COMPASS

experiment at CERN

Hard Exclusive production of π^0 at COMPASS

O.Kouznetsov - JINR (Dubna) -
for the COMPASS collaboration

3 days

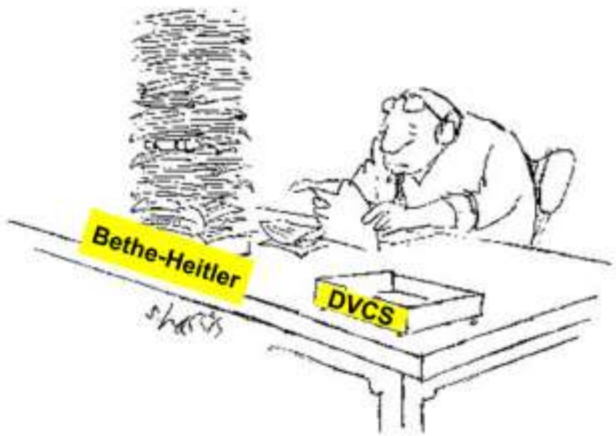
↓

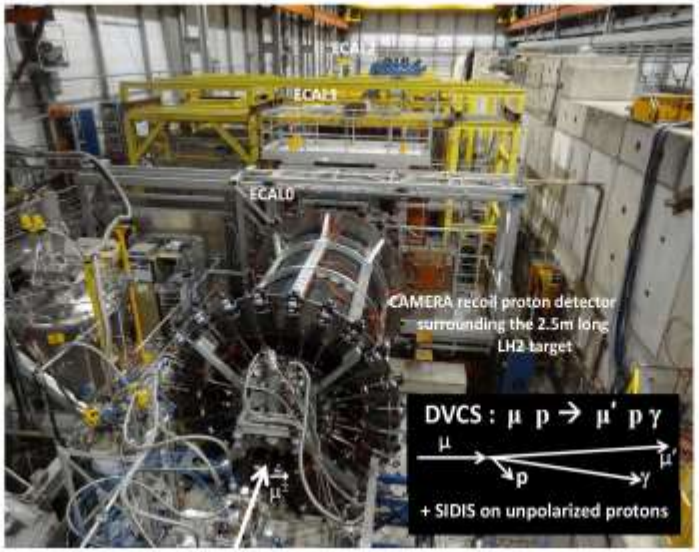
2008 DVCS test run: a first observation of exclusive single-photon production.

10 days

↓

2009 DVCS test run: first estmation of pure DVCS, pure BH and DVCS-BH interference relative contributions



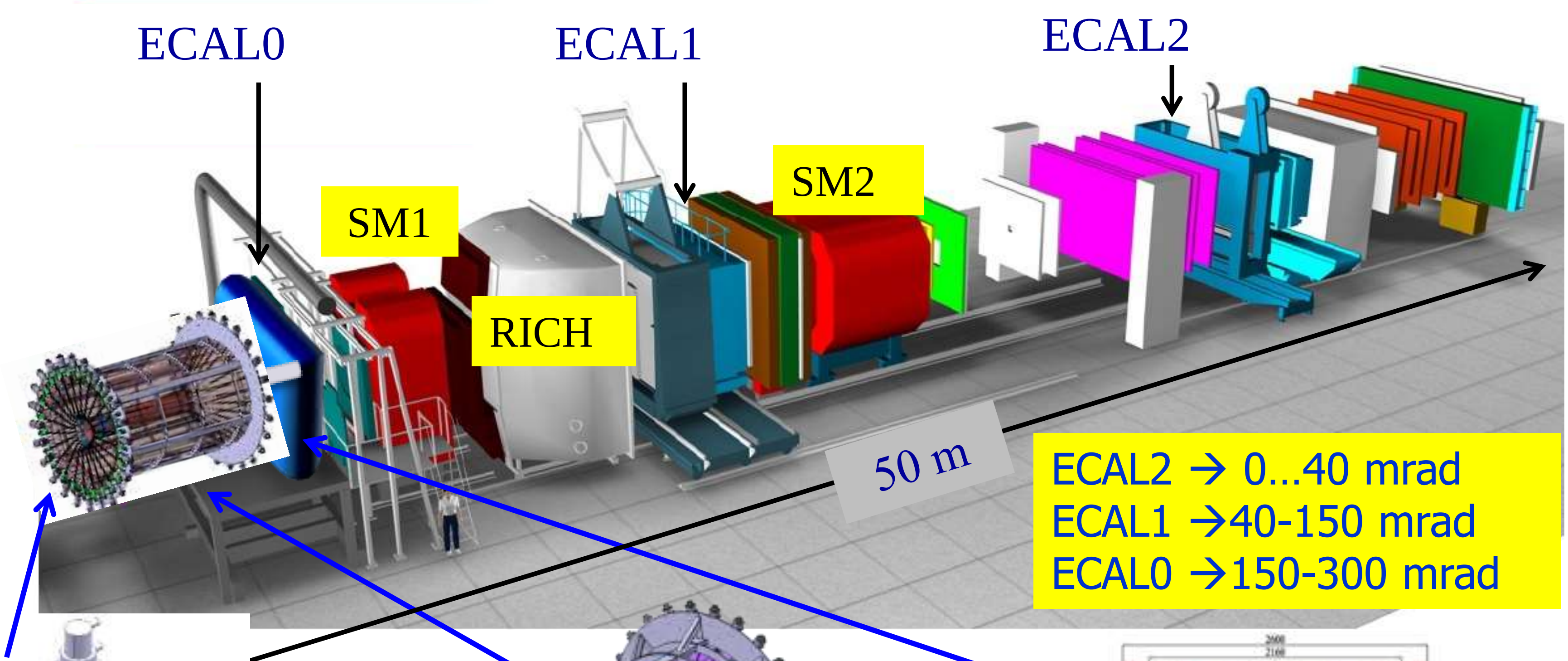


2012:
1 month pilot run

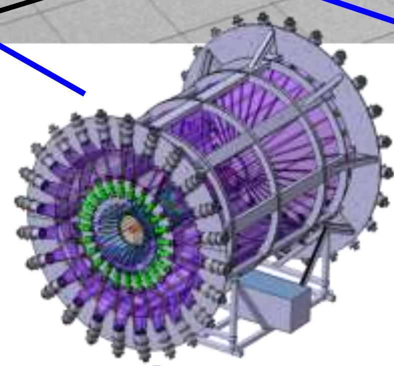
2016 -17:
2 x 6 month
data taking

COMPASS spectrometer

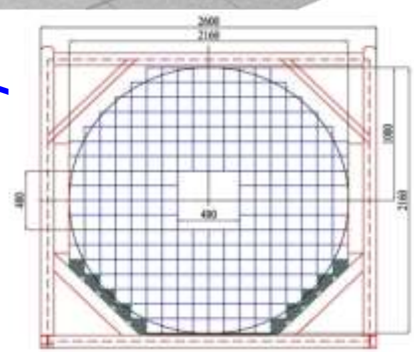
COMPASS in μ runs
NIM A 577(2007) 455



2.5 m long LH_2 target



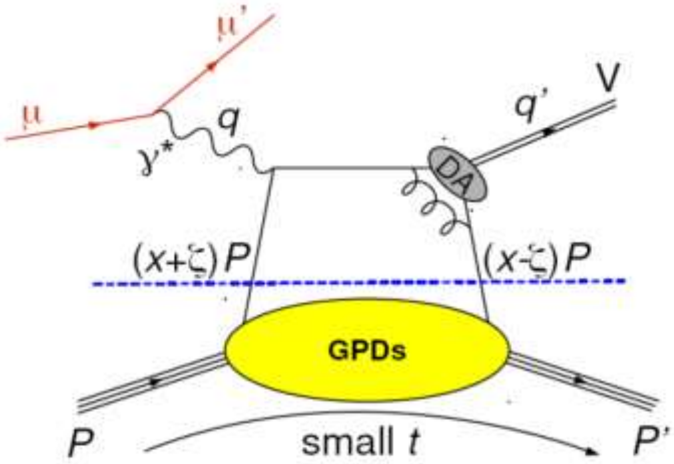
4.0 m longTime-Of-Flight detector: 24 inner and 24 outer slabs



