Transverse target spin asymmetries in exclusive $\omega$ muoproduction at COMPASS

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Abstract.

Exclusive production of $\omega$ mesons was studied at the COMPASS experiment by scattering 160 GeV/$c$ muons off transversely polarised protons. Five single-spin and three double-spin azimuthal asymmetries were measured in the range of photon virtuality $1 \text{(GeV/c)}^2 < Q^2 < 10 \text{(GeV/c)}^2$, Bjorken scaling variable $0.003 < x_{Bj} < 0.3$ and transverse momentum squared of the $\omega$ meson $0.05 \text{(GeV/c)}^2 < p_T^2 < 0.5 \text{(GeV/c)}^2$. The results are compared to recent calculations based on Goloskokov-Kroll GPD model with the $\pi\omega$ transition form factor.

1. Introduction

Exclusive leptoproduction of vector meson in the process $\gamma^* + N \rightarrow V + N'$ ($V = \rho^0, \phi, \omega$) provides information both on reaction mechanism and nucleon structure. This contribution is concentrated on transverse target spin asymmetries obtained in exclusive $\omega$ production. Studying these asymmetries give the possibility to constrain Generalized Parton Distribution (GPD). Access to GPDs relies on factorization property of the process amplitude. The process amplitude is a convolution of the lepton-quark hard-scattering amplitude with soft part which contains GPD and vector meson distribution amplitude. At leading twist chiral-even GPDs $H^{(g)}(x, \xi, t), E^{(g)}(x, \xi, t), \tilde{H}^{(g)}(x, \xi, t)$ without parton helicity flip are sufficient to describe exclusive vector meson production on spin 1/2 target. When higher twist effects are included in the Distribution Amplitude, chiral odd GPDs $H^{(g)}_T(x, \xi, t), E^{(g)}_T(x, \xi, t), \tilde{H}^{(g)}_T(x, \xi, t)$ with parton helicity flip, appear. The GPDs $H$ and $E$ are of special interest as they are related to the total angular momentum of partons in the nucleon by the Ji's relation [1]. GPDs also describe the nucleon as an extended object which correlates longitudinal momenta of parton and transverse spatial coordinates. GPDs $H$ are well constraint by the experimental data. Less is know about GPDs $E$. Production of exclusive vector meson with unpolarised target is mainly sensitive to GPDs $H$, while for transversely polarised target it is also sensitive to GPDs $E$.

The factorisation of process amplitude is proven rigorously when the lepton-quark interaction is mediated by longitudinally polarised virtual photon. However, phenomenological pQCD-inspired models taking into account parton transverse momenta have been proposed by Goloskokov and Kroll [2, 3, 4], which for both longitudinal and transverse photons describes reasonably well the

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behaviour of the cross section, spin density matrix elements, azimuthal and spin asymmetries. It will be referred to as "GK" model. It is known that in $\omega$ exclusive production Unnatural Parity Exchange (UPE) processes plays a substantial role. In the GK model the UPE processes are described by a predominant contribution of pion-pole exchange.

2. Theoretical formalism
The cross section for exclusive $\omega$ muoproduction, $\mu N \rightarrow \mu' \omega N'$, on a transversely polarised nucleon is given in Ref. [5]:

$$
\frac{d\sigma}{dE_{\mu'}dQ^2 dt d\phi d\phi_s} = \frac{1}{2} \frac{1}{(1 - \epsilon)\cos\phi}\left[ \sin (\phi - \phi_s) \text{Im} (\sigma_{++} + \epsilon\sigma_{00}^+) + \epsilon \frac{1}{2} \sin (\phi + \phi_s) \text{Im} \sigma_{+-}
\right.
\left. - \sqrt{\epsilon} (1 + \epsilon) \sin \phi \text{Re} (\sigma_{++} + \sigma_{00}^-) - P_{\ell} \sqrt{\epsilon} (1 - \epsilon) \cos \phi \text{Re} (\sigma_{++} + \sigma_{00}^-)
\right.
\left. + S_T \sin (2\phi - \phi_s) \text{Re} \sigma_{+-} + \epsilon \frac{1}{2} \sin (\phi - \phi_s) \text{Re} \sigma_{++}
\right.
\left. + \sqrt{\epsilon} (1 + \epsilon) \sin (2\phi - \phi_s) \text{Re} \sigma_{00}^+ - P_{\ell} \sqrt{\epsilon} (1 - \epsilon) \cos (\phi + \phi_s) \text{Re} \sigma_{00}^+
\right. 
$$

(1)

where only terms relevant for the present analysis are shown. Definition of angles $\phi$ and $\phi_s$ is shown in Fig 1.

Figure 1. Kinematics of exclusive meson production in the target rest frame. Here $k$, $k'$, $q$ and $v$ represent the three-momentum vectors of the incident and the scattered muons, the virtual photon and the meson respectively. The component of the target spin vector $S$ (not shown) perpendicular to the virtual-photon direction is denoted by $S_T$.

