Deeply Virtual Exclusive Vector-Meson Production at COMPASS

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Towards improved hadron femtography
with hard exclusive reactions

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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 convenient tool for studying

- mechanism of reaction
- structure of the nucleon

Two approaches to describe HEMP

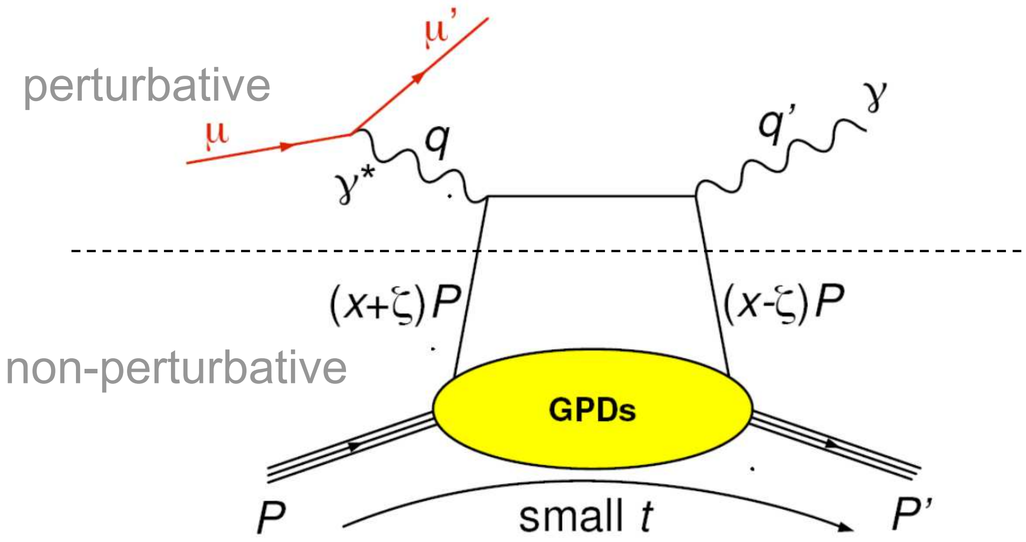
- color-dipol model (for VMs)
  color-dipol interaction with nucleon described either by Regge phenomenology or by pQCD
- GPD models (for VMs and PMs)

*for a review cf. L. Favart, M. Guidal, T. Horn, P. Kroll , Eur. Phys. J. A **52**, 158 (2016)*

Generalised Parton Distributions (GPDs)

- Provide comprehensive description of 3-D partonic structure of the nucleon
  one of the central problems of non-perturbative QCD
- GPDs can be viewed as correlation functions between different partonic states
- 'Generalised' because they encompass 1-D descriptions by PDFs or by form factors

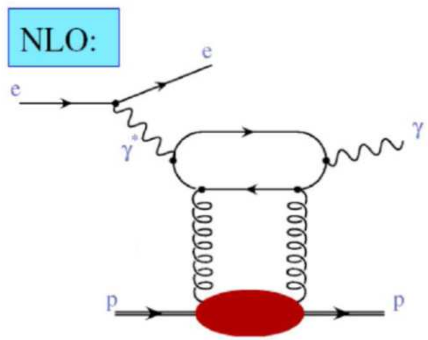
(the simplest) example: Deeply Virtual Compton Scattering (DVCS)



Factorisation for large Q^2 and | t | ‹‹ Q^2

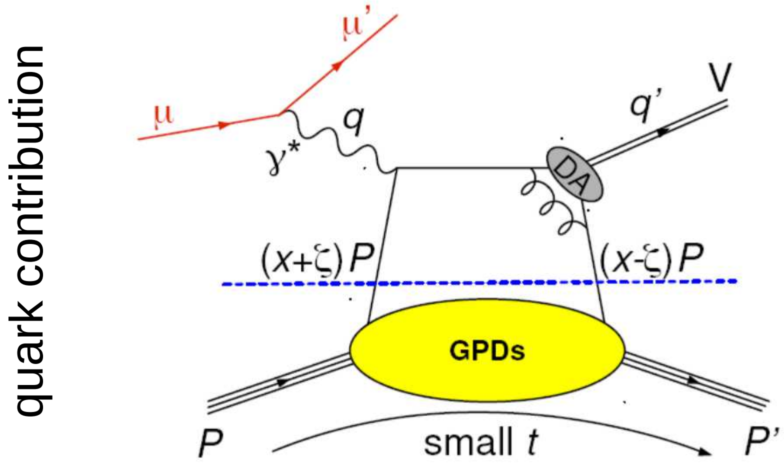
4 GPDs for each quark flavour

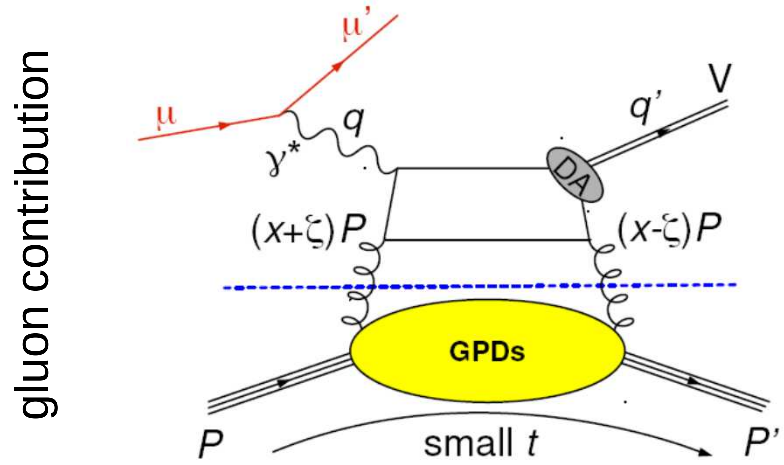
$H^q(x,\xi,t)$	$E^q(x,\xi,t)$
$\tilde{H}^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$



for DVCS **gluons** contribute at higher orders in α_s

GPDs and Hard Exclusive Meson Production





- factorisation proven only for σ_L
  σ_T suppressed by $1/Q^2$
- wave function of meson (DA)
  additional non-perturbative term

Chiral-even GPDs
helicity of parton unchanged

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

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

$$H_T^q(x,\xi,t) \qquad E_T^q(x,\xi,t)$$
$$\widetilde{H}_T^q(x,\xi,t) \qquad \widetilde{E}_T^q(x,\xi,t)$$

Flavour separation for GPDs
example:

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

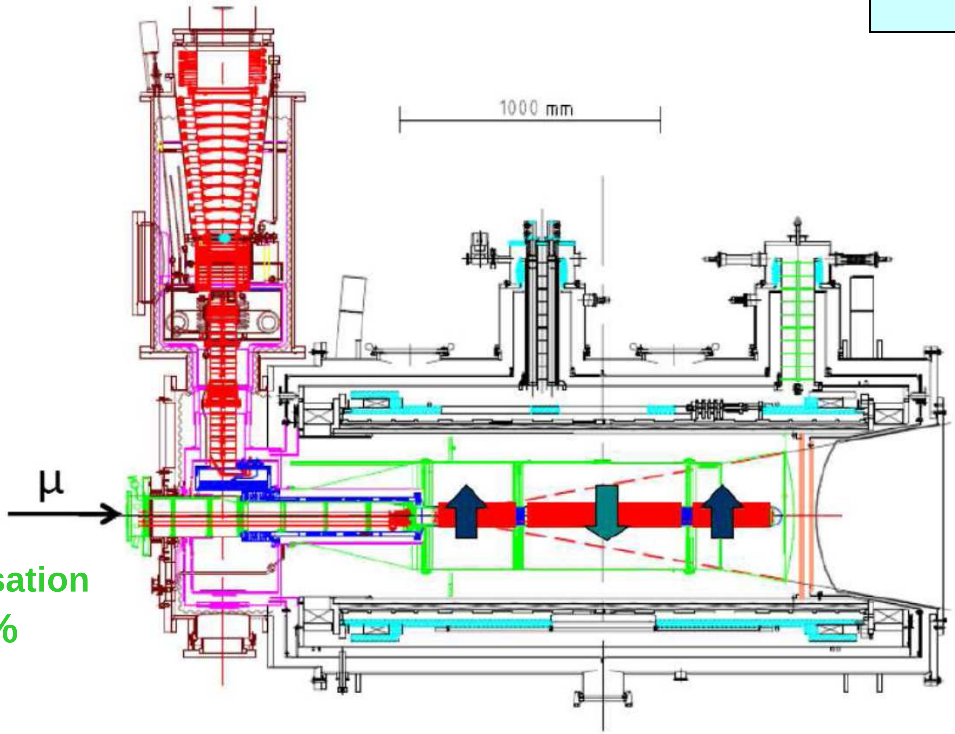
Diehl, Vinnikov PLB, 2005

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

Transverse target spin asymmetries for exclusive ρ^0 and ω production

From scattering 160 GeV*c* polarised μ^+ beam ($P \approx -80$ %)
off the COMPASS polarised target

