Spin Density Matrix Elements in Exclusive Muoproduction of ρ^0 and ω Mesons at COMPASS

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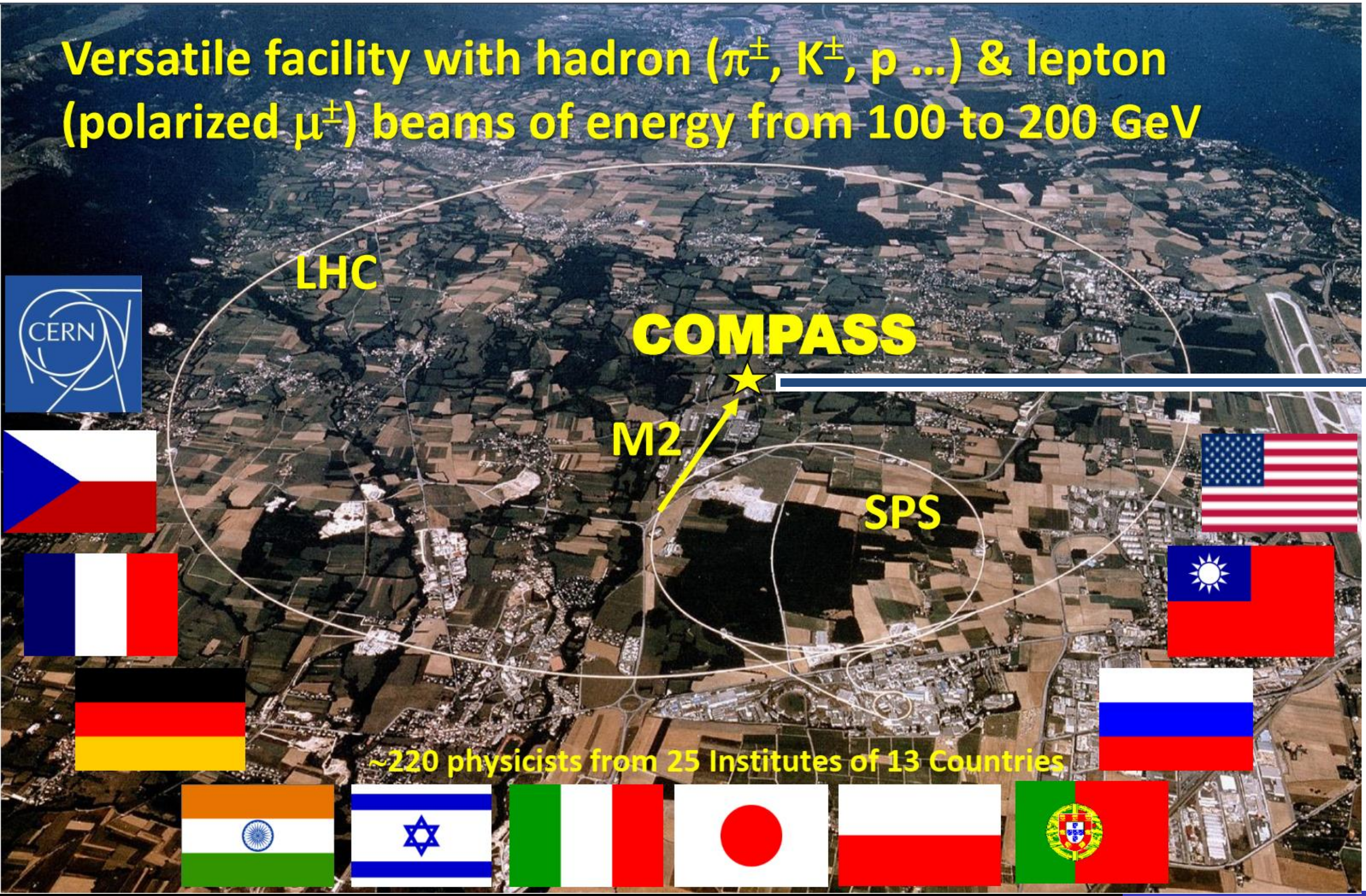
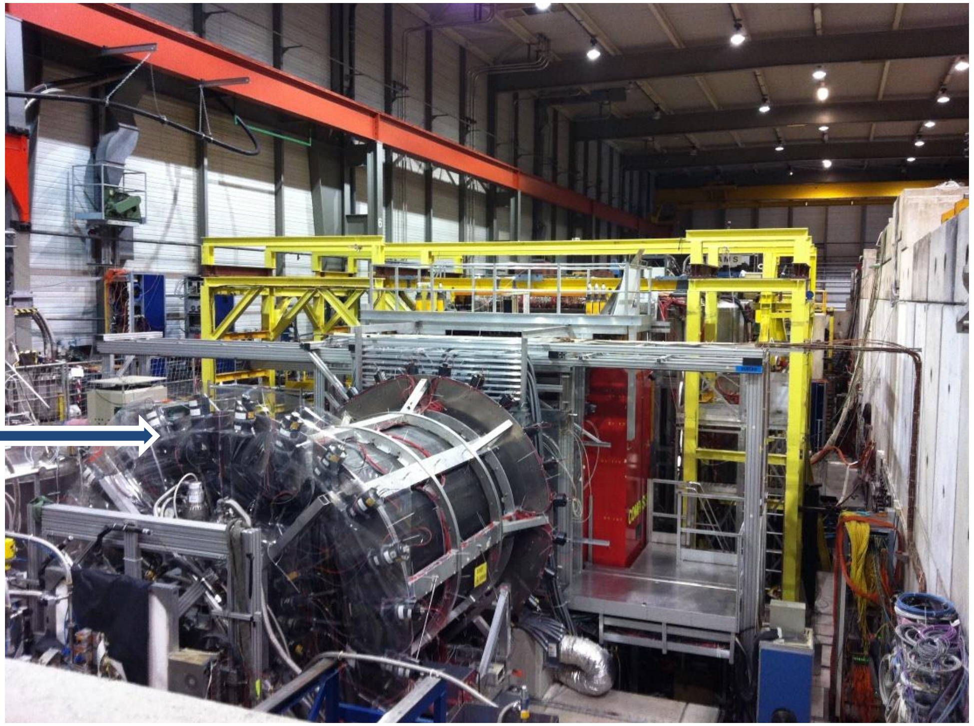
COMPASS Experiment

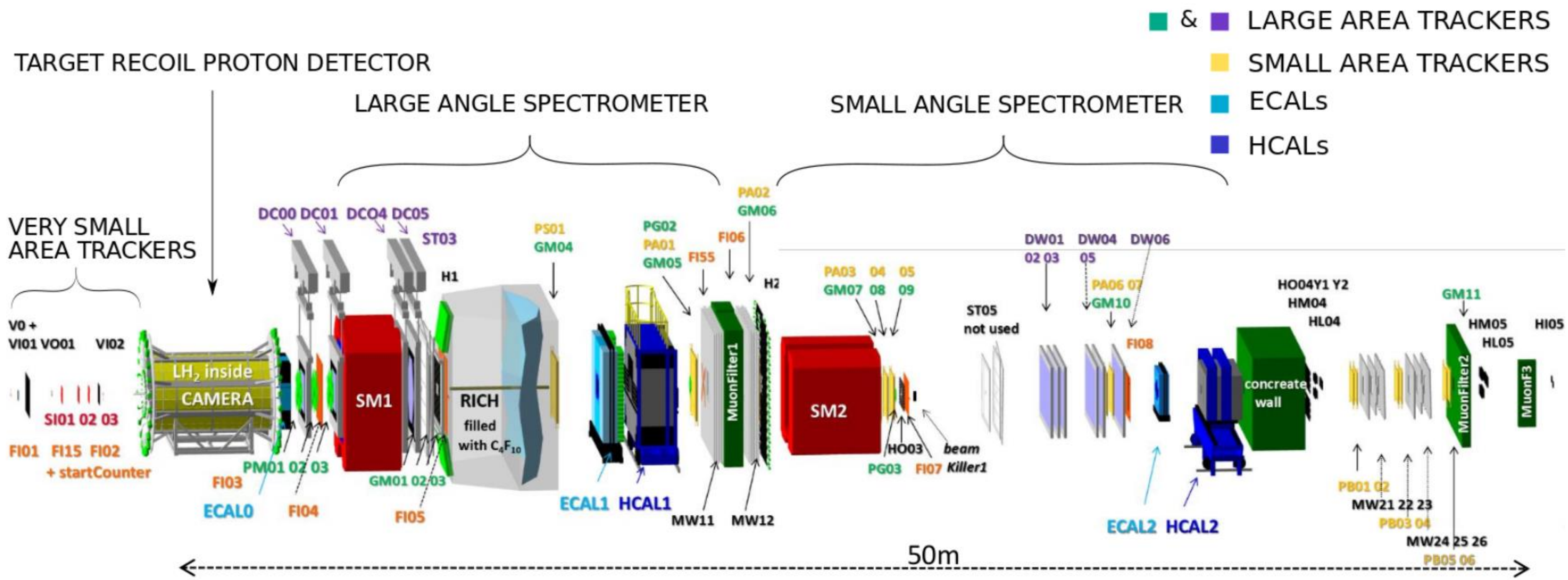
COmmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy





data taking 2002 – 2022 & longitudinally, transversely or unpolarized targets

COMPASS Experiment – setup and data



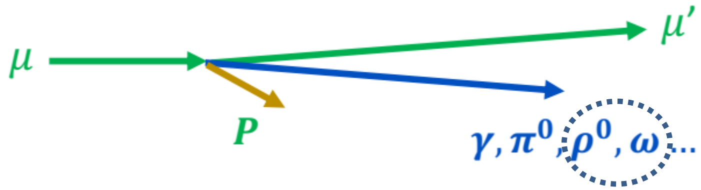
NIMA 577 (2007) 455–518
&
NIMA 779 (2015) 69

