Exclusive π^0 muoproduction at COMPASS

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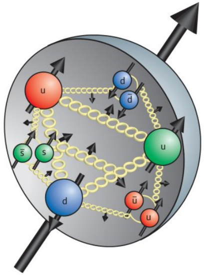
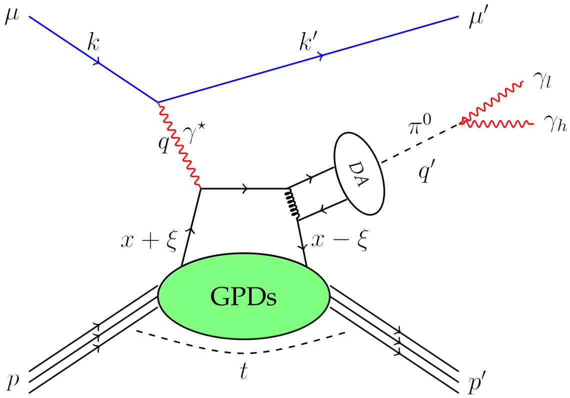
Generalized Parton Distributions (GPDs)

- Generalization of standard PDFs $\Rightarrow$ longitudinal momentum and transverse position
- Provide a 3D picture of how quarks and gluons build up the nucleons
- 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
  - $\tilde{H}(x, \xi, t)$ and $\tilde{E}(x, \xi, t)$ - chiral-even (conserving the parton helicity)
  - $H_T(x, \xi, t)$ and $\bar{E}_T(x, \xi, t)$ - chiral-odd (parton helicity flip)

Reduced cross section for hard exclusive π^0 production

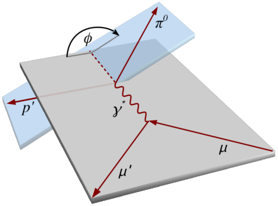
$$\frac{d^2\sigma^{\gamma^* p}}{dt\,d\phi_{\pi^0}} = \frac{1}{2\pi}\left[\epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \epsilon\cos(2\phi_{\pi^0})\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_{\pi^0})\frac{d\sigma_{LT}}{dt}\right]$$

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

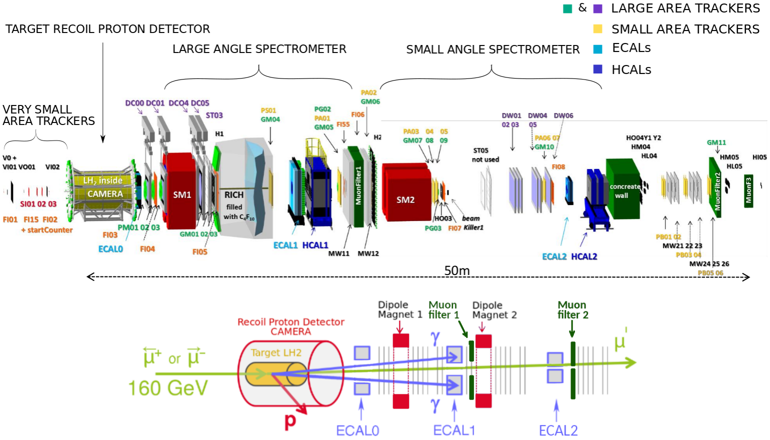
$$\frac{d\sigma_T}{dt} \propto \left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle\bar{E}_T\rangle|^2\right]$$

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

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

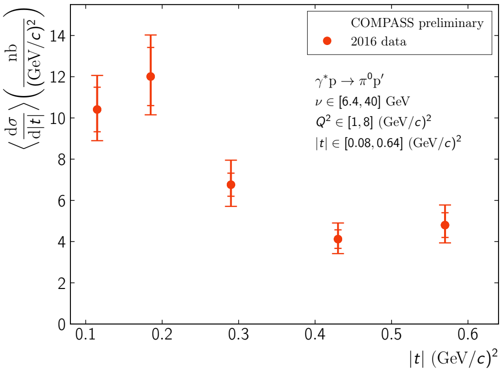


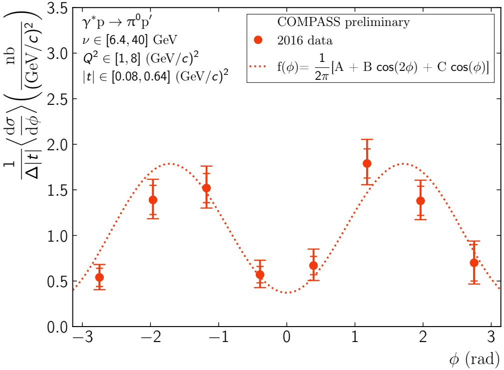
Exclusive π^0 measurement at COMPASS experiment at CERN



