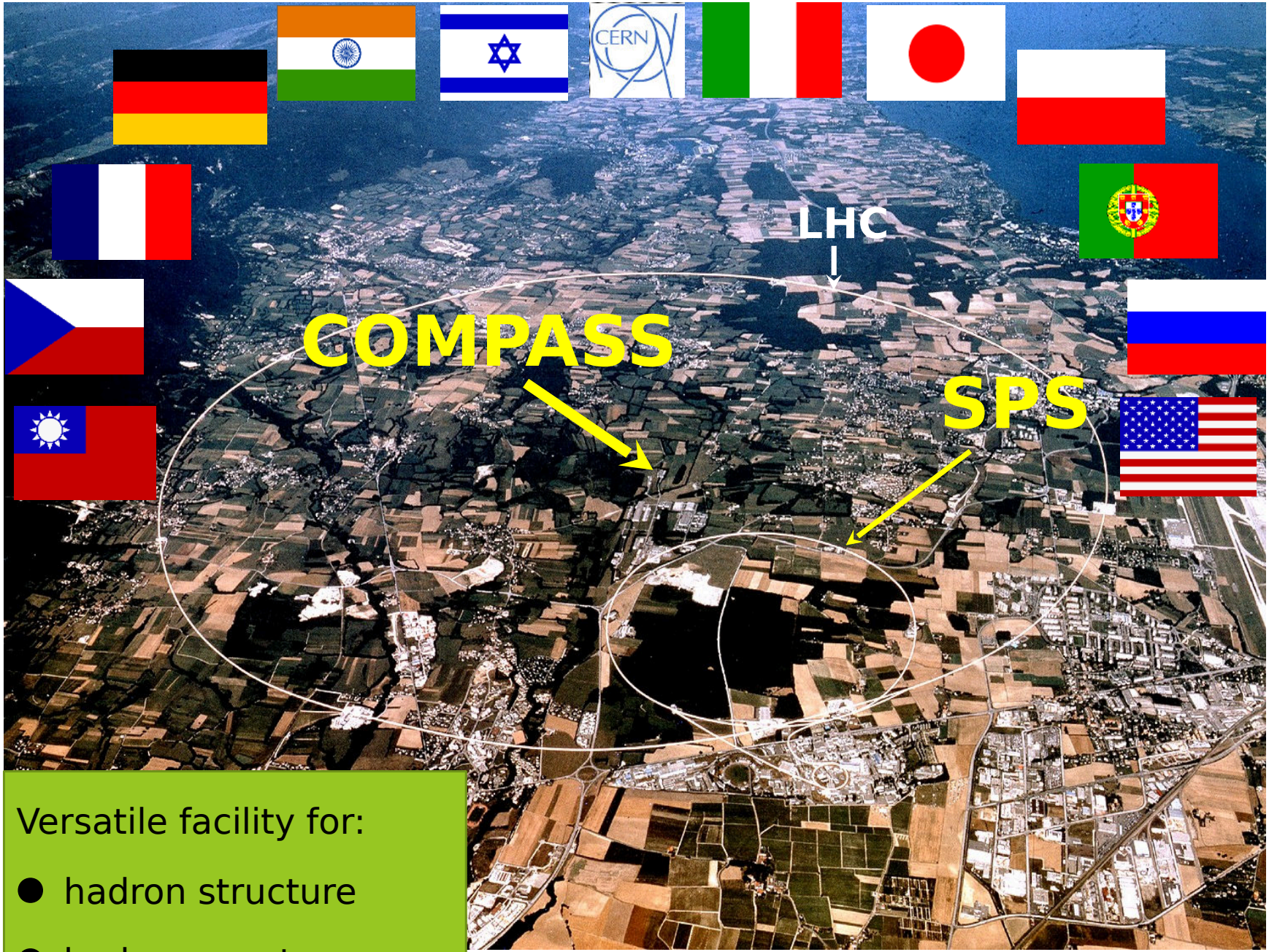
Measurement of the exclusive π^0 muoproduction cross section at COMPASS

M. Gorzellik (ALU Freiburg)

on behalf of the COMPASS Collaboration

22nd Spin, 09/2016



Versatile facility for:

- hadron structure
- hadron spectroscopy

Generalized Parton Distributions @ COMPASS

- Contribution to the nucleon spin puzzle

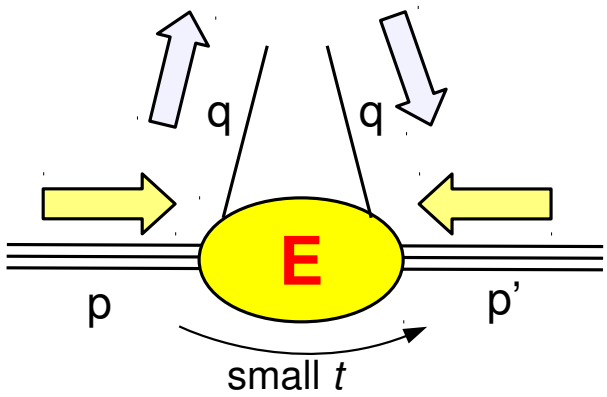
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathscr{L}$$

Jaffe&Manohar Nucl.Phys.B337 (1990)

by constraining GPD H and E

$$J^q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{+1} x[H^q + E^q]dx$$

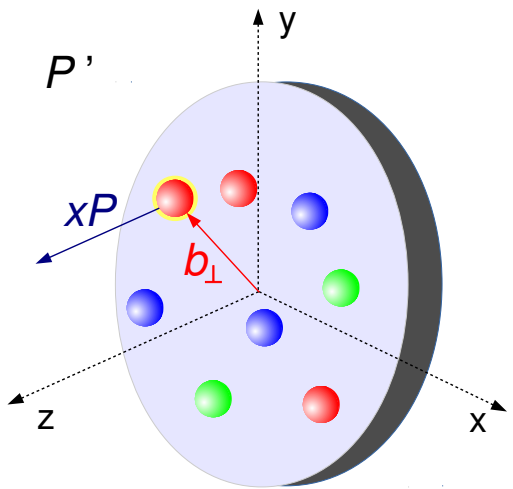
(Phys.Rev.Lett.78 (1997))



- 3D nucleon tomography via GPD H

$$H(x, \xi = 0, t) = \rho(x, b_\perp)$$

probability interpretation (Burkardt)



Generalized Parton Distributions @ COMPASS

- Contribution to the nucleon spin puzzle

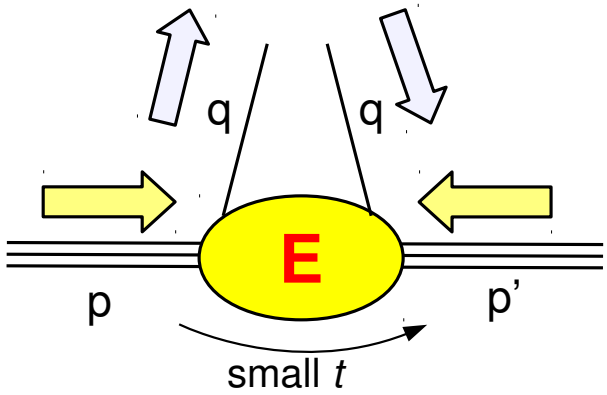
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathscr{L}$$

Jaffe&Manohar Nucl.Phys.B337 (1990)

by constraining GPD H and E

$$J^q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{+1} x[H^q + E^q]dx$$

(Phys.Rev.Lett.78 (1997))



recent work

→ Exclusive vector meson production on transversely polarised protons and deuterons

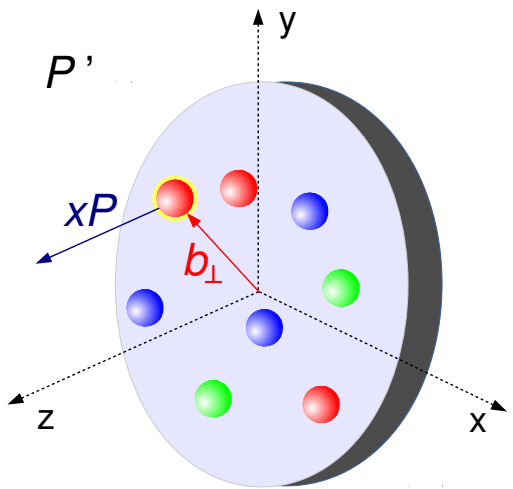
this talk

→ Exclusive π^0 production cross-section on unpolarised protons

- 3D nucleon tomography via GPD H

$$H(x, \xi = 0, t) = \rho(x, b_\perp)$$

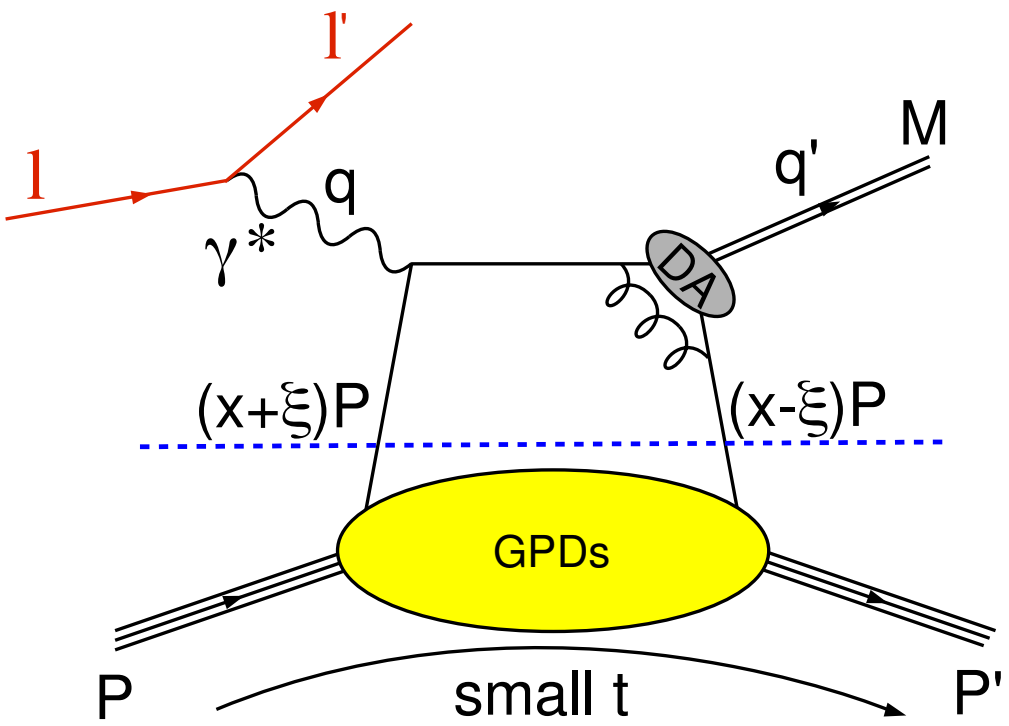
probability interpretation (Burkardt)



Andrea Ferrero

→ t-dependence of pure DVCS x-section on unpolarised protons

GPDs and Hard Exclusive Meson Production



$Q^2 = -q^2$

$\nu = \frac{P \cdot q}{M} \overset{lab.}{=} E - E'$

x : average longitudinal momentum of quark

ξ : longitudinal momentum transfer to quark

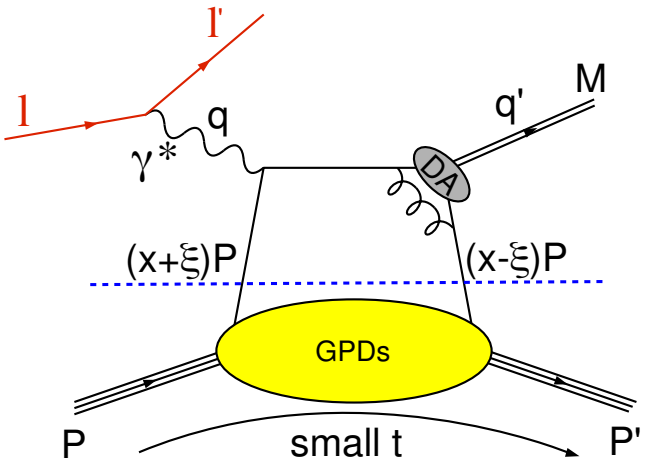
t : 4-momentum transfer to target nucleon (related to $b_\perp$)

factorisation proven for σ_L
not proven for σ_T (but suppresed by $1/Q^2$)

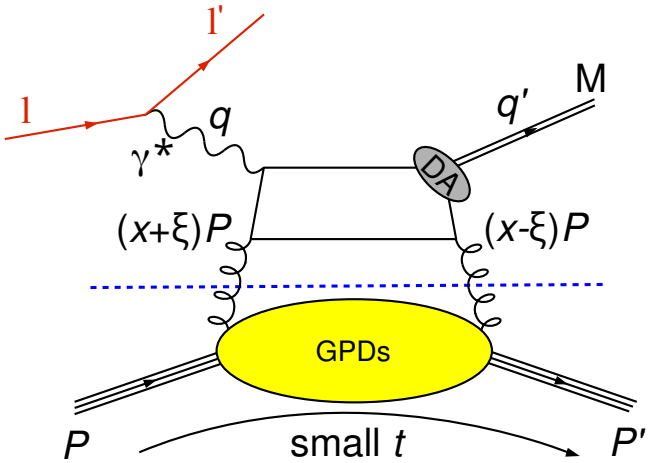
additional non perturbative term:
wave function of meson (DA)

GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution *



Chiral-even GPDs

helicity of parton unchanged

$$H^{q,g}(x,\xi,t) \qquad E^{q,g}(x,\xi,t)$$
$$\widetilde{H}^{q,g}(x,\xi,t) \qquad \widetilde{E}^{q,g}(x,\xi,t)$$

Chiral-odd GPDs

helicity of parton changed

$$H_T^q(x,\xi,t) \qquad E_T^q(x,\xi,t)$$
$$\widetilde{H}_T^q(x,\xi,t) \qquad \widetilde{E}_T^q(x,\xi,t)$$

Flavour separation

constraints for parton specific GPDs
due to different partonic content of mesons

* Gluon contribution at same order of α_s as from quarks

HEMP cross section (unpolarised target)

