [18,19], describing the fragmentation of polarised quarks, which was modified to include the Cahn effect. This is achieved by generating the azimuthal modulations of the transverse momentum of the fragmenting quark according to the lepton-quark hard cross section calculated in the simple TMD parton model for a non-zero k_T [4]. The $\langle p_T^{h\,2}\rangle$ dependence on z is built in and a suitable dependence of $\langle k_T^2\rangle$ on x has been used to reproduce the values of $A^{UU}_{\cos\phi_h}$ at $z \lesssim 0.5$. The agreement is satisfactory and the trends are similar over all bins, except for the two bins at $p_T^h > 0.5$ GeV/c and $z > 0.7$.

The same Monte Carlo simulation is also used to investigate the twist-4 azimuthal modulations generated by the $O(1/Q^2)$ Cahn effect, thus neglecting the contributions from target and produced hadron mass corrections. The resulting amplitudes $A^{UU}_{\cos 2\phi_h}$ turn out to be compatible with zero. Other contributions, which are not generated by Boer-Mulders and Collins effect, appear also at twist-4 or higher orders. Although these contributions are not very well known, they should be suppressed as $1/Q^2$, thus it is most likely that the non-zero $A^{UU}_{\cos 2\phi_h}$ values of Fig. 7 and 8 are an indication of a non-zero Boer-Mulders PDF. Specifically, the corrected data for $A^{UU}_{\cos 2\phi_h}$ for positive hadrons still show a strong z dependence in the highest p_T^h-bin, with a

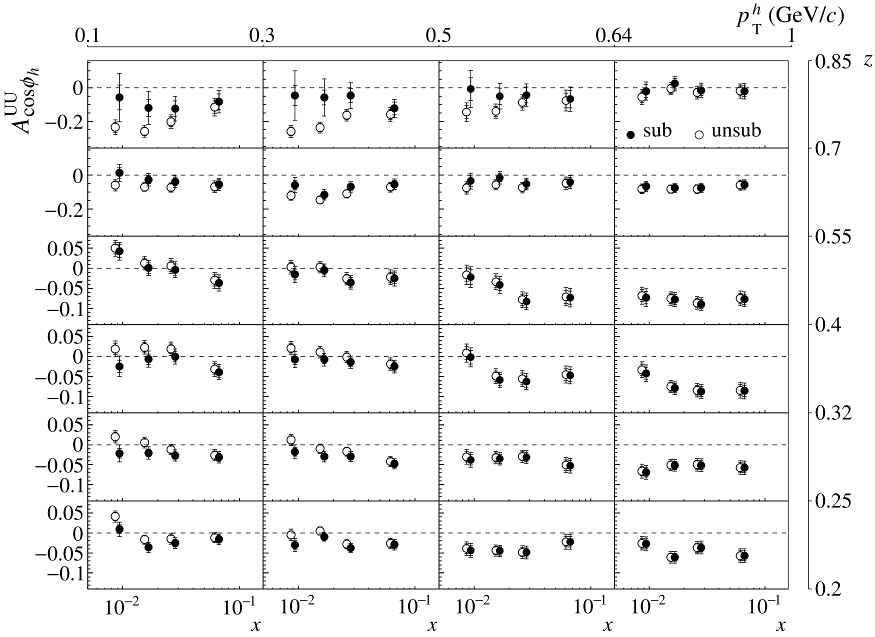

Fig. 6. Same as Fig. 5 for negative hadrons.

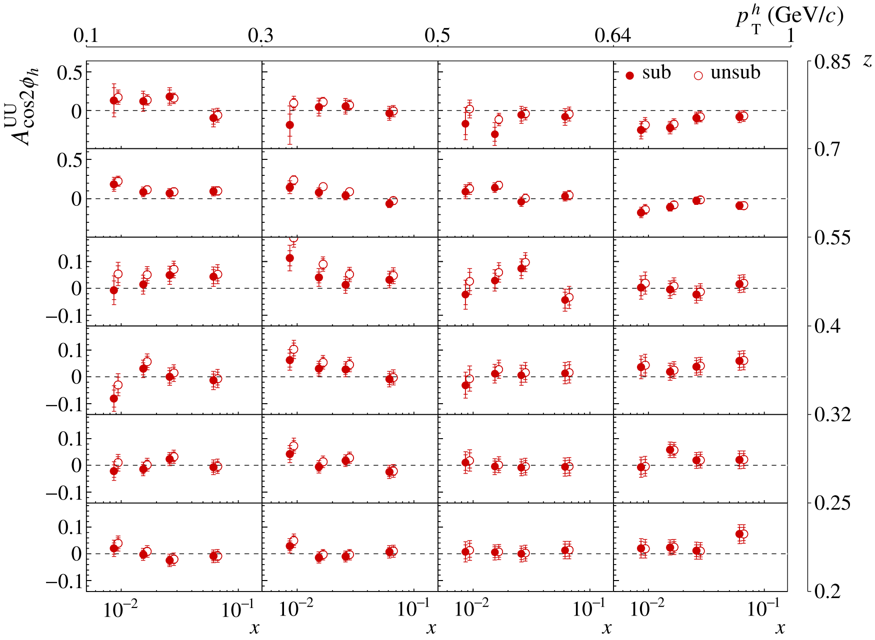

Fig. 7. $A^{UU}_{\cos 2\phi_h}$ asymmetry on ^{6}LiD for h^+ after subtracting from the asymmetry published in Ref. [3] the contribution of exclusive-VM hadrons, as function of x, in z and p_T^h bins (closed circles). Inner (outer) error bars denote statistical (total) uncertainties. The open circles show the unsubtracted asymmetry.