- Measured in 2016

Cross section for $\nu \in (6.4,40)$ GeV and $Q^2 \in (1,8)$ GeV$^2/c^2$, $\langle x_B \rangle = 0.134$





$$\left\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right\rangle = (6.6 \pm 0.3_{stat} {}^{+\,0.9}_{-\,0.8}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{dt} \right\rangle = (-4.6 \pm 0.5_{stat} {}^{+\,0.3}_{-\,0.3}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

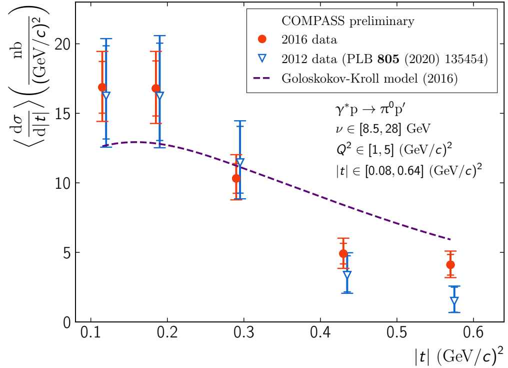
$$\left\langle \frac{d\sigma_{LT}}{dt} \right\rangle = (0.2 \pm 0.2_{stat} {}^{+\,0.2}_{-\,0.2}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

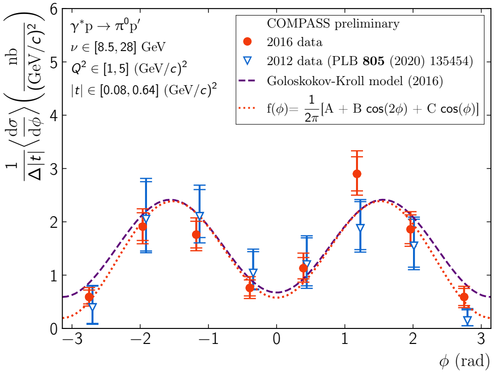
$$\langle \epsilon \rangle = 0.997$$

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

- $\frac{d\sigma_{TT}}{dt}$ as large as $\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$ $\Rightarrow$ Importance of $\bar{E}_T$

Cross section for $\nu \in (8.5,28)$ GeV and $Q^2 \in (1,5)$ GeV^2/c^2, $\langle x_B \rangle = 0.1$





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

2012 data:

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

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

$$\langle \frac{d\sigma_{LT}}{dt} \rangle = (1.4 \pm 0.5_{stat} {}^{+\,0.3}_{-\,0.2}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

$\langle \epsilon \rangle = 0.996$

2016 data:

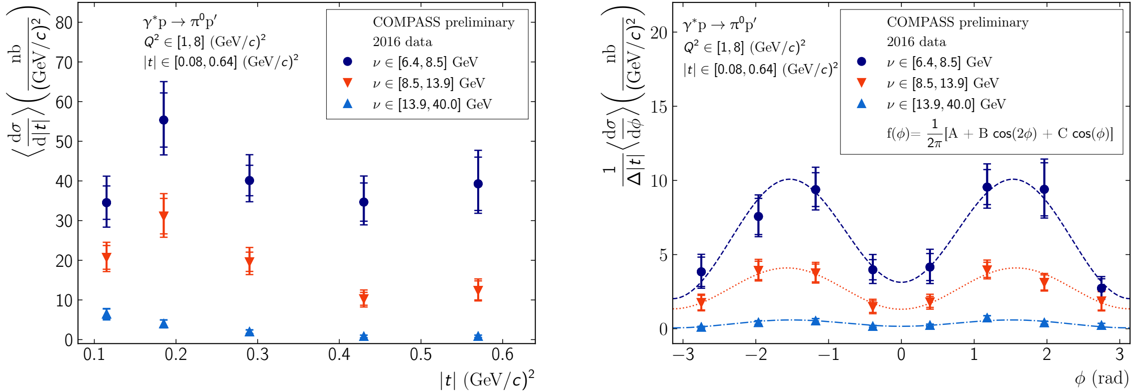
$$\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \rangle = (8.7 \pm 0.5_{stat} {}^{+\,1.0}_{-\,1.0}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

