Exclusive π^0 muoproduction at COMPASS

Diffraction and Low-x, 8-14 Sept 2024, Trabia (Palermo, Sicily)

Karolína Lavičková* on behalf of the COMPASS collaboration
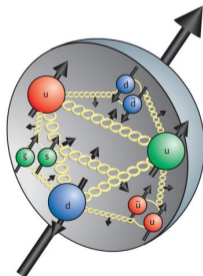
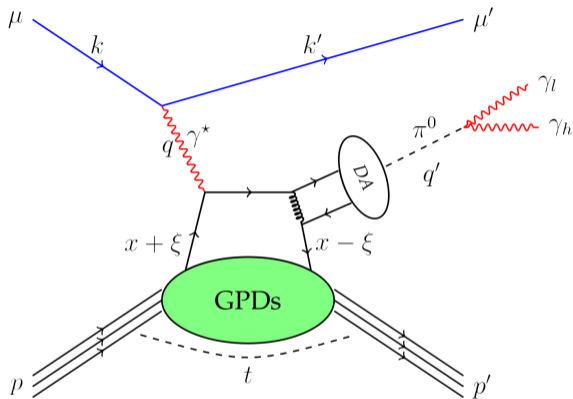*FNSPE CTU in Prague

September 12, 2024

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)

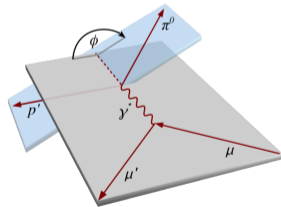# Reduced cross section for hard exclusive π^0 production

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

$$\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} \propto \left[(1-\xi^2)|\langle\tilde{H}\rangle|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle * \langle\tilde{E}\rangle\right] - \frac{t'}{4M^2}\xi^2|\langle\tilde{E}\rangle|^2\right]$$
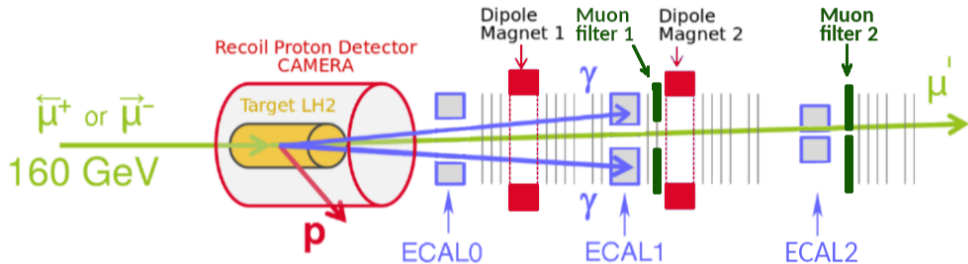
$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} \propto \left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle\bar{E}_T\rangle|^2\right]$$

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

$$\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\mathrm{Re}\left[\langle H_T\rangle * \langle\tilde{E}\rangle\right]$$
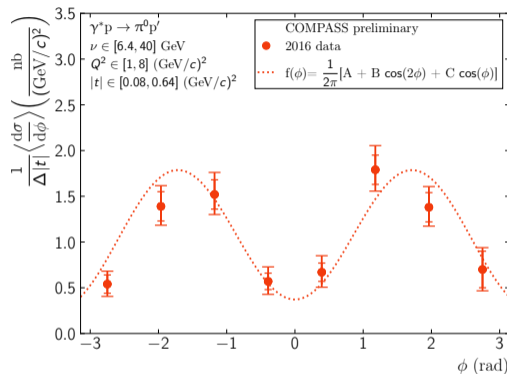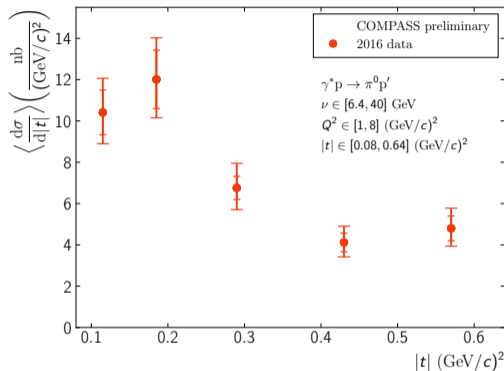
Exclusive π^0 measurement at COMPASS experiment at CERN

