Di-hadron asymmetry and interplay between transversity induced asymmetries in hadron lepton production at COMPASS

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Abstract. New results on the transverse spin azimuthal asymmetries in semi-inclusive DIS reactions extracted by the COMPASS Collaboration from the data collected with a transversely polarised proton target are presented. A noticeable similarity between the Collins asymmetry and the di-hadron asymmetry, already been observed and reported, triggered a more deep investigation on the angular correlations and the relevant kinematical variables. The resulting phenomenological analysis of the transversity induced asymmetries, presented in this talk, allows to establish quantitative relationships, providing strong indication that the underlying fragmentation mechanisms are all driven by a common physical process.

1. Introduction

The analysis of the data collected by the COMPASS Collaboration during the years 2007 and 2010 by scattering 160 GeV longitudinally polarised positive muons on a transversely polarised proton target (NH₃) has provided several interesting measurements on the transverse spin structure of the proton. In particular the year 2010 was fully dedicated to these measurements and COMPASS published precise results on the Collins asymmetries [1] obtained for positive and negative hadrons in SIDIS reactions µp → µ hX and on the di-hadron asymmetry [2] obtained using all the possible pairs formed by one positive and one negative hadron in µp → µ⁺ h⁺ h⁻ X.

The similarity between the Collins and di-hadron asymmetry shown in figure 1 inspired a new analysis in which the comparison between these asymmetries has been studied on a common data sample. In particular the angular correlation between the positive and negative hadrons forming the pairs has been investigated in the reaction µp → µ⁺ h⁺ h⁻ X and the dependence of both the Collins and the di-hadron asymmetry on the difference between the azimuthal angles of the two hadrons has been measured. The corresponding formalism has been developed in parallel [3] and the results [4] are very interesting and essentially show that the same process gives origin to these asymmetries.

2. Transversity induced single spin asymmetries

2.1. Collins-like asymmetries

A common data sample is used for the analysis of the interplay between one-hadron and di-hadron asymmetries, namely the “two-hadrons sample” which contains DIS events, selected by the cuts Q² > 1 (GeV/c)², 0.1 < y < 0.9 and W > 5 GeV/c², in which at least two oppositely...
charged hadrons having $z > 0.1$ and $p_T^h > 0.1$ GeV/c are detected. The variable $Q^2$ is the virtuality of the virtual photon exchanged in the reaction, $x$ is the Bjorken scaling variable and $y$ is the energy fraction lost by the incoming muon. The invariant mass of the hadron system after the interaction is $W$, $z$ is the fraction of the available energy carried by the hadron and $p_T^h$ its transverse momentum with respect to the virtual photon direction. The azimuthal angles $\phi_h$ of each hadron are the angle of the vectors $p_T^h$ with respect to the scattering plane. The Collins angle of the positive (negative) hadron are then defined as $\phi_{h,(-)} + \phi_S - \pi$ where $\phi_S$ is the azimuthal angle of the target polarisation. All quantities are calculated in the Gamma Nucleon System where the $z$ axis is defined by the virtual photon and the $x - z$ plane is the lepton scattering plane.

The amplitudes of the modulations in the Collins angles calculated in the “two-hadrons sample” give the Collins-like (CL) asymmetries $A_{1CL}^{\sin(\phi_{h,+} + \phi_S - \pi)}$ and $A_{2CL}^{\sin(\phi_{h,-} + \phi_S - \pi)}$ for positive and negative hadrons respectively. We have named them CL to distinguish them from the “standard” Collins asymmetries, which are defined for the hadrons in the “one-hadron sample”, namely when at least one hadron is detected. They are very similar to the “standard” Collins asymmetries as it is shown in figure 2 where their dependence on $x$ is compared.

Starting from the general expression for the cross-section of the process $\mu p \rightarrow \mu' h^+ h^- X$ [4], integrated over $x, Q^2, z_{h^+}, z_{h^-}, p_T^{h^+}$ and $p_T^{h^-}$.
the CL asymmetries for positive and negative hadrons can be written as
\[ A_{1CL}^{\sin(\phi_{h+} + \phi_{S} - \pi)} = \frac{\sigma_{U}^{-} - \sigma_{U}^{+}}{\sigma_{U}^{-} + \sigma_{U}^{+} \cos(\Delta \phi)} \]
and \[ A_{2CL}^{\sin(\phi_{h-} + \phi_{S} - \pi)} = \frac{\sigma_{U}^{-} + \sigma_{U}^{+} \cos(\Delta \phi)}{\sigma_{U}^{-} - \sigma_{U}^{+}} \]
where \( \Delta \phi = \phi_1 - \phi_2 \) and the labels 1 and 2 refer to the positive and negative hadrons respectively.

