Spin Density Matrix Elements in hard exclusive ω meson muoproduction at COMPASS

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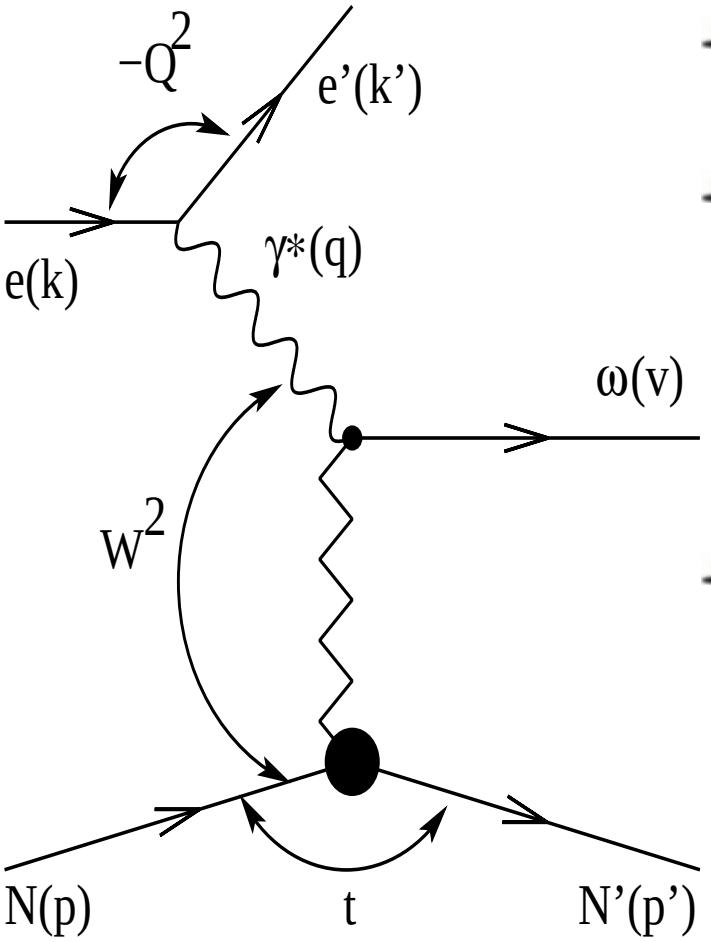
Spin Density Matrices in reaction

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



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$\times$3)Σ^α (α=0$\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).

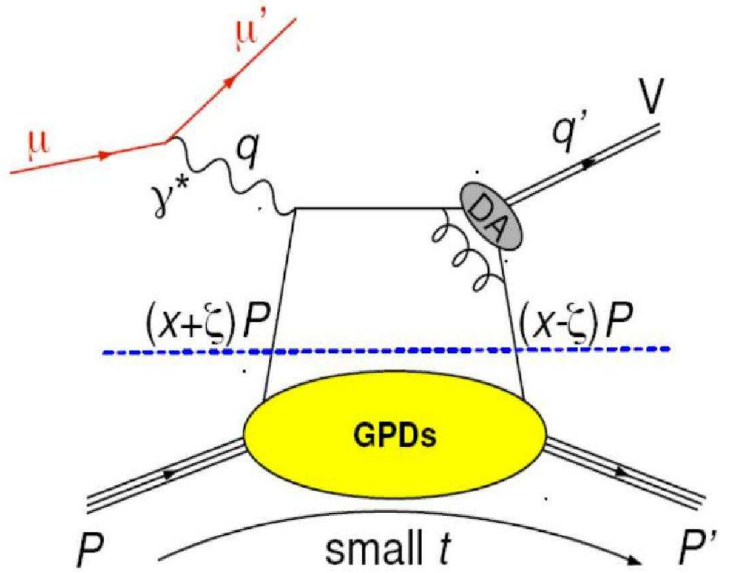
- In Regge phenomenlogy : NPE ($J^P = 0^+,\ 1^-, ...$) amplitudes $T_{\lambda_V \lambda_\gamma}$ (Two-gluon exchange = pomeron, ρ, ω,a_2,...reggeons = $q\bar{q}$ exchange).
  UPE($J^P = 0^-,\ 1^+, ...$) amplitudes $U_{\lambda_V \lambda_\gamma}$ (π, a_1, b_1,...reggeons = $q\bar{q}$ exchange)

