Hard exclusive π^0 muoproduction cross section at COMPASS

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on behalf of the COMPASS at CERN

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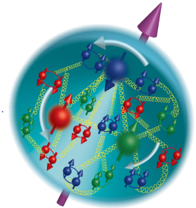
Origin of a nucleon spin

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

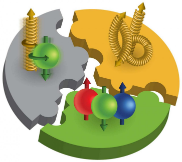
EMC Collaboration, Nucl. Phys. B328 (1989) 180



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) no.1, 012001

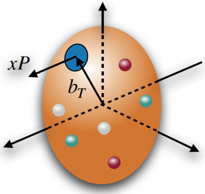
Missing component: $L_{q,g} = ?$ → GPDs provides access to the total angular momentum



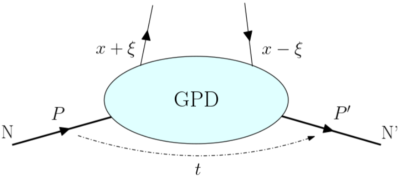
- Generalised Parton Distributions (GPD) give access to the 3D structure of a hadron
- GPDs encode the correlation between the longitudinal momentum of a parton and its position in the transverse plane

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

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



Generalised Parton Distributions



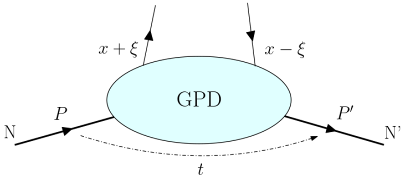
- In the leading twist there are:
  - 4 chiral-even GPDs (parton helicity conserved)
  - 4 chiral-odd (or transversity) GPDs (parton helicity flipped)

Forward limit, **GPD** $\rightarrow$ **PDF**:
$H^q(x,0,0) = q(x)$
$\tilde{H}^q(x,0,0) = \Delta q(x)$
$H_T^q(x,0,0) = \Delta_T q(x)$

Connection to **TMDs**:
E equivalent to Sivers function
$\bar{E}_T$ to Boer-Mulders function
$\tilde{E}$ and $\tilde{E}_T$ to worm-gear functions

		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, $\tilde{H}_T$

Generalised Parton Distributions



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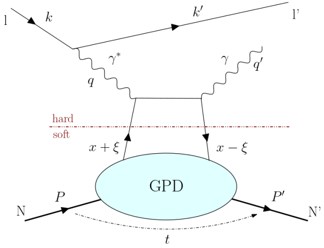
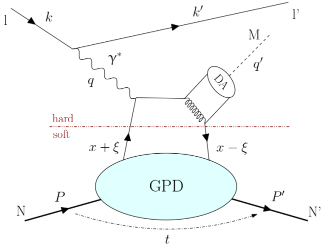
Nucleon Polarisation	Quark Polarisation: Unpolarised (U)	Longitudinally polarised (L)	Tranversely polarised (T)
U	H		$\bar{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

Generalised Parton Distributions





- 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

- **HEMP:** Flavour separation for specific GPDs due to different partonic content of mesons
- At the leading twist, pseudoscalar mesons production involves GPDs $\tilde{H}^f$, $\tilde{E}^f$, $\bar{E}_T^f = 2\tilde{H}_T^f + E_T^f$, and H_T^f

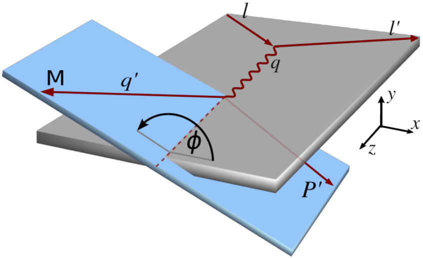
Unpolarised π^0 cross section

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

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

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



Unpolarised π^0 cross section

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

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

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

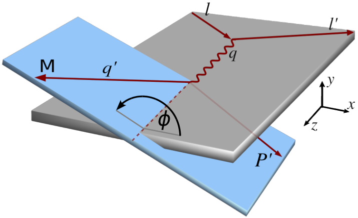
$$\left.\mp |P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{d\sigma'_{LT}}{dt}\right]$$

⇒ **study ϕ dependence**

After integration in ϕ:

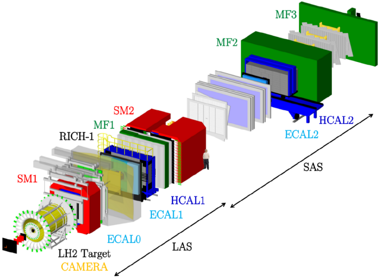
$$\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}$$

