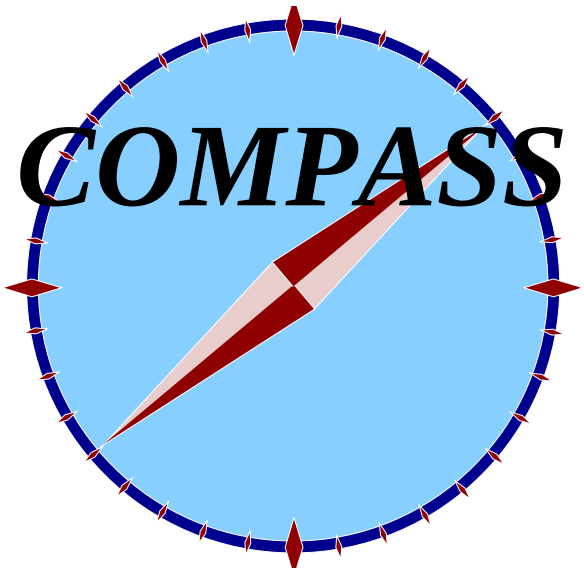
The GPD Programme at COMPASS

Heiner Wollny
CEA-Saclay Irfu/SPhN
on behalf of COMPASS



COMPASS-II @ CERN/SPS

COMPASS-II has been recommended by SPSC
and is approved by the Research Board

2012	Primakoff with π, K beam $\rightarrow$ Test of chiral perturbation theory (see talk J. Friedrich)
	+ two month pilot run of DVCS with μ^+ and μ^- beams on unpolarised protons
2013	CERN SPS shut down
2014	Drell-Yan with π beam $\rightarrow$ TMDs (see talk C. Quintans)
2015+16	Phase 1: DVCS with μ^+ and μ^- beams on unpolarised protons
	$\rightarrow$ constrain GPD H, t-slope parameter B
	In addition complementary information through HEMP
	in parallel SIDIS $\rightarrow$ PDFs, TMDs, FFs (in particular for strange)

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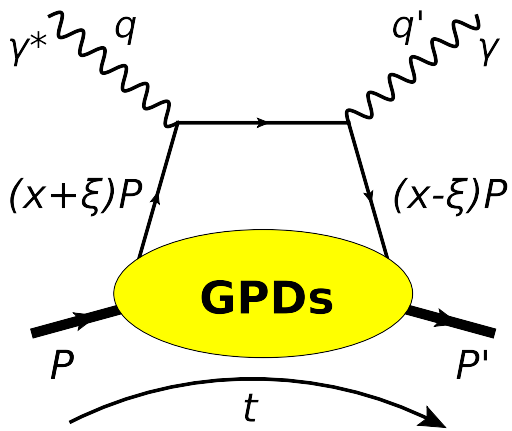
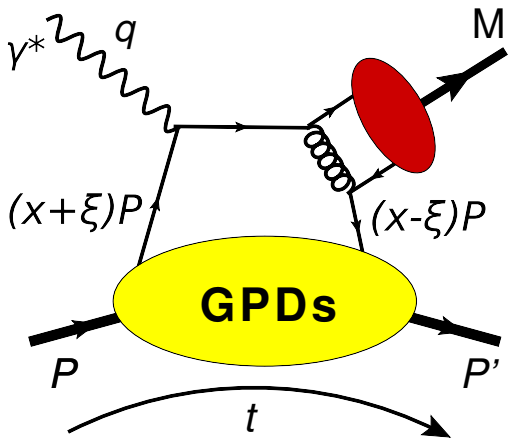
$\geq$ 2017 ?	Phase 2: DVCS & HEMP with μ^+ and μ^- beams on transversely polarised protons $\rightarrow$ constrain GPD E

GPDs and DVCS and HEMP



4 GPDs: H, E , $\tilde{H}$, $\tilde{E}$



- 'Golden process'
- GPDs appear as Compton Form Factors in DVCS amplitude i.e.:

$$\mathcal{H}(\xi,t) = \sum_f e_f^2 \int dx\, H^f(x,\xi,t)\frac{1}{x-\xi-i\epsilon}$$
$$= \sum_f e_f^2 \mathcal{P}\int dx\, H^f(x,\xi,t)\frac{1}{x-\xi} - i\pi H^f(\xi,\xi,t)$$

- Gluons contribute at higher orders in α_s

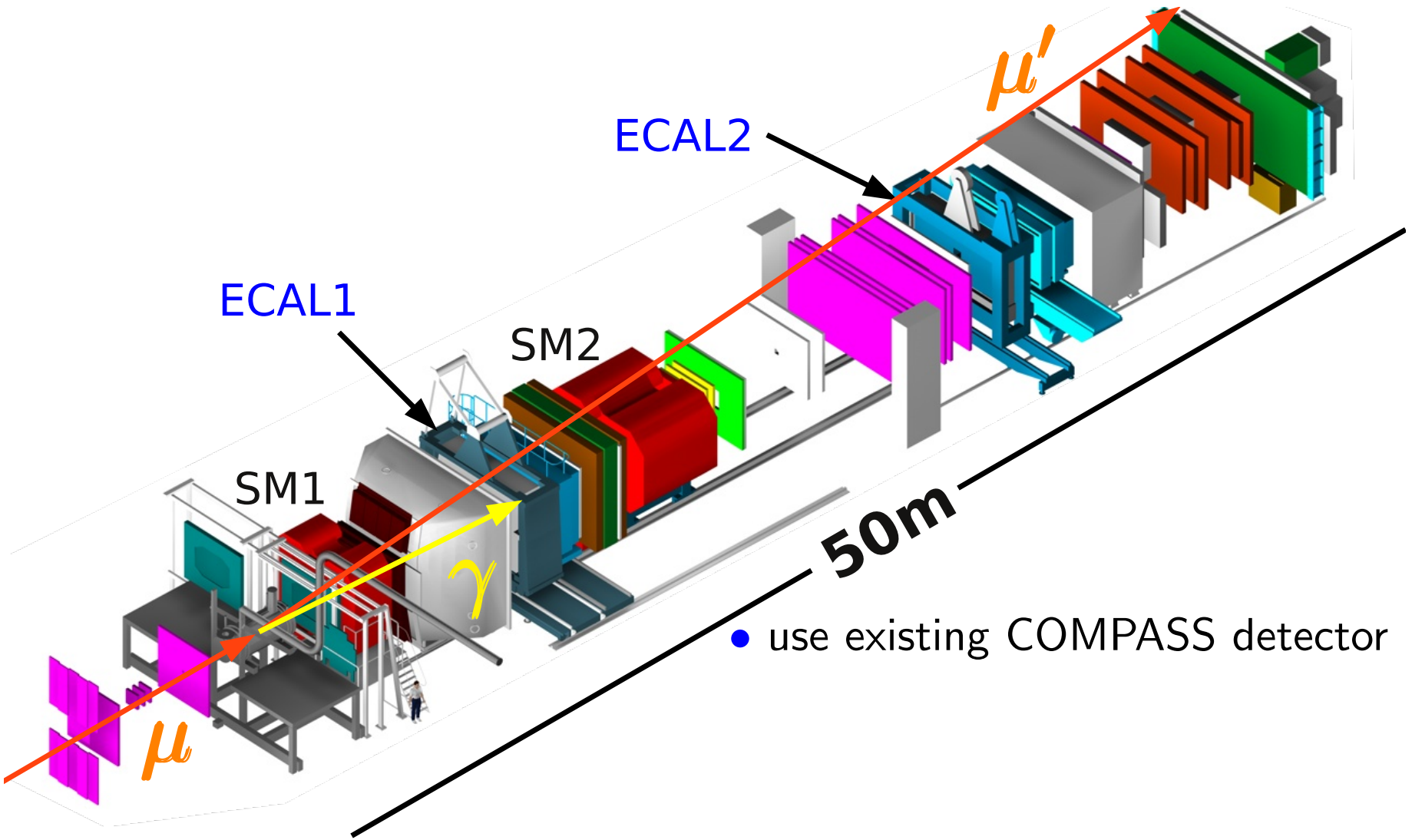
- Factorisation only proven for σ_L
- Pseudo-scalar: $\pi, \eta, .. \Rightarrow \tilde{H}, \tilde{E}$
- Vector meson: $\rho, \omega, \phi, .. \Rightarrow$ H, E

$\rightsquigarrow$ Allow for flavour separation:

$$H_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u + \frac{1}{3}H^d + \frac{3}{8}H^g\right)$$
$$H_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u - \frac{1}{3}H^d + \frac{1}{8}H^g\right)$$
$$H_{\phi} = -\frac{1}{3}H^s - \frac{1}{8}H^g$$

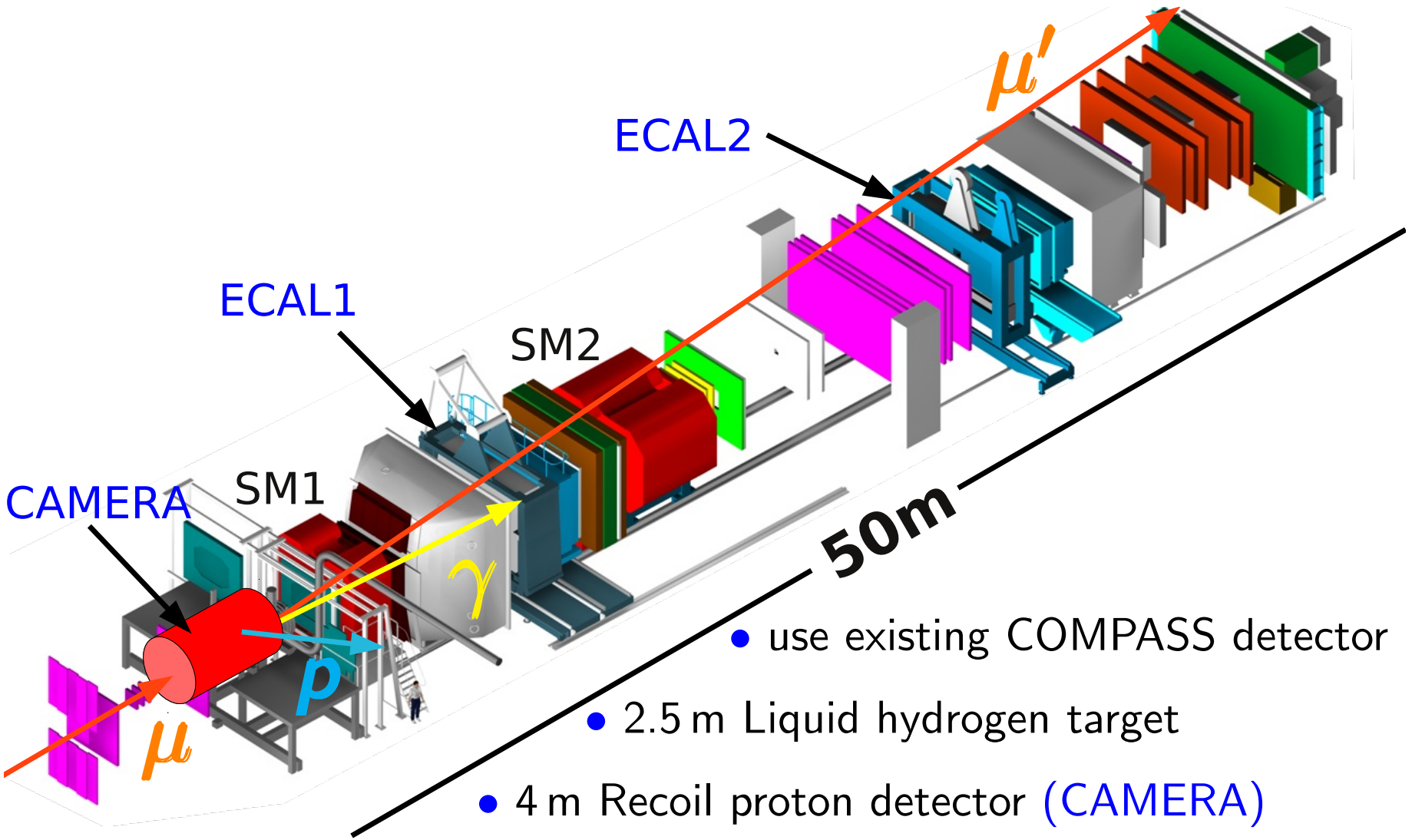
- Gluons contribute at same order in α_s

COMPASS-II (GPD programme) @ CERN/SPS



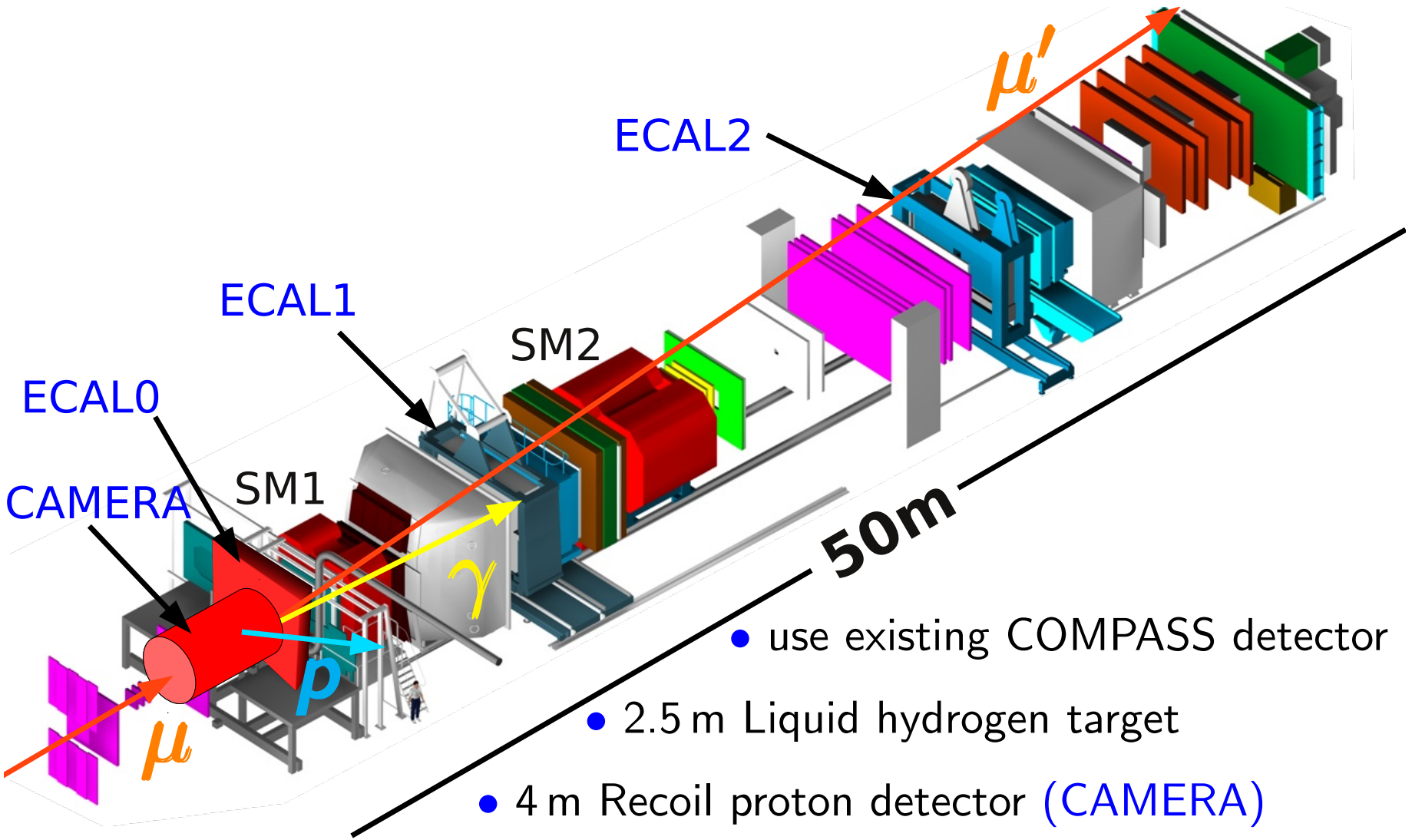
- use existing COMPASS detector

COMPASS-II (GPD programme) @ CERN/SPS



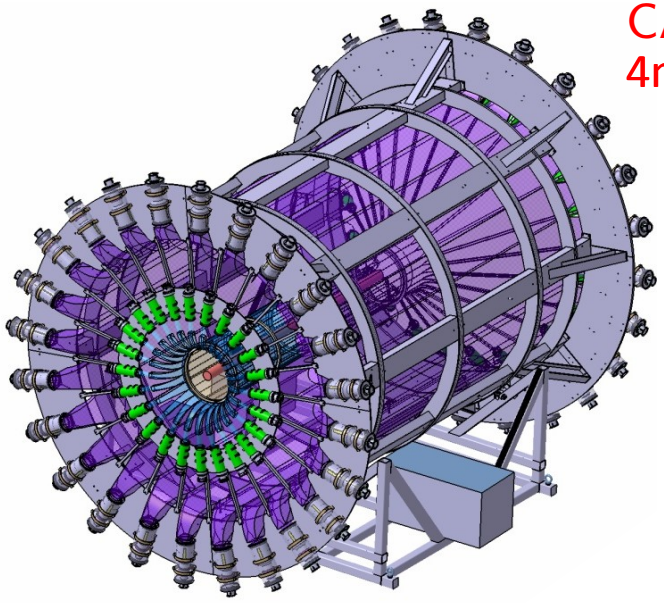
- use existing COMPASS detector
- 2.5 m Liquid hydrogen target
- 4 m Recoil proton detector (CAMERA)

