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

M. Gorzellik (ALU Freiburg)

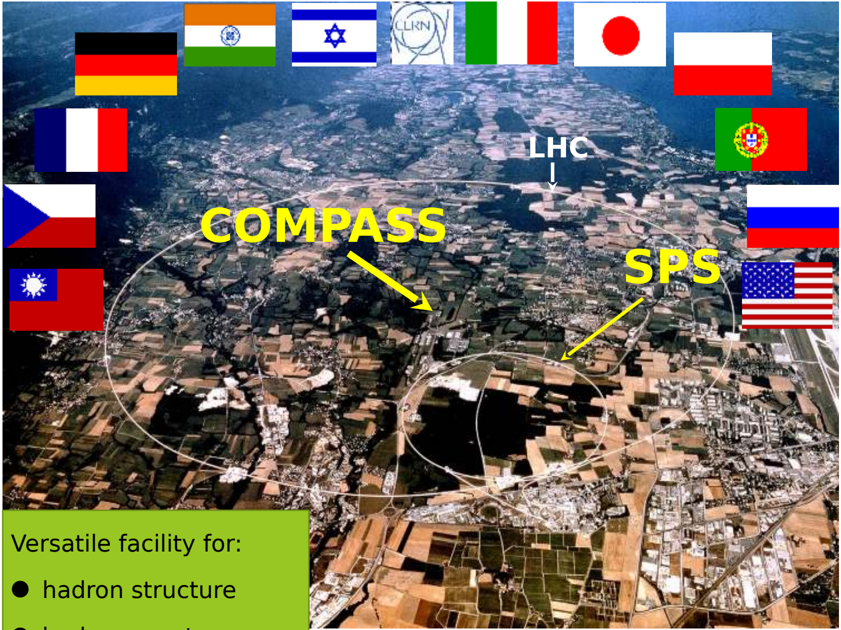
on behalf of the COMPASS Collaboration

IPN Orsay, 29/05/2017

SEVENTH FRAMEWORK PROGRAMME

COMPASS

bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung



Versatile facility for:

- hadron structure
- hadron spectroscopy

COMPASS Generalized Parton Distribution (GPD) program

- Contribution to the nucleon spin puzzle

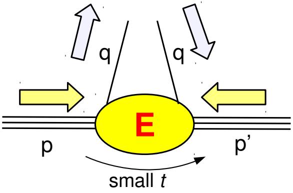
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathscr{L}$$

Jaffe&Manohar Nucl.Phys.B337 (1990)

by constraining GPD H and E

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

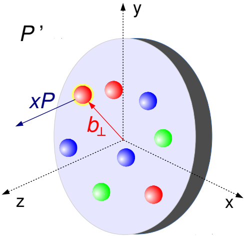
(Phys.Rev.Lett.78 (1997))



- 3D nucleon tomography via GPD H

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

probability interpretation (Burkardt)



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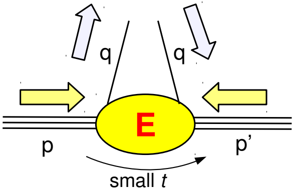

recent work

→ 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

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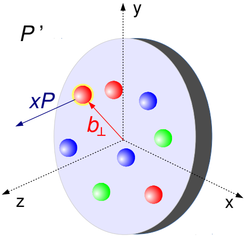
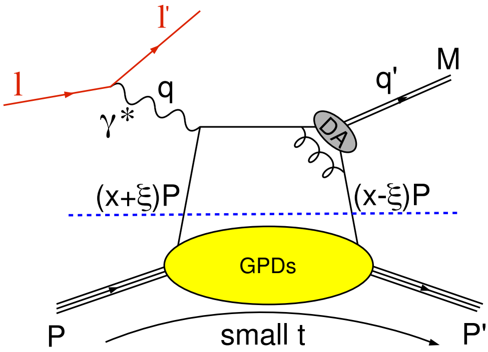


Andrea Ferrero

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

GPDs and Hard Exclusive Meson Production (HEMP)



$$Q^2 = -q^2$$

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

x : average longitudinal momentum of quark

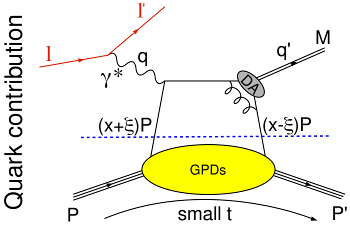
ξ : longitudinal momentum transfer to quark

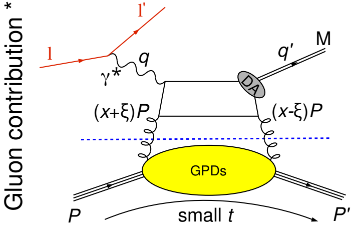
t : 4-momentum transfer to target nucleon (related to $b_\perp$)

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 (HEMP)





Chiral-even GPDs
helicity of parton conserved

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

Chiral-odd GPDs
helicity of parton flipped

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

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

* Gluon contribution at same order of α_s as from quarks

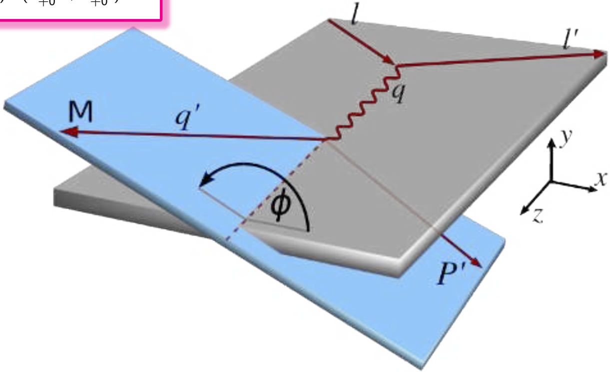
HEMP cross section (unpolarised target)

using target ToF system

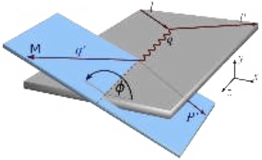
$$\left[\frac{\alpha_{em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_{Bj}}{x_{Bj}}\,\frac{1}{Q^2}\right]^{-1}\frac{\mathrm{d}\sigma}{\mathrm{d}x_{Bj}\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi} =$$

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

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



HEMP cross section (unpolarised target)



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

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

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

study ϕ dependence!

virtual photon polarisation:

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

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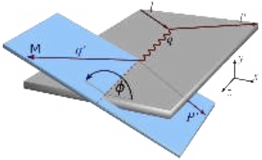

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study ϕ dependence!

after integration over ϕ:

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

study t dependence!

