Exclusive low-t measurements with muon beams at COMPASS

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on behalf of the COMPASS Collaboration

IWHSS 17, 05/04/2017

SEVENTH FRAMEWORK PROGRAMME

COMPASS

bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung

COMPASS **G**eneralized **P**arton **D**istribution (GPD) program

- Contribution to the nucleon spin puzzle

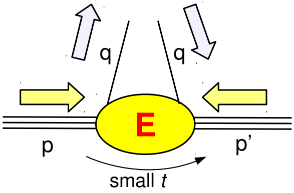
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathscr{L}$$

Jaffe&Manohar Nucl.Phys.B337 (1990)

by constraining GPD H and E

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

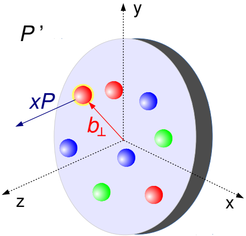
(Phys.Rev.Lett.78 (1997))



- 3D nucleon tomography via GPD H

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

probability interpretation (Burkardt)



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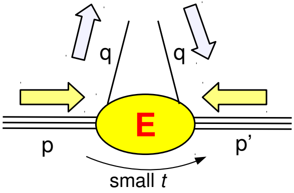

→ Exclusive vector meson production on transversely polarised protons and deuterons

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

- 3D nucleon tomography via GPD H

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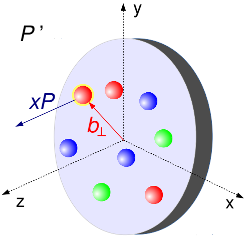
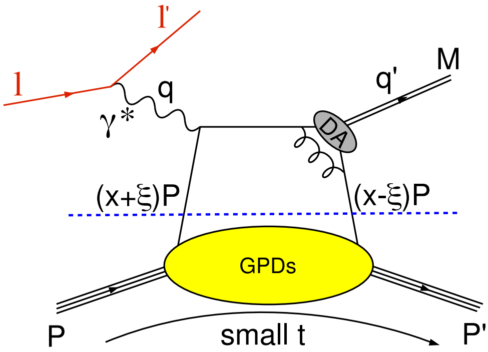


→ t-dependence of pure DVCS x-section on unpolarised protons

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

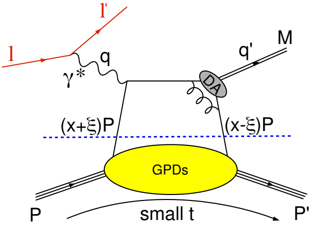
t : 4-momentum transfer to target nucleon (related to $b_\perp$)

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

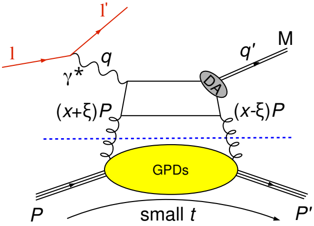
additional non perturbative term:
wave function of meson (DA)

GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution *



Chiral-even GPDs
helicity of parton 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

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

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

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

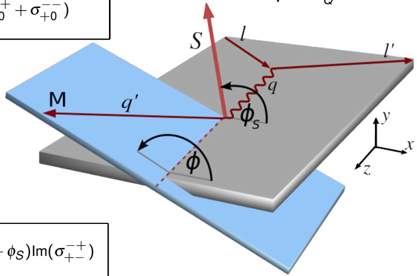
$$\boxed{\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\mathrm{Re}(\sigma_{+-}^{++})-\sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\mathrm{Re}(\sigma_{+0}^{++}+\sigma_{+0}^{--})}$$

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

$$\boxed{\begin{aligned}&-S_L\left[\varepsilon\sin(2\phi)\mathrm{Im}(\sigma_{+-}^{++})+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]\\&+S_LP_l\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\mathrm{Re}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]\end{aligned}}$$

$$\boxed{\begin{aligned}&-S_T\left[\sin(\phi-\phi_S)\mathrm{Im}(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\mathrm{Im}(\sigma_{+-}^{+-})+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\mathrm{Im}(\sigma_{+-}^{-+})\right.\\&\left.+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi_S)\mathrm{Im}(\sigma_{+0}^{+-})+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\mathrm{Im}(\sigma_{+0}^{-+})\right]\end{aligned}}$$

$$\boxed{\begin{aligned}&+S_TP_l\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)\mathrm{Re}(\sigma_{++}^{+-})\right.\\&\left.-\sqrt{\varepsilon(1-\varepsilon)}\cos(\phi_S)\mathrm{Re}(\sigma_{+0}^{+-})-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\mathrm{Re}(\sigma_{+0}^{-+})\right]\end{aligned}}$$



Helicity dependent photoabsorption x-sections and interference terms:

$$\sigma_{mn}^{ij}(x_{Bj},Q^2,t)\propto\sum(M_m^i)(M_n^j)$$

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

$$M_m^i$$

with photon helicity m
and target proton helicity i

HEMP cross section (transverse target polarisation)

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

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

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

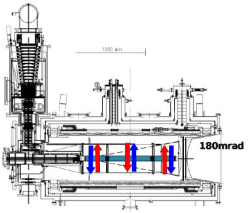
$$\cancel{-S_L\left[\varepsilon\sin(2\phi)\mathrm{Im}(\sigma_{+-}^{++})+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]}$$

$$\cancel{+S_L P_l\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\mathrm{Re}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]}$$

$$-S_T\Big[\sin(\phi-\phi_S)\mathrm{Im}(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\mathrm{Im}(\sigma_{+-}^{+-})+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\mathrm{Im}(\sigma_{+-}^{-+})$$
$$+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi_S)\mathrm{Im}(\sigma_{+0}^{+-})+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\mathrm{Im}(\sigma_{+0}^{-+})\Big]$$

$$+S_T P_l\Big[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)\mathrm{Re}(\sigma_{++}^{+-})$$
$$-\sqrt{\varepsilon(1-\varepsilon)}\cos(\phi_S)\mathrm{Re}(\sigma_{+0}^{+-})-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\mathrm{Re}(\sigma_{+0}^{-+})\Big]$$

transversely plolarised target

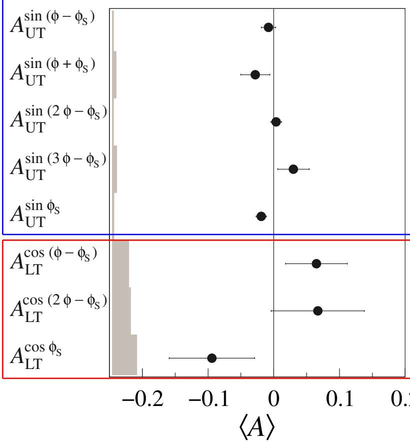


$\Rightarrow$ 5 single spin asymmetries

$\Rightarrow$ 3 double spin asymmetries

Exclusive ρ^0 and ω production on transversely polarised protons and deuterons

Asymmetries for $\mu^+ + p^\uparrow \to \mu^+ + p + \rho^0$



$$A_{UT}^{\sin(\phi-\phi_S)} := \mathrm{Im}(\sigma_{++}^{+-} + \varepsilon\sigma_{00}^{+-})/\sigma_0 \propto -\mathrm{Im}\left[\varepsilon \mathcal{E}_{LL}^{*}\mathcal{H}_{LL} + \mathcal{E}_{TT}^{*}\mathcal{H}_{TT} - \frac{1}{2}\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT}\right],$$

$$A_{UT}^{\sin(\phi+\phi_S)} := \mathrm{Im}(\sigma_{+-}^{+-})/\sigma_0 \propto \mathrm{Im}\left[\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LL}\right],$$

$$A_{UT}^{\sin(2\phi-\phi_S)} := \mathrm{Im}(\sigma_{+-}^{-+})/\sigma_0 \propto -\mathrm{Im}\left[\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}\right],$$

$$A_{UT}^{\sin(3\phi-\phi_S)} := \mathrm{Im}(\sigma_{+0}^{+-})/\sigma_0 = 0,$$

$$A_{UT}^{\sin\phi_S} := \mathrm{Im}(\sigma_{+0}^{-+})/\sigma_0 \propto \mathrm{Im}\left[\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL} - \overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}\right],$$

5 single spin asymmetries

$$A_{LT}^{\cos(\phi-\phi_S)} := \mathrm{Re}(\sigma_{++}^{+-})/\sigma_0 \propto \mathrm{Re}\left[\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT} - 2\mathcal{E}_{TT}^{*}\widetilde{\mathcal{H}}_{TT}\right],$$

$$A_{LT}^{\cos(2\phi-\phi_S)} := \mathrm{Re}(\sigma_{+0}^{+-})/\sigma_0 \propto \mathrm{Re}\left[\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT} - 2\mathcal{E}_{TT}^{*}\widetilde{\mathcal{H}}_{TT}\right],$$

$$A_{LT}^{\cos\phi_S} := \mathrm{Re}(\sigma_{+0}^{-+})/\sigma_0 \propto \mathrm{Re}\left[\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL} - \overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}\right].$$

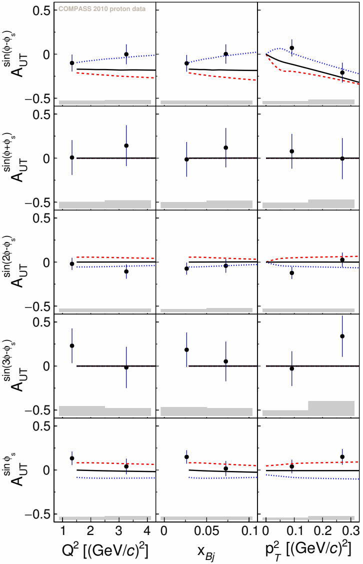
3 double spin asymmetries

$\sim E$, $\sim H$, $\sim H_T$, $\sim \overline{E}_T = 2\widetilde{H}_T - E_T$, $\sim \widetilde{H}$,

σ_0: unpolarised cross section

- Asymmetries compatible with zero, except $A_{UT}^{\sin(\phi_S)}$
- Indication of H_T “transversity GPD” contribution

Azimuthal asymmetries for $\mu^+ + p^\uparrow \rightarrow \mu^+ + p + \omega$



$< x_{Bj} >= 0.049$

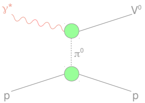
$< Q^2 >= 2.2\,(\mathrm{GeV}/c)^2$

$< p_T^2 >= 0.17\,(\mathrm{GeV}/c)^2$

$< W >= 7.1\,\mathrm{GeV}/c^2$

Comparison to modified GPD model of GK

with π^0 pole exchange added



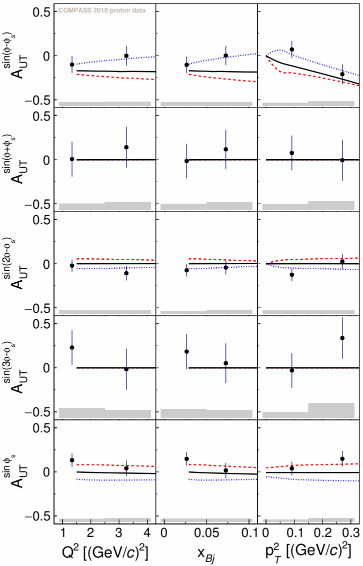
Goloskokov and Kroll (GK) predictions for COMPASS

(private communications)

- no pion pole
- positive $\pi\omega$ transition
- negative $\pi\omega$ transition

- unbinned maximum likelihood method
- **NPB 915 (2017) 454**
- extraction of 8 asymmetries (5 single spin asymmetries shown)

