Hard exclusive meson production in muon scattering at COMPASS

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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

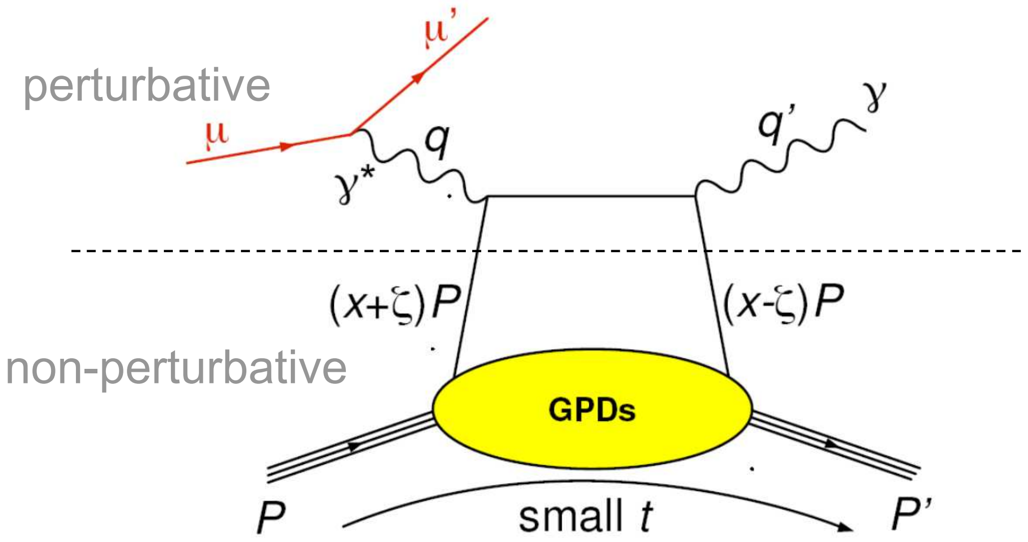
Two approaches to describe HEMP
- color-dipol model (for VMs)
  color-dipol interaction with nucleon described either by Regge phenomenology or by pQCD
- GPD models (for VMs and PMs)

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

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

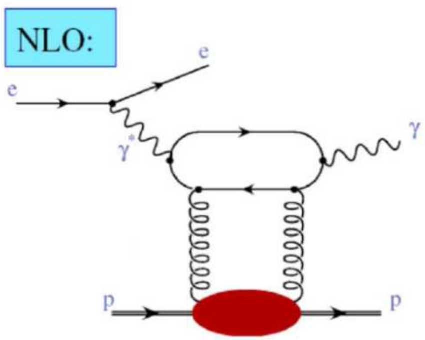
(the simplest) example: Deeply Virtual Compton Scattering (DVCS)



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

4 GPDs for each quark flavour

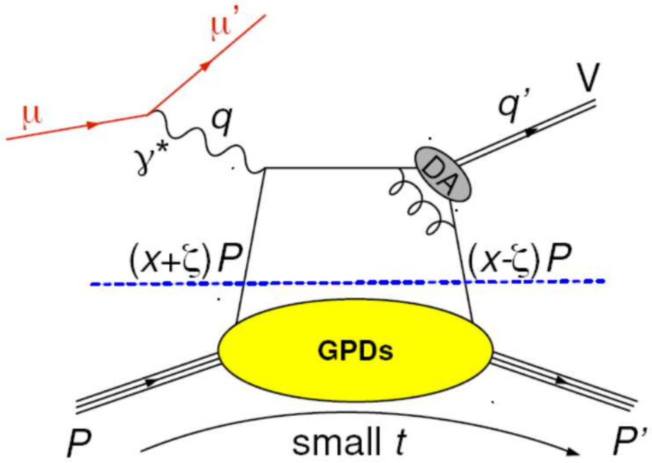
$H^q(x,\xi,t)$	$E^q(x,\xi,t)$
$\tilde{H}^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$



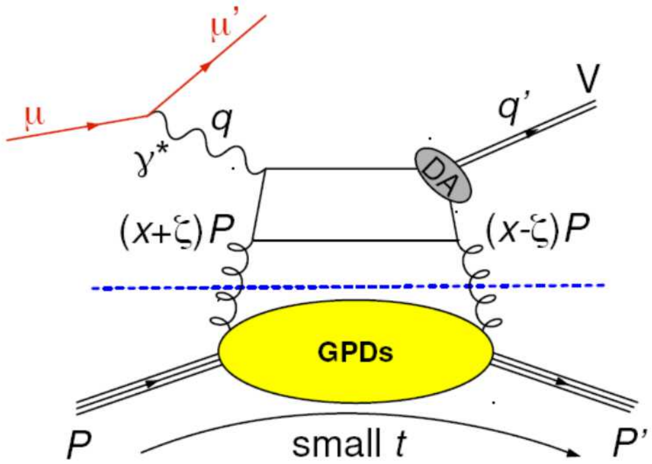
for DVCS **gluons** contribute at higher orders in α_s

GPDs and Hard Exclusive Meson Production

quark contribution



gluon contribution



- 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

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

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

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

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*

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)

