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Title: A high-statistics measurement of transverse spin effects in dihadron production from muon-proton semi-inclusive deep-inelastic scattering

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Answers to Reviewers' comments:

Reviewer #1: The results on azimuthal asymmetry in dihadron production are a continuation of previous work from the COMPASS Collaboration. However, the precision is greatly increased and combination with previous data improve the final results even further. With the increased precision, the comparison with the two theories is far more definitive than in the previous publication with Bacchetta and Radici clearly preferred over Ma et al.. The comparison with the Collins asymmetry also brings out new and interesting physics. However, I do have a few comments and questions which need to be addressed. I also have some minor comments to help improve the manuscript. Given the above, I recommend the manuscript for publication in Physics Letters B after a minor revision and answering of my questions.

Questions / comments
- Section 1, para. 2, second last sentence. I do not know what "correctly" means but would be happy to remove the word.
Done

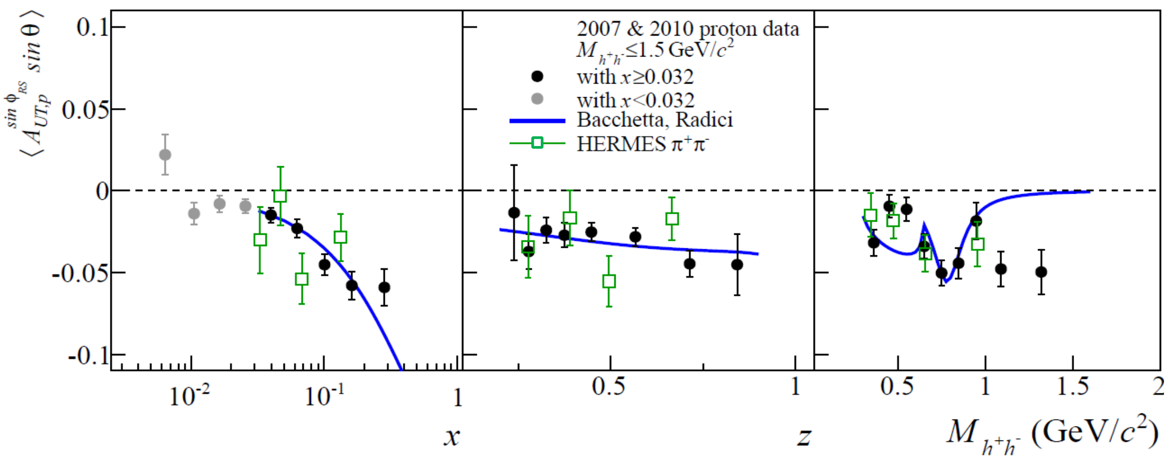
- Section 1, last line. The statistics increase by "four", but in the abstract it was "three" ?
Then in results, the number is 3.5 x 10^7, but the previous paper for NH3 had 5.8 x 10^6, i.e.
a factor of 6 difference, so I am confused by all these different numbers.
For NH_3 the old paper quoted 10.9×10^7 for 2007. 2010 data is a factor 3 larger than 2007 giving an overall factor 4 between 2007 and 2007+2010. We have modified the abstract accordingly.

- Section 3. In the previous paper, there was a cut on M_X>2.4 GeV and here on E_miss. Why the change ?
The two cuts are equivalent ($E_{miss} = \left(M_X^2 - M_p^2\right)/2M_p$ in the reaction $\ell\, p \rightarrow \ell' p_{h1}\, p_{h2}\, X$) and therefore there is no change in the analysis between this article and previous published paper (this also to answer your comment concerning different systematics between 2007 and 2010).

- Section 4. The comment about HERMES would be better made if their points were shown, so I recommend adding them to the COMPASS plot.
The reason why the HERMES data are not shown in the plots is twofold:

- **Their published data are on identified pions**
- **We evaluate gamma-nucleon asymmetries while Hermes published lepton-nucleon asymmetries (with in addition a change of sign due to an extra π in the definitions of the modulation).**

To be able to show the results on the same plot we will have therefore to scale Hermes points by $\langle 1/D_{nn} \rangle$ and change the sign of their asymmetries; something we prefer to avoid in a paper. Nevertheless hereafter a modified version of Fig.5 with Hermes points in is shown; as you may see the agreement is quite good, even if the precision of COMPASS points is much larger.



- Figure 5. How are the systematics combined in the combination of the data sets ? The resulting systematics look like those from the recent data. However, I would expect some differences given there we some differences in procedure, e.g. the M_X/Emiss cuts.

The combined result is given by the weighted mean of 2007 and 2010 data, using the statistical and systematic errors added in quadrature as weights. After this the total statistical uncertainty is subtracted back in quadrature to obtain the systematic uncertainty. For this reason it is correct to say that the 2010 data dominates both the statistical and the systematic errors.

We would like to remind that we have not observed systematic effects in the studies performed and therefore we only quote an upper limit that is proportional to the statistical error of the data.

Minor

- Section 1, para. 2, l.3. "... In this reaction, a new ... function appears ..."

Done

- Section 1, para. 2, second last sentence. "... using existing ..."; no need for "presently".

Done

- Section 1, the formatting changes: paragraphs are indented and then not.

Done

- Section 3, para. 2, second sentence. "... and the average transverse polarisation ...". Adding "transverse" helps here (if that is what is meant) as the longitudinal is also 0.8, so you think you are reading the same thing twice as is.

Done

- A few lines later. "... compensate for acceptance ... up in the opposite direction ..." makes it clearer if that is what was meant.

