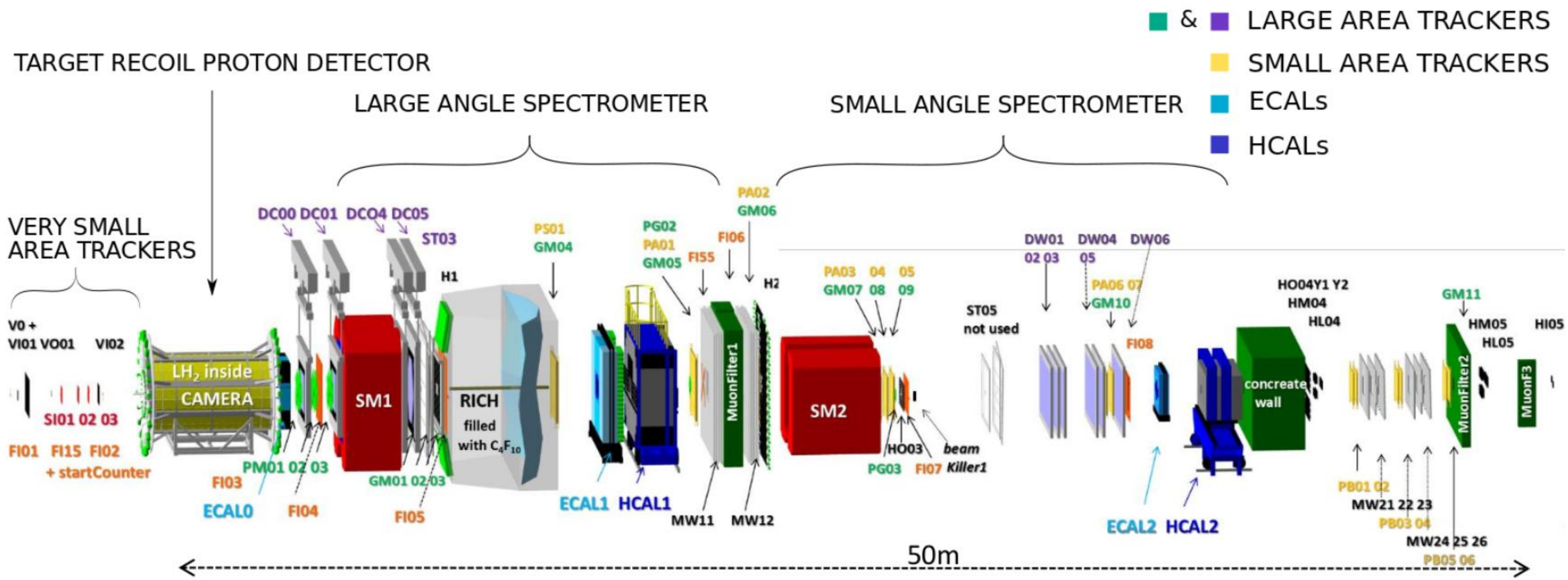
Spin Density Matrix Elements in Exclusive Muoproduction of Vector Mesons at COMPASS

Kamil Augsten (CTU in Prague) on behalf of COMPASS

RRTF: Impact of Vector Mesons on the Studies of the 3D Structure of the Nucleon

Co-funded by the European Union
Ministry of Education, Youth and Sports of the Czech Republic

COMPASS Experiment – Setup



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

μ^+, μ^- beams

polarization ~ ±80%

energy 160 GeV

Exclusive Muoproduction

2007 (DIS&SIDIS): μ^+p @160 GeV, **T polarized NH_3 target**

2010 (SIDIS): μ^+p @160 GeV, **T polarized NH_3 target**

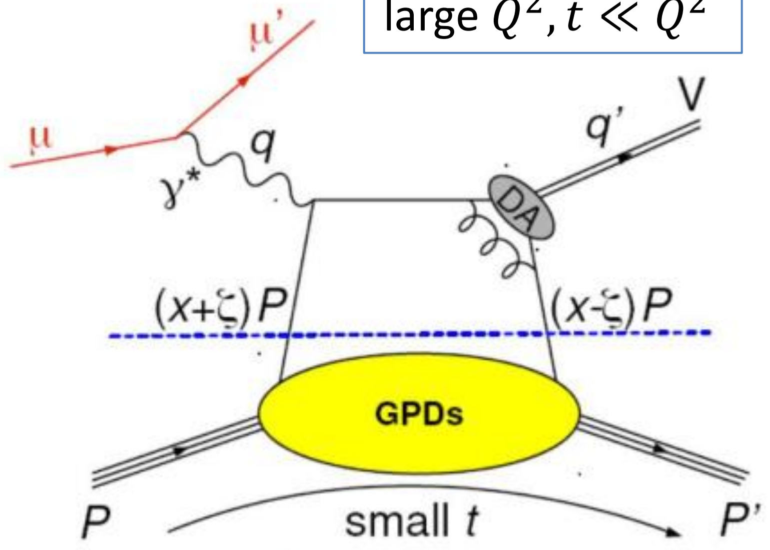
2012 pilot run (DVCS/HEMP/SIDIS): μ^+&μ^-p @160 GeV, **unpolarized LH_2 target**

2016-17 (DVCS/HEMP/SIDIS): μ^+&μ^-p @160 GeV, **unpolarized LH_2 target**

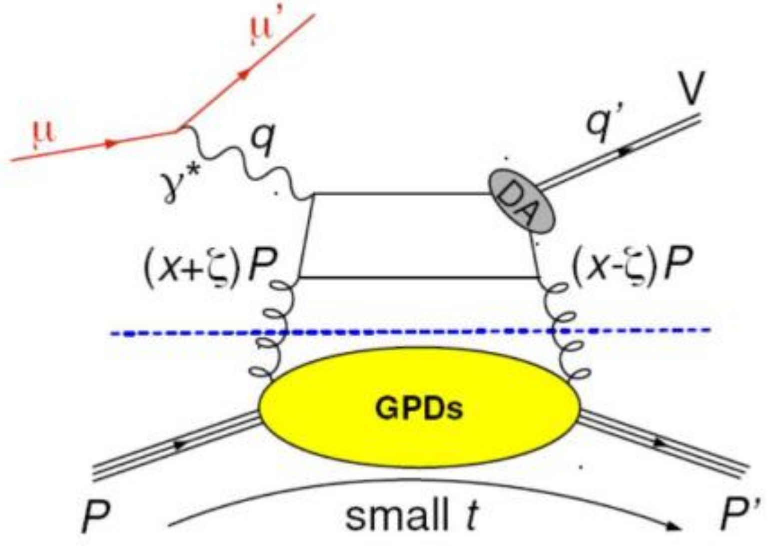
GPDs and Hard Exclusive Meson Production

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

quark contribution



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)
- **Flavor filtering:** different mesons → access to **parton-specific GPDs**
  - Vector mesons → H, E
  - Pseudoscalar mesons →$\widetilde{H}, \tilde{E}$
  - All mesons → chiral-odd $\bar{E}_T, \tilde{E}_T, H_T, \widetilde{H}_T$
- $E_{\rho_0} = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g/x)$
- $E_\omega = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}E^g/x)$
- $E_\phi = -\frac{1}{3}E^s + \frac{1}{4}E^g/x$

COMPASS can measure ω, ρ^0, ϕ, (J/ψ)

Vector Meson Spin-density Matrix

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

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

helicity of vector meson V

helicities of virtual photon γ and nucleon N

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

- **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 polarization 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)

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

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

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

23 SDMEs we actually measure

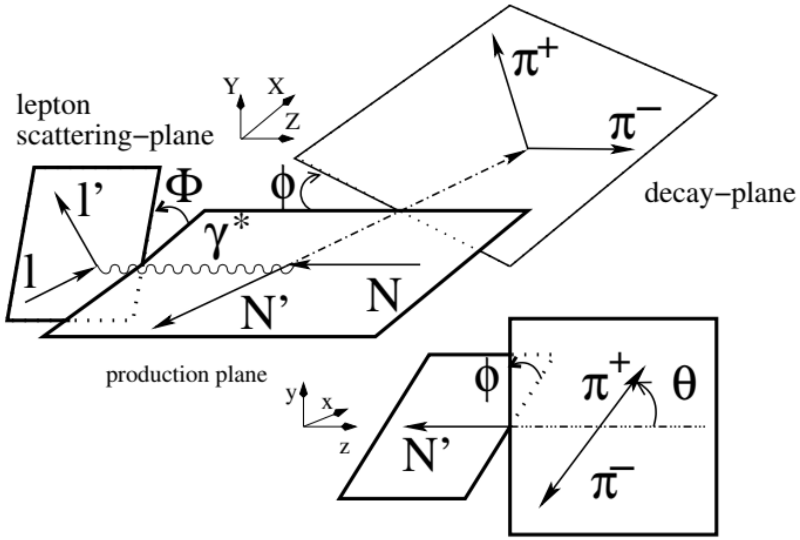
Experimental access to SDMEs

- through angular distribution

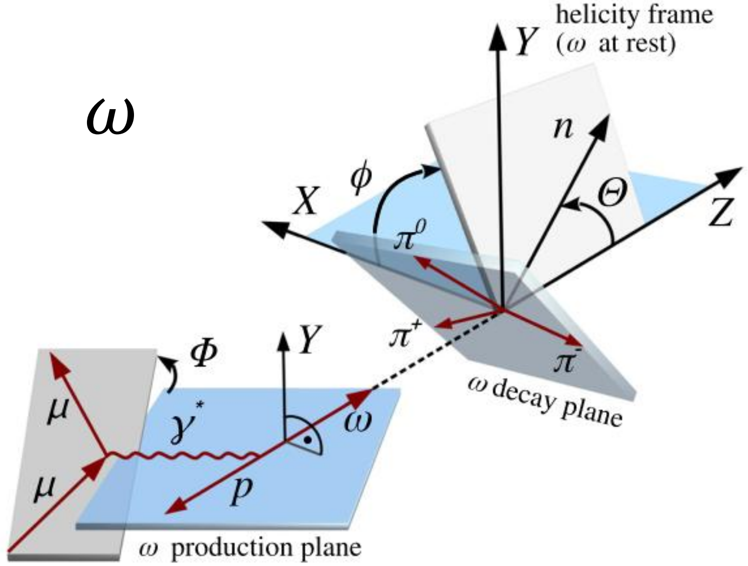
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + P_b\mathcal{W}^{L}(\Phi,$$

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

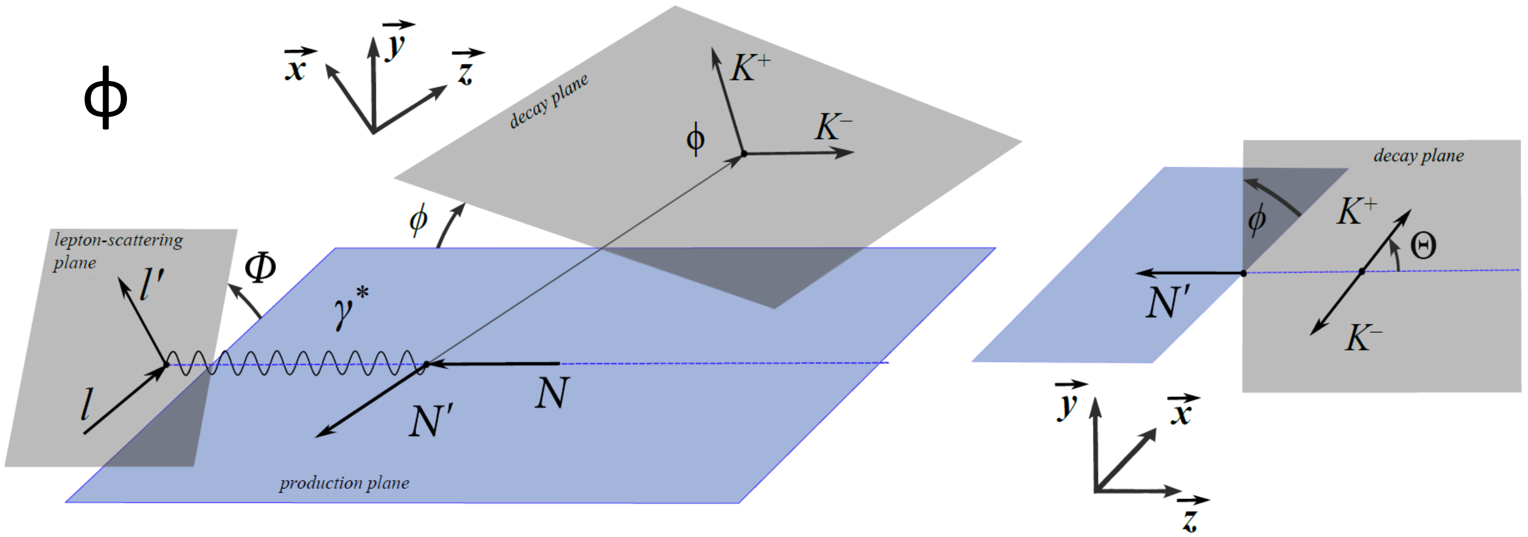
ρ_0



ω



1. exp. angular distributions



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

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

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

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

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

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

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

2. detector efficiency/acceptance correction

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

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

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

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

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

Selection ρ_0 and ω: 2012 Pilot Run

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

Recoil proton detector not included in selection

EPJC (2021) **81** 126

$$\mu + p \rightarrow \mu' + p' + \omega$$
$$\hookrightarrow \pi^+ + \pi^- + \pi^0 \quad \text{Branching ratio} \approx 89\ \%$$
$$\hookrightarrow \gamma_l + \gamma_h \quad \text{Branching ratio} \approx 99\ \%$$

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

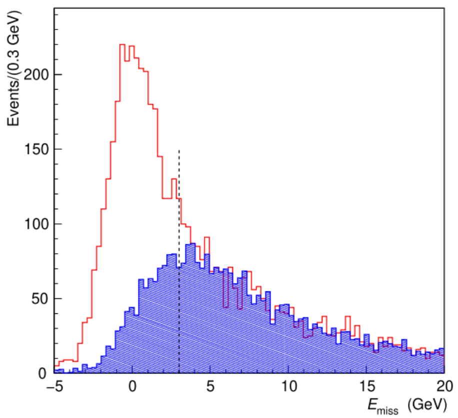
topology:

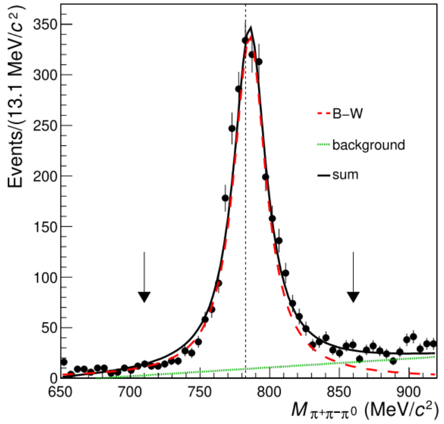
scattered muon + two hadrons with opposite charges + two neutral clusters in calorimeters

event yield: **3060 events**

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

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





EPJC (2023) **83** 924

$$\mu + p \rightarrow \mu' + p' + \rho^0$$
$$\hookrightarrow \pi^+ + \pi^- \quad \text{Branching ratio} \approx 99\ \%$$

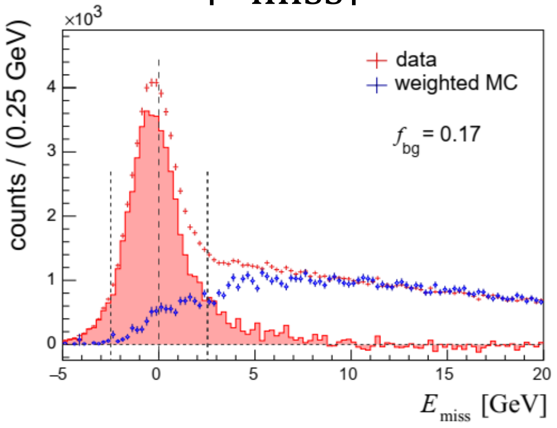
$0.5 < M_{\pi^+\pi^-} < 1.1$ GeV

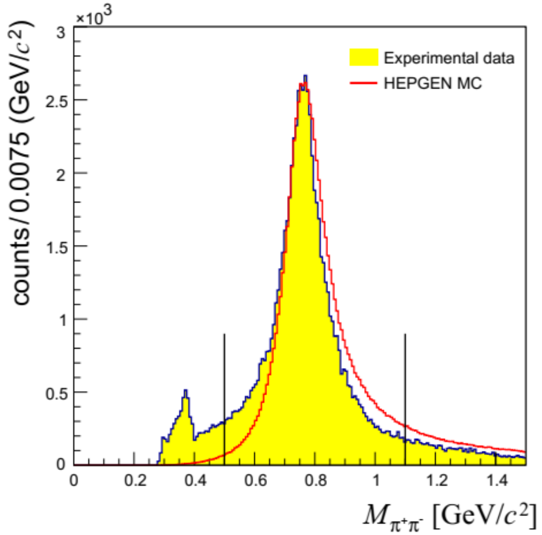
topology:

scattered muon + two hadrons with opposite charges

event yield: **52257 events**

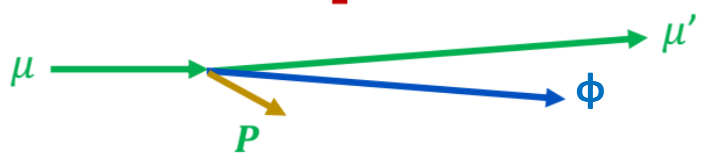
exclusivity: $|E_\mathrm{miss}| < 2.5$ GeV





Selection ϕ: 2016 run DIS2026 NEW!