μ+, μ- beams
- data separately

polarization ~ ±80%

energy 160 GeV

Exclusive Muoproduction



2.5m long LH_2 target

results in this talk: data from 2012 pilot run (4 weeks)

Hard Exclusive Meson Production (HEMP)

Selection

Common selection: $\mathbf{1} < \boldsymbol{Q^2} < \mathbf{10}$ $(\text{GeV}/c)^2$, $\boldsymbol{W} > \mathbf{5}$ GeV/c^2, $\mathbf{0.01} < \boldsymbol{p_T^2} < \mathbf{0.5}$ $(\text{GeV}/c)^2$, $\mathbf{0.1} < \boldsymbol{y} < \mathbf{0.9}$

Recoil proton detector not included in selection

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$$\mu + p \rightarrow \mu' + p' + \omega$$

$\hookrightarrow \pi^+ + \pi^- + \pi^0$ Branching ratio ≈ 89 %

$\hookrightarrow \gamma_l + \gamma_h$ Branching ratio ≈ 99 %

$$0.1 < M_{\gamma\gamma} < 0.17 \text{ GeV}, 0.71 < M_{\pi^+\pi^-\pi^0} < 0.86 \text{ GeV}$$

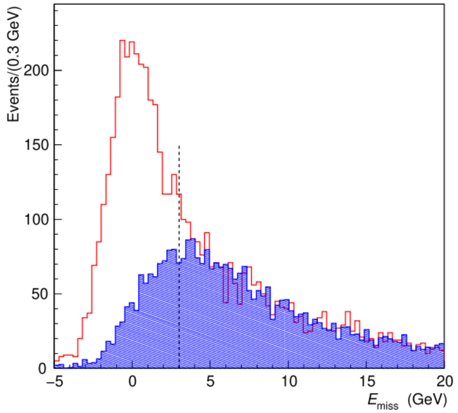
topology:

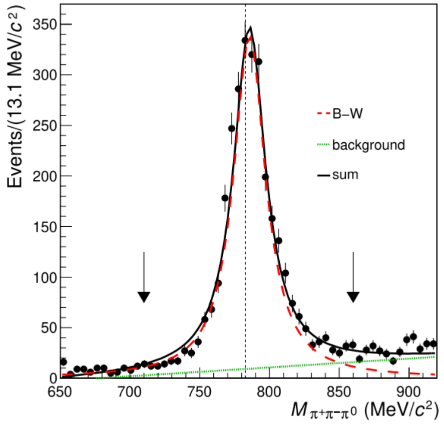
scattered muon + two hadrons with opposite charges + two neutral clusters in calorimeters

event yield: 3060 events

$|E_{\text{miss}}| < 3$ GeV

$$E_{\text{miss}} = \frac{M_X^2 - M^2}{2M}$$





Preliminary

$$\mu + p \rightarrow \mu' + p' + \rho^0$$

$\hookrightarrow \pi^+ + \pi^-$ Branching ratio ≈ 99 %

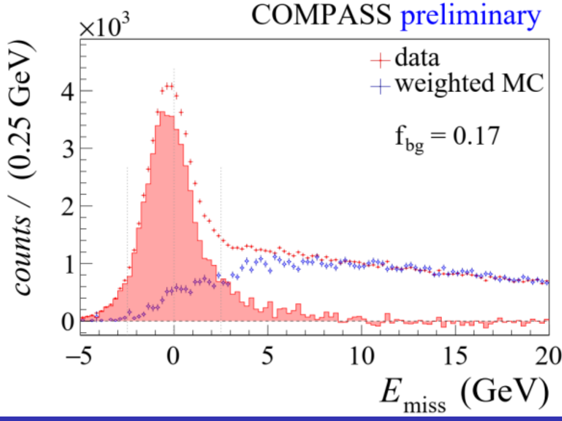
$$0.5 < M_{\pi^+\pi^-} < 1.1 \text{ GeV}$$

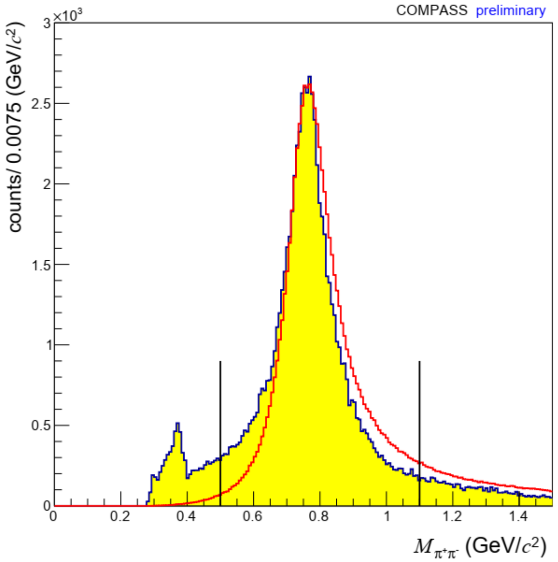
topology:

scattered muon + two hadrons with opposite charges

event yield: 52257 events

exclusivity: $|E_{\text{miss}}| < 2.5$ GeV





Vector meson spin-density matrix

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

helicity of vector meson *V*

helicities of virtual photon *γ* and nucleon *N*

photon spin density matrix ($\mu \to \mu' + \gamma^*$); calculable on QED

$$\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} = \varrho^{U}_{\lambda_\gamma \lambda'_\gamma} + P_b\, \varrho^{L}_{\lambda_\gamma \lambda'_\gamma}$$

- *F* helicity amplitudes describe transitions $\lambda_\gamma, \lambda_N \to \lambda_V, \lambda'_N$, depend on W, Q^2, p_T^2
- $\rho_{\lambda_V \lambda'_V}$ decomposes into 9 matrices $\rho^{\alpha}_{\lambda_V \lambda'_V}$ corresponding to different photon polarization states (α=0-3 transverse, α=4 longitudinal, α=5-8 interference amplitudes)
- if not possible to separate long. and transv. photon contributions, SDMEs are defined:

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

$R = d\sigma_L / d\sigma_T$ diff. longitudinal-to-transverse cross-section ratio of virtual photons and ε is the virtual-photon polarization parameter

23 SDMEs

Vector Meson SDMEs and GPDs

- access to helicity amplitudes F allows:
  - test of s-channel helicity conservation SCHC ($\lambda_\gamma = \lambda_V$)
  - decomposition into Natural (N) and Unnatural (U) Parity Exchange (NPE/UPE)
    in Regge framework: NPE $J^P = (0^+, 1^-, ...)$ (pomeron, ρ, ω, a_2…); UPE $J^P = (0^-, 1^+, ...)$ (π, a_1 …)
  - quantify the role of transitions with helicity flip $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$
  - determination of the longitudinal-to-transverse cross-section ratio
  - test of GPD models
    like SCHC-violating transitions $\gamma_T \rightarrow V_L$ to test sensitivity to GPDs with helicity-flip of „active“ quark (transversity GPDs)
- GPDs in HEMP: 4 chiral-even

$H^q(x, \xi, t)$	$E^q(x, \xi, t)$	**For Vector Meson**
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$	**For Pseudo-Scalar Meson**

  4 chiral-odd or transversity (not in DVCS)

$H_T^q(x, \xi, t)$	$E_T^q(x, \xi, t)$	$\bar{E}_T^q = 2\tilde{H}_T^q + E_T^q$
$\tilde{H}_T^q(x, \xi, t)$	$\tilde{E}_T^q(x, \xi, t)$	

  - universality of GPDs, quark flavor filter,
  additional non-perturbative term from meson wave function, insights into reaction mechanism

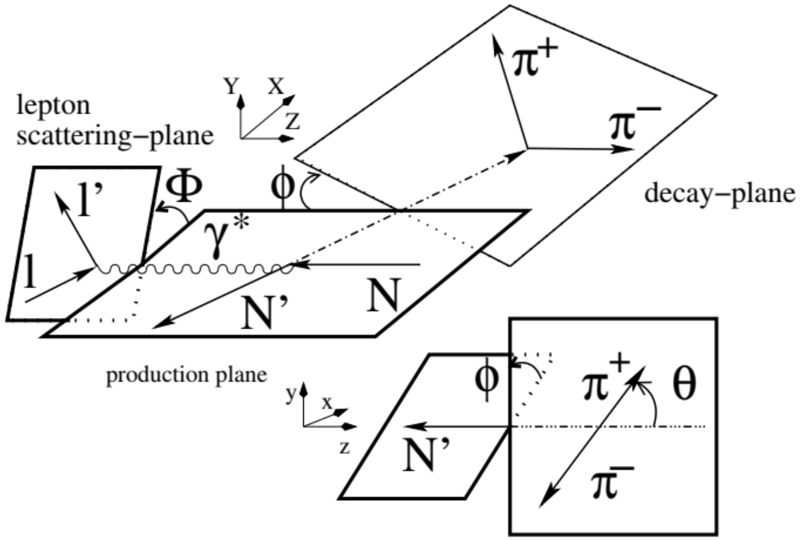
Experimental access to SDMEs

- through angular distribution K. Schilling and G. Wolf, Nucl. Phys. B **61**, 381(1973)

