Spin Density Matrix Elements for exclusive ρ^0 meson muoproduction at COMPASS

W. Augustyniak

National Centre for Nuclear Research Warsaw, Poland

on behalf of the COMPASS Collaboration

Witold.Augustyniak@ncbj.gov.pl

Contents

Vector meson spin-density martix $\rho(V)$

helicity of vector meson V

helicity of virtual photon γ and nucleon N

photon spin density matrix ($\mu \to \mu^{'} + \gamma^{*}$) calculated by QED

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

F helicity amplitudes describe transitions λ_γ, $\lambda_N \to \lambda_V$,λ_N, depend on W, Q^2 and p_T^2

$\rho_{\lambda_\gamma \lambda'_\gamma}$ **decomposes into nine $\rho^{\alpha}_{\lambda_V \lambda'_V}$, ($\alpha$=0÷3 - transv.,4 - long. 5÷8 - interf.),**
When contribution from transverse and longitudinal photons can not be separated ,
Spin Density Matrix Elements (SDMEs) are defined:

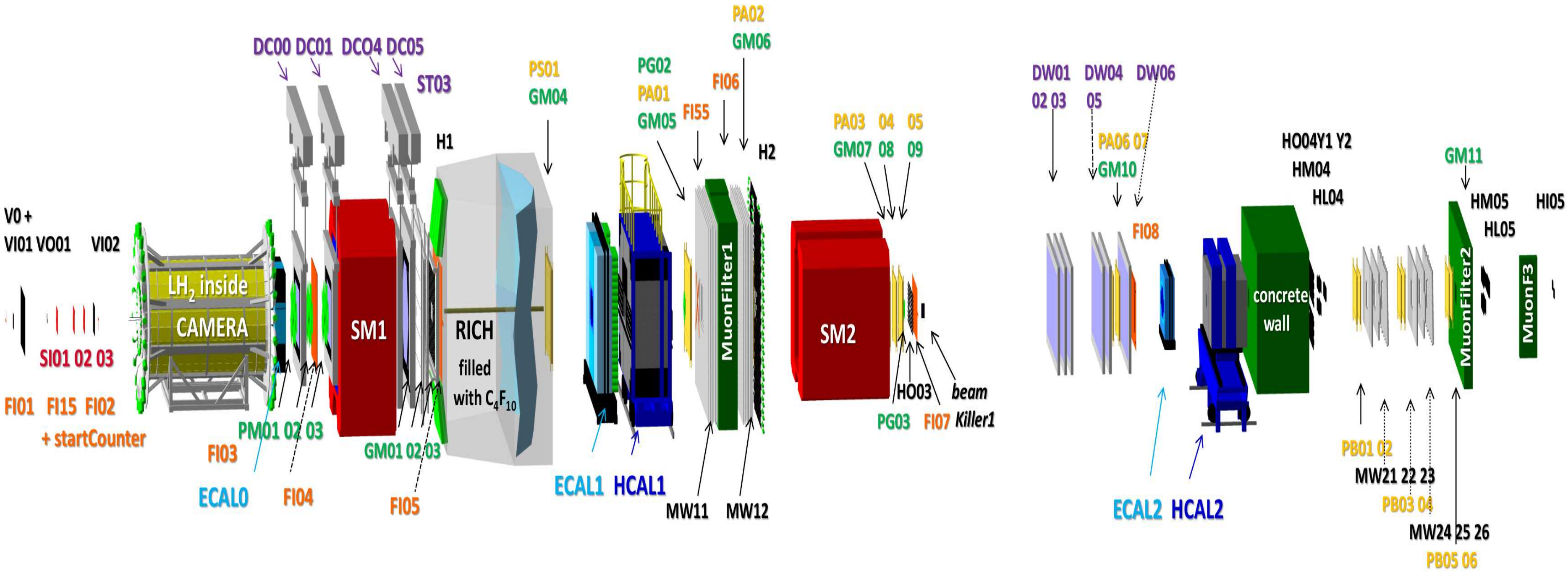
$$r^{04}_{\lambda_V \lambda'_V} = (\rho^{0}_{\lambda_V \lambda'_V} + \epsilon R \rho^{4}_{\lambda_V \lambda'_V})/(1+\epsilon R), \; r^{\alpha}_{\lambda_V \lambda'_V} = \begin{cases} \frac{\rho^{\alpha}_{\lambda_V \lambda'_V}}{(1+\epsilon R)}, & \alpha = 1,2,3, \\ \frac{\sqrt{R}\rho^{\alpha}_{\lambda_V \lambda'_V}}{(1+\epsilon R)}, & \alpha = 5,6,7,8. \end{cases} \qquad R = \sigma_L/\sigma_T$$

(K. Schiling and G. Wolf, Nucl. Phys. B61,381(1973))

Vector meson spin-density martix $\rho(V)$

- **Helicity amplitude allows**
  - **test of s-channel helicity conservation (**λ_γ**=**λ_V**)**
  - **decomposed into Natural (N) Parity and Unnatural (U) Parity exchange amplitudes**
    $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$ = $T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$ + $U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$
  - **in Rege framework NPE: J**^{P}**= (0**$^+$**,1**$^-$**, ...)**
    UPE: J^P**= (0**$^-$**,1**$^+$**, ...)**
  - **test of GPD models**
    e.g. for SCHC-violation transition $\gamma_T \rightarrow$ **V**$_L$ **test sensitivity to GPDs**
    with exchanged-quarks helicity flip (transvetsity GPDs)

COMPASS Spectrometer



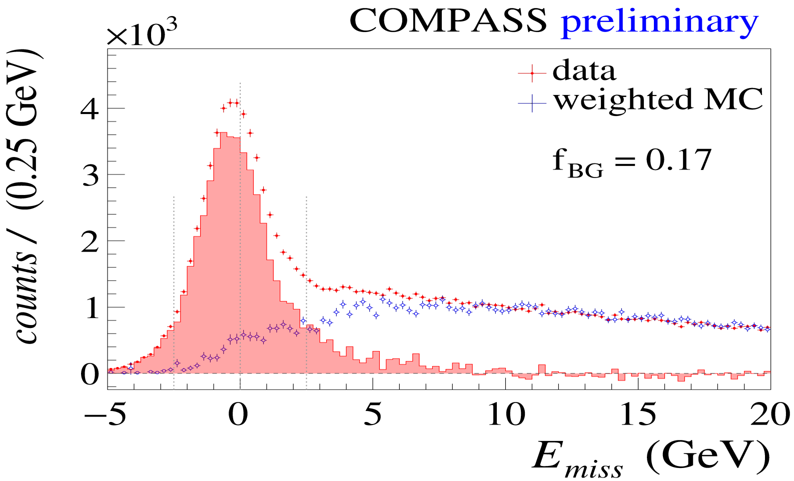
beam μ^+ and μ^-

energy: 160 GeV

beam polarization $\approx$ -80 (+80) $\%$

target LH_2.