2x2 m^2 electromagnetic calorimeter, ECAL0[3]

Exclusive π^0 production is the main source of background for DVCS process, while it provides important information on chiral-odd GPDs. The dedicated GPD program has started with a one month pilot run in 2012, followed by two full years of data taking in 2016-2017, using 160 GeV/c positive and negative muon beams, a liquid hydrogen target and new detectors such as a recoil proton detector and a large-angle electromagnetic calorimeter ECAL0.

Hard exclusive π^0 production on unpolarised protons and chiral-odd GPDs



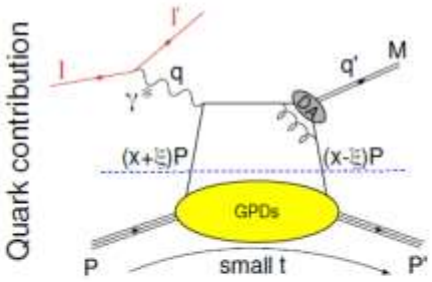
$|t| \in (0.08, 0.64)\ (\text{GeV}/c)^2$

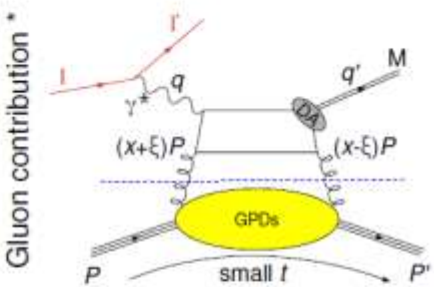
$$\mu p \to \mu' \pi^0 p'$$

μp cross-section can be reduced to γ*p

$$\gamma^* p \to \pi^0 p'$$

GPDs and Deep Virtual Exclusive Meson Production





Chiral-even GPDs
helicity of parton conserved

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

Chiral-odd GPDs
helicity of parton flipped

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

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

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

* Gluon contribution at same order of α_s as from quarks

In general hard exclusive π^0 is sensitive to the GPDs conserving the parton helicity $(\tilde{H},\ \tilde{E})$ and also to the parton helicity flip or to chiral-odd GPDs $(H_T \text{ and } \overline{E}_T)$, where $\overline{E}_T = 2\widetilde{H}_T + E_T$.

Hard exclusive π^0 production on unpolarised protons

Cross-section of the hard exclusive meson production, reduced to γ^*p, for the unpolarized target and polarized lepton beam

$$\frac{d^4\sigma_{\mu p}}{dQ^2 dt d\nu d\phi} = \Gamma \frac{d^2\sigma_{\gamma^* p}}{dt d\phi}$$

where $\Gamma = \Gamma(E_\mu, Q^2, \nu)$ is a transverse virtual-photon flux.

Spin independent cross-section of the hard exclusive meson production after averaging the two spin-dependent cross-sections looks following

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

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

$\Rightarrow$ study ϕ dependence

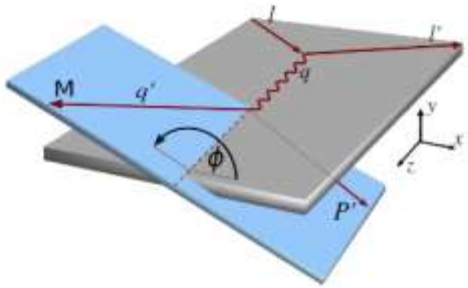
After integration in ϕ:

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

$\Rightarrow$ study t dependence

GPDs in exclusive π^0 production on unpolarised protons

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



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

leading twist
at JLAB only few% of $\frac{d\sigma_T}{dt}$

other contributions arise from coupling
of chiral-odd (quark helicity-flip) GPDs to twist-3 pion amplitude

def. $\bar{E}_T = 2\tilde{H}_T + E_T$

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

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

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

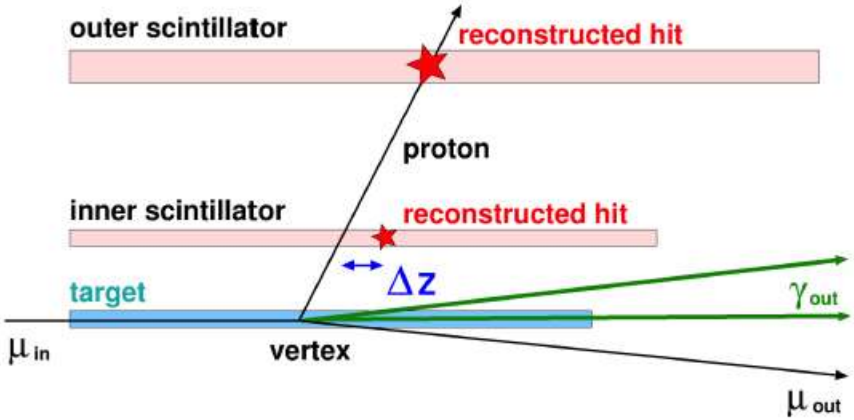
phemenological Goloskokov&Kroll model
version 2011 based on JLab results
version 2016 update energy dependance $\bar{E}_T$
to fit both JLab and COMPASS results

An impact of $\bar{E}_T$ should be visible in $\frac{\sigma_{TT}}{dt}$

and in a dip at small t' of $\frac{d\sigma_T}{dt}$

the effect of H_T should be visible

Exclusive π^0 events selection



General selection in the phase-space

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

→ Incoming and outcoming μ from the same/unique primary vertex

→ Two clusters in the ECAL0 , ECAL1 calorimeters

→ Identified proton in Time-of-flight detector CAMERA

Exclusivity variables

→ Transverse momentum constraint:

$$\Delta p_T = p^p_{T,spect} - p^p_{T,recoil}$$

→ Azimuthal angle constraint:

$$\Delta\varphi = \varphi^p_{spect} - \varphi^p_{recoil}$$

→ Z coordinate of inner CAMERA ring:

$$\Delta z = z^p_{spect} - z^p_{recoil}$$

→ Energy-momentum conservation:

$$M^2_X = \left(p_{\mu,in} + p_p - p_{\mu,out} - p_{p'} - p_{\pi^0}\right)^2$$

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

Final selection

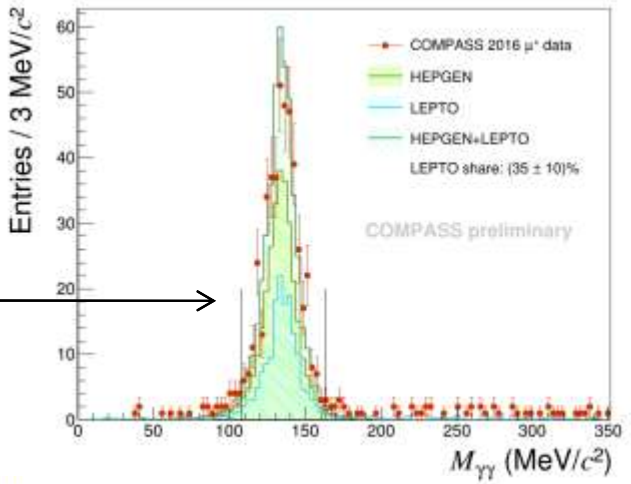
Invariant mass $M_{\gamma\gamma}$ cut

Kinematic fit

Final selection

Distribution of the 2 γγ mass 2.5 σ cut $M_{\pi 0} \in (108, 163)$ MeV/c^2

Kinematic fit



Measurement of exclusive processes at COMPASS is overconstrained → 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

