Exclusive π^0 muoproduction cross section at COMPASS

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on behalf of the COMPASS at CERN

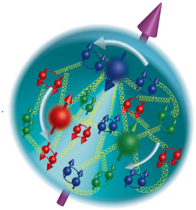
Supported by Charles University grant PRIMUS/22/SCI/017

DIS 2024, April 8.–12. 2024

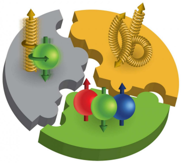
Spin Puzzle of the Nucleon

- Proton spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

EMC Collaboration, Nucl. Phys. B328 (1989) 180

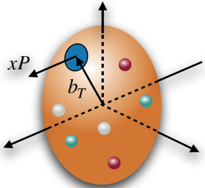


COMPASS experiment in μp DIS: $\Delta\Sigma = 0.32 \pm 0.03$
COMPASS Collaboration: Phys. Lett. B 693 (2010)
COMPASS, RHIC results: $\Delta G = 0.2^{+0.06}_{-0.07}$
de Florian et al.Phys.Rev.Lett. 113 (2014), 012001
Missing component: $L_{q,g} = ?$ → GPDs provides access to the total angular momentum

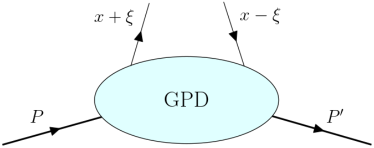


- Generalised Parton Distributions (GPD) give access to the 3D structure of a hadron
- GPDs encode the correlation between the longitudinal momentum of a parton and its position in the transverse plane

$$q^f(x, b_\perp) \xrightarrow{\int \mathrm{d}x} \textbf{Form factors}$$
$$q^f(x, b_\perp) \xrightarrow{\int \mathrm{d}b_\perp} \textbf{PDFs}$$



Generalised Parton Distributions

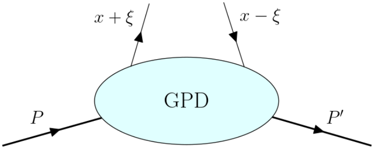


Definition of variables:
$q \ldots \gamma^*$ four-momentum
$x \ldots$ average longitudinal momentum fraction of initial and final parton
$\xi \ldots$ difference of longitudinal-momentum fraction between initial and final parton $\approx x_B/(2-x_B)$
$t \ldots$ four-momentum transfer

- In the leading twist there are:
  - 4 chiral-even GPDs (parton helicity conserved)
  - 4 chiral-odd (or transversity) GPDs (parton helicity flipped)

	Quark Polarisation		
Nucleon Polarisation	Unpolarised (U)	Longitudinally polarised (L)	Tranversely polarised (T)
U	H		$\bar{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

Generalised Parton Distributions



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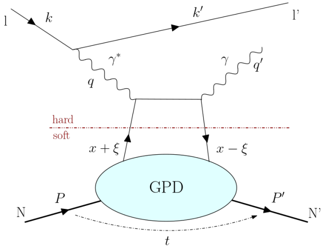
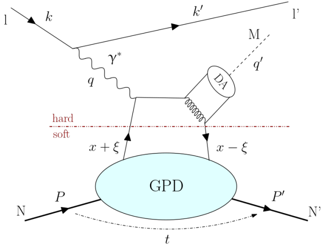
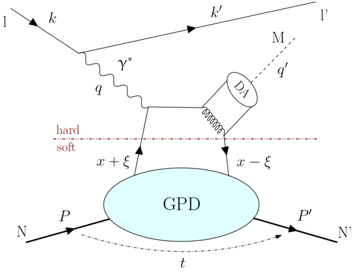




- Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)

GPDs enter the exclusive processes through Compton Form Factors in case of DVCS and Meson Production Form Factors in case of HEMP

Generalised Parton Distributions



Hard Exclusive Meson Production:

