The GPD program at COMPASS

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on behalf of the COMPASS Collaboration

DSPIN-13

XV Workshop on High Energy Spin Physics

Dubna, Russia, October 8-12, 2013

COMPASS GPD program activities

- Exclusive vector meson muoproduction from 2002-2011 data

covered by P. Sznajder, cf. next talk in this session

with longitudinally/transversely polarised proton/deuteron targets (^{6}LiD, NH_3)

no recoil detector ➡ disadvantage for exclusive measurements

opportunity to get early results which are sensitive to GPDs E and chiral odd GPDs

- 'DVCS test' runs in 2008 (1.5 day) and 2009 (10 days)

40 cm LH_2 target and small RPD (used for hadron spectroscopy program)

analyses of the 'DVCS test' data demonstrated feasibility to measure

exclusive γ (DVCS and BH) and exclusive π^0 production at COMPASS

- GPD program of COMPASS-II

a part of approved new COMPASS proposal

DVCS and HEMP with polarised μ+ and μ- beams at 160 GeV and

unpolarised and transversely polarised proton targets (LH_2 , NH_3)

with large recoil proton detector and large angular coverage by EM calorimetry

COMPASS-II

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2010–014
SPSC-P-340
May 17, 2010

- Generalized Parton Distributions (GPD)
- Drell-Yan
- Pion (and kaon) Polarizabilities

COMPASS-II Proposal

Approved December 2010, first measurements 2012

The COMPASS Collaboration

wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

GPD program in context of COMPASS-II time lines

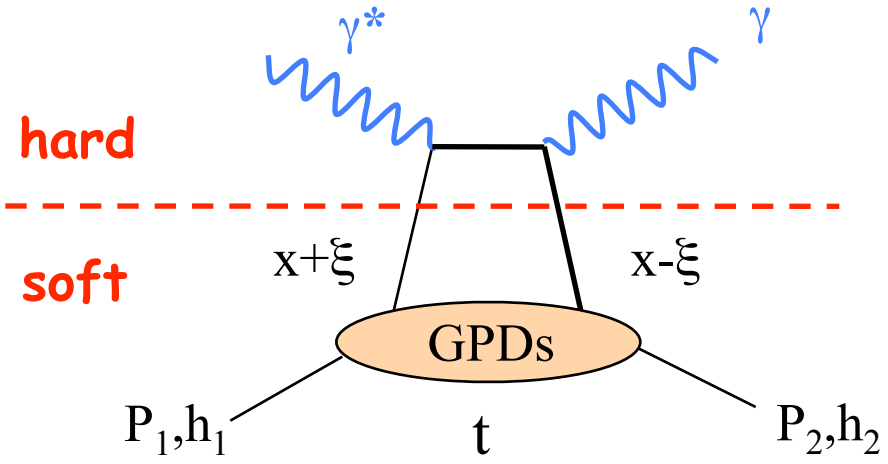
Part of the COMPASS-II proposal scheduled presently by CERN

- 2012: pion and kaon polarisabilities (Primakoff) + comissioning and pilot run for DVCS
- 2013-2014: long SPS/LHC shutdown
- 2014-2015: Drell-Yann measurements with transversely polarised protons (NH_3 target)
- 2016-2017: stage 1 of GPD program and in parallel SIDIS (LH target)

Measurements to be pursued at COMPASS-II > 2017

- ✓ Drell-Yann on transversely polarised protons, transversely polarised deuterons, unpolarised protons and nuclear targets
- ✓ stage 2 of GPD program (transversely polarised target and RPD)
- ✓ SIDIS (high statistics) from transversely polarised deuteron and proton targets
- ✓ hadron program (spectroscopy in diffractive and central production)

Generalized Parton Distributions and DVCS



Factorisation:

Q^2 large, $-t<1$ GeV^2

$$\xi = \frac{x_B}{2 - x_B}$$

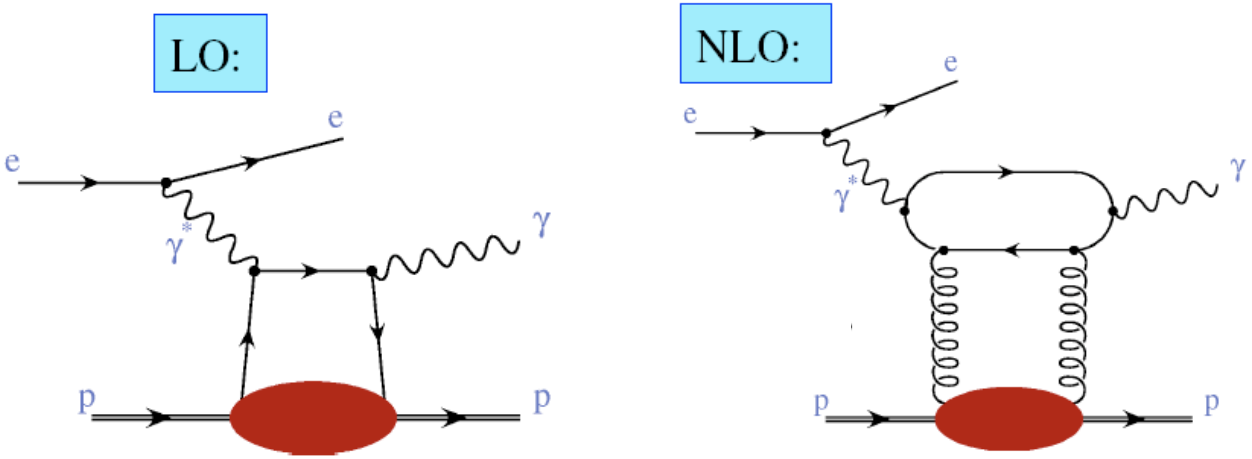
P_i, h_i – proton momentum and helicity

4 Generalised Parton Distributions : $H, E, \tilde{H}, \tilde{E}$ (chiral even)

for each quark flavour and for gluons

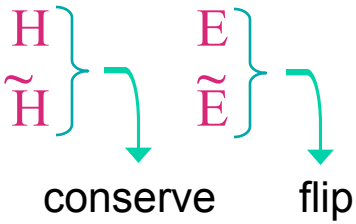
depend on 3 variables: x, ξ, t

for DVCS gluons contribute at higher orders in α_s



GPDs and Hard Exclusive Meson Production

- also sensitive to GPDs, complementary to DVCS
- amplitude contains additional non-perturbative object – meson DA
- HEMP allows separation $(H,E) \leftrightarrow (\tilde{H},\tilde{E})$



vector mesons (ρ, ω, φ)

pseudoscalar mesons (π, η)

