Exclusive π^0 muoproduction measurements at COMPASS

Markéta Pešková (Charles University, Prague)

on behalf of the COMPASS at CERN

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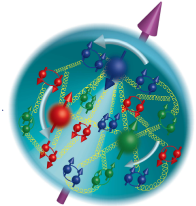
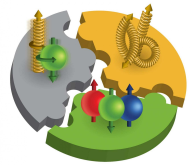
Generalised Parton Distributions

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

Jaffe&Manohar Nucl. Phys. B337 (1990)



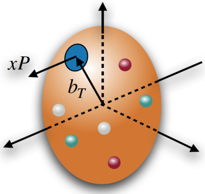
COMPASS experiment in μp DIS: $\Delta\Sigma = 0.32 \pm 0.03$
COMPASS Collaboration: Phys. Lett. B 693 (2010)
COMPASS, RHIC results: $\Delta G = 0.2^{+0.06}_{-0.07}$
de Florian et al.Phys.Rev.Lett. 113 (2014) no.1, 012001
Missing component: $L_{q,g} = ?$ → GPDs provides access



- 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

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

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



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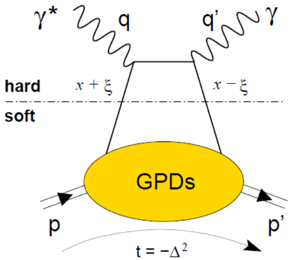


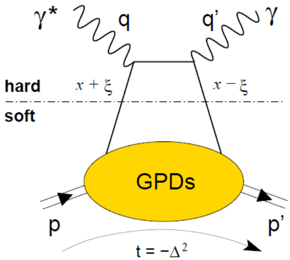
Definition of variables:
q ... γ^* four-momentum
x ... average longitudinal momentum fraction of initial and final parton (NOT accessible)
ξ ... difference of longitudinal-momentum fraction between initial and final parton $\approx x_B/(2-x_B)$
t ... four-momentum transfer

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

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

GPDs enter the exclusive processes through Compton Form Factors (CFF)

Generalised Parton Distributions



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L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T, $\tilde{H}_T$

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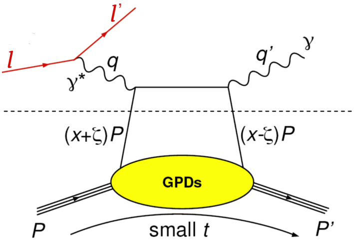
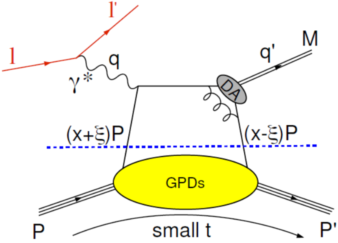
Generalised Parton Distributions

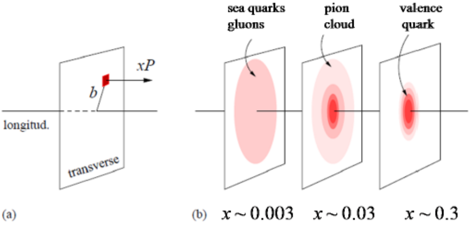




- Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)
- DVCS on an unpolarised proton target at small x_B gives access to GPD H $\rightarrow$ 3D imaging of a hadron

$$q_f(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp b_\perp} H_f(x, 0, -\Delta_\perp)$$

Burkardt PRD66 (2002)



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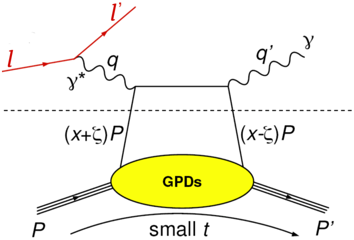
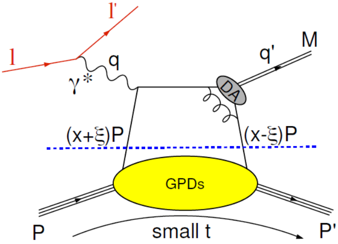
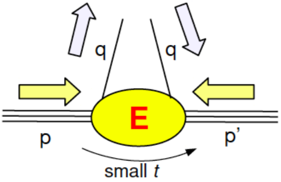