COMPASS-II (GPD programme) @ CERN/SPS



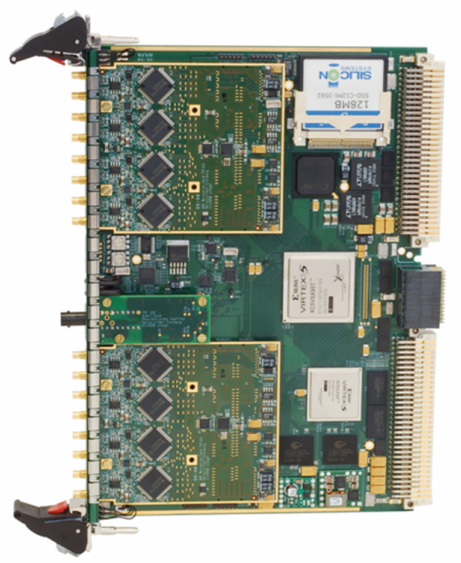
- use existing COMPASS detector
- 2.5 m Liquid hydrogen target
- 4 m Recoil proton detector (CAMERA)
- New large angle em. calorimeter in front of SM1 (ECAL0)

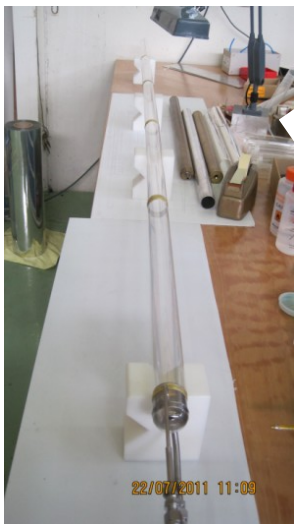
New Hardware Developments



CAMERA:
4m long ToF barrel

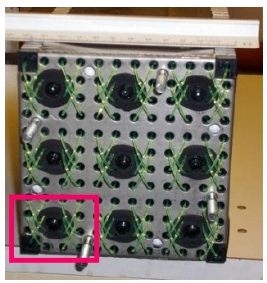
+ 1 GHz digitization of the PMT signal to cope for high rate (GANDALF boards)

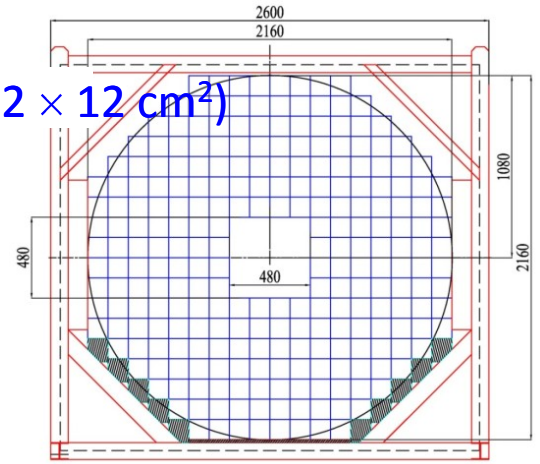




Prototype of the
2.5m long LH2 target
+ test of the cryostat

ECAL0 made of 248 modules (12×12 cm^2)
of 9 cells read by 9 MAPDs





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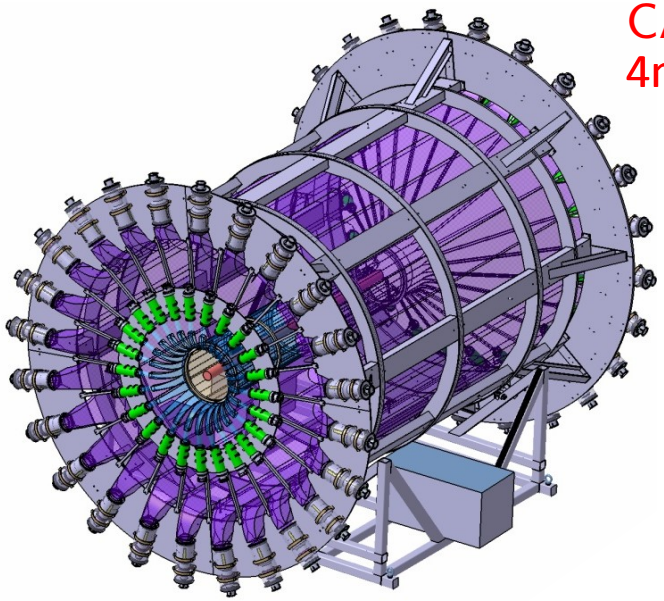

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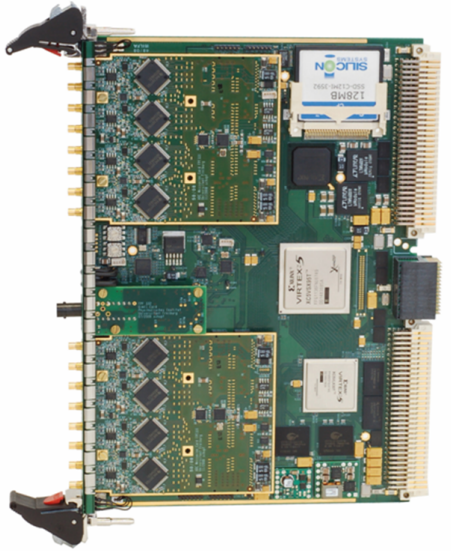
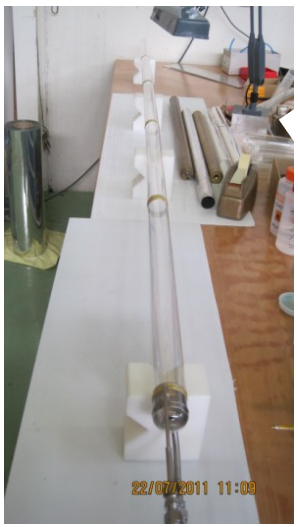


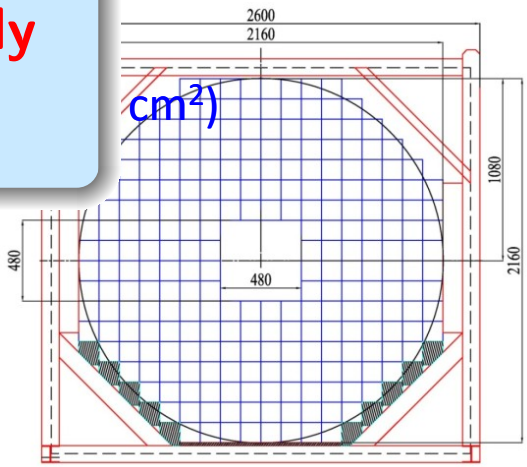


For 2012 pilot run:

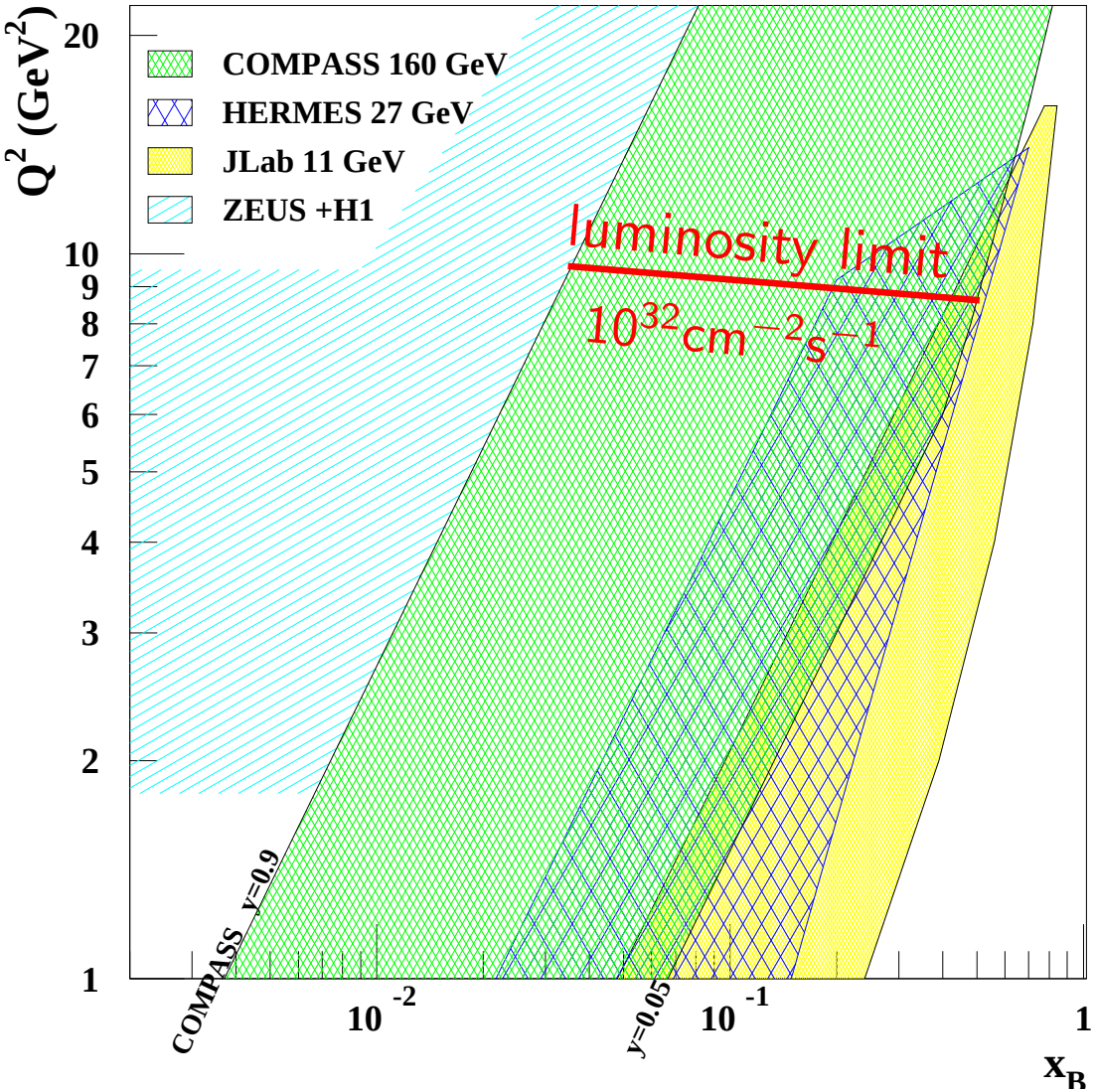
LH_2 target and CAMERA will be ready

prototype of ECAL0 will be ready

Prototype of the
2.5m long LH2 target
+ test of the cryostat



Unique Feature of COMPASS-II @ CERN/SPS



- coverage of intermediate x_{Bj}

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

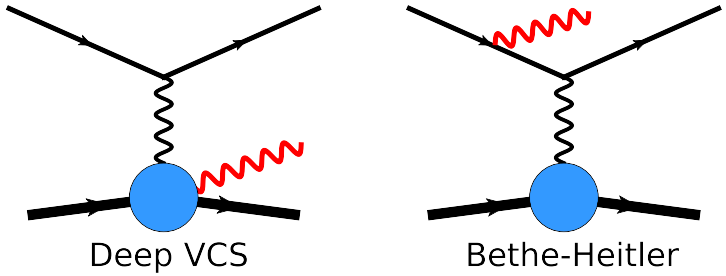
- μ^+ and μ^- beams
- momentum: $100 - 190\,\mathrm{GeV}/c$
- polarisation: 80 %

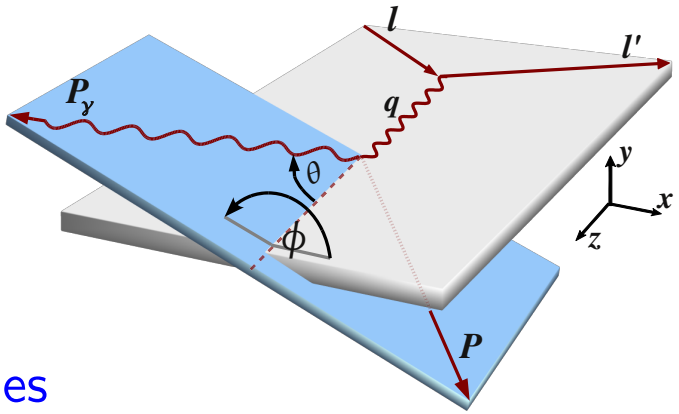
  opposite for μ^+ and μ^-

$\rightsquigarrow$ Beam Charge and Spin Sum/Difference of $\mathrm{d}\sigma_{(\mu p \to \mu' p' \gamma)}$

$\rightsquigarrow$ study its ϕ-dependence

$\mu p \to \mu' p' \gamma$: Interference with Bethe-Heitler

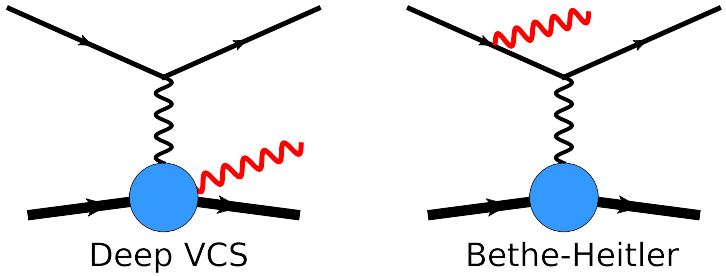


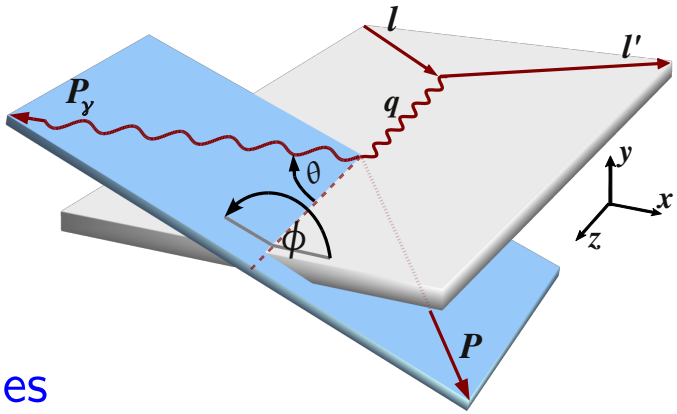


both processes interfere on level of amplitudes

$$d\sigma_{(\mu p \to \mu' p' \gamma)} \propto |T^{BH}|^2 + \text{Interference Term} + |T^{DVCS}|^2$$

