DVCS and Exclusive π^0 Measurements at COMPASS

On behalf of the COMPASS Collaboration



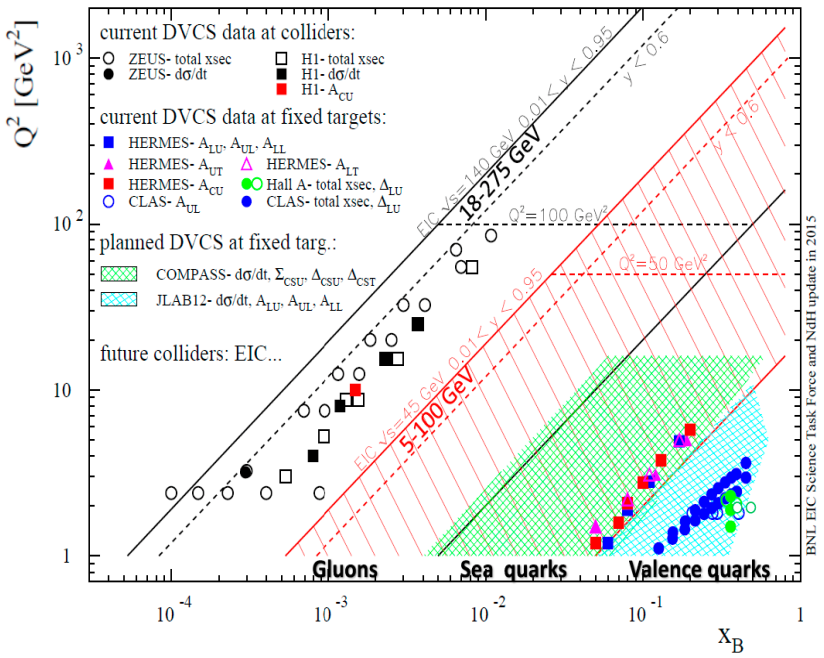
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AANL, Yerevan, Armenia
September 9, 2026

COMPASS GPD PROGRAM

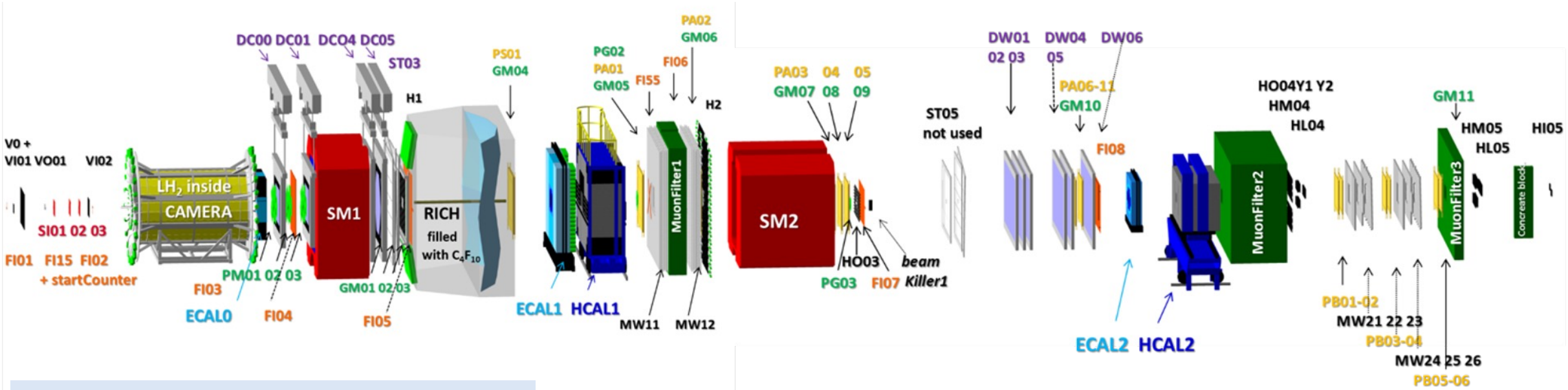
2002 – 2004	DIS & SIDIS, μ^+-d, 160 GeV, L & T polarized target
2005	*CERN accelerator shutdown, increase of COMPASS acceptance*
2006	DIS & SIDIS, μ^+-d, 160 GeV, L polarized target
2007	DIS & SIDIS, μ^+-p, 160 GeV, L & T polarized target
2008 – 2009	Hadron spectroscopy & Primakoff reaction, **π/K/p** beam
2010	SIDIS, μ^+-p, 160 GeV, T polarized target
2011	DIS & SIDIS, μ^+-p, 200 GeV, L polarized target
2012	Primakoff reaction, **π/K/p** beam
2012 pilot run	DVCS/HEMP/SIDIS, μ^+ **&** μ^--p, 160 GeV, unpolarized target
2013	*CERN accelerator shutdown, LS1*
2014 – 2015	Drell-Yan, π^--p, T polarized target
2016 – 2017	DVCS/HEMP/SIDIS, μ^+ **&** μ^--p, 160 GeV, unpolarized target
2018	Drell-Yan, π^--p, T polarized target
2019 – 2020	*CERN accelerator shutdown, LS2*
2021 – 2022	SIDIS, μ^+-d, 160 GeV, T polarized target

- COMPASS has a diverse physics program dedicated to studying hadron structure and spectroscopy

- 2012: pilot (4 weeks)
- 2016/17: dedicated run (2 x 6 months)



Spectrometer setup in 2016/17



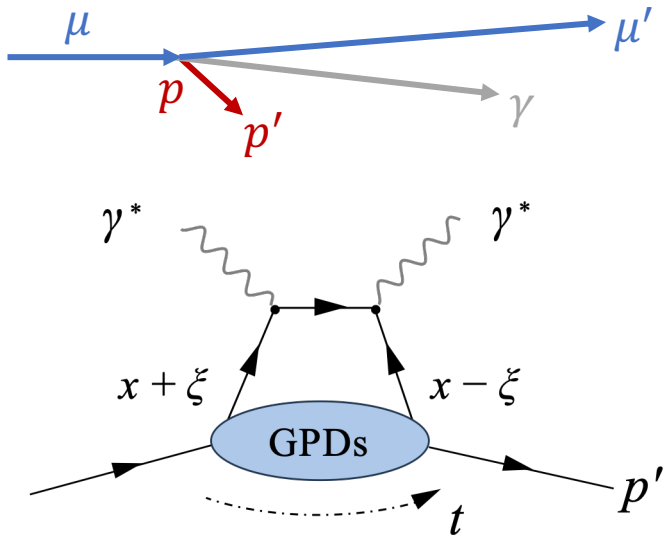
DVCS: $\mu p \to \mu' p' \gamma$
Exclusive π^0: $\mu p \to \mu' p' \pi^0$, $\pi^0 \to \gamma\gamma$

