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

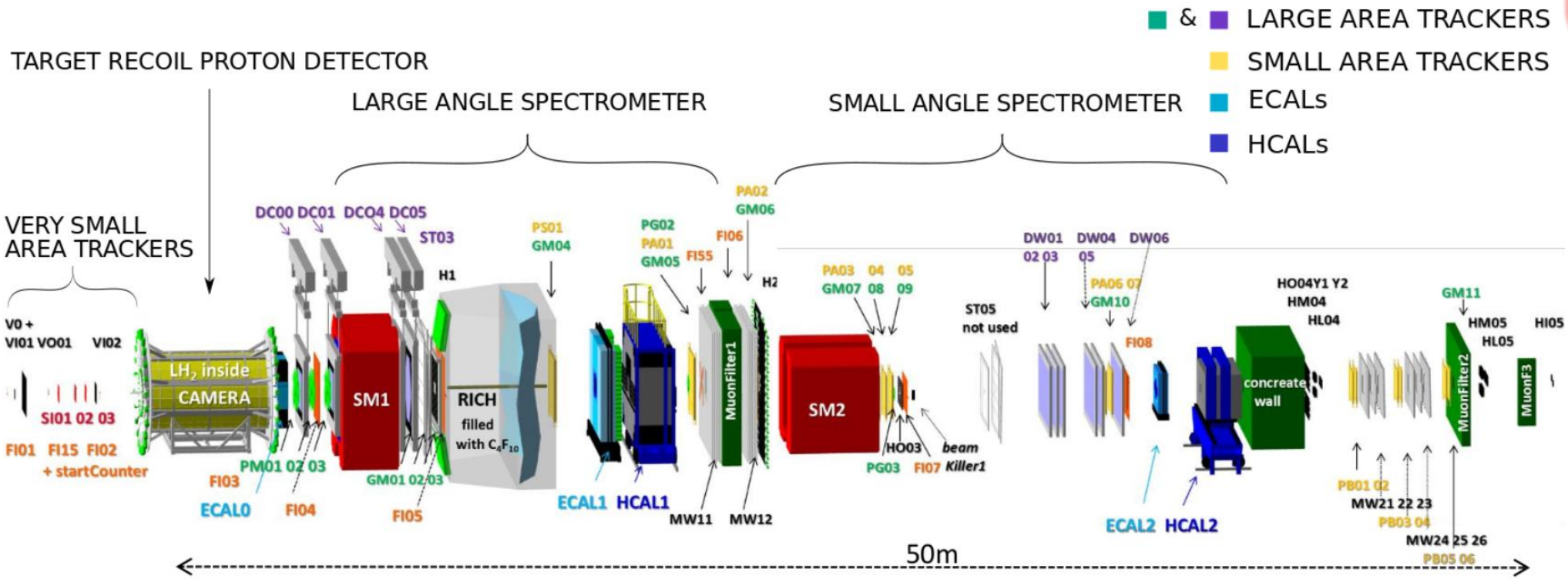
Kamil Augsten (CTU in Prague) on behalf of COMPASS

DIS2026, Bologna

Co-funded by the European Union

Ministry of Education, Youth and Sports of the Czech Republic

COMPASS Experiment – Setup



see talks by:
Po-Ju Lin &
other COMPASS

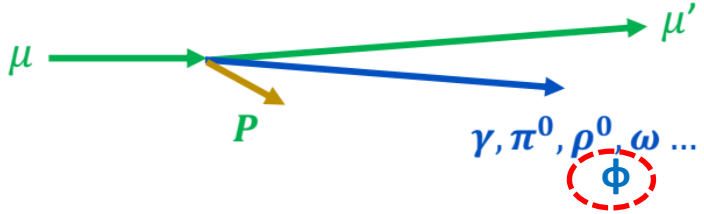
NIMA 577 (2007) 455–518
&
NIMA 779 (2015) 69

μ^+, μ^- beams

polarization ~ ±80%

energy 160 GeV

Exclusive Muoproduction



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**

Introduction to Vector Mesons and GPDs

- **Hard Exclusive Meson Production (HEMP)**
  - access to **Generalized Parton Distributions (GPDs)**
- **Flavor filtering:** different mesons → access to **parton-specific GPDs** →

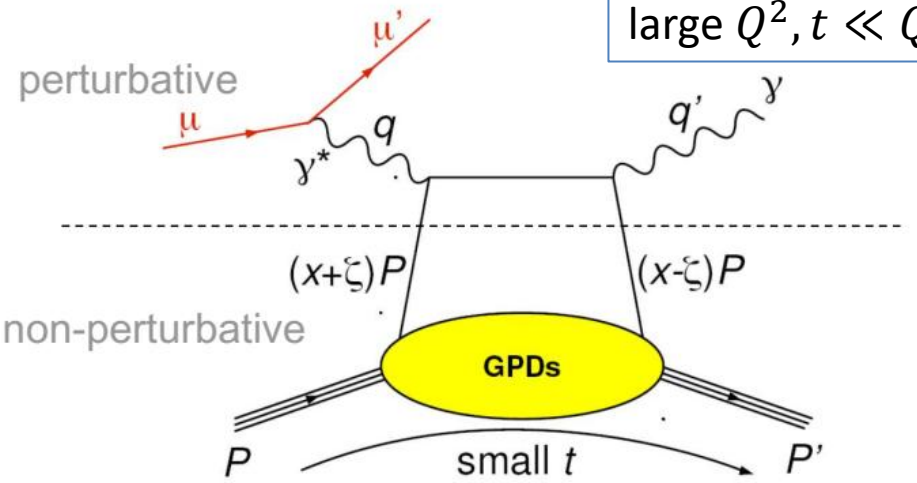
$H, E, \tilde{H}, \tilde{E}$: chiral-even
$\bar{E}_T, \tilde{E}_T, H_T, \tilde{H}_T$: chiral-odd