Azimuthal asymmetries for $\mu^+ + p^\uparrow \to \mu^+ + p + \omega$



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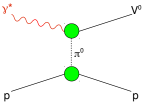

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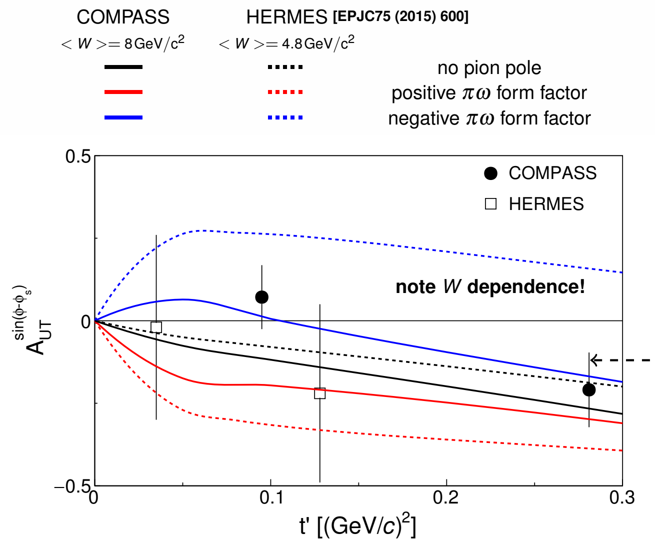
Comparison to HERMES for $\mu^+ + p^\uparrow \rightarrow \mu^+ + p + \omega$



within large errors HERMES data compatible with **all 3 scenarios**

COMPASS uncertainties smaller by a factor **2**

Future measurements at JLab12 expected to resolve the issue **[EPJ A48 (2012) 187]**

HEMP cross section (transverse target polarisation)

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

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

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

$$\cancel{-S_L\left[\varepsilon\sin(2\phi)\mathrm{Im}(\sigma_{+-}^{++})+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]}$$

$$\cancel{+S_LP_l\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\mathrm{Re}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]}$$

$$-S_T\left[\sin(\phi-\phi_S)\mathrm{Im}(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\mathrm{Im}(\sigma_{+-}^{+-})+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\mathrm{Im}(\sigma_{+-}^{-+})\right.$$
$$\left.+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi_S)\mathrm{Im}(\sigma_{+0}^{+-})+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\mathrm{Im}(\sigma_{+0}^{-+})\right]$$

$$+S_TP_l\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)\mathrm{Re}(\sigma_{++}^{+-})\right.$$
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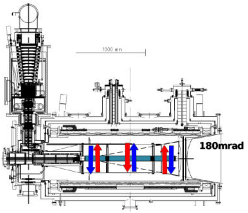
transversely plolarised target



HEMP cross section (unpolarised target)

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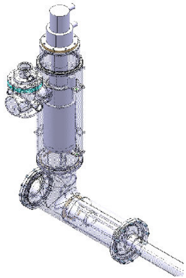
$$\xcancel{\left.+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi_S)\mathrm{Im}(\sigma_{+0}^{+-})+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\mathrm{Im}(\sigma_{+0}^{-+})\right]}$$

$$\xcancel{+S_TP_l\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)\mathrm{Re}(\sigma_{++}^{+-})\right.}$$

$$\xcancel{\left.-\sqrt{\varepsilon(1-\varepsilon)}\cos(\phi_S)\mathrm{Re}(\sigma_{+0}^{+-})-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\mathrm{Re}(\sigma_{+0}^{-+})\right]}$$

2.5 m long liquid H_2 target



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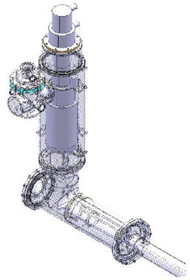
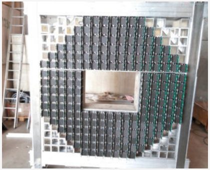
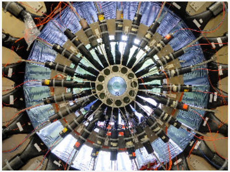


COMPASS II setup



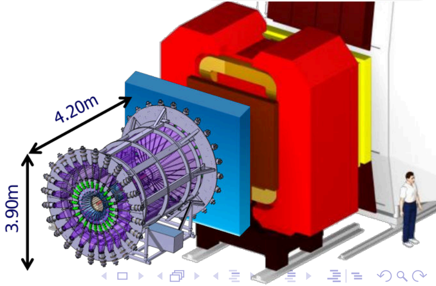
ECAL0 Calorimeter

Shashlik modules
+ MAPD readout
$2 \times 2\,\mathrm{m}^2$, 2200 channels

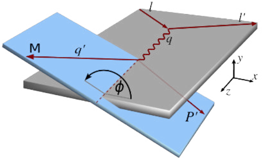


Target ToF system

24 inner & outer scintillators
1 GHz GANDALF readout
goal **310 ps** ToF resolution



HEMP cross section (unpolarised target)
Charge-Spin-Sum



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

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

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

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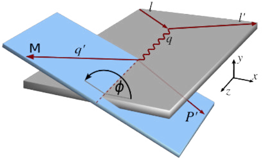

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$$\boxed{\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \varepsilon \frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \varepsilon \cos(2\phi) \frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} + \sqrt{\varepsilon(1+\varepsilon)} \cos(\phi) \frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}}$$

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

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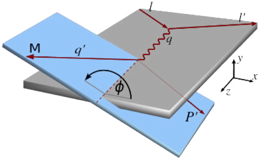
Charge-Spin-Sum



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

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

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

study ϕ dependence!

after integration in ϕ:

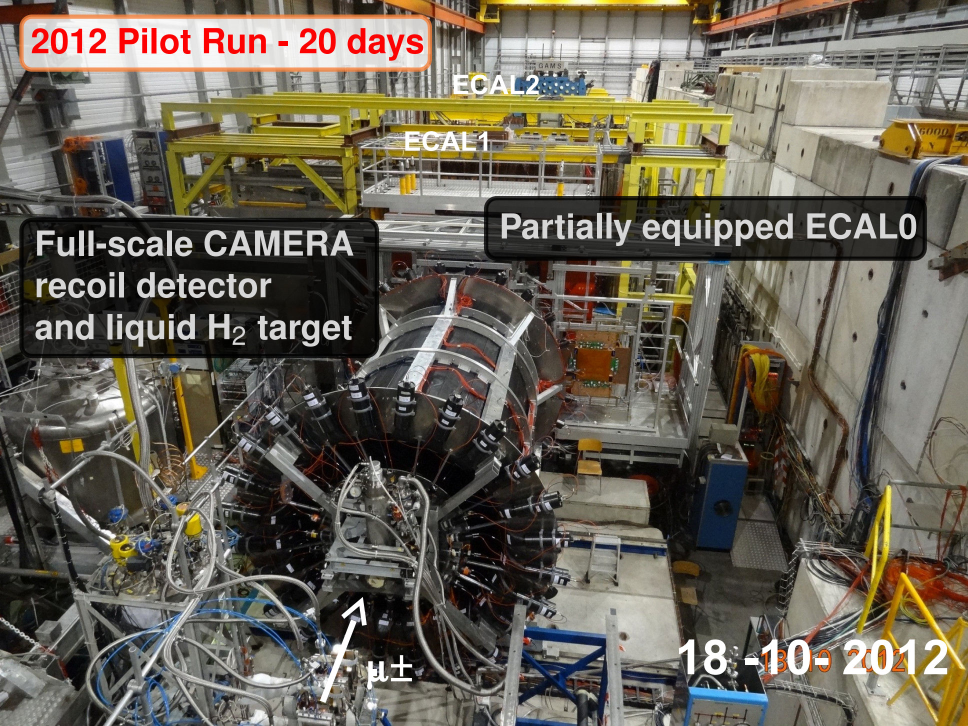
$$\boxed{\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \varepsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t}}$$

study t dependence!

virtual photon polarisation:

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

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


2012 Pilot Run - 20 days
GAMS
ECAL2
ECAL1
Partially equipped ECAL0
Full-scale CAMERA recoil detector and liquid H_2 target
$\mu^\pm$
18 -10- 2012

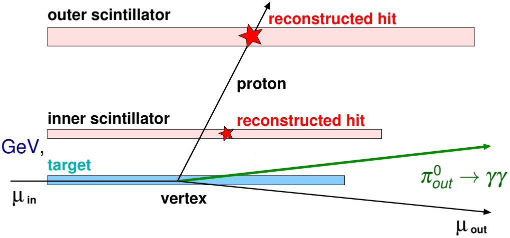
Exclusive π^0 production event selection

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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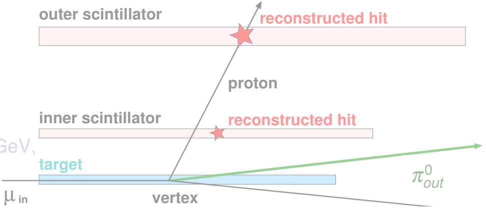
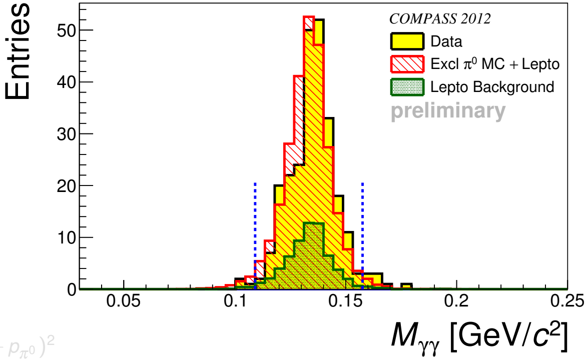


Exclusivity conditions:

- 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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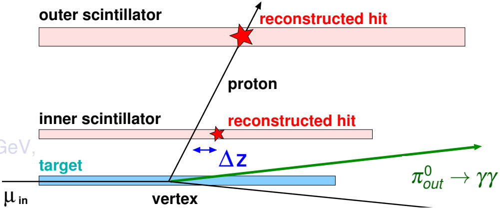

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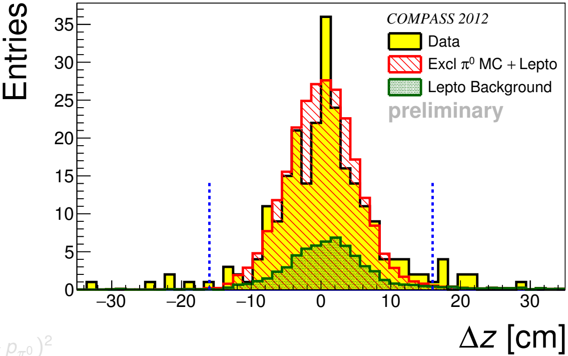

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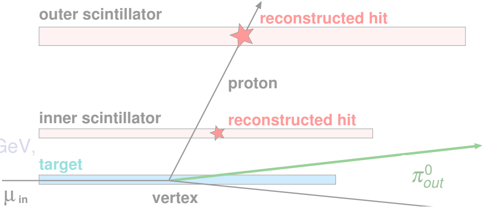

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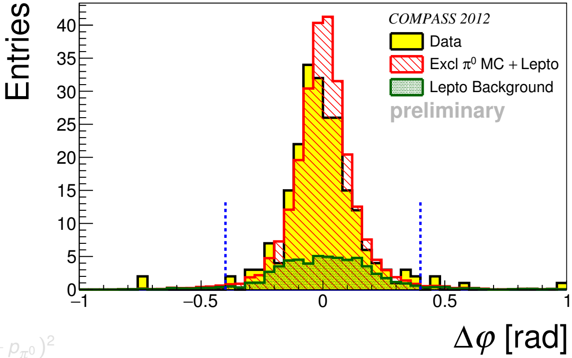