For a transversely polarised target five single (UT) and three double (LT) spin asymmetries can be defined:
\[ A_{\sin(\phi-\phi_s)}^{\text{UT}} = -\frac{\text{Im} (\sigma_{++}^+ + \epsilon \sigma_{00}^+)}{\sigma_0}, \]
\[ A_{\cos(\phi-\phi_s)}^{\text{UT}} = \frac{\text{Re} \sigma_{++}^+}{\sigma_0}, \]
\[ A_{\sin(\phi+\phi_s)}^{\text{UT}} = -\frac{\text{Im} \sigma_{++}^+}{\sigma_0}, \]
\[ A_{\cos(\phi+\phi_s)}^{\text{UT}} = \frac{\text{Re} \sigma_{++}^+}{\sigma_0}, \]
\[ A_{\sin(3\phi-\phi_s)}^{\text{UT}} = -\frac{\text{Im} \sigma_{++}^+}{\sigma_0}, \]
\[ A_{\cos(2\phi-\phi_s)}^{\text{UT}} = \frac{\text{Re} \sigma_{++}^+}{\sigma_0}. \]

Here, \( \sigma_0 \) is the total unpolarised cross section, which is the sum of the cross sections for longitudinally and transversely polarised virtual photons, \( \sigma_L \) and \( \sigma_T \), respectively:

\[ \sigma_0 = \frac{1}{2} (\sigma_{++}^+ + \sigma_{++}^-) + \epsilon \sigma_{00}^+ = \sigma_T + \epsilon \sigma_L. \]

Each asymmetry is related to a modulation of the cross section as a function of \( \phi \) and/or (see Eq. 1), which is indicated by the superscript.

3. Experimental data

The results presented in this Contribution are based on the data taken with the transversely polarised NH\(_3\) target in 2010. The \( \omega \) meson is produced in the following process

\[ \mu N \rightarrow \mu' N' \omega \]

\[ \rightarrow \pi^+ \pi^- \pi^0 \rightarrow \gamma \gamma. \]

Therefore, event contains an incident muon track and three outgoing tracks (\( \mu', h^+, h^- \)), and only two ECAL clusters which are time-correlated with beam. It is checked that clusters are not caused by charged particles.

![Distribution of \( E_{\text{miss}} \).](image)

The accepted events are denoted by the shaded area.

Exclusivity is defined by applying a constraint on missing energy. Missing energy is calculated as \( E_{\text{miss}} = \frac{M_X^2 - M_p^2}{2M_p} \) with \( M_X^2 = (p + q - p_{\pi^+} + p_{\pi^-} - p_{\pi^\circ})^2 \), where \( p, q, p_{\pi^+}, p_{\pi^-} \) and \( p_{\pi^\circ} \) are 4-momenta of proton, \( \gamma^* \) and each of three pions. The \( E_{\text{miss}} \) distribution is shown in Fig. 2.
For exclusive production one would expect the missing energy $E_{\text{miss}} = 0$. Taking into account experimental resolution the applied cut is $-3.0 \text{ GeV} < E_{\text{miss}} < 3.0 \text{ GeV}$.

The constraint on squared transverse momentum of $\omega$ with respect to virtual photon $\gamma^*$ momentum, $0.05 < P_T^2 < 0.5 \text{ GeV}^2$, is applied, in order to remove coherent production and to suppress non-exclusive background (see Fig. 3). Other constraints and mean kinematic values are the following

\[ Q^2 = -(q^2) = -(k - k')^2 = 1.0 \pm 10.0 \text{ GeV}^2, \quad \langle Q^2 \rangle = 2.2 \text{ GeV}^2, \quad W = \sqrt{(q + p)^2} > 5.0 \text{ GeV}, \quad \langle W \rangle = 7.1 \text{ GeV}, \quad x_B = Q^2 / 2pq = 0.003 \div 0.35, \quad \langle x_B \rangle = 0.049 \]

\[ p_T^2 \text{cut} \]

\[ \text{Entries} \quad 19392 \quad \text{Mean} \quad 0.1909 \quad \text{RMS} \quad 0.1188 \]

\[ \text{COMPASS 2010 proton data} \quad \text{preliminary} \]

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \]

\[ 10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \]

\[ \text{events / 0.03 (GeV/c)^2} \]

\[ \text{Figure 3. Distribution of } p_T^2. \text{ The accepted events are denoted by the shaded area.} \]

A $\pi^0$ meson is reconstructed from two calorimeter clusters as described in Ref. [6]

The limit on the invariant mass of two photons, $M_{\gamma\gamma}$, depends on the energy $E_{\gamma\gamma}$ of the $\pi^0$ candidate:

\[ |M_{\gamma\gamma} - M_{\pi^0, \text{par}}(E_{\gamma\gamma})| < 3 \sigma_{\text{par}}(E_{\gamma\gamma}) \]  

\[ (4) \]

\[ \text{Figure 4. Distribution of the invariant mass of two photons. The accepted events are denoted by the shaded area.} \]

Here, position $M_{\pi^0, \text{par}}(E_{\gamma\gamma})$ and width $\sigma_{\text{par}}(E_{\gamma\gamma})$ of the $\pi^0$ peak are parameterised using semi-inclusive data for $\pi^0$ mesons. In Fig. 4 distribution of the invariant mass of two photons is shown.

