COMPASS measurement of hard exclusive π^0 muoproduction cross-section

Markéta Pešková (Charles University, Prague)

on behalf of the COMPASS collaboration

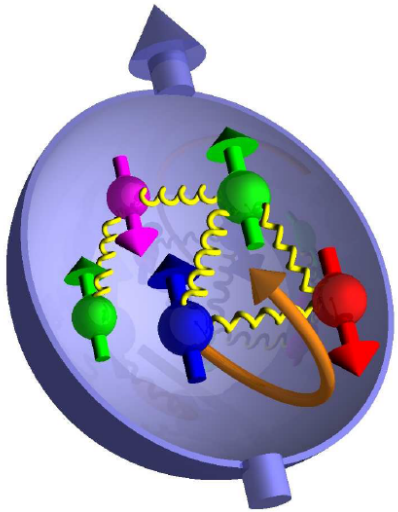
DSPIN'19, September 2.- 6., 2019

Origin of a nucleon spin

- Proton spin sum rule:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Jaffe&Manohar Nucl. Phys. B337 (1990)



Static quark model: $\Delta\Sigma = 1$
Weak baryon decays: $\Delta\Sigma \sim 0.58$
COMPASS experiment in μp DIS: $\Delta\Sigma = 0.32 \pm 0.03$
COMPASS Collaboration: Phys. Lett. B 693 (2010)

COMPASS, RHIC results: $\Delta G = 0.2^{+0.06}_{-0.07}$
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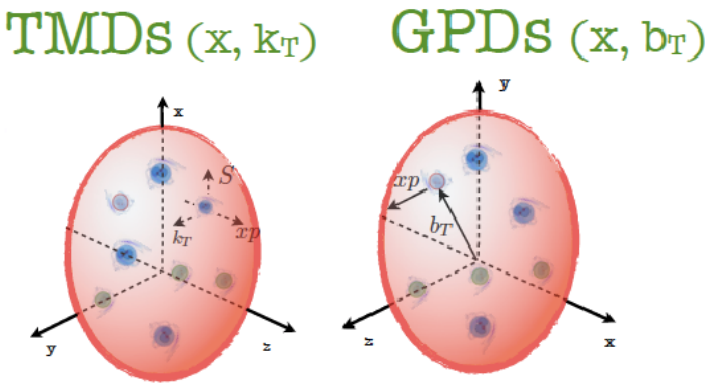
Missing component: $L_{q,g} = ??$

Experimentally accessible via TMDs and GPDs



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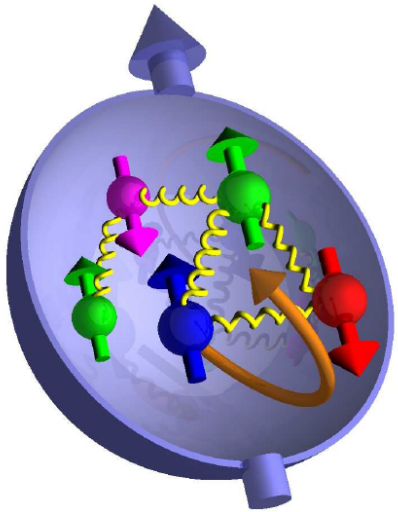

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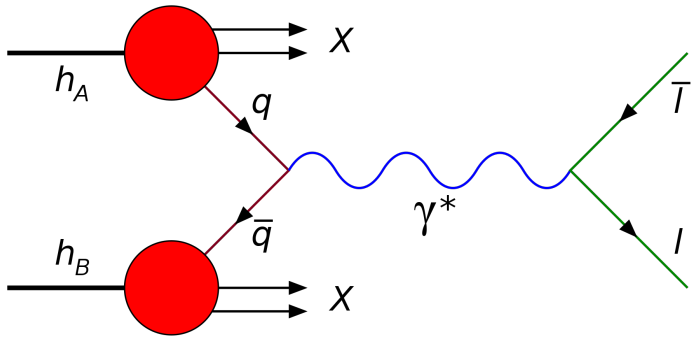

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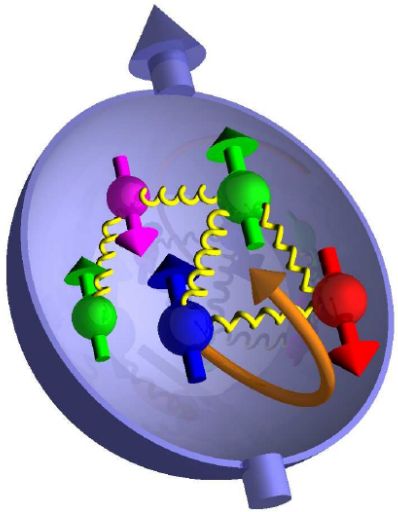

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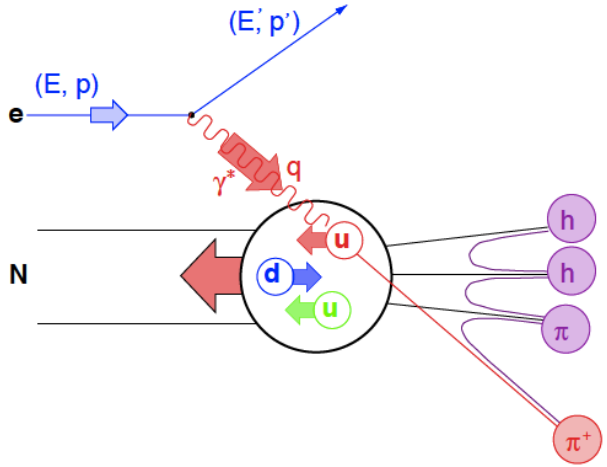

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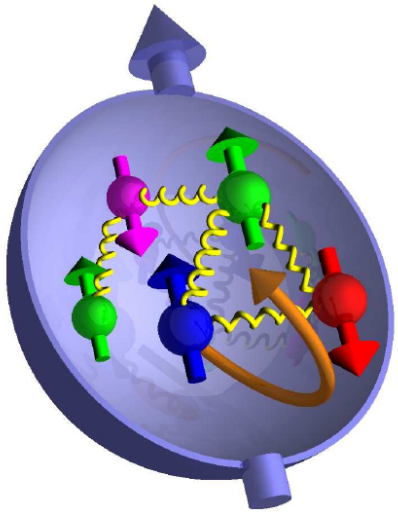

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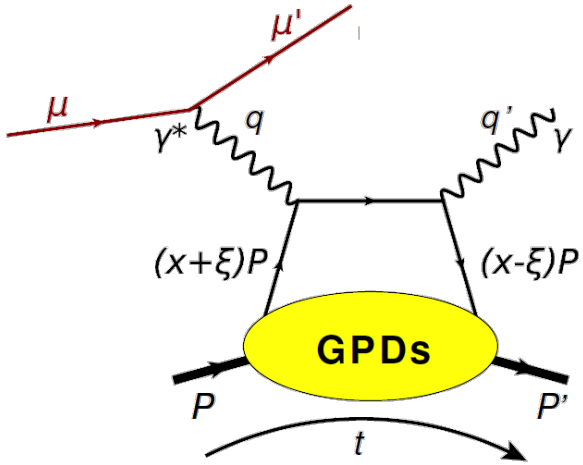

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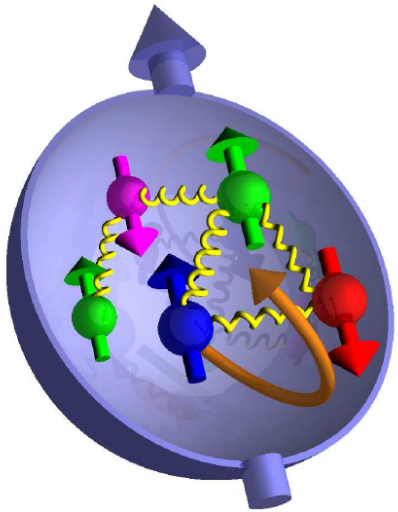

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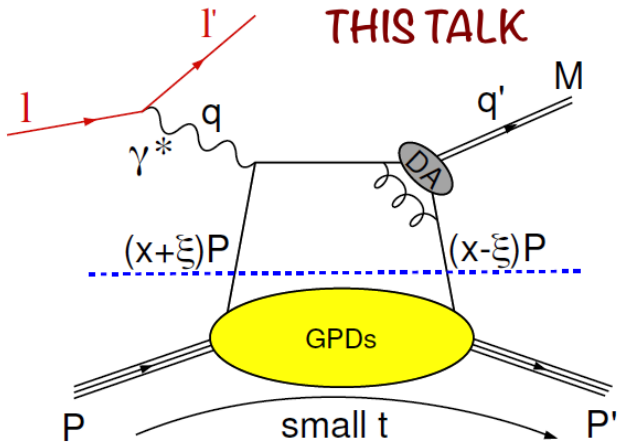


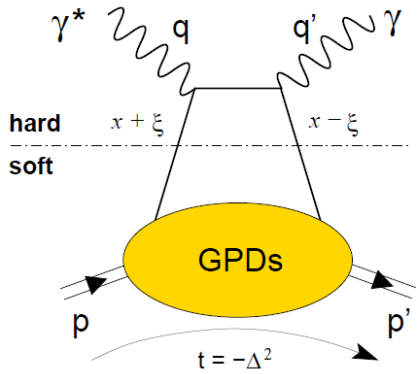
Introduction to Generalized Parton Distributions

Total angular momentum J^f for a particular parton f can be described by means of GPDs:

Ji's sum rule:

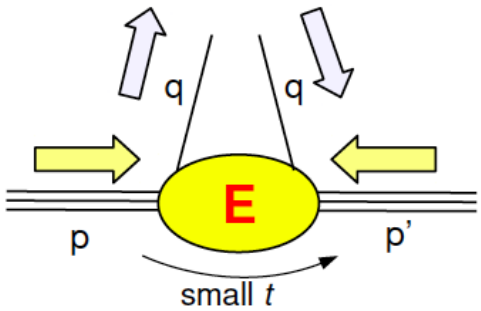
$$J^f = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x[H^f(x, \xi, t) + E^f(x, \xi, t)]$$

Phys. Rev. Lett. 78 (1997)



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

GPDs encode a 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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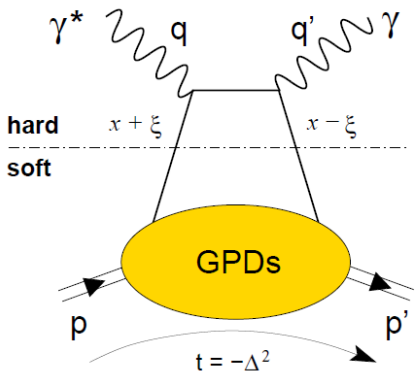

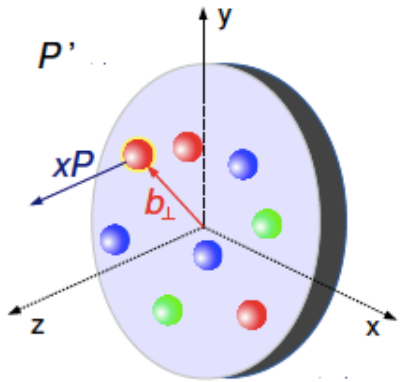

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Limits:

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

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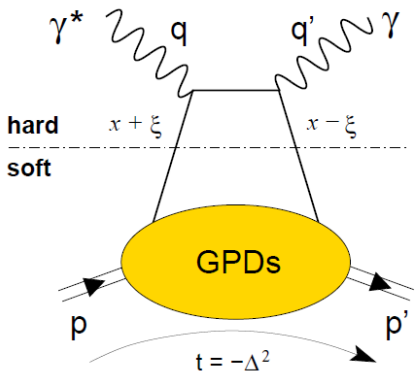
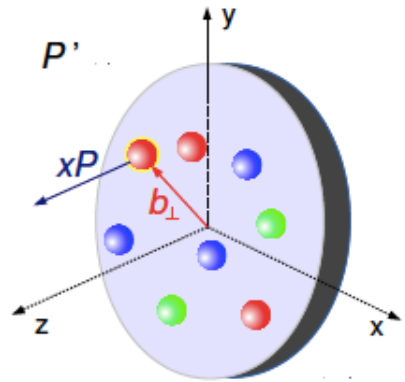
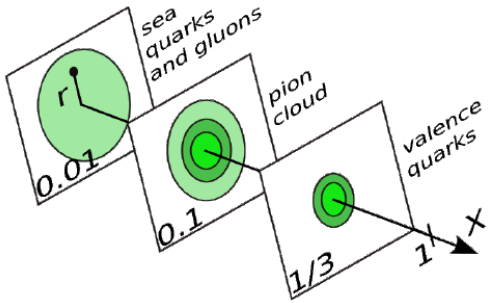