$$\langle \frac{d\sigma_{TT}}{dt} \rangle = (-6.3 \pm 0.8_{stat} {}^{+\,0.4}_{-\,0.5}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

$$\langle \frac{d\sigma_{LT}}{dt} \rangle = (0.6 \pm 0.3_{stat} {}^{+\,0.3}_{-\,0.3}\big|_{sys})\ \frac{nb}{(GeV/c)^2}$$

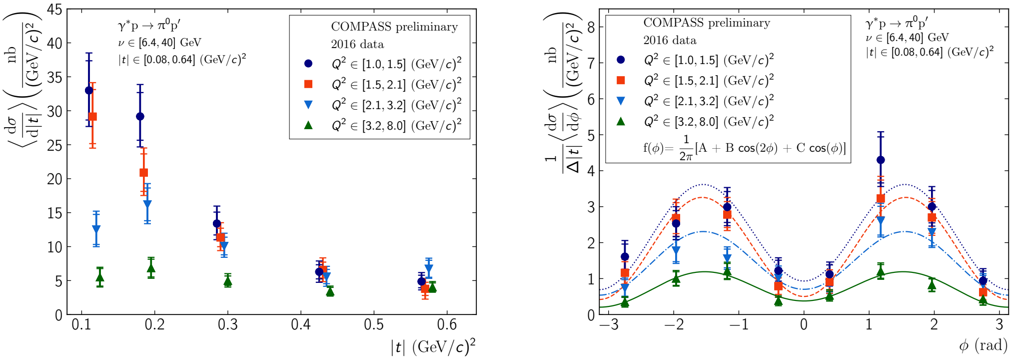
$\langle \epsilon \rangle = 0.996$

Evolution of the cross section with ν



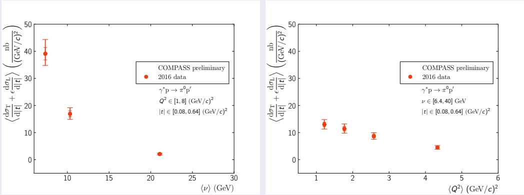
	$\langle \nu \rangle$ [GeV]	$\langle Q^2 \rangle$ [GeV$^2/c^2$]	$\langle x_B \rangle$	$\langle \epsilon \rangle$
$\nu \in [6.4, 8.5]$	7.35	2.15	0.156	0.999
$\nu \in [8.5, 13.9]$	10.32	2.50	0.131	0.998
$\nu \in [13.9, 40.0]$	21.08	2.09	0.057	0.989

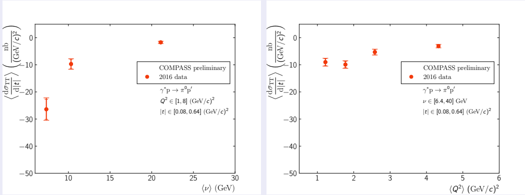
Evolution of the cross section with Q^2



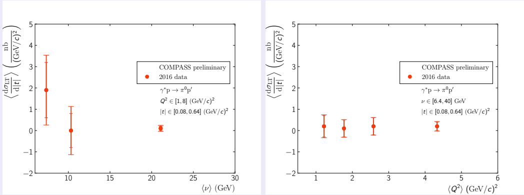
	$\langle Q^2 \rangle$ [GeV^2/c^2]	$\langle \nu \rangle$ [GeV]	$\langle x_B \rangle$	$\langle \epsilon \rangle$
$Q^2 \in [1.0, 1.5]$	1.22	10.54	0.072	0.997
$Q^2 \in [1.5, 2.1]$	1.77	9.81	0.109	0.997
$Q^2 \in [2.1, 3.2]$	2.58	9.82	0.157	0.997
$Q^2 \in [3.2, 8.0]$	4.33	10.39	0.247	0.997