Done

- Section 4. "x>0.03" -> "x>=0.032" as in figure and no need for rounding.

Done

- Line later. "... work have higher ..." rather than "show".
Done

- Secton 4, "COMPASS were calculated" -> "COMPASS was calculated".
Corrected

- Figure 5, caption. "cureves" -> "curves".
Corrected

- Section 5, para. 3, last sentence. "... such a correlation ..."
Done

- Ref. 10 looks strange with a "%" sign.

Corrected

Finally, in a footnote before the conclusions, we cite a recent publication on the same subject:
"After finalizing the present paper, a new publication appeared [42] reproducing with Monte Carlo calculations the observations of this section."

A high-statistics measurement of transverse spin effects in dihadron production from muon-proton semi-inclusive deep-inelastic scattering

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Abstract

A measurement of the azimuthal asymmetry in dihadron production in deep-inelastic scattering of muons on transversely polarised proton (NH_3) targets are presented. They provide independent access to the transversity distribution functions through the measurement of the Collins asymmetry in single hadron production. The data were taken in the year 2010 with the COMPASS spectrometer using a $160\,\mathrm{GeV}/c$ muon beam of the CERN SPS, increasing by a factor of about four the overall statistics with respect to the previously published data taken in the year 2007. The measured sizeable asymmetry is in good agreement with the published data. An approximate equality of the Collins asymmetry and the dihadron asymmetry is observed, suggesting a common physical mechanism in the underlying fragmentation.

1. Introduction

The quark structure of the nucleon can be characterised by parton distribution functions (PDFs) for each quark flavour [1]. If the quark intrinsic transverse momentum $\boldsymbol{k}_T$ is integrated over, there remain at twist-two level three PDFs depending on the Bjorken scaling variable x and the negative square of the four-momentum transfer Q^2, which exhaust the information on the partonic structure of the nucleon [2, 3, 4, 5]. The spin-independent distribution f_1^q and

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[20]Deceased

the helicity distribution g_1^q have been measured with good accuracy. However, up to ten years ago nothing was known about the transverse spin distribution h_1^q, often referred to as transversity, which describes the probability difference of finding a quark q polarised parallel or antiparallel to the spin of a transversely polarised nucleon. This distribution is difficult to measure, since it is related to soft processes correlating quarks with opposite chirality, making it a chiral-odd function [1]. As a result, transversity can only be accessed through observables in which it appears coupled to a second chiral-odd object in order to conserve chirality. Thus it does not contribute to inclusive deep-inelastic scattering (DIS) at leading twist. In semi-inclusive deep-inelastic scattering (SIDIS) reactions the chiral-odd partners of the transversity distribution function are fragmentation functions (FFs), which describe the spin-dependent hadronisation of a transversely polarised quark q into hadrons. For a recent review see Ref. [6]. Up to now, most of the information on transversity came from the Collins asymmetry measured in single hadron asymmetries [7, 8, 9, 10] and used in global analyses (e.g. [11]).

A complementary approach is to measure dihadron production in leptoproduction in SIDIS on transversely polarised nucleon, $l\,N^{\uparrow} \rightarrow l'\,h^+\,h^-\,X$ with both hadrons produced in the current fragmentation region [12, 13, 14, 15]. In this reaction a new chiral-odd fragmentation function appears, the dihadron Fragmentation Function (DiFF) $H_1^{\sphericalangle}$, which describes the spin-dependent part of the fragmentation of a transversely polarised quark into a pair of unpolarised hadrons describing a correlation of quark transverse spin with normal pseudo-vector to the dihadron momenta plane (the handedness) [16]. The transverse polarisation of the fragmenting quark is correlated with the relative momentum of the two hadrons, which gives rise to a transverse, target-spin-dependent azimuthal asymmetry around the virtual-photon direction, with respect to the lepton scattering plane. In this case, the sum of the total transverse momenta of the final state hadrons can be integrated over, leaving only the relative momentum of the two hadrons. This avoids the complexity of transverse-momentum-dependent convolution integrals as in the analysis of single hadron production utilising the Collins effect and the analysis can be performed using collinear factorisation [17, 18]. Here, the evolution equations are known at next-to-leading order [19], so that results from e^+e^- scattering and SIDIS can be connected, making it a theoretically clean way to extract transversity using existing facilities [17]. The properties of the DiFFs are described in detail in Refs. [12, 13, 14, 15, 20, 21, 22, 23].

First evidence for an azimuthal asymmetry in leptoproduction of $\pi^+\pi^-$ pairs was published by HERMES, using a transversely polarised hydrogen target [24]. The DiFFs were first measured in e^+e^- reactions by Belle [25] and BaBar[26]. These measurements indicate a sizeable u quark transversity distribution – as already known from the measurements of the Collins asymmetry [9, 27, 7] – and non-vanishing DiFFs [28, 7].
Recently, COMPASS published results on dihadron asymmetry obtained from the data collected using transversely polarised deuteron (^{6}LiD) and proton (NH_3) targets in the years 2002-2004 and 2007, respectively [29]. Due to the large acceptance of the COMPASS spectrometer and the large muon momentum of $160\,\mathrm{GeV}/c$, results with high statistics were obtained covering a large kinematic range in x and $M_{h^+h^-}$, the invariant mass of the dihadron. Sizeable asymmetries were measured on the proton target while on the deuteron target only small asymmetries were observed. These results indicate non-vanishing u quark transversity and DiFFs, as well as a cancellation of the contributions of u and d quark transversities in the deuteron. Using these data sets in conjunction with the Belle data, a first parametrisation of the u and d quark transversities was performed based on a collinear framework [30]. The same procedure was applied to directly extract u and d quark transversities in the same x bins as used to obtain the COMPASS proton and deuteron results [31]. In this Letter, the dihadron azimuthal asymmetries measured from the data collected in 2010 with a transversely polarised proton target (NH_3, as in 2007) are presented. The statistics accumulated in this data taking period increases the total available statistics on proton by a factor of four.