3D imaging by means of GPD H

$H^f(x,\xi=0,t) = q^f(x,b_\perp)$ probability interpretation (Burkardt)





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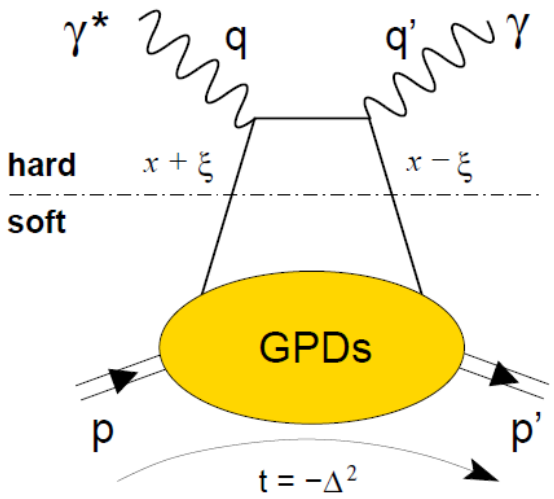
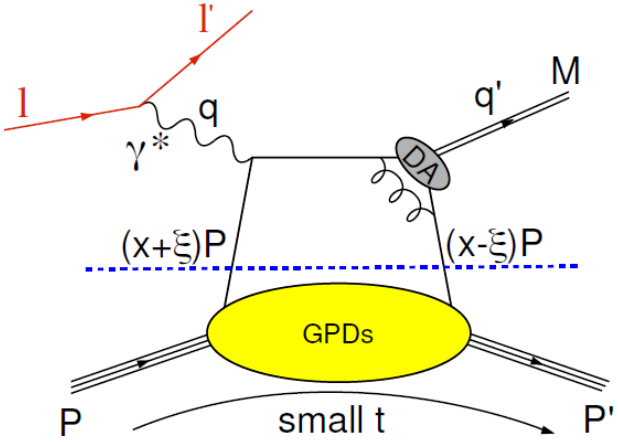
GPDs & Hard Exclusive Meson Production





8 $q^f(x, b_\perp)$: 4 chiral-even GPDs
(parton helicity conserved)

$$H^f(x,\xi,t) \quad E^f(x,\xi,t)$$
$$\tilde{H}^f(x,\xi,t) \quad \tilde{E}^f(x,\xi,t)$$

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

$$H_T^f(x,\xi,t) \quad E_T^f(x,\xi,t)$$
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Factorization proven for σ_L,
not for σ_T which is supposed to be suppressed by a factor $1/Q^2$
BUT large contributions are observed at JLab

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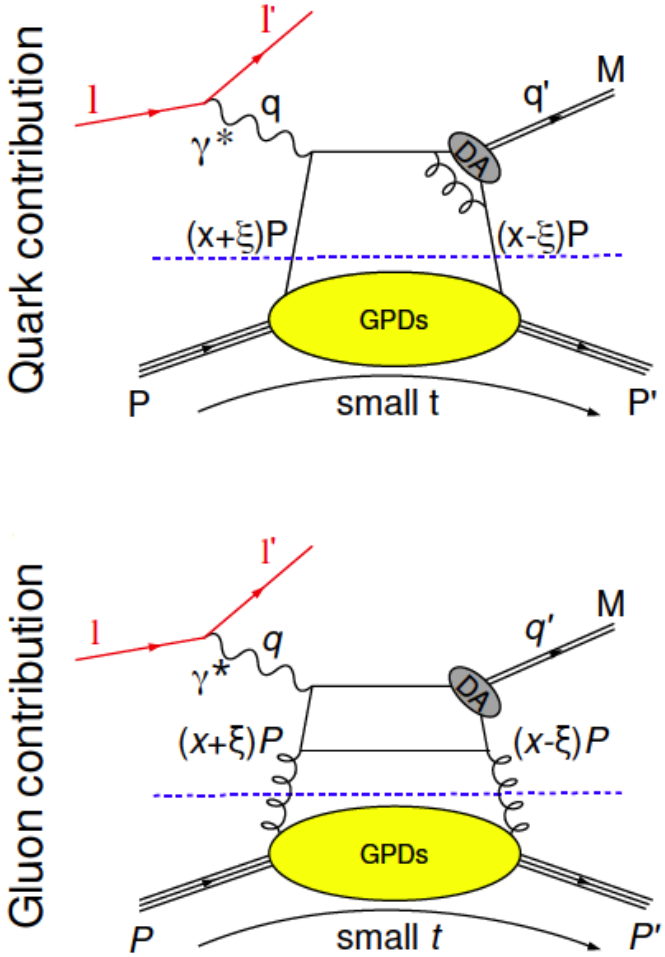

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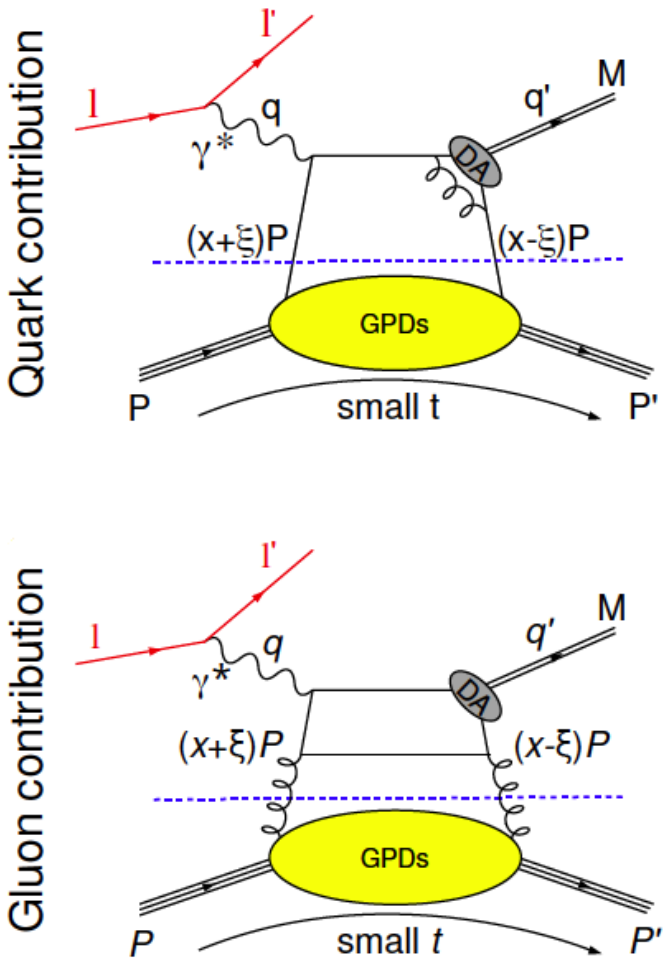

- Flavour separation for specific GPDs due to different partonic content of mesons
- Gluon and quark contributions at the same order in α_s for vector mesons
- DVCS sensitive to H^f, E^f, $\tilde{H}^f$, and $\tilde{E}^f$
- At the leading twist:
  - Vector meson production sensitive to H^f, and E^f
  - 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

Collected events corrected for:

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

$$\frac{\mathrm{d}^4\sigma_{\mu p}}{\mathrm{d}Q^2\mathrm{d}t\mathrm{d}\nu\mathrm{d}\phi} = \Gamma\frac{\mathrm{d}^2\sigma_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi}$$

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

COMPASS 2012 measurement:

- Luminosity of μ^+: $L_{\mu^+} = 18.9\,\mathrm{pb}^{-1}$
- Luminosity of μ^-: $L_{\mu^-} = 23.5\,\mathrm{pb}^{-1}$

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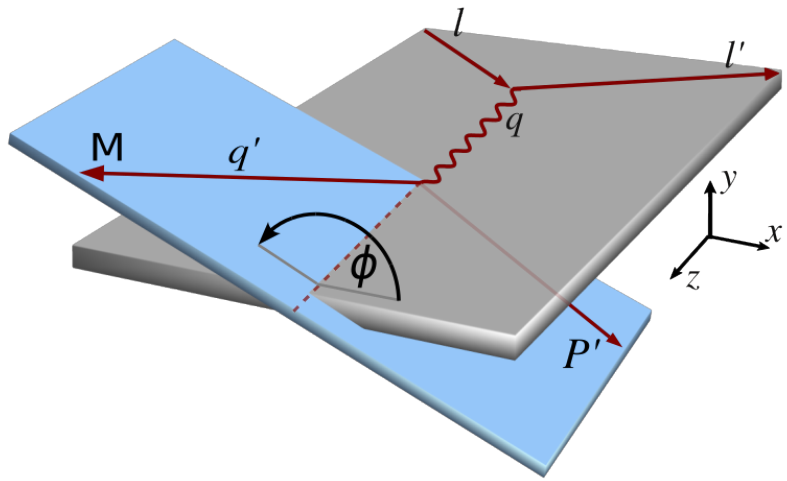
HEMP cross section

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

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

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

$$\gamma = \frac{Q^2}{\nu^2}$$



HEMP cross section

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

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

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

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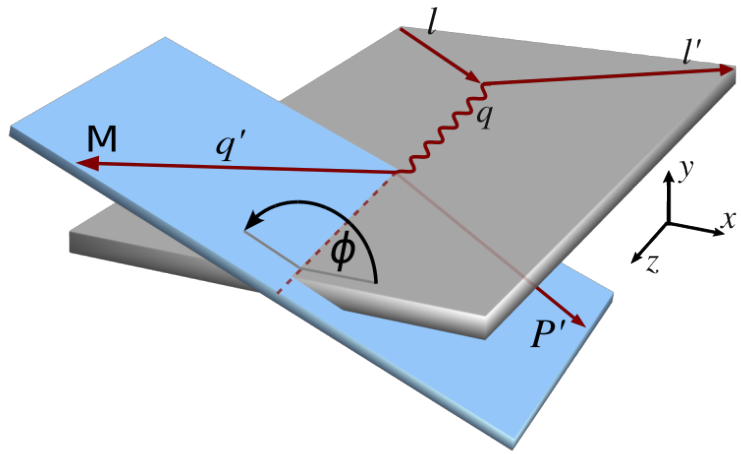
$\Rightarrow$ **study ϕ dependence**



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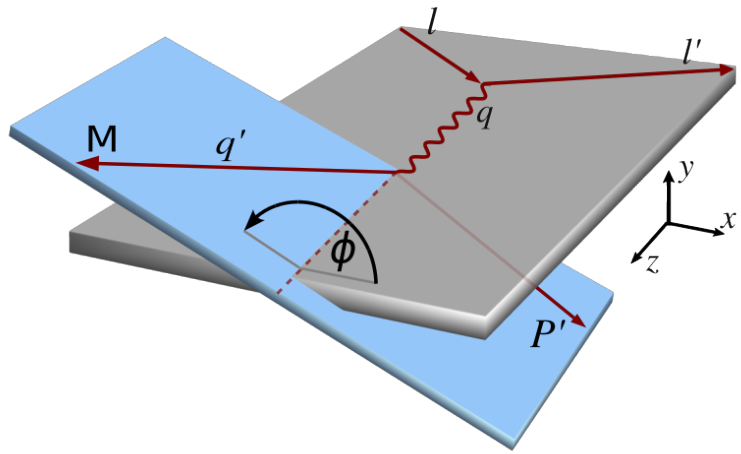
$$\left. \mp |P_l|\sqrt{\epsilon(1-\epsilon)}\sin\phi\frac{\mathrm{d}\sigma'_{LT}}{\mathrm{d}t}\right]$$

$\Rightarrow$ **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**



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GPDs in exclusive π^0 production

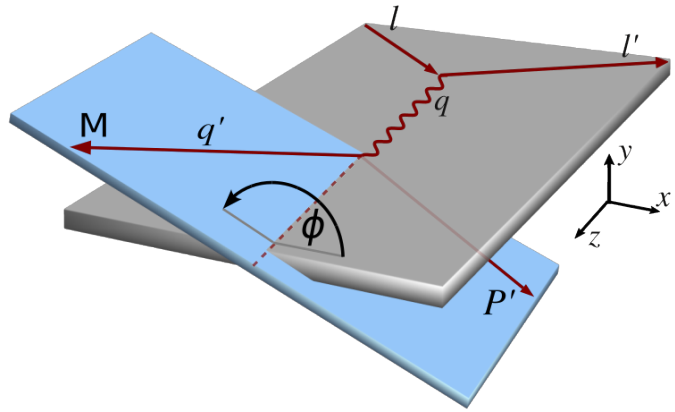
$$\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} \propto \left[(1-\xi^2)\,|\langle\tilde{H}\rangle|^2 - 2\xi^2\,\mathrm{Re}\left(\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right)\right.$$