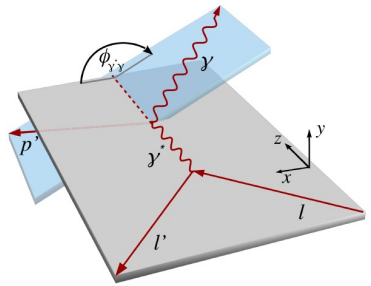
- Beam: Longitudinally polarized 160 GeV $\mu^{\pm}$ beams (polarization $\sim \mp 80\%$)
- Target: 2.5m long unpolarized liquid H_2

- Muons: Selected based on traversed material thickness (X/X_0), and identified with two dedicated muon-wall systems
- Photons: Detected in ECALs (ECAL0/1/2); ECAL0 added after CAMERA in 2016/17 setup
- Recoil protons: Detected with CAMERA surrounding the target; identified by time-of-flight and energy loss

Probing Proton Structure with DVCS

$$l + p \rightarrow l' + p' + \gamma$$





- Cross section for exclusive photon production in lepton-nucleon scattering:

$$\frac{d^4\sigma(lp \rightarrow lp\gamma)}{dx_B dQ^2 d|t| d\phi} = \underbrace{d\sigma^{BH}}_{|\mathcal{A}_{BH}|^2} + \underbrace{\left(d\sigma^{DVCS}_{unpol} + P_l d\sigma^{DVCS}_{pol}\right)}_{|\mathcal{A}_{DVCS}|^2} + \underbrace{(e_l Re\, I + e_l P_l Im\, I)}_{\text{Interference term}}$$

- Unpolarized target beam charge-spin sum ($\Sigma \equiv d\sigma^{\overleftarrow{\mp}} + d\sigma^{\overrightarrow{-}}$):

$$\Sigma = 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} cos\phi + c_2^{DVCS} cos2\phi + s_1^I sin\phi + s_2^I sin2\phi]$$

  - Integrating over ϕ eliminates the interference terms → isolate the ϕ-independent DVCS term

- At COMPASS: high muon beam energy (160 GeV) on a proton target and small $\xi \approx \frac{x_B}{2}$ → most sensitive to GPD *H*

$$\frac{d\sigma_{DVCS}}{dt} \propto (Im\mathcal{H})^2 \text{ and } Im\mathcal{H} = H(x = \xi, \xi, t)$$

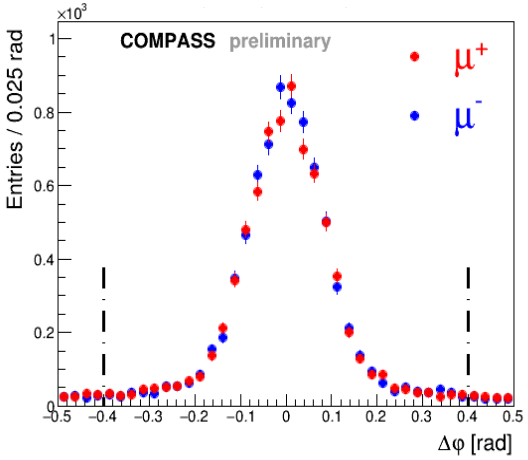
$$\frac{d\sigma_{DVCS}}{dt} \sim e^{-B|t|}$$

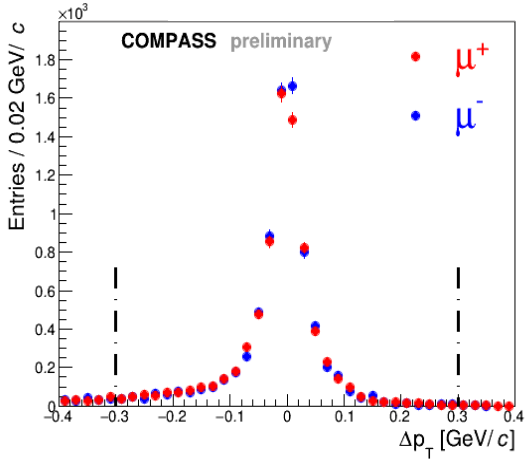
$$\langle b_\perp^2(x) \rangle \approx 2B(\xi) \quad \rightarrow \quad b_\perp \text{ is the transverse extension of partons in the proton}$$

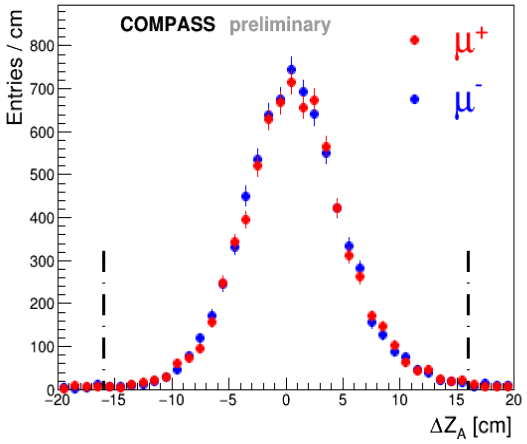
Twist-2 >> Twist-3, Twist-2 double helicity flip for gluons (NLO)