Hard exclusive vector meson production and GPDs

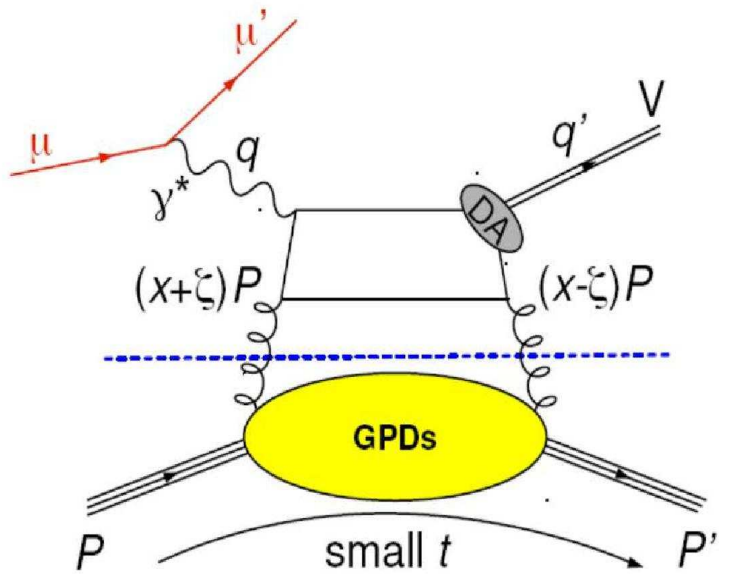
- Provide constraints on Generalized Parton Distribution (GPD) models.
- The procces amplitudes is a convolution of the lepton-quark hard-scattering amplitude with soft part which contains GPDs and vector meson distribution amplitude (DA), non-pertubative term.
- factorization is proven only for σ_L
  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