- Flavour separation for specific GPDs due to different partonic content of mesons
- DVCS sensitive to H^f, E^f, $\tilde{H}^f$, and $\tilde{E}^f$
- At the leading twist:
  - Pseudoscalar mesons production involves GPDs $\tilde{H}^f$, and $\tilde{E}^f$
  - Vector meson production involves H^f, and E^f
- All mesons are also sensitive to $\bar{E}_T^f = 2\tilde{H}_T^f + E_T^f$, and H_T^f
- This talk will concentrate on the π^0 production: $\mu p \to \mu' p' \pi^0$

Road to π^0 cross-section

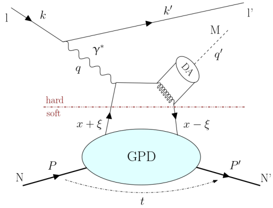
COMPASS measurement in 2012, and 2016/17 with μ^+ and μ^- beams of $E_\mu = 160$ GeV

Collected events corrected for:

- Luminosity of μ^+ and μ^- beams
- Background subtraction
- Acceptance of the experimental set-up
- Reduction of μp cross-section to $\gamma^* p$:

$$\frac{d^4\sigma_{\mu p}}{dQ^2 dt d\nu d\phi} = \Gamma \frac{d^2\sigma_{\gamma^* p}}{dt d\phi}$$

with the virtual photon flux
$\Gamma = \Gamma(E_\mu, Q^2, \nu)$



COMPASS 2012:

- 4 weeks → results published: PLB 805(2020) 135454

COMPASS 2016/17:

- 2×6 months

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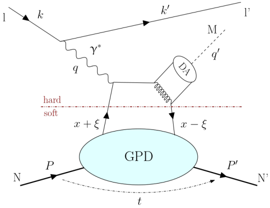

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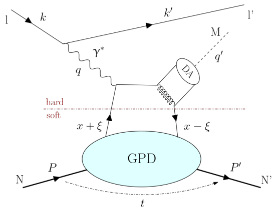

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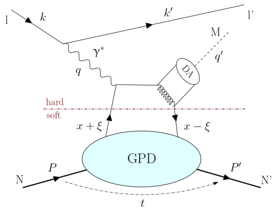

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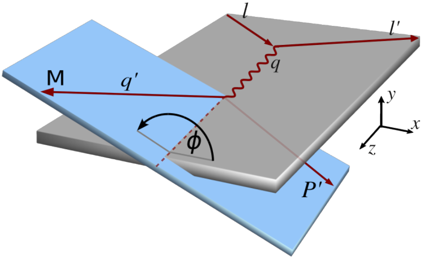
Exclusive π^0 cross section

HEMP cross-section, reduced to γ^*p, for the unpolarised target and polarised lepton beam (relevant for COMPASS 2012, 2016/2017 measurements):

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

ϵ is a kinematic factor, close to 1 in COMPASS kinematics

Factorization proven for σ_L, not for σ_T which is expected to be suppressed by a factor $1/Q^2$
BUT large contributions have been observed at JLab



Exclusive π^0 cross section

Spin independent HEMP cross-section after averaging the two spin-dependent cross-sections:

$$\frac{\mathrm{d}^2\sigma_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} = \frac{1}{2}\left(\frac{\mathrm{d}^2\sigma^{\leftarrow}_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} + \frac{\mathrm{d}^2\sigma^{\rightarrow}_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi}\right) =$$

$$\frac{1}{2\pi}\left[\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \epsilon\cos(2\phi)\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} + \sqrt{\epsilon(1+\epsilon)}\cos\phi\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}\right.$$

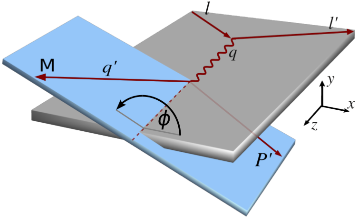
$$\left.\cancel{\mp|P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{\mathrm{d}\sigma'_{LT}}{\mathrm{d}t}}\right]$$

$\Rightarrow$ **study ϕ dependence**

After integration in ϕ:

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t}$$

$\Rightarrow$ **study t dependence**



Exclusive π^0 cross section

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

GPDs in exclusive π^0 production

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

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

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

$$\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\,\mathrm{Re}\left(\langle\mathcal{H}_T\rangle^*\langle\tilde{\mathcal{E}}\rangle\right)$$

Goloskokov and Kroll, EPJ-A 47 (2011) 112

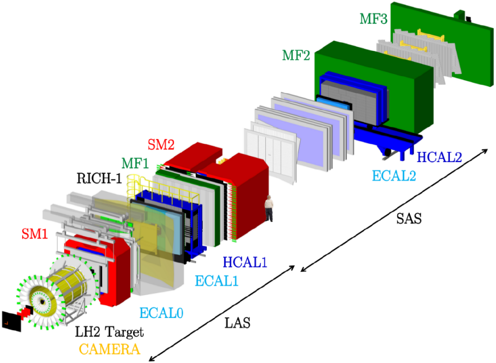
$t' = t - t_{min}$

Nucleon Polarisation \ Quark Polarisation	Unpolarised (U)	Longitudinally polarised (L)	Tranversely polarised (T)
U	H		$\bar{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

Impact of $\bar{E}_T$ should be visible in $\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t}$, and also a dip at small t of $\frac{\mathrm{d}\sigma_T}{\mathrm{d}t}$

COMPASS GPD programme

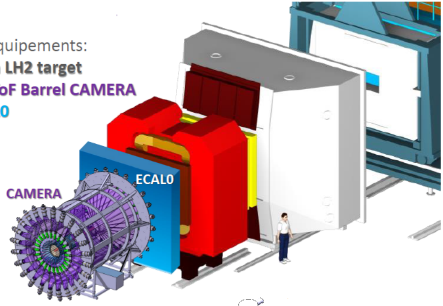
- Two stage magnetic spectrometer with large angular and momentum acceptance
- Versatile usage: hadron and muon beams
- Particle identification:
    - Ring Imaging Cherenkov (RICH) detector
    - Electromagnetic calorimeters (ECAL0, ECAL1, ECAL2)
    - Hadronic calorimeters (HCAL1, HCAL2)
    - 2 muon walls
- GPD program: 2012 pilot run, 2016/17 main measurement

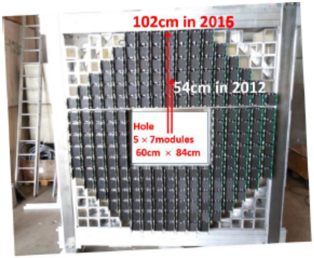


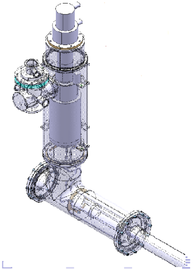
COMPASS GPD program

- Target ToF system:
  - 24 inner and outer scintillators
  - 1 GHz readout
  - 310 ps ToF resolution
- ECAL0 calorimeter:
  - shaslyk modules
  - 2 × 2 m, 2200 channels

New equipements:
- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0

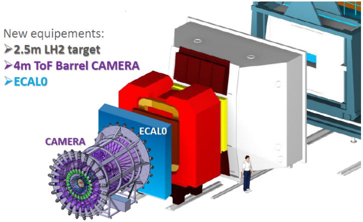






Exclusive π^0 production: Selection

- Incoming and outgoing μ connected to primary vertex
- Two photons in ECALs from π^0 decay
- Recoil proton candidate
- $1 < Q^2 < 8$ $(\mathrm{GeV}/c)^2$, $6.4 < \nu < 40$ GeV, $0.08 < |t| < 0.64$ $(\mathrm{GeV}/c)^2$