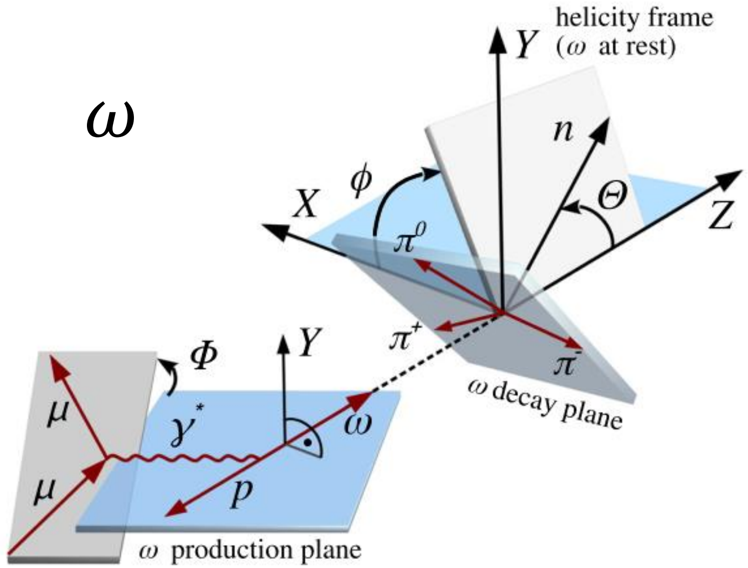
  $\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta)=\mathcal{W}^{U}(\Phi,\phi,\cos\Theta)+P_b\mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$
- decomposition into 23 terms with different angular dependences
  - 15 unpolarized - $\mathcal{W}^U$ and 8 polarized - $\mathcal{W}^L$
- extraction of SDMEs:
  - Unbinned Maximum Likelihood fit to experimental function $\mathcal{W}(\mathcal{R},\Phi,\phi,\cos\Theta)$, $\mathcal{R}$ is set of 23 SDMEs
  - total acceptance
  - fraction of background f_{bg}
  - angular distribution of background

    $\mathcal{W}^{U+L}(\mathcal{B},\Phi,\phi,\cos\Theta)$

ρ_0



ω



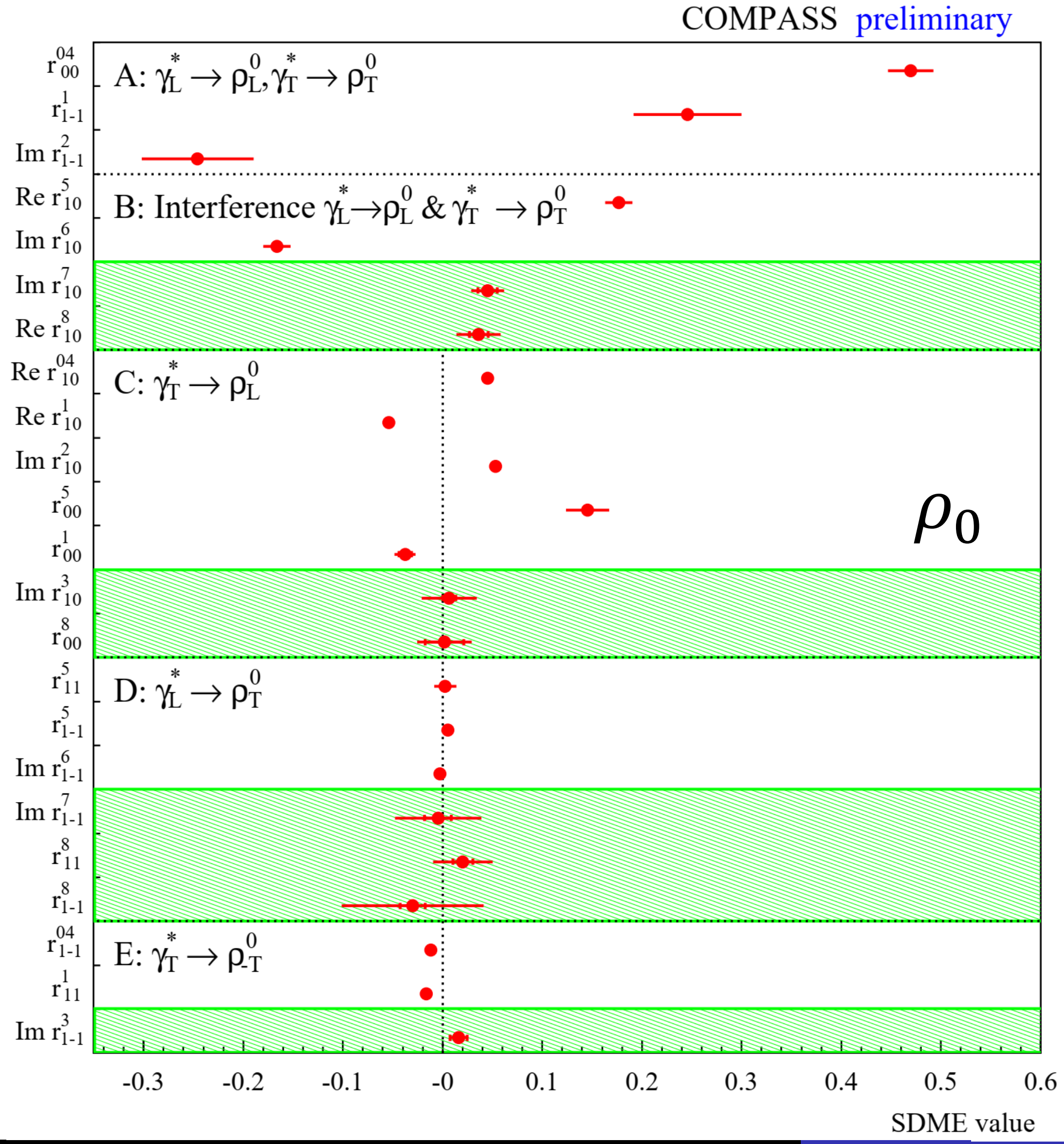
Results

$1 < Q^2 < 10$ (GeV/c)^2
$5 < W < 17$ GeV/c^2
$0.01 < p_T^2 < 0.5$ (GeV/c)^2

A, B, C, D, E classes corresponding to different helicity transitions

shaded areas show SDMEs related to beam polarization

GK model:
EPJA 50 (2014) 146
parameters constrained mostly by HERMES results for ρ^0 and ω



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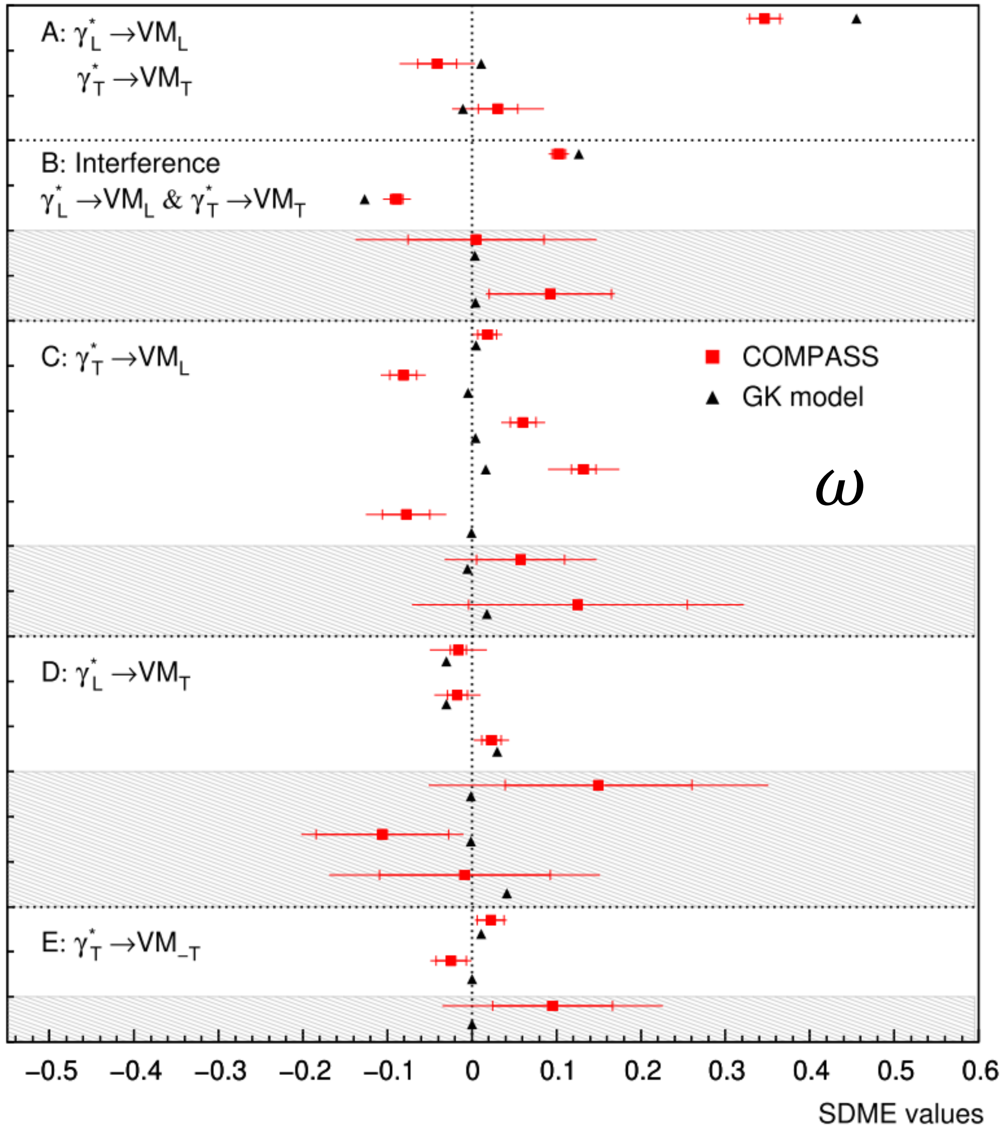