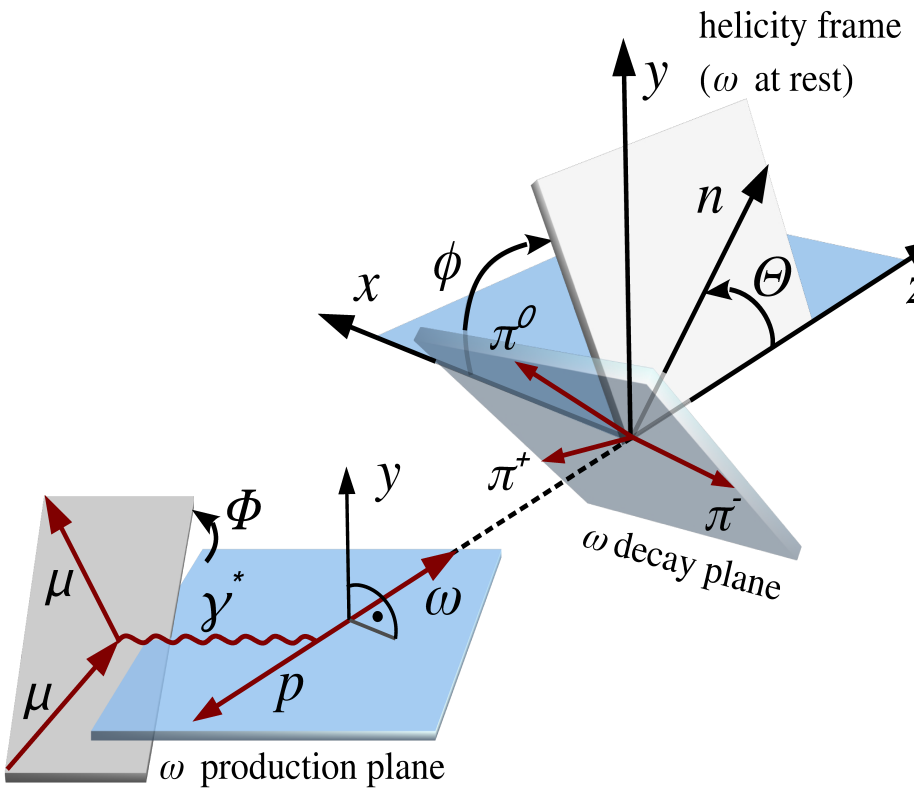


gluon contribution



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

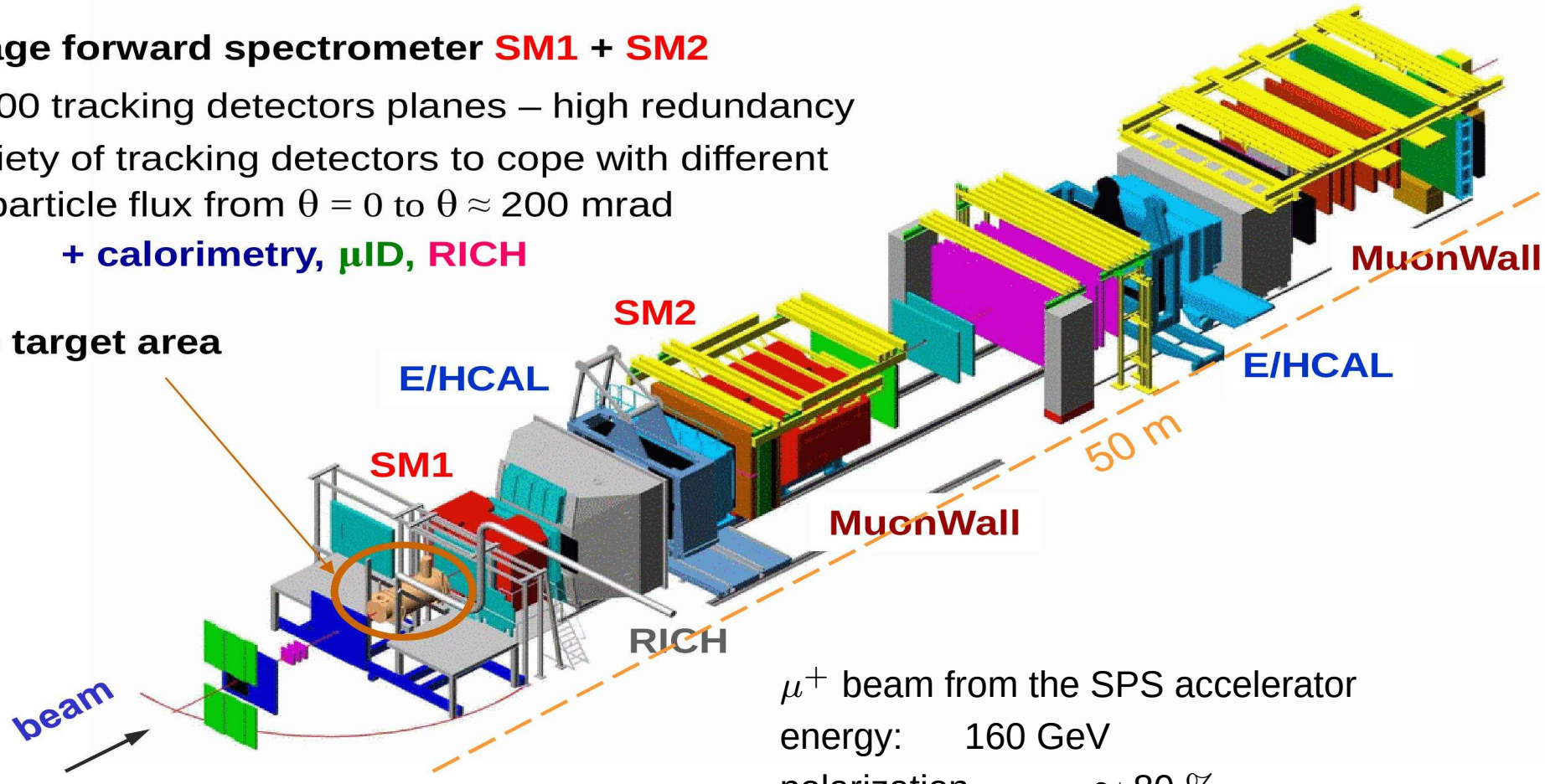
two-stage forward spectrometer SM1 + SM2

≈ 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

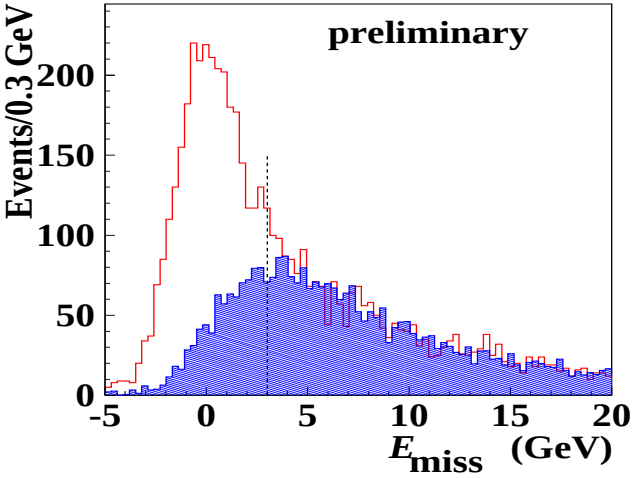


μ^+ beam from the SPS accelerator

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.

