Spin Density Matrix Elements in Exclusive Vector Meson Muoproduction at COMPASS

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- Introduction
- SDMEs for exclusive vector meson production
- Generalised Parton Distributions
- COMPASS experiment and the data
- Results on SDMEs and related observables
- Summary and outlook

Introduction

Hard exclusive meson leptoproduction (HEMP)

$l\ N \rightarrow l'\ N'\ M$ in one-photon-approx. $\gamma^*\ N \rightarrow N'\ M$

'Hard' ≡ high virtuality Q^2 of γ^*, or large mass of M (Quarkonia)

HEMP a tool for studying
- mechanism of reaction
- structure of the nucleon

Two approaches to describe HEMP
- color-dipol model (for VMs)
  color-dipol interaction with nucleon described either by Regge phenomenology or by pQCD
- GPD models (for VMs and PMs)

Numerous results (13 publications) for ρ^0 production on *p*, *d* and ^{3}*He*

cf. review by L. Favart, M. Guidal, T. Horn, P. Kroll arXiv:1511.04535v2 (2018)

Detailed studies of cross sections σ_T, σ_L, $\sigma_T + \varepsilon\sigma_L$ as functions of kinematic variables

In most cases complete information on the spin-dependent amplitudes not available then, for example, the separation σ_T vs. σ_L relies on measurements of 1D-angular distribution(s) and assumption of s-channel helcity conservation

Only in 3 publications (HERMES, H1, ZEUS) + recently from COMPASS results on complete set of SDMEs obtained from the analysis of 3D-angular distributions

Vector meson spin-density matrix

helicity of vector meson *V*

helicities of virtual photon γ and nucleon *N*

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

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

(von Neuman)

F helicity amplitudes; describe transitions $\lambda_\gamma, \lambda_N \to \lambda_V, \lambda'_N$, depend on W, Q^2 and p_T

- $\rho_{\lambda_V \lambda'_V}$ decomposes into nine matrices $\rho^{\alpha}_{\lambda_V \lambda'_V}$ corresponding to different photon polarisation states

  α = 0 – 3 - transv., 4 - long,, 5 – 8 - interf.

- when contributions from transverse and longitudinal photons cannot be separeted

  following SDMEs are introduced (K.Schilling and K. Wolf, NP B 61 (1973) 381)

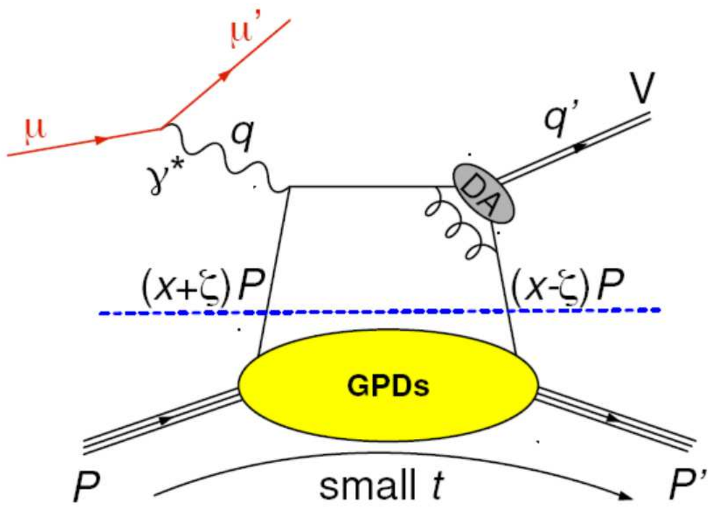
$$r^{04}_{\lambda_V \lambda'_V} = (\rho^0_{\lambda_V \lambda'_V} + \epsilon R \rho^4_{\lambda_V \lambda'_V})(1+\epsilon R)^{-1},$$

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

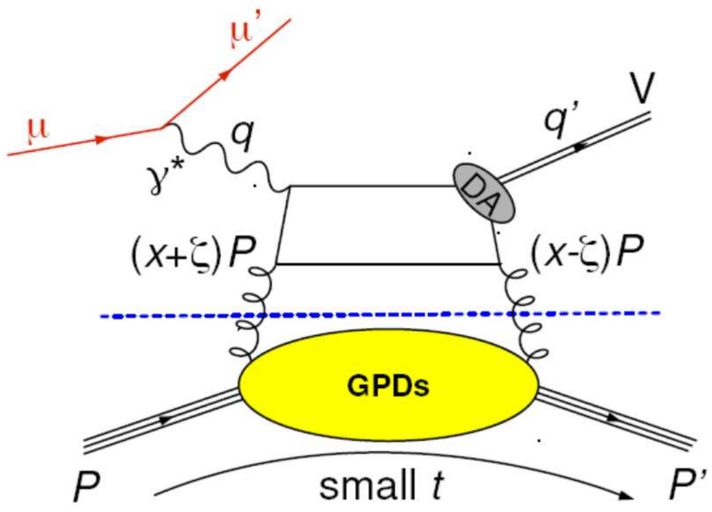
$R = \sigma_L / \sigma_T$

GPDs and Hard Exclusive Meson Production

quark contribution



gluon contribution



- wave function of meson (DA)
  additional non-perturbative term

Chiral-even GPDs
helicity of parton unchanged

$H^{q,g}(x,\xi,t)$ $E^{q,g}(x,\xi,t)$

$\tilde{H}^{q,g}(x,\xi,t)$ $\tilde{E}^{q,g}(x,\xi,t)$

Chiral-odd GPDs
helicity of parton changed (not probed by DVCS)