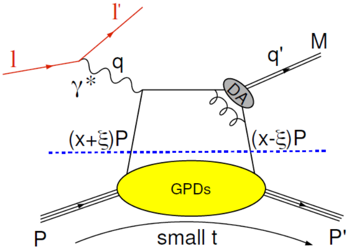


- Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)
- DVCS off neutrons, or DVCS or HEMP on transverse polarised proton target gives access to GPD E → helps constraining the total angular momentum of partons

$$J^f = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x\, x [H^f(x, \xi, t) + E^f(x, \xi, t)]$$

Phys. Rev. Lett. 78 (1997)





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

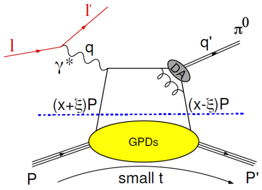
COMPASS measurement in 2012, and 2016/17 with μ^+ and μ^- beams of $E_\mu = 160$ GeV

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 $\rightarrow$ results published: PLB 805(2020) 135454

COMPASS 2016/17:

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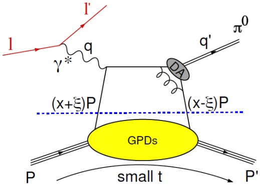

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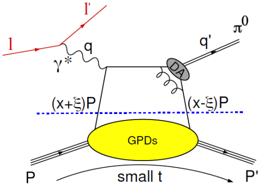

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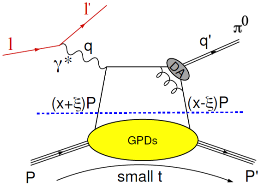

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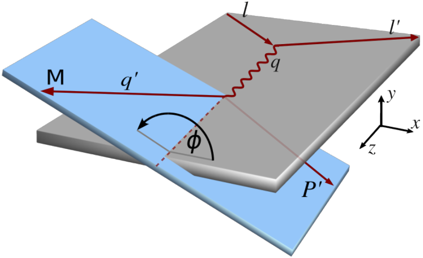
π^0 cross section

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

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

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



π^0 cross section

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

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

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

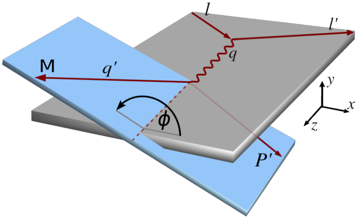
$$\left.\cancel{\mp |P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{\mathrm{d}\sigma'_{LT}}{\mathrm{d}t}}\right]$$

⇒ study ϕ dependence

After integration in ϕ:

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

⇒ study t dependence



π^0 cross section

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

GPDs in exclusive π^0 production

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

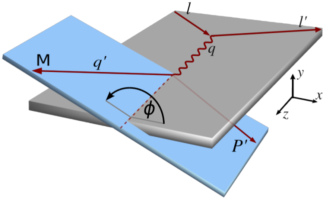
$$\frac{d\sigma_T}{dt} \propto \left[(1-\xi^2)\,|\langle\mathcal{H}_T\rangle|^2 - \frac{t'}{8M^2}|\langle\bar{\mathcal{E}}_T\rangle|^2\right]$$

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

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

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

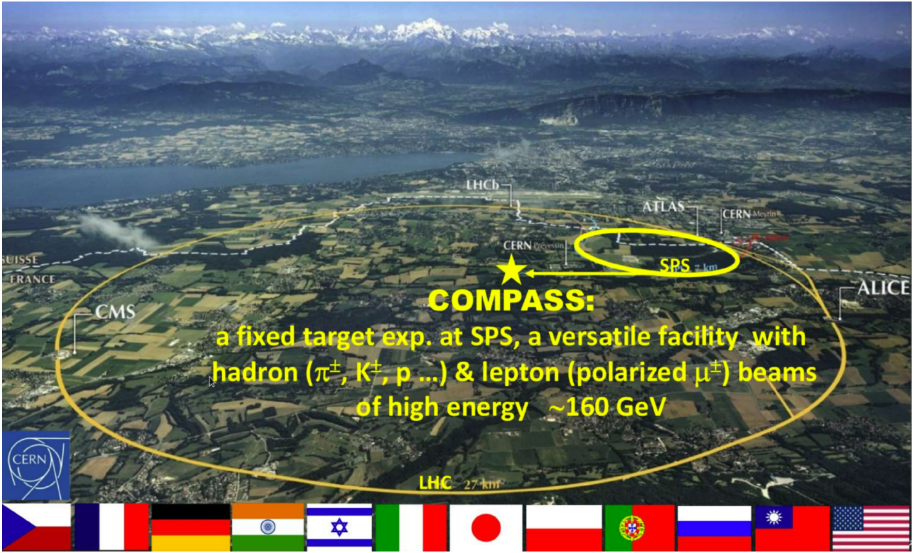
$t' = t - t_{min}$



$\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx\frac{H(x,\xi,t)}{x-\xi} + i\pi H$