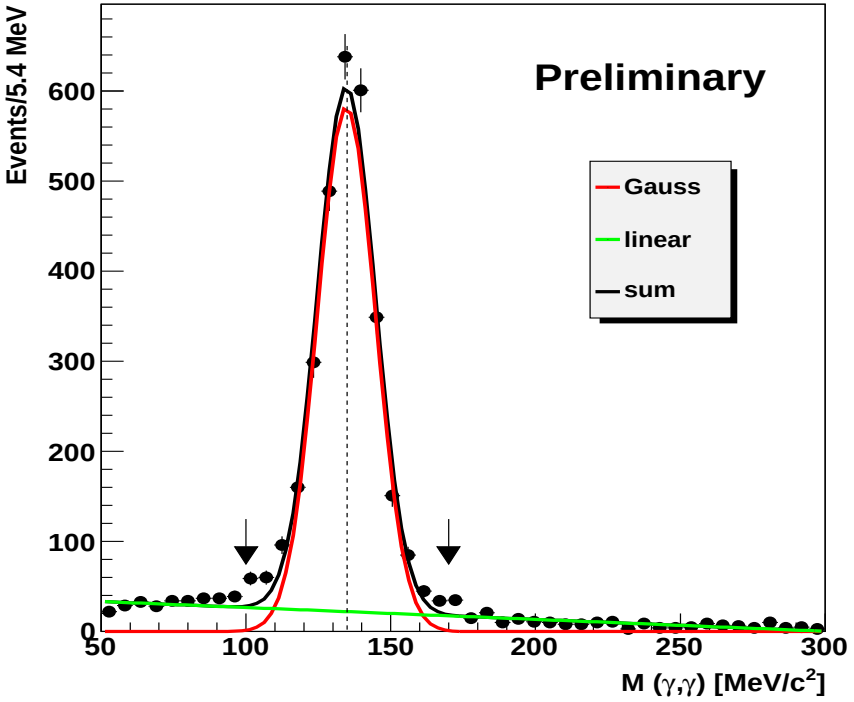
- Upolarized Target (H_2), 2012 data

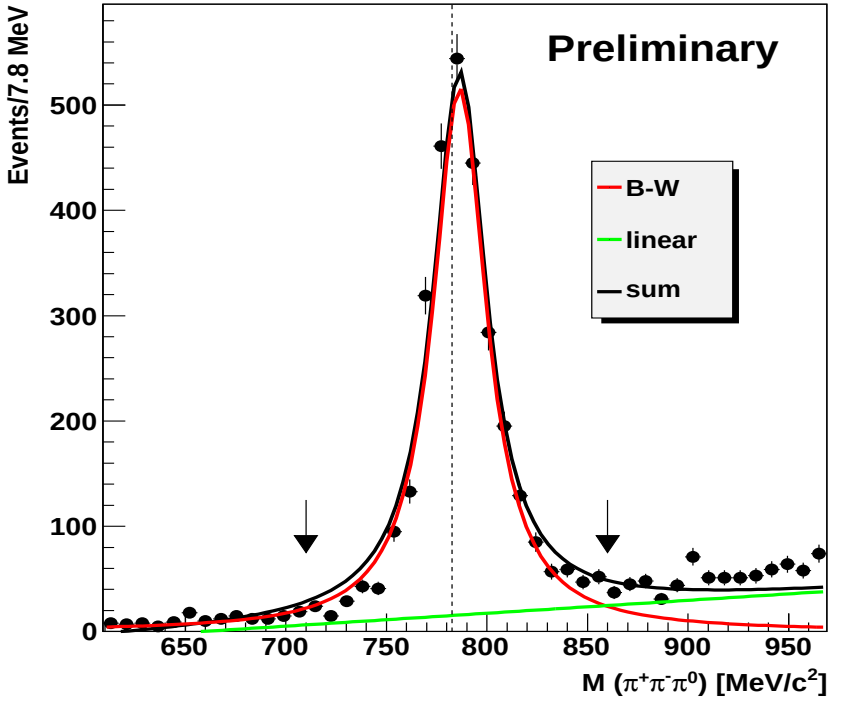
$$\mu N \to \mu' N' \omega$$
$$\hookrightarrow \pi^+\pi^-\pi^0 \qquad \mathrm{BR} \approx 89\%$$
$$\hookrightarrow \gamma\gamma \ . \qquad \mathrm{BR} \approx 99\%$$

- 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_{π^+}, p_{π^-} 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 background .

