Hard exclusive $\pi^0$ production at COMPASS

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Outline

- Introduction
- Measurement at COMPASS
- Data selection and background estimation
- Cross section determination
- Results
Introduction
Generalized Parton Distributions (GPDs)

- Tool for the investigation of the nucleon structure
- Provide a 3D picture of how quarks and gluons build up the nucleon
- Access to GPDs via
  - Deeply Virtual Compton Scattering (DVCS)
  - **Hard Exclusive Meson production (HEMP)**
    - Hard exclusive $\pi^0$ muoproduction
    - Cross section measurement of $\mu p \rightarrow \mu' \pi^0 p'$
Hard exclusive $\pi^0$ muoproduction

- Sensitive to the GPDs
  - $\tilde{H}(x, \xi, t)$ and $\tilde{E}(x, \xi, t)$ - chiral-even (conserving the parton helicity)
  - $H_T(x, \xi, t)$ and $E_T(x, \xi, t)$ - chiral-odd (parton helicity flip)
Reduced cross section for hard exclusive $\pi^0$ production

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

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

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

$$\frac{d\sigma_{TT}}{dt} \propto t'|\langle \bar{E}_T \rangle|^2$$

$$\frac{d\sigma_{LT}}{dt} \propto \xi \sqrt{1 - \xi^2} \sqrt{-t'} \text{Re} \left[ \langle H_T \rangle \ast \langle \bar{E} \rangle \right]$$
Measurement at COMPASS
Collected data

- 2012 - pilot run (results published in PLB 805 135454)
- 2016 - current analysis (2.3 times larger statistics than 2012)
- 2017 - to be included soon (2016+2017 ~ 9 times larger statistics than 2012)
Exclusive $\pi^0$ measurement at COMPASS

160 GeV

$\vec{\mu}^+$ or $\vec{\mu}^-$

Target LH2

Recoil Proton Detector

CAMERA

Dipole Magnet 1

Dipole Magnet 2

ECAL0

ECAL1

$\gamma$
Data selection and background estimation
Event selection for $\mu p \rightarrow \mu' \pi^0 p'$

- Vertex candidate
  - $\mu$ and $\mu'$ associated to the vertex
  - requirements on $\mu$ and $\mu'$
Event selection for $\mu p \rightarrow \mu'\pi^0 p'$

- **Vertex candidate**
  - $\mu$ and $\mu'$ associated to the vertex
  - Requirements on $\mu$ and $\mu'$

- **$\pi^0$ candidate from 2 photons**
  - Pair of neutral clusters in ECALs
  - Energy thresholds
  - Timing requirement
Event selection for $\mu p \rightarrow \mu'\pi^0 p'$

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- **Proton candidate**
  - CAMERA
  - exclusivity conditions
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Exclusive variables measured either by the spectrometer or by CAMERA

- $P'_{\text{spec}} = P + k - k' - p_{\pi^0}$
- $\Delta \varphi = \varphi_{\text{CAM}} - \varphi_{\text{spec}}$
- $\Delta p_T = p_{T_{\text{CAM}}} - p_{T_{\text{spec}}}$
- $M^2_x = (P + k - k' - p_{\pi^0} - P'_{\text{CAM}})^2$

- $|\Delta \varphi| < 0.4 \text{ rad}$
- $|\Delta p_T| < 0.3 \text{ GeV/c}$
- $|M^2_x| < 0.3 (\text{GeV/c}^2)^2$
- $|\Delta z_A| < 16 \text{ cm}$
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- **Kinematics**
  - Kinematic fit
  - $6.4 < \nu < 40$ GeV
  - $1 < Q^2 < 8$ (GeV/c)$^2$
  - $0.08 < |t| < 0.64$ (GeV/c)$^2$

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- **Events with only one combination:**
  - *vertex candidate* + *$\pi^0$ candidate* + *proton candidate* pass the selection

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Event selection for $\mu p \rightarrow \mu' \pi^0 p'$

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  - $\mu$ and $\mu'$ associated
  - Requirements on $\pi^0$ candidate from 2 photons
  - Energy thresholds
  - Timing requirement