Exclusive Muoproduction

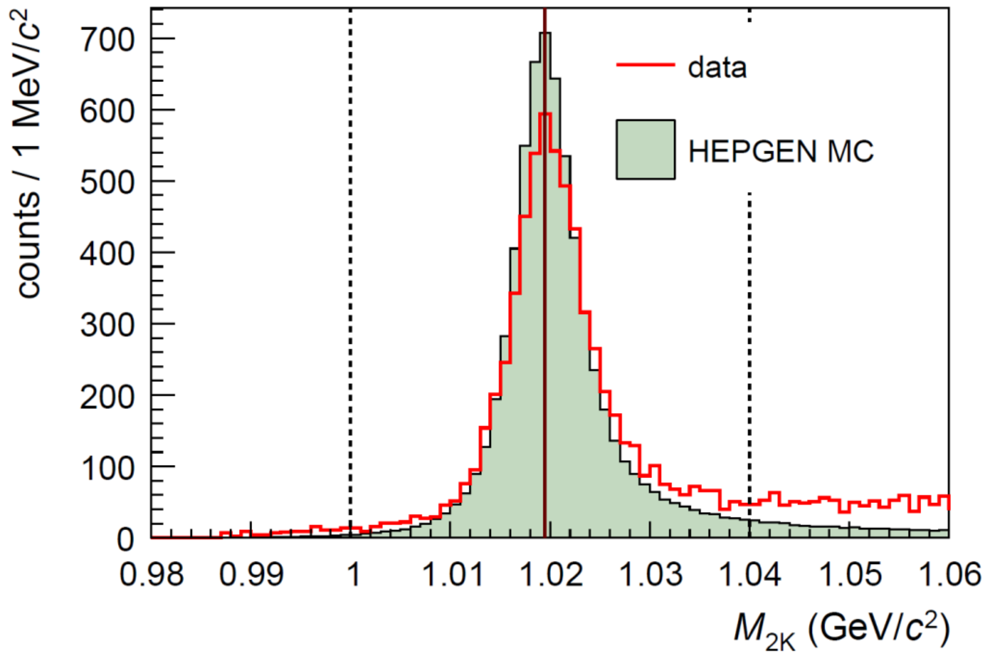


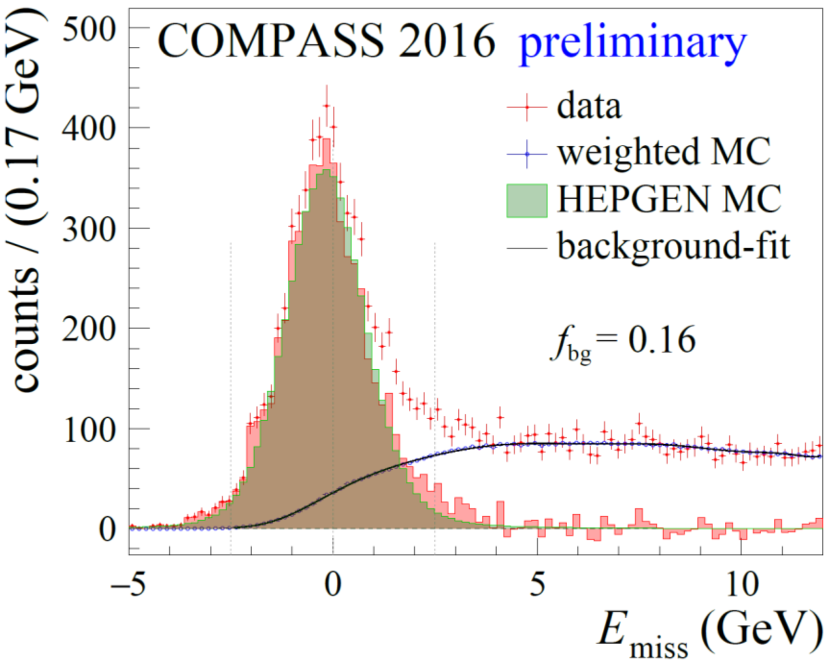
$\mu p \to \mu' p' \phi$ BR = (48.1 ± 0.5) %

$\phi \to K^+K^-$

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

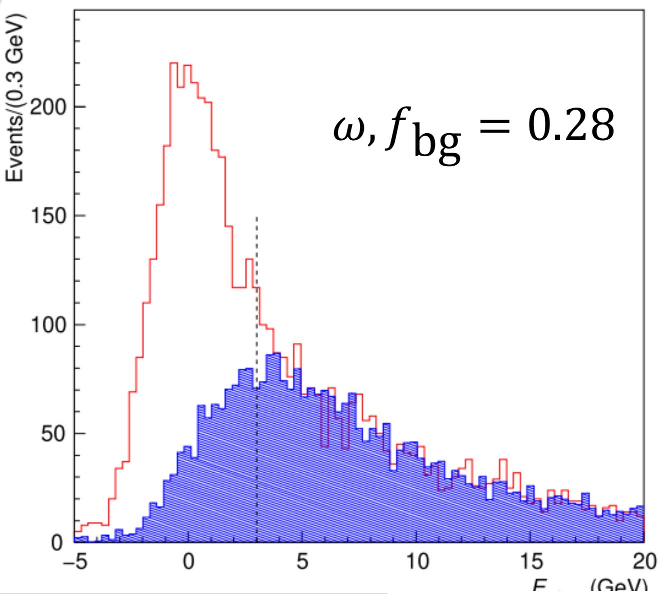
- **Exclusivity**:
- $1.00 < M_{\mathrm{K^+K^-}} < 1.04$ GeV
- $\left| E_\mathrm{miss} = \frac{M_\mathrm{X}^2 - M^2}{2M} \right| < 2.5$ GeV
- Recoil proton detector not included in selection

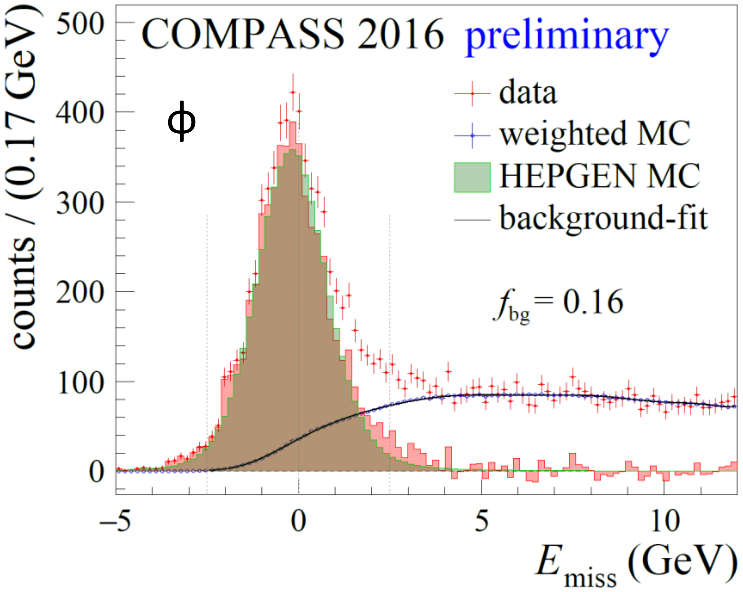


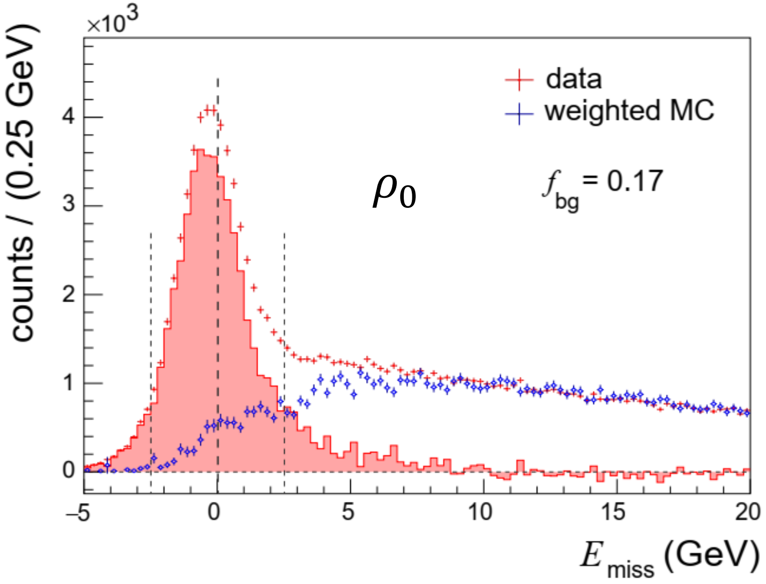


3. background fraction f_{bg}

- original approach: MC (inclusive LEPTO) normalized to data in region $7 < E_{\mathrm{miss}} < 20$ GeV (same sign) -> background fraction in exclusive region (opposite sign)
- for 2016 Phi procedure needed adjustments:
  - 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 $5.0 < E_{\mathrm{miss}} < 12.0$ GeV



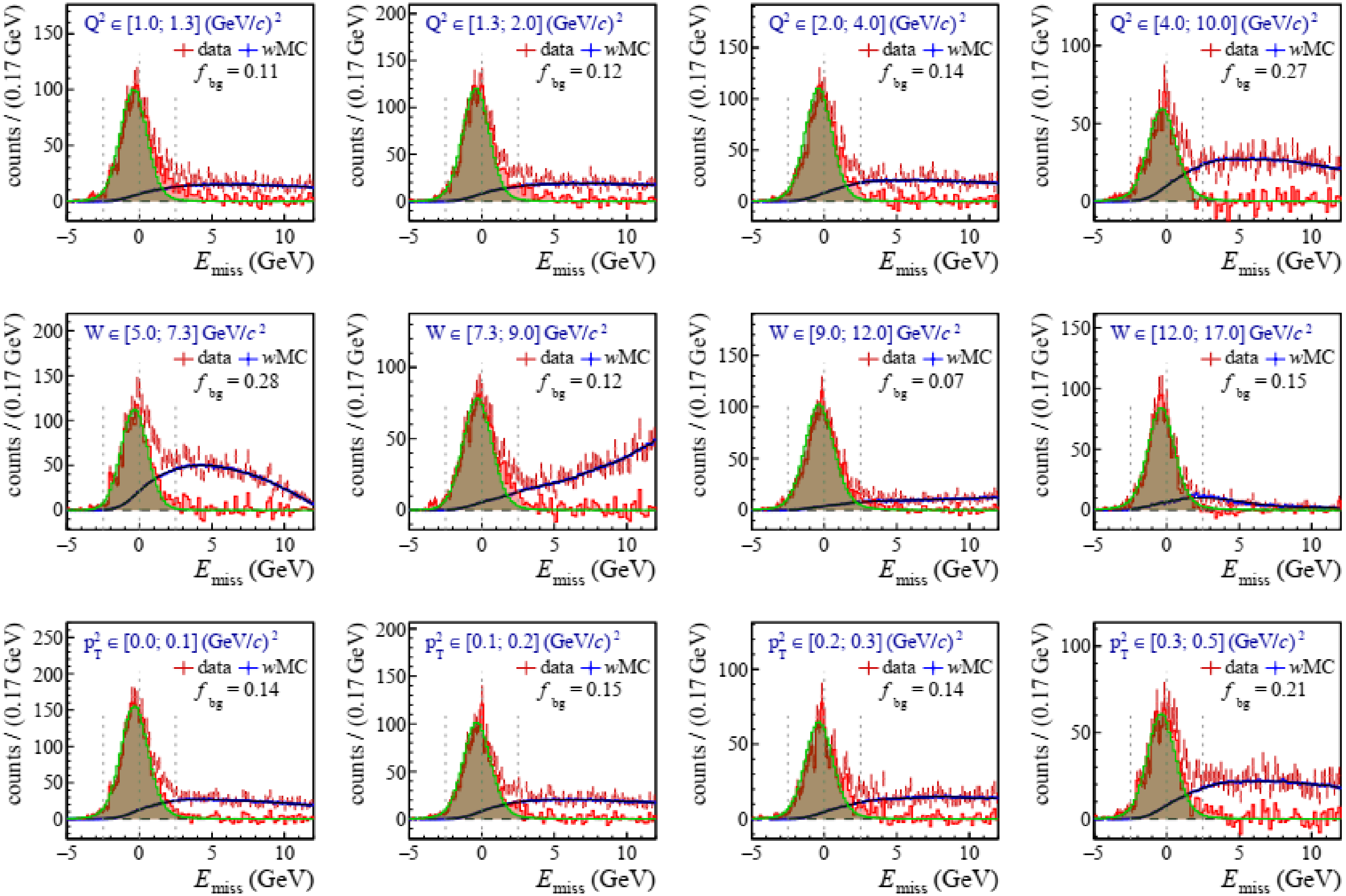




Background fraction f_{bg} - ϕ bins

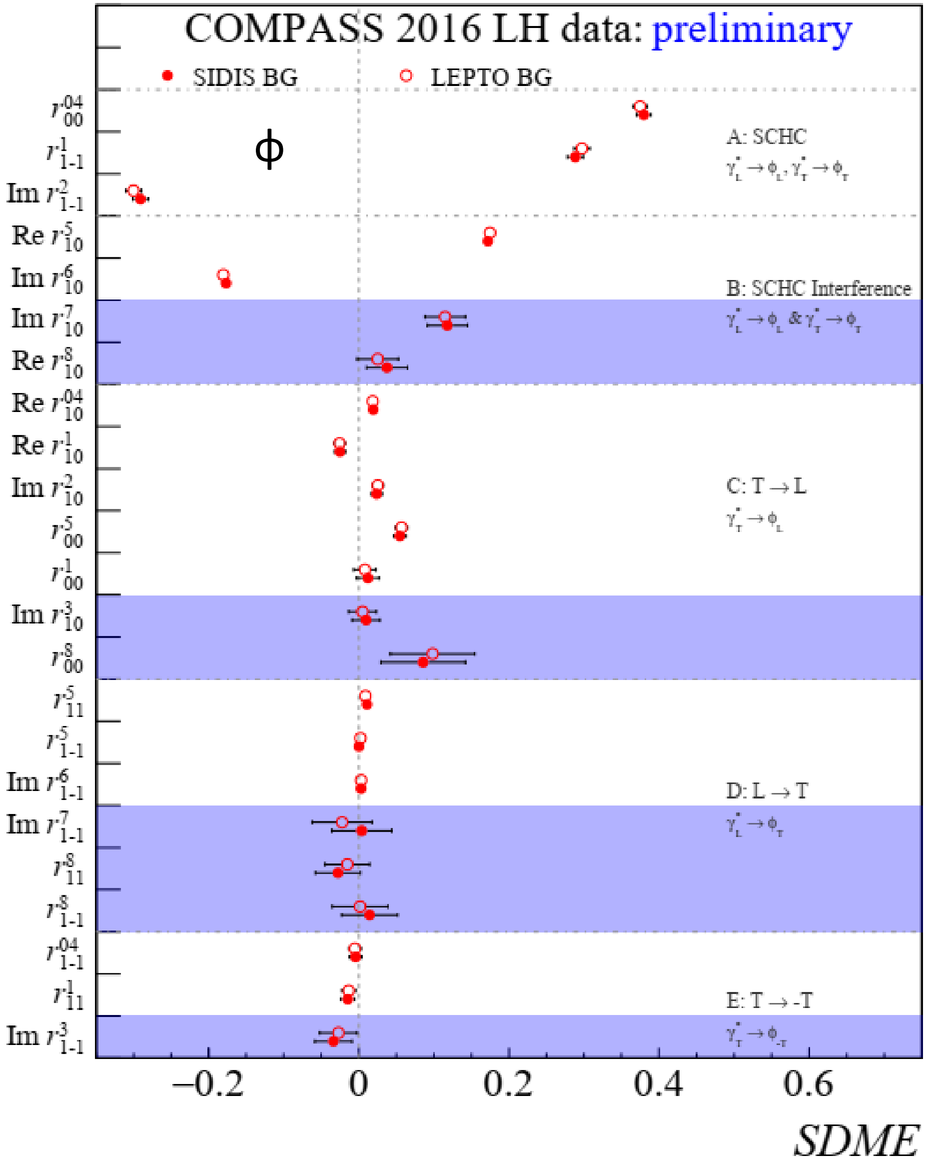
- in kinematic bins situation complicated, but manageable
- another approach:
- ~~Recoil proton detector not included in selection~~
- can reach background-free selection
- ~70% statistics (80% of signal)
- work in progress

COMPASS 2016 data: preliminary



4. background angular distribution/SDMEs

- originally (2012 omega and rho-0) simulated by LEPTO
  - UML fit to LEPTO to obtain background SDMEs
- thorough tests for 2016 phi resulted in new method:
  - data-driven SIDIS side-band, $3 < E_{\text{miss}} < 6$ GeV and $0.9 < M_{\text{inv}} < 1.4$ GeV
  - comparison to LEPTO method -> syst. uncertainty



Exclusive ρ_0 and ω SDMEs Results

Kinematic range:

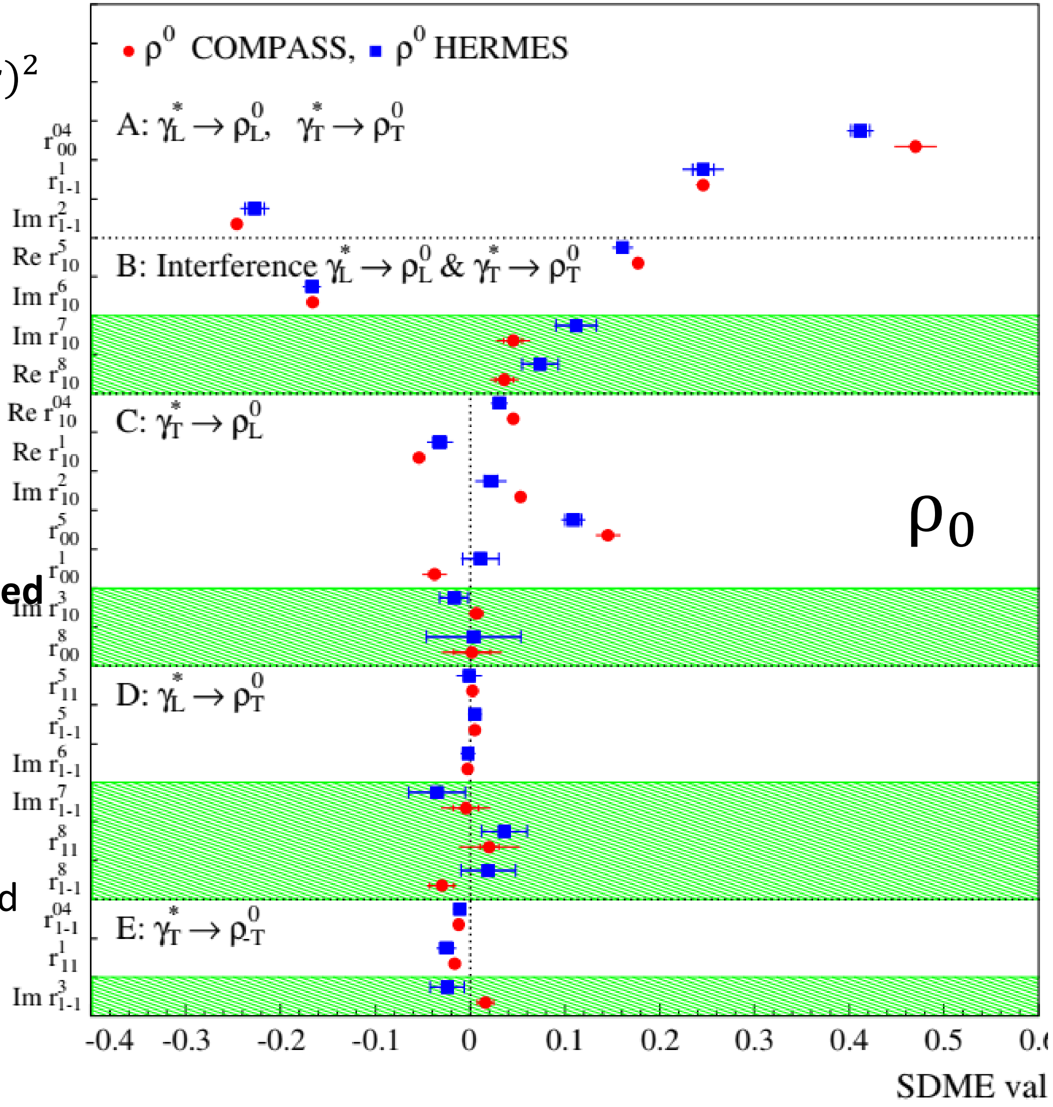
$1 < Q^2 < 10$ (GeV/c)^2
$5 < W < 17$ GeV/c^2
$0.01 < p_T^2 < 0.5$ (GeV/c)^2

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

Shaded areas = **polarized SDMEs**

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

EPJC **83** (2023) 924



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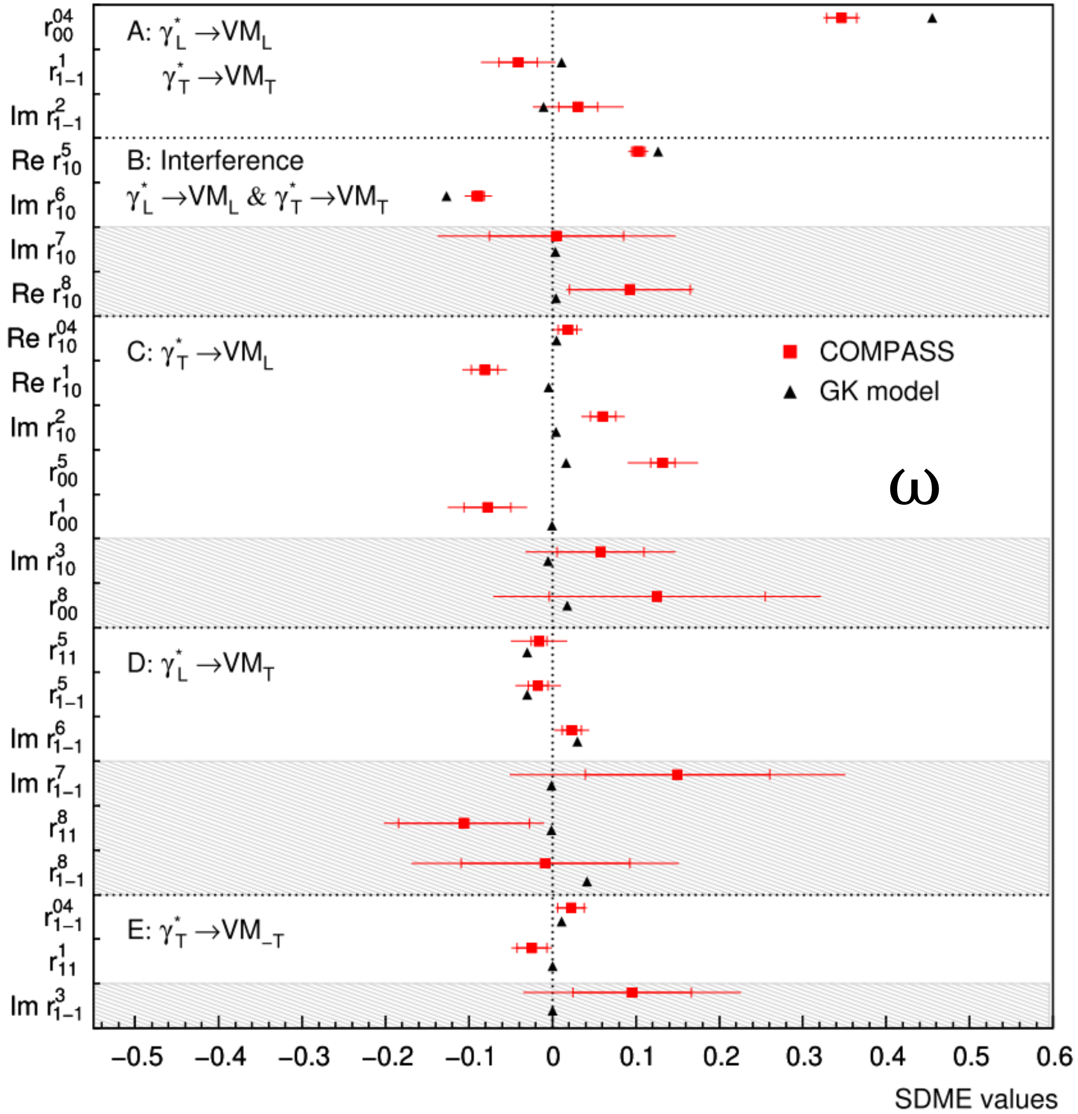


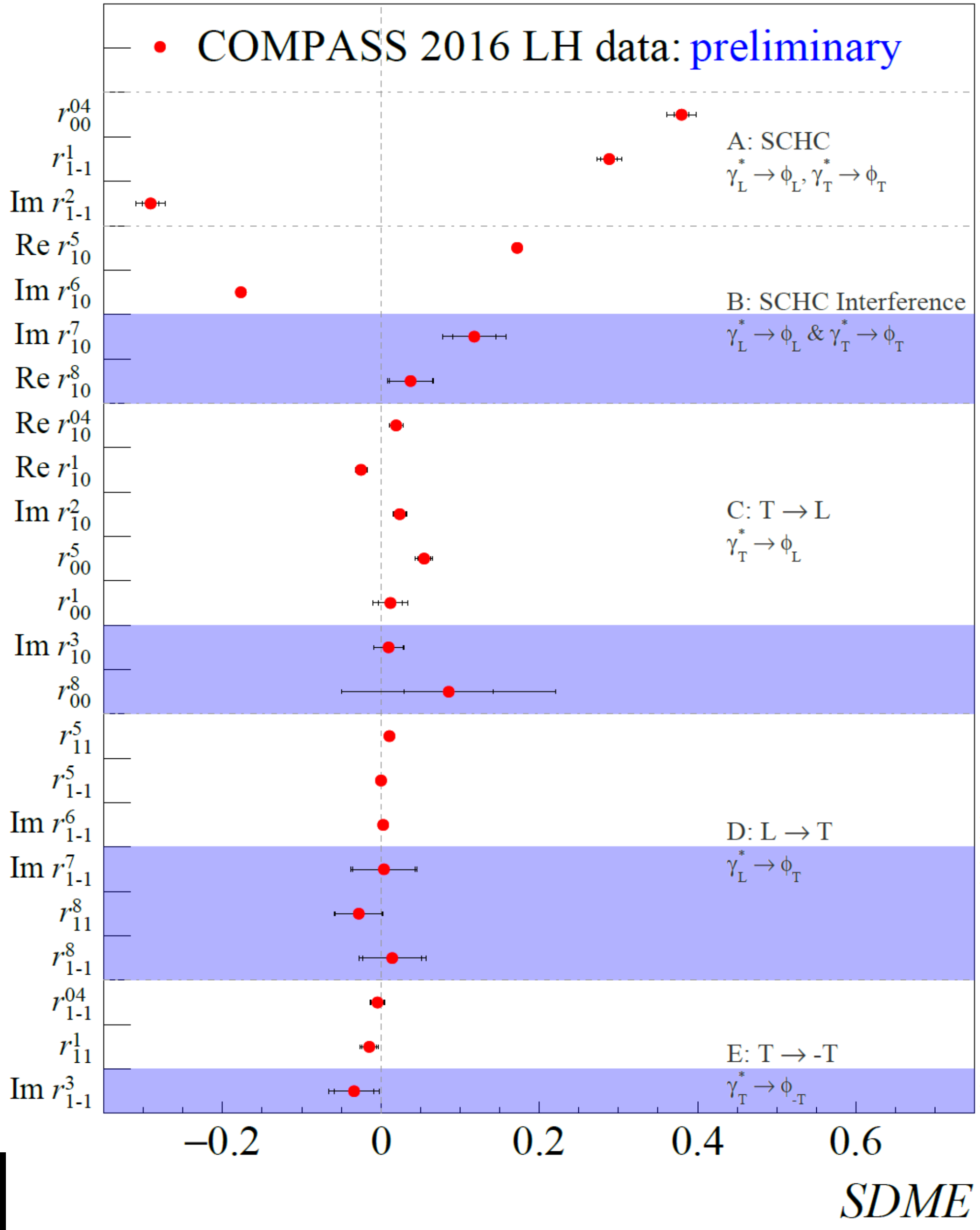
Exclusive ϕ Meson SDMEs

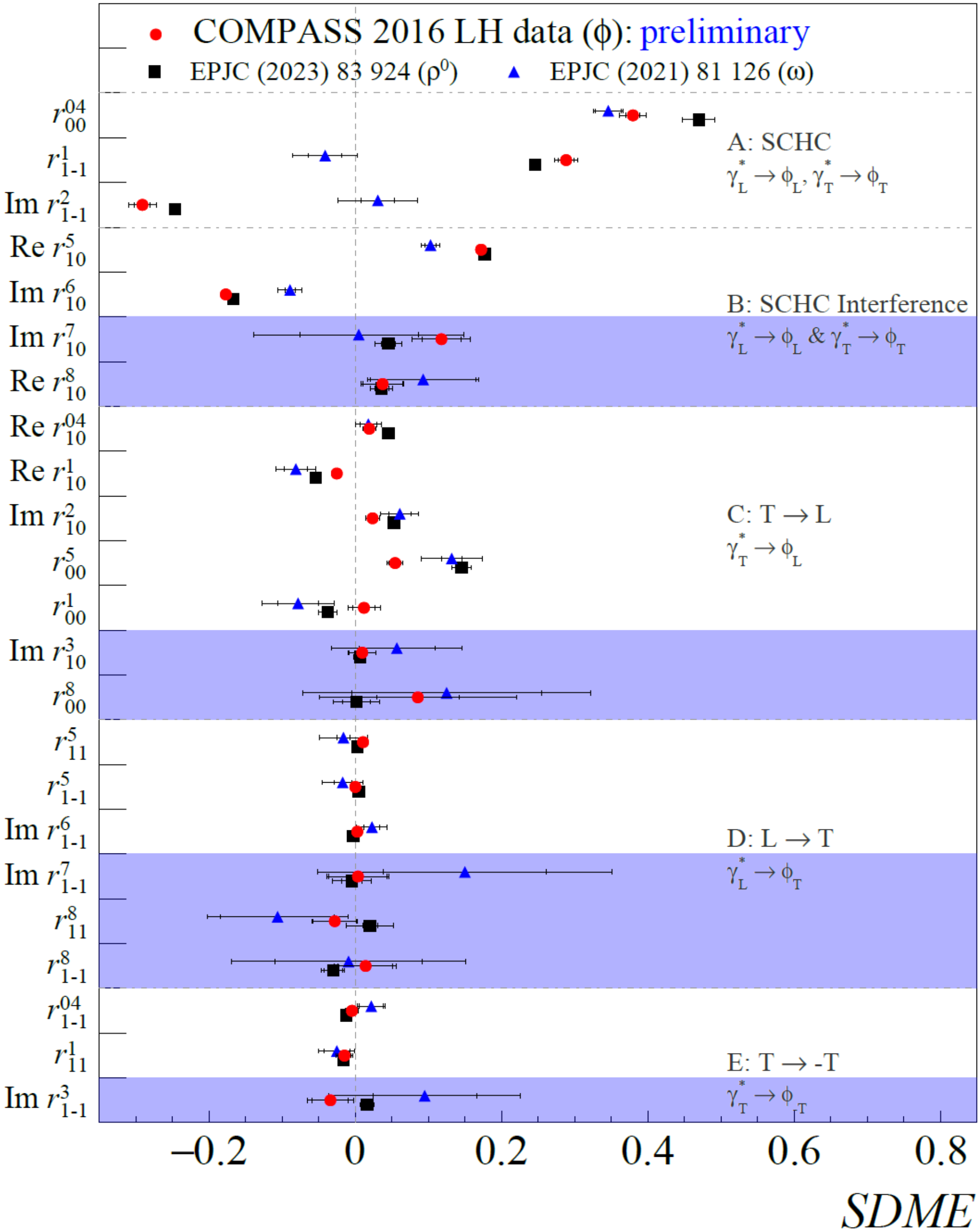
DIS2026 NEW!

- **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 = **polarized 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 $H_T, \bar{E}_T = 2\widetilde{H}_T + E_T$

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

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

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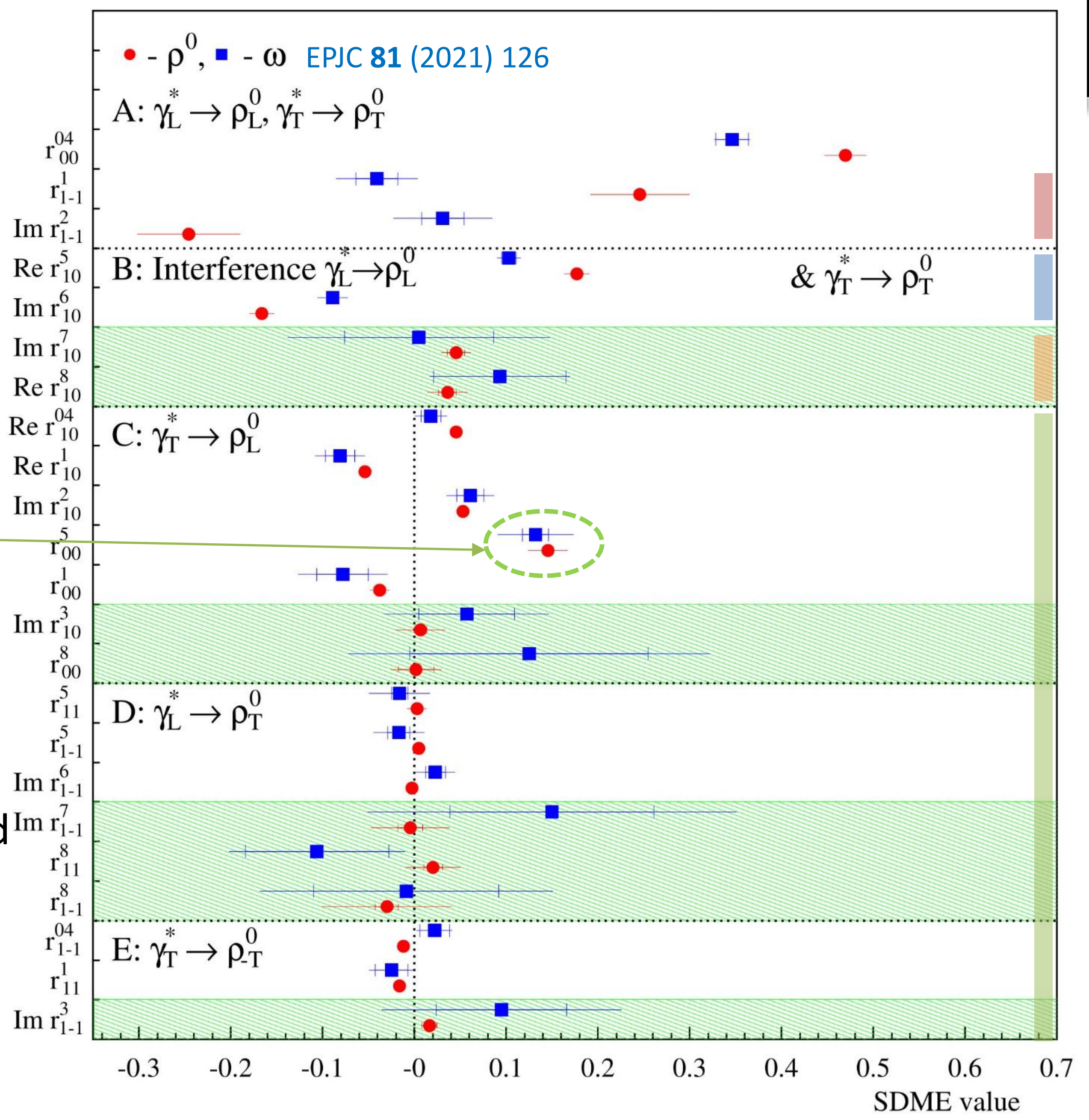
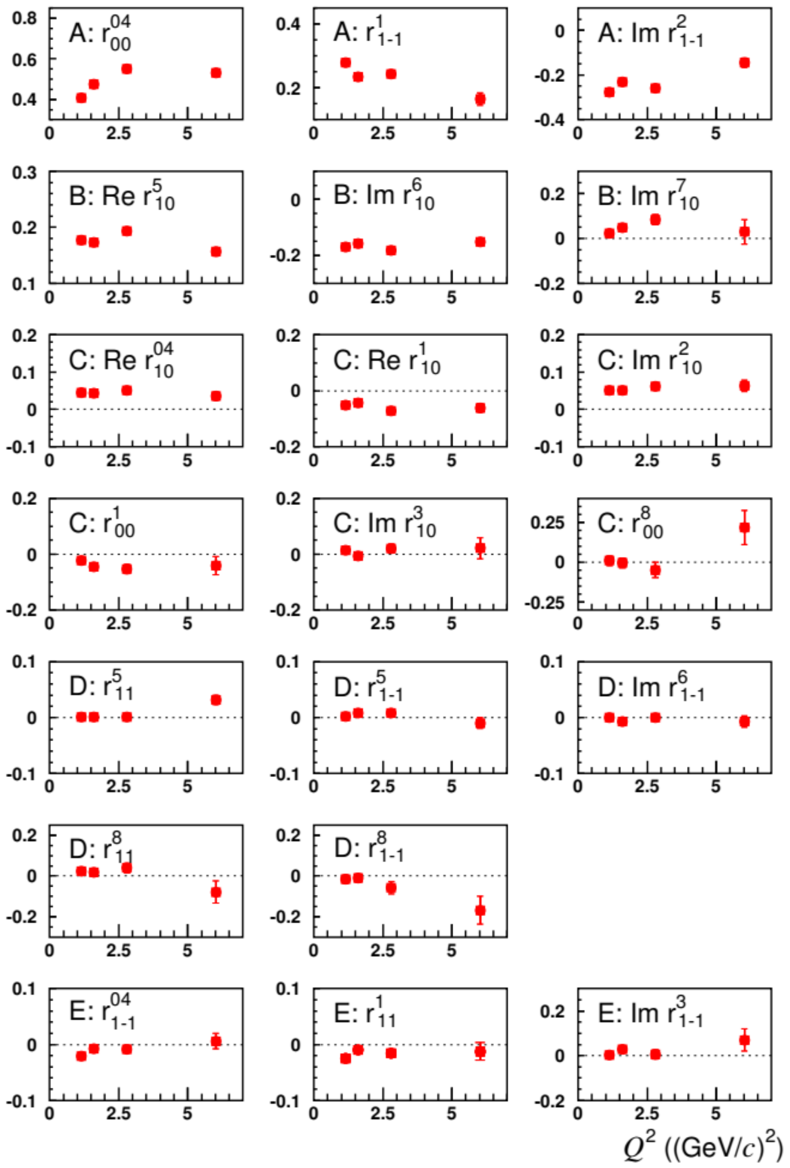