- Measured in 2016

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

$\gamma^* p \to \pi^0 p'$
$\nu \in [6.4, 40]$ GeV
$Q^2 \in [1, 8]$ (GeV/c)^2
$|t| \in [0.08, 0.64]$ (GeV/c)^2

COMPASS preliminary
2016 data

$\gamma^* p \to \pi^0 p'$
$\nu \in [6.4, 40]$ GeV
$Q^2 \in [1, 8]$ (GeV/c)^2
$|t| \in [0.08, 0.64]$ (GeV/c)^2

COMPASS preliminary
2016 data
$f(\phi) = \frac{1}{2\pi}[A + B \cos(2\phi) + C \cos(\phi)]$

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

$\langle \frac{d\sigma_{TT}}{dt} \rangle = (-4.6 \pm 0.5_{\text{stat}} {}^{+\,0.3}_{-\,0.3}|_{\text{sys}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$
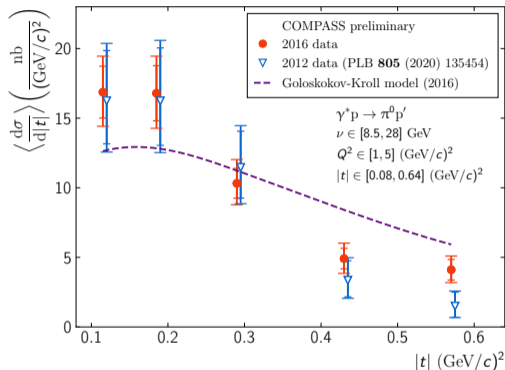
$\langle \frac{d\sigma_{LT}}{dt} \rangle = (0.2 \pm 0.2_{\text{stat}} {}^{+\,0.2}_{-\,0.2}|_{\text{sys}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$

$\langle \epsilon \rangle = 0.997$

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

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

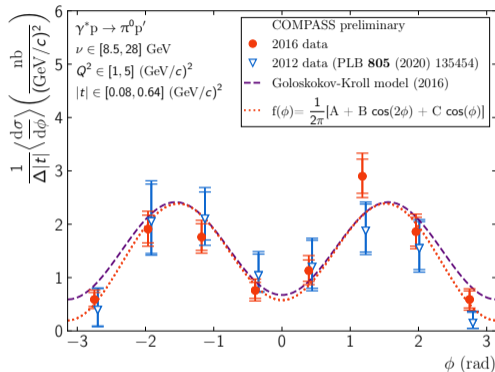# Cross section for $\nu \in (8.5, 28)$ GeV and $Q^2 \in (1,5)$ GeV^2/c^2, $\langle x_B \rangle = 0.1$

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

2012 data:

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

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

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

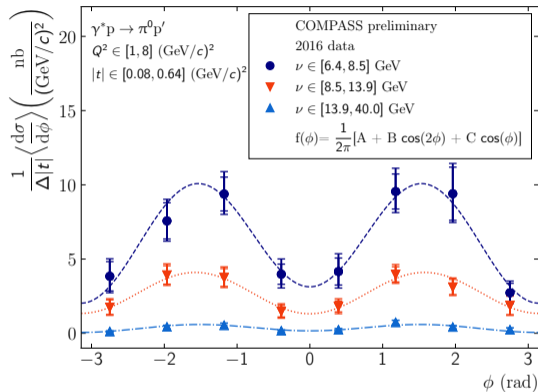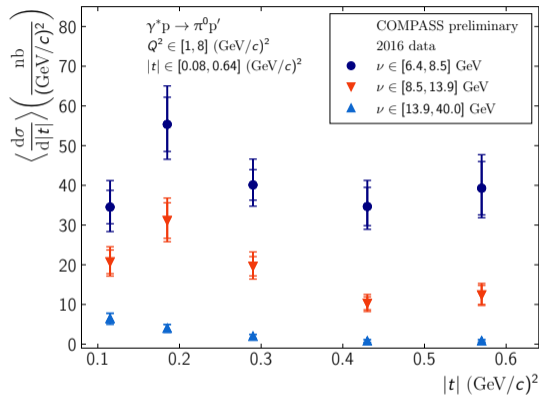$\langle \epsilon \rangle = 0.996$

2016 data:

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

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

$\langle \frac{d\sigma_{LT}}{dt} \rangle = (0.6 \pm 0.3_{\text{stat}} {}^{+\,0.3}_{-\,0.3}|_{\text{sys}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$
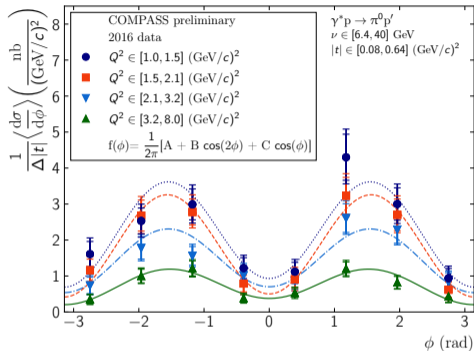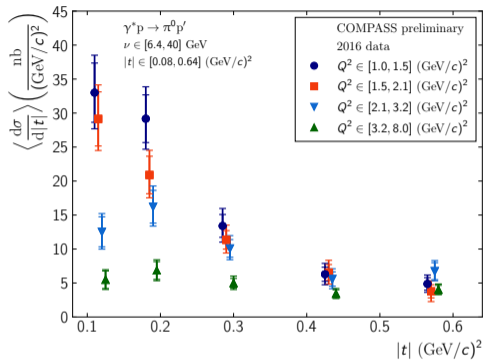
$\langle \epsilon \rangle = 0.996$

Evolution of the cross section with ν

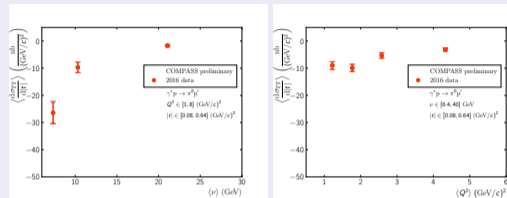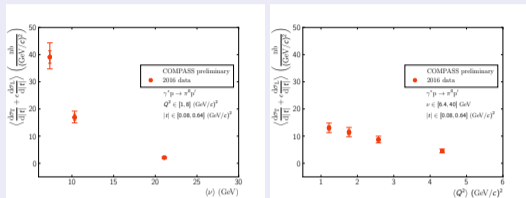Left plot: $\gamma^*p \to \pi^0 p'$, $Q^2 \in [1,8]$ $(\text{GeV}/c)^2$, $|t| \in [0.08, 0.64]$ $(\text{GeV}/c)^2$

COMPASS preliminary
2016 data
- $\nu \in [6.4, 8.5]$ GeV
- $\nu \in [8.5, 13.9]$ GeV
- $\nu \in [13.9, 40.0]$ GeV

Axes: $\left\langle \dfrac{\mathrm{d}\sigma}{\mathrm{d}|t|} \right\rangle \left(\dfrac{\text{nb}}{(\text{GeV}/c)^2} \right)$ vs $|t|$ $(\text{GeV}/c)^2$

Right plot: $\gamma^*p \to \pi^0 p'$, $Q^2 \in [1,8]$ $(\text{GeV}/c)^2$, $|t| \in [0.08, 0.64]$ $(\text{GeV}/c)^2$

COMPASS preliminary
2016 data
- $\nu \in [6.4, 8.5]$ GeV
- $\nu \in [8.5, 13.9]$ GeV
- $\nu \in [13.9, 40.0]$ GeV

$f(\phi) = \dfrac{1}{2\pi}[A + B\cos(2\phi) + C\cos(\phi)]$

Axes: $\dfrac{1}{\Delta|t|} \left\langle \dfrac{\mathrm{d}\sigma}{\mathrm{d}\phi} \right\rangle \left(\dfrac{\text{nb}}{(\text{GeV}/c)^2} \right)$ vs ϕ (rad)

	$\langle \nu \rangle$ [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

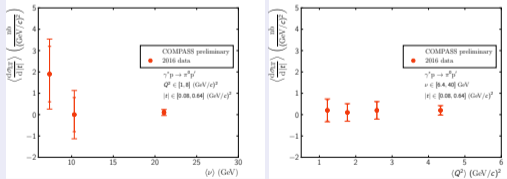# Evolution of structure functions with ν and Q^2

