Exclusive $\pi^0$ muoproduction at COMPASS

Markéta Pešková (Charles University, Prague)

on behalf of the COMPASS collaboration

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Generalised Parton Distributions

- Proton spin sum rule: \( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \)
  

COMPASS experiment in \( \mu p \) DIS: \( \Delta \Sigma = 0.32 \pm 0.03 \)
  

COMPASS, RHIC results: \( \Delta G = 0.2^{+0.06}_{-0.07} \)
  

Missing component: \( L_{q,g} = ? \) → GPDs provides access

- Generalised Parton Distributions (GPD) give access to the 3D structure of a hadron

- GPDs encode the correlation between the longitudinal momentum of a parton and its position in the transverse plane

\[ q^f(x, b_\perp) \xrightarrow{\int dx} \text{Form factors} \]

\[ q^f(x, b_\perp) \xrightarrow{\int db_\perp} \text{PDFs} \]
Definition of variables:
- $q$ ... $\gamma^*$ four-momentum
- $x$ ... average longitudinal momentum fraction of initial and final parton (NOT accessible)
- $\xi$ ... difference of longitudinal-momentum fraction between initial and final parton $\approx x_B/(2 - x_B)$
- $t$ ... four-momentum transfer

4 chiral-even GPDs (parton helicity conserved)
4 chiral-odd (or transversity) GPDs (parton helicity flipped)

GPDs enter the exclusive processes through Compton Form Factors (CFF)

$$\mathcal{H}(\xi, t) = \int_{-1}^{1} dx \frac{H^q(x, \xi, t)}{x - \xi + i\epsilon} = \mathcal{P} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} + i\pi H$$
Generalised Parton Distributions

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**Quark Polarisation**

<table>
<thead>
<tr>
<th>Nucleon Polarisation</th>
<th>Unpolarised ((U))</th>
<th>Longitudinally polarised ((L))</th>
<th>Tranversely polarised ((T))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U)</td>
<td>(H)</td>
<td>(\tilde{E}_T)</td>
<td></td>
</tr>
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</tbody>
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GPDs enter the exclusive processes through Compton Form Factors (CFF)
Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)

DVCS on an unpolarised proton target gives access to GPD $H \rightarrow 3D$ imaging of a hadron

$$H^q(x, \xi = 0, t) = \rho^q(x, b_\perp) \quad \text{(Burkardt 2000, 2003)}$$
Generalised Parton Distributions

- Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)

- DVCS on neutron target, or DVCS or HEMP on transverse polarised proton target gives access to GPD $E \rightarrow$ helps constraining the total angular momentum of partons

$$J^f = \frac{1}{2} \lim_{t \rightarrow 0} \int_{-1}^{1} dx \, x [ H^f(x, \xi, t) + E^f(x, \xi, t) ]$$

Hard Exclusive Meson Production:
- Flavour separation for specific GPDs due to different partonic content of mesons
- Gluon and quark contributions at the same order in $\alpha_s$ for vector mesons
- DVCS sensitive to $H^f$, $E^f$, $\tilde{H}^f$, and $\tilde{E}^f$
- At the leading twist:
  - Vector meson production sensitive to $H^f$, and $E^f$
  - Pseudoscalar mesons production is described by GPDs $\tilde{H}^f$, and $\tilde{E}^f$
- Both vector meson and pseudoscalar mesons (as the $\pi_0$ presented in this talk) are also sensitive to $\tilde{E}_T^f = 2\tilde{H}_T^f + E_T^f$, and $H_T^f$
COMPASS measurement in 2012, and 2016/17 with $\mu^+$ and $\mu^-$ beams of $E_\mu = 160$ GeV

Collected events corrected for:

- Luminosity of $\mu^+$ and $\mu^-$ beams
- Background subtraction
- Acceptance of the spectrometer
- Reduction of $\mu p$ cross-section to $\gamma^* p$:

\[
\frac{d^4 \sigma_{\mu p}}{dQ^2 dt d\nu d\phi} = \Gamma \frac{d^2 \sigma_{\gamma^* p}}{dt d\phi}
\]

with the virtual photon flux
\[
\Gamma = \Gamma(E_\mu, Q^2, \nu)
\]

COMPASS 2012:
- 4 weeks → results published: PLB 805(2020) 135454

COMPASS 2016/17:
- $2 \times 6$ months
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HEMP cross section

HEMP cross-section, reduced to $\gamma^*p$, for the unpolarised target and polarised lepton beam (relevant for COMPASS 2012, 2016/2017 measurements):

