Journal of Physics: Conference Series

Spin structure of exclusive ω muoproduction at COMPASS

Spin structure of exclusive ω muoproduction at COMPASS

Bohdan Mariański[1]
(on behalf of the COMPASS Collaboration)
National Institute for Nuclear Research, PL 00-681 Warsaw, Poland

E-mail: b.marianski@ncbj.gov.pl

Abstract.
Spin Density Matrix Elements (SDMEs) are determined for exclusive ω meson production on unpolarized protons, in the COMPASS kinematic region of
1.0 $(\mathrm{GeV/c})^2 < Q^2 <$ 10.0 $(\mathrm{GeV/c})^2$, 5.0 $\mathrm{GeV}/c^2 < W <$ 17.0 GeV/c^2 and
0.01 $(\mathrm{GeV/c})^2 < p_T^2 <$ 0.5 $(\mathrm{GeV/c})^2$. Using extracted the preliminary SDMEs values the hypothesis of S-Channel Helicity Conservation (SCHC) is studied. Certain matrix elements that correspond to the transition $\gamma_T^* \to V_L$ (e.g. r_{00}^5) indicate violation of SCHC in exclusive ω production. A sizable contribution of unnatural parity exchange amplitudes is found for exclusive ω meson muoproduction, and there is a clear indication of its decrease with increasing W. The extracted longitudinal-to-transverse cross section ratio is 0.553 $\pm$ 0.044 $\pm$ 0.020.

1. Spin Density Matrix Elements

The study of Hard Exclusive Meson Production (HEMP) allows to constrain models of Generalized Parton Distributions (GPDs). If the produced particle is a vector meson we can get information on GPDs $GPDs$ $H^{q(g)}$(x,ξ, t), $E^{q(g)}$(x, ξ, t), while exclusively produced pseudo-scalar mesons provide information on GPDS $\tilde{H}^{q(g)}$(x, ξ, t), $\tilde{E}^{q(g)}$(x, ξ, t). All these GPDs are called chiral-even because the helicity of struck parton is unchanged. When higher twist effects are included in the distribution amplitude, chiral odd or transversity $GPDs$ $H_T^{q(g)}$(x, ξ, t), $E_T^{q(g)}$(x, ξ, t), $\tilde{H}_T^{q(g)}$(x, ξ, t), $\tilde{E}_T^{q(g)}$(x, ξ, t), $\bar{E}_{\mathrm{T}}^{q(g)} = 2\tilde{H}_T^{q(g)} + E_T^{q(g)}$ with parton helicity flip can be constrained. These GPDs are not accessible in Deeply Virtual Compton Scattering (DVCS). Moreover, HEMP allows to study various quark-flavor combinatios of GPDs and reaction mechanism. Most of this information we get from Spin Density Matrix Elements (SDMEs), wchich determine angular distributions of the particles from the decay of the vector meson. These elements are bilinear combinations of helicity amplitudes $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$, where λ_γ is the virtual photon helicity and λ_V the vector-meson helicity, while λ_N and λ'_N are the helicities of the nucleon in the initial and final states, respectively.

In the $\gamma^* N$ Centre-of-Mass (CM) system the spin density matrix of the vector meson is given by the von Neumann equation [1] :

$$\rho_{\lambda_V \lambda'_V} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}, \tag{1}$$

[1] Work supported by the Polish NCN Grant 2017/26/M/ST2/00498

where $\mathcal{N}$ is a normalization factor [1-2] and $\varrho^{U+L}_{\lambda_\gamma\lambda'_\gamma}$ is the virtual photon spin density matrix, where U and L denote unpolarized and longitudinally polarised beam, respectively [2].