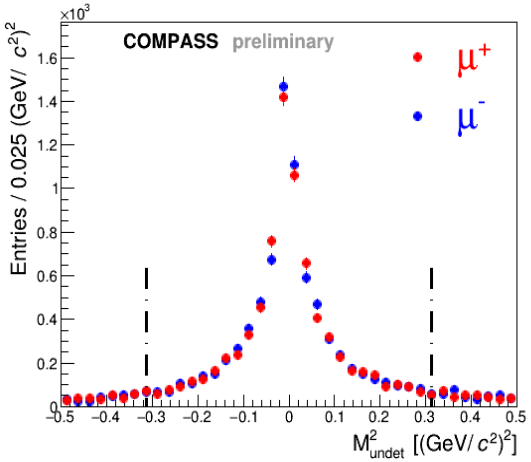
Belitsky, Müller, Kirner (NPB629 2002)

DVCS Cross section Extraction



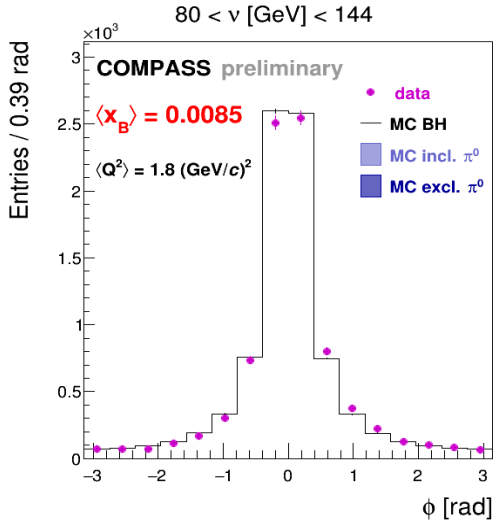


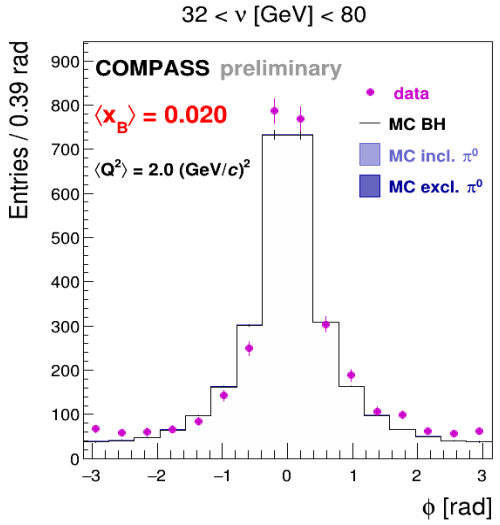


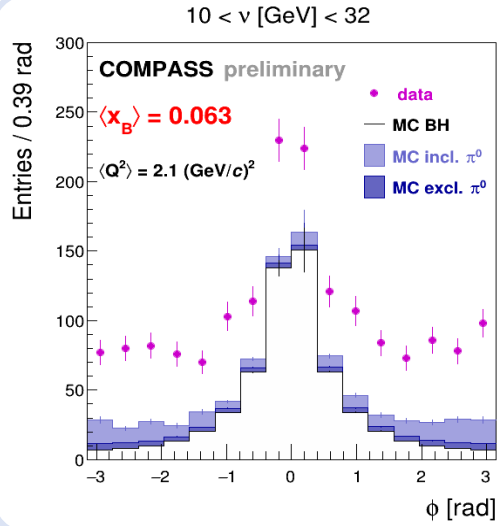


1. Identify events with exclusive photon topology: $\mu p \rightarrow \mu' p' \gamma$
   - Select the best recoil-proton candidate using exclusivity variables (difference in values measured by camera and the spectrometer)
     - Azimuthal angle: $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$
     - Transverse momentum: $\Delta p_T = p_T^{cam} - p_T^{spec}$
     - Track hit position: $\Delta Z_A = Z_A^{cam} - Z_A^{interp}$
     - Energy-momentum balance: $\Delta M_x^2 = (k + p - k' - q' - p')^2$
   - Require photon candidate is detected in ECAL0, ECAL1 or ECAL2
   - Apply a kinematic-fit to enforce energy-momentum conservation
   - Reject events with reconstructed π^0

DVCS Cross section Extraction







DVCS extraction region ($10 < \nu < 32$ GeV): DVCS dominates over BH

2. Estimate the BH contribution using HEPGEN BH MC

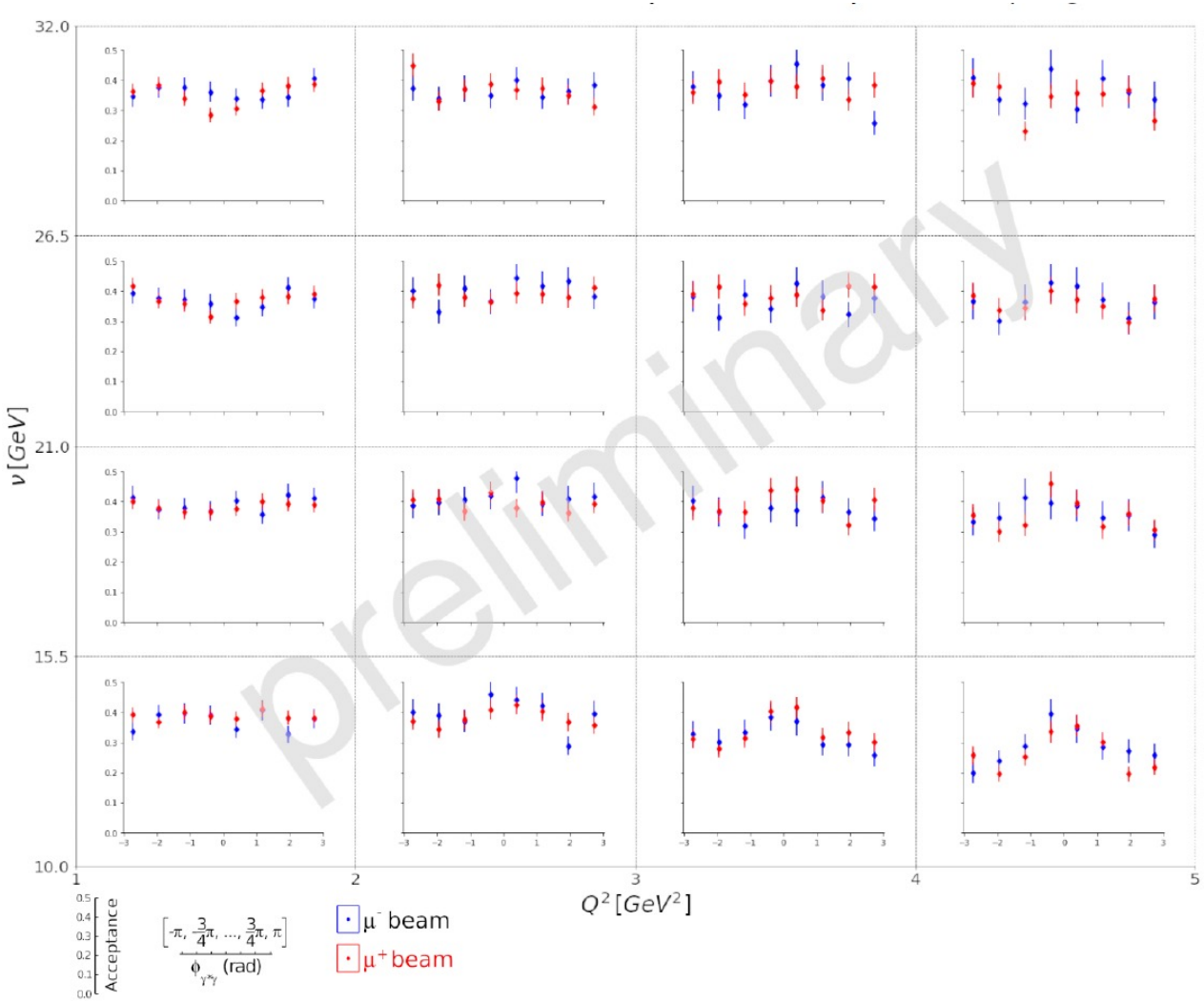
3. Estimate π^0 background
   - Dominant background: $\pi^0 \rightarrow \gamma\gamma$ with only one photon detected
   - Determine "singe-photon" π^0 contribution by fitting a combination of HEPGEN exclusive π^0 MC and LEPTO inclusive π^0 MC to the reconstructed π^0 sample

