Hard exclusive π^0 production at COMPASS

IWHSS 2023, Prague

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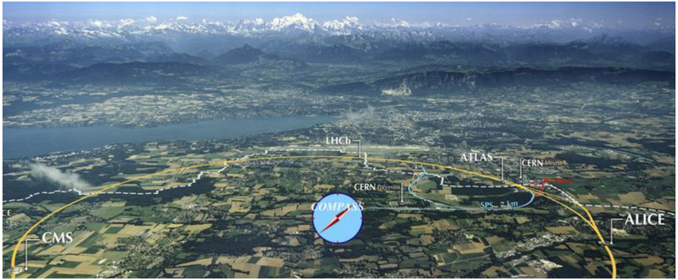
Outline

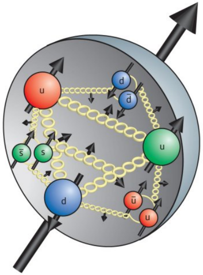
- Introduction
- Measurement at COMPASS
- Data selection and background estimation
- Cross section determination
- Results



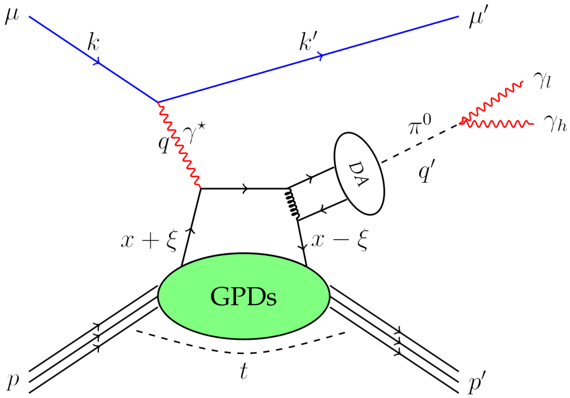
Introduction

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 π^0 muoproduction
    - Cross section measurement of $\mu p \to \mu' \pi^0 p'$



Hard exclusive π^0 muoproduction



- Sensitive to the GPDs
  - $\tilde{H}$(x, ξ, t) and $\tilde{E}$(x, ξ, t) - chiral-even (conserving the parton helicity)
  - H_T(x, ξ, t) and $\overline{E}_T$(x, ξ, t) - chiral-odd (parton helicity flip)

Reduced cross section for hard exclusive π^0 production

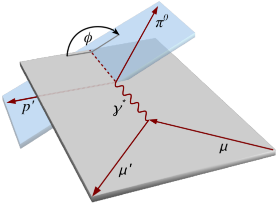
$$\frac{d^2\sigma^{\gamma^* p}}{dt\,d\phi_{\pi^0}} = \frac{1}{2\pi}\left[\epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \epsilon\cos(2\phi_{\pi^0})\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos(2\phi_{\pi^0})\frac{d\sigma_{LT}}{dt}\right]$$

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

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

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

$$\frac{d\sigma_{LT}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\mathrm{Re}\left[\langle H_T\rangle * \langle\tilde{E}\rangle\right]$$

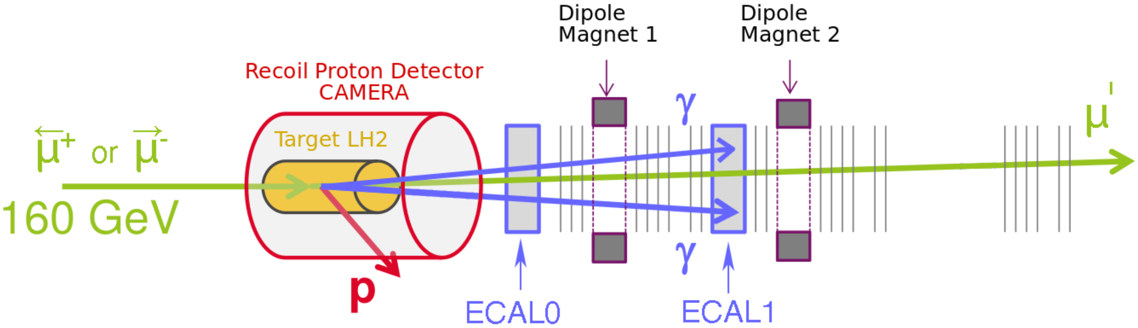


Measurement at COMPASS

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 $\sim$ 9 times larger statistics than 2012)

