Exclusive π^0 muoproduction at COMPASS

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on behalf of the COMPASS collaboration

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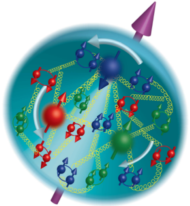
Generalised Parton Distributions

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

Jaffe&Manohar Nucl. Phys. B337 (1990)



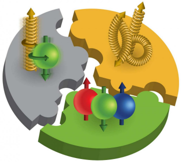
COMPASS experiment in μp DIS: $\Delta\Sigma = 0.32 \pm 0.03$

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

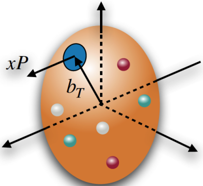
Missing component: $L_{q,g} = ?$ → GPDs provides access



- 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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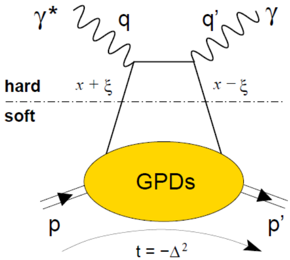


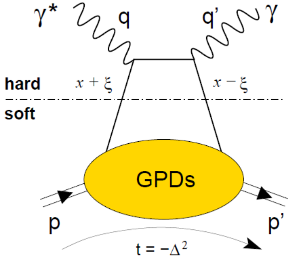
Definition of variables:
q ... γ^* four-momentum
x ... average longitudinal momentum fraction of initial and final parton (NOT accessible)
ξ ... difference of longitudinal-momentum fraction between initial and final parton $\approx x_B/(2-x_B)$
t ... four-momentum transfer

- 4 chiral-even GPDs (parton helicity conserved)
- 4 chiral-odd (or transversity) GPDs (parton helicity flipped)

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

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

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



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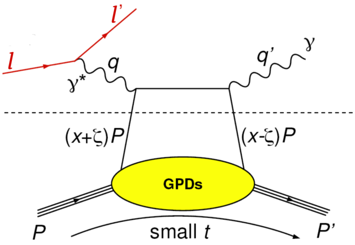
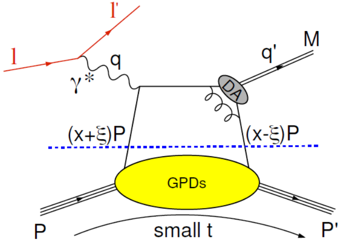
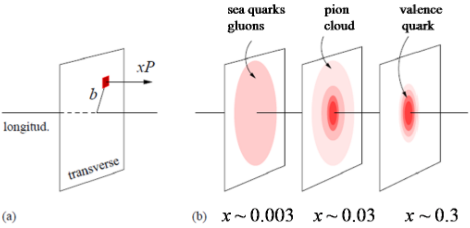
Generalised Parton Distributions



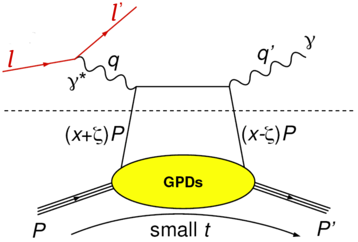


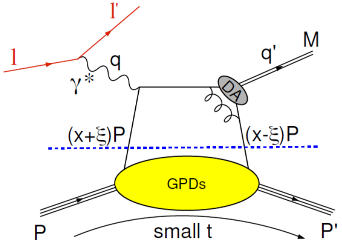
- Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)
- DVCS on an unpolarised proton target gives access to GPD $H \rightarrow$ 3D imaging of a hadron

$$H^q(x, \xi = 0, t) = \rho^q(x, b_\perp)$$ (Burkardt 2000, 2003)