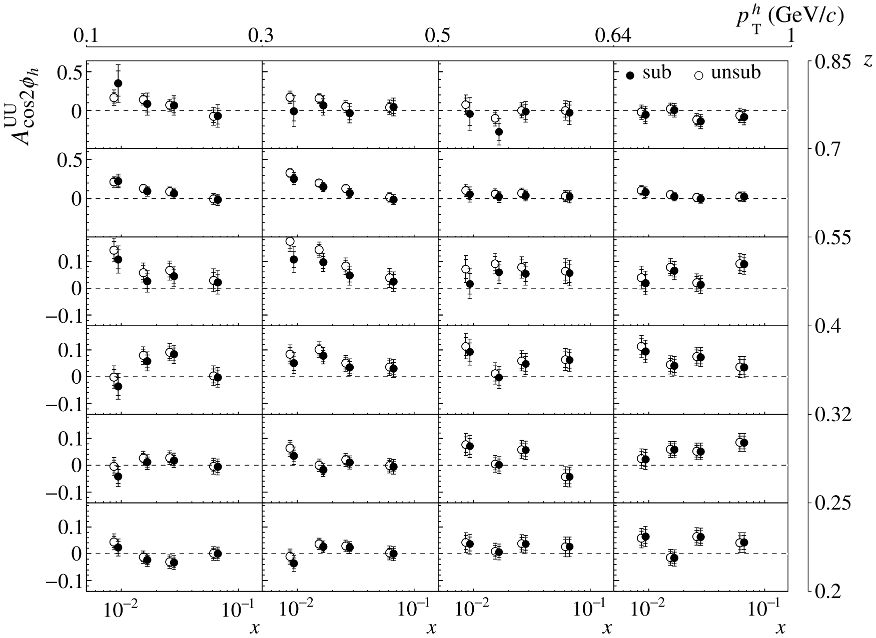

Fig. 8. Same as Fig. 7 for negative hadrons.

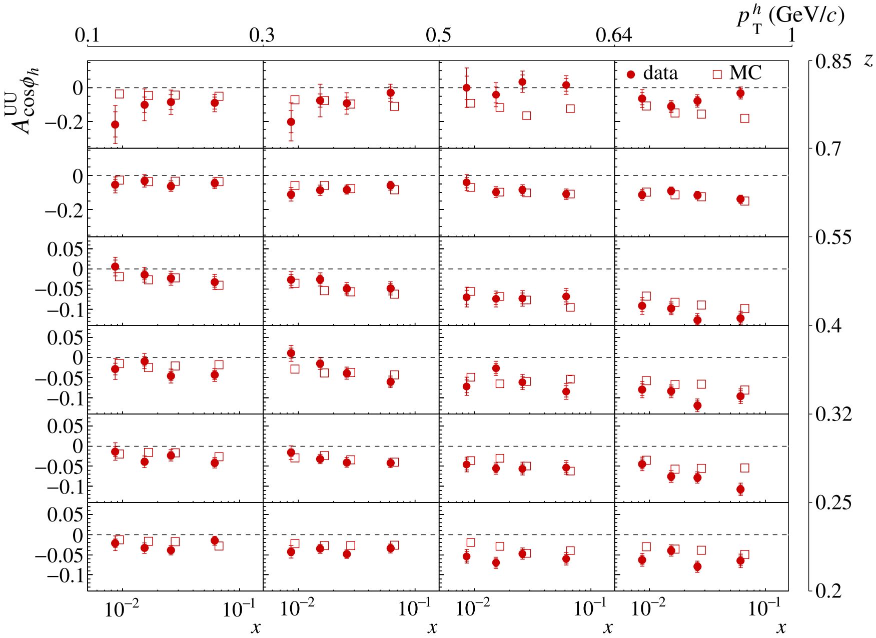

Fig. 9. Comparison between the $A^{UU}_{\cos\phi_h}$ asymmetry, as function of x, in z and p^h_T bins, for h^+ on ^{6}LiD after subtracting the exclusive-VM hadron contribution (closed circles) and the results of a Monte Carlo simulation (open squares) which includes the Cahn effect.

significance above 5 σ. The phenomenological study of this effect is, however, beyond the scope of the present paper.

5. Conclusions

The COMPASS Collaboration has measured the azimuthal modulations of positive and negative hadrons from the decay of exclusive vector mesons produced in the scattering of 160 GeV/c muons on a ^{6}LiD target. The amplitudes of the modulations are found to be large and of the same sign for positive and negative hadrons. These hadrons constitute a contamination to the SIDIS hadron sample. Their contribution to the previously published COMPASS $A_{\cos\phi_h}^{UU,uns}$ and $A_{\cos 2\phi_h}^{UU,uns}$ unpolarised azimuthal asymmetries is estimated quantitatively and shown to be non-negligible over all the explored kinematic region and in particular at large z. After subtracting their $\cos\phi_h$ amplitudes, the $A_{\cos\phi_h}^{UU}$ asymmetries turn out to be in reasonable agreement over most of the explored kinematic region with a Monte Carlo simulation implementing the Cahn effect, except for a very few bins at large z and large p_T^h. The experimental determination of this important correction to already published data, which so far was never evaluated, is expected to have significant impact onto phenomenological analyses. When implemented, it could hopefully allow for a successful disentangling of the various contributions to the data and for a first extraction of the Boer-Mulders function.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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