SDME measurements at COMPASS for exclusive VMs: recent highlights

Kamil Augsten (CTU in Prague) on behalf of COMPASS



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FORTE

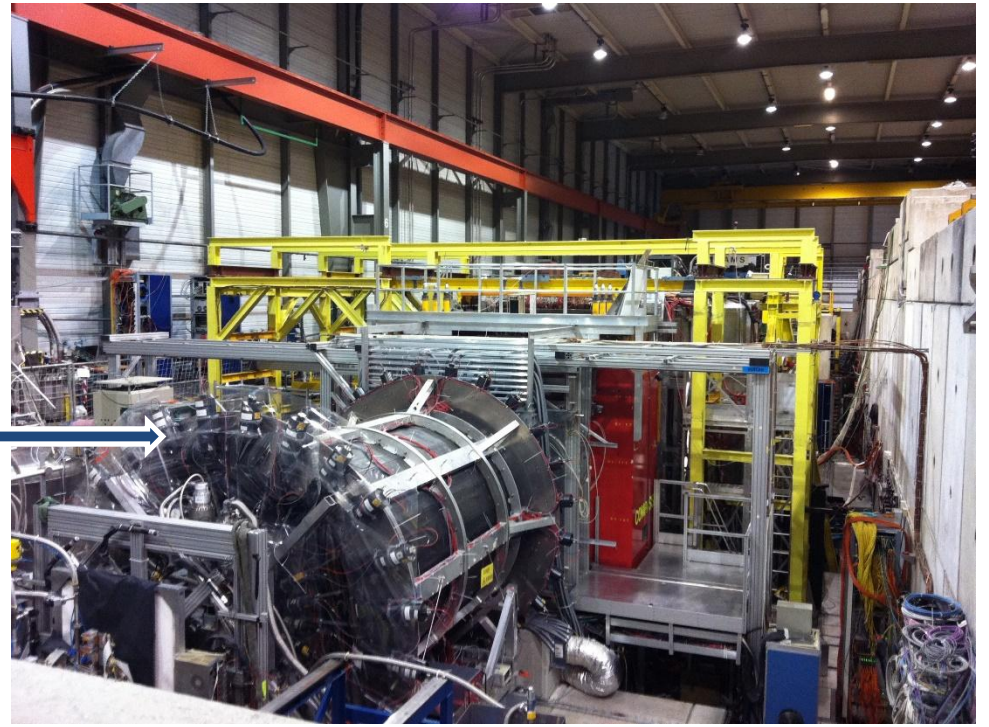
COMPASS 25 years 1997 - 2022

COMPASS Experiment

see talk by: *Franco Bradamante*

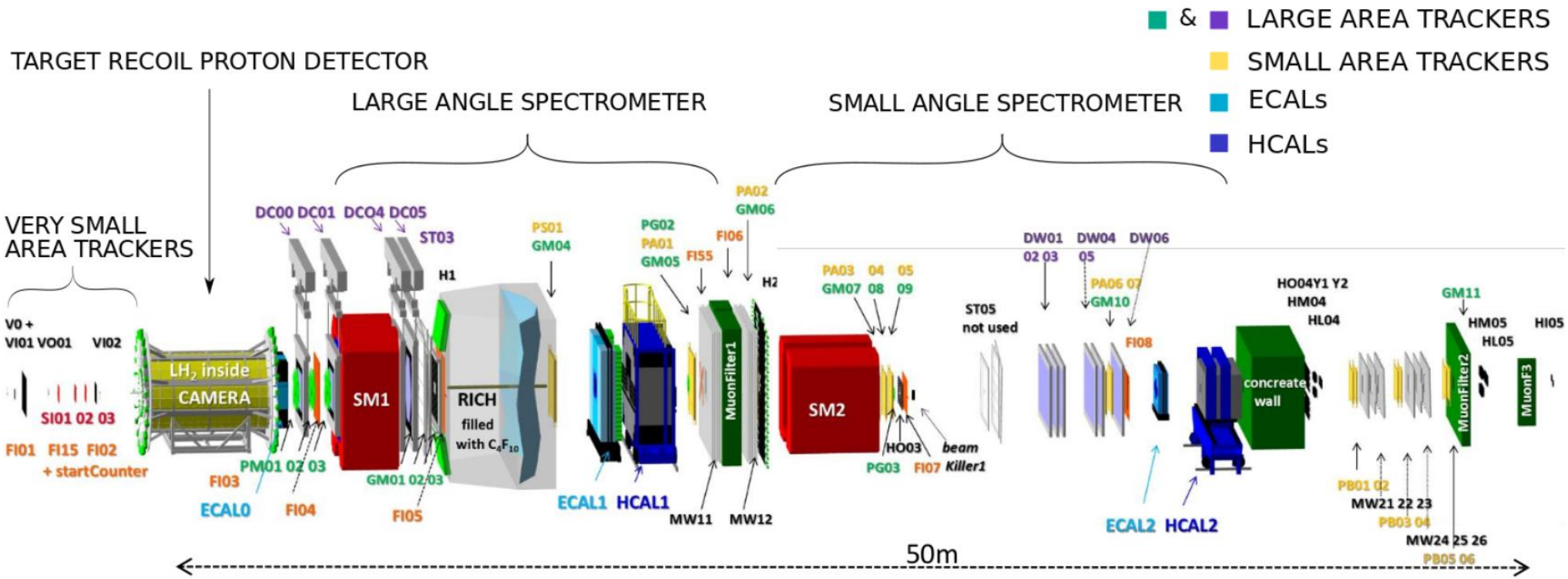
COmmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy





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

COMPASS Experiment – Setup



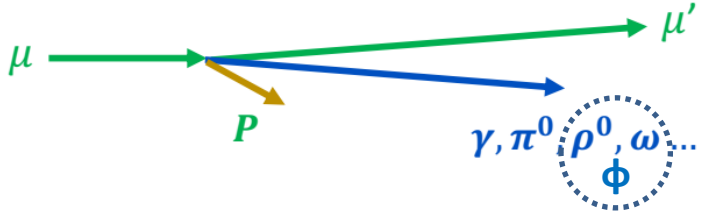
NIMA 577 (2007) 455–518
&
NIMA 779 (2015) 69

μ^+, μ^- beams

polarisation ~ ±80%

energy 160 GeV

Exclusive Muoproduction

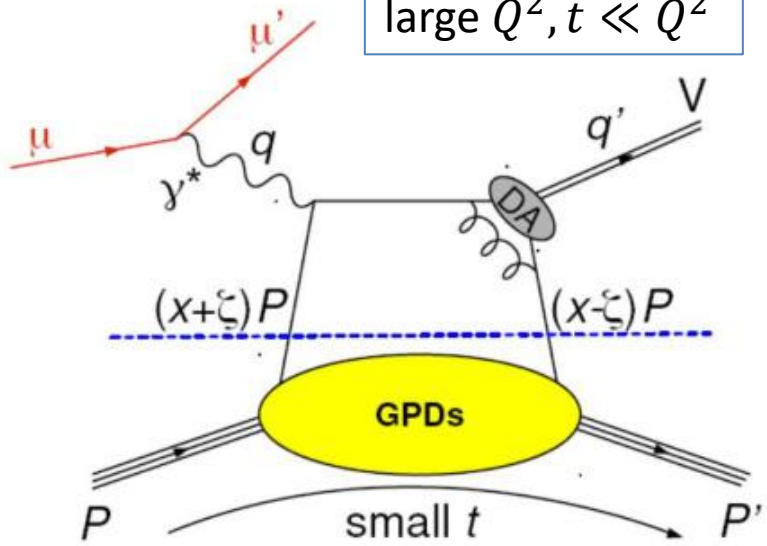


2007 (DIS&SIDIS): μ^+p @160 GeV, **T polarised NH_3 target**
2010 (SIDIS): μ^+p @160 GeV, **T polarised NH_3 target**
2012 pilot run (DVCS/HEMP/SIDIS): μ^+&μ^-p @160 GeV, **unpolarised LH_2 target**
2016-17 (DVCS/HEMP/SIDIS): μ^+&μ^-p @160 GeV, **unpolarised LH_2 target**

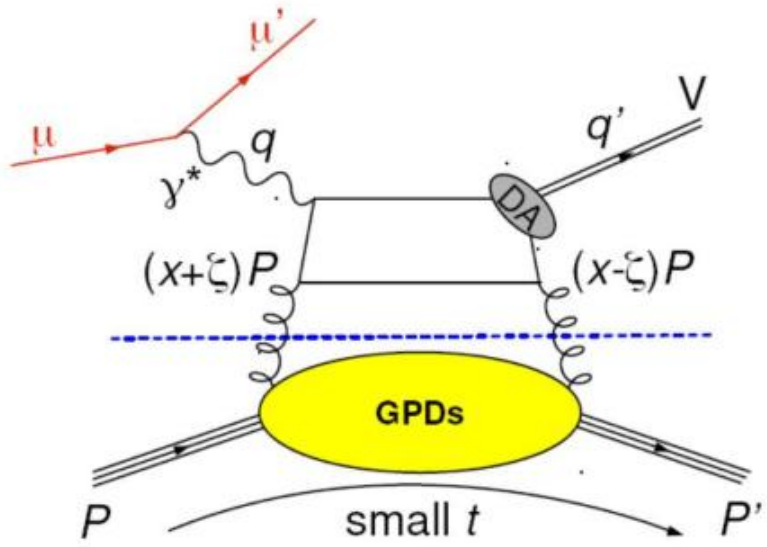
GPDs and Hard Exclusive Meson Production

quark contribution

large $Q^2, t \ll Q^2$



gluon contribution



- Meson described by **Distribution Amplitude (DA)** (additional non-perturbative input)
- **Quark & gluon contributions** enter at the same order in α_s (for vector mesons)
- **Flavour filtering:** different mesons → access to **parton-specific GPDs**
  - Vector mesons → H, E
  - Pseudoscalar mesons → $\widetilde{H}, \widetilde{E}$
  - All mesons → chiral-odd $\bar{E}_T, \widetilde{E}_T, H_T, \widetilde{H}_T$
- $E_{\rho_0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g/x\right)$
- $E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}E^g/x\right)$
- $E_{\phi} = -\frac{1}{3}E^s + \frac{1}{4}E^g/x$

$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

COMPASS can measure ω, ρ⁰, ϕ, (J/ψ)

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

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

- **Helicity amplitudes *F*:** 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 polarisation states (α=0-3 transverse, α=4 longitudinal, α=5-8 interference terms)
- No **L/T separation** at COMPASS → **23** "unseparated" SDMEs:

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

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

$R = d\sigma_L / d\sigma_T$ differential L/T cross-section ratio of virtual photons and ε virtual-photon polarisation

23 SDMEs we actually measure

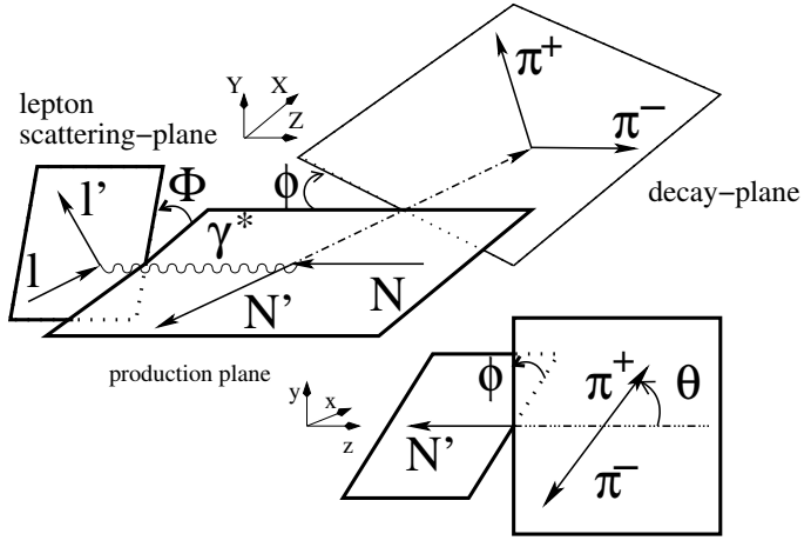
Vector Mesons and GPDs

- **access to helicity amplitudes *F* allows:**
  - Test of **s-channel helicity conservation (SCHC)** ($\lambda_{\gamma^*} = \lambda_V$)
  - **Natural vs. Unnatural Parity Exchange (NPE/UPE)** in Regge framework
    - NPE: $J^P = (0^+, 1^-, \dots)$ → pomeron, ρ, ω, a_2 …
    - UPE: $J^P = (0^-, 1^+, \dots)$ → π, a_1 …
  - Quantify **helicity-flip transitions** $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$
  - Determine $\boldsymbol{\sigma_L/\sigma_T}$ ratio
  - Probe **GPD models** → e.g. SCHC violation ($\gamma_T^* \to V_L$) tests sensitivity to **transversity GPDs** (not accessible in DVCS)
- GPDs in HEMP:
  - 4 chiral-even and 4 chiral-odd/transversity (not in DVCS)
  - universality of GPDs, quark flavour filter, insights into reaction mechanism

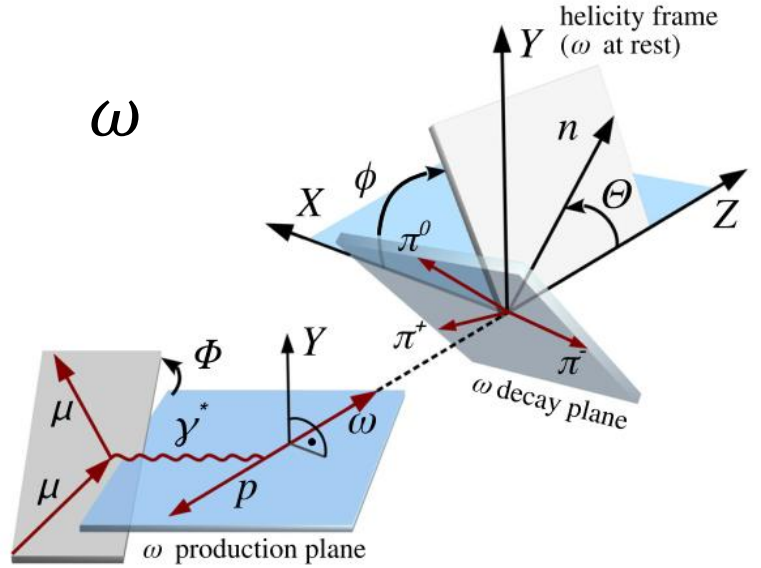
Experimental access to SDMEs

- through angular distribution
  $\mathcal{W}^{U+L}(\Phi, \phi, \cos\Theta) = \mathcal{W}^{U}(\Phi, \phi, \cos\Theta) + P_b \mathcal{W}^{L}(\Phi, \phi, \cos\Theta)$
- decomposition into 23 terms with different angular dependences
  - 15 unpolarised - $\mathcal{W}^U$ and 8 polarised - $\mathcal{W}^L$
- extraction of SDMEs:
  - Unbinned Maximum Likelihood
  - Input:
    1. exp. distribution $\mathcal{W}(\mathcal{R}, \Phi, \phi, \cos\Theta)$, $\mathcal{R}$ is set of 23 SDMEs,
    2. detector efficiency (total acceptance etc.),
    3. fraction of background f_{bg},
    4. angular distribution of background $\mathcal{W}^{U+L}(\mathcal{B}, \Phi, \phi, \cos\Theta)$