Exclusive π^0 production event selection

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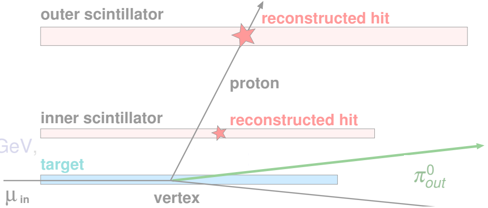

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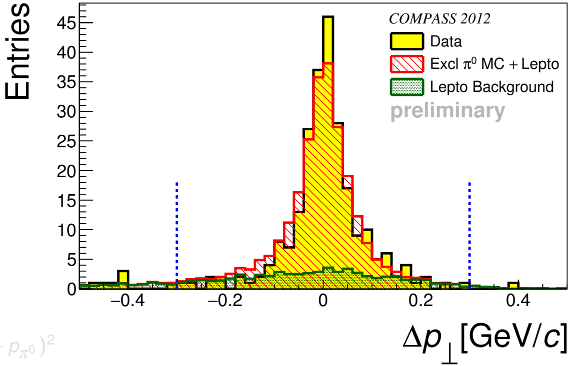

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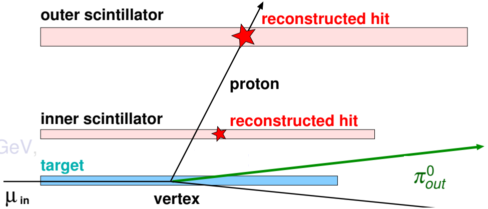

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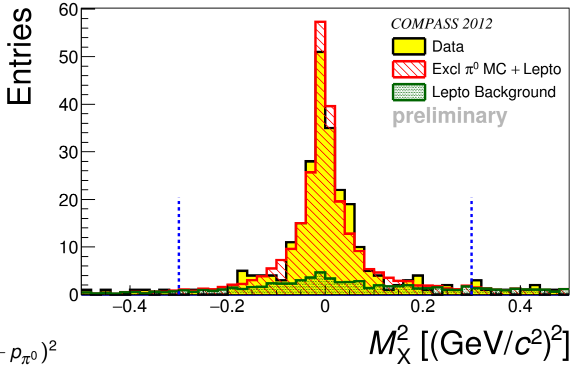
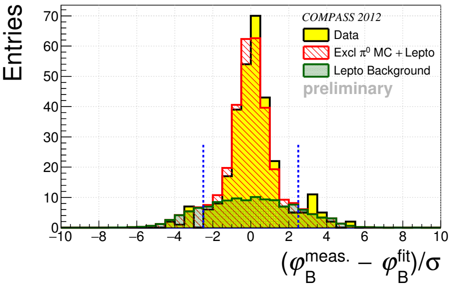
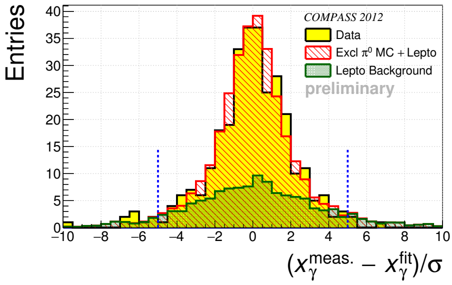


Kinematically constrained fit for exclusive π^0

- 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

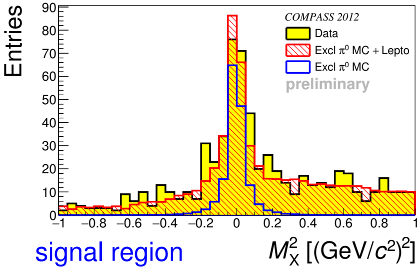
$\Rightarrow$ most accurate determination of t
$\Rightarrow$ good separation between signal and background



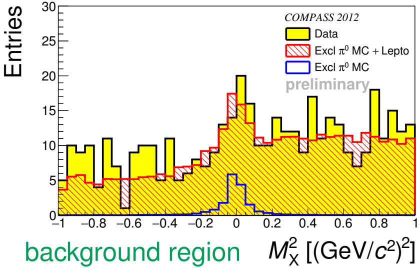


SIDIS background estimation

- 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

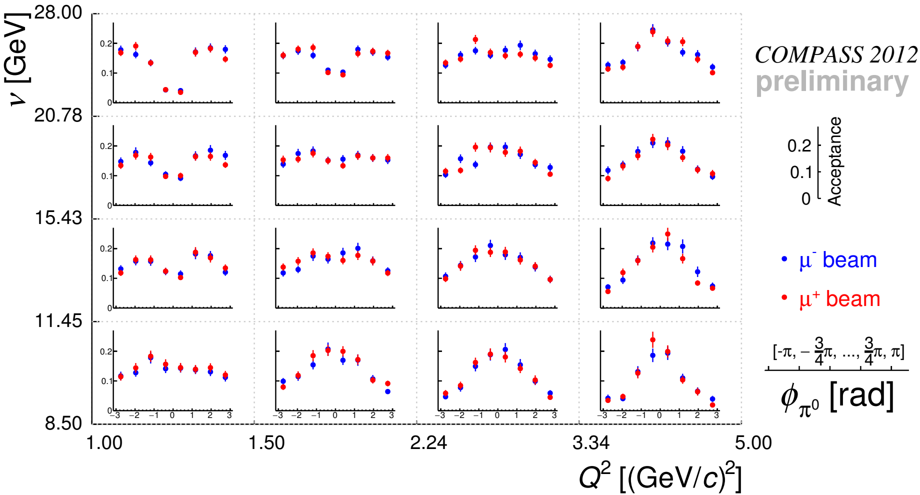


signal region



background region

COMPASS acceptance for exclusive π^0 production



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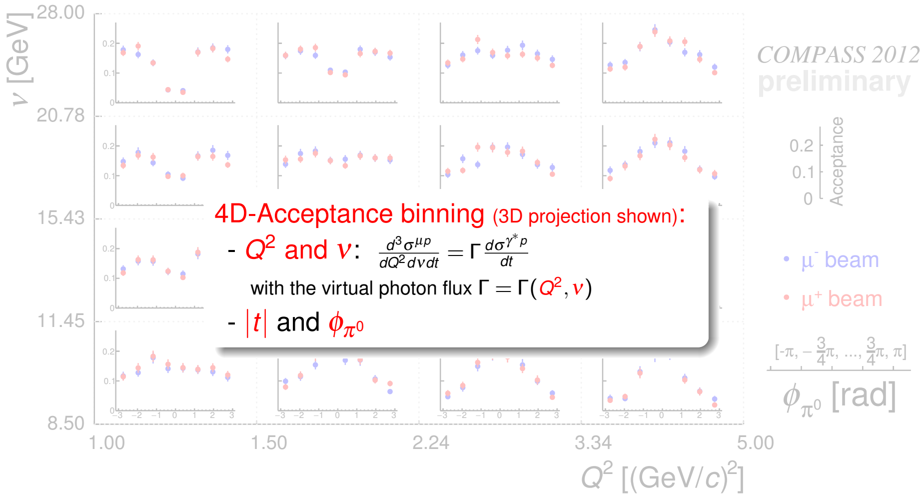
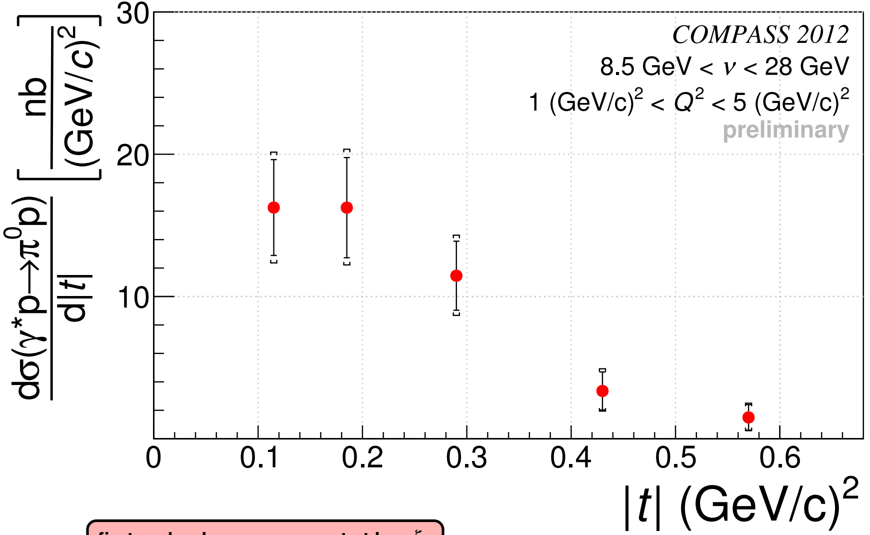


4D-Acceptance binning (3D projection shown):

- 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 $|t|$

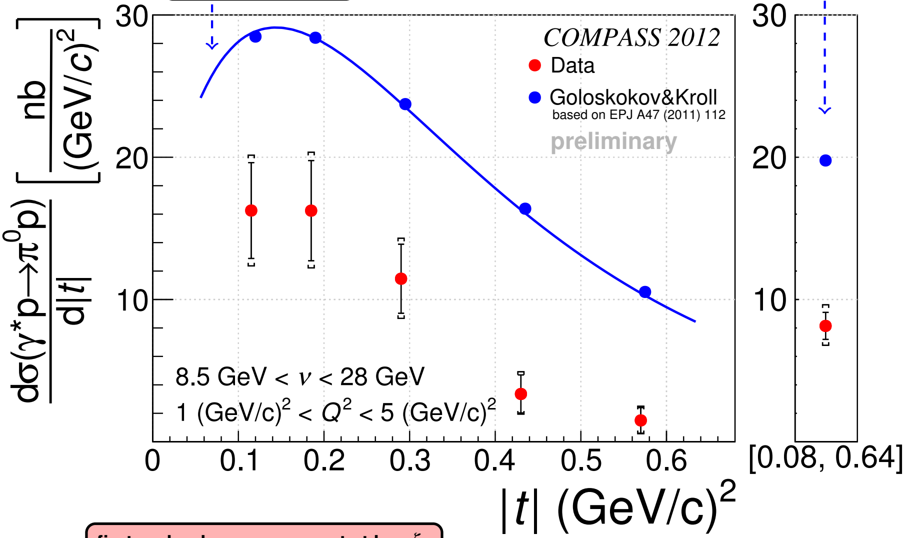


first and only measurement at low ξ

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

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

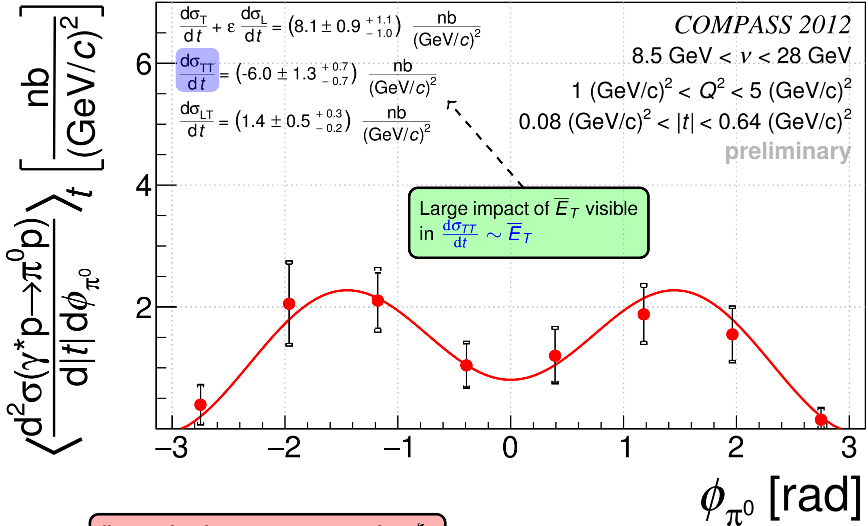
a factor of ~ 2 discrepancy to Goloskokov&Kroll model



