Exclusive low-t measurements with muon beams at COMPASS

P. Jörg (ALU Freiburg)

on behalf of the COMPASS Collaboration

IWHSS - Seeon, 06/09/2016

COMPASS GPD program

- Contribution to the nucleon spin puzzle

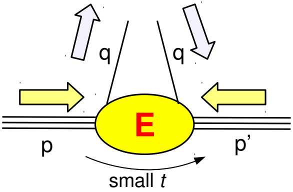
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathscr{L}$$

Jaffe&Manohar Nucl.Phys.B337 (1990)

by constraining GPD *H* and *E*

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

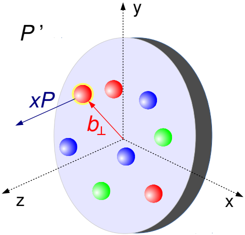
(Phys.Rev.Lett.78 (1997))



- 3D nucleon tomography via GPD *H*

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

probability interpretation (Burkardt)



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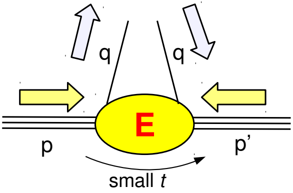

this talk

→ Exclusive vector meson production on transversely polarised protons and deuterons

→ Exclusive π^0 unpolarised x-section on protons

- 3D nucleon tomography via GPD H

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

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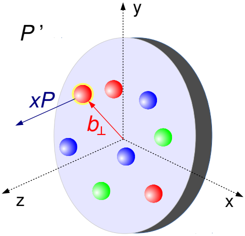
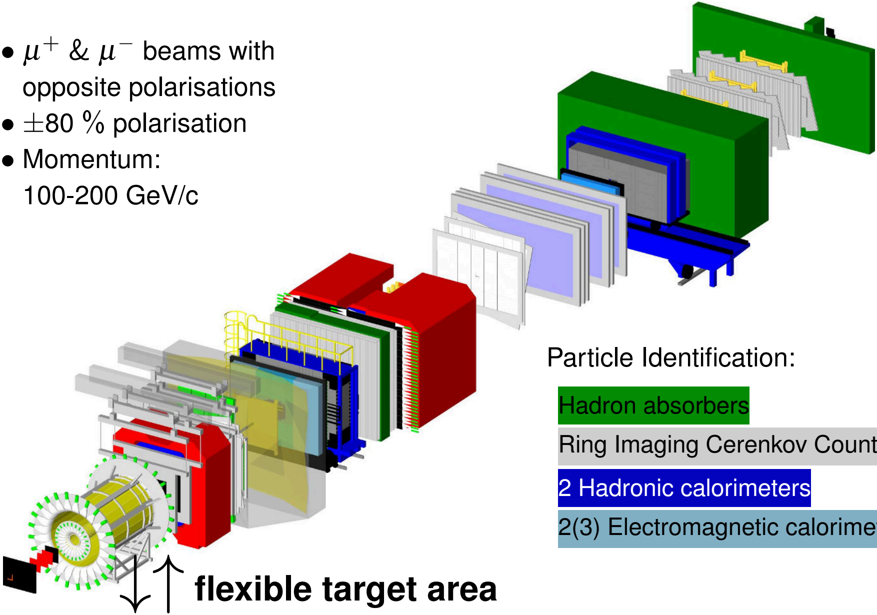


this talk

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

COMPASS spectrometer

- μ^+ & μ^- beams with opposite polarisations
- ± 80 % polarisation
- Momentum: 100-200 GeV/c



Particle Identification:

Hadron absorbers

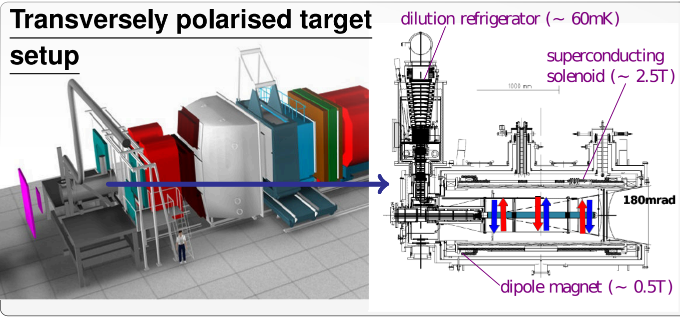
Ring Imaging Cerenkov Counter

2 Hadronic calorimeters

2(3) Electromagnetic calorimeters

$\downarrow\uparrow$ **flexible target area**

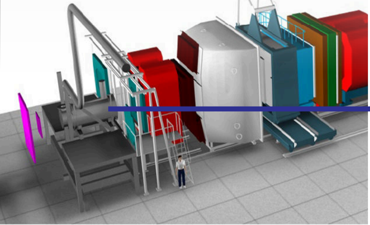
Transversely polarised target setup

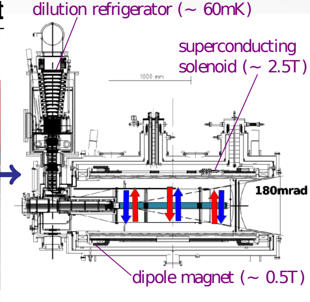


- Target material: NH_3, ^{6}LiD
- 2 magnets:
  solenoid 2.5 T, dipole 0.5 T
- Acceptance: ± 180 mrad
  upstream edge (since 2006)
- ^{3}He - ^{4}He dilution refrigeration
- Microwave reversal
  every week

results on exclusive ρ^0 and ω available

Transversely polarised target setup





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results on exclusive ρ^0
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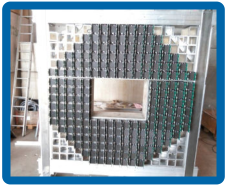
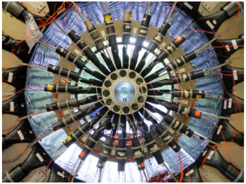
$\downarrow\uparrow$ **flexible target area**

COMPASS II setup



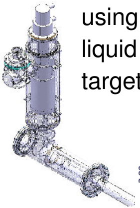
ECAL0 Calorimeter

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

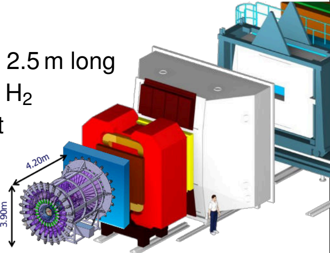


Target ToF system

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



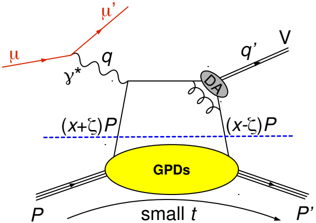
using 2.5 m long
liquid H_2
target



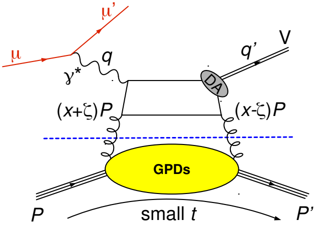
results on exclusive π^0
and DVCS available

GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution *



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

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

Chiral-even GPDs

helicity of parton unchanged

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

Chiral-odd GPDs

helicity of parton changed (not probed by DVCS)

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

Flavour separation

constraints for parton specific GPDs e.g.

$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^{u(+)} + \frac{1}{3}E^{d(+)} + \frac{3}{4}E^{g(+)}/x\right)$$
$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^{u(+)} - \frac{1}{3}E^{d(+)} + \frac{1}{4}E^{g(+)}/x\right)$$

Diehl, Vinnikov
PLB, 2005

* Gluon contribution at same order of α_s as from quarks

HEMP cross section

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

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

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

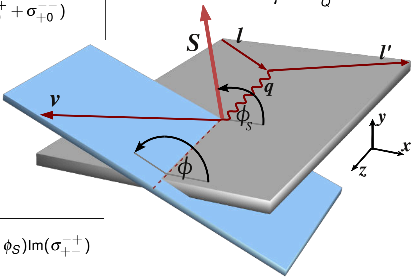
$$-S_L\left[\varepsilon\sin(2\phi)\mathrm{Im}(\sigma_{+-}^{++})+\sqrt{\varepsilon(1+\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]$$
$$+S_L P_l\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1+\varepsilon)}\cos(\phi)\mathrm{Re}(\sigma_{+0}^{++}+\sigma_{+0}^{--})\right]$$

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

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

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

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



Helicity dependent photoabsorption x-sections and interference terms:

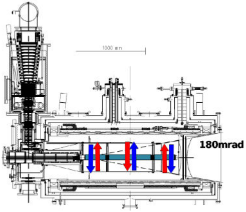
$$\sigma_{mn}^{ij}(x_{Bj},Q^2,t)\propto\sum(M_m^i)(M_n^j)$$

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)



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

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

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

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

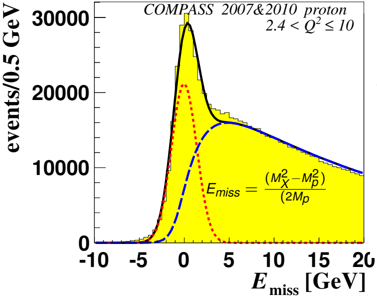
⇒ 5 single spin asymmetries

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

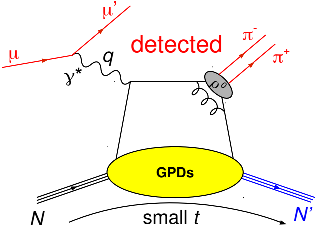
⇒ 3 double spin asymmetries

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

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



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



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

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

$0.1 < y < 0.9$

$0.003 < x_{Bj} < 0.35$

$|E_{miss}| < 2.5 GeV$

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

Shape of semi-inclusive background

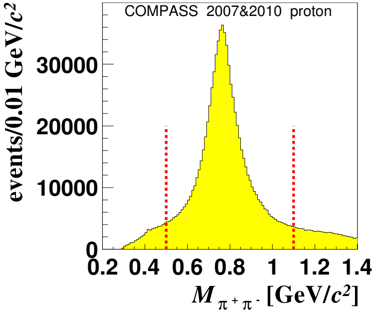
full Monte Carlo (MC) chain using Lepto

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

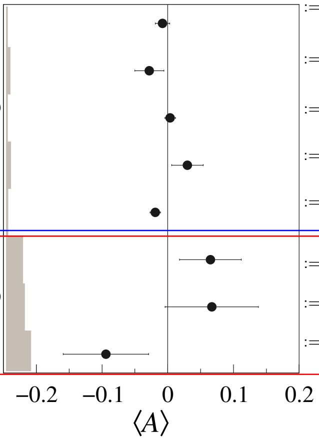
$$w(E_{miss}) = \frac{N_{RD}^{h^+h^+\gamma\gamma} + N_{RD}^{h^-h^-\gamma\gamma}}{N_{MC}^{h^+h^+\gamma\gamma} + N_{MC}^{h^-h^-\gamma\gamma}}$$