Exclusive π^0 measurement at COMPASS



Data selection and background estimation

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

- Vertex candidate
  - μ and μ' associated to the vertex
  - requirements on μ and μ'

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  - pair of neutral clusters in ECALs
  - energy thresholds
  - timing requirement

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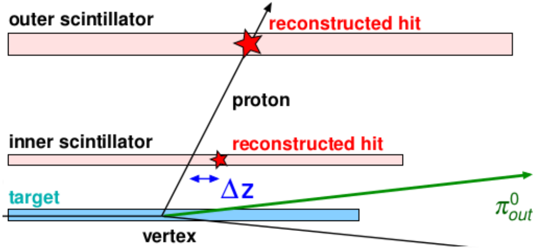
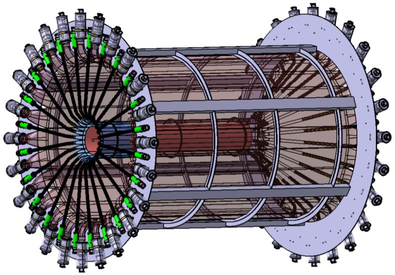
Exclusive variables measured either by the spectrometer or by CAMERA

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

- $|\Delta\varphi| < 0.4$ rad
- $|\Delta p_T| < 0.3$ GeV/c
- $|M_x^2| < 0.3\ (\mathrm{GeV}/c^2)^2$
- $|\Delta z_A| < 16$ 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* + π^0 *candidate* + *proton candidate* pass the selection

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$)^2$

eV
$V/c)^2$
4 $(GeV/c)^2$

e combination:
π^0 *candidate* +
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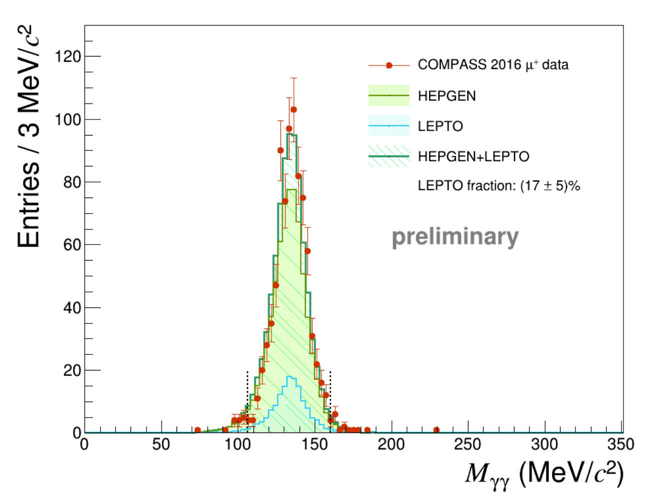
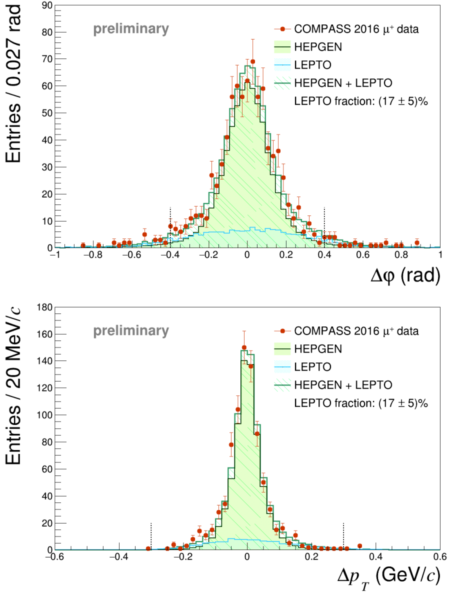
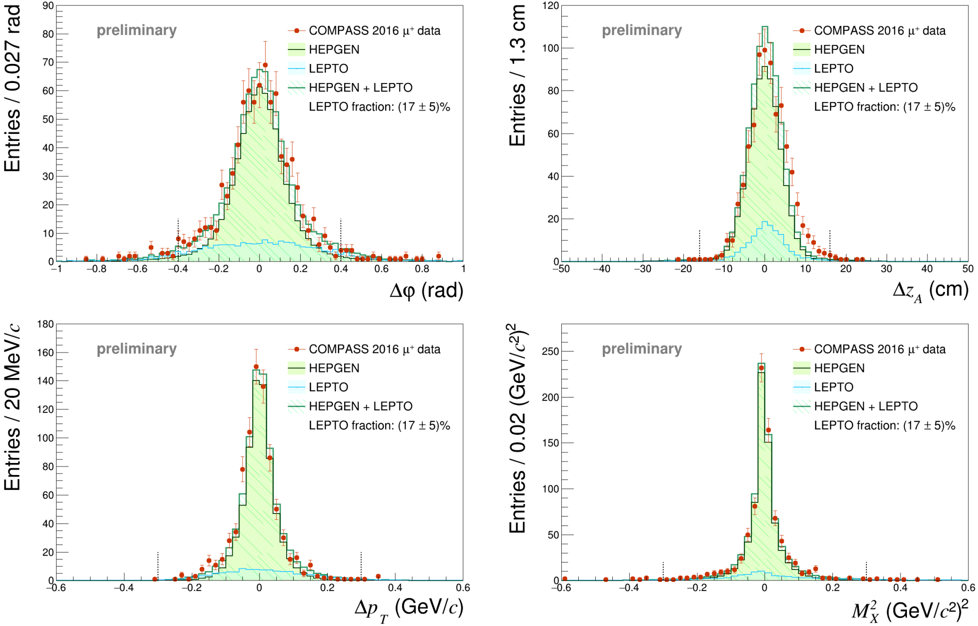