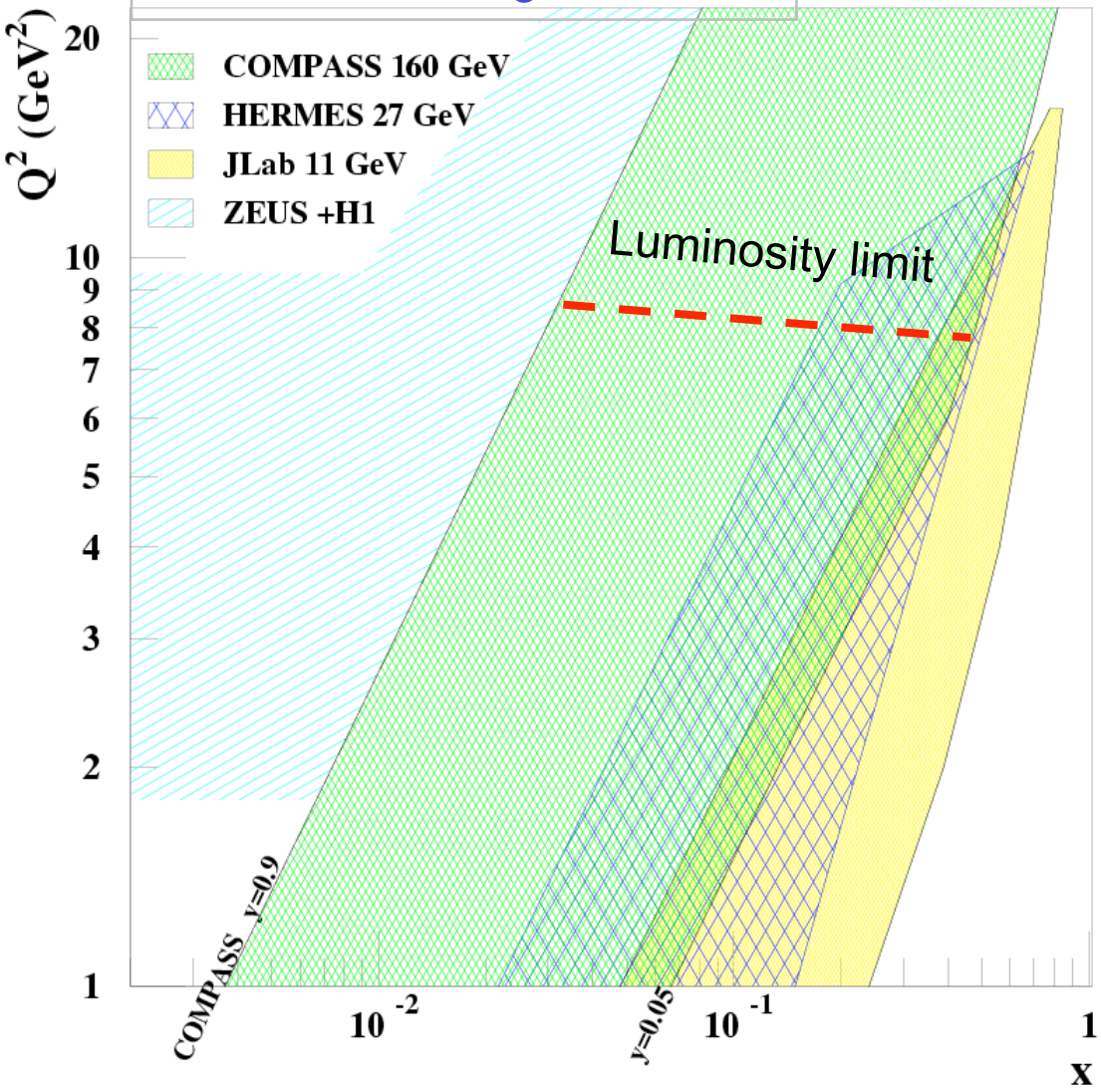
- in addition to chiral-even GPDs, HEMP sensitive also to chiral-odd GPDs
- quark flavour 'filter' - various mesons sensitive to different quark flavours
- quarks and gluons enter at the same order of α_s
- rigorous proof of collinear factorisation only for meson production by γ^*_L

GPDs in HEMP covered by talks of P. Sznajder and S.Goloskokov

What makes COMPASS unique for GPD studies

CERN SPS high energy polarised muon beam

kinematic coverage for DVCS



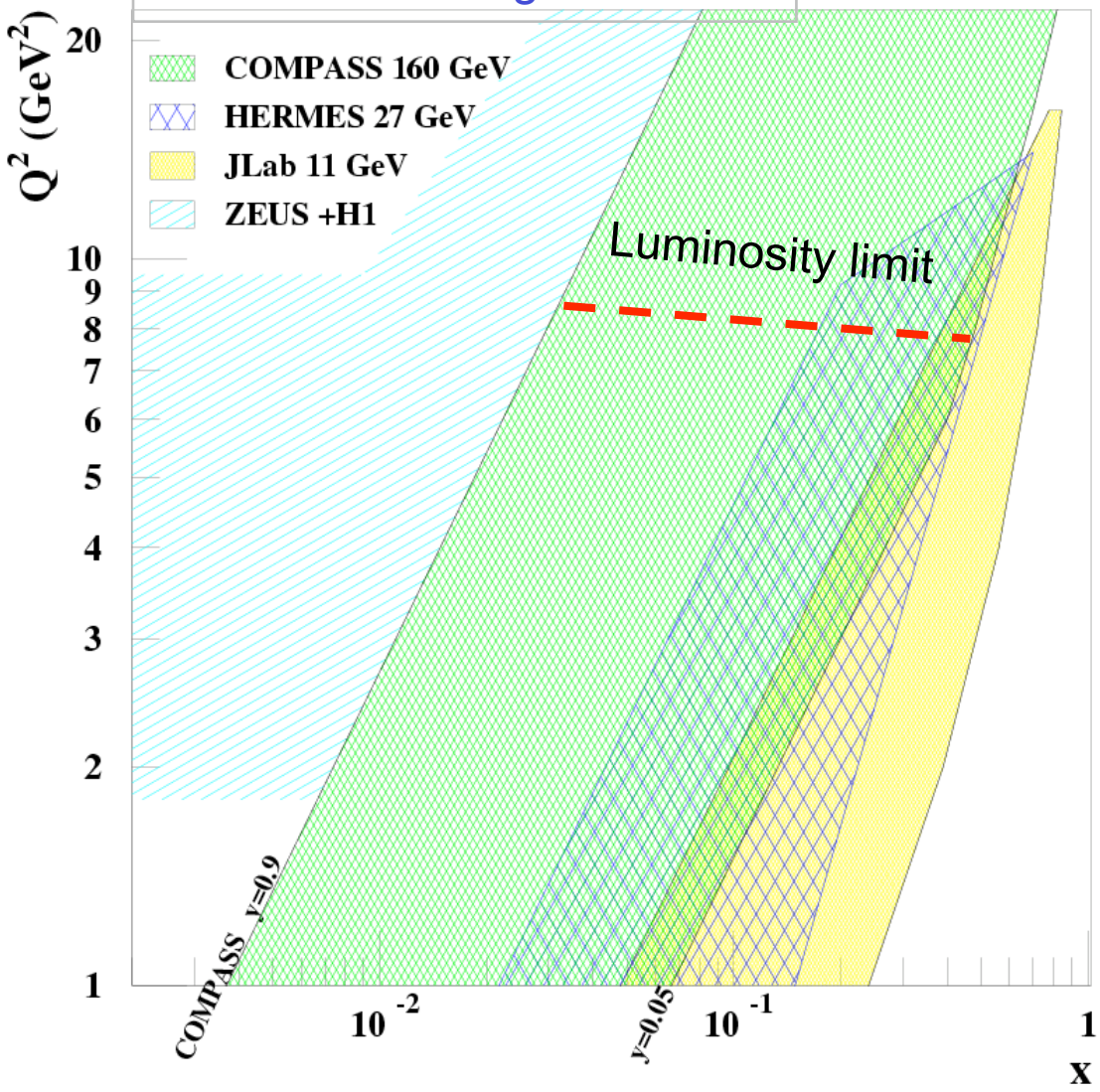
$Q^2 \rightarrow$ 8 GeV^2

$\sim 10^{-2} < x < \sim 10^{-1}$

$x \rightarrow$ 0.20 with extension of present calorimetry

What makes COMPASS unique for GPD studies

kinematic coverage for DVCS



CERN SPS high energy polarised muon beam

- ✓ 100 – 190 GeV
- ✓ polarisation 80%
- ✓ μ^+ and μ^- available
  - opposite polarisation
  - $4.6 \cdot 10^8$ μ^+ /spill
  - $I(\mu^+) \approx 2.4\, I(\mu^-)$
- ✓ L = 10^{32} cm^{-2} s^{-1}
  with 2.5 m long LH_2 target