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

COMPASS can measure ω, ρ⁰, ϕ, J/ψ

ℓ N → ℓ' N' M
γ* N → N' M (one-photon approx.)
'hard' = high virtuality Q^2 of γ*

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



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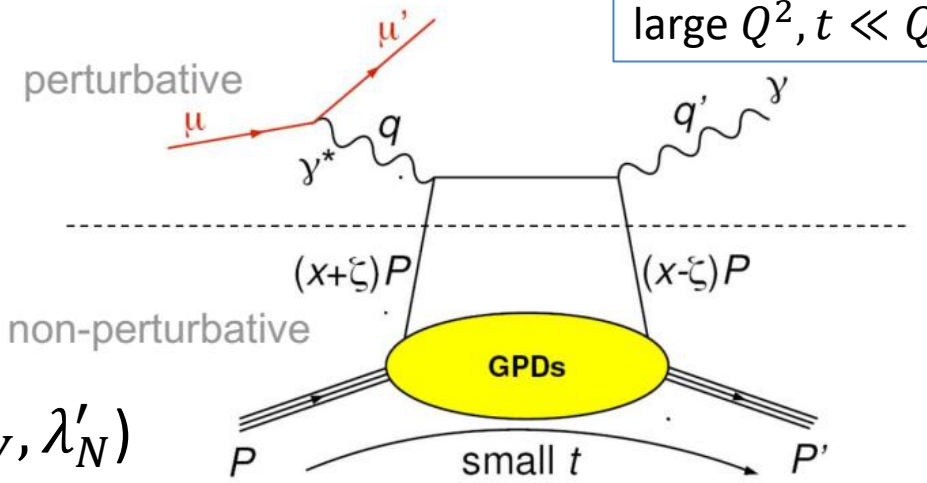


- **Helicity amplitudes *F*:** describe transitions $(\lambda_\gamma, \lambda_N \to \lambda_V, \lambda'_N)$

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

helicity of vector meson *V*

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

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

No **L/T separation** at COMPASS –> define **23** "unseparated" SDMEs through angular dist.

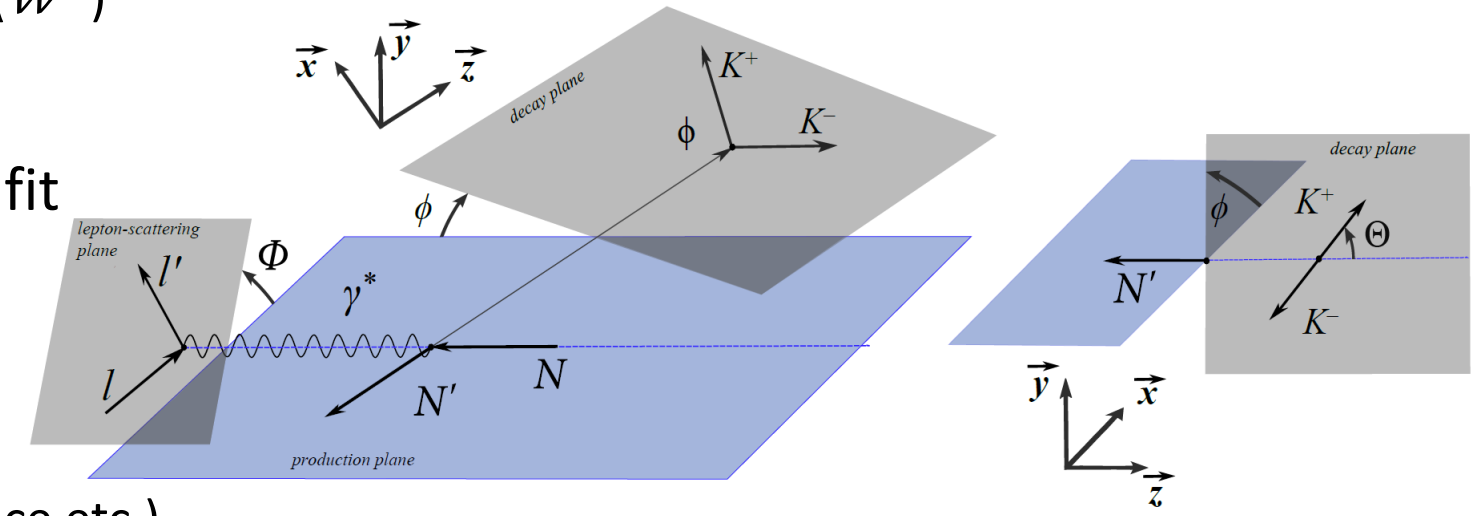
Experimental Access to SDMEs

- Setup: **Unpolarized target**, **L polarized beam** (COMPASS run 2016)
- 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**:
  - 15 unpolarized ($\mathcal{W}^U$) and 8 polarized ($\mathcal{W}^L$)
- **Extraction of SDMEs**:
  - Unbinned Maximum Likelihood fit
  - Inputs:
    - $\mathcal{W}^{U+L}(\mathcal{R}, \Phi, \phi, \cos\Theta)$,
    - where $\mathcal{R}$ set of 23 SDMEs,
    - detector efficiency (total acceptance etc.),
    - background fraction f_{bg},
    - background distribution $\mathcal{W}^{U+L}(\mathcal{B}, \Phi, \phi, \cos\Theta)$.