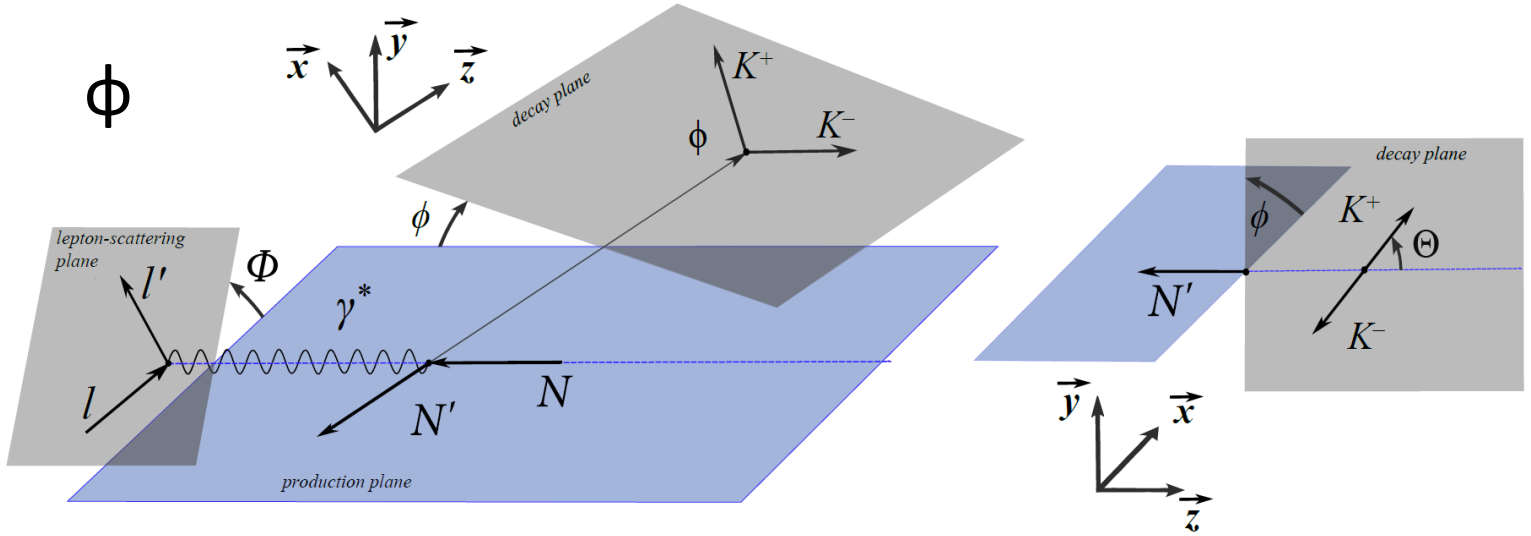
ρ_0



ω



1. Angular distributions



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

$$\cos\phi = \frac{(\mathbf{q}\times\mathbf{v})\cdot(\mathbf{v}\times\mathbf{p}_{\pi^+})}{|(\mathbf{q}\times\mathbf{v})|\cdot|\mathbf{v}\times\mathbf{p}_{\pi^+}|},$$

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

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

$$\cos\Theta = -\frac{\mathbf{P}'\cdot\mathbf{P}_{\pi^+}}{|\mathbf{P}'|\cdot|\mathbf{P}_{\pi^+}|}$$

$$W_U(\phi,\cos\theta) = \frac{3}{8\pi^2}\left[\begin{array}{l}
\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\theta - \\
\sqrt{2}\,\mathrm{Re}\{r^{04}_{10}\}\sin 2\theta\cos\phi - \\
r^{04}_{1-1}\sin^2\theta\cos 2\phi - \\
\varepsilon\cos 2\Phi\left(\begin{array}{l} r^{1}_{11}\sin^2\theta + \\ r^{1}_{00}\cos^2\theta - \\ \sqrt{2}\,\mathrm{Re}\{r^{1}_{10}\}\sin 2\theta\cos\phi - \\ r^{1}_{1-1}\sin^2\theta\cos 2\phi \end{array}\right) - \\
\varepsilon\ \sin 2\Phi\left(\begin{array}{l} \sqrt{2}\,\mathrm{Im}\{r^{2}_{10}\}\sin 2\theta\sin\phi + \\ \mathrm{Im}\{r^{2}_{1-1}\}\sin^2\theta\sin 2\phi \end{array}\right) + \\
\sqrt{2\varepsilon(1+\varepsilon)}\cos\Phi\left(\begin{array}{l} r^{5}_{11}\sin^2\theta + r^{5}_{00}\cos^2\theta - \\ \sqrt{2}\,\mathrm{Re}\{r^{5}_{10}\}\sin 2\theta\cos\phi - \\ r^{5}_{1-1}\sin^2\theta\cos 2\phi \end{array}\right) + \\
\sqrt{2\varepsilon(1+\varepsilon)}\sin\Phi\left(\begin{array}{l} \sqrt{2}\,\mathrm{Im}\{r^{6}_{10}\}\sin 2\theta\sin\phi + \\ \mathrm{Im}\{r^{6}_{1-1}\}\sin^2\theta\sin 2\phi \end{array}\right)
\end{array}\right].$$

$$W_L(\phi,\cos\theta) = \frac{3}{8\pi^2}\left[\begin{array}{l}
\sqrt{1-\varepsilon^2}\left(\begin{array}{l} \sqrt{2}\,\mathrm{Im}\{r^{3}_{10}\}\sin 2\theta\sin\phi + \\ \mathrm{Im}\{r^{3}_{1-1}\}\sin^2\theta\sin 2\phi \end{array}\right) + \\
\sqrt{2\varepsilon(1-\varepsilon)}\cos\Phi\left(\begin{array}{l} \sqrt{2}\,\mathrm{Im}\{r^{7}_{10}\}\sin 2\theta\sin\phi + \\ \mathrm{Im}\{r^{7}_{1-1}\}\sin^2\theta\sin 2\phi \end{array}\right) + \\
\sqrt{2\varepsilon(1-\varepsilon)}\sin\Phi\left(\begin{array}{l} r^{8}_{11}\sin^2\theta + \\ r^{8}_{00}\cos^2\theta - \\ \sqrt{2}\,\mathrm{Re}\{r^{8}_{10}\}\sin 2\theta\cos\phi - \\ r^{8}_{1-1}\sin^2\theta\cos 2\phi \end{array}\right)
\end{array}\right].$$

2. Detector efficiency/acceptance correction

- in the extraction (UML fit) we normalize to HEPGEN (exclusive ρ_0, ω, ϕ… MC generator)

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

$$\widetilde{\mathcal{N}}(\mathcal{R}) = \sum_{j=1}^{N_{\mathrm{MC}}} \mathcal{W}^{U+L}(\mathcal{R};\Phi_j,\phi_j,\cos\Theta_j)$$

$$-\ln L(\mathcal{R}_{\mathrm{sig}}) = -\sum_{i=1}^{N} \ln\left[\frac{(1-f_{\mathrm{bg}})\,\mathcal{W}^{U+L}(\mathcal{R}_{\mathrm{sig}};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R}_{\mathrm{sig}},\mathcal{R}_{\mathrm{bg}})} + \frac{f_{\mathrm{bg}}\,\mathcal{W}^{U+L}(\mathcal{R}_{\mathrm{bg}};\Phi_i,\phi_i,\cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R}_{\mathrm{sig}},\mathcal{R}_{\mathrm{bg}})}\right]$$

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

Selection ρ_0 and ω: 2012 Pilot Run

Common selection: $\mathbf{1 < Q^2 < 10}$ (GeV/c)^2, $\boldsymbol{W > 5}$ GeV/c^2, $\mathbf{0.01 < p_T^2 < 0.5}$ (GeV/c)^2, $\mathbf{0.1 < y < 0.9}$
Recoil proton detector not included in selection

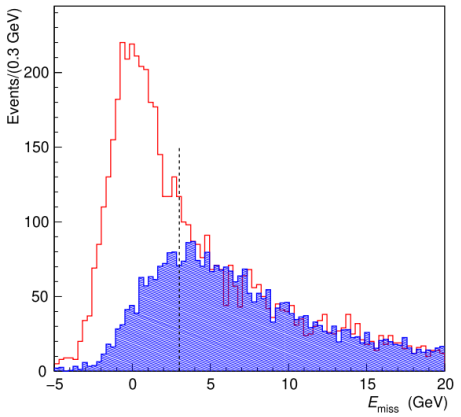
$\mu + p \rightarrow \mu' + p' + \omega$ EPJC (2021) **81** 126

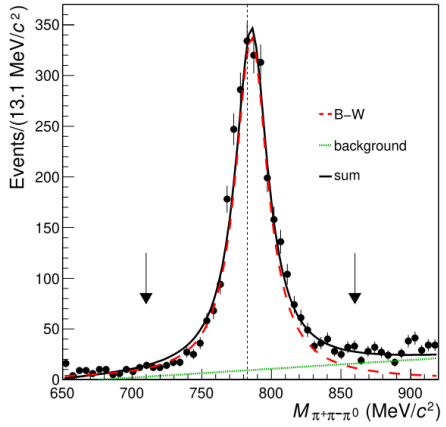
$\hookrightarrow \pi^+ + \pi^- + \pi^0$ Branching ratio $\approx 89\ \%$

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

$0.1 < M_{\gamma\gamma} < 0.17$ GeV, $0.71 < M_{\pi^+\pi^-\pi^0} < 0.86$ GeV
topology:
scattered muon + two hadrons with opposite charges
+ two neutral clusters in calorimeters
event yield: **3060 events**

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





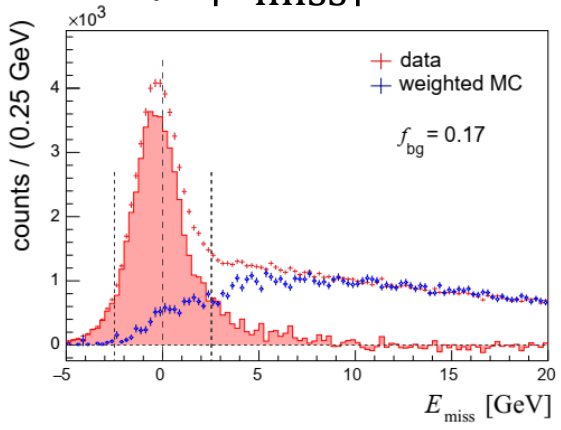
$$E_{\text{miss}} = \frac{M_X^2 - M^2}{2M}$$

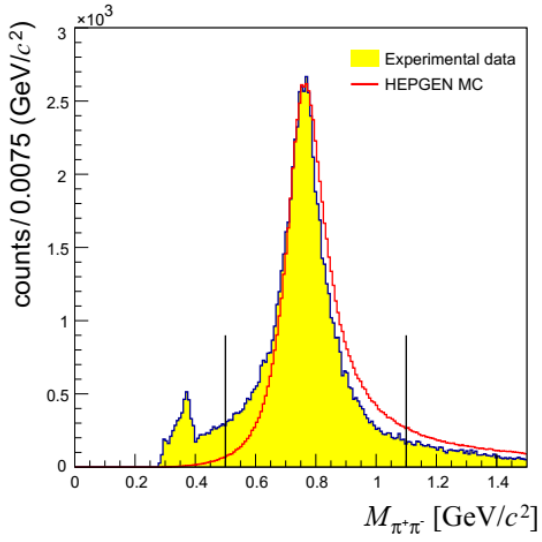
$\mu + p \rightarrow \mu' + p' + \rho^0$ EPJC (2023) **83** 924

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

$0.5 < M_{\pi^+\pi^-} < 1.1$ GeV
topology:
scattered muon + two hadrons with opposite charges
event yield: **52257 events**

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





Selection ϕ: 2016 run DIS2026

- topology: scattered muon + two hadrons with opposite charges
  - $1 < Q^2 < 10\ (\mathrm{GeV}/c)^2$
  - $5 < W < 17\ \mathrm{GeV}/c^2$
  - $0.01 < p_T^2 < 0.5\ (\mathrm{GeV}/c)^2$
  - $0.1 < y < 0.9$
- event yield **6406 events**

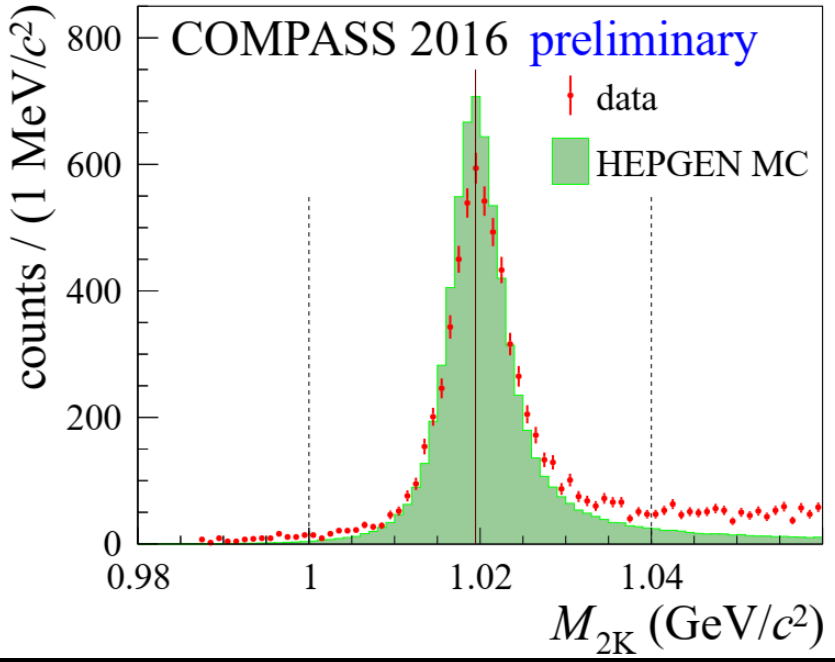
- **Exclusivity**:
- $1.00 < M_{K^+K^-} < 1.04$ GeV
- $\left| E_{\mathrm{miss}} = \frac{M_X^2 - M^2}{2M} \right| < 2.5$ GeV
- Recoil proton detector not included in selection

