Measurement of the exclusive $\pi^0$ muoproduction cross section at COMPASS

M. Gorzellik (ALU Freiburg) on behalf of the COMPASS Collaboration

22nd Spin, 09/2016
COMPASS
LHC
SPS
Versatile facility for:
- hadron structure
- hadron spectroscopy

Exclusive $\pi^0$ muoproduction @ COMPASS

Matthias Gorzellik

September 2016 / 22nd Spin
Generalized Parton Distributions @ COMPASS

- Contribution to the nucleon spin puzzle

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L} \]  
\[ \text{Jaffe&Manohar Nucl.Phys.B337 (1990)} \]

by constraining GPD \( H \) and \( E \)

\[ J^q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{+1} x [H^q + E^q] dx \]  
\[ \text{(Phys.Rev.Lett.78 (1997))} \]

- 3D nucleon tomography via GPD \( H \)

\[ H(x, \xi = 0, t) = \rho(x, b_\perp) \]  
probability interpretation (Burkardt)
Generalized Parton Distributions @ COMPASS

- Contribution to the nucleon spin puzzle

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L} \]

by constraining GPD $H$ and $E$

\[ J^q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{+1} x \left[ H^q + E^q \right] dx \]

recent work

→ Exclusive vector meson production on transversely polarised protons and deuterons

this talk

→ Exclusive $\pi^0$ production cross-section on unpolarised protons

- 3D nucleon tomography via GPD $H$

\[ H(x, \xi = 0, t) = \rho(x, b_{\perp}) \]

probability interpretation (Burkardt)

Andrea Ferrero

→ $t$-dependence of pure DVCS x-section on unpolarised protons
GPDs and Hard Exclusive Meson Production

\[ Q^2 = -q^2 \]
\[ \nu = \frac{P \cdot q}{M} \equiv E - E' \]

- \( x \): average longitudinal momentum of quark
- \( \xi \): longitudinal momentum transfer to quark
- \( t \): 4-momentum transfer to target nucleon (related to \( b_\perp \))

Factorisation proven for \( \sigma_L \)
Not proven for \( \sigma_T \) (but suppressed by \( 1/Q^2 \))

Additional non-perturbative term:
Wave function of meson (DA)
GPDs and Hard Exclusive Meson Production

Quark contribution

Gluon contribution *

Chiral-even GPDs
helicity of parton unchanged

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

Chiral-odd GPDs
helicity of parton changed

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

Flavour separation
constraints for parton specific GPDs due to different partonic content of mesons

* Gluon contribution at same order of \( \alpha_s \) as from quarks
HEMP cross section (unpolarised target)

\[
\frac{\alpha_{em}}{8\pi^3} \frac{y^2}{1-\varepsilon} \frac{1-x_{Bj}}{x_{Bj}} \frac{1}{Q^2} \left[ \begin{array}{ccc} x_{Bj} & y^2 & 1 - x_{Bj} \\ \frac{1}{Q^2} & 1 - \varepsilon & 1 - x_{Bj} \end{array} \right]^{-1} \frac{d\sigma}{dx_{Bj} \ dQ^2 \ dt \ d\phi} = \\
\frac{1}{2} \left( \sigma_{++}^{++} + \sigma_{--}^{--} \right) + \varepsilon \sigma_{00}^{++} - \varepsilon \cos(2\phi) \Re(\sigma_{+0}^{++}) - \sqrt{\varepsilon(1+\varepsilon)} \cos(\phi) \Re(\sigma_{+0}^{++} + \sigma_{+0}^{--}) \\
- P_l \sqrt{\varepsilon(1-\varepsilon)} \sin(\phi) \Im(\sigma_{+0}^{++} + \sigma_{+0}^{--})
\]

Helicity dependent photoabsorption
x-sections and interference terms:

\[
\sigma_{mn}^{ij}(x_{Bj}, Q^2, t) \propto \Sigma(M_m^i)(M_n^j)
\]

amplitude for subprocess \( \gamma^* p \rightarrow Mp \):

\[
M_m^i
\]

with photon helicity \( m \)
and target proton helicity \( i \)

\[
\varepsilon = \frac{1-y-y^2}{1-y+\frac{y^2}{2}+\frac{y^2}{4}}
\]

\[
\gamma = \frac{2x_{Bj}M_p}{Q}
\]
HEMP cross section (unpolarised target)

\[ S_{CS,U} = \frac{(d\sigma^{\leftarrow} + d\sigma^{\rightarrow})}{2} = \]

\[
\frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \varepsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{\varepsilon(1+\varepsilon)\cos(\phi)} \frac{d\sigma_{LT}}{dt} \\
-P \sqrt{\varepsilon(1-\varepsilon)} \sin(\phi) \text{Im}(\sigma^{++}_0 + \sigma^{--}_0) \\
\]

after integration in \( \phi \):