first and only measurement at low ξ

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

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



first and only measurement at low ξ

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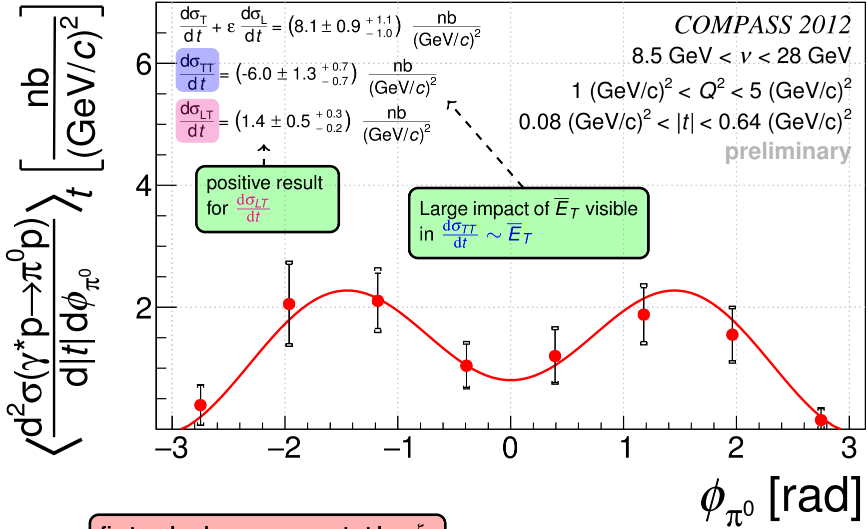
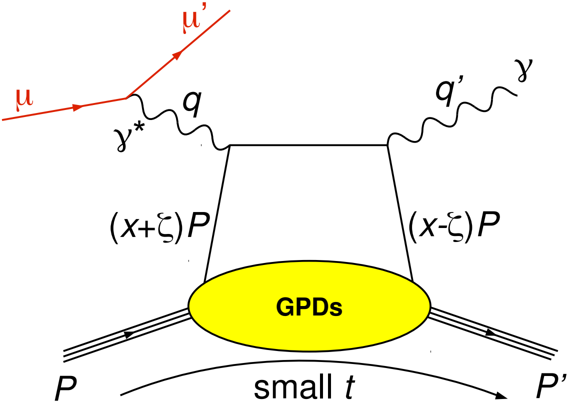
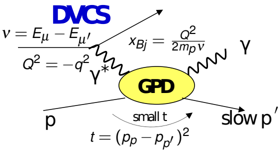


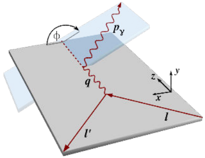
first and only measurement at low ξ

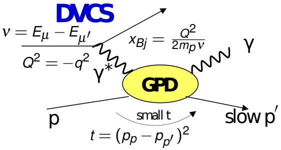
Deeply Virtual Compton Scattering

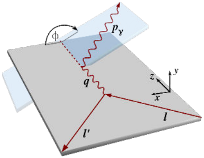


t-dependence of pure DVCS x-section on unpolarised protons

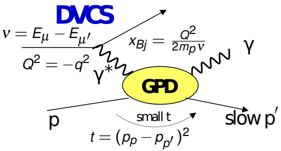

DVCS
$\nu = E_\mu - E_{\mu'}$
$Q^2 = -q^2$
$x_{Bj} = \frac{Q^2}{2m_p\nu}$
γ
γ*
GPD
p
small t
slow p′
$t = (p_p - p_{p'})^2$

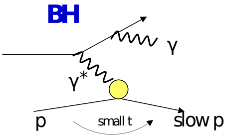

ϕ
p_γ
q
z
y
x
l
l′

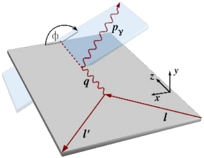




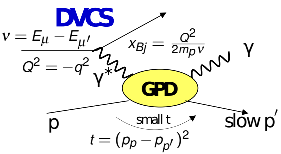
$$d\sigma \propto \underbrace{\left|T_{DVCS}\right|^2}_{\text{bilinear combination of GPDs}}$$

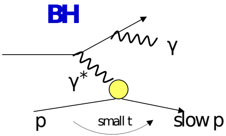


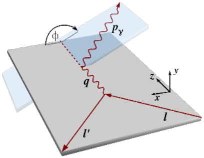




$$d\sigma \propto \underbrace{\left|T_{DVCS}\right|^2}_{\text{bilinear combination of GPDs}} + \underbrace{\left|T_{BH}\right|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$







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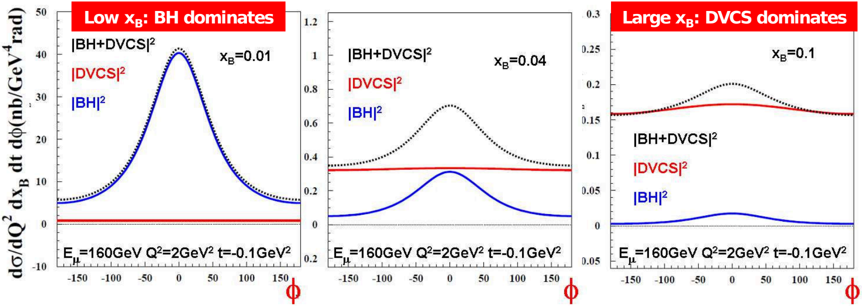

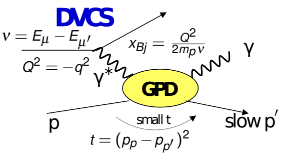

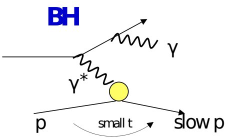

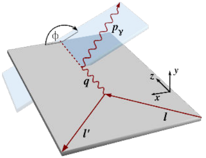

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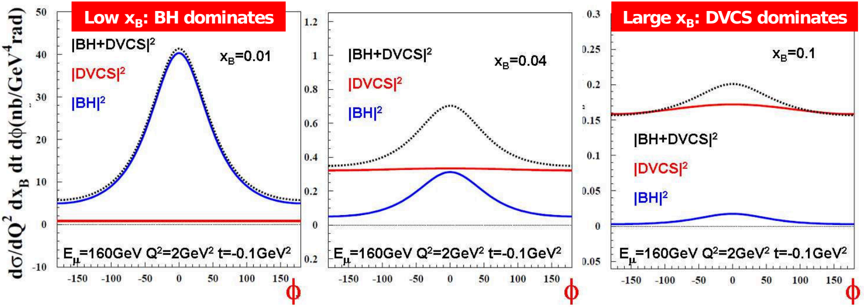
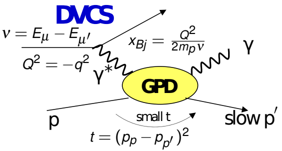
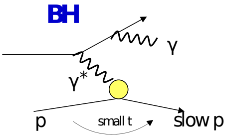
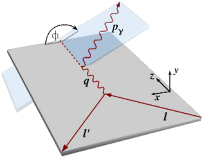


reference yield of
almost pure
Bethe-Heitler







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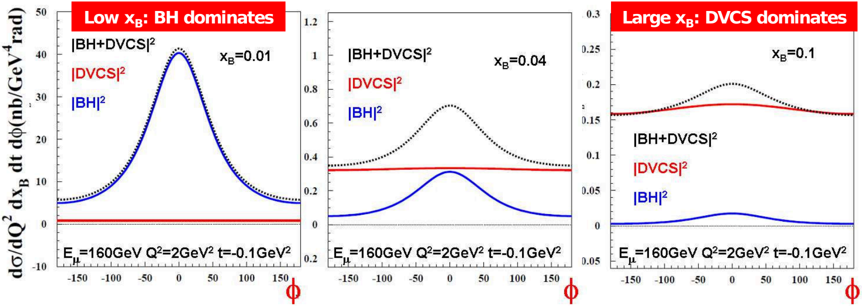
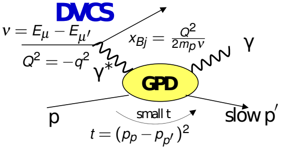
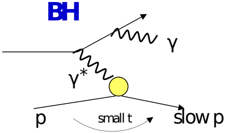
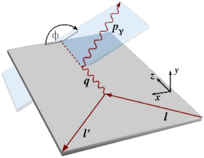


reference yield of almost pure Bethe-Heitler

Study DVCS with:
$\mathrm{Re}(\mathcal{T}^{DVCS})$ & $\mathrm{Im}(\mathcal{T}^{DVCS})$
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$







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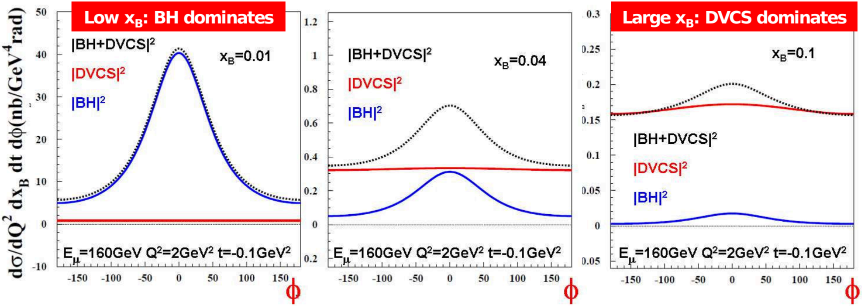
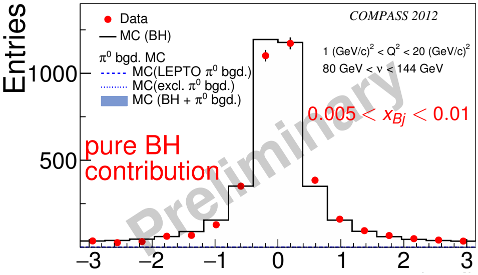


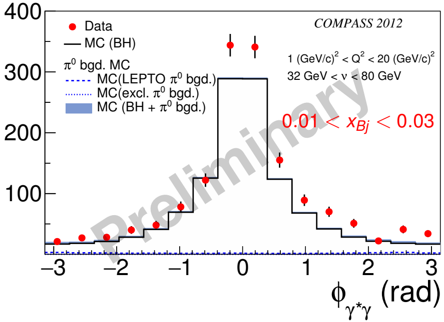
reference yield of almost pure Bethe-Heitler

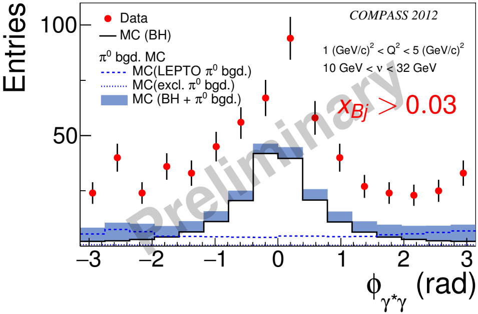
Study DVCS with:
Re(T^{DVCS}) & Im(T^{DVCS})
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$