4. Extract the cross section in 4D bins and apply acceptance and luminosity corrections

$$\left\langle \frac{d\sigma_{DVCS}}{d|t|d\phi dQ^2 d\nu} \right\rangle^{\pm}_{t_i \phi_j Q^2_k \nu_l} = \frac{1}{\mathcal{L}^{\pm} \Delta t_i \Delta\phi_j \Delta Q^2_k \Delta\nu_l} \left[\frac{1}{A^{\pm}_{ijkl}} (\text{data} - \text{BH}_{\text{MC}} - \pi^0_{\text{MC}}) \right]$$

- Systematic error studies include:
  - Statistical fluctuations across periods
  - Varying the BH and "single photon" π^0 contributions
  - Varying the χ^2 limit of the kinematic fit
  - Radiative corrections

Acceptance for DVCS



- The acceptance is calculated using the HEPGEN BH MC sample

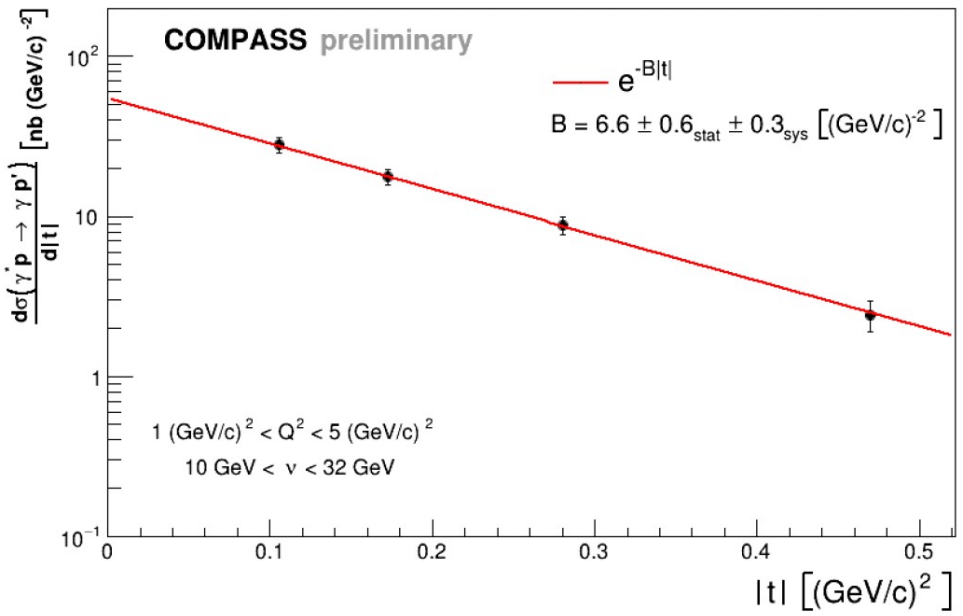
$$A(\Delta\Omega) = \frac{N_{rec}}{N_{gen}}$$