Exclusive ρ^0-meson production at COMPASS



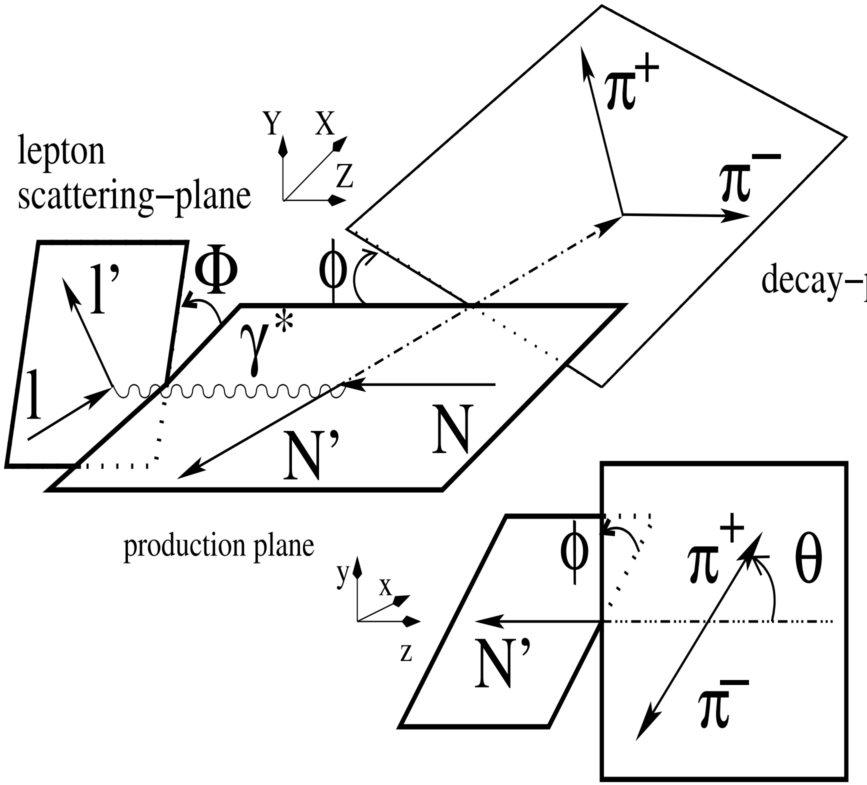
Distribution of missing energy (red points) for data. Shape of semi-inclusive background (blue points) was determined using LEPTO generator. Background fraction f$_{BG}$ was determined as ratio of MC and data in E$_{miss}$ -2.5 GeV $\div$ 2.5 GeV region. Red histogram presents E$_{miss}$ with subtracted background.

stat. μ^+=23785, μ^-=28472

- Selection of exclusive events
  - Selection of event contains three outgoing tracks (μ', h$^+$, h$^-$),
  - Exclusive region : -2.5 GeV < E$_{miss}$ < 2.5 GeV $E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$ and M_X being missing mass, p, q, p_{π^+}, p_{π^-} are 4-momenta of proton target photon and pions.
  - 0.01 < p$_T^2$ < 0.5 (GeV/c)^2, p_T^2 - squared transverse momentum of ρ^0 w.r.t γ^*
  - Q^2 1.0 < Q^2 <10.0 (GeV/c)^2
  - 5.0 < W < 17.0 (GeV/c^2),

Angular distribution in reaction

$$\mu + p \rightarrow \mu' + p' + \rho^0 \rightarrow (\pi^+\pi^-)$$

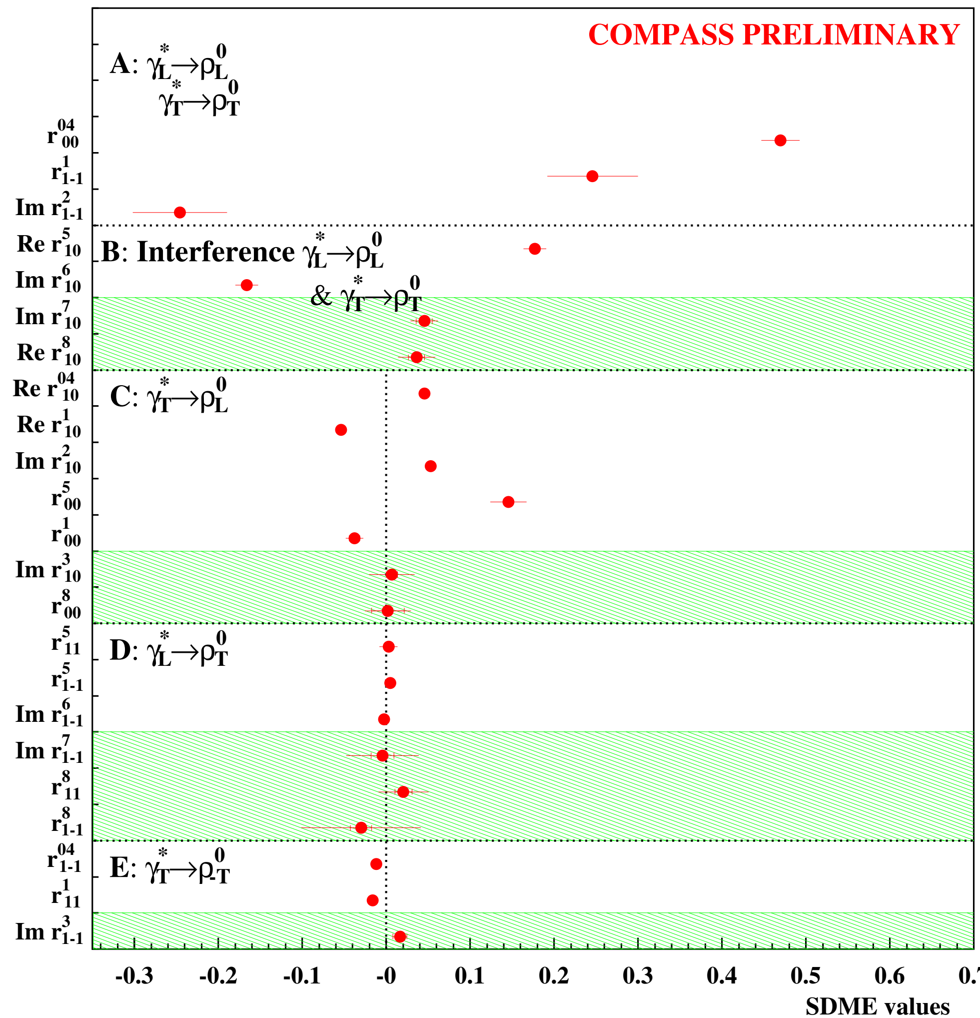


- Experimental access to SDMEs via angular distributions of ρ^0 production and decay
- Angular distribution $\mathcal{W}(\Phi, \phi, \cos\Theta)$ depends linearly on SDMEs and beam polariztion P_b.
- For longitudinally polarized beam and unpolarized target there are 23 SDMEs,(15 unpolarized and 8 polarized).
- The SDMEs are determined from the fit of angular distributions of ρ^0 production and decay $\mathcal{W}(\Phi, \phi, \cos\Theta)$, with Unbinned Maximum Likelihood method.