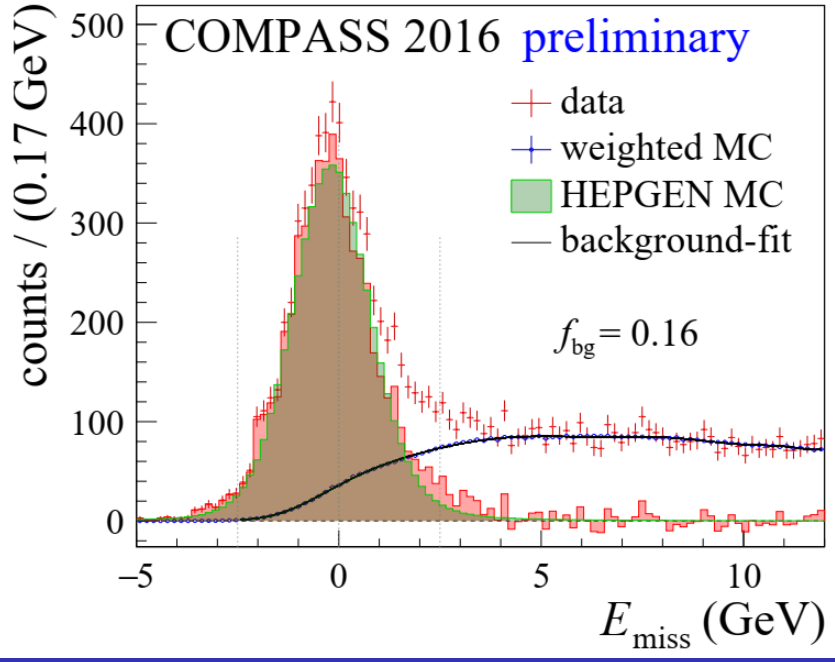
Exclusive Muoproduction



$\mu p \rightarrow \mu' p' \phi$ BR = (48.1 ± 0.5) %

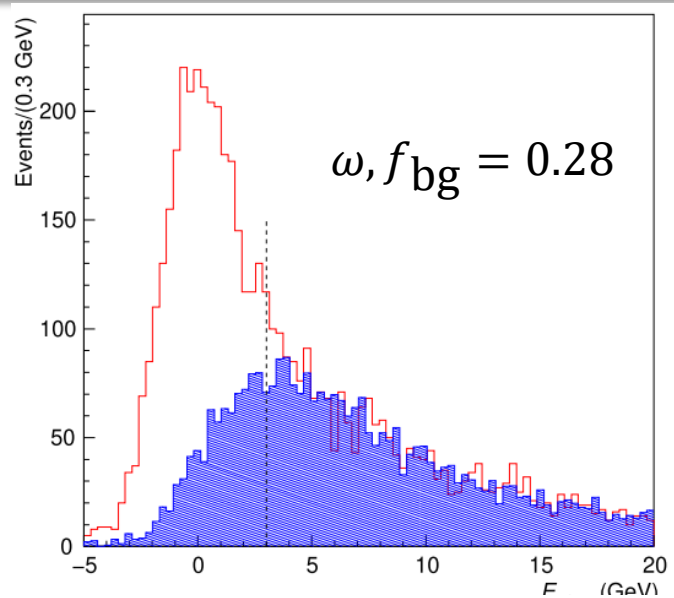
$\rightarrow K^+K^-$

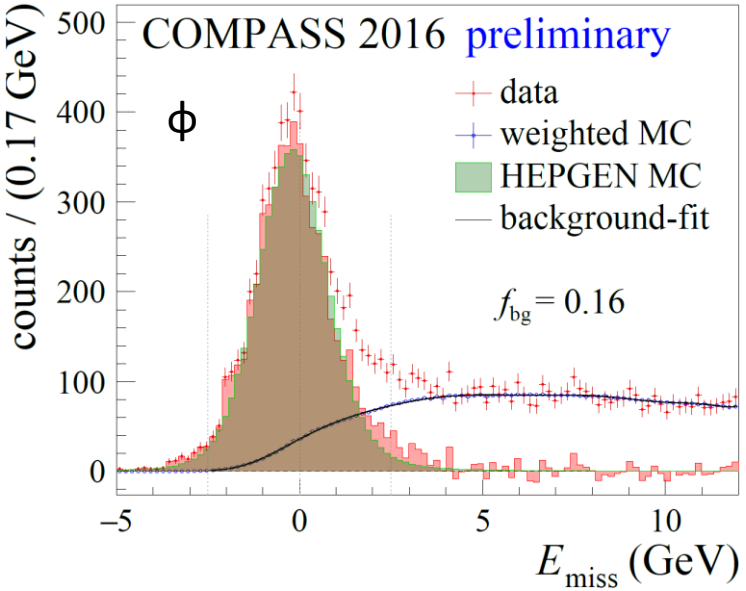


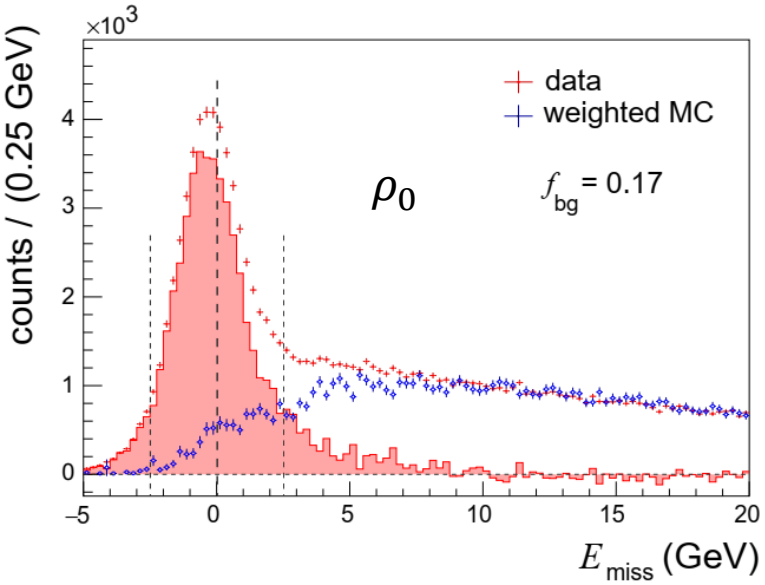


3. background fraction f_{bg}

- ρ_0 and ω (2012 data):
  - MC (inclusive LEPTO) normalized to data in region $7 < E_{miss} < 20$ GeV (same sign) => background fraction in exclusive region (opposite sign)
- for ϕ (2016 data) new procedure:
  - opposite sign LEPTO in widened M_{inv} (0.9-1.4 GeV) with LUJET removal of generated $\phi \to K^+K^-$ signal
  - fit and normalization in $5.0 < E_{miss} < 12.0$ GeV

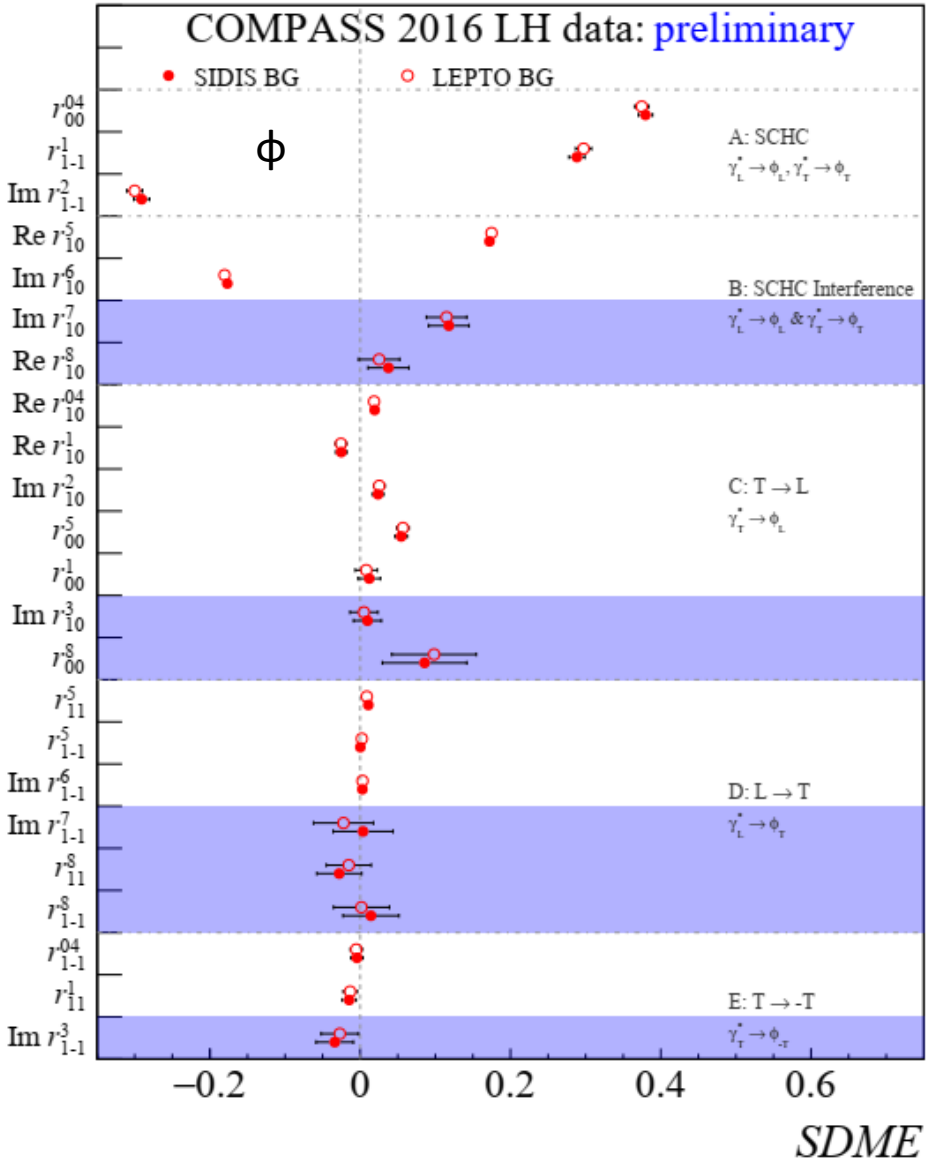






4. background angular distribution/SDMEs

- ρ_0 and ω (2012 data):
  - simulated by LEPTO
  - UML fit to LEPTO to obtain background SDMEs
- ϕ (2016 data) new method:
  - data-driven SIDIS side-band:
    $3 < E_{miss} < 6$ GeV and
    $0.9 < M_{inv} < 1.4$ GeV
  - comparison to LEPTO method -> systematic uncertainty



Exclusive ρ_0 and ω SDMEs Results

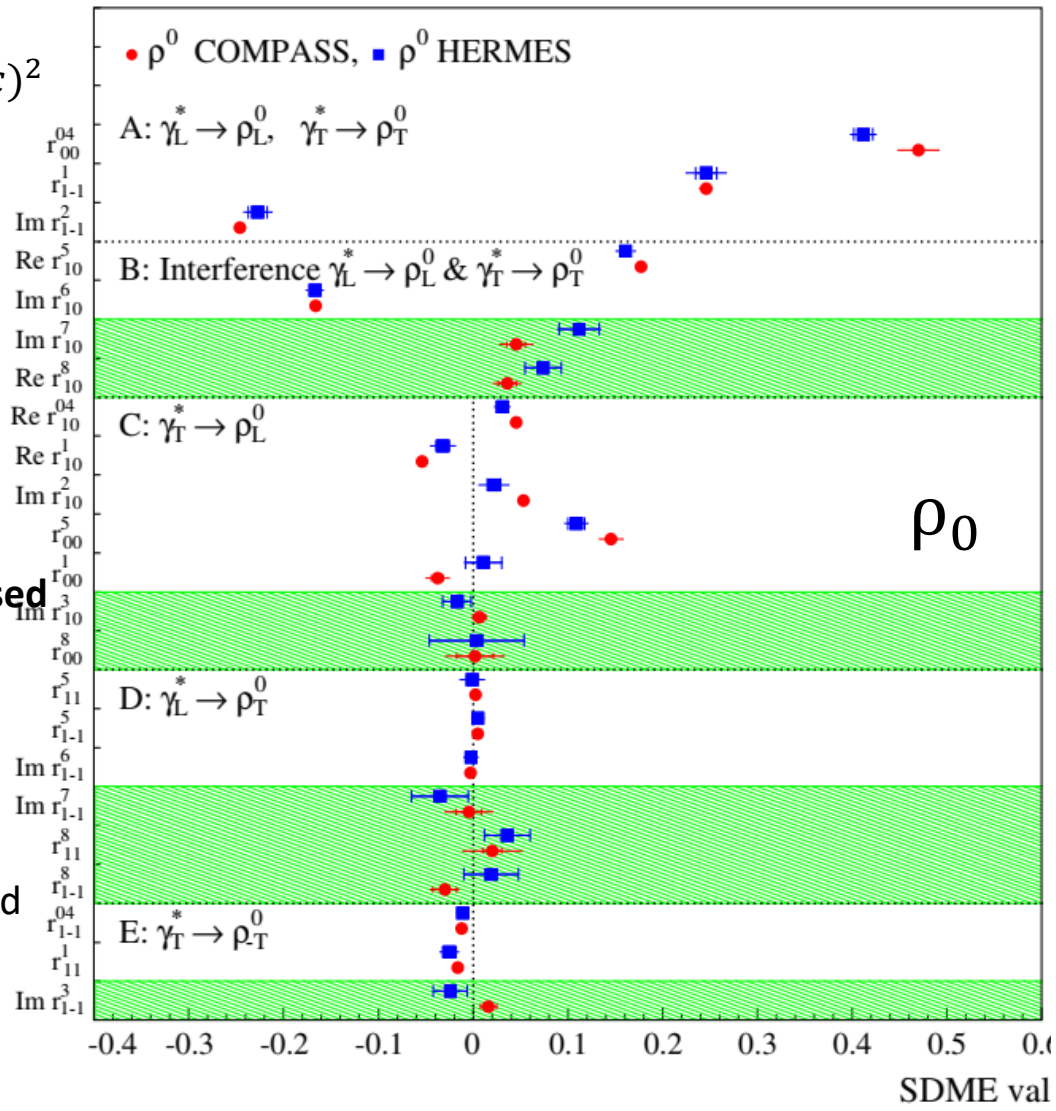
Kinematic range:
$\mathbf{1 < Q^2 < 10}$ $(\mathrm{GeV}/c)^2$
$\mathbf{5 < W < 17}$ GeV/c^2
$\mathbf{0.01 < p_T^2 < 0.5}$ $(\mathrm{GeV}/c)^2$

SDME classes (A–E):
Different helicity transitions
(γ,N→V,N')

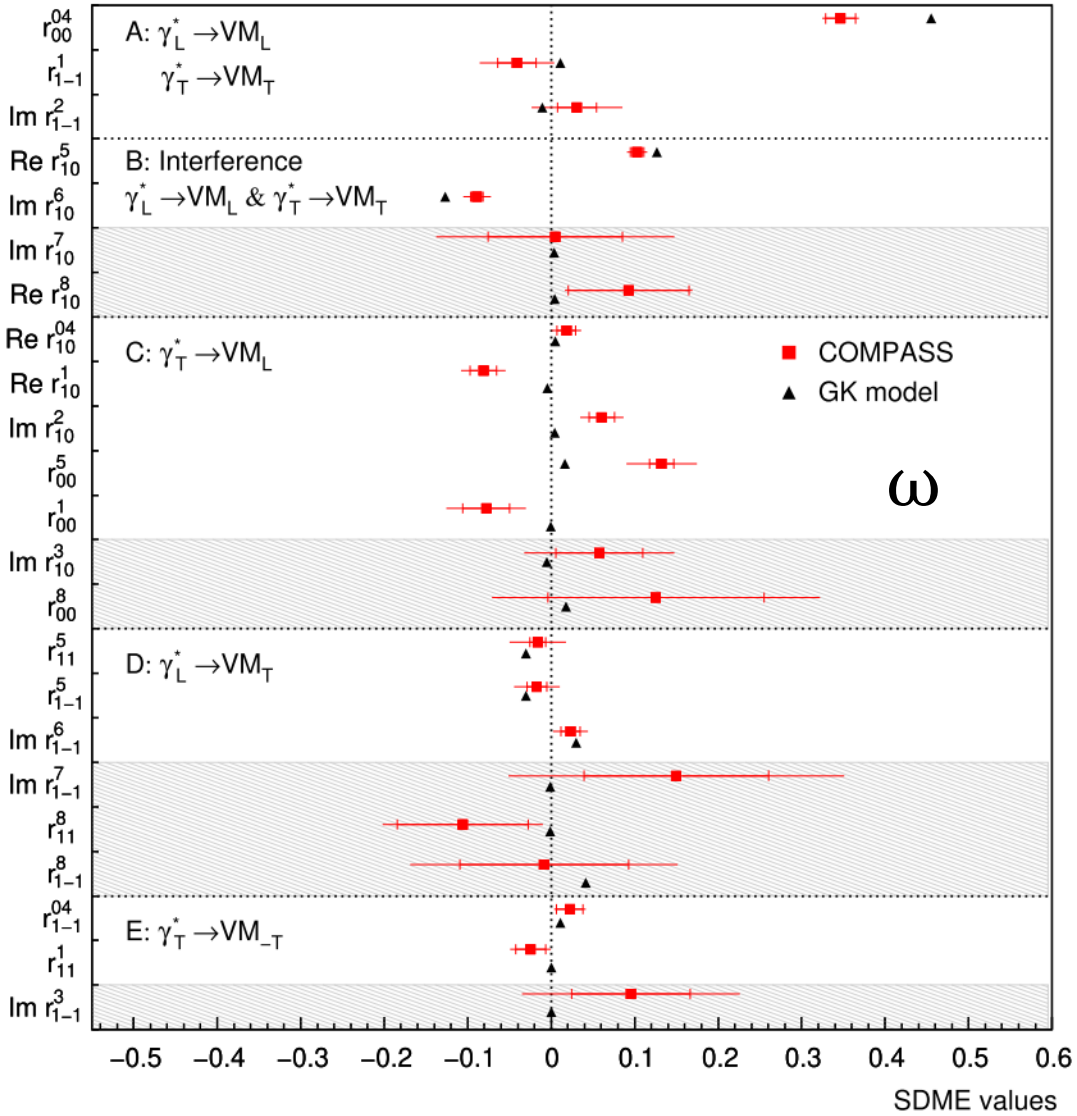
Shaded areas = **polarised SDMEs**

GK model
(Goloskokov & Kroll, EPJA 50 (2014) 146)
Parameters constrained mainly
by HERMES ρ^0, ω data