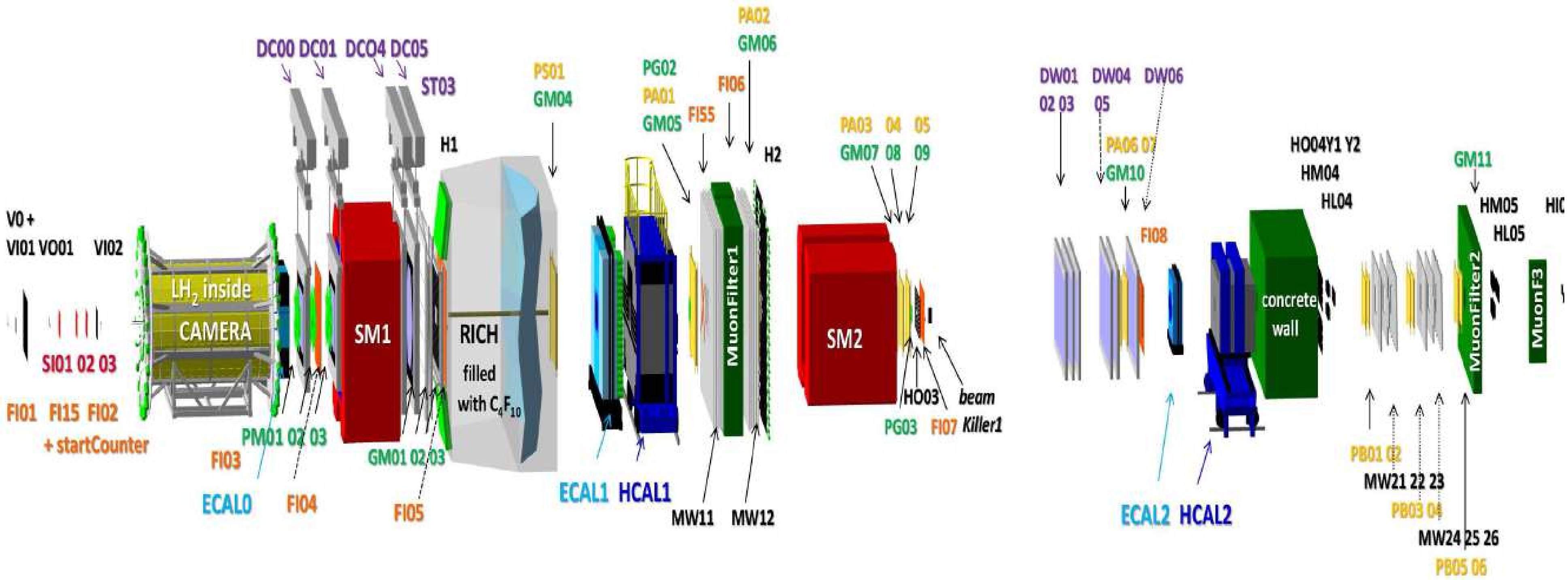
- determination of the longitudinal-to-transverse cross-section ratio

COMPASS experimental setup

Basic ingredients:

❖ **unique secondary beam line M2 from the SPS**

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



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

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

❖ **flexible target area** • for the presented results 2.5m long LH_2 target used

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
- Three paralell analyses:

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

$\hookrightarrow \pi^+\pi^-$ BR $\approx$ 99%.

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

$\hookrightarrow \pi^+\pi^-\pi^0$ BR $\approx$ 89%

$\hookrightarrow \gamma\gamma$ BR $\approx$ 99%.

(iii) $\mu\, p \rightarrow \mu'\, p'\, \pi^0$

$\hookrightarrow \gamma\gamma$ BR $\approx$ 99%

- (i) preliminary results (first shown at DIS 2021)
- (ii) published - EPJC **81**,126 (2021)
- (iii) published - PLB **81**,135454 (2020)

Selection of exclusive ρ^0 sample for SDMEs analysis

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

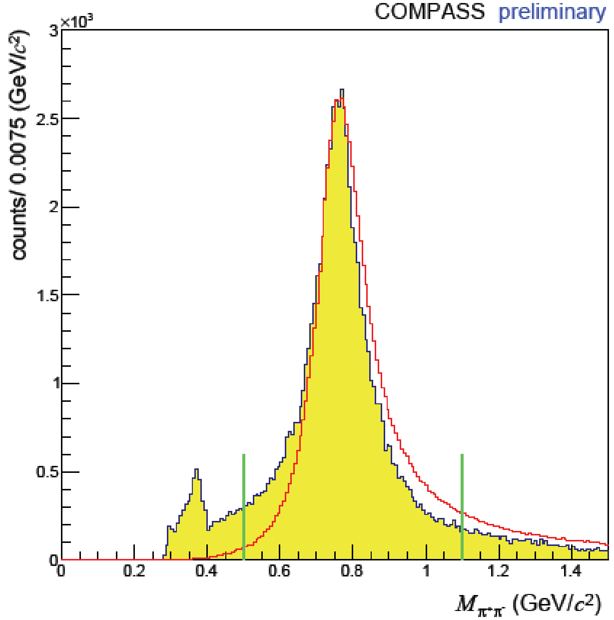
Topological selection: scattered muon
+ two hadrons with opposite charges

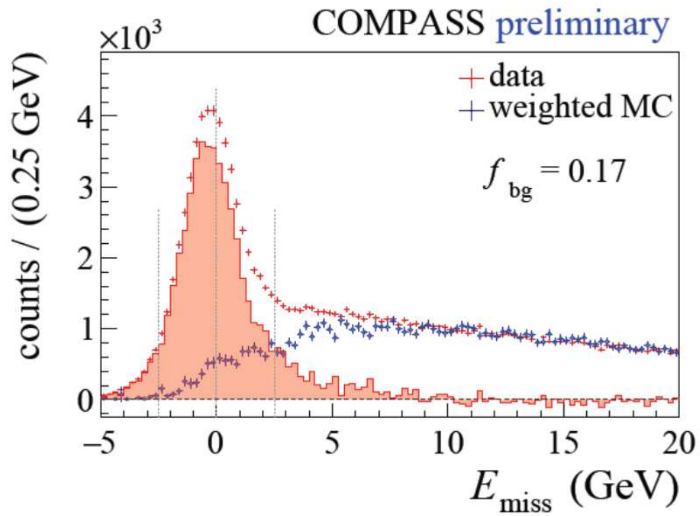
$1 < Q^2 < 10$ GeV/c^2
$W > 5$ GeV
$0.01 < p_T^2 < 0.5$ (GeV/c)^2
$0.1 < y < 0.9$
$\nu > 20$ GeV
$|E_{miss}| < 2.5$ GeV

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

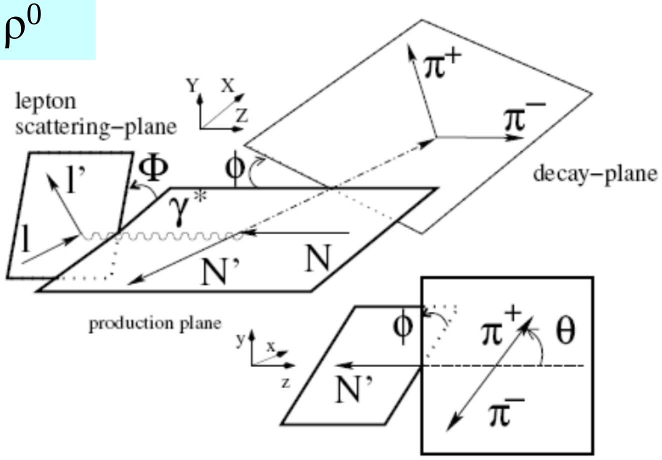
$$W^{U+L}(\Phi,\phi,\cos\Theta) = W^{U}(\Phi,\phi,\cos\Theta) + P_B W^{L}(\Phi,\phi,\cos\Theta) \propto \frac{d\sigma}{d\Phi\, d\phi\, d\cos\Theta}$$