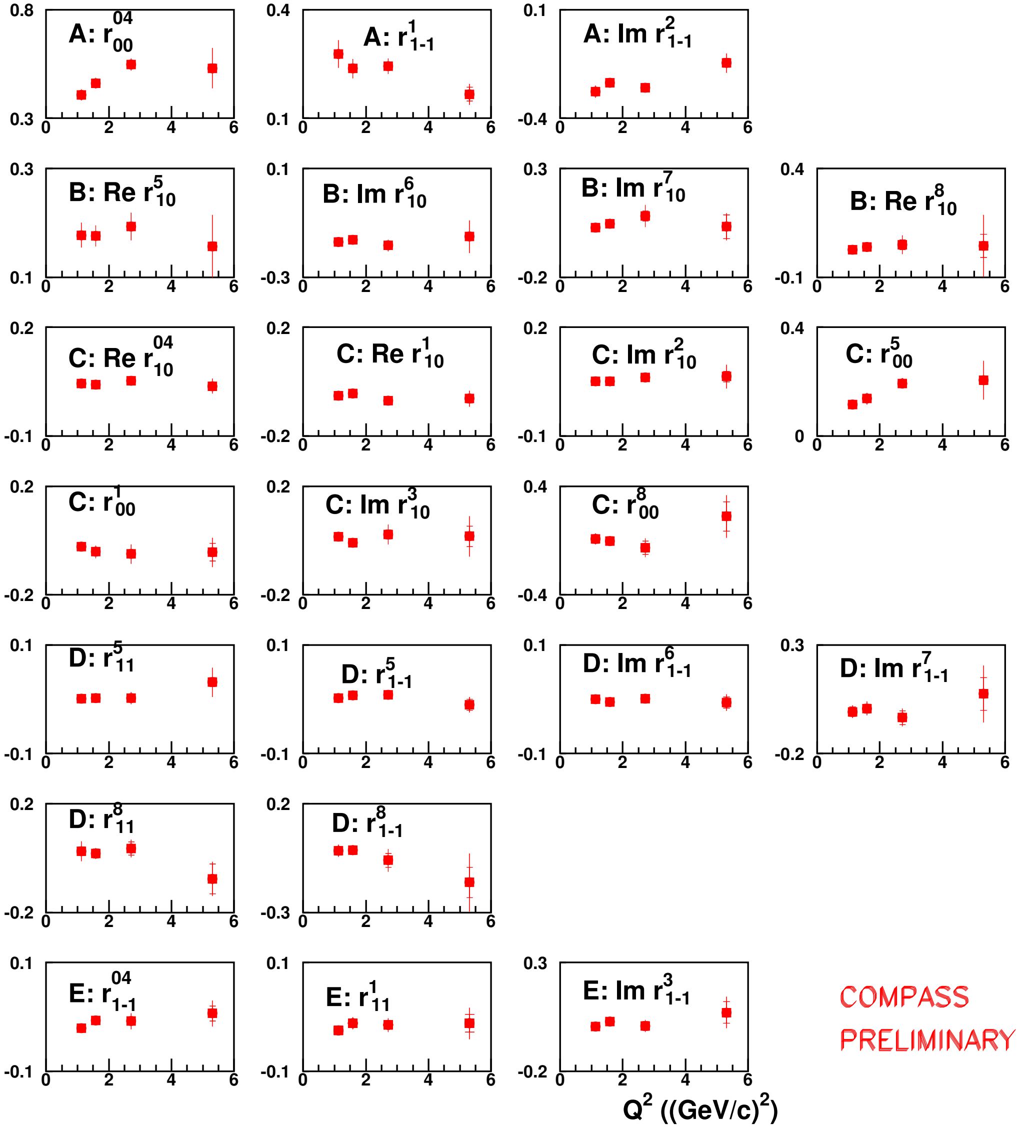
SDMEs and Amplitudes for: ρ^0

1.0 (GeV/c)^2 < Q^2 <10.0 (GeV/c)^2
5.0 GeV/c^2 < W < 17.0 GeV/c^2
0.01 (GeV/c)^2 < p_T^2 < 0.5 (GeV/c)^2
$\langle W \rangle$ = 9.90 GeV/c^2 ,
$\langle Q^2 \rangle$ = 2.40 (Gev/c)^2 ,
$\langle p_T^2 \rangle$= 0.18 (GeV/c)^2.

- SDMEs grouped in classes: A, B, C, D, E corresponding to different helicity transitions
- SDMEs related to beam polarisation shown within shaded areas