Foreseen measurements

DVCS and HEMP off unpolarised and transversely polarised protons

Kinematic range for DVCS

$Q^2 \rightarrow$ 8 GeV^2

$\sim 10^{-2} < x < \sim 10^{-1}$

$x \rightarrow$ 0.20 with extension of present calorimetry

The GPDs in the next several years

- **H1, ZEUS, HERMES, JLab 6 GeV** provided/providing first results

- The **energy upgrade** of the **CEBAF** accelerator will allow access to the **high x_B** region which requires **large luminosity**.

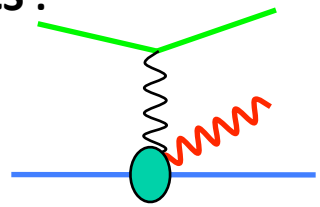
- The **GPD** project at **COMPASS** will explore **intermediate x_B** (0.01-0.10) and **large Q^2** (up to ~8(16) GeV^2) range

  COMPASS will be **the only experiment in this range** before availability of new colliders (2025 (?))

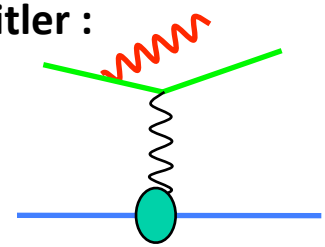
  for several years COMPASS **unique** due to availability of lepton **beams of both charges**

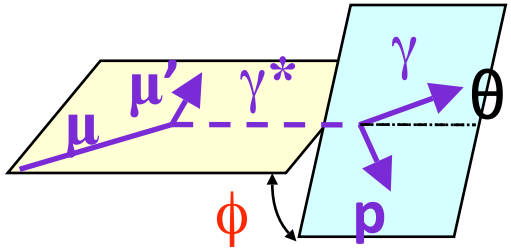
Interplay of DVCS and BH at 160 GeV

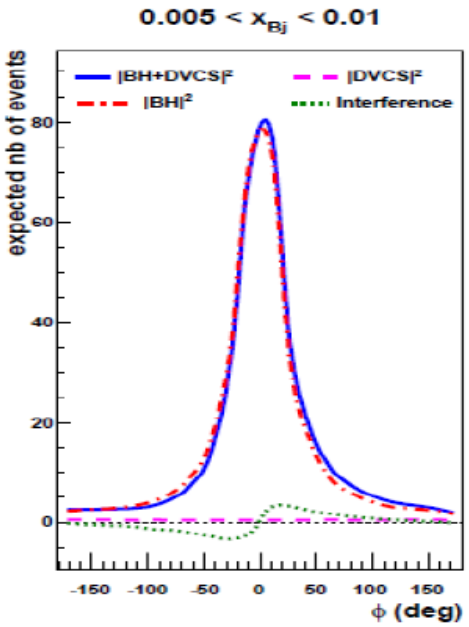
DVCS :

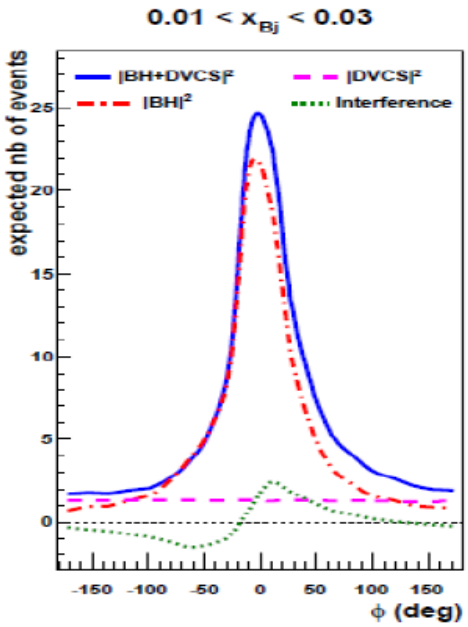


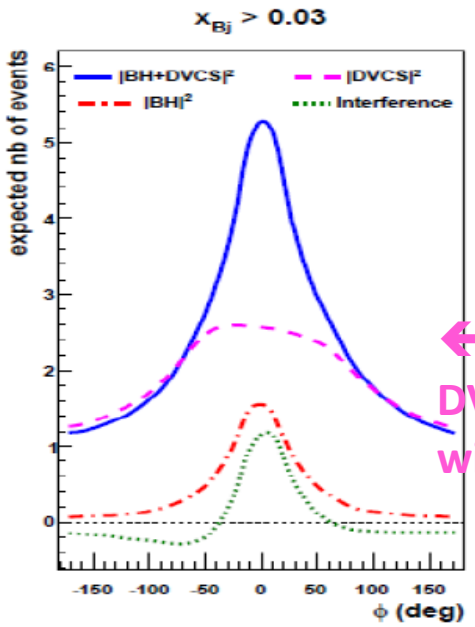
Bethe-Heitler :











Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

←Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

BH and DVCS at the same level

access to DVCS amplitude through the interference

DVCS dominates

study of $d\sigma^{DVCS}/dt$

‘Stage 1’ of COMPASS GPD program

DVCS and HEMP with unpolarised proton target

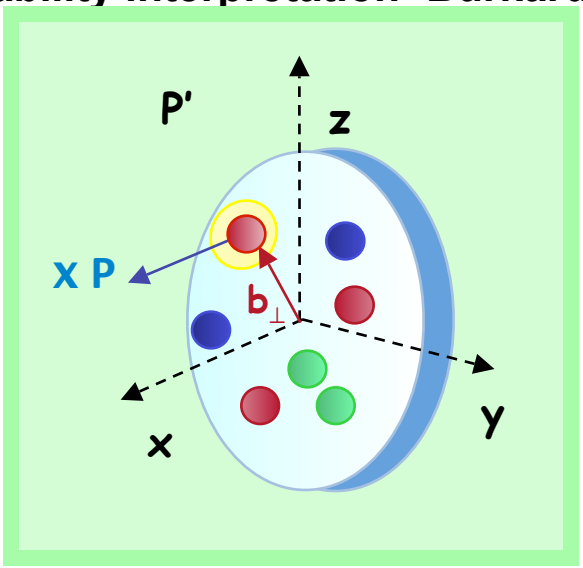
to constrain GPD H

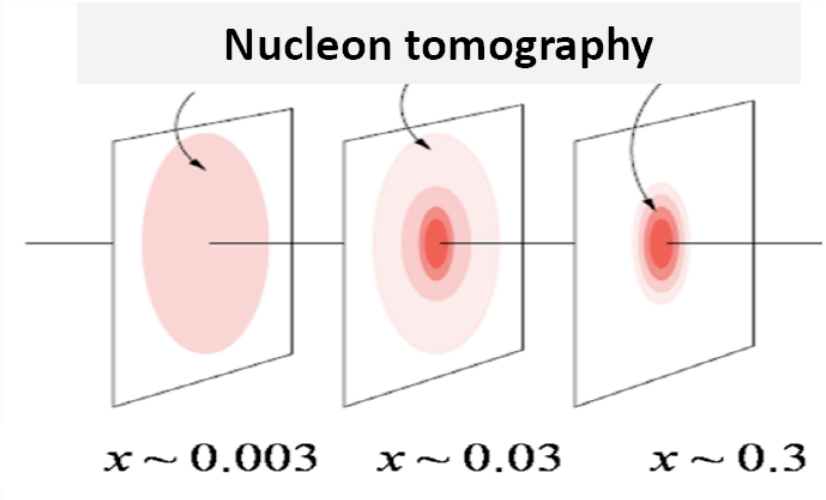
3-dimensional picture of the partonic nucleon structure