$H_T^q(x,\xi,t)$ $E_T^q(x,\xi,t)$

$\tilde{H}_T^q(x,\xi,t)$ $\tilde{E}_T^q(x,\xi,t)$

Flavour separation for GPDs
example:

$$E_{\rho^0} = \frac{1}{\sqrt{2}}(\frac{2}{3}E^{u(+)} + \frac{1}{3}E^{d(+)} + \frac{3}{4}E^g / x)$$

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

$$E_\phi = -\frac{1}{3}E^{s(+)} + \frac{1}{4}E^g / x$$

Diehl, Vinnikov PLB, 2005

- *contribution from gluons at the same order of α_s as from quarks*

Measured processes and COMPASS experimental setup

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

(ii) $\mu\, p \rightarrow \mu'\, p'\, \omega$, $\omega \rightarrow \pi^+ \pi^- \pi^0$, $\pi^0 \rightarrow \gamma\, \gamma$

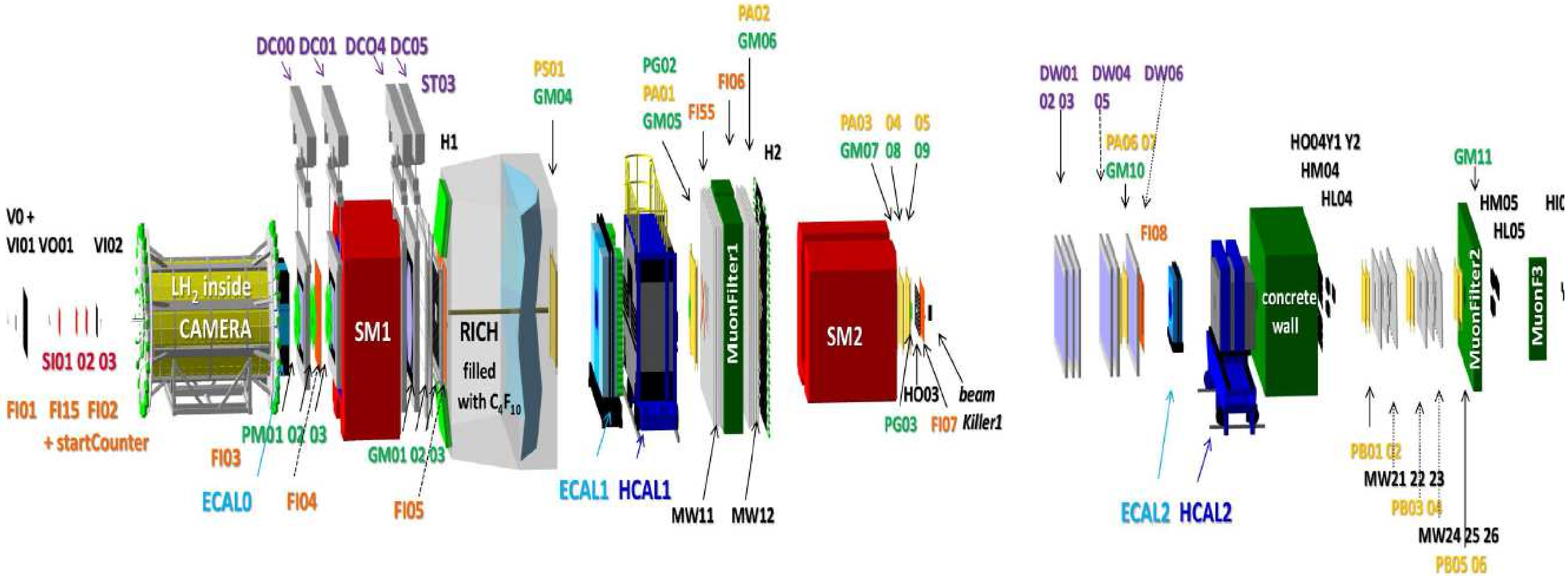
- **secondary beam line M2 from the SPS**