SIDIS background estimation

Main background for exclusive π^0 production $\Rightarrow$ non-exclusive DIS processes

Two Monte Carlo simulations with the same π^0 selection criteria were used:

➔LEPTO for the non-exclusive DIS background
➔HEPGEN++ shape of distributions of exclusive π^0 production (signal contribution)

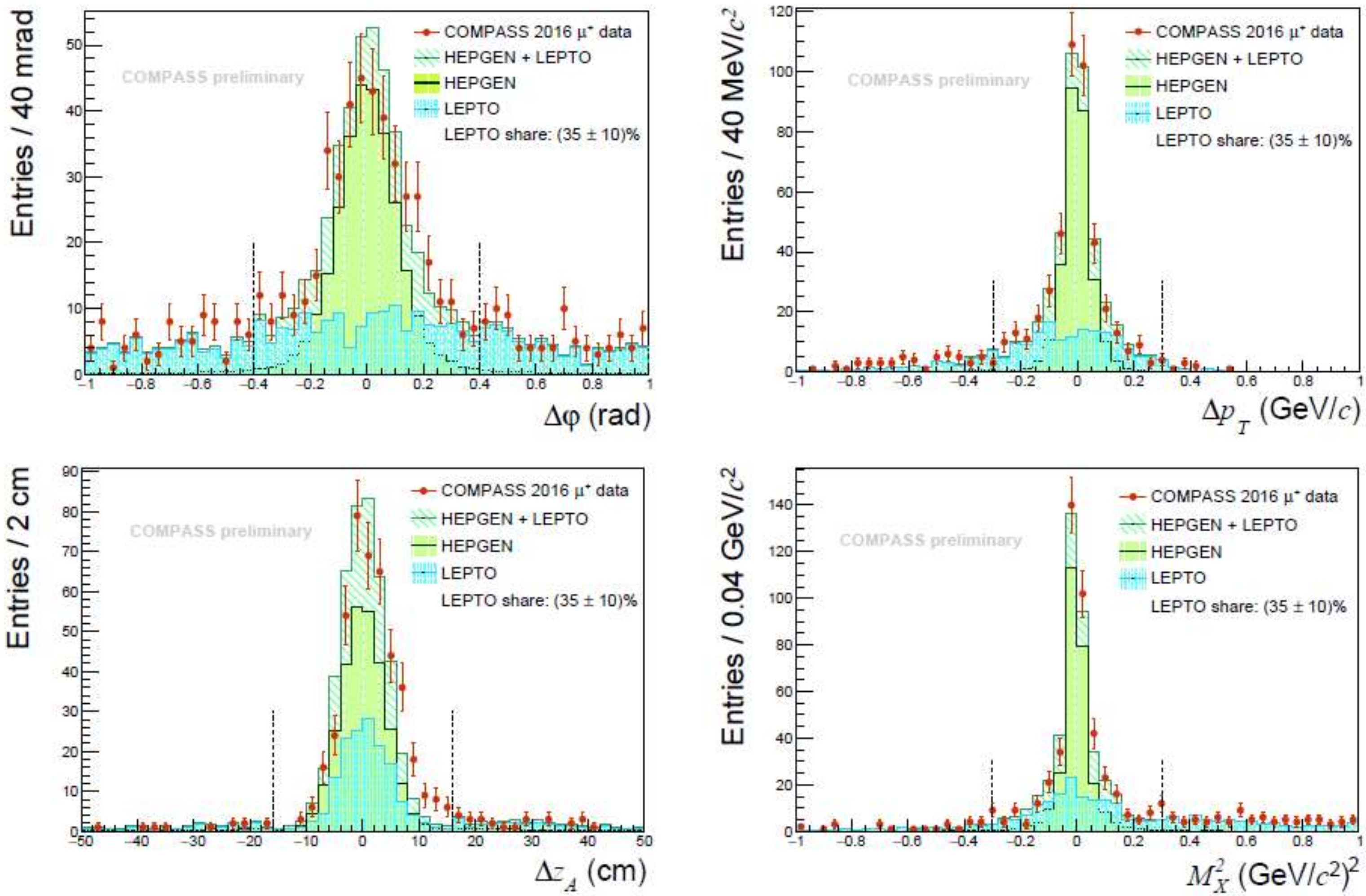
Search for best description of data fitting by mixture of both MC
Both MC samples normalized to the experimental $M_{\gamma\gamma}$ distribution
The ratio of background events r_{LEPTO} is determined by a fit on the exclusivity distributions

The fraction of non-exclusive back-ground in the 2016 data is estimated to be (35 ± 10)%
Background fit method is currently the main source of systematic uncertainty.

For the moment the contributions of other background sources are considered to be negligible. For example, the production of single ω mesons, where the ω decays into a π^0 and a photon that remains undetected, was found in Monte Carlo studies to contribute at the level of 1% (2012 analysis).