or spatial parton distribution in the transverse plane

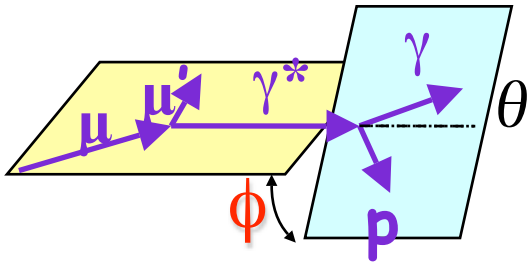
$$H(x, \xi=0, t) \rightarrow H(x, r_{x,y})$$

probability interpretation -Burkardt





Azimuthal dependence of exclusive photon xsec.



from Belitsky, Kirchner, Müller :
polarized beam off unpolarized target

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

$$d\sigma^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)}\left(c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right)$$ ← Known expression

$$d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2Q^2}\left(c_0^{DVCS} + c_1^{DVCS}\cos\varphi + c_2^{DVCS}\cos 2\varphi\right)$$

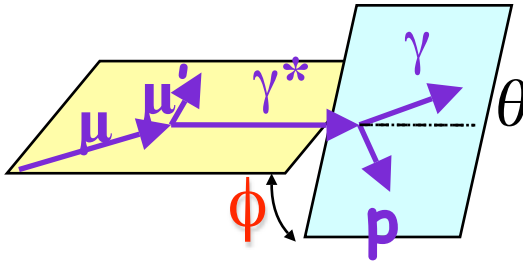
$$P_\mu \times \quad d\sigma^{DVCS}_{pol} = \frac{e^6}{y^2Q^2}\left(s_1^{DVCS}\sin\varphi\right)$$

$$e_\mu \times a^{BH}\,\Re e A^{DVCS} = \frac{e^6}{xy^3tP_1(\varphi)P_2(\varphi)}\left(c_0^{Int} + c_1^{Int}\cos\varphi + c_2^{Int}\cos 2\varphi + c_3^{Int}\cos 3\varphi\right)$$

$$e_\mu P_\mu \times a^{BH}\,\Im m A^{DVCS} = \frac{e^6}{xy^3tP_1(\varphi)P_2(\varphi)}\left(s_1^{Int}\sin\varphi + s_2^{Int}\sin 2\varphi\right)$$

Twist-2 >> Twist-3 Twist-2 gluon

Extraction of DVCS cross section and amplitude



Beam Charge & Spin Sum

$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH}\, Im T^{DVCS})$$

$$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \qquad s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi$$

$c_0^{DVCS} \rightarrow d\sigma^{DVCS}/dt$

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

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

Beam Charge & Spin Difference

$$D_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) = 2(e_\mu\, a^{BH}\, Re T^{DVCS} + P_\mu\, d\sigma^{DVCS}_{pol})$$

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi \qquad s_1^{DVCS}\sin\phi$$

$c_{0,1}^{Int} \rightarrow Re(F_1\mathcal{H})$

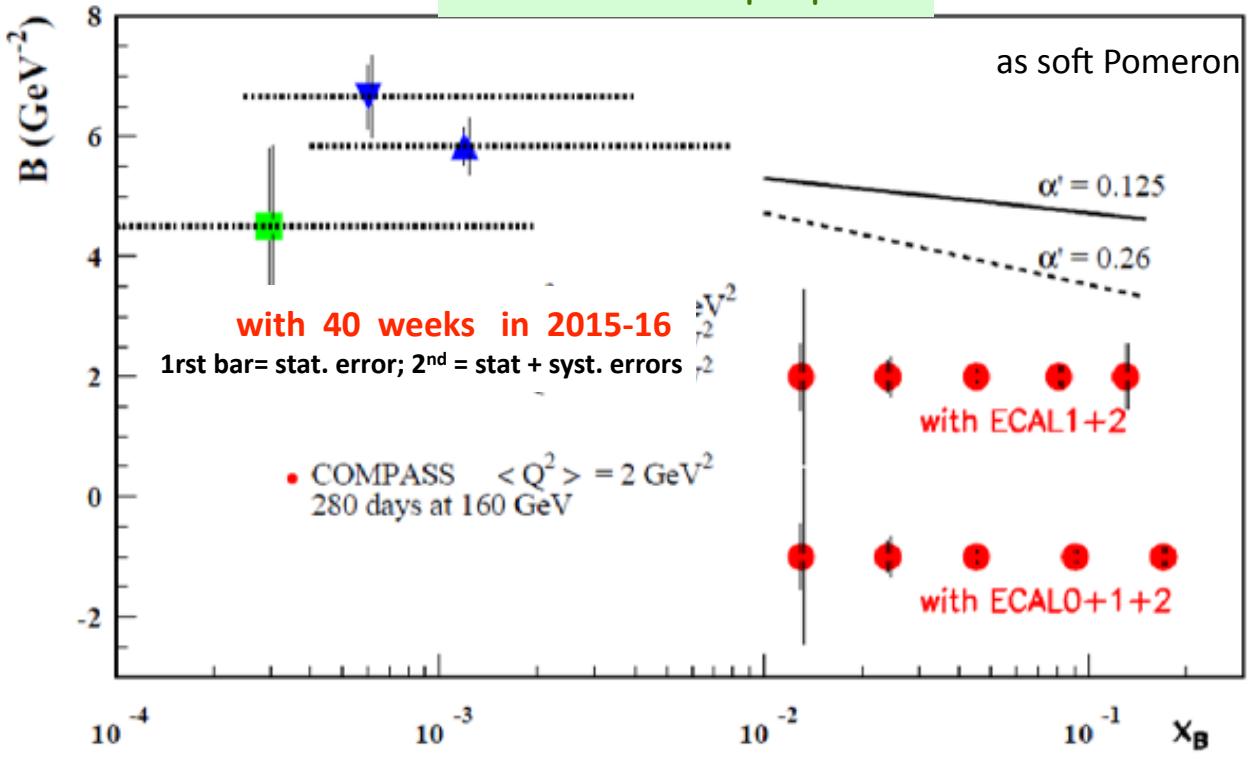
$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

Transverse imaging of the proton using $d\sigma^{DVCS}/dt$

integrating $S_{CS,U}$ over ϕ and subtracting BH → $d\sigma_{DVCS}/dt \sim \exp(-B|t|)$