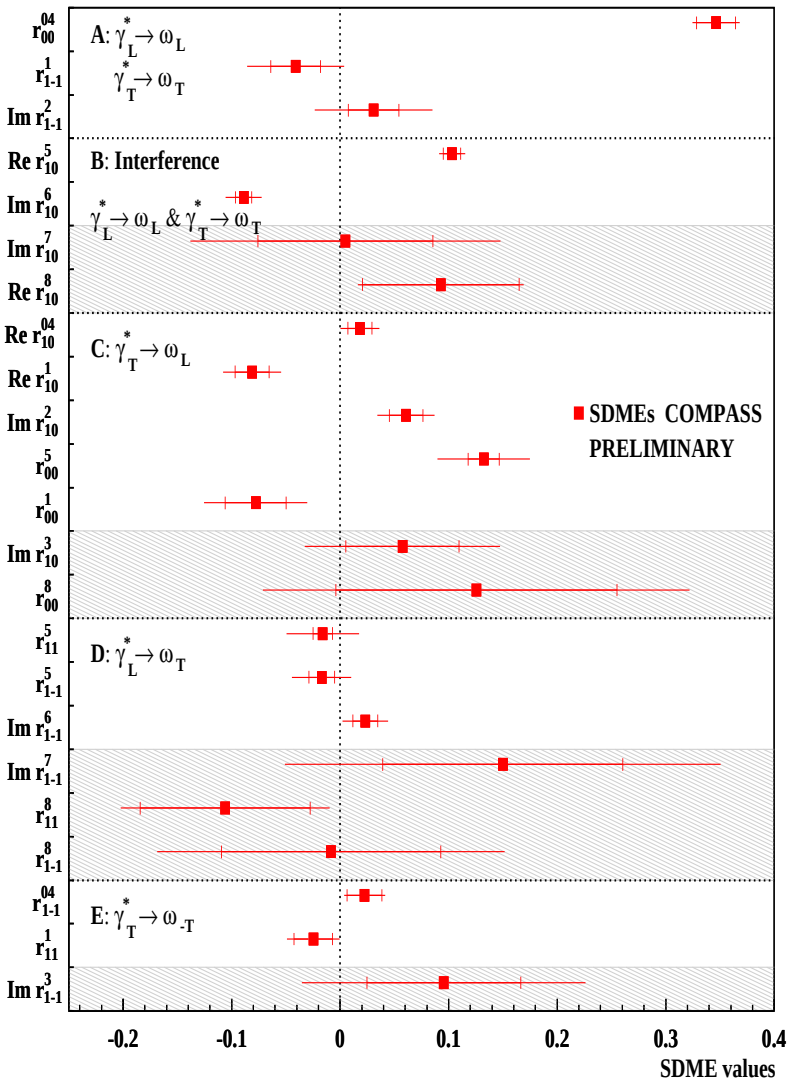
Exclusive ω-meson production at COMPASS

- $Q^2 = -q^2 = -(k - k')^2 = 1.0 \div 10.$ 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





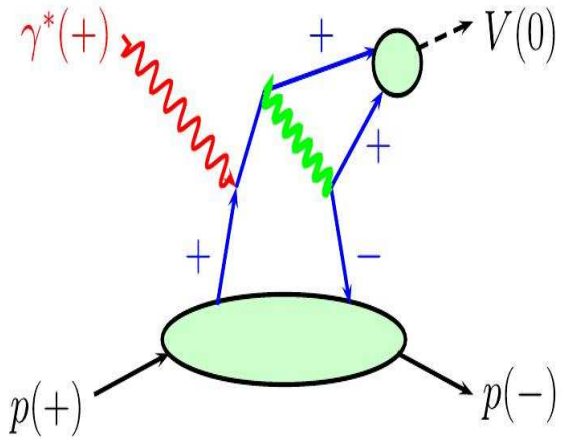
SDMEs of exclusive ω production for the integrated data



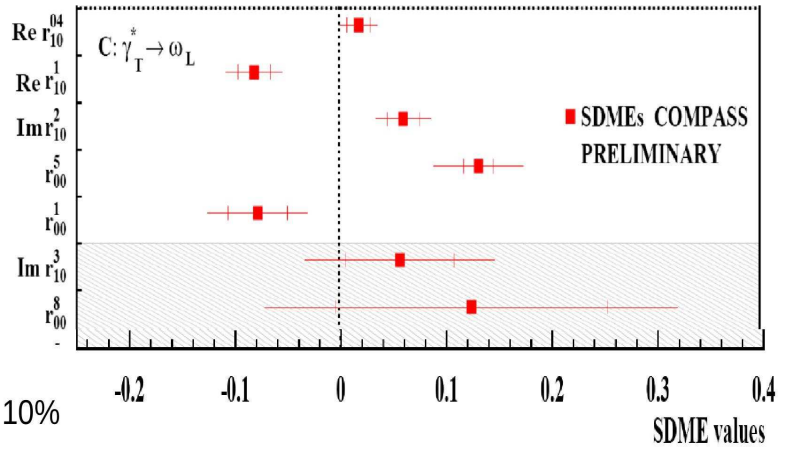
- A, $\gamma^*_L \to \omega_L$ and $\gamma^*_T \to \omega_T$
  B, Interference: $\gamma^*_L \to \omega_L$,$\gamma^*_T \to \omega_T$
  C, $\gamma^*_T \to \omega_L$
  D, $\gamma^*_L \to \omega_T$
  E, $\gamma^*_T \to \omega_{-T}$
- Test of s-channel conservation (SCHC)
  If SCHC obeyed (λ_{γ^*} = λ_V)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

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

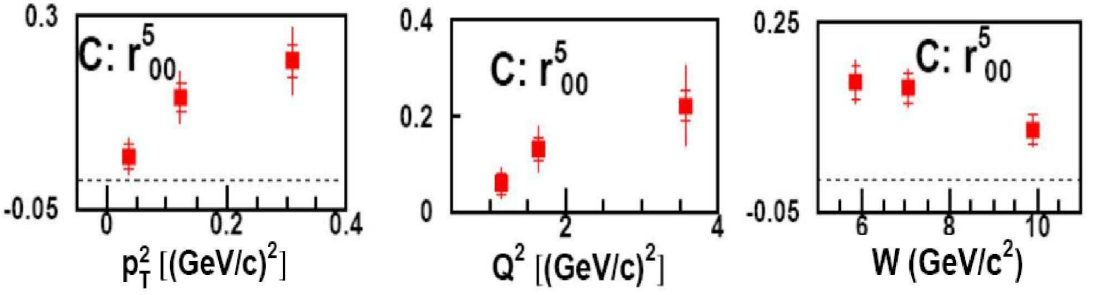
example graph for amplitude $F_{0-,++}$



- 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
  - $r^5_{00} \propto$ Re$[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$

