Hard exclusive meson production in muon scattering at COMPASS

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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 \( \gamma^* \) 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)

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 $|t| \ll Q^2$

4 GPDs for each quark flavour

$$H^q(x, \xi, t) \quad E^q(x, \xi, t)$$

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

for DVCS **gluons** contribute at higher orders in $\alpha_s$
GPDs and Hard Exclusive Meson Production

- Factorisation proven only for $\sigma_L$
- $\sigma_T$ suppressed by $1/Q^2$
- Wave function of meson (DA)
- Additional non-perturbative term

Chiral-even GPDs
Helicity of parton unchanged

\[
\begin{align*}
H^{q,g}(x,\xi,t) & \quad E^{q,g}(x,\xi,t) \\
\widetilde{H}^{q,g}(x,\xi,t) & \quad \widetilde{E}^{q,g}(x,\xi,t)
\end{align*}
\]

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

\[
\begin{align*}
H_T^q(x,\xi,t) & \quad E_T^q(x,\xi,t) \\
\widetilde{H}_T^q(x,\xi,t) & \quad \widetilde{E}_T^q(x,\xi,t)
\end{align*}
\]

Flavour separation for GPDs
Example:

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

\[
E_{\phi} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^{u(+)} - \frac{1}{3} E^{d(+)} + \frac{1}{4} E^g / x \right)
\]

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

- Contribution from gluons at the same order of $\alpha_s$ as from quarks

Diehl, Vinnikov
PLB, 2005

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Vector meson spin-density matrix

- Helicity amplitudes describe transitions $\lambda_V \gamma N \rightarrow \lambda V, \lambda' N$, depend on $W, Q^2$ and $p_T$ (or $t$).

- Decomposes into nine matrices corresponding to different photon polarisation states:
  - $\rho_{\lambda V' \lambda V}$
  - $\rho_{\lambda V' \lambda V}^{\alpha}$

- When contributions from transverse and longitudinal photons cannot be separated:

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

  - $r_{\lambda V' \lambda V}^{04} = \left( \rho_{\lambda V' \lambda V}^{0} + \epsilon R \rho_{\lambda V' \lambda V}^{4} \right) (1 + \epsilon R)^{-1}$
  - $r_{\lambda V' \lambda V}^{\alpha} = \left\{ \begin{array}{ll}
  \rho_{\lambda V' \lambda V}^{\alpha} (1 + \epsilon R)^{-1}, & \alpha = 1, 2, 3, \\
  \sqrt{R} \rho_{\lambda V' \lambda V}^{\alpha} (1 + \epsilon R)^{-1}, & \alpha = 5, 6, 7, 8.
  \end{array} \right.$

- $R = \sigma_L / \sigma_T$
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, \( \rho \), \( \omega \), \( a_2 \ldots \) reggeons)
    - UPE: \( J^p = (0^-, 1^+, \ldots) \) (\( \pi \), \( a_1 \), \( b_1 \ldots \) 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 $\mu^+$ or $\mu^-$ beams, $P \approx -80\% / +80\%$
  - negative or positive hadron beams

- two-stage forward spectrometer SM1 + SM2
  - $\approx 300$ tracking detectors planes – high redundancy + calorimetry, $\mu$ID, RICH

- flexible target area
  - for the presented results 2.5m long LH$_2$ target used

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Data and selected samples

- Data collected within four weeks in 2012 pilot run
- Data with polarised (\(|P| \approx 0.8\)) \(\mu^+\) and \(\mu^-\) beams taken separately
- Three parallel analyses:

  (i) \(\mu p \rightarrow \mu' p' \rho^0\)
      \[\rightarrow \pi^+ \pi^-\]
      \(\text{BR} \approx 99\%\).

  (ii) \(\mu p \rightarrow \mu' p' \omega\)
      \[\rightarrow \pi^+ \pi^- \pi^0\]
      \(\text{BR} \approx 89\%\).

  (iii) \(\mu p \rightarrow \mu' p' \pi^0\)
        \[\rightarrow \gamma \gamma\]
        \(\text{BR} \approx 99\%\).