The asymmetries \( A_{1CL}^{\sin(\phi_{h+} + \phi_{S} - \pi)} \) and \( A_{2CL}^{\sin(\phi_{h-} + \phi_{S} - \pi)} \) measured as function of \( \Delta \phi \) are shown in figure 3. They are both larger in magnitude when \( \Delta \phi \) gets near to \( \pm \pi \), namely when the two hadrons have opposite directions in the transverse plane, as expected in the \( 3P_0 \) recursive string fragmentation model [7, 8]. There is also a clear mirror effect between the two asymmetries which have the same magnitude and opposite sign. This implies \( \sigma_{1CL}^{h^+h^-} = -\sigma_{2CL}^{h^+h^-} \)
and the expression of the asymmetries simplifies into
\[ A_{1CL}^{\sin(\phi_{h+} + \phi_{S} - \pi)} = \frac{\sigma_{U}^{h^+h^-} - (1 - \cos(\Delta \phi))}{\sigma_{U}^{h^+h^-}} \]
and
\[ A_{1CL}^{\sin(\phi_{h+} + \phi_{S} - \pi)} = \frac{\sigma_{U}^{h^+h^-} (1 - \cos(\Delta \phi))}{\sigma_{U}^{h^+h^-}} \].
The red dashed and the dot-dashed black lines show the curves obtained from the fits using the function \( \pm c \cdot (1 - \cos(\Delta \phi)) \) where \( c \) is a constant parameter. Its values given by the fits are \( 0.014 \pm 0.003 \) and \( 0.016 \pm 0.003 \).

Figure 3. Collins-like asymmetries as function of \( \Delta \phi \) the difference of the azimuthal angles of the two hadrons. The red points give the \( A_{1CL}^{\sin(\phi_{h+} + \phi_{S} - \pi)} \) asymmetry measured for the positive hadrons and the black triangles give the \( A_{2CL}^{\sin(\phi_{h-} + \phi_{S} - \pi)} \) asymmetry for the negative hadrons. The signal is clearly bigger for values of \( \Delta \phi \) which are near \( \pm \pi \) for both. There is also a mirror effect between the two asymmetries. The bands give the size of the systematic error.

2.2. Interplay between one-hadron and di-hadron asymmetries

A new definition of the azimuthal angle of the pair has been introduced to determine the relation between di-hadron and one-hadron asymmetries, namely \( \phi_{2h} = \left[ \phi_{h+} + \phi_{h-} + \pi \cdot \text{sgn}(\Delta \phi) \right] / 2 \), where \( \text{sgn} \) is the signum function. It is a very simple definition and allows, together with \( \sigma_{1C}^{h^+h^-} = \sigma_{2C}^{h^+h^-} \), to rewrite the differential cross section of equation 1 as follows:
\[ \frac{d\sigma}{d\phi_{2h} d\phi d\phi_S} = \sigma_{U}^{h^+h^-} + S_T \cdot \sigma_{1C}^{h^+h^-} \cdot \sqrt{2(1 - \cos(\Delta \phi))} \cdot \sin(\phi_{2h} + \phi_{S} - \pi) \]
which exhibits a \( \sin(\phi_{2h} + \phi_{S} - \pi) \) modulation with the amplitude \( A_{2h,CL}^{\sin(\phi_{2h} + \phi_{S} - \pi)} = \frac{\sigma_{1C}^{h^+h^-} \cdot \sqrt{2(1 - \cos(\Delta \phi))}}{\sigma_{U}^{h^+h^-}} \).
In [2, 4] it is shown that the $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$ asymmetry and the one measured in [6, 2] using \( \phi_R \) as the azimuthal angle of the vector \( R = \frac{z_{h^-}+z_{h^+}-z_{s^-}+z_{s^+}}{z_{h^-}-z_{h^+}+z_{s^-}-z_{s^+}} \) [7] are essentially the same. To establish a relation between the CL and the di-hadron asymmetries it is then enough to unveil the relationship between the CL and the \( \phi_{2h} \) asymmetries.

The figure 4 shows the $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$ asymmetry with the curves of figure 3 superimposed together with the one obtained from the fit using a $-c \cdot \sqrt{2 \cdot (1 - \cos(\Delta \phi))}$ function where $c = 0.017 \pm 0.002$ (continous line). It is clear that the behaviour expected from the calculations is well in agreement with the di-hadron data. Also, the values of the constants $c$ appearing in the fits of the $\Delta \phi$ dependence of the CL asymmetries are in agreement with the value of the constant $c$ fitted on the di-hadron asymmetry. This implies that the Collins-like (and hence the Collins) mechanism and the di-hadron mechanism are all generated by the same physics process.

The factor by which the magnitude of the di-hadron asymmetry measured as function of $x$ is larger than the one of the Collins asymmetries, figure 1, can be calculated by integrating the curves over $\Delta \phi$ and it is $4/\pi$.

![Figure 4](image_url)

**Figure 4.** The di-hadron asymmetry in the $\phi_{2h}$ angle $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$ as function of $\Delta \phi$ (black full squares). The red dashed line is the curve $-c \cdot \sqrt{2 \cdot (1 - \cos(\Delta \phi))}$ fitted on the Collins-like asymmetries for positive hadrons $A_{1CL}^{\sin(\phi_h+\phi_S-\pi)}$, the black dot-dashed line is the curve $c \cdot (1 - \cos(\Delta \phi))$ fitted on the Collins-like asymmetries for negative hadrons $A_{2CL}^{\sin(\phi_{h^-}+\phi_S-\pi)}$ and the grey continuous line is the curve $-c \cdot \sqrt{2 \cdot (1 - \cos(\Delta \phi))}$ fitted on the di-hadron asymmetry $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$. The values obtained for the parameter $c$ from the three fits are: $0.014 \pm 0.003$, $0.016 \pm 0.003$ and $0.017 \pm 0.002$ respectively. The band gives the systematic error for $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$.

**References**

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