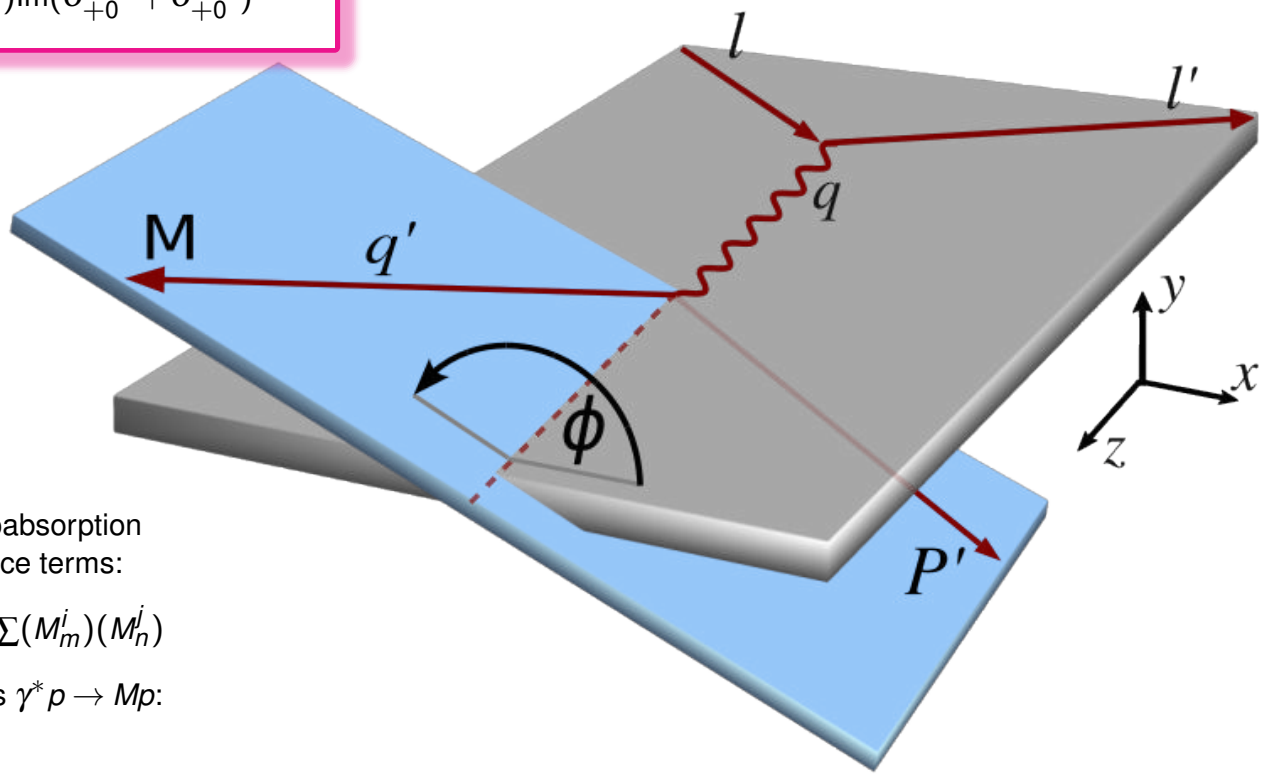
$$\left[\frac{\alpha_{em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_{Bj}}{x_{Bj}}\,\frac{1}{Q^2}\right]^{-1}\frac{\mathrm{d}\sigma}{\mathrm{d}x_{Bj}\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi}=$$

$$\frac{1}{2}\left(\sigma^{++}_{++}+\sigma^{--}_{++}\right)+\varepsilon\sigma^{++}_{00}-\varepsilon\cos(2\phi)\mathrm{Re}(\sigma^{++}_{+-})-\sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\mathrm{Re}(\sigma^{++}_{+0}+\sigma^{--}_{+0})$$

$$-P_l\sqrt{\varepsilon(1-\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma^{++}_{+0}+\sigma^{--}_{+0})$$

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

$$\gamma=\frac{2x_{Bj}M_p}{Q}$$



Helicity dependent photoabsorption x-sections and interference terms:

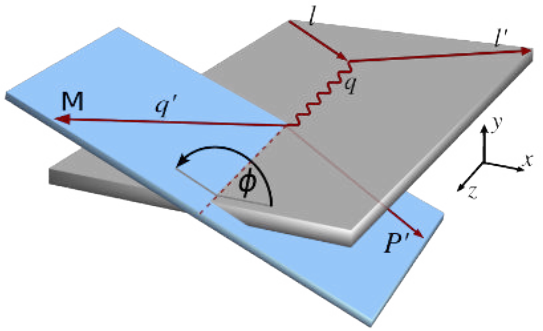
$$\sigma^{ij}_{mn}(x_{Bj},Q^2,t)\propto\sum(M^i_m)(M^j_n)$$

amplitude for subprocess $\gamma^* p\to Mp$:

$$M^i_m$$

with photon helicity m
and target proton helicity i

HEMP cross section (unpolarised target)



$$S_{CS,U} = (\mathrm{d}\sigma^{+\leftarrow} + \mathrm{d}\sigma^{-\rightarrow})/2 =$$

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \varepsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \varepsilon\cos(2\phi)\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} + \sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}$$

$$\cancel{-P_l\sqrt{\varepsilon(1-\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma^{++}_{+0} + \sigma^{--}_{+0})}$$

study ϕ dependence!

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

$$\gamma = \frac{2x_{Bj}M_p}{Q}$$

after integration in ϕ:

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

study t dependence!

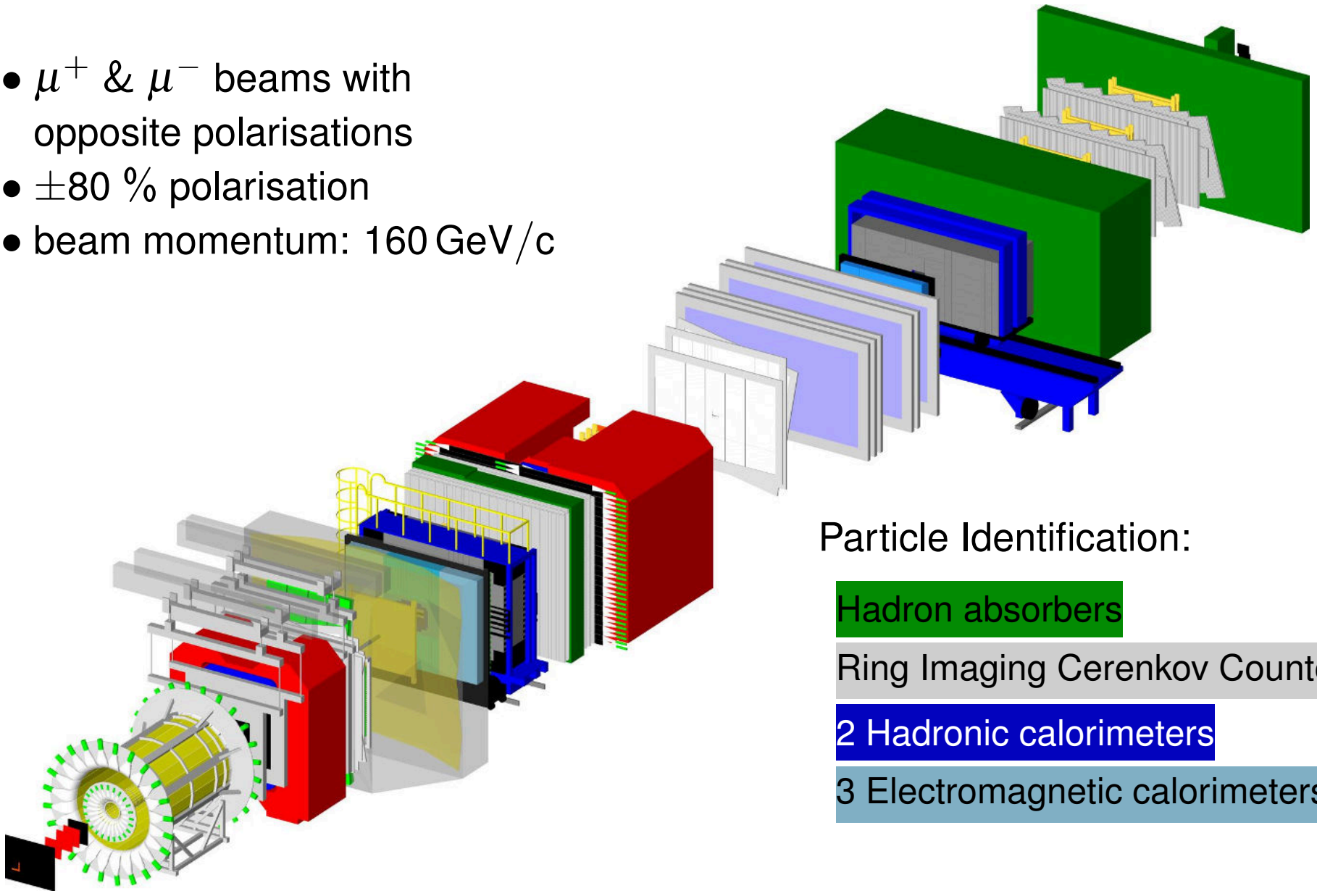
virtual photon polarisation:

- **T**ransverse: $-$, $+$
- **L**ongitudinal: 0

Exclusive π^0 unpolarised x-section extraction on protons

COMPASS spectrometer

- μ^+ & μ^- beams with opposite polarisations
- ± 80 % polarisation
- beam momentum: 160 GeV/c



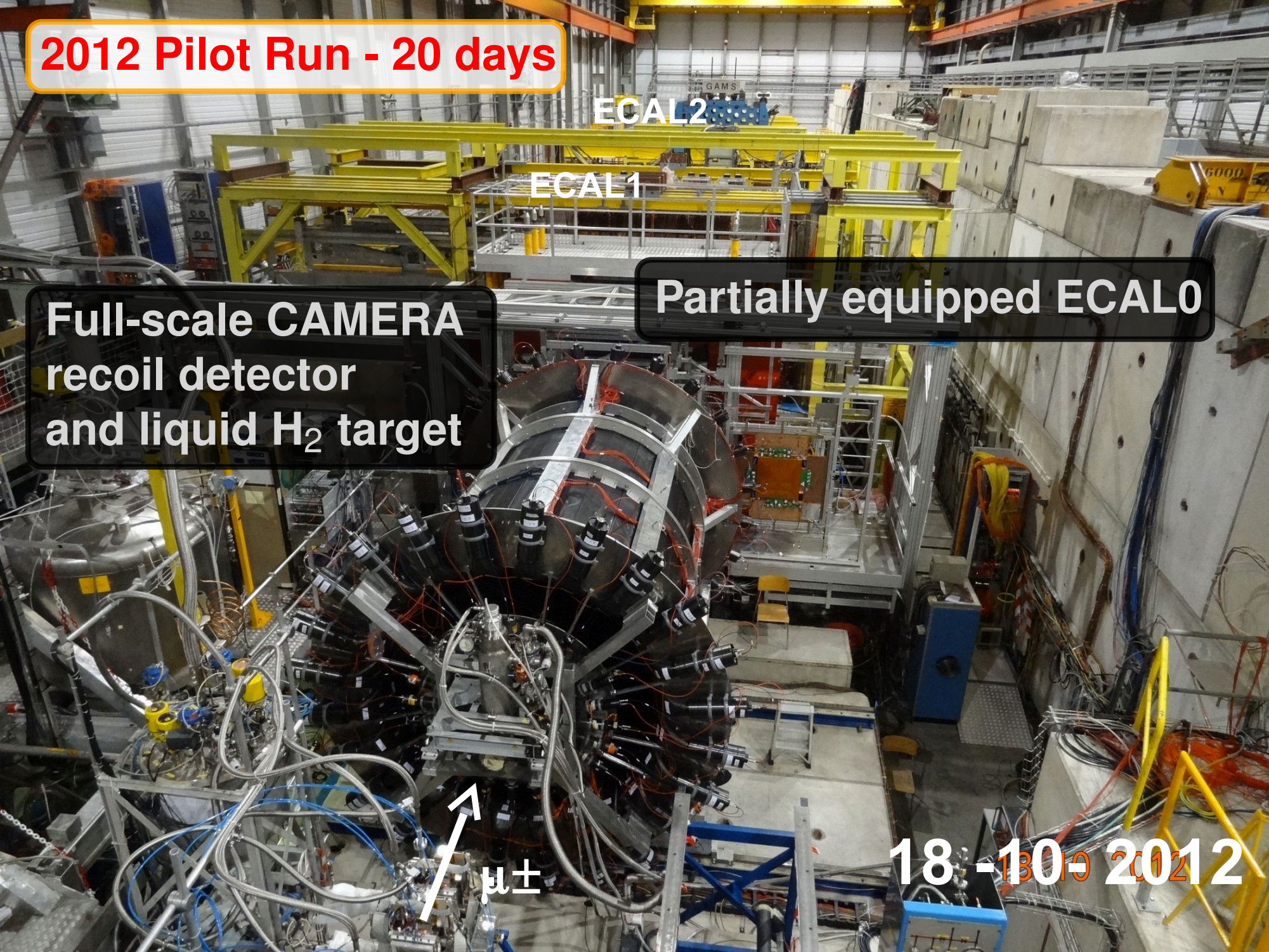
Particle Identification:

Hadron absorbers

Ring Imaging Cerenkov Counter

2 Hadronic calorimeters

3 Electromagnetic calorimeters


2012 Pilot Run - 20 days
ECAL2
ECAL1
Partially equipped ECAL0
Full-scale CAMERA
recoil detector
and liquid H_2 target
μ±
18 -10- 2012

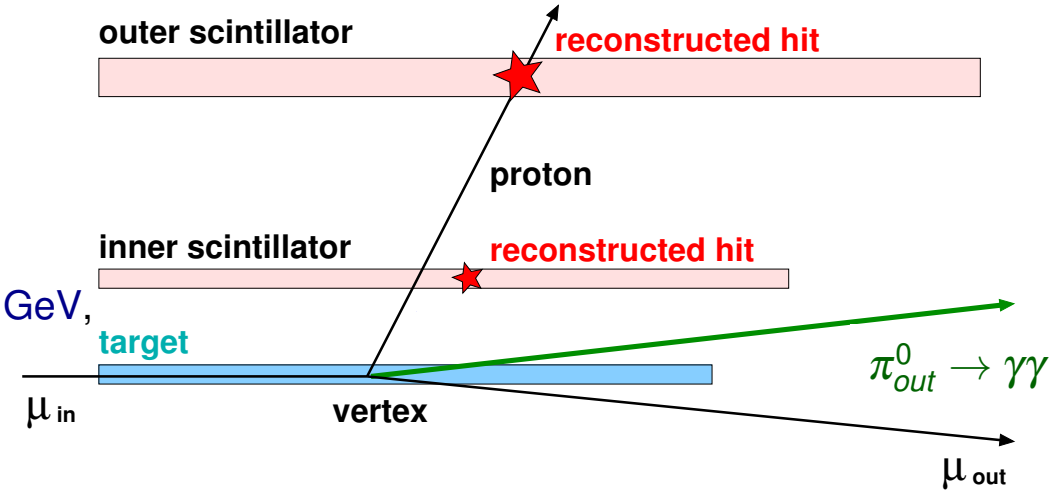
Exclusive π^0 event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

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

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



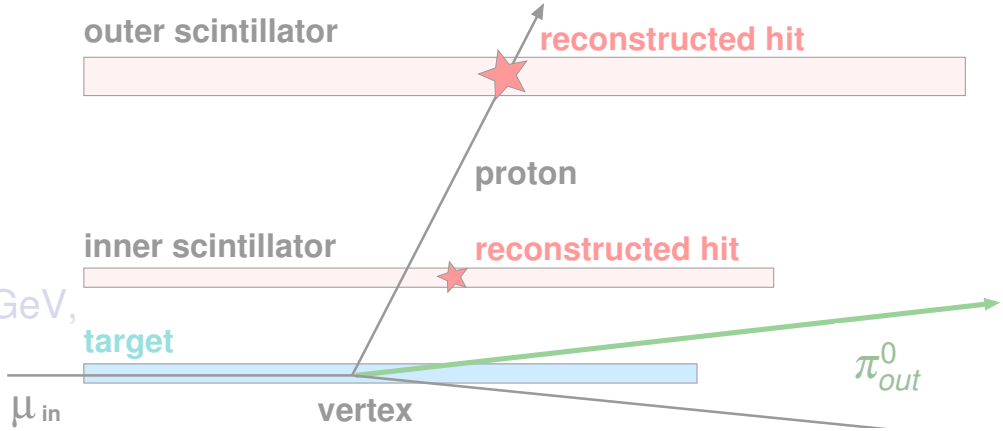
Exclusive π^0 event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