2. Theoretical Framework

Here, only a short summary of the theoretical framework is given. For a more detailed view, we recommend the references given above and our recent paper [29] on the same topic.
At leading twist and after integration over total transverse momenta, the cross section of semi-inclusive dihadron leptoproduction on a transversely polarised target is given as a sum of a spin-independent and a spin-dependent part

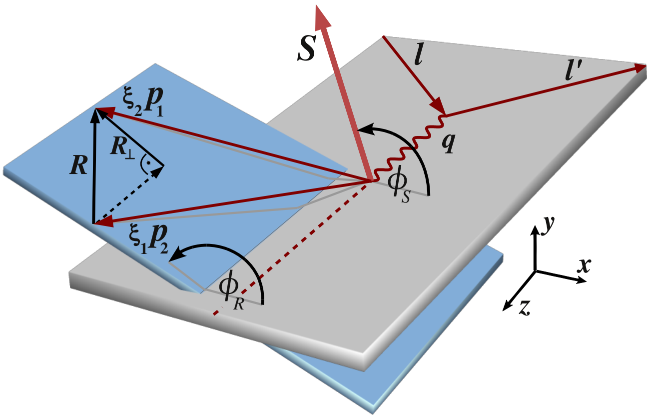


Figure 1: Schematic view of the azimuthal angles ϕ_R and ϕ_S for dihadron production in deep-inelastic scattering, where $\boldsymbol{l}$, $\boldsymbol{l}'$, $\boldsymbol{q}$ and $\boldsymbol{p}_i$ are the three-momenta of beam, scattered muon, virtual photon and hadrons respectively, in the γ^*-nucleon system. Note that the azimuthal plane is defined by the directions of the relative hadron momentum and the virtual photon.

[21, 22]:

$$\frac{d^7\,\sigma_{UU}}{d\cos\theta\,dM^2_{h^+h^-}\,d\phi_R\,dz\,dx\,dy\,d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\left(1-y+\frac{y^2}{2}\right) \times \sum_q e_q^2 f_1^q(x)\,D_{1,q}\big(z, M^2_{h^+h^-}, \cos\theta\big), \tag{1}$$

$$\frac{d^7\,\sigma_{UT}}{d\cos\theta\,dM^2_{h^+h^-}\,d\phi_R\,dz\,dx\,dy\,d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\,S_\perp\,(1-y) \times \sum_q e_q^2 \frac{|\boldsymbol{p}_1-\boldsymbol{p}_2|}{2M_{h^+h^-}}\,\sin\theta\,\sin\phi_{RS}\,h_1^q(x)\,H^{\sphericalangle}_{1,q}\big(z, M^2_{h^+h^-}, \cos\theta\big). \tag{2}$$

Here, the sums run over all quark and antiquark flavours q, $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ denote the three-momenta of the two hadrons of the dihadron, where the subscript 1 always refers to the positive hadron in this analysis. The first subscript (U) indicates an unpolarised beam and the second (U or T), an unpolarised and transversely polarised target, respectively. Note that the contribution from a longitudinally polarised beam and a transversely polarised target, σ_{LT}, is neglected in this analysis since it exhibits a different azimuthal angle and is suppressed by a factor of $1/Q$ [22]. The fine-structure constant is denoted by α, y is the fraction of the muon energy transferred to the virtual photon, $D_{1,q}(z, M^2_{h^+h^-}, \cos\theta)$ is the spin-independent dihadron fragmentation function for a quark of flavour q, $H^{\sphericalangle}_{1,q}(z, M^2_{h^+h^-}, \cos\theta)$ is the spin-dependent DiFF and z_1, z_2 are the fractions of the virtual-photon energy carried by these two hadrons with $z = z_1 + z_2$. The symbol $S_\perp$ denotes the component of the target spin vector $\boldsymbol{S}$ perpendicular to the virtual-photon direction, and θ is the polar angle of one of the hadrons – commonly the positive one – in the dihadron rest frame with respect to the dihadron boost axis. The azimuthal angle ϕ_{RS} is defined as

$$\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi\,, \tag{3}$$

where ϕ_S is the azimuthal angle of the initial nucleon spin and $\phi_{S'}$ is the azimuthal angle of the spin vector of the fragmenting quark with $\phi_{S'} = \pi - \phi_S$ (Fig. 1). The azimuthal angle ϕ_R is defined by

$$\phi_R = \frac{(\boldsymbol{q}\times\boldsymbol{l})\cdot\boldsymbol{R}}{|(\boldsymbol{q}\times\boldsymbol{l})\cdot\boldsymbol{R}|}\arccos\left(\frac{(\boldsymbol{q}\times\boldsymbol{l})\cdot(\boldsymbol{q}\times\boldsymbol{R})}{|\boldsymbol{q}\times\boldsymbol{l}||\boldsymbol{q}\times\boldsymbol{R}|}\right), \tag{4}$$

where $\boldsymbol{l}$ is the incoming lepton momentum, $\boldsymbol{q}$ the virtual-photon momentum and $\boldsymbol{R}$ the relative hadron momentum [13, 32] given by

$$\boldsymbol{R} = \frac{z_2\boldsymbol{p}_1 - z_1\boldsymbol{p}_2}{z_1+z_2} =: \xi_2\boldsymbol{p}_1 - \xi_1\boldsymbol{p}_2\,. \tag{5}$$