SDMEs dependences



ρ_0

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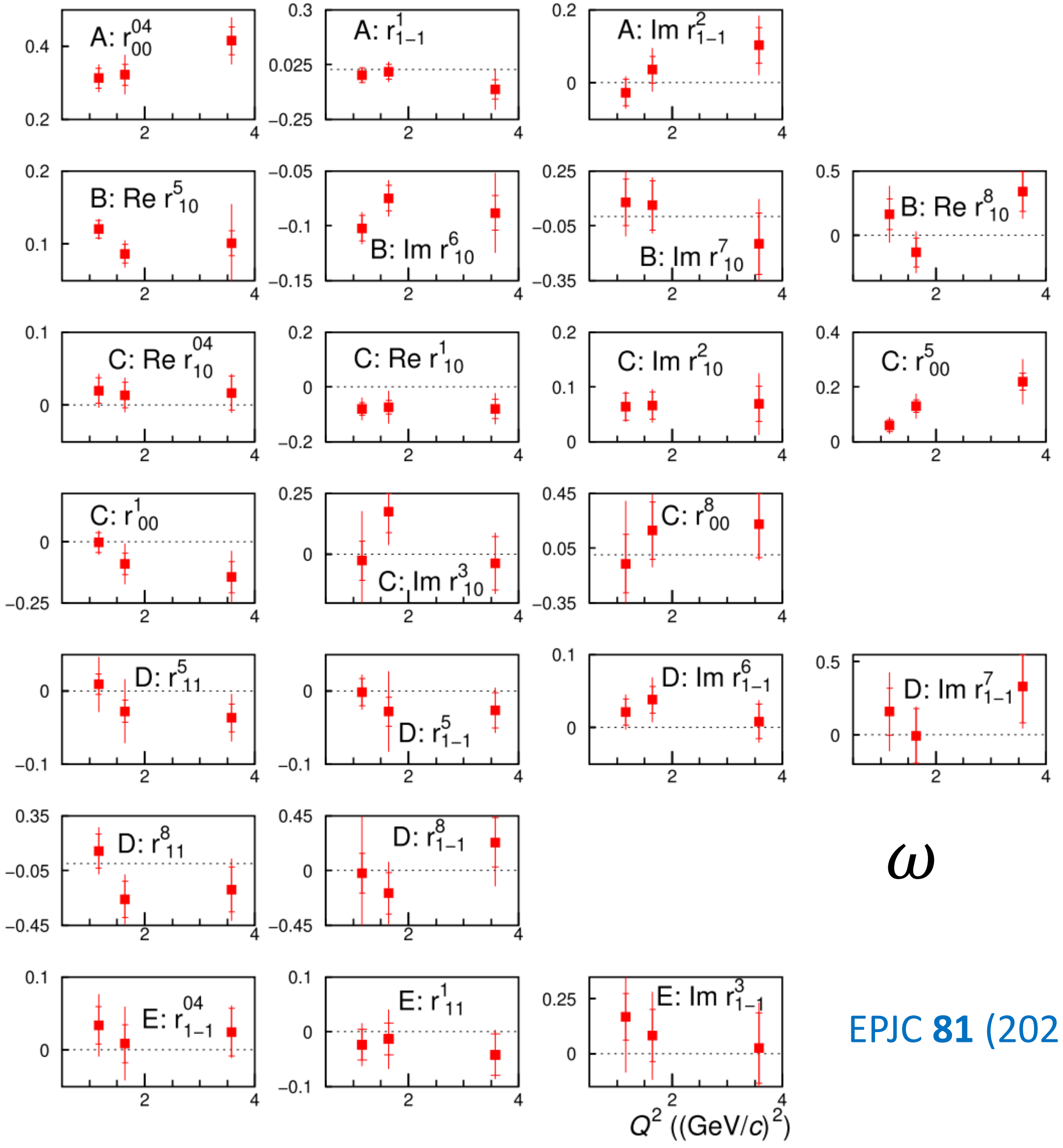


ω

EPJC **81** (2021) 126

Results: SCHC ϕ

- SCHC implies:

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

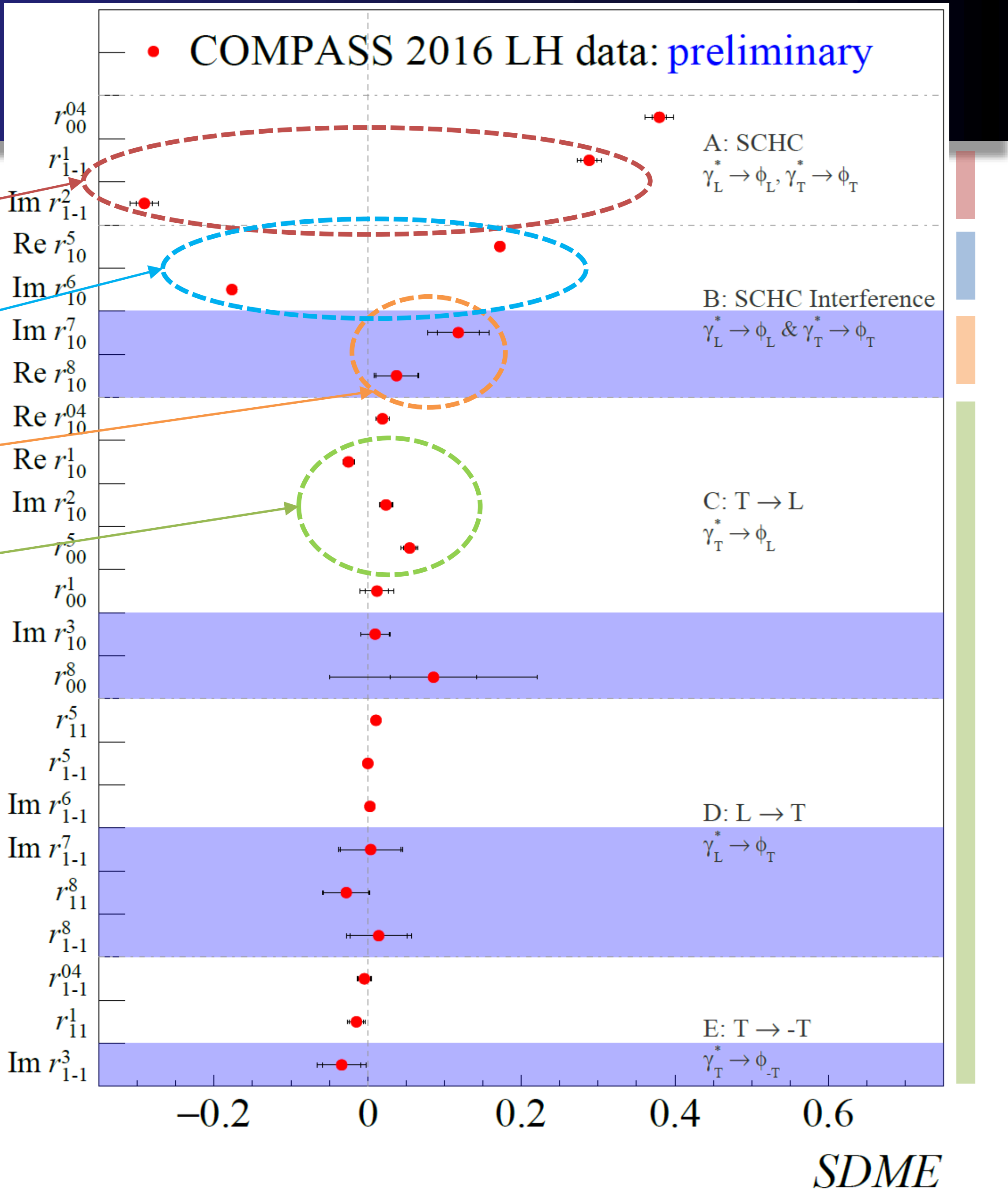
$$\mathrm{Re}\, r^5_{10} + \mathrm{Im}\, r^6_{10} = 0$$ OK

$$\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$$ 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 $H_T, \bar{E}_T = 2\widetilde{H}_T + E_T$

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



Results – Helicity-Flip NPE Amplitudes ρ^0

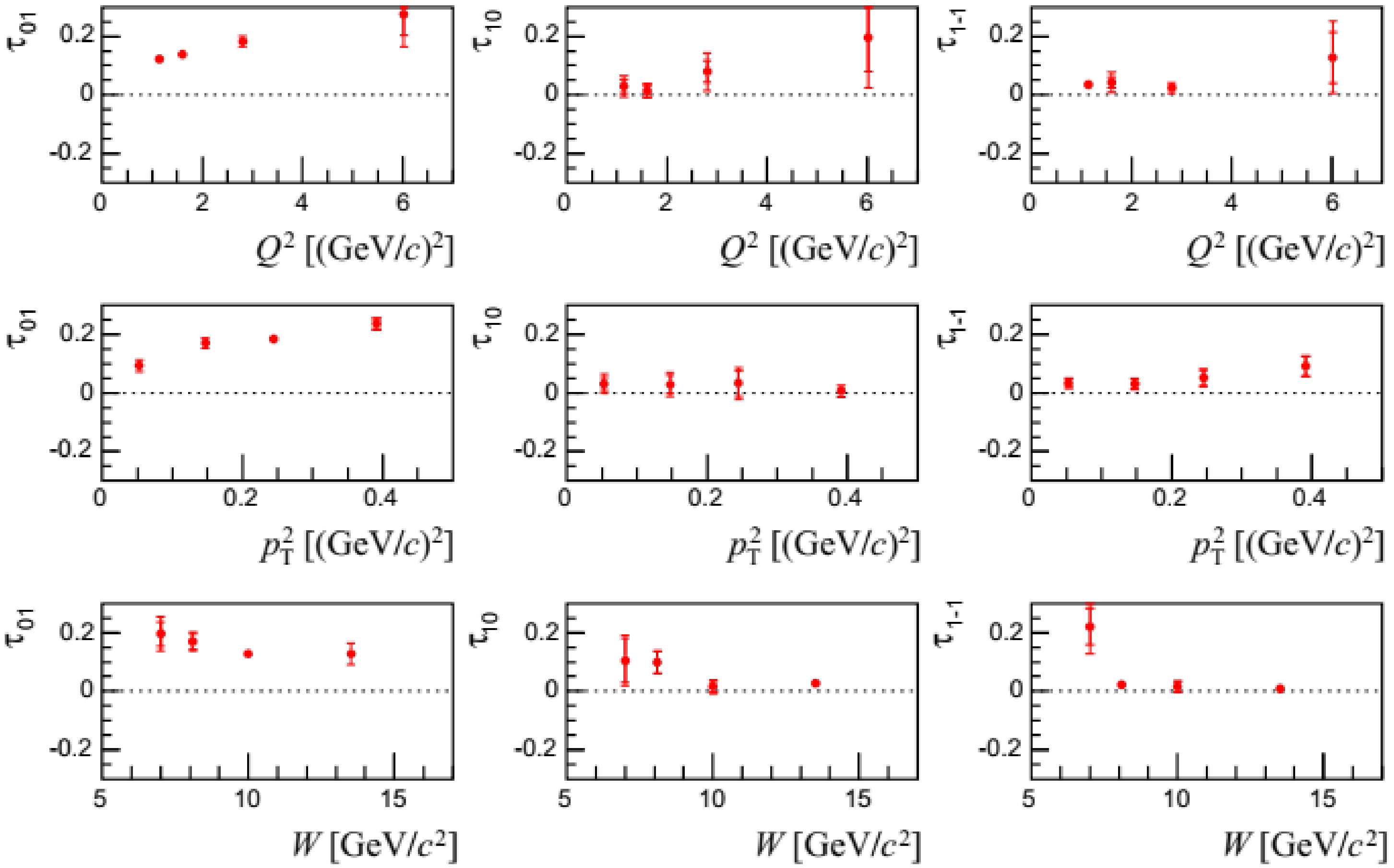
- described as $\tau_{ij} = \dfrac{|T_{ij}|}{\mathcal{N}}$

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

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

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

- only $\boldsymbol{\tau_{01}}$ **significantly differs from 0**, consistent with SCHC violation in class C



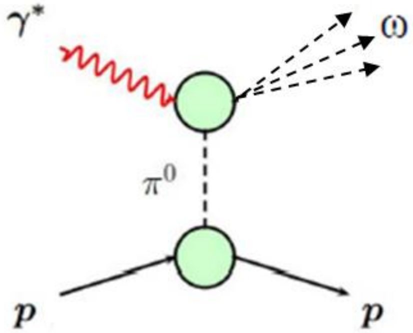
Results – NPE to UPE Asymmetry

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

$$= \frac{2r_{1-1}^1}{1 - r_{00}^{04} - 2r_{1-1}^{04}}$$

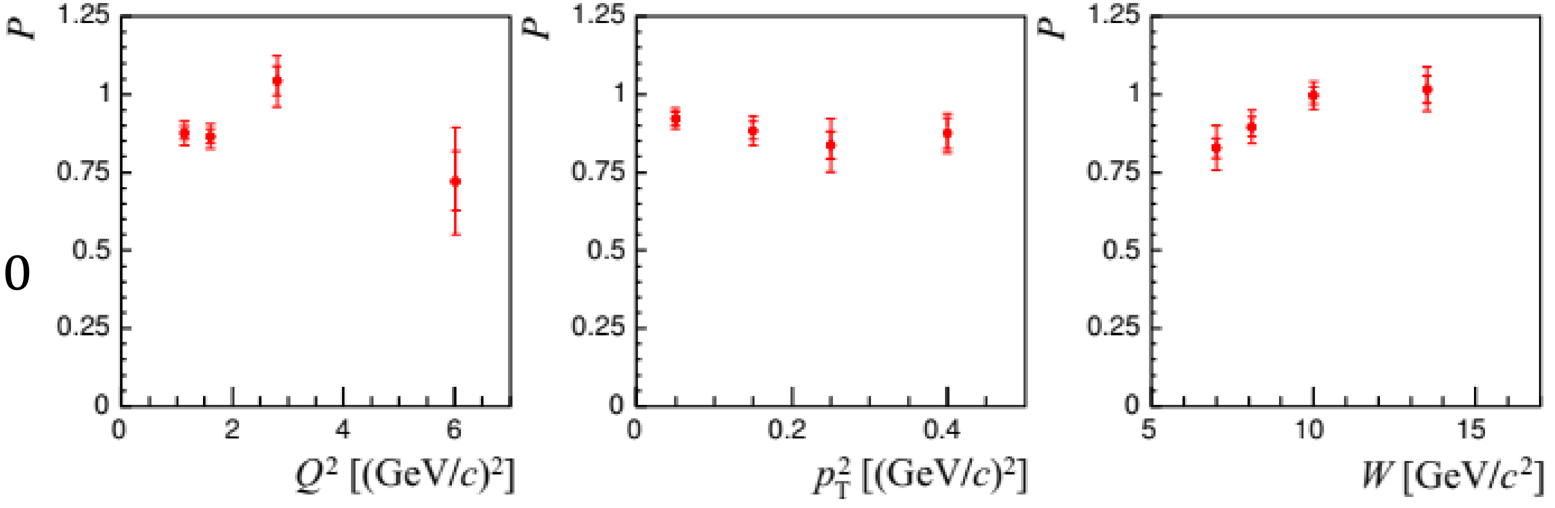
- **ρ_0 NPE dominance**
  NPE $\longrightarrow$ GPDs E, H