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

study \( \phi \) dependence!

study \( t \) dependence!

virtual photon polarisation:

- Transverse: \(-, +\)
- Longitudinal: 0

Exclusive \( \pi^0 \) unpolarised x-section extraction on protons

Matthias Gorzellik

Exclusive \( \pi^0 \) muoproduction @ COMPASS

September 2016 / 22nd Spin
COMPASS spectrometer

- $\mu^+$ & $\mu^-$ beams with opposite polarisations
- $\pm 80\%$ polarisation
- beam momentum: 160 GeV/c

Particle Identification:
- Hadron absorbers
- Ring Imaging Cerenkov Counter
- 2 Hadronic calorimeters
- 3 Electromagnetic calorimeters
2012 Pilot Run - 20 days

Full-scale CAMERA recoil detector and liquid H₂ target

Partially equipped ECAL0

ECAL2

ECAL1

18-10-2012

ECAL2

ECAL1

µ±

18-10-2012

µ±
Exclusive $\pi^0$ event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

$1 \text{(GeV/c)}^2 < Q^2 < 5 \text{(GeV/c)}^2$, \hspace{0.5cm} $8.5 \text{GeV} < \nu < 28 \text{GeV}$,

$0.08 \text{(GeV/c)}^2 < |t| < 0.64 \text{(GeV/c)}^2$
Exclusive $\pi^0$ event selection

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Exclusivity conditions:

- Mass of $\gamma\gamma$ system: \[ M_{\gamma\gamma} = (p_{\gamma,i} + p_{\gamma,ii})^2 \]
- Vertex pointing ($\Delta z$)
- $\Delta \varphi = \varphi_{\text{meas}}^{\text{proton}} - \varphi_{\text{reco}}^{\text{proton}}$
- Transv. momentum balance: \[ \Delta p_{\perp} = p_{\perp,\text{meas}}^{\text{proton}} - p_{\perp,\text{reco}}^{\text{proton}} \]
- Four-momentum balance: \[ M_X^2 = (p_{\mu,\text{in}} + p_{p,\text{in}} - p_{\mu,\text{out}} - p_{p,\text{out}} - p_{\pi^0})^2 \]
**Exclusive $\pi^0$ event selection**

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**Graph:**

- COMPASS 2012
- Data
- Excl $\pi^0$ MC + Lepto
- Lepto Background

**Legend:**
- Preliminary
Exclusive $\pi^0$ event selection

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Reconstructed interaction vertex in target volume

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  $\Delta p_\perp = p_{\perp,\text{meas}}^{\text{proton}} - p_{\perp,\text{reco}}^{\text{proton}}$

- Four-momentum balance:
  $M_X^2 = (p_{\mu in} + p_{\rho in} - p_{\mu out} - p_{\rho out} - p_{\pi^0})^2$

\[\Delta p_\perp \text{ [GeV/c]}\]
Exclusive $\pi^0$ event selection

Reconstructed interaction vertex in target volume

Two photons, one photon above threshold

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- Transv. momentum balance:
  $\Delta p_{\perp} = p_{\perp,\text{meas}} - p_{\perp,\text{reco}}$

- Four-momentum balance:
  $M_X^2 = (p_{\mu,\text{in}} + p_{\mu,\text{in}} - p_{\mu,\text{out}} - p_{\text{out}} - p_{\pi^0})^2$
Kinematically constrained fit for exclusive $\pi^0$

- constrained $\chi^2$ minimisation
- full 4-momentum conservation of the reaction $\mu p \rightarrow \mu p \pi^0$
- $\pi^0$ mass constrained to PDG mass
- vertex constraints for $\mu, \mu'$ and $p'$ included in the fit

$\Rightarrow$ most accurate determination of $t$
$\Rightarrow$ good separation between signal and background
**SIDIS background estimation**

- use **LEPTO** MC to describe non exclusive background
- use exclusive $\pi^0$ MC to describe signal contribution
- find best description of data
  - in **signal region**
  - in **background region**

![Graphs showing signal and background regions](image-url)
COMPASS acceptance for exclusive $\pi^0$

$\nu$ [GeV]