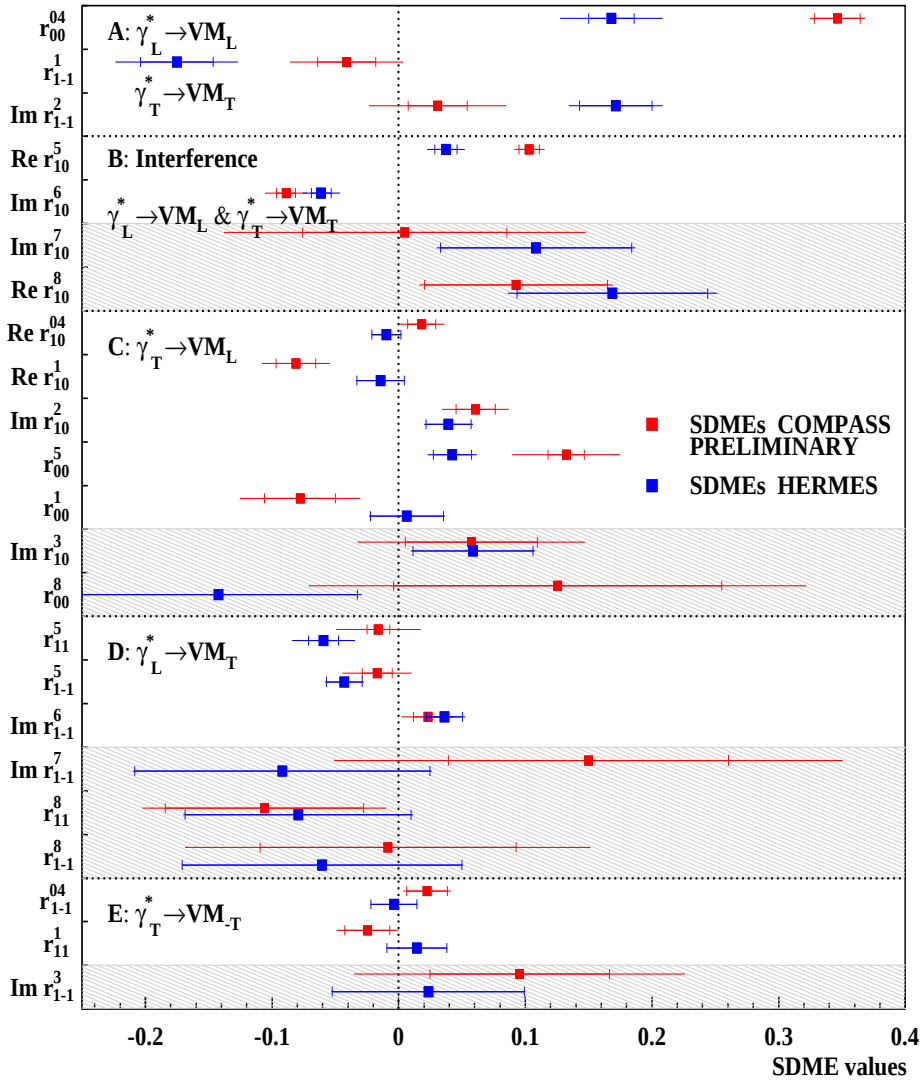


preliminary



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

Comparison of SDMEs in exclusive ω production in COMPASS and HERMES



COMPASS $\langle W \rangle = 7.6$ GeV^2 ,$\langle P_T^2 \rangle = 0.16$ (GeV/c)^2