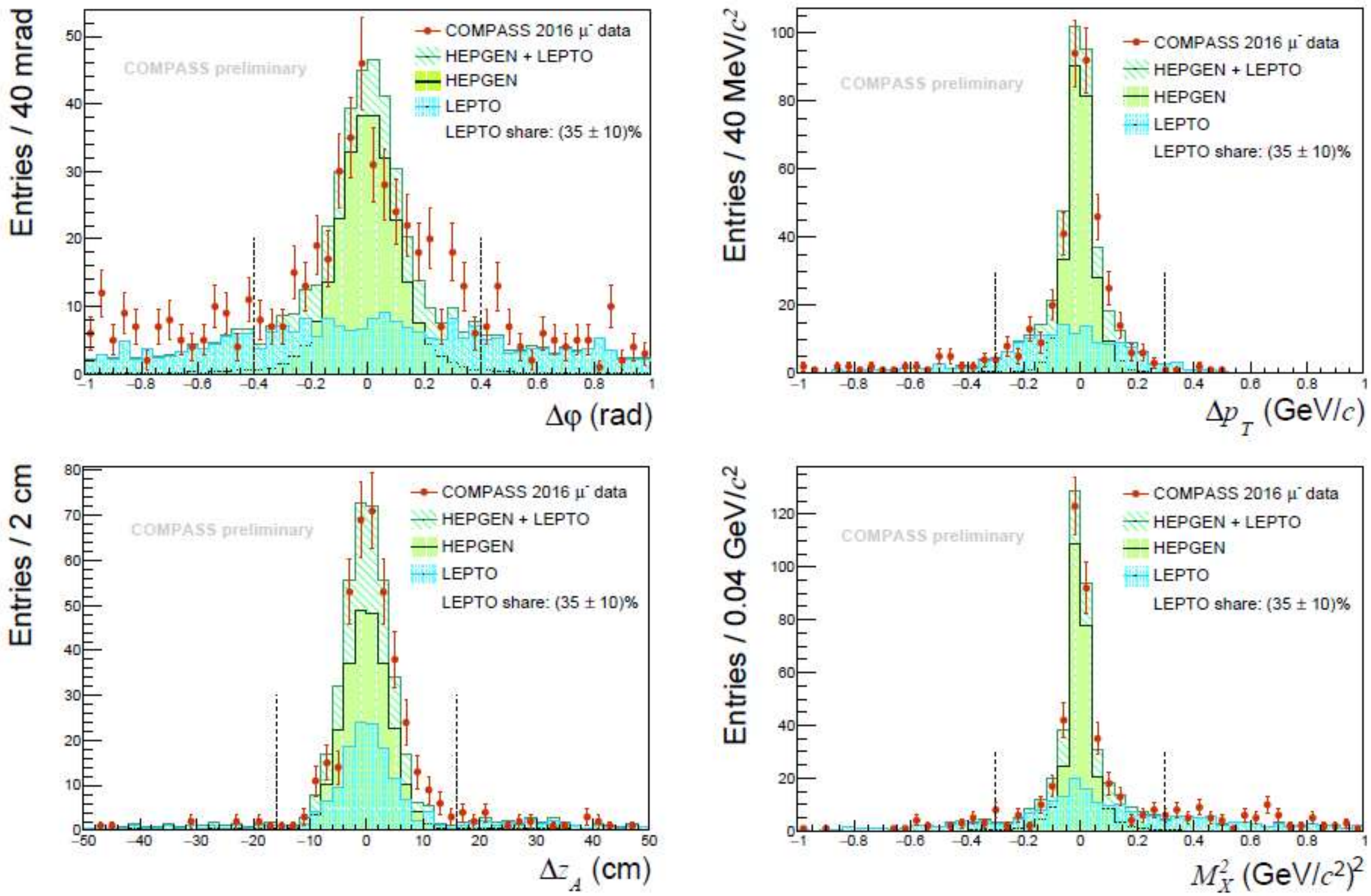
Distributions of the exclusivity variables for μ^+

Cuts: $|\Delta\varphi| < 0.4$ rad $\quad |\Delta p_T| < 0.3$ GeV/c $\quad |\Delta Z_A| < 16$ cm $\quad |M^2_X| < 0.3$ (GeV/c^2)^2



Distributions of the exclusivity variables for μ^-

Cuts: $|\Delta\varphi| < 0.4$ rad $|\Delta p_T| < 0.3$ GeV/c $|\Delta Z_A| < 16$ cm $|M^2_X| < 0.3$ (GeV/c^2)^2



Exclusive π^0 production: COMPASS acceptance

The cross section is determined presently in the same phase space as for the 2012 data analysis:

- 8.5 GeV < ν < 28 GeV
- 1 $(GeV/c)^2$ < Q^2 < 5 $(GeV/c)^2$
- 0.08 $(GeV/c)^2$ < |t| < 0.64 $(GeV/c)^2$

For the acceptance determination, the HEPGen-π^0 MC simulation is used.

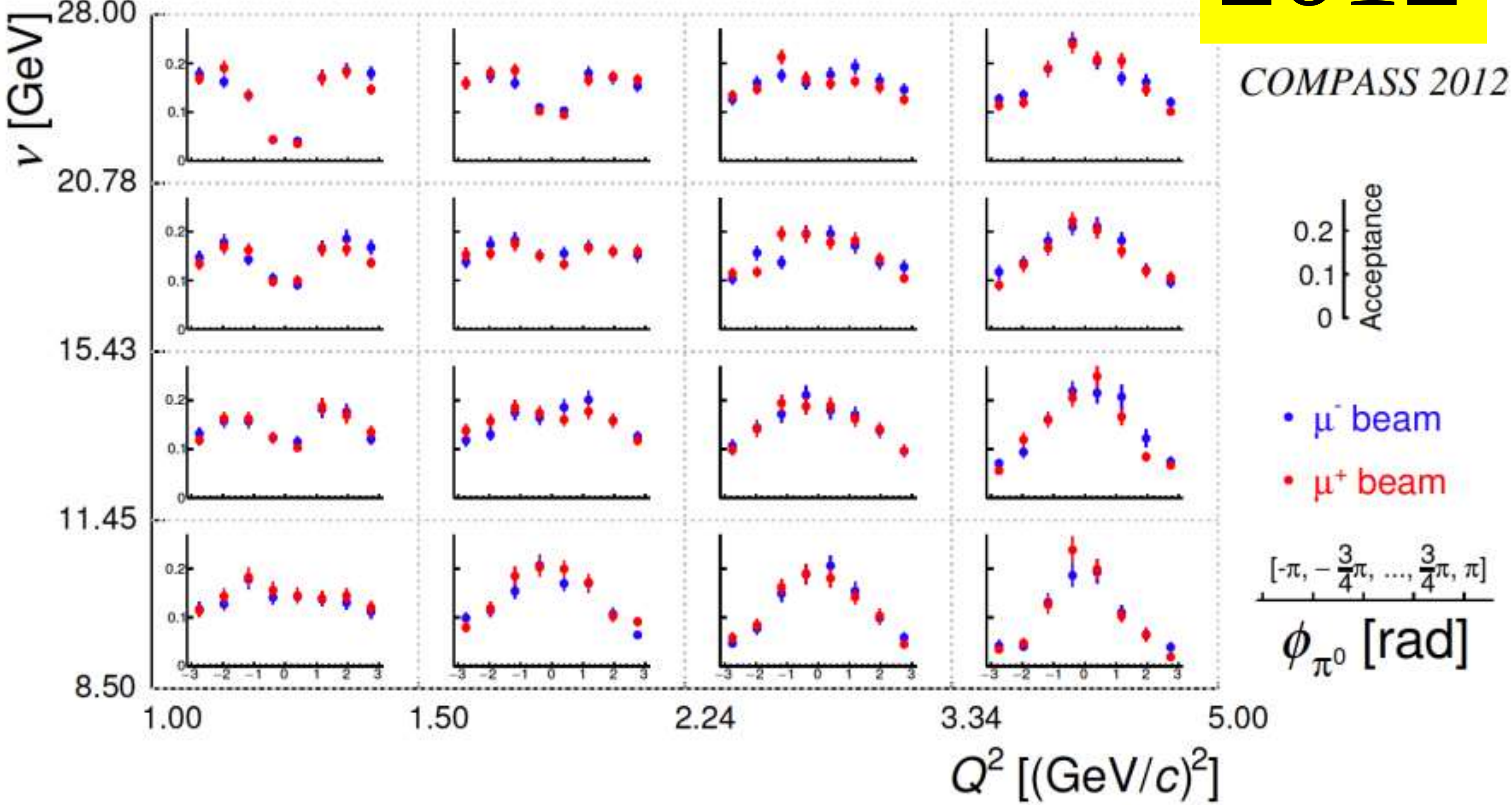
4D acceptance in bins of φ_{π^0}, ν, $|t|$, Q^2

- 5 bins in |t| with binning [0.08, 0.15], [0.15 0.22], [0.22 0.36], [0.36 0.5] [0.5 0.64] $(GeV/c)^2$,
- 8 bins in ϕ equally spaced from $-\pi$ to $+\pi$
- 4 bins in Q^2 with binning [1, 1.5], [1.5 2.24], [2.24 3.34], [3.34 5] $(GeV/c)^2$,
- 4 bins in ν with binning [8.5, 11.45], [11.45 15.43], [15.43 20.78], [20.78 28] (GeV).