$\mu p \to \mu' p' \gamma$: Interference with Bethe-Heitler





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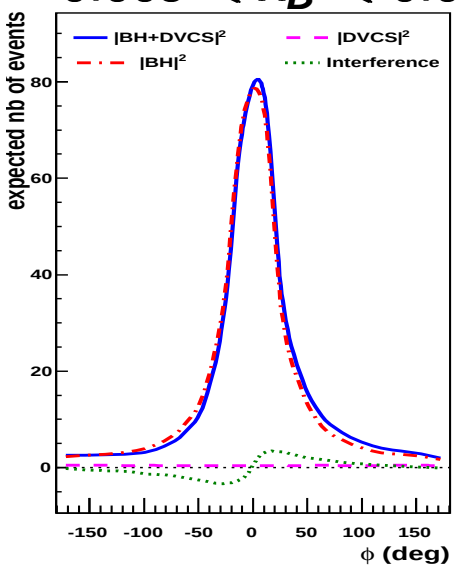
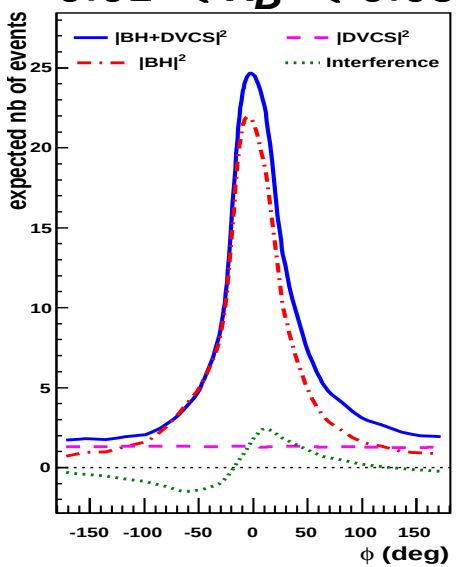
$0.005 < x_B < 0.01$



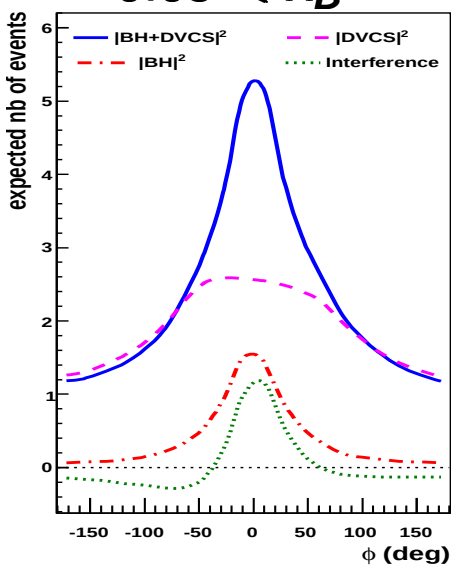
BH dominates

$0.01 < x_B < 0.03$



Interference

$0.03 < x_B$



DVCS dominates

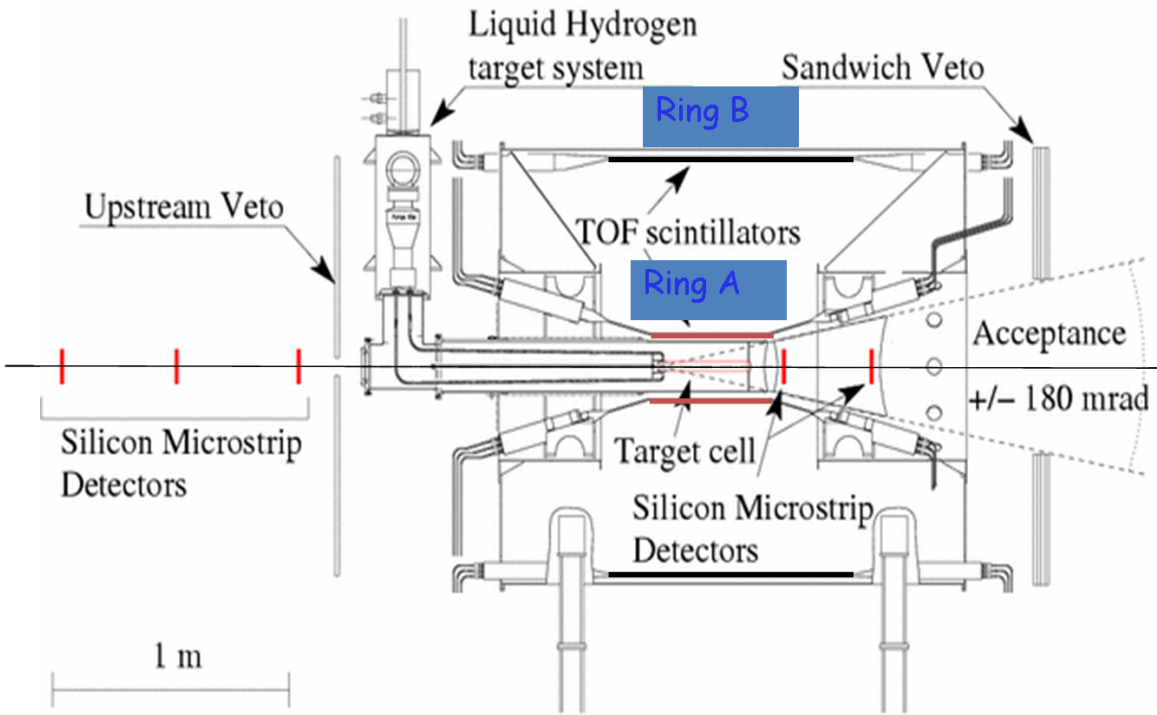
MC simulation for COMPASS without ECAL0

$\rightsquigarrow$ reference yield

DVCS: Testrun 2008 and 2009

Beam Tests @ COMPASS during hadron programme:

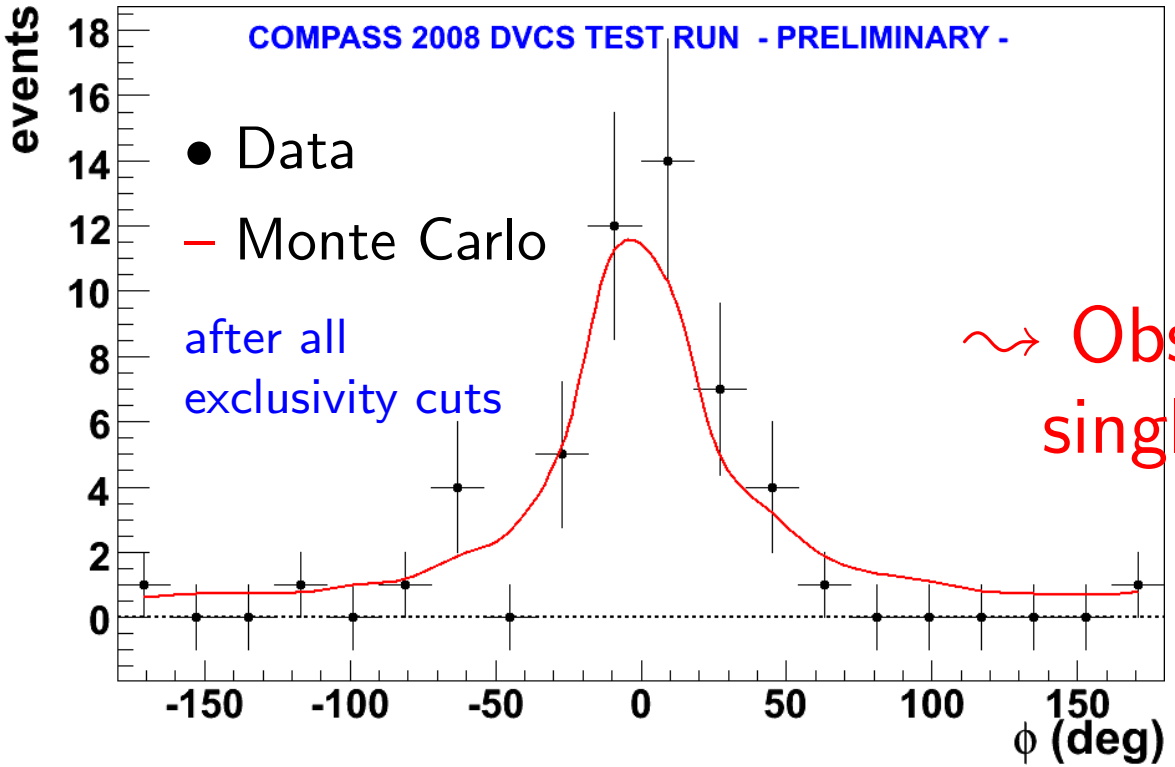
- 2008 (8 hours)
- 2009 (10 times statistics of 2008)



Target Setup for the Hadron Programme (2008-2009):

- Target: 40 cm LH_2
- Recoil Detector (1 m long)
- ECAL1 & ECAL2

2008 test: Bethe-Heitler Signal



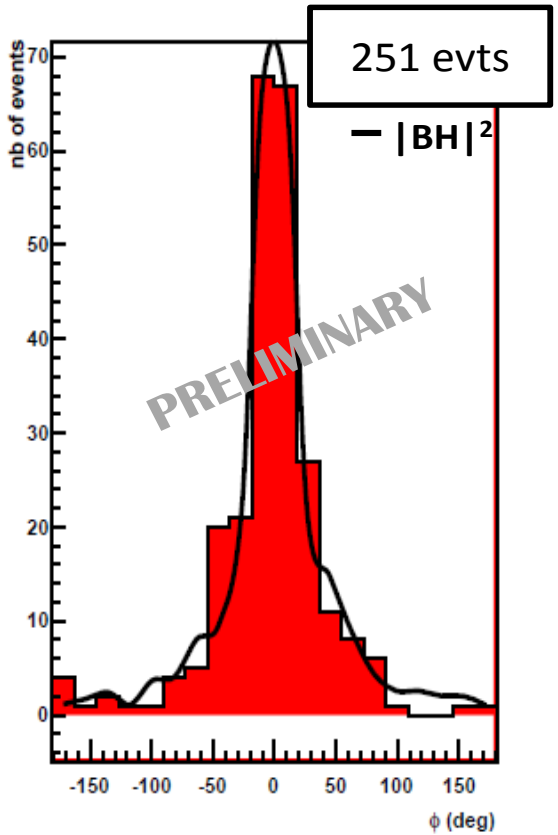
$\rightsquigarrow$ Observation of exclusive single photon production

- $\epsilon_{\mu p \to \mu' p' \gamma} = 0.32 \pm 0.13$
- SPS & COMPASS availability
- DAQ dead time
- Trigger efficiency

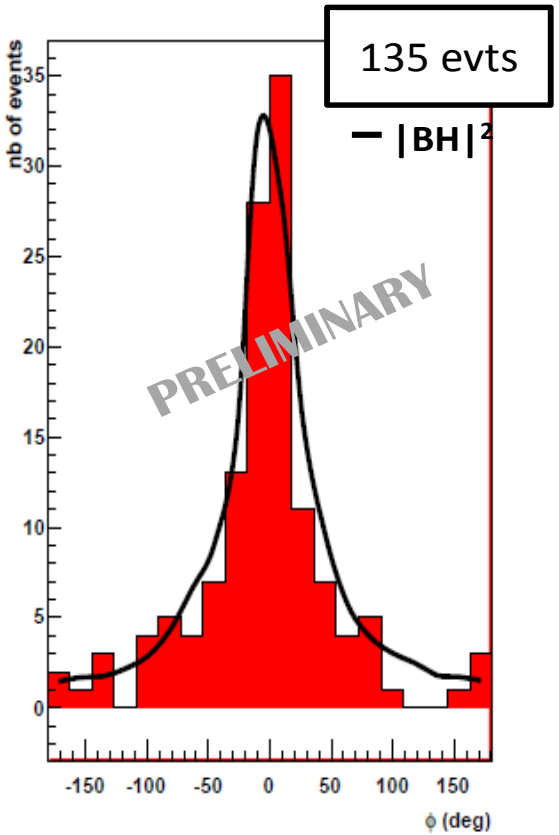
global efficiency: $\epsilon_{global} = 0.13 \pm 0.05$

Important input for projections!

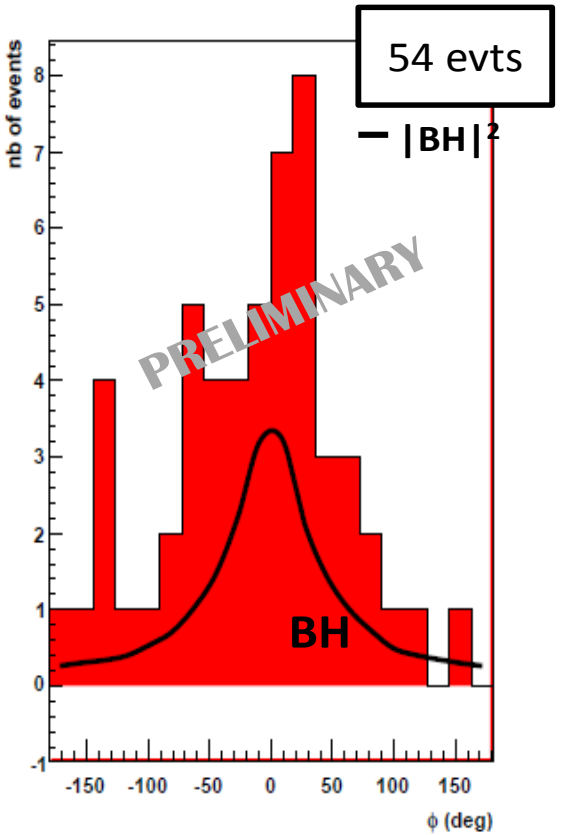
2009 test: DVCS and BH Signal



$0.005 < x_B < 0.01$



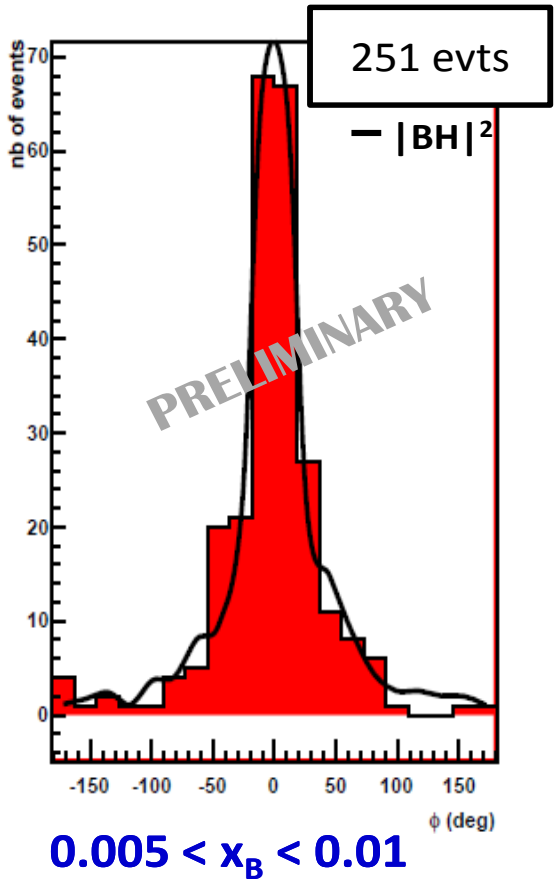
$0.01 < x_B < 0.03$



$0.03 < x_B$

- measurement with 40 cm LH_2 target + 1 m RPD
- Excess of events for $x_B > 0.03 \rightsquigarrow$ DVCS events

2009 test: DVCS and BH Signal



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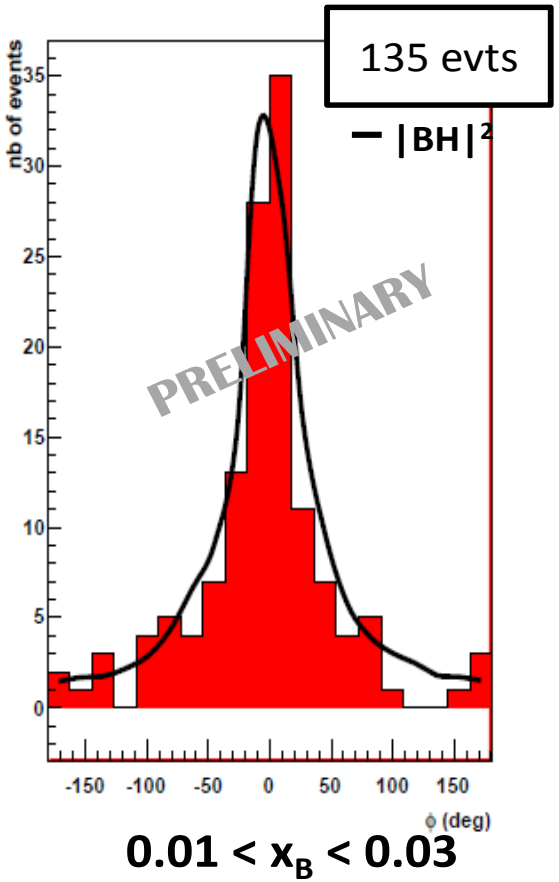