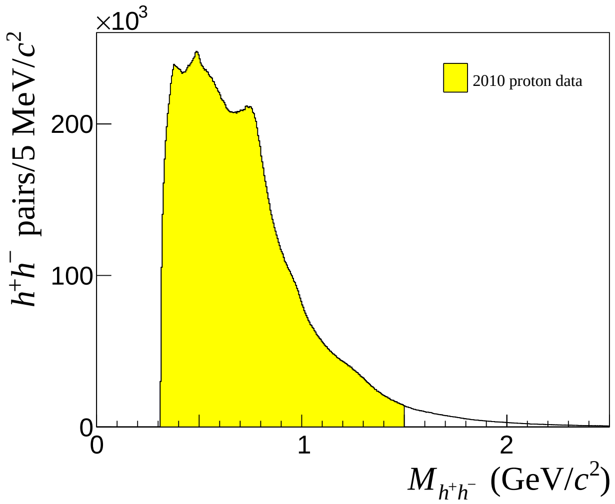


Figure 2: Invariant mass distributions of the final samples. The cut $M_{h^+h^-} < 1.5\,\mathrm{GeV}/c^2$ is indicated. The K^0, ρ and f_1 resonances are visible.

The number $N_{h^+h^-}$ of pairs of oppositely charged hadrons produced on a transversely polarised target can be written as

$$N_{h^+h^-}(x,\, y,\, z,\, M^2_{h^+h^-},\, \cos\theta,\, \phi_{RS}) \;\propto \sigma_{UU}\left(1 + f(x,y)\, P_T\, D_{nn}(y)\, A_{UT}^{\sin\phi_{RS}} \sin\theta \sin\phi_{RS}\right)\,, \tag{6}$$

omitting luminosity and detector acceptance. Here, P_T is the transverse polarisation of the target protons and $D_{nn}(y) = \frac{1-y}{1-y+y^2/2}$ the transverse-spin-transfer coefficient, while $f(x,y)$ is the target polarisation dilution factor calculated for semi-inclusive reactions depending on kinematics. It is given by the abundance-weighted ratio of the total cross section for scattering on polarisable protons to that for scattering on all nuclei in the target. The dependence of the dilution factor on the hadron transverse momenta appears to be weak in the kinematic range of the COMPASS experiment. Dilution due to radiative events is taken into account by the ratio of the one-photon exchange cross section to the total cross section. For $^{14}\mathrm{NH}_3$, f contains corrections for the polarisation of the spin-1 $^{14}\mathrm{N}$ nucleus.

The asymmetry

$$A_{UT}^{\sin\phi_{RS}} = \frac{|\boldsymbol{p}_1 - \boldsymbol{p}_2|}{2M_{h^+h^-}} \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1,q}^{\sphericalangle}(z,\, M^2_{h^+h^-},\, \cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z,\, M^2_{h^+h^-},\, \cos\theta)} \tag{7}$$

is then proportional to the product of the transversity distribution function and the spin-dependent dihadron fragmentation function, summed over the quark and antiquark flavours.

3. Experimental Data and Analysis

The analysis presented in this Letter is performed using data taken in the year 2010 with the COMPASS spectrometer [33], which was obtained by scattering positive muons of $160\,\mathrm{GeV}/c$ produced from the M2 beamline of CERNs SPS off a transversely polarised solid-state NH_3 target. Details on data taking, data quality, event selection and analysis can be found in Refs. [27, 29].

The beam muons are naturally polarised with an average longitudinal polarisation of about 0.8 with a relative uncertainty of $5\,\%$. The average dilution factor for NH_3 is $\langle f \rangle \sim 0.15$ and the average transverse polarisation is $\langle P_T \rangle \sim 0.8$. The same target as in the year 2007 was used. It consisted of three cylindrical cells with different orientations of the polarisation vector. In order to compensate for acceptance effects the polarisation was destroyed and built up in opposite direction every four to five days, for a total of 12 data-taking sub-periods.

For the analysis, events with incoming and outgoing muons and at least two reconstructed hadrons from the reaction vertex inside the target cells are selected. Equal flux through the whole target is obtained by requiring that the extrapolated beam track crosses all three cells. In order to select events in the DIS regime, cuts are applied on the squared four-momentum transfer, $Q^2 > 1\,(\mathrm{GeV}/c)^2$, and on the invariant mass of the final hadronic state, $W > 5\,\mathrm{GeV}/c^2$. Furthermore, the fractional energy transfer to the virtual photon is required to be $y > 0.1$ and $y < 0.9$ to remove events with poorly reconstructed virtual photon energy and events with large radiative corrections, respectively.