Results - SCHC

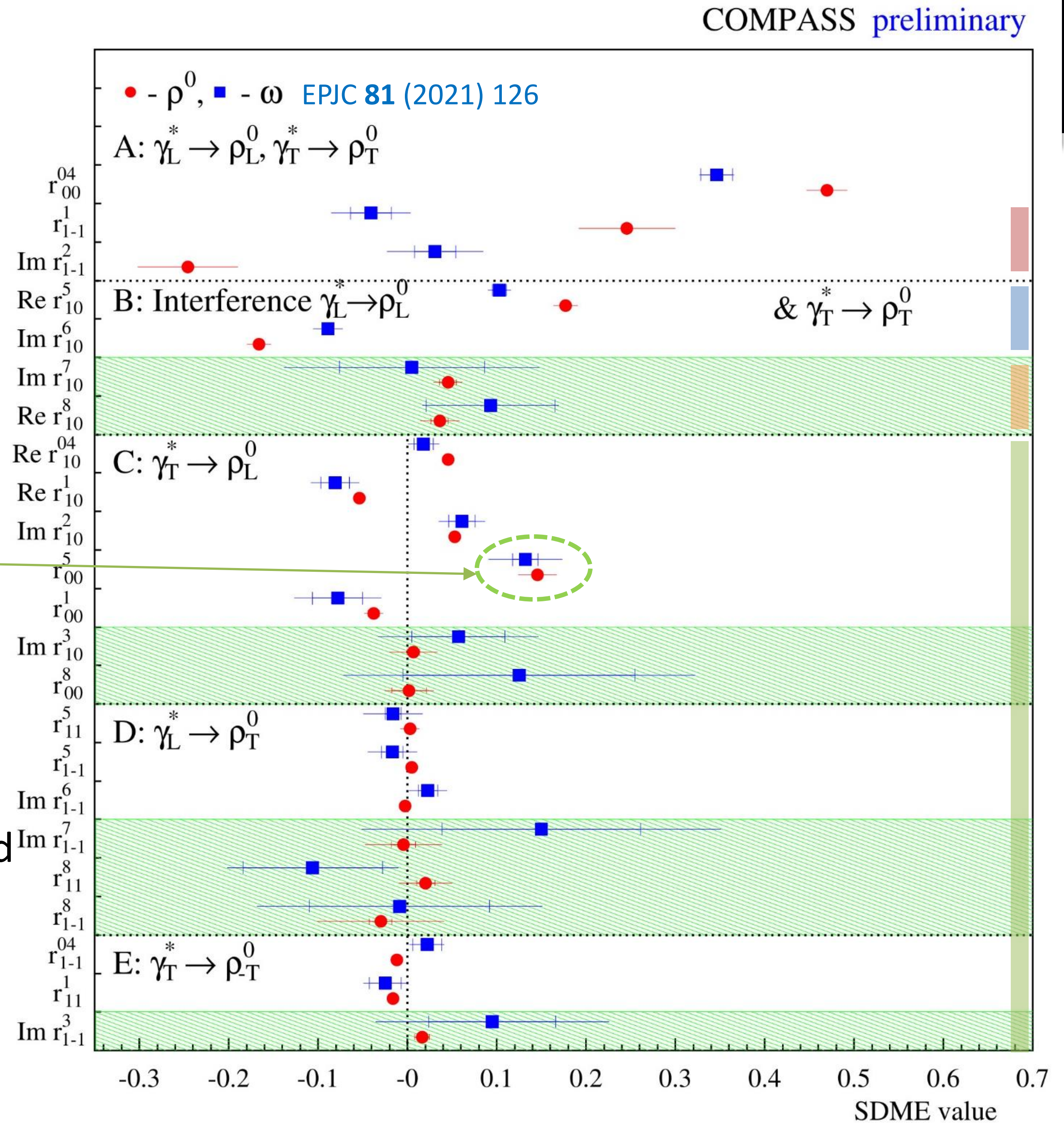
- SCHC implies:
  - $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$ **OK**
  - $\mathrm{Re}\, r^5_{10} + \mathrm{Im}\, r^6_{10} = 0$ **OK**
  - $\mathrm{Im}\, r^7_{10} + \mathrm{Re}\, r^8_{10} = 0$ **OK**

all elements of classes C, D, E should be 0

- not observed in class C – transition $\gamma_T^* \to \rho_L^0$
- possible GPD interpretation **Goloskokov and Kroll, EPJC 74 (2014) 2725**:
- contribution of amplitudes depending on chiral-odd ("transversity") GPDs $H_T, \bar{E}_T = 2\widetilde{H}_T + E_T$

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

- first term dominates, r^5_{00} essentially probes $\bar{E}_T$



Results – Helicity-Flip NPE Amplitudes ρ^0

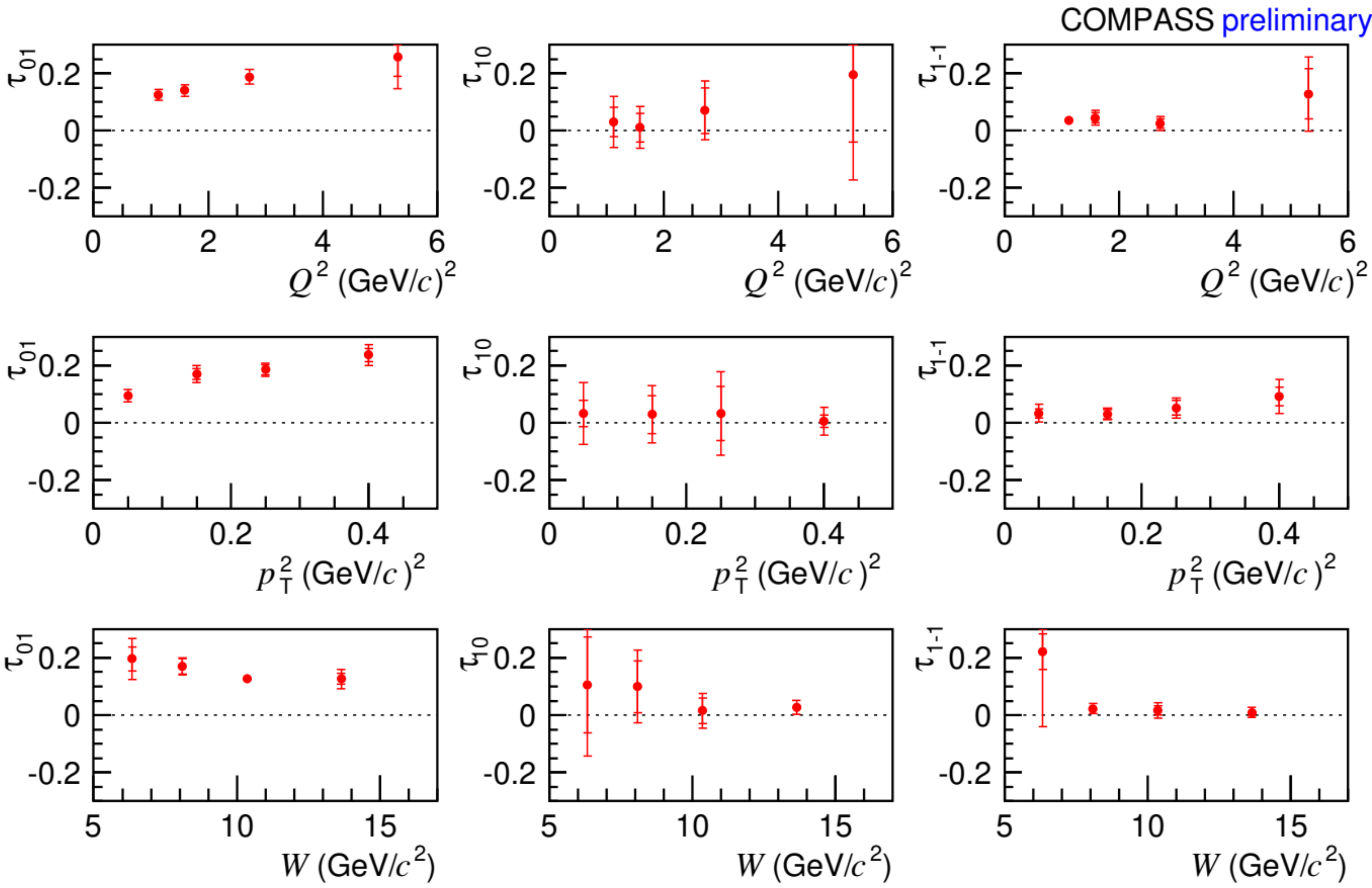
- described as $\tau_{ij} = \frac{|T_{ij}|}{\mathcal{N}}$

$$\tau_{01} \approx \sqrt{\epsilon}\frac{\sqrt{(r^5_{00})^2 + (r^8_{00})^2}}{\sqrt{2r^{04}_{00}}} \qquad \gamma^*_T \to \rho^0_L$$

$$\tau_{10} = \frac{\sqrt{(r^5_{11} + \mathrm{Im}\{r^6_{1-1}\})^2 + (\mathrm{Im}\{r^7_{1-1}\} - r^8_{11})^2}}{\sqrt{2(r^1_{1-1} - \mathrm{Im}\{r^2_{1-1}\})}} \qquad \gamma^*_L \to \rho^0_T$$

$$\tau_{1-1} = \frac{\sqrt{(r^1_{11})^2 + (\mathrm{Im}\{r^3_{1-1}\})^2}}{\sqrt{r^1_{1-1} - \mathrm{Im}\{r^2_{1-1}\}}} \qquad \gamma^*_T \to \rho^0_{-T}$$