Normalisation of MC using two component fit

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



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

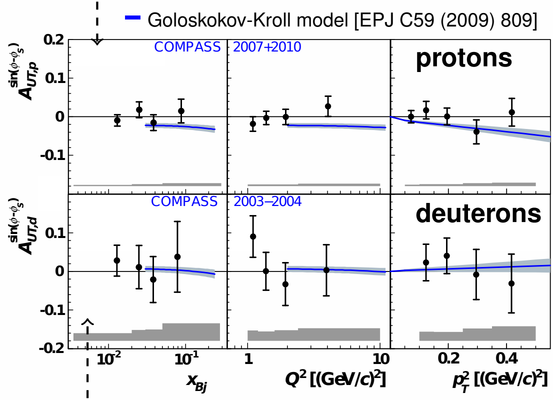
$\sim E$, $\sim H$, $\sim H_T$, $\sim \overline{E}_T = 2\widetilde{H}_T - E_T$, $\sim \widetilde{H}$,

σ_0: unpolarised cross section

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

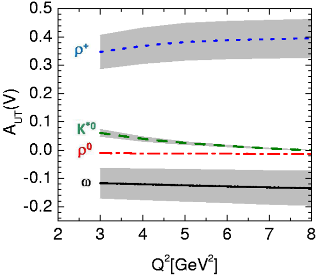
Results on $A_{UT}^{\sin(\phi-\phi_S)}$ for exclusive ρ^0 production

- agreement with HERMES for **protons**
- COMPASS improved statistical errors by a factor **3** and extended kinematic coverage



→ **NPB 865 (2012) 1**

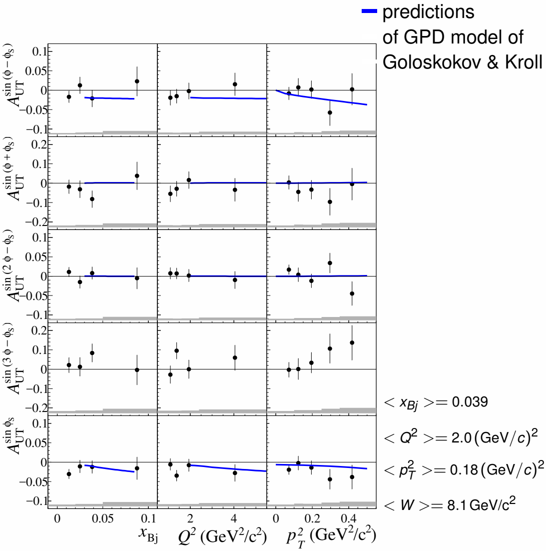
small values for ρ^0 expected due to approximate cancelation of E^u and E^d



$A_{UT}^{\sin(\phi-\phi_S)}$ contains twist-2 terms depending on $E^{q,g}$

- first measurement for **deuterons**

Azimuthal asymmetries for $\mu^+ + p^\uparrow \rightarrow \mu^+ + p + \rho^0$



$< x_{Bj} >= 0.039$

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

$< p_T^2 >= 0.18\,(\mathrm{GeV}/c)^2$

$< W >= 8.1\,\mathrm{GeV/c}^2$

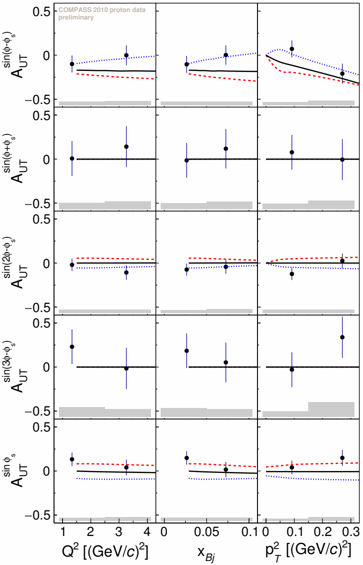
- 2D binned maximum likelihood method
- Simultaneous extraction of:

  5 single spin asymmetries (shown)

  3 double spin asymmetries

  → **PLB 731 (2014) 19**
- reasonable agreement with GK model

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



$< x_{Bj} >= 0.049$

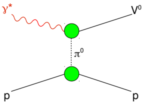
$< Q^2 >= 2.2\,(\mathrm{GeV}/c)^2$

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

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

Comparison to modified GPD model of GK

with π^0 pole exchange added



Goloskokov and Kroll (GK) predictions for COMPASS

(private communications)

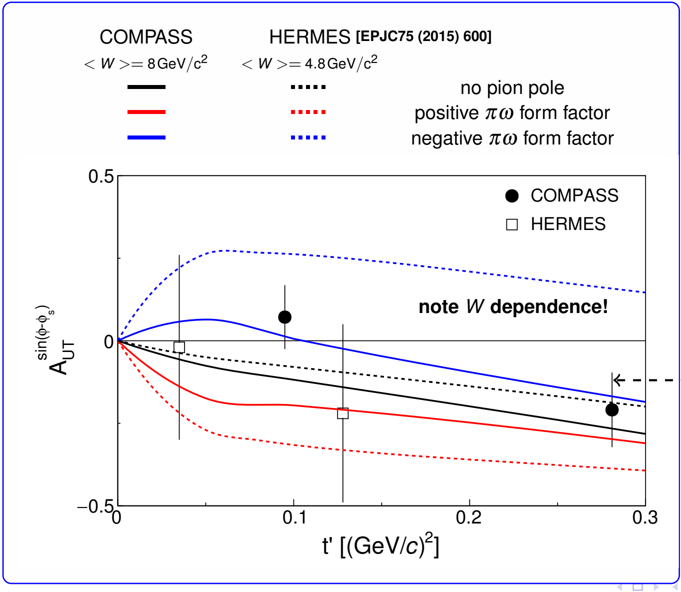
— no pion pole

- - - positive $\pi\omega$ transition

···· negative $\pi\omega$ transition

- unbinned maximum likelihood method
- **submitted** to PLB
- extraction of 8 asymmetries (5 single spin asymmetries shown)

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



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

COMPASS uncertainties smaller by a factor **2**

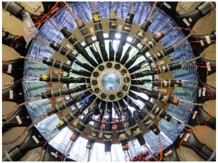
Future measurements at JLab12 expected to resolve the issue **[EPJ A48 (2012) 187]**

HEMP cross section (unpolarised target)

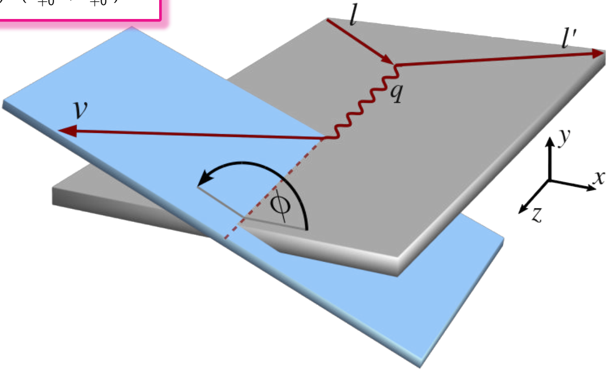
$$\left[\frac{\alpha_{em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_{Bj}}{x_{Bj}}\,\frac{1}{Q^2}\right]^{-1}\frac{\mathrm{d}\sigma}{\mathrm{d}x_{Bj}\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi\,\mathrm{d}\phi_S} =$$

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

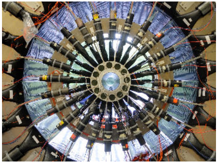
$$\boxed{-P_l\sqrt{\varepsilon(1-\varepsilon)}\sin(\phi)\mathrm{Im}(\sigma_{+0}^{++}+\sigma_{+0}^{--})}$$



using target ToF system



HEMP cross section (unpolarised target)



using target ToF system

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

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

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

↑ ***study ϕ dependence!***

after integration in ϕ:

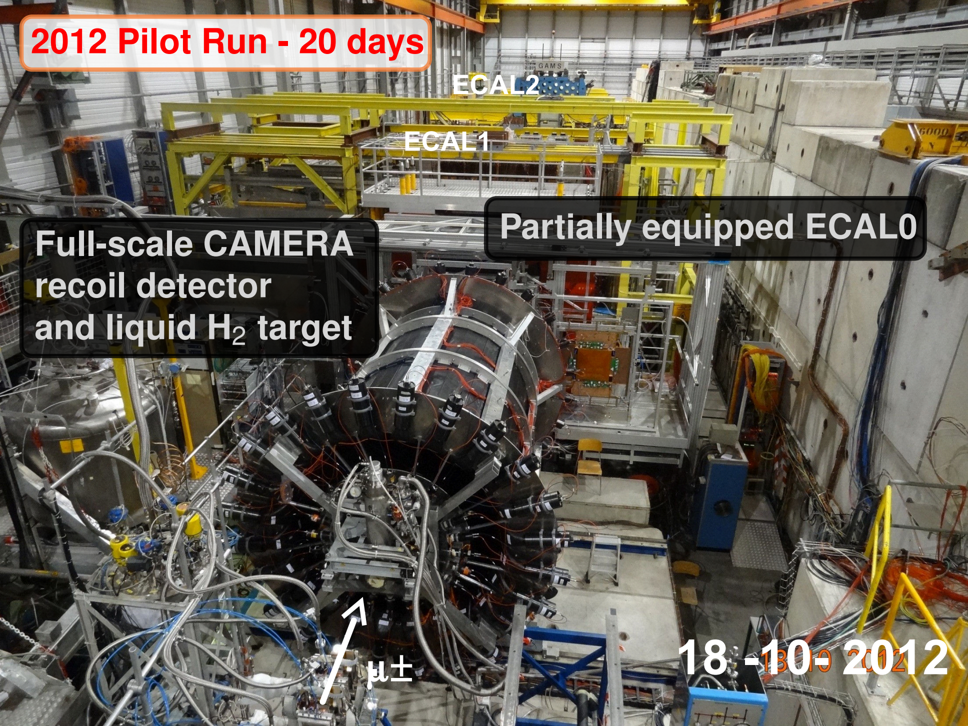
$$\boxed{\frac{1}{2}\left(\sigma_{++}^{++} + \sigma_{++}^{--}\right) + \varepsilon\sigma_{00}^{++}}$$