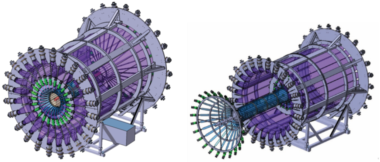
⇒ **study t dependence**



COMPASS GPD programme

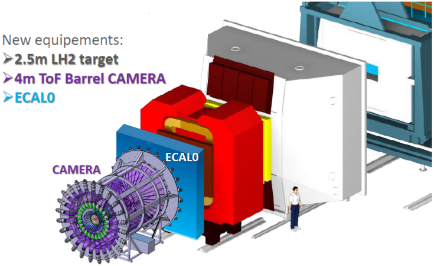
- COMPASS measurement in 2012, and 2016/17 with μ^+ and μ^- beams of $E_\mu = 160$ GeV
- COMPASS 2012:
  - 4 weeks → results published: PLB 805(2020) 135454
- COMPASS 2016/17:
  - 2×6 months
- 2.5m lH target, equipped with ToF system (CAMERA):
  - 24 inner and outer scintillators
  - 1 GHz readout
  - 310 ps ToF resolution





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, $0.08 < |t| < 0.64$ $(\mathrm{GeV}/c)^2$



Overconstrainment of the measurement:

- Recoiled proton transverse momentum: $\Delta p_T = p^p_{T,spect} - p^p_{T,recoil}$
- $\Delta\varphi = \varphi^p_{spect} - \varphi^p_{recoil}$
- Longitudinal position of CAMERA hits: $\Delta z = z^p_{spect} - z^p_{recoil}$
- Energy-momentum conservation: $M_X^2 = (p_\mu + p_p - p_{\mu'} - p_{p'} - p_{\pi^0})^2$
- Kinematic fit of reaction $\mu p \to \mu' p' \pi^0$

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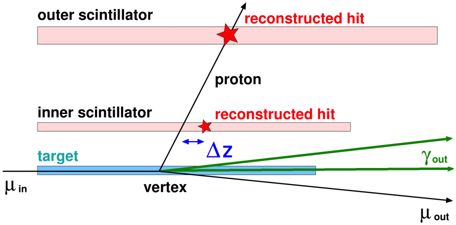

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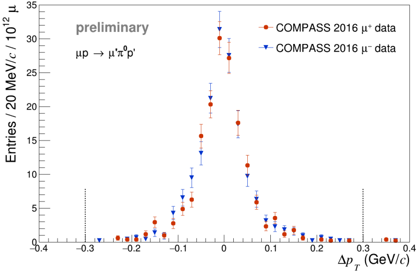

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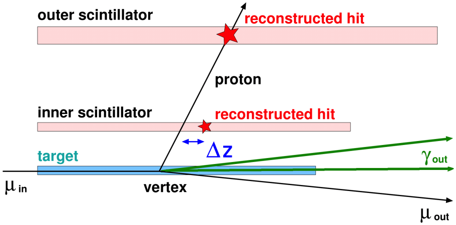

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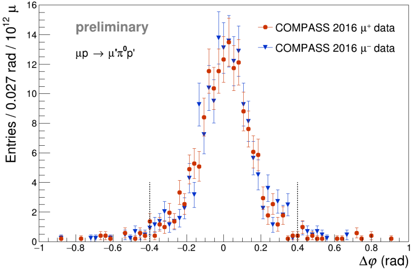

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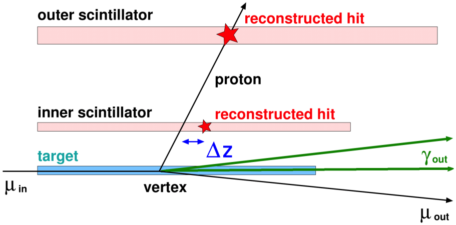

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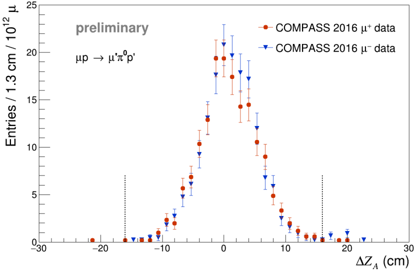