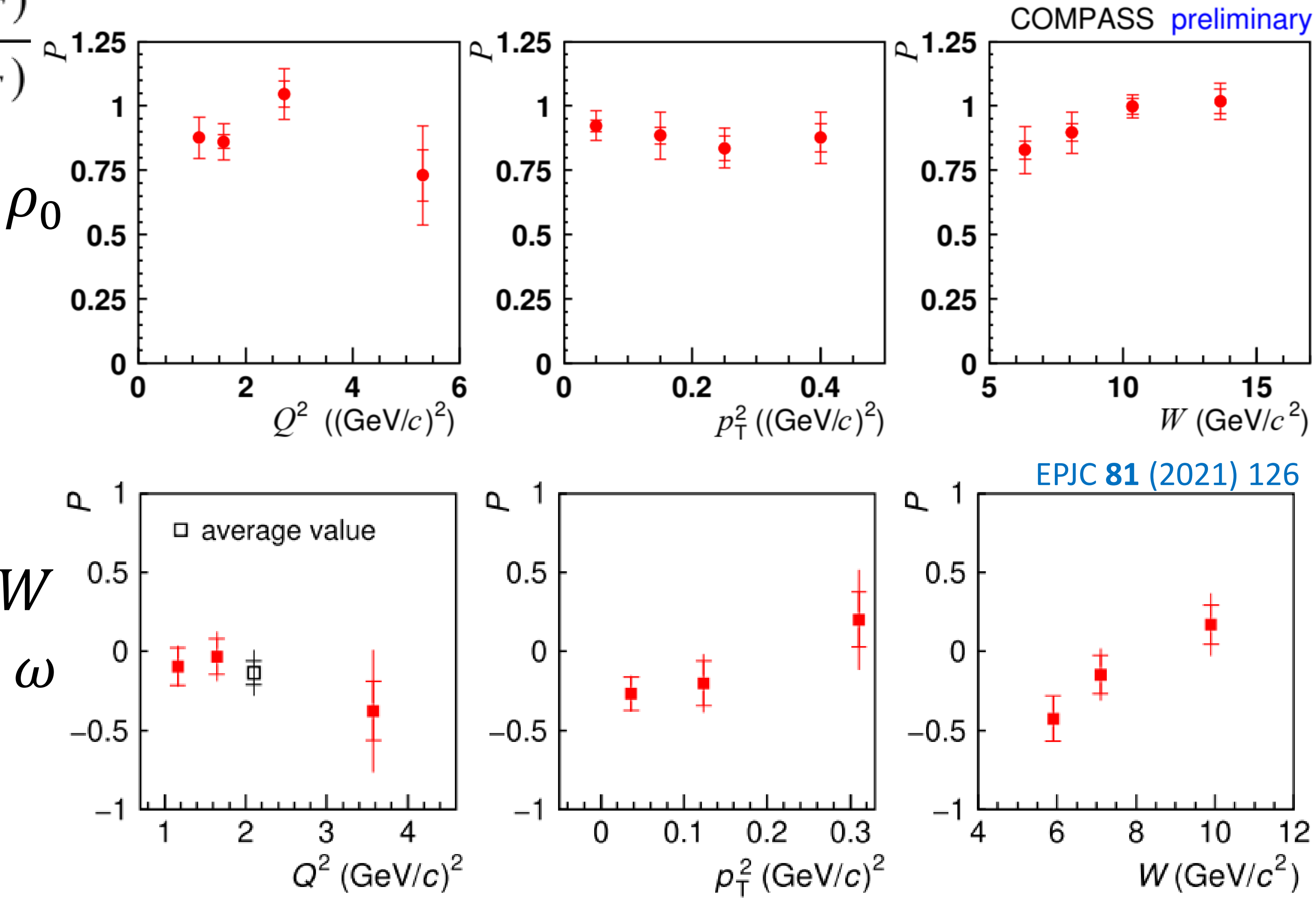
- only τ_{01} significantly differs from 0, consistent with SCHC violation in C, D, E



Results – NPE to UPE asymmetry

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

- ρ_0 NPE dominance
  NPE $\longrightarrow$ GPDs E, H
- ω NPE≈UPE on average
  UPE dominance at small W and p_T^2
  UPE $\longrightarrow$ GPDs $\tilde{E}, \tilde{H}$
  + pion pole (dominant)



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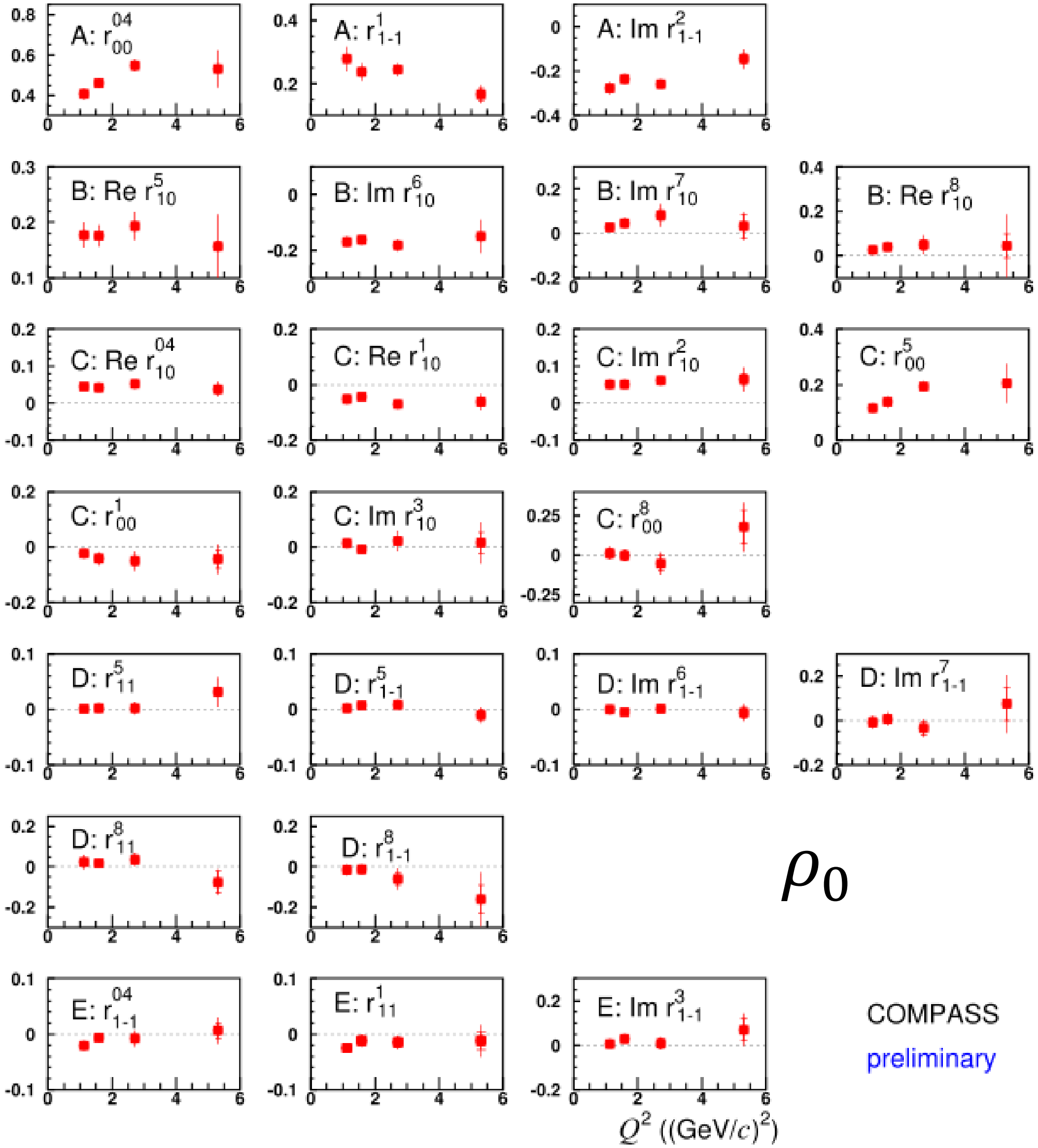
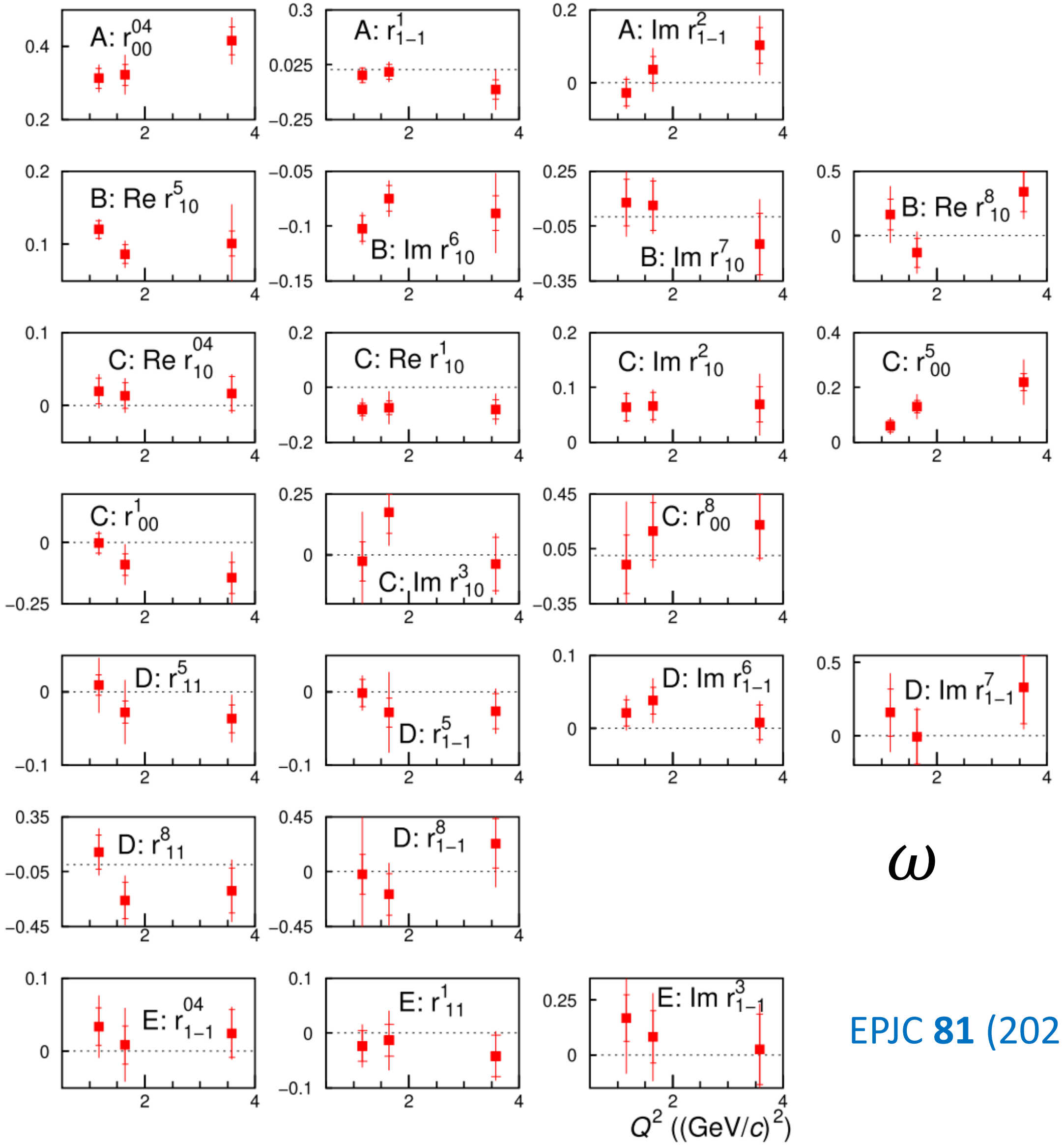
Summary and outlook