Transverse Imaging:
$d\sigma^{DVCS}/dt$
via $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$

Exclusive γ Azimuthal Distributions for DVCS







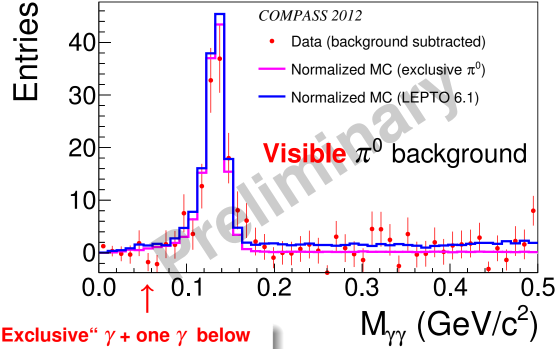
- normalisation of BH Monte Carlo to the data using beam flux
- dominant BH process at small x_{Bj} clearly visible
- π^0 background contributing at large x_{Bj}
- clear excess of DVCS at large x_{Bj}

π^0 Background Estimation

Major background source for exclusive photon events

Two cases:

- **Visible** (both γ detected, easy to reject)
- **Invisible** (one γ “lost”, estimated with MC)



„Exclusive“ γ + one γ below DVCS production threshold

Invisible π^0 background:

Semi inclusive — LEPTO MC

or

exclusive — HEPGen++ MC (Golosgokov & Kroll model)

π^0 contribution **normalized** to visible $M_{\gamma\gamma}$ peak from real data

Transverse Nucleon Imaging at $x_{Bj} > 0.03$

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

$$S_{CS,U} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I$$

note:

$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS} \cos\phi_{\gamma^*\gamma} + c_2^{DVCS} \cos 2\phi_{\gamma^*\gamma}$

$\mathrm{Im}\, I \propto s_1^I \sin\phi_{\gamma^*\gamma} + s_2^I \sin 2\phi_{\gamma^*\gamma}$

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$$S_{CS,U} \propto d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I$$

$$S_{CS,U} \propto c_0^{DVCS}$$

$\Rightarrow$ PURE DVCS CONTRIBUTION

note:

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + \cancel{c_1^{DVCS} \cos\phi_{\gamma^*\gamma}} + \cancel{c_2^{DVCS} \cos 2\phi_{\gamma^*\gamma}}$$

$$\cancel{\mathrm{Im}\, I \propto s_1^I \sin\phi_{\gamma^*\gamma} + s_2^I \sin 2\phi_{\gamma^*\gamma}}$$

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- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
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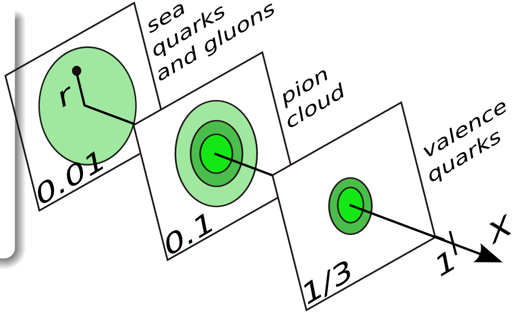
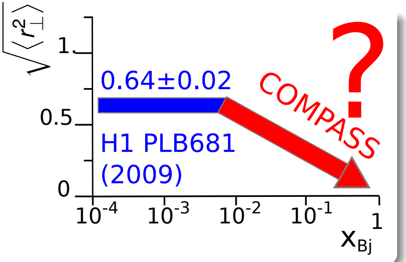
- Integrate over $\phi_{\gamma^*\gamma}$

$$\frac{d\sigma^{DVCS}}{d|t|} \propto e^{-B|t|}; \; < r_\perp^2 > \underset{\text{at small } x_{Bj}}{\sim} 2B(x_{Bj})$$





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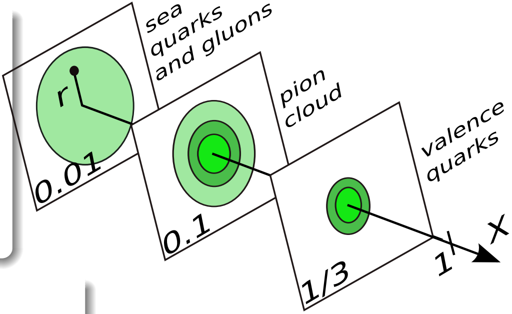
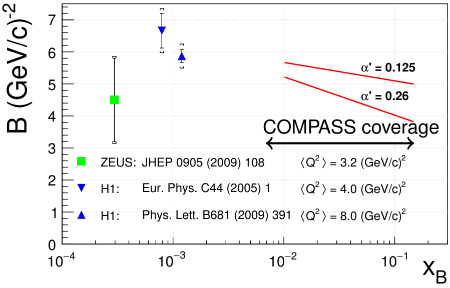
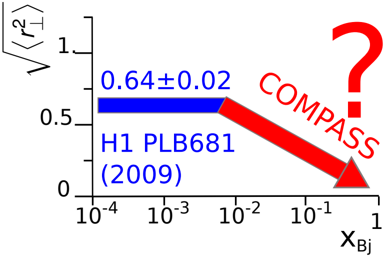
at small x_{Bj}



$B(x_{Bj}) = b_0 + 2\alpha' \ln(x_0/x_{Bj})$
(inspired by Regge Phenomenology)





Transverse Nucleon Imaging at $x_{Bj} > 0.03$

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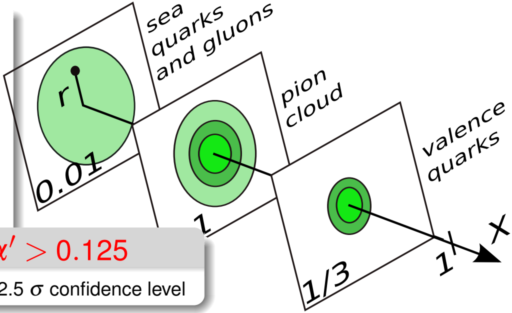
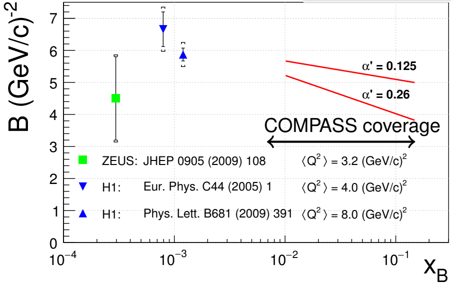
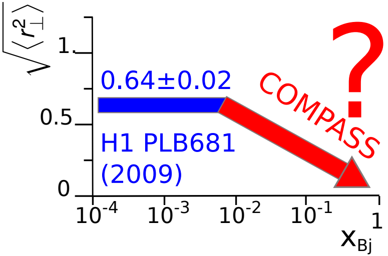


Measure $\alpha' > 0.125$

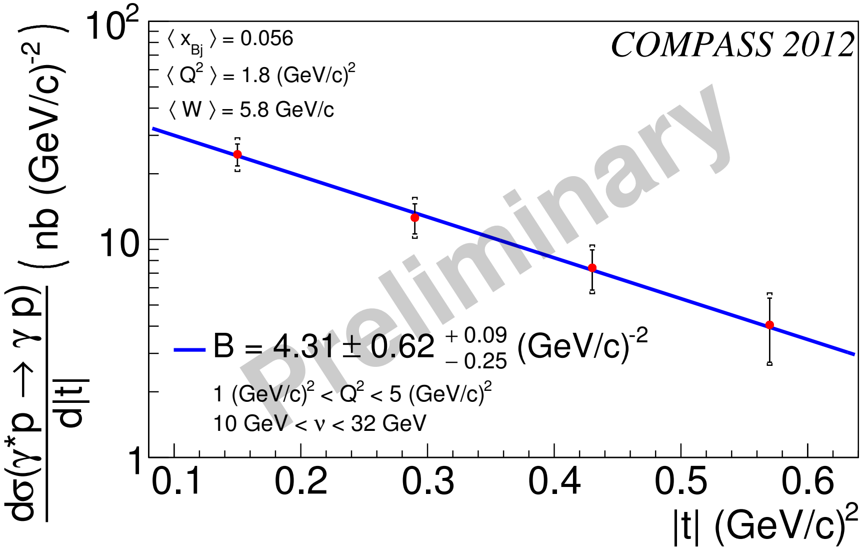
with more than 2.5 σ confidence level

$B(x_{Bj}) = b_0 + 2\alpha' \ln$
(inspired by Regge Pheno...)

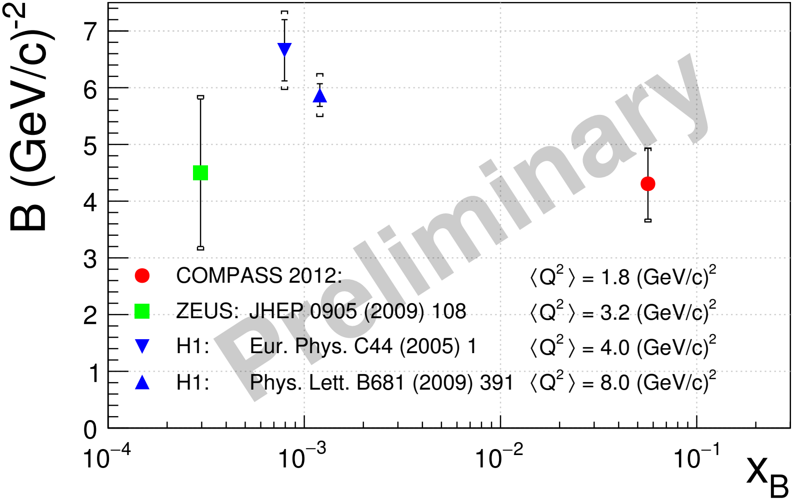




DVCS x-section and t-slope extraction

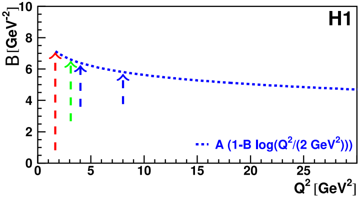


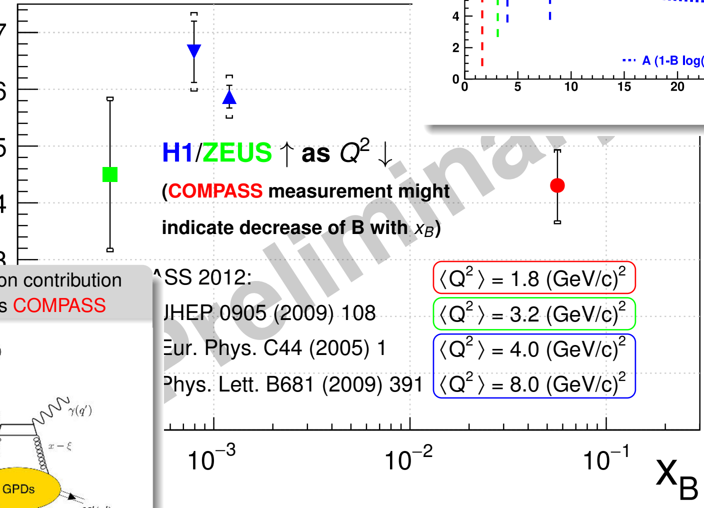
Comparison with HERA



Comparison with HERA

H1: “B increases as Q^2 decreases”