Generalised Parton Distributions

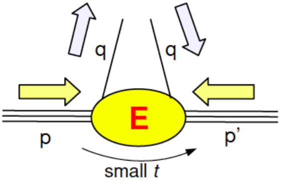


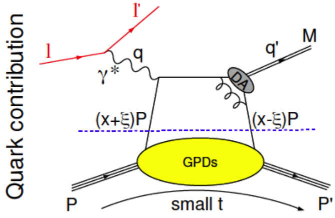


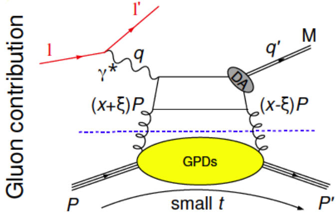
- Most commonly used processes for GPDs parametrisation are Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP)
- DVCS on neutron target, or DVCS or HEMP on transverse polarised proton target gives access to GPD E $\rightarrow$ helps constraining the total angular momentum 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
- Gluon and quark contributions at the same order in α_s for vector mesons
- DVCS sensitive to H^f, E^f, $\tilde{H}^f$, and $\tilde{E}^f$
- At the leading twist:
  - Vector meson production sensitive to H^f, and E^f
  - Pseudoscalar mesons production is described by GPDs $\tilde{H}^f$, and $\tilde{E}^f$
- Both vector meson and pseudoscalar mesons (as the π_0 presented in this talk) are also sensitive to $\bar{E}^f_T = 2\tilde{H}^f_T + E^f_T$, and H^f_T

Road to HEMP cross-section

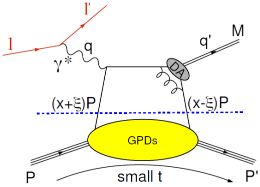
COMPASS measurement in 2012, and 2016/17 with μ^+ and μ^- beams of $E_\mu = 160$ GeV

Collected events corrected for:

- Luminosity of μ^+ and μ^- beams
- Background subtraction
- Acceptance of the spectrometer
- 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:

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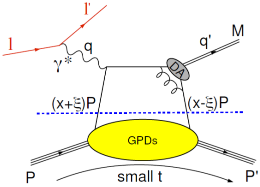

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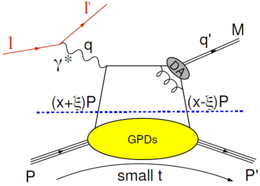

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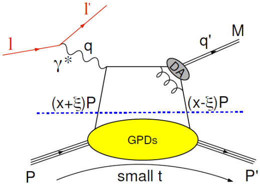

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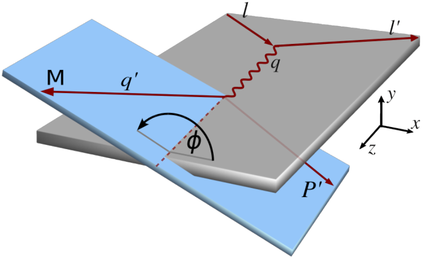
HEMP cross-section, reduced to $\gamma^* p$, for the unpolarised target and polarised lepton beam (relevant for COMPASS 2012, 2016/2017 measurements):

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

$$\mp |P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{d\sigma'_{LT}}{dt}\Big]$$

$$\epsilon = \frac{1 - y - \frac{y^2\gamma^2}{4}}{1 - y + \frac{y^2}{2} + \frac{y^2\gamma^2}{4}}$$

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



HEMP cross section

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

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

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

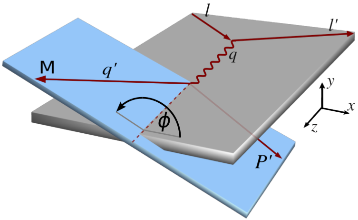
$$\left.\mp|P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{\mathrm{d}\sigma'_{LT}}{\mathrm{d}t}\right]$$

