Spin structure of exclusive ω muoproduction at COMPASS

B. Marianski

National Centre for Nuclear Research Warsaw, Poland

for COMPASS Collaboration

DSPIN-19 - XVIII Workshop on High Energy Spin Physics

Dubna, Russia September 02 - 06, 2019

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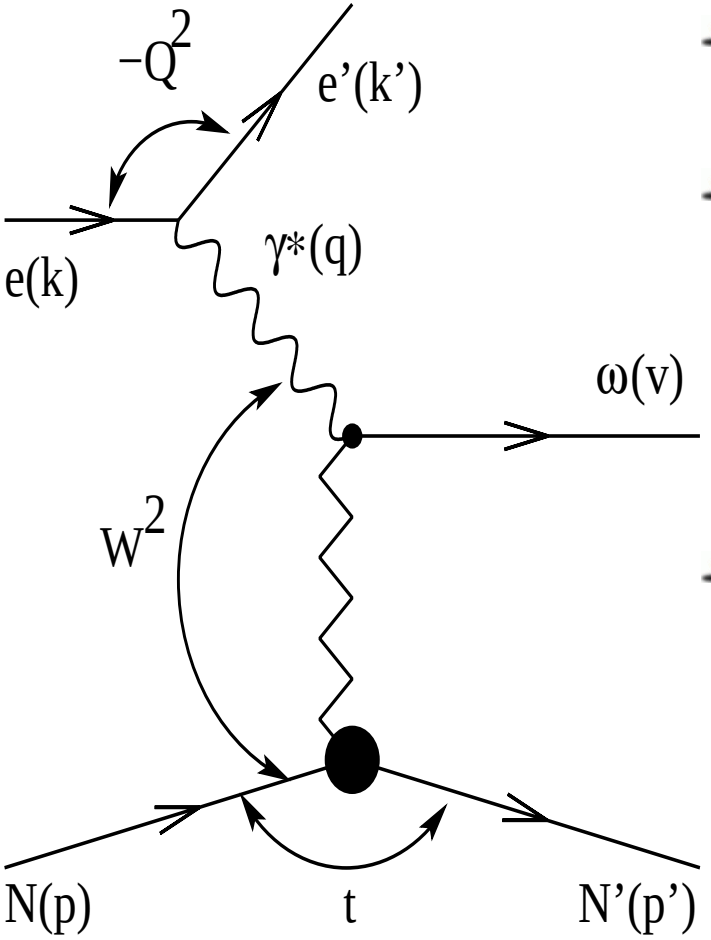
Spin Density Matrices in reaction

$$\mu + N \to \mu' + \omega + N$$



Exclusive electroproduction of vector meson in inelastic scattering of leptons provides information both on reaction mechanism and nucleon structure.

- Photon spin-density matrix $\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma}$ $\mu \to \mu' + \gamma^*$ (calculable in QED). U - unpolarized, L - polarized beam
- Vector-meson spin-density matrix $\rho_{\lambda_V \lambda'_V}$ is expressed by helicity amplitudes $F_{\lambda_V \lambda'_N;\lambda_\gamma \lambda_N}(W, Q^2, t')$. In CM frame of $\gamma^* N$ is given by the von Neumann formula:

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

- $\varrho^{L+U}_{\lambda_\gamma \lambda'_\gamma}$ decomposes into the set of nine hermitian matrices$(3\times3)\Sigma^\alpha$ (α=0$\div$3 - transv.,4 - long. 5$\div$8 - interf.), $\rho_{\lambda_V \lambda'_V} \to \rho^\alpha_{\lambda_V \lambda'_V}$. When we can not separate transverse and longitudinal photons, Spin Density Matrix Elements (SDMEs) are defined:

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

$$r^\alpha_{\lambda_V \lambda'_V} = \begin{cases} \frac{\rho^\alpha_{\lambda_V \lambda'_V}}{(1+\epsilon R)}, & \alpha = 1,2,3, \\ \frac{\sqrt{R}\rho^\alpha_{\lambda_V \lambda'_V}}{(1+\epsilon R)}, & \alpha = 5,6,7,8. \end{cases} \qquad R = \sigma_L/\sigma_T$$

General properities of helicity amplitudes

- $F_{\lambda_V \lambda'_N, \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N}$
  T - natural-parity exchange (NPE)($P = (-1)^J$)
  U - unnatural - parity exchange (UPE)($P = -(-1)^J$)

- On unpolarized target nucleon-helicity-flip amplitudes are suppresed.
  $T_{\lambda_V \lambda_\gamma} = T_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}}$, $U_{\lambda_V \lambda_\gamma} = U_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}}$
  Helicity concerving - T_{00}, T_{11}, U_{11}, helicity non concerving - $T_{01}, T_{10}, T_{1-1}, U_{01}, U_{10}, U_{1-1}$
  The dominance of diagonal transitions is called s-channel helicity concervation (SCHC).