Exclusive π^0 production: COMPASS acceptance |t| averaged

4D acceptance in bins of ϕ_{π^0}, ν, $|t|$, Q^2
figure shows 3D projection, as a function of ϕ_{π^0}

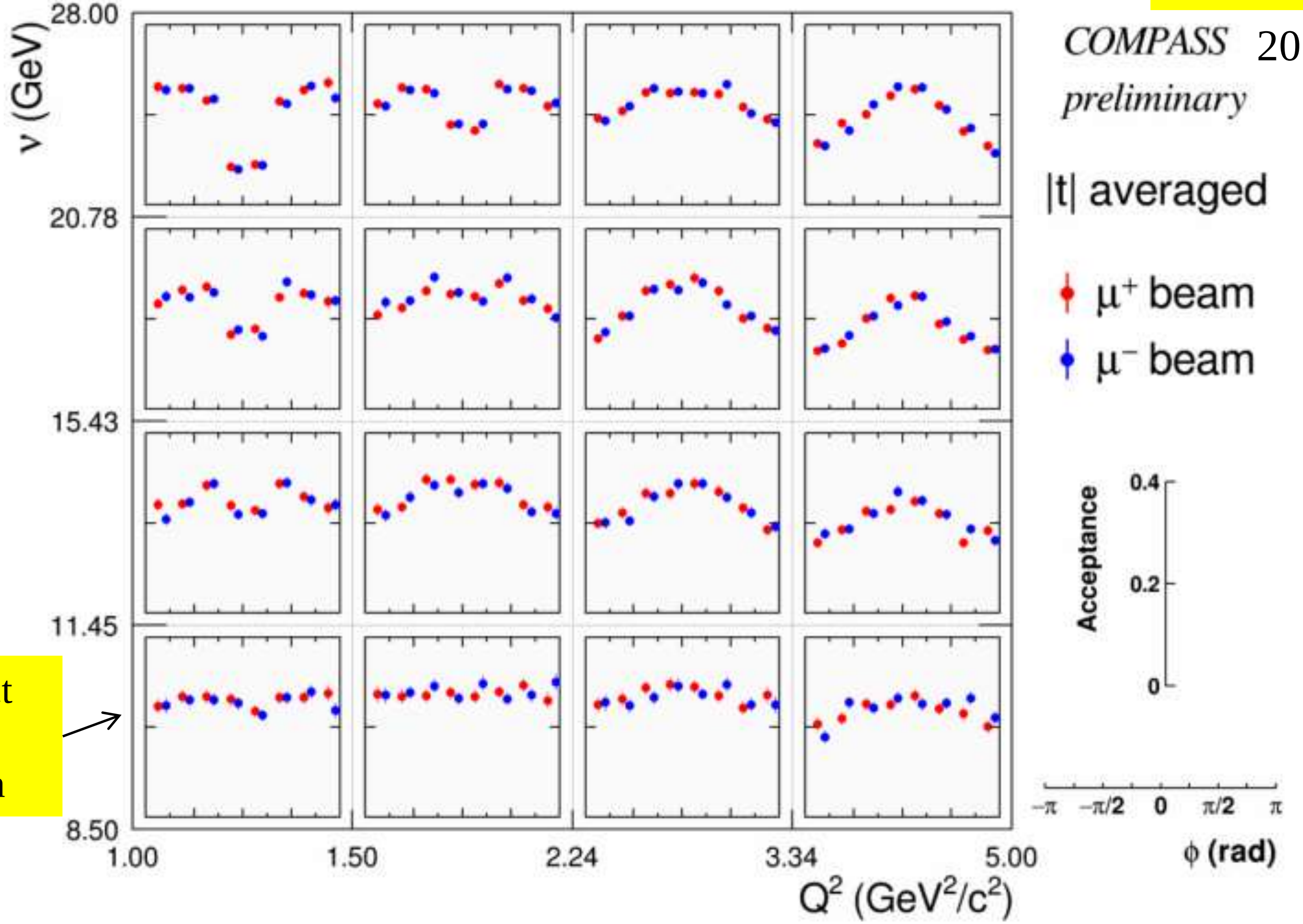
2012



Exclusive π^0 production: COMPASS acceptance |t| averaged

4D acceptance in bins of ϕ_{π^0}, ν, $|t|$, Q^2
figure shows 3D projection, as a function of ϕ_{π^0}