⇒ 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



HEMP cross section

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

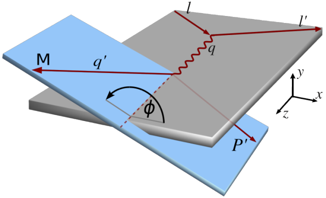
GPDs in exclusive π^0 production

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

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

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

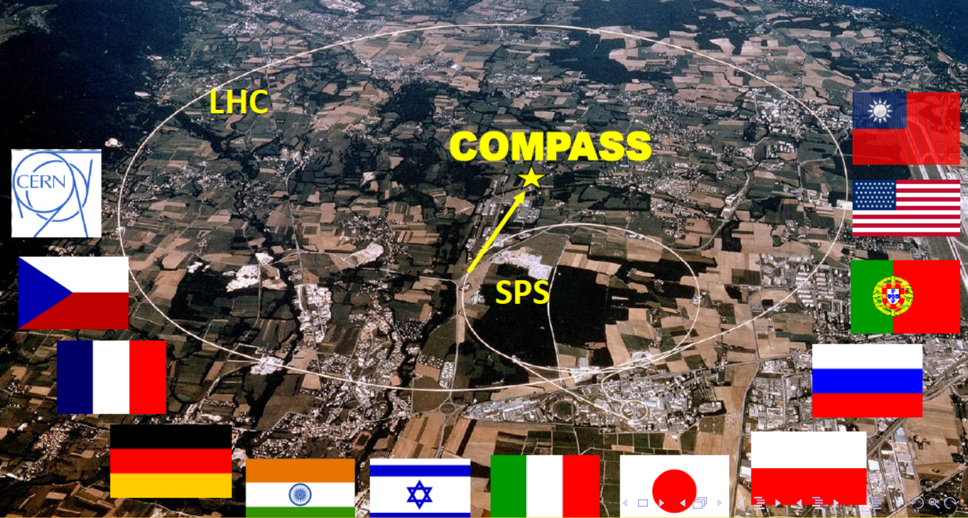
$$\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\,\mathrm{Re}\,(\langle\mathcal{H}_T\rangle^*\langle\tilde{\mathcal{E}}\rangle)$$



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 $\frac{\mathrm{d}\sigma_T}{\mathrm{d}t}$

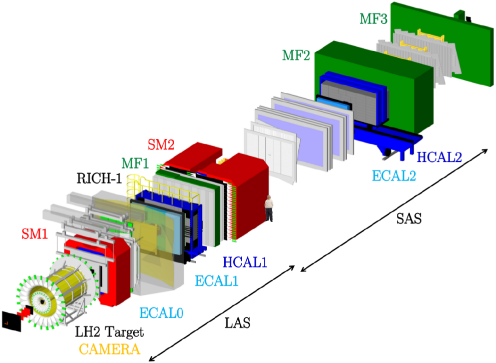
$t' = t - t_{min}$, t_{min} is the minimum value of $|t|$

COMPASS: Versatile facility to study QCD with hadron ($\pi^{\pm}$, $K^{\pm}$, p ...) and lepton (polarized $\mu^{\pm}$) beams of ~200 GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP...



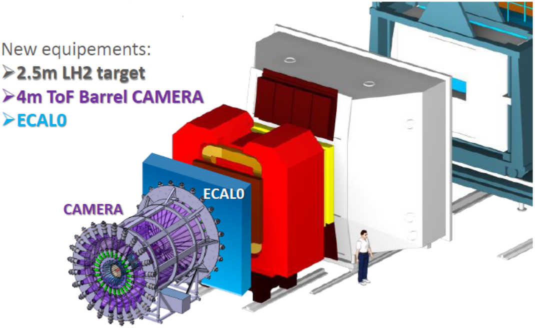
COMPASS GPD program

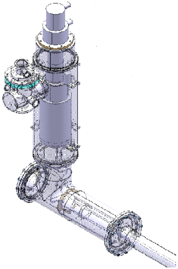
- Two stage magnetic spectrometer with large angular and momentum acceptance
- Versatile usage: hadron and muon beams
- Particle identification:
  - Ring Imaging Cherenkov (RICH) detector
  - Electromagnetic calorimeters (ECAL0, ECAL1, ECAL2)
  - Hadronic calorimeters (HCAL1, HCAL2)
  - 2 muon walls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

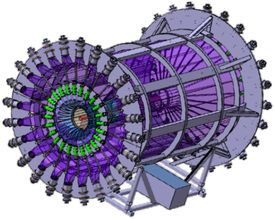


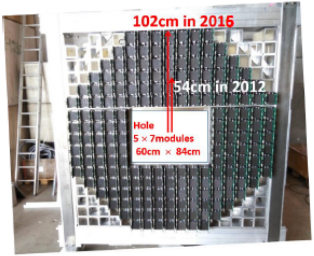
COMPASS GPD program

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



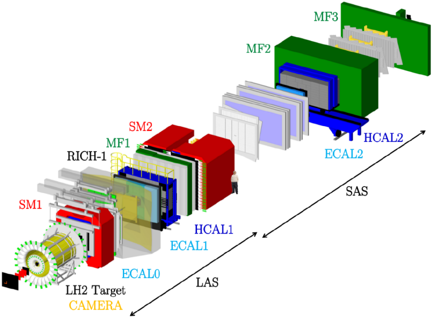






Exclusive π^0 production: Selection

- Incoming and outgoing μ connected to primary vertex
- Two photons in ECALs from π^0 decay, attached to the vertex
- Recoil proton candidate
- $1 < Q^2 < 5\ (\mathrm{GeV}/c)^2$, $8.5 < \nu < 28$ 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: $M_X^2 = \left(p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0}\right)^2$
- Invariant mass $M_{\gamma\gamma}$ cut