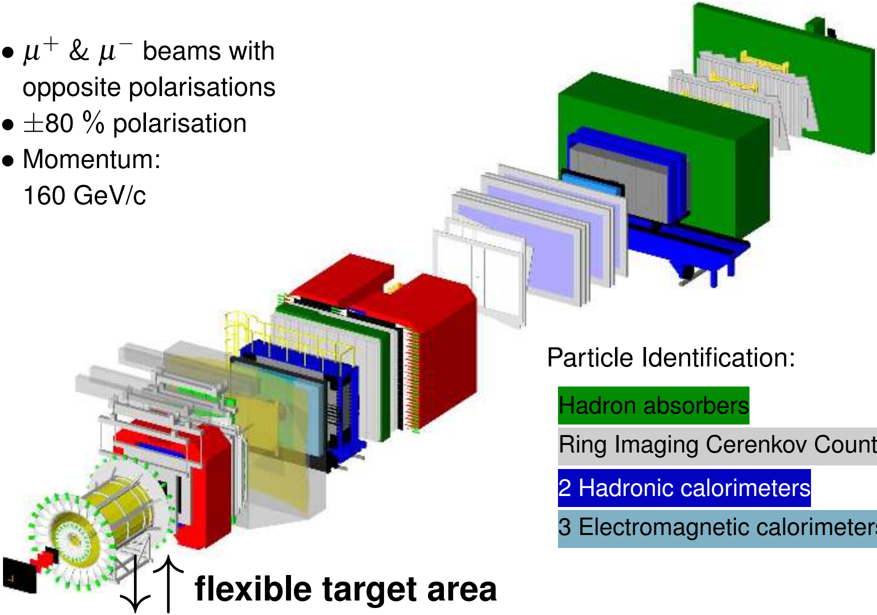
virtual photon polarisation:

- Transverse: $-, +$
- Longitudinal: 0

Exclusive π^0 production x-section extraction on unpolarised protons

COMPASS spectrometer

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



↓↑ **flexible target area**

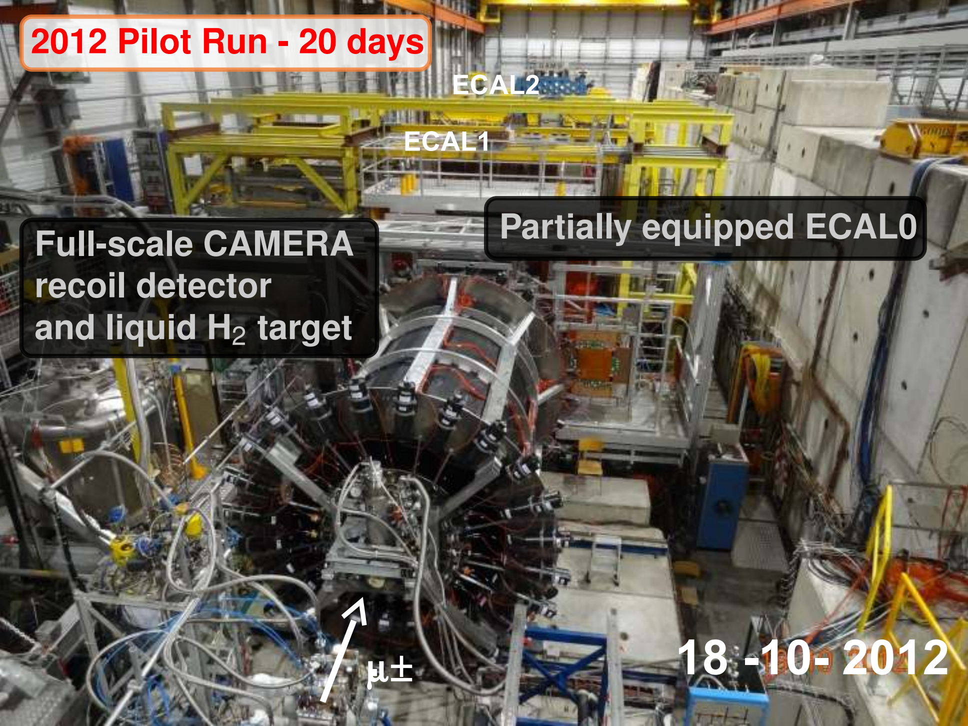
Particle Identification:

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
$\mu\pm$
18 -10- 2012

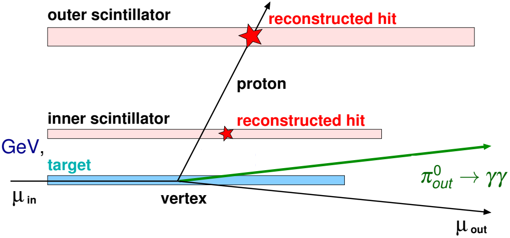
Exclusive π^0 production event selection

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

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

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



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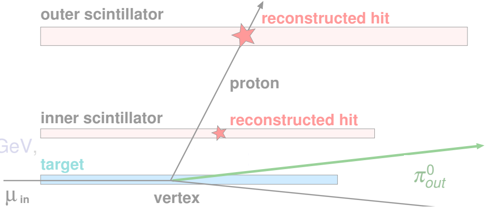
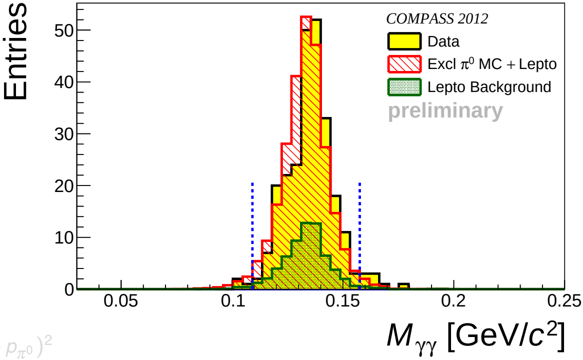