The dihadron sample consists of all combinations of oppositely charged hadrons originating from the reaction vertex. Hadrons produced in the current fragmentation region are selected requiring $z > 0.1$ for the fractional energy and $x_F > 0.1$ of each hadron. Exclusive dihadron production is suppressed by requiring the missing energy $E_{miss} = \big((P + q - p_1 - p_2)^2 - m_P^2\big)/(2\,m_P)$ to be greater than $3.0\,\mathrm{GeV}$, where P is the target protons four-momentum and m_P its mass. As the azimuthal angle ϕ_R is only defined for non-collinear vectors $\boldsymbol{R}$ and $\boldsymbol{q}$, a minimum value is required on the component of $\boldsymbol{R}$ perpendicular to $\boldsymbol{q}$, $|\boldsymbol{R}_\perp| > 0.07\,\mathrm{GeV}/c$. After all cuts, 3.5×10^7 h^+h^- combinations remain. Figure 2 shows the invariant mass distributions of the dihadron system, always assuming the pion mass for each hadron. A cut of $M_{h^+h^-} < 1.5\,\mathrm{GeV}/c^2$ is applied in order to allow for the analysis of the data suggested by [21], where both the spin-dependent and spin-independent dihadron fragmentation functions are expanded in terms of Legendre polynomials of $\cos\theta$. While removing only a negligible part of the data, this cut allows for a convenient restriction to relative s- and p-waves in this analysis.

In the analysis we extract the product $A = \langle A_{UT}^{\sin\phi_{RS}} \sin\theta\rangle$, integrated over the angle θ. For a detailed discussion we refer to Ref. [29]. It is important to stress that in the COMPASS acceptance the opening angle θ peaks close to $\pi/2$ with $\langle\sin\theta\rangle = 0.94$ and the $\cos\theta$ distribution is symmetric around zero. In order to allow for a detailed consideration of the expansion mentioned above, the mean values of all three relevant distributions ($\sin\theta$, $\cos\theta$ and $\cos^2\theta$) for the individual kinematic bins can be found on HEPDATA [34]. The asymmetry is evaluated in kinematic bins of x, z or $M_{h^+h^-}$, while always integrating over the other two variables. As estimator the extended unbinned maximum likelihood function in ϕ_R and ϕ_S is used, already described in Ref. [29].

In order to avoid false asymmetries, care was taken to select only such data for the analysis for which the spectrometer performance was stable in consecutive periods of data taking. This was ensured by extensive data quality tests described in detail in Ref. [27]. The remaining data sample was carefully scrutinised for a possible systematic bias in the final asymmetry. Here, the two main sources for uncertainties are false asymmetries, which can be evaluated by combining data samples with same target spin orientation, and effects of acceptance, which can be evaluated by comparing sub-samples corresponding to different ranges in the azimuthal angle of the scattered muon. No significant systematic bias could be found and the results from all 12 sub-periods of data taking proved to be compatible. Therefore, an upper limit was estimated comparing the results of the systematic studies to expected statistical fluctuations. The resulting systematic uncertainty for each data point amounts to about $75\,\%$ of the statistical uncertainty. An additional scale uncertainty of $2.2\,\%$ accounts for uncertainties in the determination of target polarisation and target dilution factor calculated for semi-inclusive reactions [35].

4. Results

The obtained asymmetry is shown in Fig. 3 as a function of x, z and $M_{h^+h^-}$. Large negative asymmetry amplitudes are observed in the high x region, which implies that both, the transversity distributions and the spin-dependent dihadron fragmentation functions do not vanish. Over the measured range of the invariant mass $M_{h^+h^-}$ and z, the asymmetry is negative and shows no strong dependence on these variables. Figure 4 shows the comparison of the present results to the previously published COMPASS results on the proton target from 2007 data [29]. The results obtained from the data of 2010 have significantly smaller statistical uncertainties then the previous results from 2007 data and both are in good agreement (CL of 25%). Figure 5 (top) shows the final result obtained by combining both data sets together with predictions from model calculations [36, 37]. The bottom plot shows the same data with a cut on the quark valence region ($x > 0.032$) enhancing the observed signal as a function of z and $M_{h^+h^-}$. In comparison to the published HERMES results [24], the results on the proton target presented in this work have higher statistics and cover a larger kinematic range in x and $M_{h^+h^-}$. In the theoretical approach [21, 22, 23], all dihadron fragmentation functions for di-pion production were calculated in the framework of a spectator model for the fragmentation process. Predictions were made for the DiFF $H_1^{\sphericalangle}$ as well as for the s- and p-wave contributions to the spin-independent

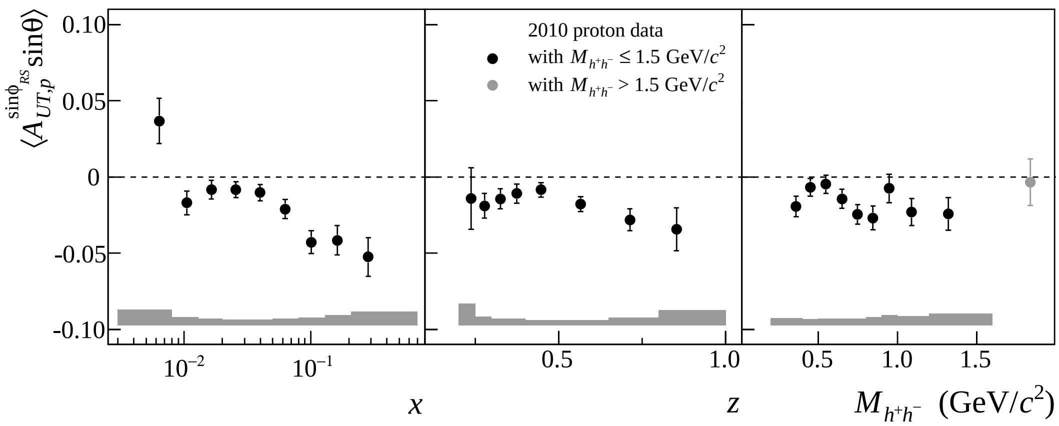


Figure 3: Proton asymmetry, integrated over the angle θ, as a function of x, z and $M_{h^+h^-}$, for the data taken with the proton (NH_3) target in the year 2010. The grey bands indicate the systematic uncertainties. The last bin in $M_{h^+h^-}$ contains events which were removed from the sample used for results shown as a function of x and z.