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- Transverse momentum constraint: $\Delta p_T = p^p_{T,spect} - p^p_{T,recoil}$
- $\Delta\varphi = \varphi^p_{spect} - \varphi^p_{recoil}$
- Z coordinate of inner CAMERA ring: $\Delta z = z^p_{spect} - z^p_{recoil}$
- Energy-momentum conservation: $M_X^2 = \left(p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0}\right)^2$
- Invariant mass $M_{\gamma\gamma}$ cut
- Kinematic fit of reaction $\mu p \to \mu' p' \pi^0$

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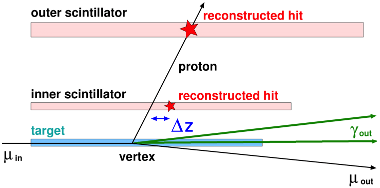

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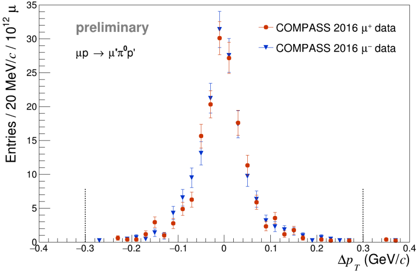

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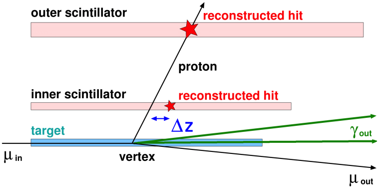

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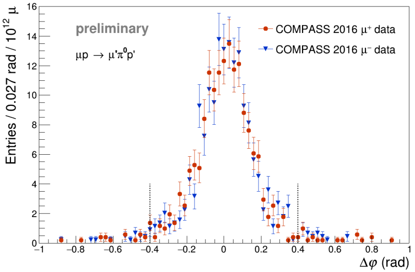

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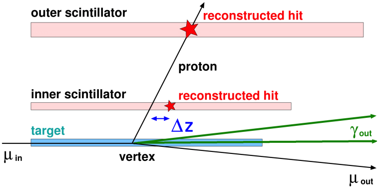

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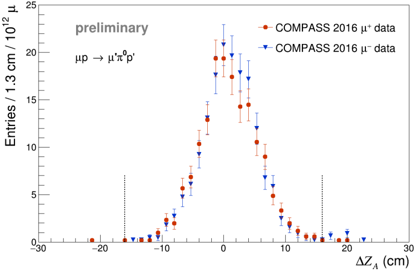

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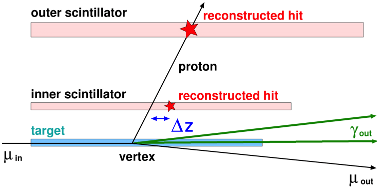

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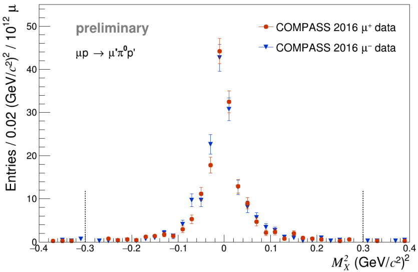

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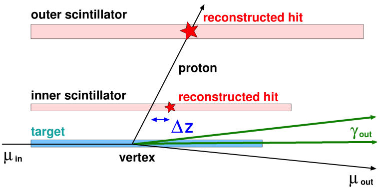

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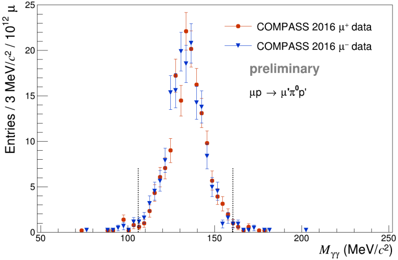

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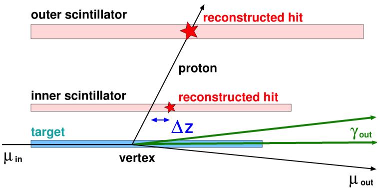
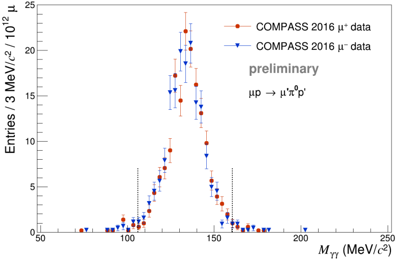