← ***study t dependence!***

Exclusive π^0 unpolarised x-section extraction on protons

(see talk at SPIN16 of Matthias Gorzellik for details on the analysis)

2012 Pilot Run - 20 days



Full-scale CAMERA recoil detector and liquid H_2 target

Partially equipped ECAL0

18 -10- 2012

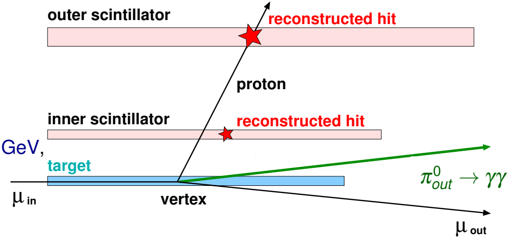
Exclusive π^0 event selection (similar selections for DVCS)

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

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

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



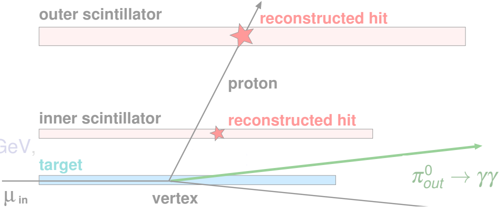
Exclusive π^0 event selection (similar selections for DVCS)

Reconstructed interaction vertex in **target volume**

Two photons, **one photon** above threshold

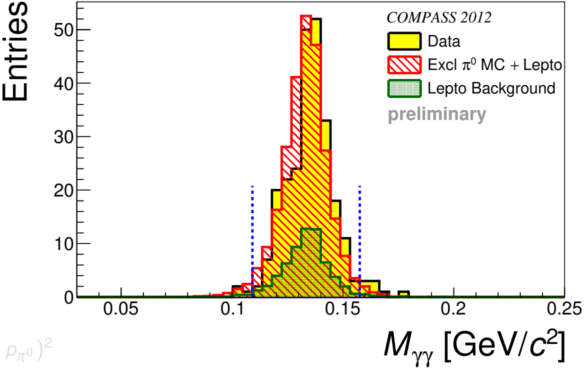
$1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $8.5\,\mathrm{GeV} < \nu < 28\,\mathrm{GeV}$,

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

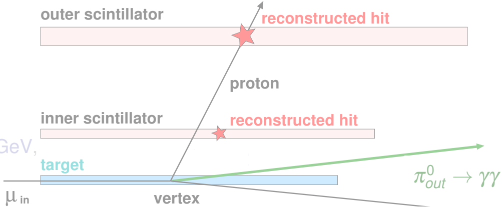


Exclusivity conditions:

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



Exclusive π^0 event selection (similar selections for DVCS)



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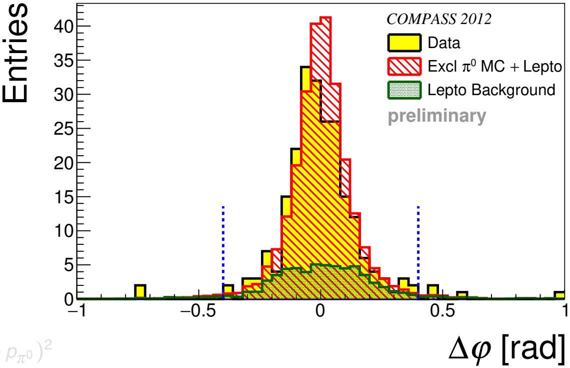

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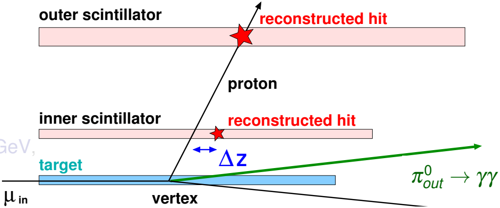

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- Vertex pointing (Δz)
- Transv. momentum balance:
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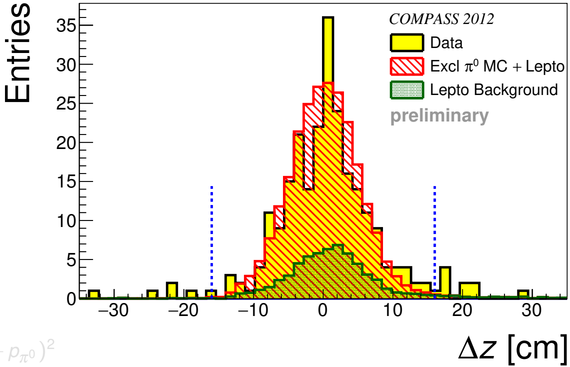
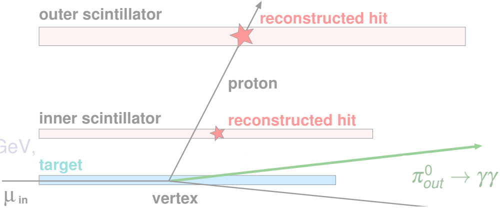
- Four-momentum balance:
  $M^2_X = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$



Exclusive π^0 event selection (similar selections for DVCS)



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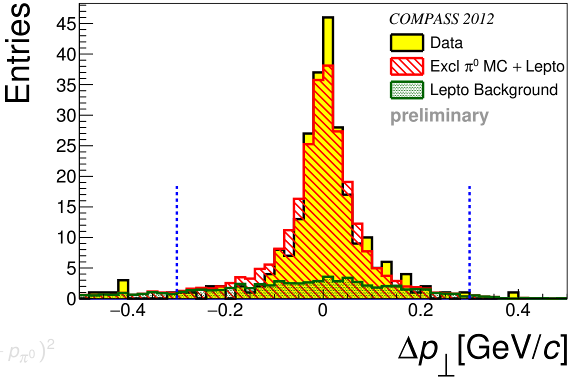

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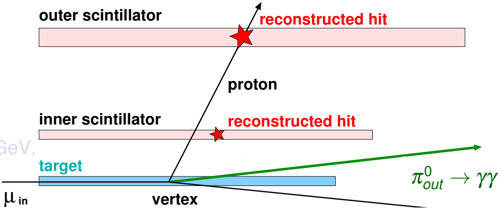

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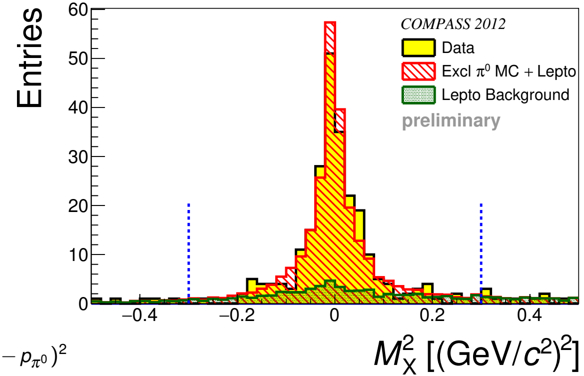
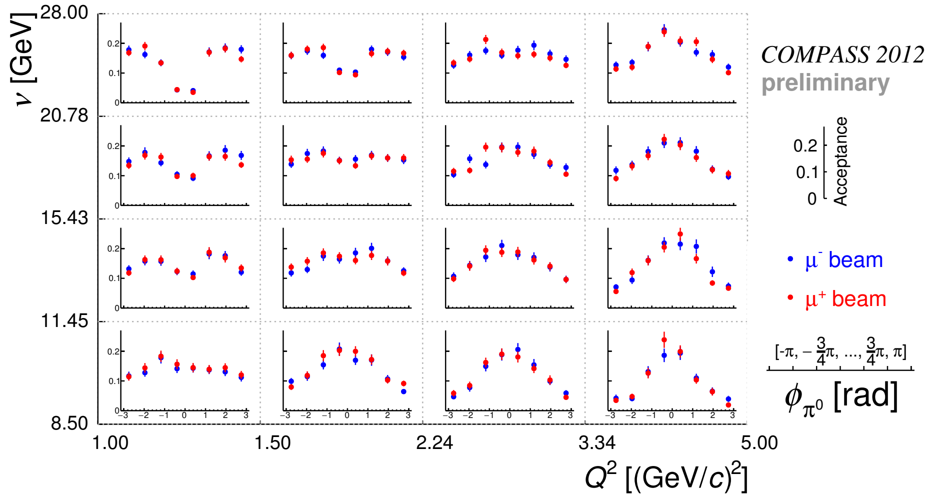
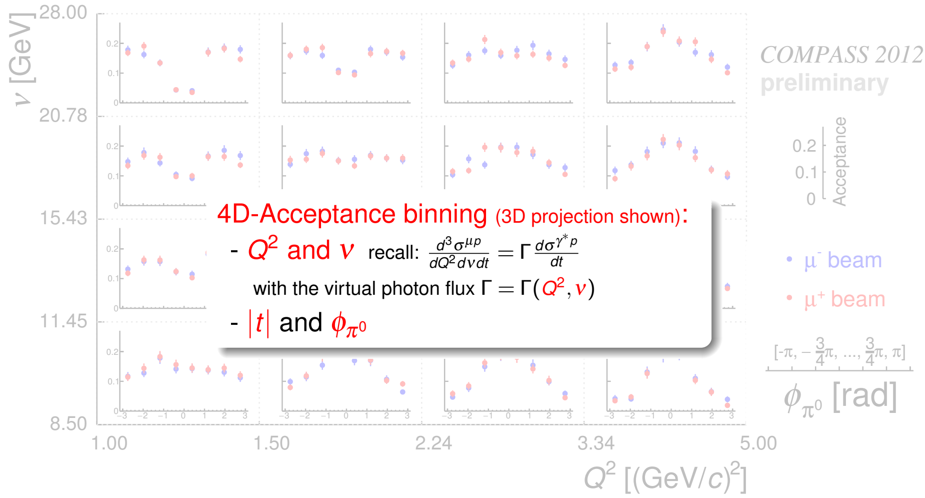