  delivers: high energy naturally **polarised μ^+ or μ^- beams**, P ≈ -80% / +80%

- **liquid H2 target** 2.5 m long

- **two-stage forward spectrometer SM1 + SM2**

  ≈ 300 tracking detectors planes – high redundancy **+ calorimetry, μID, RICH**



Selection of exclusive ω sample for SDME analysis

$\mu\, p \rightarrow \mu'\, \omega\, p'$

$\hookrightarrow \pi^{+}\, \pi^{-}\, \pi^{0}$

$\hookrightarrow \gamma + \gamma$

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

Recoil proton detector
not included in selections

$1 < Q^2 < 10$ GeV/c^2

$0.01 < p_T^{\,2} < 0.5$ (GeV/c)^2

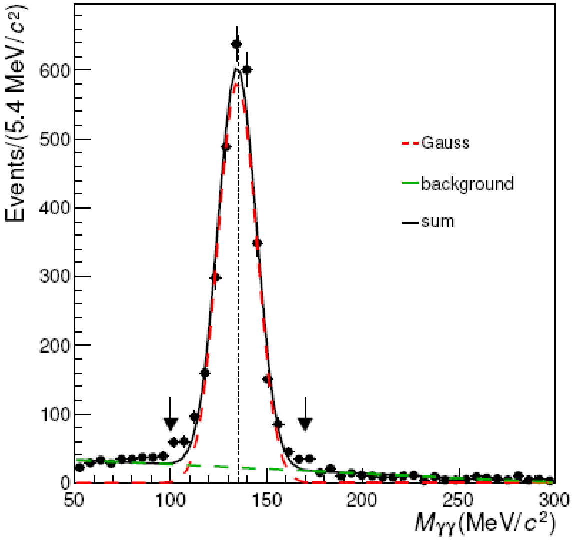
$W > 5$ GeV

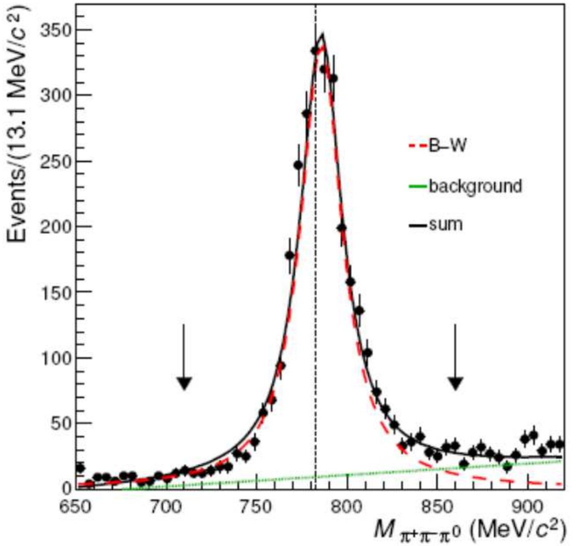
$0.1 < y < 0.9$

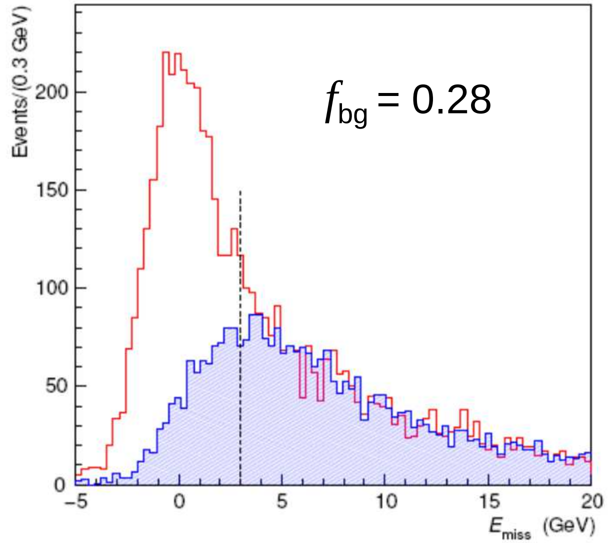
$|E_{miss}| < 3$ GeV

After all selections
≈ 3 000 evts

$$E_{miss} = \frac{(M_X^2 - M_p^2)}{(2M_p)}$$



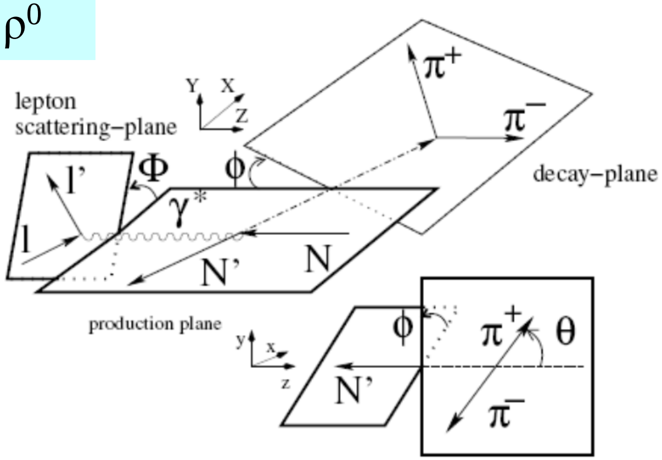




Experimental access to SDMEs

$$W^{U+L}(\Phi,\phi,\cos\Theta) = W^{U}(\Phi,\phi,\cos\Theta) + P_B W^{L}(\Phi,\phi,\cos\Theta) \propto \frac{d\sigma}{d\Phi\, d\phi\, d\cos\Theta}$$

for ρ^0



SDMEs: „amplitudes" of decomposition of W^{U+L} in the sum of 23 terms with different angular dependences