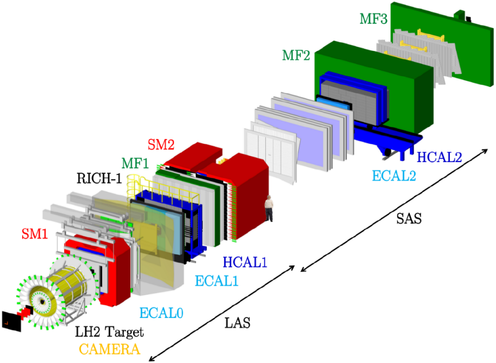
Impact of $\bar{E}_T$ should be visible in $\frac{d\sigma_{TT}}{dt}$, and also a dip at small t of $\frac{d\sigma_T}{dt}$

COMPASS experiment



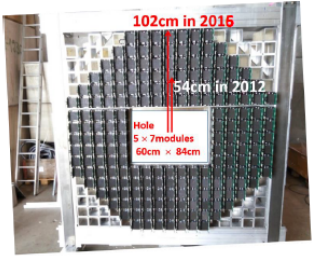
COMPASS GPD programme

- 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

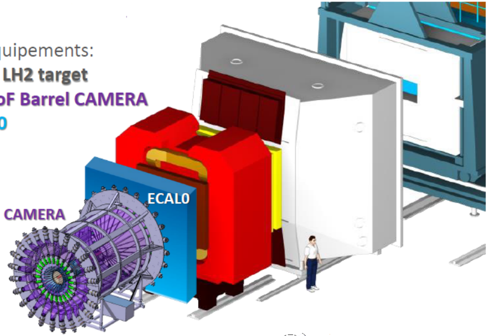


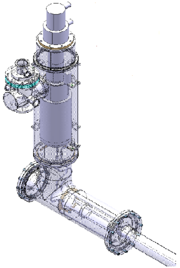
COMPASS GPD program

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



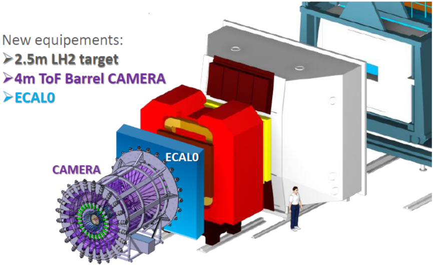
New equipements:
- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0





Exclusive π^0 production: Selection

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



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: $M_X^2 = (p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0})^2$
- Invariant mass $M_{\gamma\gamma}$ cut
- Kinematic fit of reaction $\mu p \to \mu' p' \pi^0$

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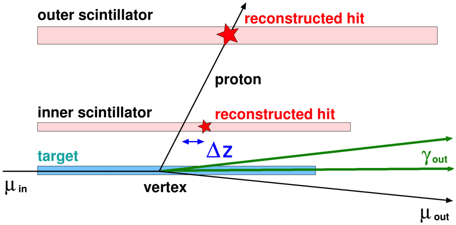

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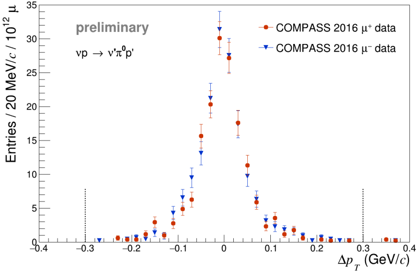

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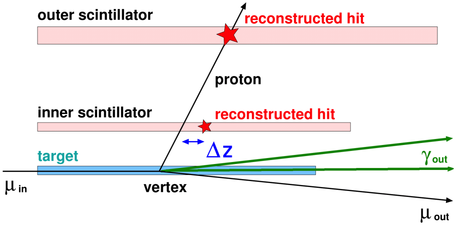