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})

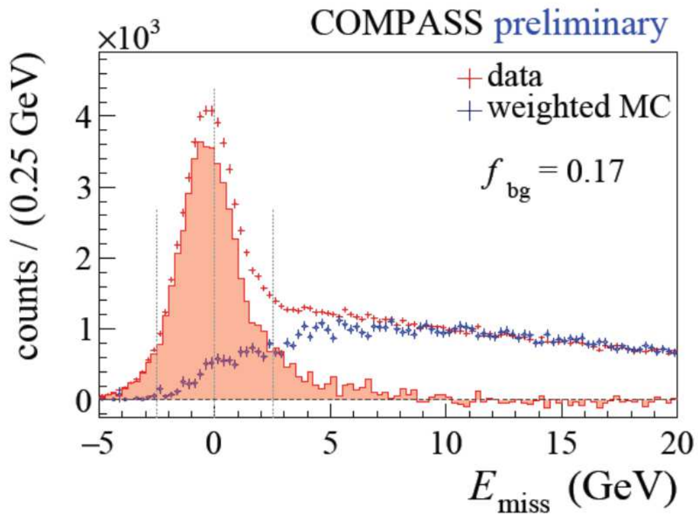
for ρ^0



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 from real data side band)



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

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

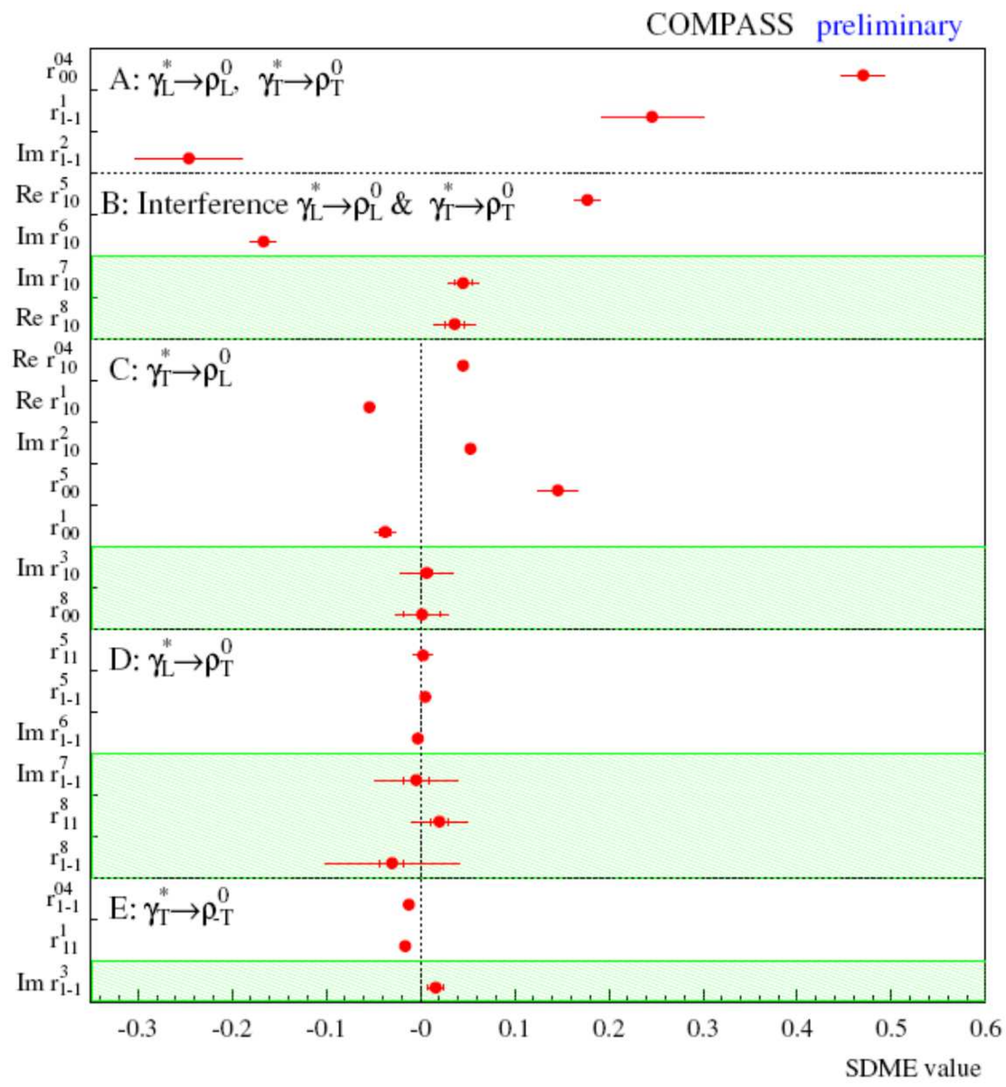
$5\ \mathrm{GeV} < W < 17\ \mathrm{GeV}$

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

$< Q^2 > = 2.4\ \mathrm{GeV}^2$

$< W > = 9.9\ \mathrm{GeV}$

$< p_T^2 > = 0.18\ \mathrm{GeV}^2$



- 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

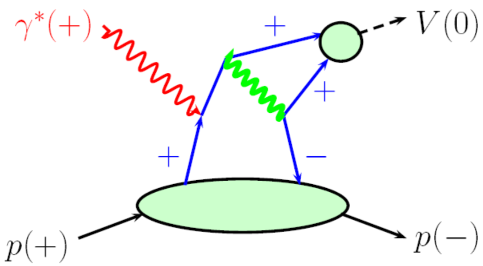
not obeyed for class C transitions $\gamma^*_T \rightarrow \rho_L$