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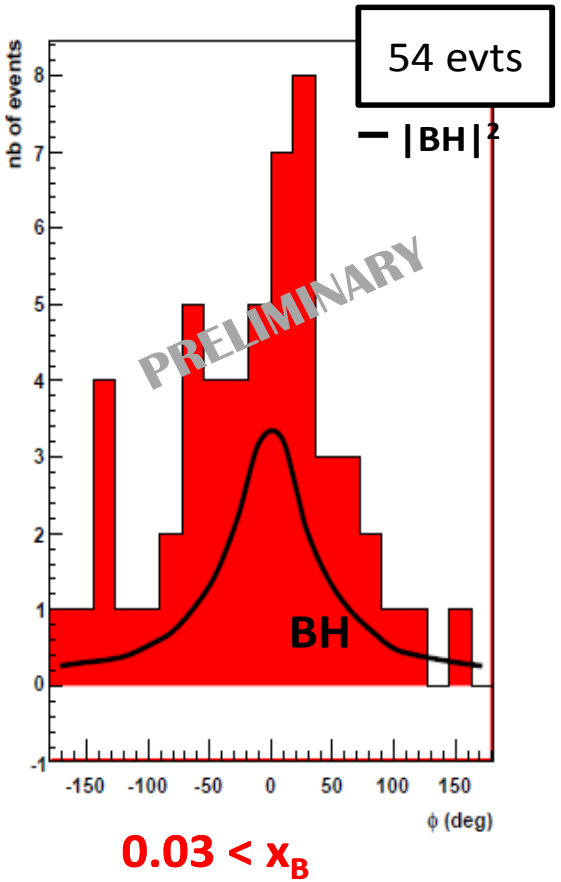
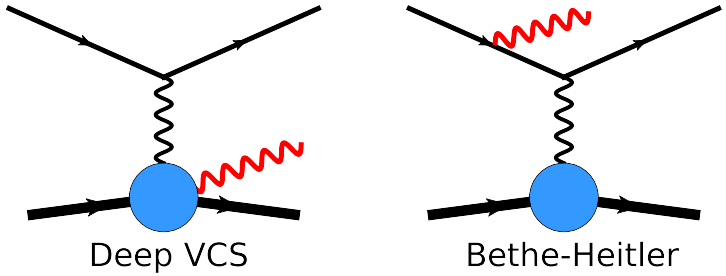


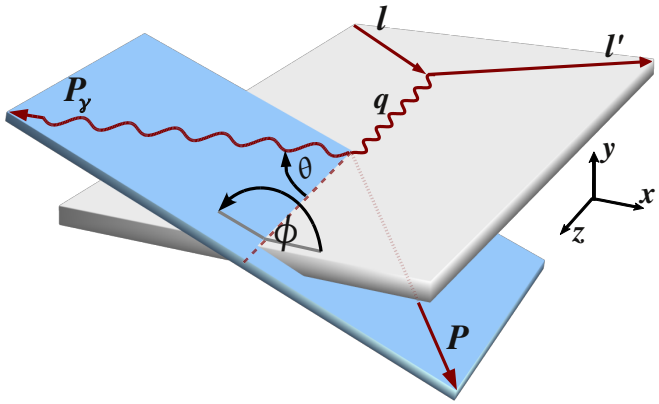
$0.03 < x_B$

- measurement with 40 cm LH_2 target + 1 m RPD
- Excess of events for $x_B > 0.03 \rightsquigarrow$ DVCS events

This year we expect to increase statistics by factor 10!

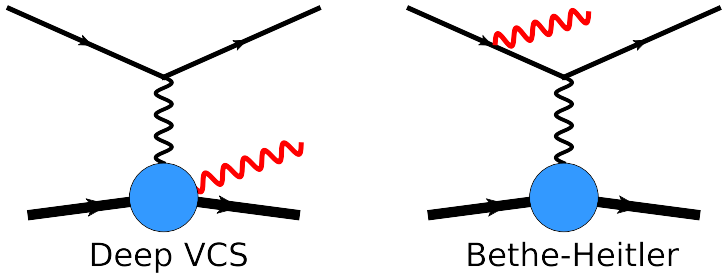
Deeply Virtual Compton Scattering

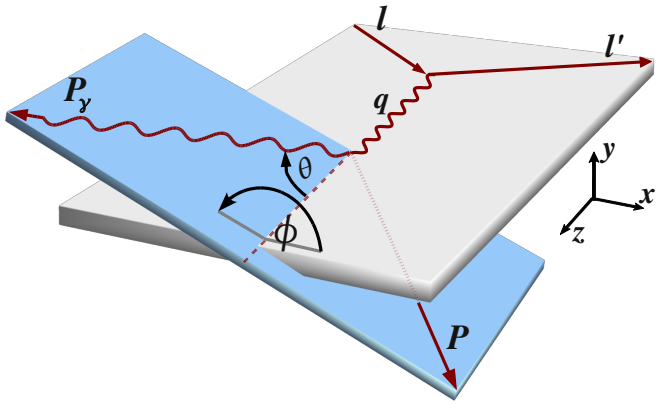




$$d\sigma_{(\mu p \to \mu' p' \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathrm{Re}(T^{DVCS}) + e_\mu P_\mu a^{BH} \mathrm{Im}(T^{DVCS})$$

Deeply Virtual Compton Scattering





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- Beam charge and Spin sum:

$$\mathcal{S}_{CS,U} \equiv d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH} \mathrm{Im}(T^{DVCS})\right)$$

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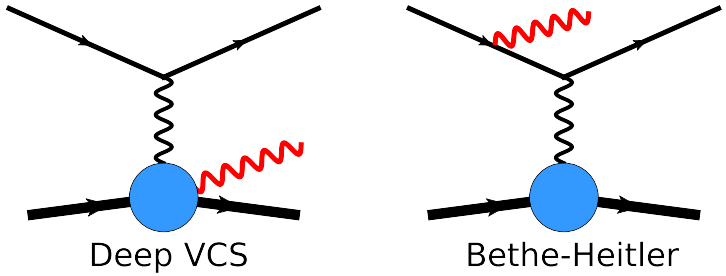

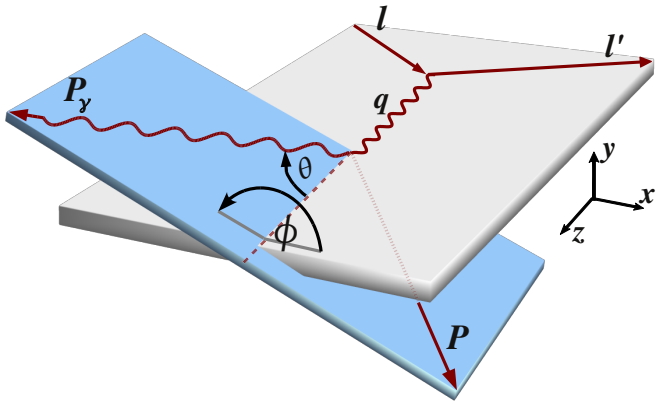

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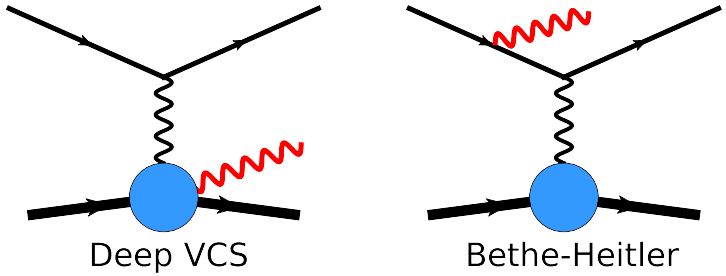
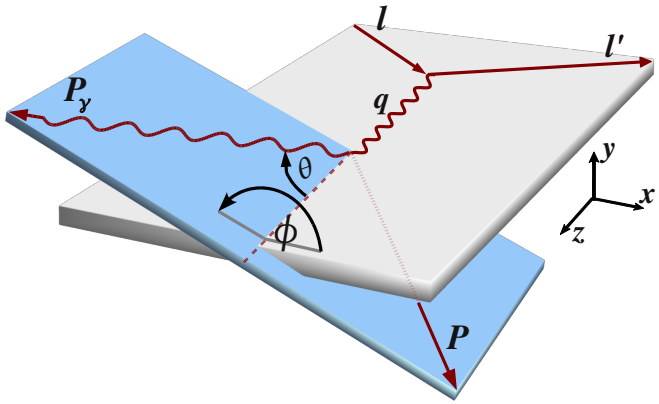
- ϕ dependence gives access to GPD H

$$\propto s_1^{Int} \sin\phi$$
$$s_1^{Int} \propto \mathrm{Im}(\mathrm{F}_1\mathcal{H})$$

Deeply Virtual Compton Scattering





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- ϕ dependence gives access to GPD H

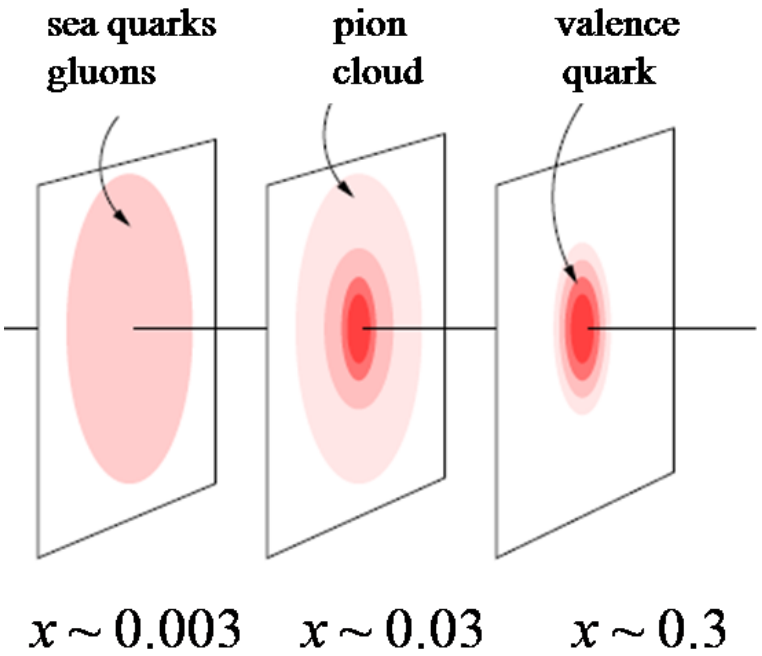
$$\mathcal{H}(\xi,t) = \sum_f e_f^2 \int dx\, H^f(x,\xi,t) \frac{1}{x-\xi-i\epsilon}$$

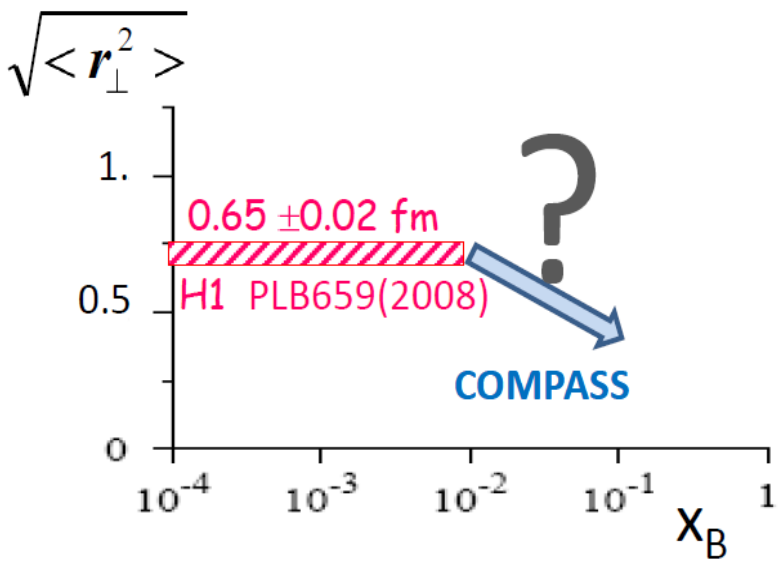
$$\rightsquigarrow \mathrm{Im}(\mathcal{H}(\xi,t)) \propto H(x=\xi,\xi,t)$$

$\propto s_1^{Int} \sin\phi$

$s_1^{Int} \propto \mathrm{Im}(F_1\mathcal{H})$

DVCS: Transverse Size of the Nucleon



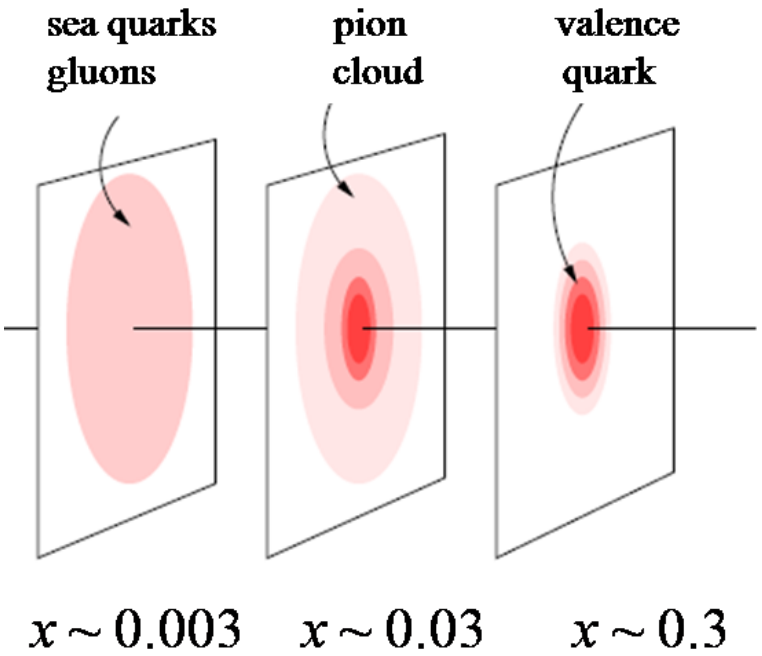


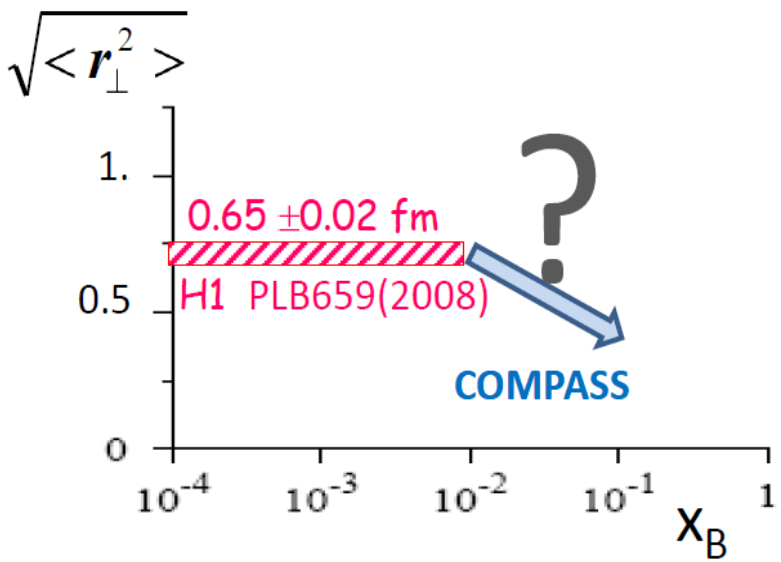
- Integration over ϕ and subtracting BH:

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

  $B(x_B) \sim \frac{1}{2}\langle r^2_\perp(x_B)\rangle$

DVCS: Transverse Size of the Nucleon





- Integration over ϕ and subtracting BH:

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

  $B(x_B) \sim \frac{1}{2}\langle r^2_\perp(x_B)\rangle$

- Ansatz at small x_B: $(x \sim x_B)$

  $B(x_B) = b_0 + 2\alpha' ln(x_0/x_B)$

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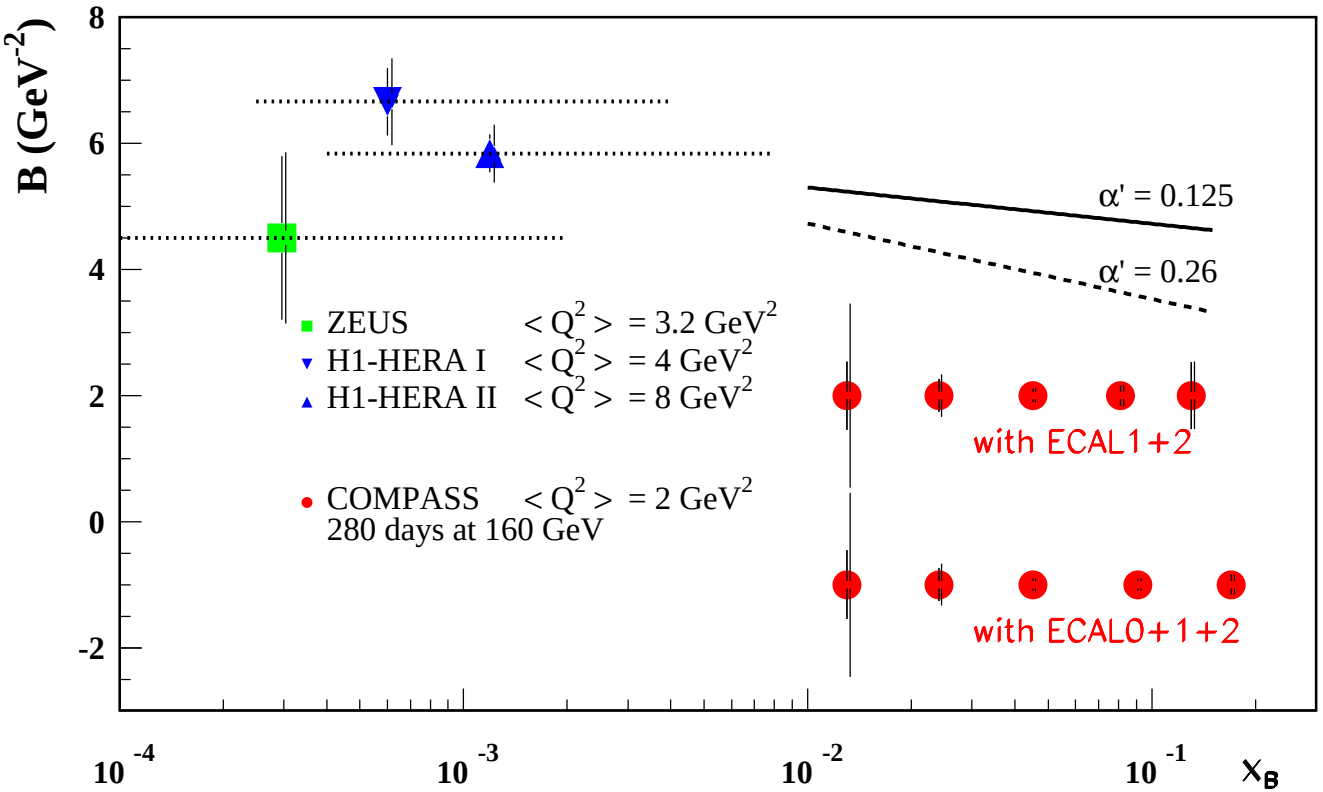


Input for projections:

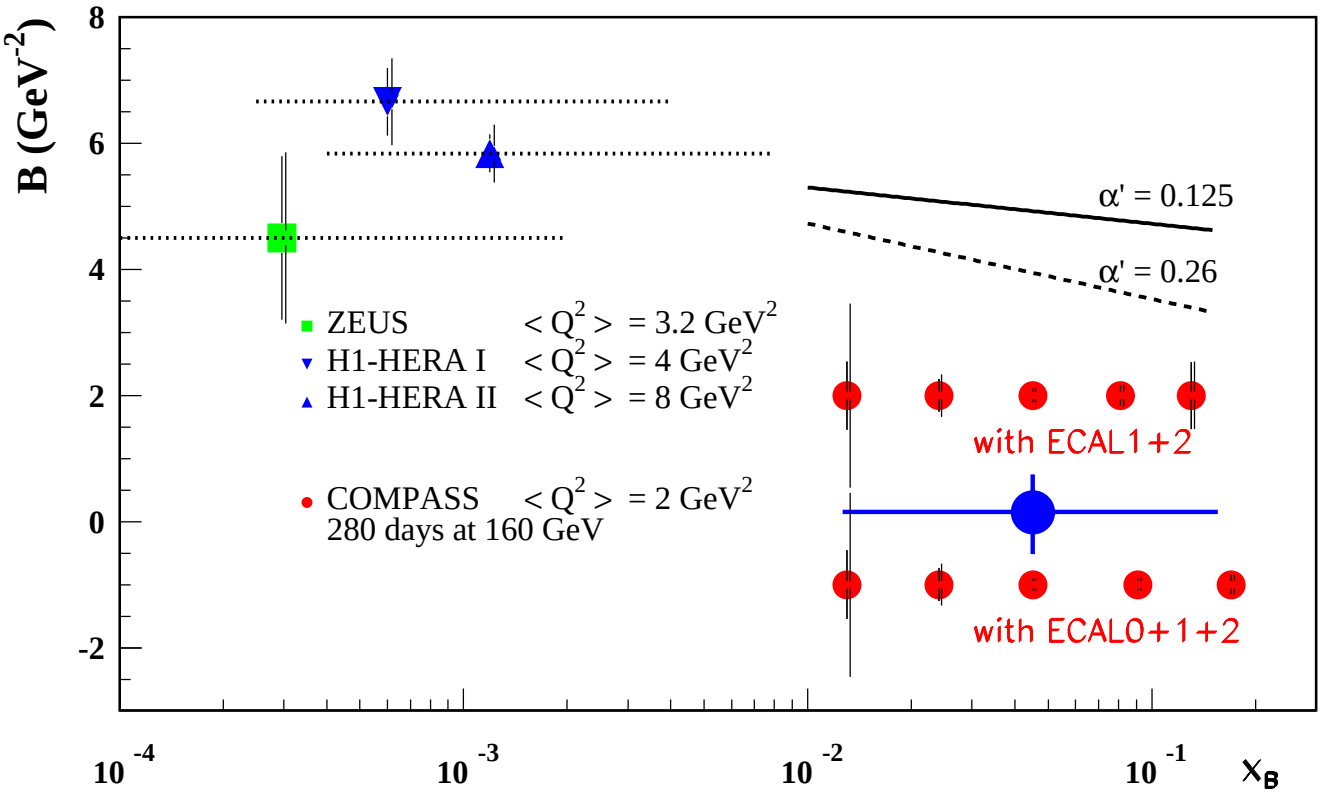
- L=1222 pb^{-1}
  2 years of data
- 160 GeV/c muon beam
- 4.6×10^8 μ^+ / per spill
  (9.6 s every 48 s)
- 2.5 m LH_2 target
- $\epsilon_{global} = 10\,\%$

- At low x_B systematic error is dominated by BH subtraction
  (with assumption that BH yield is known within 3 %)
- Accuracy $> 2.5\,\sigma$

  for: $\alpha' > 0.26$ (with ECAL 1+2)

  for: $\alpha' > 0.125$ (with ECAL 0+1+2)

DVCS: Transverse Size of the Nucleon



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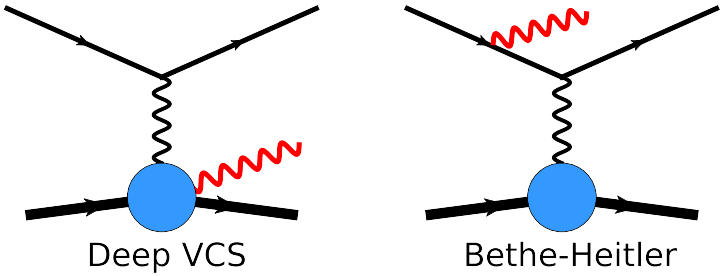
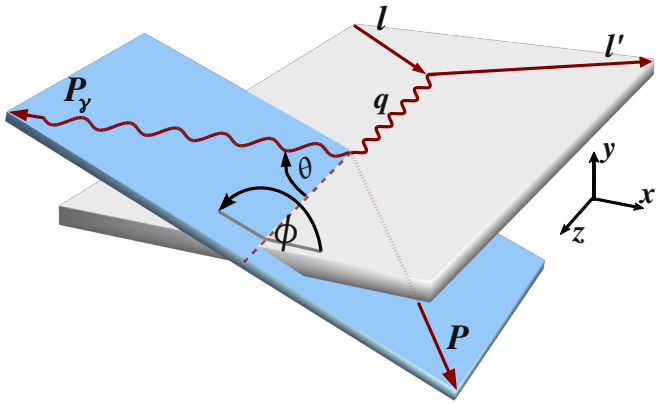
- 2.5 m LH_2 target
- $\epsilon_{global} = 10\,\%$

In 2012 we can determine one mean value of B

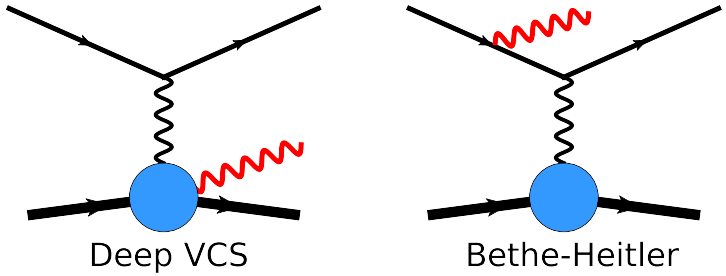
Deeply Virtual Compton Scattering

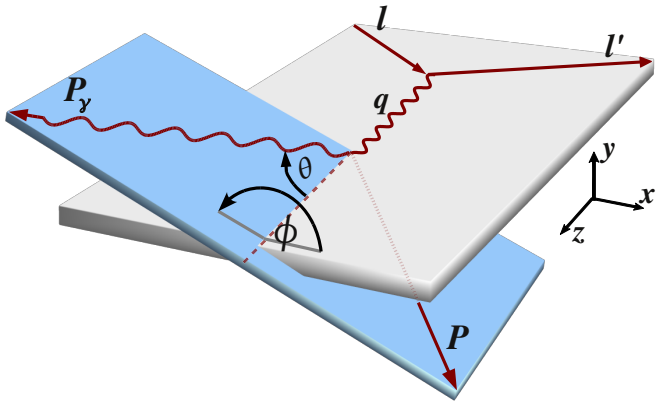




$$d\sigma_{(\mu p \to \mu' p' \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathrm{Re}(T^{DVCS}) + e_\mu P_\mu a^{BH} \mathrm{Im}(T^{DVCS})$$

Deeply Virtual Compton Scattering





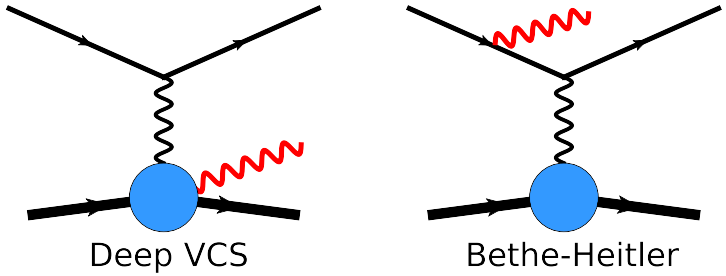
$$d\sigma_{(\mu p \to \mu' p' \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathrm{Re}(T^{DVCS}) + e_\mu P_\mu a^{BH} \mathrm{Im}(T^{DVCS})$$

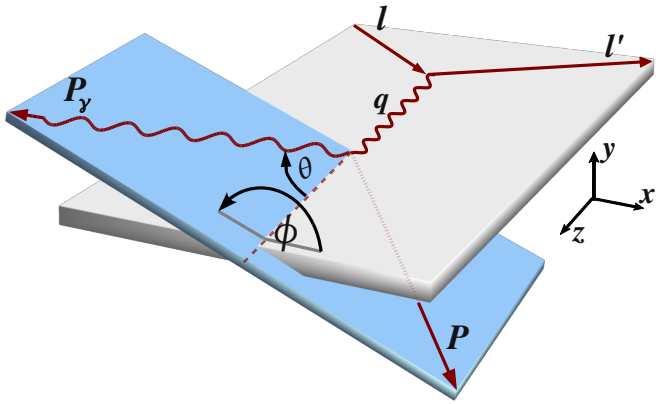
- Beam charge and Spin difference:

$$\mathcal{D}_{CS,U} \equiv d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathrm{Re}(T^{DVCS})\right)$$

$\Rightarrow$ BH contribution cancels

Deeply Virtual Compton Scattering





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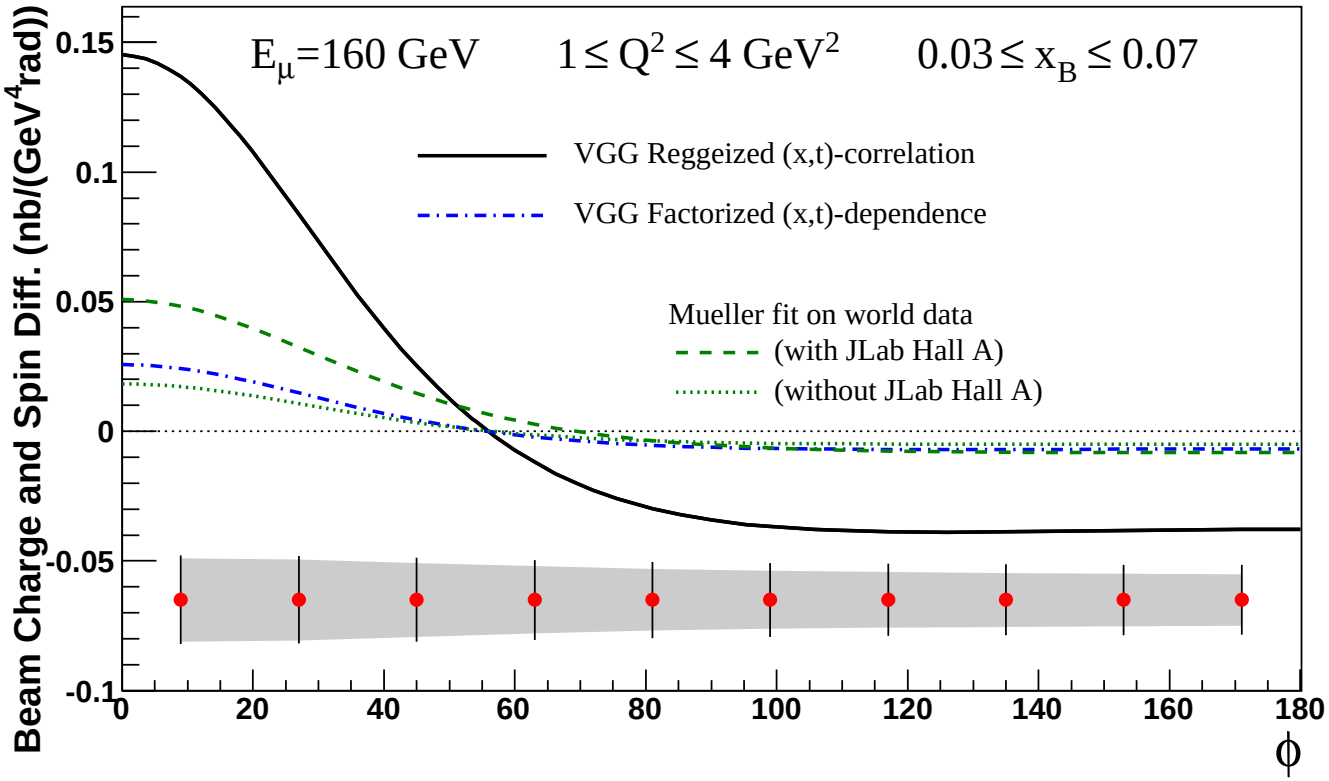
$$\propto c_0^{Int} + c_1^{Int}\cos\phi;\quad c_{0,1}^{Int} \propto \mathrm{Re}(F_1\mathcal{H})$$

$$\mathrm{Re}(\mathcal{H}(\xi,t)) = \sum_f e_f^2\left[\mathcal{P}\int dx\, H^f(x,\xi,t)\frac{1}{x-\xi}\right]$$

DVCS: Beam Charge and Spin Difference



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- 2.5 m LH_2 target
- ECAL0 + 1 + 2
- $\epsilon_{global} = 10\,\%$

- Systematic error assumes 3% charge dependent effect between μ^+ and μ^-
- Statistics permit 2 dimensional analysis:
  e.g. 6 bins in x_B and 6 in t