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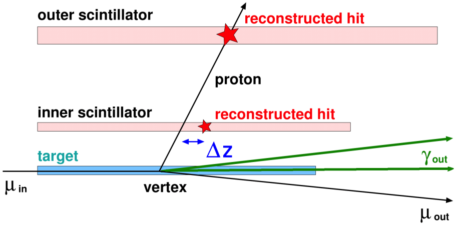

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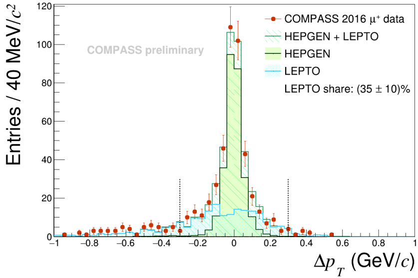

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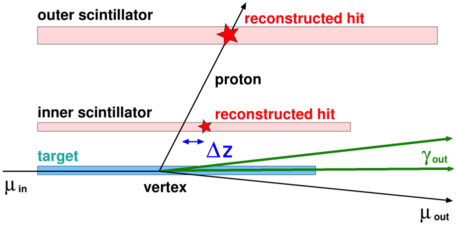

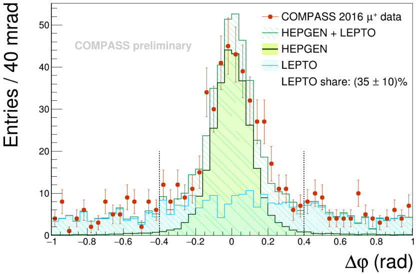

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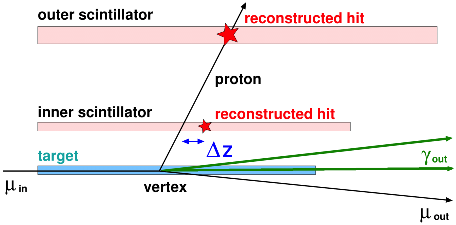

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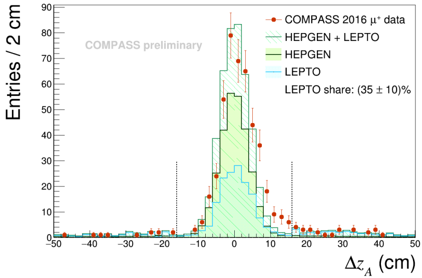

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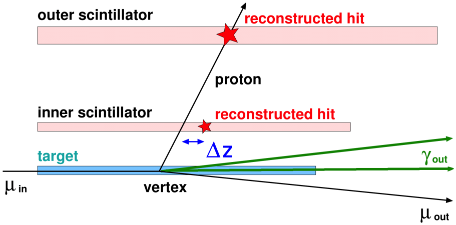
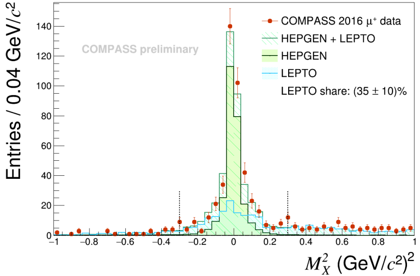
- $1 < Q^2 < 5\ (\mathrm{GeV}/c)^2$, $8.5 < \nu < 28$ GeV, $0.08 < |t| < 0.64\ (\mathrm{GeV}/c)^2$



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



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
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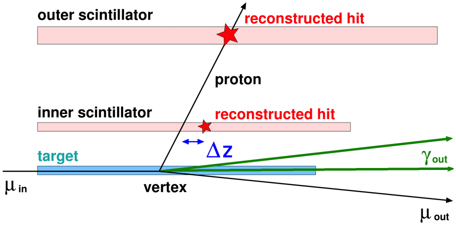