EPJC **83** (2023) 924



EPJC **81** (2021) 126

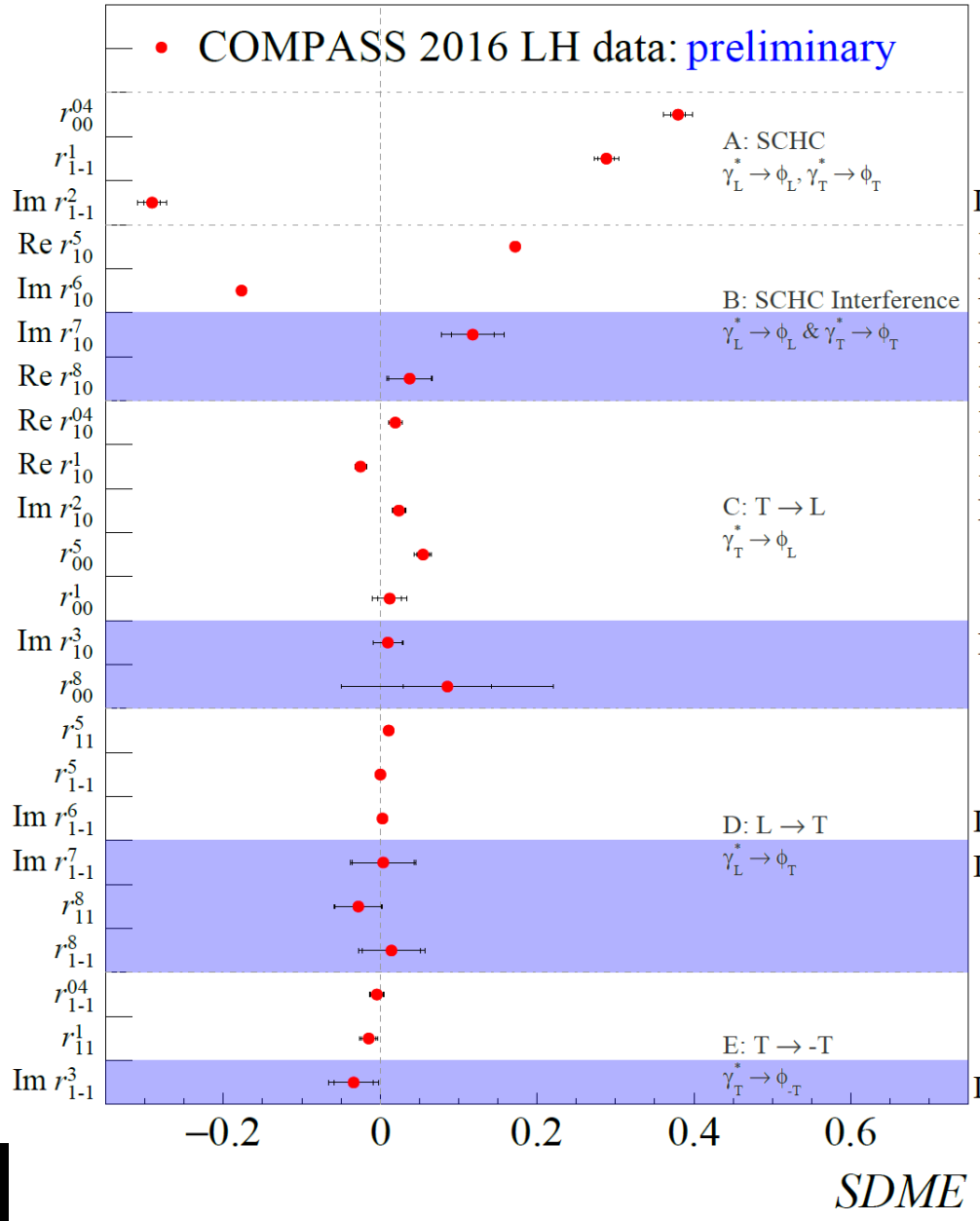


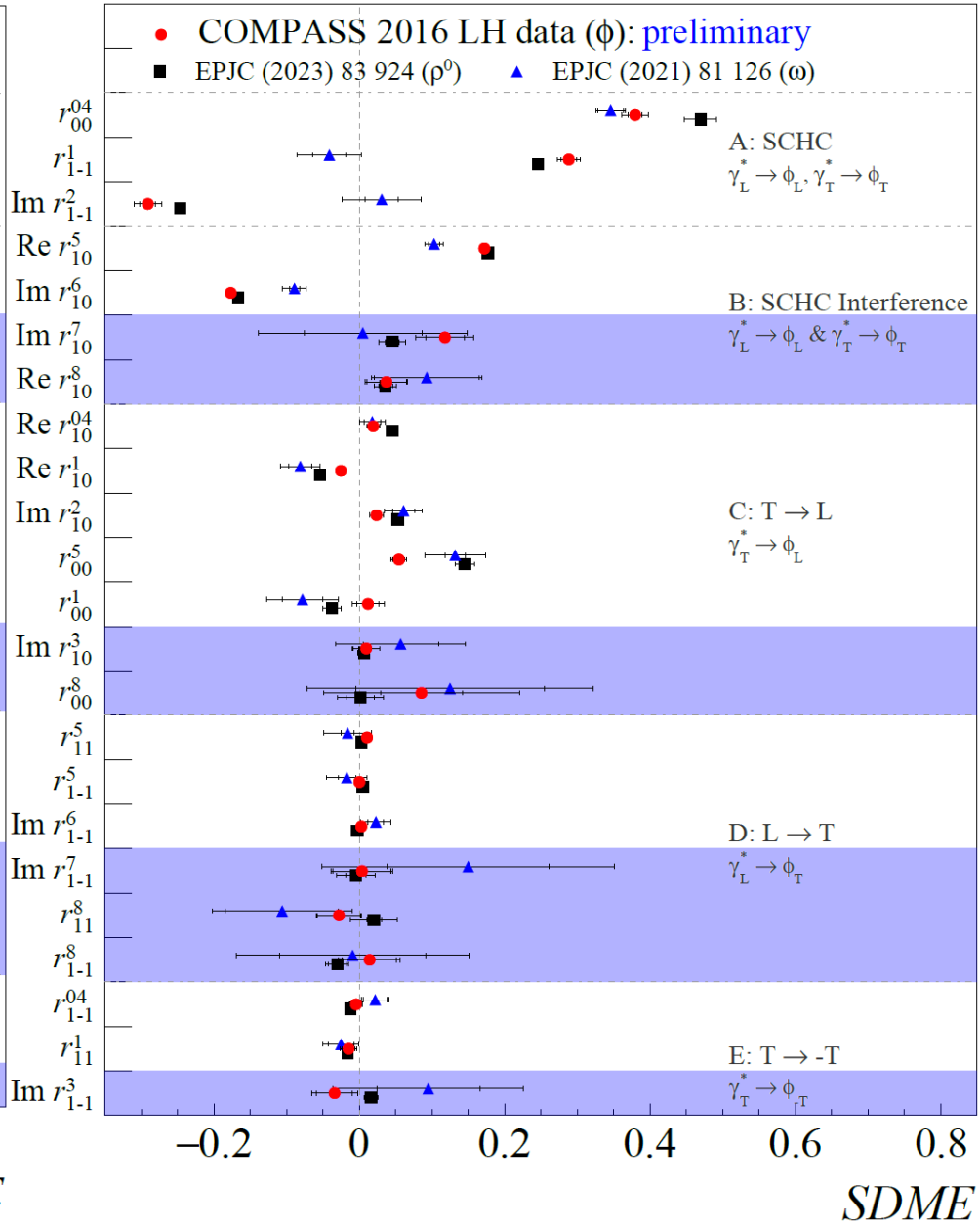
Exclusive ϕ Meson SDMEs DIS2026

- **Kinematic range:**
  $\mathbf{1 < Q^2 < 10}$ $(\mathrm{GeV}/c)^2$
  $\mathbf{5 < W < 17}$ GeV/c^2
  $\mathbf{0.01 < p_T^2 < 0.5}$ $(\mathrm{GeV}/c)^2$

- **SDME classes (A–E):** Different helicity transitions (γ,N→V,N′)

- Blue shaded areas = **polarised SDMEs**





Results: SCHC ρ_0 and ω

- 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**

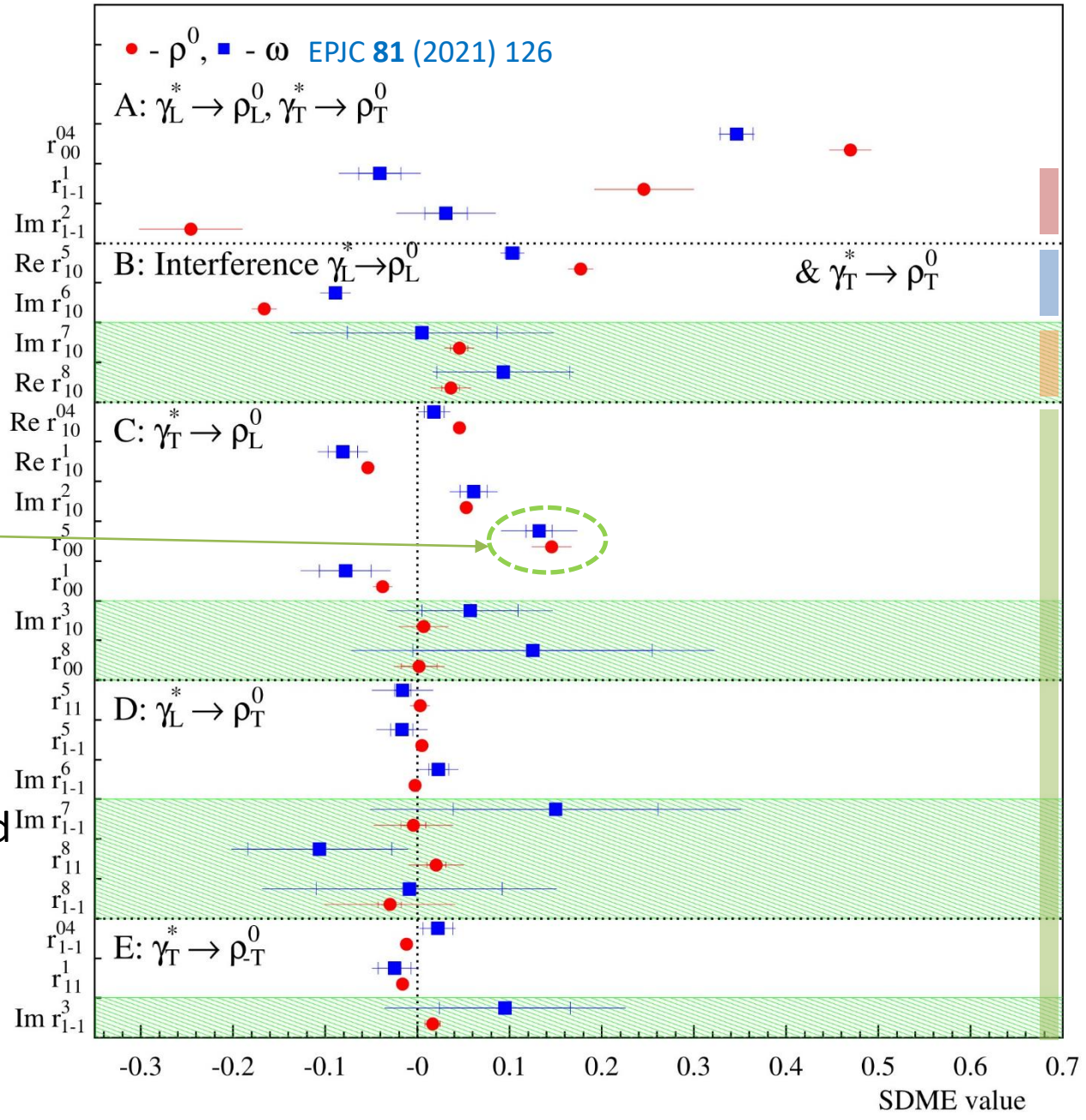
all elements of classes C, D, E should be 0

- **SCHC violation in class C** – transition $\gamma^*_T \to V_L$
- 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 $\bar{E}_T$

EPJC **83** (2023) 924



Results: SCHC ϕ

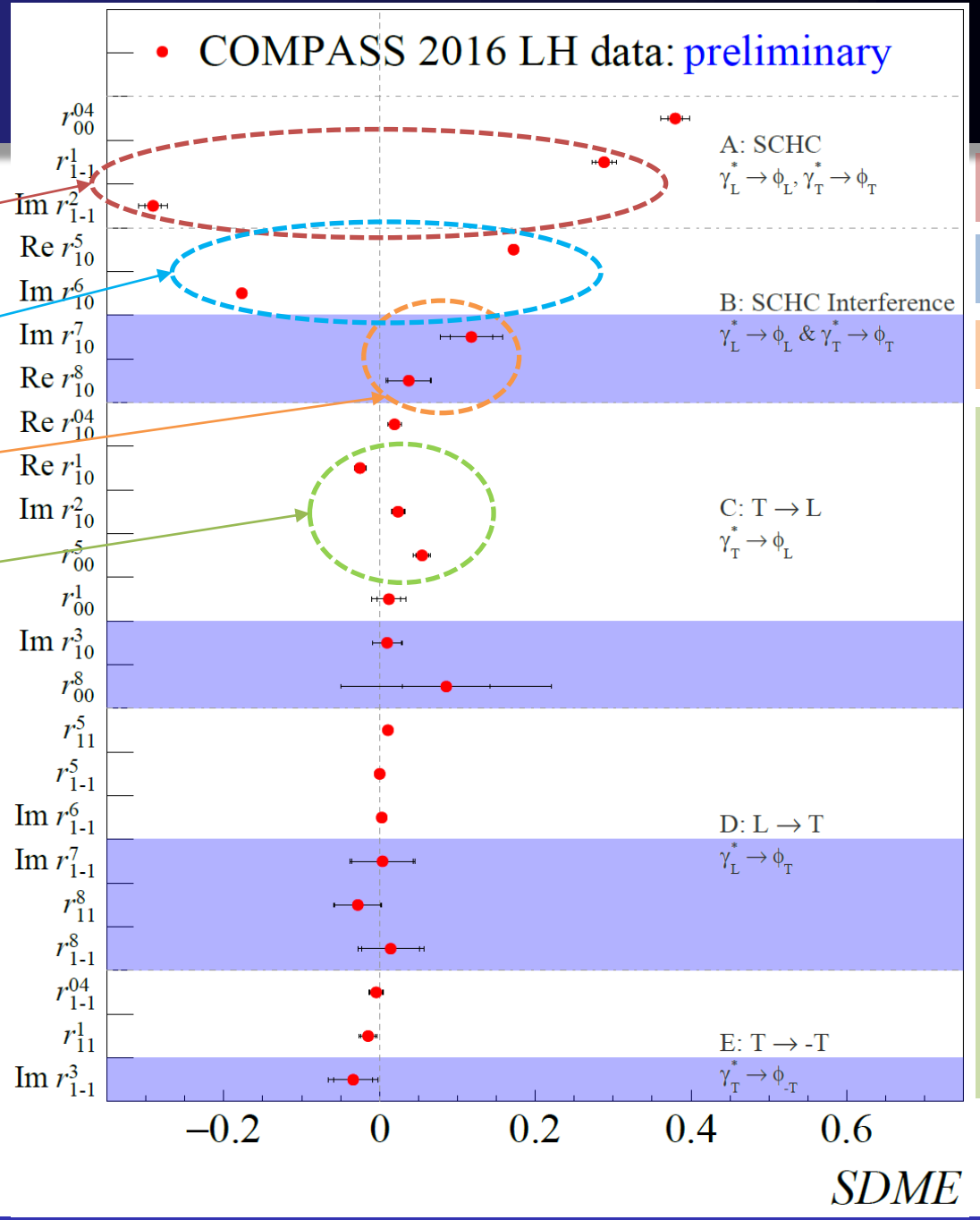
- SCHC implies:

$r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$ — OK

$\mathrm{Re}\, r^5_{10} + \mathrm{Im}\, r^6_{10} = 0$ — OK

$\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$ — small tension

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



- **SCHC violation in class C** – transition $\gamma^*_T \to V_L$
- possible GPD interpretation **Goloskokov and Kroll, EPJC 74 (2014) 2725**:
- contribution of amplitudes depending on chiral-odd (transversity) GPDs $H_T, \bar{E}_T = 2\widetilde{H}_T + E_T$