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

$$\left. - \frac{t'}{4M^2}\xi^2|\langle\tilde{E}\rangle|^2\right]$$

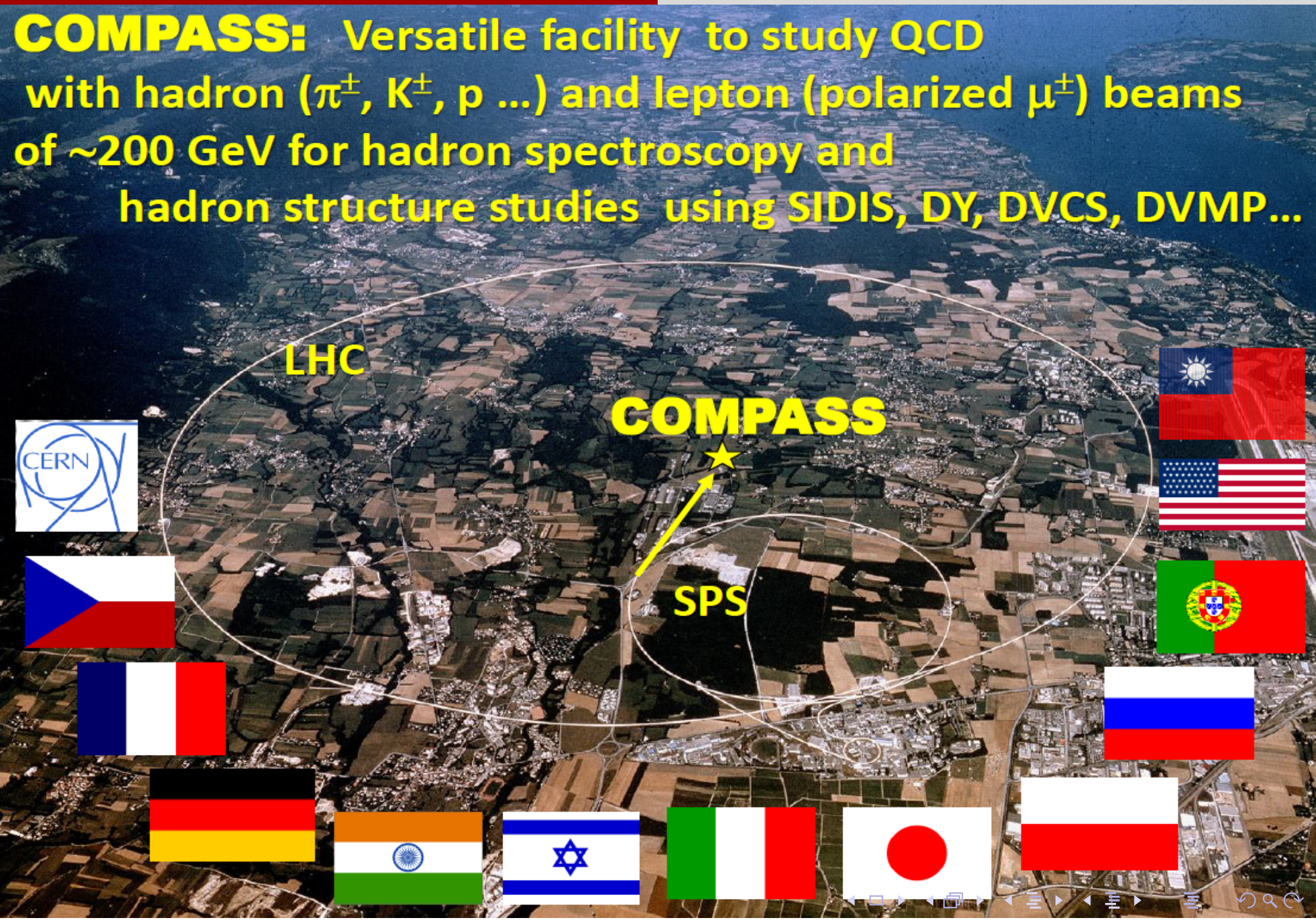
$$\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} \propto t'|\langle\bar{E}_T\rangle|^2$$

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

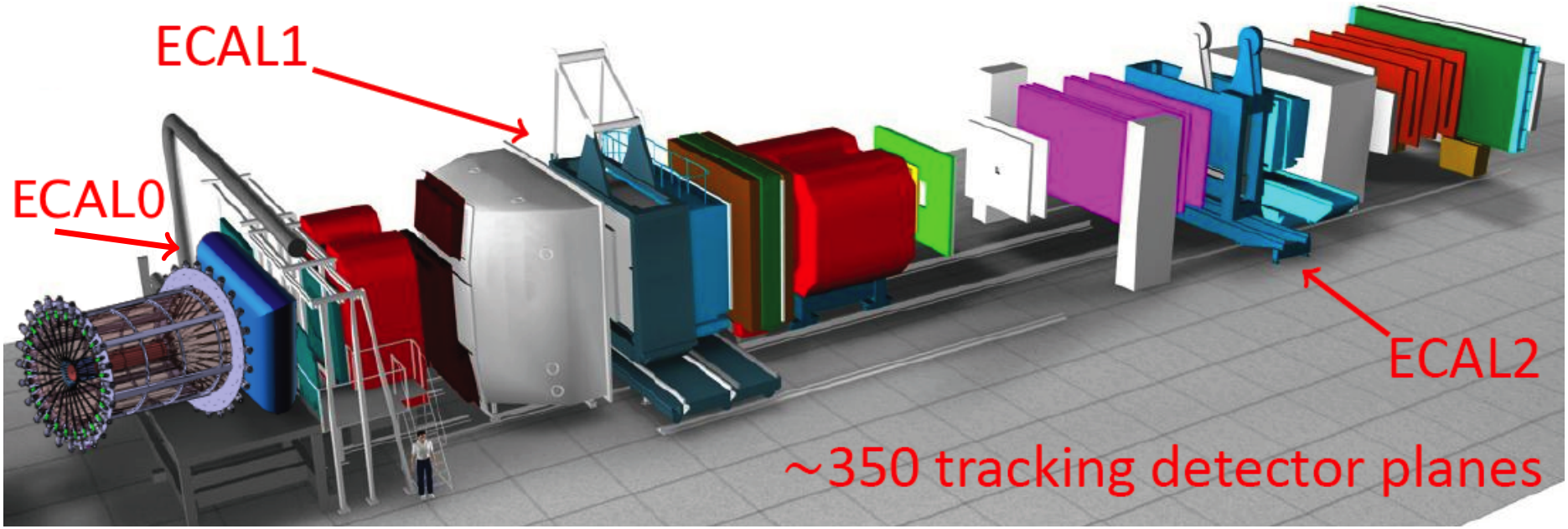


Impact of $\bar{E}_T$ should be visible in $\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t}$, and also a dip at small t of $\frac{\mathrm{d}\sigma_T}{\mathrm{d}t}$

COMPASS: 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...



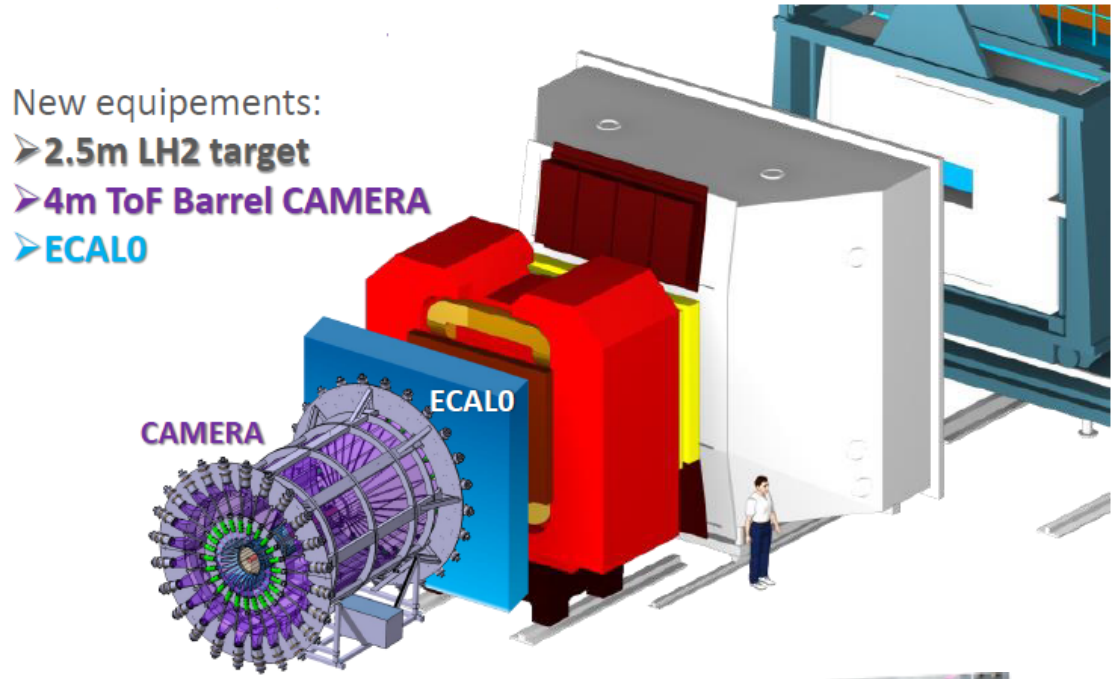
COMPASS GPD program

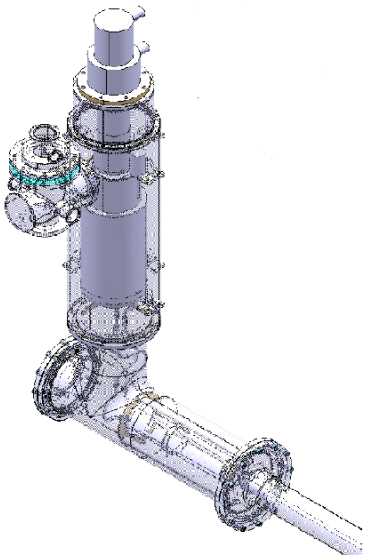


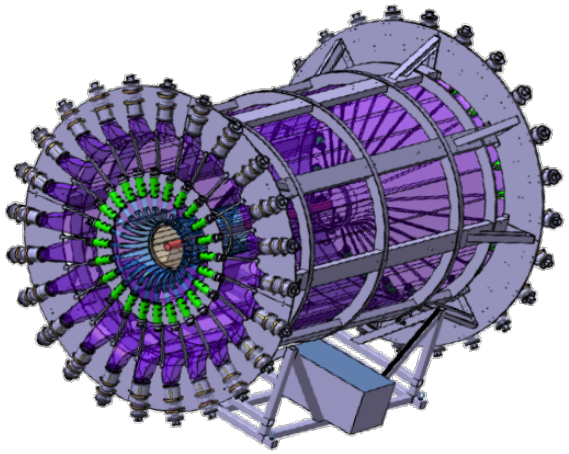
- Two stage magnetic spectrometer with large angular and momentum acceptance
- Versatile usage: hadron and muon beams
- Particle identification:
  - Ring Imaging Cherenkov (RICH) detector
  - Electromagnetic calorimeters (ECAL0, ECAL1, ECAL2)
  - Hadronic calorimeters (HCAL1, HCAL2)
  - 2 muon walls