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



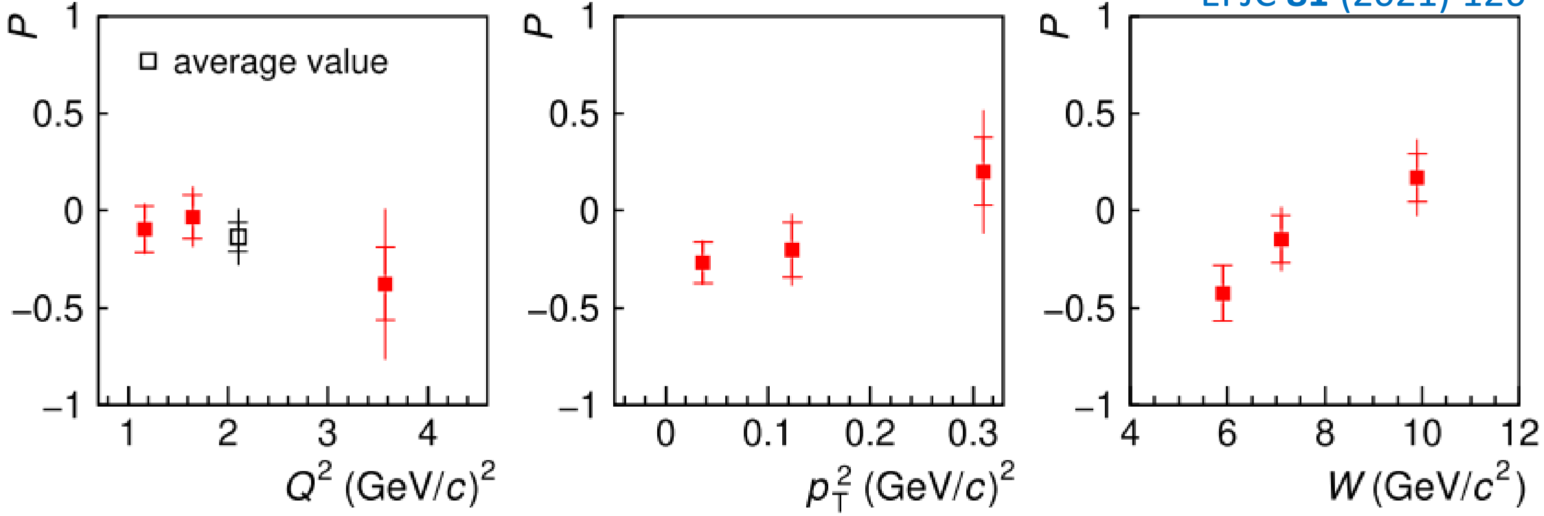
EPJC **83** (2023) 924

ρ_0



EPJC **81** (2021) 126

ω



Results: Unnatural Parity Exchange Contribution

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

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

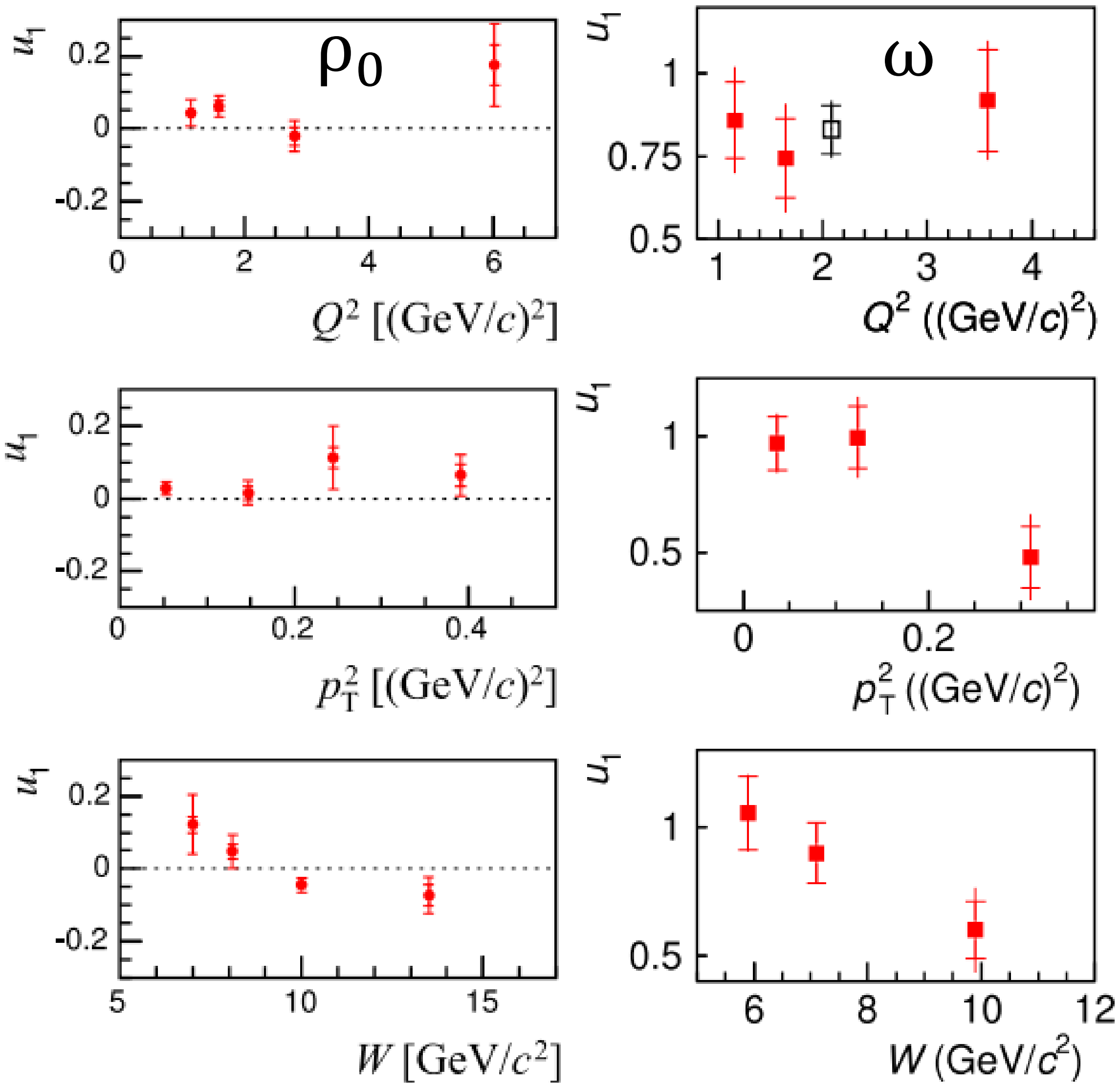
$$\tau^2_{\mathrm{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$$

- numerator in u_1 depends only on UPE amplitudes -> u_1>0
- **ρ⁰ 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
  - $\boldsymbol{u_1} = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1} = \mathbf{0.064 \pm 0.029\,(stat.) \pm 0.032(syst.)}$

    $u_2 = r^{5}_{11} + r^{5}_{1-1} = 0.011 \pm 0.006\,(\text{stat.}) \pm 0.002(\text{syst.})$

    $u_3 = r^{8}_{11} + r^{8}_{1-1} = -0.014 \pm 0.051\,(\text{stat.}) \pm 0.022(\text{syst.})$
  - $u_1 = \tilde{\sum} \frac{4\epsilon|U_{10}|^2 + 2|U_{11} + U_{-11}|^2}{\mathcal{N}}$ $\Delta_{\text{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$
- **ϕ: very small UPE** contribution observed
  - $\Delta_{\text{UPE}} \approx$ 0.03 averaged (UPE fractional contribution)

UPE Contribution, NPE to UPE Asymmetry ϕ

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

- NPE to UPE Asymmetry
  - $P = \frac{d\sigma_T^N(\gamma_T^* \to V_T) - d\sigma_T^U(\gamma_T^* \to V_T)}{d\sigma_T^N(\gamma_T^* \to V_T) + d\sigma_T^U(\gamma_T^* \to V_T)} \approx \frac{2r^{1}_{1-1}}{1 - r^{04}_{00} - 2r^{04}_{1-1}}$
  - $\boldsymbol{P = 0.917 \pm 0.039\,(stat.) \pm 0.045(syst.)}$
- **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 $\gamma_T^* \to V_L$ → 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

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

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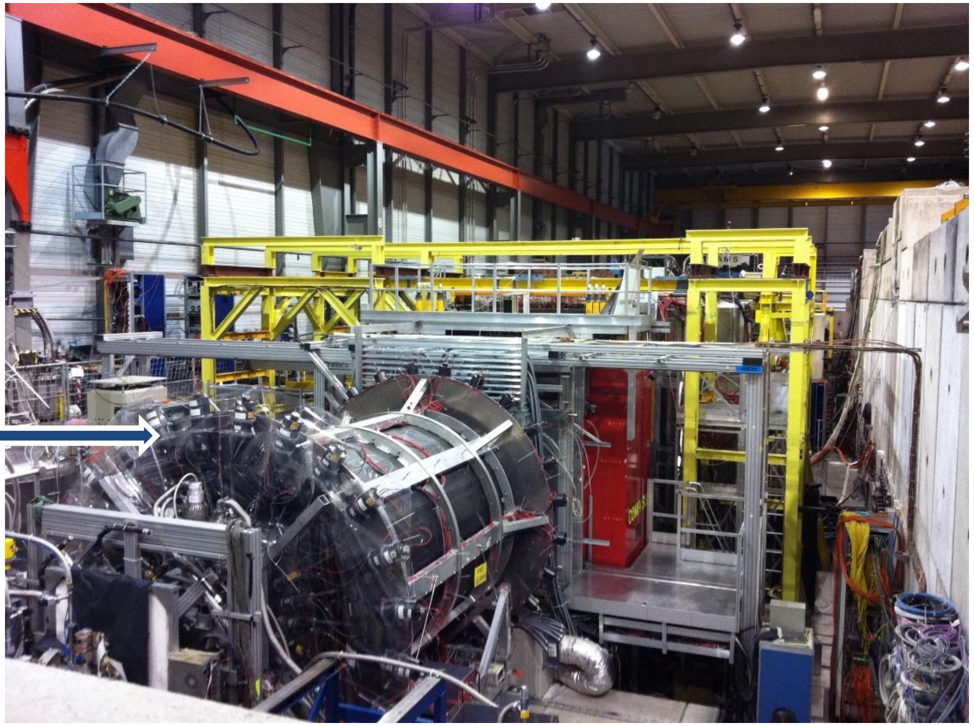
Ministry of Education, Youth and Sports of the Czech Republic

FORTE

COMPASS 25 years 1997 - 2022

COMPASS Experiment

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



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

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: $J^P = (0^+, 1^-, \dots) \rightarrow$ pomeron, ρ, ω, a_2 …
    - UPE: $J^P = (0^-, 1^+, \dots) \rightarrow$ 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 **σ_L/σ_T** ratio
  - Probe **GPD models** → e.g. SCHC violation $(\gamma_T^* \rightarrow V_L)$ 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 flavor filter, insights into reaction mechanism