$Q^2$ [(GeV/c)^2]

$\phi_{\pi^0}$ [rad]

COMPASS 2012 preliminary

- $\mu^-$ beam
- $\mu^+$ beam

$[\pi, -\frac{3}{4}\pi, ..., \frac{3}{4}\pi, \pi]$
COMPASS acceptance for exclusive $\pi^0$

4D-Acceptance binning (3D projection shown):
- $Q^2$ and $\nu$: \[
\frac{d^3\sigma_{\mu p}}{dQ^2 d\nu dt} = \Gamma \frac{d\sigma_{\gamma^* p}}{dt}
\]
with the virtual photon flux $\Gamma = \Gamma(Q^2, \nu)$
- $|t|$ and $\phi_{\pi^0}$

[π, $-\frac{3\pi}{4}$, ..., $\frac{3\pi}{4}$, π] $\phi_{\pi^0}$ [rad]

- $\mu^-$ beam
- $\mu^+$ beam
Exclusive $\pi^0$ cross section as a function of $|t|$
Exclusive $\pi^0$ cross section as a function of $|t|$.

- Dip indicates contribution of $E_T$.
- A factor of $\sim 2$ discrepancy to Goloskokov & Kroll model.

COMPASS 2012
- Data
- Goloskokov & Kroll
  EPJ A47 (2011) 112
  preliminary

First and only measurement at low $\xi$. 

8.5 GeV < $\nu$ < 28 GeV
1 (GeV/c)$^2$ < $Q^2$ < 5 (GeV/c)$^2$
Exclusive $\pi^0$ cross section as a function of $\phi_{\pi^0}$

$$\frac{d^2\sigma_{\gamma^* p}^{\pi^0}}{dt d\phi_{\pi^0}} = \frac{1}{2\pi} \left[ \left( \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} \right) + \varepsilon^\cos(2\phi_{\pi^0}) \frac{d\sigma_{TT}}{dt} + \sqrt{\varepsilon(1+\varepsilon)} \cos(\phi_{\pi^0}) \frac{d\sigma_{LT}}{dt} \right]$$

$$\frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} = (8.1 \pm 0.9 \pm 1.1) \frac{\text{nb}}{(\text{GeV/c})^2}$$

$$\frac{d\sigma_{TT}}{dt} = (-6.0 \pm 1.3 \pm 0.7) \frac{\text{nb}}{(\text{GeV/c})^2}$$

$$\frac{d\sigma_{LT}}{dt} = (1.4 \pm 0.5 \pm 0.3) \frac{\text{nb}}{(\text{GeV/c})^2}$$

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

**COMPASS 2012**

- $8.5 \text{ GeV} < \nu < 28 \text{ GeV}$
- $1 \text{ (GeV/c)^2} < Q^2 < 5 \text{ (GeV/c)^2}$
- $0.08 \text{ (GeV/c)^2} < |t| < 0.64 \text{ (GeV/c)^2}$

*preliminary*
Exclusive $\pi^0$ cross section as a function of $\phi_{\pi^0}$

\[
\frac{d^2\sigma_{\gamma^*p}}{dt d\phi_{\pi^0}} = \frac{1}{2\pi} \left[ \left( \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right) + \epsilon \cos(2\phi_{\pi^0}) \frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1+\epsilon)} \cos(\phi_{\pi^0}) \frac{d\sigma_{LT}}{dt} \right]
\]

\[
\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} = (8.1 \pm 0.9 ^{+1.1}_{-1.0}) \frac{\text{nb}}{\text{(GeV/c)}^2}
\]

\[
\frac{d\sigma_{TT}}{dt} = (-6.0 \pm 1.3 ^{+0.7}_{-0.7}) \frac{\text{nb}}{\text{(GeV/c)}^2}
\]

\[
\frac{d\sigma_{LT}}{dt} = (1.4 \pm 0.5 ^{+0.3}_{-0.2}) \frac{\text{nb}}{\text{(GeV/c)}^2}
\]

**COMPASS 2012**

- $8.5 \text{ GeV} < \nu < 28 \text{ GeV}$
- $1 \text{ (GeV/c)}^2 < Q^2 < 5 \text{ (GeV/c)}^2$
- $0.08 \text{ (GeV/c)}^2 < |t| < 0.64 \text{ (GeV/c)}^2$