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



Exclusive ϕ Meson Selection

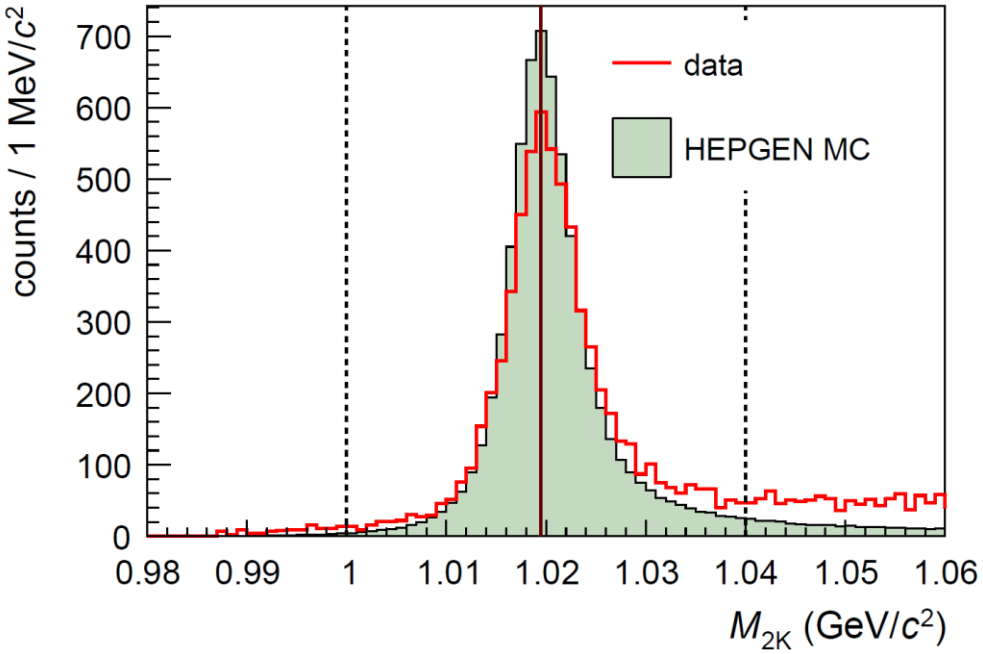
- topology: scattered muon + two hadrons with opposite charges
  - $1 < Q^2 < 10\ (\mathrm{GeV}/c)^2$
  - $5 < W < 17\ \mathrm{GeV}/c^2$
  - $0.01 < p_{\mathrm{T}}^2 < 0.5\ (\mathrm{GeV}/c)^2$
  - $0.1 < y < 0.9$
- event yield > **6k events**

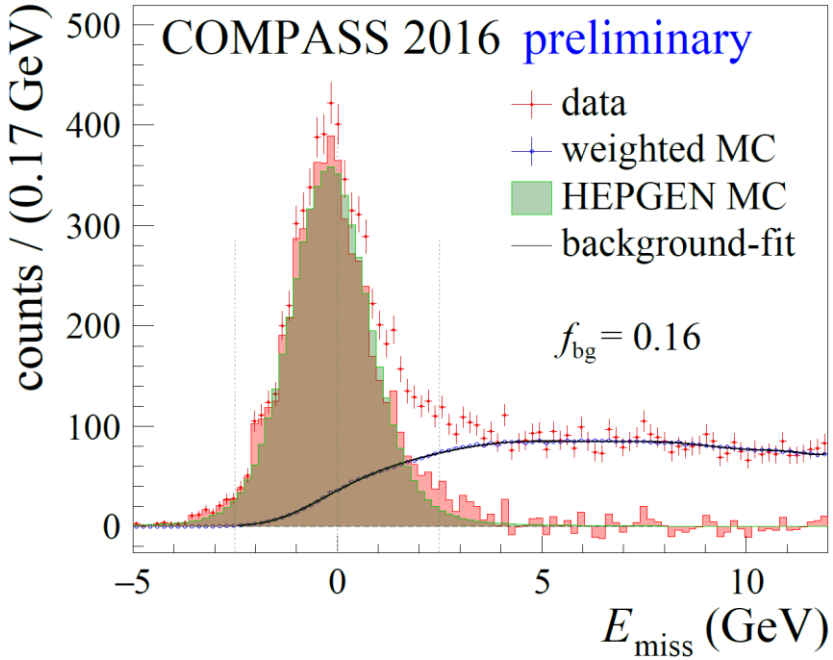
- **Exclusivity**:
- $1.00 < M_{\mathrm{K^+K^-}} < 1.04$ GeV
- $\left| E_{\mathrm{miss}} = \frac{M_{\mathrm{X}}^2 - M^2}{2M} \right| < 2.5$ GeV
- Recoil proton detector not included in selection