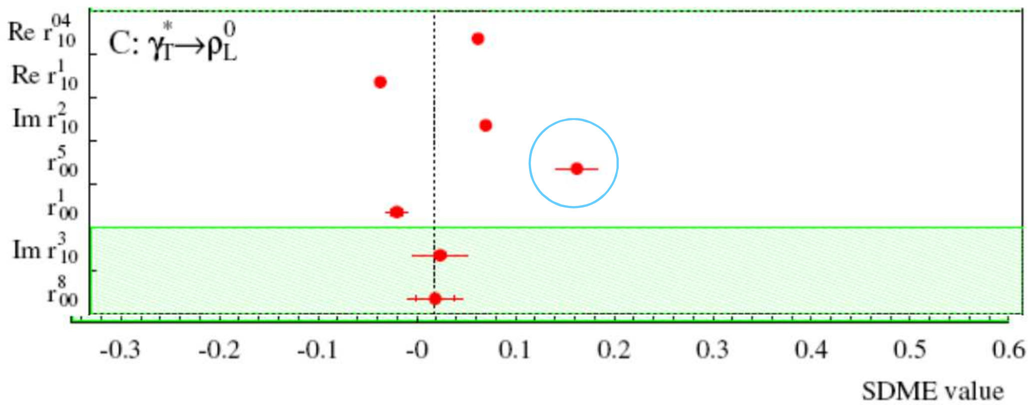
Transitions $\gamma^*_T \to \rho_L$

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 $F_{0-,++}$

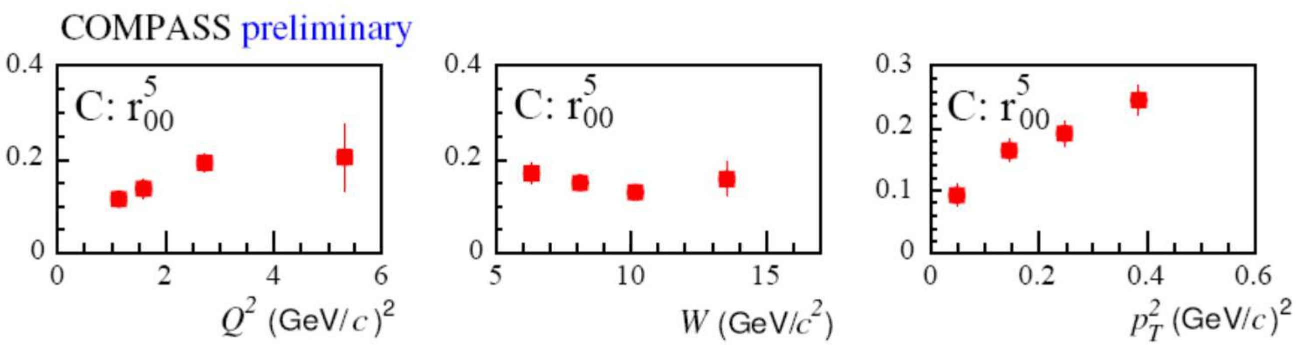




- $r^5_{00} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$ *Goloskokov and Kroll, ref. above*

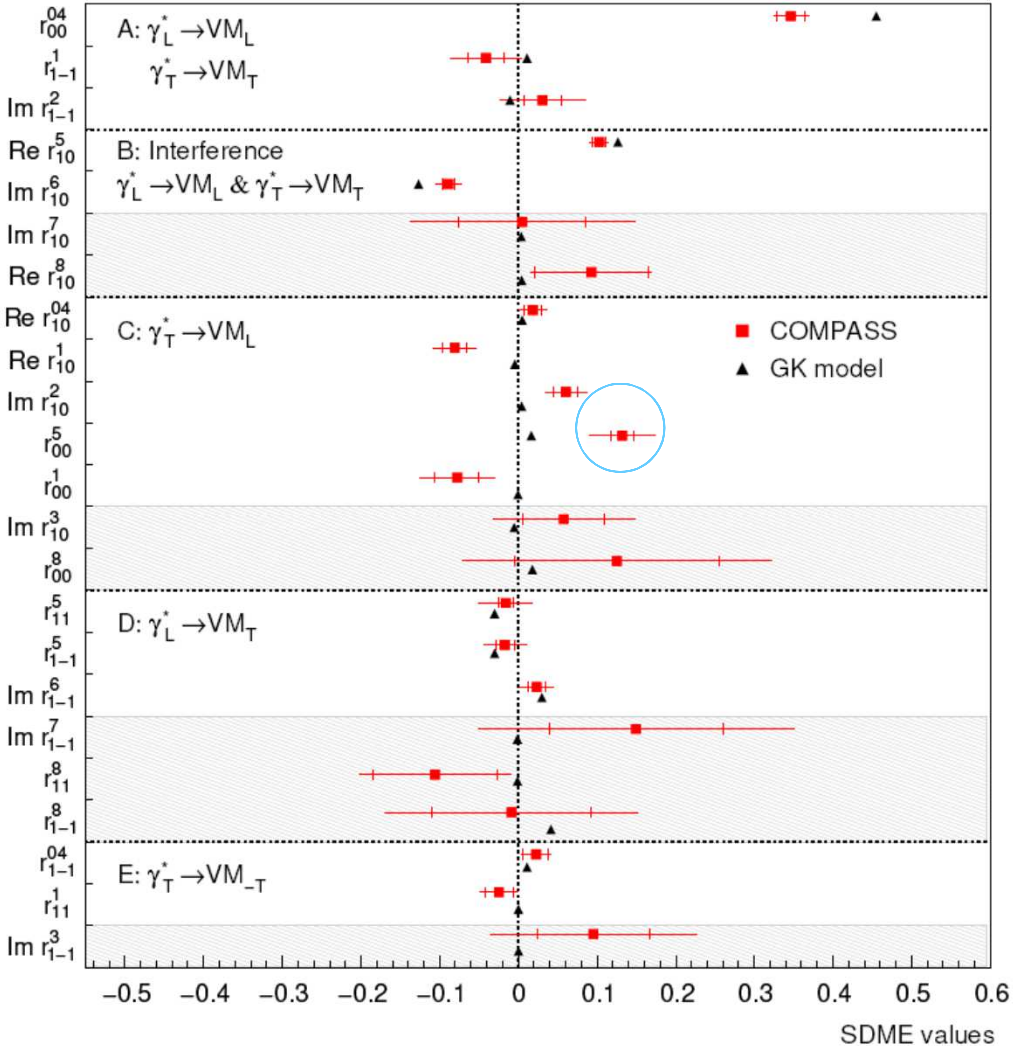
interplay of interference of transversity GPDs $H_T, \bar{E}_T = 2\tilde{H}_T + E_T$ with GPDs E and H

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

EPJC **81**,126 (2021)