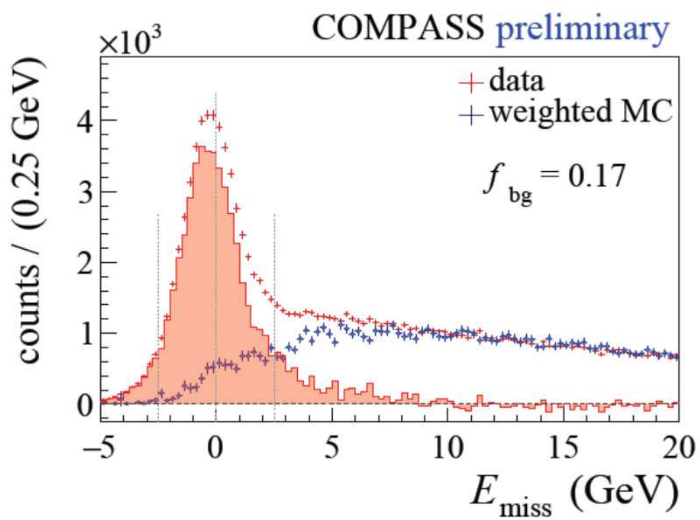
[K. Schilling and G. Wolf, Nucl. Phys. B61, 381 (1973)]

15 unpolarised SDMEs (in W^U) and 8 polarised (in W^L)

Extraction of SDMEs

for ω: angle Θ between direction of ω and normal to decay plane

- Unbinned ML fit to experimental W^{U+L} taking into account
  - total acceptance
  - fraction of background in the signal window
  - anglar distribution of background W^{U+L}_{bkg} (determined either from LEPTO MC or real data side band)



Results on SDMEs for exclusive ρ^0 production for total kin. range

1 GeV² < Q² < 10 GeV²

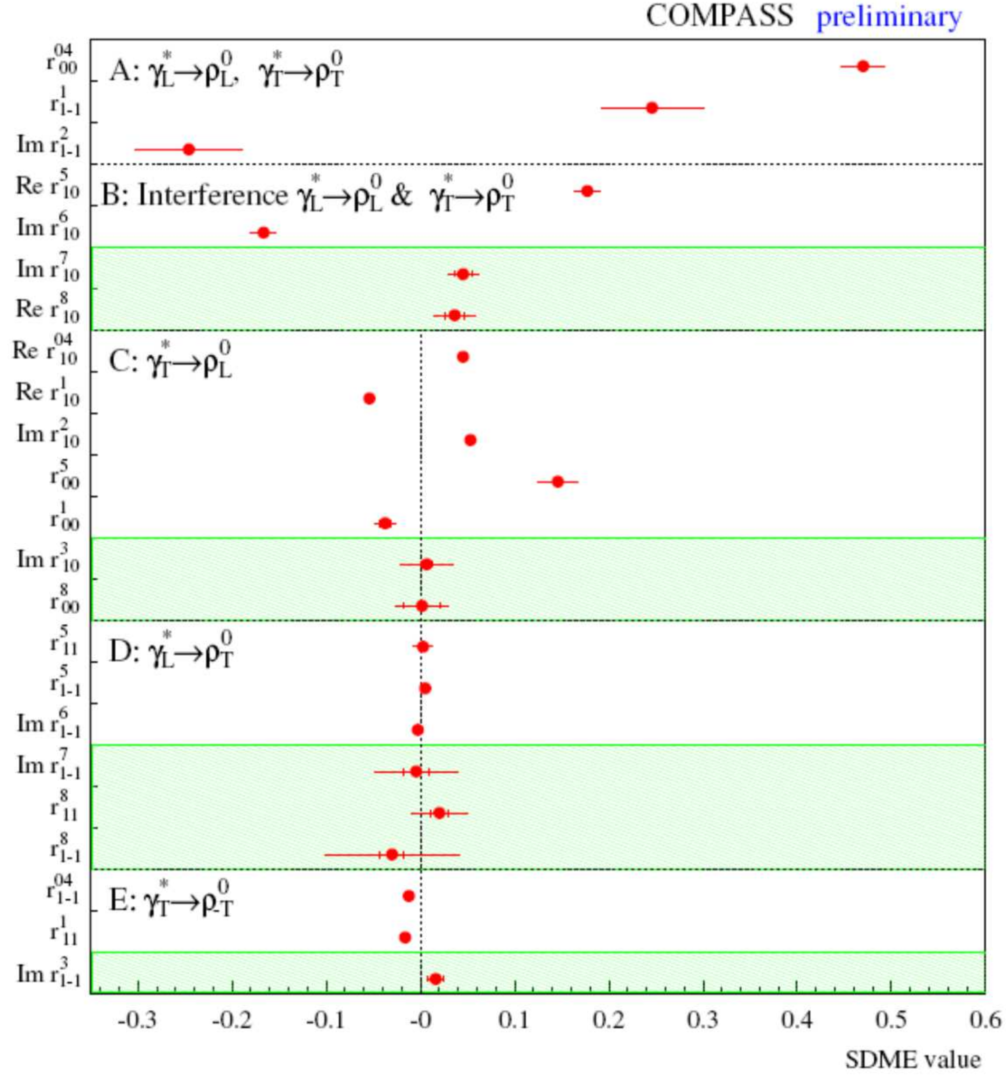
5 GeV < W < 17 GeV

0.01 GeV² < p_T^2 < 0.5 GeV²

< Q²> = 2.4 GeV²

<W> = 9.9 GeV

<p_T^2> = 0.18 GeV²



- SDMEs grouped in clasess: A, B, C, D, E corresponding to different helicity transitions
- SDMEs coupled to the beam polarisation shown within green areas
- if SCHC holds all elements in classes C, D, E should be 0