Evolution of structure functions with ν and Q^2





- when ν increases by a factor 3
  - $\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \rangle$ decreases by a factor 18
  - $|\langle \frac{d\sigma_{TT}}{dt} \rangle|$ decreases by a factor 16
- when Q^2 increases by a factor 4
  - $\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \rangle$ decreases by a factor 3 only
  - $|\langle \frac{d\sigma_{TT}}{dt} \rangle|$ decreases by a factor 3 only

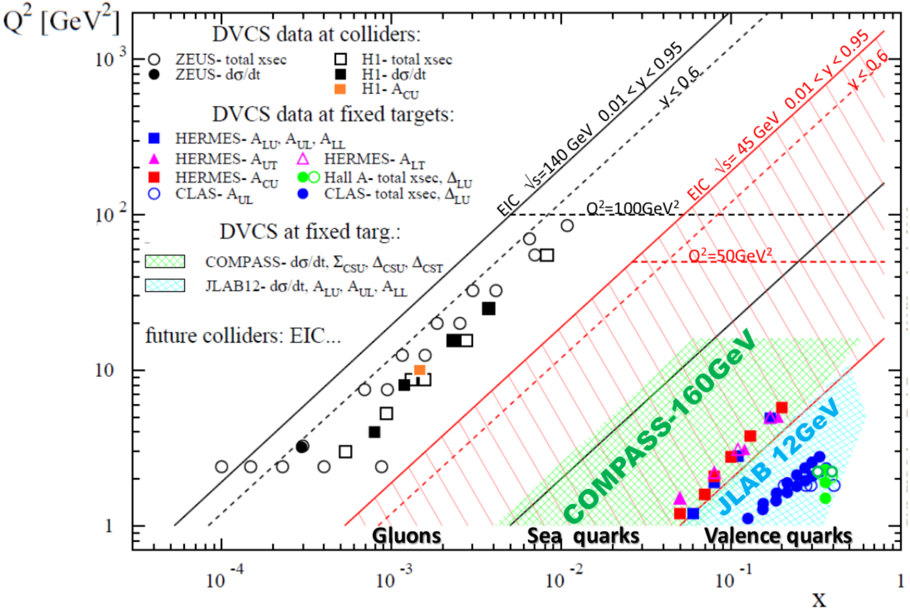


$\Rightarrow$ important inputs for a theoretical description of the major $\bar{E}_T$ contribution

Summary

- Cross section from 2016 COMPASS data calculated in:
  - $\nu \in (6.4,40)$ GeV and $Q^2 \in (1,8)$ GeV^2/c^2
  - $\nu \in (8.5,28)$ GeV and $Q^2 \in (1,5)$ GeV^2/c^2
    - same as used for 2012 data (PLB 805 135454), now $\sim$ 2.3 times larger statistics
  - Study evolution in
    - 3 bins in ν
    - 4 bins in Q^2
- Prospects:
  - New theoretical model from Peter Kroll and Kornelia Passek-Kumerički, Sergei Goloskokov, Simonetta Liuti...
  - Paper with results from 2016 data
  - 2017 data - to be analyzed

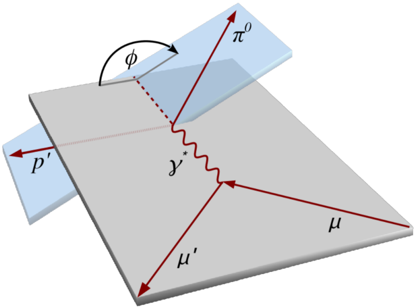
BACKUP



Q² [GeV²]
DVCS data at colliders:
ZEUS- total xsec
ZEUS- dσ/dt
H1- total xsec
H1- dσ/dt
H1- A_CU
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
CLAS- total xsec, Δ_LU
DVCS at fixed targ.:
COMPASS- dσ/dt, Σ_CSU, Δ_CSU, Δ_CST
JLAB12- dσ/dt, A_LU, A_UL, A_LL
future colliders: EIC...
EIC √s=140 GeV 0.01 < y < 0.95
y < 0.6
Q²=100GeV²
EIC √s= 45 GeV 0.01 < y < 0.95
y < 0.6
Q²=50GeV²
COMPASS-160GeV
JLAB 12GeV
Gluons
Sea quarks
Valence quarks
x

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

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

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

- spin-independent cross section:

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

virtual 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 polarization parameter:

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

reduced cross section (full vesrion):

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