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

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

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

$< Q^2> = 2.1\ \mathrm{GeV}^2$

$<W> = 7.6\ \mathrm{GeV}$

$<p_T^2> = 0.16\ \mathrm{GeV}^2$

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

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

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

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

Unnatural parity exchange contribution

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

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

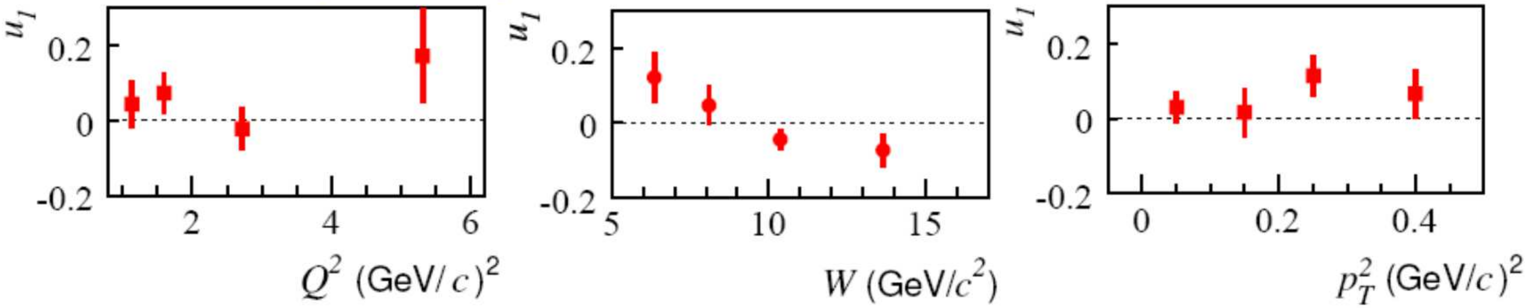
numerator depends only on UPE amplitudes

$u1 > 0$ signature of UPE contribution

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

COMPASS preliminary

ρ^0

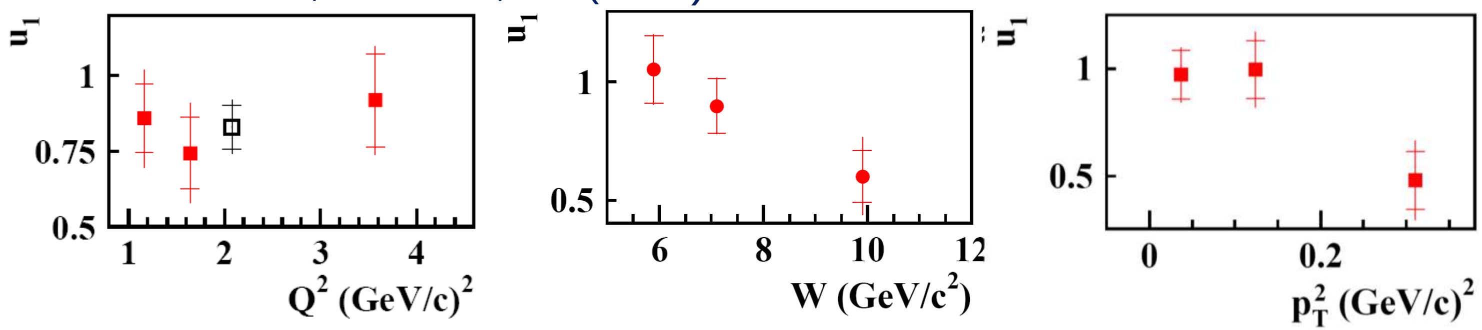


➢ very small UPE contribution

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

COMPASS, EPJC **81**,126 (2021)

ω



➢ large UPE contribution decreasing with increasing W
still non-negligible even at W = 10 GeV/c²