not obeyed for transitions $\gamma^*_T \to \rho_L$

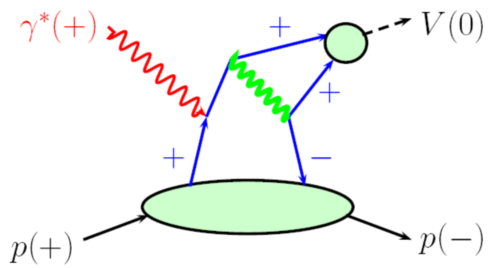
Transitions $\gamma^*_T \rightarrow \rho_L$

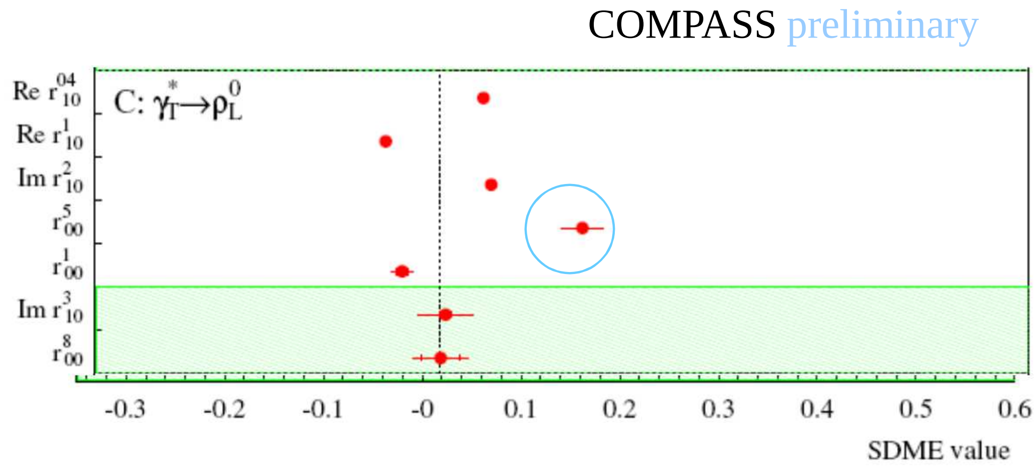
possible GPD interpretation **Goloskokov and Kroll, EPJC 74 (2014) 2725**

contribution of amplitudes depending on chiral-odd ("transversity") GPDs $H_T, \bar{E}_T = 2\tilde{H}_T + E_T$