- **$\pi^0$ candidate**
  - Pair of neutral clusters in ECALs

- **Proton candidate**
  - CAMERA
  - Exclusivity conditions:
    - $|\Delta \varphi| < 0.4 \text{ rad}$
    - $|\Delta p_T| < 0.3 \text{ GeV/c}$
    - $M_{2\pi} < 0.3 (\text{GeV/c})^2$
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  - Kinematic fit
  - $6.4 < \nu < 40 \text{ GeV}$
  - $1 < Q^2 < 8 (\text{GeV/c})^2$
  - $0.08 < |t| < 0.64 (\text{GeV/c})^2$

Events with only one combination:
- Vertex candidate $+$ $\pi^0$ candidate $+$ Proton candidate pass the selection

preliminary
Background estimation

- $\pi^0$ from deep inelastic scattering
- LEPTO MC - non exclusive
- HEPGEN++ MC - excl. $\pi^0$
- Scaling of HEPGEN and "LEPTO background"
- Background fraction $r_{\text{LEPTO}}$
- $r_{\text{LEPTO}} = 17 \pm 5\%$
Cross section determination
Cross section determination

- $6.4 < \nu < 40$ GeV
- $1 < Q^2 < 8$ (GeV/c)$^2$
- $0.08 < |t| < 0.64$ (GeV/c)$^2$
- $-\pi < \phi < \pi$ rad

\[
\frac{d^2 \sigma \gamma^* p \rightarrow \pi^0 p'}{dt d\phi_{\pi^0}} = \frac{1}{\Gamma(Q^2, \nu)} \frac{d^4 \sigma \mu p \rightarrow \mu' \pi^0 p'}{dQ^2 d\nu dt d\phi_{\pi^0}}
\]

- $\Gamma(Q^2, \nu)$ - virtual photon flux

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Cross section determination

\[
\left\langle \frac{d^2\sigma^{\gamma^*p}}{dtd\phi} \right\rangle_{\Delta\Omega}^{\pm} = \left( N_{data}^{\Delta\Omega} \sum_{i=1}^{\pm} \frac{1}{\Gamma(\Omega_i) a(\Omega_i) L^{\pm}\Delta\Omega} - f^{\pm} \sum_{i=1}^{\pm} \frac{1}{\Gamma(\Omega_i) a(\Omega_i) L^{\pm}\Delta\Omega} \right)
\]

- phase space element \( \Delta\Omega = \Delta|t|\Delta\Phi\Delta Q^2\Delta\nu \)
- acceptance \( a(\Omega_i) \)
- luminosity \( L \)
- background normalization

\[
f^{\pm} = r_{LEPTO}^{\pm} \cdot \frac{N_{data}^{\pm}}{N_{LEPTO}^{\pm}}
\]
Cross section determination

\[
\left\langle \frac{d^2 \sigma \gamma^* p}{dt d\phi} \right\rangle_{\Delta \Omega}^\pm = \left( \sum_{i=1}^{N_{data}^\pm} \frac{1}{\Gamma(\Omega_i) a(\Omega_i) L^\pm \Delta \Omega} - f^\pm \sum_{i=1}^{N_{LEPTO}^\pm} \frac{1}{\Gamma(\Omega_i) a(\Omega_i) L^\pm \Delta \Omega} \right) 
\]

- phase space element \( \Delta \Omega = \Delta |t| \Delta \Phi \Delta Q^2 \Delta \nu \)
- acceptance \( a(\Omega_i) \)
- luminosity \( L \)
- background normalization

\[
f^\pm = r_{LEPTO}^\pm \cdot \frac{N_{data}^\pm}{N_{LEPTO}^\pm}
\]

- spin-independent cross section

\[
\left\langle \frac{d^2 \sigma \gamma^* p}{dt d\phi} \right\rangle_{\Delta \Omega} = \frac{1}{2} \left( \left\langle \frac{d^2 \sigma \gamma^* p}{dt d\phi} \right\rangle_{\Delta \Omega}^+ + \left\langle \frac{d^2 \sigma \gamma^* p}{dt d\phi} \right\rangle_{\Delta \Omega}^- \right)
\]
Acceptance averaged over $\phi$