Events corresponding to incoherent exclusive $\omega$ production are selected using additional cuts on the invariant mass of the $\pi^+\pi^-\pi^0$ system, $M_{\pi^+\pi^-\pi^0}$,

\[ |M_{\pi^+\pi^-\pi^0} - M_{\omega}^{\text{PDG}}| < 70 \text{ MeV}/c^2, \]  

\[ (5) \]

where $M_{\omega}^{\text{PDG}} = 782.65 \text{ MeV}/c^2$ is the nominal $\omega$ resonance mass. The distribution of $M_{\pi^+\pi^-\pi^0}$ is shown in Fig. 5.
Figure 5. Distribution of $M_{\pi^+\pi^-\pi^0}$. The accepted events are denoted by the shaded area.

Figure 6. Left: Average azimuthal asymmetries for exclusive $\omega$ production. The error bars (left bands) represent the statistical (systematic) uncertainties. Right: Single spin azimuthal asymmetries as a function of $Q^2$, $x_{Bj}$ and $p_T^2$. The curves show the predictions of the $GPD$-based model [7] for the average $Q^2$, $W$ and $p_T^2$ values of the COMPASS data. The dashed red and dotted blue curves represent the predictions with the positive and negative $\pi\omega$ form factors, respectively, while the solid black curve represents the predictions without the pion pole.

4. Results
Asymmetries were extracted using unbinned maximum likelihood method with simultaneous fit of signal and background asymmetries (16-parameter fit). In this fit it is assumed that asymmetries of seminclusive deep inelastic scattering (SIDIS) background in exclusive region is the same as in region 7.0 GeV < $E_{miss}$ < 20.0 GeV.
The extracted azimuthal asymmetries, for the entire kinematic region, are shown in Fig. 6 (left). In addition, the single-spin asymmetries are measured in bins of $Q^2$, $x_{Bj}$ or $p_T^2$ with the results shown in Fig. 6 (right). The double-spin asymmetries are not not shown in separate kinematic bins because of large uncertainties. In Figure 6 (right) the COMPASS results are compared to the calculations of the GK model [7].
Figure 7. The asymmetry $A_{UT}^{\sin(\phi - \phi_S)UT}$ for exclusive $\omega$ muoproduction by the COMPASS (filled circles) and HERMES [8] (open squares) collaborations as a function of $t'$. The curves show the predictions of the GPD-based model [7] given for the average $Q^2$ and $W$ values of the COMPASS (solid lines) and HERMES (dashed lines) data. For each set of curves, the upper (blue) and lower (red) ones are for the negative and positive $\pi\omega$ form factors, respectively, while the middle (black) one represents the predictions without the pion pole.

The latter are obtained for the average $W$, $Q^2$ and $x_{Bj}$ values of the COMPASS data: $W = 7.1$ GeV/$c^2$ and $p_T^2 = 0.17$ (GeV/$c$)$^2$ for the $x_{Bj}$ and $Q^2$ dependences, and $W = 7.1$ GeV/$c^2$ and $Q^2 = 2.2$ (GeV/$c$)$^2$ for the $p_T^2$ dependence. The predictions are given for three versions of the model: with the pion-pole contribution using a positive or negative $\pi\omega$ transition form factor, and without the pion-pole contribution. The interpretation of $\omega$ results is challenging in terms of GPDs, as exclusive $\omega$ meson production is significantly influenced by the pion-pole exchange contribution, and at present the sign of $\pi\omega$ transition form factor is unknown. By comparing the COMPASS results with the calculations of the GK model (see Fig. 6 (right)), one finds that the asymmetries $A_{UT}^{\sin(\phi - \phi_S)UT}$ and $A_{UT}^{\sin(2\phi - \phi_S)UT}$ prefer the negative $\pi\omega$ transition form factor, while the asymmetry $A_{UT}^{\sin\phi_SUT}$ prefers the positive one. The other measured asymmetries are not sensitive to the sign of the $\pi\omega$ form factor.

The single-spin azimuthal asymmetries for $\omega$ production on transversely polarised protons were measured also by the HERMES collaboration [8]. They conclude that their data seem to favour the positive $\pi\omega$ form factor, although within large experimental uncertainties. A direct comparison of published asymmetry values measured in both experiments is not straightforward, because the HERMES definition of physics asymmetries differs from that given in Eq. 3. Such comparison is only possible for the asymmetry $A_{UT}^{\sin(\phi - \phi_S)UT}$. The results from both experiments are shown as a function of $t'$ in Fig. 7 indicating their compatibility within experimental uncertainties. Note that the COMPASS results cover a wider kinematic range and they have smaller uncertainties, for example for the asymmetry $A_{UT}^{\sin(\phi - \phi_S)UT}$ by a factor larger than two.

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