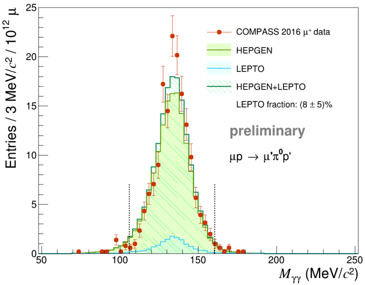
Selections for exclusive π^0 events:

- Transverse momentum constraint: $\Delta p_T = p^p_{T,spect} - p^p_{T,recoil}$
- $\Delta\varphi = \varphi^p_{spect} - \varphi^p_{recoil}$
- Z coordinate of inner CAMERA ring: $\Delta z = z^p_{spect} - z^p_{recoil}$
- Energy-momentum conservation: $M_X^2 = \left(p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0}\right)^2$
- Invariant mass $M_{\gamma\gamma}$ cut
- Kinematic fit of reaction $\mu p \to \mu' p' \pi^0$



Exclusive π^0 production: SIDIS background estimation

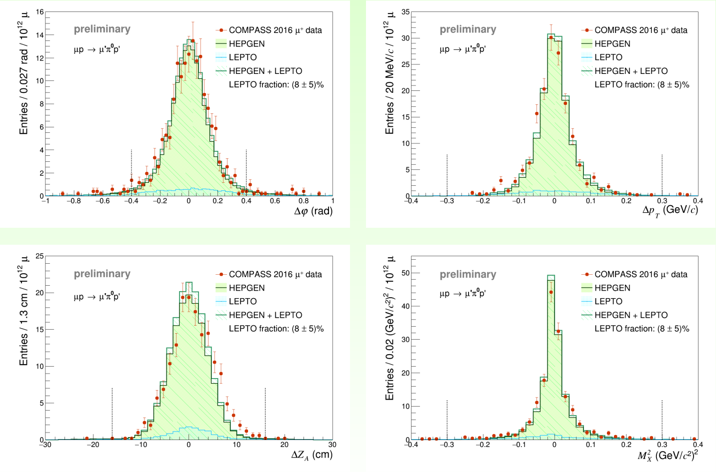
- Main background of π^0 production $\Rightarrow$ non-exclusive DIS processes
- 2 Monte Carlo simulations with the same π^0 selection criteria:
  - LEPTO for the non-exclusive background
  - HEPGEN++ shape of distributions of exclusive π^0 production (signal contribution)
- Both MC samples normalised to the experimental $M_{\gamma\gamma}$ distribution
- The fraction of background events r_{LEPTO} from fitting MC mixture on the exclusivity distributions



- Fraction of non-exclusive background in data $\Rightarrow$ $(8 \pm 5)\,\%$
- Background fit method is the main source of systematic uncertainty

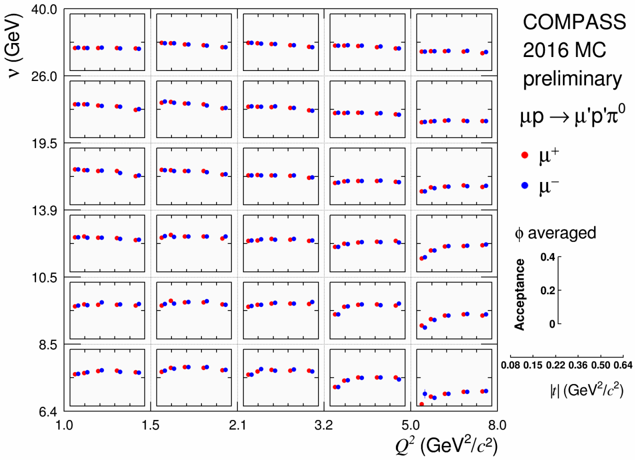
Exclusive π^0 production: SIDIS background estimation