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

Results: Helicity-Flip NPE Amplitudes ρ_0

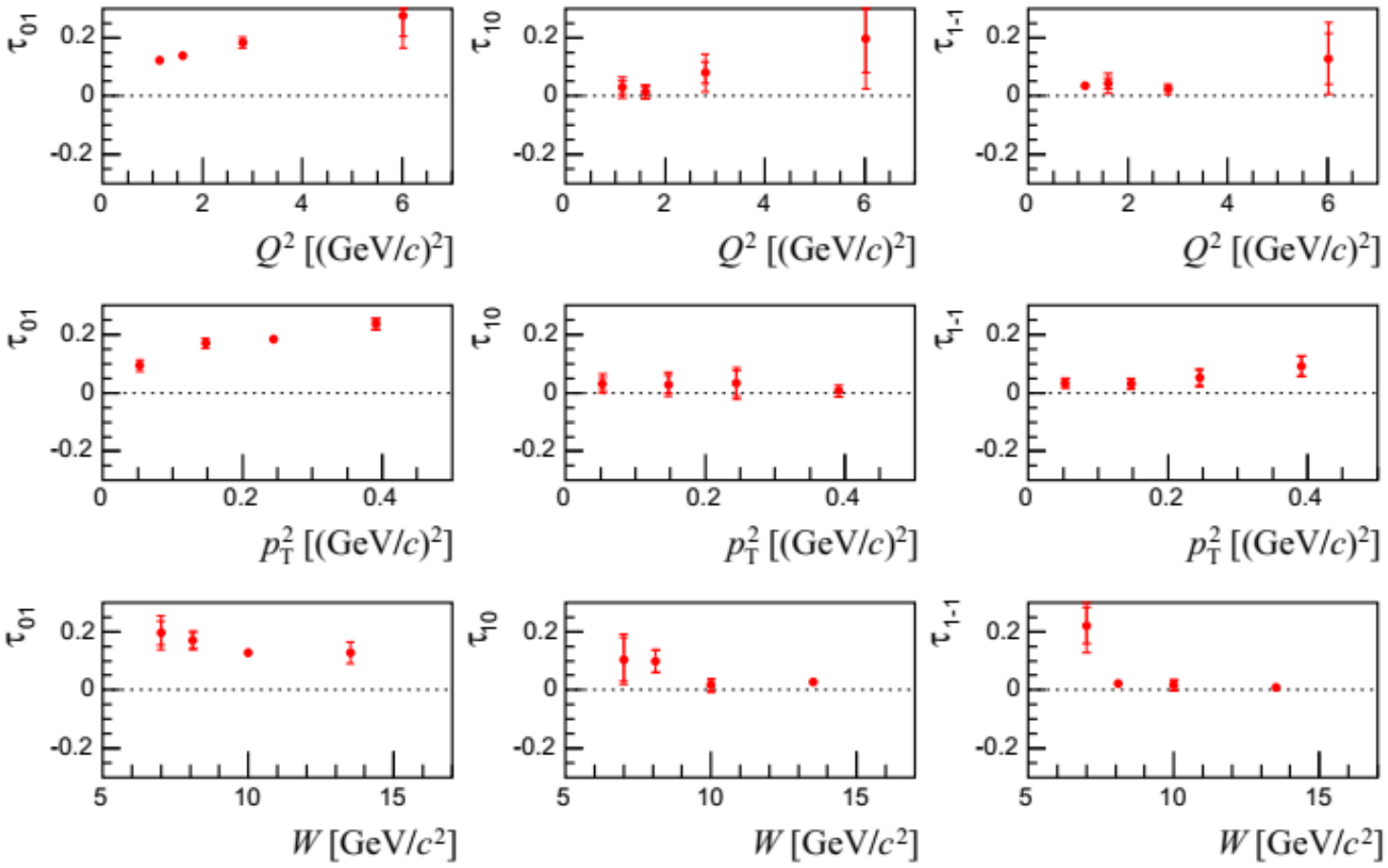
- described as $\tau_{ij} = \frac{|T_{ij}|}{\mathcal{N}}$

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

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

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

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

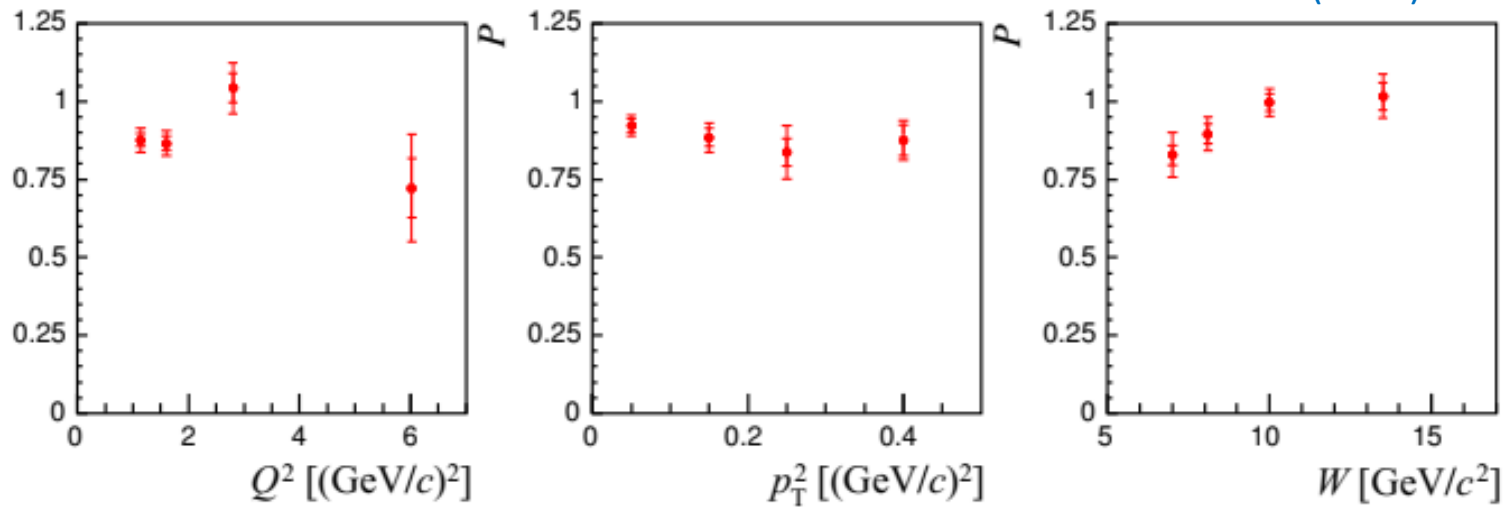


Results: NPE to UPE Asymmetry

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

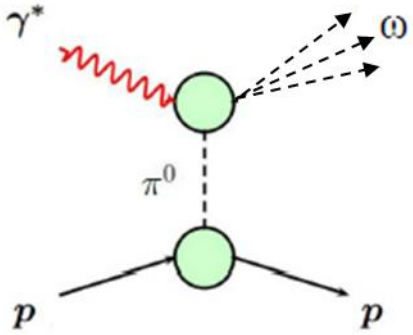
EPJC **83** (2023) 924

ρ_0



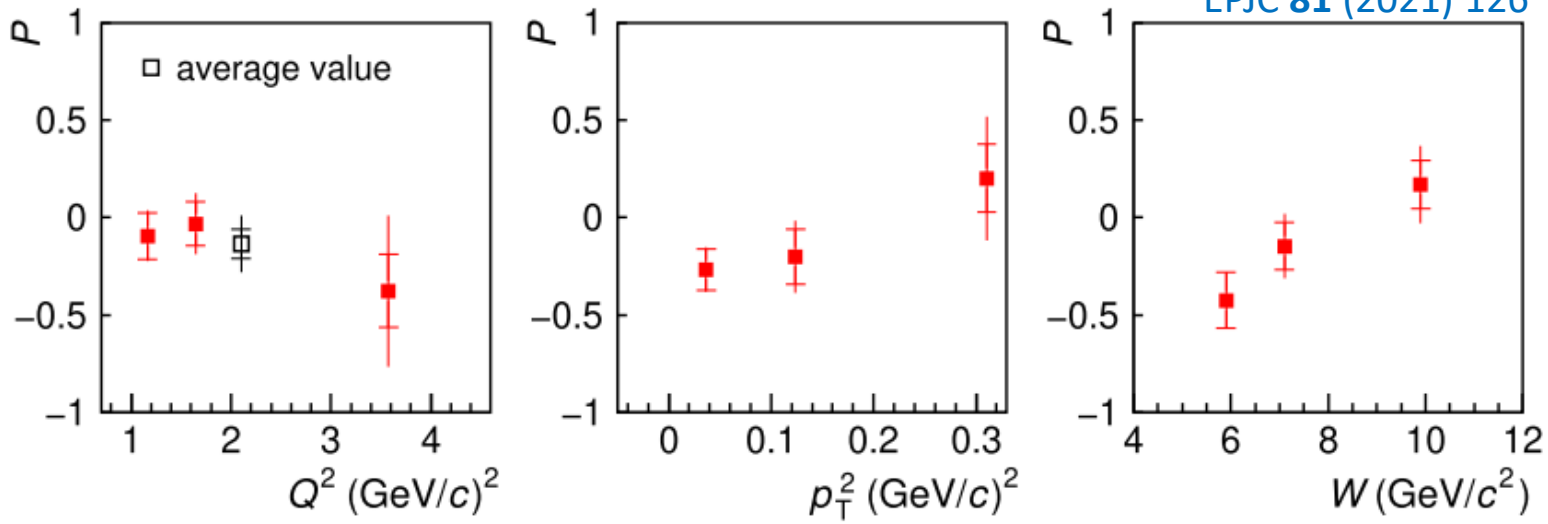
- **ρ_0 NPE dominance**
  NPE $\longrightarrow$ GPDs E, H

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



EPJC **81** (2021) 126

ω



Results: Unnatural Parity Exchange Contribution

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

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

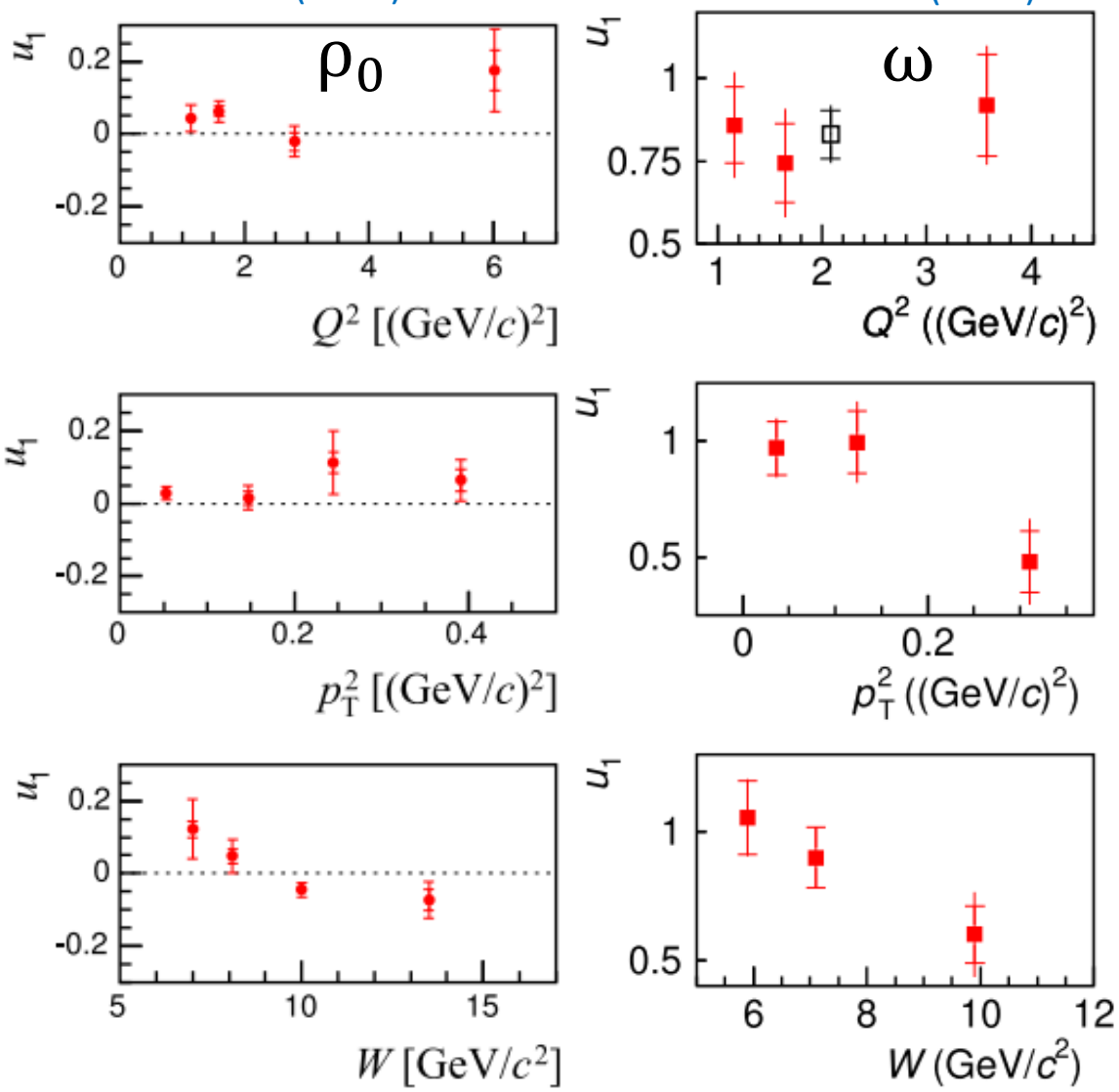
$$\tau^2_{\mathrm{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$$

- numerator in u_1 depends only on UPE amplitudes -> u_1>0
- **ρ^0 very small UPE** contribution observed
  - τ^2_{UPE} 0.03 averaged (UPE fractional contribution)
- **ω large UPE** contribution decreasing with increasing W in u_1
  - τ^2_{UPE} = 0.5 ⟶ 0.3
- u_2 and u_3 consistent with zero $u_2 = r^5_{11} + r^5_{1-1}$

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

EPJC **83** (2023) 924

EPJC **81** (2021) 126



UPE Contribution ϕ

- UPE strength indicators
  - $\boldsymbol{u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1} = 0.064 \pm 0.029\,(\mathbf{stat.}) \pm 0.032(\mathbf{syst.})}$
    $u_2 = r_{11}^{5} + r_{1-1}^{5} = 0.011 \pm 0.006\,(\mathrm{stat.}) \pm 0.002(\mathrm{syst.})$
    $u_3 = r_{11}^{8} + r_{1-1}^{8} = -0.014 \pm 0.051\,(\mathrm{stat.}) \pm 0.022(\mathrm{syst.})$
  - $u_1 = \widetilde{\sum} \frac{4\epsilon|U_{10}|^2 + 2|U_{11} + U_{-11}|^2}{\mathcal{N}}$ $\qquad \Delta_{\mathrm{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$
- **ϕ: very small UPE** contribution observed
  - $\Delta_{\mathrm{UPE}} \approx 0.03$ averaged (UPE fractional contribution)

UPE Contribution, NPE to UPE Asymmetry ϕ

- UPE strength indicators
  - $\boldsymbol{u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1} = 0.064 \pm 0.029\,(\mathbf{stat.}) \pm 0.032(\mathbf{syst.})}$
    $u_2 = r_{11}^{5} + r_{1-1}^{5} = 0.011 \pm 0.006\,(\mathrm{stat.}) \pm 0.002(\mathrm{syst.})$
    $u_3 = r_{11}^{8} + r_{1-1}^{8} = -0.014 \pm 0.051\,(\mathrm{stat.}) \pm 0.022(\mathrm{syst.})$
  - $u_1 = \widetilde{\sum} \frac{4\epsilon|U_{10}|^2 + 2|U_{11} + U_{-11}|^2}{\mathcal{N}}$ $\qquad \Delta_{\mathrm{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$
- **ϕ: very small UPE** contribution observed
  - $\Delta_{\mathrm{UPE}} \approx 0.03$ averaged (UPE fractional contribution)

- NPE to UPE Asymmetry
  - $P = \frac{d\sigma_T^N(\gamma_T^* \to V_T) - d\sigma_T^U(\gamma_T^* \to V_T)}{d\sigma_T^N(\gamma_T^* \to V_T) + d\sigma_T^U(\gamma_T^* \to V_T)} \approx \frac{2r_{1-1}^1}{1 - r_{00}^{04} - 2r_{1-1}^{04}}$
  - $\boldsymbol{P = 0.917 \pm 0.039\,(stat.) \pm 0.045(syst.)}$
- **ϕ: NPE dominance** => sensitivity to GPDs E, H, but not $\widetilde{H}, \widetilde{E}$

Summary and outlook

- **Measured SDMEs in exclusive ω, ρ_0, ϕ production**
  - **SCHC violation** in $\gamma_T^* \rightarrow V_L$ → sensitivity to chiral-odd GPDs $\bar{E}_T, H_T$
  - **NPE dominance in ρ_0 and ϕ** → sensitivity to chiral-even GPDs
  - **Large UPE in ω** → pion pole contribution
- **Outlook**:
  - More from 2016/17 unpolarized LH_2 target data: ϕ, ω, ρ_0 (SDMEs & cross-section)
  - → Analysis ongoing — **stay tuned from COMPASS!**

Thank you for your attention

Kamil Augsten

kamil.augsten@cern.ch

- Project name: Fundamental constituents of matter through frontier technologies (FORTE)
- Project ID: CZ.02.01.01/00/22_008/0004632

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Ministry of Education, Youth and Sports of the Czech Republic