'tomography': $B(x) \Leftrightarrow \langle r_T^2 \rangle(x)$

COMPASS-II proposal



40 weeks of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

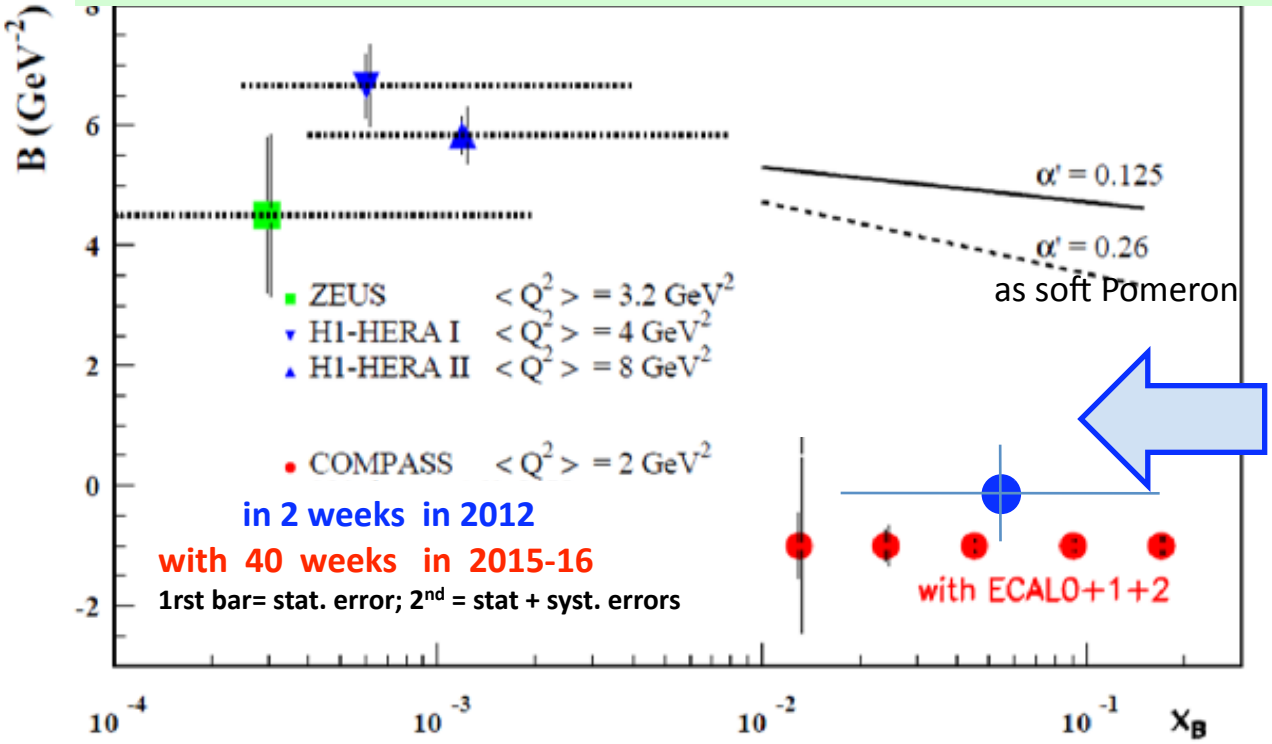
ansatz at small x_B
inspired by
Regge Phenomenology:

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

α' slope of Regge traject

Transverse imaging of the proton using $d\sigma^{DVCS}/dt$

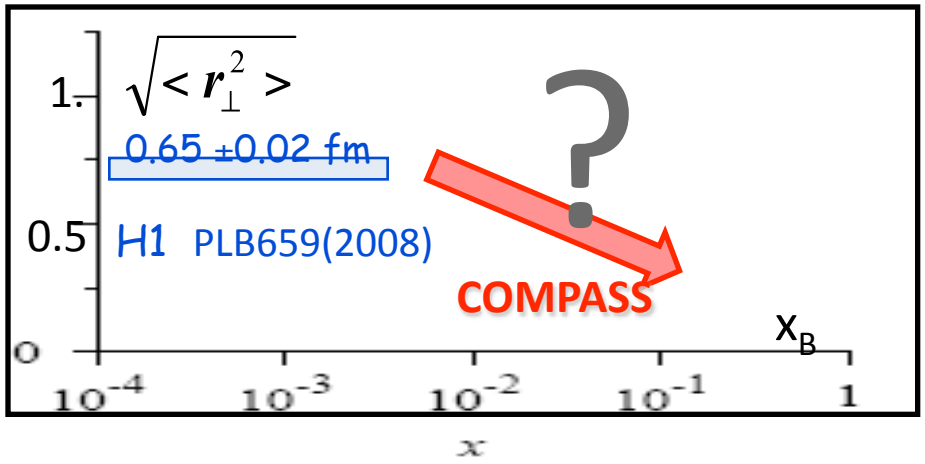
Projection for statistical uncertainty on B-slope from 2012 DVCS pilot run data