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

$$\mp \left| P_l \right| \sqrt{\epsilon(1-\epsilon)} \sin \phi \frac{d\sigma'_{LT}}{dt}$$

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

Factorization proven for $\sigma_L$, not for $\sigma_T$ which is expected to be suppressed by a factor $1/Q^2$

BUT large contributions are observed at JLab
Spin independent HEMP cross-section after averaging the two spin-dependent cross-sections:

\[
\frac{d^2\sigma_{\gamma^*p}}{dt d\phi} = \frac{1}{2} \left( \frac{d^2\sigma_{\gamma^*p}}{dt d\phi} + \frac{d^2\sigma_{\gamma^*p}}{dt d\phi} \right) = \frac{1}{2}\pi \hbar \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1+\epsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} + |P_l| \sqrt{\epsilon(1-\epsilon)} \sin \phi \frac{d\sigma'_{LT}}{dt}
\]

After integration in \(\phi\):

\[
\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}
\]

\(\Rightarrow\) study \(t\) dependence
HEMP cross section

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

GPDs in exclusive \(\pi^0\) production

\[
\frac{d \sigma_L}{dt} \propto \left[ (1 - \xi^2) |\langle \tilde{H} \rangle|^2 - 2\xi^2 \Re(\langle \tilde{H} \rangle^* \langle \tilde{E} \rangle) \right]
- t' \frac{\xi^2}{4M^2} |\langle \tilde{E} \rangle|^2
\]

\[
\frac{d \sigma_T}{dt} \propto \left[ (1 - \xi^2) |\langle \tilde{H}_T \rangle|^2 - \frac{t'}{8M^2} |\langle \tilde{E}_T \rangle|^2 \right]
\]

\[
\frac{d \sigma_{TT}}{dt} \propto t' |\langle \tilde{E}_T \rangle|^2
\]

\[
\frac{d \sigma_{LT}}{dt} \propto \xi \sqrt{1 - \xi^2} \sqrt{-t'} \Re(\langle \tilde{H}_T \rangle^* \langle \tilde{E} \rangle)
\]

\(t' = t - t_{\text{min}}\), \(t_{\text{min}}\) is the minimum value of \(|t|\)

Impact of \(\tilde{E}_T\) should be visible in \(\frac{d \sigma_{TT}}{dt}\), and also a dip at small \(t\) of \(\frac{d \sigma_T}{dt}\). 
COMPASS: Versatile facility to study QCD with hadron ($\pi^{\pm}, K^{\pm}, p \ldots$) and lepton (polarized $\mu^{\pm}$) beams of $\sim 200$ GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP...
COMPASS GPD program

- Two stage magnetic spectrometer with large angular and momentum acceptance
- Versatile usage: hadron and muon beams
- Particle identification:
  - Ring Imaging Cherenkov (RICH) detector
  - Electromagnetic calorimeters (ECAL0, ECAL1, ECAL2)
  - Hadronic calorimeters (HCAL1, HCAL2)
  - 2 muon walls
- GPD program: 2012 pilot run, 2016/17 main measurement
COMPASS GPD program

- Target ToF system:
  - 24 inner and outer scintillators
  - 1 GHz readout
  - 310 ps ToF resolution

- ECAL0 calorimeter:
  - shaslyk modules
  - 2 × 2 m, 2200 channels

New equipment:
- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0

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Exclusive \( \pi^0 \) muoproduction at COMPASS
Exclusive $\pi^0$ production: Selection

- Incoming and outgoing $\mu$ connected to primary vertex
- Two photons in ECALs from $\pi^0$ decay, attached to the vertex
- Recoil proton candidate
- $1 < Q^2 < 5 \text{ (GeV/c)}^2$, $8.5 < \nu < 28 \text{ GeV}$, $0.08 < |t| < 0.64 \text{ (GeV/c)}^2$

Selections for exclusive $\pi^0$ events:
- Transverse momentum constraint:
  $\Delta p_T = p_{T,\text{spect}} - p_{T,\text{recoil}}$
- $\Delta \varphi = \varphi_{\text{spect}} - \varphi_{\text{recoil}}$
- Z coordinate of inner CAMERA ring:
  $\Delta z = z_{\text{spect}} - z_{\text{recoil}}$
- Energy-momentum conservation:
  $M^2_{\gamma\gamma} = (p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0})^2$
- Invariant mass $M_{\pi^0}$ cut
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![Diagram of exclusive $\pi^0$ production with selection criteria]
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Exclusive $\pi^0$ muoproduction at COMPASS