COMPASS polarised target



μ^+ polarisation
≈ -80%

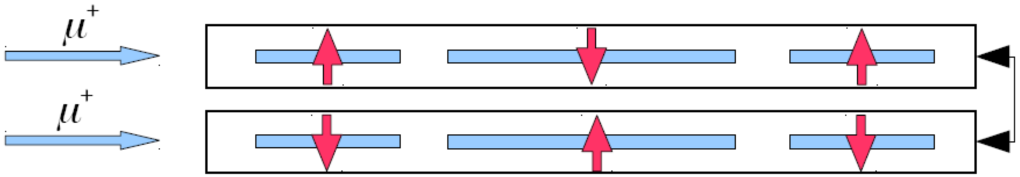
^3He - ^4He dilution refrigirator (T~50 mK)

solenoid 2.5 T
dipole magnet 0.6 T

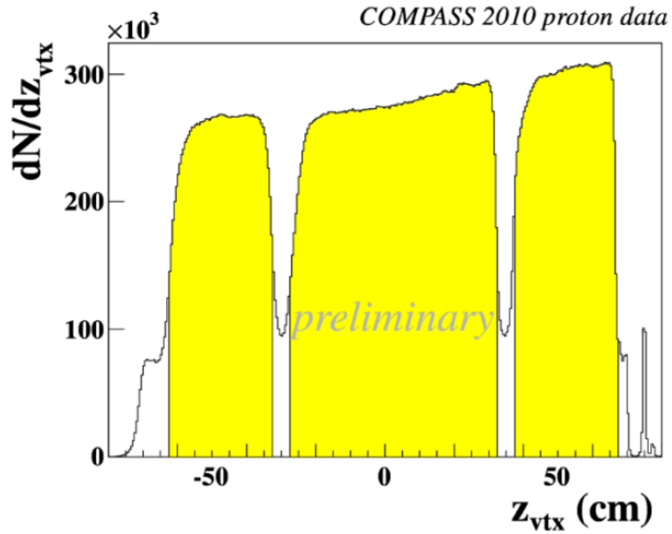
Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization

material:	NH_3 (protons)	[^{6}LiD (deuterons)]
polarization:	≈90%	[≈50%]
dilution factor for exclusive ρ^0 production:	≈25%	[≈44%]

Luminosity $5 \cdot 10^{32}$ cm^{-2}s^{-1}

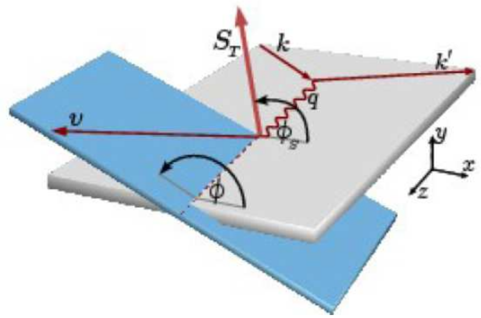


Microwave reversal every week



Spin-dependent cross section for exclusive meson leptoproduction

$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\epsilon}\frac{1-x_{Bj}}{x_{Bj}}\frac{1}{Q^2}\right]^{-1}\frac{\mathrm{d}\sigma}{\mathrm{d}x_{Bj}\mathrm{d}Q^2\mathrm{d}t\mathrm{d}\phi\mathrm{d}\phi_s}$$



$$= \underbrace{\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}} - \varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++} - \sqrt{\varepsilon(1+\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$- P_\ell\sqrt{\varepsilon(1-\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$- S_L\left[\varepsilon\sin(2\phi)\,\mathrm{Im}\,\sigma_{+-}^{++}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

$$+ S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

$$- S_T\left[\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}\right.$$

$$\left.+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\right]$$

$$+ S_T P_\ell\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}\right.$$

$$\left.-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\,\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\right].$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

$$\gamma^2 = (2x_{Bj}M_p)^2/Q^2$$

$\sigma_{\mu\sigma}^{\nu\lambda}$ helicity-dependent photoabsorption cross sections and interference terms

$\sigma_{\mu\sigma}^{\nu\lambda} = \sum \mathcal{M}^*_{\mu'\nu',\mu\nu}\mathcal{M}_{\mu'\nu',\sigma\lambda}$ $\mathcal{M}$ amplitude for $\gamma^* p \to V p'$

Azimuthal TTS asymmetries of cross section for exclusive meson leptoproduction

5 single spin asymmetries

$$A_{UT}^{\sin(\varphi-\varphi_s)} = -\frac{\mathrm{Im}\left(\sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-}\right)}{\sigma_0}$$

$$A_{UT}^{\sin(\varphi+\varphi_s)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{+-}}{\sigma_0}$$

$$A_{UT}^{\sin(2\varphi-\varphi_s)} = -\frac{\mathrm{Im}\,\sigma_{+0}^{-+}}{\sigma_0}$$

$$A_{UT}^{\sin(3\varphi-\varphi_s)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{-+}}{\sigma_0}$$

$$A_{UT}^{\sin\varphi_s} = -\frac{\mathrm{Im}\,\sigma_{+0}^{+-}}{\sigma_0}$$

3 double spin asymmetries

$$A_{LT}^{\cos(\varphi-\varphi_s)} = \frac{\mathrm{Re}\,\sigma_{++}^{+-}}{\sigma_0}$$

$$A_{LT}^{\cos(2\varphi-\varphi_s)} = -\frac{\mathrm{Re}\,\sigma_{+0}^{-+}}{\sigma_0}$$

