

# Exclusive $\omega$ meson production at COMPASS

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**Abstract.** Exclusive  $\omega$  meson production is studied by the COMPASS Collaboration using the CERN 160 GeV/ $c$  muon beam and a transversely polarised proton target. Single-spin and double-spin asymmetries are measured, some of which are sensitive to the Generalised Parton Distributions  $E$  that are related to quark orbital angular momenta. The results, which are sensitive also to the pion-pole contribution to the production mechanism, are compared to the predictions of a phenomenological model.

## 1 Introduction

Hard exclusive electro and muoproduction of mesons on nucleons has been playing an important role in studies of the hadron structure. Renewed interest arose when it was shown that it allows access to Generalised Parton Distributions (GPDs), which provide a comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. For example, using GPDs the nucleon can be described as an extended object, which is referred to as 3-dimensional nucleon tomography, and access to quark orbital angular momentum becomes possible in principle.

At leading twist, the chiral-even GPDs  $H$  and  $E$  are sufficient to describe exclusive vector meson production on a spin- $\frac{1}{2}$  target. These GPDs are of special interest as they are related to the total angular momentum carried by partons in the nucleon [1]. Presently, the GPDs  $H$  are already well constrained in the accessible  $x_{Bj}$  range covered by HERA, HERMES and JLAB data. The constraints on the GPDs  $E$  are weak and come mainly from measurements of the nucleon Pauli form factor. The interpretation of the COMPASS results presented in this article is done in the framework of the GPD-based model developed by Goloskokov and Kroll [2, 3]. The model also includes some estimation of the pion-pole contribution to the mechanism of exclusive  $\omega$  production [2], which is sizeable at COMPASS kinematics. A full account of the content of this article is given in Ref. [4].

## 2 Formalism

For exclusive  $\omega$  meson production by a virtual photon,  $\gamma^* p \rightarrow \omega p$ , the total unpolarised cross section can be written as

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

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It is given by the sum of the cross sections for longitudinally and transversely polarised virtual photons,  $\sigma_L$  and  $\sigma_T$ , respectively. The virtual-photon polarisation parameter can be approximated by  $\epsilon \simeq (1-y)/(1-y+y^2/2)$ .

For the various possible combinations of the helicity of the virtual photon, denoted by  $m, n = -1, 0, +1$ , and the helicity of the initial-state proton, denoted by  $i, j = -\frac{1}{2}, +\frac{1}{2}$ , the photoabsorption cross sections or the interference terms are proportional to bilinear combinations of helicity amplitudes  $\mathcal{M}$ :

$$\sigma_{mn}^{ij} \propto \sum \mathcal{M}_{m'i',mi}^* \mathcal{M}_{m'j',nj} \quad (2)$$

The sum runs over all spin combinations for the final state, given by the spin of the meson,  $m' = -1, 0, +1$ , and the spin of the final-state proton,  $i' = -\frac{1}{2}, +\frac{1}{2}$ . For brevity, a dependence on the kinematic variables is omitted here and in the following the helicities are labelled by only their signs or zero.

For exclusive meson production off a transversely polarised target, five single-spin asymmetries  $A_{UT}$  and three double-spin asymmetries  $A_{LT}$  can be defined:

$$\begin{aligned} A_{UT}^{\sin(\phi-\phi_s)} &= -\frac{\text{Im}(\sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-})}{\sigma_0}, & A_{LT}^{\cos(\phi-\phi_s)} &= \frac{\text{Re}\sigma_{++}^{+-}}{\sigma_0}, & A_{UT}^{\sin(\phi+\phi_s)} &= -\frac{\text{Im}\sigma_{+-}^{+-}}{\sigma_0}, \\ A_{UT}^{\sin(2\phi-\phi_s)} &= -\frac{\text{Im}\sigma_{+0}^{+-}}{\sigma_0}, & A_{LT}^{\cos(2\phi-\phi_s)} &= -\frac{\text{Re}\sigma_{+0}^{+-}}{\sigma_0}, & A_{UT}^{\sin(3\phi-\phi_s)} &= -\frac{\text{Im}\sigma_{+-}^{-+}}{\sigma_0}, \\ A_{UT}^{\sin\phi_s} &= -\frac{\text{Im}\sigma_{+0}^{+-}}{\sigma_0}, & A_{LT}^{\cos\phi_s} &= -\frac{\text{Re}\sigma_{+0}^{+-}}{\sigma_0}. \end{aligned} \quad (3)$$

Here, U and L denote unpolarised and longitudinally polarised beam, respectively, and T denotes transverse target polarisation. Each asymmetry is related to a specific modulation of the cross section in the angles  $\phi$  and  $\phi_s$ , as indicated by the superscript. The angle  $\phi$  is the azimuthal angle between the lepton plane spanned by incoming and scattered lepton momenta, and the hadron plane spanned by virtual-photon and meson momenta. The angle  $\phi_s$  is the azimuthal angle about the virtual-photon momentum, between the lepton plane and the direction of the transverse component of the polarisation of the target nucleon. The complete formula for the cross section can be found in Ref. [5].