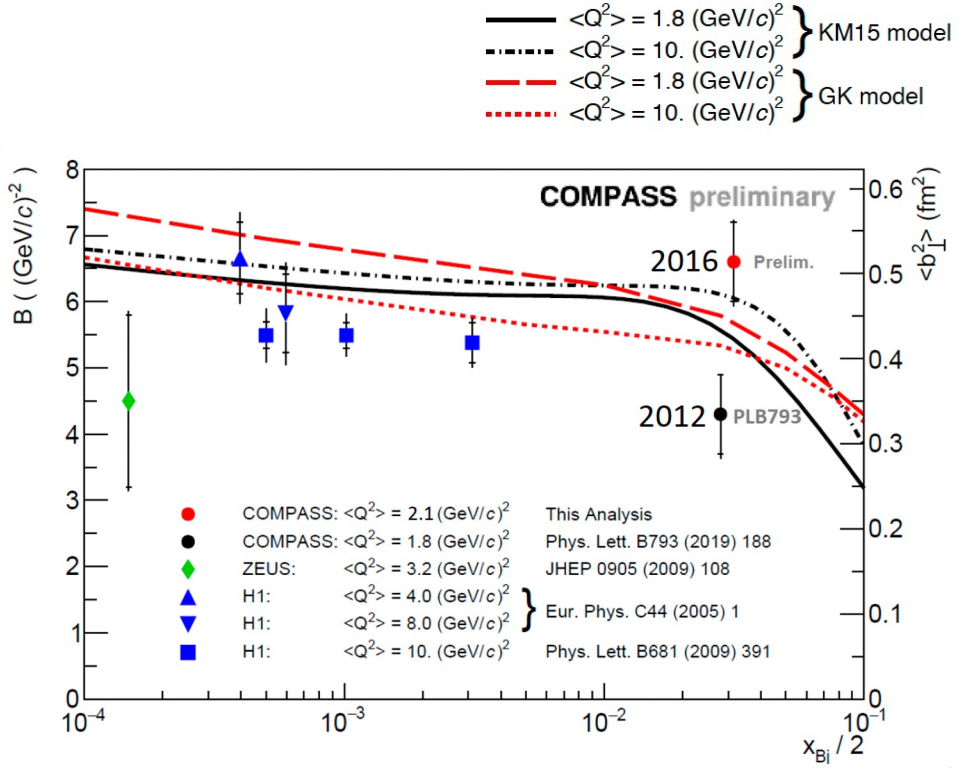
- Determines the phase space that will be used for the cross-section extraction → only extract the cross-section in the regions where the acceptance is flat
- Similar acceptance between $\overleftarrow{\mu^+}$ and $\overrightarrow{\mu^-}$ ~40%
- Use 4D binning (t, ϕ, Q^2, ν) in the cross-section calculation

Good agreement in $\overleftarrow{\mu^+}$ and $\overrightarrow{\mu^-}$ is imperative for,
$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$

|t|-dependence of the DVCS Cross section

$$\frac{d\sigma_{DVCS}}{dt} \sim e^{-B|t|}$$



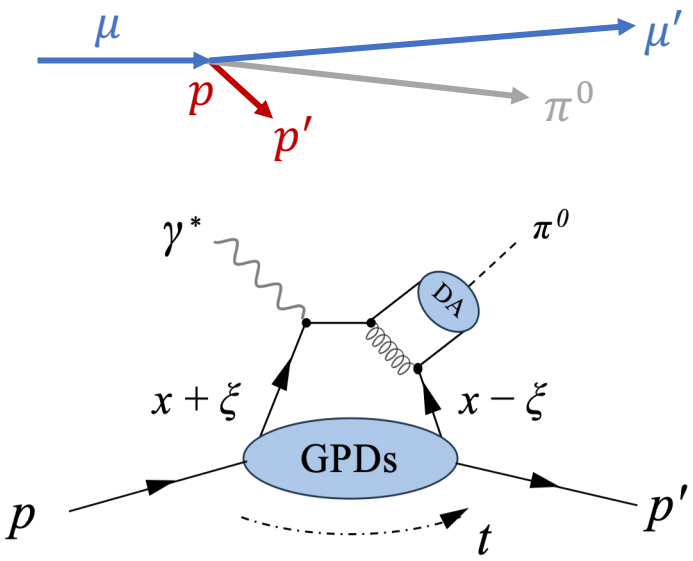


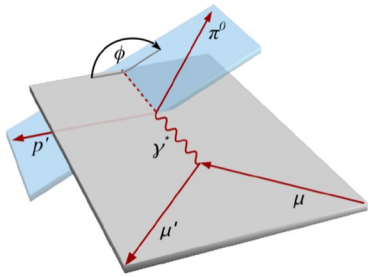
- The |t|-dependence is well described by $e^{-B|t|}$
- Extract B using a binned maximum-likelihood method
- Slope parameter: $6.6 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}}\ [(\text{GeV/c})^2]$

- $\langle b_\perp^2(x) \rangle \approx 2B \rightarrow \langle b_\perp(x) \rangle \approx 0.72$ fm
- Access to the transverse spatial extension of partons in the proton

Probing Proton Structure with Exclusive π^0

$$l + p \rightarrow l' + p' + \pi^0$$





- Unpolarized exclusive π^0 cross section:

$$\frac{d\sigma}{dtd\phi} = \frac{1}{2\pi}\left[\varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \varepsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)\frac{d\sigma_{LT}}{dt}\right]$$

Chiral odd GPDs

- At leading-twist and sufficiently large Q^2, longitudinal photon contributions are expected to dominate ($\sigma_L \gg \sigma_T$)

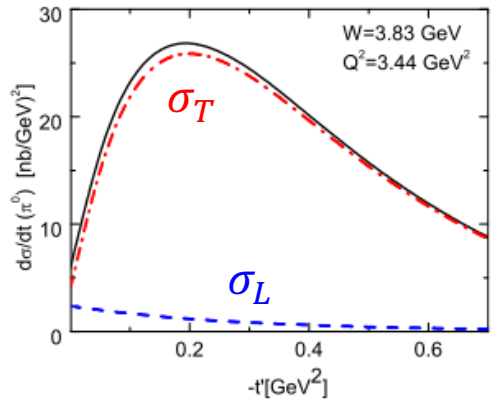
$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)|\langle\tilde{H}\rangle|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t}{4m^2}\xi^2|\langle\tilde{E}\rangle|^2\right\}$$

- At experimentally accessible Q^2, large transverse contributions are observed/predicted. They arise from twist-3 pion amplitudes coupled to chiral-odd GPDs H_T and $\bar{E}_T = 2\tilde{H}_T + E_T$

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2\right]$$

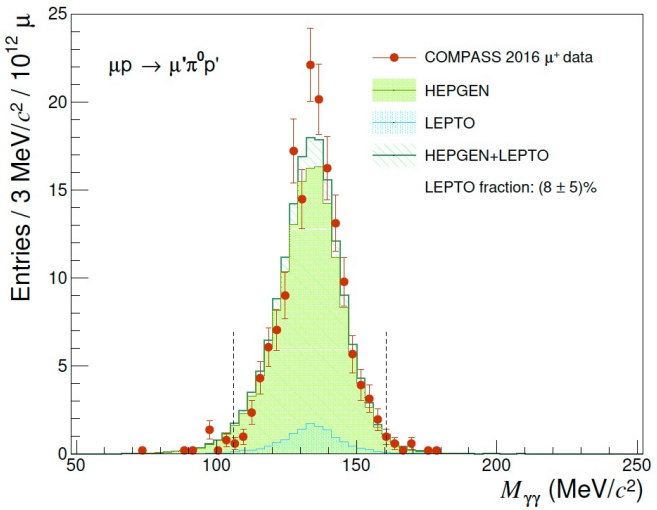
$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