Exclusive variables



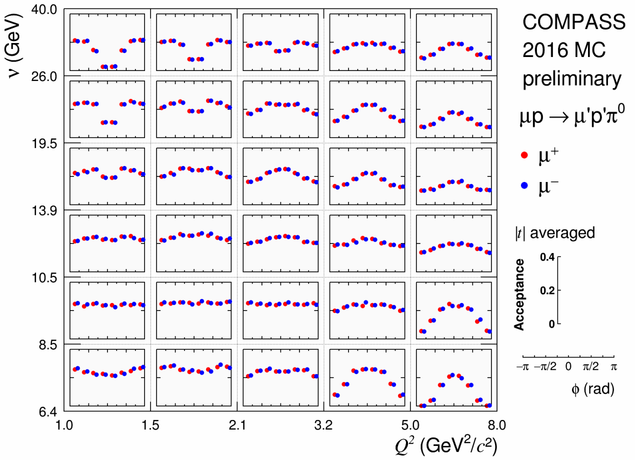
Exclusive π^0 production: COMPASS acceptance

- 4D acceptance in bins of ϕ_{π^0}, ν, $|t|$, Q^2
- figure shows 3D projection, as a function of $|t|$



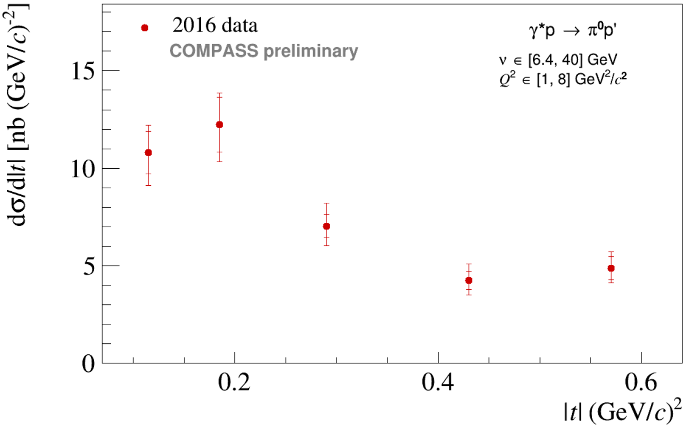
Exclusive π^0 production: COMPASS acceptance

- 4D acceptance in bins of ϕ_{π^0}, ν, $|t|$, Q^2
- figure shows 3D projection, as a function of ϕ_{π^0}



Exclusive π^0 cross-section as a function of $|t|$

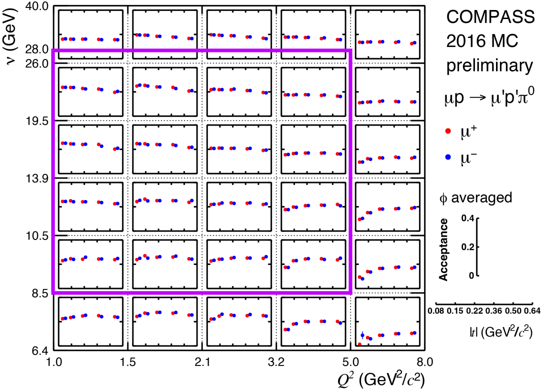
- Differential $\gamma^* p \to p' \pi^0$ cross-section as function of $|t|$, integrated over ϕ
- Newest 2016 data release



Exclusive π^0 cross-section as a function of $|t|$

- Differential $\gamma^* p \to p' \pi^0$ cross-section as function of $|t|$, integrated over ϕ
- Newest 2016 data release