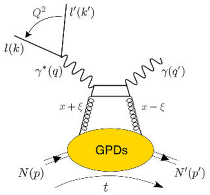




H1/ZEUS $\uparrow$ as Q^2 $\downarrow$

(COMPASS measurement might indicate decrease of B with x_B)

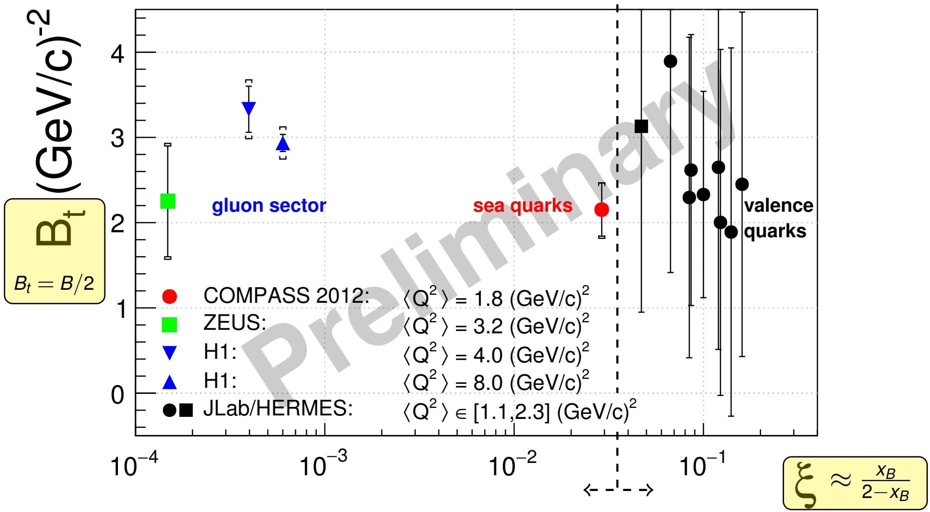
but: large gluon contribution at H1/ZEUS vs COMPASS



Comparison with HERA + JLab/HERMES

Model independent extraction
(from x-section measurements)
$\sigma \propto e^{Bt} \propto \mathcal{H}_{Im}^2 + \mathcal{H}_{Re}^2 \approx \mathcal{H}_{Im}^2 \propto e^{2B_t t}$

Self consistent extraction
$\mathcal{H}_{Im}(\xi,t) = H_+(\xi,\xi,t) \propto e^{B_t t}$
[Phys. Rev. D 95, 011501(R)]

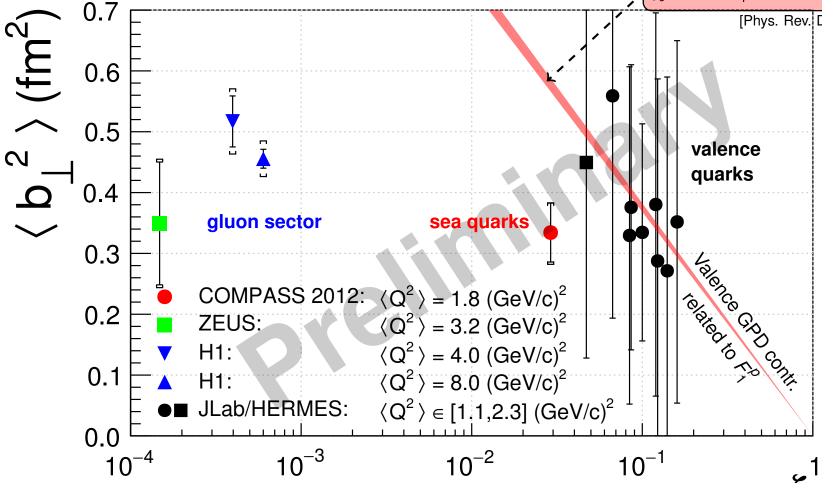


Nucleon tomography

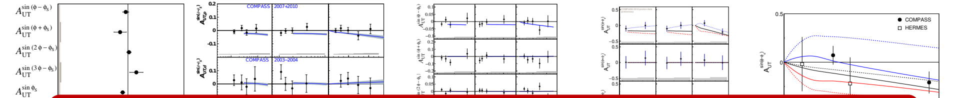
ansatz for the valence GPD $H\_$ at $\xi = 0$:
$H\_(x, \xi = 0, t) = \sum_q e_q q_v(x) e^{B_0(x)t}$
with Regge type B_0:
$B_0(x) = a_B \ln(1/x)$
a_B constraint to F_1^p via first moment:
$\int_0^1 dx\, H\_ = F_1^p$

nucleon radius: $< b_\perp^2 > (X) \approx 4\hbar^2 B_t(X)$
(*up to small but model dependent corrections*)

[Phys. Rev. D 95, 011501(R)]

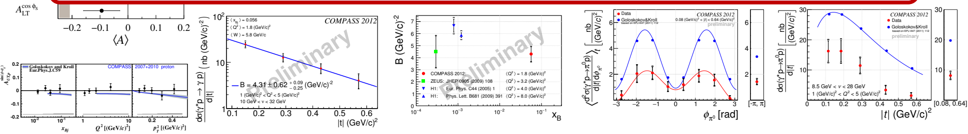


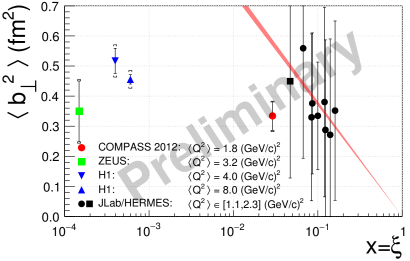
$< b_\perp^2 >$ **"to be compared to"** $4 \frac{d}{dt} F_1^p|_{t=0} = (0.44 \pm 0.01)\,\text{fm}^2 \neq 6 \frac{d}{dt} G_E^p|_{t=0}$

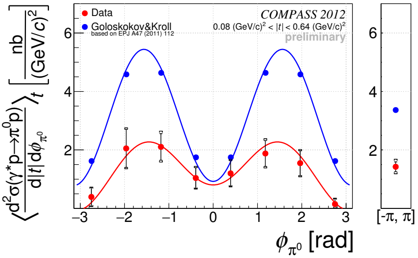


Summary:

- 5 single and 3 double spin asymmetries from exclusive ρ^0 and ω production on polarised protons and deuterons
- exclusive π^0 production cross section for a proton target
- t-dependance of pure DVCS cross section on proton target
- extraction of SDMEs upcoming







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Near future:

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

  $\Rightarrow$ GPD H extraction (real and imaginary part in case of DVCS)

Transverse imaging at COMPASS

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

$B(x_B) = ½ < r_\perp^2(x_B) >$

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

Transverse size of the nucleon

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

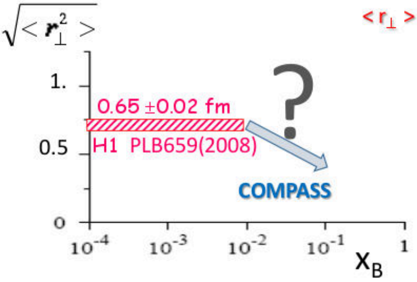
related to $½ < b_\perp^2(x_B) >$

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

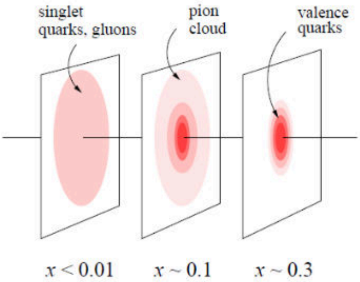
Impact Parameter Representation

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

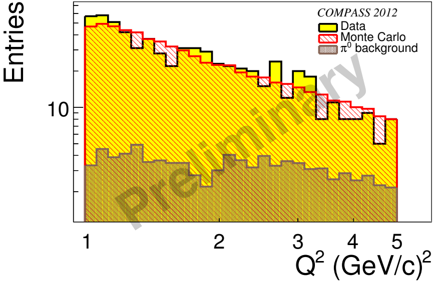
$< r_\perp > \sim < b_\perp > / (1-x)$

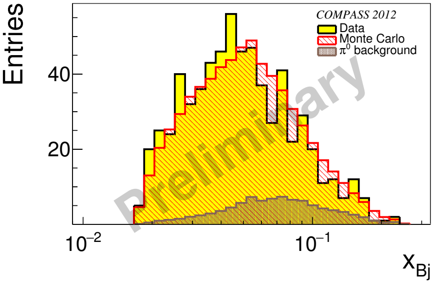


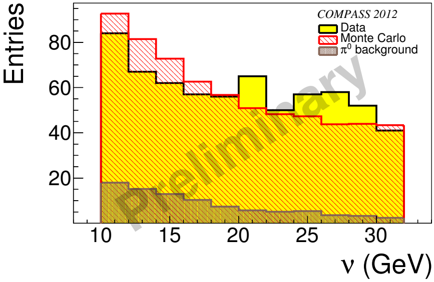
Note 0.65 fm = $\sqrt{2/3} \times 0.8$ fm



Kinematic distributions for DVCS







Q^2 and ν (resp. x_{Bj}) after kinematic fit!

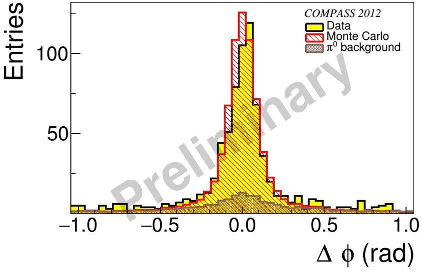
Monte Carlo prediction (the sum is shown)

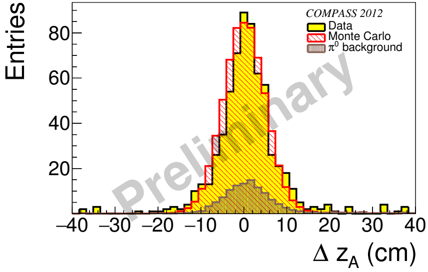
-(DVCS/BH): based on phenomenological model of DVCS x-section*

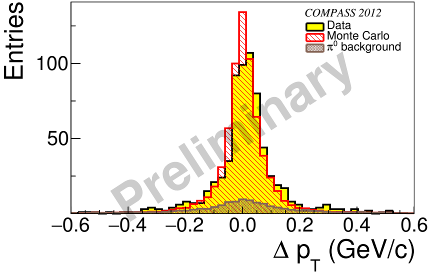
-π^0: parametrisation* linked to Golosgokov & Kroll + LEPTO (shown seperately)

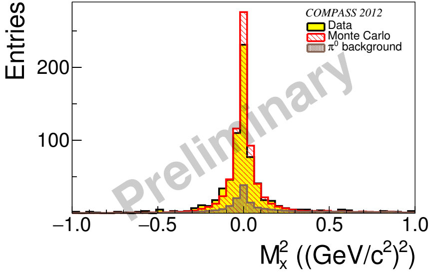
*HEPGen++: Andrzej Sandacz, Christopher Regali