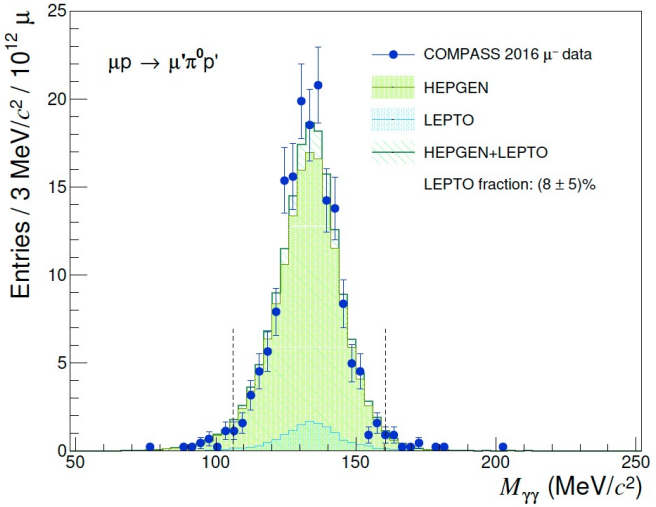
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}|\langle\bar{E}_T\rangle|^2$$



S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))

Exclusive π^0 Cross section Extraction





1. Identify events with dominant $\pi^0 \to \gamma\gamma$ decay topology: $\mu p \to \mu' p' \pi^0$, $\pi^0 \to \gamma\gamma$
   - Select the best recoil-proton candidate using exclusivity variables
   - Require two photon candidates are detected in ECAL0 and/or ECAL1
   - Apply a kinematic-fit to enforce energy-momentum conservation

2. The dominant background is non-exclusive DIS π^0 production
   - Signal: HEPGEN exclusive π^0 MC
   - Background: LEPTO inclusive π^0 MC
   - Determine their relative contributions using a fit to the $M_{\gamma\gamma}$ distribution
   - **LEPTO fraction: (8 ± 5) %**

3. Extract the cross section in 4D bins and apply acceptance and luminosity corrections

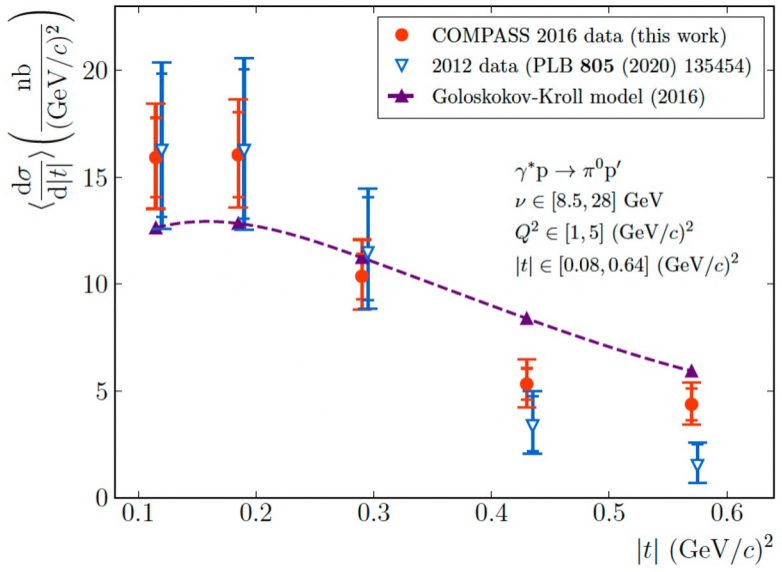
$$\left\langle \frac{d\sigma_{excl.\,\pi^0}}{d|t|d\phi dQ^2 d\nu} \right\rangle^{\pm}_{t_i \phi_j Q_k^2 \nu_l} = \frac{1}{\mathcal{L}^{\pm} \Delta t_i \Delta\phi_j \Delta Q_k^2 \Delta\nu_l} \left[\frac{1}{A^{\pm}_{ijkl}} (\text{data} - \text{LEP}_{\text{MC}}) \right]$$

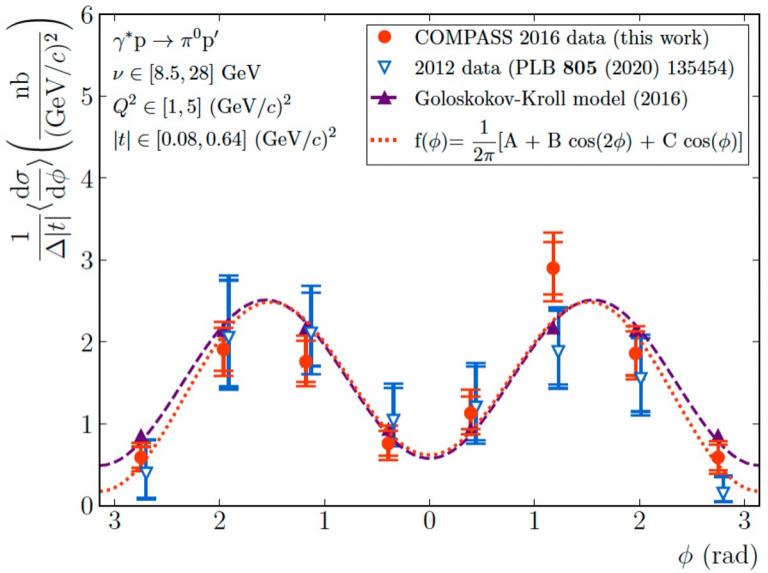
- Systematic error studies include:
  - Varying the LEPTO inclusive π^0 contribution
  - Including ω background
  - Varying the χ^2 limit of the kinematic fit
  - Radiative corrections