Exclusivity conditions:

- 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:
  $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$



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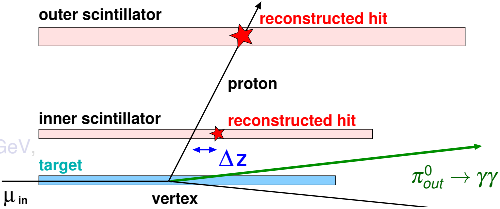

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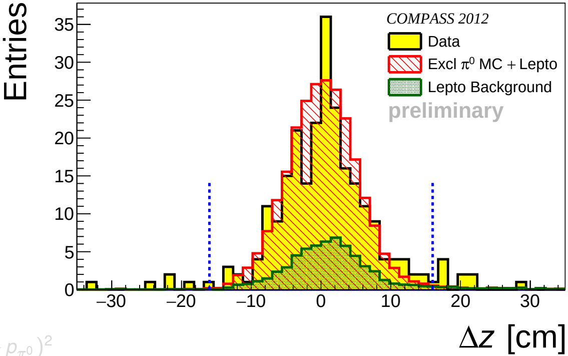

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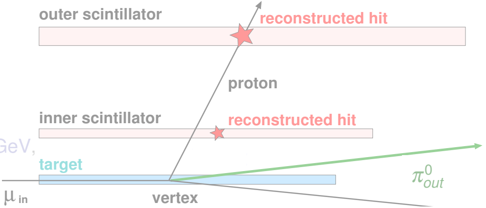

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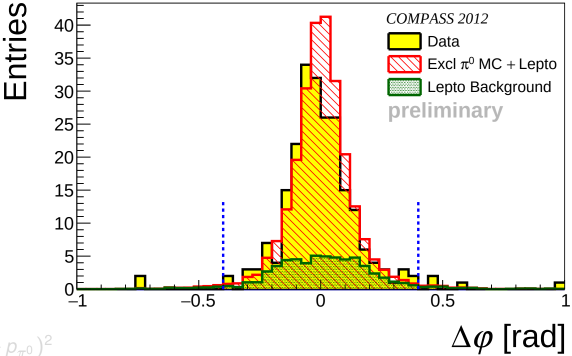

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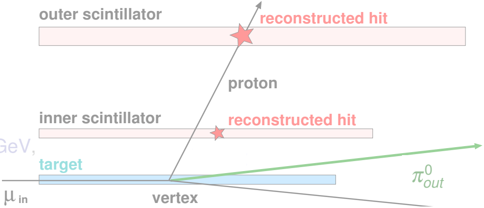

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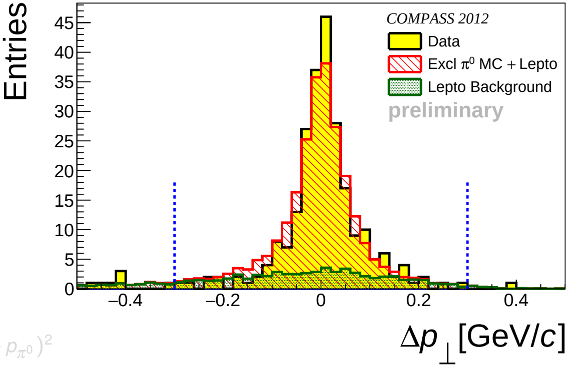

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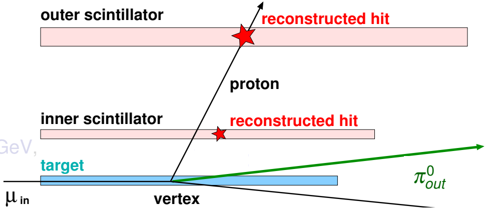

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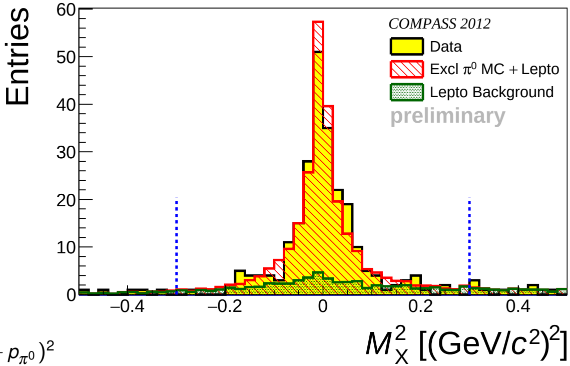
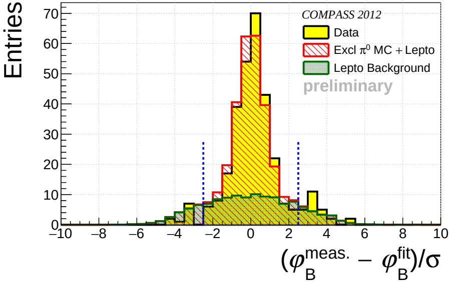
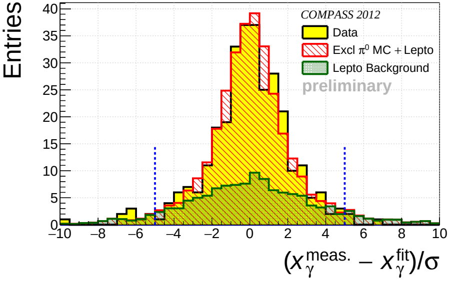


Kinematically constrained fit for exclusive π^0 production

- 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

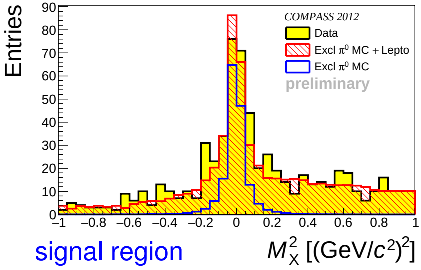
$\Rightarrow$ most accurate determination of t
$\Rightarrow$ good separation between signal and background