- measured 23 SDMEs in HEMP ρ^0 and ω muoproduction
  - for kinematic range: $\mathbf{1 < Q^2 < 10}$ $(\mathrm{GeV}/c)^2$, $\mathbf{5 < W < 17}$ GeV/c^2, $\mathbf{0.01 < p_T^2 < 0.5}$ $(\mathrm{GeV}/c)^2$
  - with dependences on W, Q^2, p_T^2
- hypothesis of SCHC is violated for transitions $\gamma_T^* \to \rho_L^0$
  - in GPD framework described by contribution of chiral-odd "transversity" GPD
  - corresponding τ_{01} helicity-flip NPE amplitudes in ρ^0 observed with dependences on W, Q^2, p_T^2
  - observed also at other experiments HERMES, CLAS, H1 and ZEUS
- NPE dominant in ρ^0 => role of GPDs E and H
- NPE≈UPE in ω => role of GPDs $E, H, \tilde{E}, \tilde{H}$ and pion pole
- on-going analysis of 2016-17 data (~9 times larger statistics)

Thank you for your attention

SDMEs dependences





ω

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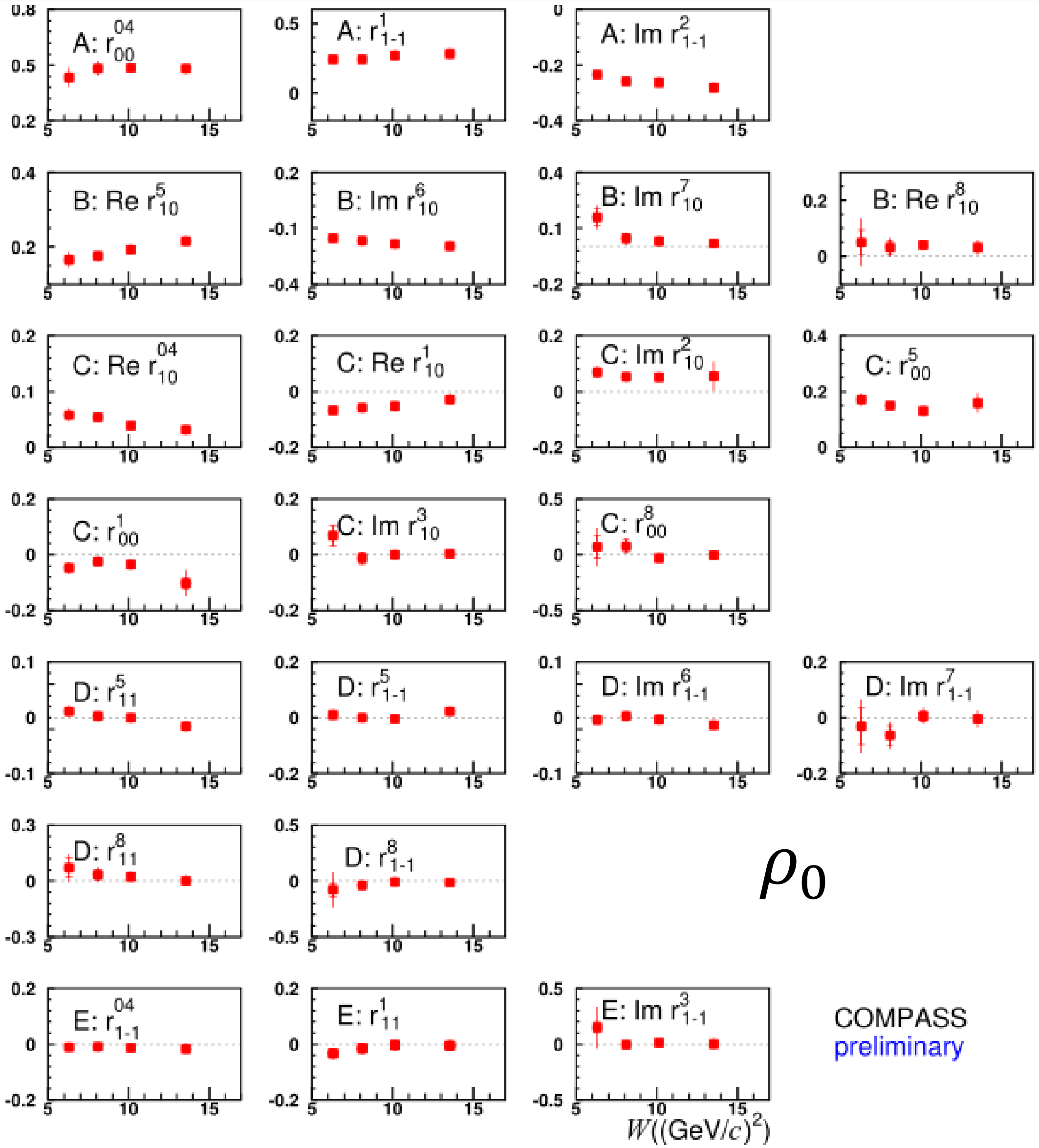
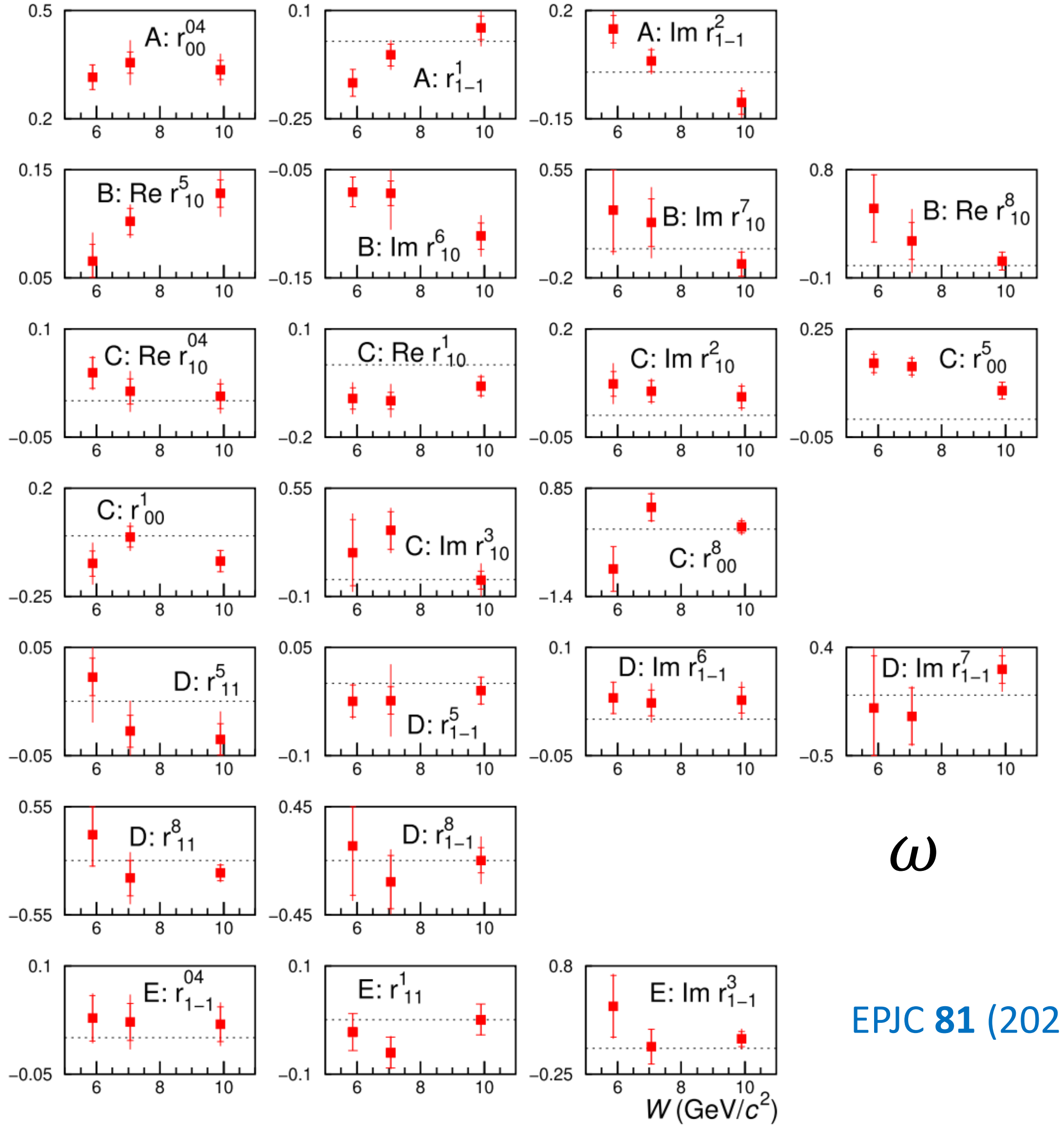
SDMEs dependences