Background estimation

- π^0 from deep inelastic scattering
- LEPTO MC - non exclusive
- HEPGEN++ MC - excl. π^0
- scaling of HEPGEN and "LEPTO background"
- background fraction r_{LEPTO}
- $r_{\mathrm{LEPTO}} = 17 \pm 5$ %


Entries / 0.027 rad
preliminary
COMPASS 2016 μ⁺ data
HEPGEN
LEPTO
HEPGEN + LEPTO
LEPTO fraction: (17 ± 5)%
Δφ (rad)
Entries / 1.3 cm
preliminary
COMPASS 2016 μ⁺ data
HEPGEN
LEPTO
HEPGEN + LEPTO
LEPTO fraction: (17 ± 5)%
Δz_A (cm)
Entries / 20 MeV/c
preliminary
COMPASS 2016 μ⁺ data
HEPGEN
LEPTO
HEPGEN + LEPTO
LEPTO fraction: (17 ± 5)%
Δp_T (GeV/c)
Entries / 0.02 (GeV/c^2)^2
preliminary
COMPASS 2016 μ⁺ data
HEPGEN
LEPTO
HEPGEN + LEPTO
LEPTO fraction: (17 ± 5)%
M_X^2 (GeV/c^2)^2

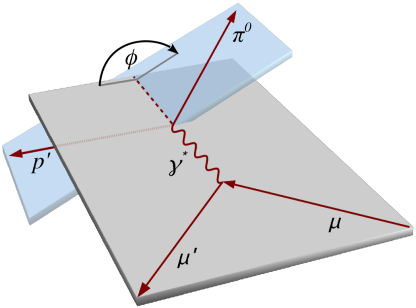
Cross section determination

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

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

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



Cross section determination

$$\left\langle \frac{\mathrm{d}^2\sigma^{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} \right\rangle^{\pm}_{\Delta\Omega} = \left(\sum_{i=1}^{N^{\Delta\Omega}_{data^\pm}} \frac{1}{\Gamma(\Omega_i)a(\Omega_i)\mathcal{L}^\pm \Delta\Omega} - f^\pm \sum_{i=1}^{N^{\Delta\Omega}_{LEPTO^\pm}} \frac{1}{\Gamma(\Omega_i)a(\Omega_i)\mathcal{L}^\pm \Delta\Omega} \right)$$