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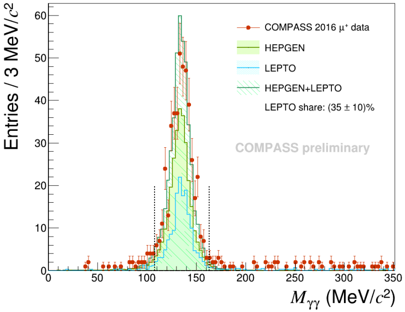

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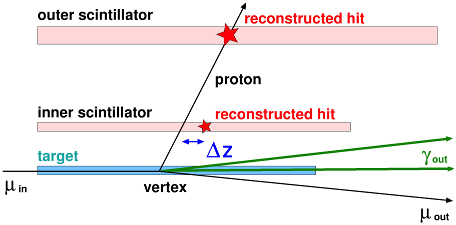

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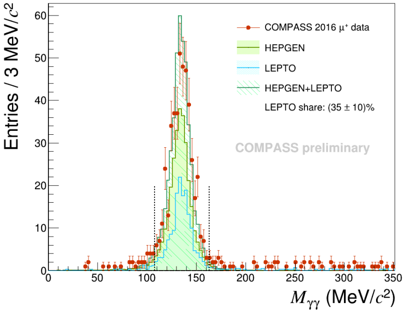
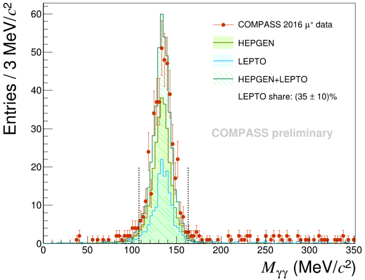


Exclusive π^0 production: SIDIS background estimation

- 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 ratio of background events r_{LEPTO} is determined by a fit on the exclusivity distributions



- Resulting fraction of non-exclusive background in data $\Rightarrow$ $(35 \pm 10)\,\%$
- Background fit method is currently the main source of systematic uncertainty

Exclusive π^0 production: SIDIS background estimation

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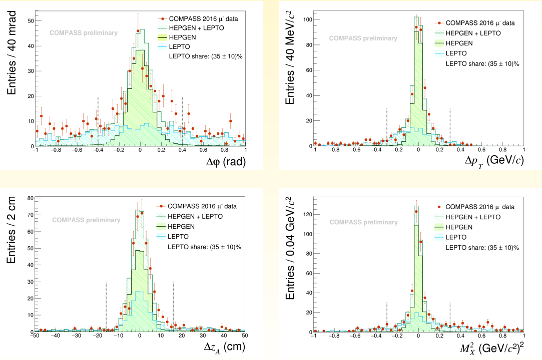
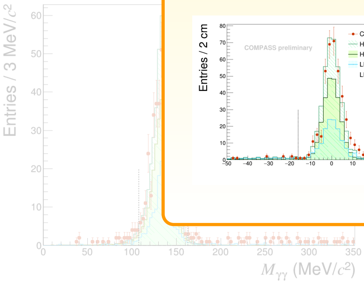
Exclusive variables



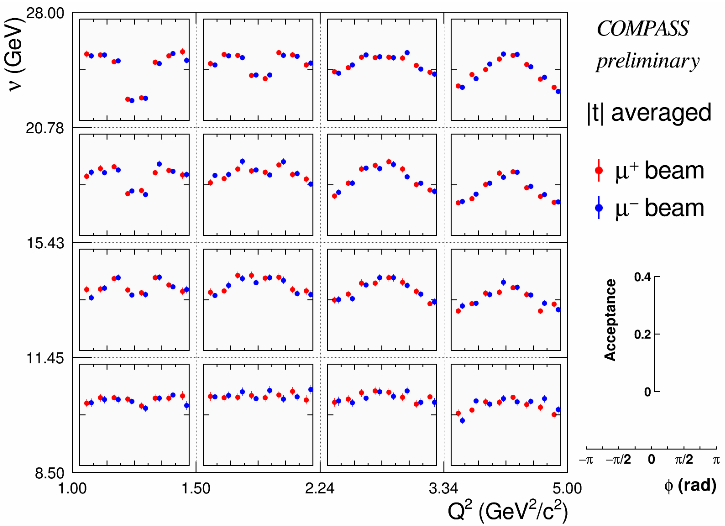


$(35 \pm 10)\,\%$

uncertainty

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 production: COMPASS acceptance