DVCS test in 2012

2 weeks of data taking using the 4m long RPD + the 2.5m long LH2 target

1/20 of the total statistics foreseen in the proposal

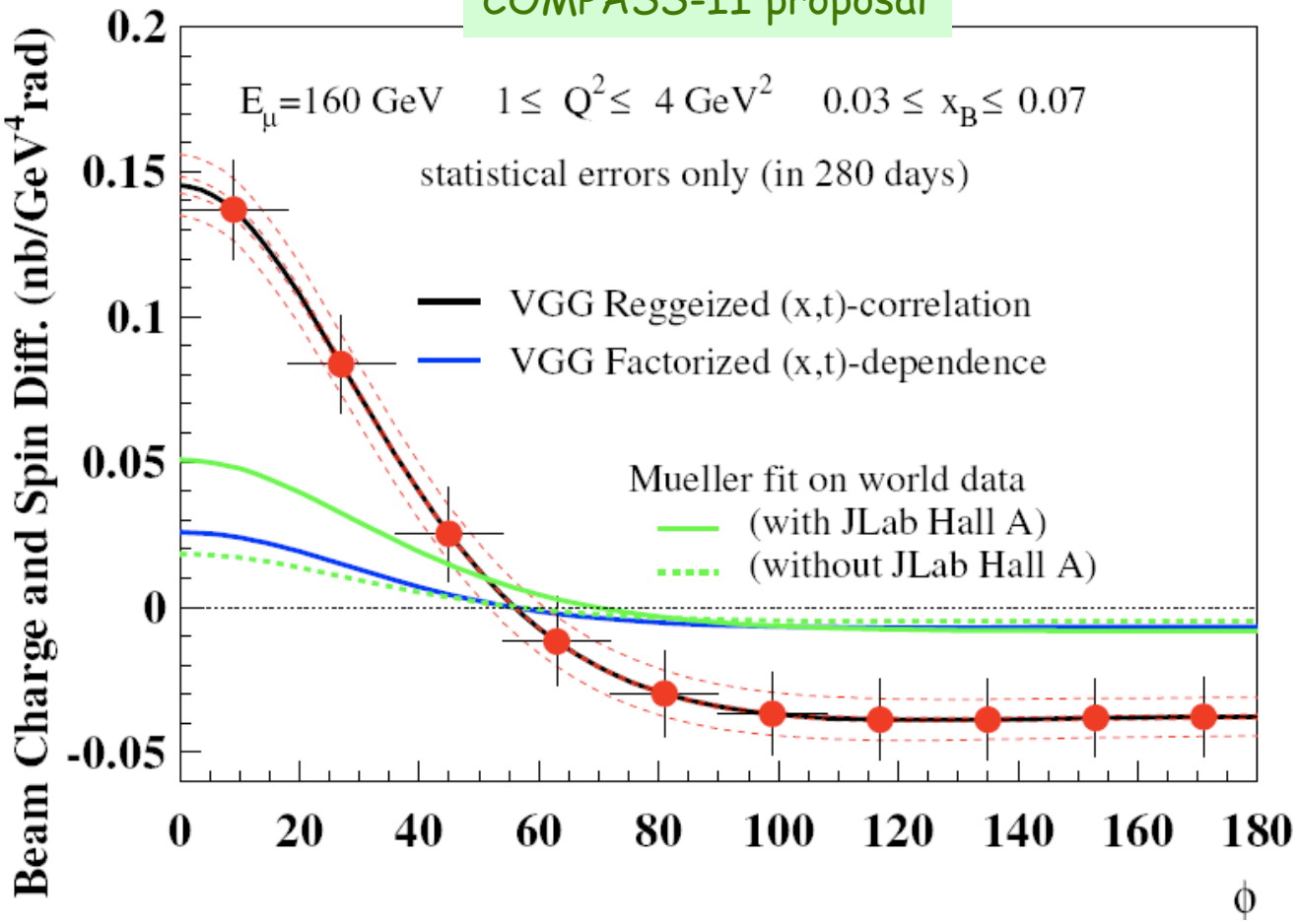


From 2012 data expected the first measurement of B-slope for DVCS at an x_{Bj} value above HERA range

Beam Charge&Spin Difference of cross sections

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) = c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi + s_1^{DVCS}\sin\phi$$

COMPASS-II proposal



160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
L = 1222pb^{-1}

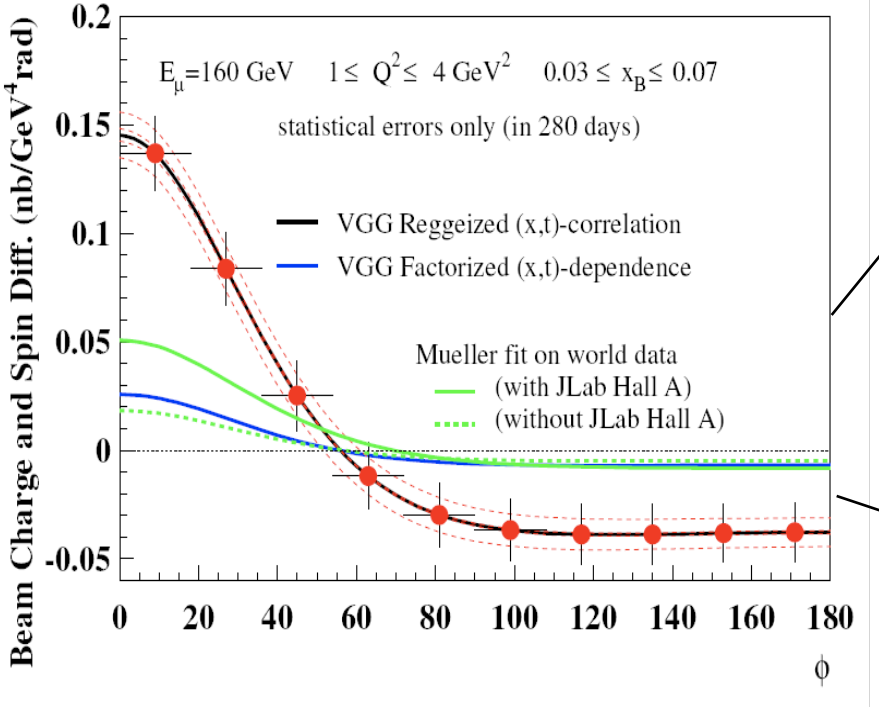
$0.06 < |t| < 0.64$ GeV^2

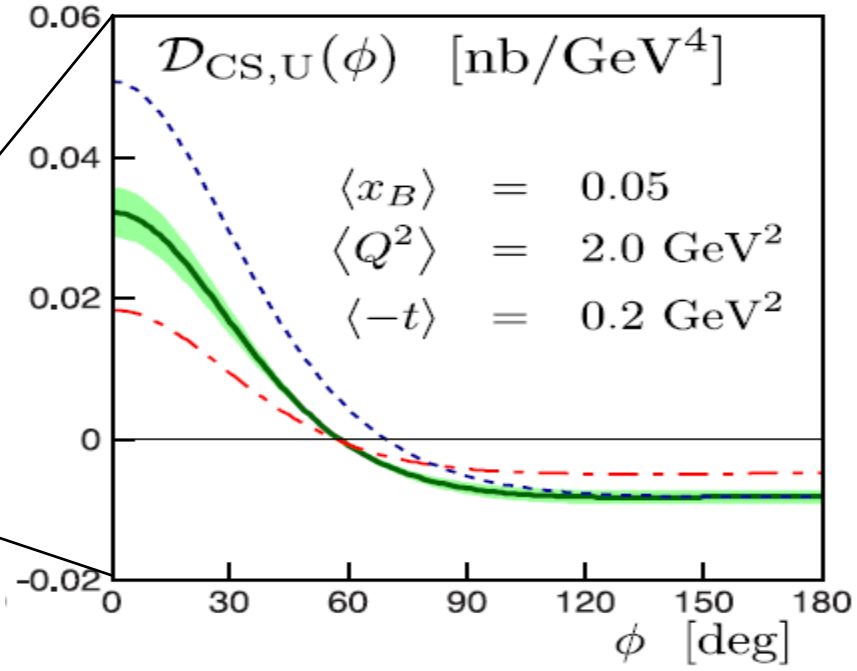
$$c_{0,1}^{Int} \rightarrow Re(\mathcal{F}_1\mathcal{H})$$

Systematic errors : 3% charge-dependent effect between μ+ and μ-

Beam Charge&Spin Difference of cross sections

New predictions
by Kroll, Moutarde and Sabatié





Kroll, Moutarde, Sabatié

KM10a

KM10b

Sensitivity of COMPASS; cosϕ modulation

$$BCSA = \mathcal{D}_{cs,U} / \mathcal{S}_{cs,U} = A_0 + A^{\cos\phi}_{cs,U} \cos\phi + A_2 \cos 2\phi$$

$A^{\cos\phi}_{CS,U}$ => c_1^{Int} => $\mathcal{Re}(F_1\mathcal{H})$

Mueller's fits to world data

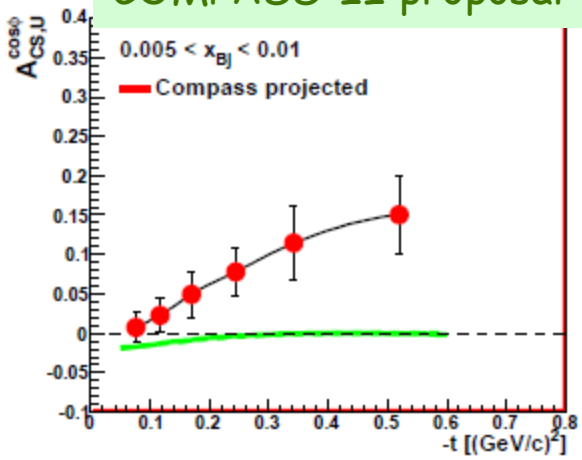
VGG

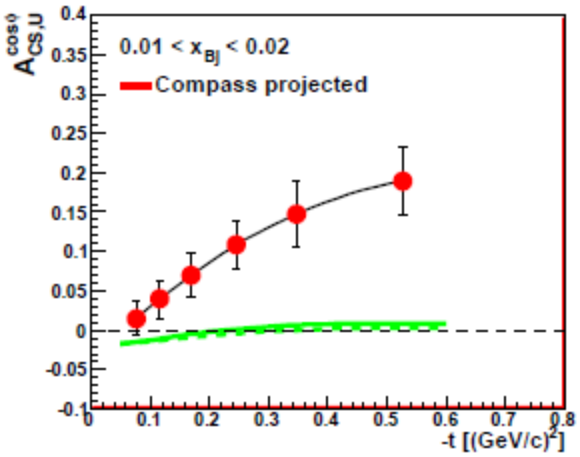
$\mathcal{Re}(F_1\mathcal{H})$ > 0 at H1