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

$$f^\pm = r^\pm_{LEPTO} \cdot \frac{N_{data^\pm}}{N_{LEPTO^\pm}}$$

Cross section determination

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- phase space element $\Delta\Omega = \Delta|t|\Delta\Phi\Delta Q^2\Delta\nu$
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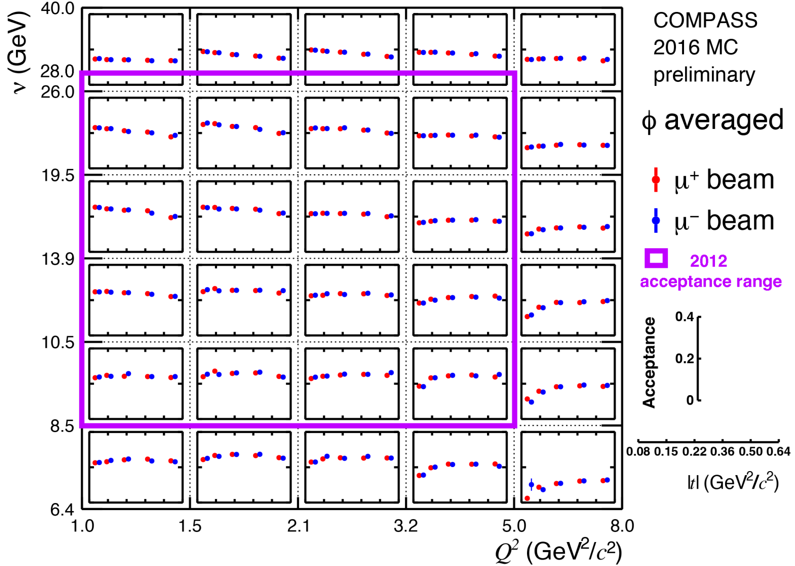
- background normalization

$$f^{\pm} = r^{\pm}_{LEPTO} \cdot \frac{N_{data^\pm}}{N_{LEPTO^\pm}}$$

- spin-independent cross section

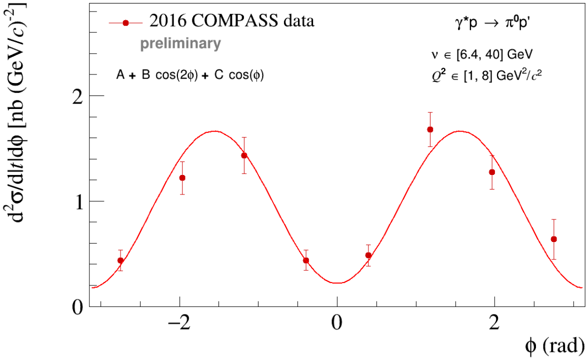
$$\left\langle \frac{\mathrm{d}^2\sigma^{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} \right\rangle_{\Delta\Omega} = \frac{1}{2} \left(\left\langle \frac{\mathrm{d}^2\sigma^{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} \right\rangle^{+}_{\Delta\Omega} + \left\langle \frac{\mathrm{d}^2\sigma^{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} \right\rangle^{-}_{\Delta\Omega} \right)$$