COMPASS acceptance for exclusive π^0



COMPASS acceptance for exclusive π^0



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

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

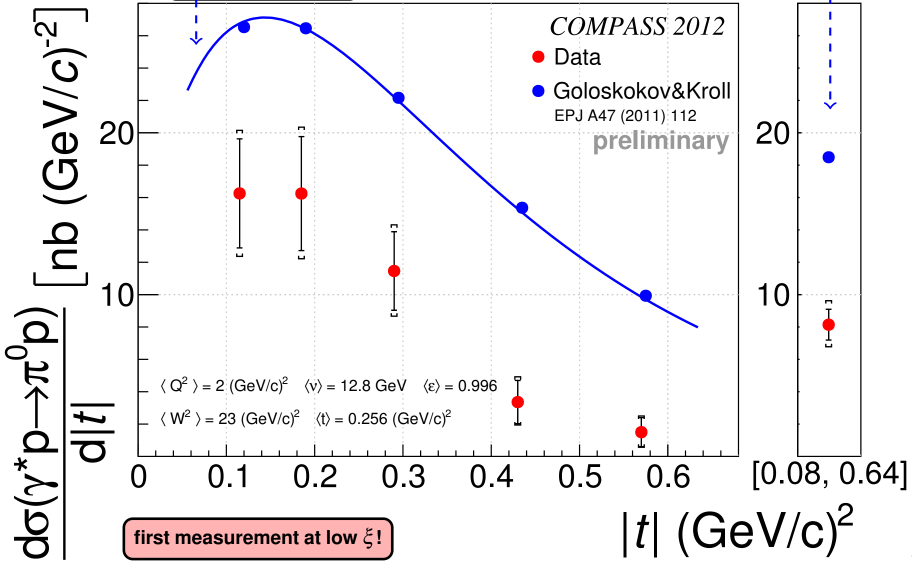
  with the virtual photon flux $\Gamma = \Gamma(Q^2, \nu)$
- $|t|$ and ϕ_{π^0}

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

Kinematically constrained vertex fit applied

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

a factor of $\sim$ 0.5 discrepancy to Goloskokov & Kroll model

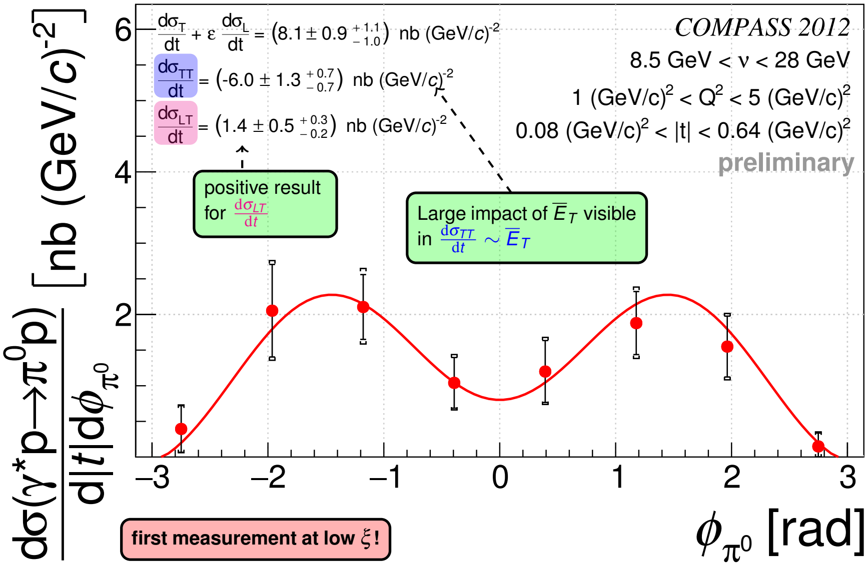


first measurement at low ξ!

Kinematically constrained vertex fit applied

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

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



$$\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} = \left(8.1 \pm 0.9\, ^{+1.1}_{-1.0}\right) \text{ nb } (\text{GeV}/c)^{-2}$$

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

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

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

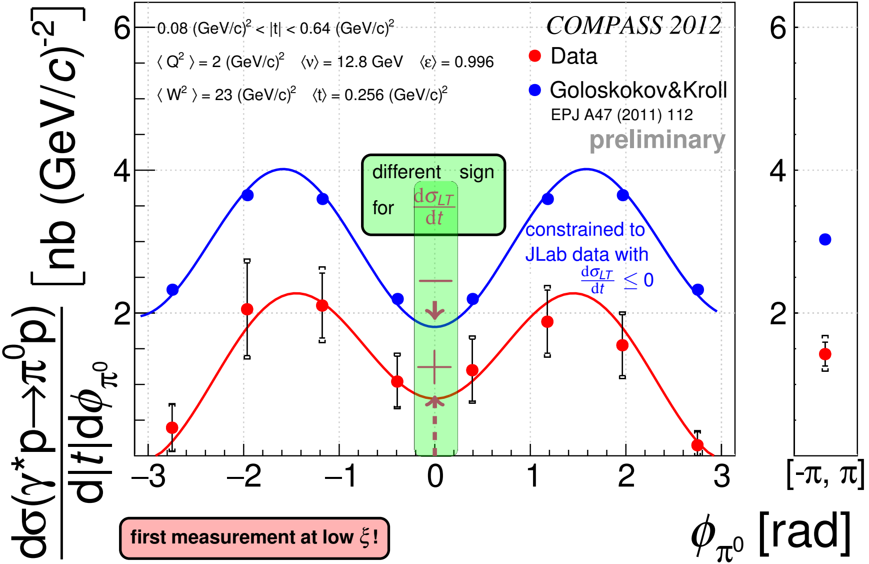
Large impact of $\overline{E}_T$ visible in $\frac{d\sigma_{TT}}{dt} \sim \overline{E}_T$

first measurement at low ξ!

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

Kinematically constrained vertex fit applied

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



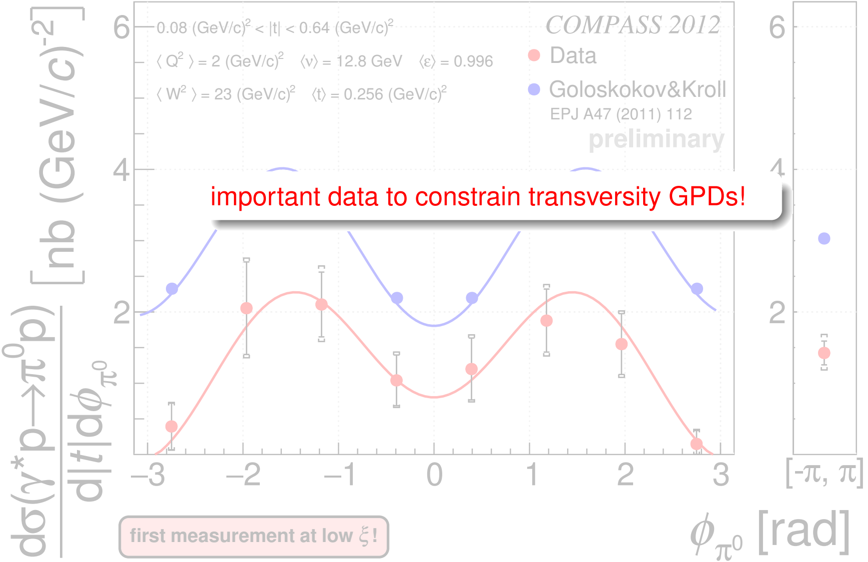
different sign for $\frac{d\sigma_{LT}}{dt}$

constrained to JLab data with $\frac{d\sigma_{LT}}{dt} \leq 0$

first measurement at low ξ!

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

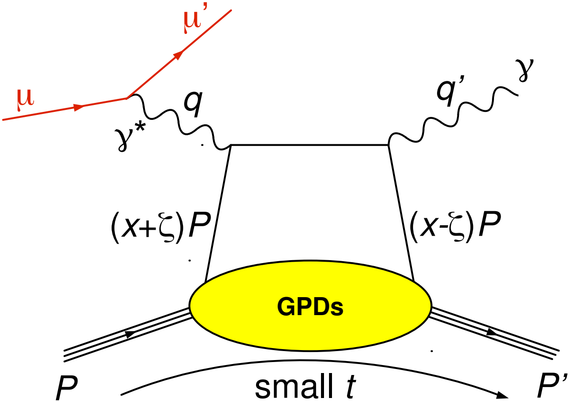
Kinematically constrained vertex fit applied



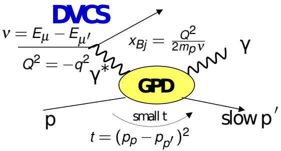
important data to constrain transversity GPDs!

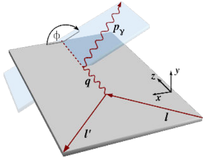
first measurement at low ξ!

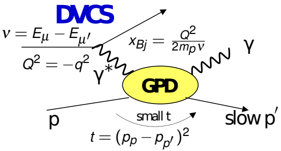
Deeply Virtual Compton Scattering



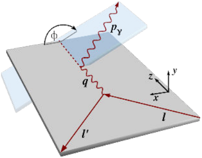
t-dependence of pure DVCS x-section on unpolarised protons

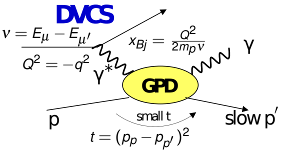

DVCS
$\nu = E_\mu - E_{\mu'}$
$Q^2 = -q^2$
$x_{Bj} = \frac{Q^2}{2m_p \nu}$
γ^*
γ
GPD
p
small t
slow p$'$
$t = (p_p - p_{p'})^2$

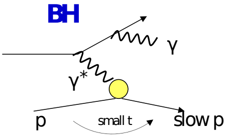

ϕ
p_γ
q
z
y
x
l
l'

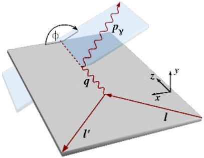


$$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}}$$

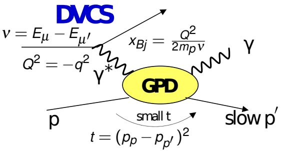


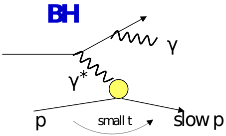


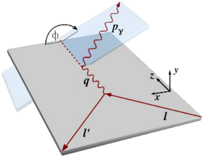




$$d\sigma \propto \underbrace{\left|T_{DVCS}\right|^2}_{\text{bilinear combination of GPDs}} + \underbrace{\left|T_{BH}\right|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$