COMPASS, Phys Lett B 805 (2020) 135454

COMPASS, Phys Lett B 870 (2025) 139832

Composition of the Exclusive π^0 Cross section





2016 data:

$$\left\langle \frac{d\sigma_T}{d|t|} + \varepsilon \frac{d\sigma_L}{d|t|} \right\rangle = 9.0 \pm 0.5_{\text{stat}} \, {}^{+1.1}_{-1.0}|_{\text{sys}} \, \frac{\text{nb}}{(\text{GeV/c})^2}$$

$$\left\langle \frac{d\sigma_{TT}}{d|t|} \right\rangle = -6.6 \pm 0.8_{\text{stat}} \, {}^{+0.5}_{-0.5}|_{\text{sys}} \, \frac{\text{nb}}{(\text{GeV/c})^2}$$

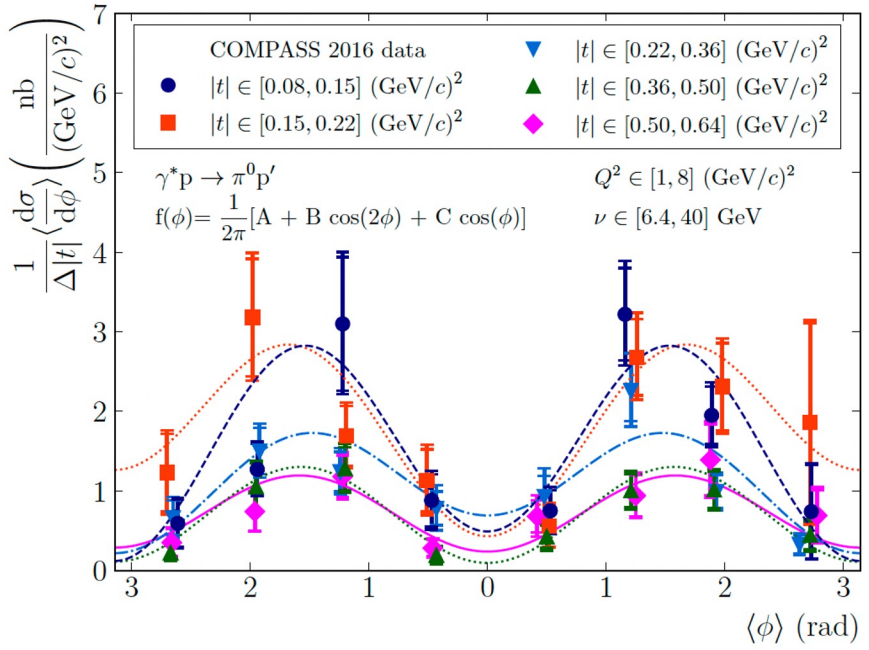
$$\left\langle \frac{d\sigma_{LT}}{d|t|} \right\rangle = 0.7 \pm 0.3_{\text{stat}} \, {}^{+0.4}_{-0.4}|_{\text{sys}} \, \frac{\text{nb}}{(\text{GeV/c})^2}$$

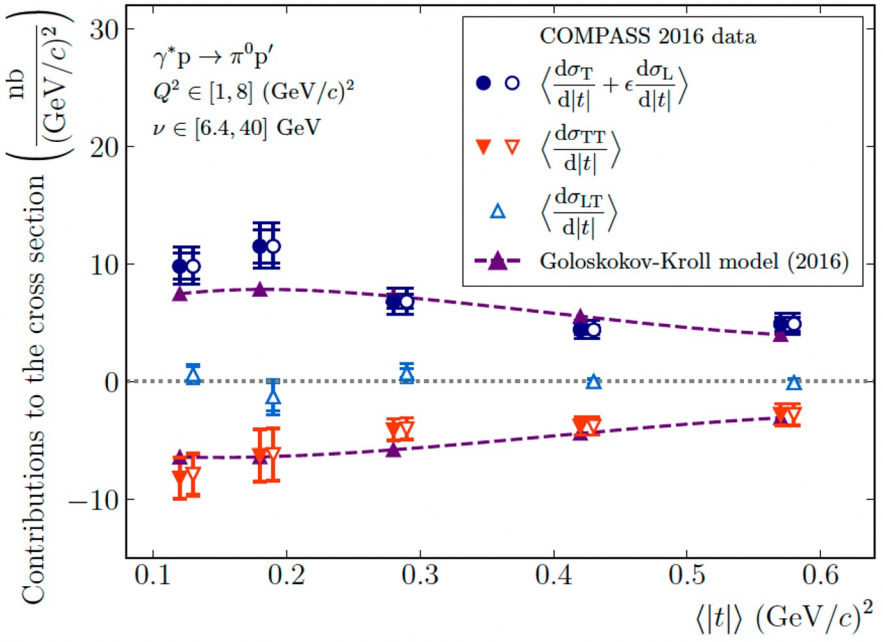
$$\langle \varepsilon \rangle = 0.996$$

- The cross-section $\left\langle \frac{d\sigma}{d|t|} \right\rangle$ as a function of |t| (integrate over ϕ) shows a decrease towards t → 0 indicating a dominant $\bar{E}_T$ contribution
- The cross-section $\frac{1}{\Delta|t|}\left\langle \frac{d\sigma}{d\phi} \right\rangle$ as a function of ϕ (averaged over |t|) can be used to extract the different longitudinal and transverse contributions