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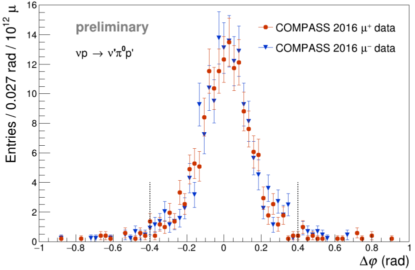

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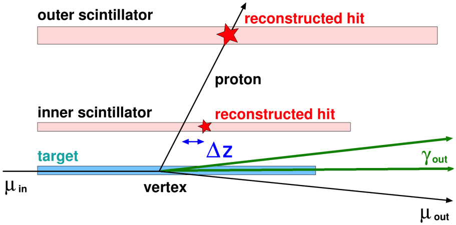

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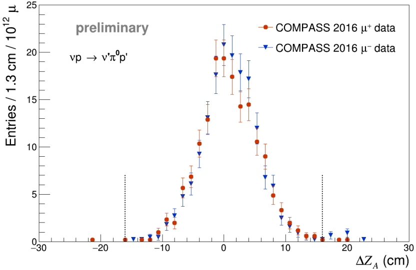

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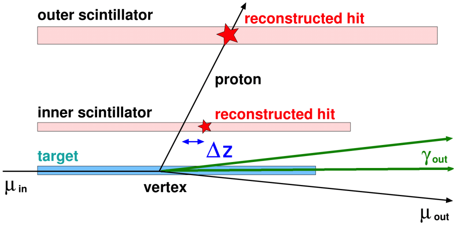

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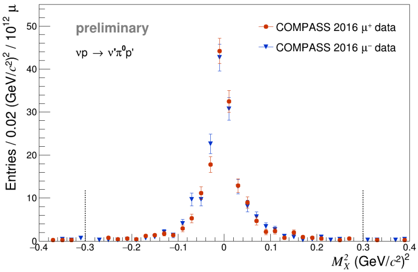
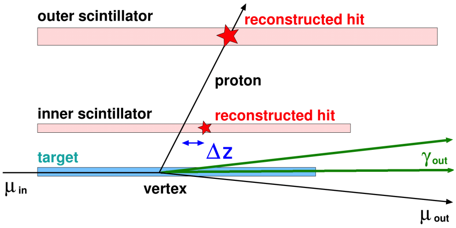
- Kinematic fit of reaction $\mu p \to \mu' p' \pi^0$



Exclusive π^0 production: Selection

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



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: $M_X^2 = (p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0})^2$
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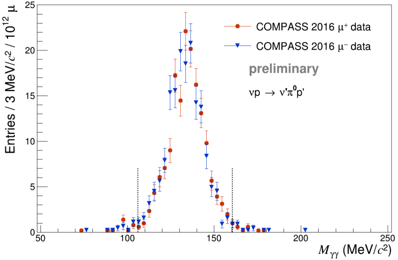

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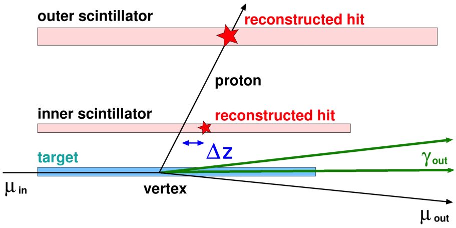

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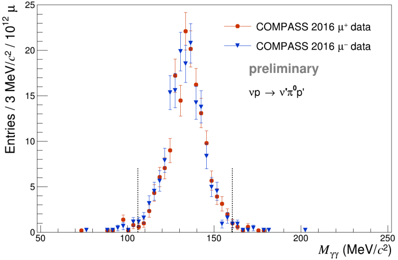
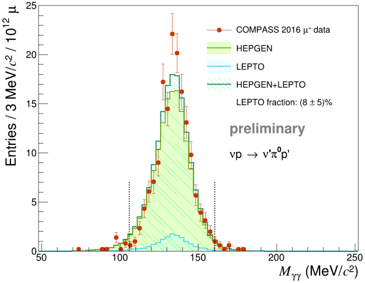


Exclusive π^0 production: SIDIS background estimation

- 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)
- Search for best description of data fitting by mixture of both MC
- Both MC samples normalised to the experimental $M_{\gamma\gamma}$ distribution
- The fraction of background events r_{LEPTO} is determined by a fit on the exclusivity distributions