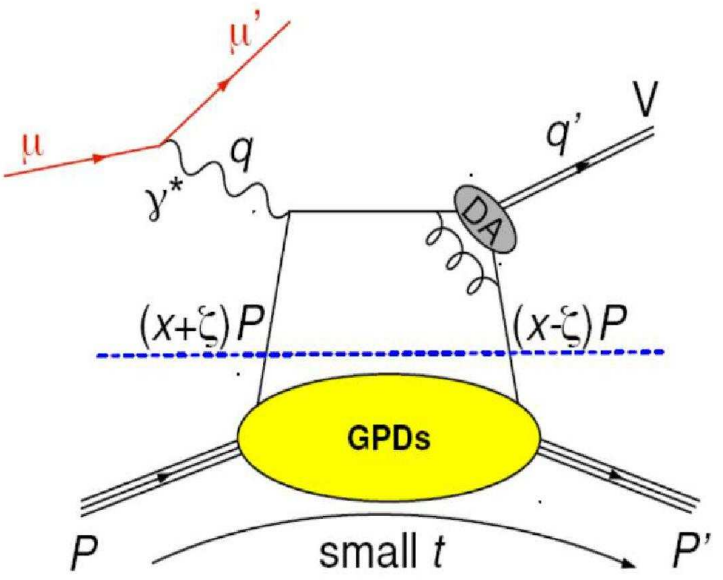
- In Regge phenomenlogy : NPE ($J^P = 0^+,\ 1^-, ...$) amplitudes $T_{\lambda_V \lambda_\gamma}$ (Two-gluon exchange = pomeron, ρ, ω,a_2,...reggeons = $q\bar{q}$ exchange).
  UPE($J^P = 0^-,\ 1^+, ...$) amplitudes $U_{\lambda_V \lambda_\gamma}$ (π, a_1, b_1,...reggeons = $q\bar{q}$ exchange)

Hard exclusive vector meson production and GPDs

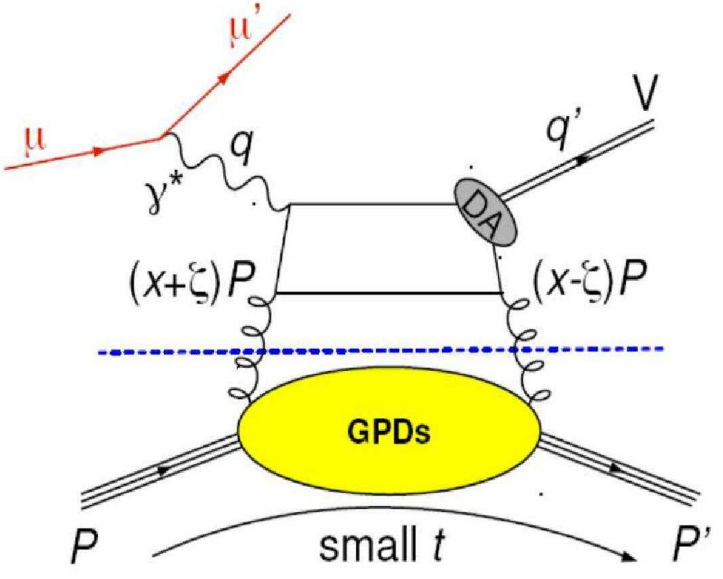
- Provide constraints on Generalized Parton Distribution (GPD) models.
- The procces amplitudes is a convolution of the lepton-quark hard-scattering amplitude with soft part which contains GPDs and vector meson distribution amplitude (DA), non-pertubative term.
- factorization is proven only for σ_L
  σ_T suppressed by $1/Q^2$.
- Chiral-even GPDs (helicity of parton unchanged)
  $H^{q(g)}(x, \xi, t)$, $E^{q(g)}(x, \xi, t)$
  $\tilde{H}^{q(g)}(x, \xi, t)$, $\tilde{E}^{q(g)}(x, \xi, t)$
- Chiral-odd GPDs (helicity of parton changed)
  $H_T^{q(g)}(x, \xi, t)$, $E_T^{q(g)}(x, \xi, t)$
  $\tilde{H}_T^{q(g)}(x, \xi, t)$, $\tilde{E}_T^{q(g)}(x, \xi, t)$
- Ji's Sum Rules

$$\frac{1}{2}\lim_{t\to 0}\int x[H^{q(g)}(x,\xi,t)+E^{q(g)}(x,\xi,t)]dx = \langle J^{q(g)}\rangle$$

quark contribution

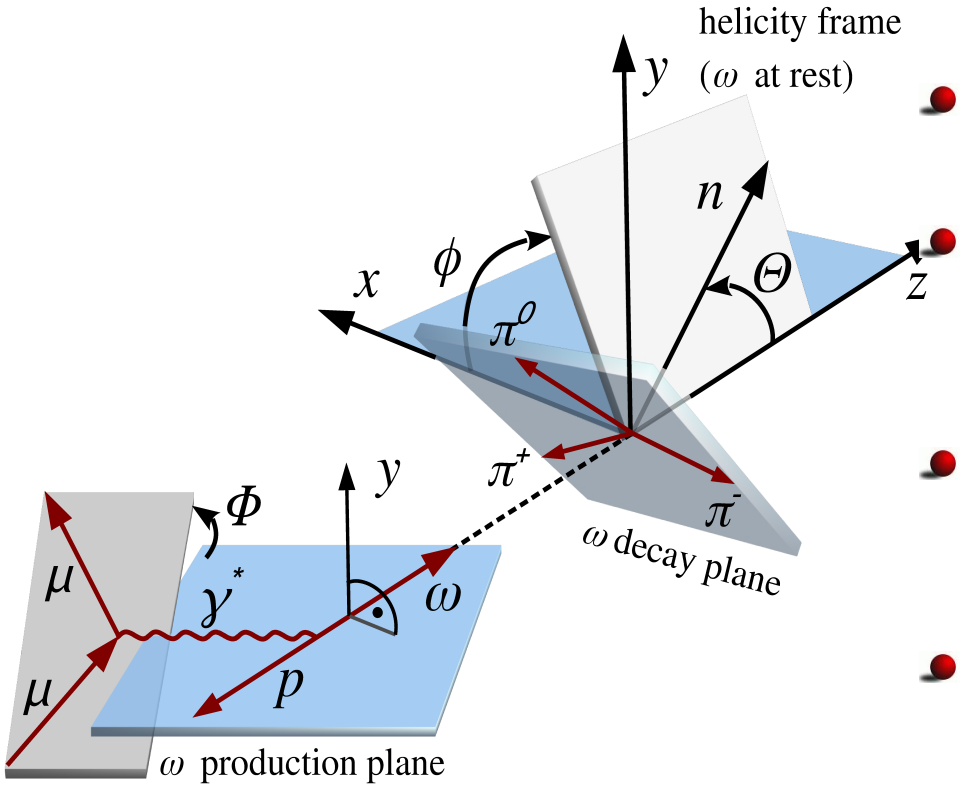


gluon contribution



Angular distribution in reaction

$$\mu + p \rightarrow \mu' + p' + \omega \rightarrow (\pi^+\pi^-\pi^0(\rightarrow 2\gamma))$$