$$A_{LT}^{\cos\varphi_s} = -\frac{\mathrm{Re}\,\sigma_{+0}^{+-}}{\sigma_0}$$

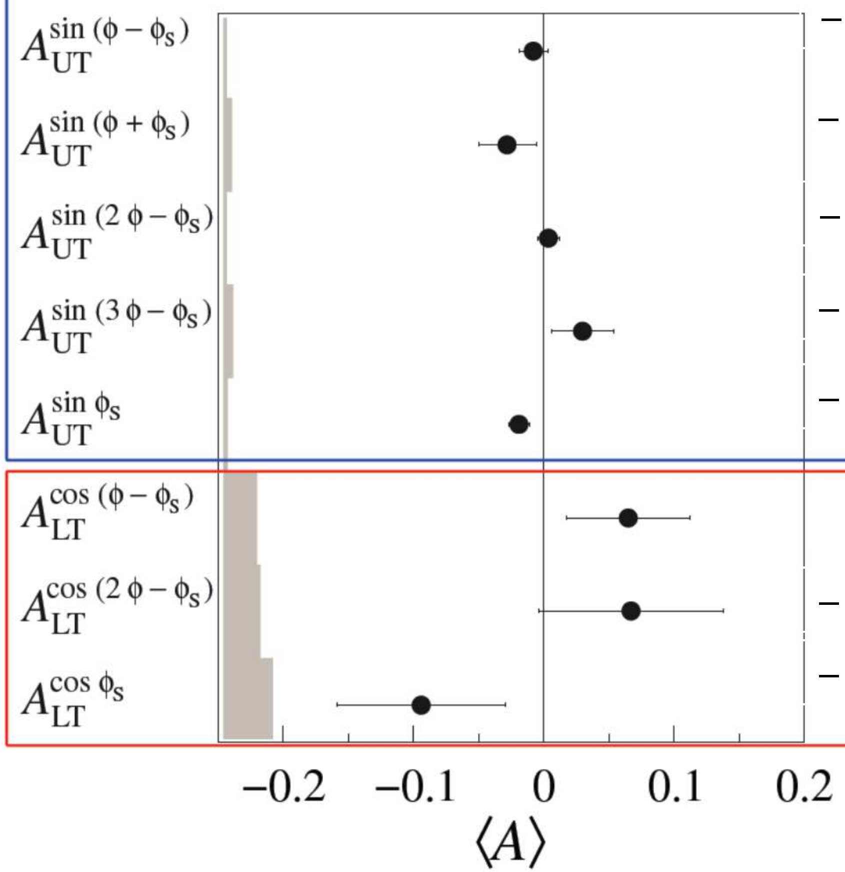
σ_0 - ‘unpolarised cross section’

$$\sigma_0 = \frac{1}{2}(\sigma_{++}^{++}+\sigma_{++}^{--})+\varepsilon\sigma_{00}^{++} = \sigma_T+\varepsilon\sigma_L$$

Transverse target spin asymmetries for exlusive ρ^0 production on $p^{\uparrow}$

PLB 731 (2014) 19

$\langle x_{Bj} \rangle = 0.039$, $\langle Q^2 \rangle = 2.0$ GeV²
$\langle p_T^2 \rangle = 0.18$ GeV², $\langle W \rangle = 8.1$ GeV²



$-\,\mathrm{Im}(\sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-})/\sigma_0 \propto -\mathrm{Im}\left[\epsilon\mathcal{E}_{LL}^{*}\mathcal{H}_{LL}+\mathcal{E}_{TT}^{*}\mathcal{H}_{TT}-\frac{1}{2}\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT}\right],$

$-\,\mathrm{Im}(\sigma_{+-}^{+-})/\sigma_0 \propto \mathrm{Im}\left[\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LL}\right],$

$-\,\mathrm{Im}(\sigma_{+-}^{-+})/\sigma_0 \propto -\mathrm{Im}\left[\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}\right],$

$-\,\mathrm{Im}(\sigma_{+0}^{+-})/\sigma_0 = 0,$

$-\,\mathrm{Im}(\sigma_{+0}^{-+})/\sigma_0 \propto \mathrm{Im}\left[\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL}-\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}\right],$

5 single spin asymmetries

$\mathrm{Re}(\sigma_{++}^{+-})/\sigma_0 \propto \mathrm{Re}\left[\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT}-2\mathcal{E}_{TT}^{*}\widetilde{\mathcal{H}}_{TT}\right],$

$-\,\mathrm{Re}(\sigma_{+0}^{+-})/\sigma_0 \propto \mathrm{Re}\left[\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT}-2\mathcal{E}_{TT}^{*}\widetilde{\mathcal{H}}_{TT}\right],$

$-\,\mathrm{Re}(\sigma_{+0}^{-+})/\sigma_0 \propto \mathrm{Re}\left[\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL}-\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}\right].$

3 double spin asymmetries

$\sim E$, $\sim H$, $\sim H_T$, $\sim \bar{E}_T = 2\widetilde{H}_T - E_T$, $\sim \widetilde{H}$

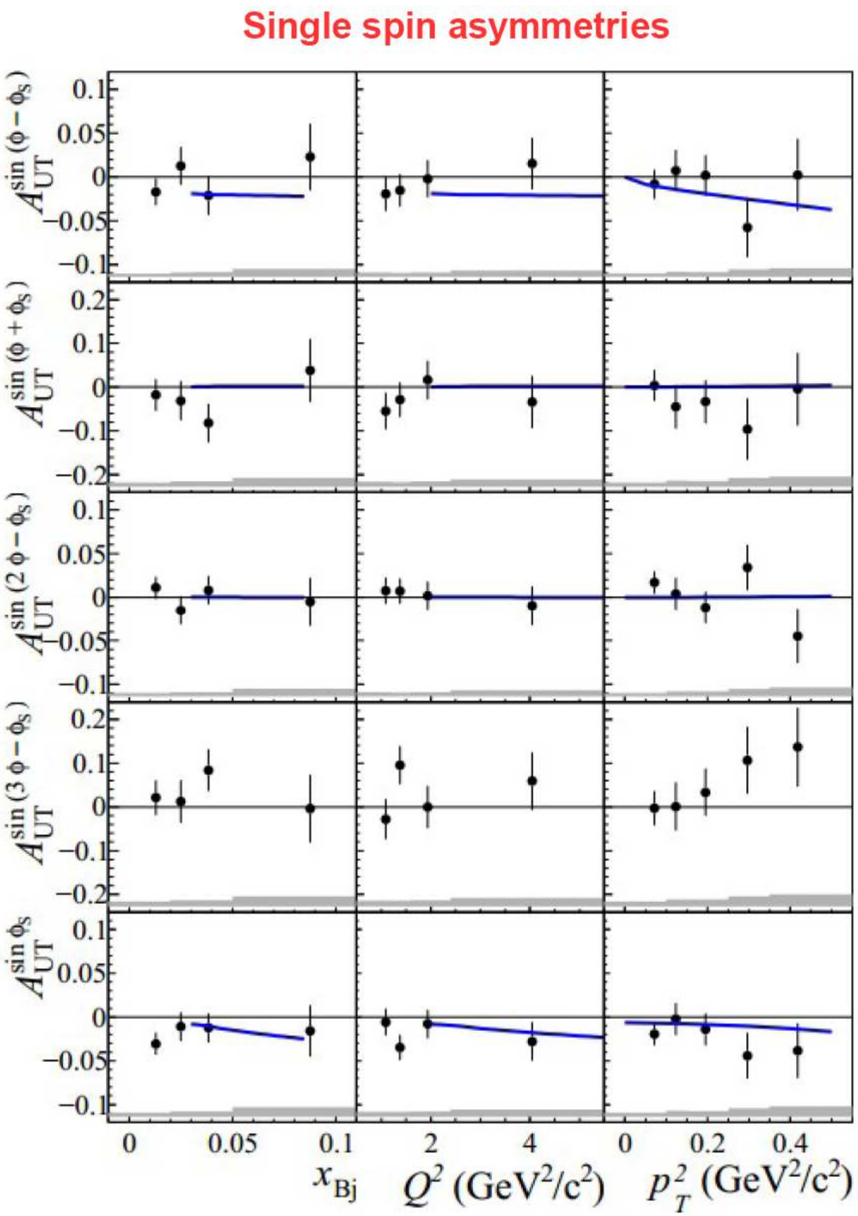
- asymmetries small, compatible with 0, except