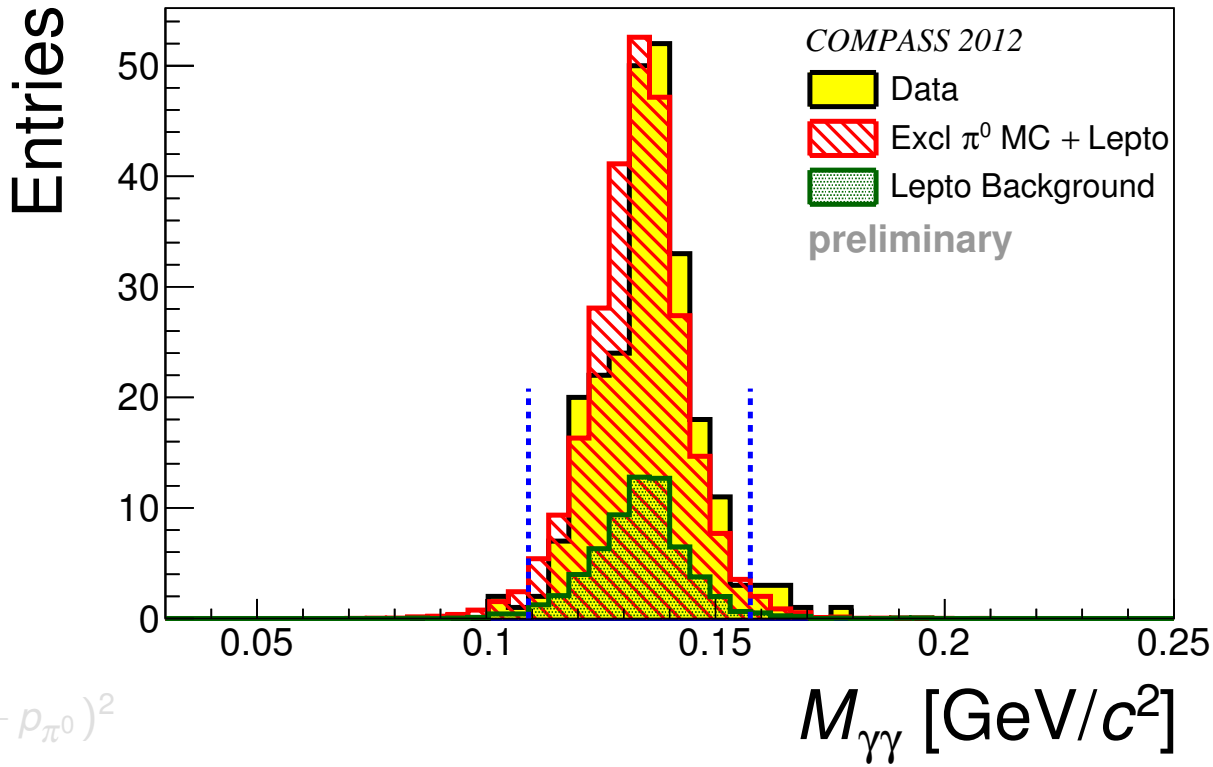
$1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $8.5\,\mathrm{GeV} < \nu < 28\,\mathrm{GeV}$,

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



Exclusivity conditions:

- Mass of $\gamma\gamma$ system: $M_{\gamma\gamma} = (p_{\gamma,i} + p_{\gamma,ii})^2$
- Vertex pointing (Δz)
- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Transv. momentum balance: $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M^2_X = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$



Exclusive π^0 event selection

Reconstructed interaction vertex in **target volume**

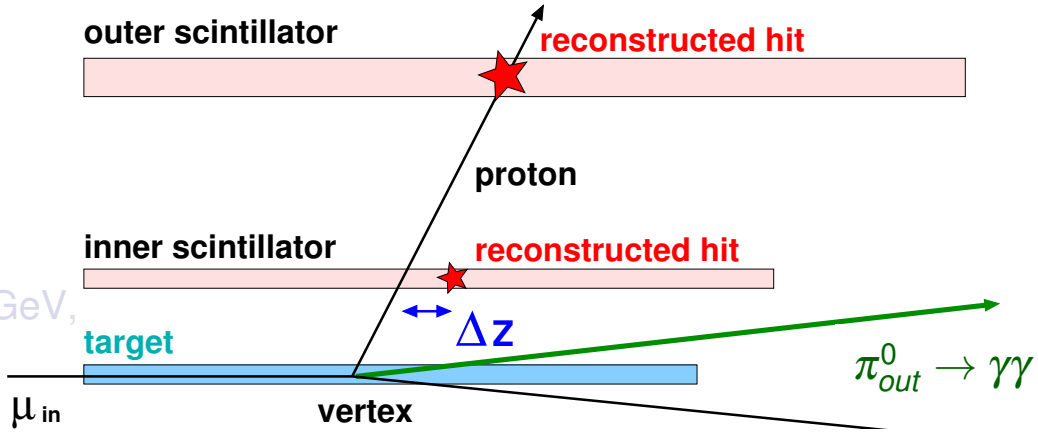
Two photons, **one photon** above threshold

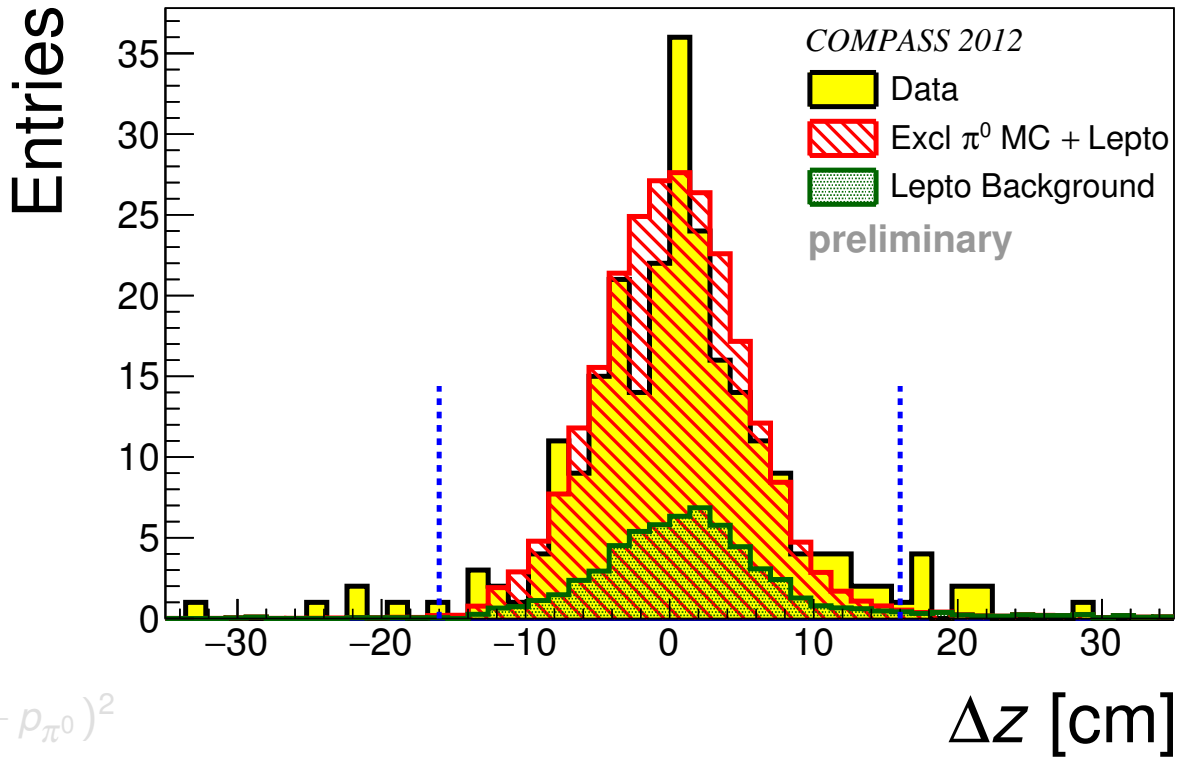
$1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $8.5\,\mathrm{GeV} < \nu < 28\,\mathrm{GeV}$,

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

Exclusivity conditions:

- Mass of $\gamma\gamma$ system: $M_{\gamma\gamma} = (p_{\gamma,i} + p_{\gamma,ii})^2$
- Vertex pointing (Δz)
- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Transv. momentum balance: $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$





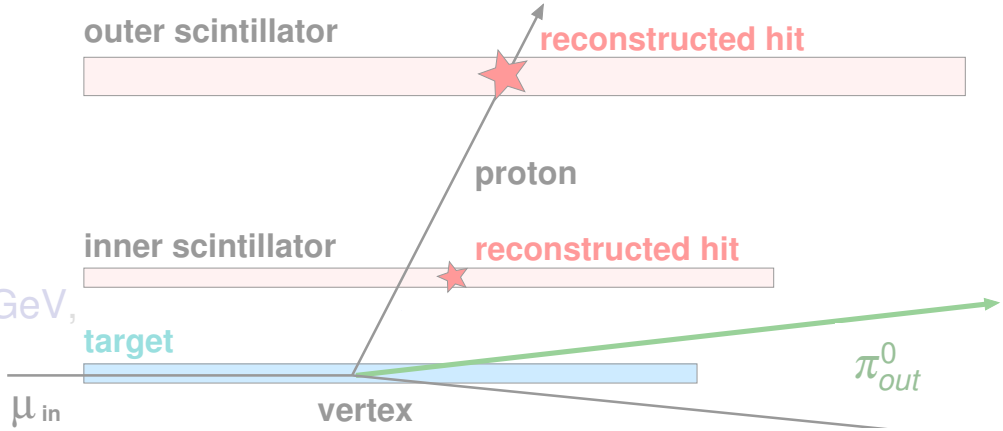
Exclusive π^0 event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

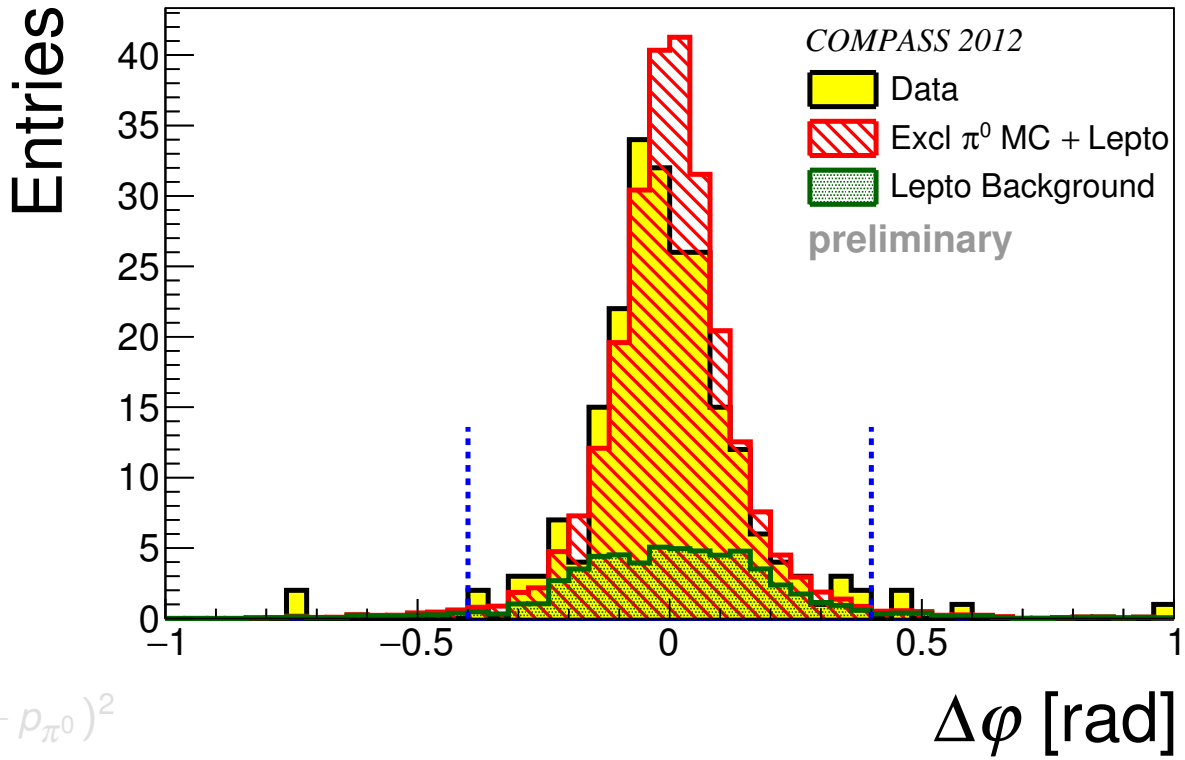
$1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $8.5\,\mathrm{GeV} < \nu < 28\,\mathrm{GeV}$,

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



Exclusivity conditions:

- Mass of $\gamma\gamma$ system: $M_{\gamma\gamma} = (p_{\gamma,i} + p_{\gamma,ii})^2$
- Vertex pointing (Δz)
- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Transv. momentum balance: $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$



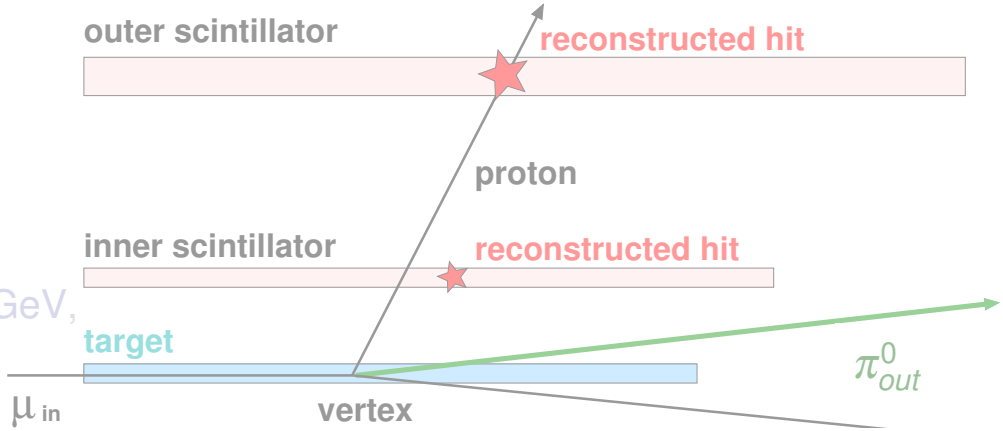
Exclusive π^0 event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

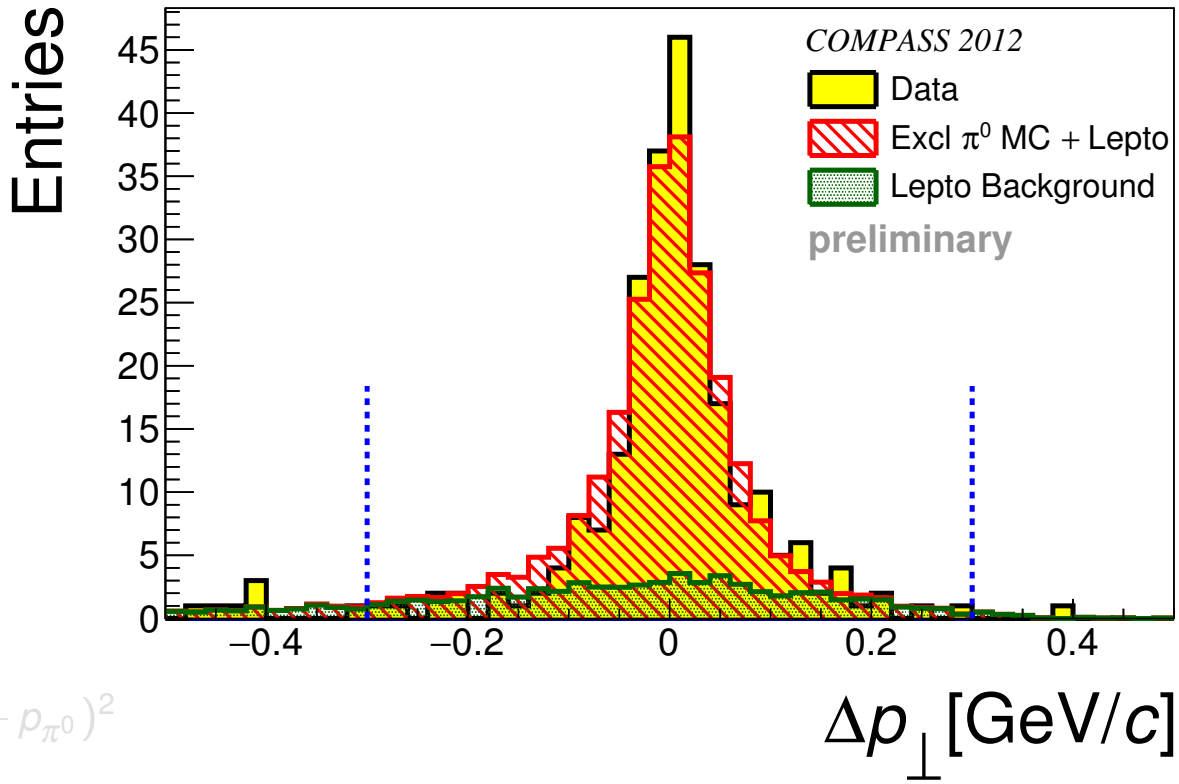
$1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $8.5\,\mathrm{GeV} < \nu < 28\,\mathrm{GeV}$,