- Experimental access to SDMEs via angular distribution of decaying particles.
- Angular distribution $\mathcal{W}(r^{\alpha}_{\lambda_V \lambda'_V}, \Phi, \phi, \cos\Theta)$ depends linearly on $r^{\alpha}_{\lambda_V \lambda'_V}$ and beam polariztion P_b.
- For longitudinally polarized beam and unpolarized target there are 23 SDMEs,(15 unpolarized and 8 polarized).
- The SDMEs are determined from the fit of angular distribution of pions from decay $\omega \Rightarrow \pi^+\pi^-\pi^0$, by angular distribution $\mathcal{W}(r^{\alpha}_{\lambda_V \lambda'_V}, \Phi, \phi, \cos\Theta)$, with Maximum Likelihood method.

COMPASS Spectrometer

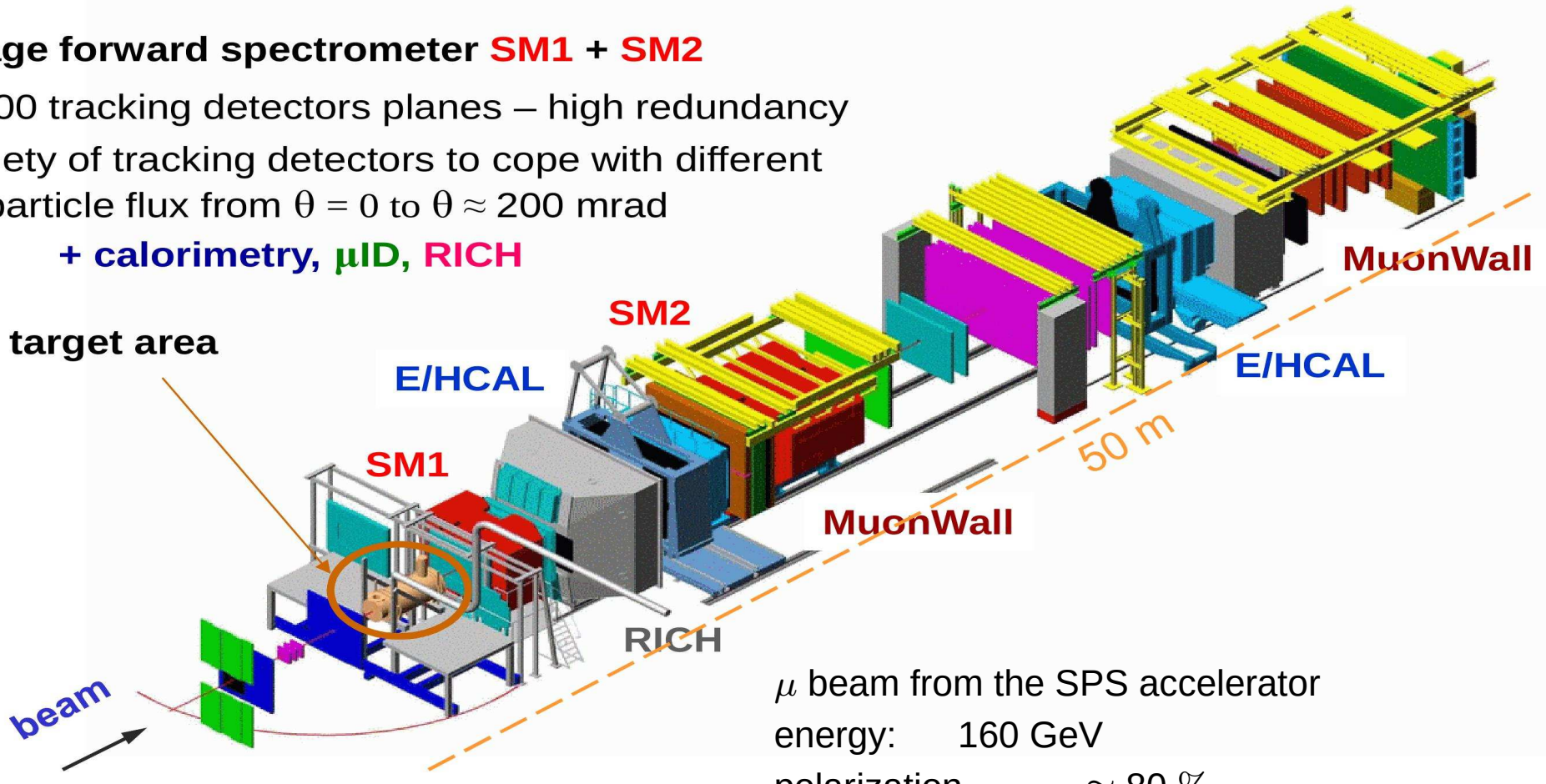
two-stage forward spectrometer SM1 + SM2