COMPASS 2016 MC preliminary

$\phi$ averaged

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

2012 acceptance range

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

$\nu$ (GeV)
Results
$\phi$-dependent cross section for $\nu \in (6.4,40) \text{ GeV}$ and $Q^2 \in (1,8) \text{ GeV}^2/c^2$

- Only statistical uncertainties
- The systematic uncertainties are preliminary evaluated using the main contributor $r_{\text{LEPTO}}$
  - $\sim 10\%$ for the largest values around $\pm \pi/2$
  - $\sim 20\%$ for the smallest values around $-\pi, 0, \pi$

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$\phi$-dependent cross section for $\nu \in (6.4, 40)$ GeV and $Q^2 \in (1, 8)$ GeV$^2/c^2$

$$\chi^2/NDF = 1.2$$

$$\frac{d^3\sigma}{dtd\phi_{\pi^0}} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi_{\pi^0}) \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos(2\phi_{\pi^0}) \frac{d\sigma_{LT}}{dt} \right]$$
|t|-dependent cross section for $\nu \in (6.4, 40)\, \text{GeV}$ and $Q^2 \in (1, 8)\, \text{GeV}^2/c^2$

- Only statistical uncertainties
- The systematic uncertainties are preliminary evaluated using the main contributor $r_{\text{LEPTO}}$
  - $\sim 10\%$ in each $|t|$-bin
$\phi$-dependent cross section for $\nu \in (8.5, 28)$ GeV and $Q^2 \in (1, 5)$ GeV/$c^2$

2012 results (PLB 805 135454):

$$\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \rangle = (8.1 \pm 0.9_{\text{stat}} \pm 1.1_{\text{sys}}) \frac{\text{nb}}{\text{(GeV/c)}^2}$$

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

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

$\epsilon = 0.996$

- 2012 - statistical and systematic uncertainties are displayed
- 2016 - only statistical uncertainties
\( \phi \)-dependent cross section for \( \nu \in (8.5, 28) \text{ GeV} \) and \( Q^2 \in (1, 5) \text{ GeV}^2/c^2 \)

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

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

\[
\langle \frac{d\sigma_{LT}}{dt} \rangle = (1.4 \pm 0.5_{\text{stat}} \pm 0.3_{\text{sys}}) \text{ nb} \left( \frac{\text{GeV}}{c} \right)^2
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\( \epsilon = 0.996 \)

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$|t|$-dependent cross section for $\nu \in (8.5, 28)$ GeV and $Q^2 \in (1, 5)$ GeV$^2/c^2$

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S. Goloskokov, P. Kroll EPJC47 (2011) + private communication
Conclusion

- New preliminary results in a larger kinematic domain
  \( \nu \in (6.4,40) \text{ GeV} \) and \( Q^2 \in (1,8) \text{ GeV}^2/c^2 \)

- Comparison with published results (PLB 805 135454) in a smaller kinematic domain
  \( \nu \in (8.5,28) \text{ GeV} \) and \( Q^2 \in (1,5) \text{ GeV}^2/c^2 \)

- All theoreticians are invited to present their predictions, namely S. Goloskokov, P. Kroll, K. Passek-Kumericki and S. Liuti

- Prospects
  - Complete systematic studies
  - 2017 data
  - Evolution in 3 \( \nu \) bins
BACKUP
Determine $\sin \phi$ contribution (for $\mu^+$ and $\mu^-$ beam)

\[
\frac{d^2 \sigma_{\gamma^* p}}{d t d \phi_{\pi^0}} = \frac{1}{2\pi} \left[ \frac{d \sigma_T}{d t} + \epsilon \frac{d \sigma_L}{d t} + \epsilon \cos(2\phi_{\pi^0}) \frac{d \sigma_{TT}}{d t} + \sqrt{2\epsilon(1 + \epsilon)} \cos(2\phi_{\pi^0}) \frac{d \sigma_{LT}}{d t} \right. \\
+ \left. |P_l| \sqrt{2\epsilon(1 - \epsilon)} \sin(2\phi_{\pi^0}) \frac{d \sigma'_{LT}}{d t} \right]
\]
Photon flux