### 3 COMPASS apparatus

The COMPASS experiment uses the high-intensity M2 muon beam line of the CERN SPS. During data taking, the nominal momentum of the  $\mu^+$  beam was 160 GeV/c with a spread of 5% and a longitudinal polarisation of about  $-80\%$ . The average beam intensity was  $3.5 \cdot 10^8 \mu^+$ /spill with a spill length of about 10 s every 40 s. Trajectory and momentum of each incoming beam particle were measured upstream the target.

The solid-state ammonia ( $\text{NH}_3$ ) target contained transversely polarised protons with a polarisation of about 90%, which was generated by Dynamic Nuclear Polarisation. The target dilution factor, which is defined as cross-section-weighted fraction of polarisable to total material, had a value of about 25%. The direction of the target polarisation was reversed periodically, and three consecutive target cells with alternating polarisation direction ( $++$  or  $--$ ) were used to minimise systematic effects due to possible spectrometer instabilities and/or acceptance variation.

The COMPASS spectrometer is a 50 m long two-stage spectrometer with excellent tracking and particle identification capabilities. Each stage is defined by a dipole magnet with tracking detectors before and after it. High redundancy for track reconstruction is accomplished by about 300 tracking-detector planes in total. For muon identification, both stages are equipped with hadron absorbers that

are situated between hodoscope stations. Each spectrometer stage contains an electromagnetic and a hadron calorimeter. The former are crucial to identify exclusive  $\omega$  production, as they allow for the reconstruction of  $\pi^0$  mesons originating from  $\omega \rightarrow \pi^+\pi^-\pi^0$  decays. A detailed description of the apparatus can be found in Ref. [6].

## 4 Event selection

Data taken in the year 2010 are used for the analysis of exclusive  $\omega$  production. Each selected event contains a primary vertex with exactly one incoming and one outgoing muon track and with exactly two outgoing hadron tracks of opposite charges, which are assumed to be pions. In the electromagnetic calorimeters, exactly two clusters have to be reconstructed that are correlated in time with the vertex and not associated to any charged particle. These clusters are assumed to originate from a pair of photons that was emitted from the primary vertex. The  $\omega$  resonance is selected by constraining the reconstructed invariant mass as  $|M_{\pi^+\pi^-\pi^0} - M_{\omega}^{\text{PDG}}| < 0.07 \text{ GeV}/c^2$ , where  $M_{\omega}^{\text{PDG}} \approx 0.783 \text{ GeV}/c^2$ .

The recoiling target particle was not detected during 2010 data taking. The ‘‘exclusivity’’ of the reaction is instead accomplished by constraining the missing energy  $E_{\text{miss}} = ((p + q - v)^2 - p^2)/2M_p$ , where  $M_p$  is the proton mass and  $p$ ,  $q$  and  $v$  are the four-momenta of proton, photon and meson, respectively. For exclusive events, the reconstructed value of  $E_{\text{miss}}$  has to be close to zero, and the constraint  $|E_{\text{miss}}| < 3.0 \text{ GeV}$  is used to account for the experimental resolution in this measured variable. The squared transverse momentum with respect to the virtual-photon direction is required to be in the interval  $0.05 \text{ (GeV}/c)^2 < p_T^2 < 0.5 \text{ (GeV}/c)^2$ , where the lower limit suppresses contributions from coherent production on target nuclei and the upper one provides further reduction of non-exclusive background.

The kinematic region is defined by requiring  $1 \text{ (GeV}/c)^2 < Q^2 < 10 \text{ (GeV}/c)^2$  on the negative invariant mass squared of the virtual photon,  $Q^2 = -q^2$ ;  $0.1 < y < 0.9$  on the fraction of lepton energy lost in the laboratory system,  $y = (p \cdot q)/(p \cdot k)$ ;  $0.003 < x_{Bj} < 0.35$  on the Bjorken- $x$  variable;  $W > 5 \text{ GeV}/c^2$  on the invariant mass of the system of virtual photon and nucleon,  $W = \sqrt{(p + q)^2}$ . In the analysis of  $\omega$  meson the signal and background asymmetries are extracted simultaneously using the unbinned maximum-likelihood method.