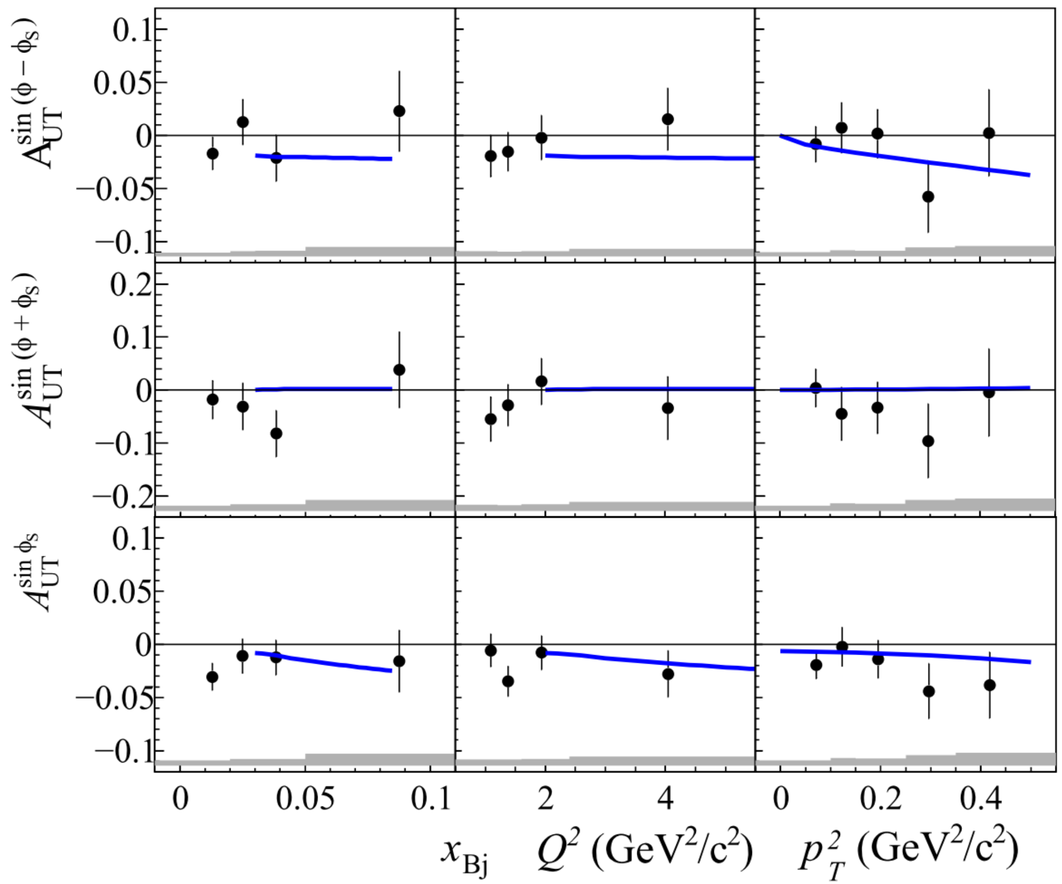
Angular distributions

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

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

ρ_0 and ω Asymmetries with T Polarized Target

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

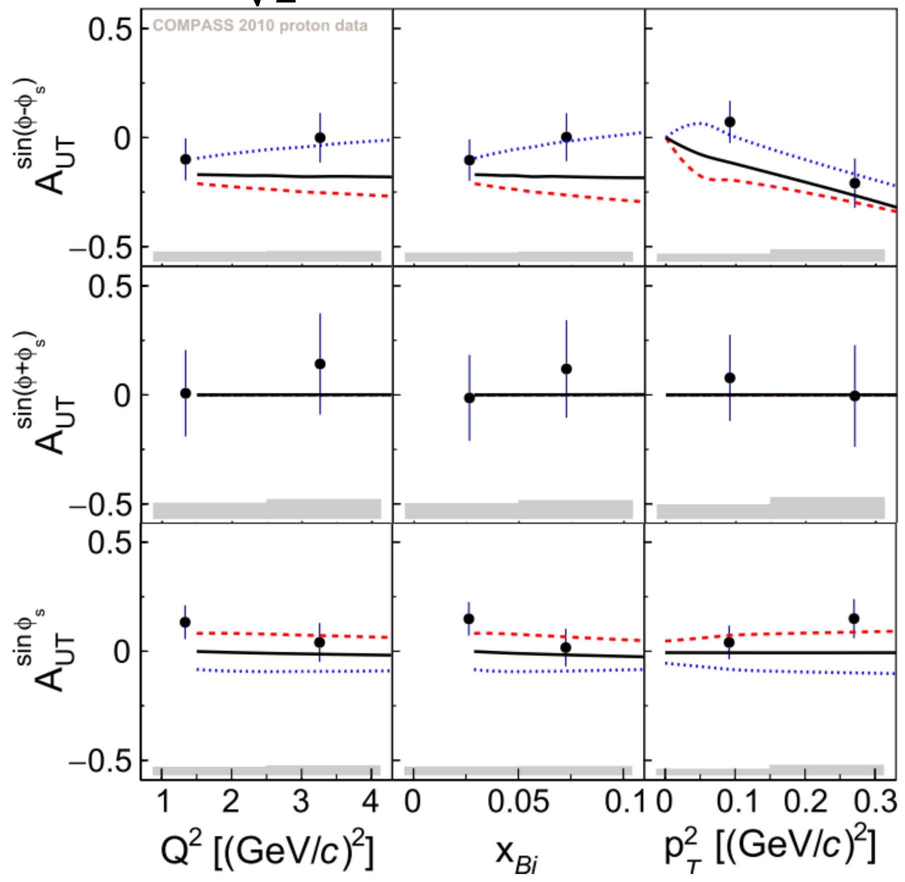


$\propto \mathrm{Im}\,(E * H)$

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

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

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



No pion pole

Negative $\pi\omega$ form factor

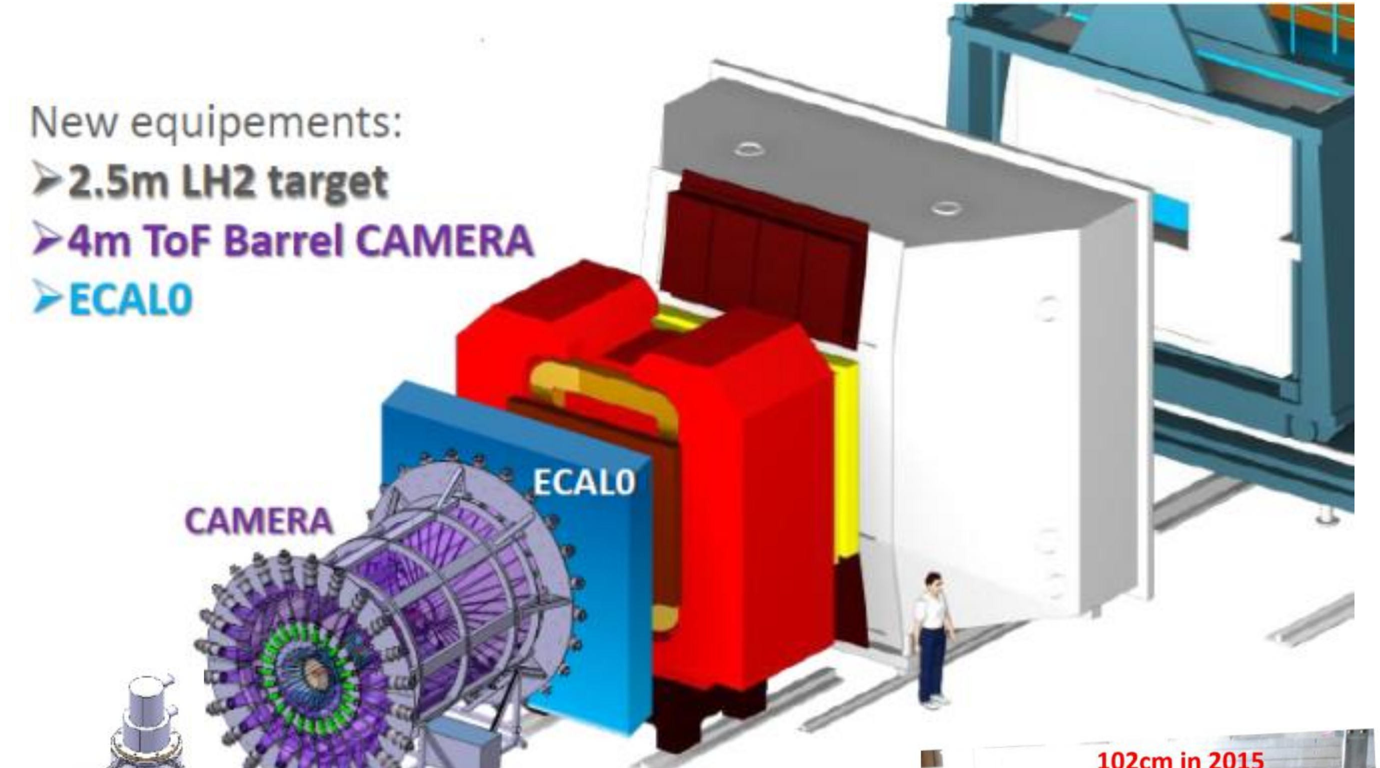
Positive $\pi\omega$ form factor

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

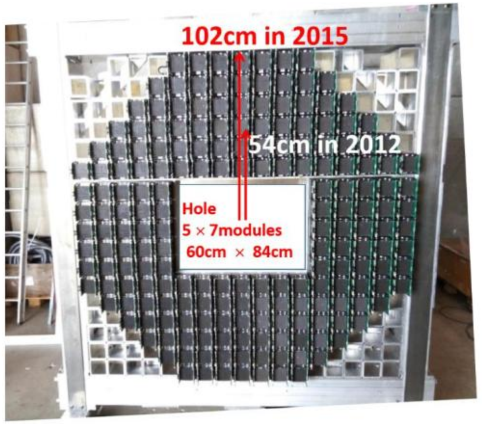
Sensibility to $\boldsymbol{E}, \boldsymbol{H_T}$

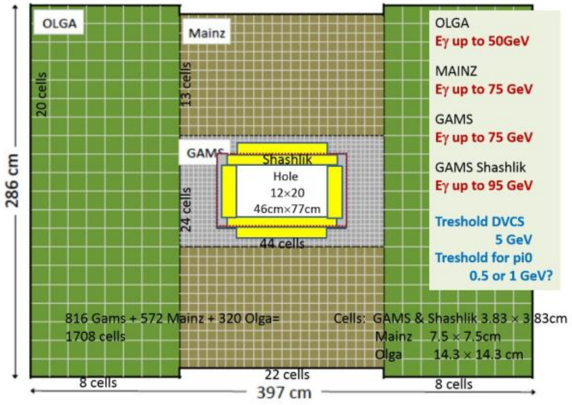
NPB **915** (2017) 454

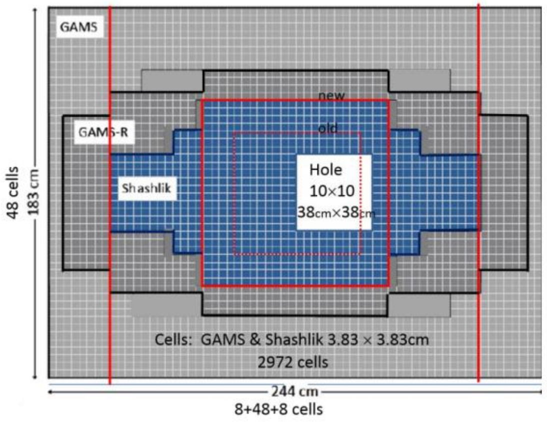
Key parts of setup



- 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



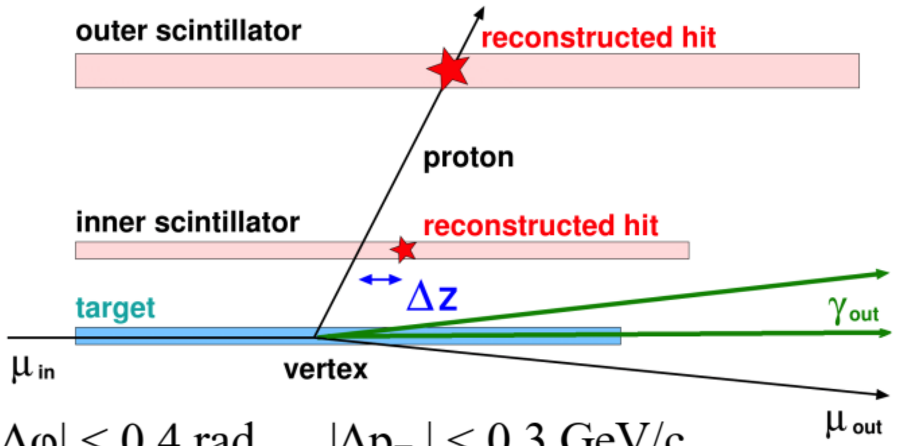




Selection π_0 — 2016 run

- topology: scattered muon + two neutral clusters in calorimeters + recoil proton candidate
- $\mu + p \rightarrow \mu' + p' + \pi^0$
- $\mathbf{1} < \boldsymbol{Q^2} < \mathbf{8}\ (\mathrm{GeV}/c)^2$

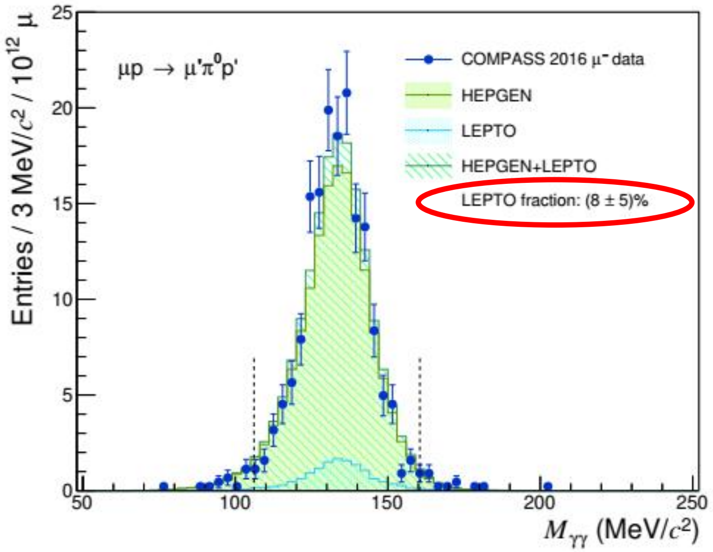
  $\mathbf{0.08} < |\boldsymbol{t}| < \mathbf{0.64}\ (\mathrm{GeV}/c)^2$
- transverse momentum constraint:
- $\Delta\varphi = \varphi^{p}_{spect} - \varphi^{p}_{recoil}$
- z-coordinate of inner RPD ring:
- energy-momentum conservation:
- invariant mass $M_{\gamma\gamma}$ (106.1, 160.5) MeV/c^2
- kinematic fit

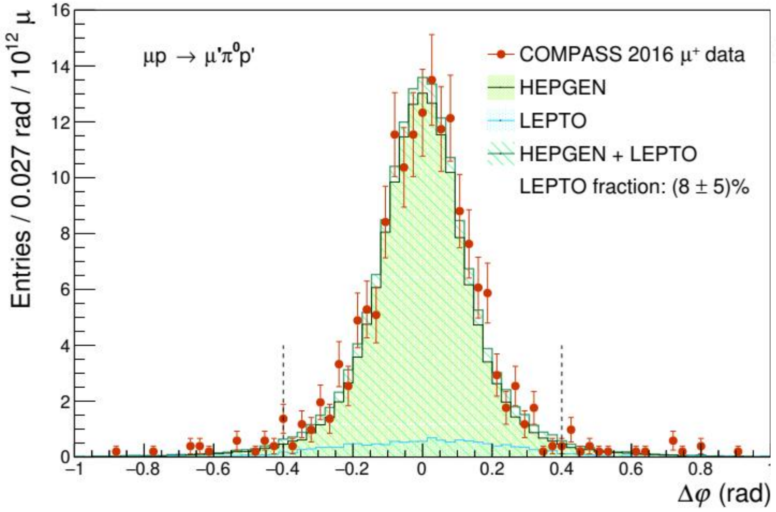


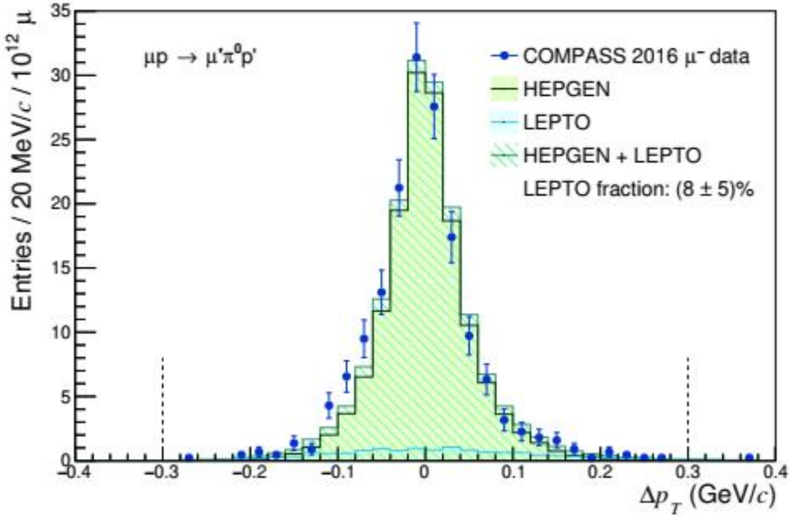
$|\Delta\varphi| < 0.4$ rad $|\Delta p_T| < 0.3$ GeV/c

$|\Delta Z_A| < 16$ cm $|M^2_X| < 0.3\ (\mathrm{GeV}/c^2)^2$

$M_X^2 =$



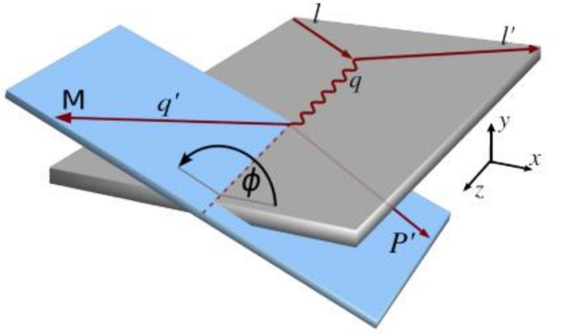




exclusive π_0 HEMP cross-section

- μp cross-section reduced to $\gamma^* p$ $\quad \dfrac{d^4\sigma_{\mu p}}{dQ^2 dt d\nu d\phi} = \Gamma \dfrac{d^2\sigma_{\gamma^* p}}{dt d\phi} \qquad \Gamma = \Gamma(E_\mu, Q^2, \nu)$

$$\frac{d\sigma^{\gamma^* p}}{dt d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)\frac{d\sigma_{LT}}{dt}\right]$$



- spin independent cross-section after averaging:

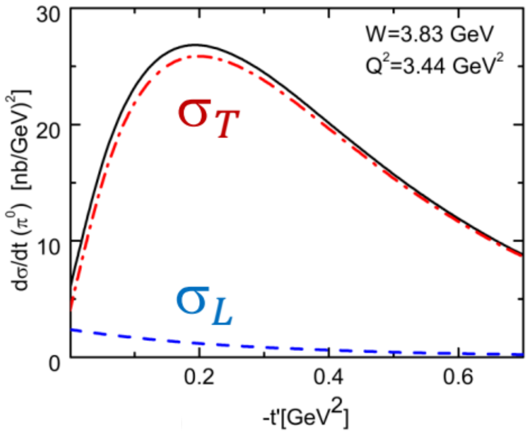
$$\frac{d^2\sigma_{\gamma^* p}}{dt d\phi} = \frac{1}{2}\left(\frac{d^2\sigma^{\leftarrow}_{\gamma^* p}}{dt d\phi} + \frac{d^2\sigma^{\rightarrow}_{\gamma^* p}}{dt d\phi}\right) \Rightarrow \textbf{study } \phi \textbf{ dependence}$$

- after integration in ϕ

$$\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} \Rightarrow \textbf{study } t \textbf{ dependence}$$

- 2012: PLB 805 (2020) 135454
- 2016: accepted in PLB NEW!

S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))



GPDs in exclusive π^0 production

$$\frac{d\sigma_L}{dt} \propto \left[(1-\xi^2)\,|\langle\tilde{\mathcal{H}}\rangle|^2 - 2\xi^2\,\mathrm{Re}\,(\langle\tilde{\mathcal{H}}\rangle^*\langle\tilde{\mathcal{E}}\rangle) - \frac{t}{4M^2}\xi^2|\langle\tilde{\mathcal{E}}\rangle|^2\right]$$

$$\frac{d\sigma_T}{dt} \propto \left[(1-\xi^2)\,|\langle\mathcal{H}_T\rangle|^2 - \frac{t'}{8M^2}|\langle\bar{\mathcal{E}}_T\rangle|^2\right]$$

$$\frac{d\sigma_{TT}}{dt} \propto t'\,|\langle\bar{\mathcal{E}}_T\rangle|^2$$

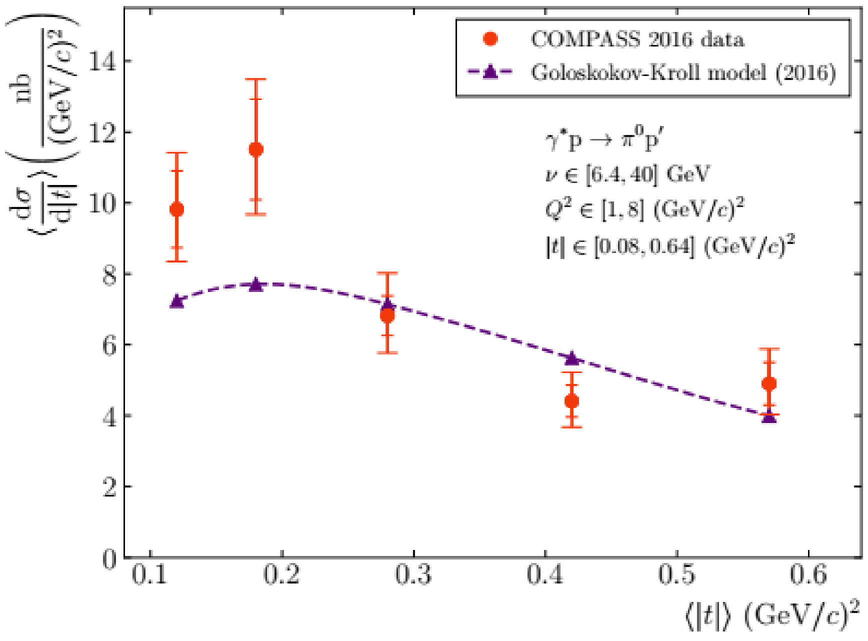
$$\frac{d\sigma_{LT}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\,\mathrm{Re}\,(\langle\mathcal{H}_T\rangle^*\langle\tilde{\mathcal{E}}\rangle)$$

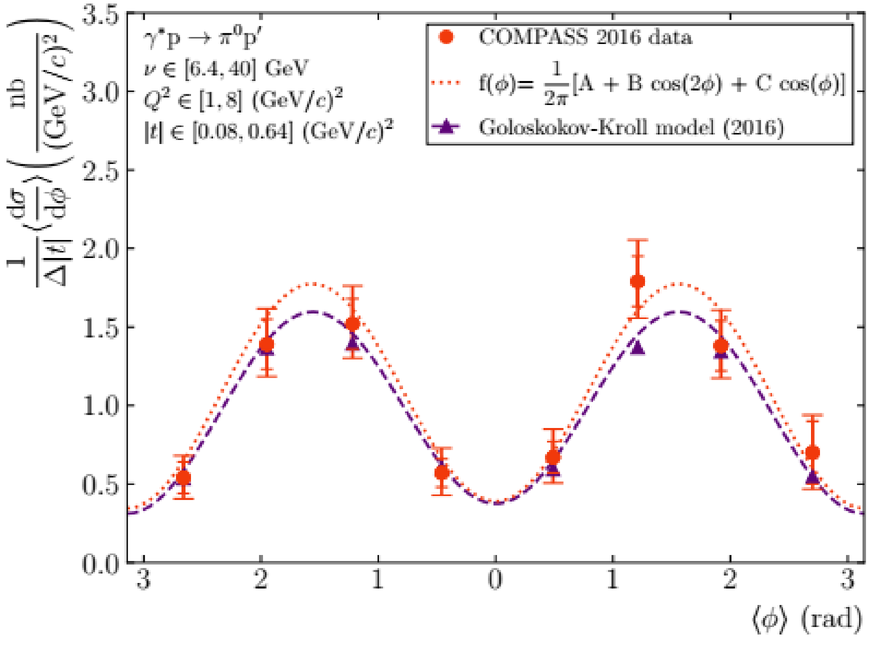
exclusive π_0 HEMP cross-section – results