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



Exclusivity conditions:

- Mass of $\gamma\gamma$ system: $M_{\gamma\gamma} = (p_{\gamma,i} + p_{\gamma,ii})^2$
- Vertex pointing (Δz)
- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Transv. momentum balance: $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$



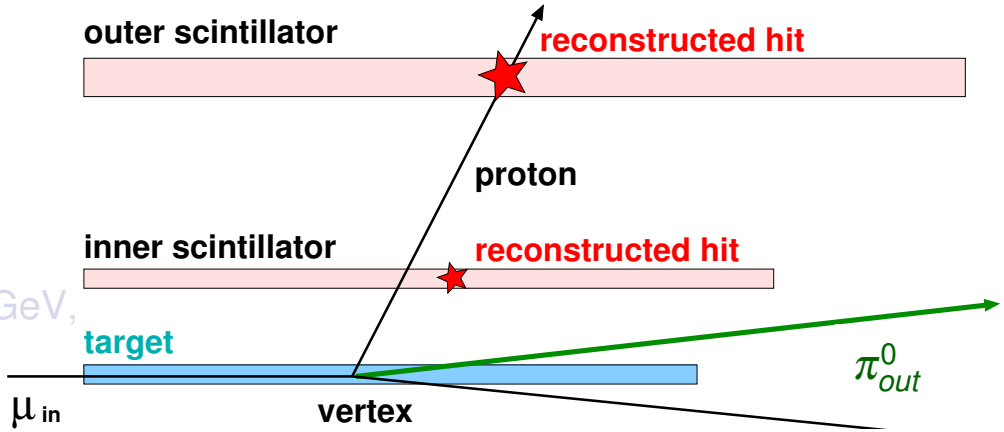
Exclusive π^0 event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

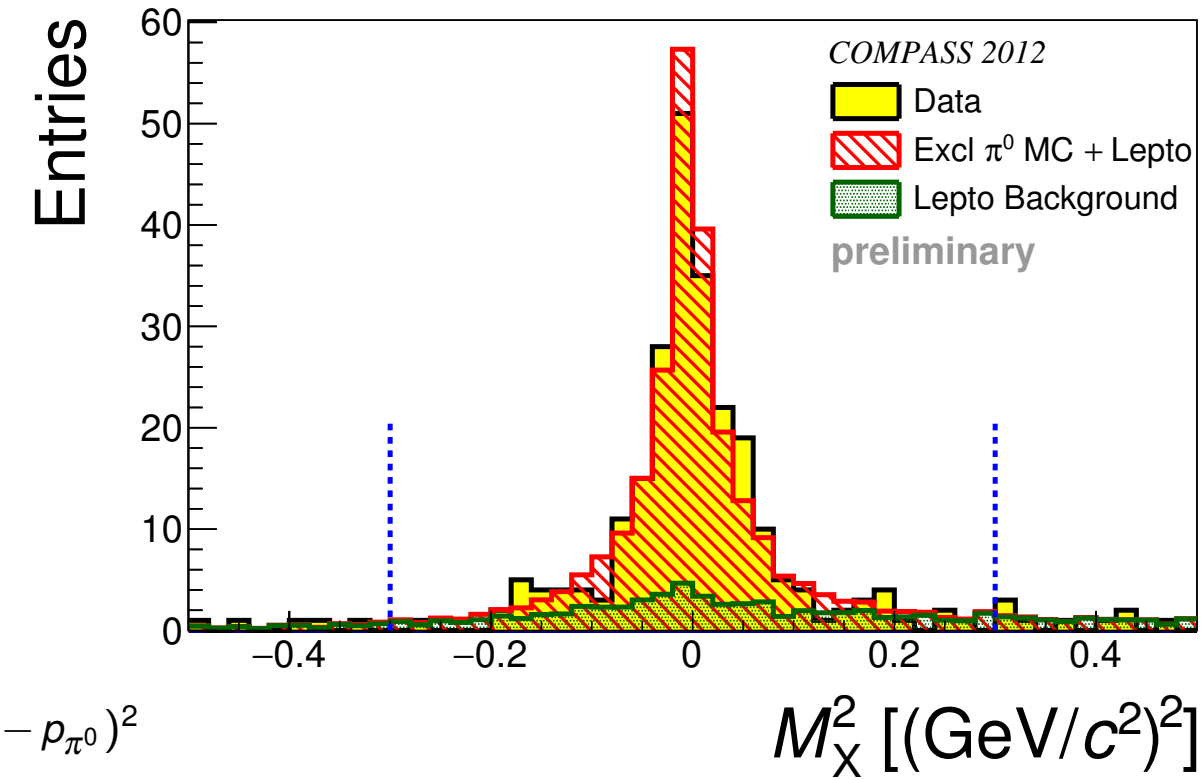
$1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $8.5\,\mathrm{GeV} < \nu < 28\,\mathrm{GeV}$,

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



Exclusivity conditions:

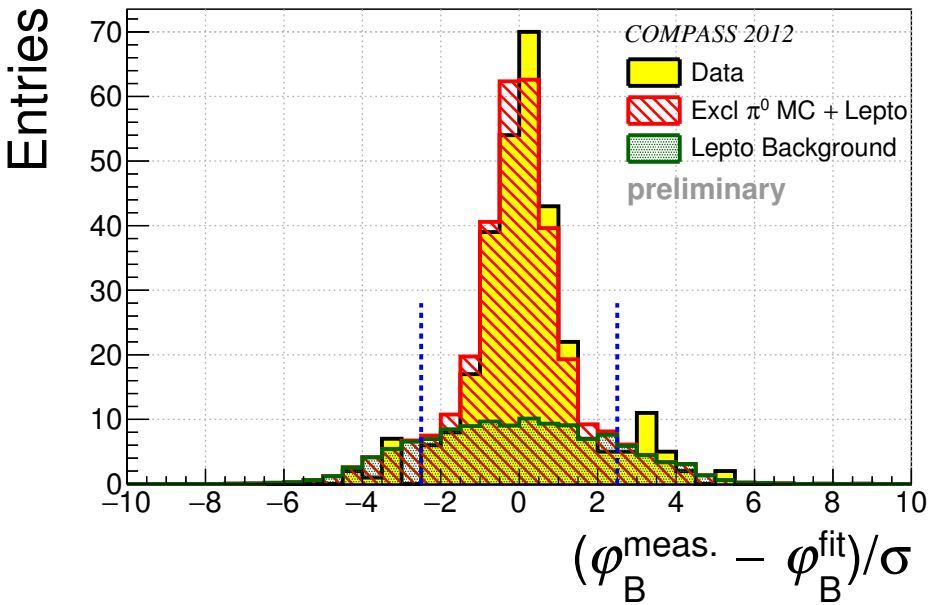
- Mass of $\gamma\gamma$ system: $M_{\gamma\gamma} = (p_{\gamma,i} + p_{\gamma,ii})^2$
- Vertex pointing (Δz)
- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Transv. momentum balance: $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$

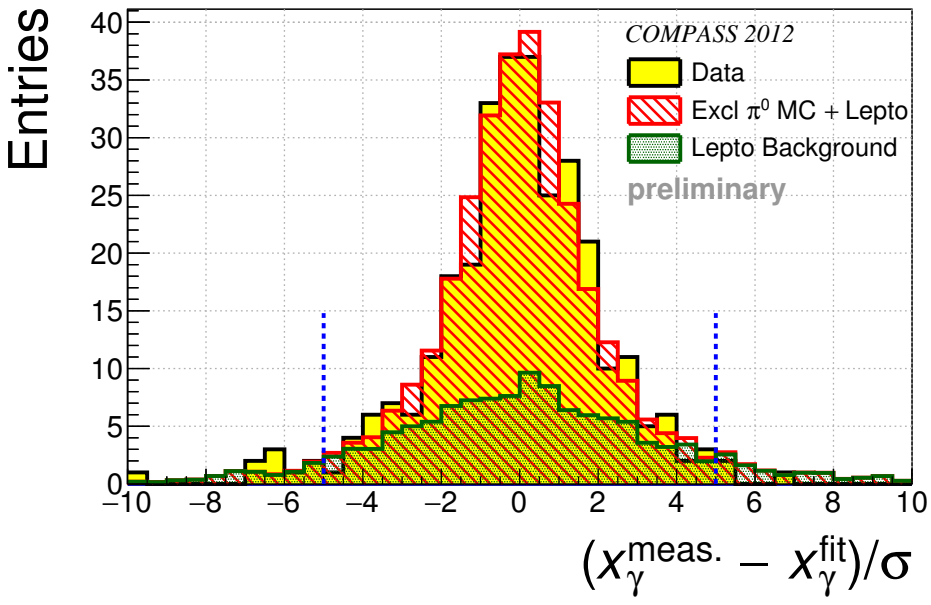


Kinematically constrained fit for exclusive π^0

- constrained χ^2 minimisation
- full 4-momentum conservation of the reaction $\mu p \to \mu p \pi^0$
- π^0 mass constrained to PDG mass
- vertex constraints for μ,μ' and p' included in the fit

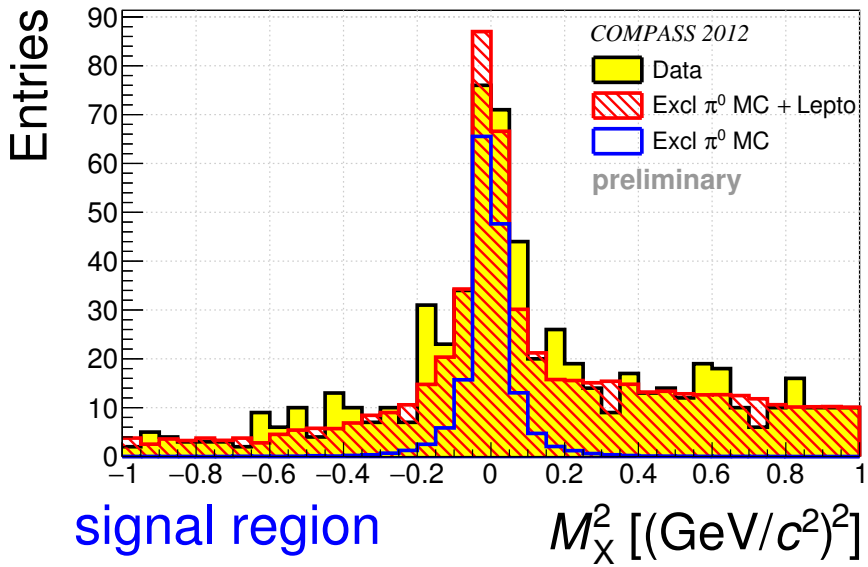
$\Rightarrow$ most accurate determination of t
$\Rightarrow$ good separation beween signal and background



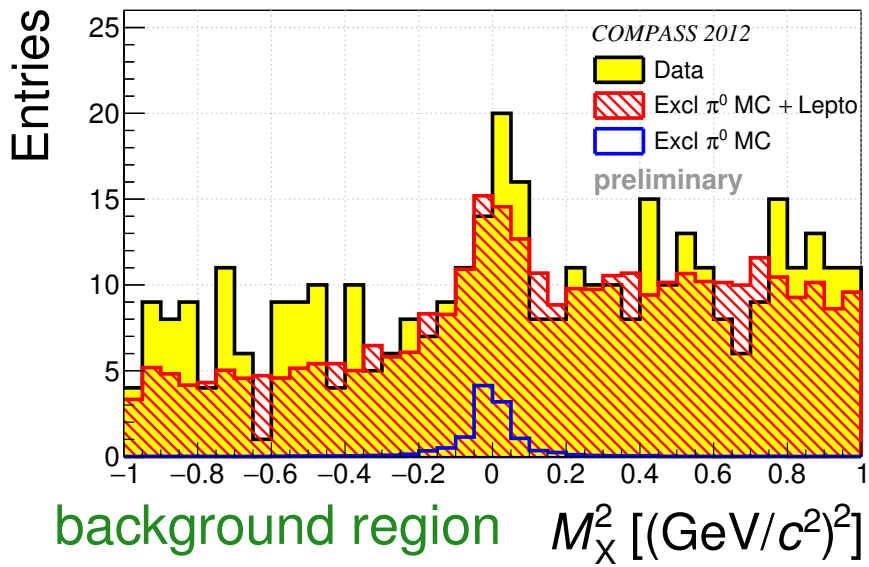


SIDIS background estimation

- use LEPTO MC to describe non exclusive background
- use exclusive π^0 MC to describe signal contribution
- find best description of data
  - in signal region
  - in background region