  $A_{UT}^{\sin\varphi_s} = -0.019 \pm 0.008 \pm 0.003$

- indication of transversity GPD H_T contribution

$H_T(x, 0, 0) = h_1(x)$

Transverse target spin asymmetries for exlusive ρ^0 production on $p^{\uparrow}$



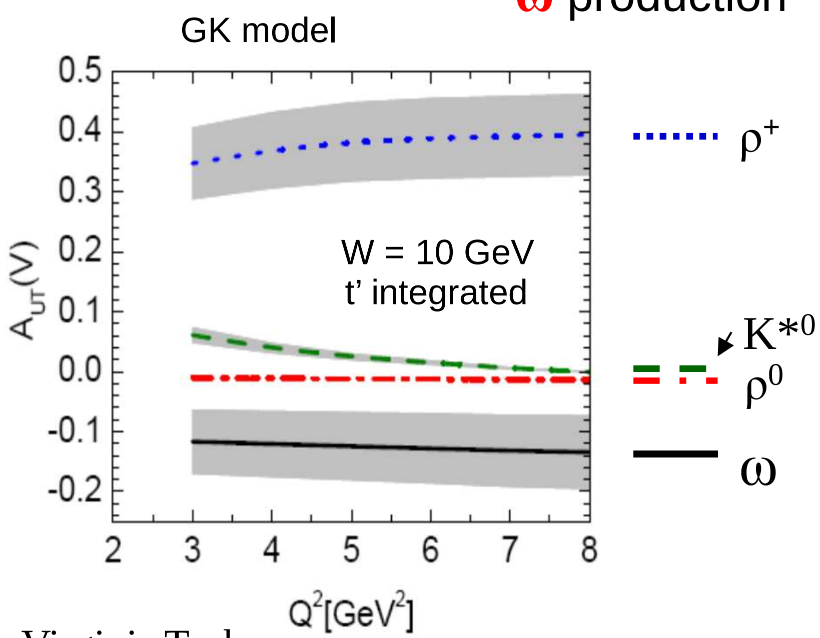
predictions of GPD model of Goloskokov-Kroll

- reasonable agreement with GK model (also for not-shown double spin asym.)

$A_{UT}^{\sin(\phi-\phi_S)}$ contains twist-2 terms depending on $E^{q,g}$

its small values due to approximate cancellation of contributions from E^u and E^d, $E^u \approx -E^d$

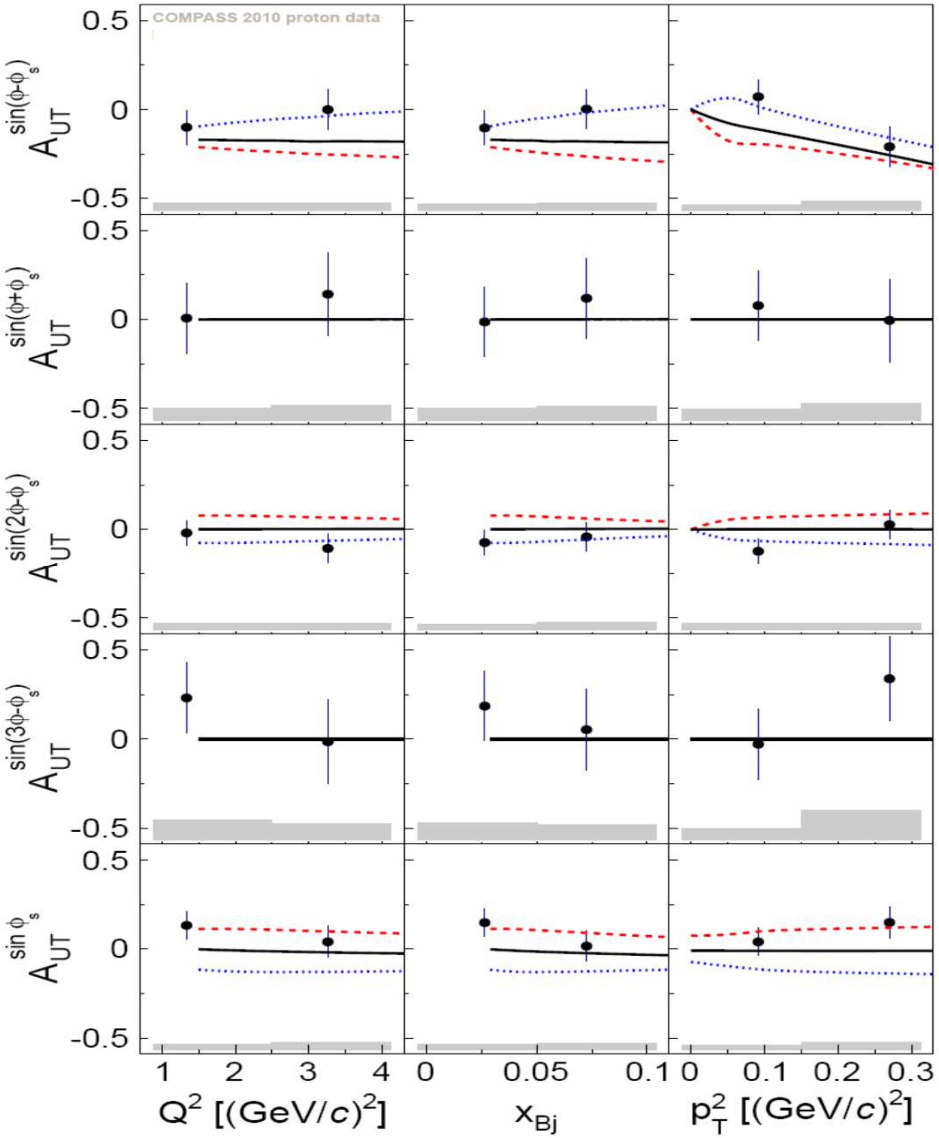
- larger effects expected for exclusive ω production



Azimuthal asymmetries for exlusive ω production on $p^{\uparrow}$

Single spin asymmetries

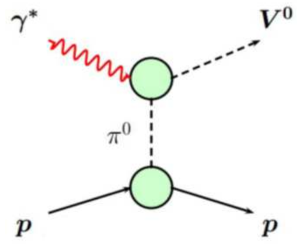
Nucl. Phys. B 915 (2017) 454



$\langle x_{Bj} \rangle = 0.049$, $\langle Q^2 \rangle = 2.2$ GeV²
$\langle p_T^2 \rangle = 0.17$ GeV², $\langle W \rangle = 7.1$ GeV²

comparison to modified GPD model of GK

with added π^0 pole exchange



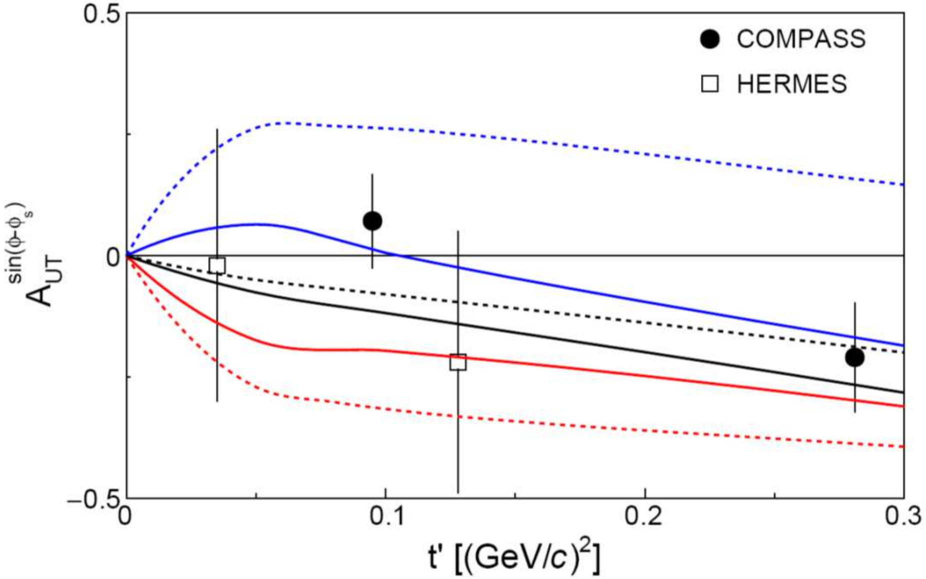
EPJ A50 (2014) 146

parameters constrained by HERMES SDMEs for ω
except sign of πω transition form factor
more sensitivity in azimuthal asymmetries

GK predictions for COMPASS, private com.
- no pion pole (solid black)
- positive πω form factor (dashed red)
- negative πω form factor (dotted blue)