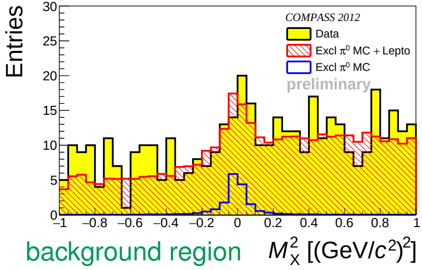


SIDIS background estimation

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

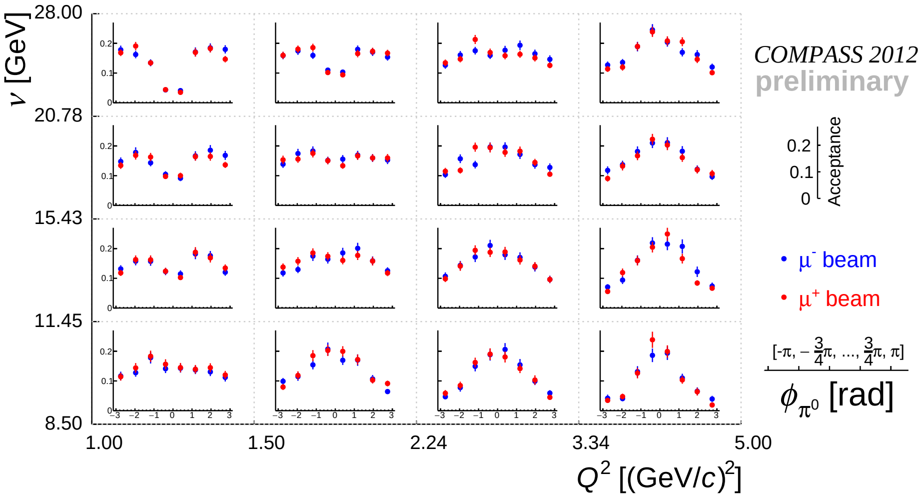


signal region



background region

COMPASS acceptance for exclusive π^0 production



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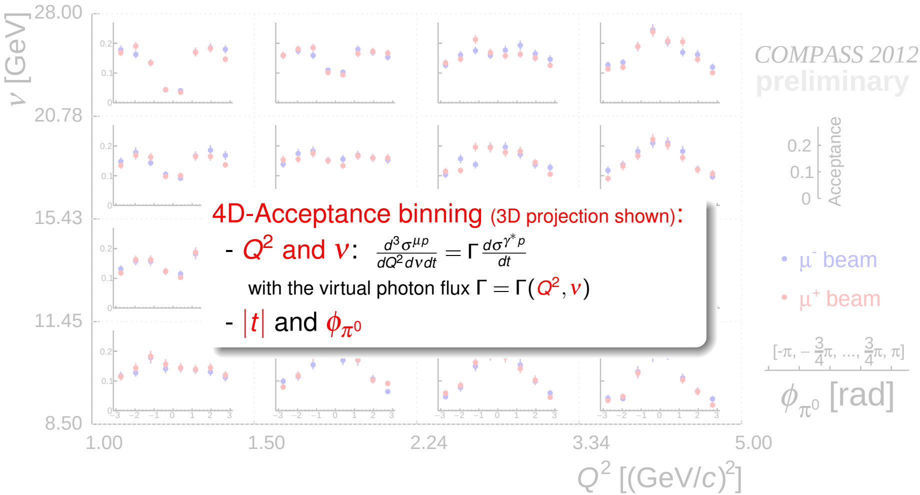
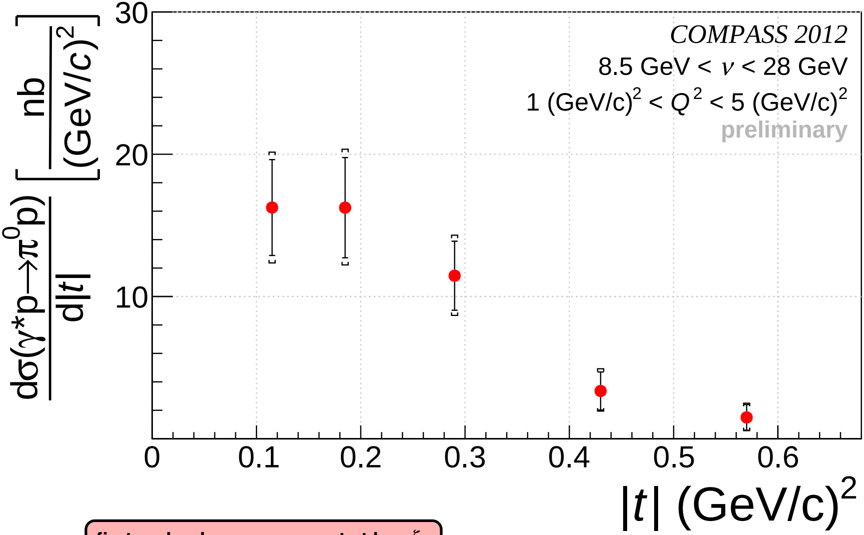


4D-Acceptance binning (3D projection shown):

- 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 production cross section as a function of $|t|$