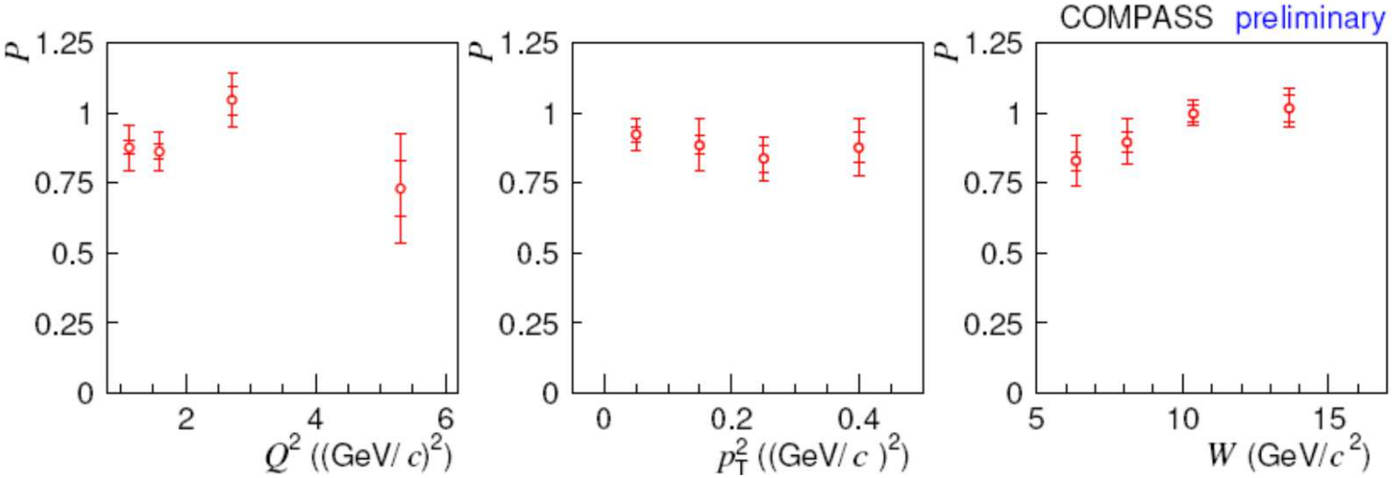
$\Delta_{UPE} \approx 0.5 \searrow 0.3$

NPE-to-UPE asymmetry of cross sections

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

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

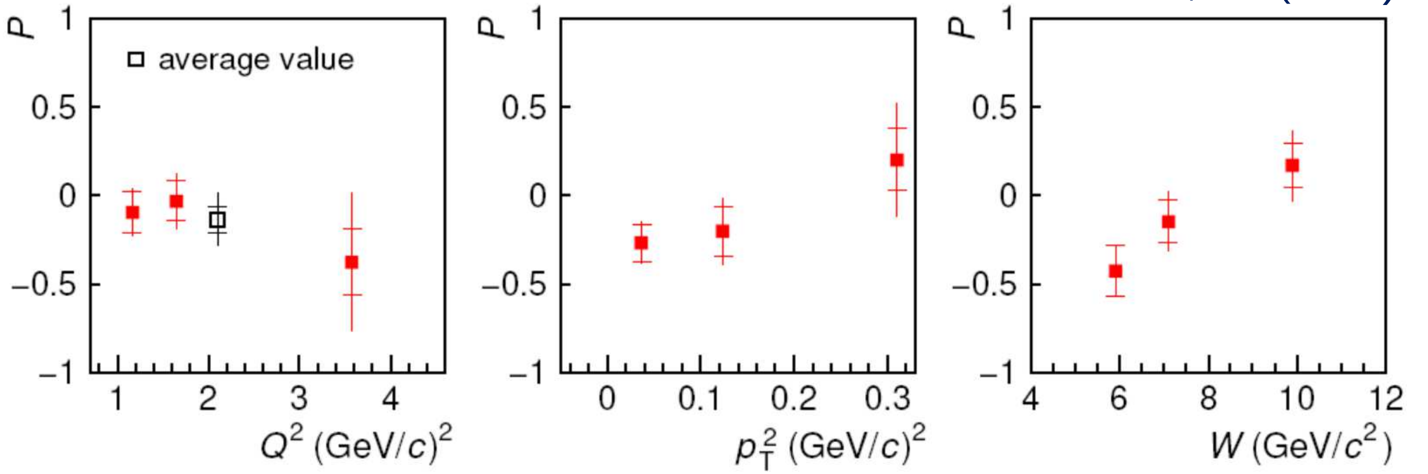
ρ^0



➢dominance of NPE

EPJC **81**,126 (2021)

ω

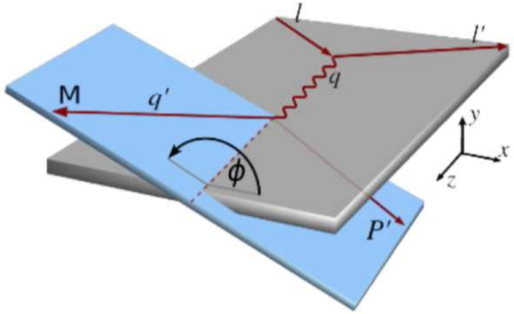


➢UPE dominates at small W and p^2_T

averaged over kin. range
NPE ≈ UPE

GPDs in exclusive π^0 production on unpolarised protons

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



averaged over muon beams polarisations

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

leading twist

at JLAB only few% of $\frac{d\sigma_T}{dt}$

other contributions arise from coupling
of chiral-odd (quark helicity-flip) GPDs to twist-3 pion amplitude

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

def. $\bar{E}_T = 2\tilde{H}_T + E_T$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

Impact of $\bar{E}_T$ should be visible in $\frac{\sigma_{TT}}{dt}$
and in a dip at small t' of $\frac{d\sigma_T}{dt}$

Selection of exclusive π^0 production events

μ, μ' and vertex in the target volume

1 GeV² < Q² < 5 GeV², 8.5 GeV < ν < 28 GeV

0.08 GeV² < | t | < 0.64 GeV²

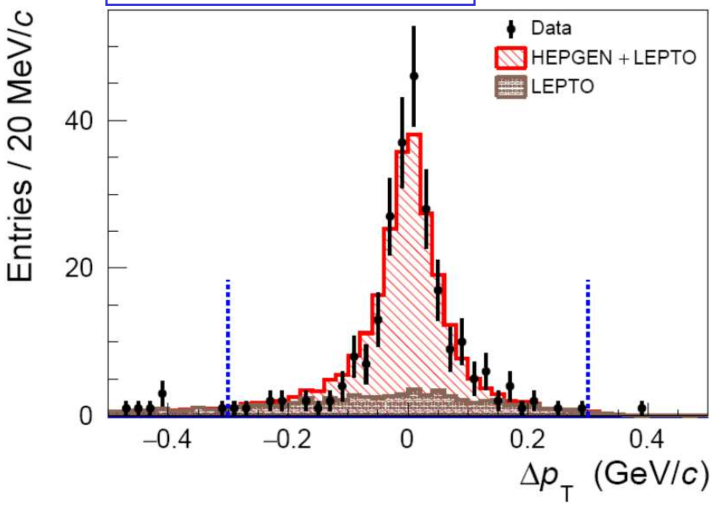
two photons with invariant mass consistent with π^0

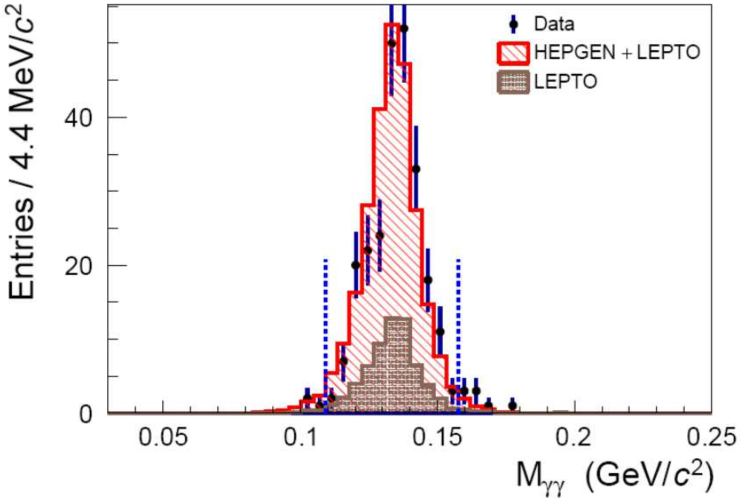
Recoil Proton Detector essential for extraction of exclusive π^0 events

Overconstrained kinematics => a number of „exclusivity cuts" allows to select the exclusive sample

example

$$\Delta p_T = p^p_{T,meas} - p^p_{T,pred}$$





kinematic fit applied to determine the most precise particle kinematics and enhance purity of the sample