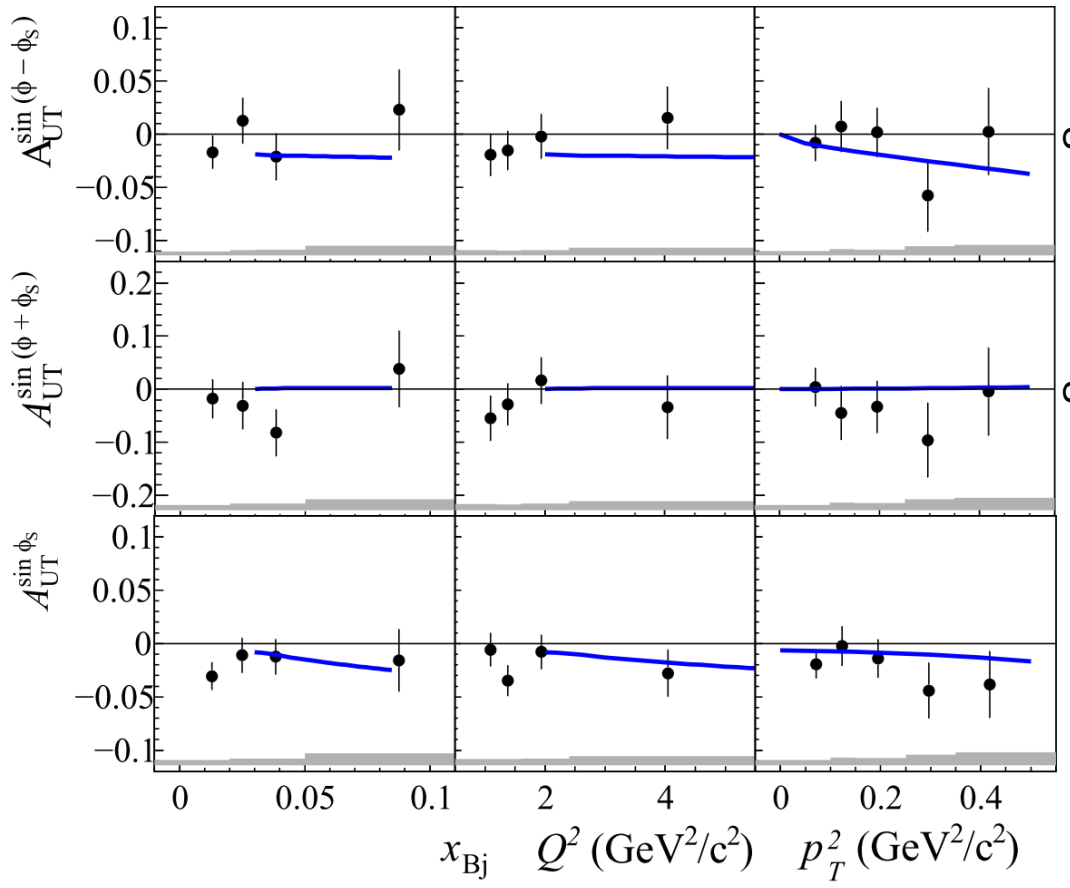
Angular distributions

$$W_U(\Phi,\phi,\cos\Theta)=\frac{3}{8\pi^2}\left[\begin{array}{llll}
\frac{1}{2}+ & & & \\
+1 & 1 & -\frac{1}{2} \quad 1 & \cos^2\Theta\ 1 \\
+1 & 1 & \left(\begin{array}{lll} -\frac{1}{2} & r_{00}^{04} & \sin^2\Theta\ 1 \\ + & r_{00}^{04} & \cos^2\Theta\ 1 \end{array}\right) & \\
+1 & 1 & \left(\begin{array}{lll} -\sqrt{2} & \mathrm{Re}\{r_{10}^{04}\} & \sin 2\Theta\cos\phi \\ - & r_{1-1}^{04} & \sin^2\Theta\cos 2\phi \end{array}\right) & \\
+\varepsilon & \cos 2\Phi & \left(\begin{array}{lll} - & r_{11}^{1} & \sin^2\Theta\ 1 \\ - & r_{00}^{1} & \cos^2\Theta\ 1 \\ +\sqrt{2} & \mathrm{Re}\{r_{10}^{1}\} & \sin 2\Theta\cos\phi \\ + & r_{1-1}^{1} & \sin^2\Theta\cos 2\phi \end{array}\right) & \\
+\varepsilon & \sin 2\Phi & \left(\begin{array}{lll} -\sqrt{2} & \mathrm{Im}\{r_{10}^{2}\} & \sin 2\Theta\sin\phi \\ - & \mathrm{Im}\{r_{1-1}^{2}\} & \sin^2\Theta\sin 2\phi \end{array}\right) & \\
+\sqrt{2\varepsilon(1+\varepsilon)}\cos\Phi & & \left(\begin{array}{lll} + & r_{11}^{5} & \sin^2\Theta\ 1 \\ + & r_{00}^{5} & \cos^2\Theta\ 1 \\ -\sqrt{2} & \mathrm{Re}\{r_{10}^{5}\} & \sin 2\Theta\cos\phi \\ - & r_{1-1}^{5} & \sin^2\Theta\cos 2\phi \end{array}\right) & \\
+\sqrt{2\varepsilon(1+\varepsilon)}\sin\Phi & & \left(\begin{array}{lll} \sqrt{2} & \mathrm{Im}\{r_{10}^{6}\} & \sin 2\Theta\sin\phi \\ + & \mathrm{Im}\{r_{1-1}^{6}\} & \sin^2\Theta\sin 2\phi \end{array}\right) &
\end{array}\right]$$

$$W_L(\phi,\cos\theta)=\frac{3}{8\pi^2}\left[\begin{array}{lll}
\sqrt{1-\varepsilon^2} & 1 & \left(\begin{array}{lll} \sqrt{2} & \mathrm{Im}\{r_{10}^{3}\} & \sin 2\Theta\sin\phi \\ + & \mathrm{Im}\{r_{1-1}^{3}\} & \sin^2\Theta\sin 2\phi \end{array}\right) \\
+\sqrt{2\varepsilon(1-\varepsilon)}\cos\Phi & & \left(\begin{array}{lll} \sqrt{2} & \mathrm{Im}\{r_{10}^{7}\} & \sin 2\Theta\sin\phi \\ + & \mathrm{Im}\{r_{1-1}^{7}\} & \sin^2\Theta\sin 2\phi \end{array}\right) \\
+\sqrt{2\varepsilon(1-\varepsilon)}\sin\Phi & & \left(\begin{array}{lll} + & r_{11}^{8} & \sin^2\Theta\ 1 \\ + & r_{00}^{8} & \cos^2\Theta\ 1 \\ -\sqrt{2} & \mathrm{Re}\{r_{10}^{8}\} & \sin 2\Theta\cos\phi \\ - & r_{1-1}^{8} & \sin^2\Theta\cos 2\phi \end{array}\right)
\end{array}\right]$$

ρ_0 and ω Asymmetries with T Polarized Target

ρ_0 $E_{\rho_0} = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g/x)$



$\propto \mathrm{Im}\,(\boldsymbol{E} * H)$

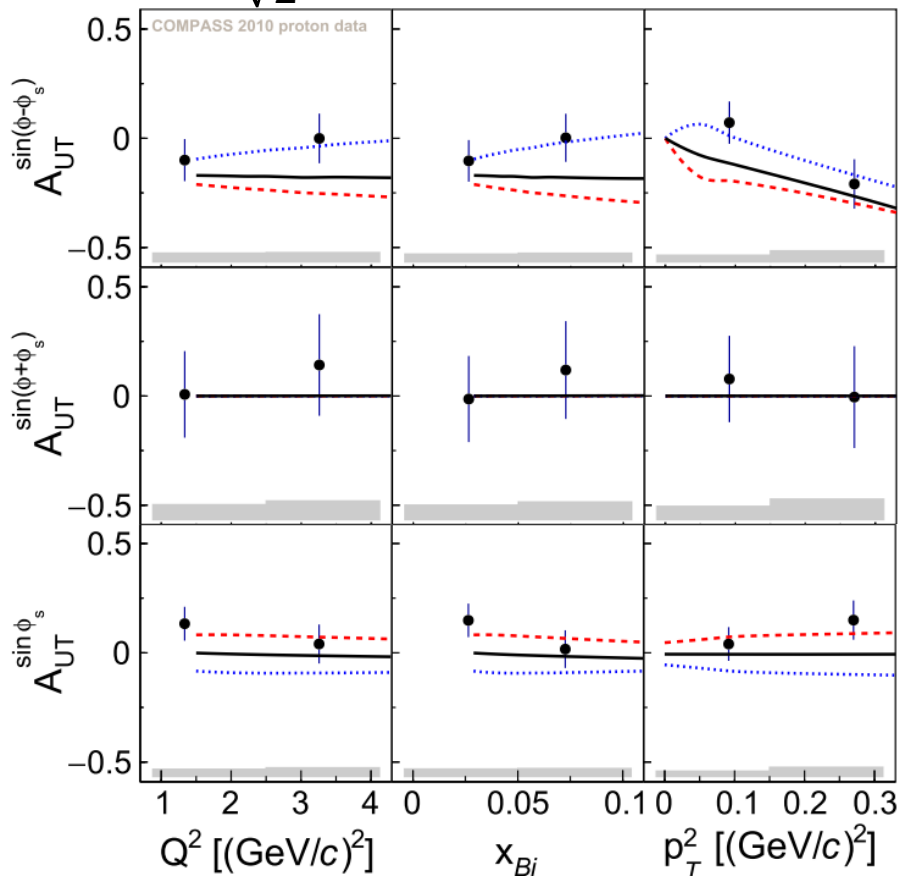
$\propto \mathrm{Im}\,(E * \bar{E}_T)$ ~0

$\propto \mathrm{Im}\,(E * \bar{E}_T - H * \boldsymbol{H_T})$

PLB **731** (2014) 19
NPB **865** (2012) 1

Sensibility to $\boldsymbol{E}, \boldsymbol{H_T}$

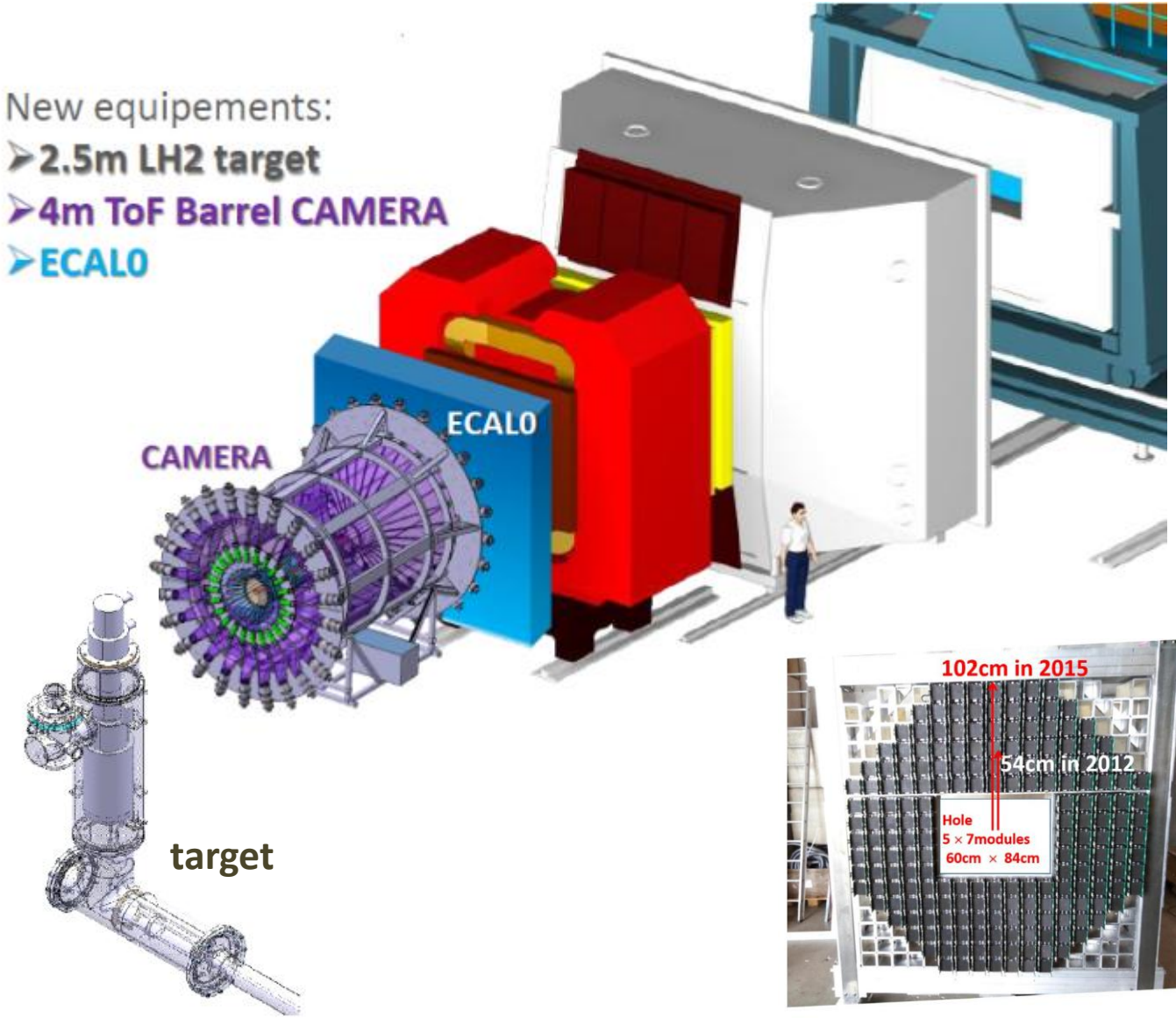
ω $E_\omega = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}E^g/x)$



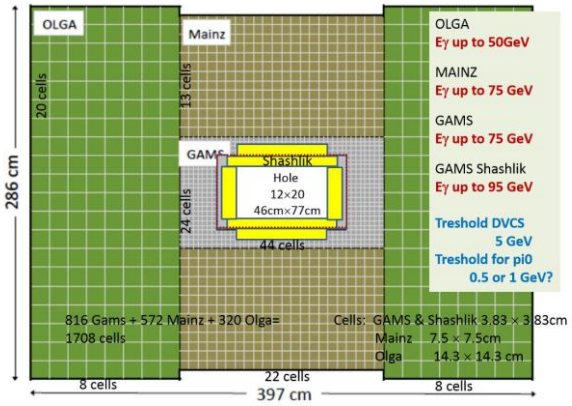
No pion pole
Negative $\pi\omega$ form factor
Positive $\pi\omega$ form factor