example ➡

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

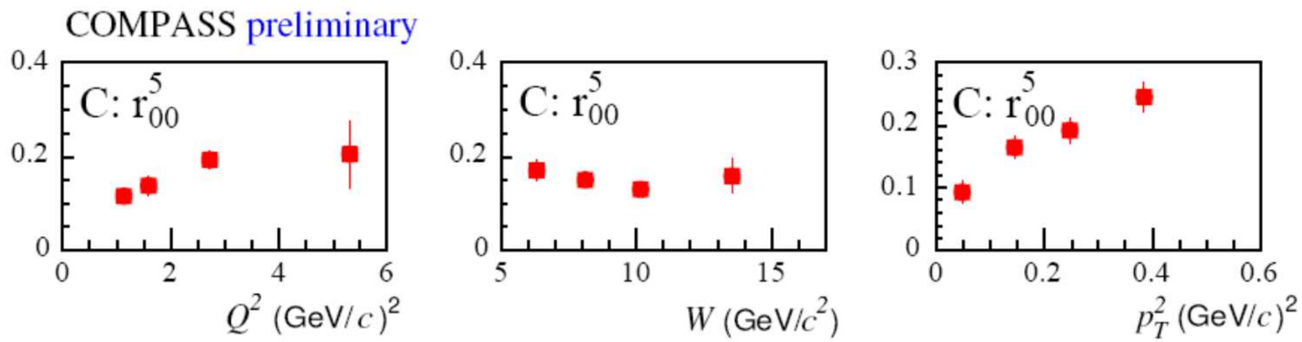




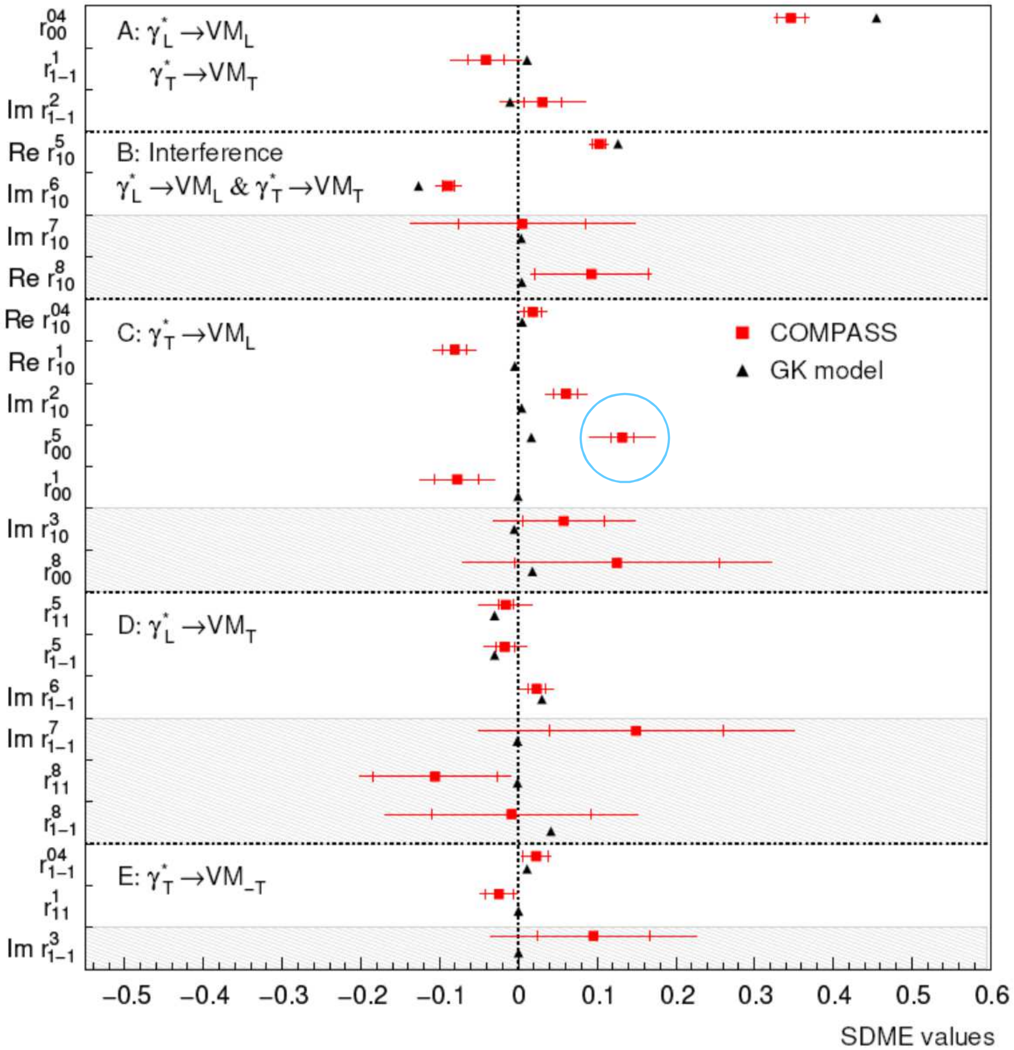
- $r^5_{00} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$ *Goloskokov and Kroll, ref. above*

interplay of interference of transversity GPDs $H_T, \bar{E}_T = 2\tilde{H}_T + E_T$ with GPDs E and H

for ρ^0 the first term in Eq. (●) dominates, thus r^5_{00} essentially probes $\bar{E}_T$



Results on SDMEs for exclusive ω production for total kin. range



1 GeV² < Q² < 10 GeV²

5 GeV < W < 17 GeV

0.01 GeV² < p_T^2 < 0.5 GeV²

< Q²> = 2.1 GeV²

<W> = 7.6 GeV

<p_T^2> = 0.16 GeV²

GK model, EPJA 50 (2014) 146 (1st version)

parameters constrained mostly by HERMES results for ρ^0 and ω

➢COMPASS provides new constraints for parameterisation of the model

❖ ρ^0 and ω results for class C complementary

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

$\bar{E}_T$ and H have the same signs for *u* and *d* quarks

H_T and E have opposite signs for *u* and *d* quarks

$< K >_{XY} =$ for ρ^0 $< e_u K_u - e_d K_d + \ldots >_{XY}$

for ω $< e_u K_u + e_d K_d + \ldots >_{XY}$

for ω the first term in Eq. (●) still dominates, but sensitivity to H_T is enhanced compared to ρ^0