Exclusive Muoproduction

$\mu p \rightarrow \mu' p' \phi \qquad \mathrm{BR} = (48.1 \pm 0.5)\ \%$

$\phi \rightarrow K^+K^-$



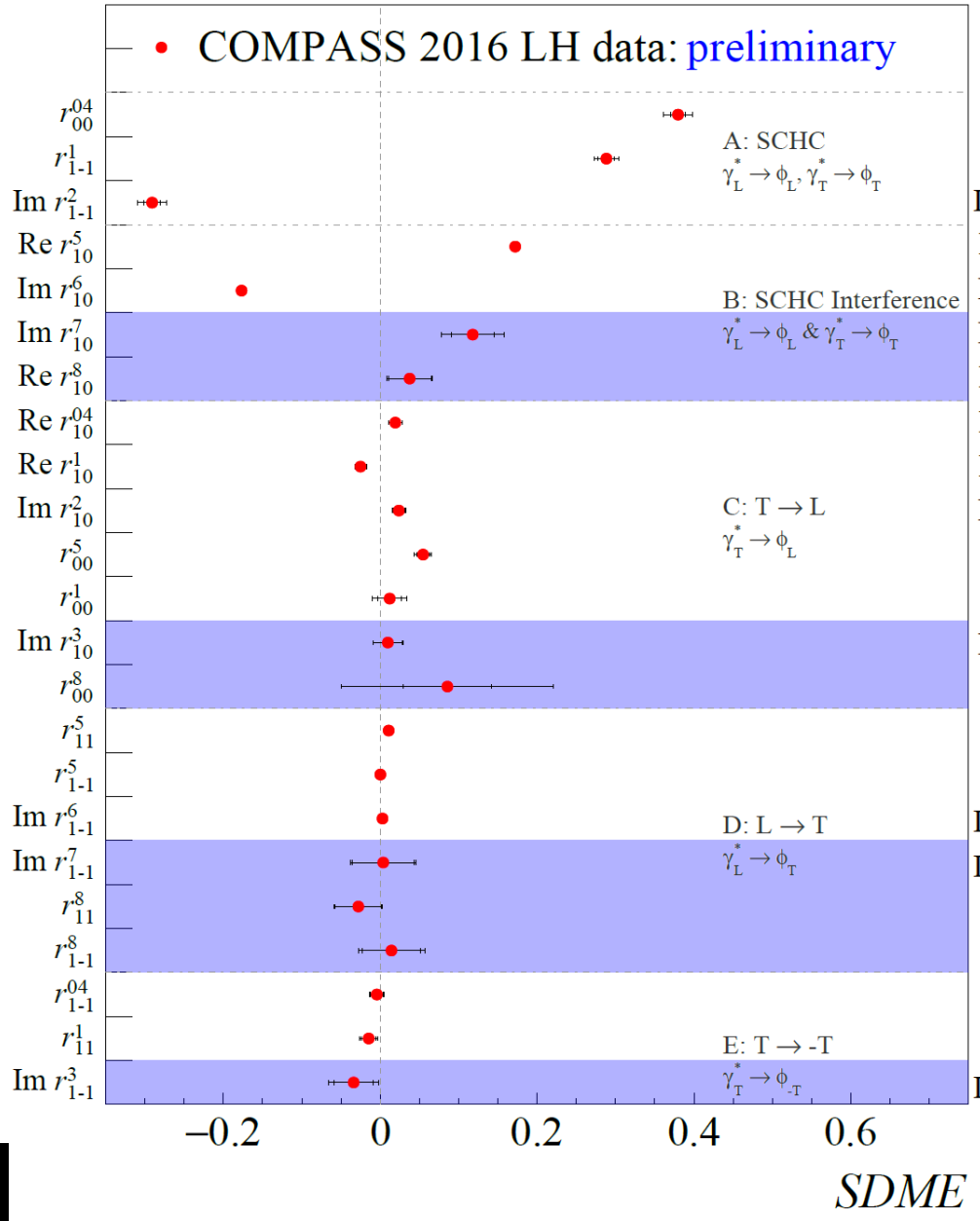