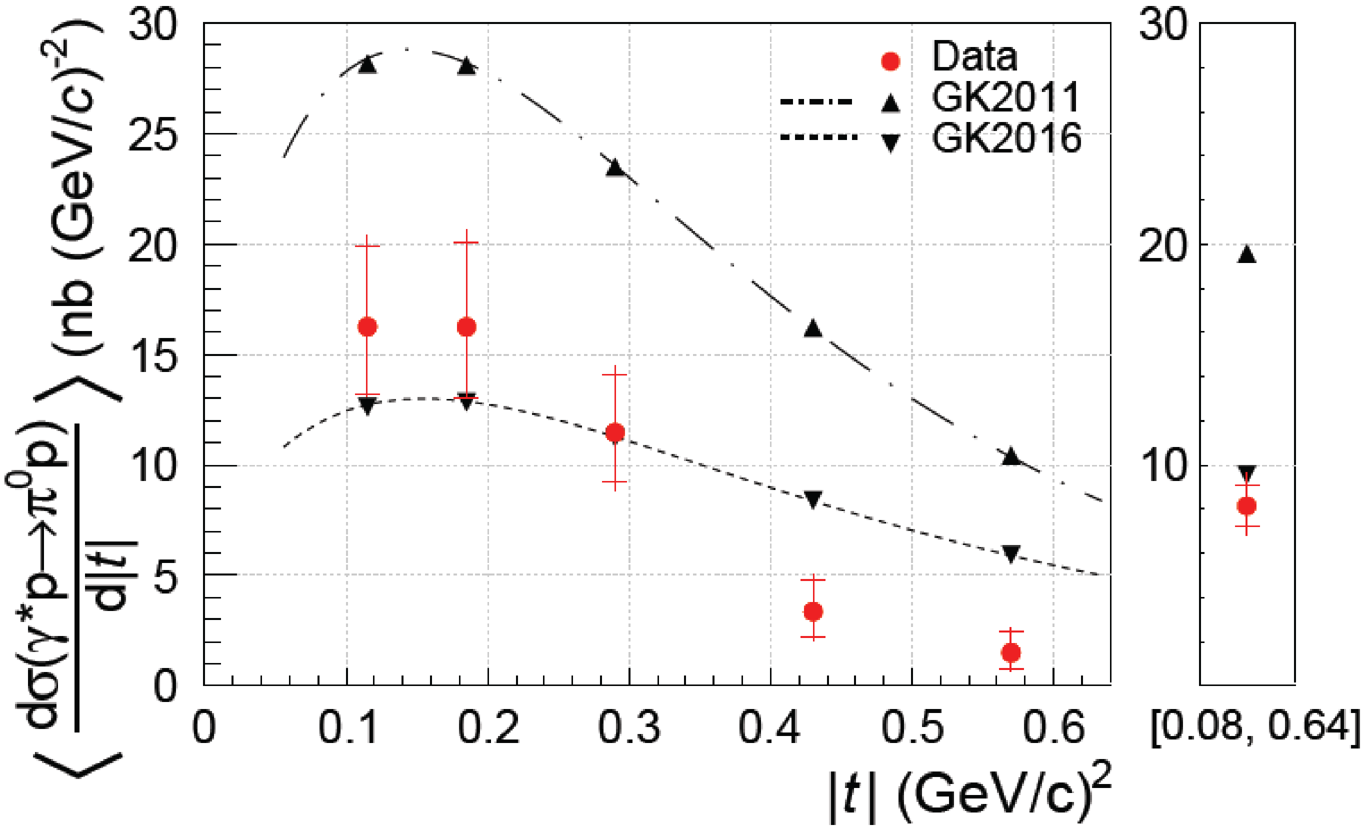
background fraction $(29^{+2}_{-6}|_{sys})\%$

Exclusive π^0 production cross sections as a function of $|t|$

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt}$$

An impact of $\overline{E}_T$ contribution in $\frac{d\sigma_T}{dt}$

PLB **81**,135454 (2020)



$\langle Q^2 \rangle = 2.0\ (\mathrm{GeV}/c)^2$, $\langle \nu \rangle = 12.8\ \mathrm{GeV}$,

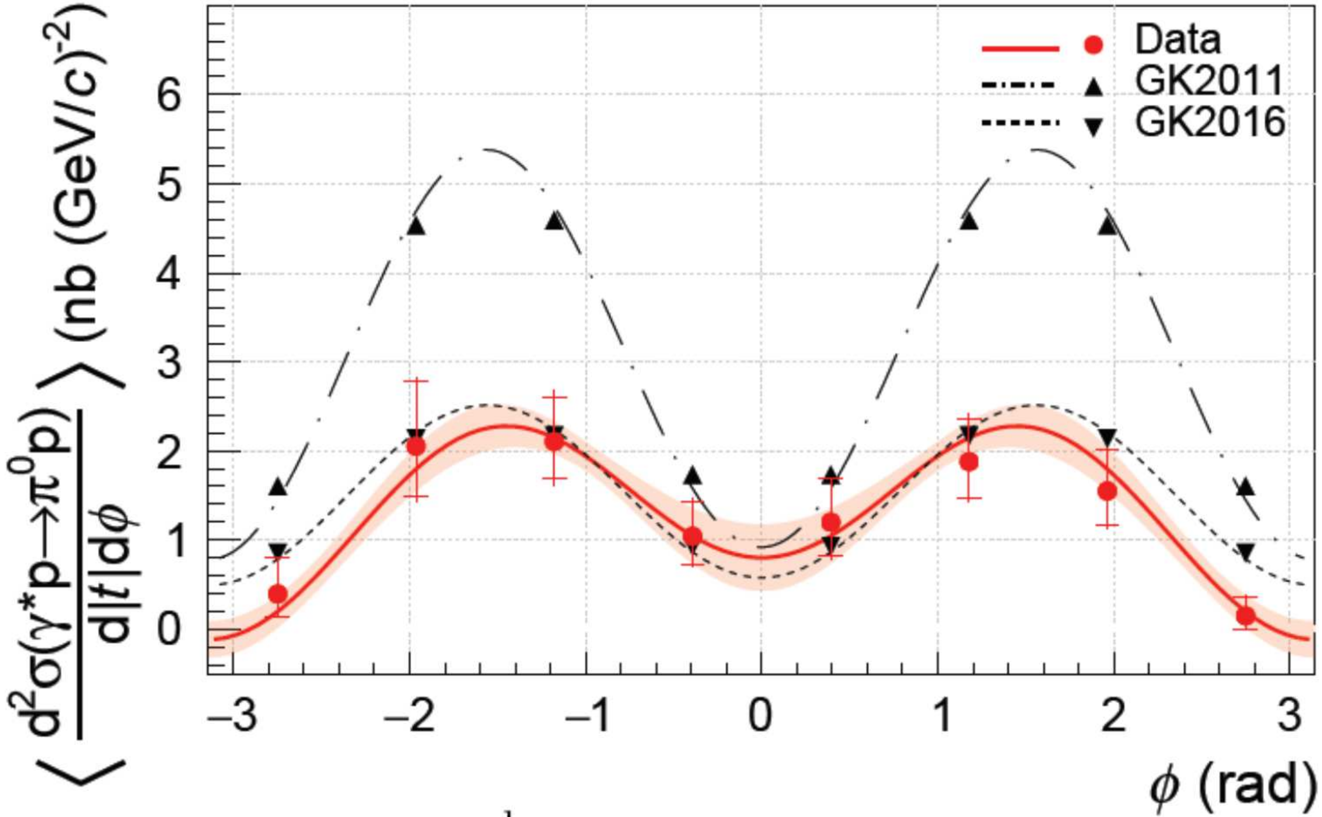
$\langle x_{Bj} \rangle = 0.093$ and $\langle -t \rangle = 0.256\ (\mathrm{GeV}/c)^2$