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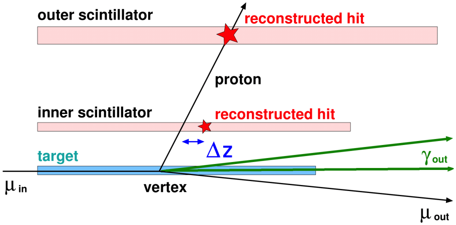

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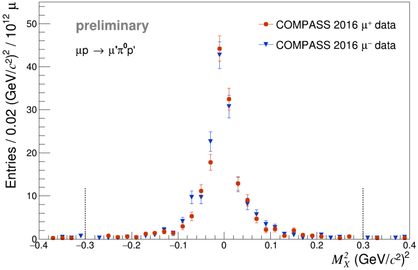

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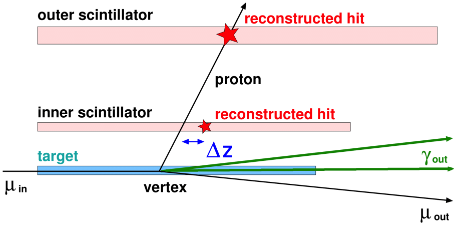

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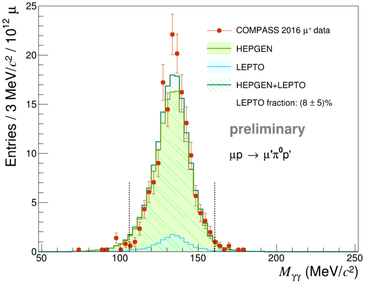
Exclusive π^0 production: SIDIS background estimation

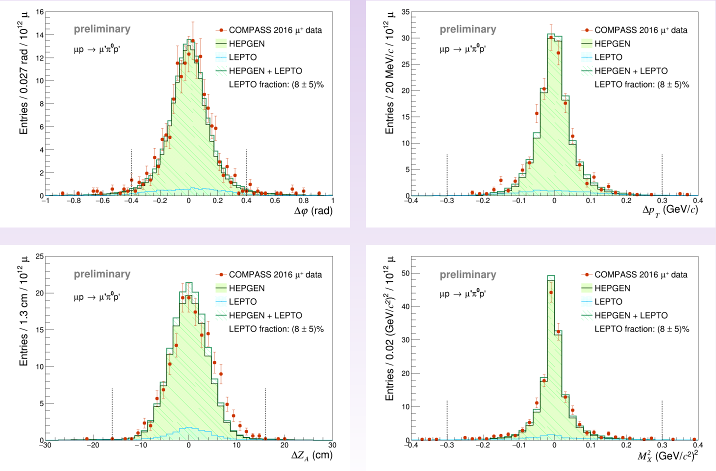
- Main background of π^0 production $\Rightarrow$ non-exclusive DIS processes
- 2 Monte Carlo simulations with the same π^0 selection criteria:
  - LEPTO for the non-exclusive background
  - HEPGEN++ shape of distributions of exclusive π^0 production (signal contribution)
- Both MC samples normalised 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

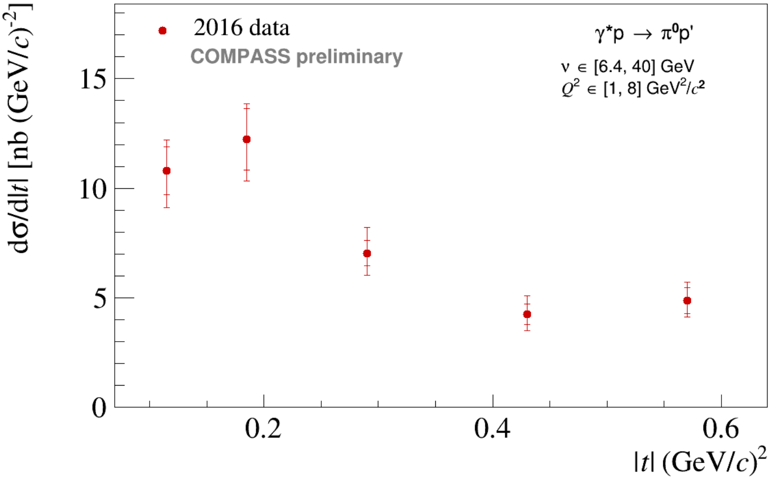
Exclusive π^0 production: SIDIS background estimation