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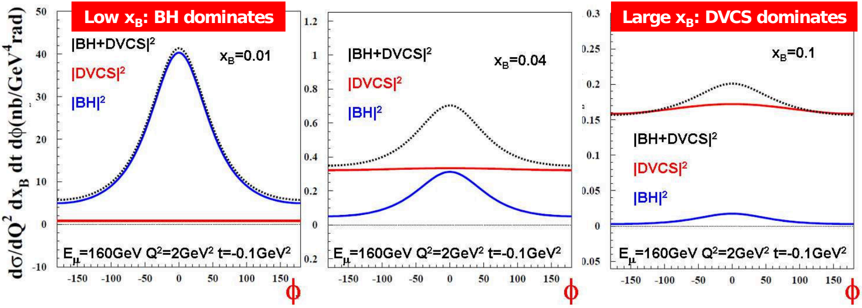
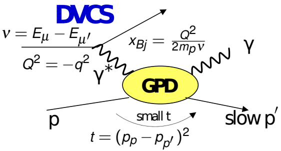
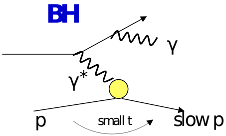
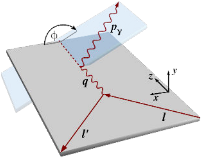

Low x_B: BH dominates

Large x_B: DVCS dominates







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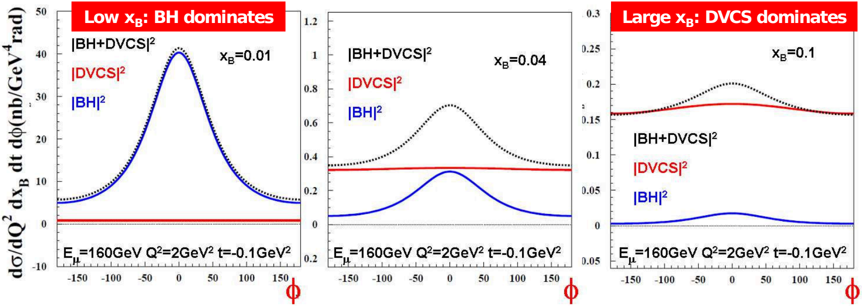
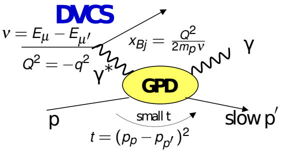
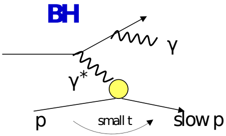


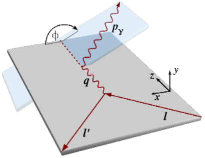
Low x_B: BH dominates

Large x_B: DVCS dominates

reference yield of
almost pure
Bethe-Heitler







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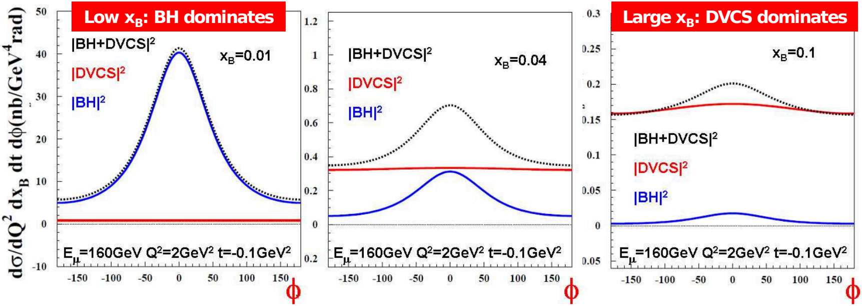
Low x_B: BH dominates

Large x_B: DVCS dominates

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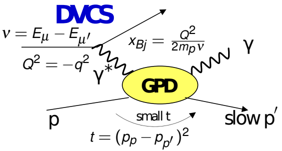
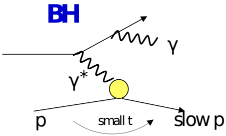
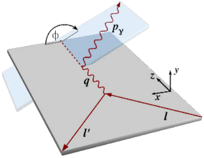
Study DVCS with:
$\mathrm{Re}(T^{DVCS})$ & $\mathrm{Im}(T^{DVCS})$
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$







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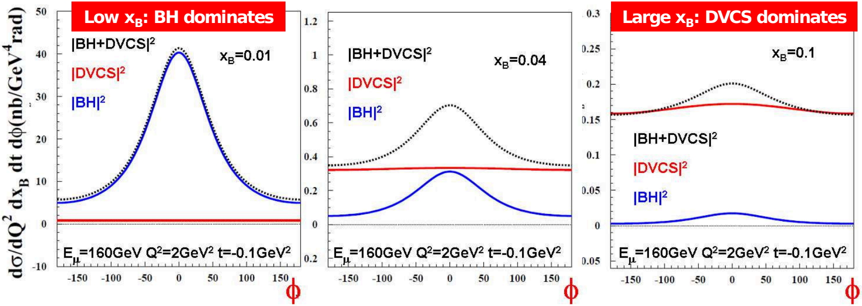


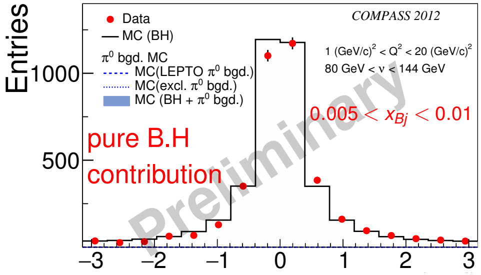
reference yield of
almost pure
Bethe-Heitler

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

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

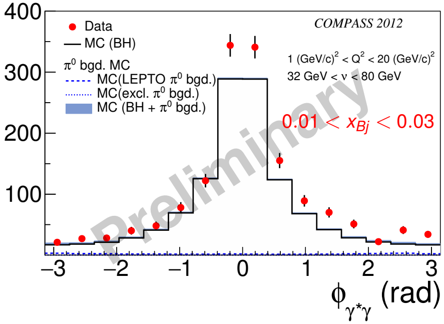
Kinematically constrained vertex fit applied

Exclusive γ Azimuthal Distributions for DVCS

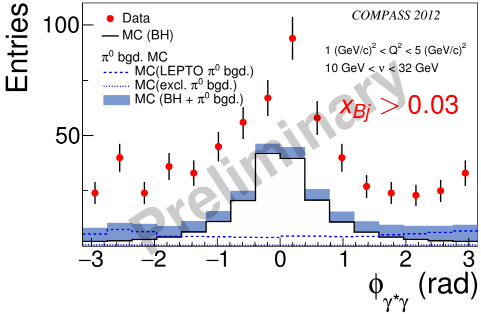


$0.005 < x_{Bj} < 0.01$

pure B.H contribution



$0.01 < x_{Bj} < 0.03$



$x_{Bj} > 0.03$

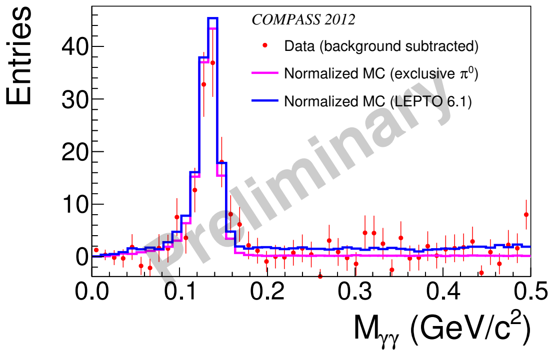
- normalisation of BH Monte Carlo to the data using beam flux
- dominant BH process at small x_{Bj} clearly visible
- π^0 background contributing at large x_{Bj}
- clear excess of DVCS at large x_{Bj}

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)



$M_{\gamma\gamma}$ distribution (“Visible” π^0)

„Exclusive“ γ (E_γ>4,5,10 GeV /Ecal0,1,2)
+ one γ below energy threshold

Semi inclusive LEPTO MC
or
exclusive HEPGen++ MC (Golosgokov & Kroll model)

π^0 contribution normalized to $M_{\gamma\gamma}$ 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:

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

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

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

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

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

note:

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

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

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

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- Integrate over $\phi_{\gamma^*\gamma}$

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

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

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

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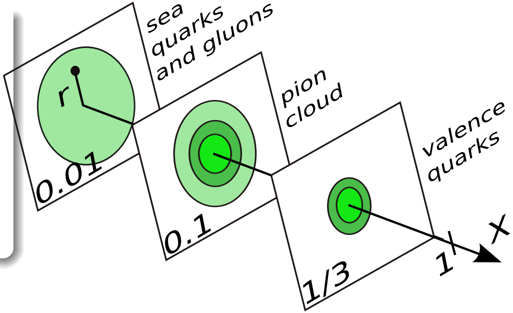
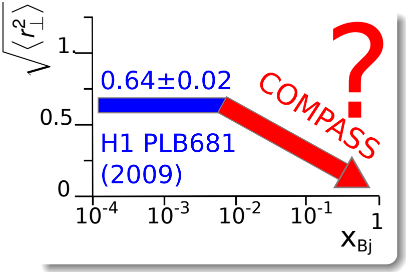
- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Subtract Bethe-Heitler (BH)
- Integrate over $\phi_{\gamma^*\gamma}$

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





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

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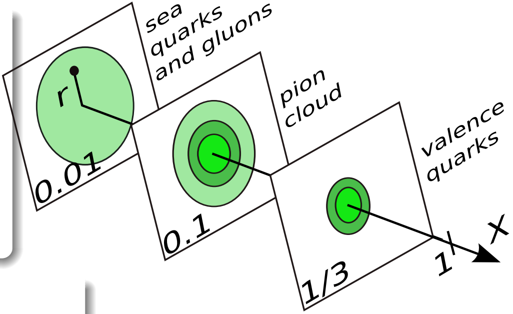
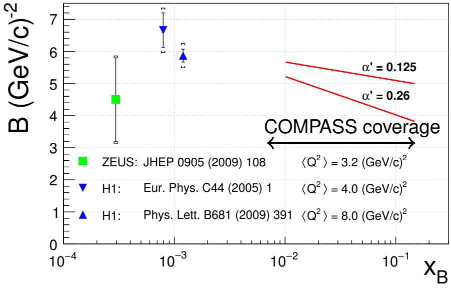
$$\frac{d\sigma^{DVCS}}{d|t|} \propto e^{-B|t|};\ < r_\perp^2 > \sim 2B(x_{Bj})$$