\[ \Gamma(Q^2, \nu) = \frac{\alpha_{em}(1 - x_{Bj})}{2\pi Q^2 y E_\mu} \left[ y^2 \left( 1 - \frac{2m_\mu^2}{Q^2} \right) + \frac{2}{1 + Q^2/\nu^2} \left( 1 - y - \frac{Q^2}{4E_\mu^2} \right) \right] \]
Virtual photon polarisation parameter

$$\epsilon = \frac{1 - y - \frac{1}{4}y^2 Q^2/\nu^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}y^2 Q^2/\nu^2}$$

- $\epsilon = 0.997$ (it was 0.996 in 2012 analysis)
Kinematic fit

- Measurements of exclusive processes at COMPASS are over-constrained
- This can be used to improve the resolution on the measured kinematic quantities by the usage of a kinematically constrained fit
- In case of exclusive $\pi^0$ analysis, the fit can be used to improve signal to background ratio

- The goal is to minimize the least square function $\chi^2(\vec{k}) := (\vec{k}_{\text{fit}} - \vec{k})^T \hat{C}^{-1}(\vec{k}_{\text{fit}} - \vec{k})$
- $\vec{k}$ is the vector of measured quantities (e.g. variables such as momentum and transverse position corresponding to the incoming/scattered muon, initial/final proton and lower/higher energetic photon)
- $\hat{C}$ is the covariance matrix corresponding to the measured quantities
- The Lagrange multiplier method with constraints $g_i$ is used for the minimization:

$$L(\vec{k}, \vec{\alpha}) = \chi^2(\vec{k}) + 2 \sum_{i=1}^{N} \alpha_i g_i. \quad (1)$$
Kinematic fit - introduction - kinematic constraints

- Momentum and energy conservation
  \[ g_i = p_{\mu,i}^{\text{fit}} - p_{\mu,i}^{\text{fit}} - p_{\gamma,h,i}^{\text{fit}} - p_{\gamma,l,i}^{\text{fit}} = 0, \quad i = 1, 2, 3 \]
  \[ g_4 = E_{\mu}^{\text{fit}} + m_p c^2 - E_{\mu}^{\text{fit}} - E_{\gamma,h}^{\text{fit}} - E_{\gamma,l}^{\text{fit}} = 0 \]

- Common vertex for all tracks (except initial and final state proton)
  \[ g_{5+i} = p_{j,3}^{\text{fit}} (x_v - x_j^{\text{fit}}) - p_{j,1}^{\text{fit}} (z_v - z_j^{\text{fit}}) = 0 \quad (i, j) \in \{(0, \mu), (2, \mu'), (4, \gamma_h), (6, \gamma_l)\} \]
  \[ g_{6+i} = p_{j,3}^{\text{fit}} (y_v - y_j^{\text{fit}}) - p_{j,2}^{\text{fit}} (z_v - z_j^{\text{fit}}) = 0, \quad (i, j) \in \{(0, \mu), (2, \mu'), (4, \gamma_h), (6, \gamma_l)\} \]

- Constraints for final state proton
  \[ g_{13+i} = p_{p',3}^{\text{fit}} (x_j^{\text{fit}} - x_v) - p_{p',1}^{\text{fit}} (z_j^{\text{fit}} - z_v) = 0, \quad (i, j) \in \{(0, A), (2, B)\} \]
  \[ g_{14+i} = p_{p',3}^{\text{fit}} (y_j^{\text{fit}} - y_v) - p_{p',2}^{\text{fit}} (z_j^{\text{fit}} - z_v) = 0, \quad (i, j) \in \{(0, A), (2, B)\} \]

- Mass constraint
  \[ g_{17} = (E_{\gamma_h}^{\text{fit}} + E_{\gamma_l}^{\text{fit}})^2 - (p_{\gamma_h}^{\text{fit}} + p_{\gamma_l}^{\text{fit}})^2 - m_{\pi_0}^2 = 0 \]

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