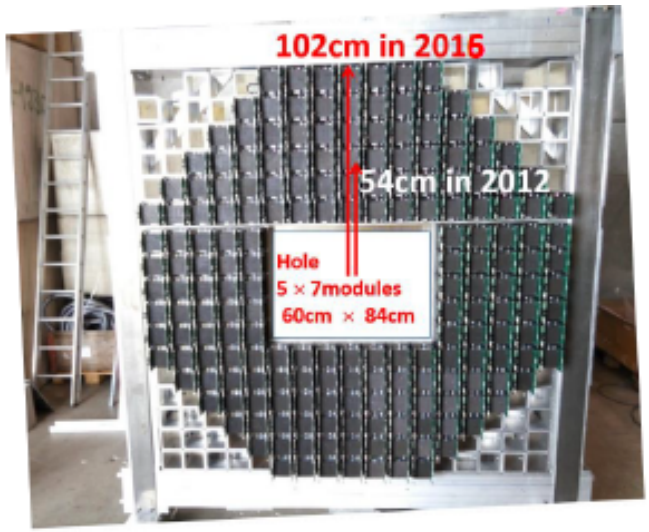
COMPASS GPD program

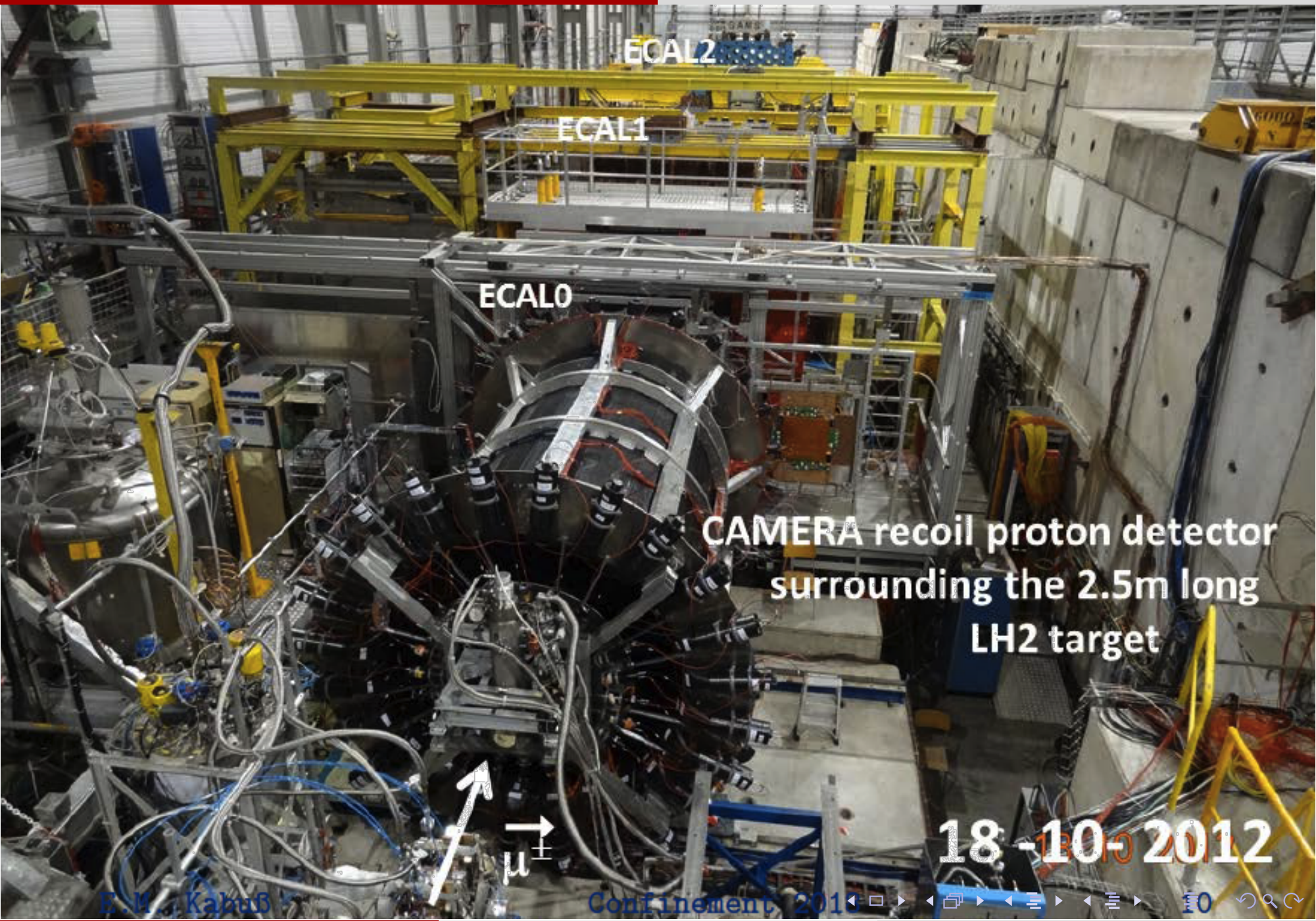
- Target ToF system:
  - 24 inner and outer scintillators
  - 1 GHz readout
  - 310 ps ToF resolution
- ECAL0 calorimeter:
  - shaslyk modules
  - 2×2 m, 2200 channels





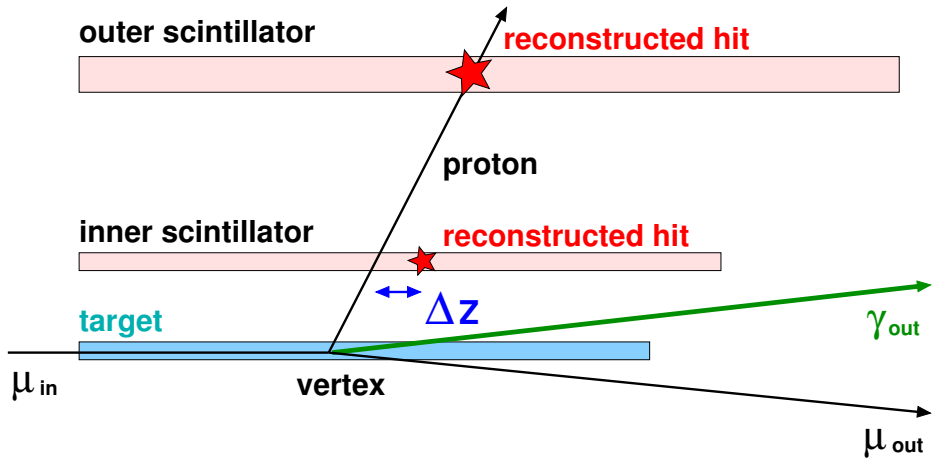





ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\mu^{\pm}$
18-10-2012
E.M. Kabuß
Confinement 2012

Exclusive π^0 production: Selection

- π^0 selected by two-photon decay, one γ above threshold
- Interaction vertices reconstructed within the target
- $1 < Q^2 < 5\ (\mathrm{GeV}/c)^2$, $8.5 < \nu < 28$ GeV, $0.08 < |t| < 0.64\ (\mathrm{GeV}/c)^2$, and $\langle x_B \rangle = 0.093$



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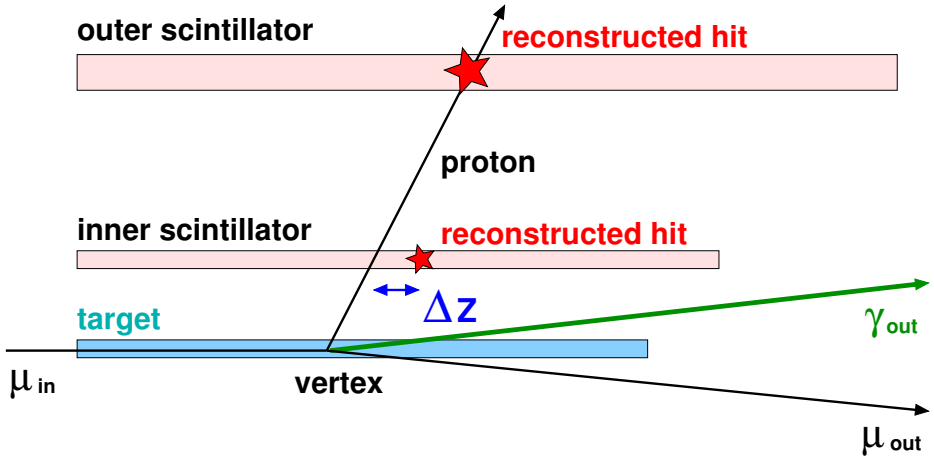

Selections for exclusivity of events:

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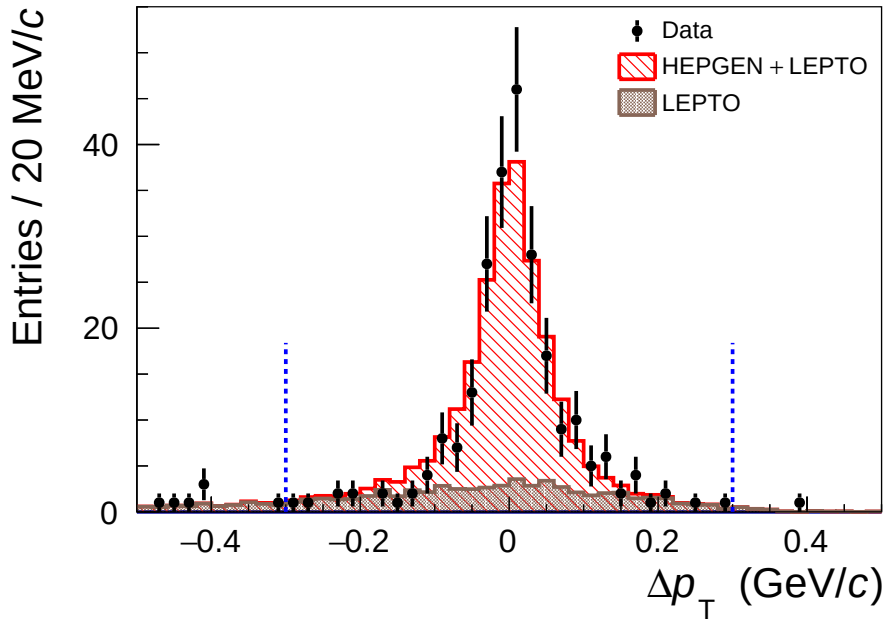

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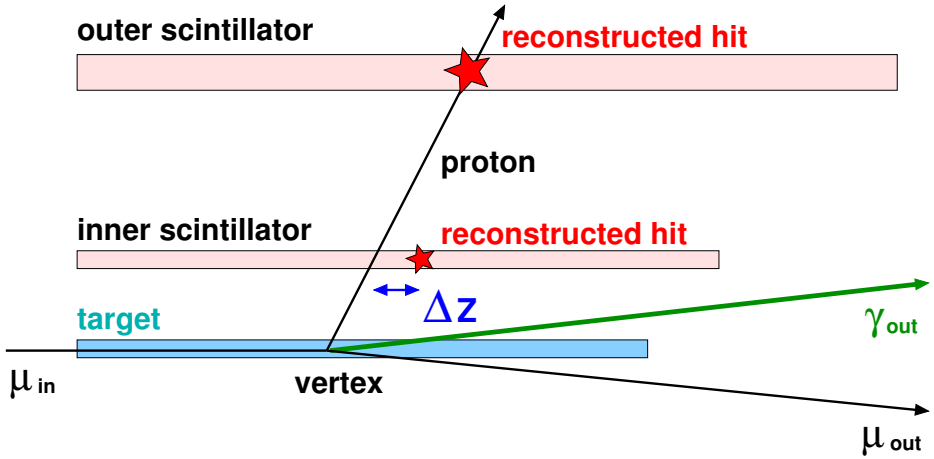

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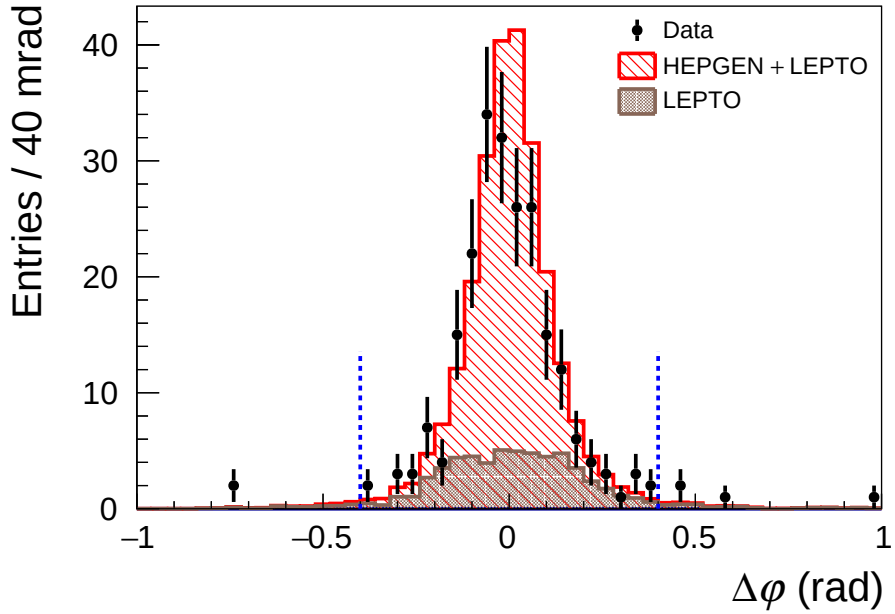