- when 'global' comparison to the data
  no clear preference for any version

Comparison to HERMES asymmetries for ω production on p↑



COMPASS <W> = 8 GeV	HERMES <W> = 4.8 GeV	← **EPJ C75 (2015) 600**
solid black	dotted black	no pion pole
solid red	dotted red	positive πω form factor
solid blue	dotted blue	negative πω form factor

- ✓ Note: contribution of pion pole decreases with W
  → each experiment to be compared to corresp. predictions
- ✓ COMPASS uncertainties smaller by a factor > 2
- ✓ within large errors combined HERMES data compatible with all 3 scenarios

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- ✓ Measurements at JLab12 **EPJ A48 (2012) 187**
  expected to resolve the issue of πω transition form factor

Prospects to separate GPDs E_u and E_d from TTS asymmetries

Section in PhD thesis of P. Sznajder, Warsaw 2015

In the framework of GK model an attempt to constrain $L^{u\ val}$ and $L^{d\ val}$ using COMPASS $A_{UT}^{\sin(\phi - \phi_S)}$ for exclusive ρ^0 and ω production

☺ $-L^{u\ val} \approx L^{d\ val} > 0$ (as expected)

☺ adding ω result reduces allowed region in ($L^{u\ val}$, $L^{d\ val}$) space

☹ constraints are rather weak due to limited statistics of COMPASS ω sample (1/40 of that of ρ^0)

A promissing alternative method

Future combined analysis of TTS asymmetries for exclusive ρ^0 production on transversely polarised protons (1) and deuterons (2)

(1) existing measurements and

(2) expected results from one-year data taking in 2022

SDMEs for exclusive ρ^0 and ω production on unpolarised protons

From scattering 160 GeV*c* polarised μ^+ and μ^- beams
(P ≈ – 80 % and + 80 %, respectively)
off the 1.2 m-long liquid hydrogen target

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 in 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 (or 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)

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

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

$R = \sigma_L / \sigma_T$

Vector meson spin-density matrix (2)

Access to helicity amplitudes allows:

- test of s-channel helicity conservation ($\lambda_\gamma = \lambda_V$)
- quantify the role of transitions with helicity flip
- decomposition into Natural (N) Parity and Unnatural (U) Parity exchange amplitudes

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

  - in Regge framework NPE: $J^P = (0^+, 1^-, \ldots)$ (pomeron, ρ, ω, a_2 … reggeons)
    UPE: $J^P = (0^-, 1^+, \ldots)$ (π, a_1 , b_1… reggeons)

- tests of GPD models
  - e.g. for SCHC-violating transitions $\gamma_T \rightarrow V_L$ test sensitivity to GPDs with exchanged-quark helicity flip (transversity GPDs)

- determination of the longitudinal-to-transverse cross-section ratio

Data and selected samples

- Data collected within four weeks in 2012 pilot run
- Data with polarised (|P| ≈ 0.8) μ^+ and μ^- beams taken separately
- Two parallel analyses:

(i) $\mu p \rightarrow \mu' p' \rho^0$

$\quad \hookrightarrow \pi^+\pi^-$ $\qquad$ $\mathrm{BR} \approx 99\%.$

(ii) $\mu p \rightarrow \mu' p' \omega$

$\quad \hookrightarrow \pi^+\pi^-\pi^0$ $\qquad$ $\mathrm{BR} \approx 89\%$

$\qquad \hookrightarrow \gamma\gamma$ $\qquad$ $\mathrm{BR} \approx 99\%.$

- (i) preliminary results (first shown at DIS 2021)
- (ii) published - EPJC **81**,126 (2021)

Selection of exclusive ρ^0 sample for SDMEs analysis

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

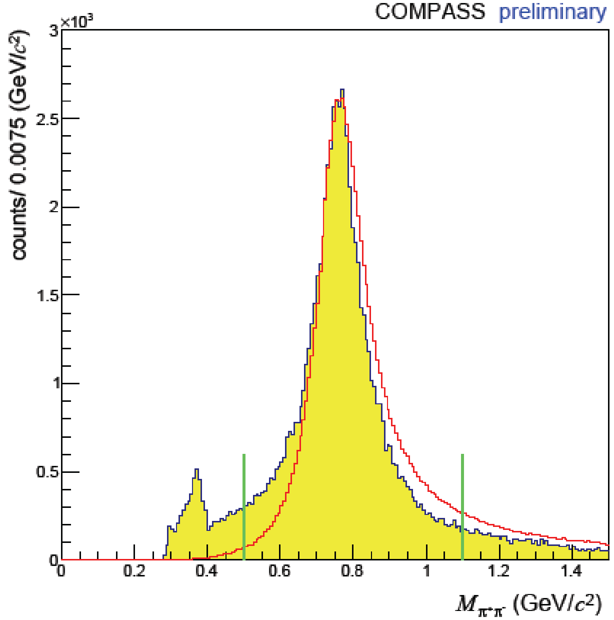
Topological selection: scattered muon
+ two hadrons with opposite charges

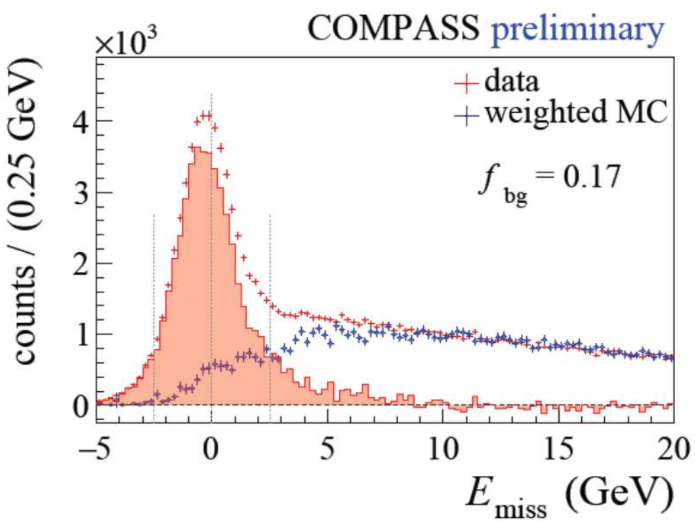
$1 < Q^2 < 10$ GeV/c^2
$W > 5$ GeV
$0.01 < p_T^2 < 0.5$ (GeV/c)^2
$0.1 < y < 0.9$
$\nu > 20$ GeV
$|E_{miss}| < 2.5$ GeV

As Recoil Proton Detector restricts kinematic coverage towards low p_T^2, it's not included in selections for ρ^0 and ω channels

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

After all selections and cuts
≈ 52 200 evts





Experimental access to SDMEs

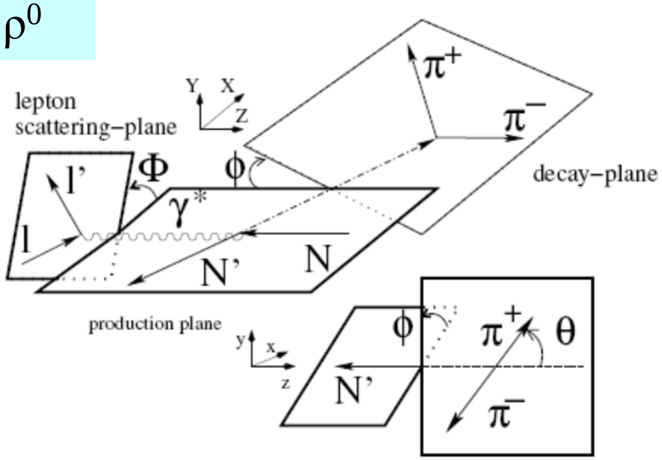
$$W^{U+L}(\Phi, \phi, \cos\Theta) = W^{U}(\Phi, \phi, \cos\Theta) + P_B W^{L}(\Phi, \phi, \cos\Theta) \propto \frac{d\sigma}{d\Phi\, d\phi\, d\cos\Theta}$$

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)