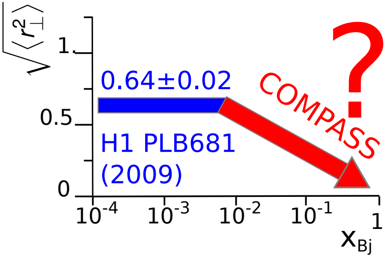
at small x_{Bj}



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

(inspired by Regge Phenomenology)





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

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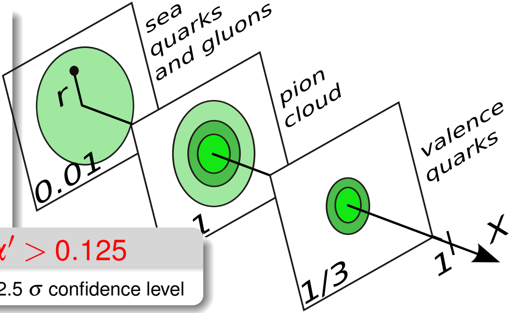
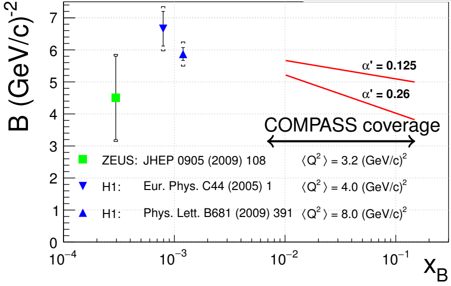


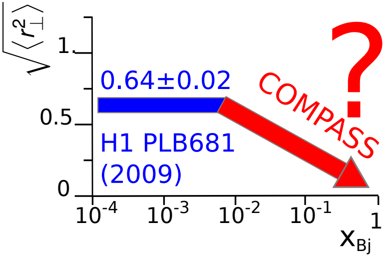
Measure $\alpha' > 0.125$

with more than 2.5 σ confidence level

$B(x_{Bj}) = b_0 + 2\alpha'$

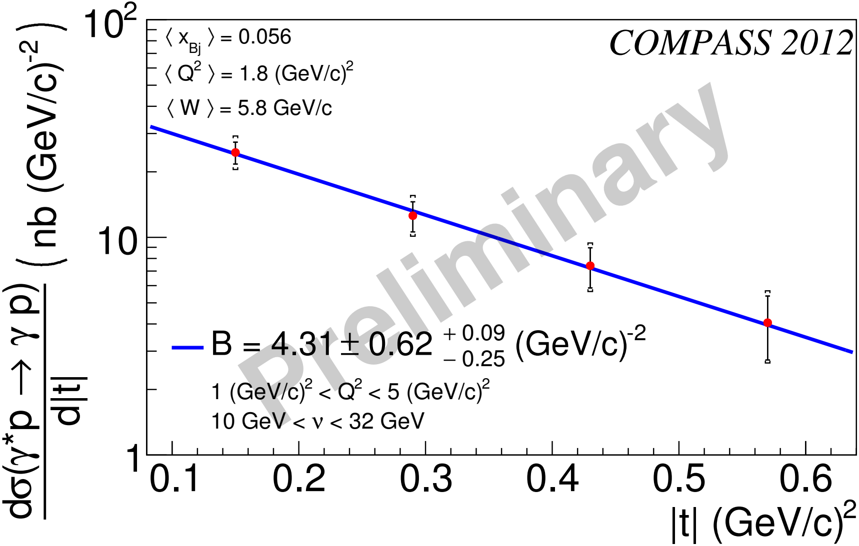
(inspired by Regge Pheno





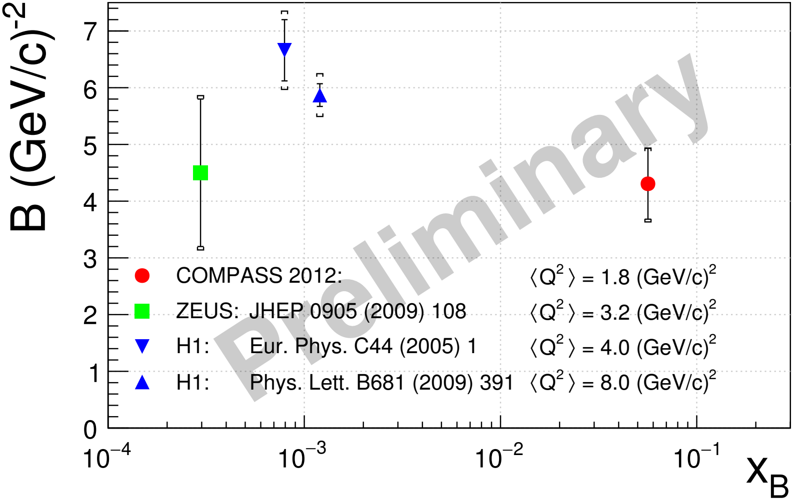
DVCS x-section and t-slope extraction

Kinematically constrained vertex fit applied



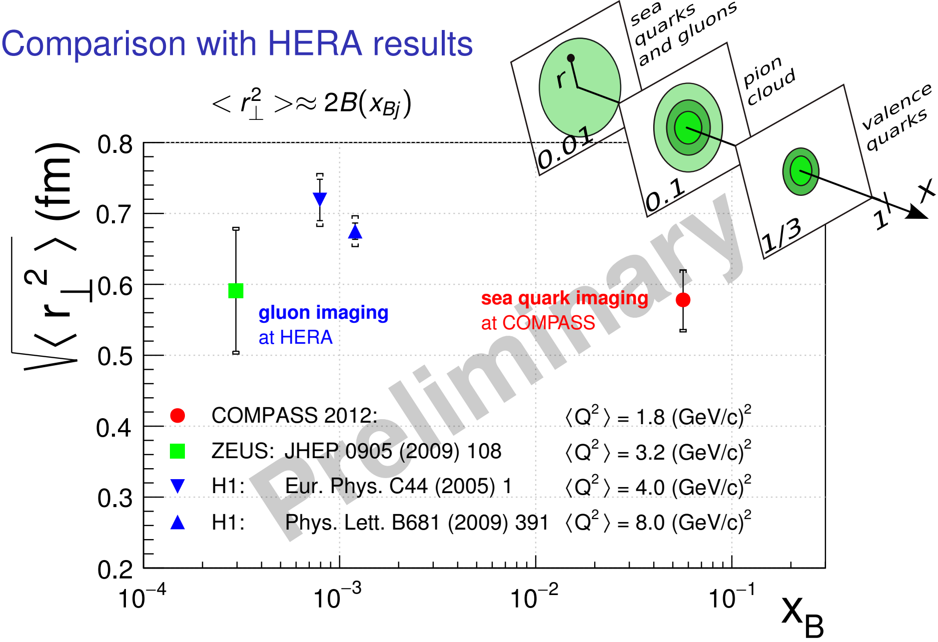
Comparison with HERA results

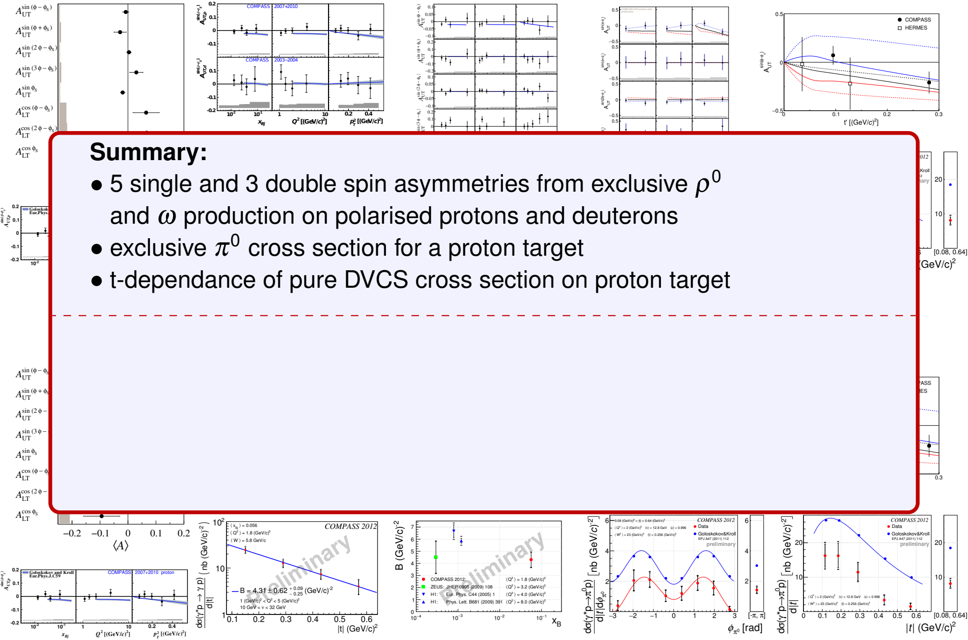
Model independent result



Comparison with HERA results

$$< r_\perp^2 > \approx 2B(x_{Bj})$$

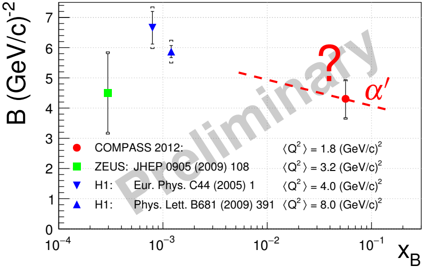


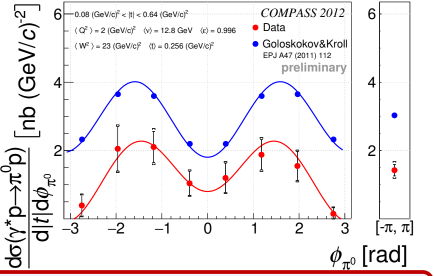


Summary:

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

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





Summary:

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

Near future:

- Dedicated beam time for DVCS and HEMP 2016-2017
- ≈ a factor of 15 increase in statistics compared to pilot run
- Beam charge sum and difference extraction
  ⇒ GPD *H* extraction (real and imaginary part in case of DVCS)