After the decomposition of $\varrho^{U+L}_{\lambda_\gamma\lambda'_\gamma}$ into the standard set of 3×3 Hermitian matrices Σ^α, the vector-meson spin density matrix is expressed in terms of a set of nine matrices $\rho^\alpha_{\lambda_V\lambda'_V}$ related to various photon polarization states: transversely polarised photon (α=0,...,3), longitudinally polarised photon (α=4), and terms describing their interference (α=5,...,8) [1]. In case when contributions of transverse and longitudinal photons cannot be separated, the SDMEs are customarily defined as

$$r^{04}_{\lambda_V\lambda'_V} = (\rho^0_{\lambda_V\lambda'_V} + \epsilon R\rho^4_{\lambda_V\lambda'_V})(1+\epsilon R)^{-1},$$

$$r^{\alpha}_{\lambda_V\lambda'_V} = \begin{cases} \rho^\alpha_{\lambda_V\lambda'_V}(1+\epsilon R)^{-1}, \ \alpha = 1,2,3, \\ \sqrt{R}\rho^\alpha_{\lambda_V\lambda'_V}(1+\epsilon R)^{-1}, \ \alpha = 5,6,7,8. \end{cases} \tag{2}$$

The quantity $R = d\sigma_L/d\sigma_T$ is the longitudinal-to-transverse virtual-photon differential cross-section ratio and ϵ is the virtual photon polarisation parameter.

The helicity amplitudes are decomposed into the sum of the amplitudes T for Natural-Parity Exchange (NPE) (P=(-1)^J) and the amplitudes U for Unnatural-Parity Exchange (UPE) (P=-(-1)^J), hence given by $F_{\lambda_V\lambda'_N,\lambda_\gamma\lambda_N} = T_{\lambda_V\lambda'_N,\lambda_\gamma\lambda_N} + U_{\lambda_V\lambda'_N,\lambda_\gamma\lambda_N}$. For an unpolarized target there is no interference between NPE and UPE. Also for an unpolarized target there is no linear contribution of nucleon-helicity-flip amplitudes to SDMEs. Bilinear contributions of nucleon helicity flip amplitudes are neglected as they are suppressed by a factor $(\sqrt{-t'}/M)^2$, where t' is a measure of the transverse momentum of the vector meson with respect to the direction of the virtual photon. So it is convenient to use the following abbreviation $T_{\lambda_V\lambda_\gamma} \equiv T_{\lambda_V\frac{1}{2}\lambda_\gamma\frac{1}{2}}$. This reduces the number of amplitudes to nine: the helicity conserving amplitudes T_{00}, T_{11}, U_{11}, and the helicity non-conserving amplitudes T_{01}, T_{10}, T_{1-1}, U_{01}, U_{10}, U_{1-1}. The dominance of diagonal transitions is called S-Channel Helicity Conservation (SCHC).

For a longitudinally polarized beam and unpolarized target there are 23 SDMEs; 15 which do not depend on beam polarization, and 8 which depend on beam polarization. They can be determined from a fit of the angular distribution of produced ω and pions from its decay.

2. Data processing

The analysis is based on data taken by COMPASS in 2012 with a 160 GeV longitudinally polarised muon beam and an unpolarised liquid hydrogen target. The studied process of exclusive ω meson production is the following:

$$\begin{array}{llll} \mu N \to \mu' N' \omega & & & \\ \quad\quad\quad\ \ \hookrightarrow & \pi^+\pi^-\pi^0 & & \text{BR} \approx 89\ \% \\ & \quad\quad\ \hookrightarrow & \gamma\gamma\ . & \text{BR} \approx 99\ \% \end{array}$$

So an event accepted for further analysis should consist of a track of scattered muon two tracks of hadrons with opposite charges and two neutral clusters.

The exclusivity of the omega production is characterized by the missing energy $E_{\text{miss}} = (M_X^2 - M_p^2)/2M_p$, with the missing mass squared $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-} - p_{\pi^0})^2$, where p, q, p_{π^+}, p_{π^-} and p_{π^0} are the four-momenta of the proton, virtual photon and each of the three ω-decay pions, respectively.