Graph showing distributions of $M_{\gamma\gamma}$.
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Exclusive $\pi^0$ production: SIDIS background estimation

- Main background of $\pi^0$ production $\Rightarrow$ non-exclusive DIS processes
- 2 Monte Carlo simulations with the same $\pi^0$ selection criteria:
  - LEPTO for the non-exclusive background
  - HEPGEN++ shape of distributions of exclusive $\pi^0$ production (signal contribution)
- Search for best description of data fitting by mixture of both MC
- Both MC samples normalised to the experimental $M_{\gamma\gamma}$ distribution
- The ratio of background events $r_{\text{LEPTO}}$ is determined by a fit on the exclusivity distributions

Resulting fraction of non-exclusive background in data $\Rightarrow (35 \pm 10)\%$

Background fit method is currently the main source of systematic uncertainty
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Exclusive $\pi^0$ muoproduction at COMPASS 10 / 15
Exclusive $\pi^0$ production: COMPASS acceptance

- 4D acceptance in bins of $\phi_{\pi^0}$, $\nu$, $|t|$, $Q^2$
- figure shows 3D projection, as a function of $\phi_{\pi^0}$
Exclusive $\pi^0$ production: COMPASS acceptance

- 4D acceptance in bins of $\phi_{\pi^0}$, $\nu$, $|t|$, $Q^2$
- figure shows 3D projection, as a function of $|t|$
Exclusive $\pi^0$ cross-section as a function of $|t|$

Systematic error is of the order of the statistical one.

2016 data

COMPASS preliminary
Exclusive $\pi^0$ cross-section as a function of $|t|$
Exclusive $\pi^0$ cross-section as a function of $\phi$

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

| $t$ | $0.08 - 0.64$ GeV |
Exclusive $\pi^0$ cross-section as a function of $\phi$

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

- 2016 data with fit
- 2012 data
- GK16 model

$|t| \in (0.08, 0.64)$ GeV
Summary

|$t|$-dependence and $\phi$-dependence of exclusive $\pi^0$ cross-section on unpolarised proton target:

- New, preliminary results of 2016 COMPASS measurement at low $\xi$ (or $\langle x_B \rangle = 0.096$), input for constraining phenomenological models (e.g. Goloskokov&Kroll, Goldstein&Luiti, etc.)

Statistics of 2016 shown here is about $2.3\times$ larger than of published results from 2012 pilot run (PLB 805 (2020) 135454)

- The whole collected 2016/2017 statistics $\sim 9 \times$ larger than 2012 → plan to process all available data

- Heading towards publication of 2016/2017 results soon
Thank you for your attention!
Kinematic fit

- Measurement of exclusive processes at COMPASS is overconstrained → can be used to improve precision of kinematic quantities using kinematically constrained fit
- Kinematic fit improves the resolution of the signal and lowers the background
- It works in a principle of minimisation of least square function
  \( \chi^2(\vec{k}) = (\vec{k}_{fit} - \vec{k})^T \hat{C}^{-1}(\vec{k}_{fit} - \vec{k}) \), where \( \vec{k} \) is a vector of measured quantities and \( \hat{C} \) is their covariance matrix
- Method used for the minimisation is Lagrange multipliers with constraints \( g_i \):
  \[
  L(\vec{k}, \vec{\alpha}) = \chi^2(\vec{k}) + 2 \sum_{i=1}^{N} \alpha_i g_i
  \]
- Constraints include momentum and energy conservation, common vertex for all tracks (except proton), constraints for final proton, and mass constraint
Past and future GPD measurements

Current DVCS data at colliders:
- ZEUS- total xsec
- ZEUS- dσ/dt
- H1- total xsec
- H1- dσ/dt
- H1- A_{CU}

Current DVCS data at fixed targets:
- HERMES- A_{LU}, A_{UL}, A_{LL}
- HERMES- A_{UT}
- HERMES- A_{LT}
- HERMES- A_{CU}
- Hall A- total xsec, Δ_{LU}
- CLAS- A_{UL}

Planned DVCS at fixed targets:
- COMPASS- dσ/dt, Δ_{CSU}, Δ_{CST}
- JLAB12- dσ/dt, A_{LU}, A_{UL}, A_{LL}

Future colliders: EIC...

After 2025

Gluons
Sea quarks
Valence quarks