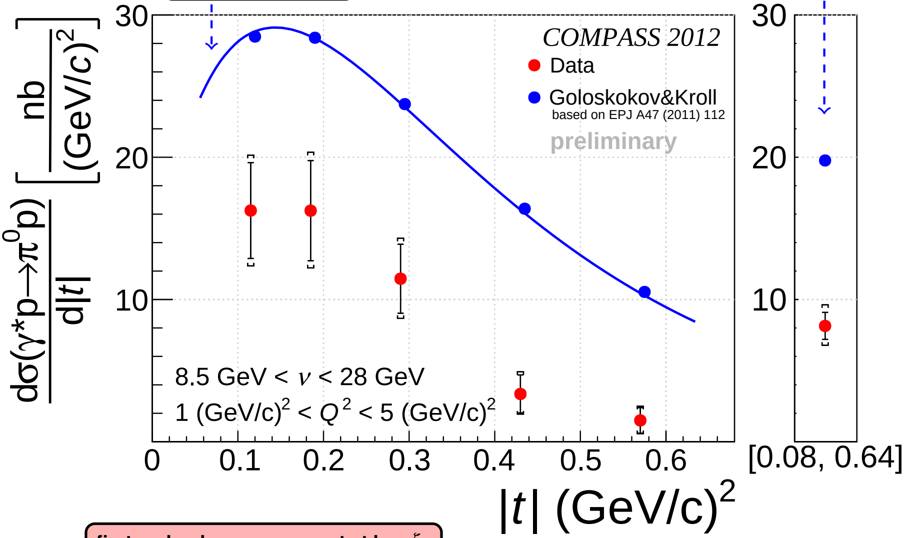


first and only measurement at low ξ

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

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

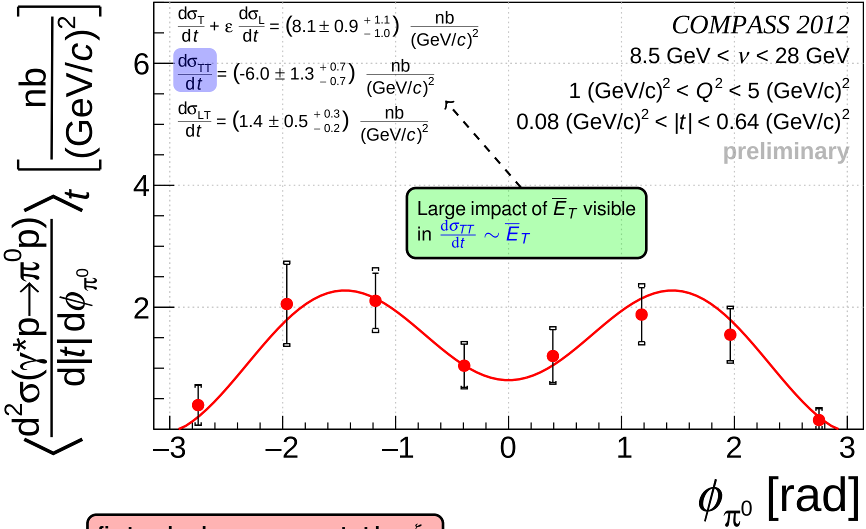
a factor of ~ 2 discrepancy to Goloskokov&Kroll model



first and only measurement at low ξ

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

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



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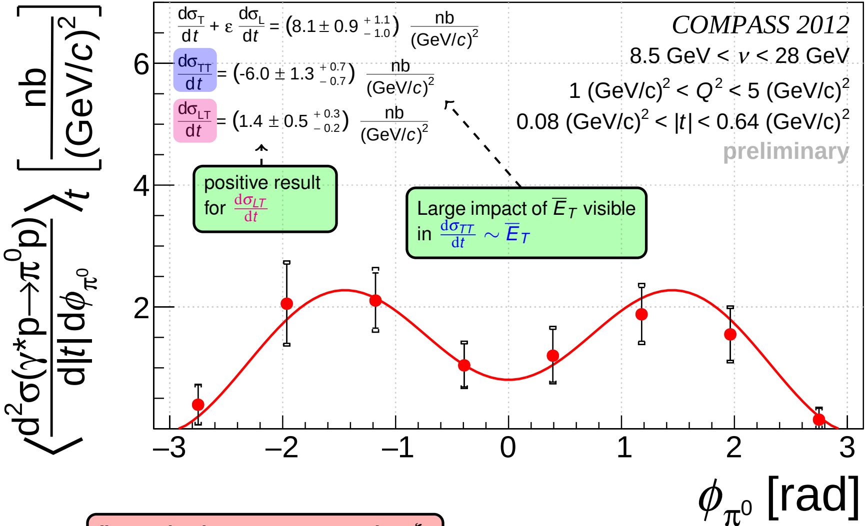
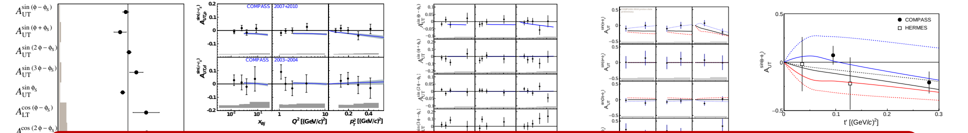
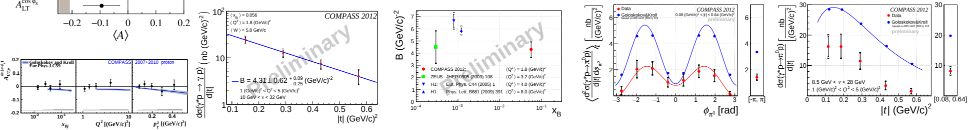


first and only measurement at low ξ

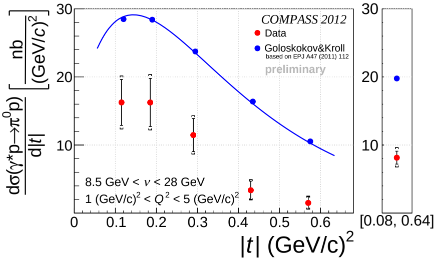


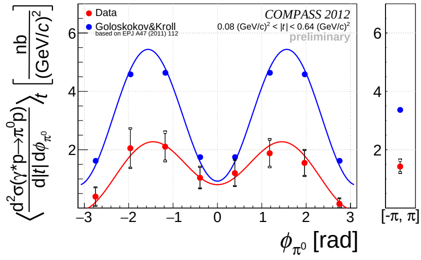
Summary:

- exclusive π^0 production cross section for a proton target
- t- and ϕ_{π^0}- dependences yield valuable input to model parametrisation
- extraction of spin density matrix elements upcoming



7% data of COMPASS II proposal / data taking 2016-2017





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Near future:

- Dedicated beam time for **D**eeply **V**irtual **C**ompton **S**cattering and **H**ard **E**xclusive **M**eson **P**roduction 2016-2017
- $\approx$ a factor of 15 increase in statistics compared to pilot run
- Beam charge sum and difference extraction