2016



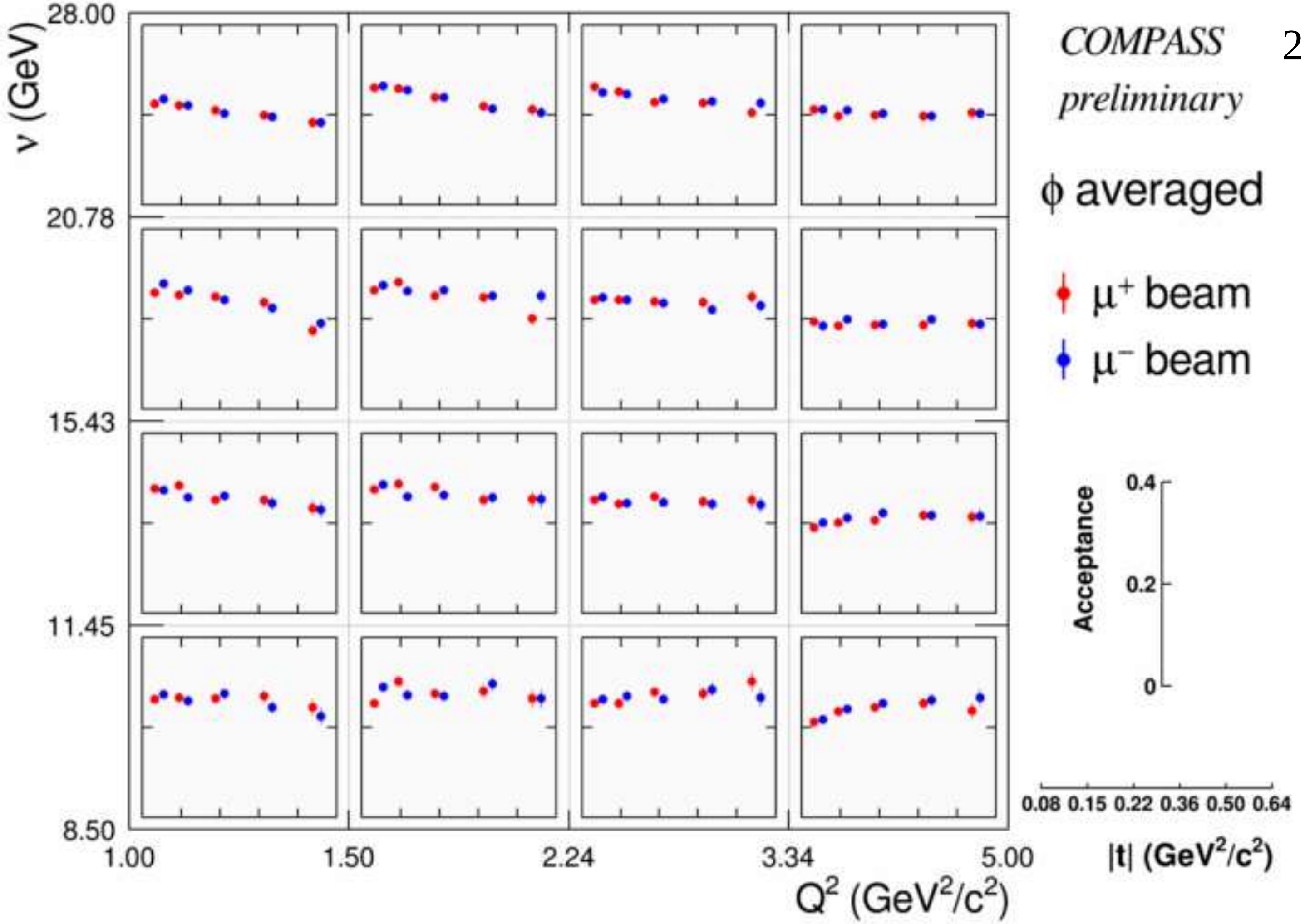
2016

Clear effect of ECAL0 installation

Exclusive π^0 production: COMPASS acceptance ϕ averaged

4D acceptance in bins of ϕ_{π^0}, ν, $|t|$, Q^2
figure shows 3D projection, as a function of $|t|$

2016



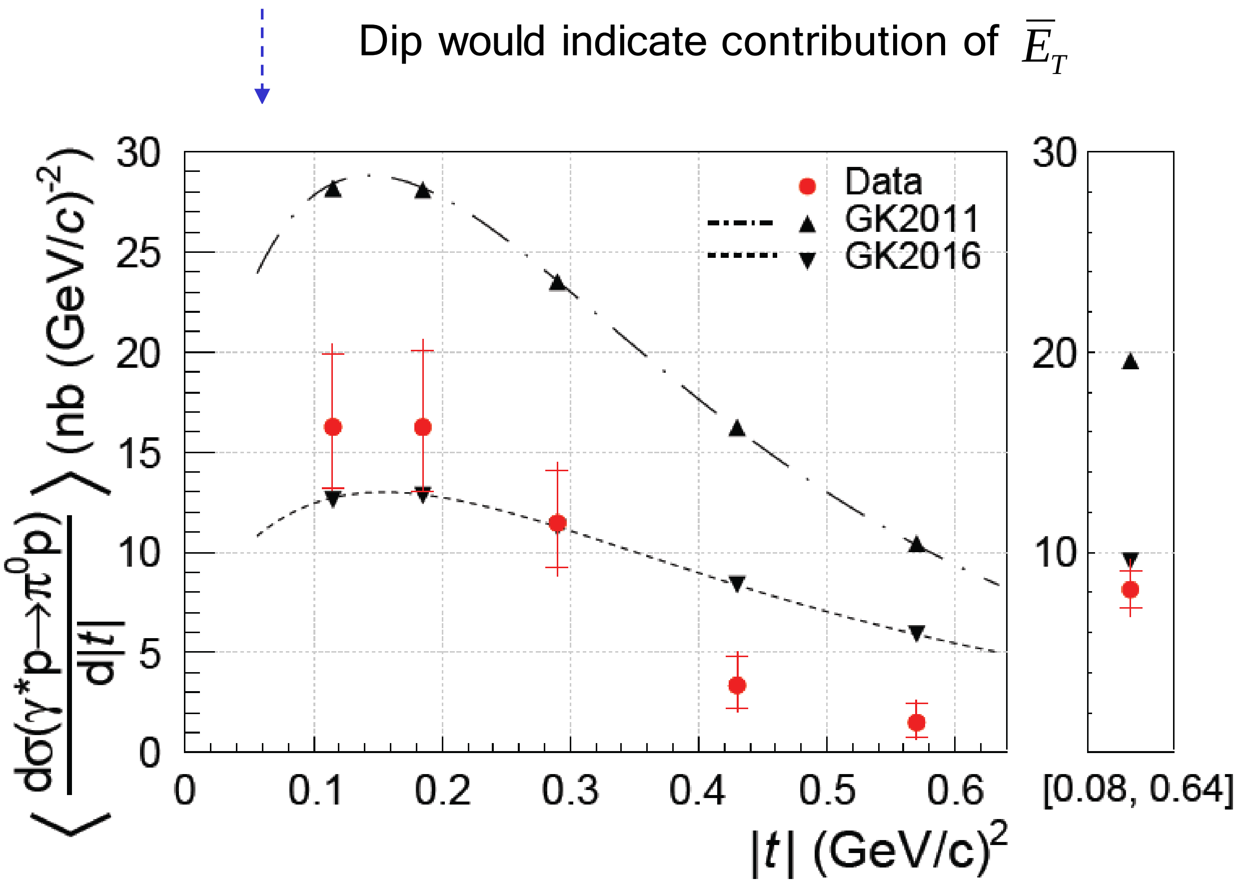
Exclusive π^0 production cross sections as a function of $|t|$

PLB 805 (2020) 135454

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt}$$

2012 data

Dip would indicate contribution of $\overline{E}_T$



$\langle Q^2 \rangle = 2.0\ (\mathrm{GeV}/c)^2$, $\langle \nu \rangle = 12.8$ GeV, $\langle x_{Bj} \rangle = 0.093$ and $\langle -t \rangle = 0.256\ (\mathrm{GeV}/c)^2$