Acceptance averaged over ϕ



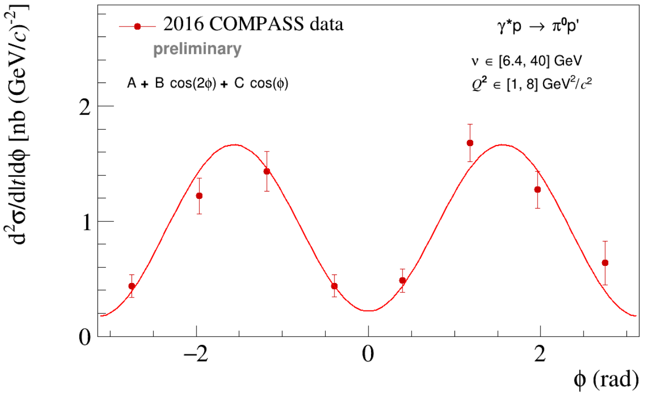
Results

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



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

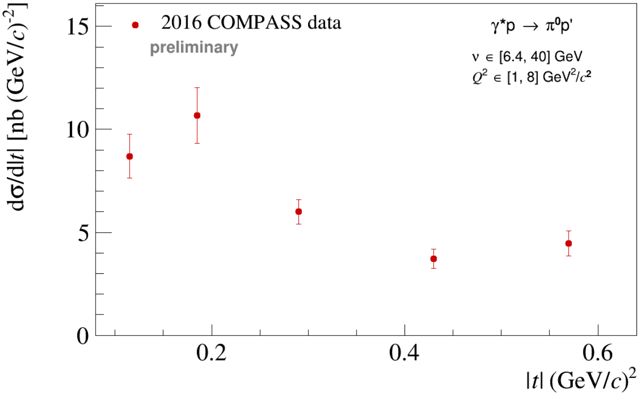
ϕ-dependent cross section for $\nu \in (6.4,40)$ GeV and $Q^2 \in (1,8)$ GeV^2/c^2



$\chi^2/NDF = 1.2$

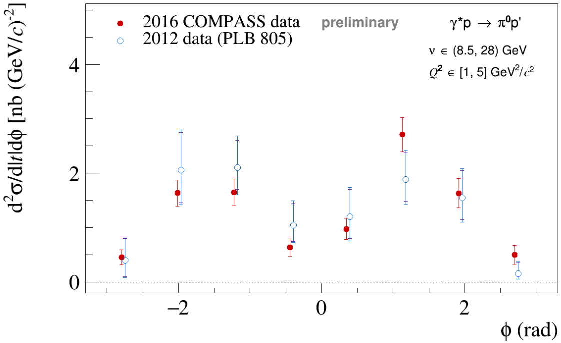
$$\frac{d^2\sigma^{\gamma^* p}}{dt d\phi_{\pi^0}} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi_{\pi^0})\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos(2\phi_{\pi^0})\frac{d\sigma_{LT}}{dt}\right]$$

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



- Only statistical uncertainties
- The systematic uncertainties are preliminary evaluated using the main contributor r_{LEPTO}
  - $\sim$ 10% in each $|t|$-bin

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



2012 results (PLB 805 135454):

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

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

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

$$\epsilon = 0.996$$

- 2012 - statistical and systematic uncertainties are displayed
- 2016 - only statistical uncertainties

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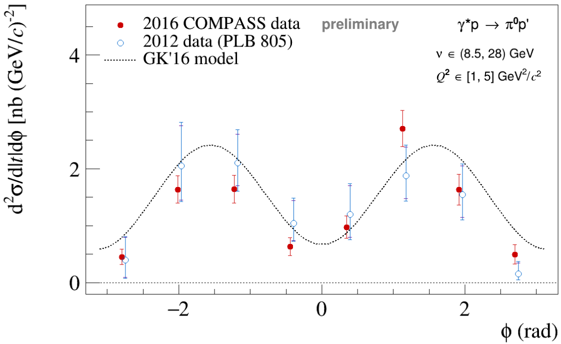

S. Goloskokov, P. Kroll EPJC47 (2011) + private communication

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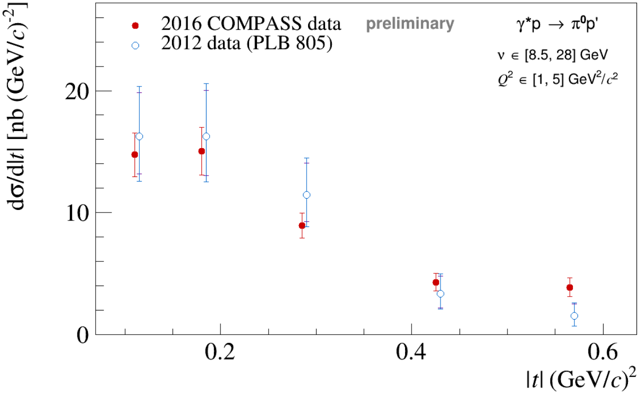