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

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

**first and only measurement at low $\xi$**
Summary:
- exclusive $\pi^0$ production cross section for a proton target
- $t$- and $\phi_{\pi^0}$-dependence yield valuable input to model parametrisation
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Near future:
- Dedicated beam time for DVCS and HEMP in 2016 and 2017
- $\approx$ a factor of 15 increase in statistics compared to pilot run 2012
- Beam charge sum and difference extraction
Summary:
- exclusive $\pi^0$ production cross section for a proton target
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Near future:
- Dedicated beam time for DVCS and HEMP in 2016 and 2017
- $\approx$ a factor of 15 increase in statistics compared to pilot run 2012
- Beam charge sum and difference extraction

Thank you for your attention!
Kinematic distributions

Mean values:

\[< Q^2 > = 2.0 \text{ (GeV/c)}^2 \]
\[< \nu > = 12.8 \text{ GeV} \]
\[< x_{Bj} > = 0.093 \]
\[< \varepsilon > = 0.996 \]
\[< |t| > = 0.256 \text{ (GeV/c)}^2 \]
Invisible/visible $\omega$ background estimation

$\mu\rho \rightarrow \mu\rho\omega \rightarrow \mu\rho\pi^0\gamma$

$M_{\pi^0\gamma}$ [GeV]

Entries

COMPASS 2012

Data

Exclusive $\omega$ MC (scaled to data)

preliminary
Look for other GPDs: the chiral-odd $H_T$ and $E_T$

$$e\,p \rightarrow e\,\pi^0\,p$$

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

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

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

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu^2_{\pi}}{\sqrt{2k'Q^7}} \xi^2 \frac{\sqrt{1-\xi^2}}{2m} \text{Re} [\langle H_T \rangle^* \langle E \rangle]$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha\mu^2_{\pi}}{k'Q^8} \frac{t'}{16m^2} |\langle E_T \rangle|^2$$

Large impact of $E_T$

clearly visible in $\sigma_{TT}$

and in the dip at small $t$ of $\sigma_T$

solid lines : GK EPJA47 (2011)

CLAS Coll, Bedlinskiy et al., PRC90(2014)2-025205
Past, Present and Future GPD Experiments

![Graph showing current and planned DVCS data at colliders and fixed targets, with regions marked for COMPASS and JLab experiments. The graph is labeled with $Q^2$ and $x$ axes, and different experiments and datasets are indicated with various symbols and colors.]

- **Gluons**, **Sea quarks**, and **Valence quarks** are indicated on the graph.

- **Planned DVCS at fixed target**: COMPASS- $\sigma/dt$, $A_{CSU}$, $A_{CT}$
- **EIC $\gamma$ at 45 GeV, 0.01 $\leq y \leq 0.95$**
- **EIC $\gamma$ at 140 GeV, 0.01 $\leq y \leq 0.95$**
- **EIC $\gamma$ at 50 GeV**

**Note**: The graph provides a visual summary of past, present, and future experiments in GPD studies, highlighting the areas of research interest for COMPASS and JLab.
CAMERA Readout

GANDALF
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

TIGER
Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express
The recoil proton detector **CAMERA**

- **two barreells, each 24 scintillators / 48 PMTs**
- **inner: 275 cm × 4 mm, radius 25 cm**
- **outer: 360 cm × 5 cm, radius 110 cm**
- **readout with 12 bit / 1 GSps**
- **ToF resolution ≈ 310 ps**
Time Resolutions Measured with Cosmics

**Ring A - performances**

After deconvolute from ref. resolution and apply Software corrections

Goal was 300ps

Att length better than 200 cm was expected

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<th>Raw Time resolution (ps)</th>
<th>Measurement with cosmics</th>
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**Time Resolutions**

- **A**: Time Resolution: 350 ps
- **B**: Time Resolution: 160 ps
Summary of Present CAMERA Performances

momtum resolution

\[ \sigma \left( \frac{\Delta p}{p_{\text{Spectr.}}} \right) \]

\[ p_{\text{Spectr.}} \text{ [GeV/c]} \]

polar angle resolution

\[ \sigma \approx 2.6^\circ \]

\[ (\theta_{\text{Spectr.}} - \theta_{\text{CAMERA}}) / \text{rad} \]

z_A position resolution

\[ \sigma \approx 4.0 \text{ cm} \]

\[ (z_{A,\text{Spectr.}} - z_{A,\text{CAMERA}}) / \text{cm} \]

z_B position resolution

\[ \sigma \approx 3.4 \text{ cm} \]

\[ (z_{B,\text{Spectr.}} - z_{B,\text{CAMERA}}) / \text{cm} \]