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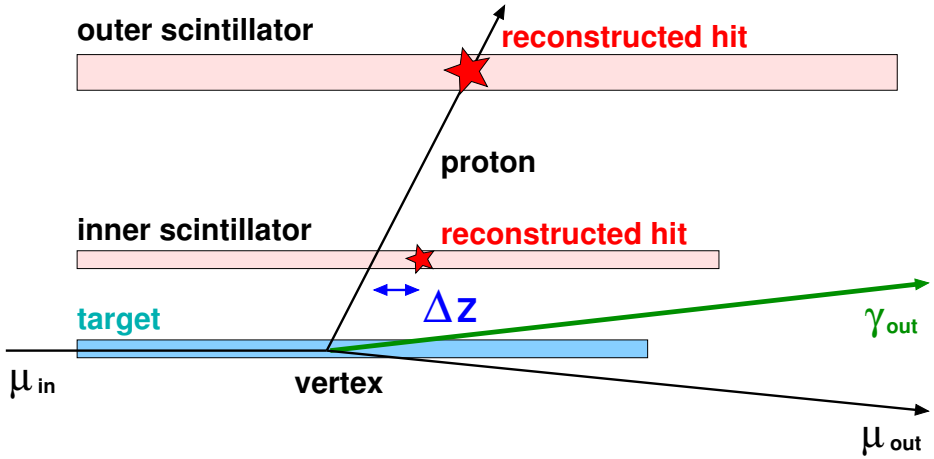

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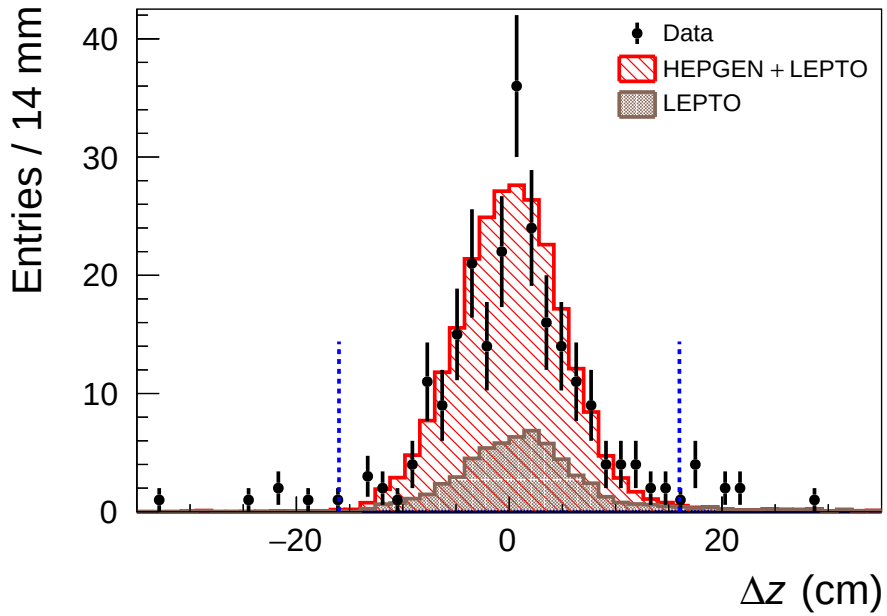
- Z coordinate of vertex constraint: $\Delta z = z^p_{spect} - z^p_{recoil}$



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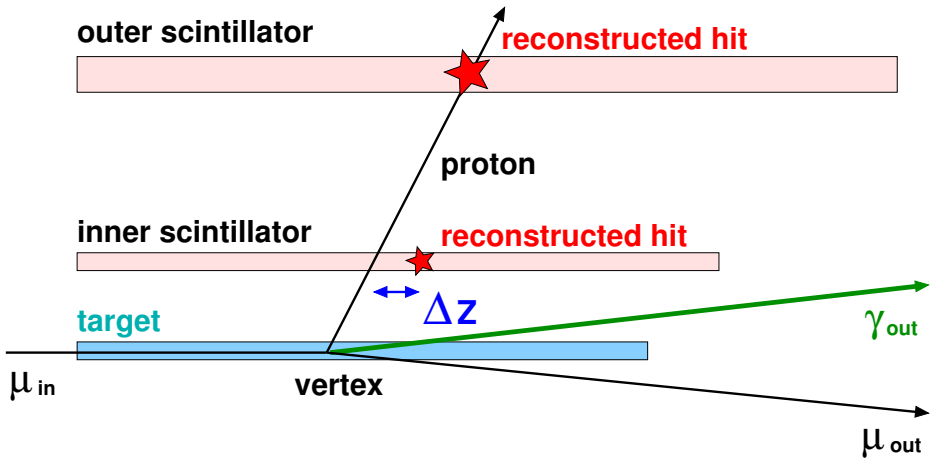

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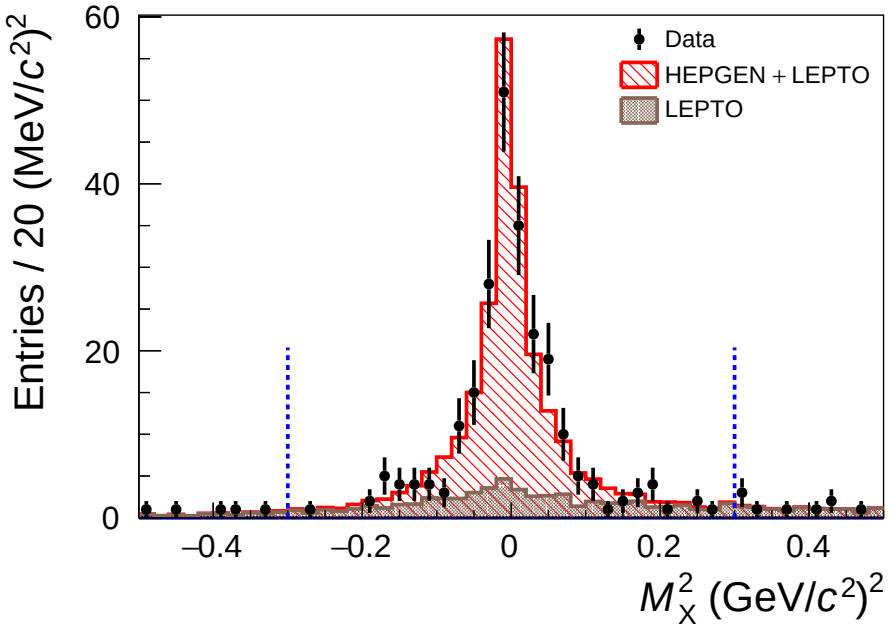
- Missing mass constraint: $M_X^2 = \left(p_{\mu,in} + p_p - p_{\mu,out} - p_{p'} - p_{\pi^0}\right)^2$



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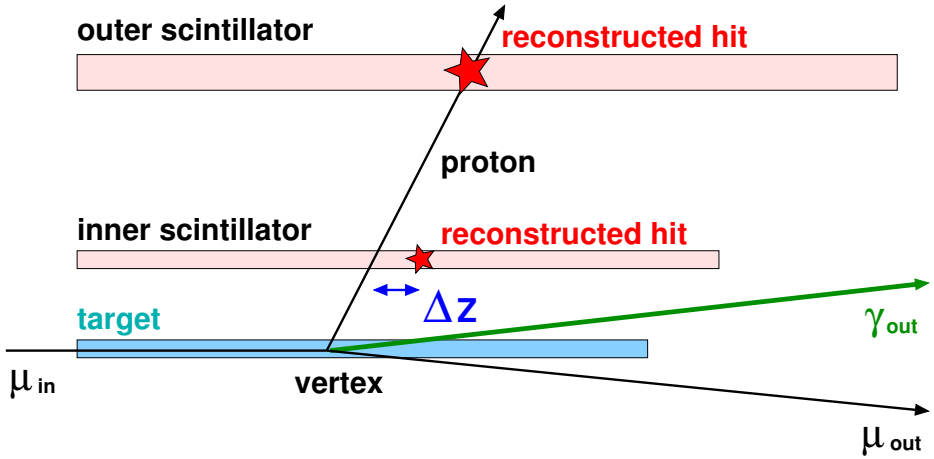

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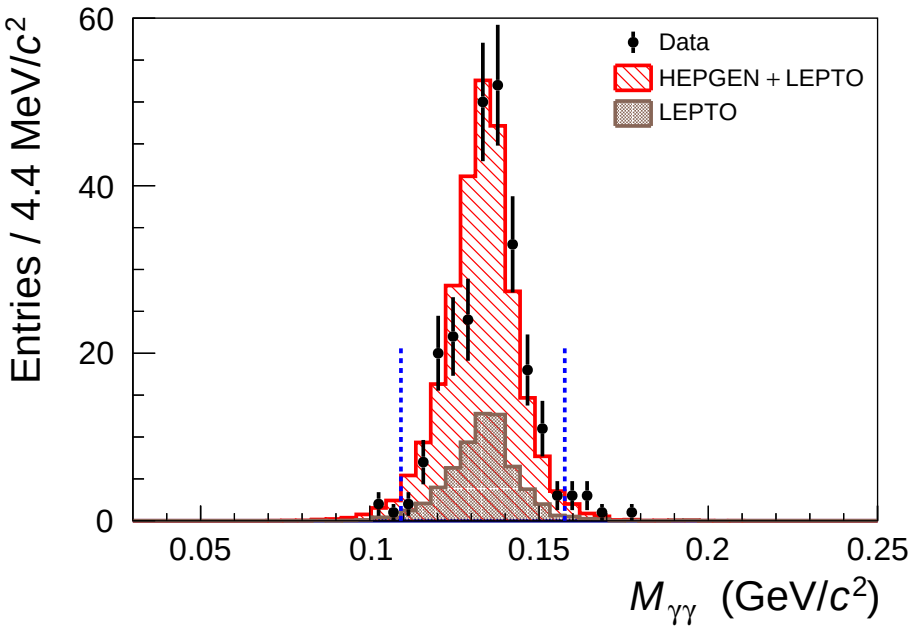
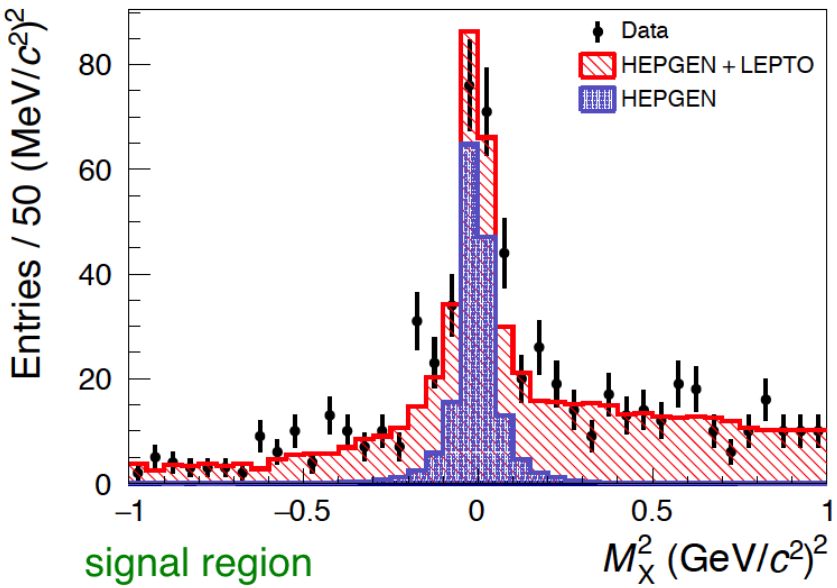
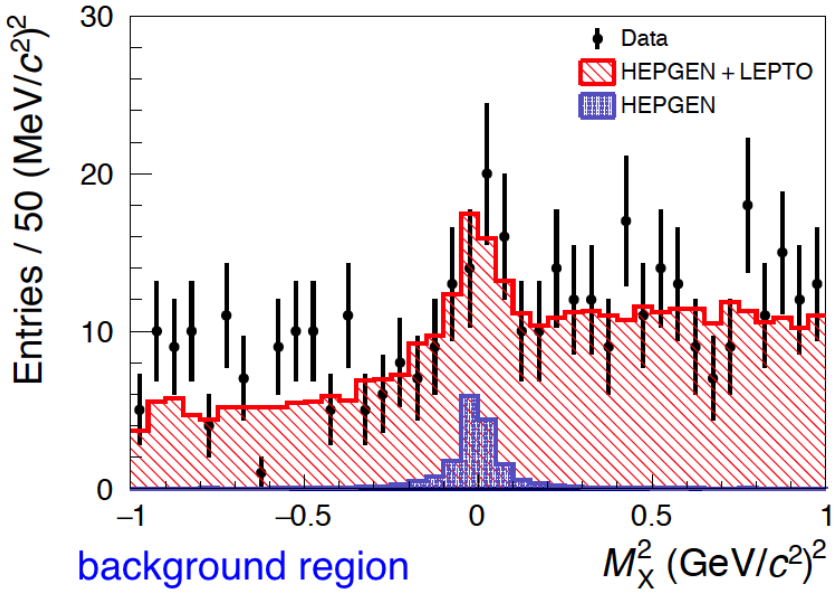
- Invariant mass $M_{\gamma\gamma}$ cut