HERMES $\langle W \rangle = 4.8$ GeV^2 ,$\langle t' \rangle = 0.08$ GeV^2

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

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

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

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

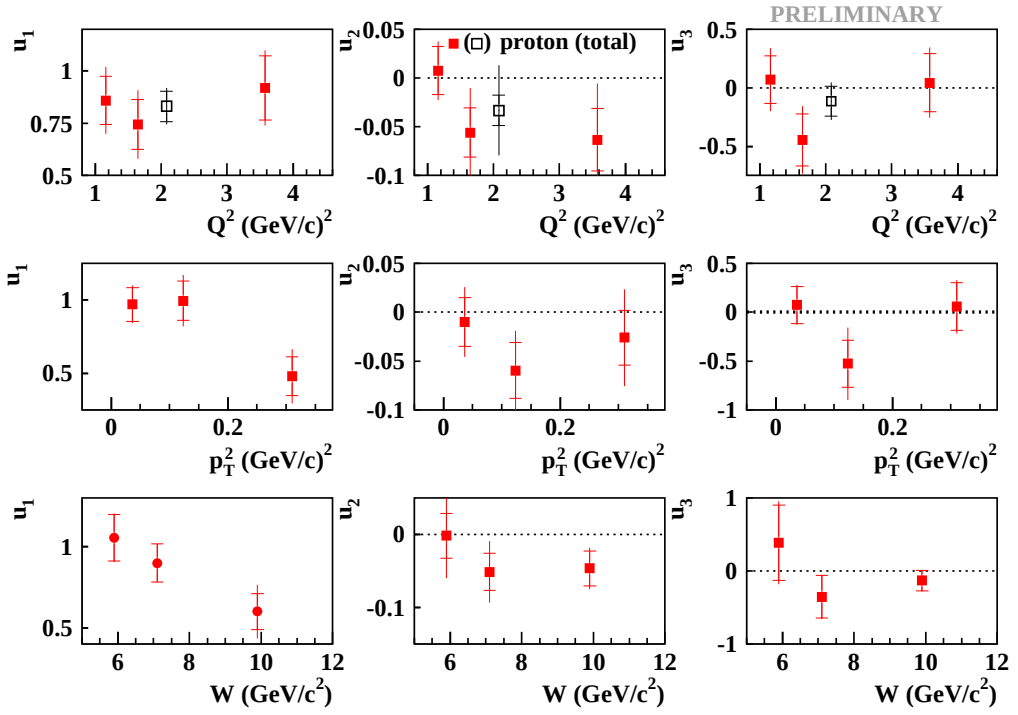
$|U_{11}|^2 \approx |T_{11}|^2$

HERMES $\mathrm{Im}\{r^2_{1-1}\} - r^1_{1-1}$= 0.35$\pm$0.06 > 0

$|U_{11}|^2 > |T_{11}|^2$

Fractional contribution of UPE (pion exchange) decreases as W increases.

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 $\pm$ 0.07$\pm$0.05,

HERMES u_1= 1.15 $\pm$ 0.09 $\pm$0.12

An additional information one gets from the following combinations

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

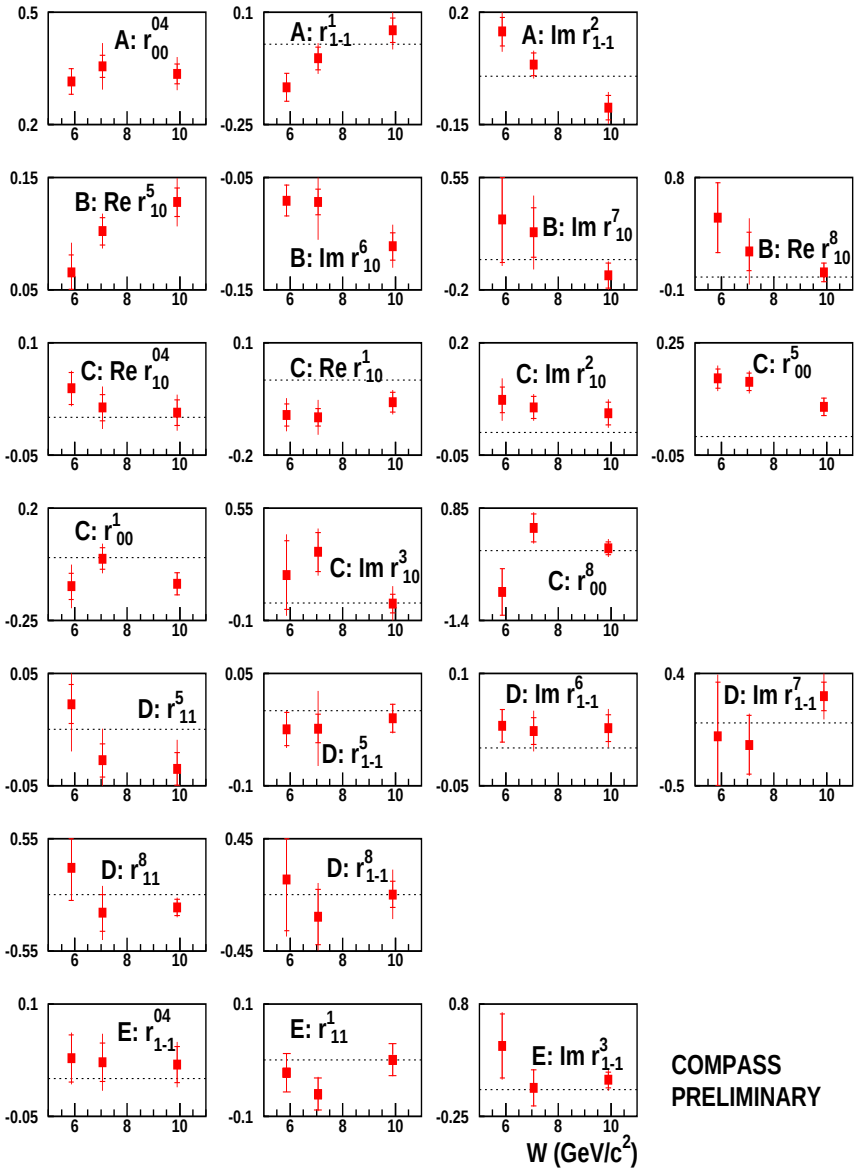
$$u_2 + iu_3 = \sqrt{2}\widetilde{\sum} \frac{(U_{11}+U_{-11})U^*_{10}}{\mathcal{N}},$$