Exclusive variables



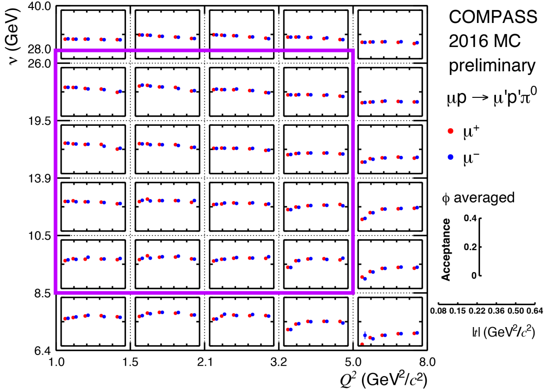
Exclusive π^0 cross-section as a function of $|t|$

- Differential $\gamma^* p \rightarrow p' \pi^0$ 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), the 2016 data also analysed in a smaller kinematic domain
- $8.5 < \nu < 28$ GeV, $1 < Q^2 < 5$ $(\mathrm{GeV}/c)^2$, $0.08 < |t| < 0.64$ $(\mathrm{GeV}/c)^2$



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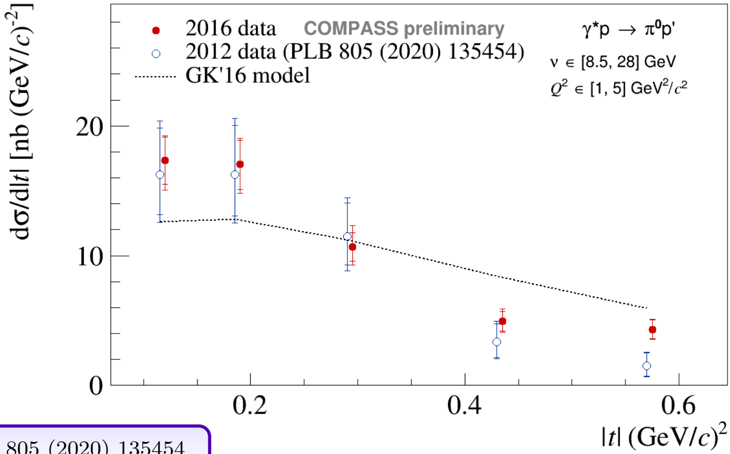
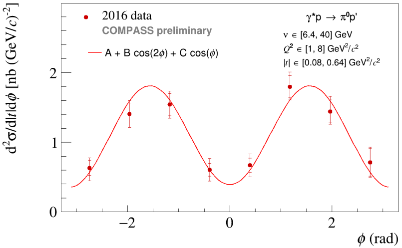
Goloskokov&Kroll model EPJ A47 (2011) 112



∘ PLB 805 (2020) 135454

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

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



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

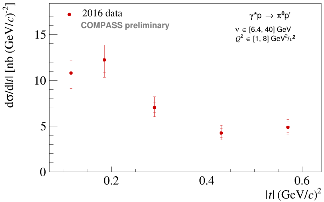
$$\left\langle \frac{\sigma_{TT}}{|t|} \right\rangle = (-4.5 \pm 0.5_{stat} \pm 0.2_{syst}) \frac{nb}{(GeV/c)^2}$$

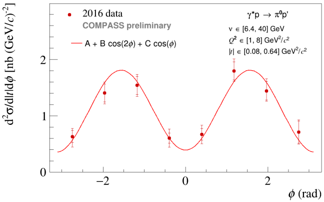
$$\left\langle \frac{\sigma_{LT}}{|t|} \right\rangle = (0.06 \pm 0.2_{stat} \pm 0.1_{syst}) \frac{nb}{(GeV/c)^2}$$

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× 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 and then combined 2016/2017 results soon