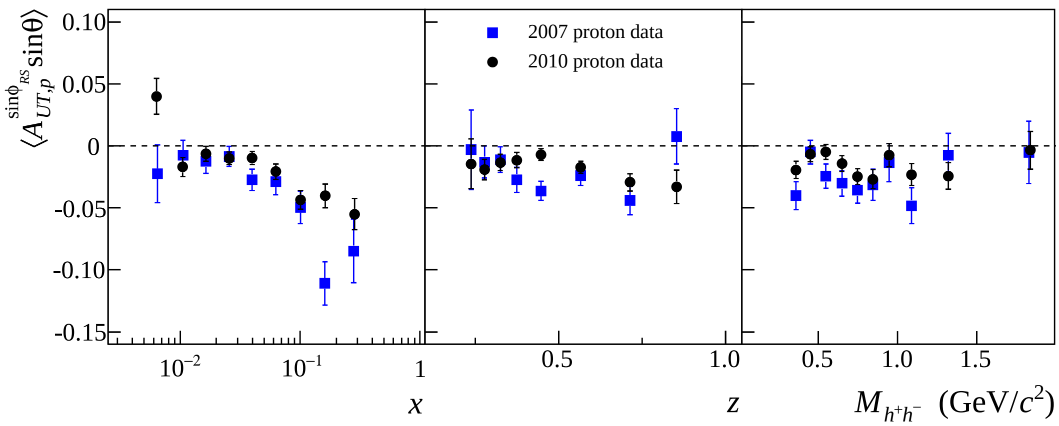
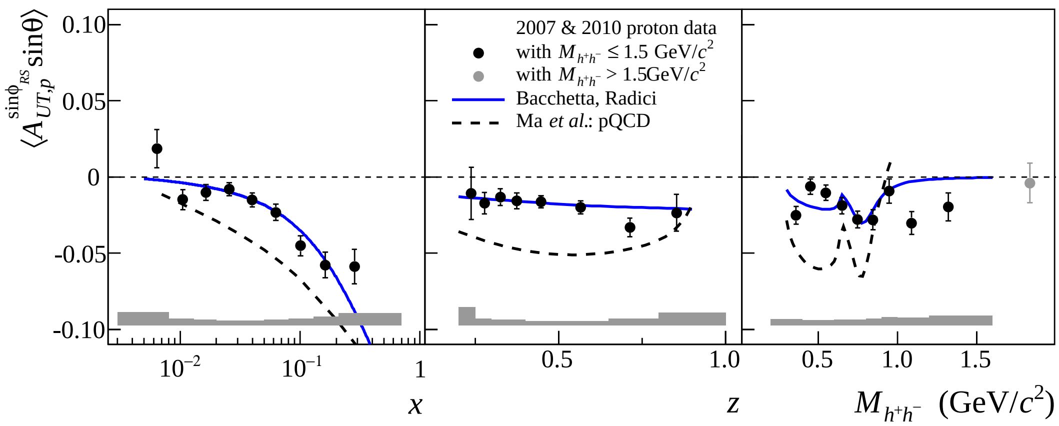


Figure 4: Comparison of the asymmetry obtained from the data taken in the years 2007 and 2010, integrated over the angle θ, as a function of x, z and $M_{h^+h^-}$, respectively.

fragmentation functions D_1 and in Ref. [23] the expected asymmetries for COMPASS were calculated assuming different models for the transversity distributions. Recently, these parametrisations of the dihadron fragmentation functions from Ref. [23] were also used together with the transversity distributions extracted from single hadron production [11] to make predictions for both proton and deuteron targets in the kinematic range covered by COMPASS. The calculated asymmetry is shown as solid blue lines in Fig. 5 (top and bottom). The latter adapted for the cut in x, shows a good agreement of these predictions with our data. Significant asymmetry amplitudes are predicted and the x dependent shape is well described, as well as for the dependence on z in the case of the calculations by Bacchetta *et al.*. A good agreement in terms of the $M_{h^+h^-}$ dependence is only in the mass region of the ρ meson; no optimization of parameters in the calculation of the dihadron fragmentation function to extend the agreement over a larger $M_{h^+h^-}$ region (as e.g., the fraction of the ω to 3π decay in the $s-p$ interference) was performed by the authors. The predic-