ρ_0

COMPASS preliminary



ω

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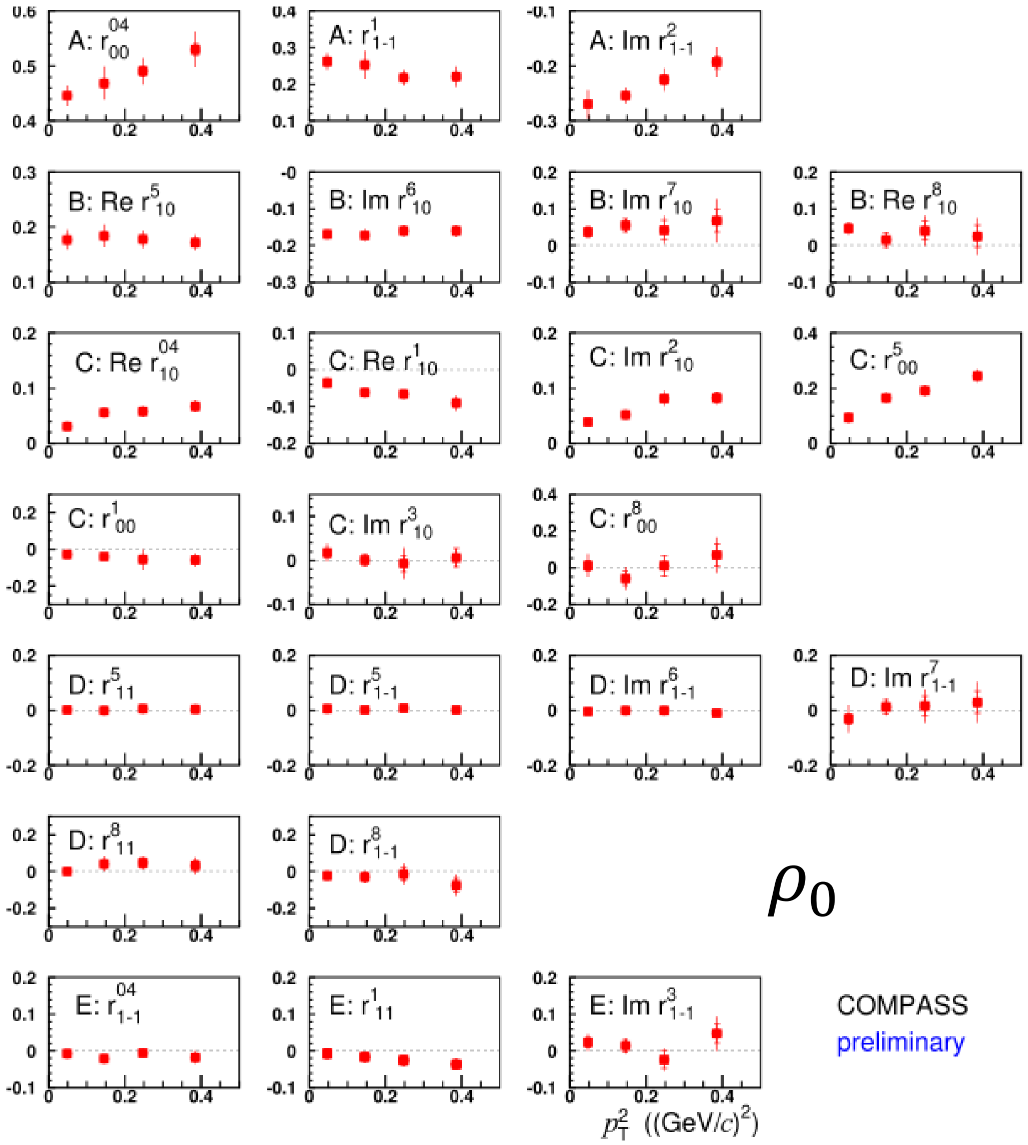
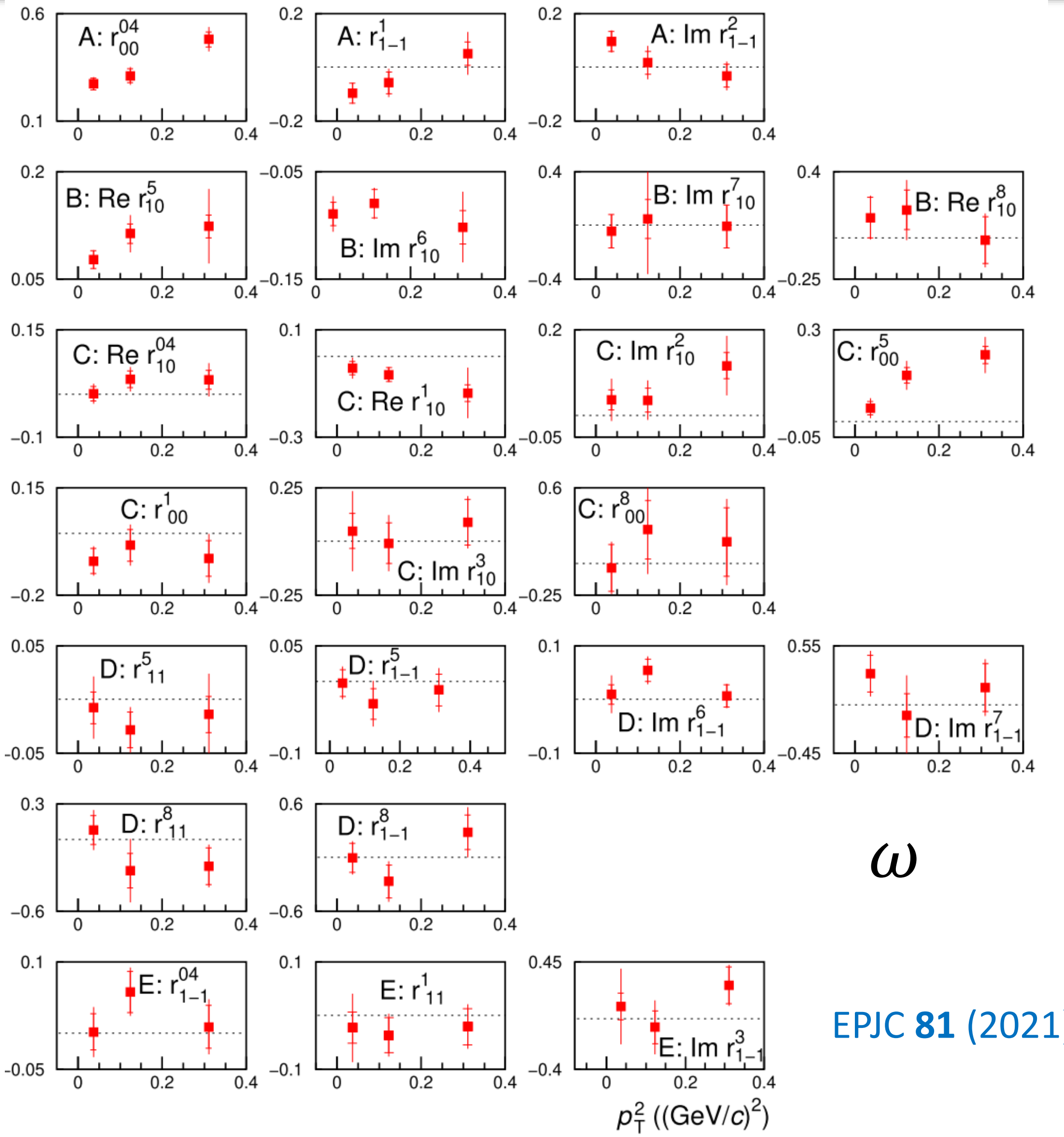
SDMEs dependences