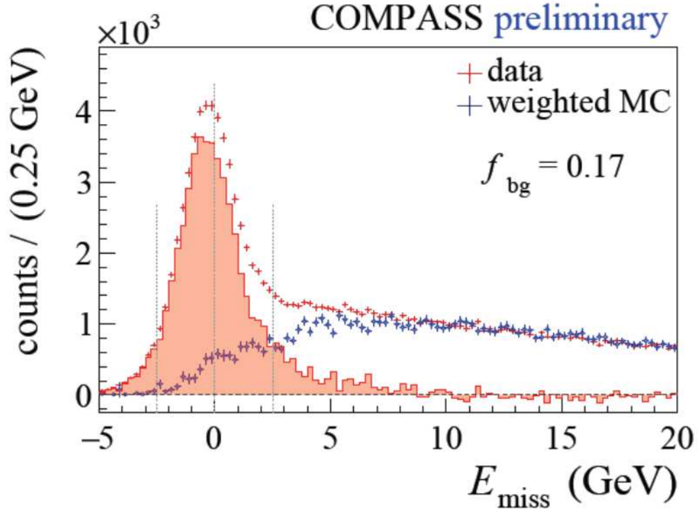
for ρ^0



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

Extraction of SDMEs

- 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 from real data side band)



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

$1\ \text{GeV}^2 < Q^2 < 10\ \text{GeV}^2$

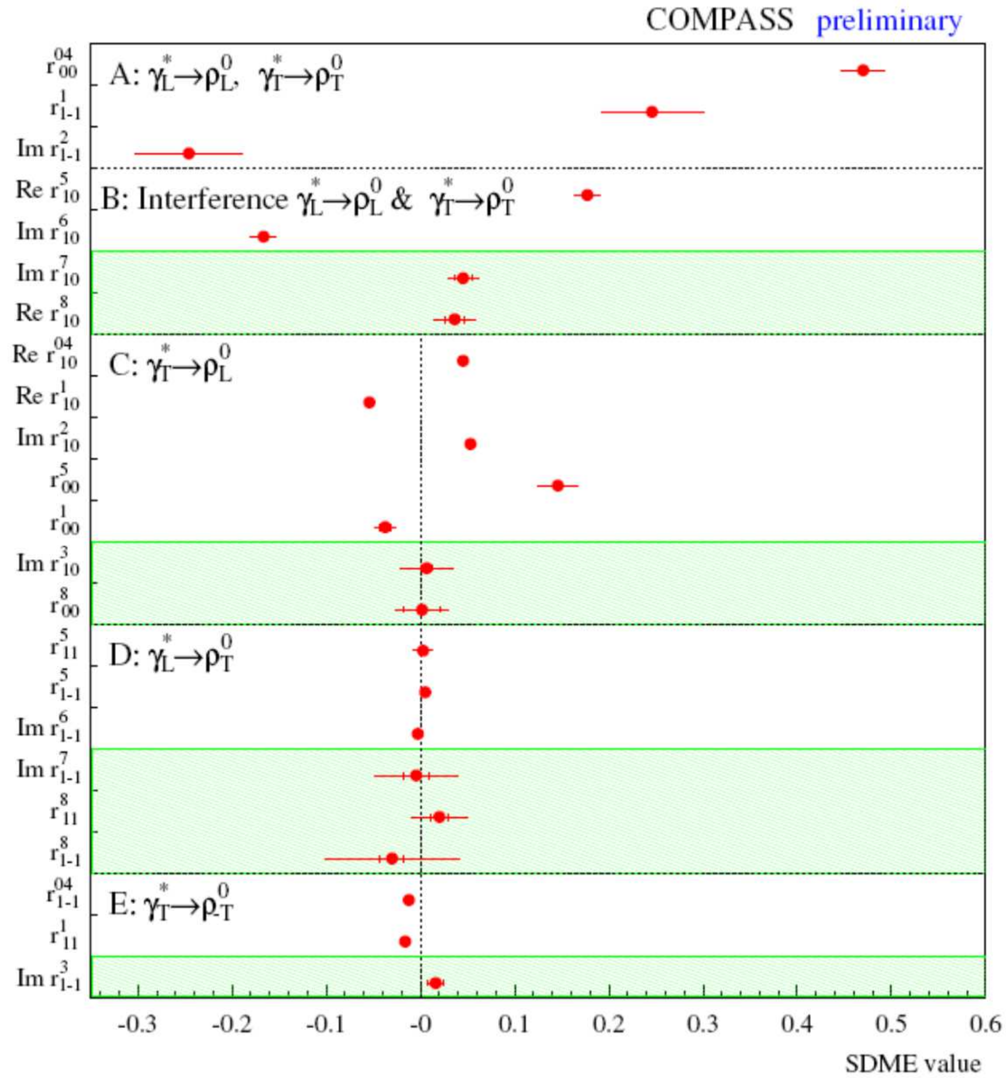
$5\ \text{GeV} < W < 17\ \text{GeV}$

$0.01\ \text{GeV}^2 < p_T^2 < 0.5\ \text{GeV}^2$

$\langle Q^2 \rangle = 2.4\ \text{GeV}^2$

$\langle W \rangle = 9.9\ \text{GeV}$

$\langle p_T^2 \rangle = 0.18\ \text{GeV}^2$



- 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

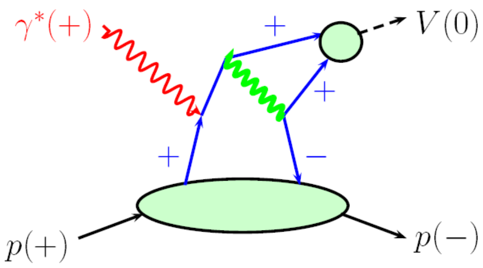
not obeyed for class C transitions $\gamma^*_T \to \rho_L$

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

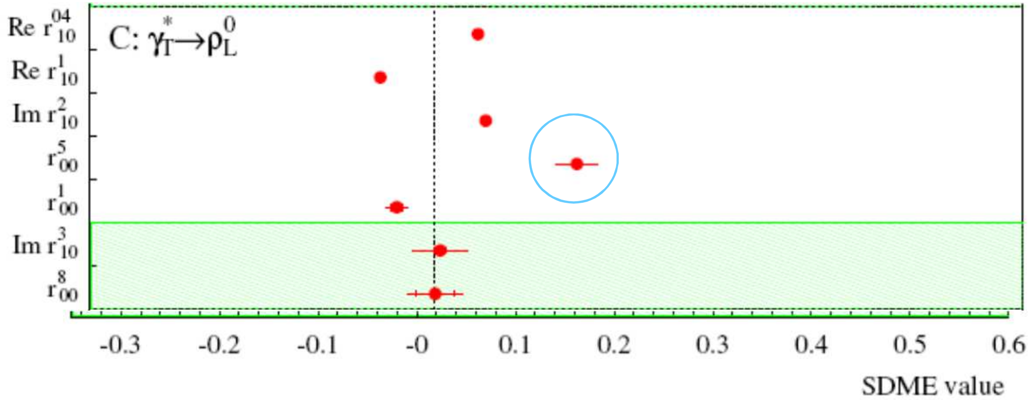
possible GPD interpretation **Goloskokov and Kroll, EPJC 74 (2014) 2725**

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

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



COMPASS preliminary

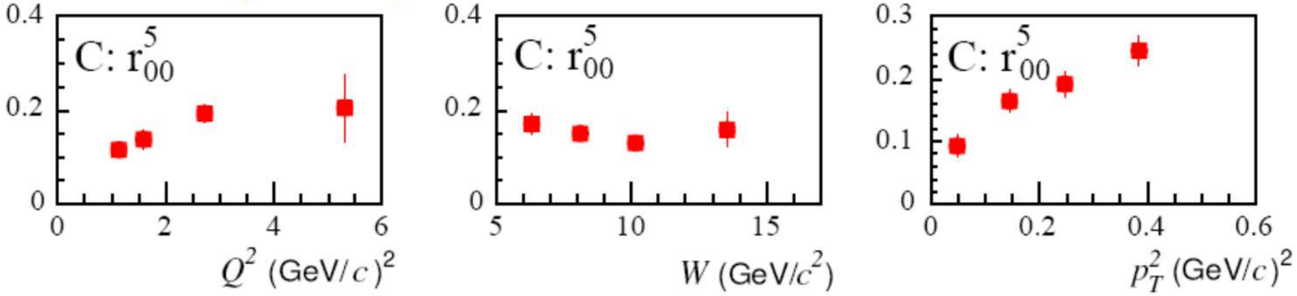


- $r^5_{00} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$ *Goloskokov and Kroll, ref. above*