- 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
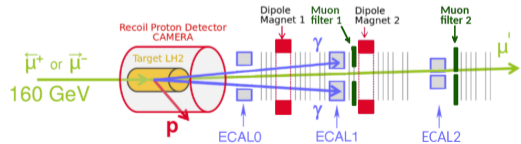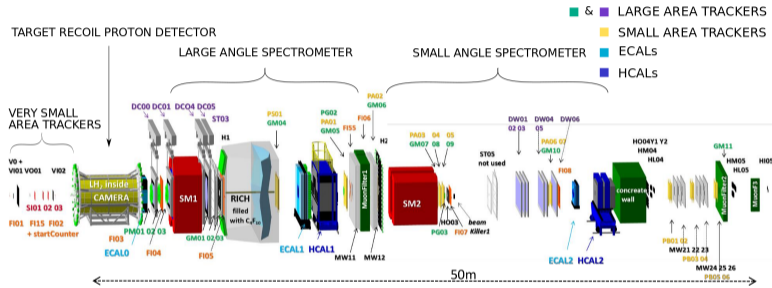 - $|\langle \frac{d\sigma_{TT}}{dt} \rangle|$ decreases by a factor 3 only

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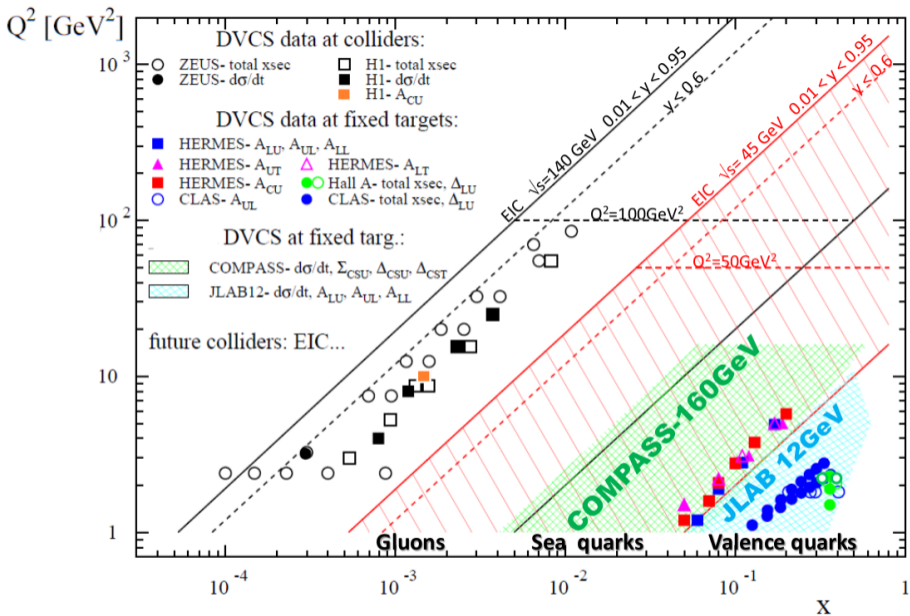
Summary

- 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 ~ 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-Kumeriĉki, Sergei Goloskokov, Simonetta Liuti...
    - Paper with results from 2016 data
    - 2017 data - to be analyzed
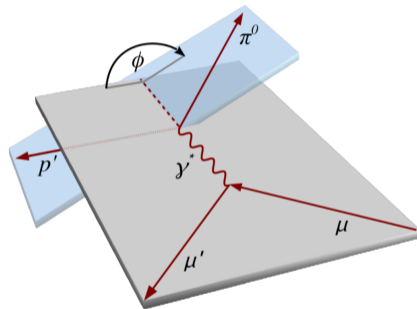
BACKUP

Exclusive π^0 measurement at COMPASS

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

$$\frac{\mathrm{d}^2\sigma^{\gamma^* p \to \pi^0 p'}}{\mathrm{d}t\mathrm{d}\phi_{\pi^0}} = \frac{1}{\Gamma(Q^2,\nu)}\frac{\mathrm{d}^4\sigma^{\mu p \to \mu'\pi^0 p'}}{\mathrm{d}Q^2\mathrm{d}\nu\mathrm{d}t\mathrm{d}\phi_{\pi^0}}$$

- $\Gamma(Q^2,\nu)$ - 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:

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

reduced cross section (full vesrion):

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