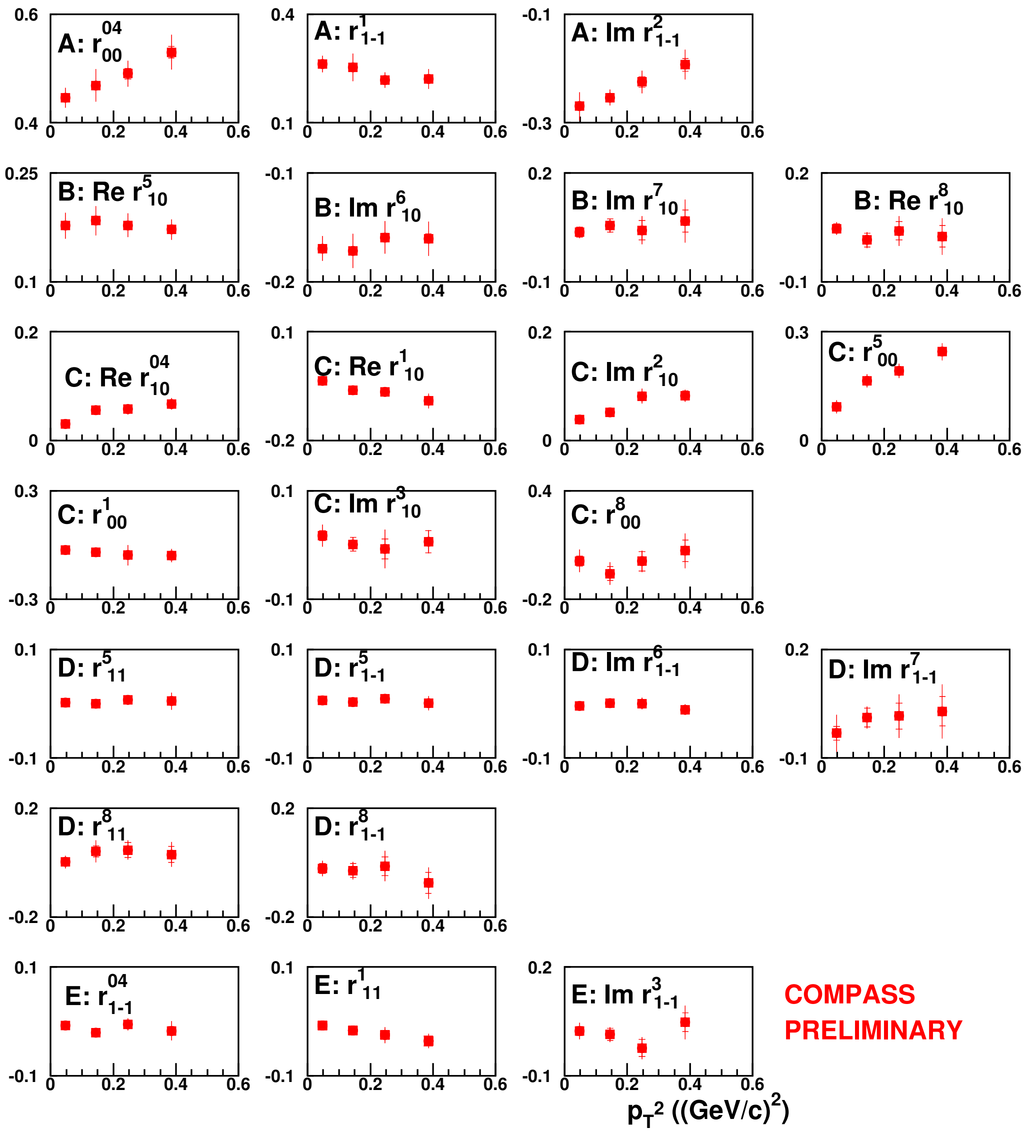


SDMEs Q^2 dependence



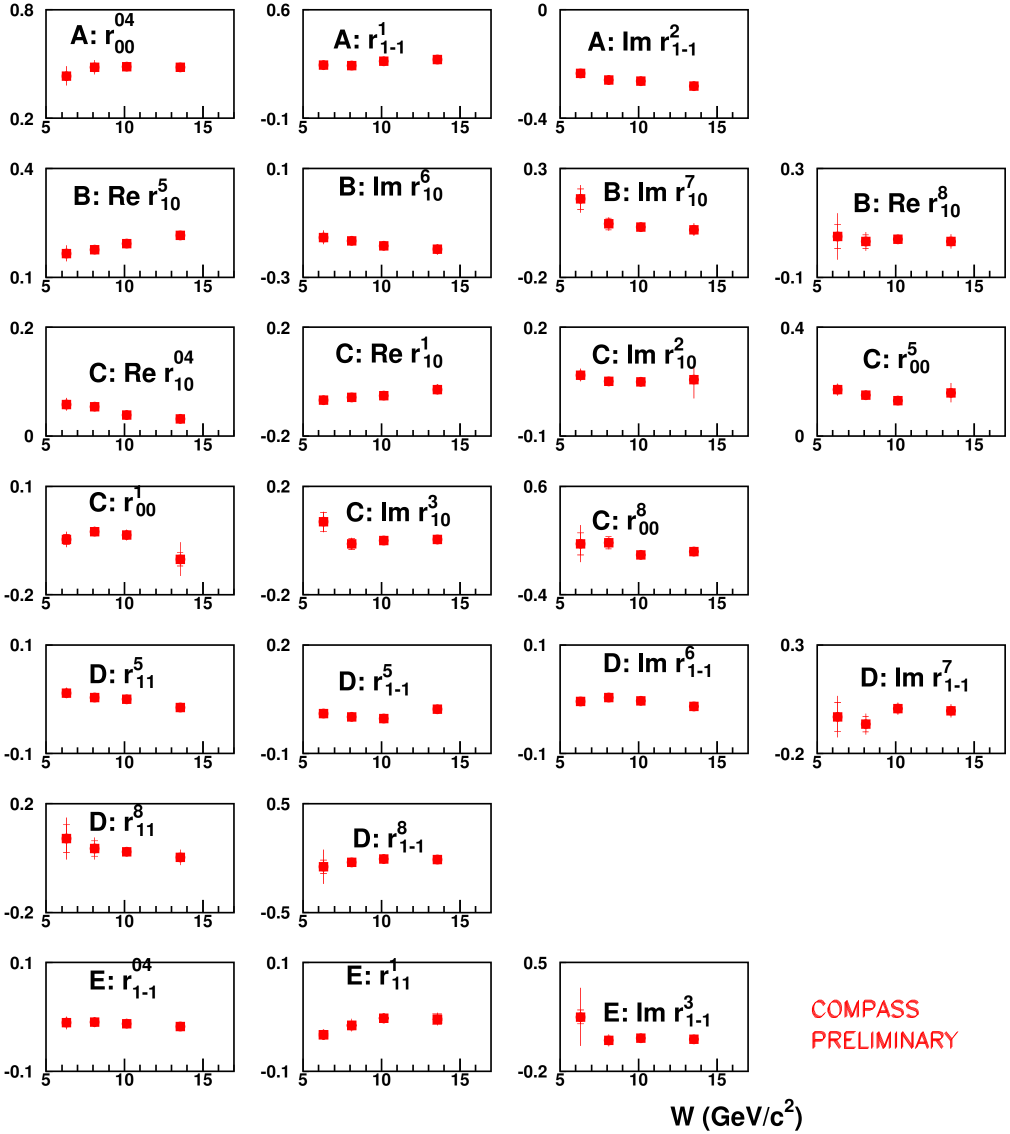
Preliminary results with statistical and total errors. The results are averaged over 0.01 (GeV/c)^2 < p_T^2 < 0.50 (GeV/c)^2 and 5.0 GeV/c^2 < W < 17.0 GeV/c^2

SDMEs p_T^2 dependence



Preliminary results with statistical and total errors. The results are averaged over $1.0\ (GeV/c)^2 < Q^2 < 10.0\ (GeV/c)^2$, $5.0\ GeV/c^2 < W < 17.0\ GeV/c^2$

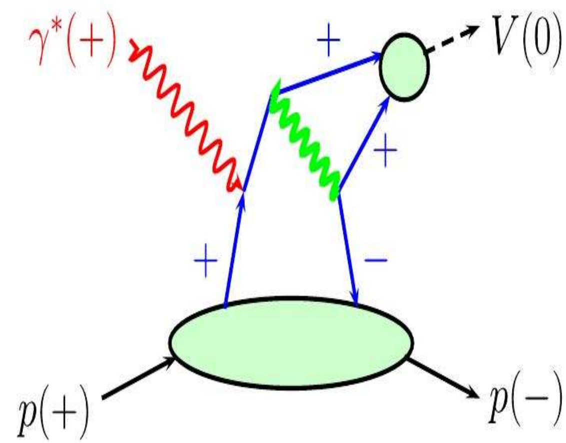
SDMEs W dependence



Preliminary results with statistical and total errors. The results are averaged over $1.0\ (\mathrm{GeV}/c)^2 < Q^2 < 10.0\ (\mathrm{GeV}/c)^2$, $0.01\ (\mathrm{GeV}/c)^2 < p_T^2 < 0.5\ (\mathrm{GeV}/c)^2$,

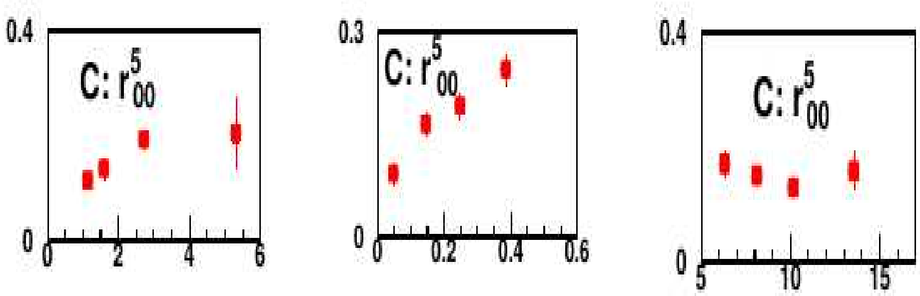
Transitions of class C, $\gamma^*_T \to \rho^0_L$