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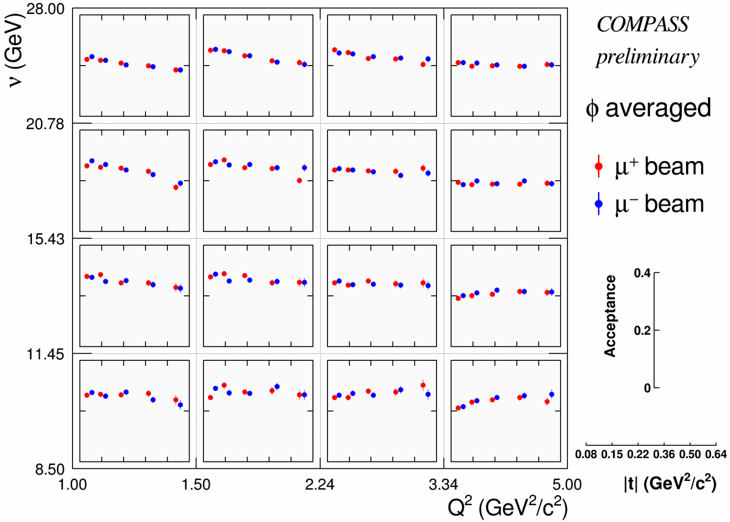
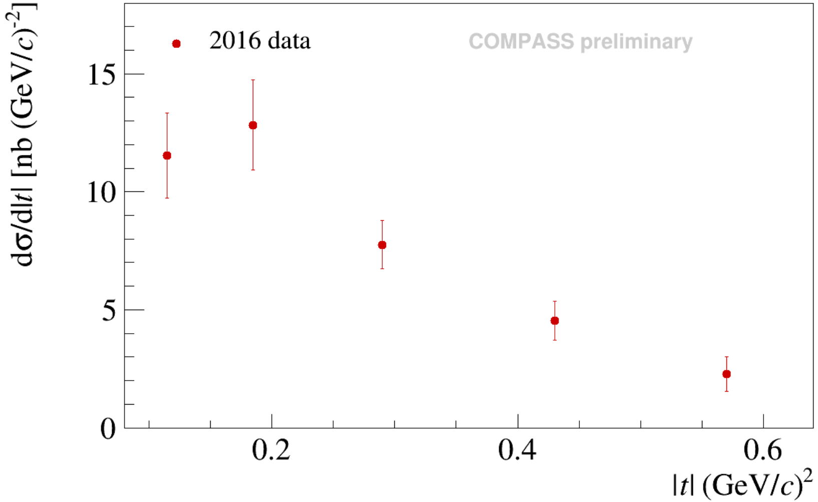


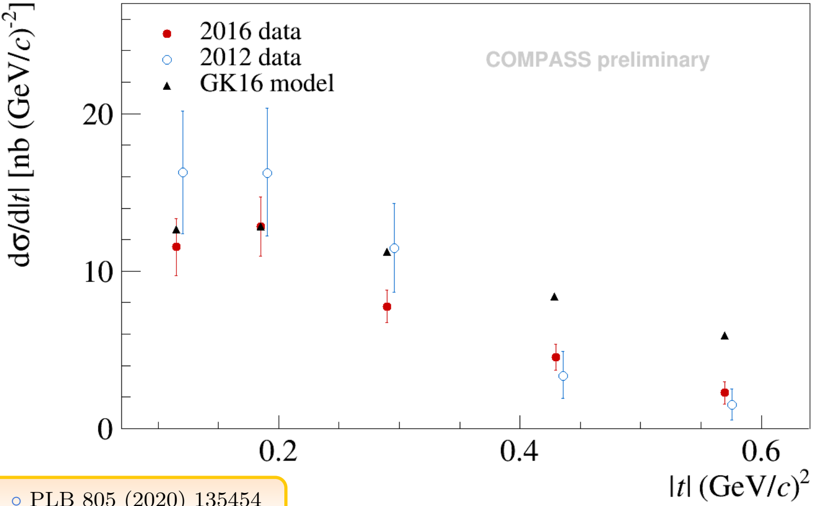
Exclusive π^0 cross-section as a function of $|t|$