≈ 300 tracking detectors planes – high redundancy

variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

+ calorimetry, μID, RICH

flexible target area

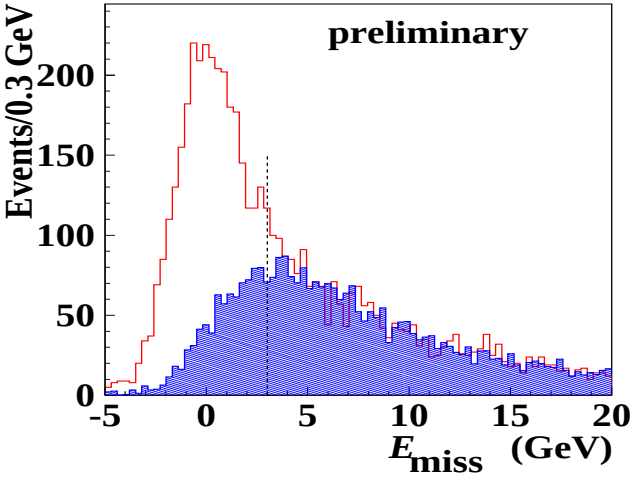


μ beam from the SPS accelerator

energy: 160 GeV

polarization $\approx 80\ \%$

Exclusive ω-meson production at COMPASS



Distribution of missing energy.

Shape of semi-inclusive background

full MC chain using LEPTO.

The estimated SIDIS background is subtracted

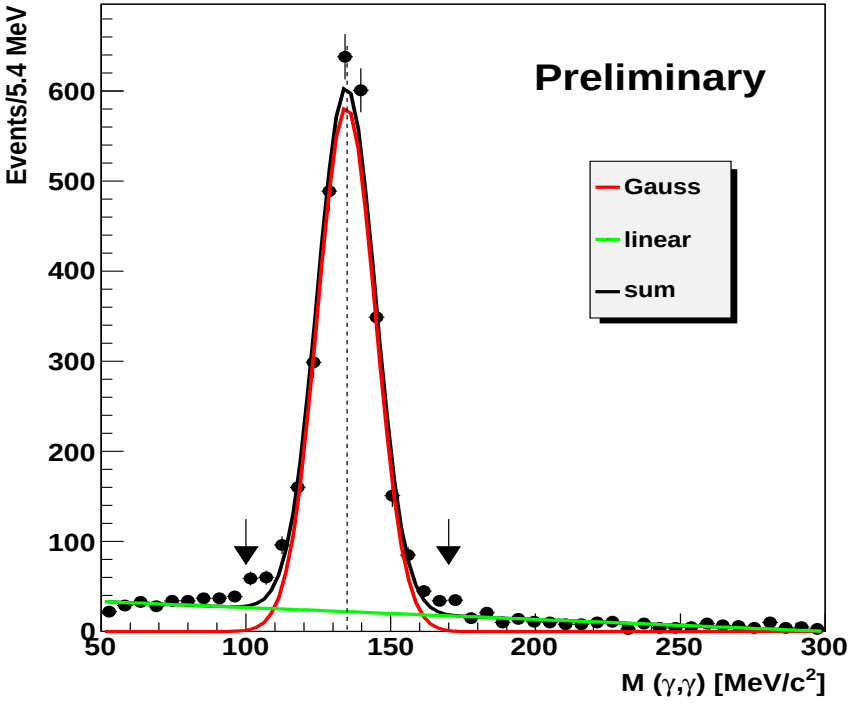
- Upolarized Target (H_2), 2012 data

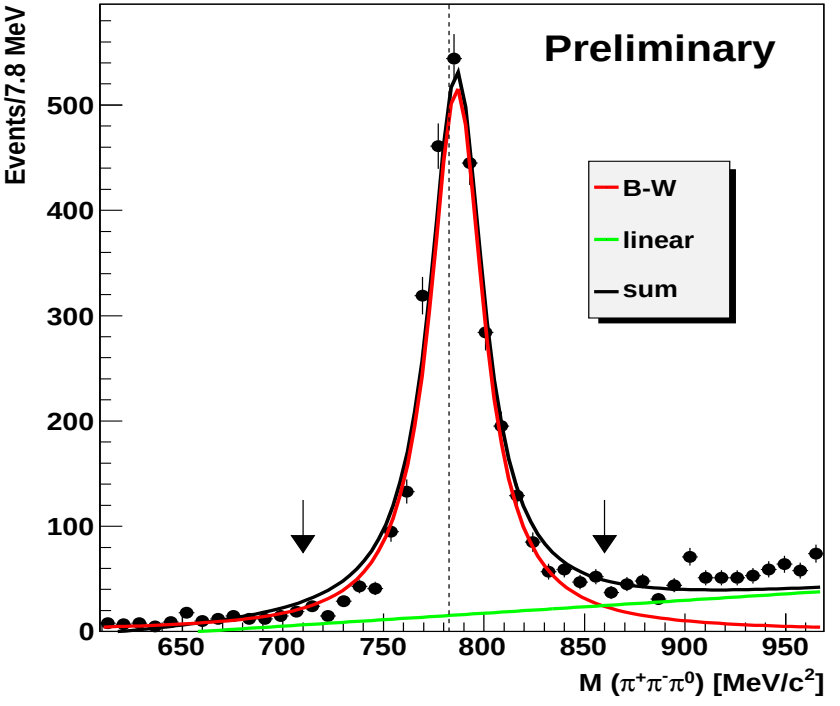
$$\mu N \to \mu' N' \omega$$
$$\hookrightarrow \pi^+\pi^-\pi^0 \qquad \mathrm{BR} \approx 89\%$$
$$\hookrightarrow \gamma\gamma \ . \qquad \mathrm{BR} \approx 99\%$$