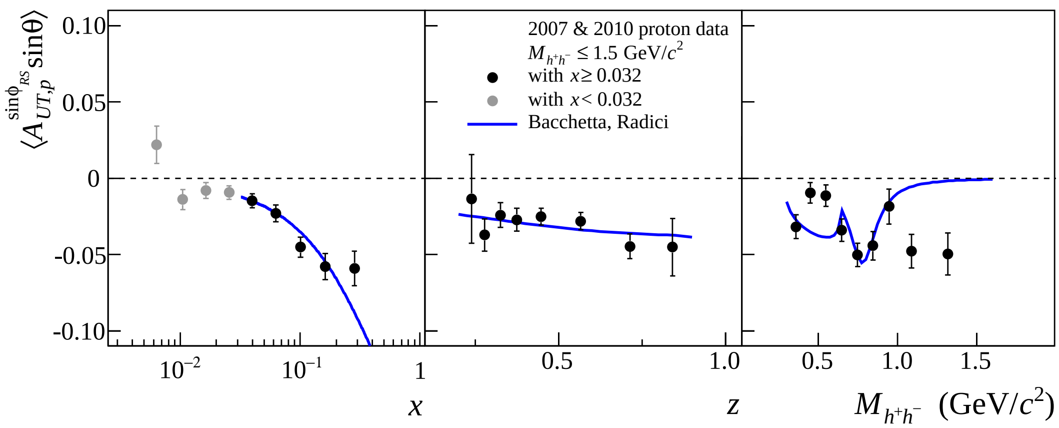


Figure 5: Proton asymmetry, integrated over the angle θ, as a function of x, z and $M_{h^+h^-}$, for the combined data taken with the proton (NH_3) target in the years 2007 and 2010 (top plot). The grey bands indicate the systematic uncertainties. The bottom plot shows the same data for the valence quark region ($x \geq 0.032$). The curves in the upper plots show predictions [36, 37] made using the transversity functions extracted in Ref. [11] (solid lines) or a pQCD based counting rule analysis (dotted lines). The curves in the lower plots show the predictions of [36] in the same $x \geq 0.032$ region. Note that the sign of the original predictions was changed to accommodate the phase π in the definition of the angle ϕ_{RS} used in the COMPASS analysis.

tion of Ma *et al.* [37] (dashed lines in Fig. 5 (top)) uses the parametrisations of [23] for the dihadron fragmentation, together with a model for the transversity distributions, based on a pQCD counting rule analysis. This prediction describes the main trend of the data but tends to overestimate the measured asymmetry.

5. Comparing the dihadron asymmetry and the Collins asymmetry

There is a striking similarity among the Collins asymmetry for positive and for negative hadrons [27] and the dihadron asymmetry as functions of x, as clearly shown in Fig. 6, where the combined results from the 2007 and 2010 COMPASS runs are presented. First, there is a mirror symmetry between the Collins asymmetry for positive and for negative hadrons, the magnitude of the asymmetry being essentially identical and the sign being opposite. This symmetry has been phenomenologically described in terms of opposite signs of u and d quark transversity distributions with almost equal magnitude and opposite sign for favoured and unfavoured Collins fragmentation functions [11].

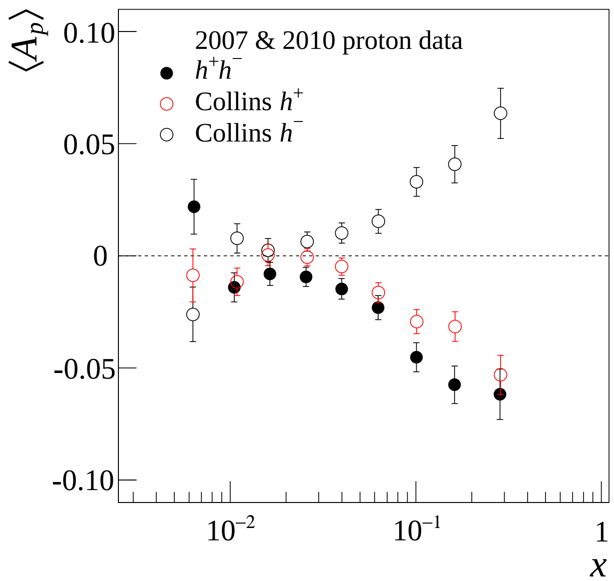


Figure 6: Comparison of the asymmetry *vs.* x obtained in the analysis of dihadron production to the corresponding Collins asymmetry for the combined 2007 and 2010 data.

The new results show that the values of the dihadron asymmetry are slightly larger in magnitude, but very close to the values of the Collins asymmetry for positive hadrons and to the mean of the values of the Collins asymmetry for positive and negative hadrons, after changing the sign of the asymmetry of the negative hadrons. The hadron samples on which these asymmetries are evaluated are different [29, 27] since at least one hadron with $z > 0.2$ is required to evaluate the Collins asymmetry, while all the combinations of positive and negative hadrons with $z > 0.1$ are used in the case of the dihadron asymmetry. It has been checked, however, that the similarity between the two different asymmetries stays the same when measuring the asymmetries for the common hadron sample, selected with the requirement of at least two oppositely charged hadrons produced in the primary vertex. This gives a strong indication that the analysing powers of the single and dihadron channels are almost the same.

More work has been done to understand these similarities. Since the Collins asymmetries are the amplitudes of the sine modulations of the Collins angles $\phi_{C^\pm} = \phi_{h^\pm} + \phi_S - \pi$, where $\phi_{h^\pm}$ are the azimuthal angles of positive and negative hadrons in the γ^*-nucleon system, the mirror symmetry suggests that in the multi-hadrons fragmentation of the struck quark azimuthal angles of positive and negative hadrons created in the event differ by $\approx \pi$, namely that when a transversely polarised quark fragments, oppositely charged hadrons have antiparallel transverse momenta. This anti-correlation between ϕ_{h^+} and ϕ_{h^-} could be due to a local transverse momentum conservation in the fragmentation, as it is present in the LEPTO [38] generator for spin-independent DIS. The relevant point here is that such a correlation shows up also in the Collins fragmentation function that describes the spin-dependent hadronisation of a transversely polarised quark q into hadrons.