First measurement at low ξ

Exclusive π^0 production cross sections as a function of ϕ

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

PLB **81**,135454 (2020)



$$\left\langle \frac{d\sigma_T}{d|t|} + \epsilon\frac{d\sigma_L}{d|t|} \right\rangle = (8.1 \pm 0.9_{stat}{}^{+\,1.1}_{-\,1.0}|_{sys})\frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{d|t|} \right\rangle = (-6.0 \pm 1.3_{stat}{}^{+\,0.7}_{-\,0.7}|_{sys})\frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{LT}}{d|t|} \right\rangle = (1.4 \pm 0.5_{stat}{}^{+\,0.3}_{-\,0.2}|_{sys})\frac{nb}{(GeV/c)^2}$$

Large impact of $\overline{E}_T$ visible in $\frac{d\sigma_{TT}}{dt} \sim \overline{E}_T$

positive result for $\frac{d\sigma_{LT}}{dt}$

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 $\gamma^*_T \to V_L$
  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 $\boldsymbol{\pi^0}$ pole exchange
- differential cross section for π^0 production is a sensitive probe of GPD $\overline{E}_T$
- predictions for π^0 production from model of Goldstein, Gozales and Liuti PRD 91 (2015)
  expected to be available soon for COMPASS kinematics
- ongoing COMPASS analyses of exclusive production of π^0, φ, ω and J/ψ
  using 2016+2017 data statistics ~ 10 times larger than from 2012

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

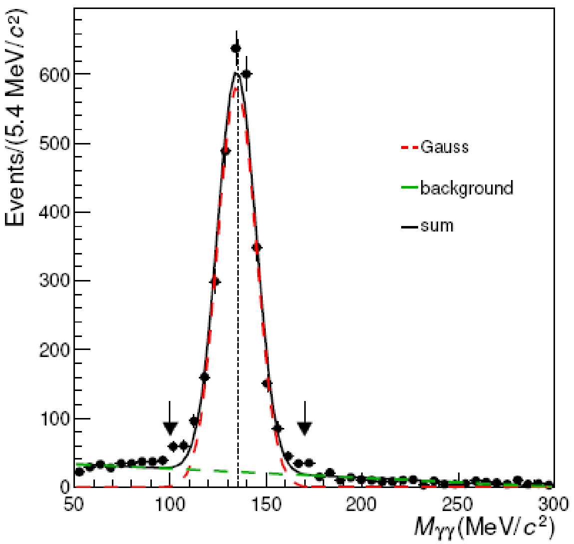
$0.1 < y < 0.9$

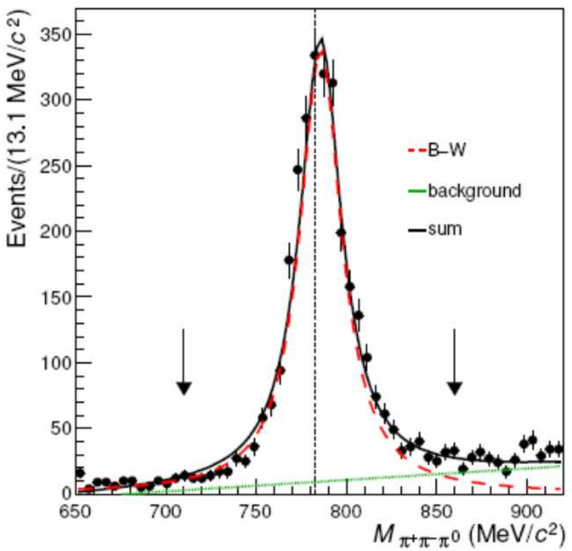
$|E_{miss}| < 3$ GeV

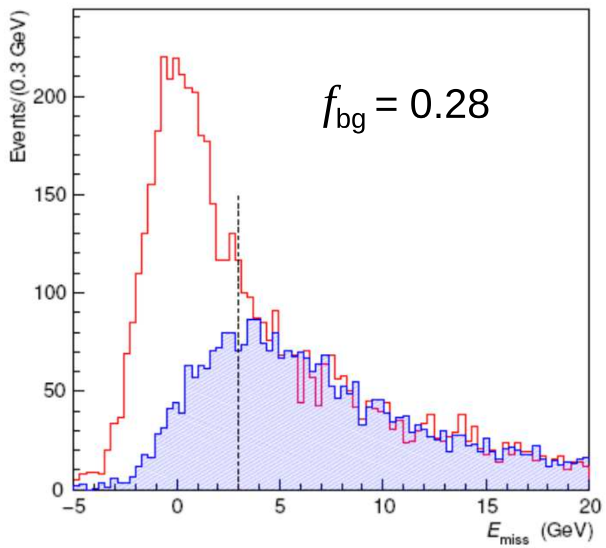
After all selections

≈ 3 000 evts

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





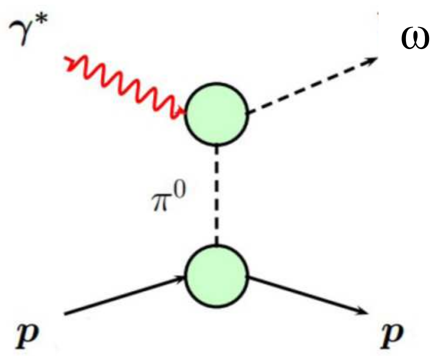


UPE and NPE contributions (contd.)

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