Exclusive π^0 production: SIDIS background estimation

- Main background of π^0 production $\Rightarrow$ non-exclusive DIS processes
- 2 reference samples (wider kinematic range) described by MC:
  - LEPTO for describing the shape of non-exclusive background distribution
  - HEPGEN++ for the shape of distributions of exclusive π^0 production (signal contribution)
- Search for best description of data in signal region and background region





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  - HEPGEN: exclusive π^0 production (signal)
- Search for background region

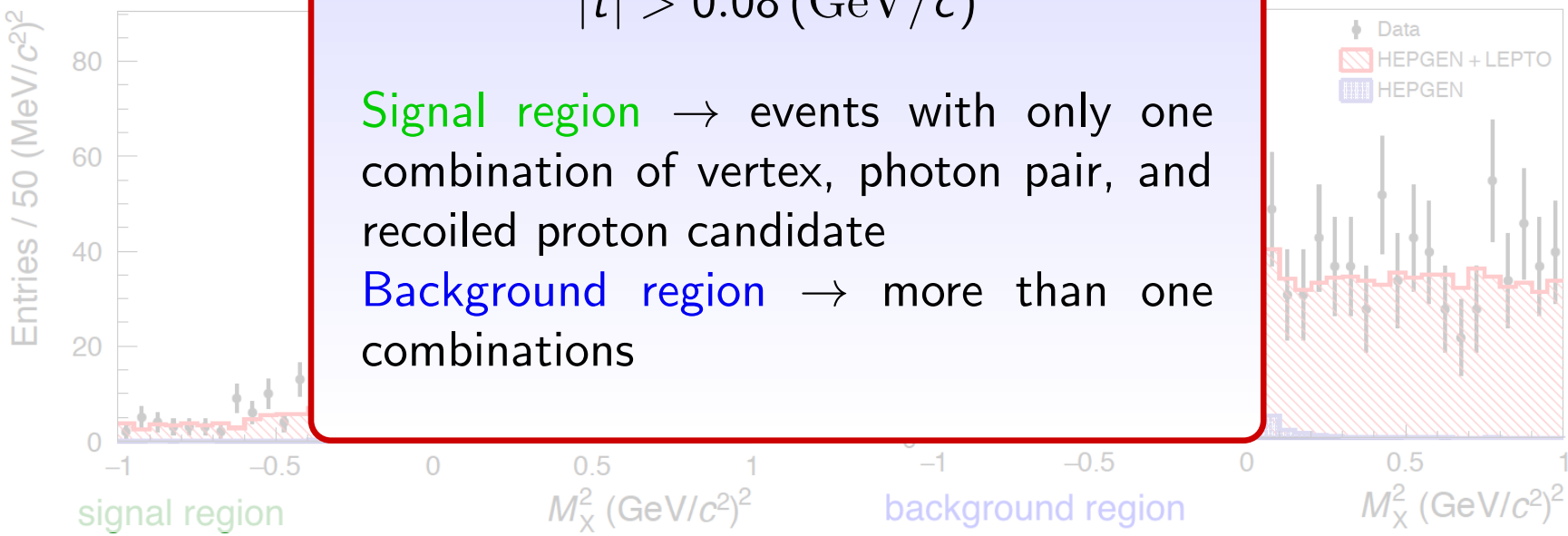
Reference samples

Extended kinematic region for the reference samples:

$$Q^2 > 1\,(\mathrm{GeV}/c)^2$$
$$\nu > 8.5\,\mathrm{GeV}$$
$$|t| > 0.08\,(\mathrm{GeV}/c)^2$$

Signal region $\rightarrow$ events with only one combination of vertex, photon pair, and recoiled proton candidate

Background region $\rightarrow$ more than one combinations



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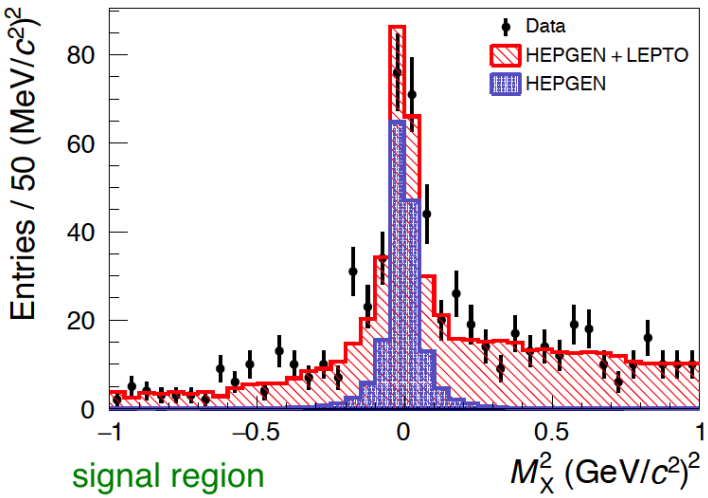
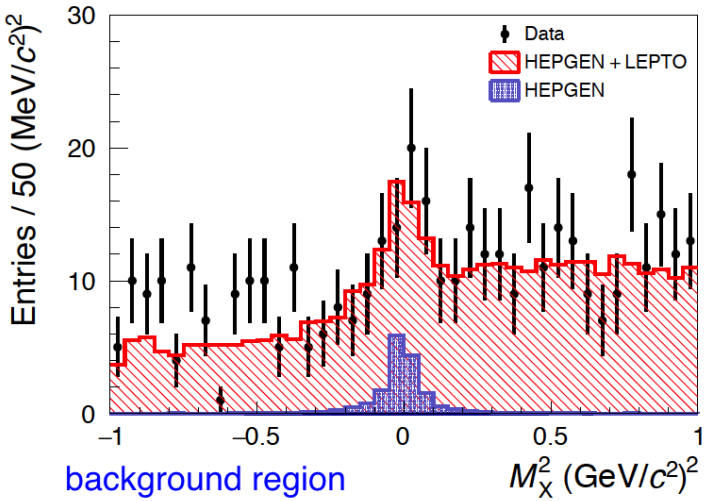
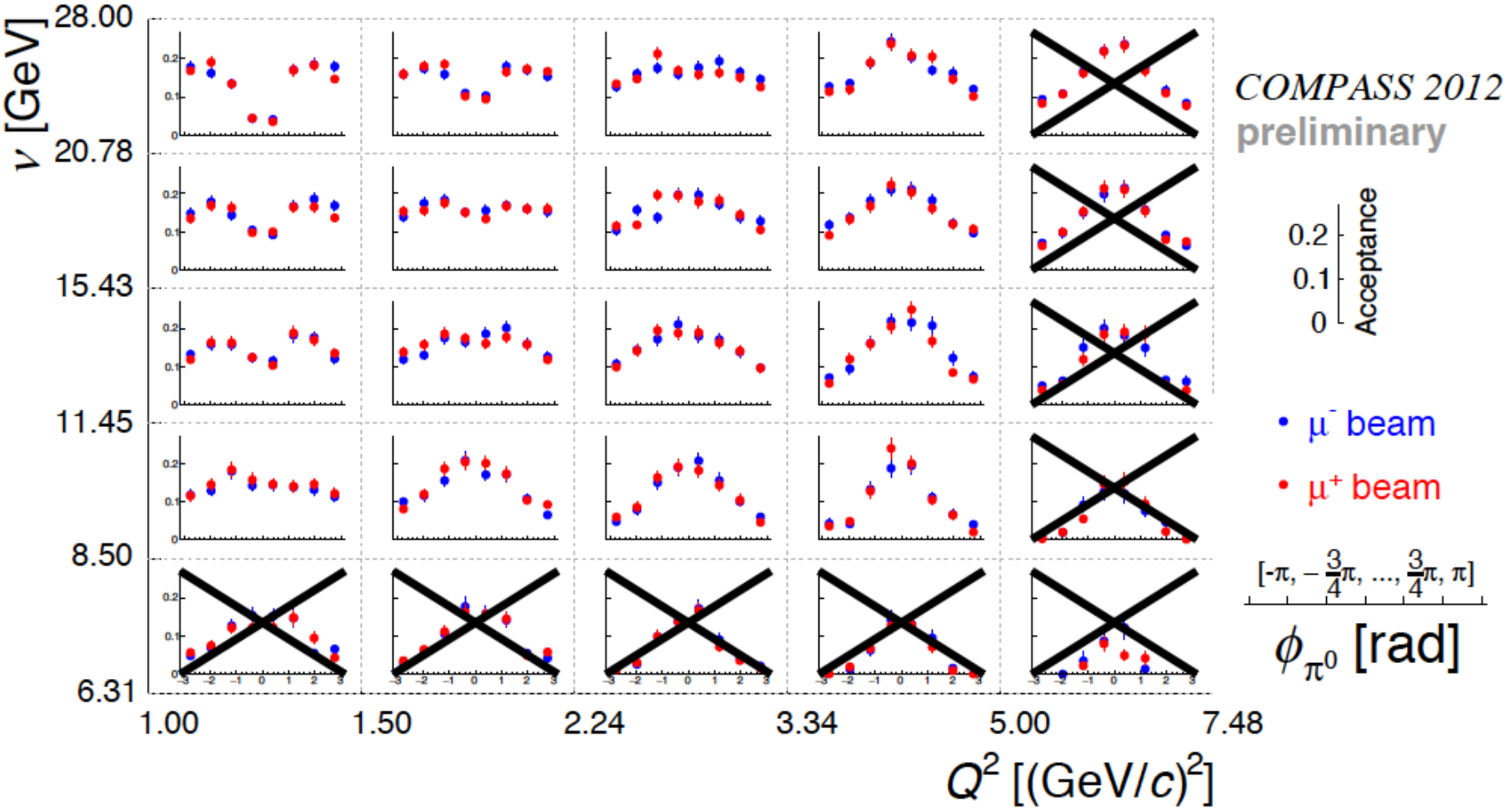




Resulting fraction of non-exclusive background in data: $\left(29^{+2}_{-6}|_{sys}\right)$ %