For the exclusive reaction the target nucleon remains intact, which corresponds to $E_{\text{miss}} = 0.0$ GeV. Taking into account the spectrometer resolution the missing energy is required to be in the interval -3.0 GeV $< E_{\text{miss}} <$ 3.0 GeV. In Fig. 1 the missing energy distribution is shown by the red histogram. The blue dashed area coresponds to the E_{miss} distribution for the

Journal of Physics: Conference Series **1435** (2020) 012040 doi:10.1088/1742-6596/1435/1/012040

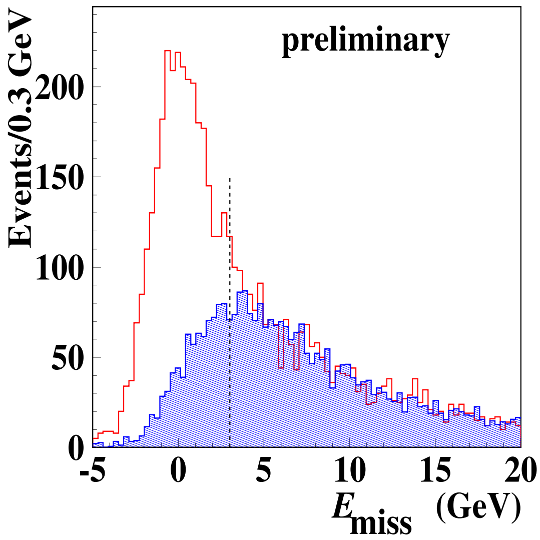

Figure 1. The E_{miss} distribution of data for exclusive ω production (red line) is compared with the SIDIS E_{miss} distribution from LEPTO MC (shaded blue area).

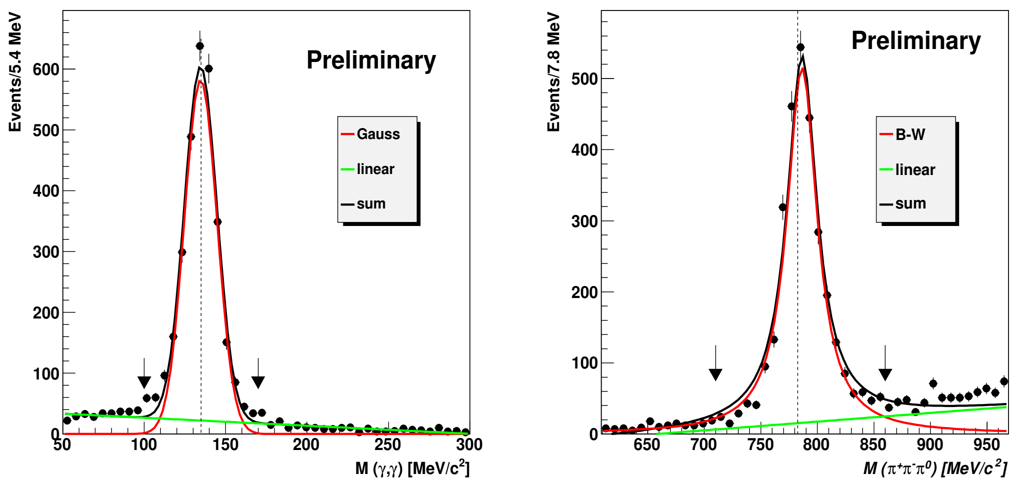

Figure 2. Left panel: Distributions of $\gamma\gamma$ invariant mass (left) fitted by Gaussian function and linear background. Dashed vertical line denotes PDG value. Right panel: Distributions of $\pi^+\pi^-\pi^0$ invariant mass (right) fitted by Breit-Wigner function and linear background. Vertical arrows denote cuts for the invariant mass. Dashed vertical line denotes PDG value.

LEPTO MC simulation reweighted in the same way as in Ref. [?]. The fraction of background for the entire kinematic region is 20 %. In Fig. 2 the distributions of the invariant mass of $\gamma\gamma$ and of $\pi^+\pi^-\pi^0$ are shown. After all cuts we have 3060 exclusive events.

3. Results for the entire kinematic region

The SDMEs for the entire kinematic region have been determined in the COMPASS kinematic region of 1.0 (GeV/c)^2 $< Q^2 <$ 10.0 (GeV/c)^2, 5.0 GeV/c^2 $< W$ 17.0 GeV/c^2 and 0.01 (GeV/c)^2 $< p_T^2 <$ 0.5 (GeV/c)^2, which corresponds to $\langle Q^2 \rangle$ = 2.1 (GeV/c)^2, $\langle W \rangle$ =