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

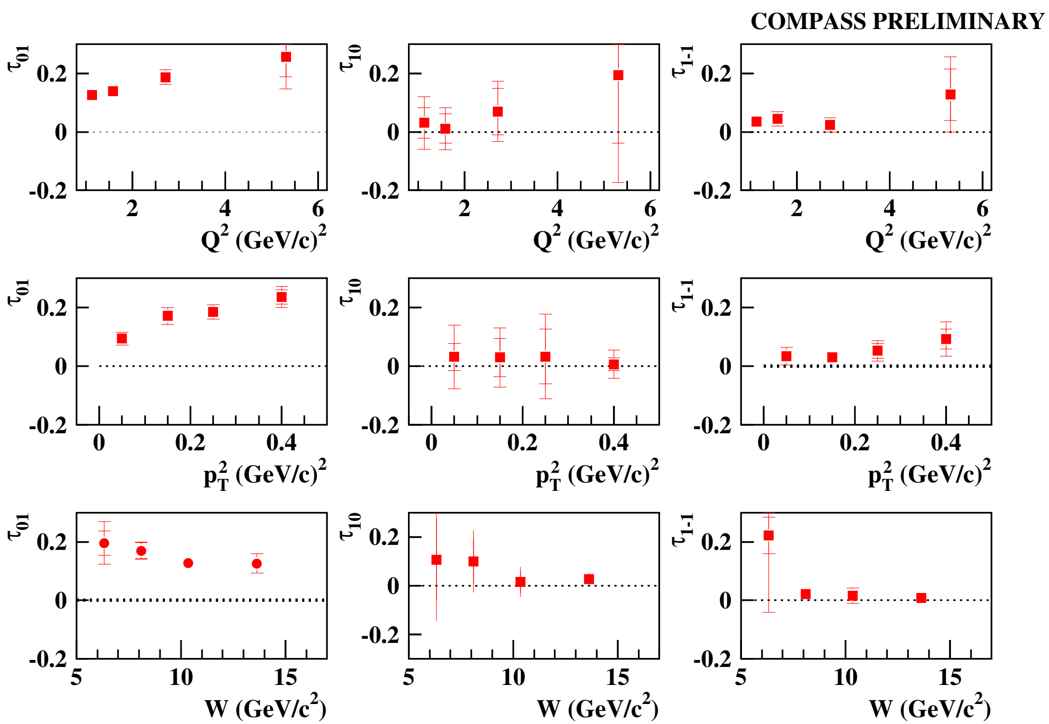


- possible GPD interpretation **Goloskokov Kroll EPJC 74 (2014)2725**
  contribution of amplitudes depending on transversity GPDs H_T, $\bar{E}_T = 2\tilde{H}_T + E_T$
  - $r^5_{00} \propto \text{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle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

preliminary



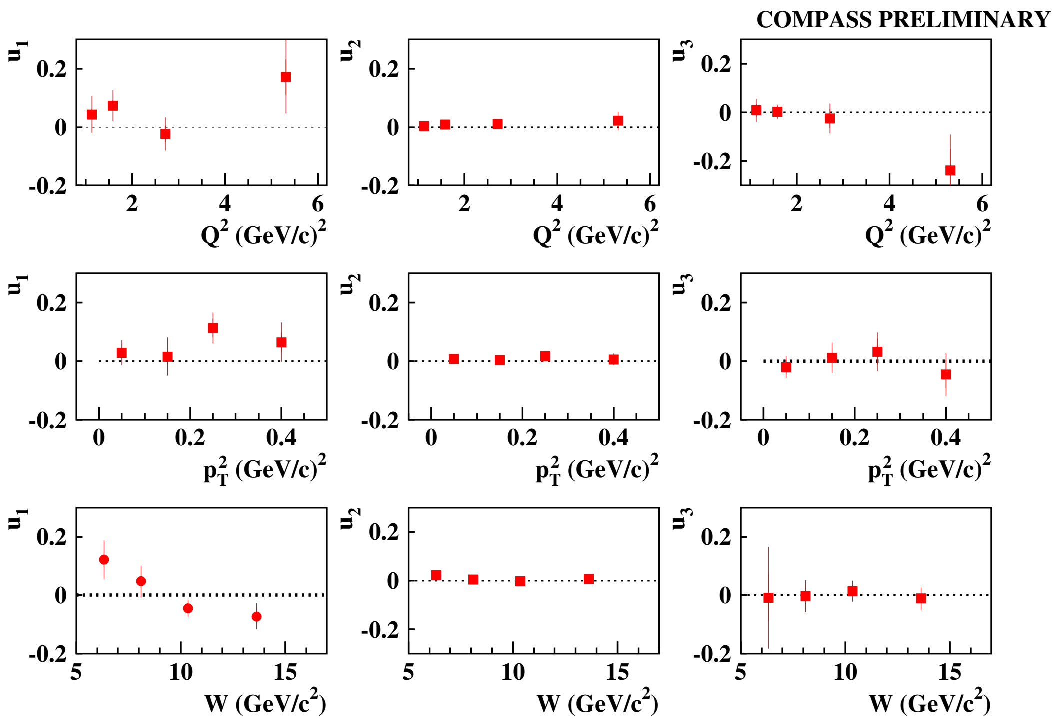
Helicity-Flip Transitions



$$\tau_{ij} = \frac{|T_{ij}|}{\sqrt{\mathcal{N}}}. \qquad (1)$$

Clear observed SCHC violation for transition $\gamma_T \rightarrow \rho^0_L$. τ_{01}, τ_{10} and τ_{1-1} were calculated using combination of SDME cf. HERMES Eur. Phys. J. C62,(2009)659

Unnatural-Parity-Exchange



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

fraction of UPE

$$u_2 + i u_3 = \sqrt{2} \widetilde{\sum} \frac{(U_{11} + U_{-11}) U_{10}^*}{\mathcal{N}} \quad (3)$$

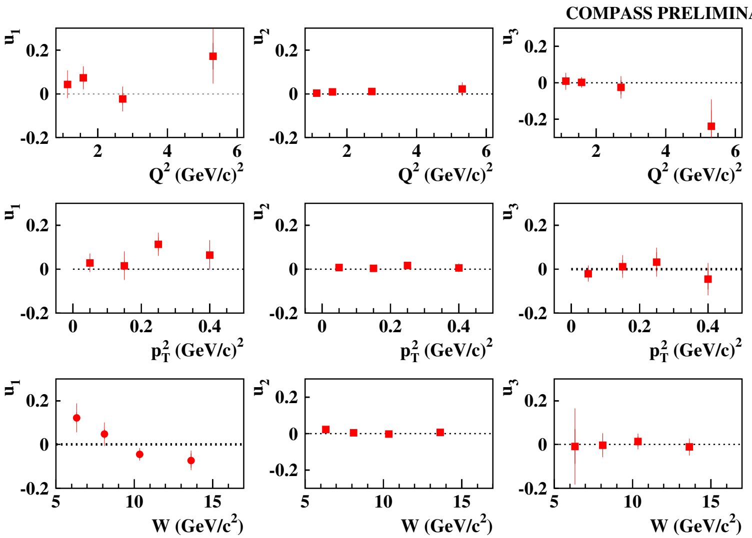
$$u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1}, \quad (4)$$

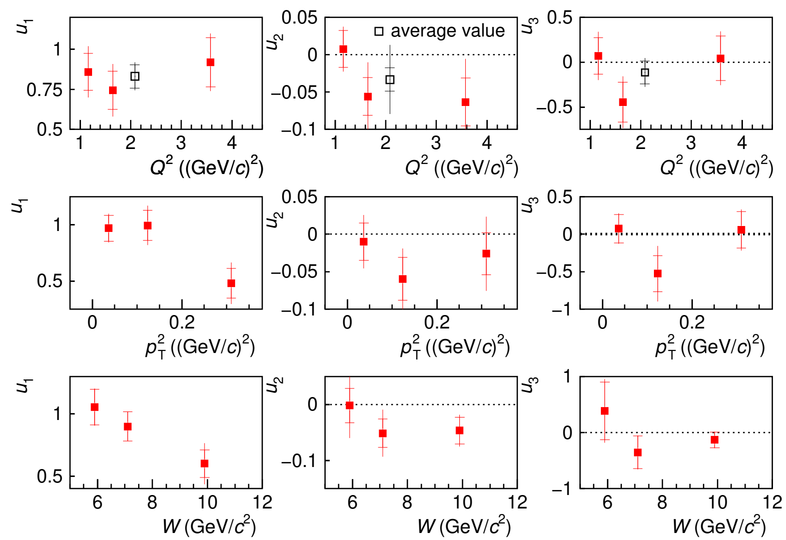
$$u_2 = r_{11}^{5} + r_{1-1}^{5}, \quad (5)$$

$$u_3 = r_{11}^{8} + r_{1-1}^{8}. \quad (6)$$

Existance of unnatural parity exchange is estimated by value of u_1 defined by combination of SDMEs. Small contribution of UPE can be seen only at low value of W.