SPARES

Unpolarised 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

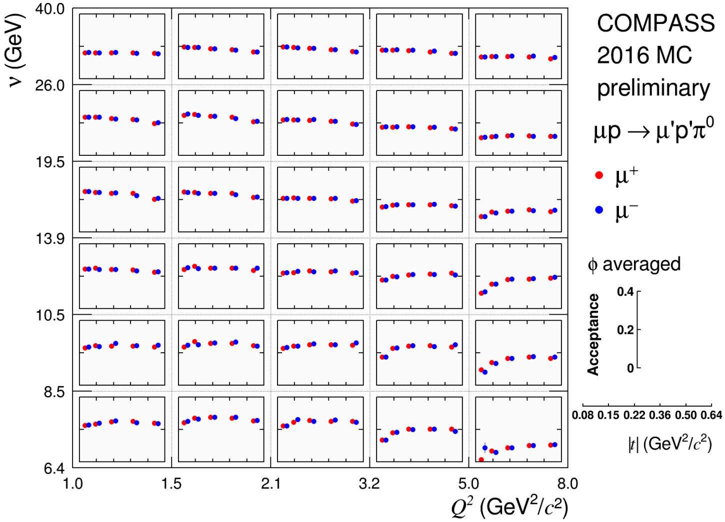
$t' = t - t_{min}$

		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, $\tilde{H}_T$

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

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 $|t|$



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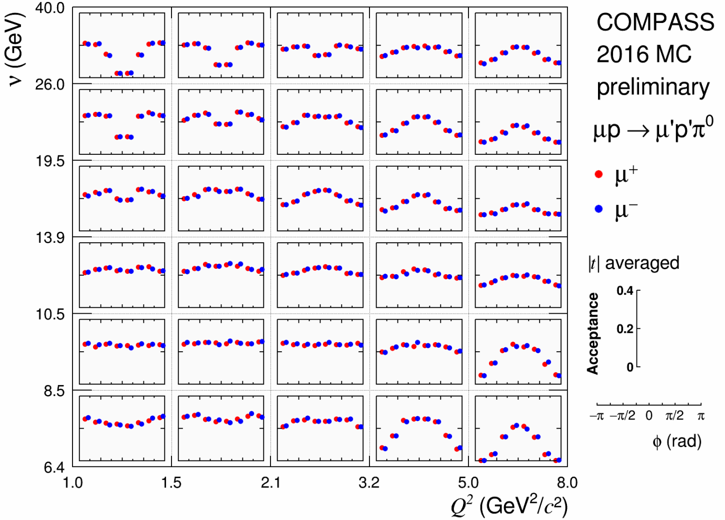
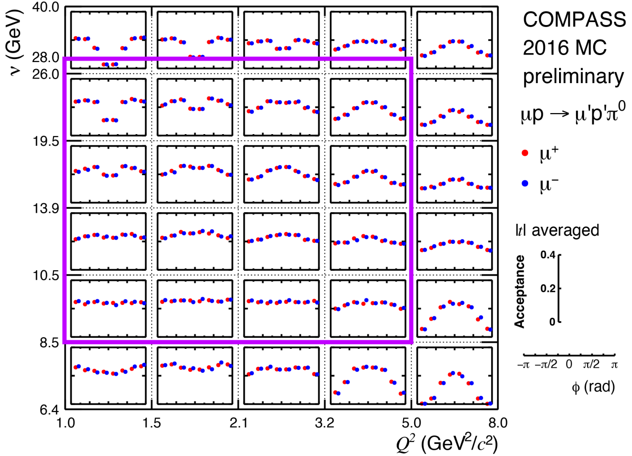
- figure shows 3D projection, as a function of ϕ_{π^0}



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

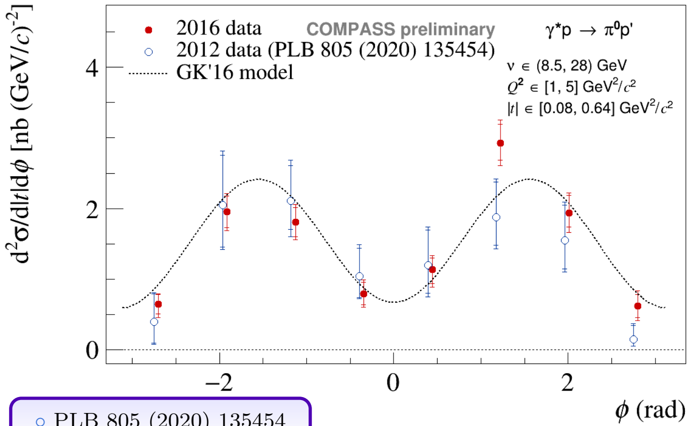
- In order to compare with the results from 2012 (PLB 805 (2020) 135454), the 2016 data were also analysed in a smaller kinematic domain
- $8.5 < \nu < 28$ GeV, $1 < Q^2 < 5$ $(\mathrm{GeV}/c)^2$, $0.08 < |t| < 0.64$ $(\mathrm{GeV}/c)^2$



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 exclusive π^0 measurements