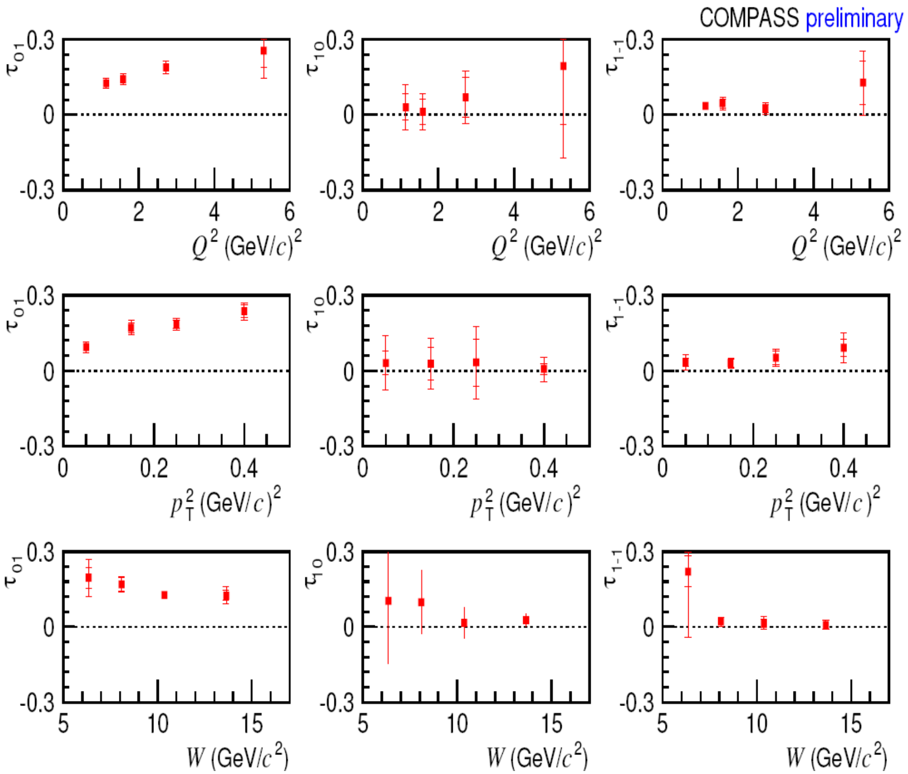
Contribution of helicity-flip NPE amplitudes to ρ^0 cross section

quantified by the ratios $\tau_{ij} = \frac{|T_{ij}|}{\sqrt{\mathcal{N}}}$ calculated as combinations of SDMEs

cf. HERMES Collab., EPJC 63, 659 (2009)

T_{01}, T_{10} and T_{1-1} are the NPE amplitudes for the transitions $\gamma^*_T \to \rho^0_L$, $\gamma^*_L \to \rho^0_T$, $\gamma^*_T \to \rho^0_{-T}$

and $\mathcal{N}$ is a normalisation constant



- only τ_{01} significantly different from zero much smaller τ_{01} and τ_{01}
- pattern consistent with different degrees of SCHC violation in classes C, D and E
- increase of τ_{01} with increasing Q^2 and p_T^2

fractional contribution of helicity-flip NPE amplitudes to the full cross section

$$\tau^2_{NPE} = (2\epsilon|T_{10}|^2 + |T_{01}|^2 + |T_{1-1}|^2)/\mathcal{N} \approx 2\epsilon\tau^2_{10} + \tau^2_{01} + \tau^2_{1-1}$$

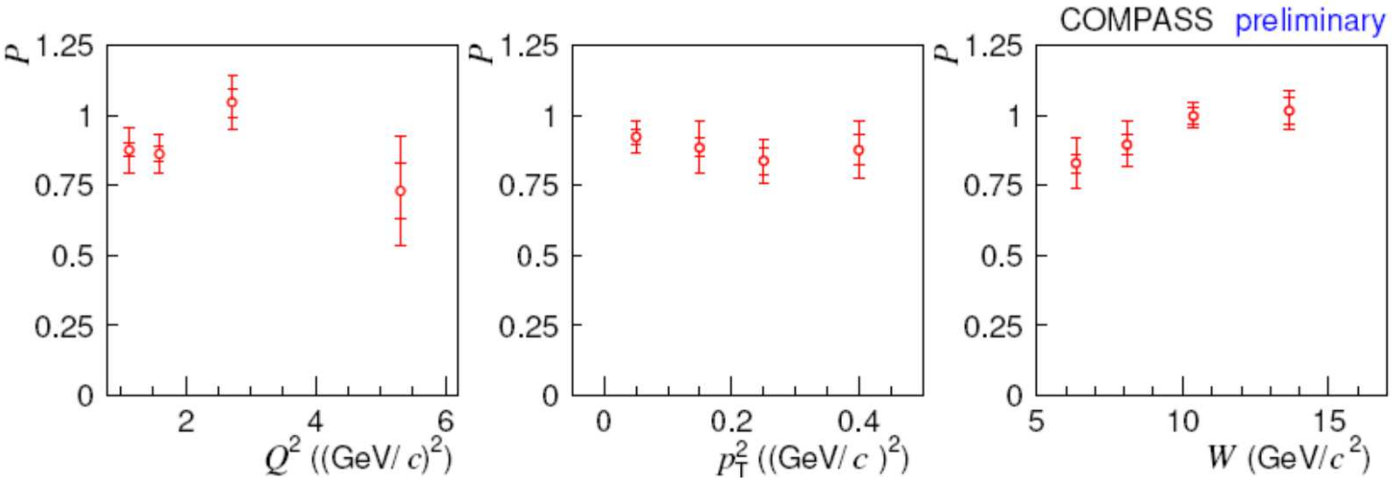
≈ 0.03 averaged over total kinematic range

NPE-to-UPE asymmetry of cross sections

NPE-to-UPE asymmetry of cross sections for transitions $\gamma^*_T \rightarrow V_T$