ρ_0



ω

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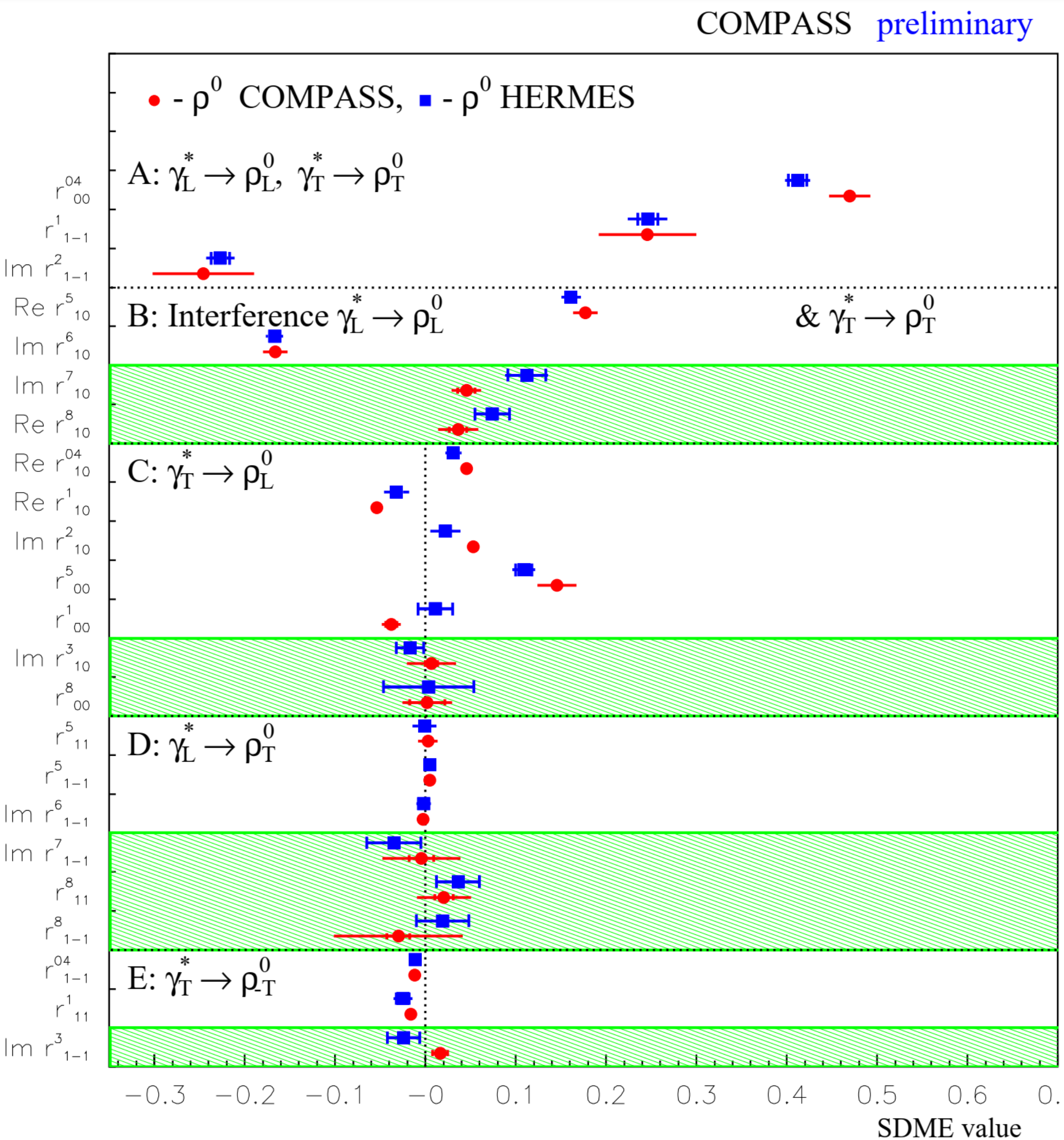
SDMEs comparison with HERMES

HERMES SDMEs results:
ω - EPJC **74** (2014) 3110,
ρ^0 - EPJC **62** (2009) 659–695



Unnatural Parity Exchange contribution ρ^0

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

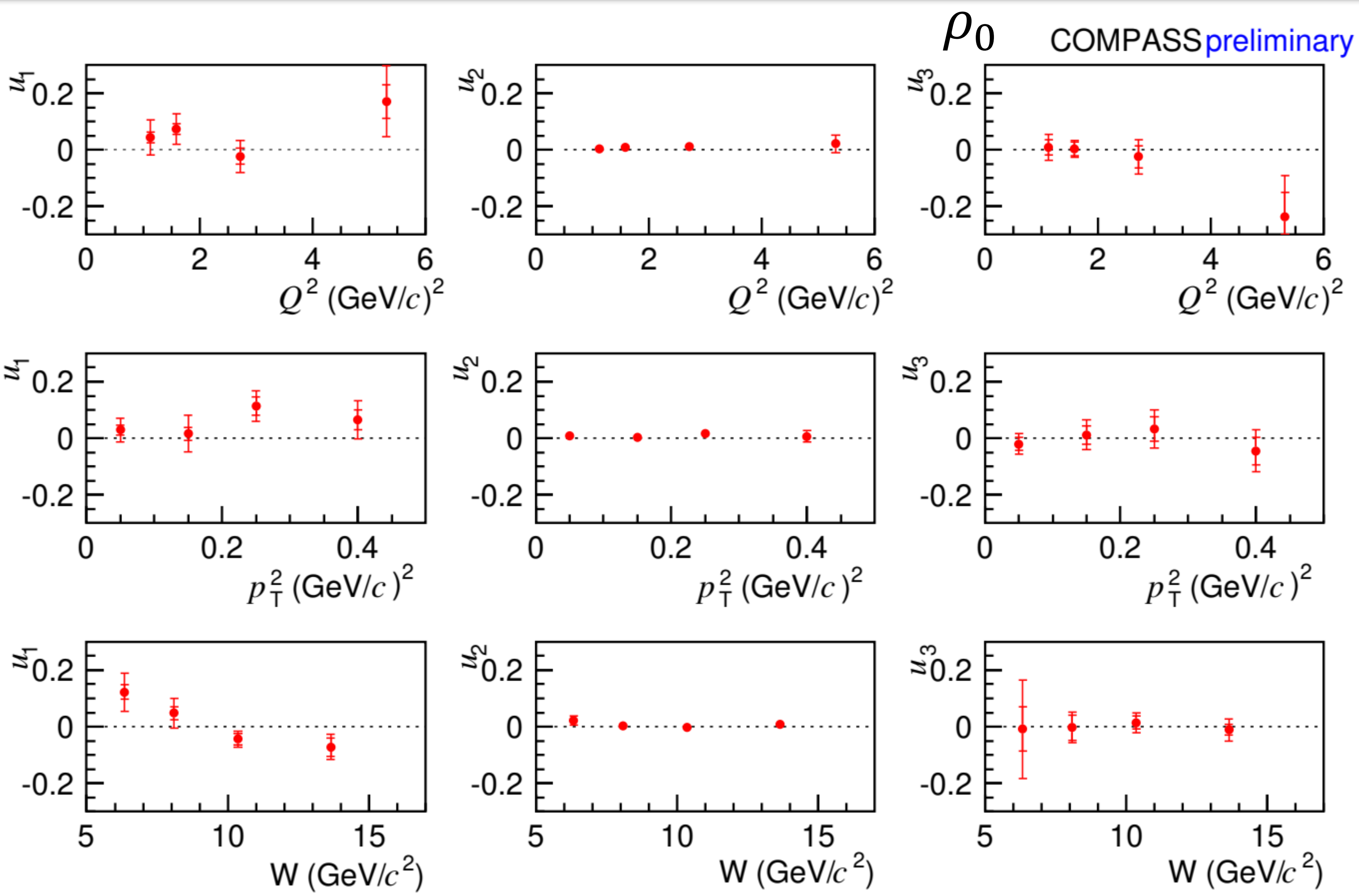
$$u_1 = \widetilde{\sum} \frac{4\epsilon|U_{10}|^2 + 2|U_{11} + U_{-11}|^2}{\mathcal{N}}$$

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

$$u_3 = r^{8}_{11} + r^{8}_{1-1}$$

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

- numerator in u_1 depends only on UPE amplitudes -> u_1>0
- very small UPE contribution observed in ρ^0
- τ^2_{UPE} 0.03 averaged



Unnatural Parity Exchange contribution ω

- ω large UPE contribution decreasing with increasing *W* in u_1
- u_2 and u_3 consistent with zero

$$\tau^2_{\mathrm{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$$

- UPE fractional contribution: τ^2_{UPE} = 0.5 ⟶ 0.3