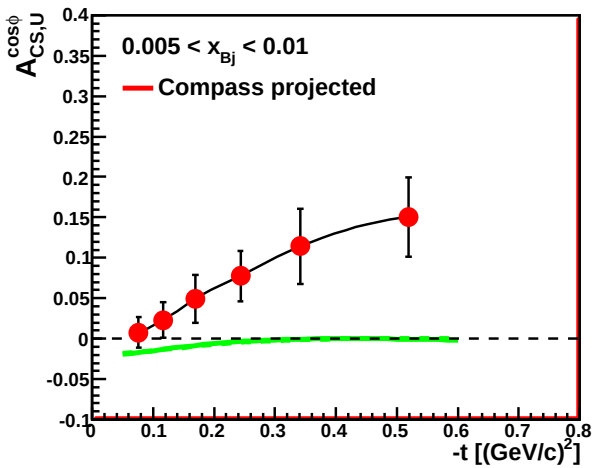
DVCS: $\mathcal{BCSA} = \mathcal{D}_{CS,U}/\mathcal{S}_{CS,U} \rightsquigarrow A_{CS,U}^{\cos\phi} \cos\phi$

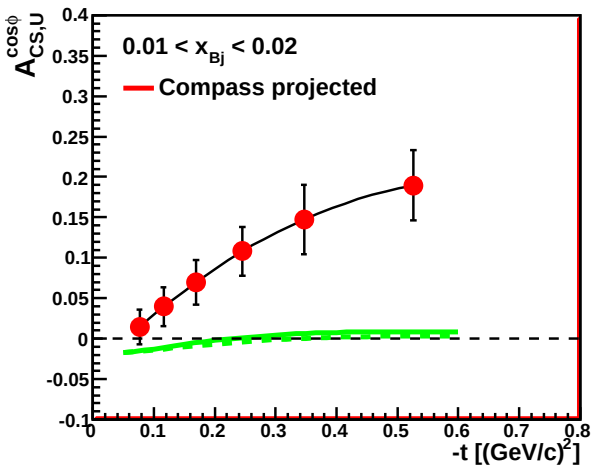
Related to $c_1^{Int} \rightsquigarrow \propto \mathrm{Re}(F_1\mathcal{H})$

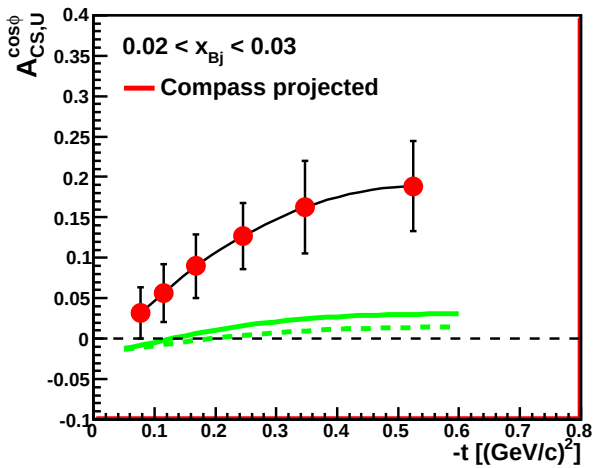
$\mathrm{Re}(F_1\mathcal{H}) > 0$ at H1; $\mathrm{Re}(F_1\mathcal{H}) < 0$ at HERMES/JLab

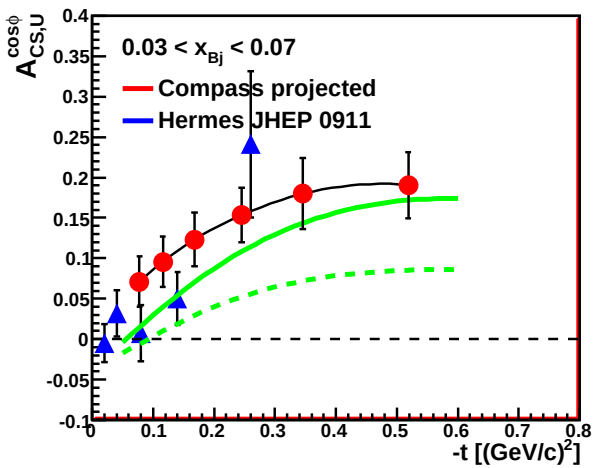
Mueller's fits to world data

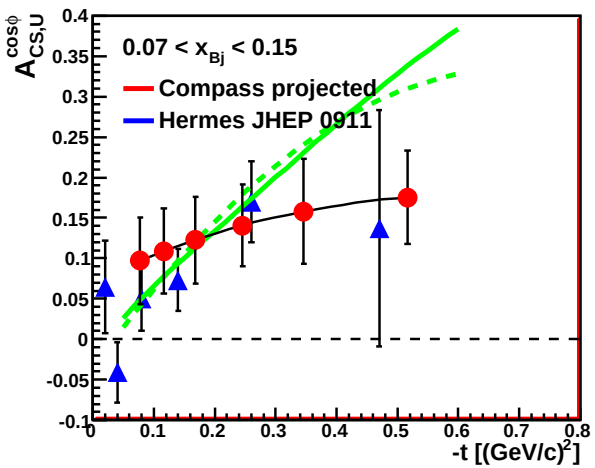
VGG

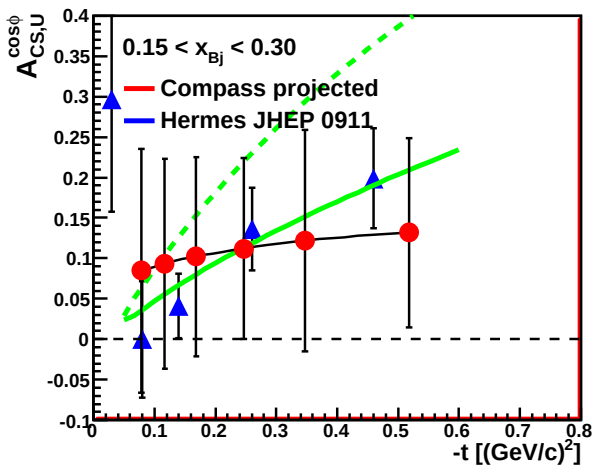












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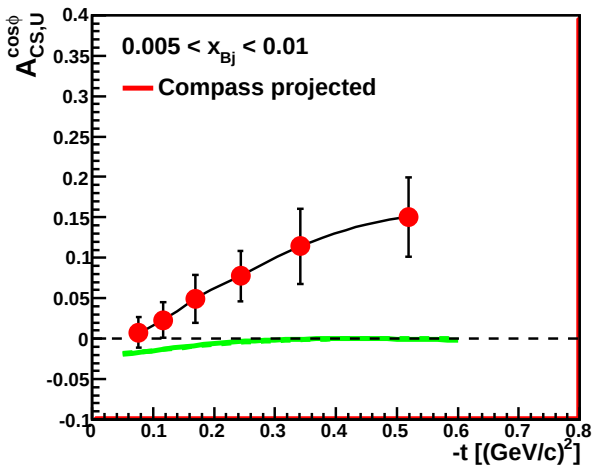
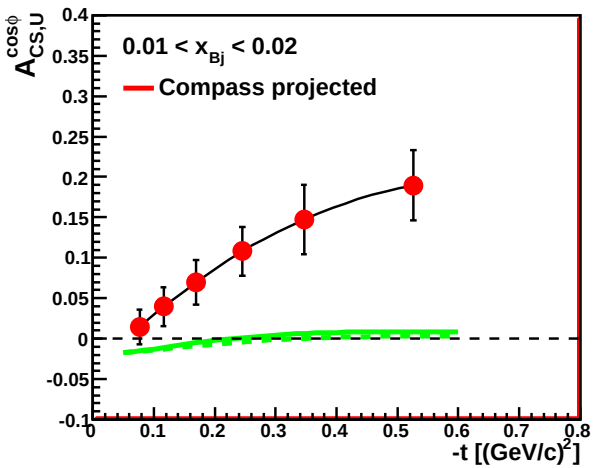
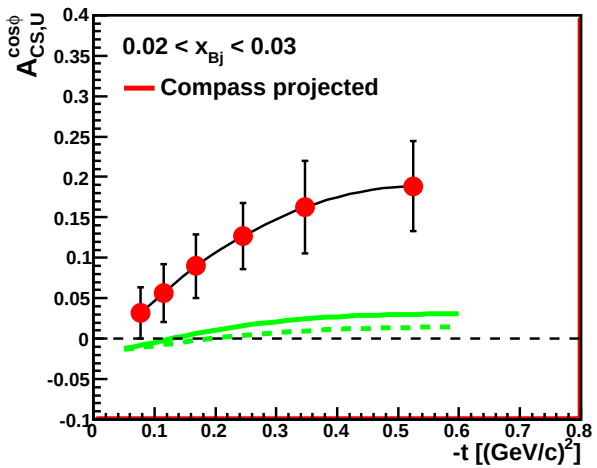
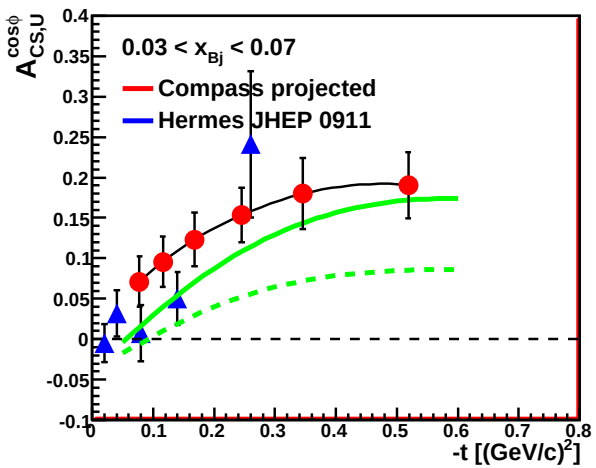
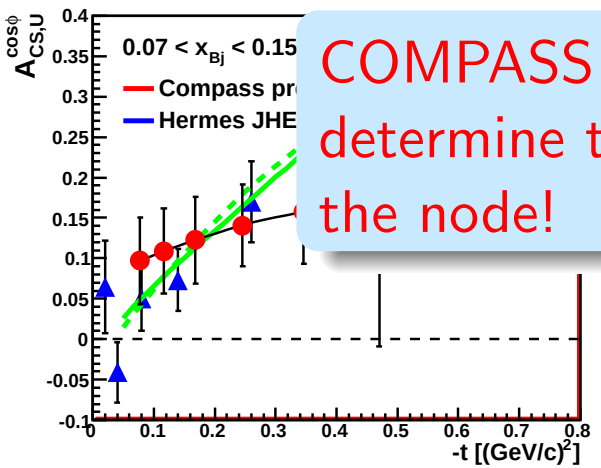
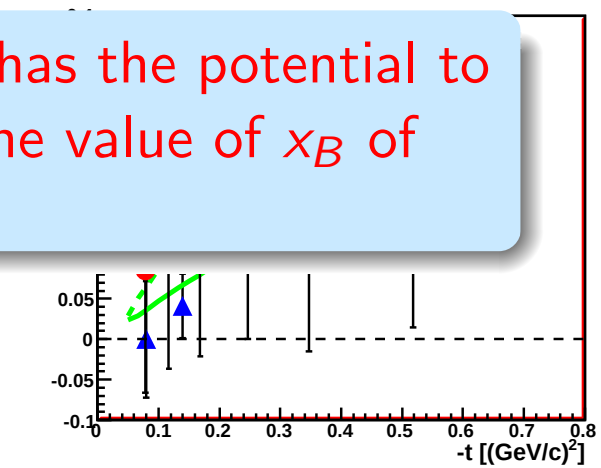






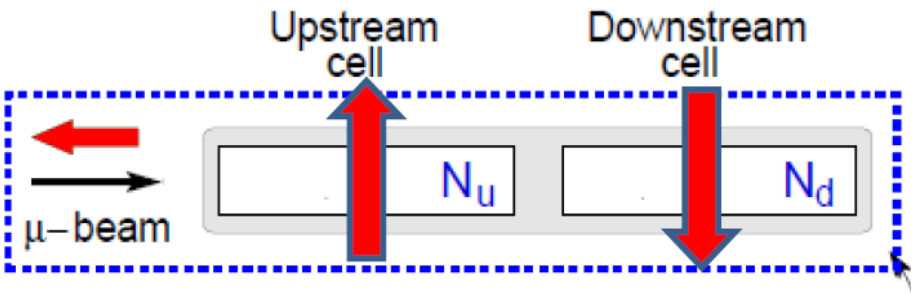


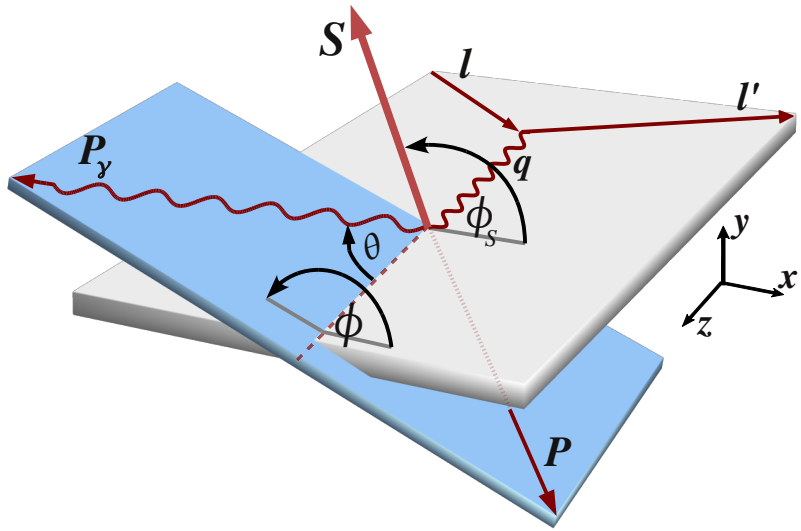




COMPASS has the potential to determine the value of x_B of the node!

Phase 2: Constraints on GPD E





DVCS measurements with $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams and transversely polarised proton target (NH_3):

$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\leftarrow}) - d\sigma_T(\mu^{-\rightarrow})$$

with $d\sigma_{T,(\mu p \to \mu' p' \gamma)} \equiv d\sigma(\phi_S) - d\sigma(\phi_S + \pi)$

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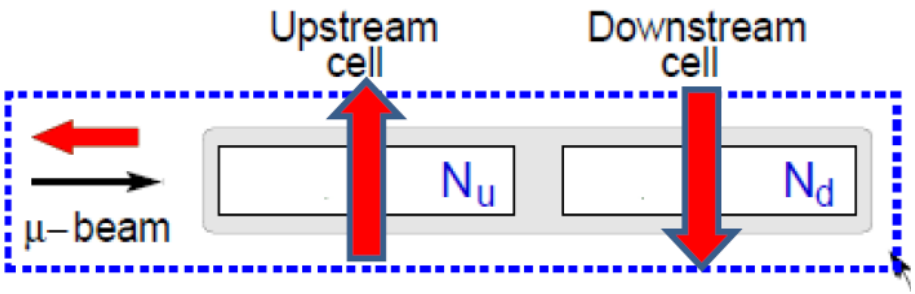

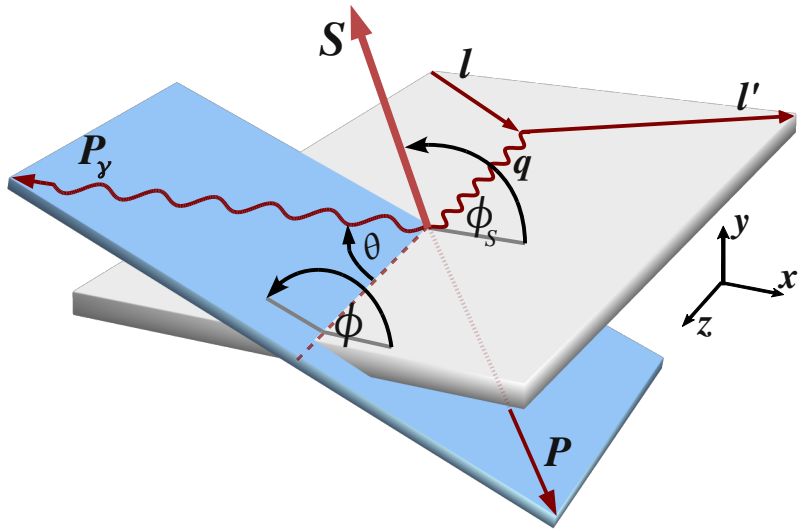

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$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\leftarrow}) - d\sigma_T(\mu^{-\rightarrow}) \propto \mathrm{Im}(F_2\mathcal{H} - F_1\mathcal{E}) \sin(\phi - \phi_S) \cos\phi$$