Comparison of Unnatural-Parity Exchange for ρ^0 and ω



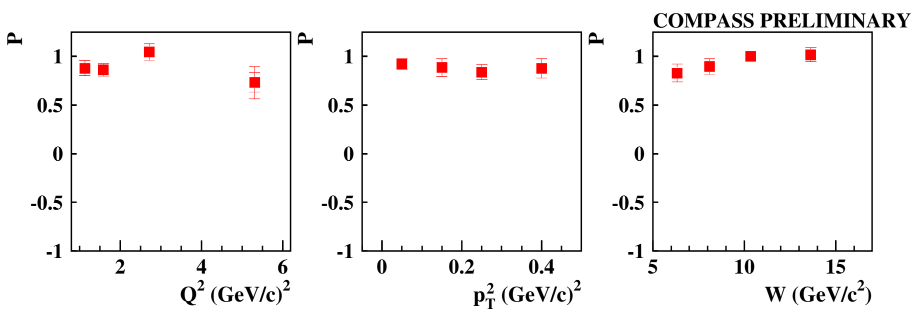


ρ^0 preliminary

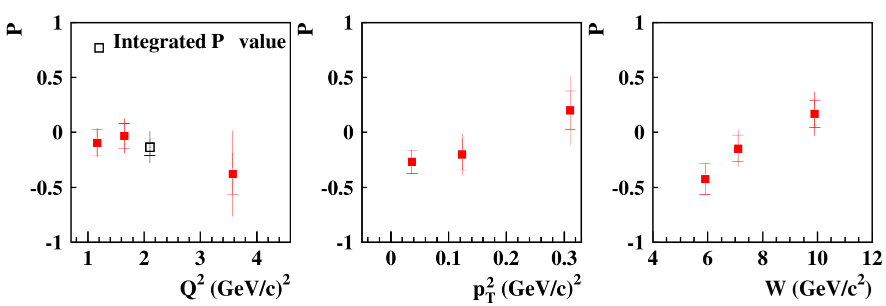
ω - Eur. Phys. J.C81 (2021)126

UPE amplitudes are found very small for ρ^0, while they are large for ω.

NPE-to-UPE ASYMMETRY P for ρ^0 and ω



ρ^0



ω

P NPE-to-UNP relation for Q^2, p_T^2, W .

NPE - Natural-Parity-Exchange,

UPE- Unnalural-Parity-Exchange

$$\mathrm{P} = \frac{d\sigma_T^N(\gamma_T^* \to V_T) - d\sigma_T^U(\gamma_T^* \to V_T)}{d\sigma_T^N(\gamma_T^* \to V_T) + d\sigma_T^U(\gamma_T^* \to V_T)} = \frac{2r_{1-1}^1}{1 - r_{00}^{04} - 2r_{1-1}^{04}},$$

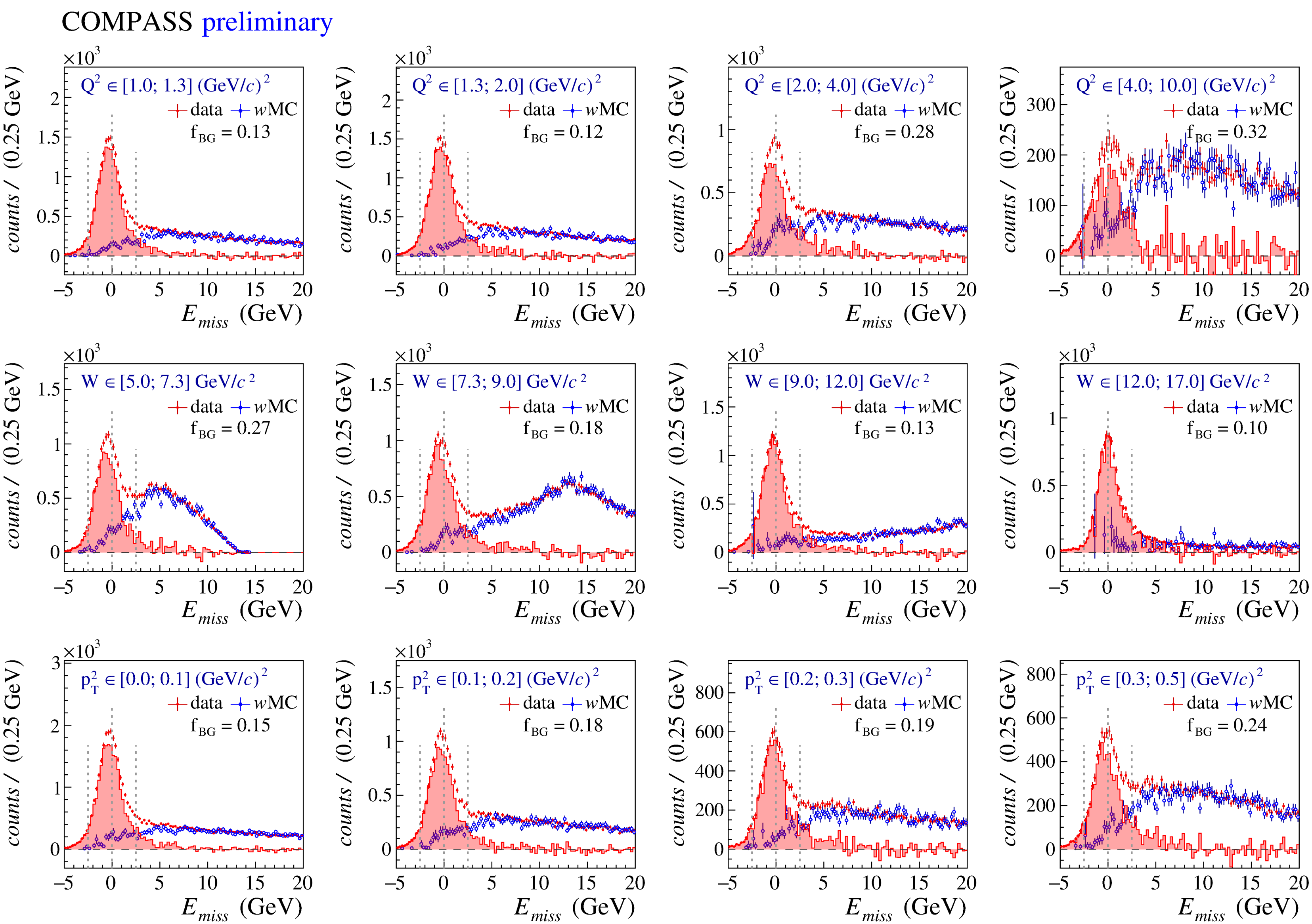
For ρ^0 small contribution of $d\sigma_T^U$ is observed while for ω case $d\sigma_T^U$ and $d\sigma_T^N$ are of comparable magnitude.

Summary

- The 23 SDMEs are extracted for muoproduction of ρ^0 meson on proton at COMPASS.
- SDMEs grouped into five classes according to the helicity transition were presented.
- Dependences of SDMEs on Q^2, p_T^2 and W were determined.
- The Hypothesis of SCHC in ρ^0 meson production is violated. Contribution of $\gamma_T^* \to \rho_L^0$ transition gives access to transversity GPDs.
- Clearly observed dependences of τ_{01} on Q^2, p_T^2 and W .
- A small contribution of UPE is observed at low W .
- The UPE-to-NPE asymmetry of the transverse cross section indicate dominance of NPE amplitude.