- (i) preliminary results (first shown at DIS 2021)
- (ii) published - EPJC 81,126 (2021)
- (iii) published - PLB 81,135454 (2020)
Selection of exclusive $\rho^0$ sample for SDMEs analysis

\[
\mu p \rightarrow \mu' \rho^0 p' \quad \pi^+ \pi^-
\]

Topological selection: scattered muon
+ two hadrons with opposite charges

\[
E_{\text{miss}} = \frac{(M_X^2-M_p^2)}{(2M_p)}
\]

1. \( Q^2 < 10 \text{ GeV}/c^2 \)
2. \( W > 5 \text{ GeV} \)
3. \( 0.01 < p_T^2 < 0.5 \text{ (GeV}/c)^2 \)
4. \( 0.1 < y < 0.9 \)
5. \( \nu > 20 \text{ GeV} \)
6. \( |E_{\text{miss}}| < 2.5 \text{ GeV} \)

As Recoil Proton Detector restricts kinematic coverage towards low \( p_T^2 \), it’s not included in selections for $\rho^0$ and $\omega$ channels

After all selections and cuts
\( \approx 52,200 \text{ evts} \)

\( 10^{28} \text{ Jun 2022 Andrzej Sandacz} \)
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

[For \( \rho^0 \): 
\[ \sin \Theta \] 
angle \( \Theta \) between direction of \( \omega \) 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
    - angular distribution of background \( W^{U+L}_{bkg} \)
      (determined either from LEPTO MC or from real data side band)

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Results on SDMEs for exclusive $\rho^0$ production for total kin. range

1 GeV$^2$ < $Q^2$ < 10 GeV$^2$
5 GeV < $W$ < 17 GeV
0.01 GeV$^2$ < $p_T^2$ < 0.5 GeV$^2$

< $Q^2$> = 2.4 GeV$^2$
< $W$> = 9.9 GeV
< $p_T^2$> = 0.18 GeV$^2$

- SDMEs grouped in classes: 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 $\gamma^*_T \rightarrow \rho_L$
possible GPD interpretation

Goloskokov and Kroll, EPJC 74 (2014) 2725

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

COMPASS preliminary

example graph for amplitude \( F_{0-,++} \)

\[ \gamma^* \rightarrow \rho_L \]

\[ r_{00}^5 \sim \text{Re} \left[ \langle \bar{E}_T \rangle_{LT}^* \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle_{LT}^* \langle E \rangle_{LL} \right] \]

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 \( \rho^0 \) the first term in Eq. (●) dominates, thus \( r_{00}^5 \) essentially probes \( \bar{E}_T \)

COMPASS preliminary

\[ C: r_{00}^5 \]

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\[ Q^2 (\text{GeV}/c)^2 \]

\[ W (\text{GeV}/c)^2 \]

\[ p_T^2 (\text{GeV}/c)^2 \]

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Results on SDMEs for exclusive $\omega$ production for total kin. range

1 GeV$^2 < Q^2 < 10$ GeV$^2$
5 GeV $< W < 17$ GeV
0.01 GeV$^2 < p_T^2 < 0.5$ GeV$^2$

\[ \langle Q^2 \rangle = 2.1 \text{ GeV}^2 \]
\[ \langle W \rangle = 7.6 \text{ GeV} \]
\[ \langle p_T^2 \rangle = 0.16 \text{ GeV}^2 \]

GK model, EPJA 50 (2014) 146  (1st version)
parameters constrained mostly by HERMES results for $\rho^0$ and $\omega$

- COMPASS provides new constraints for parameterisation of the model
- $\rho^0$ and $\omega$ results for class C complementary

$E_T$ and $H$ have the same signs for $u$ and $d$ quarks
$H_T$ and $E$ have opposite signs for $u$ and $d$ quarks

for $\omega$ the first term in Eq. (●) still dominates, but sensitivity to $H_T$ is enhanced compared to $\rho^0$
Unnatural parity exchange contribution

\[ u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{01} - 2r_{1-1}^{01} \]
\[ u_1 = \sum \frac{4\epsilon |U_{10}|^2 + 2|U_{11} + U_{1-1}|^2}{N} \]

numerator depends only on UPE amplitudes
\[ u_1 > 0 \] signature of UPE contribution

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

\[ \rho^0 \]

- very small UPE contribution

\[ \Delta_{\text{UPE}} \approx 0.03 \] averaged

\[ \omega \]

- large UPE contribution decreasing with increasing \( W \)
still non-negligible even at \( W = 10 \text{ GeV}/c^2 \)

\[ \Delta_{\text{UPE}} \approx 0.5 \Rightarrow 0.3 \]
NPE-to-UPE asymmetry of cross sections