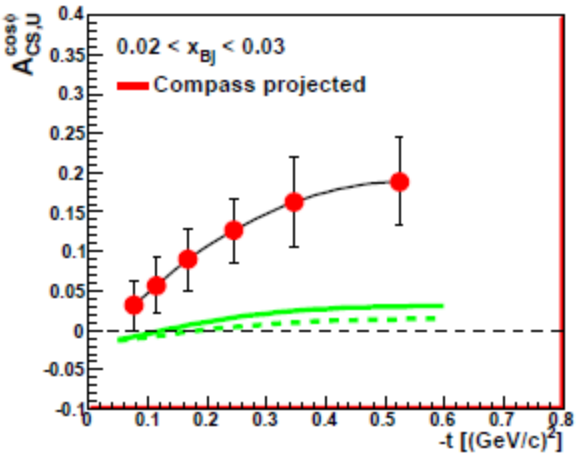
< 0 at HERMES/JLab

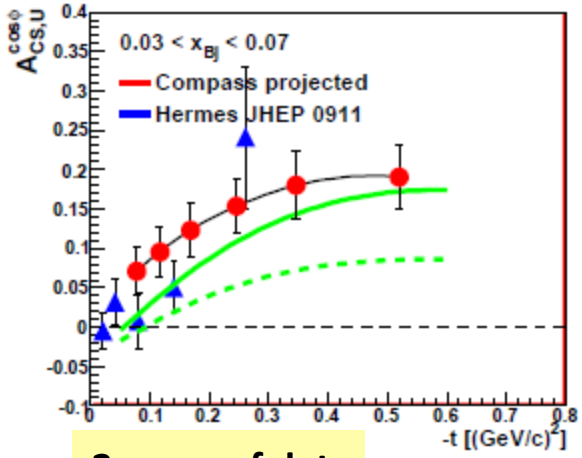
Value of x_B for the node?

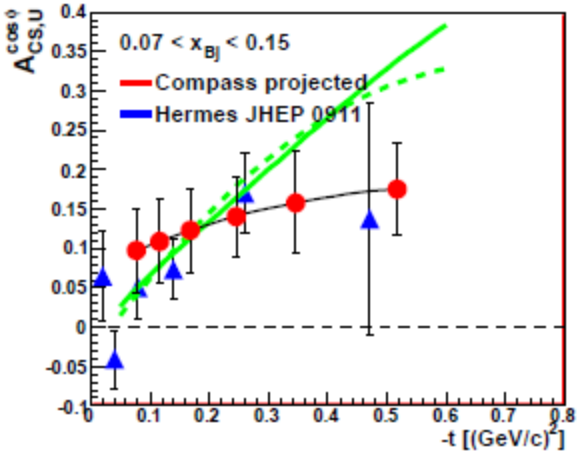
COMPASS-II proposal

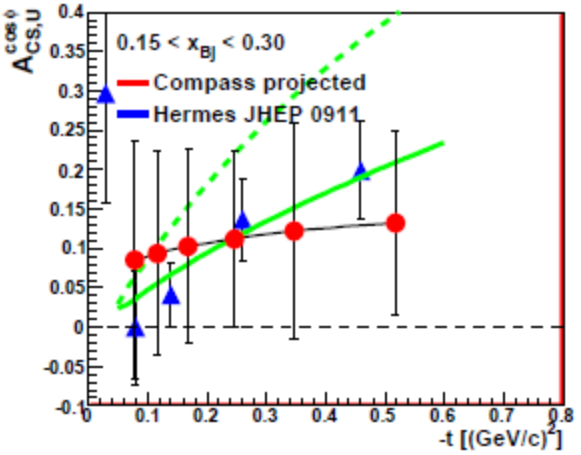












2 years of data

with ECAL2 + ECAL1 + ECAL0

‘Stage 2’ of COMPASS GPD program

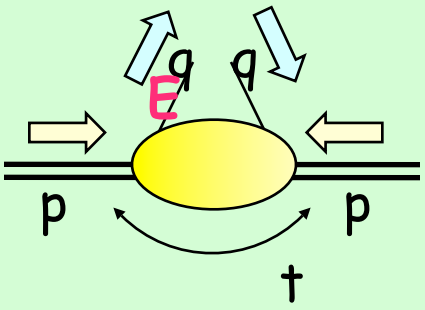
DVCS and HEMP with transversely polarised proton target (NH_3)

to constrain GPD E

Contribution to the nucleon spin puzzle

E related to the orbital angular momentum

$$J_q = \frac{1}{2} \int x \left(H^q(x,\xi,0) + E^q(x,\xi,0)\right) dx$$



Study of azimuthal asymmetries from transversely polarized NH_3 target

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

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

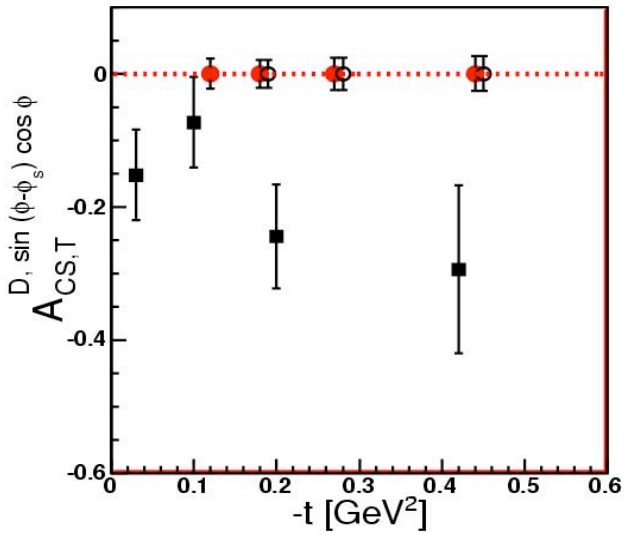
$d\sigma_0$ - unpolarised, charge averaged cross section

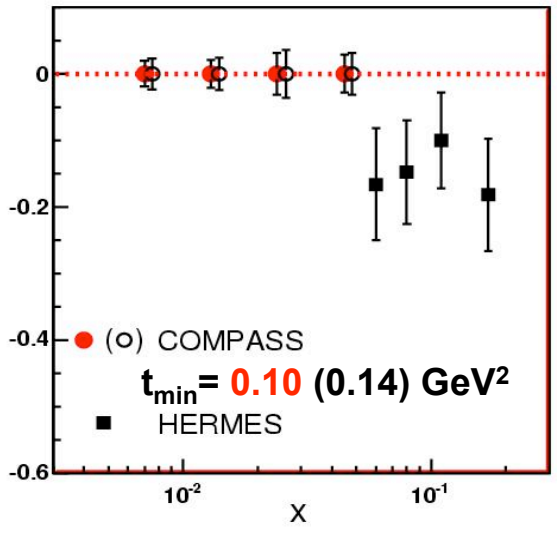
160 GeV muon beam
1.2m NH_3 target
ε_{global} = 10%
with ECAL1+ ECAL2
40 weeks