ADDITIONAL SLIDES

ADDITIONAL SLIDES



Function for the Fit of 23 SDME r^{α}_{ij}

$\mathbf{W}(\cos\Theta,\phi,\Phi) = W^{unpol} + W^{long.pol}$,

$\mathbf{W}^{unpol}(\cos\Theta,\phi,\Phi) = \frac{3}{8\pi^2}\Big[\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta-$
$\sqrt{2}\mathrm{Re}\{\mathrm{r}^{04}_{10}\}\sin 2\Theta\cos\phi - \mathrm{r}^{04}_{1-1}\sin^2\Theta\cos 2\phi$

$-\ \epsilon\cos 2\Phi\Big(r^1_{11}\sin^2\Theta+r^1_{00}\cos^2\Theta-\sqrt{2}\mathrm{Re}\{\mathrm{r}^1_{10}\}\sin 2\Theta\cos\phi-$
$\mathrm{r}^1_{1-1}\sin^2\Theta\cos 2\phi\Big)$

$-\ \epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{\mathrm{r}^2_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{\mathrm{r}^2_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$

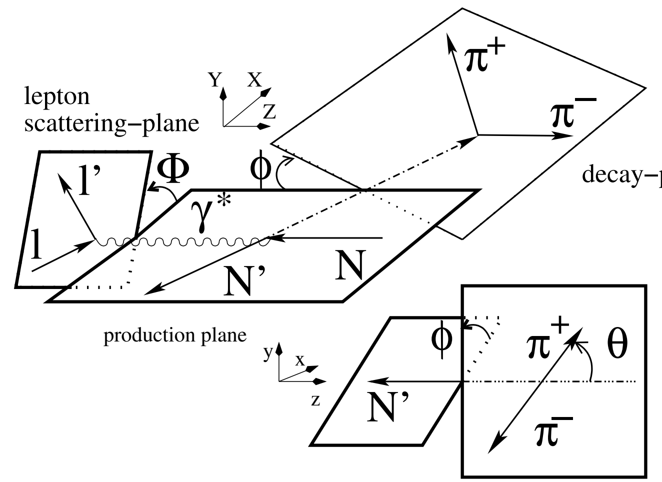
$+\ \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^5_{11}\sin^2\Theta+r^5_{00}\cos^2\Theta-\sqrt{2}\mathrm{Re}\{\mathrm{r}^5_{10}\}\sin 2\Theta\cos\phi-$
$\mathrm{r}^5_{1-1}\sin^2\Theta\cos 2\phi\Big)$

$+\ \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{\mathrm{r}^6_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{\mathrm{r}^6_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Big]$,

$\mathbf{W}^{long.pol.}(\cos\Theta,\phi,\Phi) = \frac{3}{8\pi^2}P_{beam}\Big[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{\mathrm{r}^3_{10}\}\sin 2\Theta\sin\phi+$
$\mathrm{Im}\{\mathrm{r}^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$

$+\ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{\mathrm{r}^7_{10}\}\sin 2\Theta\sin\phi+\mathrm{Im}\{\mathrm{r}^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$

$+\ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta+r^8_{00}\cos^2\Theta-\sqrt{2}\mathrm{Re}\{\mathrm{r}^8_{10}\}\sin 2\Theta\cos\phi-$
$\mathrm{r}^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Big]$



$\cos\Phi = \frac{(q\times v)\cdot(k\times k')}{|(q\times v)|\cdot|(k\times k')|}$, $\sin\Phi = \frac{[(q\times v)\times(k\times k')]\cdot q}{|(q\times v)|\cdot|(k\times k')|\cdot|q|}$,

$\cos\phi = \frac{(q\times v)\cdot(v\times p_{\pi^+})}{|(q\times v)|\cdot|(v\times p_{\pi^+})|}$, $\sin\phi = \frac{[(q\times v)\times v]\cdot(p_{\pi^+}\times v)}{|(q\times v)\times v|\cdot|(p_{\pi^+}\times v|}$,

$\cos\Theta = \frac{-P'\cdot p_{\pi^+}}{|P'|\cdot|p_{\pi^+}|}$, $\epsilon = \frac{1-y-y^2\frac{Q^2}{4\nu^2}}{1-y+\frac{1}{4}y^2(\frac{Q^2}{\nu^2}+2)}$.

Unbinned Max. Likelihood Method BKG. subtr.

Background correction in Likelihood method is a two step process. Using the same negative log-likelihood function Eq.5 to be minimized, where the input for the log-likelihood function is the angular distribution of SIDIS background.
We can determined parameters $\mathcal{B}$(" SIDIS - background SDMEs ") characterizing SIDIS background

$$-\ln L(\mathcal{B}) = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}^{U+L}(\mathcal{B};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{B})}, \quad (8)$$

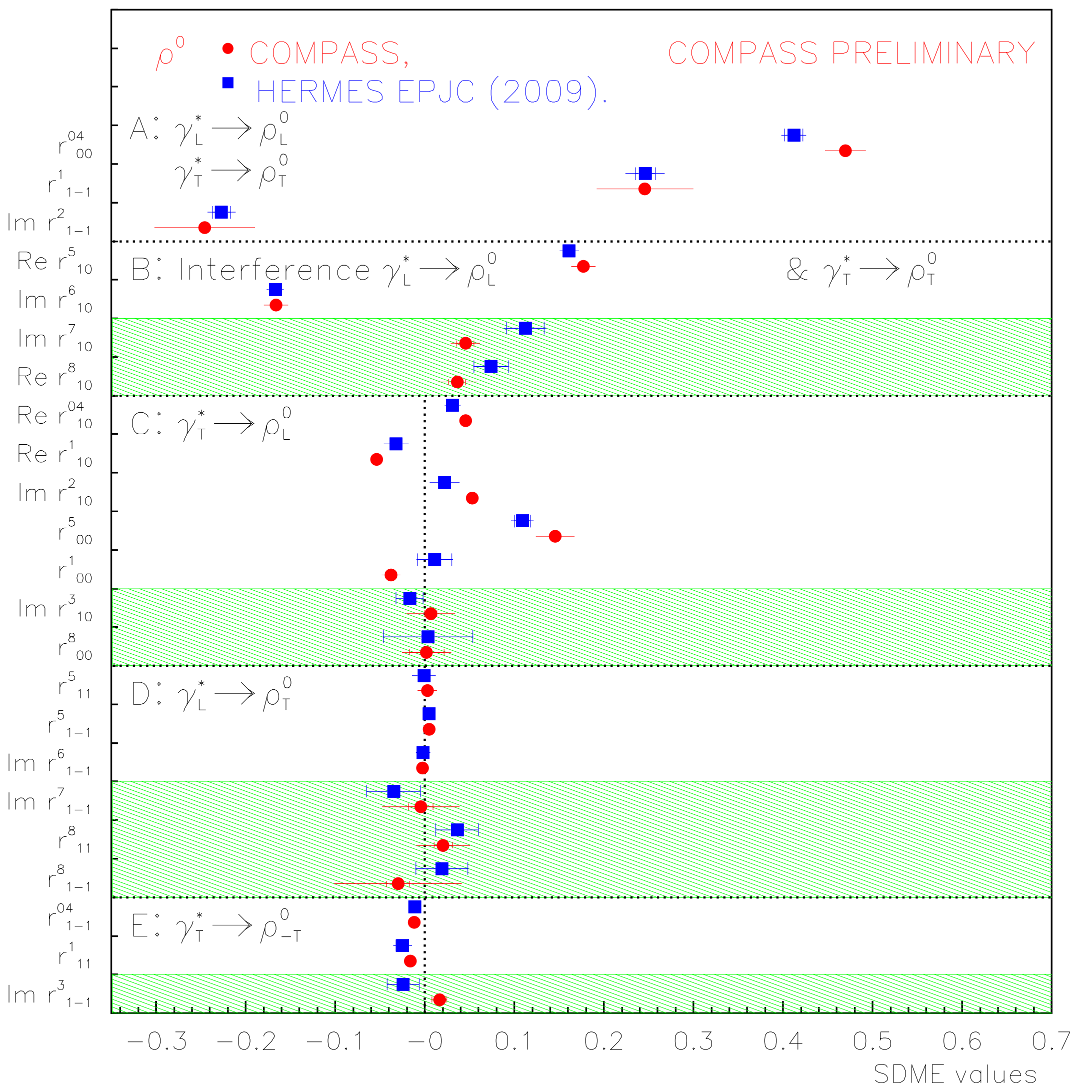
Using parameters characterising SIDIS background $\mathcal{B}$, SDMEs corrected for SIDIS background are obtained with the following negative log-likelihood function