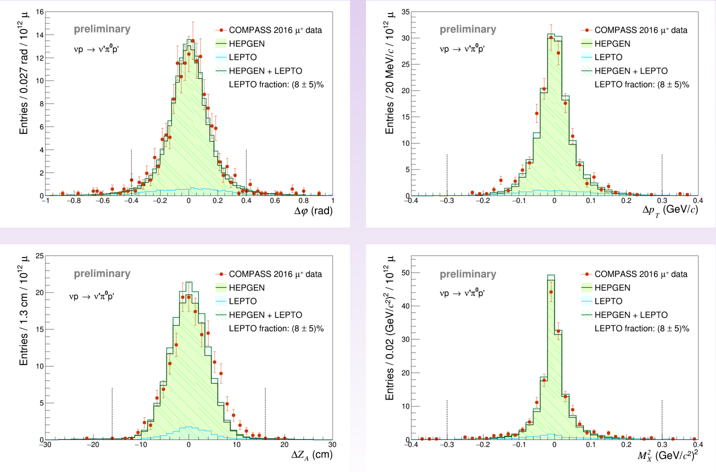


- Fraction of non-exclusive background in data $\Rightarrow$ $(8 \pm 5)\,\%$
- Background fit method is the main source of systematic uncertainty

Exclusive π^0 production: SIDIS background estimation

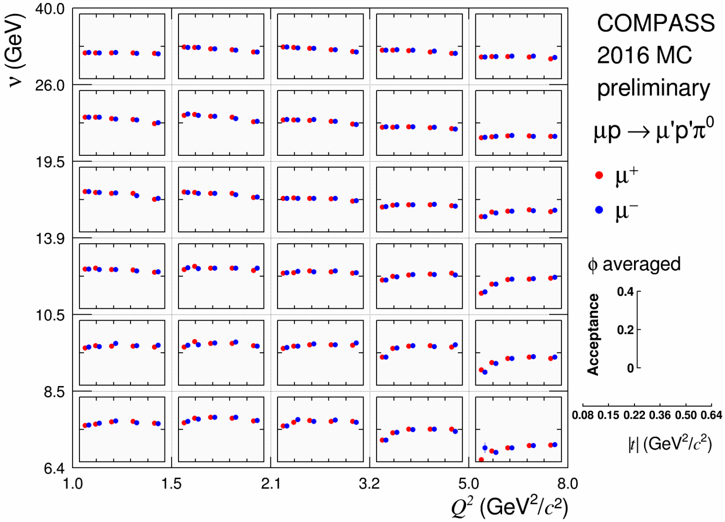
- Main background of π^0 production $\Rightarrow$ non-exclusive DIS processes

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

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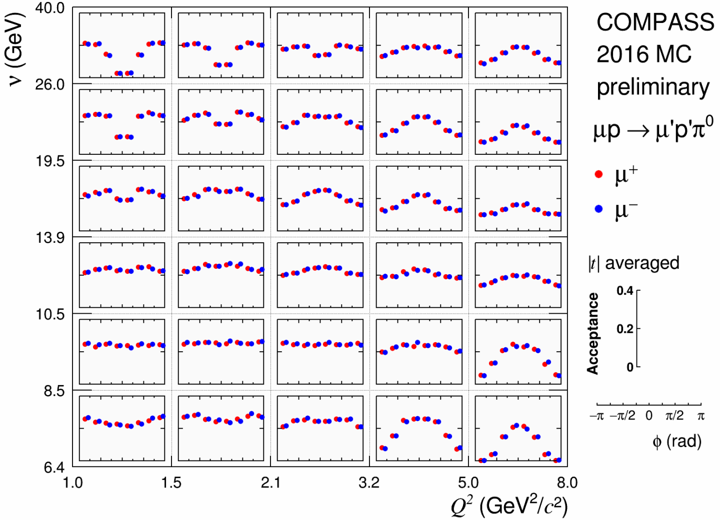
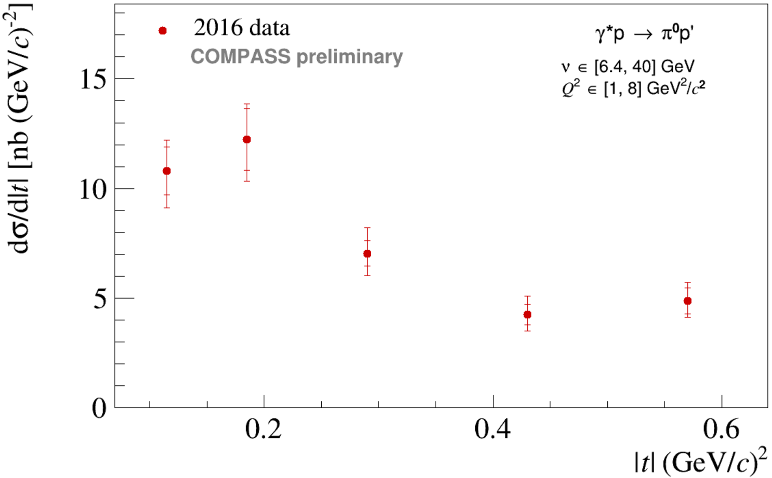