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

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

$P_0$

- dominance of NPE

$\omega$

- UPE dominates at small $W$ and $p^2_T$

averaged over kin. range
NPE $\approx$ UPE

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GPDs in exclusive $\pi^0$ production on unpolarised protons

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

averaged over muon beams polarisations

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

leading twist

at JLAB only few% of

other contributions arise from coupling

of chiral-odd (quark helicity-flip) GPDs to twist-3 pion amplitude

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

\[
\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha \mu_{\pi}}{\sqrt{2k'}Q^3} \xi \sqrt{1-\xi^2} \sqrt{-\frac{t'}{2m}} \text{Re} \left[ \langle H_T \rangle^* \langle E \rangle \right]
\]

\[
\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha \mu^2_{\pi}}{k'Q^8 \cdot 16m^2} \left| \langle E_T \rangle \right|^2
\]

Impact of $\overline{E_T}$ should be visible in $\frac{\sigma_{TT}}{dt}$

and in a dip at small $t'$ of $\frac{d\sigma_T}{dt}$

\[
\text{def. } \overline{E_T} = 2\tilde{H}_T + E_T
\]
Selection of exclusive $\pi^0$ production events

$\mu$, $\mu'$ and vertex in the target volume

$1 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$, $8.5 \text{ GeV} < \nu < 28 \text{ GeV}$

$0.08 \text{ GeV}^2 < |t| < 0.64 \text{ GeV}^2$

two photons with invariant mass consistent with $\pi^0$

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

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

Recoil Proton Detector essential for extraction of exclusive $\pi^0$ events

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

background fraction $(29^{+2}_{-6})\%_{\text{sys}}$
Exclusive $\pi^0$ 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 $E_T$ contribution in $\frac{d\sigma_T}{dt}$

First measurement at low $\xi$

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

$\langle x_{Bj} \rangle = 0.093$ and $\langle -t \rangle = 0.256 \text{ (GeV}/c)^2$
Exclusive $\pi^0$ production cross sections as a function of $\phi$

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

PLB 81,135454 (2020)

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

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

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

Large impact of $E_T$ visible in $\frac{d\sigma_{TT}}{dt} \sim E_T$

Positive result for $\frac{d\sigma_{LT}}{dt}$
Summary and outlook

- measured SDMEs in hard exclusive $\rho^0$ and $\omega$ muoproduction at energies 5 – 17 GeV
- access to helicity amplitudes $\Rightarrow$ constraints on GPD models
- SDMEs a sensitive tool to access subleading amplitudes (via interference)
- violation 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 $\omega$, only a few % for $\rho^0$
  in GK model described predominantly by the $\pi^0$ pole exchange
- differential cross section for $\pi^0$ production is a sensitive probe of GPD $\bar{E}_T$
- predictions for $\pi^0$ 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 $\pi^0$, $\varphi$, $\omega$ and $J/\psi$
  using 2016+2017 data statistics $\sim$ 10 times larger than from 2012
Thank you for your attention
Topological selection: scattered muon

\[ \mu p \rightarrow \mu' \omega p' \]

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

Recoil proton detector not included in selections

After all selections
≈ 3 000 evts

\begin{align*}
E_{\text{miss}} &= \frac{(M_X^2 - M_P^2)}{(2M_P)} \\
1 &< Q^2 < 10 \text{ GeV}/c^2 \\
0.01 &< p_T^2 < 0.5 \text{ (GeV/c)}^2 \\
W &> 5 \text{ GeV} \\
0.1 &< y < 0.9 \\
|E_{\text{miss}}| &< 3 \text{ GeV}
\end{align*}

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\[ f_{\text{bg}} = 0.28 \]
UPE and NPE contributions (contd.)

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

**UPE** amplitudes depend on helicity GPDs $\tilde{E}, \tilde{H}$  
the former supplemented by $\pi^0$ pole contribution treated as one-boson exchange  
parameters constrained by HERMES SDMEs for $\omega$
(except the sign of $\pi\omega$ transition form factor)

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

**NPE** amplitudes depend on GPDs $H$ and $E$

NPE contribution for $\rho^0$ production about 3 times larger than for $\omega$ 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 $\omega$ and $\rho^0$ production

Thus on the cross section level, leaving aside other small contributions
\[
d\sigma_T^N \approx d\sigma_T^U \quad \text{for } \omega \quad P \text{ asymmetry} \approx 0
\]
\[
d\sigma_T^N \approx 9 d\sigma_T^U \quad \text{for } \rho^0 \quad P \text{ asymmetry} \approx 1
\]

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