$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln\Big[\frac{(1-f_{bg})*\mathcal{W}^{U+L}(\mathcal{R};\Phi_i,\phi_i,\cos\Theta_i) + f_{bg}*\mathcal{W}^{U+L}(\mathcal{B};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B})}\Big].$$

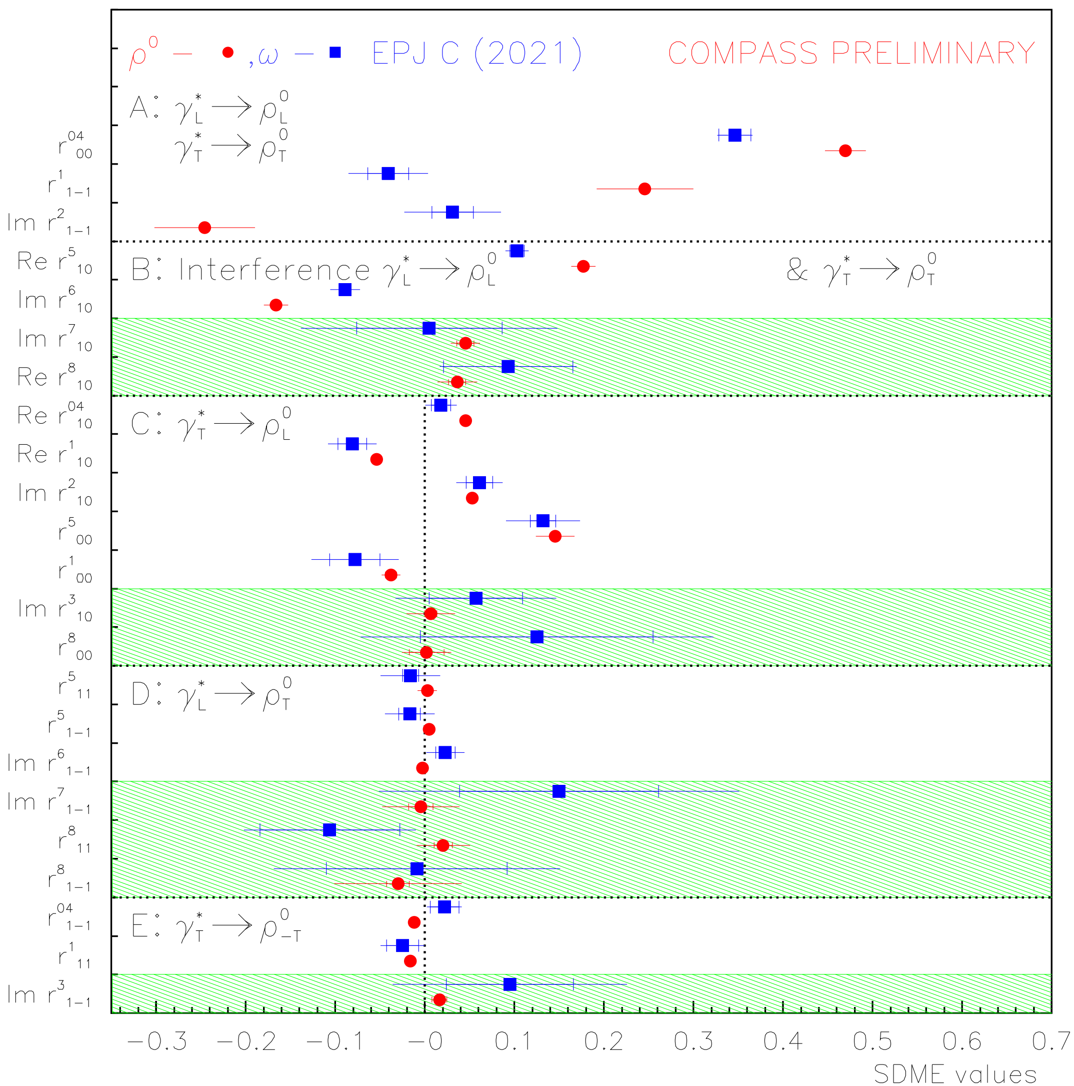
The normalization factor reads correspondingly

$$\widetilde{\mathcal{N}}(\mathcal{R},\mathcal{B}) = \sum_{j=1}^{N_{MC}} [(1-f_{bg})*\mathcal{W}^{U+L}(\mathcal{R};\Phi_j,\phi_j,\cos\Theta_j) + f_{bg}*\mathcal{W}^{U+L}(\mathcal{B};\Phi_j,\phi_j,\cos\Theta_j)].$$

SDME comparison with HERMES



SDME comparison with Omega



SDMEs and Amplitudes for: ρ^0

A- SCHC $\gamma^*_L \to \rho_L$ **and** $\gamma^*_T \to \rho_T$

$|T_{11}|^2 \propto 1 - r^{04}_{00} \propto r^1_{1-1} \propto$ -Im$\{r^2_{1-1}\}$

B- Interference: $\gamma^*_L \to \rho_L$ **and** $\gamma^*_T \to \rho_T$

Re$\{T_{00}T^*_{11}\} \propto$ Re $\{r^5_{10}\} \propto$ -Im$\{r^6_{10}\}$

Im $\{T_{11}T^*_{00}\} \propto$ Im $\{r^7_{10}\} \propto$ Re$\{r^8_{10}\}$

C- Spin Flip: $\gamma^*_T \to \rho_L$

Re$\{T_{11}T^*_{01}\} \propto$ Re$\{r^{04}_{10}\}$

$\propto$ Re $\{r^1_{10}\} \propto$ Im $\{r^2_{10}\}$

Re $\{T_{01}T^*_{00}\} \propto r^5_{00}$

$|T_{01}|^2 \propto r^1_{00}$

Im $\{T_{01}T^*_{11}\} \propto$ Im$\{r^3_{10}\}$

Im $\{T_{01}T^*_{00}\} \propto r^8_{00}$

D-Spin Flip: $\gamma^*_L \to \rho_T$

Re $\{T_{10}T^*_{11}\} \propto r^5_{11} \propto r^5_{1-1} \propto$ Im$\{r^6_{1-1}\}$

Im $\{T_{10}T^*_{11}\} \propto$ Im $\{r^7_{1-1}\} \propto r^8_{11} \propto r^8_{1-1}$

E- Double Spin Flip: $\gamma^*_T \to \rho_{-T}$

Re$\{T_{1-1}T^*_{11}\} \propto r^{04}_{1-1} \propto r^1_{11}$

Im $\{T_{1-1}T^*_{11}\} \propto$ Im $\{r^3_{1-1}\}$