GK2016 + an updated model with another energy dependence of $\bar{E}_T$

Courtesy of S.Goloskokov & P.Kroll

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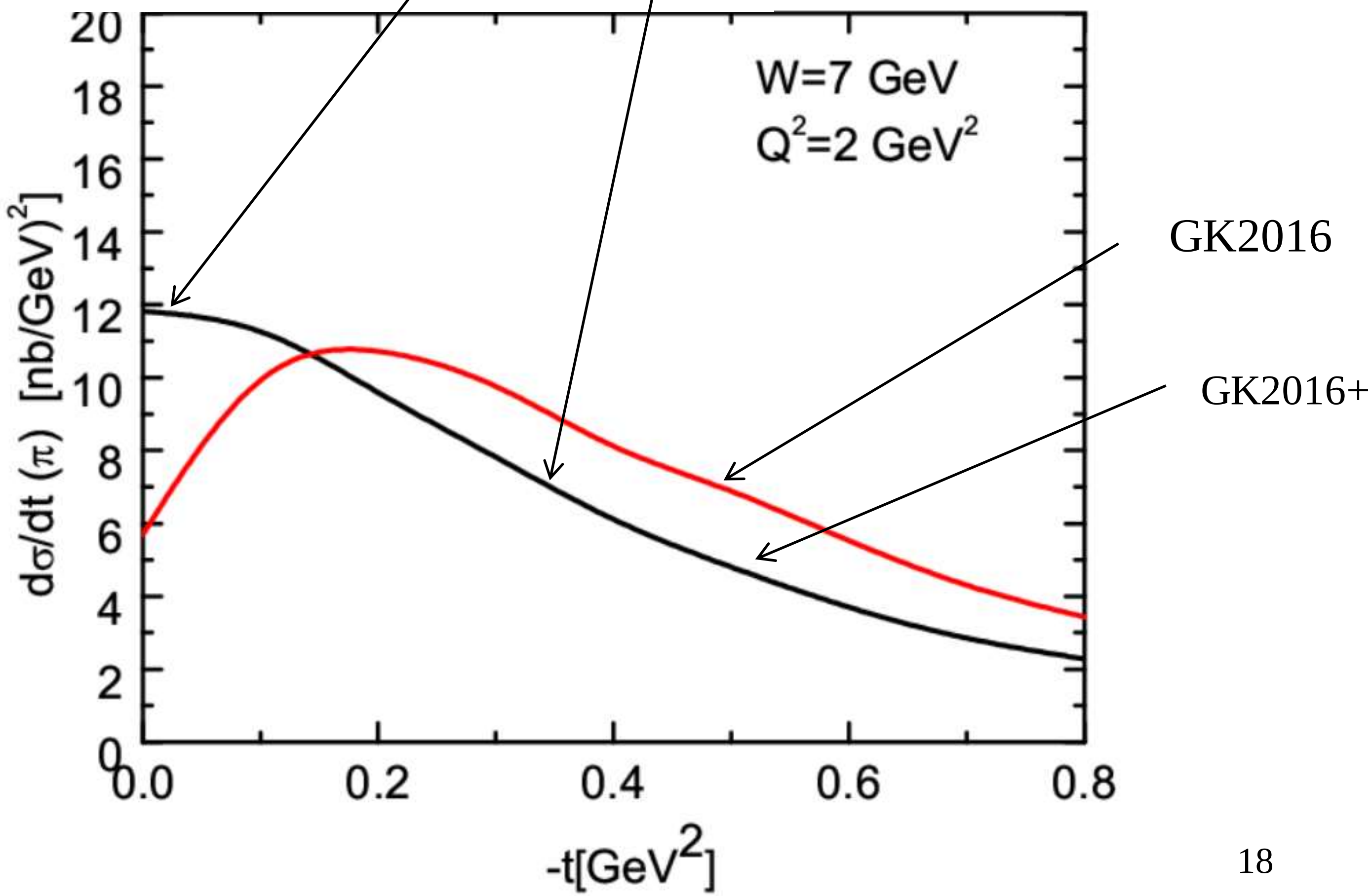
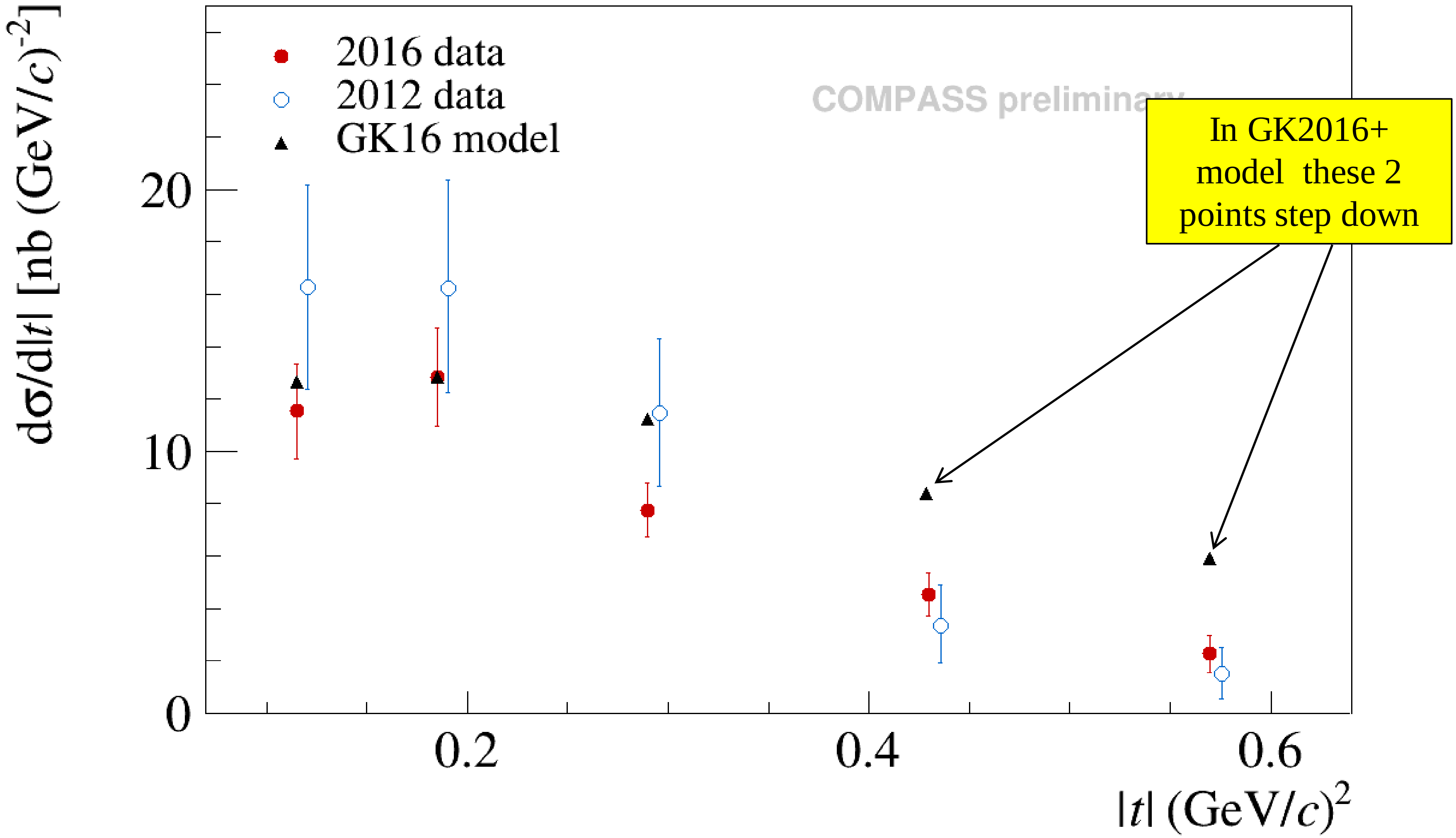
$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[\left(1-\xi^2\right)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle \bar{E}_T\rangle\right|^2\right]$$