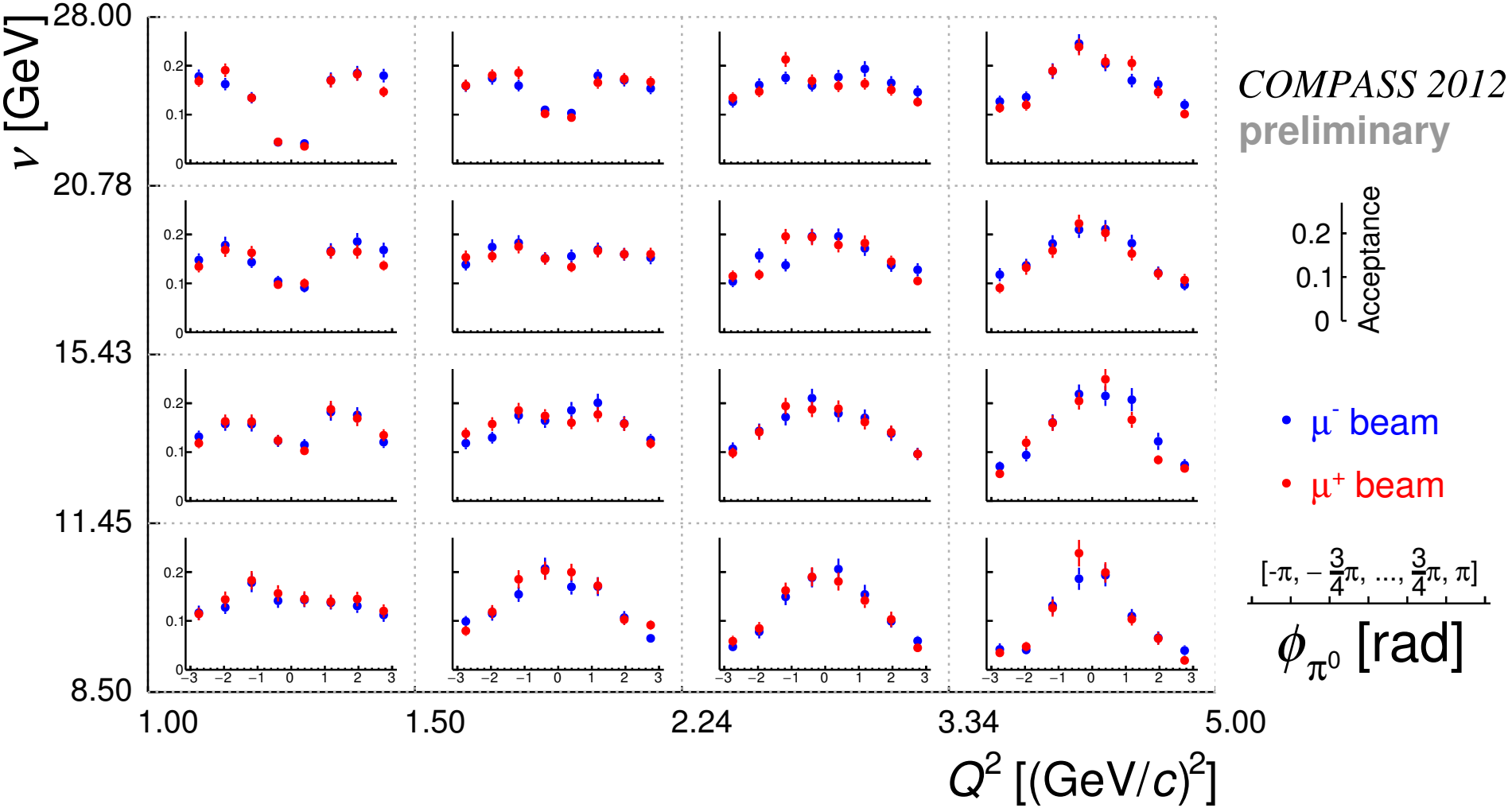


signal region

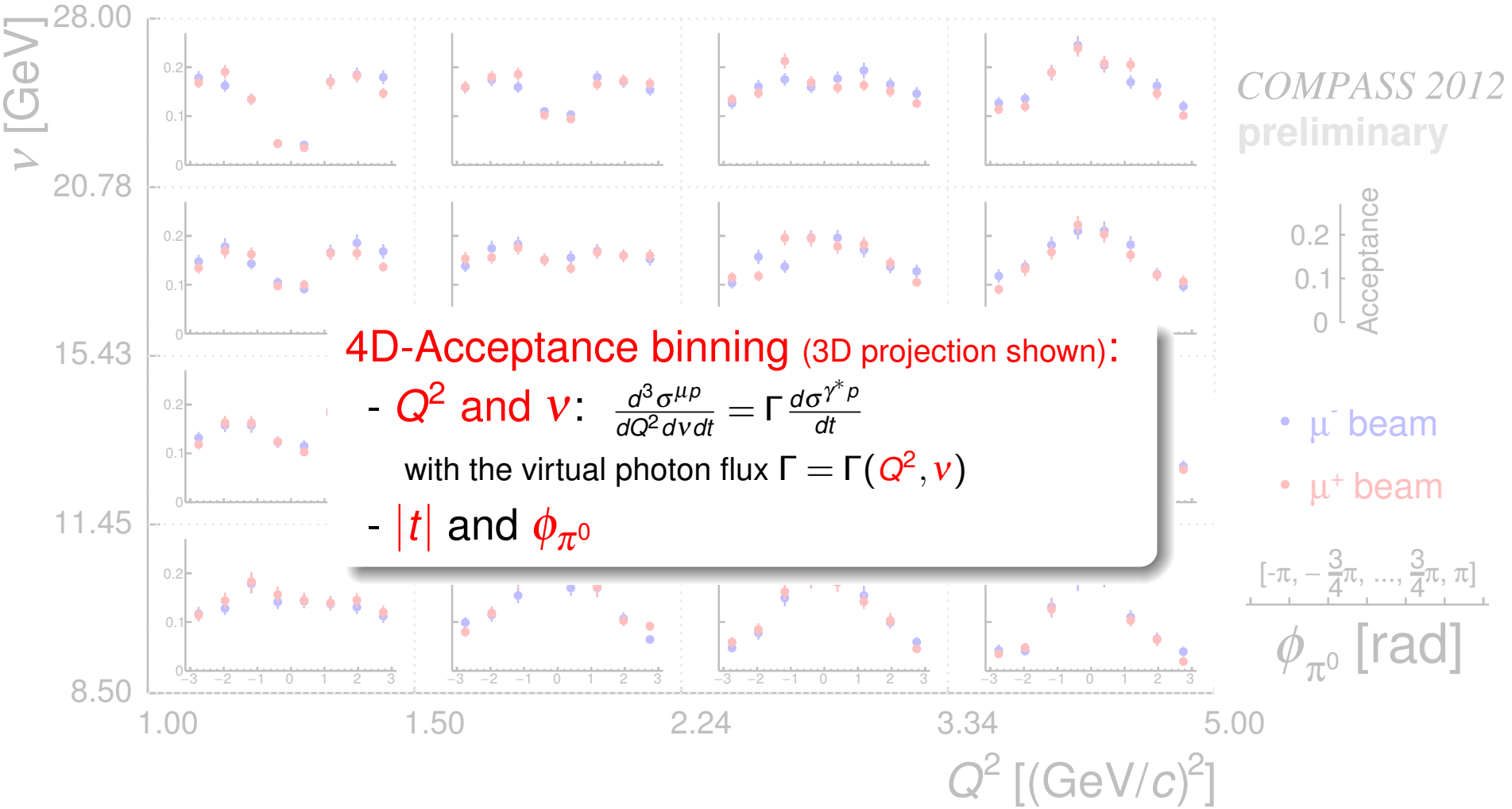


background region

COMPASS acceptance for exclusive π^0



COMPASS acceptance for exclusive π^0



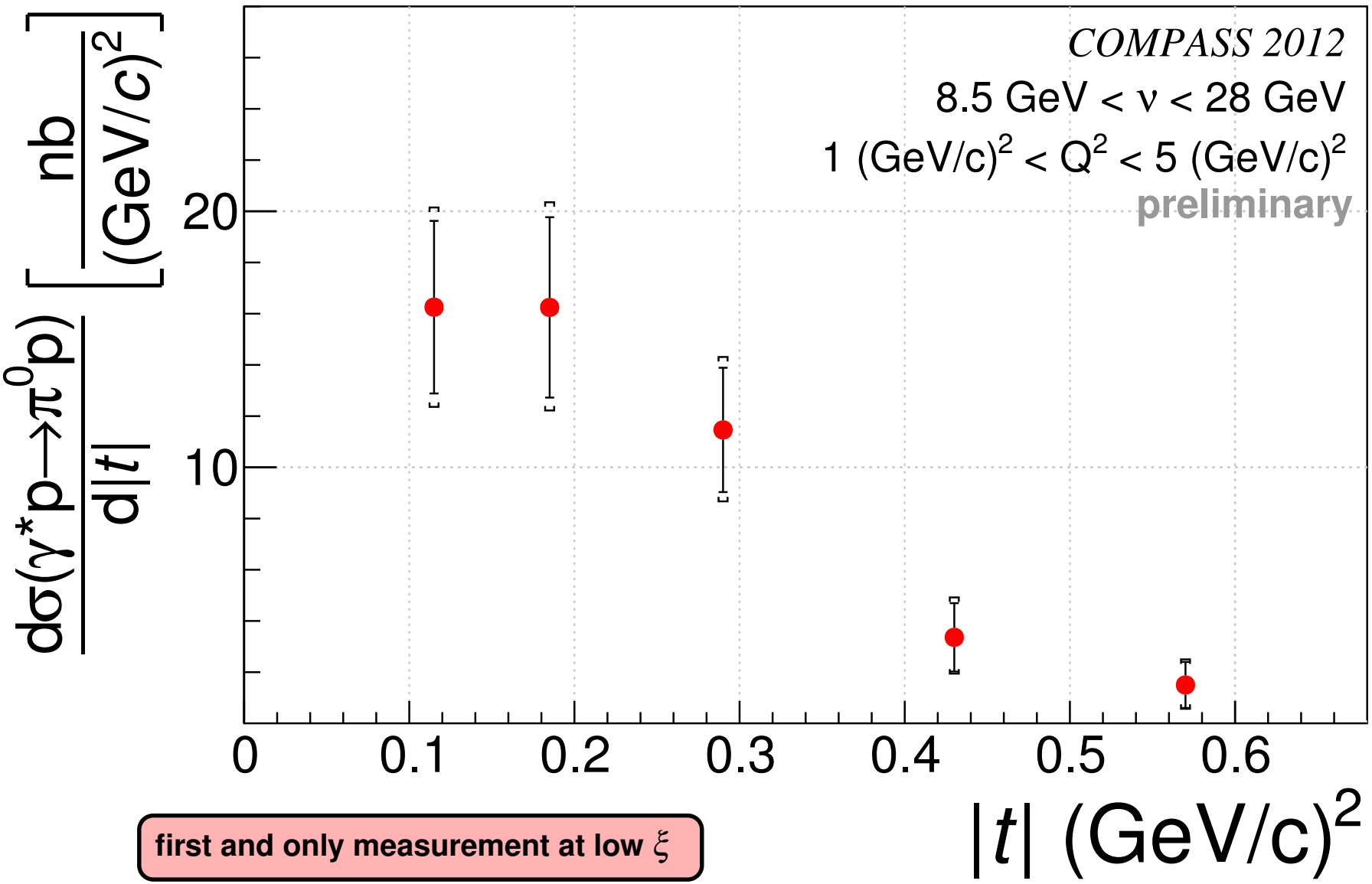
4D-Acceptance binning (3D projection shown):

- Q^2 and ν: $\frac{d^3\sigma^{\mu p}}{dQ^2 d\nu dt} = \Gamma \frac{d\sigma^{\gamma^* p}}{dt}$

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

- $|t|$ and ϕ_{π^0}

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

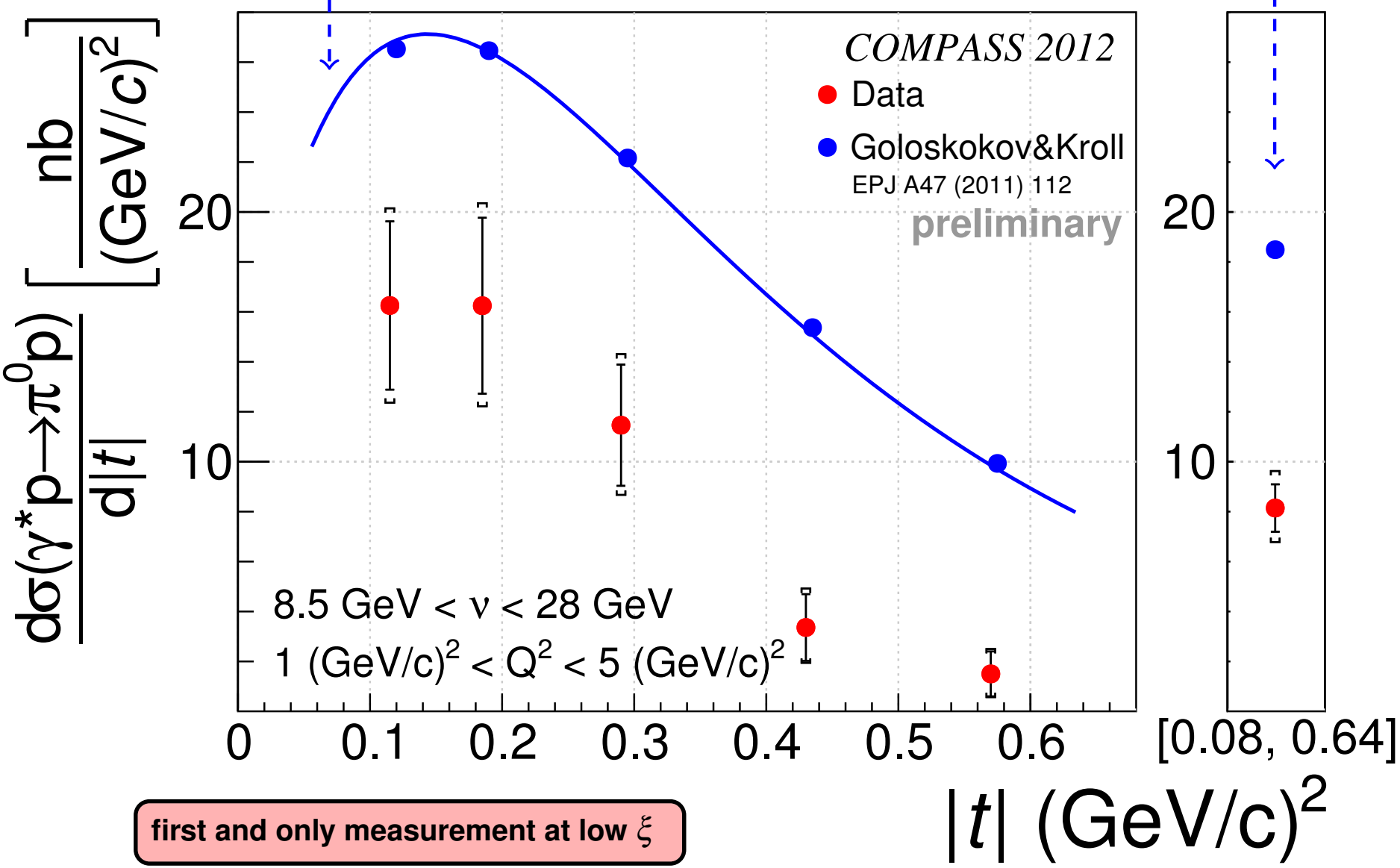


first and only measurement at low ξ

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

dip indicates contribution of $\overline{E}_T$

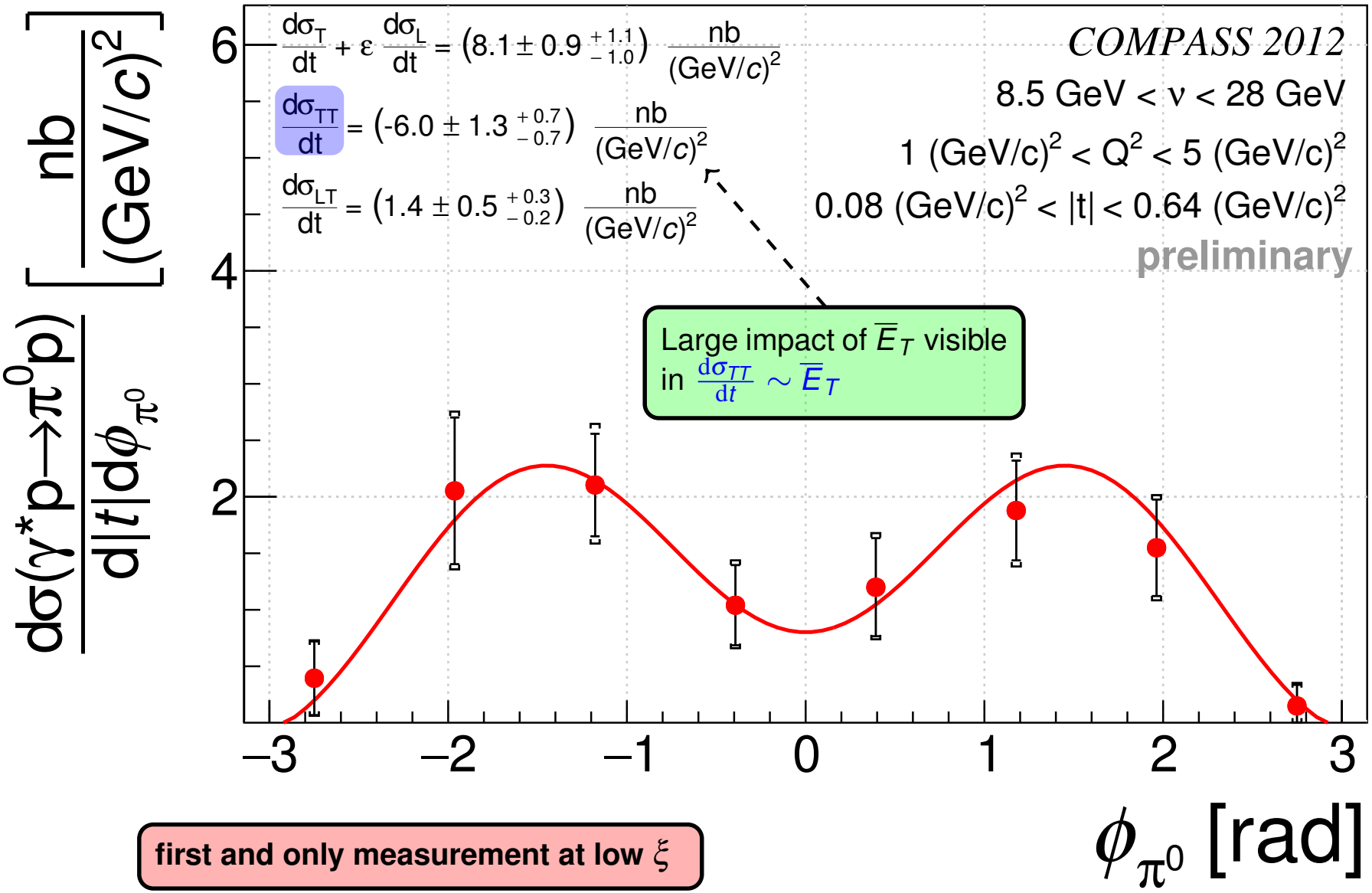
a factor of ~ 2 discrepancy to Goloskokov&Kroll model