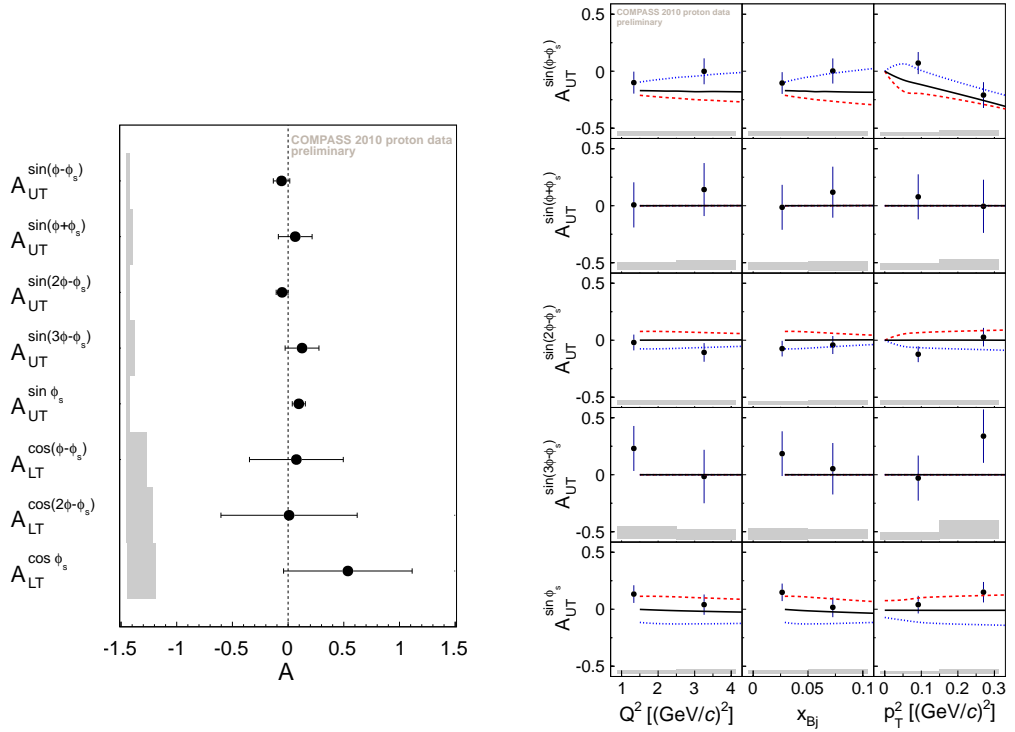
## 5 Results and interpretation

All eight transverse target asymmetries for exclusive  $\omega$  meson production are shown in Fig. 1 (left). They are given for the mean values of kinematic variables,  $\langle Q^2 \rangle = 2.2 \text{ (GeV}/c)^2$ ,  $\langle x_{Bj} \rangle = 0.049$ ,  $\langle p_T^2 \rangle = 0.17 \text{ (GeV}/c)^2$ ,  $\langle W \rangle = 7.1 \text{ GeV}/c^2$  and  $\langle y \rangle = 0.18$ . The single spin asymmetries measured as a function of  $Q^2$ ,  $x_{Bj}$  or  $p_T^2$  are shown in Fig. 1 (right).

In Fig. 1 (right) the measured asymmetries are compared to the predictions of the Goloskokov-Kroll model [2, 7]. The authors have provided three sets of predictions: one without the pion pole contribution and two with the contribution that differ by the sign of  $\pi - \omega$  transition form factor. While the results for  $A_{UT}^{\sin(\phi - \phi_s)}$  and  $A_{UT}^{\sin(\phi - \phi_s)}$  asymmetries prefer the positive sign of the  $\pi - \omega$  transition form factor, the results for  $A_{UT}^{\sin \phi_s}$  asymmetry prefer the negative sign. At present the reason for this discrepancy between the model and the experimental data is unknown. The remaining asymmetries are not sensitive to the sign of  $\pi - \omega$  transition form factor.

## References

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**Figure 1.** Left: The azimuthal asymmetries for exclusive  $\omega$  meson production on transversely polarised protons. Error bars and left bands represent statistical and systematic uncertainties, respectively. Mean values of kinematic variables are indicated in the text. Right: Single spin azimuthal asymmetries for exclusive  $\omega$  meson production on transversely polarised protons. The curves show the predictions of the GPD-based model [2, 7]. The dashed red and dotted blue curves represent the predictions with positive and negative  $\pi\omega$  form factor, respectively, while the solid black curves represents the predictions without pion-pole contribution.

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