If this is the case, asymmetries correlated with the dihadrons can also be obtained in a way different from the one described above. For each pair of oppositely charged hadrons, using the unit vectors of their transverse momenta, we have evaluated the angle ϕ_{2h} of the vector $\boldsymbol{R}_N = \hat{\boldsymbol{p}}_{T,h^+} - \hat{\boldsymbol{p}}_{T,h^-}$ which is the arithmetic mean of the azimuthal angles of the two hadrons after correcting for the discussed π phase difference between both angles. This azimuthal angle of the dihadron is strongly correlated with ϕ_R, as can be seen in Fig. 7 where the difference of the two angles is shown. The same correlation is present also in the LEPTO generator for spin-independent DIS. Introducing the angle $\phi_{2h,S} = \phi_{2h} - \phi_{S'}$, one simply obtains the mean of the Collins angle of the positive and negative hadrons (again after correcting for the discussed π phase difference between the two angles), *i.e.* a mean Collins type angle of the dihadron. The amplitudes of the modulations of $\sin \phi_{2h,S}$, which could then be called the *Collins asymmetry* for the dihadron, are shown as a function of x in Fig. 8 for all the h^+h^- pairs with $z > 0.1$ in the 2010 data, and compared with the

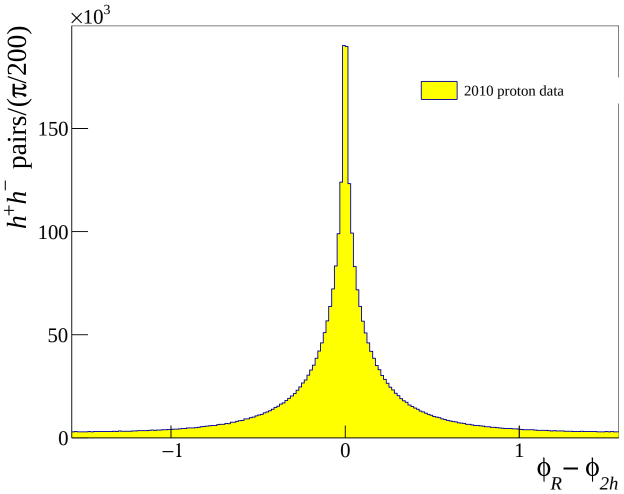


Figure 7: Difference between the two dihadron angles ϕ_R and ϕ_{2h}.

dihadron asymmetry already given in Fig. 3, where an additional cut of $p_T > 0.1\,\mathrm{GeV}/c$ on the transverse momentum of the individual hadrons was applied for a precise determination of the azimuthal angles. The asymmetries are very close, hinting at a common physical origin for the Collins mechanism and the dihadron fragmentation function, as originally suggested in the $^3P_0$ Lund model [39], in the recursive string fragmentation model [32, 40] and in recent theoretical work [41][21].

6. Conclusions

In this paper we present the results of a new measurement of the transverse spin asymmetry in dihadron production in DIS of 160 GeV$/c$ muons off a transversely polarised proton (NH_3) target. The measured asymmetry amplitudes are in agreement with our previous measurement performed with data collected in 2007. The statistical and systematic uncertainties are considerably reduced. The combined results show a clear signal in the x range of the valence quarks and are in agreement with a recent theoretical calculation, using as input the transversity distribution obtained from global fits to the Collins asymmetry. As expected, the results do not show a strong z dependence. Clear structures are exhibited as a function of the dihadrons' invariant mass, with values compatible with zero at about $0.5\,\mathrm{GeV}/c^2$ and a sharp fall to -0.05 at the ρ mass. These new combined results will allow a more precise extraction of the transversity distributions along the lines of the models recently developed. The high precision and the large kinematic range of the COMPASS proton data allows us to compare the dihadron asymmetry and the Collins asymmetry. In the paper we underline the striking similarity between them and give arguments in favour of a common underlying physics mechanism, as already suggested in the past by several authors. In particular we show that in our data the angle commonly used in the dihadron asymmetry analysis is very close to the mean Collins angle of the two hadrons, and that thus the asymmetries evaluated using the two angles turn out to be very similar.

Acknowledgements

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[21] After finalizing the present paper, a new publication appeared [42] reproducing with Monte Carlo calculations the observations of this section.

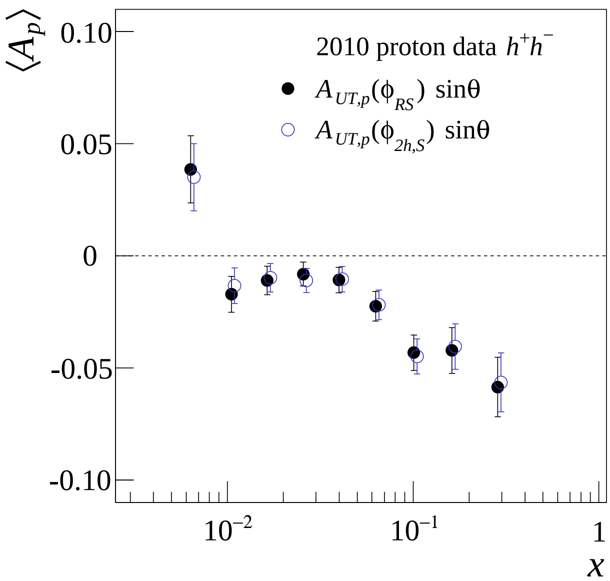

Figure 8: Comparison between the dihadron asymmetry (black points) and the Collins-like asymmetry for the dihadron (open blue points) as a function of x for the 2010 data.

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