first and only measurement at low ξ

Exclusive π^0 cross section as a function of ϕ_{π^0}

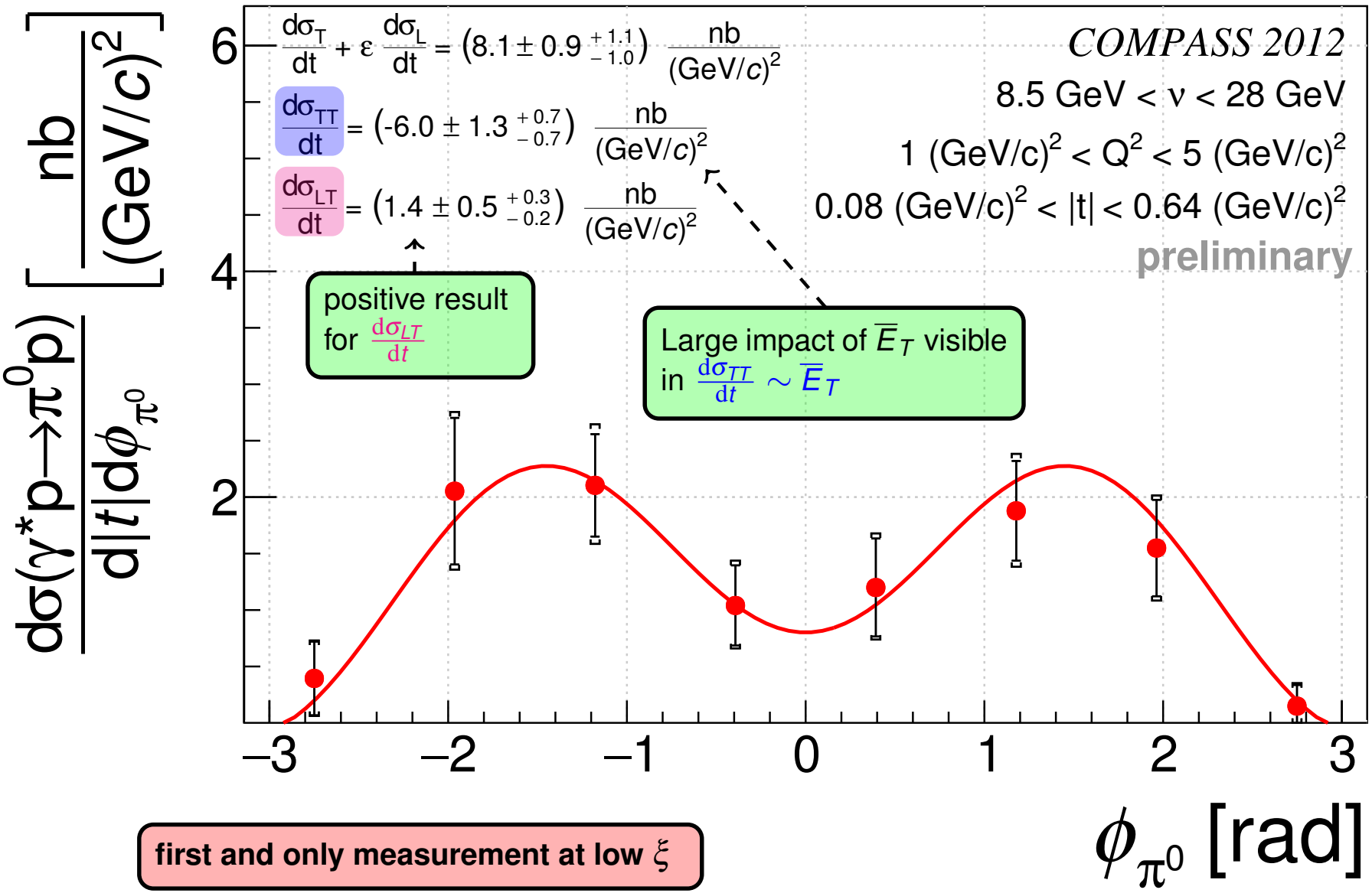
$$\frac{d^2\sigma^{\gamma^* p}}{dt\,d\phi_{\pi^0}} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt}\right) + \varepsilon\cos(2\phi_{\pi^0})\frac{d\sigma_{TT}}{dt} + \sqrt{\varepsilon(1+\varepsilon)}\cos(\phi_{\pi^0})\frac{d\sigma_{LT}}{dt}\right]$$



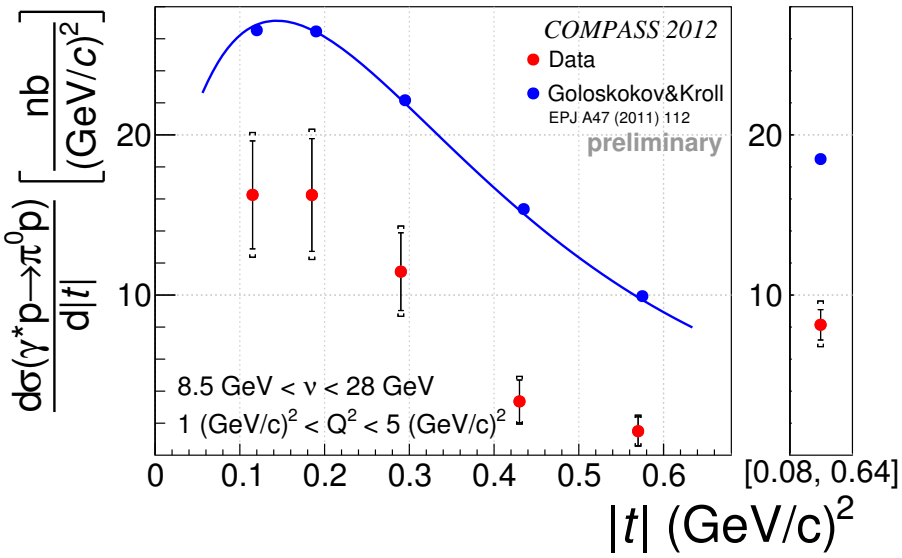
first and only measurement at low ξ

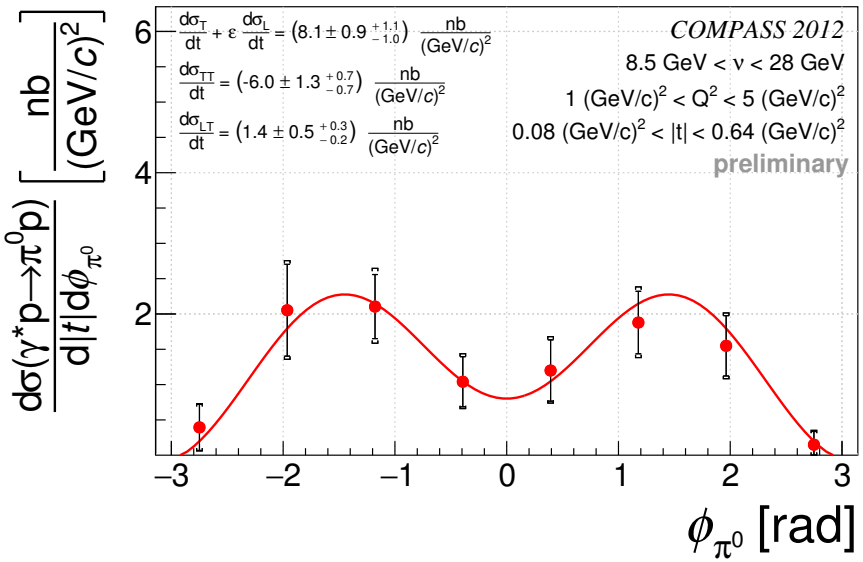
Exclusive π^0 cross section as a function of ϕ_{π^0}

$$\frac{d^2\sigma^{\gamma^* p}}{dt\,d\phi_{\pi^0}} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt}\right) + \varepsilon\cos(2\phi_{\pi^0})\frac{d\sigma_{TT}}{dt} + \sqrt{\varepsilon(1+\varepsilon)}\cos(\phi_{\pi^0})\frac{d\sigma_{LT}}{dt}\right]$$



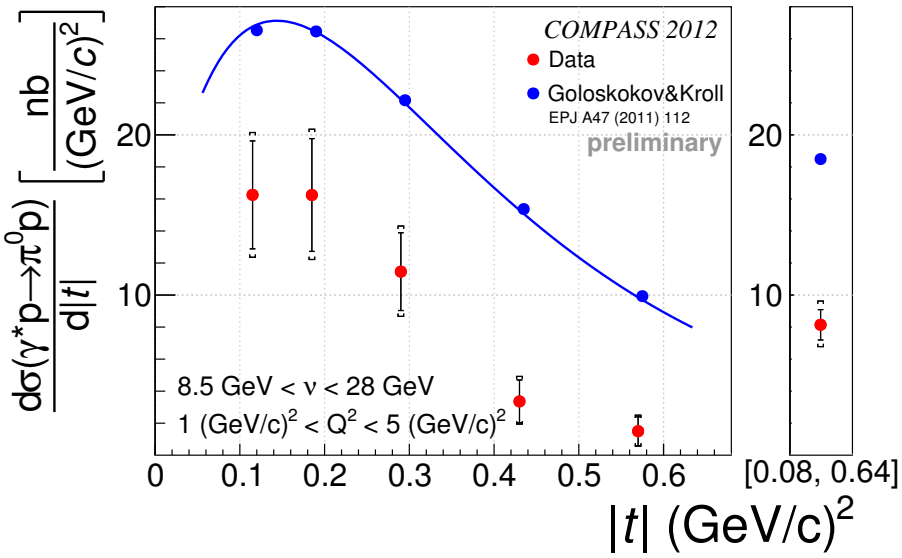
first and only measurement at low ξ

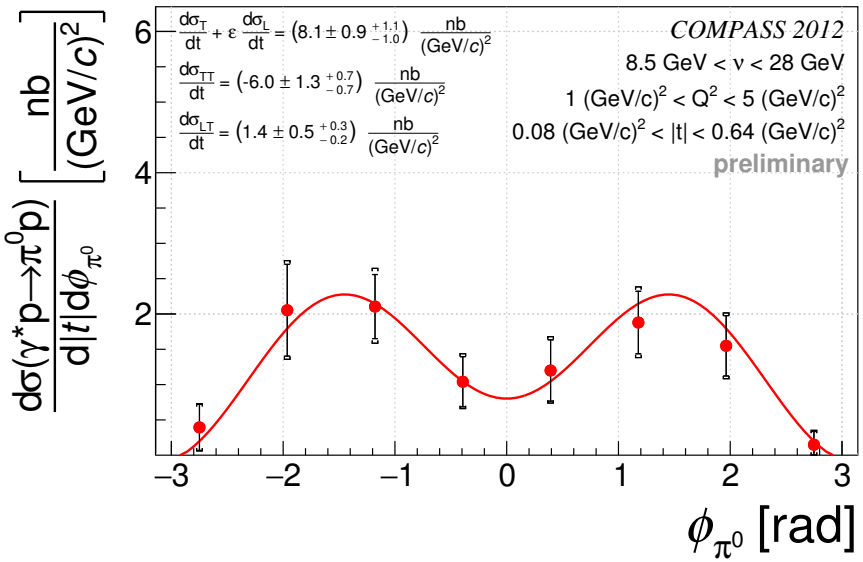




Summary:

- exclusive π^0 production cross section for a proton target
- t- and ϕ_{π^0}-dependance yield valuable input to model parametrisation



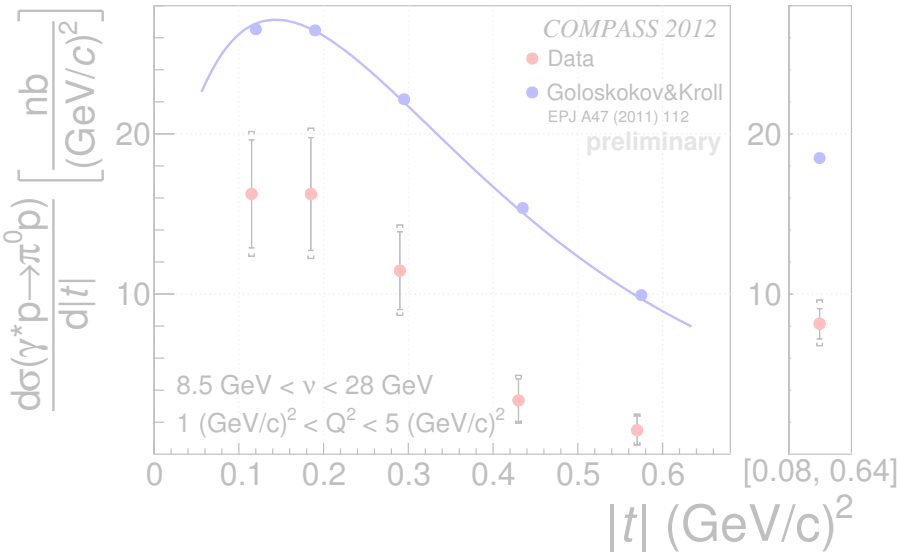


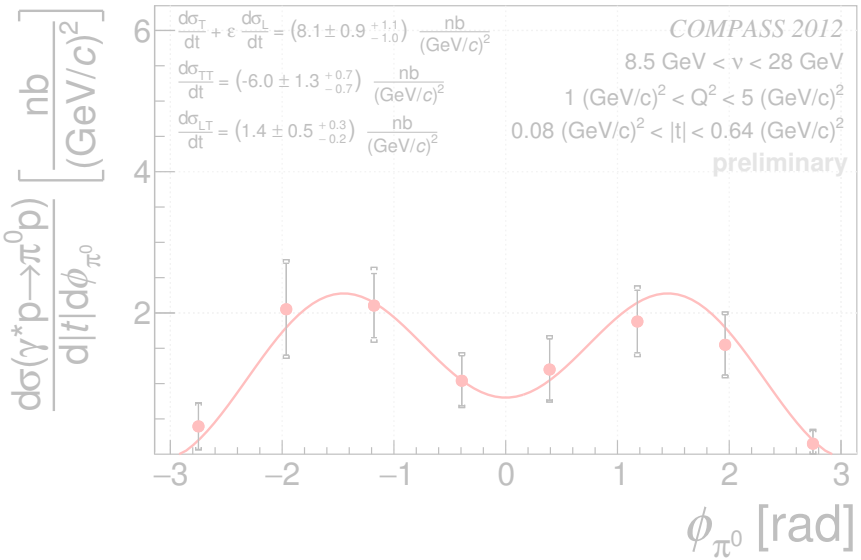
Summary:

- exclusive π^0 production cross section for a proton target
- t- and ϕ_{π^0}-dependance yield valuable input to model parametrisation

Near future:

- Dedicated beam time for DVCS and HEMP in 2016 and 2017
- $\approx$ a factor of 15 increase in statistics compared to pilot run 2012
- Beam charge sum and difference extraction





Summary:

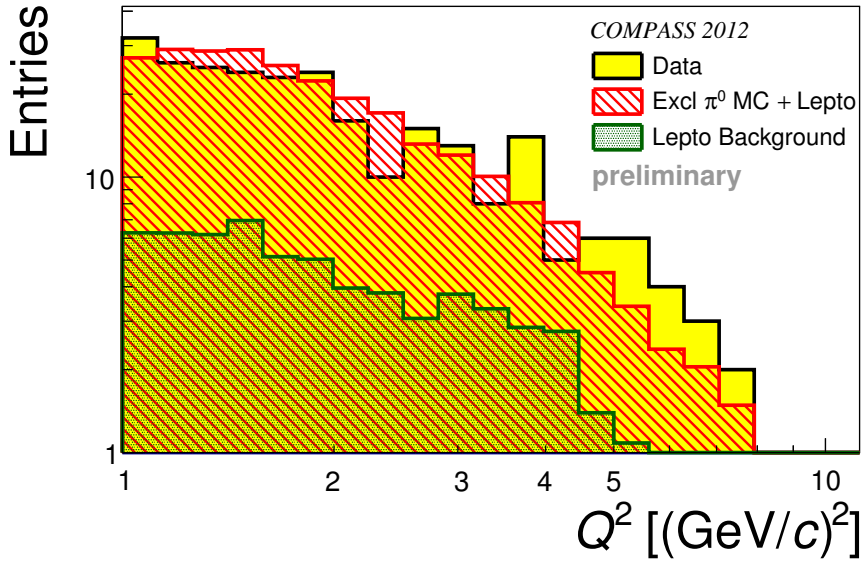
- exclusive π
- t- and ϕ_{π^0}-d

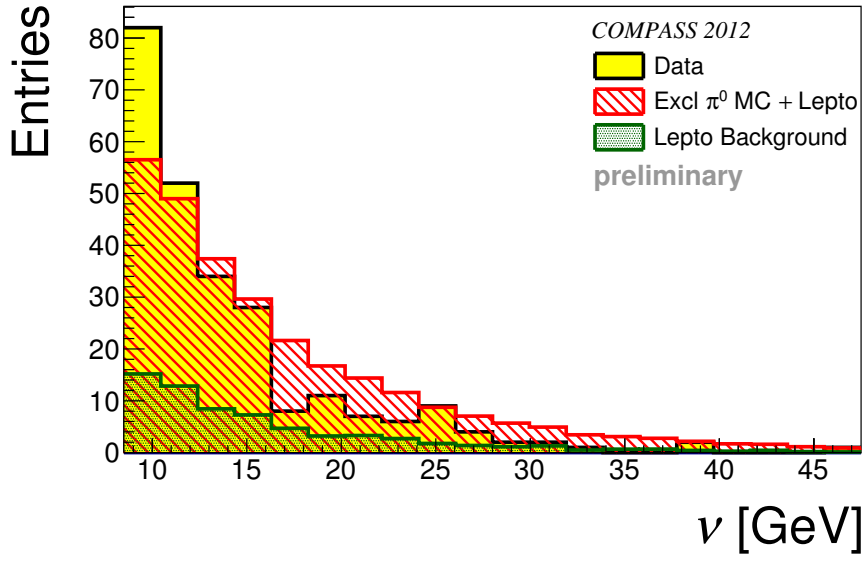
Thank you for your attention!

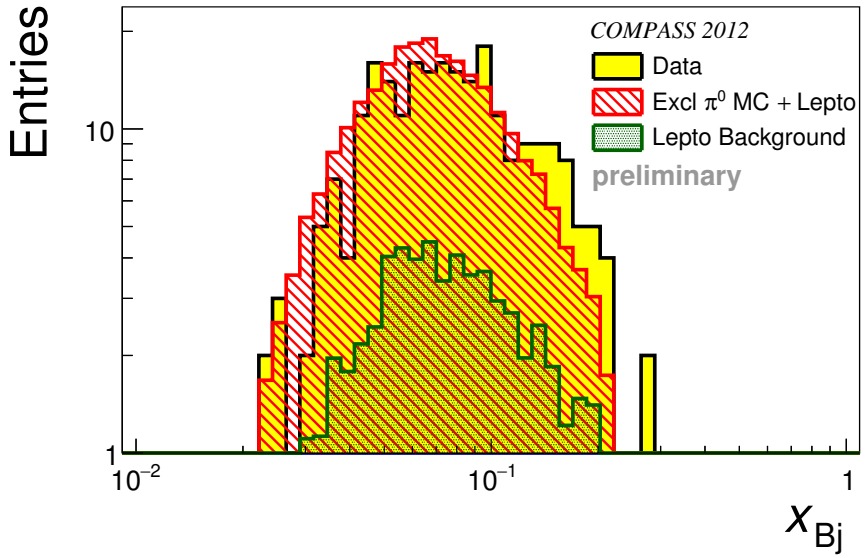
Near future:

- Dedicated beam time for DVCS and HEMP in 2016 and 2017
- $\approx$ a factor of 15 increase in statistics compared to pilot run 2012
- Beam charge sum and difference extraction

Kinematic distributions







Mean values:

$$< Q^2 > = 2.0\,(\mathrm{GeV/c})^2$$

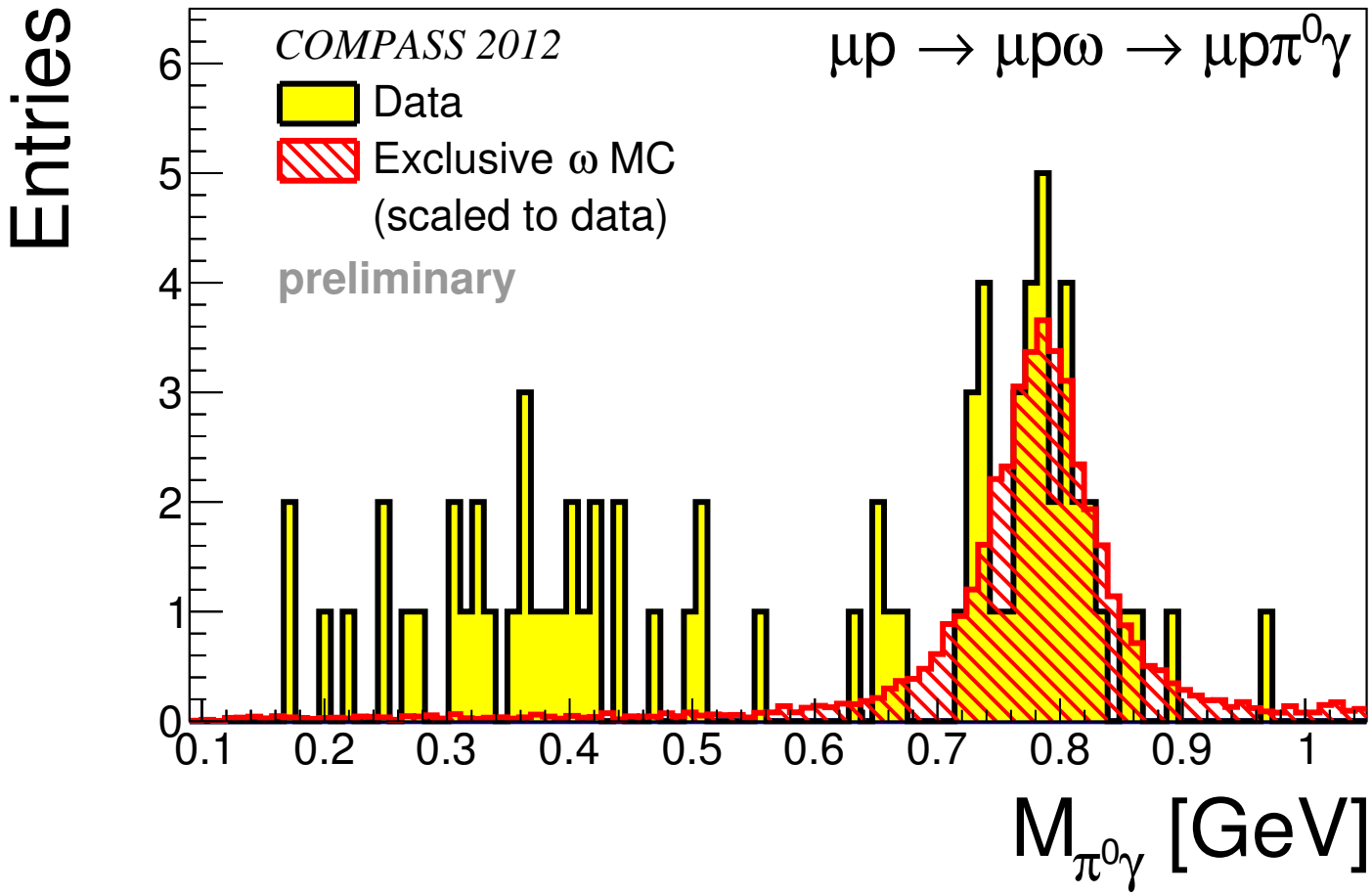
$$< \nu > = 12.8\,\mathrm{GeV}$$

$$< x_{Bj} > = 0.093$$

$$< \varepsilon > = 0.996$$

$$< |t| > = 0.256\,(\mathrm{GeV/c})^2$$

Invisible/visible ω background estimation



Look for other GPDs: the chiral-odd H_T and $\bar{E}_T$

e p → e π^0 p

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

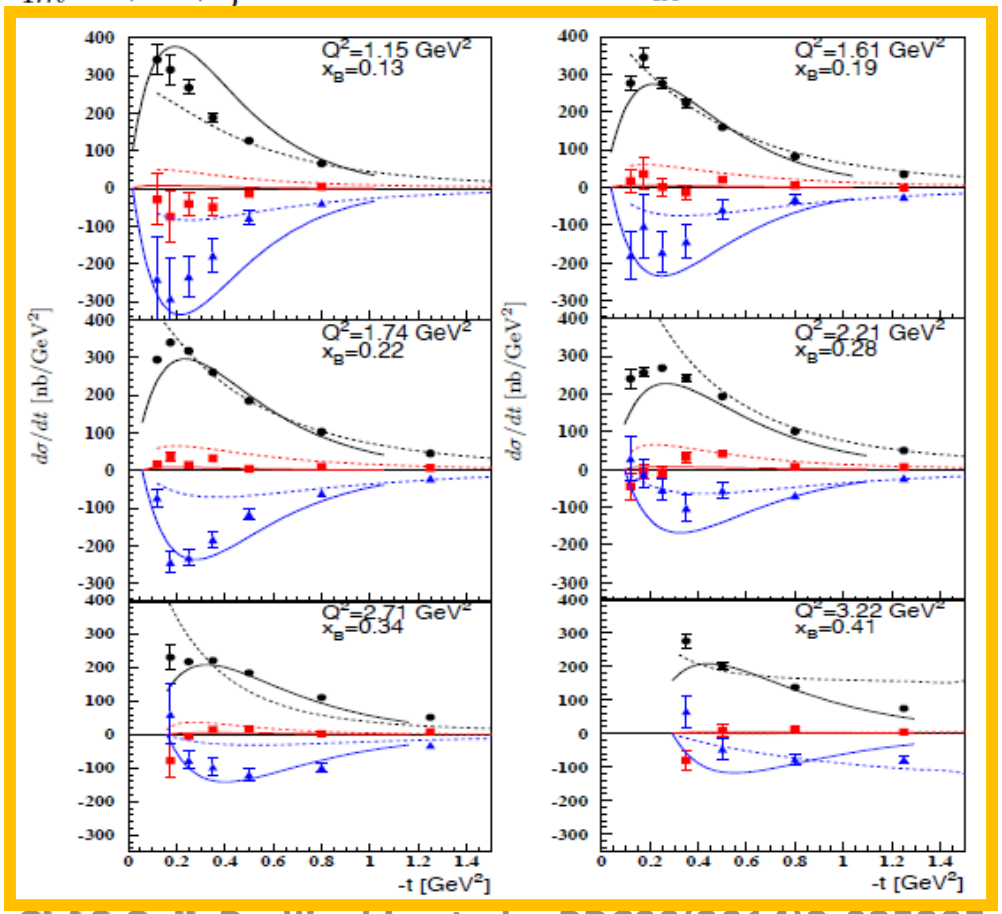
$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\} \approx \text{ only a few \% of } \frac{d\sigma_T}{dt}$$

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

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

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

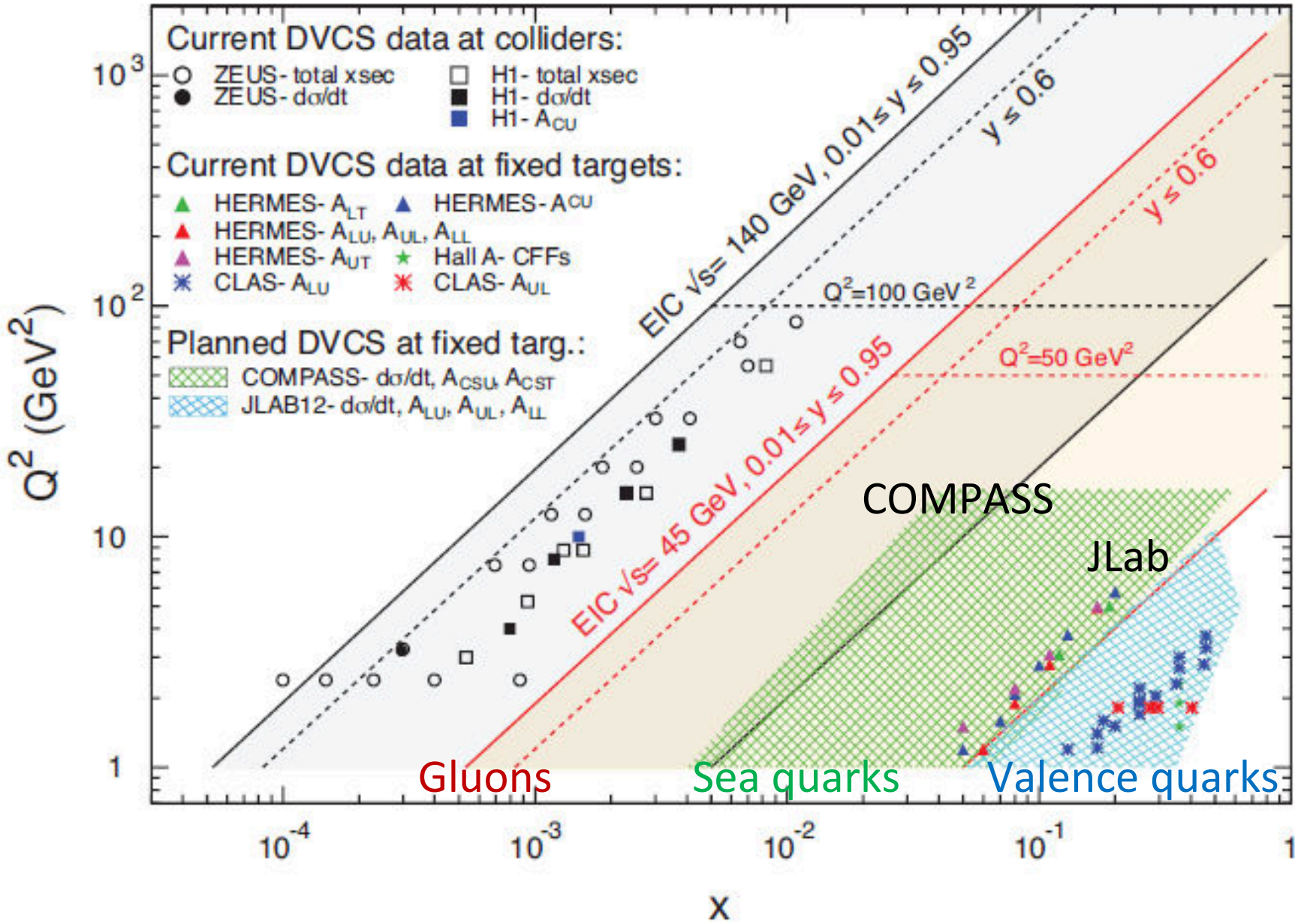
Large impact of $\bar{E}_T$ clearly visible in σ_{TT} and in the dip at small t of σ_T