COMPASS, Phys Lett B 870 (2025) 139832

Composition of the Exclusive π^0 Cross section



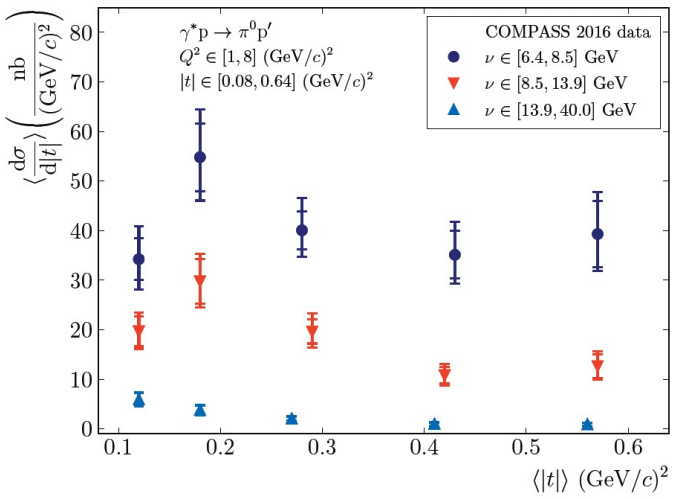


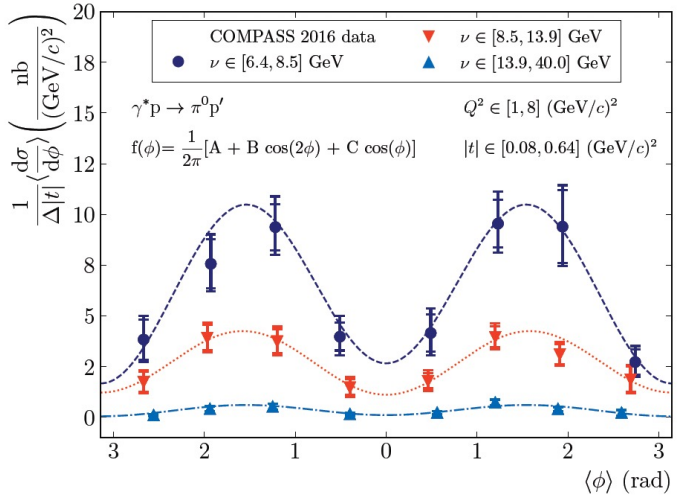
- Extract the contributions to the unseparated cross-section by fitting the ϕ-dependence of the cross-section for 5 $|t|$ bins using a binned maximum likelihood fit
- Observe a large negative σ_{TT} contribution towards t → 0 indicating a dominant $\bar{E}_T$ contribution
- The σ_{LT} contribution is consistent with zero over the measured |t| range

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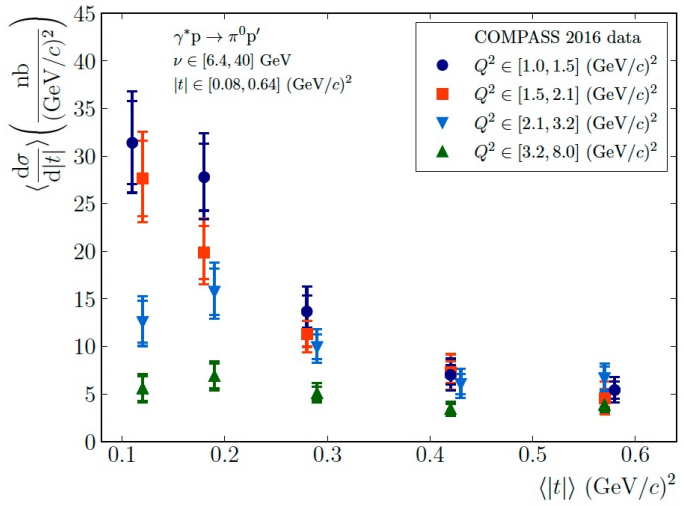
Kinematic dependence of the Exclusive π^0 Cross section

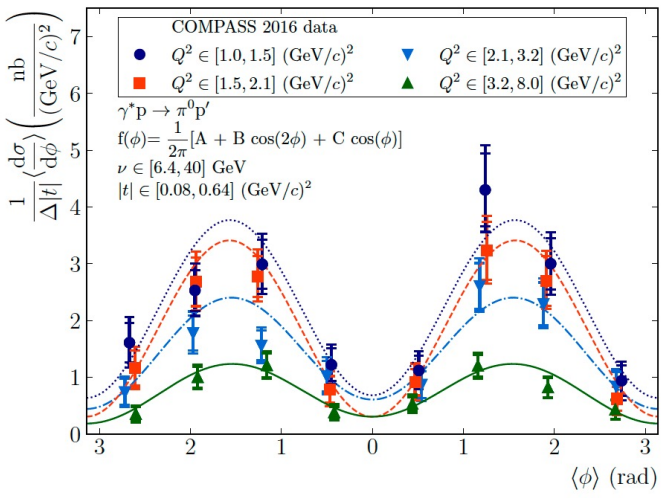
ν dependence





Q^2 dependence





- The cross-section decreases with increasing ν at approximately fixed Q^2
- Increasing $\nu \Leftrightarrow$ decreasing x_B

ν range	$\langle Q^2 \rangle$ [GeV²/c²]	$\langle \nu \rangle$ [GeV]	$\langle x_B \rangle$	$\langle \varepsilon \rangle$
6.4 – 8.5	2.15	7.35	0.156	0.999
8.5 – 13.9	2.50	10.32	0.131	0.998
13.9 – 40.0	2.09	21.08	0.057	0.989

- The cross-section decreases with increasing Q^2 at approximately fixed ν
- Increasing $Q^2 \Leftrightarrow$ decreasing x_B

Q^2 range	$\langle Q^2 \rangle$ [GeV²/c²]	$\langle \nu \rangle$ [GeV]	$\langle x_B \rangle$	$\langle \varepsilon \rangle$
1.0 – 1.5	1.22	10.54	0.072	0.997
1.5 – 2.1	1.77	9.81	0.109	0.997
2.1 – 3.2	2.58	9.82	0.157	0.997
3.2 – 8.0	4.33	10.39	0.247	0.997

COMPASS, Phys Lett B 870 (2025) 139832

Summary and Outlook

- Current analyses are done only using 2016 data
  - Extend both analyses to use full statistics for 2016 and 2017 (3 times more data than 2016)

- DVCS cross section:
  - Current analysis looks at beam charge-spin sum → $Im\mathcal{H}$ → transverse extension of partons as a function of x_B
  - Current analysis studies |t|-dependence of cross-section → DVCS amplitude
  - Extend analysis to look at beam charge-spin difference → $Re\mathcal{H}$ → quark pressure distribution
  - Extend analysis to study azimuthal dependence of cross-section → Interference amplitude

- Exclusive π^0 cross section:
  - 2016 results published (COMPASS, Phys Lett B 870 (2025) 139832) → only part of the results were shown in this presentation!



Thank you!