Transverse imaging at COMPASS

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

$B(x_B) = \frac{1}{2} \langle r_\perp^2(x_B) \rangle$

distance between the active quark
and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by $H(x, \xi=x, t)$

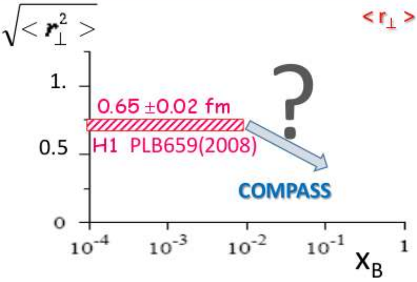
related to $\frac{1}{2} \langle b_\perp^2(x_B) \rangle$

distance between the active quark
and the center of momentum of the nucleon

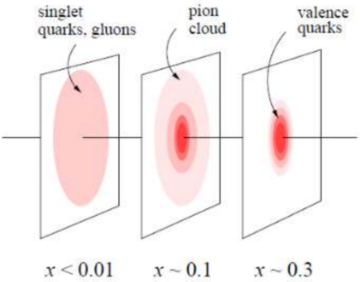
Impact Parameter Representation

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

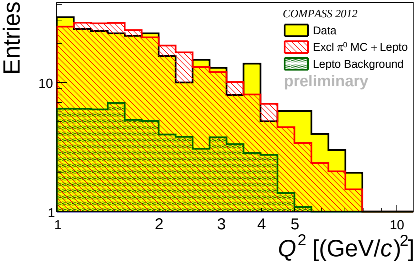
$\langle r_\perp \rangle \sim \langle b_\perp \rangle / (1-x)$

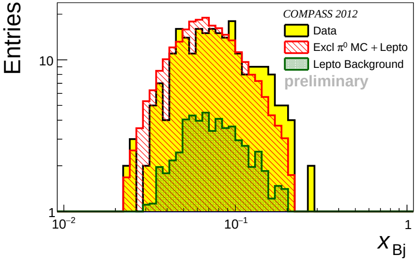


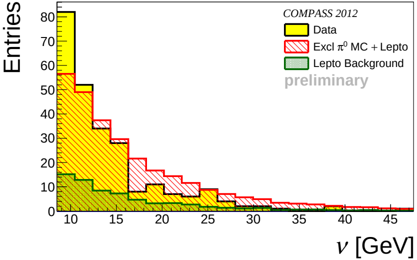
Note 0.65 fm $= \sqrt{2/3} \times 0.8$ fm



Kinematic distributions for exclusive π^0 production







Mean values:

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

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

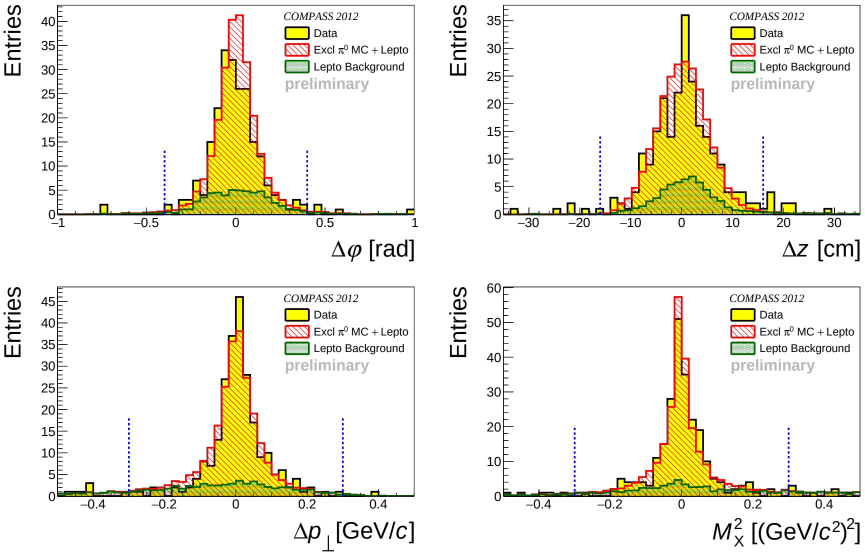
$$< x_{Bj} > = 0.093$$

$$< \varepsilon > = 0.996$$

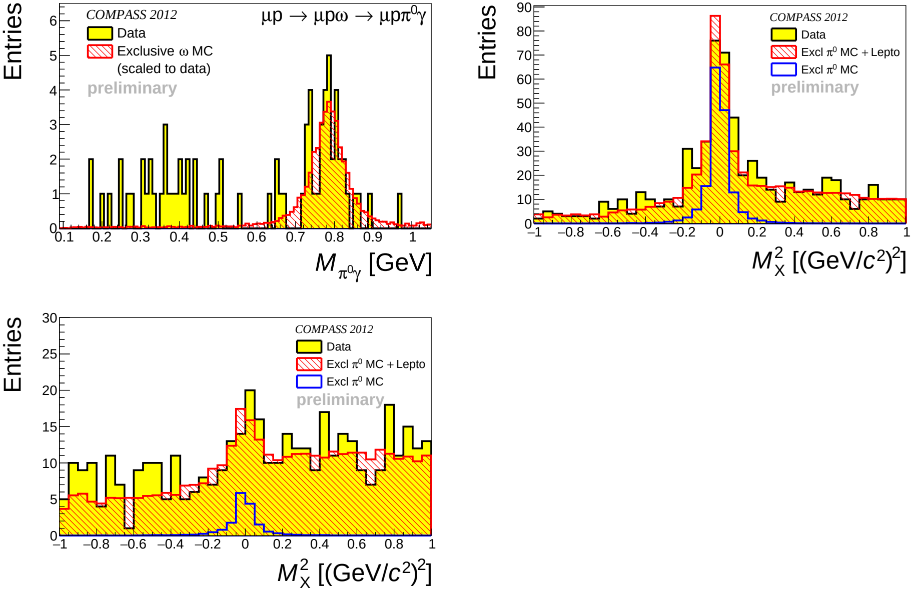
$$< W^2 > = 23\,(\mathrm{GeV}/c^2)^2$$

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

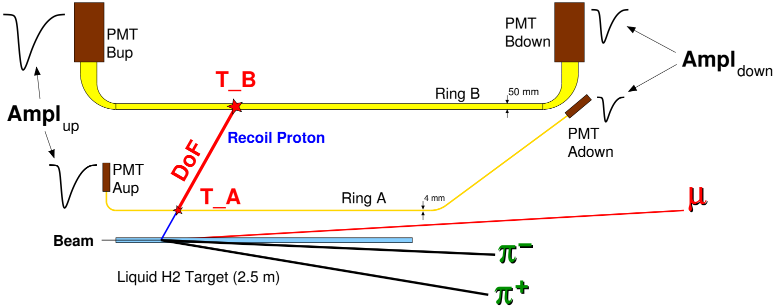
Exclusivity variables for exclusive π^0 production

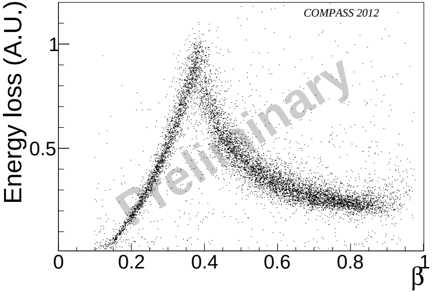


Background treatment for exclusive π^0 production



Recoil particle Measurement in CAMERA





$E_{loss} \sim \sqrt{Ampl_{up} * Ampl_{down}}$

TOF $\rightarrow (t_{up} + t_{down})_{A,B}$

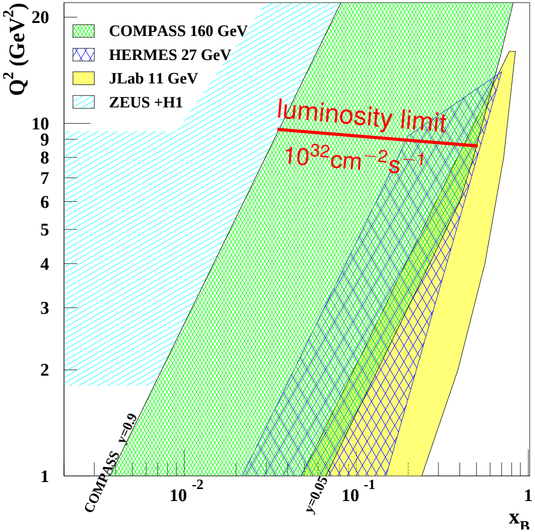
z $\rightarrow t_{up} - t_{down}$

Count rates: $>$ 5 MHz in ring A

$\sim$1 MHz in ring B

What Makes COMPASS Unique?

COMPASS covers the unexplored region between collider (H1+Zeus) and low-energy fixed target (Hermes+JLab) experiments



- μ^+ and μ^- beams
- momentum: $100 - 190$ GeV/c
- beam polarization: 80 %

  opposite for μ^+ and μ^-

- coverage of intermediate x_B

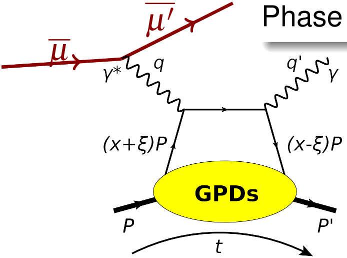
  $\rightarrow$ low x_B: **pure BH**

  useful for normalization

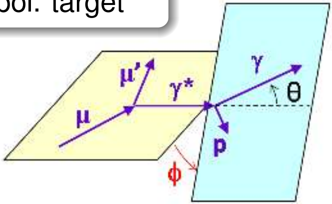
  $\rightarrow$ high x_B: **DVCS predominan**

$\rightsquigarrow$ **unexplored region between ZEUS+H1 and HERMES+JLab**

DVCS: What Can We Learn?



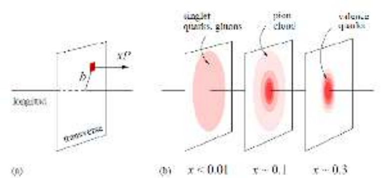
Phase 1: Polarized beam, unpol. target



DVCS dominance at large x_B

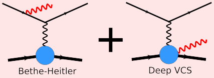
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



$\mathbf{r}_\perp$ parameter from slope of $d\sigma^{DVCS}/dt$

Interference between BH and DVCS



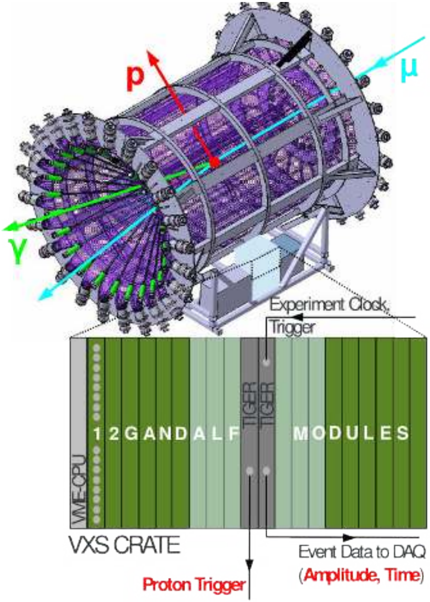
→ "Boost" of DVCS through int. term

Measurement of $Re\mathcal{H}(\xi,t)$ and $Im\mathcal{H}(\xi,t)$ via ϕ-modulation of cross section

- $\mathbf{Re}\mathcal{H}(\xi,\mathbf{t}) = \mathbf{P}\int \mathbf{dx}\ \mathbf{H}(\mathbf{x},\xi,\mathbf{t})/(\mathbf{x}-\xi)$
- $\mathbf{Im}\mathcal{H}(\xi,\mathbf{t}) = \mathbf{H}(\mathbf{x}=\xi,\xi,\mathbf{t})$