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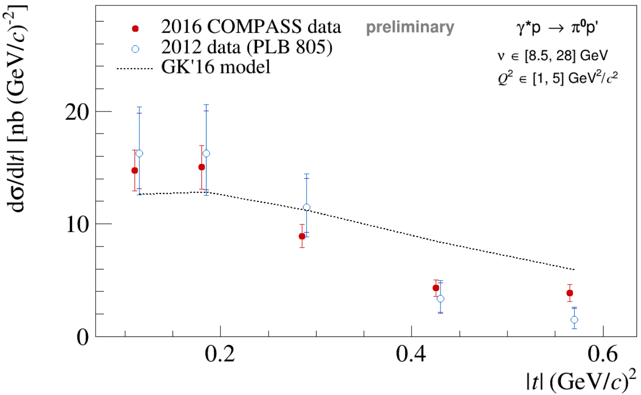

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Conclusion

- New preliminary results in a larger kinematic domain
  $\nu \in (6.4,40)$ GeV and $Q^2 \in (1,8)$ GeV^2/c^2
- Comparison with published results (PLB 805 135454) in a smaller kinematic domain
  $\nu \in (8.5,28)$ GeV and $Q^2 \in (1,5)$ 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 ν bins

BACKUP

Prospects

Determine $\sin\phi$ contribution (for μ^+ and μ^- beam)

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

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 π^0 analysis, the fit can be used to improve signal to background ratio

- The goal is to minimize the least square function $\chi^2(\vec{k}) := (\vec{k}_{fit} - \vec{k})^T \widehat{C}^{-1}(\vec{k}_{fit} - \vec{k})$
- $\vec{k}$ 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)
- $\widehat{C}$ 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**

$$g_i = p^{fit}_{\mu,i} - p^{fit}_{\mu\prime,i} - p^{fit}_{p\prime,i} - p^{fit}_{\gamma_h,i} - p^{fit}_{\gamma_l,i} = 0, \;\; i = 1,2,3$$

$$g_4 = E^{fit}_{\mu} + m_p c^2 - E^{fit}_{\mu\prime} - E^{fit}_{p\prime} - E^{fit}_{\gamma_h} - E^{fit}_{\gamma_l} = 0$$

- **Common vertex for all tracks (except initial and final state proton)**

$$g_{5+i} = p^{fit}_{j,3}\left(x_v - x^{fit}_j\right) - p^{fit}_{j,1}\left(z_v - z^{fit}_j\right) = 0 \;\; (i,j) \in \{(0,\mu),(2,\mu\prime),(4,\gamma_h),(6,\gamma_l)\}$$

$$g_{6+i} = p^{fit}_{j,3}\left(y_v - y^{fit}_j\right) - p^{fit}_{j,2}\left(z_v - z^{fit}_j\right) = 0, \;\; (i,j) \in \{(0,\mu),(2,\mu\prime),(4,\gamma_h),(6,\gamma_l)\}$$

- **Constraints for final state proton**

$$g_{13+i} = p^{fit}_{p\prime,3}\left(x^{fit}_j - x_v\right) - p_{p\prime,1}\left(z^{fit}_j - z_v\right) = 0, \;\; (i,j) \in \{(0,A),(2,B)\}$$

$$g_{14+i} = p^{fit}_{p\prime,3}\left(y^{fit}_j - y_v\right) - p_{p\prime,2}\left(z^{fit}_j - z_v\right) = 0, \;\; (i,j) \in \{(0,A),(2,B)\}$$

- **Mass constraint** $g_{17} = (E^{fit}_{\gamma_h} + E^{fit}_{\gamma_l})^2 - (p^{fit}_{\gamma_h} + p^{fit}_{\gamma_l})^2 - m^2_{\pi^0} = 0$