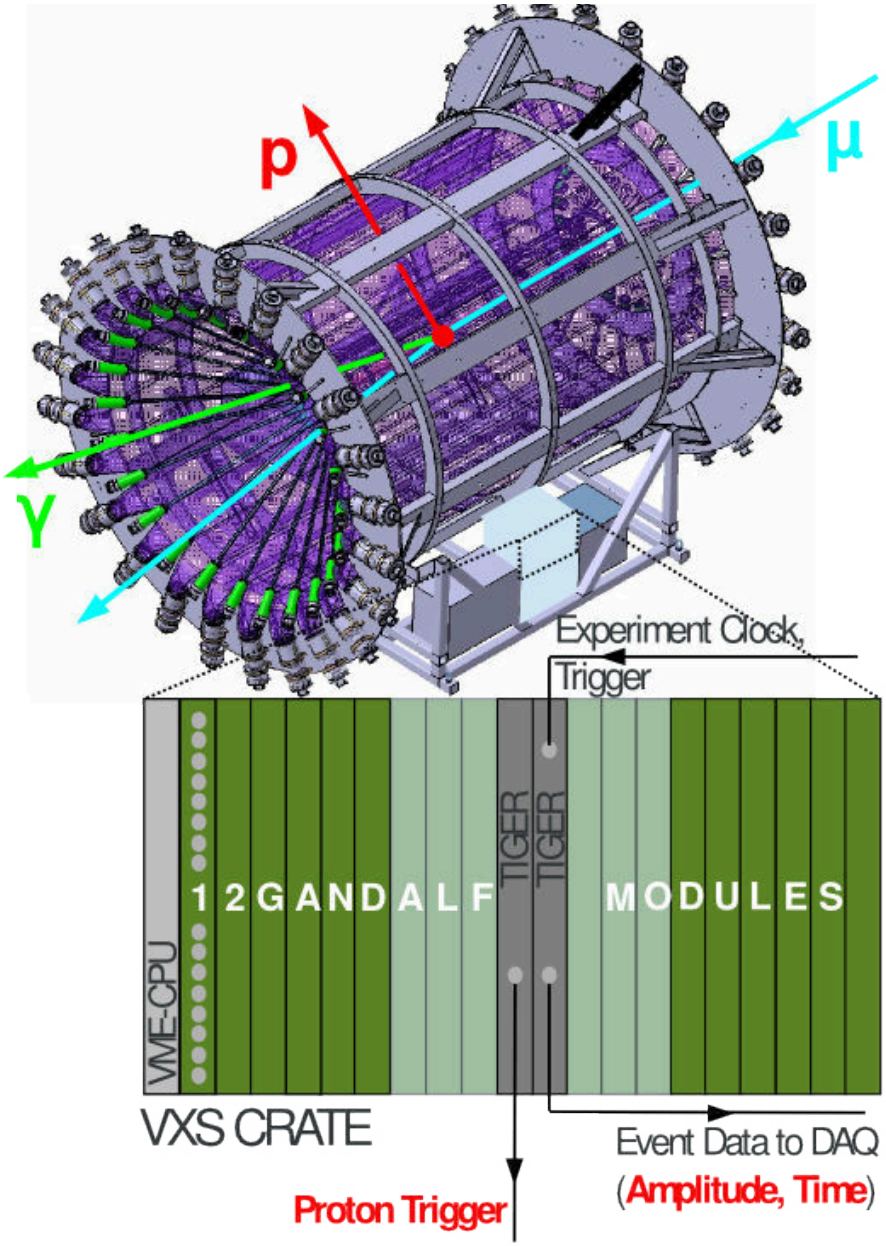
solid lines : **GK** EPJA47 (2011)
Dotted lines: **GHL** JPG:NPP39 (2012)

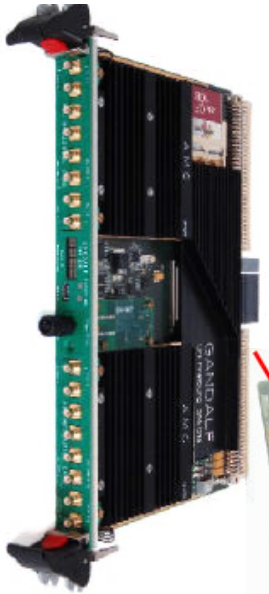
CLAS Coll, Bedlinskiy et al., PRC90(2014)2-025205

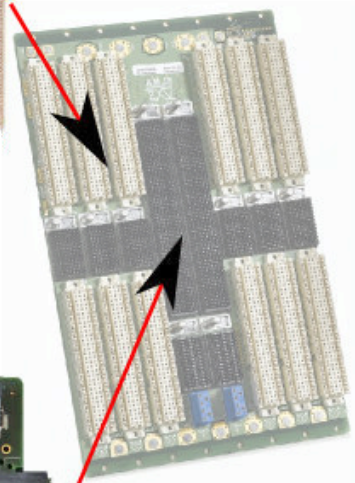
Past, Present and Future GPD Experiments



CAMERA Readout







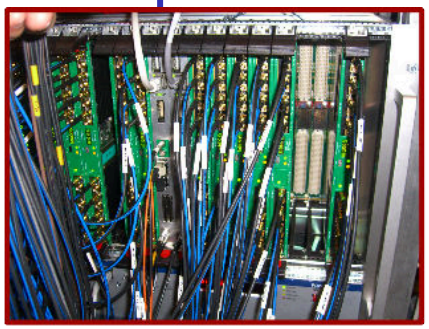
GANDALF

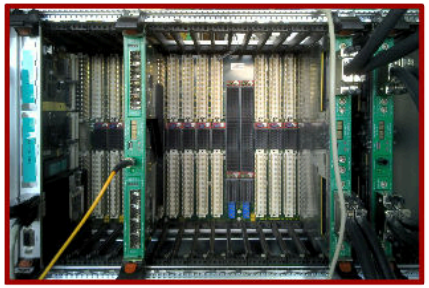
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

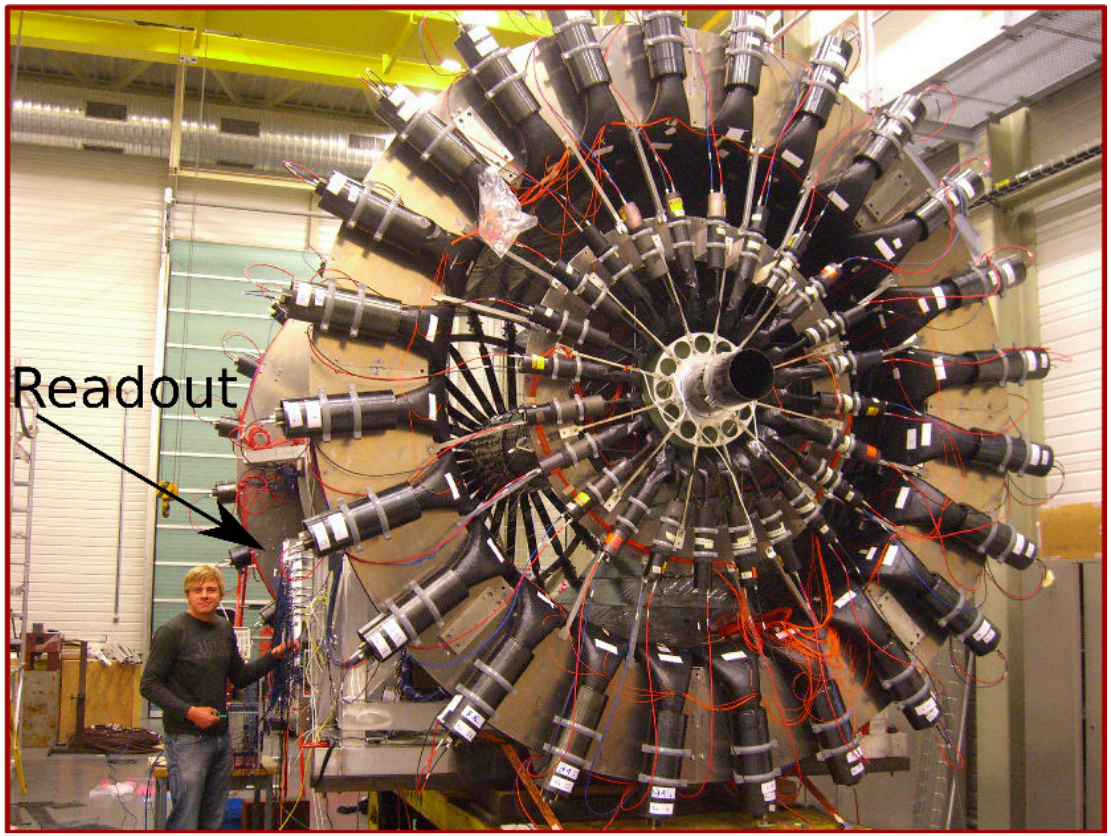
TIGER

Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express

The recoil proton detector CAMERA

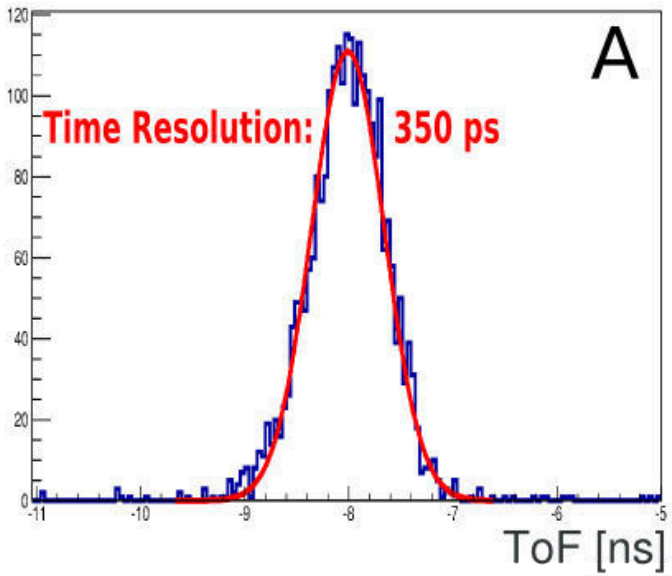


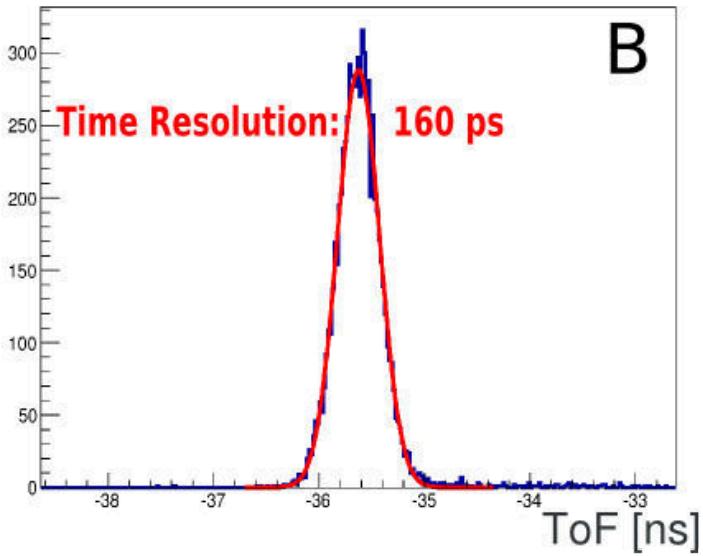


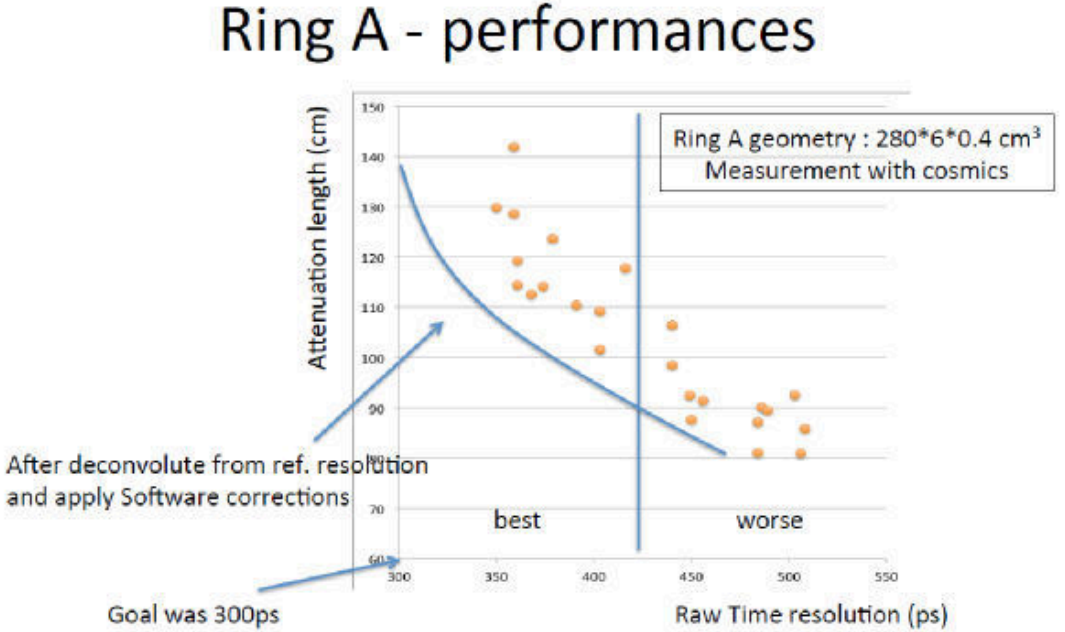


- two barrells, each 24 scintillators / 48 PMTs
- inner: 275 cm $\otimes$ 4 mm, radius 25 cm
- outer: 360 cm $\otimes$ 5 cm, radius 110 cm
- readout with 12 bit / 1 GSps
- ToF resolution $\approx$ 310 ps

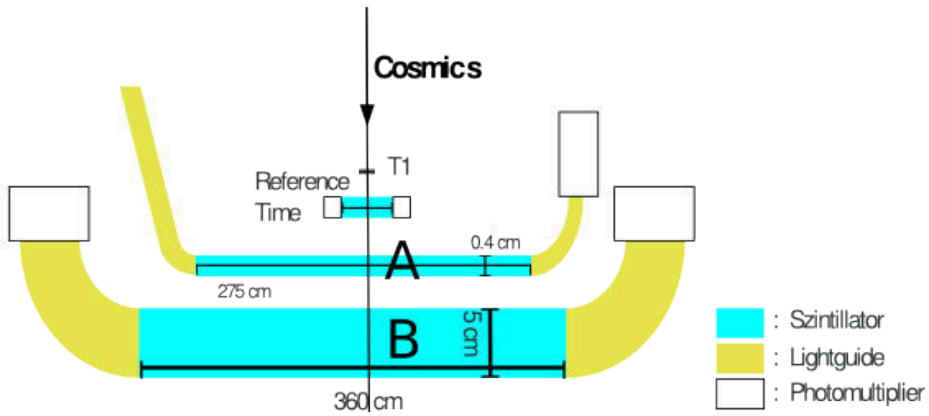
Time Resolutions Measured with Cosmics







Att length better than 200 cm was expected



Summary of Present CAMERA Performances