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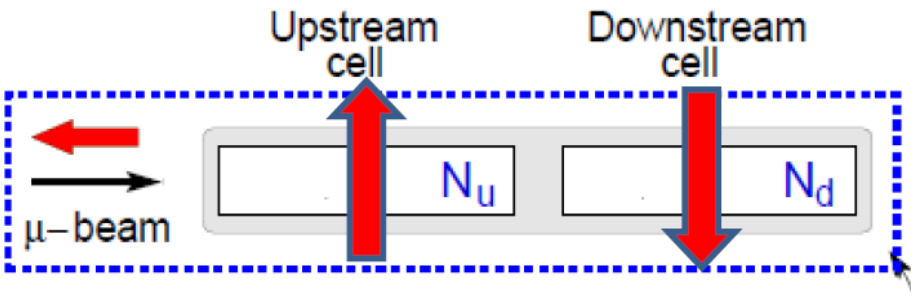
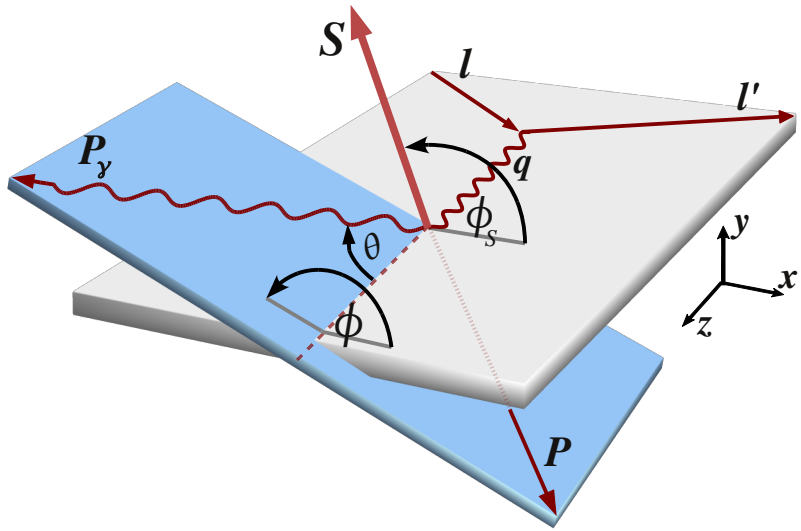
Phase 2: Constraints on GPD E





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with $d\sigma_{T,(\mu p \to \mu' p' \gamma)} \equiv d\sigma(\phi_S) - d\sigma(\phi_S + \pi)$

Ji's sum rule:

$$J^q = S^q + L^q = \frac{1}{2}\int_{-1}^{1} dx\, x\, [H^q(x,\xi,0) + E^q(x,\xi,0)]$$

Phase 2: DVCS Transverse Target Spin Asymmetry

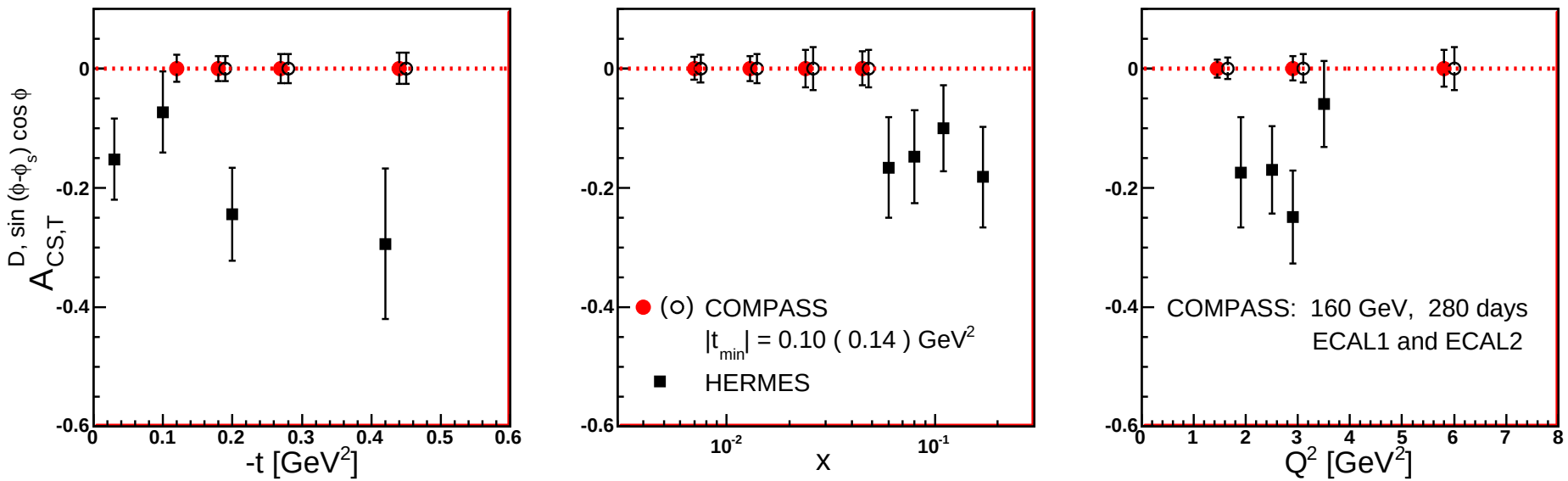
Projections for Asymmetry:

$$A^D_{CS,T} \equiv \mathcal{D}_{CS,T}/\mathrm{d}\sigma_0$$

$\mathrm{d}\sigma_0$ is unpolarised charge averaged cross-section

Input for projections:

- L=1222 pb^{-1} (2 years of data)
- $\epsilon_{global} = 10\,\%$
- 160 GeV/c muon beam
- 1.2 m polarised NH_3 target
- ECAL1 + 2



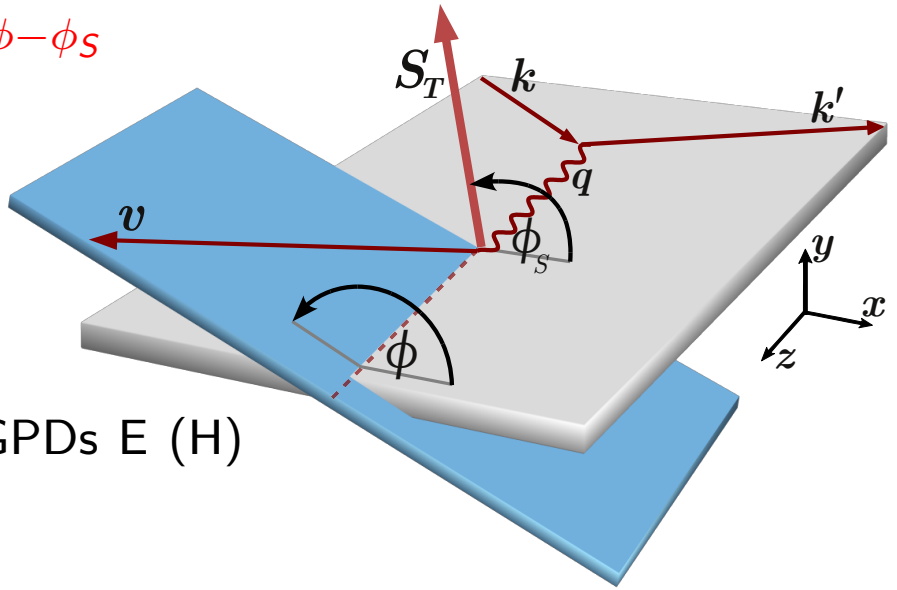
- compact RPD inside existing COMPASS polarised target
- ○ transversely polarised target inside RPD

HEMP: Transverse Target Spin Asymmetry

Transverse target spin asymmetry: $A_{UT}^{\sin\phi-\phi_S}$

$$A_{UT}^{\sin\phi-\phi_S} \propto \sqrt{|-t'|}\,\frac{\mathrm{Im}(\mathcal{E}^*\,\mathcal{H})}{|\mathcal{H}|^2}$$

$\rightsquigarrow$ sensitive to GPD E



$\mathcal{E}$ ($\mathcal{H}$) are weighted sums of convolutions of GPDs E (H) with hard scattering kernel and meson GDA

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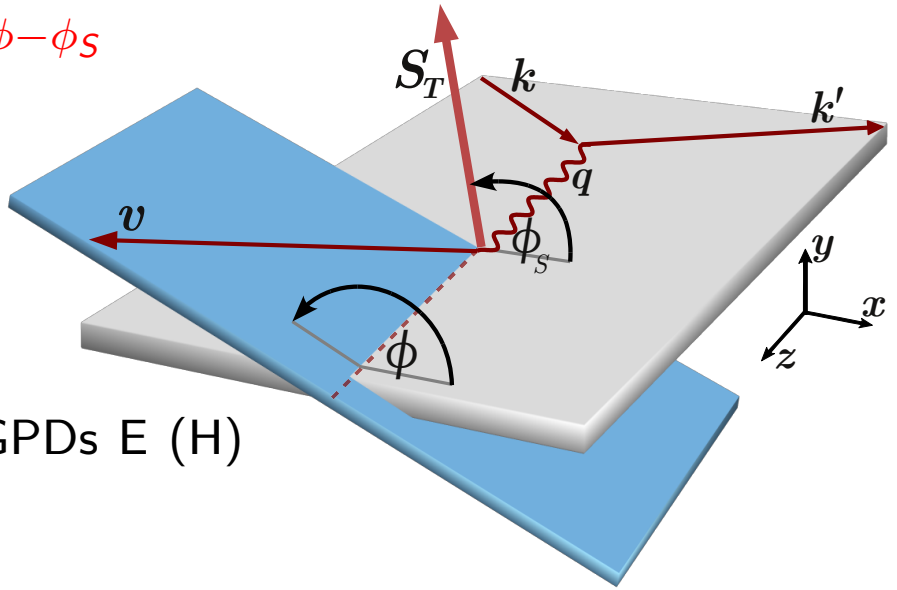


$\mathcal{E}$ ($\mathcal{H}$) are weighted sums of convolutions of GPDs E (H) with hard scattering kernel and meson GDA

$A_{UT}^{\sin\phi-\phi_S}$ in exclusive ρ^0 production studied at COMPASS using technique of missing energy

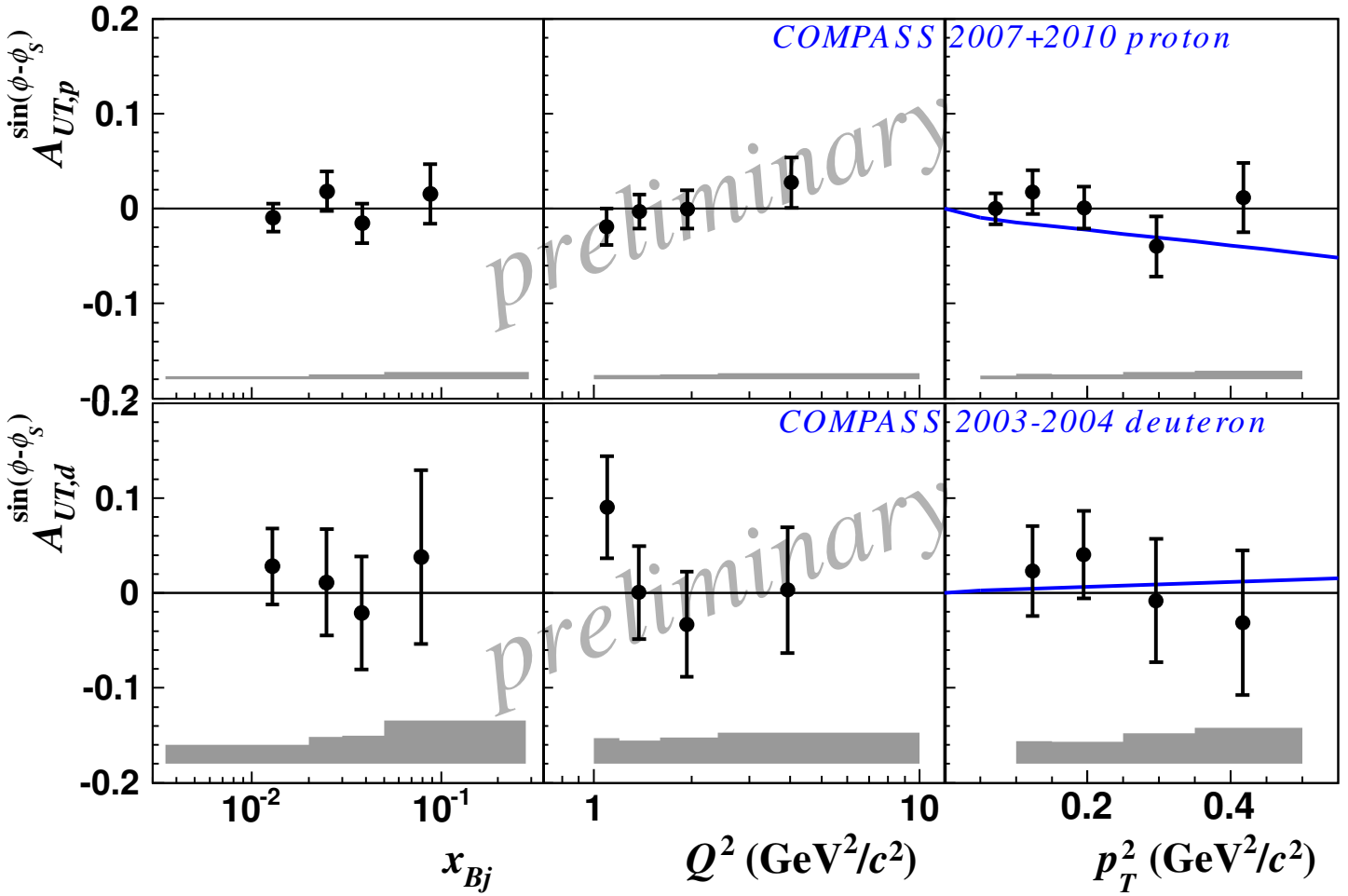
- Analysed data:

  2003 & 2004 ^{6}LiD target (transv. polarised deuterons)

  2007 & 2010 NH_3 target (transv. polarised protons)

- Subtraction of SIDIS background, suppression of coherent production, suppression of non-resonant $\pi^+\pi^-$ production

Result $A_{UT}^{\sin\phi-\phi_S}$ - for proton and deuteron



- Asymmetries are small, compatible with zero within uncertainties
- In agreement with model: Goloskokov and Kroll, Eur. Phys. J. C 59 4 (2009)

$\rightsquigarrow$ approximate cancellation of sizable E^u and E^d $\left(E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{8}E^g\right)\right)$

Summary

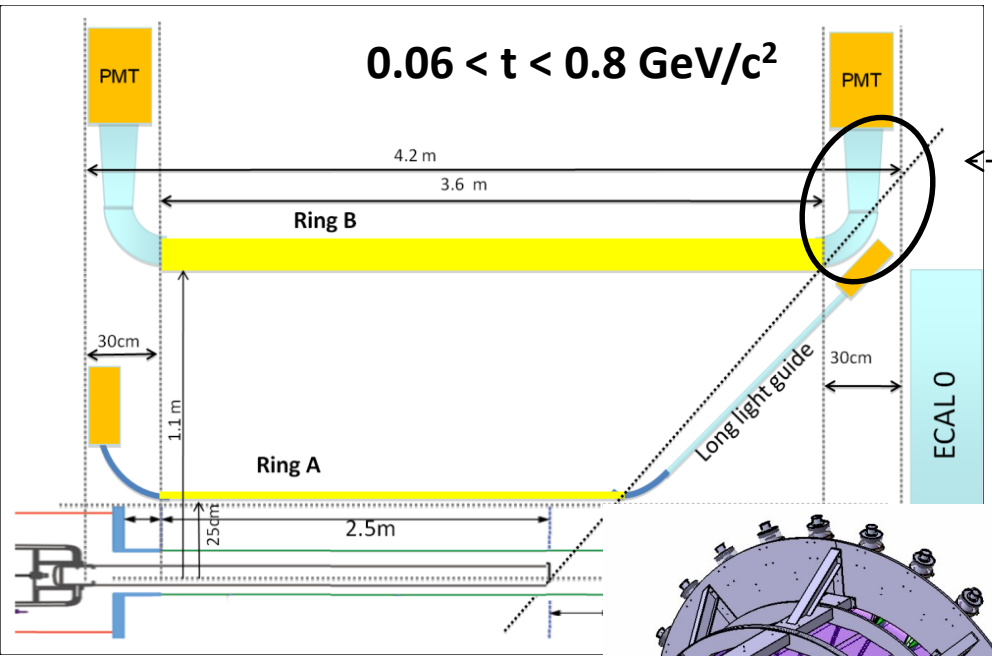
- COMPASS-II will investigate quark GPDs with DVCS
  - Covered x_B/Q^2 regime not accessible to any other experiment in the near future
  - Change of beam charge and polarisation - UNIQUE
  - Constrain GPD H through ϕ dependence of $\mathcal{D}_{CS,U}$ and $\mathcal{S}_{CS,U}$
  - Study nucleon transversal dimension as function of x_B (Tomography)
- Complementary information from hard exclusive meson production
- One month pilot run in 2012; two years running in 2015 and 2016
- $A_{UT}^{\sin(\phi-\phi_S)}$ in exclusive ρ^0 production measured for protons and deuterons. Paper will be published soon!