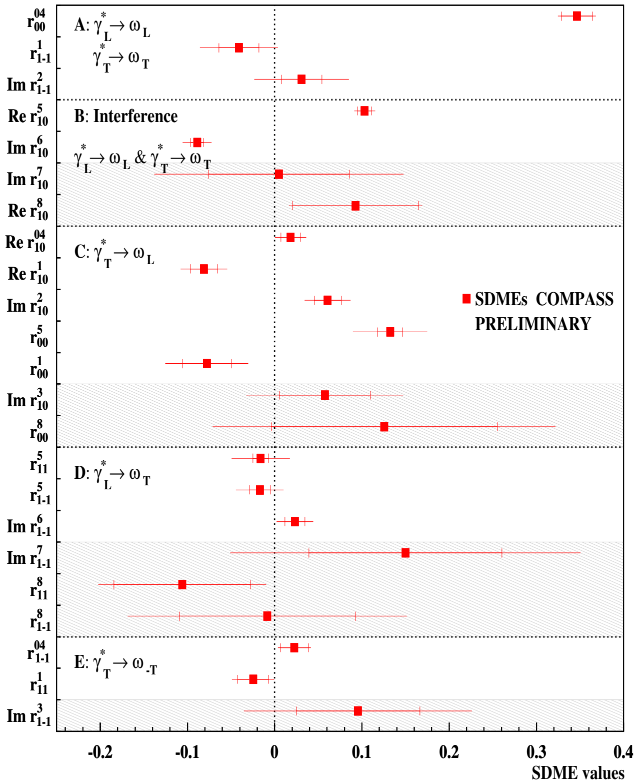

Figure 3. The 23 SDMEs extracted for exclusive ω production in the entire COMPASS kinematic region with $\langle Q^2 \rangle$ = 2.1 (GeV/c)^2, $\langle W \rangle$ = 7.6 GeV/c^2 and$\langle p_T^2 \rangle$ = 0.16 (GeV/c)^2 mean values. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature. SDMEs measured with unpolarized (polarized) beam are displayed in the unshaded (shaded) areas.

7.6 GeV/c^2 and $\langle p_T^2 \rangle = 0.16$ (GeV/c)^2. Here, Q^2 represents the negative-square of the virtual-photon four-momentum, W the invariant mass of the photon-nucleon system and p_T^2 the squared transverse momentum of ω with respect to virtual photon γ^*. The preliminary SDMEs of the ω meson for the integrated data are presented in Fig. 3. The presented SDMEs are divided into five classes corresponding to different helicity transitions. Class A corresponds to the transition of longitudinal virtual photons to longitudinal mesons $\gamma_L^* \to V_L$ and transverse virtual photons to transverse mesons $\gamma_T^* \to V_T$. Class B corresponds to the interference of these two transitions. Class C corresponds to the $\gamma_T^* \to V_L$ transition, class D to the $\gamma_L^* \to V_T$ transition, and class E to the $\gamma_T^* \to V_{-T}$ transition.

In the case of SCHC only the seven SDMEs of class A and class B (r_{00}^{04}, r_{1-1}^1, Im$\{r_{1-1}^2\}$, Re$\{r_{10}^5\}$, Im$\{r_{10}^6\}$, Im$\{r_{10}^7\}$, Re$\{r_{10}^8\}$), are not restricted to be zero, but six of them have to obey the following relations [1]: $r_{1-1}^1 = -\text{Im}\{r_{1-1}^2\}$, $\text{Re}\{r_{10}^5\} = -\text{Im}\{r_{10}^6\}$, $\text{Im}\{r_{10}^7\} = \text{Re}\{r_{10}^8\}$.

For these SDMEs we found: $r_{1-1}^1 + \text{Im}\{r_{1-1}^2\} = -0.01 \pm 0.038 \pm 0.047$,
$\text{Re}\{r_{10}^5\} + \text{Im}\{r_{10}^6\} = 0.044 \pm 0.011 \pm 0.013$, $\text{Im}\{r_{10}^7\} - \text{Re}\{r_{10}^8\} = -0.088 \pm 0.110 \pm 0.196$.

These relations for classes A and B fulfill the requirements of SCHC. All other SDMEs are required by SCHC to be zero. However, from Fig. 3 one can see that few SDMEs of class C, like Re r^5_{00}, Rer^1_{10}, Imr^2_{10}, are inconsistent with the hypothesis of SCHC. In the GK model [3] these SDMEs are related to transversity GPDs. The data presented here may help to constrain the model.