Thank you for your attention

Thank you for your attention

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 $H(x, \xi=x, t)$

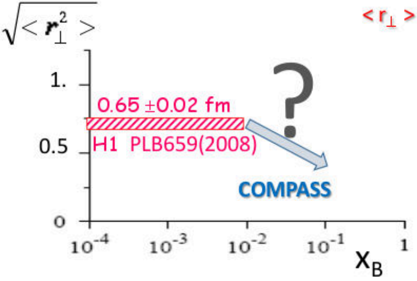
related to $½ < b_\perp^2(x_B) >$

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

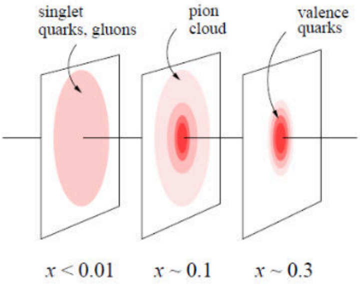
Impact Parameter Representation

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

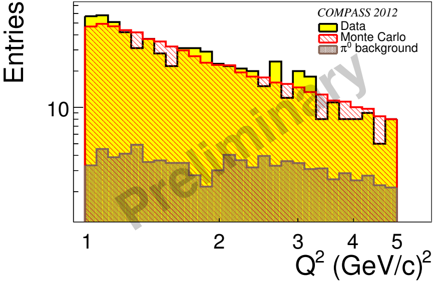
$< r_\perp > \sim < b_\perp > / (1-x)$

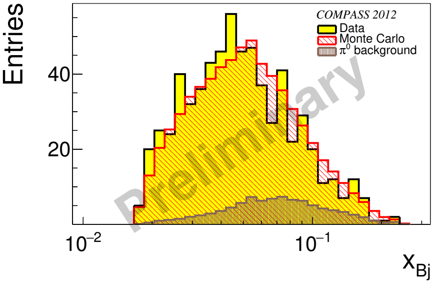


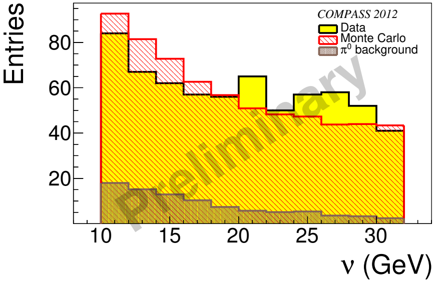
Note 0.65 fm = $\sqrt{2/3} \times 0.8$ fm



Kinematic distributions for DVCS







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

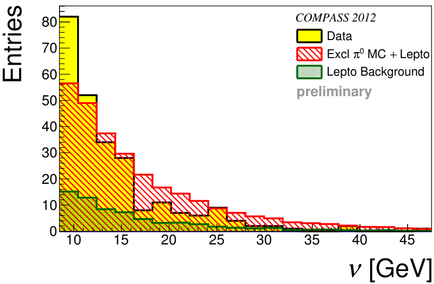
Monte Carlo prediction (the sum is shown)

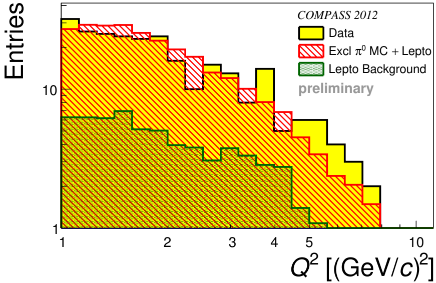
-(DVCS/BH): based on phenomenological model of DVCS x-section*

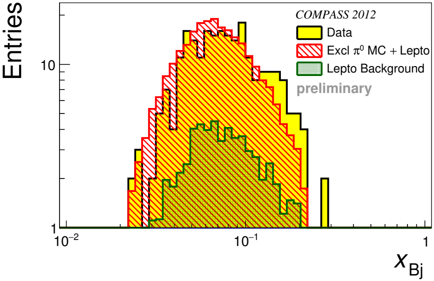
-π^0: parametrisation* linked to Golosgokov & Kroll + LEPTO (shown seperately)

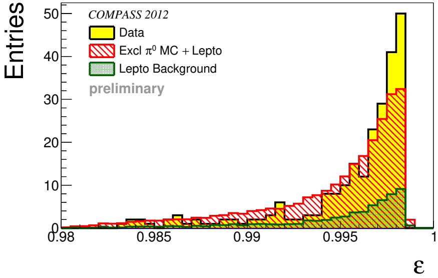
*HEPGen++: Andrzej Sandacz, Christopher Regali

Kinematic distributions for exclusive π^0

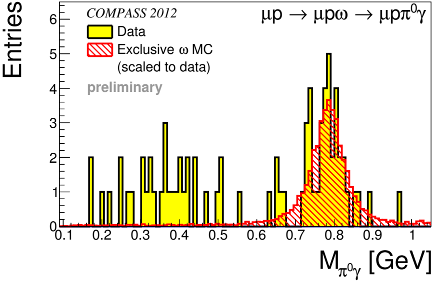


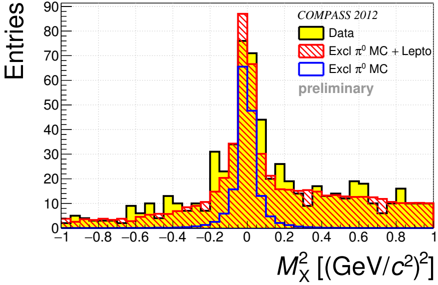


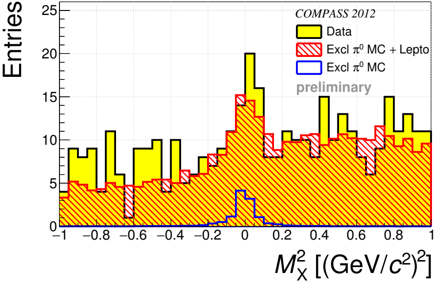




Background treatment for exclusive π^0



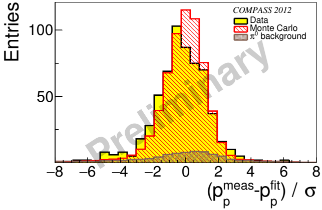




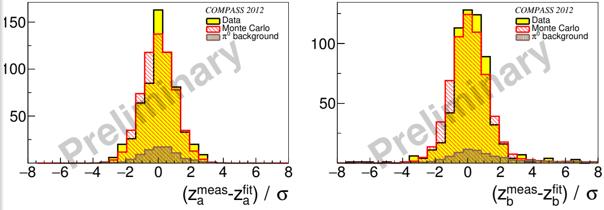
Kinematically constrained fit for DVCS

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

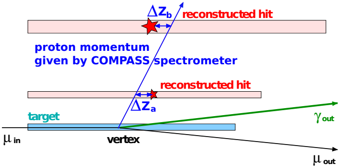
$\Rightarrow$ most accurate determination of t



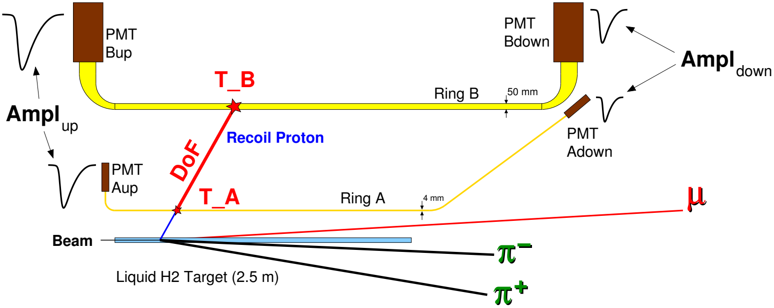
recoil proton momentum

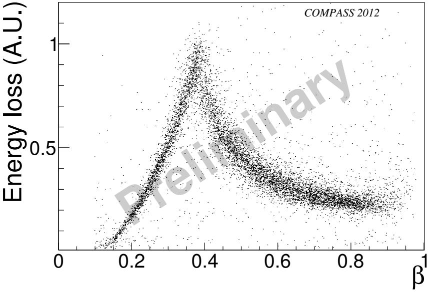


recoil proton direction



Recoil particle Measurement in CAMERA





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

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

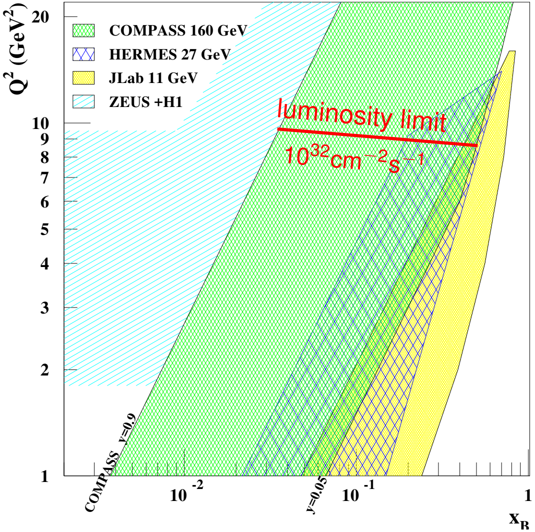
$$\textbf{z} \rightarrow t_{up} - t_{down}$$

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 GeV/c
- beam polarization: 80 %

  opposite for μ^+ and μ^-

- coverage of intermediate x_B

  → low x_B: **pure BH**

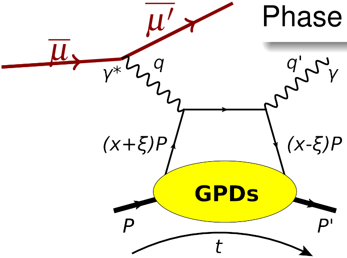
  useful for normalization

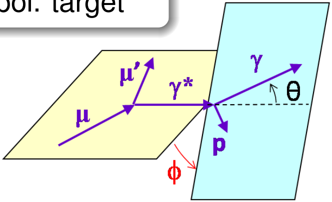
  → high x_B: **DVCS predomina**

⇝ **unexplored region between ZEUS+H1 and HERMES+JLab**

DVCS: What Can We Learn?