- Measured t and ϕ-dependence on unpolarized proton at low at low ξ ($\langle x_B \rangle = 0.134$)
- Provides key input for **phenomenological models**
  - Strong sensitivity to **chiral-odd GPDs**
  - Especially constrains the poorly known $\bar{E}_T$
- 2016 data: **2.3× statistics** vs 2012
  - Full 2016/17 dataset: up to **9× larger**

$\langle \varepsilon \rangle = 0.997$

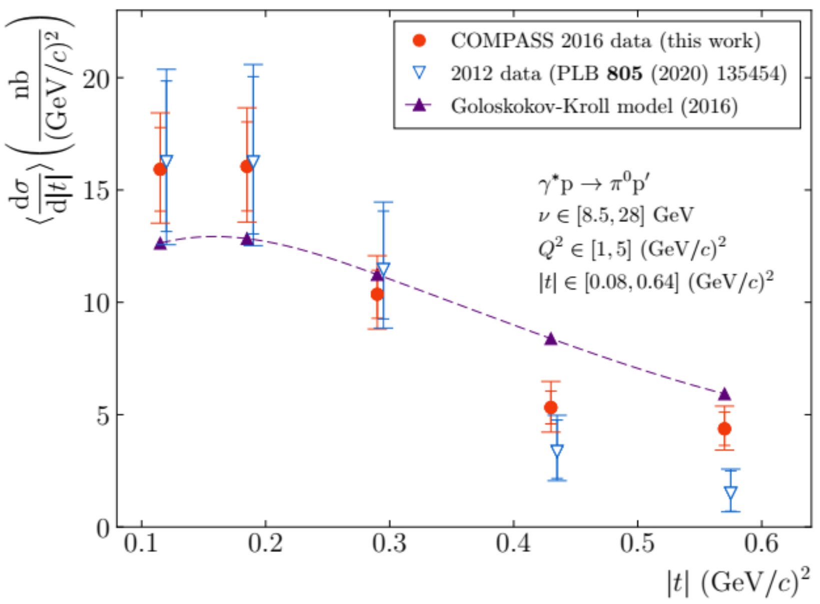
$\left\langle \frac{d\sigma_T}{d\|t\|} + \varepsilon \frac{d\sigma_L}{d\|t\|} \right\rangle$	$\left\langle \frac{d\sigma_{TT}}{d\|t\|} \right\rangle$	$\left\langle \frac{d\sigma_{LT}}{d\|t\|} \right\rangle$
$6.7 \pm 0.3_{\text{stat}} \, {}^{+0.9}_{-0.8}\big\|_{\text{sys}}$	$-4.4 \pm 0.5_{\text{stat}} \, {}^{+0.3}_{-0.3}\big\|_{\text{sys}}$	$0.1 \pm 0.2_{\text{stat}} \, {}^{+0.1}_{-0.1}\big\|_{\text{sys}}$

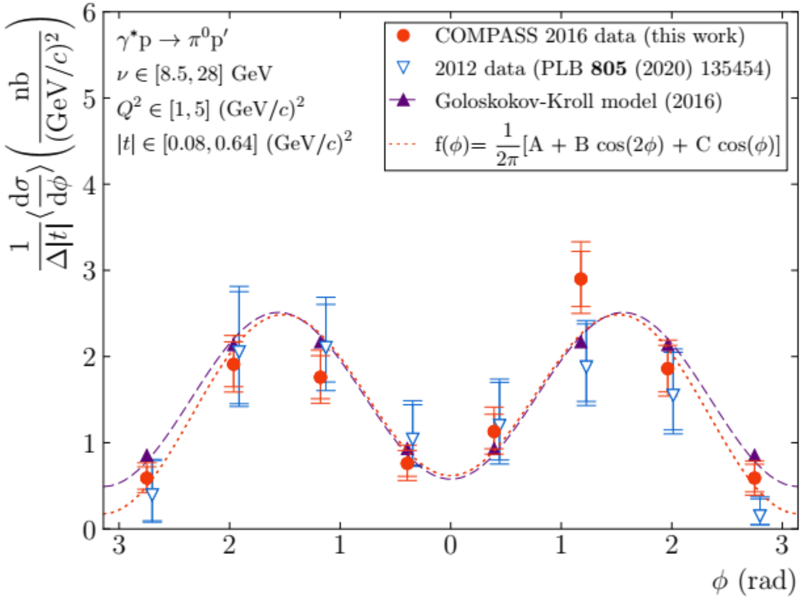




exclusive π_0 HEMP cross-section – 2012 comp.

- Kinematic domain: ν (8.5, 28) GeV and Q^2 (1,5) GeV$^2/c^2$, <x_B> = 0.10

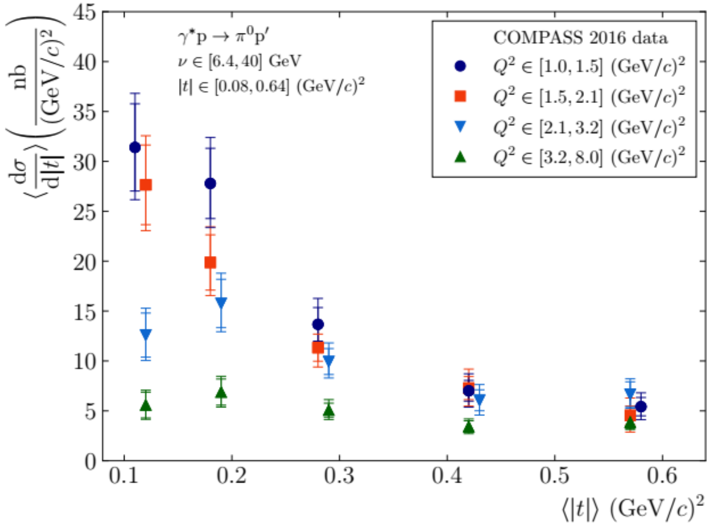


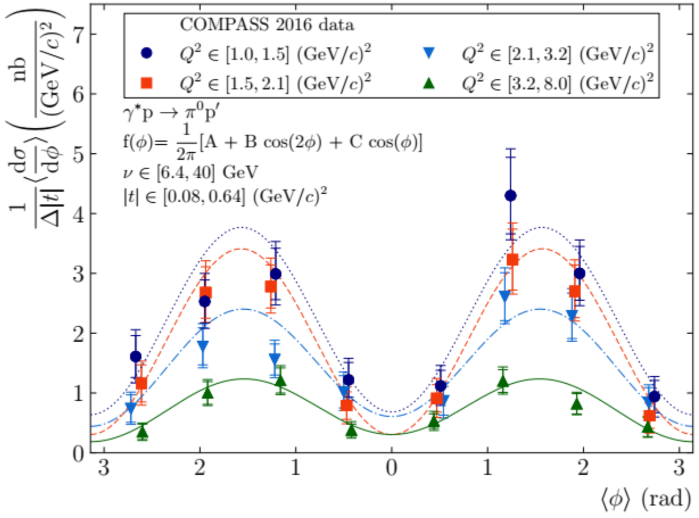


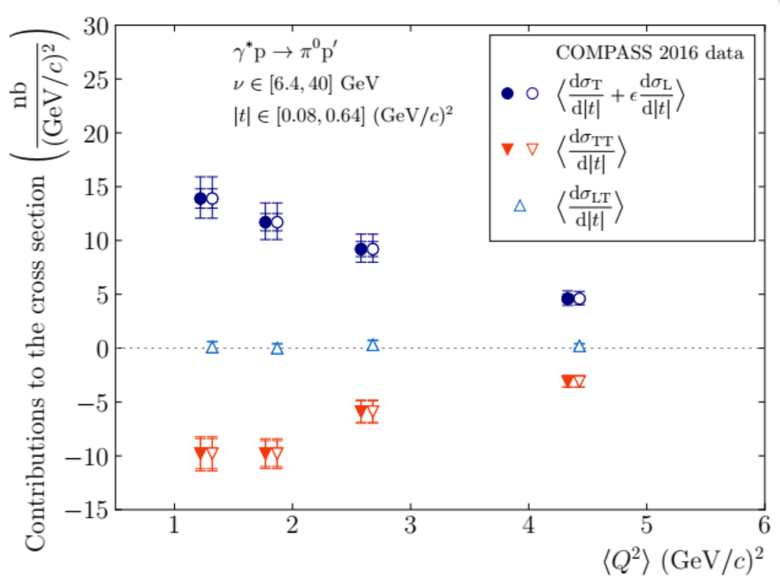
	$\left\langle \frac{d\sigma_T}{d\|t\|} + \varepsilon \frac{d\sigma_L}{d\|t\|} \right\rangle$	$\left\langle \frac{d\sigma_{TT}}{d\|t\|} \right\rangle$	$\left\langle \frac{d\sigma_{LT}}{d\|t\|} \right\rangle$
2016 data	$9.0 \pm 0.5_{stat} \,{}^{+1.1}_{-1.0}\big\|_{sys}$	$-6.6 \pm 0.8_{stat} \,{}^{+0.5}_{-0.5}\big\|_{sys}$	$0.7 \pm 0.3_{stat} \,{}^{+0.4}_{-0.4}\big\|_{sys}$
2012 data	$8.1 \pm 0.9_{stat} \,{}^{+1.1}_{-1.0}\big\|_{sys}$	$-6.0 \pm 1.3_{stat} \,{}^{+0.7}_{-0.7}\big\|_{sys}$	$1.4 \pm 0.5_{stat} \,{}^{+0.3}_{-0.2}\big\|_{sys}$

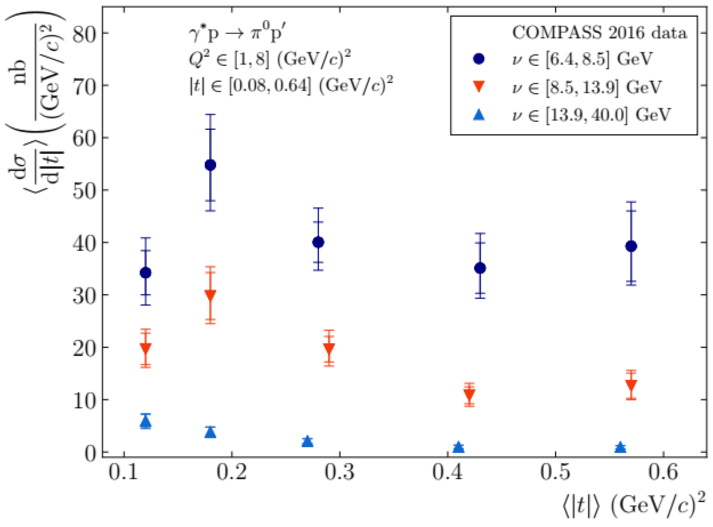
exclusive π_0 HEMP cross-section – results