Exclusivity variables for DVCS

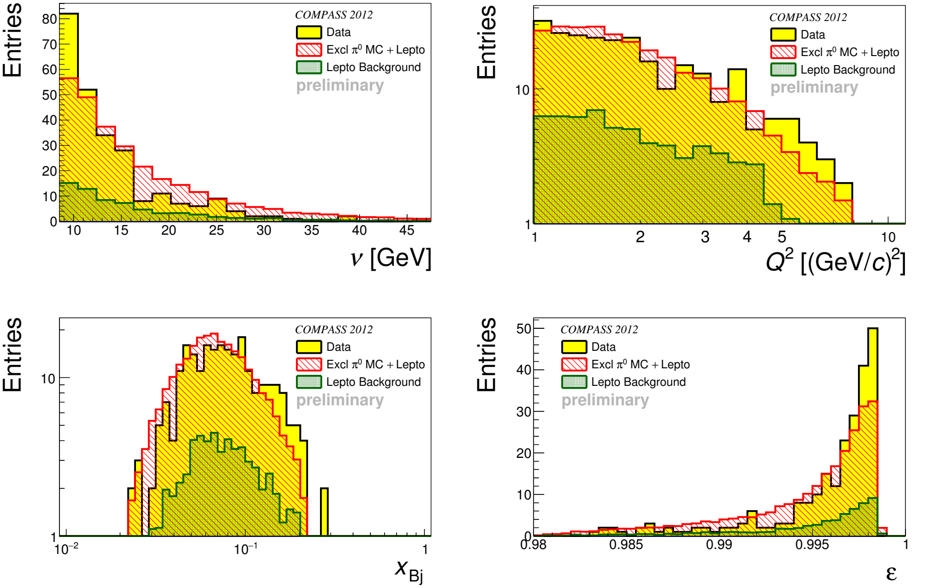




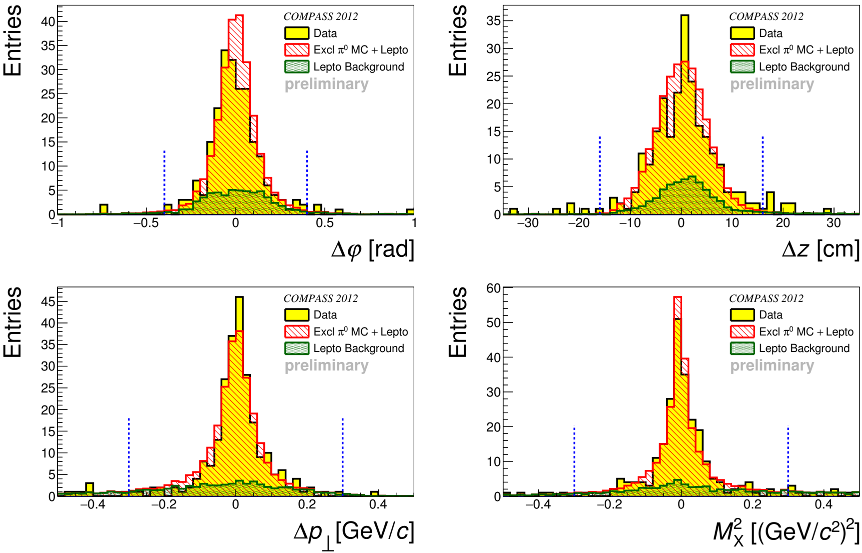




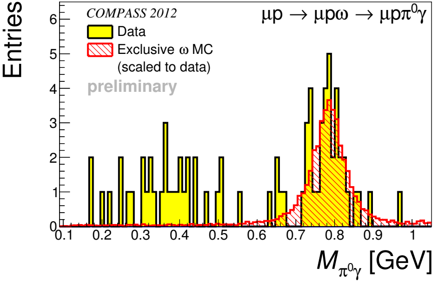
Kinematic distributions for exclusive π^0

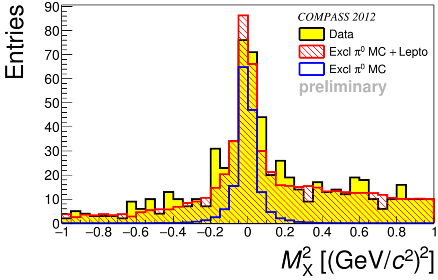


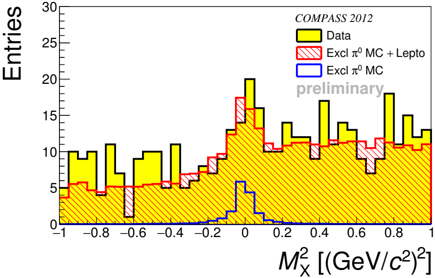
Exclusivity variables for exclusive π^0



Background treatment for exclusive π^0



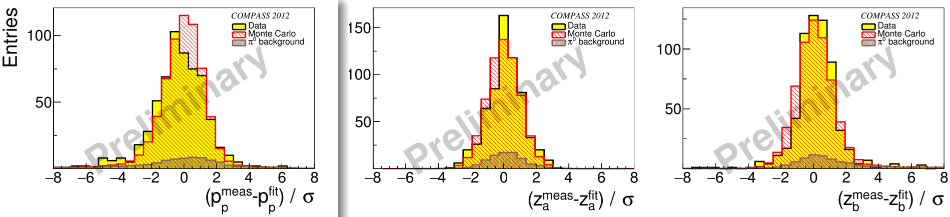




Kinematically constrained fit for DVCS

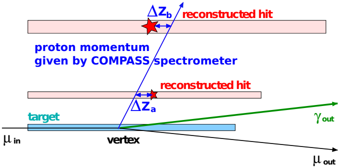
- constrained χ^2 minimisation with NDF=7
- full 4-momentum conservation of the reaction $\mu p \to \mu p \gamma$
- vertex constraints for μ,μ' and p' included in the fit

$\Rightarrow$ most accurate determination of t

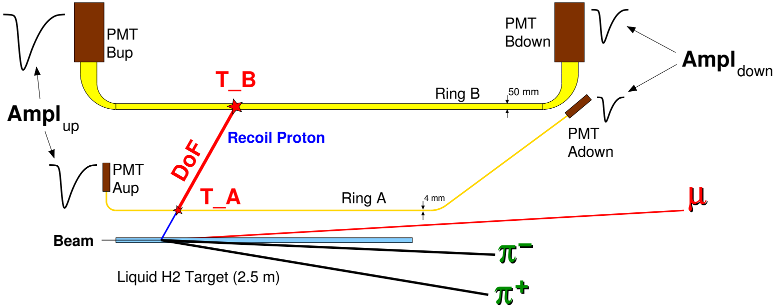


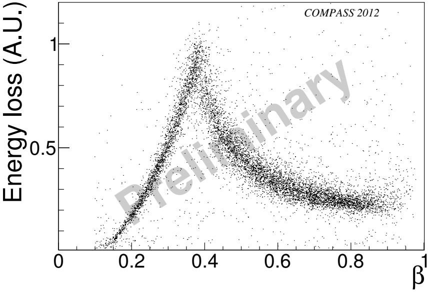
recoil proton momentum

recoil proton direction



Recoil particle Measurement in CAMERA





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

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

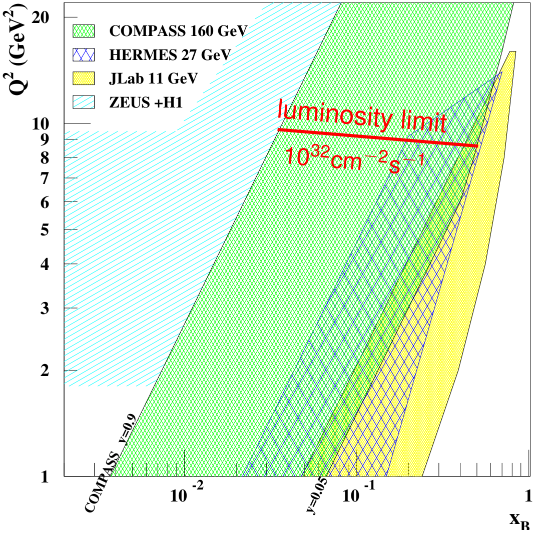
$$\textbf{z} \rightarrow t_{up} - t_{down}$$

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

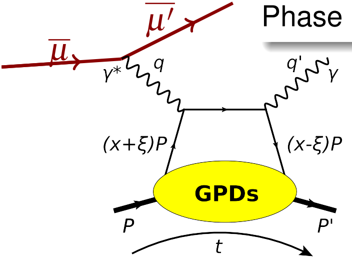


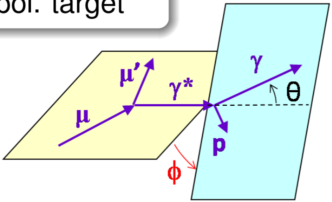
- μ^+ and μ^- beams
- momentum: $100 - 190\,\mathrm{GeV}/c$
- beam polarization: 80 %
  opposite for μ^+ and μ^-
- coverage of intermediate x_B
  $\rightarrow$ low x_B: **pure BH**
  useful for normalization
  $\rightarrow$ high x_B: **DVCS predominar**

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

DVCS: What Can We Learn?

Phase 1: Polarized beam, unpol. target

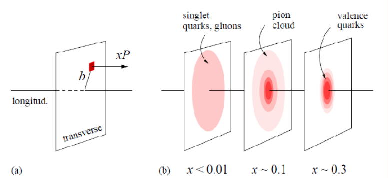




DVCS dominance at large x_B

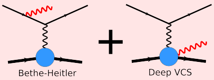
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



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

Interference between BH and DVCS



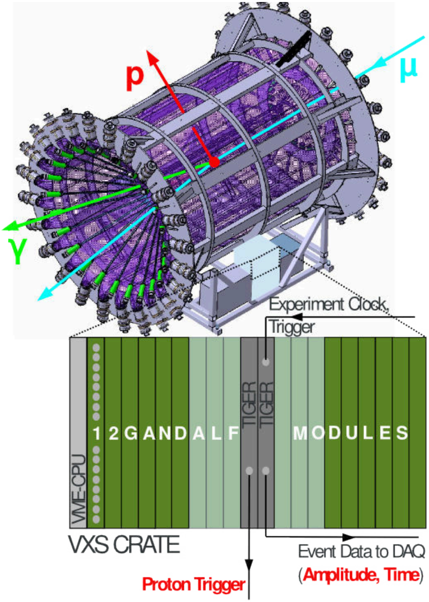
→ "Boost" of DVCS through int. term

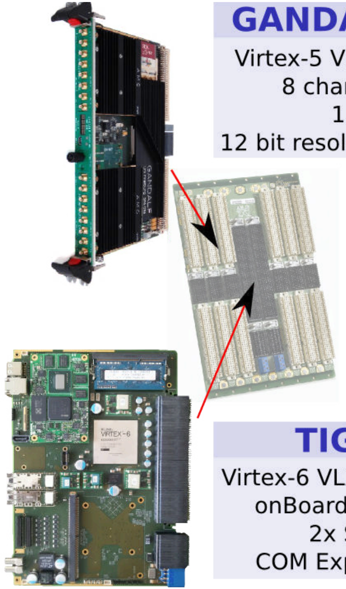
Measurement of $Re\mathscr{H}(\xi,t)$ and $Im\mathscr{H}(\xi,t)$ via ϕ-modulation of cross section

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

Exp. constrain to GPD H

CAMERA Readout





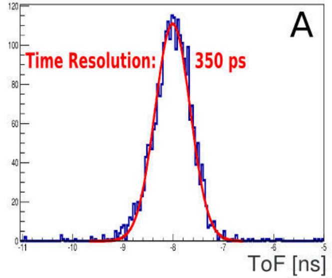
GANDALF

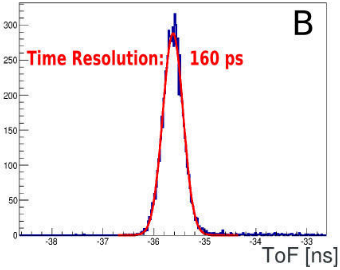
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