Phase 1: Polarized beam, unpol. target

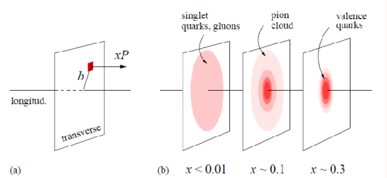




DVCS dominance
at large x_B

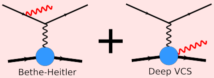
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



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

Interference between BH and DVCS



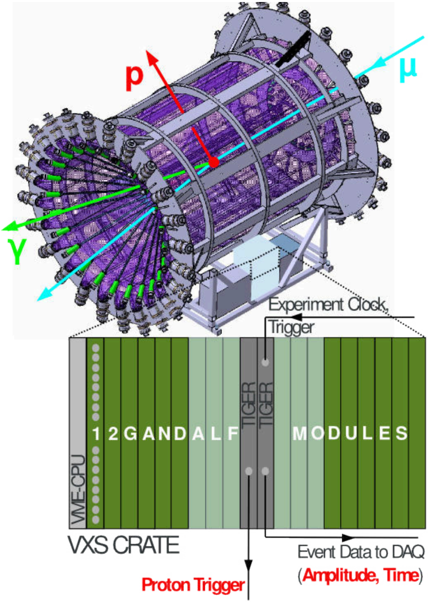
→ ”Boost” of DVCS through int. term

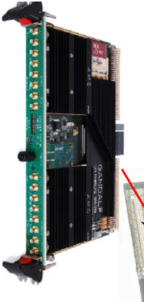
Measurement of $Re\mathscr{H}(\xi,t)$ and $Im\mathscr{H}(\xi,t)$ via ϕ-modulation of cross section

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

Exp. constrain to GPD H

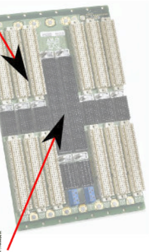
CAMERA Readout





GANDALF

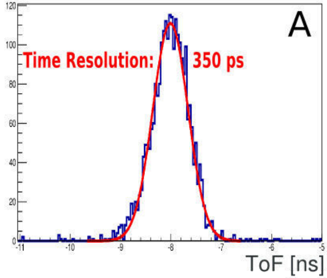
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

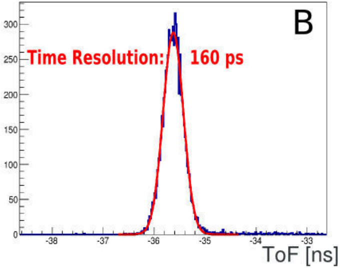


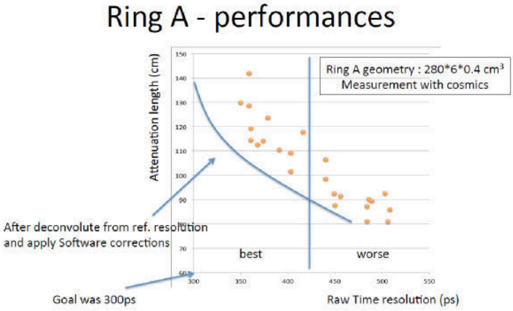
TIGER

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

Time Resolutions Measured with Cosmics







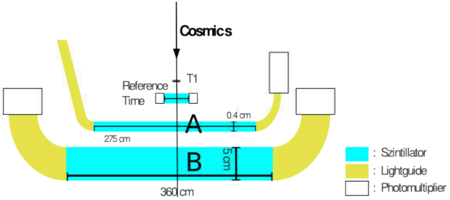
Ring A - performances

Ring A geometry : 280*6*0.4 cm^3
Measurement with cosmics

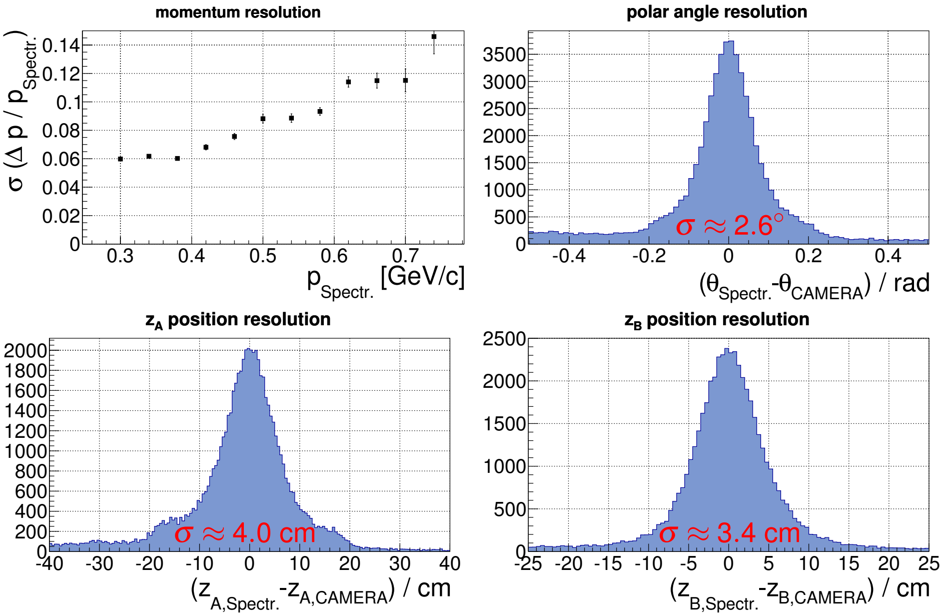
After deconvolute from ref. resolution
and apply Software corrections

Goal was 300ps

Att length better than 200 cm was expected



Summary of Present CAMERA Performances



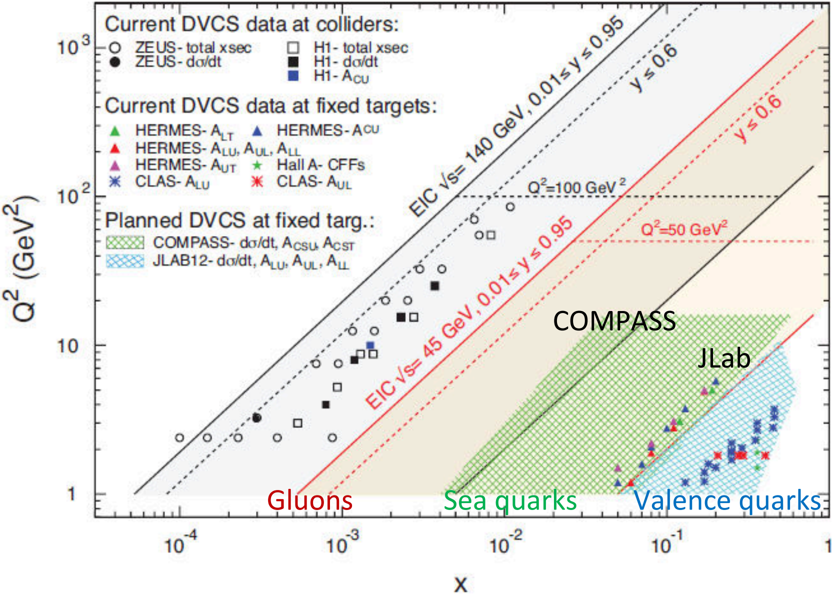
momentum resolution

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:

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

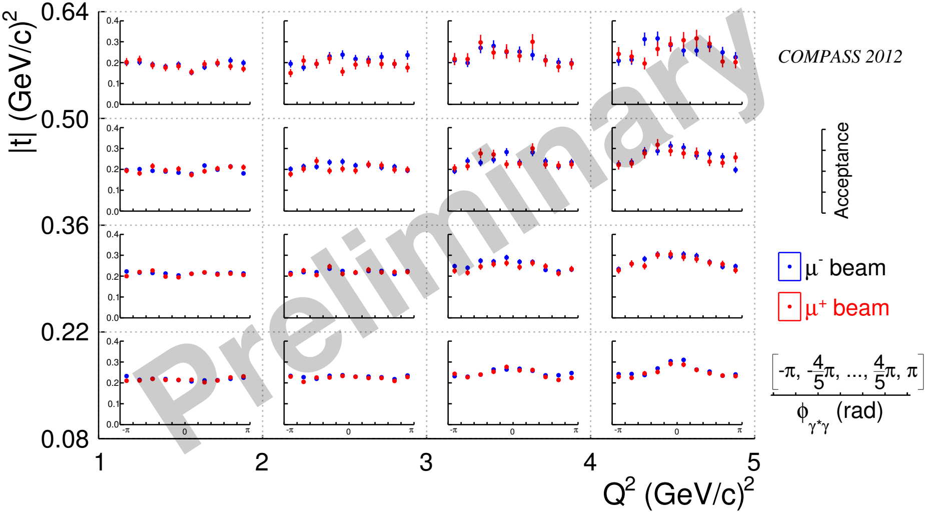
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto \boxed{d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi}$$ and $s_1^{Int} \sim F_1\, \mathcal{I}m\, \mathcal{H}$

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

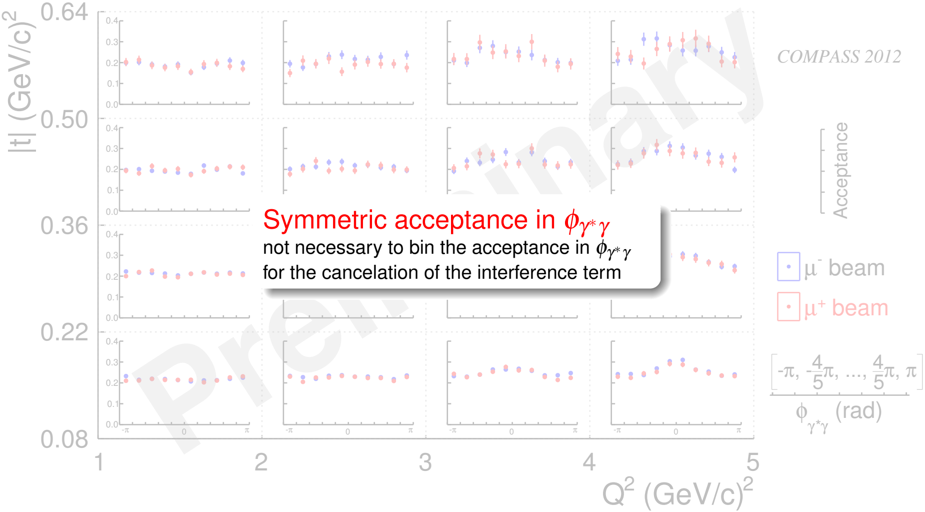
NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics

✓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