- Event contains three outgoing tracks (μ', h^+, h^-), only two ECAL clusters time-correlated with beam , checked that they are not caused by charged particles.
- $E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - p_{\pi+} - p_{\pi-} - p_{\pi^0})^2$ and M_X being missing mass, p, q, $p_{\pi+}$, $p_{\pi-}$ p_{π^0} are 4-momenta of proton target, γ^* and pions.
- Exclusive process E_{miss} = 0
- -3.0 GeV < E_{miss} < 3.0 GeV
- 0.01 < P_T^2 < 0.5 GeV^2, $\langle P_T^2 \rangle = 0.16$ (GeV/c)^2 Squared transverse momentum of ω w.r.t γ^* to remove events with poorly determined azimuthal angle of the meson, to suppress non-exclusive

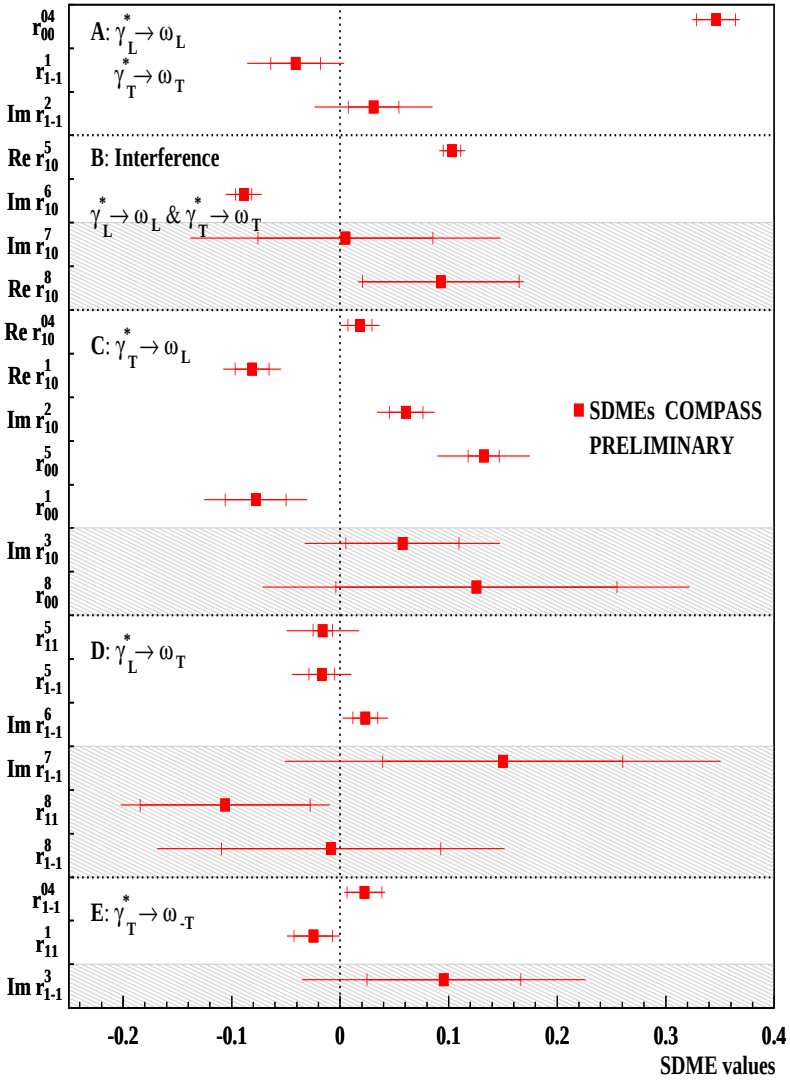
Exclusive ω-meson production at COMPASS

- $Q^2 = -q^2 = -(k - k')^2 = 1.0 \div 10.$ GeV^2, $\langle Q^2 \rangle = 2.1$ GeV^2
- $W = \sqrt{(q+p)^2}$ > 5.0 GeV, $\langle W \rangle = 7.6$ GeV/c^2
- 0.1< $M_{\gamma\gamma}$ < 0.17 GeV/c^2
- 0.71< $M_{\pi^+\pi^-\pi^0}$ < 0.87 GeV/c^2
- Number of ω events : 3060





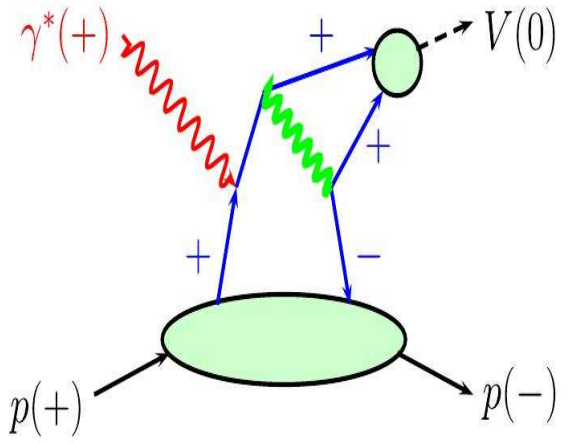
SDMEs of exclusive ω production for the integrated data