Exclusive π^0 production: COMPASS acceptance

Acceptance as a function of ϕ_{π^0} for bins of ν and Q^2

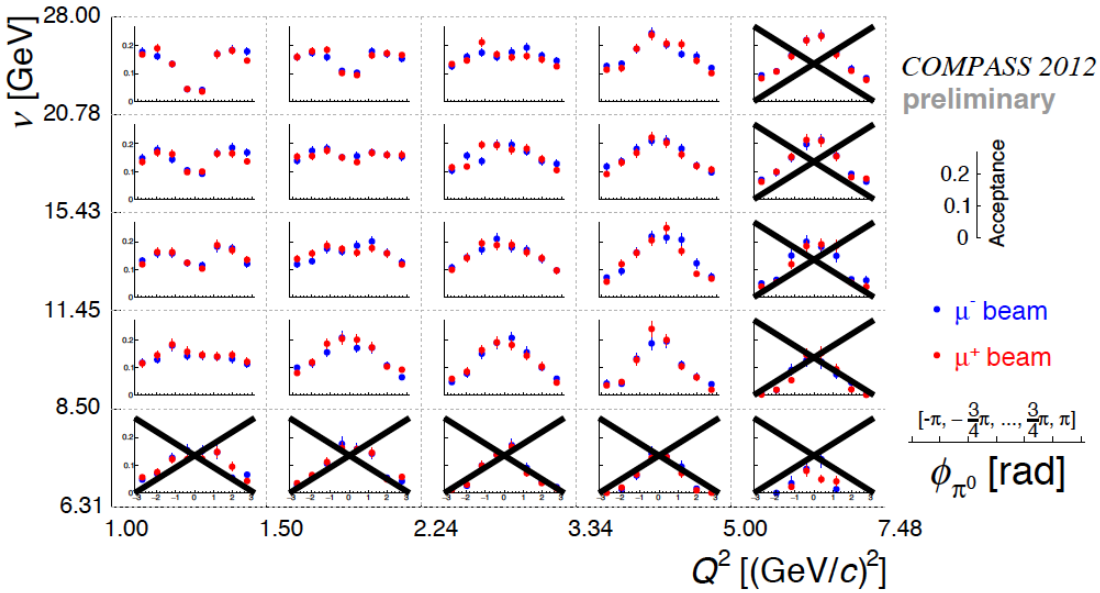


Exclusive π^0 production: COMPASS acceptance

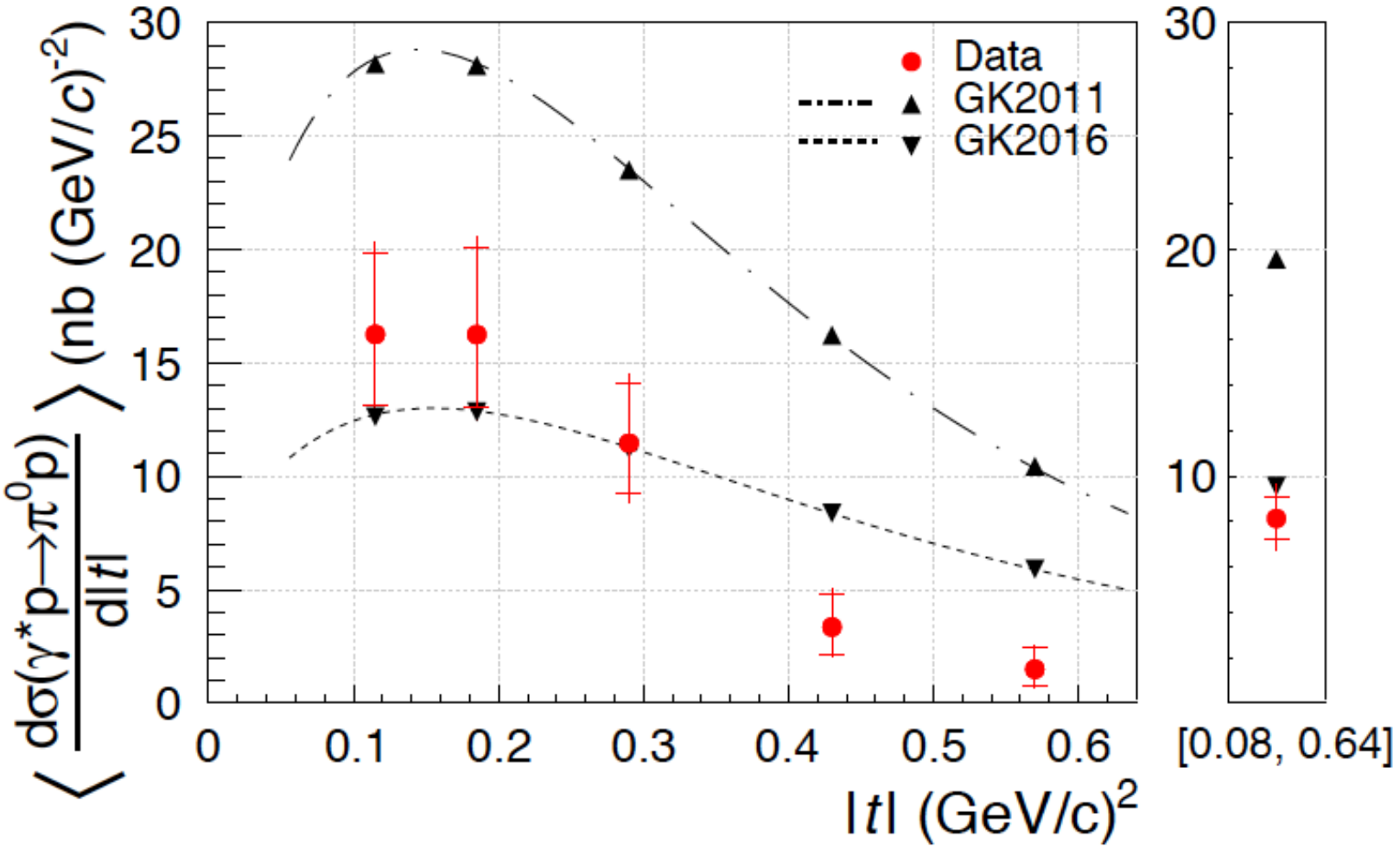
Acceptance as a function of ϕ_{π^0} for bins of ν and Q^2

4D acceptance binning (3D projection on fig.):

- Q^2 and ν: $\frac{\mathrm{d}^4\sigma_{\mu p}}{\mathrm{d}Q^2\mathrm{d}t\mathrm{d}\nu\mathrm{d}\phi} = \Gamma\frac{\mathrm{d}^2\sigma_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi}$ with the virtual photon flux $\Gamma = \Gamma(E_\mu, Q^2, \nu)$
- $|t|$ and ϕ_{π^0}



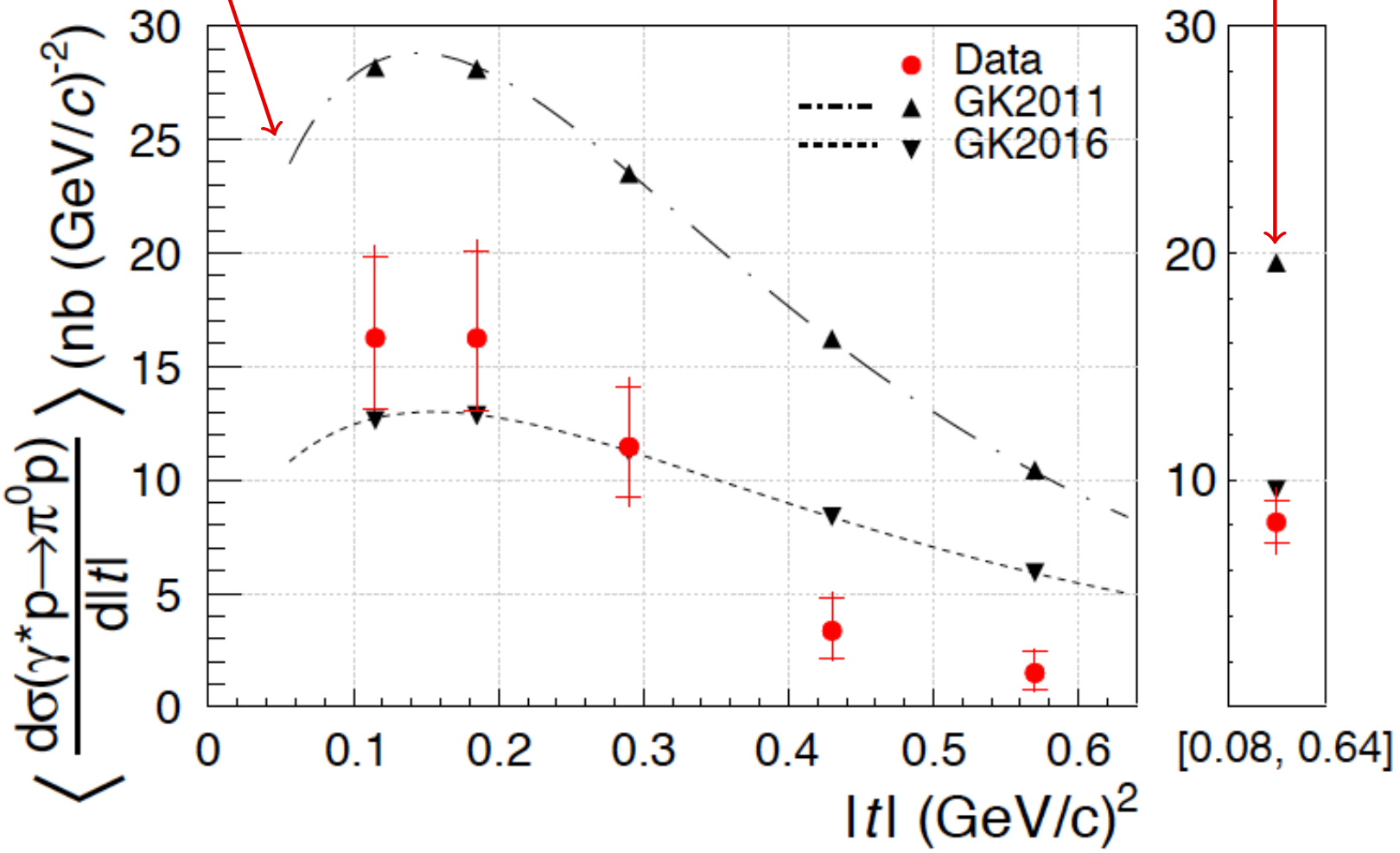
Exclusive π^0 cross-section as a function of $|t|$



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

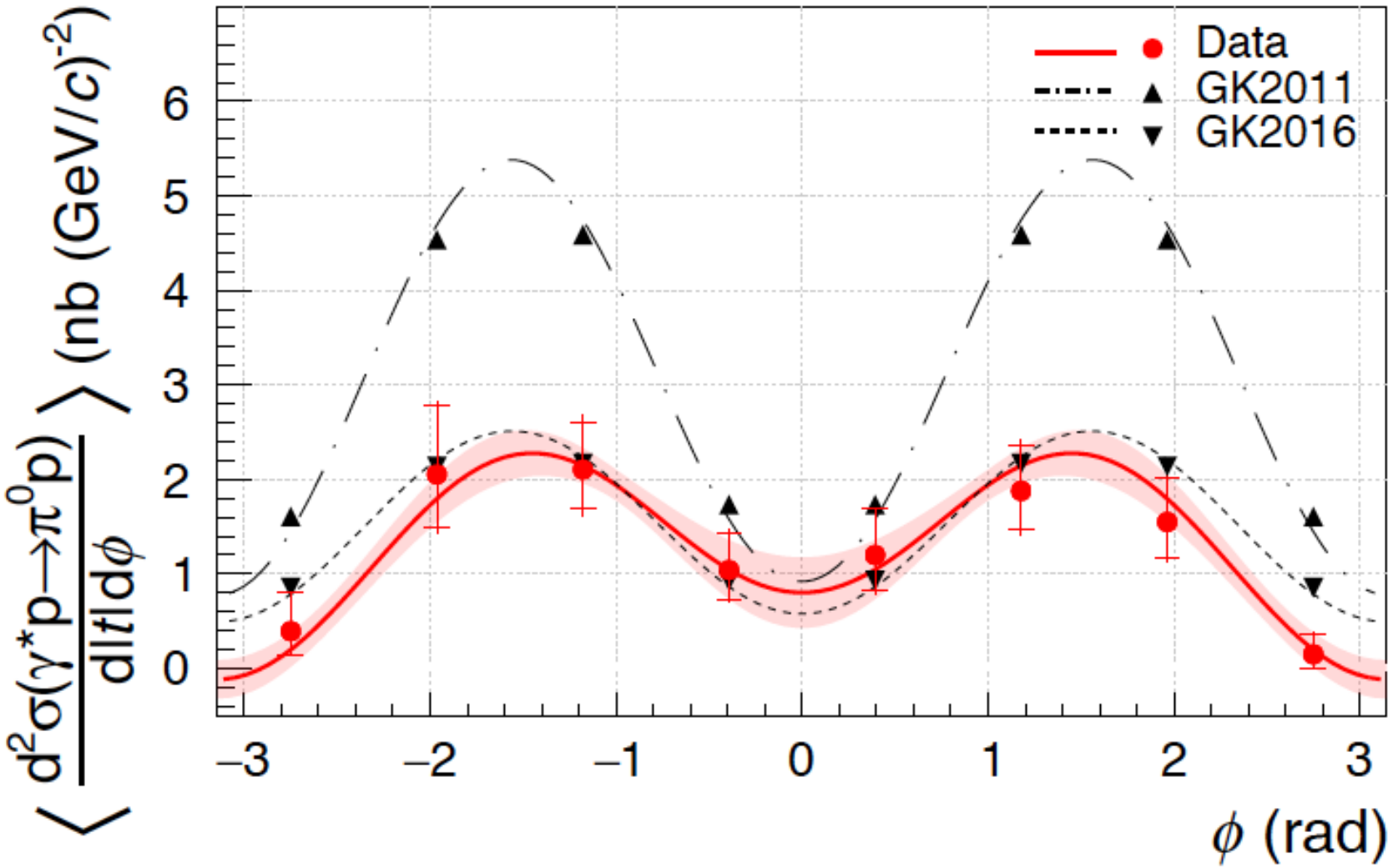
Dip would indicate contribution of $\bar{E}_T$ (not visible in COMPASS data)