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

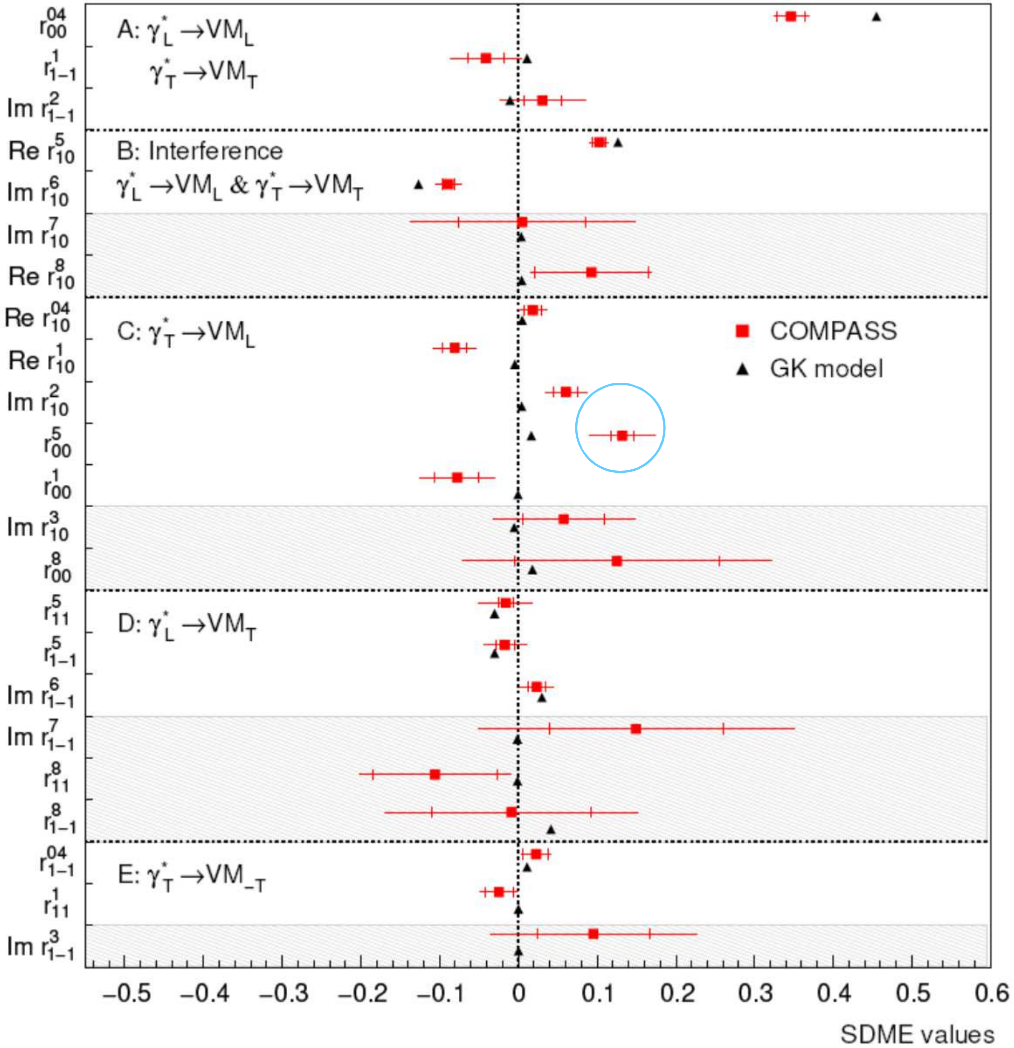
for ρ^0 the first term in Eq. (●) dominates, thus r^5_{00} essentially probes $\bar{E}_T$

COMPASS preliminary



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

EPJC **81**,126 (2021)



1 GeV² < Q² < 10 GeV²

5 GeV < W < 17 GeV

0.01 GeV² < p_T^2 < 0.5 GeV²

$\langle Q^2 \rangle$ = 2.1 GeV²

$\langle W \rangle$ = 7.6 GeV

$\langle p_T^2 \rangle$ = 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

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

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

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

$$\langle K \rangle_{XY} = \begin{cases} \text{for } \rho^0 & \langle e_u K_u - e_d K_d + \ldots \rangle_{XY} \\ \text{for } \omega & \langle e_u K_u + e_d K_d + \ldots \rangle_{XY} \end{cases}$$

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

Unnatural parity exchange contribution

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

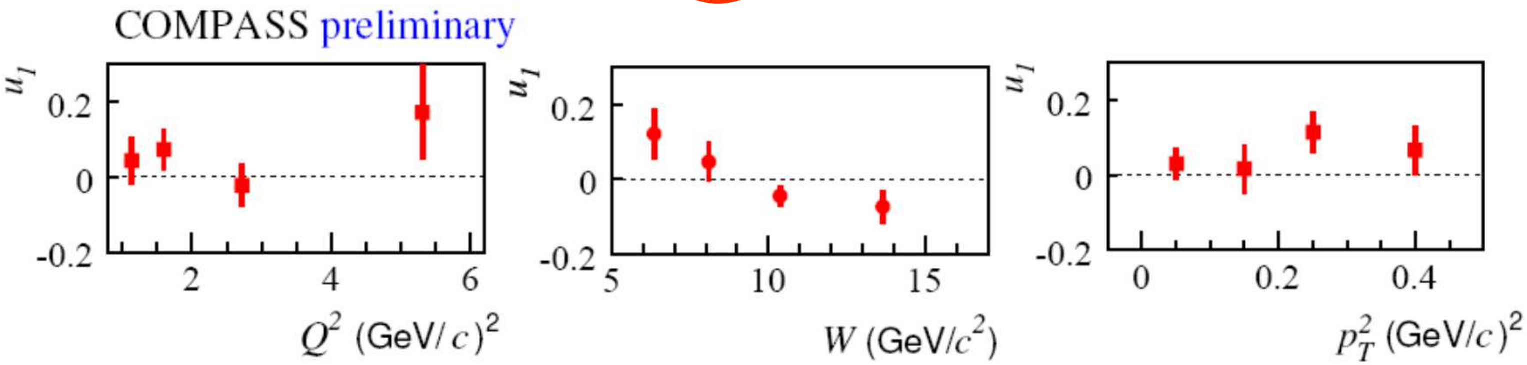
$$u_1 = \widetilde{\sum} \frac{4\epsilon |U_{10}|^2 + 2|U_{11} + U_{-11}|^2}{\mathcal{N}}$$

numerator depends only on UPE amplitudes

$u1 > 0$ signature of UPE contribution

UPE fractional contribution to the cross section $\Delta_{\mathrm{UPE}} = (2\epsilon|U_{10}|^2 + |U_{01}|^2 + |U_{1-1}|^2 + |U_{11}|^2)/\mathcal{N} \approx u_1/2$