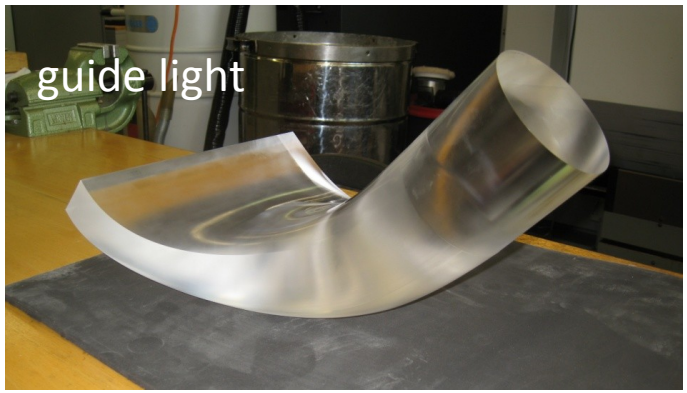
Thank You!

Back Up

Recoil Proton Detector: CAMERA

ToF between 2 rings of scintillators $\sigma(\text{ToF}) < 300\text{ps}$

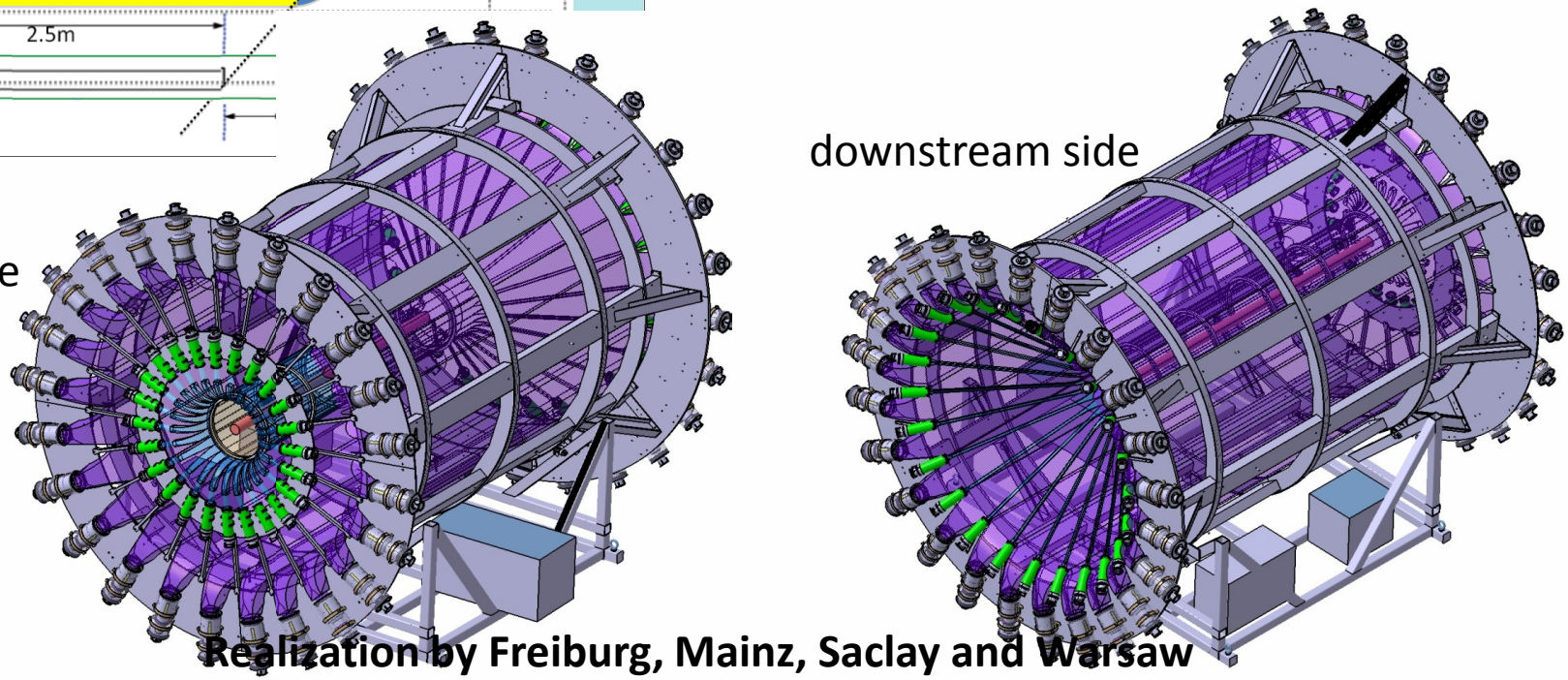




upstream side

3.90m

downstream side



Realization by Freiburg, Mainz, Saclay and Warsaw

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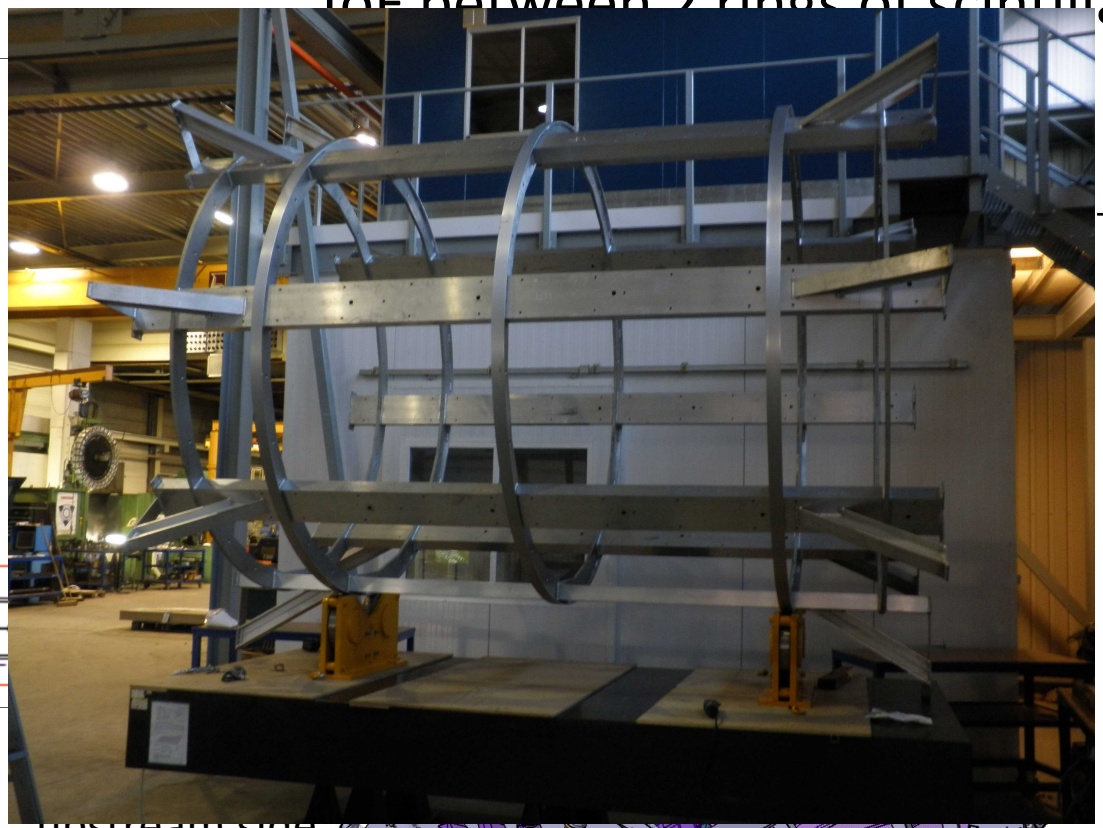

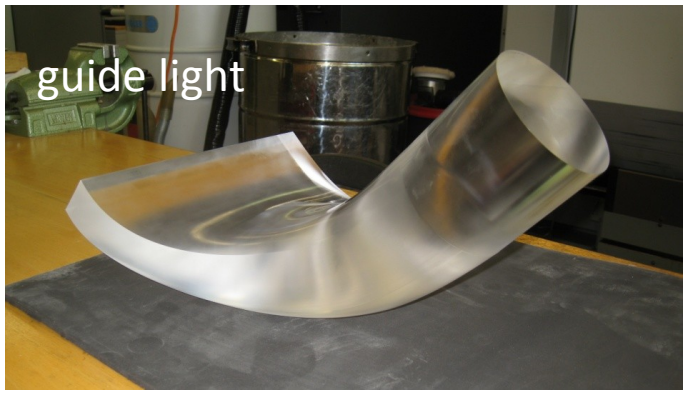

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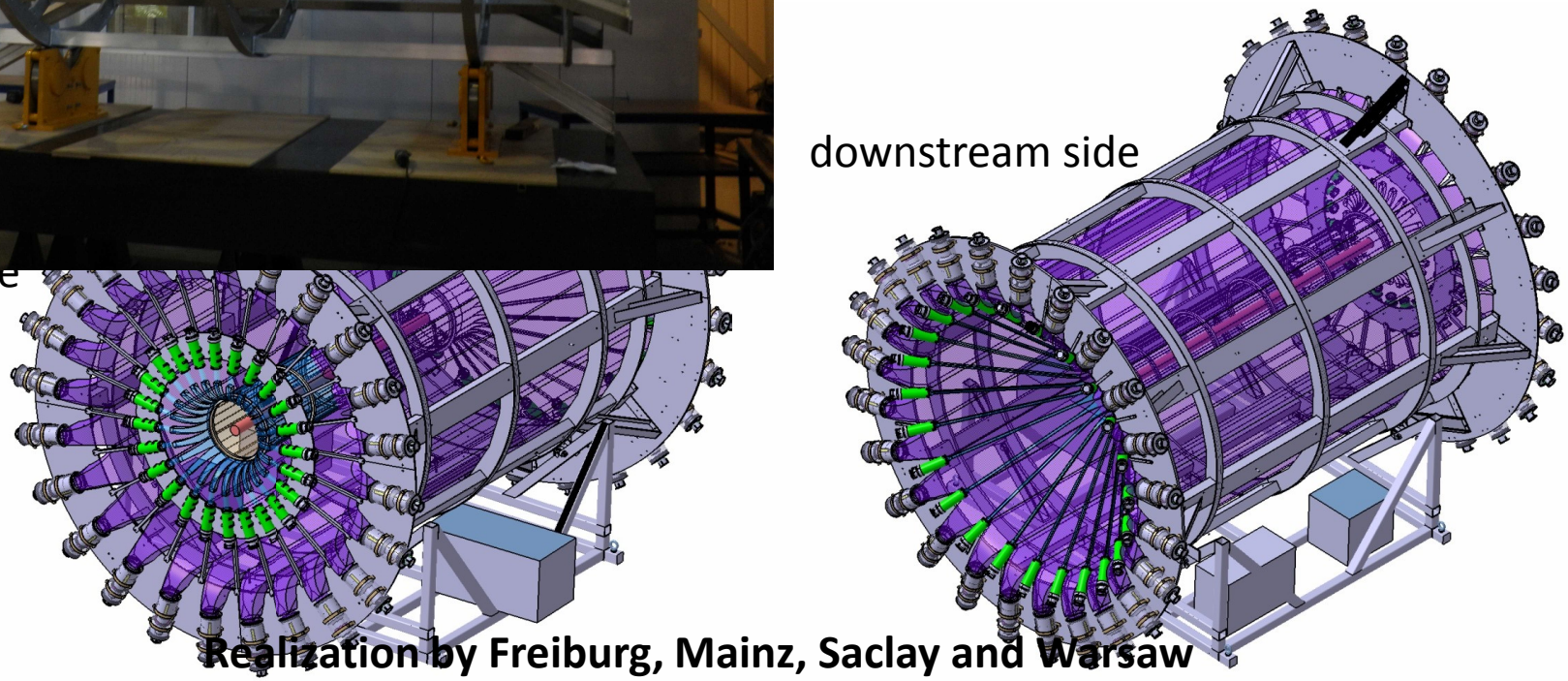

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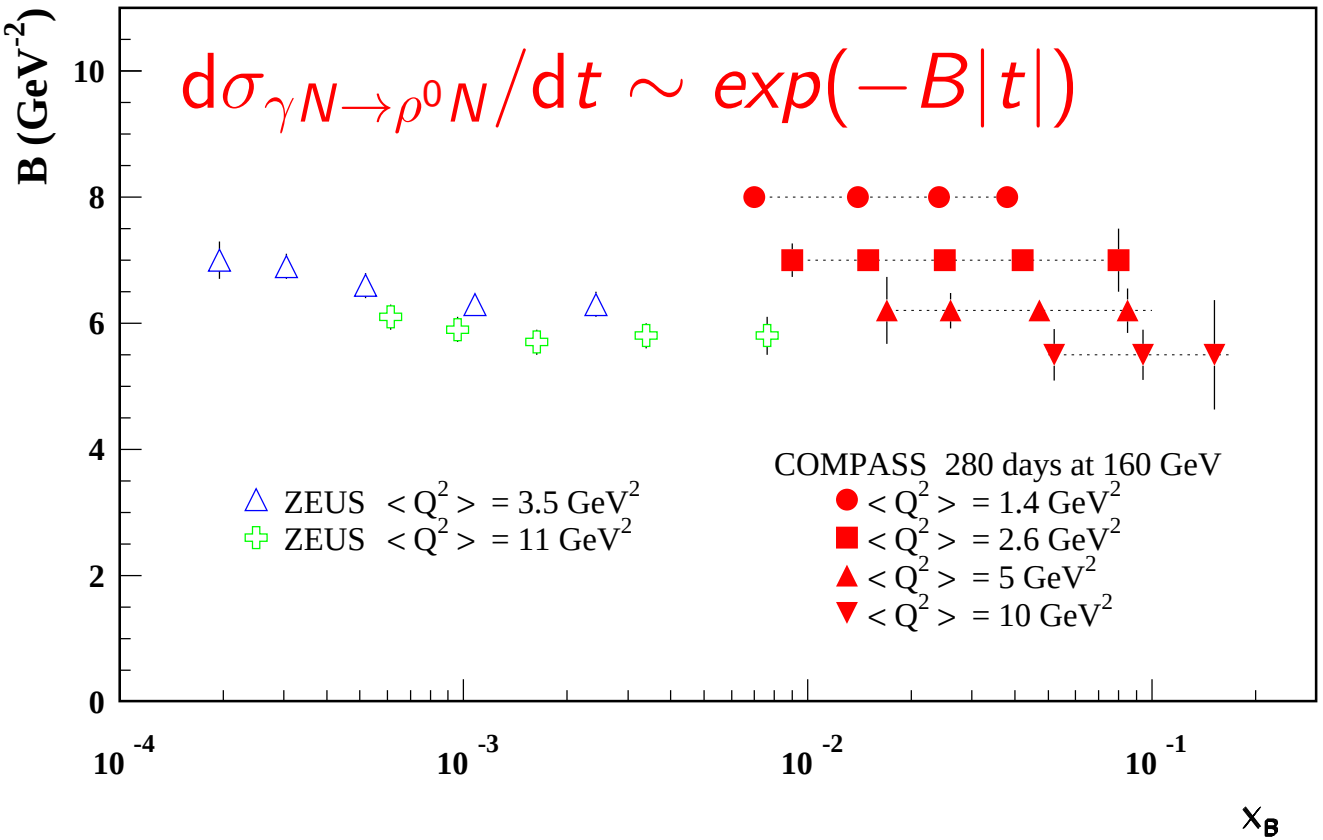

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  (9.6 s every 48 s)
- 2.5 m LH_2 target
- $\epsilon_{global} = 10\,\%$

Model by A.Sandacz normalised by prediction of Goloskokov and Kroll

- Measurement sensitive to transverse nucleon + transverse meson size
- At large Q^2 mostly sensitive to nucleon size

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