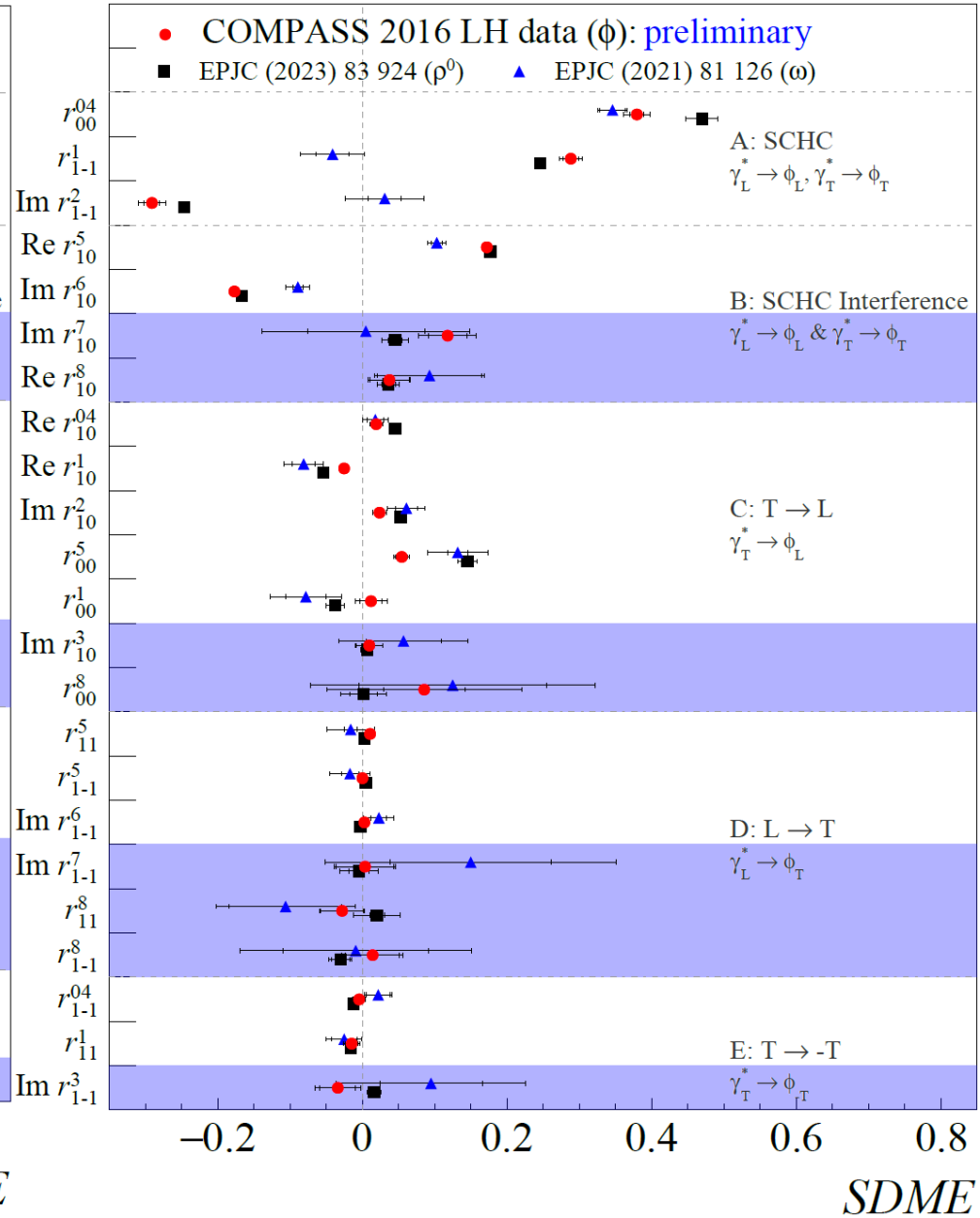
Exclusive ϕ Meson SDMEs

- **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

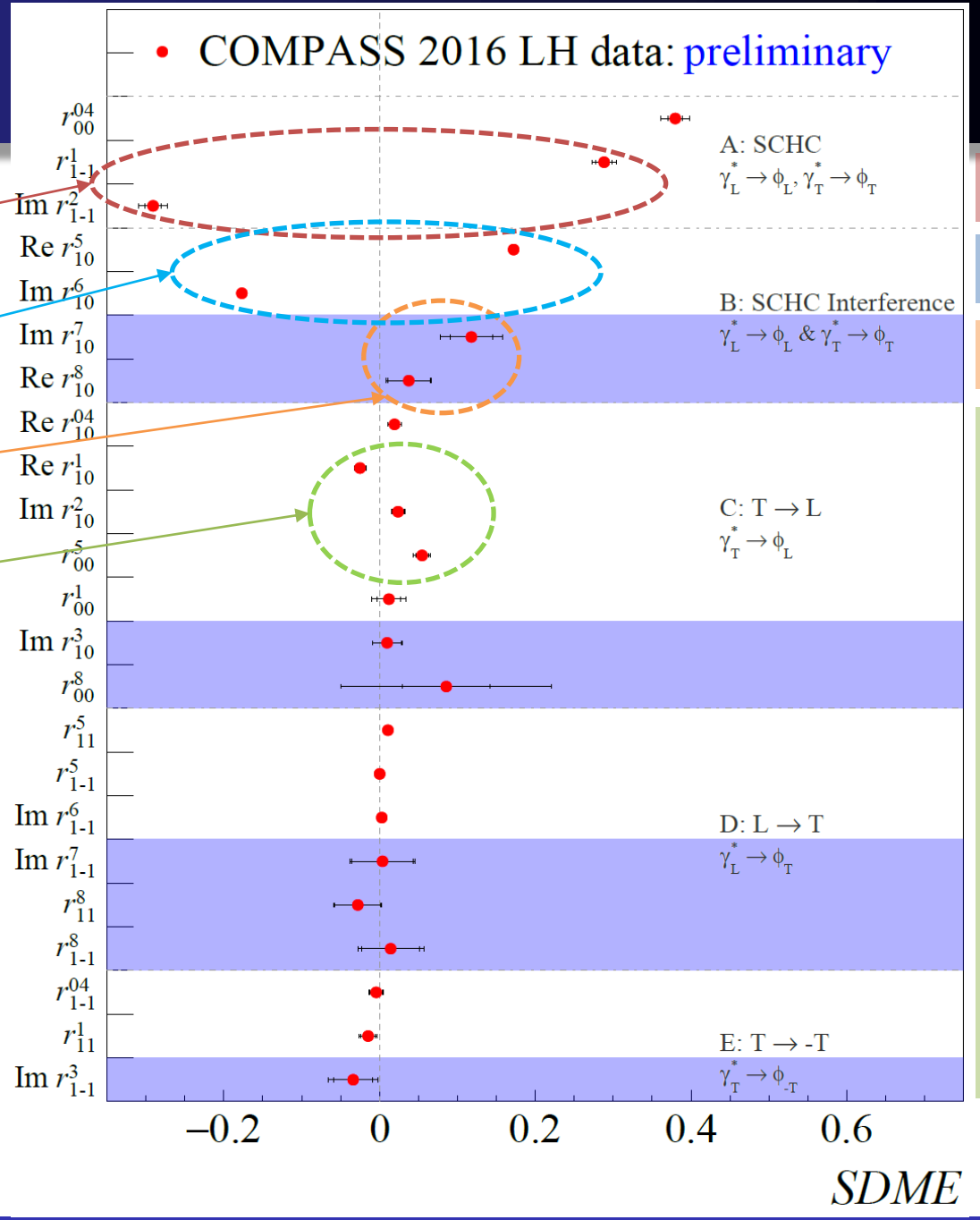
- SCHC implies:

$r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$ — 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 $H_T, \bar{E}_T = 2\widetilde{H}_T + E_T$

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

UPE Contribution

- 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

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- 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 ϕ production**
  - **SCHC violation** in $\gamma_T^* \rightarrow V_L$ → sensitivity to chiral-odd GPDs $\bar{E}_T, H_T$
  - **NPE dominance in ϕ** → sensitivity to chiral-even GPDs
- **Outlook**:
  - Add kinematic variables dependences
  - 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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COMPASS Experiment

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

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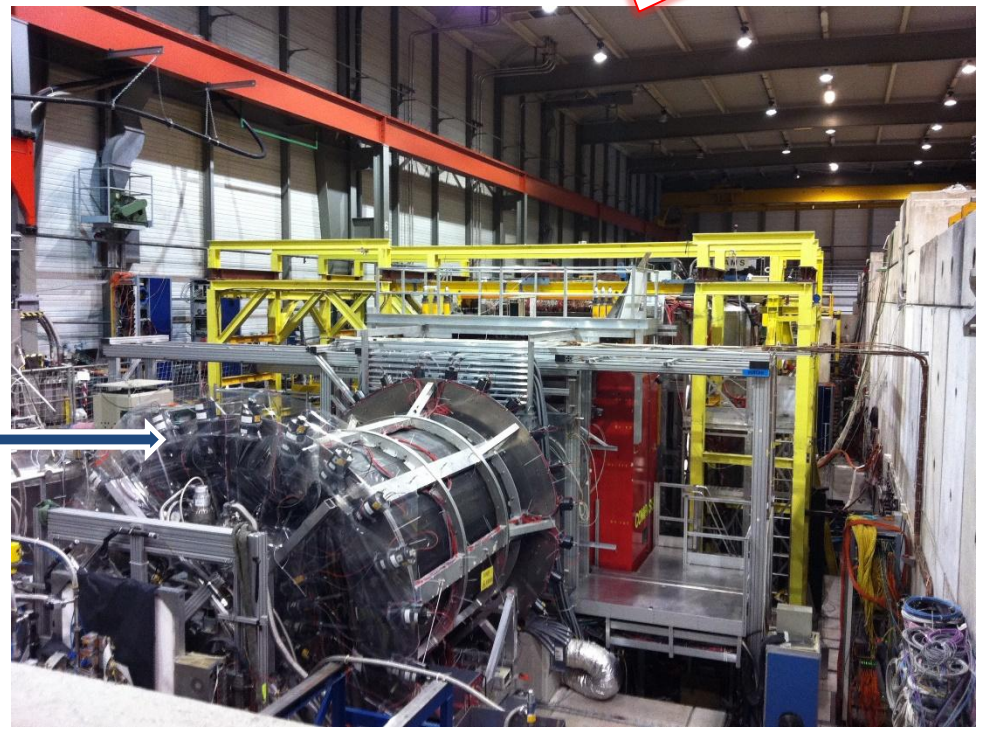


data taking 2002 – 2022 &
longitudinally, transversely or
unpolarized targets

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 polarization states (α=0-3 transverse, α=4 longitudinal, α=5-8 interference terms)
- When **L/T separation not possible** → SDMEs are defined using:

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

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

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

23 SDMEs we actually measure

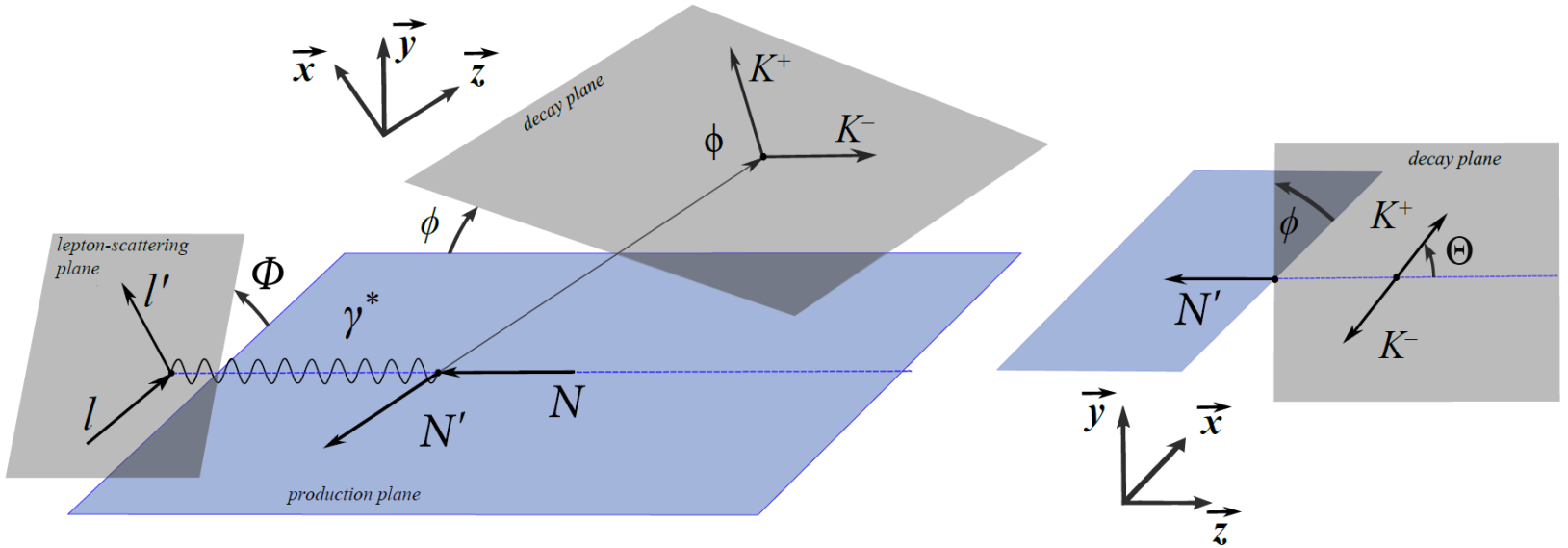
Vector Mesons and GPDs

- **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 σ_L/σ_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 flavor filter, insights into reaction mechanism