4. Contribution of UPE processess in exclusive ω production

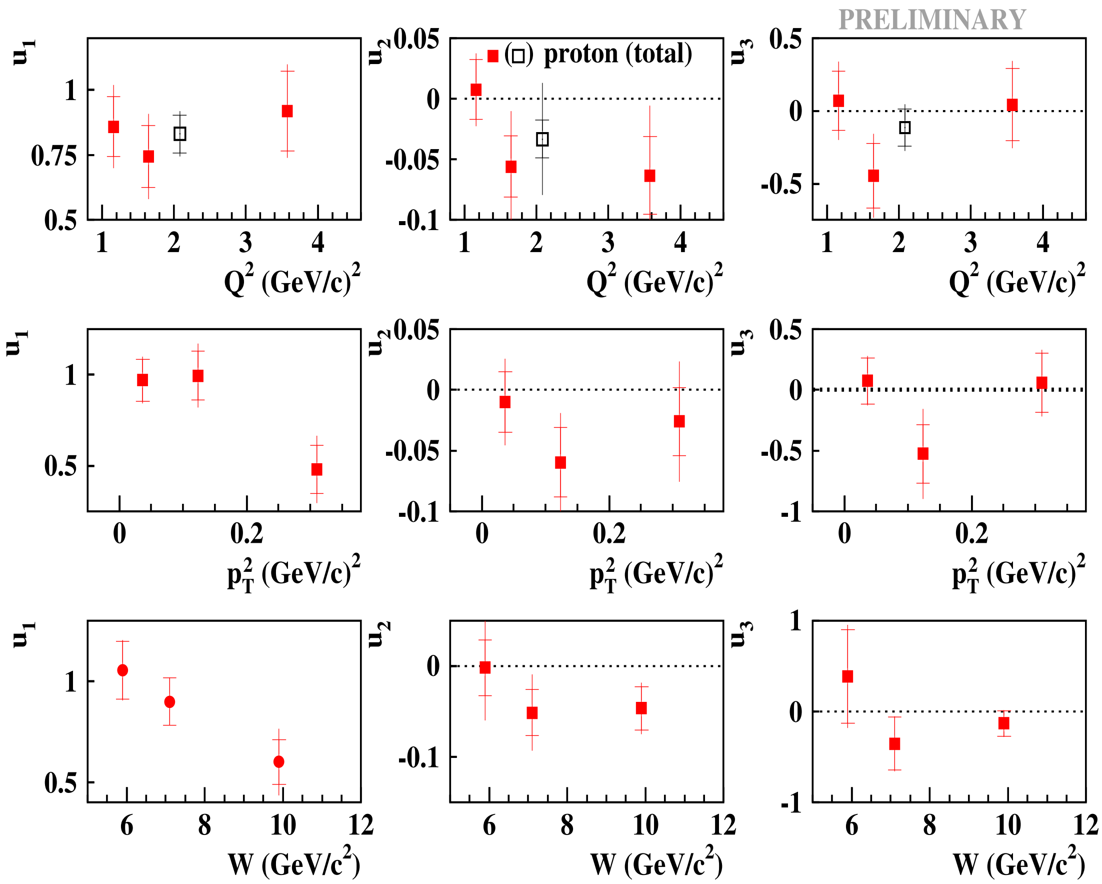

Figure 4. Q^2, p^2_{T} and W dependences of u_1, u_2, u_3. The open symbols represent the values over entire kinematic region. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature.