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

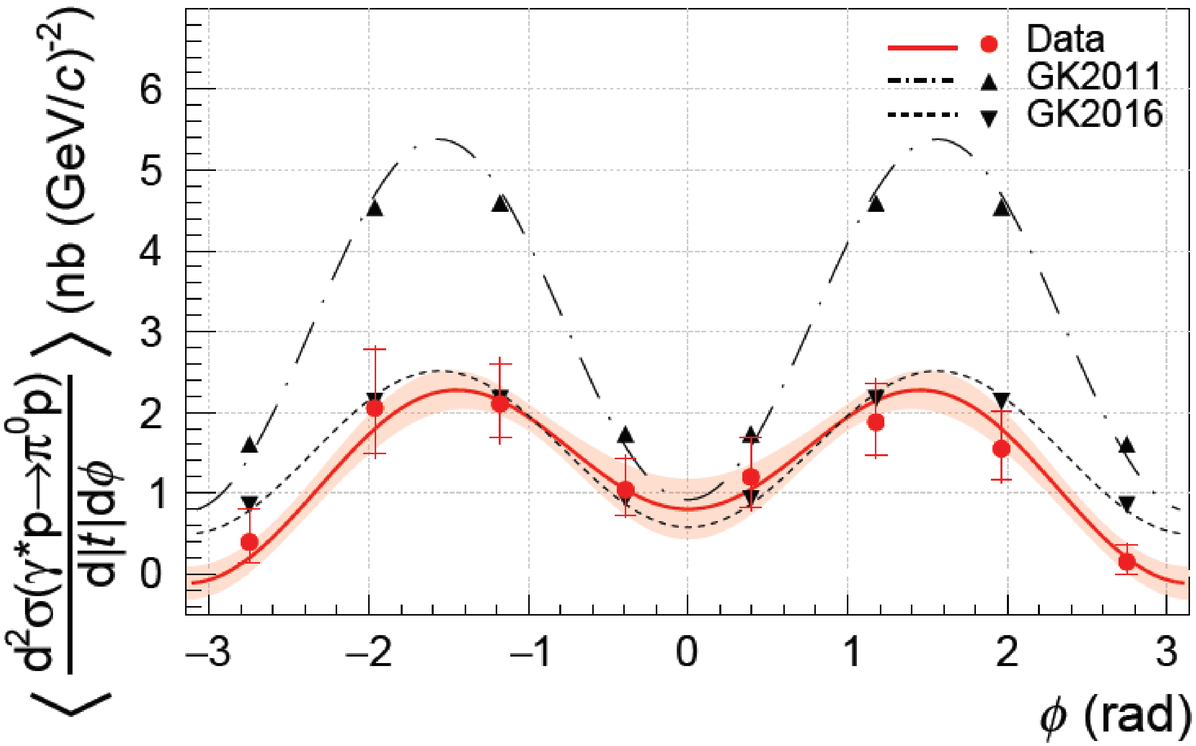
2012 data PLB 805 (2020) 135454
GK16 model EPJ A47 (2011) 112 + private communications



Exclusive π^0 production cross sections as a function of ϕ

PLB 805 (2020) 135454

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



2012 data

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

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

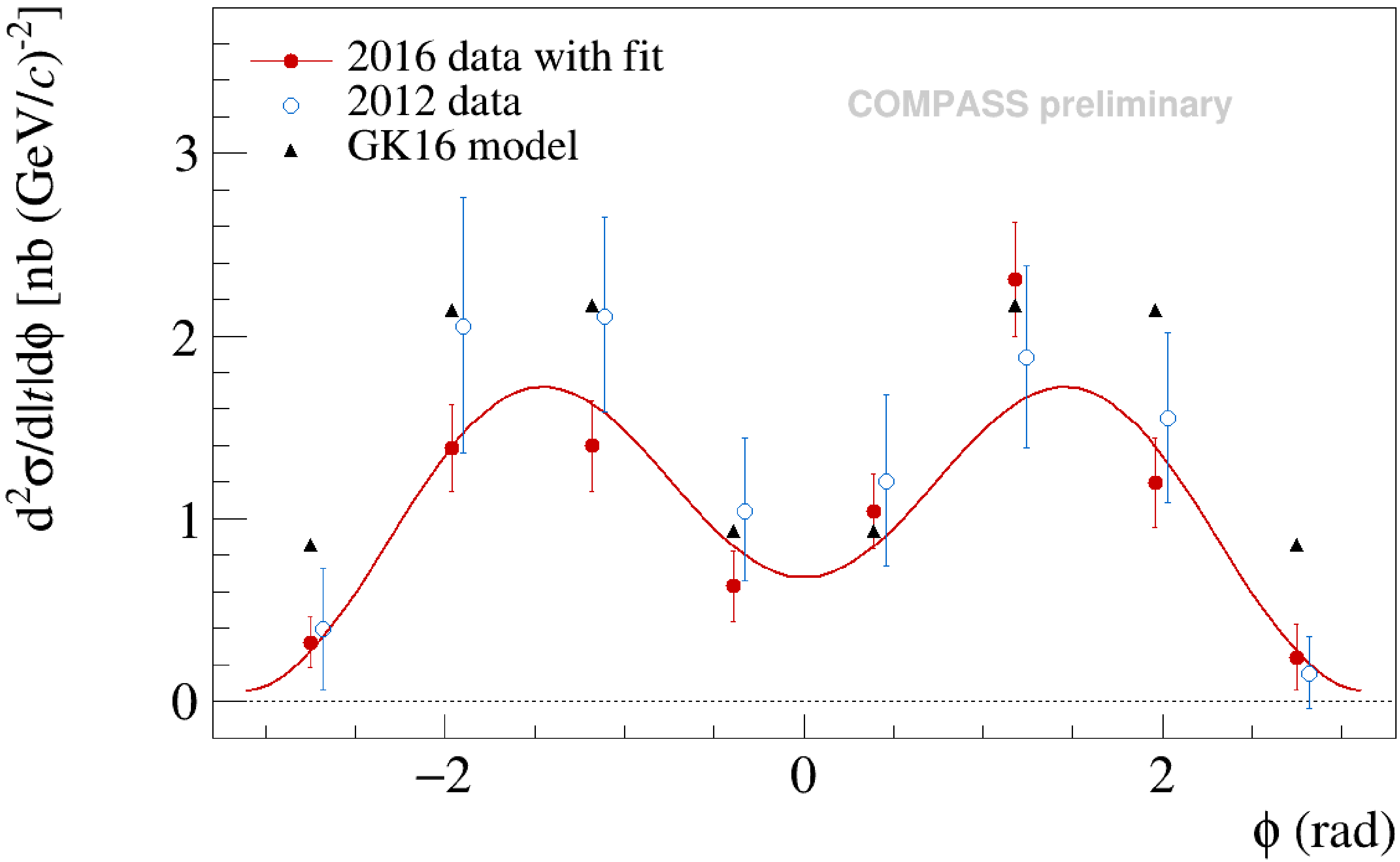
$$\left\langle \frac{d\sigma_{LT}}{d|t|} \right\rangle = (1.4 \pm 0.5_{stat}{}^{+0.3}_{-0.2}|_{sys})\frac{nb}{(GeV/c)^2}$$

Large impact of $\overline{E}_T$ visible in $\frac{d\sigma_{TT}}{dt} \sim \overline{E}_T$

positive result for $\frac{d\sigma_{LT}}{dt}$

Exclusive π^0 production cross sections as a function of ϕ

2012 data PLB 805 (2020) 135454
GK16 model EPJ A47 (2011) 112 + private communications



Summary

➔The differential virtual-photon proton cross sections are extracted from the 2016 data as a function of the squared four-momentum transfer t, and of the azimuthal angle ϕ between the scattering plane and the π^0 production plane.

➔The average differential cross sections from the 2016 data are compared to the published results of the 2012 data and no significant difference is observed.

➔A slightly different t-shape is seen in 2016 data (as in 2012 one) with respect to GK2016 model prediction, which however can be reduced in the GK2016 + model with another energy dependence of $\overline{E}_T$

➔From the results we observe a large contribution of σ_{TT} and a small positive contribution of σ_{LT} . This supports the expectation of the exclusive π^0 cross section to be dominated by transverse polarized virtual photon, which indicates a significant effect of the chiral-odd GPD $\overline{E}_T$

➔Total statistics 2017+2016 data is estimated to be 10 times higher than the 2012 one

➔ Input to constrain phenomenological models such as those provided by Goloskokov&Kroll, Goldstein&Luiti, etc