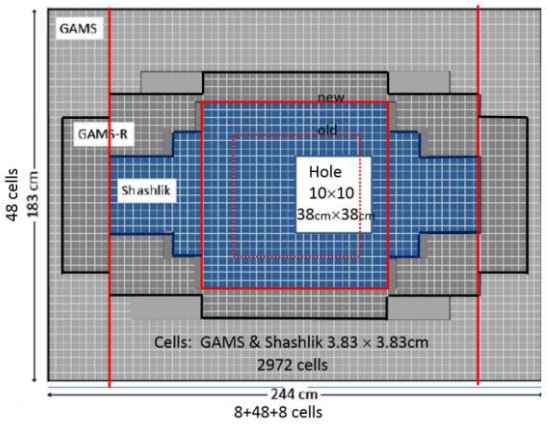
NPB **915** (2017) 454

Key parts of setup

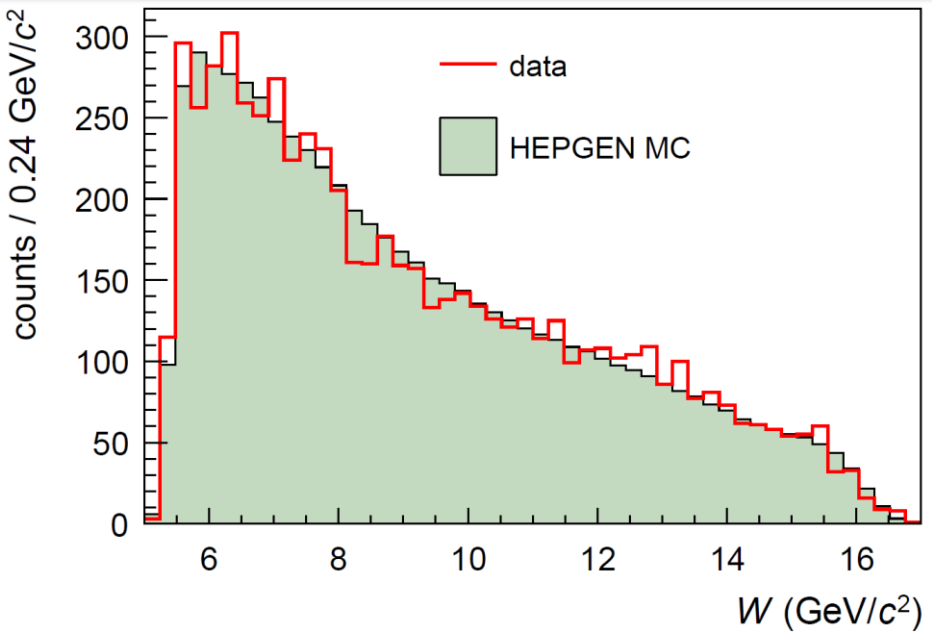


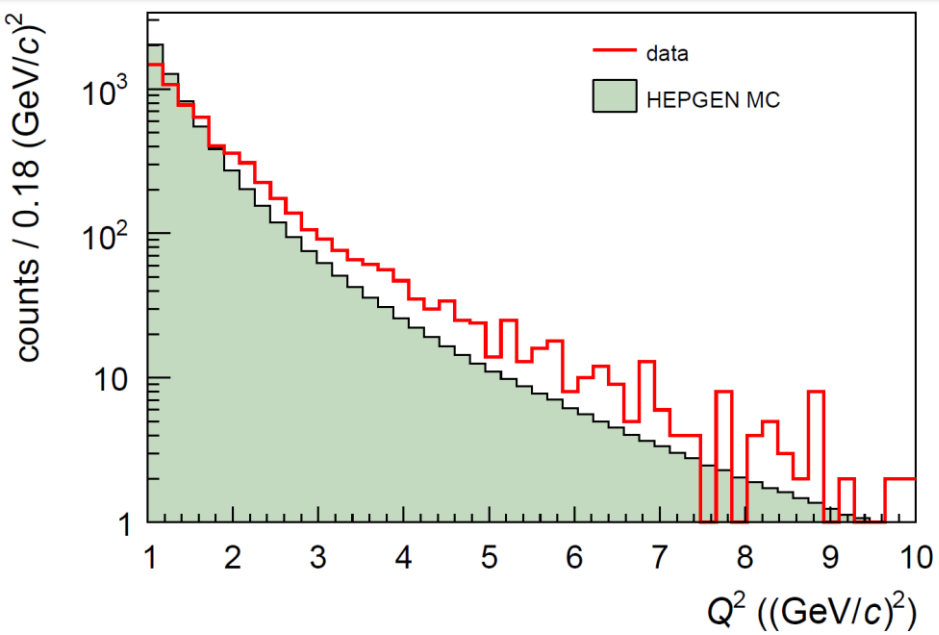
- Target ToF system (CAMERA)
  - 24 inner and 24 outer scintillators
  - 1 GHz readout and 310ps ToF resolution
- Particle ID:
  - Ring Imaging Cherenkov (RICH) detector
  - EM calorimeters (ECAL0 0-40 mrad, ECAL1 40-150 mrad, ECAL2 150-300 mrad)
  - Hadronic calorimeters (HCAL1, HCAL2)
  - 2 muon walls

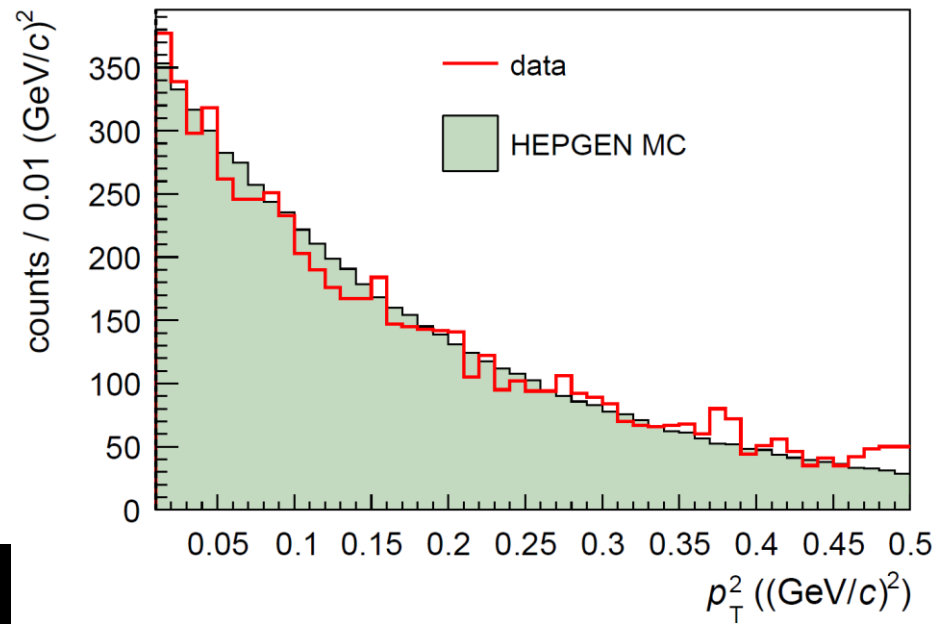


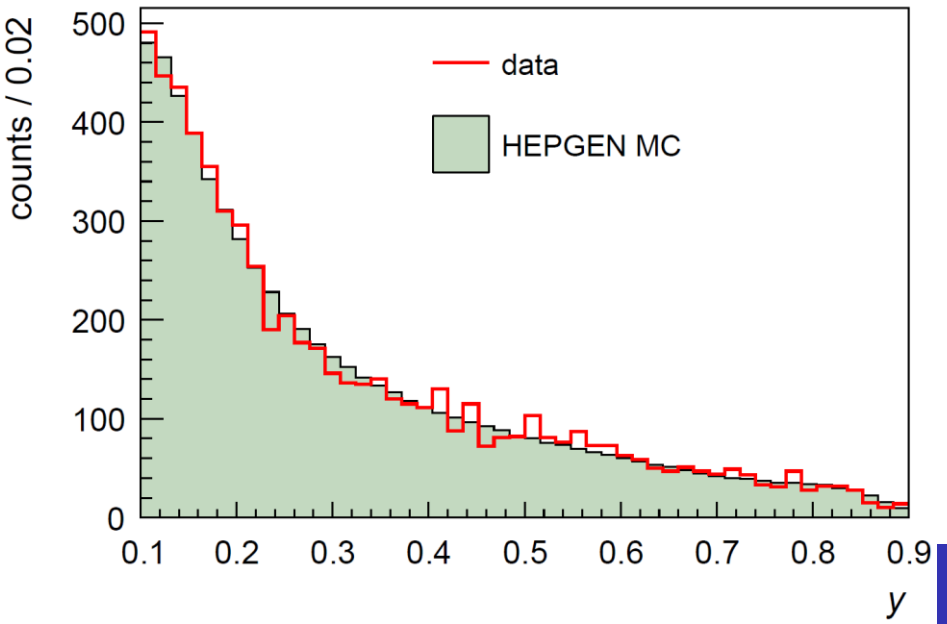


Exclusive ϕ Meson - Kinematic variables







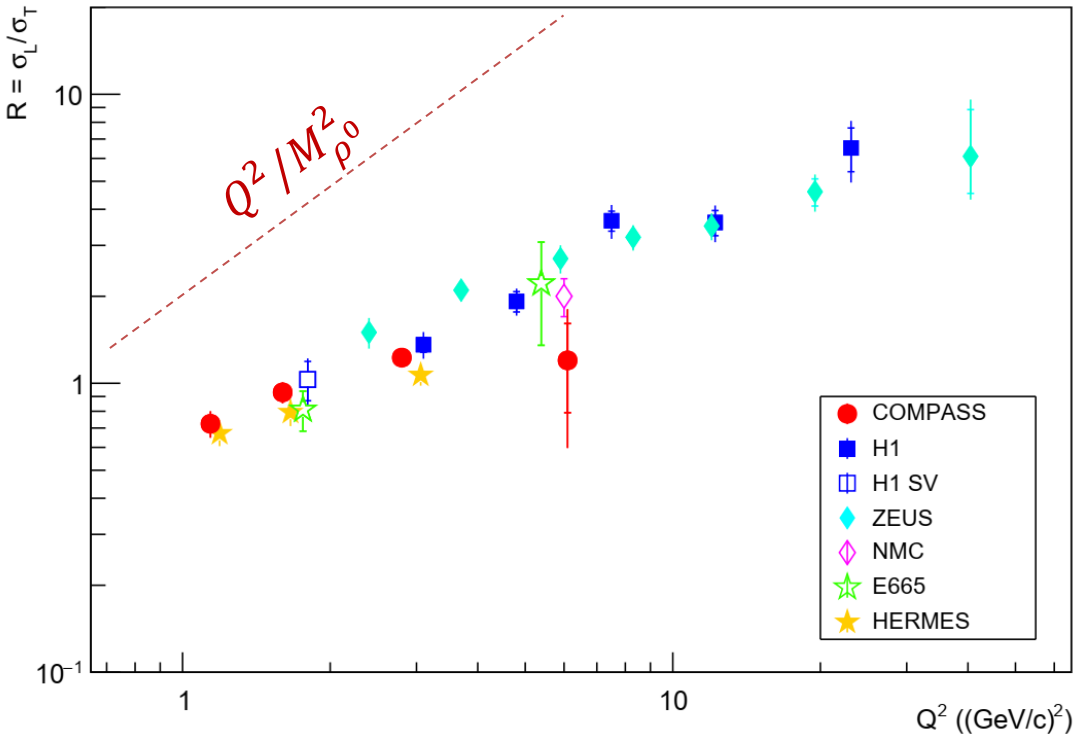


L/T cross-section ratio

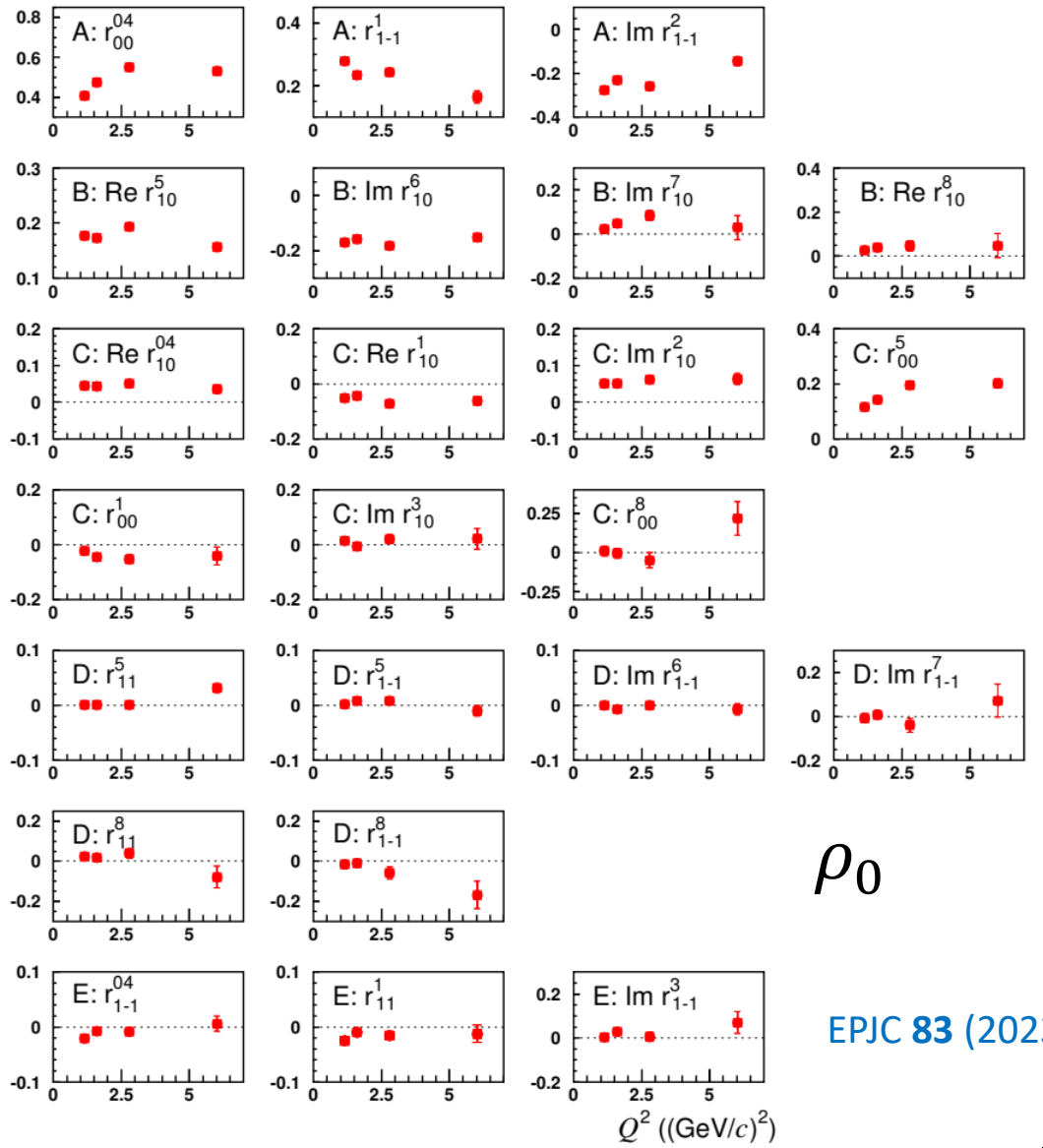
- ρ^0: **L/T cross-section ratio**

$$R = \frac{\sigma_L(\gamma_L^* \to V)}{\sigma_T(\gamma_T^* \to V)} \text{ in case of SCHC } = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

  - compared to previous data at $Q^2 > 1.0$ GeV^2
  - deviation from LO pQCD prediction ($Q^2/M_{\rho^0}^2$)->
    -> QCD evolution & q_T effects
  - meson transverse size effects smaller for σ_L than for σ_T