The existence of UPE contribution in exclusive ω production can be tested by examining linear combination of SDMEs such as

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1}. \tag{3}$$

The quantity u_1 can be expressed in terms of helicity amplitudes as

$$u_1 = \widetilde{\sum} \frac{4\epsilon |U_{10}|^2 + 2|U_{11} + U_{-11}|^2}{\mathcal{N}}. \tag{4}$$

As one can see the numerator depends only on UPE amplitudes. Therefore a u_1 with value different from zero would indicate a contribution of UPE processes. For the entire kinematic

Journal of Physics: Conference Series **1435** (2020) 012040 doi:10.1088/1742-6596/1435/1/012040

region of COMPASS u_1 is equal to $0.830 \pm 0.073 \pm 0.049$, which is a signal of large UPE contribution. An additional information one gets from the following combinations

$$u_2 = r^5_{11} + r^5_{1-1}, \tag{5}$$

$$u_3 = r^8_{11} + r^8_{1-1}. \tag{6}$$

When expressed in terms of helicity amplitudes, the quantities u_2 and u_3 combine to

$$u_2 + iu_3 = \sqrt{2}\widetilde{\sum}\frac{(U_{11} + U_{-11})U^*_{10}}{\mathcal{N}}. \tag{7}$$

For COMPASS we get $u_2 = -0.033 \pm 0.016 \pm 0.043$ and $u_3 = -0.114 \pm 0.126 \pm 0.099$

In Fig. 4 the dependence of quantities u_1, u_2, u_3 on Q^2, p^2_{T} and W is presented. As one can see u_1 decreases with increasing W and p^2_{T}, which indicate that UPE contributions becomes smaller, while u_2, u_3 fluctuate around zero.

5. Longitudinal-to-transverse cross section ratio

Usually, the longitudinal-to-transverse virtual-photon differential cross section ratio

$$R = \frac{d\sigma_L(\gamma^*_L \to V)}{d\sigma_T(\gamma^*_T \to V)}$$

is experimentally determined using the measured SDME r^{04}_{00} and the approximate relation [4].

$$R \approx \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}. \tag{8}$$

This relation is exact in the case of SCHC. The obtained ratio R is equal to $0.553 \pm 0.044 \pm 0.020$. The kinematic dependences of the longitudinal to transverse virtual-photon differential cross-section ratio are shown in Fig. 5. It is seen that the ratio increases as Q^2 and p^2_{T} increase.

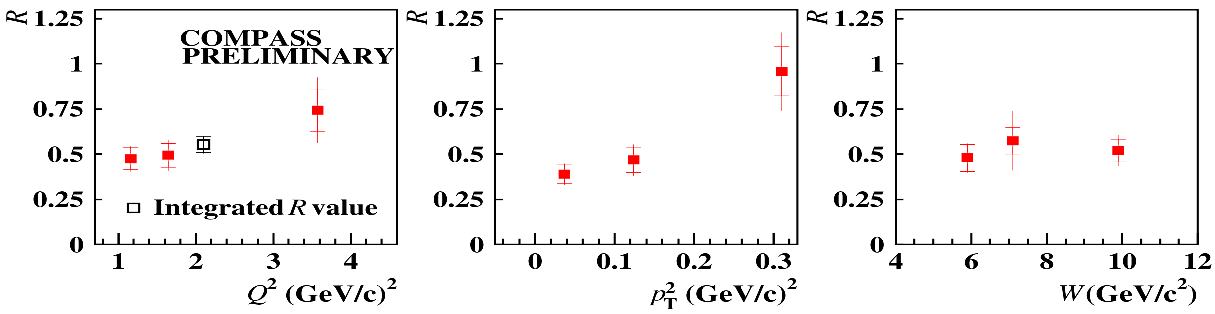

Figure 5. Q^2, p^2_{T} and W dependences of the longitudinal-to-transverse cross section ratio R. The open symbol represents the value over entire kinematic region. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature.

References

[1] K Schilling K and Wolf G 1973 How to analyze vector mesonproduction in inelastic scattering *Nucl. Phys.* C **61** 361
[2] HERMES Collaboration 2009 Spin Density Matrix Elements in Exclusive ρ^0 Electroproduction on ^{1}H and ^{2}H Targets at 27.5 GeV Beam Energy *Eur.Phys. J.* C **62** 659
[3] Goloskokov S and Kroll P 2009 The target asymmetry in hard vector-meson electroproduction and parton angula momenta *Eur. Phys. J.* C **59** 809
[4] HERMES Collaboration 2014 Spin Density Matrix Elements in Exclusive ω Electroproduction on ^{1}H and ^{2}H Targets at 27.6 GeV Beam Energy *Eur. Phys. J. C* **74** 3110 Erratum: 2016 *Eur. Phys.J.* C **76** 162