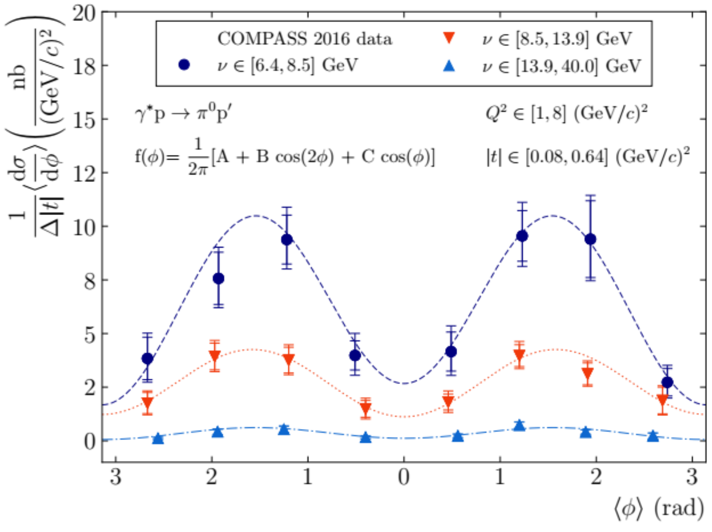
- ν and Q^2 evolution

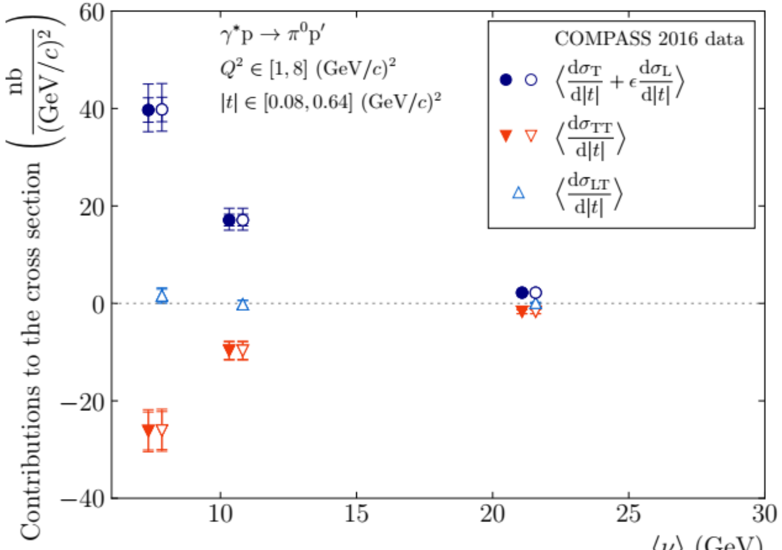




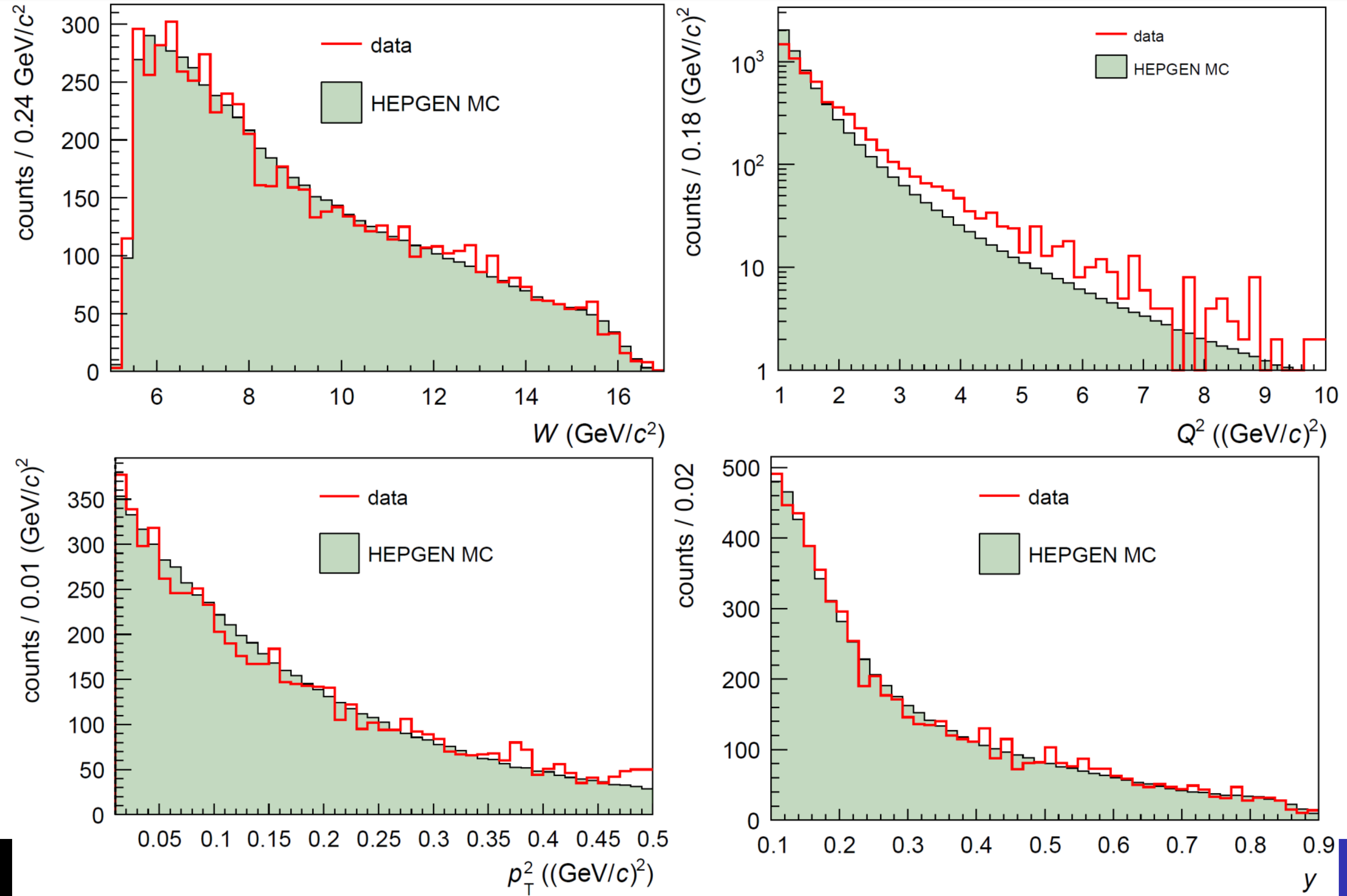








Exclusive ϕ Meson - Kinematic variables

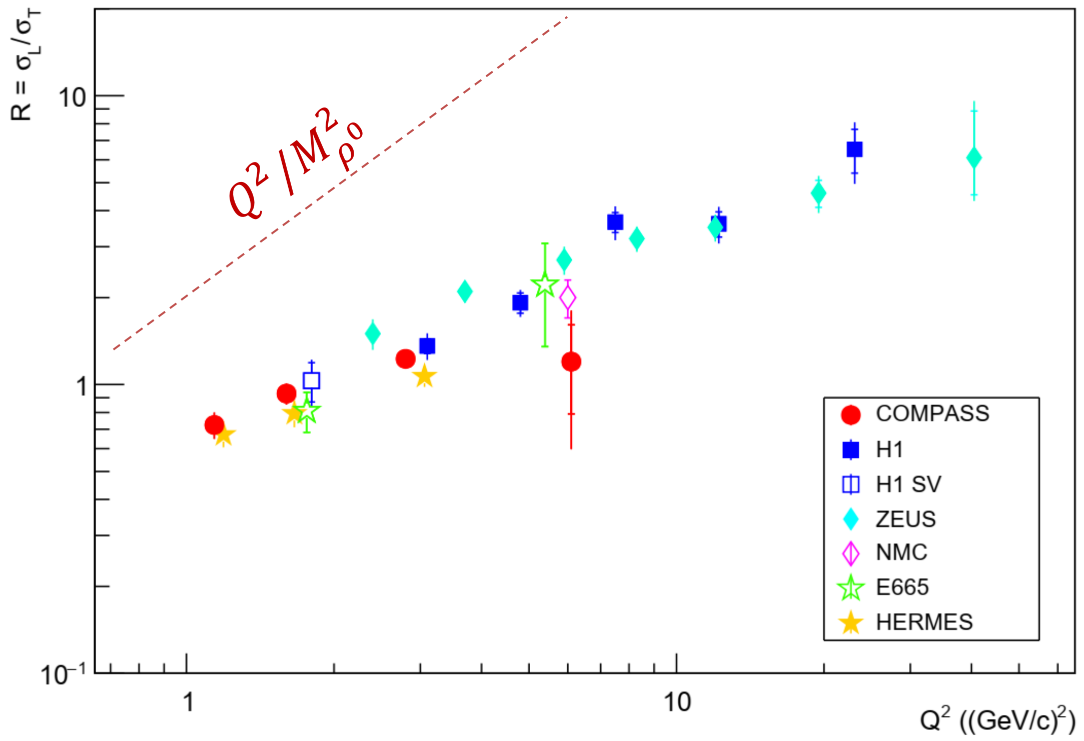


L/T cross-section ratio

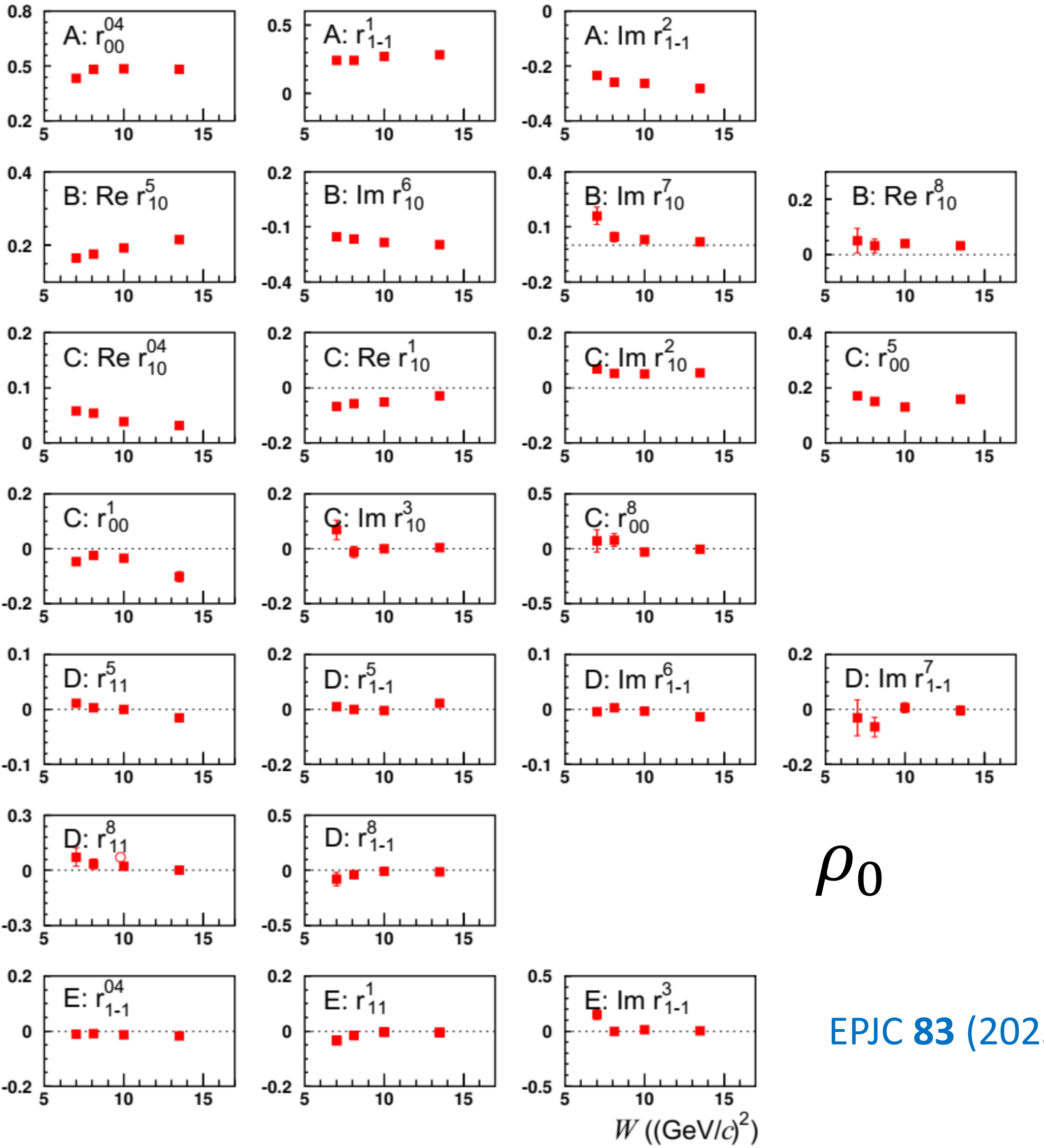
- ρ^0: **L/T cross-section ratio**

  $R = \frac{\sigma_L(\gamma_L^* \to V)}{\sigma_T(\gamma_T^* \to V)}$ 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 $(Q^2/M^2_{\rho^0})$->
    -> QCD evolution & q_T effects
  - meson transverse size effects smaller for σ_L than for σ_T



SDMEs dependences



ρ_0

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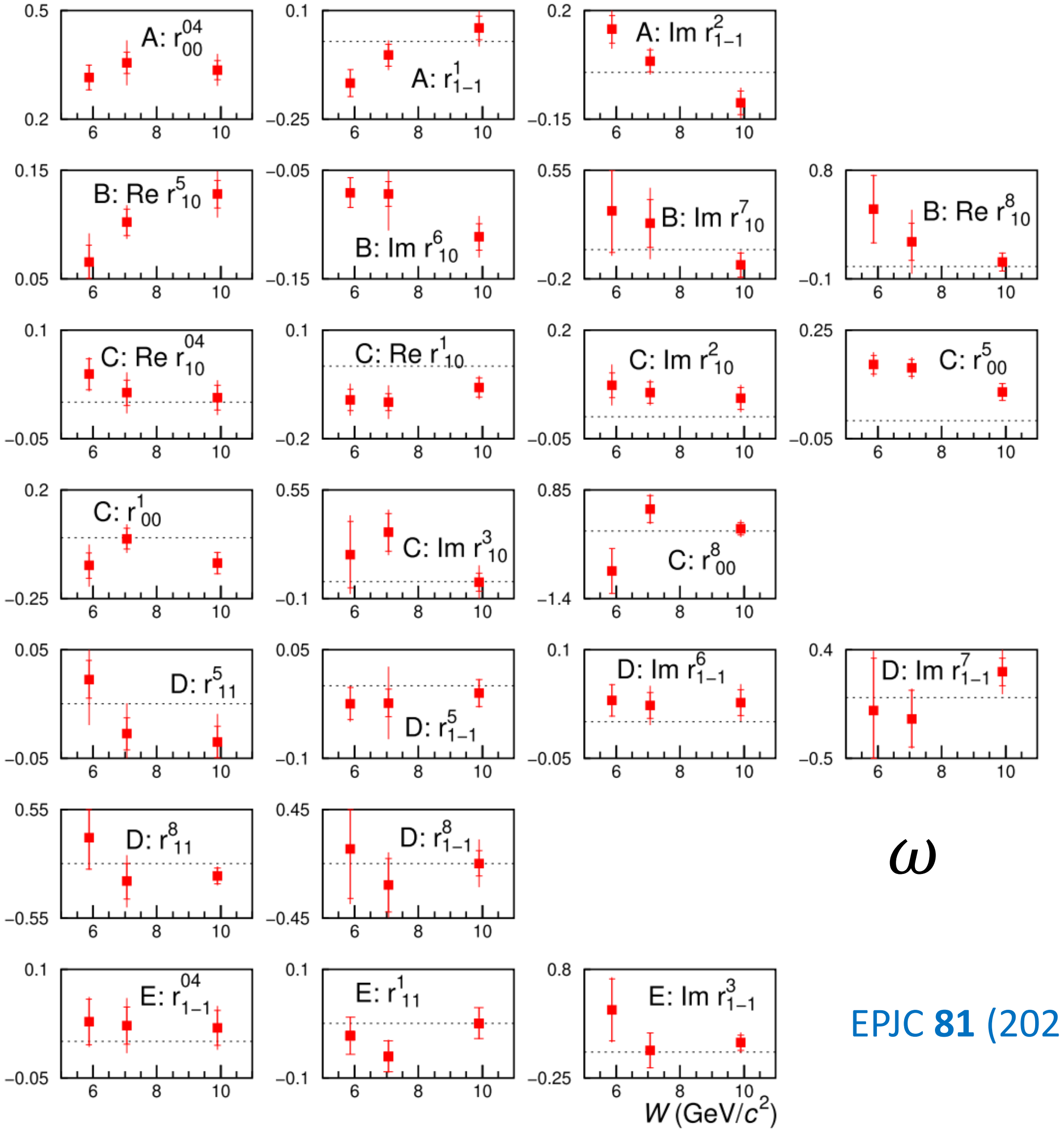

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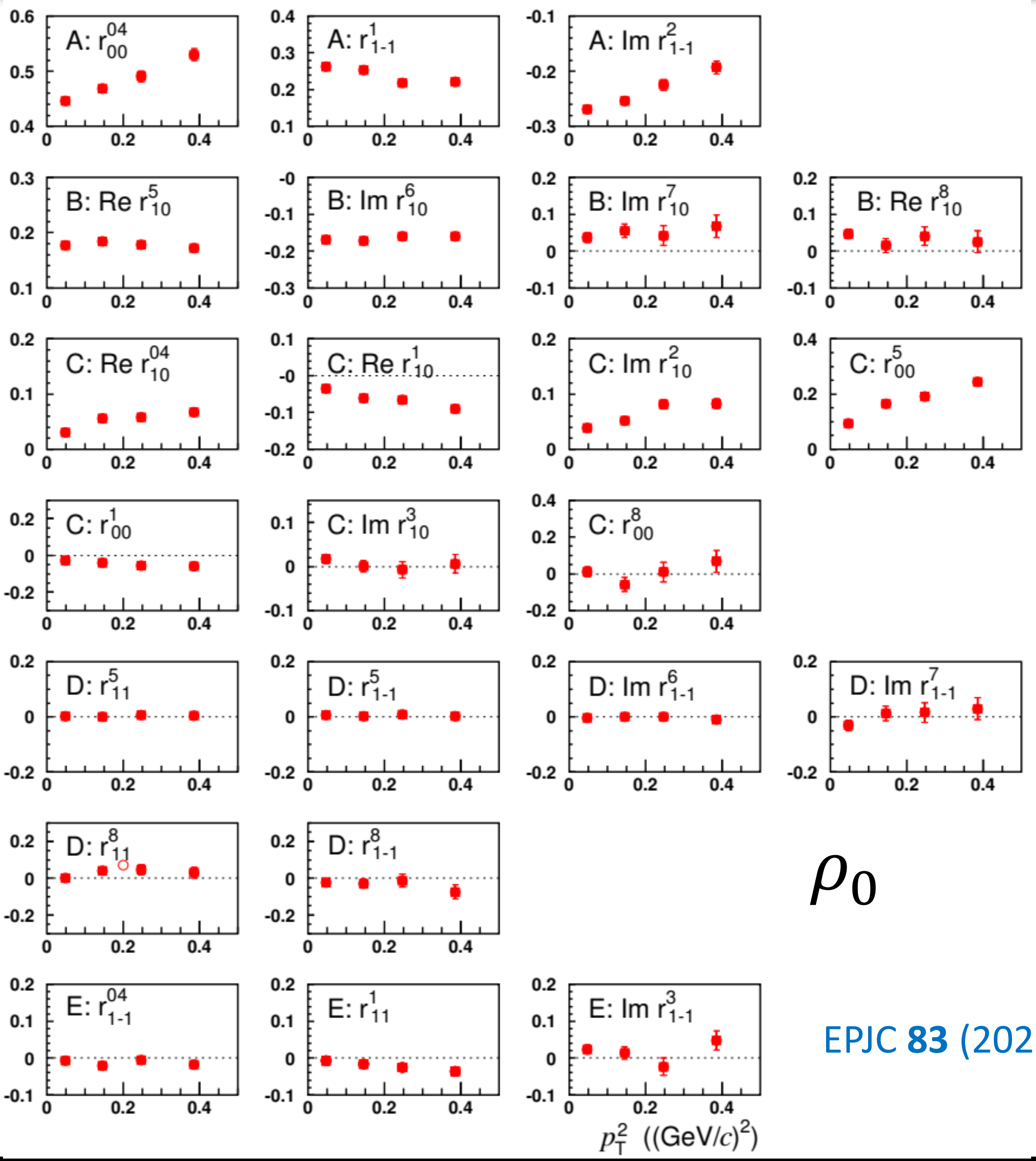
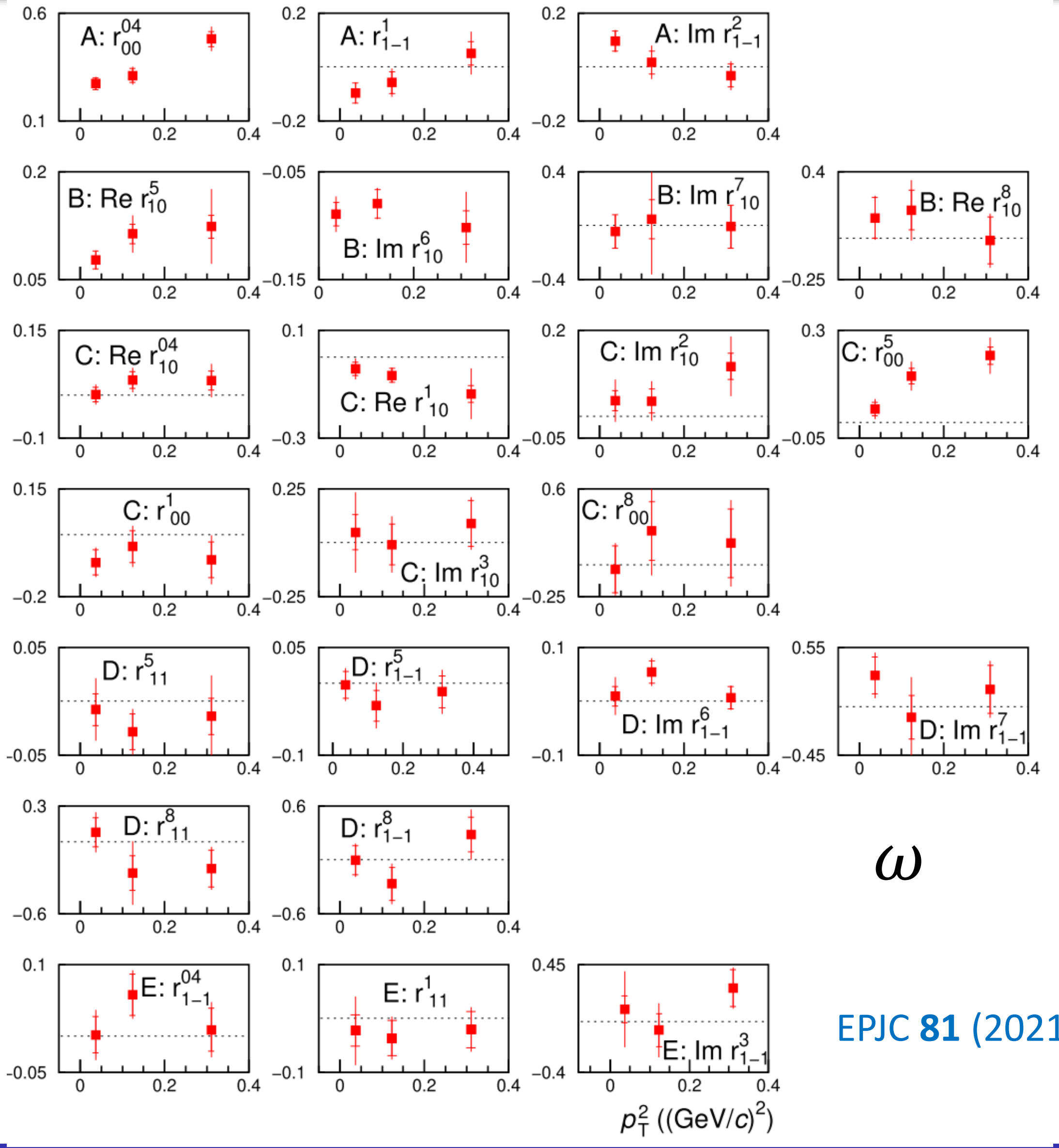
SDMEs dependences



ρ_0

EPJC **83** (2023) 924



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EPJC **81** (2021) 126