Factor of ~ 2 discrepancy with Goloskokov&Kroll model EPJ A47 (2011) 112



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

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



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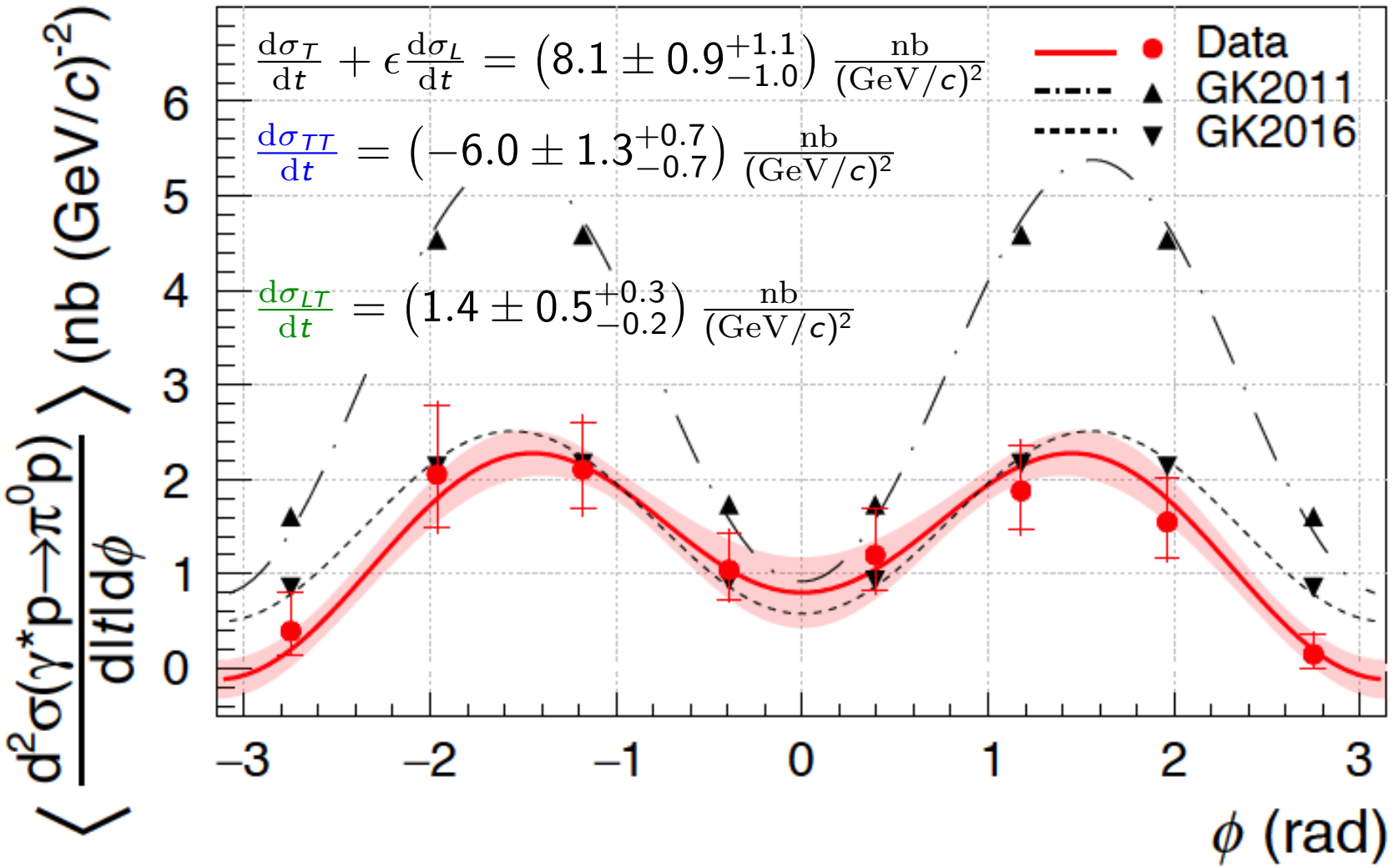


Summary and Outlook

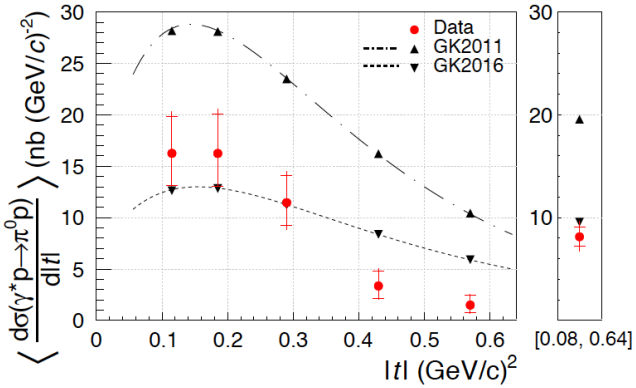
t-dependence and ϕ-dependence of exclusive π^0 cross-section on unpolarised proton target:

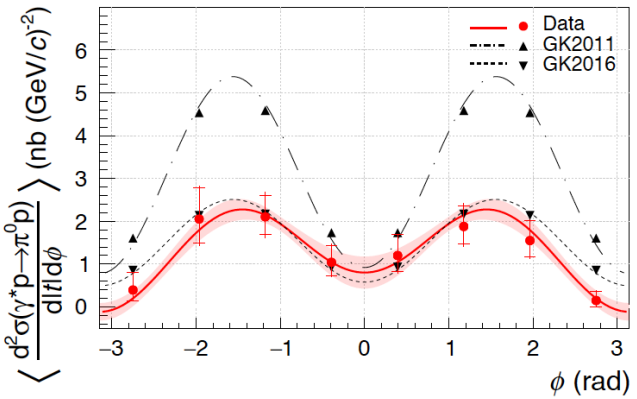
- First results at low ξ (or $\langle x_B \rangle = 0.093$) from COMPASS 2012 pilot measurement, input for constraining the Goloskokov&Kroll model

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon \frac{\mathrm{d}\sigma_L}{\mathrm{d}t} = \left(8.1 \pm 0.9^{+1.1}_{-1.0}\right) \frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

$$\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} = \left(-6.0 \pm 1.3^{+0.7}_{-0.7}\right) \frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

$$\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t} = \left(1.4 \pm 0.5^{+0.3}_{-0.2}\right) \frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$





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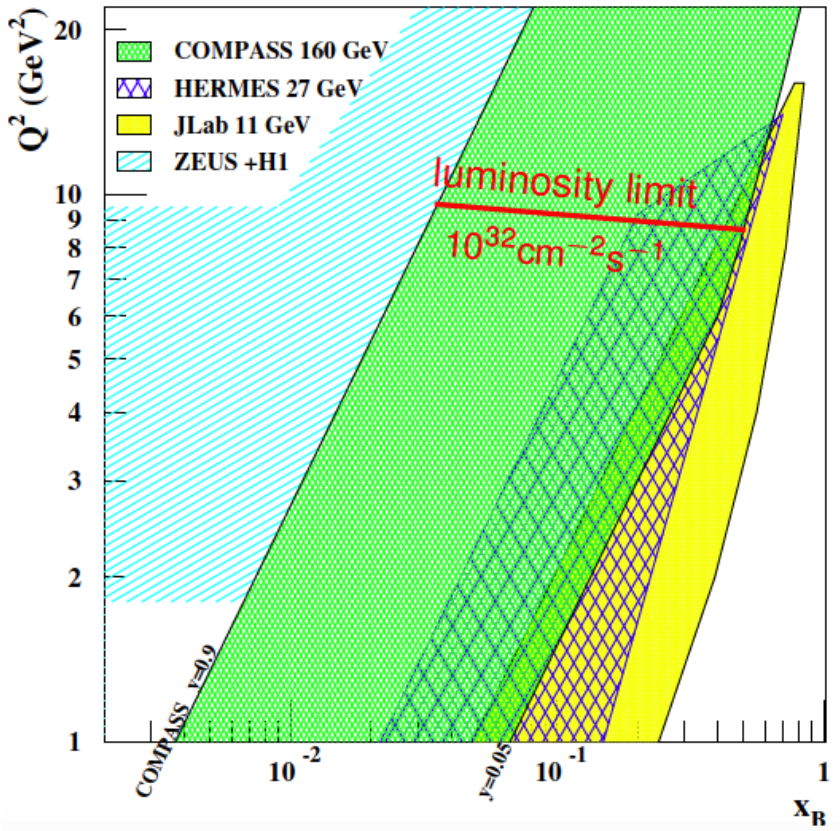
- New results expected from the measurement in 2016/2017 for DVCS, vector and pseudoscalar meson production
- Collected 2016/2017 statistics $\sim 10\times$ larger then from 2012 pilot run
- New results expected on differential cross-section for π^0 wrt Q^2, ν, t, and ϕ


Thank you for your attention!

SPARES

COMPASS GPD measurement

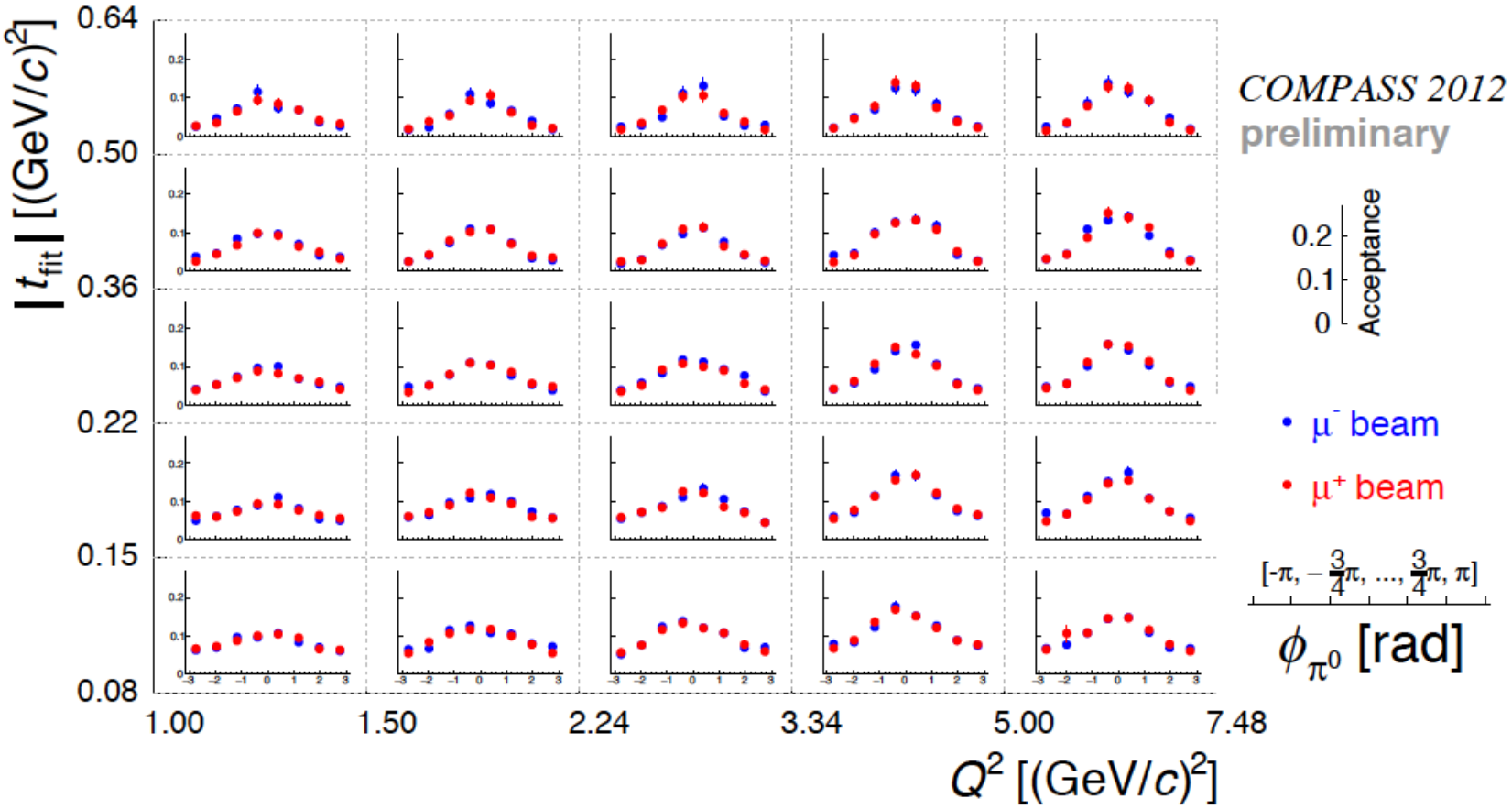
- COMPASS covers the unexplored phase space between colliders (H1 & Zeus) and low-energy fixed target (HERMES & JLab) experiments



- μ^+ and μ^- beams with momentum $160\,\mathrm{GeV}/c^2$
- Beams naturally polarised from pion decay, $P = 80\%$
- Luminosity of μ^+: $L_{\mu^+} = 18.9\,\mathrm{pb}^{-1}$ collected with negative polarisation
- Luminosity of μ^-: $L_{\mu^-} = 23.5\,\mathrm{pb}^{-1}$ with positive polarisation

Exclusive π^0 production: COMPASS acceptance

Acceptance as a function of ϕ_{π^0} for bins of $|t|$ and Q^2



Exclusive π^0 production: COMPASS acceptance

Acceptance as a function of $|t|$ for bins of ν and Q^2