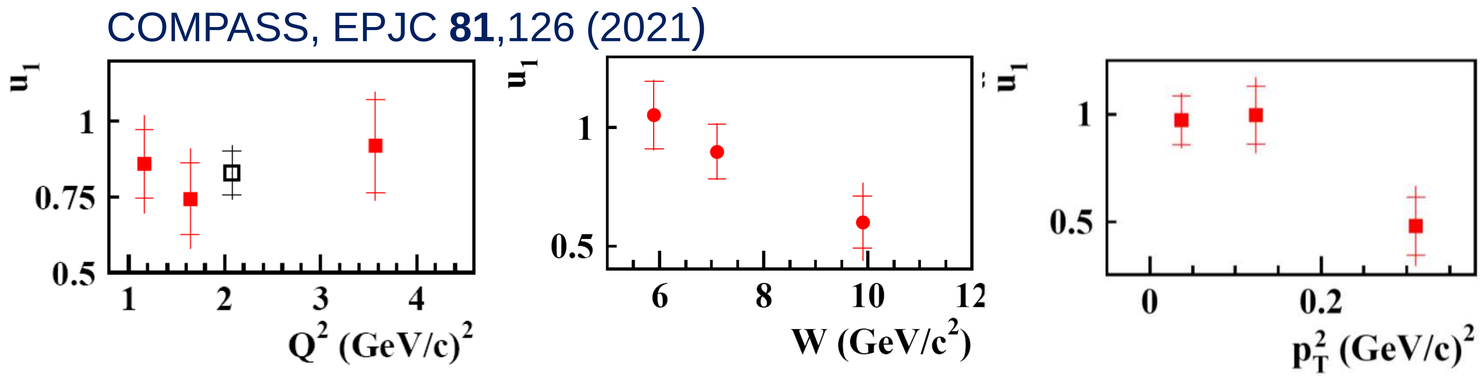
ρ^0



➢ very small UPE contribution

$\Delta_{\mathrm{UPE}} \approx 0.03$ *averaged*

ω



➢ large UPE contribution decreasing with increasing W
still non-negligible even at W = 10 GeV/c^2

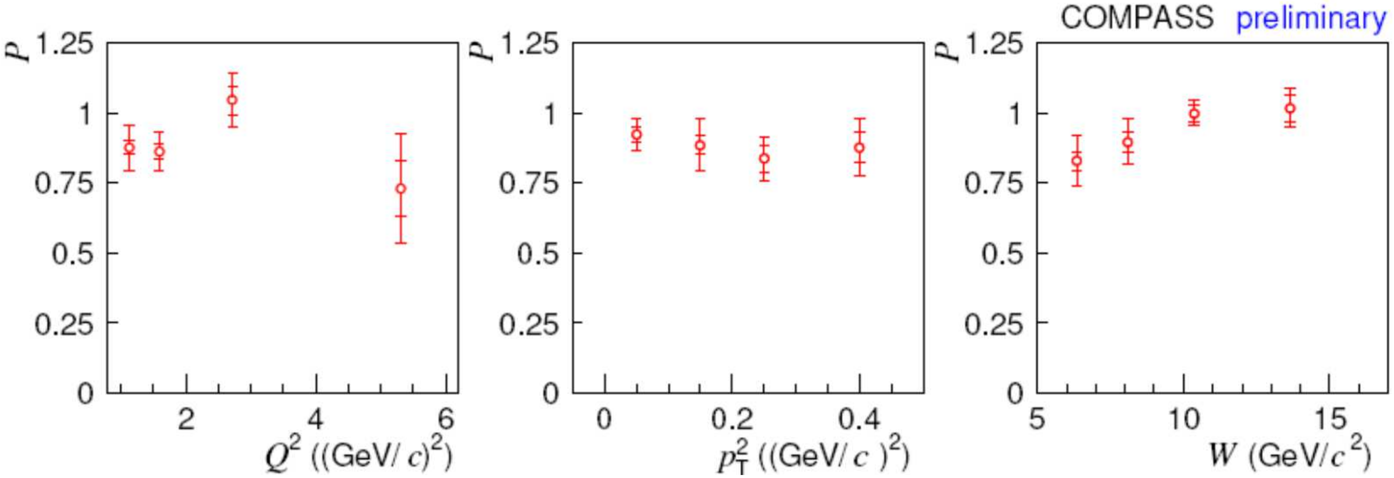
$\Delta_{\mathrm{UPE}} \approx 0.5 \searrow 0.3$

NPE-to-UPE asymmetry of cross sections

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

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

ρ^0



➢dominance of NPE

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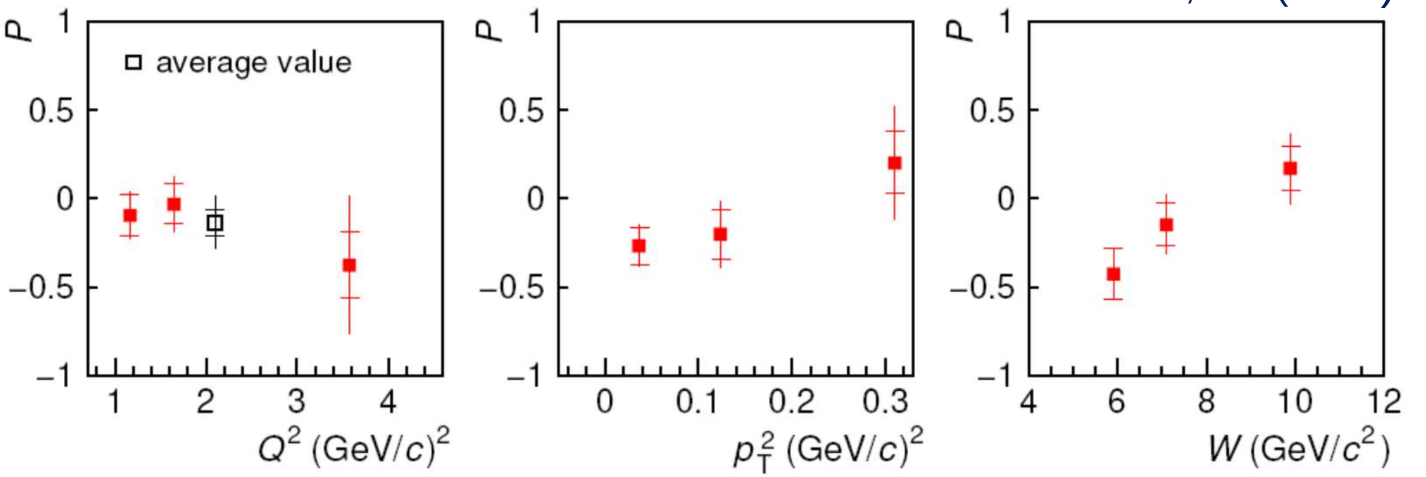
ω



➢UPE dominates at small *W* and p^2_T

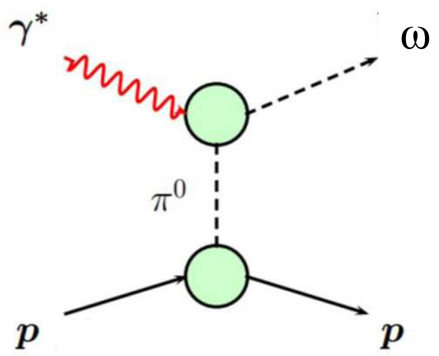
averaged over kin. range
NPE ≈ UPE

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

Summary and outlook

- TTS asymmetries for hard exclusive ρ^0 and ω production small and compatible with 0
  except $A_{UT}^{\sin\varphi_S} = -0.019 \pm 0.008 \pm 0.003$ for ρ^0
  indication for chiral-odd ("transversity") GPD H_T from excl. ρ^0 prod.

- measured SDMEs in hard exclusive ρ^0 and ω muoproduction at W = 5 -17 GeV
  allow 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 π^0 pole exchange

- ongoing COMPASS analyses of exclusive production of ϕ, ω and J/ψ
  using 2016+2017 data statistics ~ 10 times larger than from 2012

- prospect to separate E_u and E_d contributions including 2022 COMPASS data for
  exclusive ρ^0 production off transversely polarised ^{6}LiD target

Thank you for your attention

Spares

Selection of exclusive ω sample for SDMEs analysis

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

↳ $\pi^+ \pi^- \pi^0$

↳ $\gamma + \gamma$

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

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

After all selections
≈ 3 000 evts