Exclusive π^0 cross-section as a function of $|t|$

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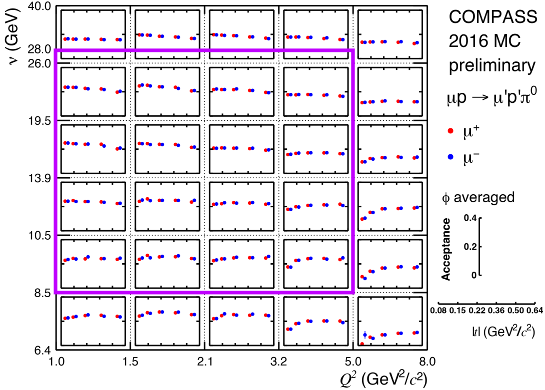
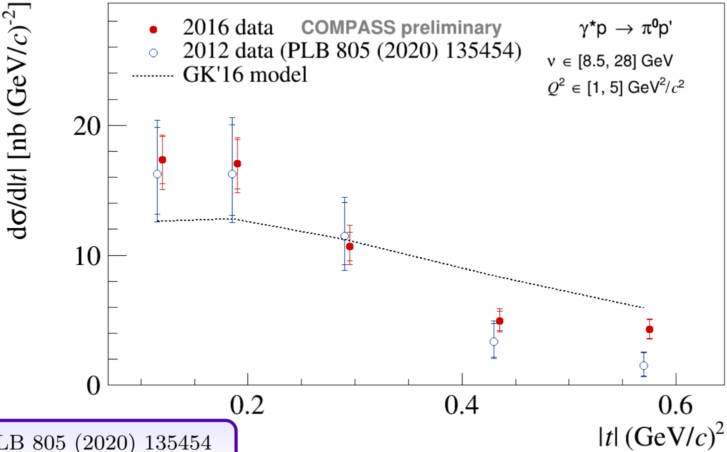
- For comparison with the results from 2012 (PLB 805 (2020) 135454), the 2016 data also analysed in a smaller kinematic domain
- $8.5 < \nu < 28$ GeV, $1 < Q^2 < 5$ $(\mathrm{GeV}/c)^2$, $0.08 < |t| < 0.64$ $(\mathrm{GeV}/c)^2$



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

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

Goloskokov&Kroll model EPJ A47 (2011) 112

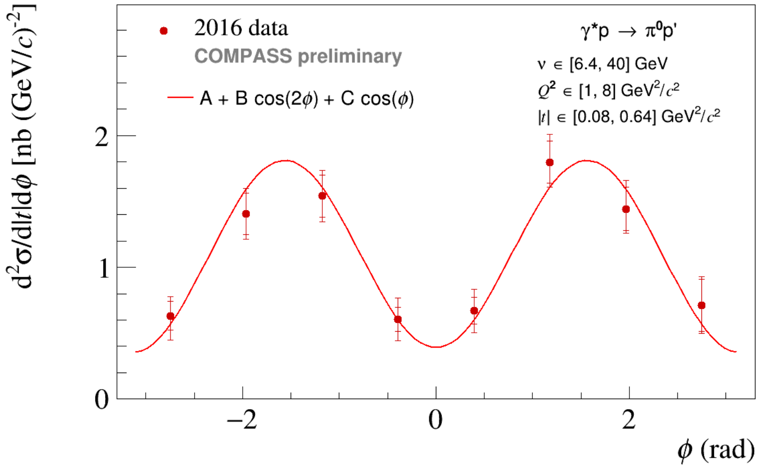


○ PLB 805 (2020) 135454

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 $|t|$:

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



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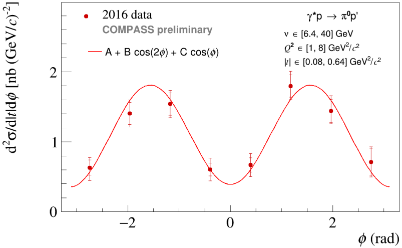
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} = \frac{1}{2\pi}\left[\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \epsilon\cos(2\phi)\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} + \sqrt{\epsilon(1+\epsilon)}\cos\phi\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}\right]$$



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

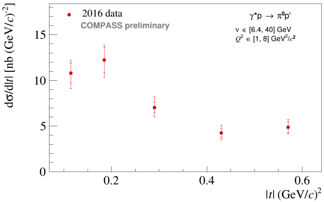
$$\left\langle\frac{\sigma_{\mathrm{TT}}}{|t|}\right\rangle = (-4.5 \pm 0.5_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

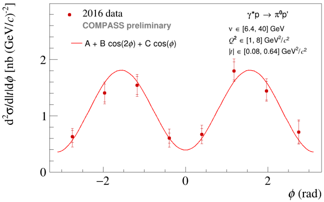
$$\left\langle\frac{\sigma_{\mathrm{LT}}}{|t|}\right\rangle = (0.06 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

Summary

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

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





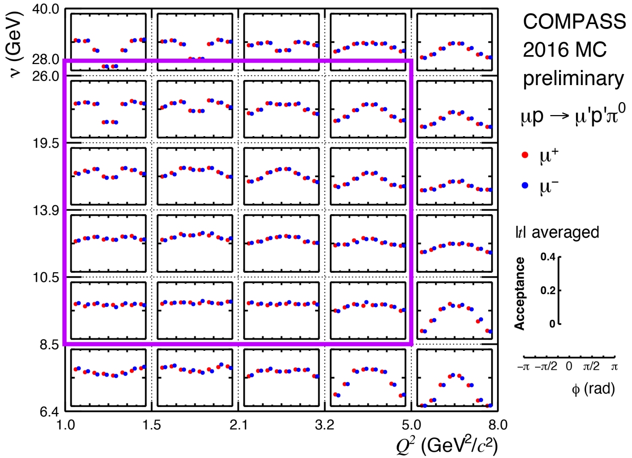
- Statistics of 2016 shown here is about $2.3\times$ larger than of published results from 2012 pilot run (PLB 805 (2020) 135454)
- The whole collected 2016/2017 statistics $\sim 9\times$ larger then 2012 $\rightarrow$ plan to process all available data
- Heading towards publication of 2016 and then combined 2016/2017 results soon

Thank you for your attention!

SPARES

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

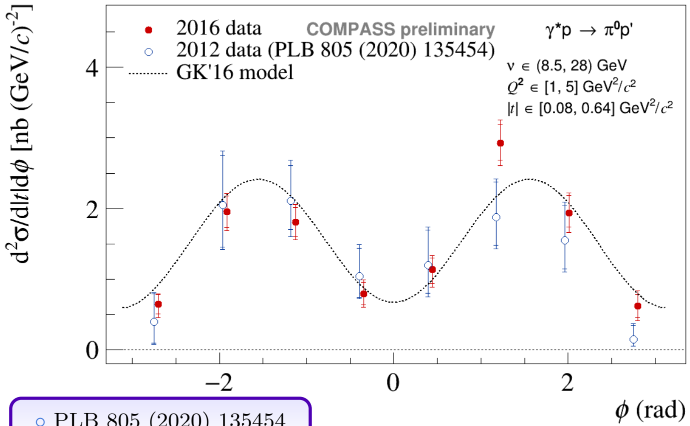
- In order to compare with the results from 2012 (PLB 805 (2020) 135454), the 2016 data were also analysed in a smaller kinematic domain
- $8.5 < \nu < 28$ GeV, $1 < Q^2 < 5$ (GeV/c)^2, $0.08 < |t| < 0.64$ (GeV/c)^2



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