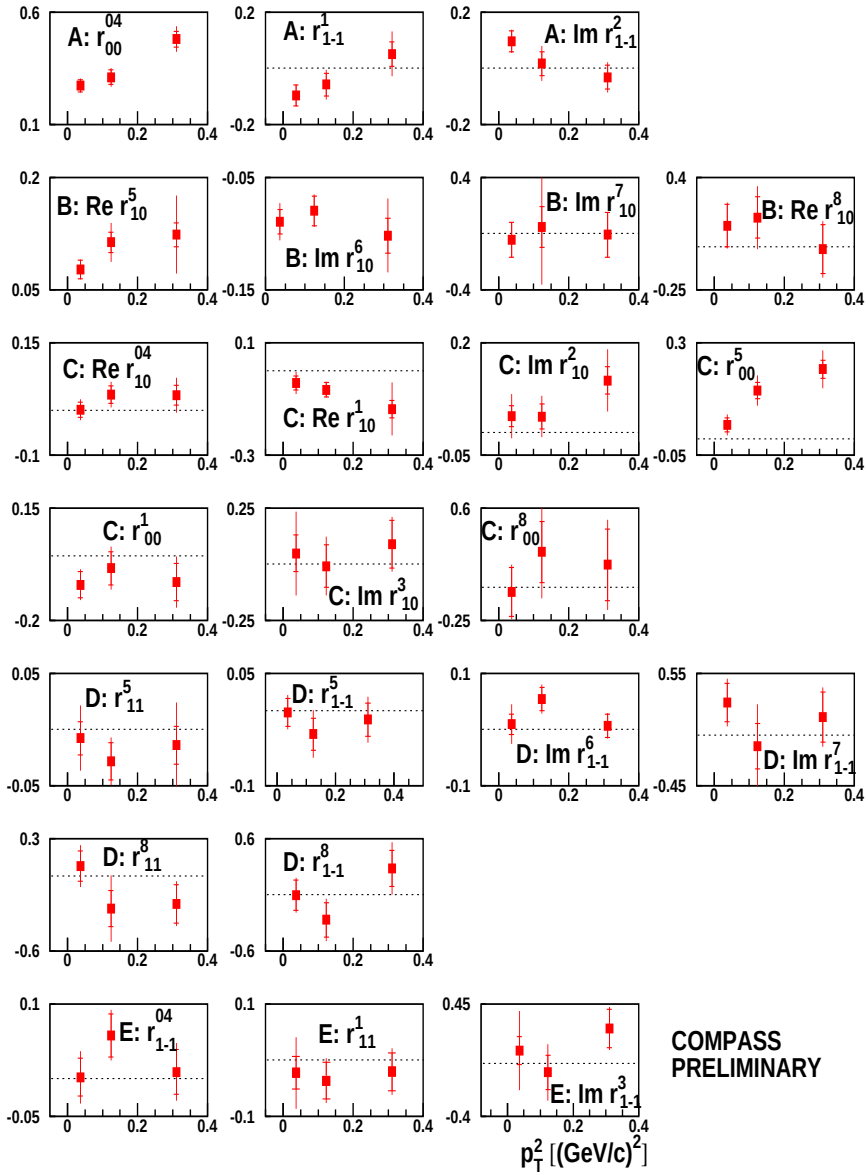
Dependence of u1, u2, u3 on Q^2, P^2_T and W.

Empty symbols denote results for the entire kinematic region.

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





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$\pm$0.043$\pm$0.003	-0.044$\pm$0.036$\pm$0.033	0.052$\pm$0.038$\pm$0.047
Imr^2_{1-1}	0.139$\pm$0.044$\pm$0.046	0.037$\pm$0.036$\pm$0.024	-0.098$\pm$0.038$\pm$0.033
u1	1.05$\pm$0.14$\pm$0.039	0.90$\pm$0.12$\pm$0.021	0.60$\pm$0.11$\pm$0.12

- at $\langle W \rangle$ = 5.9 GeV, Compass SDMEs do not differ much from Hermes SDMEs ($\langle W \rangle$=4.8 GeV, r^1_{1-1}= -0.175 $\pm$ 0.029, Imr^2_{1-1}= 0.171 $\pm$ 0.029). 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 became less then T$_{11}$.
  Contribution of UPE is nevertheless large because U$_{11}$ is comparable with T$_{11}$.

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 seems to be violated. Contribution of $\gamma_T^* \to \omega_L$ transition gives access to transversity GPDs.
- Results indicate that at Compass kinemtic helicity amplitude $U_{11} \approx T_{11}$ and became less then T_{11}.
- Clearly seen dependence of UPE on W.
- The UPE contribution is still large for ω meson production.