The formalism

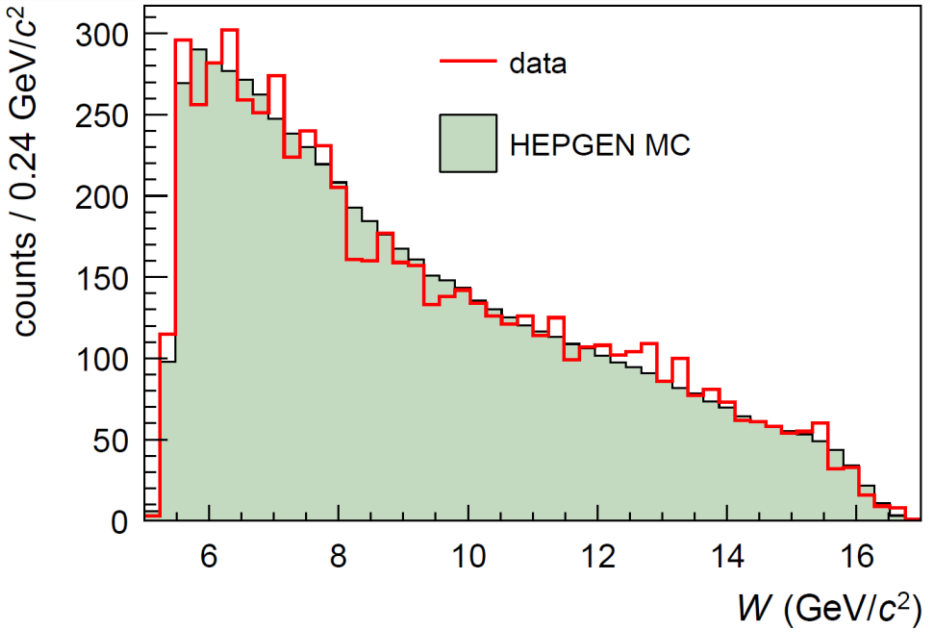
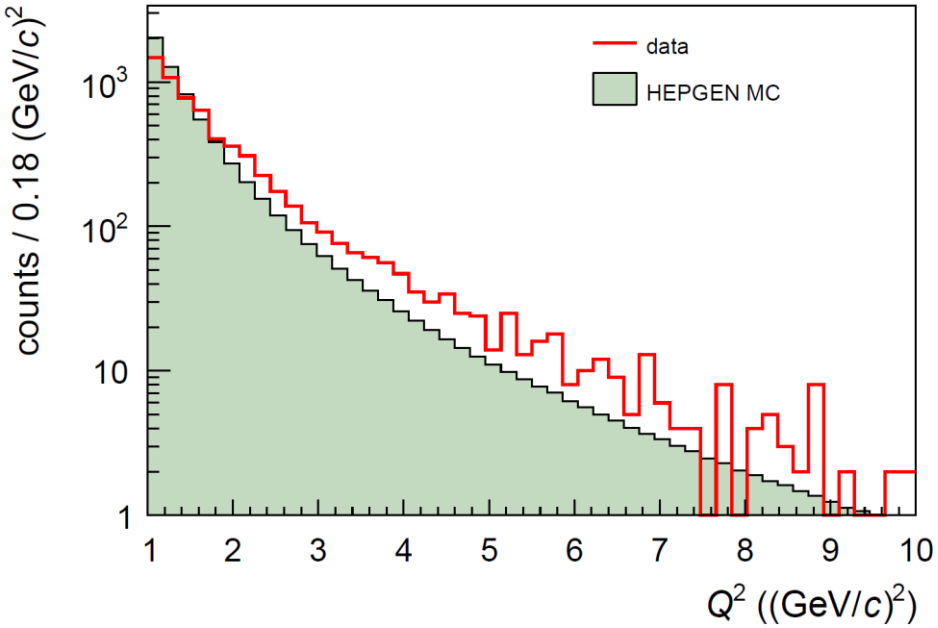
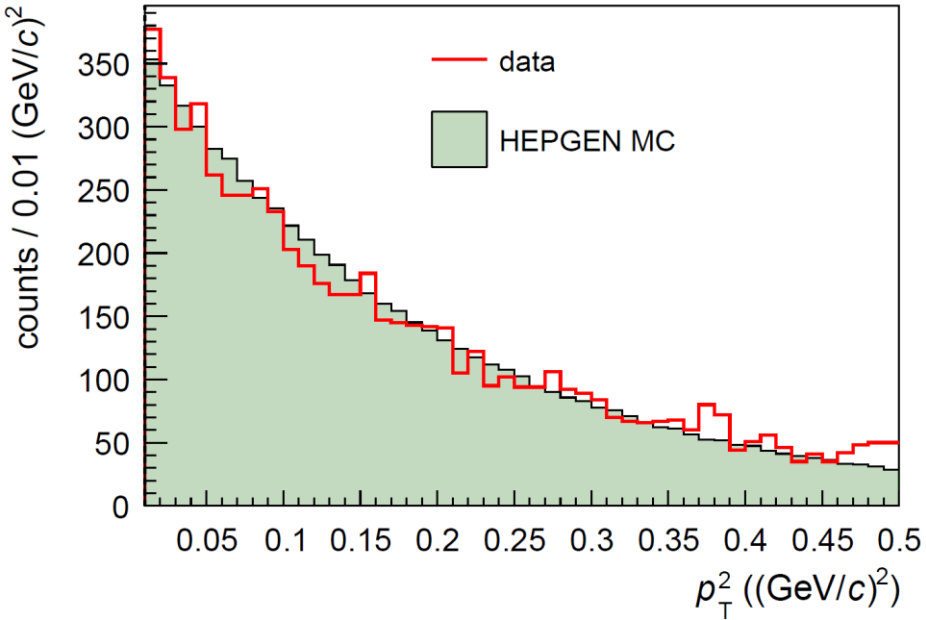
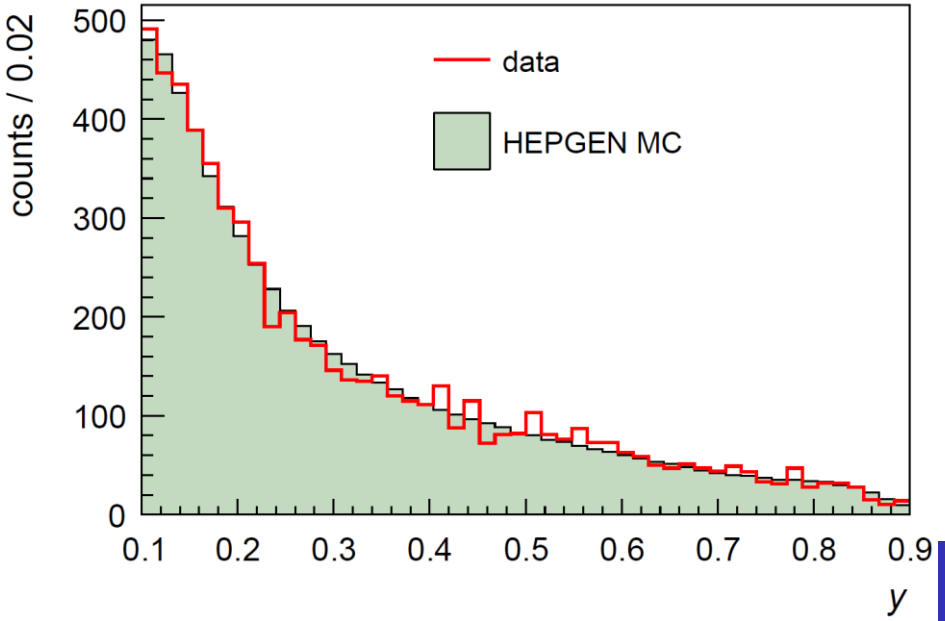
$$W_U(\phi,\cos\theta)=\frac{3}{8\pi^2}\left[\begin{array}{l}\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\theta- \\ \sqrt{2}\,\mathrm{Re}\{r^{04}_{10}\}\sin 2\theta\cos\phi- \\ r^{04}_{1-1}\sin^2\theta\cos 2\phi- \\ \varepsilon\cos 2\Phi\left(\begin{array}{l} r^{1}_{11}\sin^2\theta+ \\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

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



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

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

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

Exclusive ϕ Meson - Kinematic variables