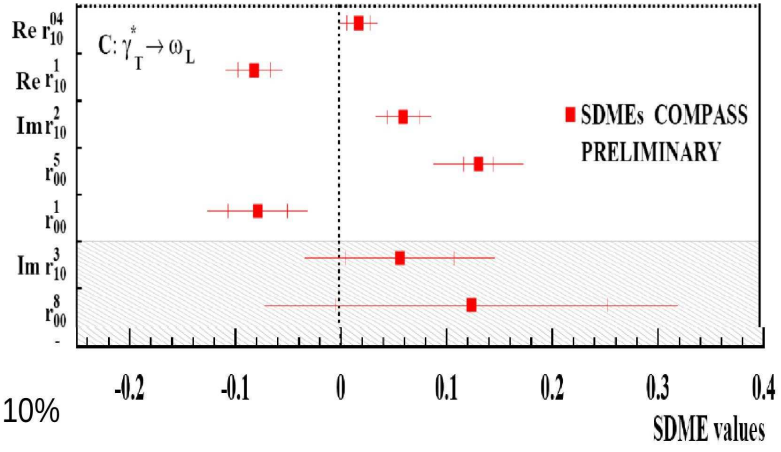
- A, $\gamma^*_L \to \omega_L$ and $\gamma^*_T \to \omega_T$
  B, Interference: $\gamma^*_L \to \omega_L$,$\gamma^*_T \to \omega_T$
  C, $\gamma^*_T \to \omega_L$
  D, $\gamma^*_L \to \omega_T$
  E, $\gamma^*_T \to \omega_{-T}$
- Test of s-channel conservation (SCHC)
  If SCHC obeyed ($\lambda_{\gamma^*} = \lambda_V$)
  $r^1_{1-1} = -Im\{r^2_{1-1}\}$
  $Re\ \{r^5_{10}\} = -Im\{r^6_{10}\}$
  $Im\{r^7_{10}\} = Re\{r^8_{10}\}$
  $r^1_{1-1} + Imr^2_{1-1} = -0.01 \pm 0.038 \pm 0.047,$
  $Rer^5_{10} + Imr^6_{10} = 0.014 \pm 0.011 \pm 0.013,$
  $Imr^7_{10} - Rer^8_{10} = -0.088 \pm 0.110 \pm 0.196,$
- all SDMEs of classes C, D, E should be 0.
  Obeyed for D,E not for C.
- SDMEs of class C violate the Hypothesis of SCHC.

Transitions of class C, $\gamma_T^* \to \omega_L$

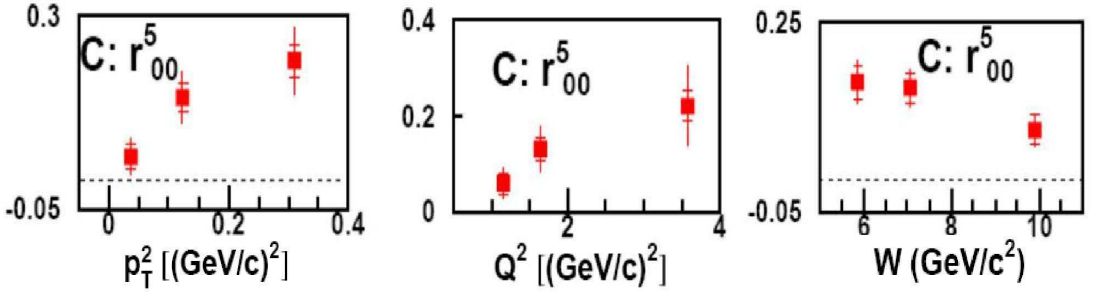
example graph for amplitude $F_{0-,++}$



- possible GPD interpretation **Goloskokov Kroll EPJC 74 (2014)2725**
  contribution of amplitudes depending on transversity GPDs H_T, $\bar{E}_T = 2\tilde{H}_T + E_T$
  - $r^1_{00} \propto |\langle \bar{E}_T \rangle^*_{LT} \langle \bar{E}_T \rangle_{LT}|$
    $\langle \bar{E}_T \rangle_{LT}$ - convolution of GPD $\bar{E}_T$ with $\gamma^*_T \to V_L$ amplitude
  - $r^5_{00} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$

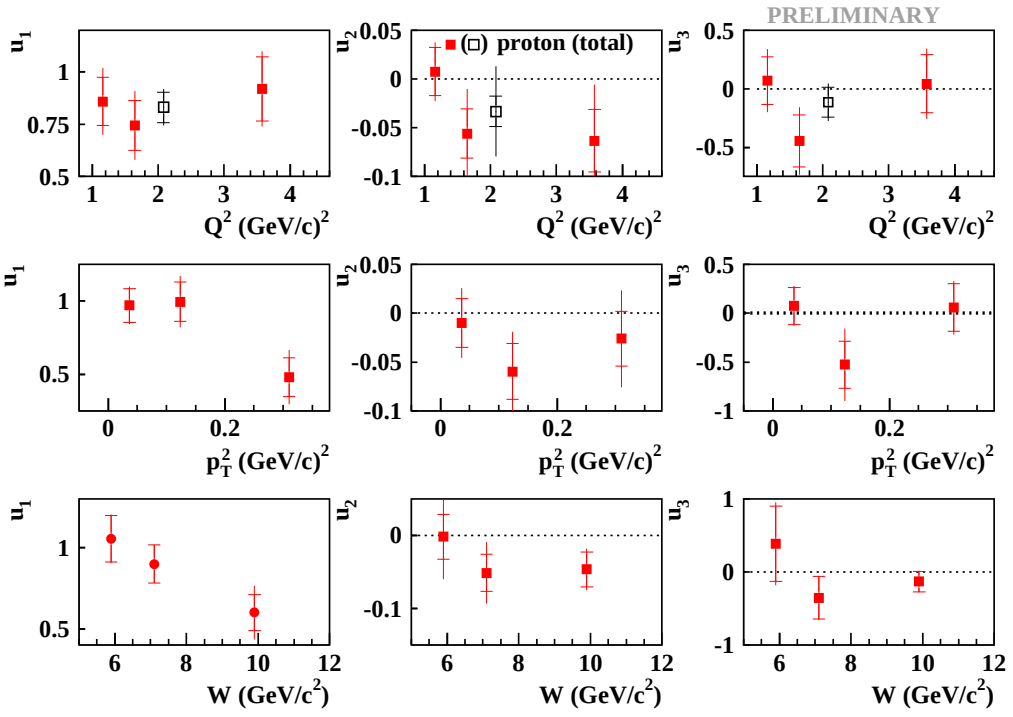


preliminary



$\mathrm{Re}r^{04}_{10} \approx -\mathrm{Re}r^1_{10} \approx \mathrm{Im}r^2_{10} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle^N_{TT} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle^N_{TT}]$