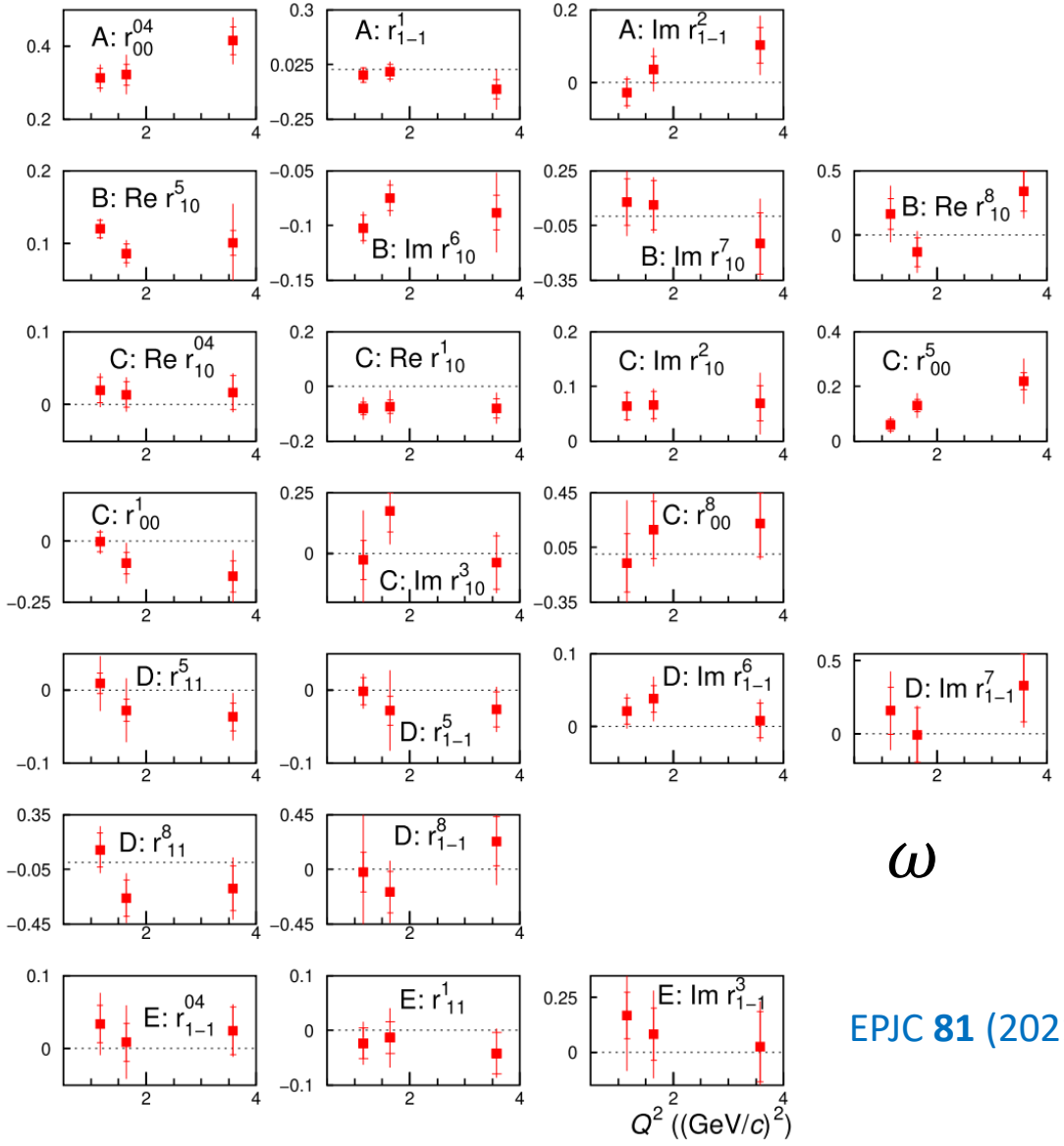


SDMEs dependences



ρ_0

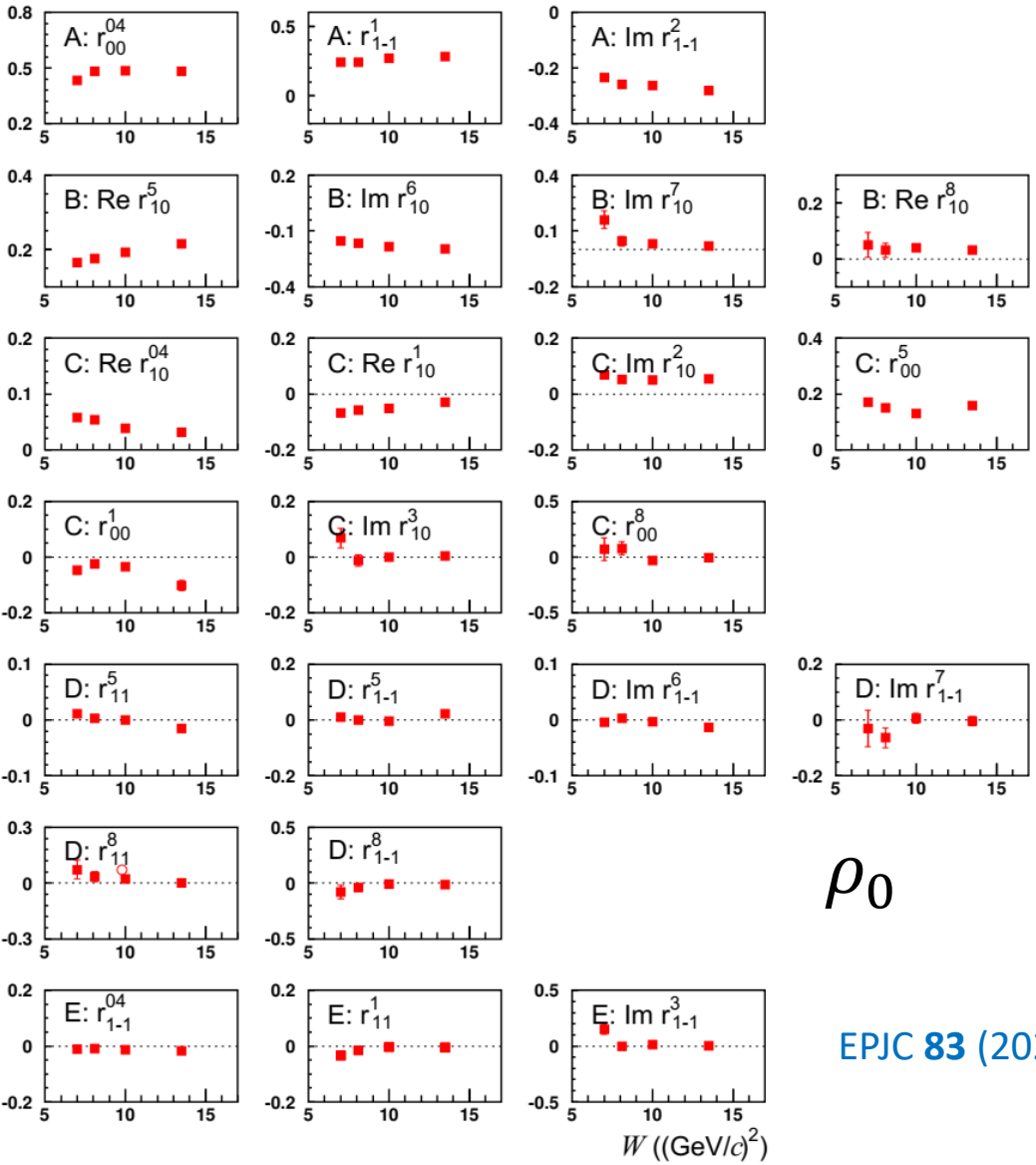
EPJC **83** (2023) 924



ω

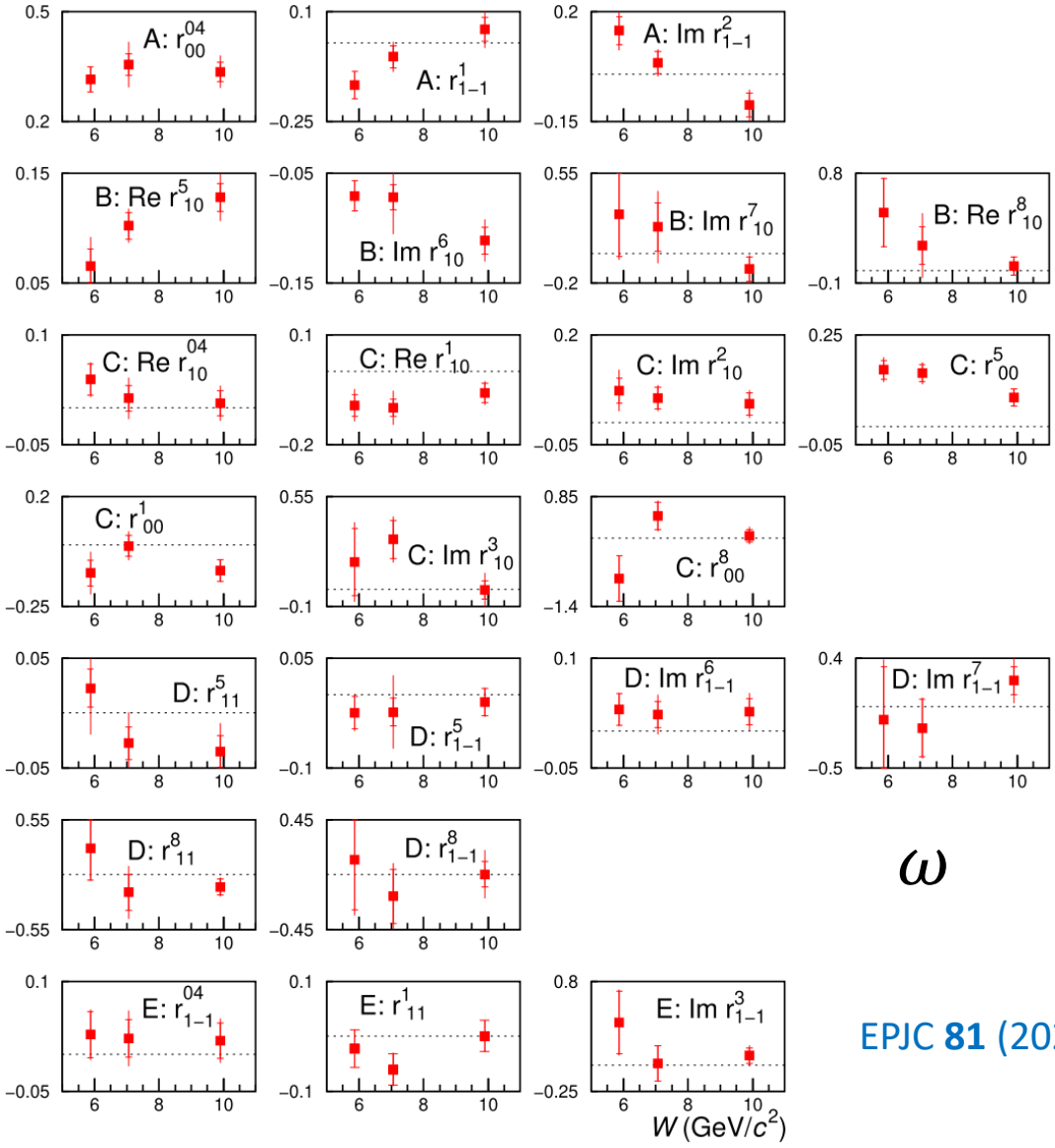
EPJC **81** (2021) 126

SDMEs dependences



ρ_0

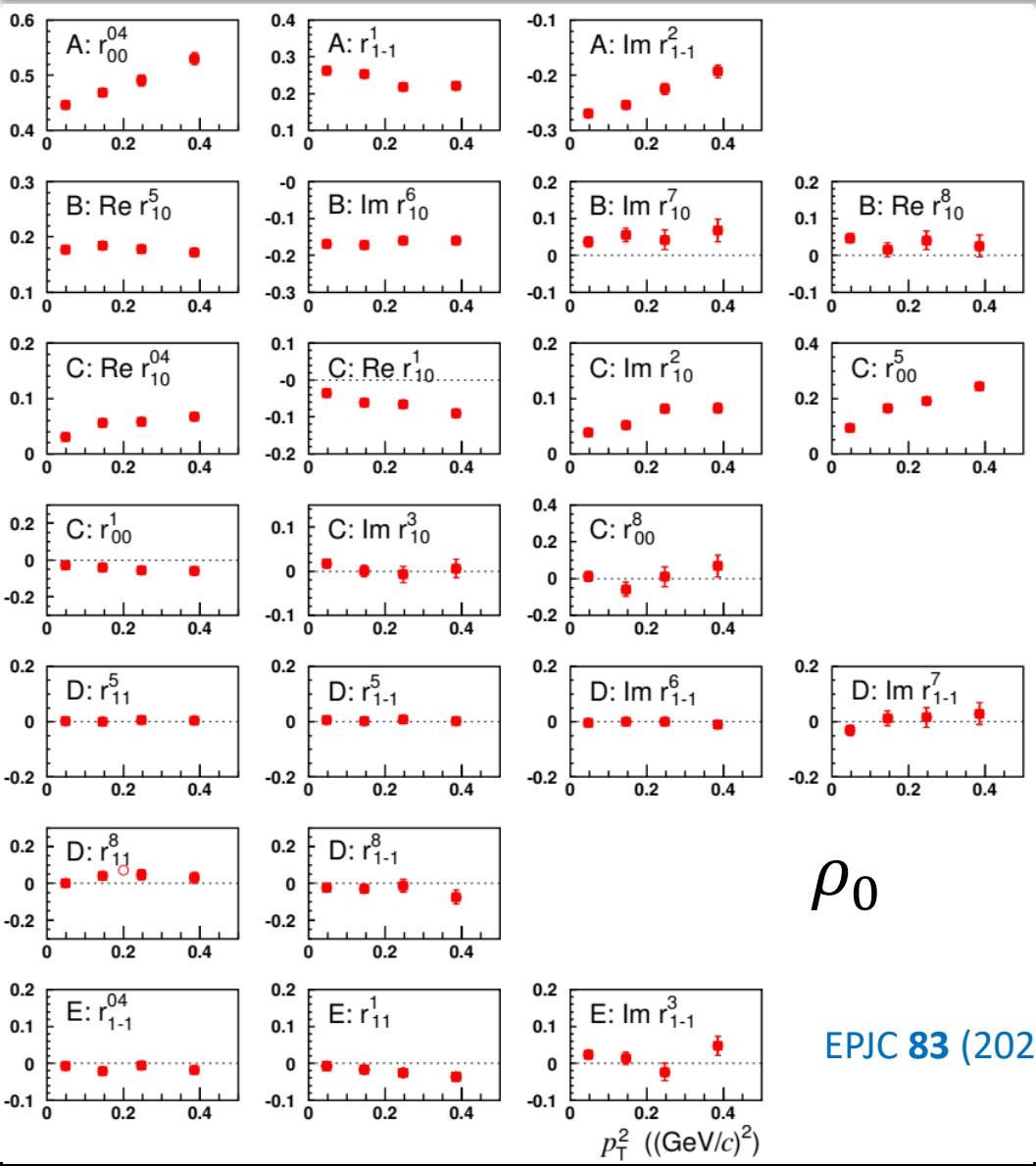
EPJC **83** (2023) 924



ω

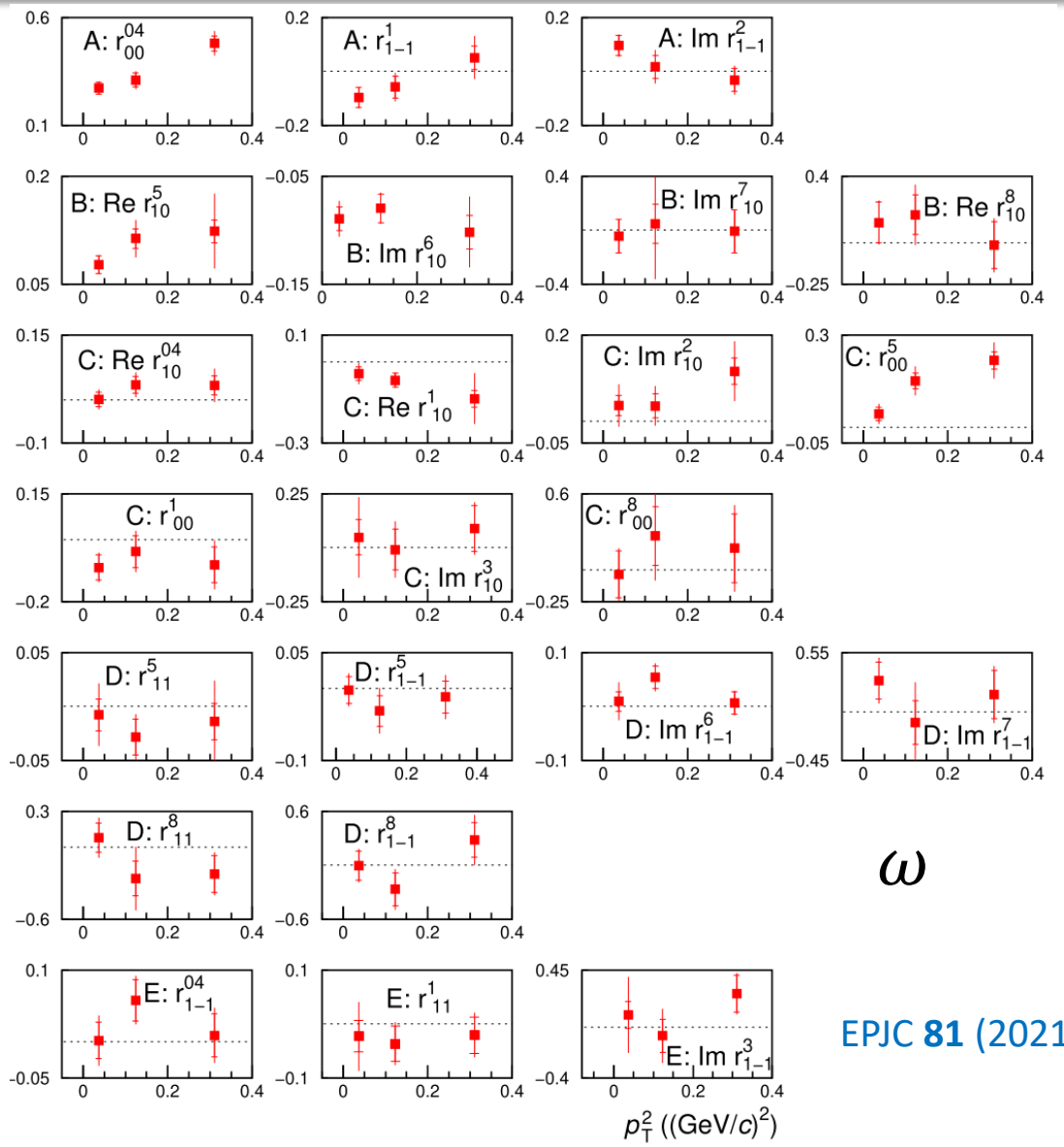
EPJC **81** (2021) 126

SDMEs dependences



ρ_0

EPJC **83** (2023) 924



ω

EPJC **81** (2021) 126