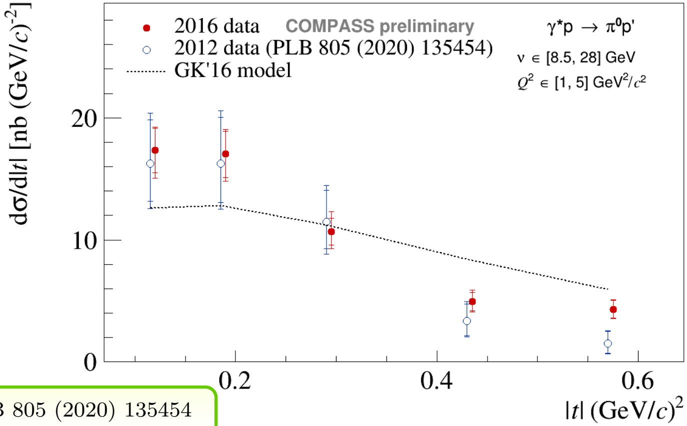
- For comparison with the results from 2012 (PLB 805 (2020) 135454), 2016 data analysed in a smaller kinematic domain:
- $8.5 < \nu < 28$ GeV, $1 < Q^2 < 5$ (GeV$/c)^2$, $0.08 < |t| < 0.64$ (GeV$/c)^2$



Exclusive π^0 cross-section as a function of $|t|$

- Differential $\gamma^* p \to p'\pi^0$ cross-section as function of $|t|$, integrated over ϕ
- Newest 2016 data release

Goloskokov&Kroll model EPJ A47 (2011) 112

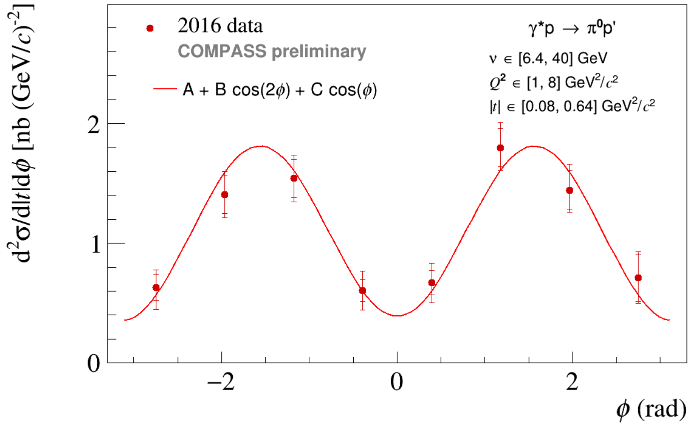


○ PLB 805 (2020) 135454

Exclusive π^0 cross-section as a function of ϕ

- Newest 2016 data release
- Differential $\gamma^* p \to p' \pi^0$ cross-section as function of ϕ, averaged over $|t|$:

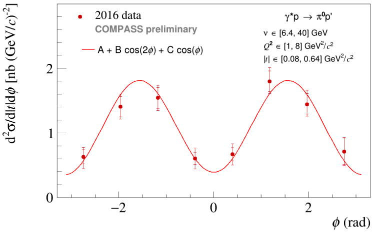
$$\frac{d^2\sigma_{\gamma^* p}}{dt d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$



Exclusive π^0 cross-section as a function of ϕ

- Newest 2016 data release
- Differential $\gamma^* \mathrm{p} \to \mathrm{p}'\pi^0$ cross-section as function of ϕ, averaged over $|t|$:

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



$$\left\langle \frac{\sigma_{\mathrm{T}}}{|t|} + \epsilon\frac{\sigma_{\mathrm{L}}}{|t|} \right\rangle = (6.9 \pm 0.3_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

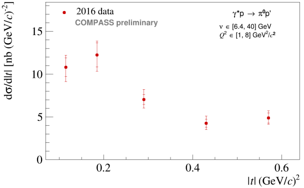
$$\left\langle \frac{\sigma_{\mathrm{TT}}}{|t|} \right\rangle = (-4.5 \pm 0.5_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

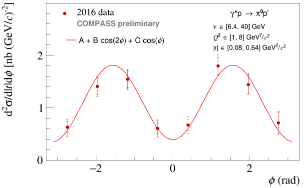
$$\left\langle \frac{\sigma_{\mathrm{LT}}}{|t|} \right\rangle = (0.06 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