Test of Unnatural-Parity Exchange for ω meson



Signal of UPE in the SDMEs

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1},$$

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

u1 > 0 UPE contribution

COMPASS u_1 = 0.83 ± 0.07±0.05,

An additional information one gets from the following combinations

$$u_2 = r^{5}_{11} + r^{5}_{1-1},\ u_3 = r^{8}_{11} + r^{8}_{1-1}.$$

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

UPE contribution is large at COMPASS

Dependence of u1, u2, u3 on Q^2, P_T^2 and W.

Empty symbols denote results for the entire kinematic region.

Analysis of SDMEs of class A $\mathrm{Im}\{r^2_{1-1}\}$ and r^1_{1-1}

$$\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1} = \frac{1}{\mathcal{N}}(-|T_{1\,\frac{1}{2}\,1\,\frac{1}{2}}|^2 - |T_{1-\frac{1}{2}\,1\,\frac{1}{2}}|^2 + |U_{1\,\frac{1}{2}\,1\,\frac{1}{2}}|^2 + |U_{1-\frac{1}{2}\,1\,\frac{1}{2}}|^2)$$

$T_{1-\frac{1}{2}\,1\,\frac{1}{2}} \approx U_{1-\frac{1}{2}\,1\,\frac{1}{2}} \approx 0$ at small value of t' (P_T^2) and unpolarized target

$$\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1} = \frac{1}{\mathcal{N}}(-|T_{1\,\frac{1}{2}\,1\,\frac{1}{2}}|^2 + |U_{1\,\frac{1}{2}\,1\,\frac{1}{2}}|^2) = \frac{1}{\mathcal{N}}(-|T_{11}|^2 + |U_{11}|^2)$$

COMPASS $\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1}$ = 0.07$\pm$0.07 $\pm$0.06

$|U_{11}|^2 \approx |T_{11}|^2$

W dependence of selected of SDMEs

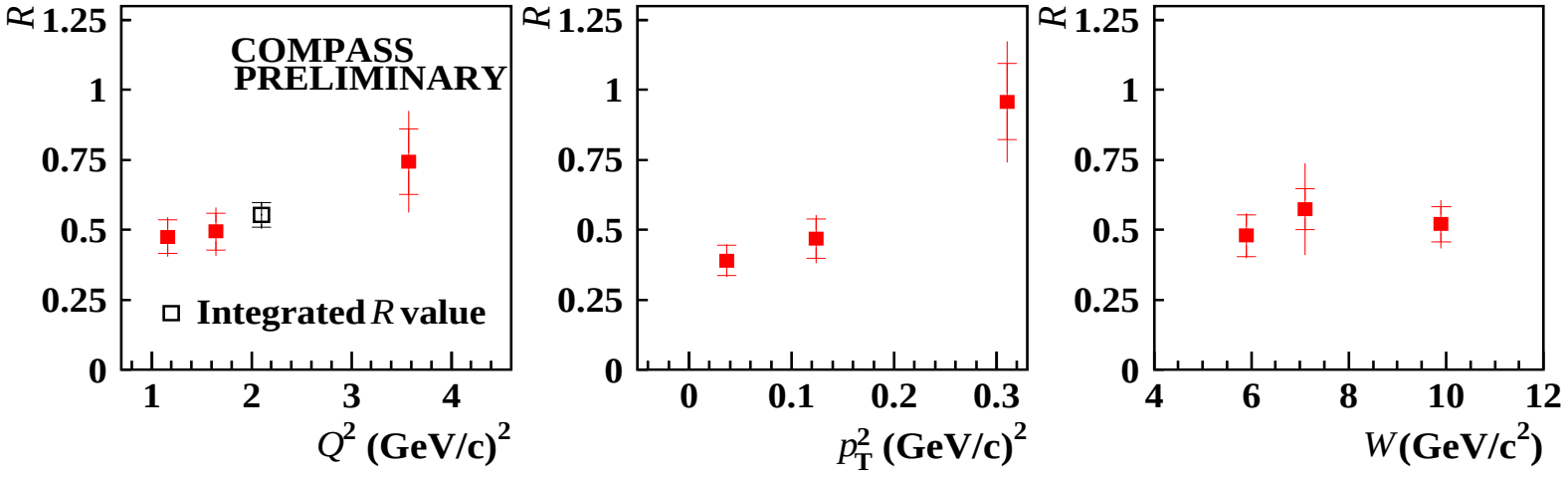
Values of SDMEs r^1_{1-1} and Imr^2_{1-1} as a function of $\langle W \rangle$

$\langle W \rangle$	5.9 GeV	7.1 GeV	9.9 GeV
r^1_{1-1}	-0.134±0.043±0.003	-0.044±0.036±0.033	0.052±0.038±0.047
Imr^2_{1-1}	0.139±0.044±0.046	0.037±0.036±0.024	-0.098±0.038±0.033
Im$r^2_{1-1} - r^1_{1-1}$	0.273±0.061±0.046	0.081±0.050±0.041	-0.151±0.053±0.057