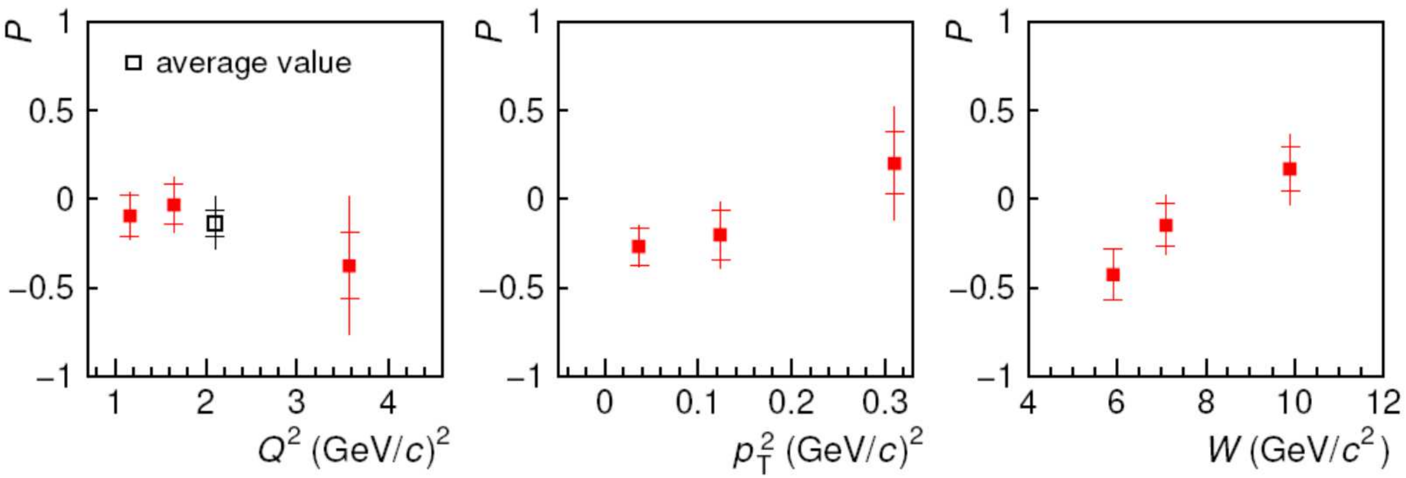
$$P = \frac{2r^1_{1-1}}{1 - r^{04}_{00} - 2r^{04}_{1-1}} \approx \frac{d\sigma^N_T(\gamma^*_T \rightarrow V_T) - d\sigma^U_T(\gamma^*_T \rightarrow V_T)}{d\sigma^N_T(\gamma^*_T \rightarrow V_T) + d\sigma^U_T(\gamma^*_T \rightarrow V_T)}$$

ρ^0



➢dominance of NPE

ω



➢UPE dominates at small W and p^2_T

averaged over kin. range
NPE ≈ UPE

Summary and outlook

- measured SDMEs in hard exclusive ρ^0 and ω muoproduction at energies 5 – 17 GeV
- access to helicity amplitudes => constraints on GPD models
- SDMEs a sensitive tool to access subleading amplitudes (via interference)
- violatation of SCHC observed for transitions $\gamma^*_T \rightarrow V_L$

  in GPD framework described by contribution of chiral-odd ”transversity” GPDs
- large contribution of UPE transitions for ω, only a few % for ρ^0

  in GK model described predominantly by the $\pi^{\mathbf{0}}$ pole exchange
- planned analysis of SDMEs and cross sections for exclusive φ, ω and J/ψ production

  collected in 2016+2017 with statistic ~ 10 times larger than from 2012

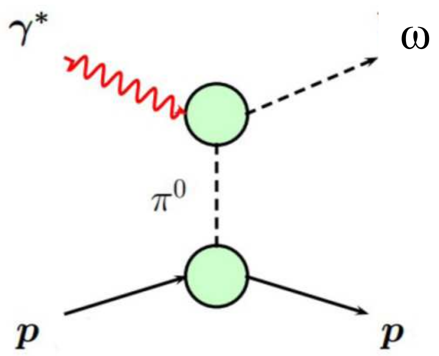
Backup slide

UPE and NPE contributions (contd.)

GPD interpretation **Goloskokov and Kroll, EPJA 50 (2014) 146**

UPE amplitudes depend on helicity GPDs $\widetilde{E}, \widetilde{H}$

the former supplemented by π^0 pole contribution treated as one-boson exchange



parameters constrained by HERMES SDMEs for ω

(except the sign of πω transition form factor)

- the pion pole contribution dominates UPE at small W and p_T^2
- πω transition form factor ($g_{\pi\omega}$) about **3 times larger** than $\pi\rho^0$ transition f.f. ($g_{\pi\rho}$): $g_{\pi\rho} \simeq \frac{e_u + e_d}{e_u - e_d} g_{\pi\omega}$

NPE amplitudes depend on GPDs H and E

NPE contribution for ρ^0 production about **3 times larger** than for ω production (for amplitudes)

this factor 3 is due to the dominant contribution from gluons and sea quark GPDs

while the contribution from valence quarks is about the same for ω and ρ^0 production

Thus on the cross section level *leaving aside other small conributions*

$d\sigma_T^N \approx d\sigma_T^U$ for ω *P* asymmetry ≈ 0

$d\sigma_T^N \approx 9\, d\sigma_T^U$ for ρ^0 *P* asymmetry ≈ 1