Summary

$|t|$-dependence and ϕ-dependence of exclusive π^0 cross-section on unpolarised proton target:

- New, preliminary 2016 COMPASS results at low ξ (or $\langle x_B \rangle = 0.134$), input for constraining phenomenological models (Goloskokov&Kroll, Goldstein&Liuti)



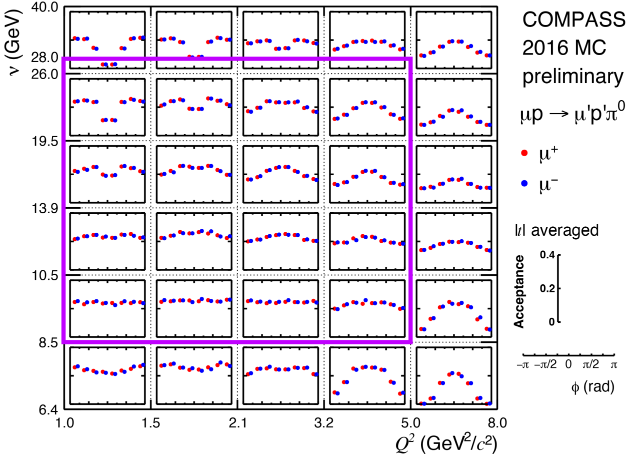


- Statistics of 2016 about 2.3× larger than of published results from 2012 pilot run
- The whole collected 2016/2017 statistics $\sim 9\times$ larger then 2012 $\rightarrow$ planned to process all available data and head towards publication of 2016 and then combined 2016/2017 results

SPARES

Exclusive π^0 cross-section as a function of ϕ

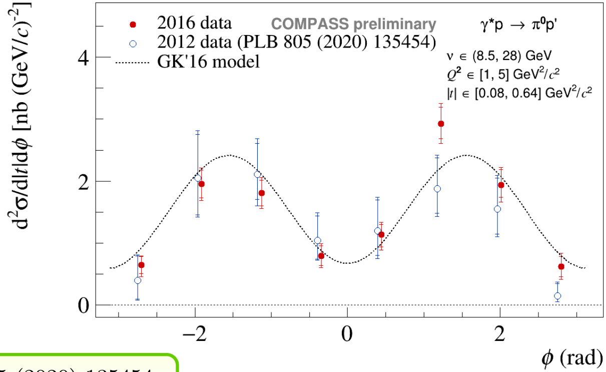
- In order to compare with the results from 2012 (PLB 805 (2020) 135454), the 2016 data were analysed in a smaller kinematic domain
- $8.5 < \nu < 28$ GeV, $1 < Q^2 < 5$ $(\mathrm{GeV}/c)^2$, $0.08 < |t| < 0.64$ $(\mathrm{GeV}/c)^2$



Exclusive π^0 cross-section as a function of ϕ

- Differential $\gamma^* p \to p' \pi^0$ cross-section as function of ϕ, averaged over $|t|$ in the smaller kinematic domain:

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



- PLB 805 (2020) 135454

Kinematic fit

- Measurement of exclusive processes at COMPASS is overconstrained $\rightarrow$ can be used to improve precision of kinematic quantities using kinematically constrained fit
- Kinematic fit improves the resolution of the signal and lowers the background
- It works in a principle of minimisation of least square function $\chi^2(\vec{k}) = (\vec{k}_{fit} - \vec{k})^T \hat{C}^{-1} (\vec{k}_{fit} - \vec{k})$, where $\vec{k}$ is a vector of measured quantities and $\hat{C}$ is their covariance matrix
- Method used for the minimisation is Lagrange multipliers with constraints g_i:
$$L(\vec{k}, \vec{\alpha}) = \chi^2(\vec{k}) + 2 \sum_{i=1}^{N} \alpha_i g_i$$
- Constraints include momentum and energy conservation, common vertex for all tracks (except proton), constraints for final proton, and mass constraint

Past and future GPD measurements