- at $\langle W \rangle$ = 5.9 GeV, we have
  Im$r^2_{1-1} - r^1_{1-1}$ > 0 $\Rightarrow U_{11} > T_{11}$
- at $\langle W \rangle$= 7.1 SDMEs are close to zero and Im$r^2_{1-1} - r^1_{1-1} \approx 0 \Rightarrow U_{11} \approx T_{11}$
- at $\langle W \rangle$ = 9.9 SDMEs reverse the sign and Im$r^2_{1-1} - r^1_{1-1} \leq 0 \Rightarrow U_{11} \leq T_{11}$
  These results indicate that at Compass kinemtic $U_{11} \approx T_{11}$ and gets smaller then T_{11} at large W .
  Contribution of UPE is nevertheless large because U_{11} is comparable with T_{11}.

Longitudinal to Transverse cross section ratio for ω meson

$$R = \frac{d\sigma_L(\gamma_L^* \to V)}{d\sigma_T(\gamma_T^* \to V)} \qquad R \approx \frac{1}{\epsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}}$$



Dependence of R on Q^2 and P_T^2. Empty symbol denote values for entire kinematic bin.

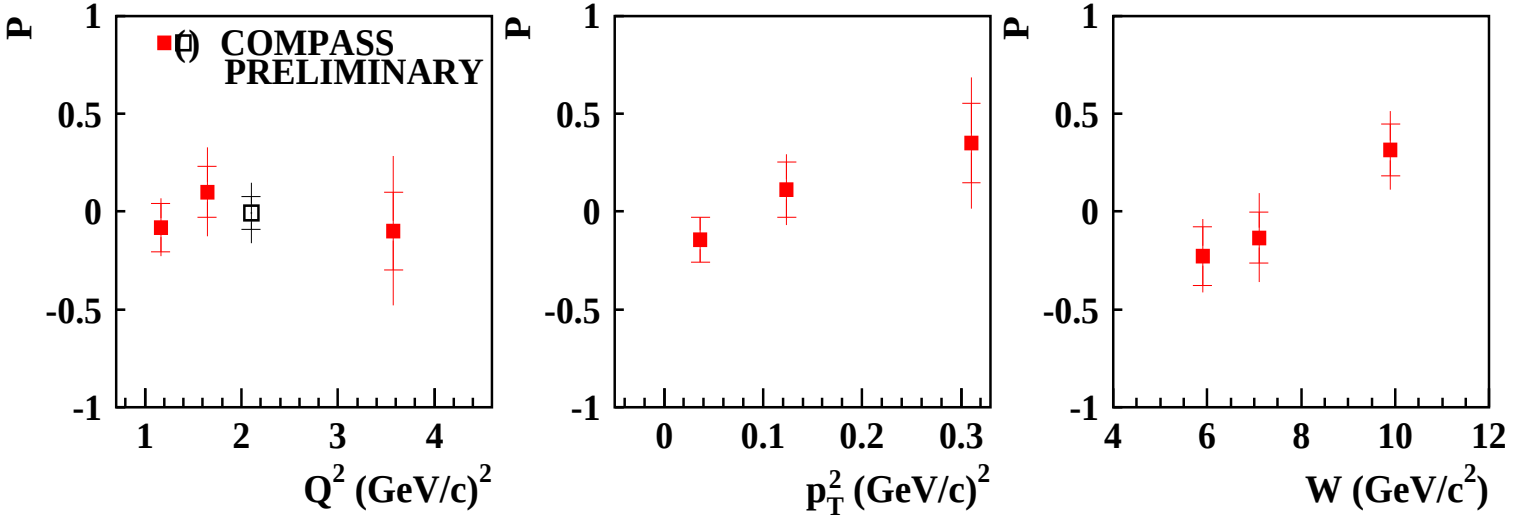
The UPE-to-NPE asymmetry of the transverse cross section

$$P = \frac{d\sigma_T^N - d\sigma_T^U}{d\sigma_T^N + d\sigma_T^U} \equiv \frac{d\sigma_T^N/d\sigma_T^U - 1}{d\sigma_T^N/d\sigma_T^U + 1}$$
$$= (1 + \epsilon R)(2r^1_{1-1} - r^1_{00}), \quad (1)$$

where σ_T^N and σ_T^U denote the parts of the transverse cross section due to NPE and UPE.

$$P \approx \frac{2r^1_{1-1} - r^1_{00}}{1 - r^{04}_{00}}. \quad (2)$$

The value of P obtained in the entire kinematic region is equal to -0.067 $\pm$ 0.040 $\pm$ 0.107



Dependence of P on Q^2 and P_T^2. Empty symbol denote values for entire kinematic bin.

Summary

- The 23 SDMEs are extracted for muoproduction of ω meson on proton at COMPASS.
- They are presented grouped into five classes according to the helicity transition.
- The Hypothesis of SCHC in ω meson production is violated. Contribution of $\gamma^*_T \to \omega_L$ transition gives access to transversity GPDs.
- Results indicate that amplitude U_{11} is greater than T_{11} at small values of W as W increases, becomes equal to T_{11} and gets smaller than T_{11} at large W.
- Clearly seen decrease of UPE with W.
- The UPE contribution is still large for ω meson production.
- Longitudinal to Transverse cross section ratio for ω meson is determined.
- The UPE-to-NPE asymmetry of the transverse cross section is determined.

Dependence of SDMEs on W and P_T^2

Left plot: Dependence of SDMEs on W, Right plot: Dependence of SDMEs on P_T^2