Systematic error is of the order of the statistical one

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

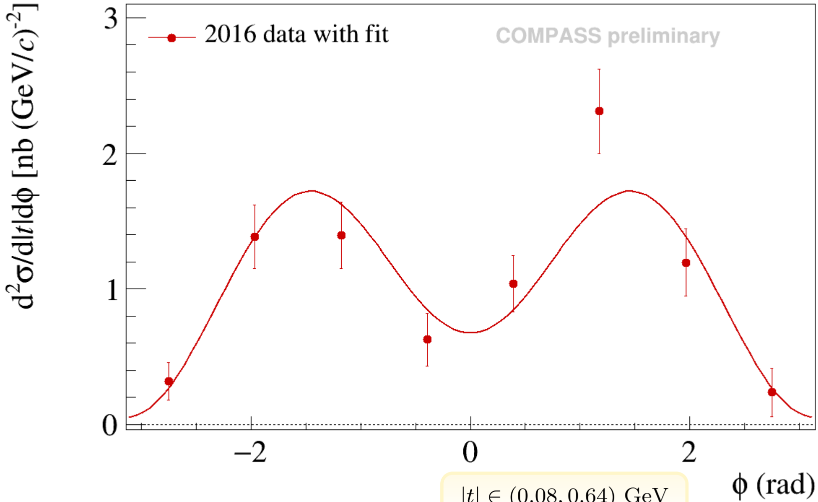
Goloskokov&Kroll model EPJ A47 (2011) 112



- PLB 805 (2020) 135454

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

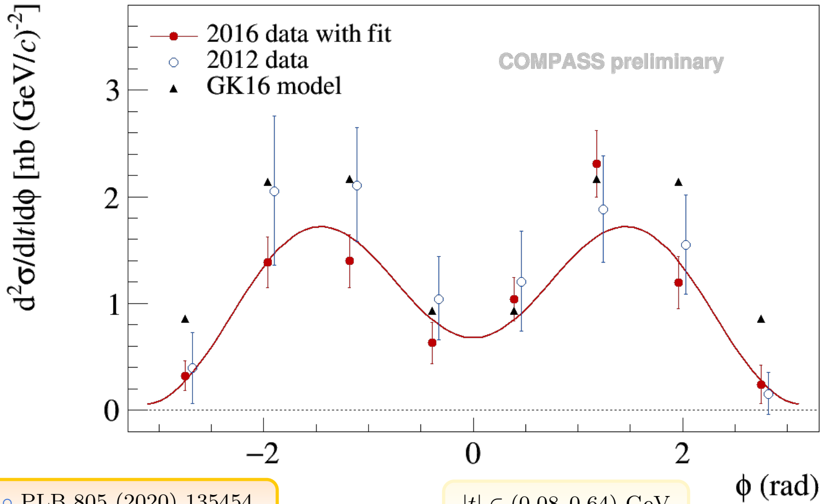
$$\frac{\mathrm{d}^2\sigma_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} = \frac{1}{2\pi}\left[\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \epsilon\cos(2\phi)\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} + \sqrt{\epsilon(1+\epsilon)}\cos\phi\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}\right]$$



$|t| \in (0.08, 0.64)$ GeV

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

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



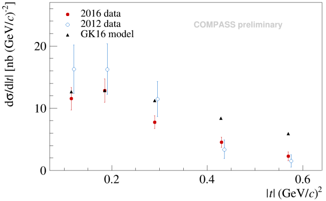
- PLB 805 (2020) 135454

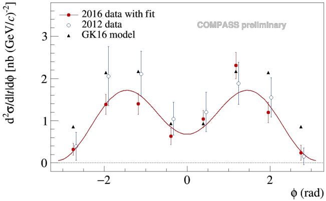
$|t| \in (0.08, 0.64)$ GeV

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 $\langle x_B \rangle = 0.096$), input for constraining phenomenological models (e.g. Goloskokov&Kroll, Goldstein&Luiti, etc.)





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

Thank you for your attention!

SPARES

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