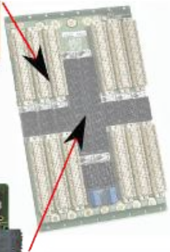
Exp. constrain to GPD H

CAMERA Readout



GANDALF

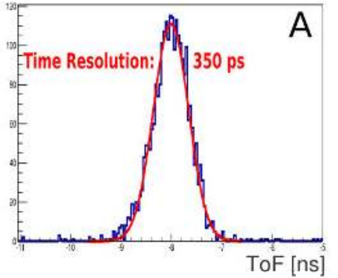
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

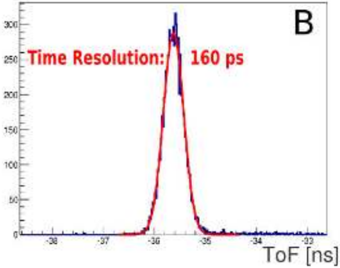


TIGER

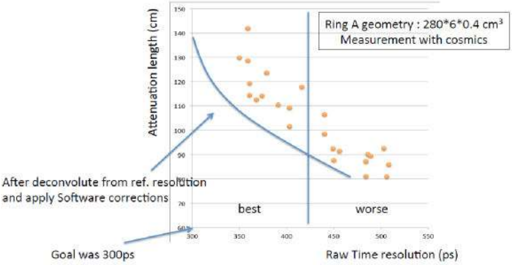
Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express

Time Resolutions Measured with Cosmics

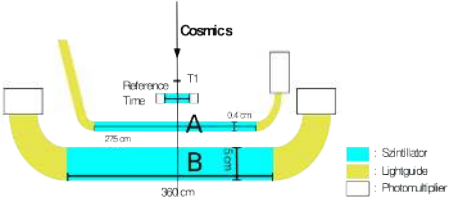




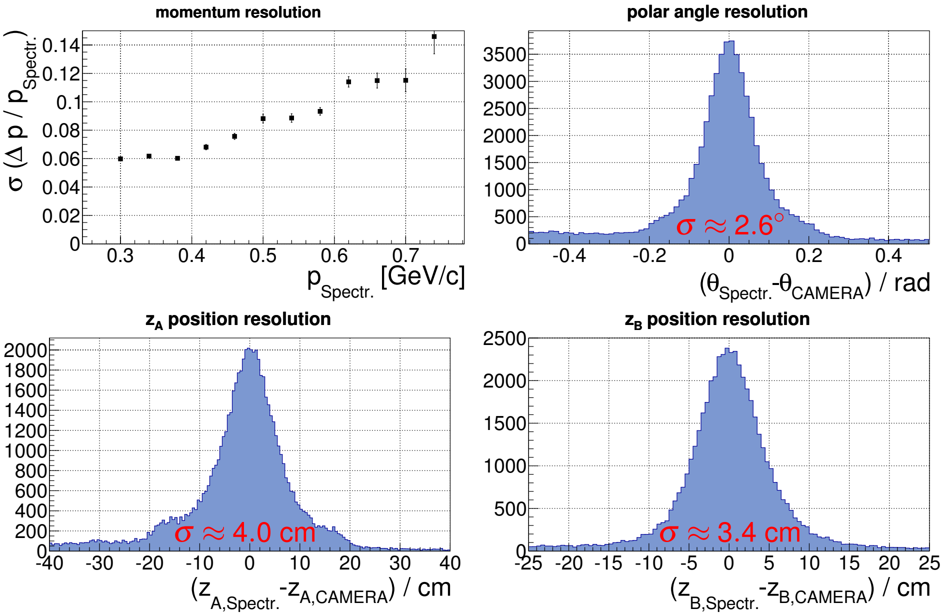
Ring A - performances



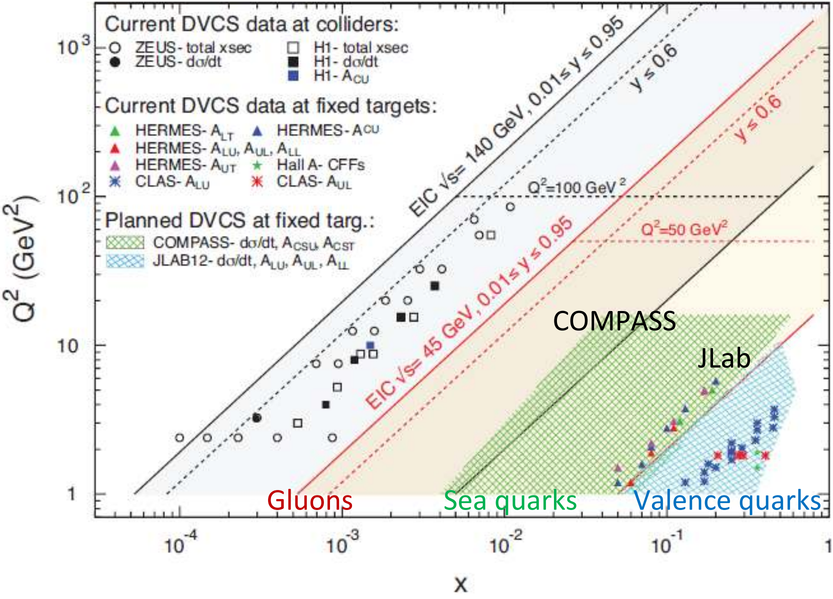
Att length better than 200 cm was expected



Summary of Present CAMERA Performances



Past, Present and Future GPD Experiments



Measurements of DVCS and BH Cross-sections

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu \, d\sigma^{DVCS}_{pol} + e_\mu \, a^{BH} \, \mathcal{Re}\, A^{DVCS} + e_\mu \, P_\mu \, a^{BH} \, \mathcal{Im}\, A^{DVCS}$$

Charge & Spin Difference and Sum:

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim F_1 \, \mathcal{Re}\, \mathcal{H}$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi \quad \text{and} \quad s_1^{Int} \sim F_1 \, \mathcal{Im}\, \mathcal{H}$$

$$c_1^{Int} \propto \mathcal{Re}\left(F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - t/4m^2 F_2 \mathcal{E}\right)$$

NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics

✓only leading twist and LO