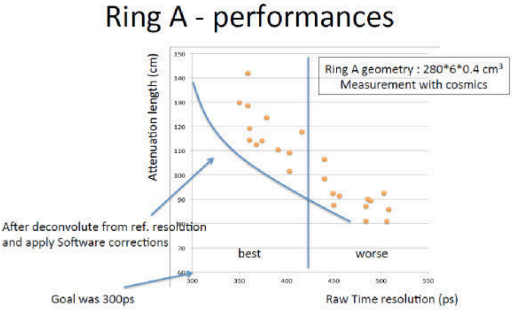
TIGER

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

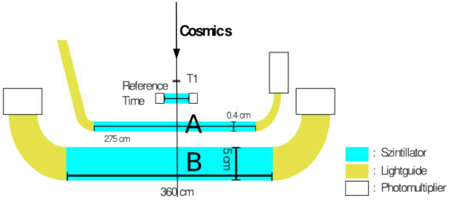
Time Resolutions Measured with Cosmics





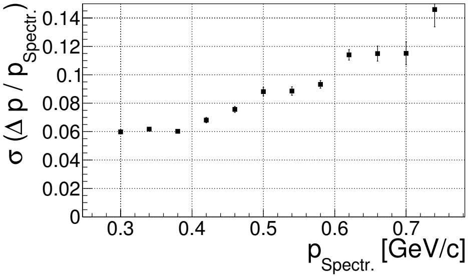


Att length better than 200 cm was expected

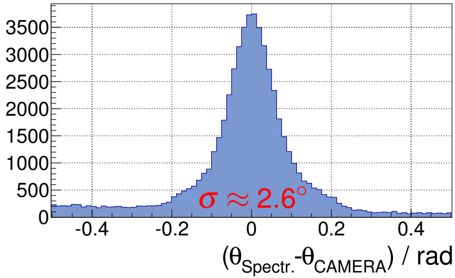


Summary of Present CAMERA Performances

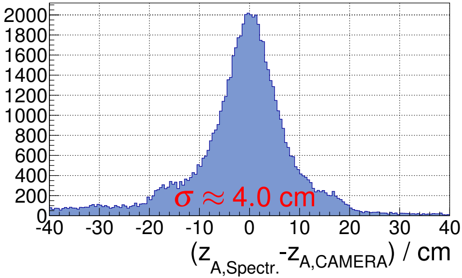
momentum resolution



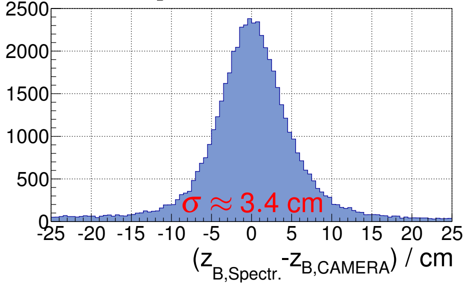
polar angle resolution



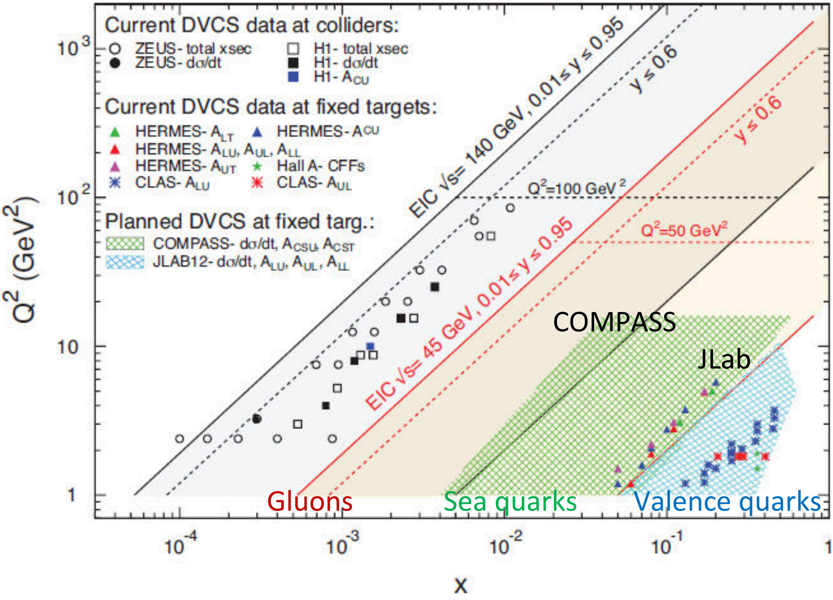
z_A position resolution



z_B position resolution



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)

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

Charge & Spin Difference and Sum:

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

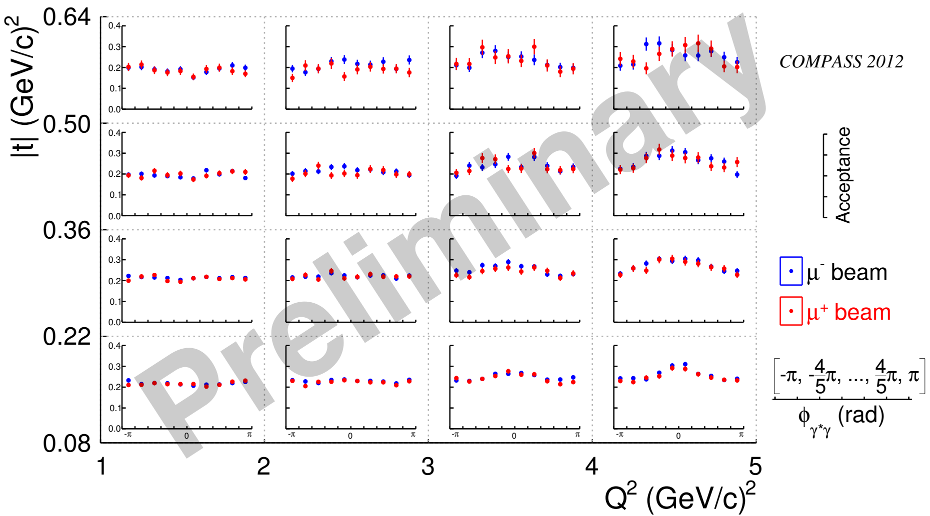
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto \boxed{d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int}\sin\phi} \quad \text{and} \quad s_1^{Int} \sim F_1\, \mathcal{I}m\, \mathcal{H}$$

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

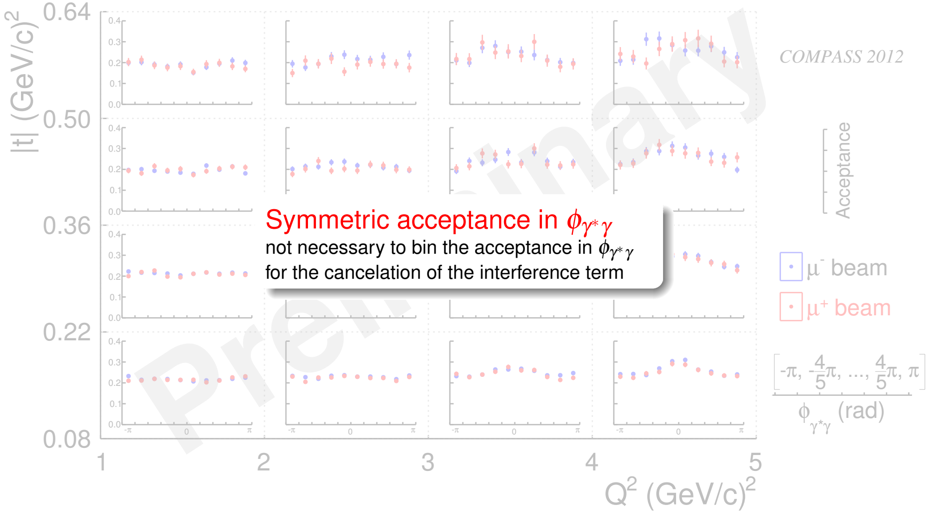
NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics

✓ only leading twist and LO

COMPASS acceptance for DVCS



COMPASS acceptance for DVCS

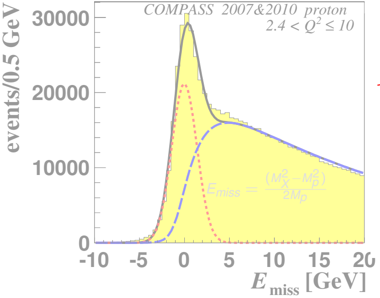


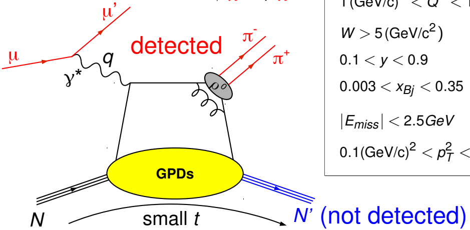
Symmetric acceptance in $\phi_{\gamma^*\gamma}$

not necessary to bin the acceptance in $\phi_{\gamma^*\gamma}$ for the cancelation of the interference term

Selections for exclusive ρ^0 sample (similar selections for ω)

$$\mu + N^{\uparrow} \rightarrow \mu' + N' + \rho^0$$
$$\hookrightarrow \pi^+ + \pi^-$$





$1\,(\text{GeV}/c)^2 < Q^2 < 10\,(\text{GeV}/c^2$

$W > 5\,(\text{GeV}/c^2)$

$0.1 < y < 0.9$

$0.003 < x_{Bj} < 0.35$

$|E_{miss}| < 2.5 GeV$

$0.1(\text{GeV}/c)^2 < p_T^2 < 0.5(\text{GeV}/c)^2$

Shape of semi-inclusive background

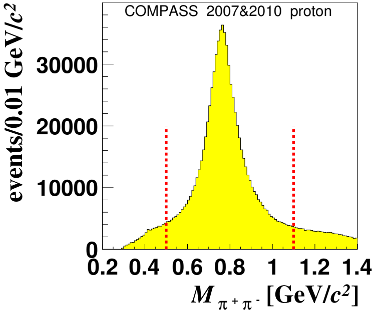
full Monte Carlo (MC) chain using Lepto

MC weighted using real data (RD) from wrong sign sample

$$w(E_{miss}) = \frac{N_{RD}^{h^+h^+\gamma\gamma} + N_{RD}^{h^-h^-\gamma\gamma}}{N_{MC}^{h^+h^+\gamma\gamma} + N_{MC}^{h^-h^-\gamma\gamma}}$$

Normalisation of MC using two component fit

Gaussian function (signal)+shape from weighted MC (bgd.)



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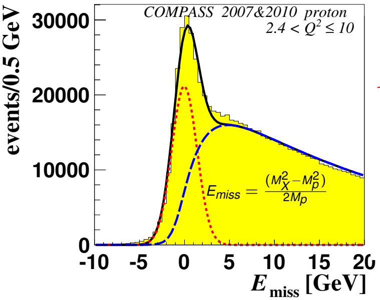

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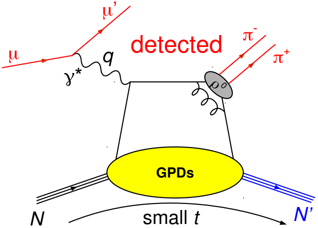

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