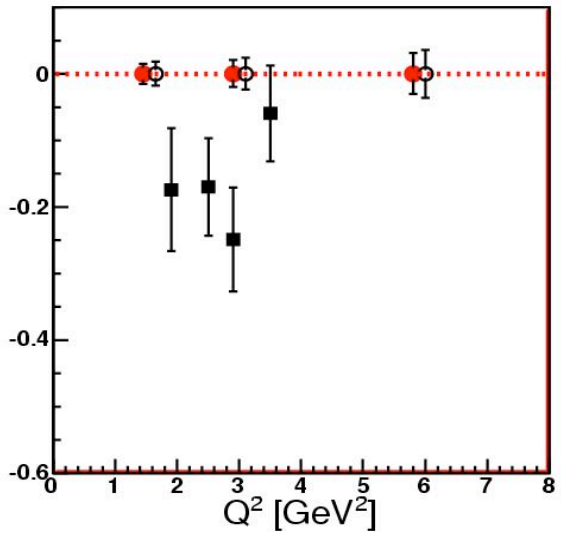
for $\mu\, p^{\uparrow} \rightarrow \mu\, \gamma\, p$ from NH_3
dilution factor f=0.26

$0.10\ (0.14) < |t| < 0.64\ GeV^2$

COMPASS-II proposal







DVCS test runs in 2008-2009

Goal: evaluate feasibility to detect DVCS/BH in the COMPASS setup

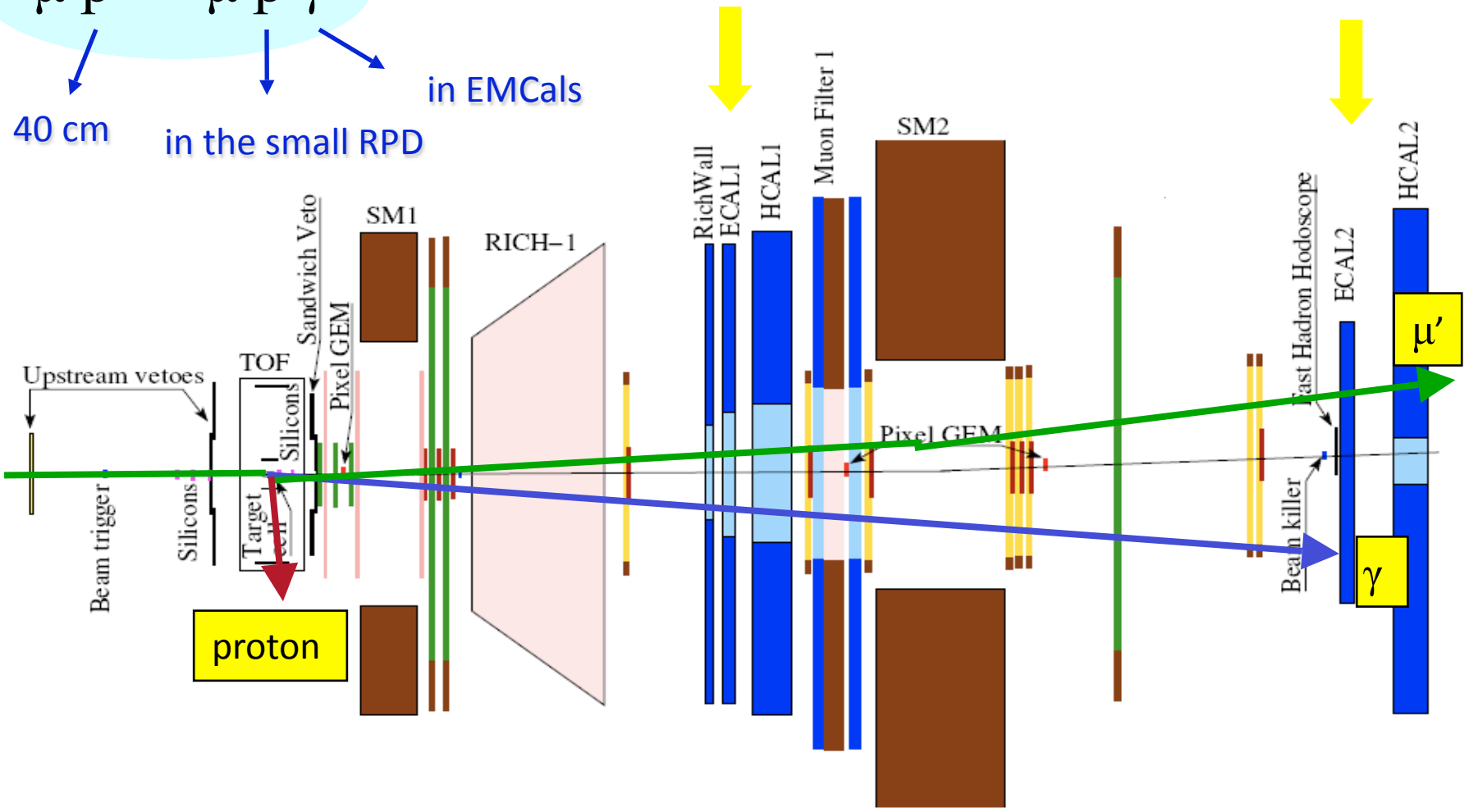
$$\mu\, p \rightarrow \mu\, p\, \gamma$$

LH 40 cm

in the small RPD

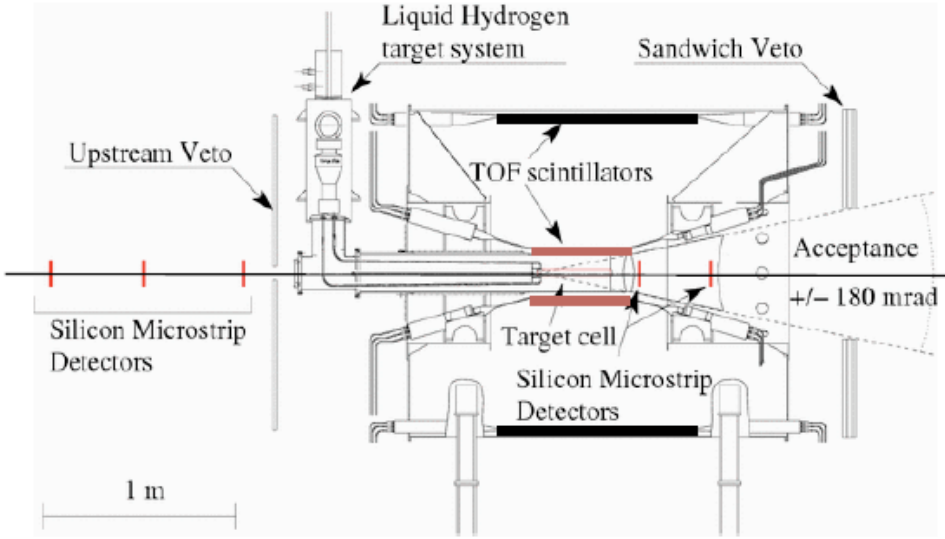
in EMCals

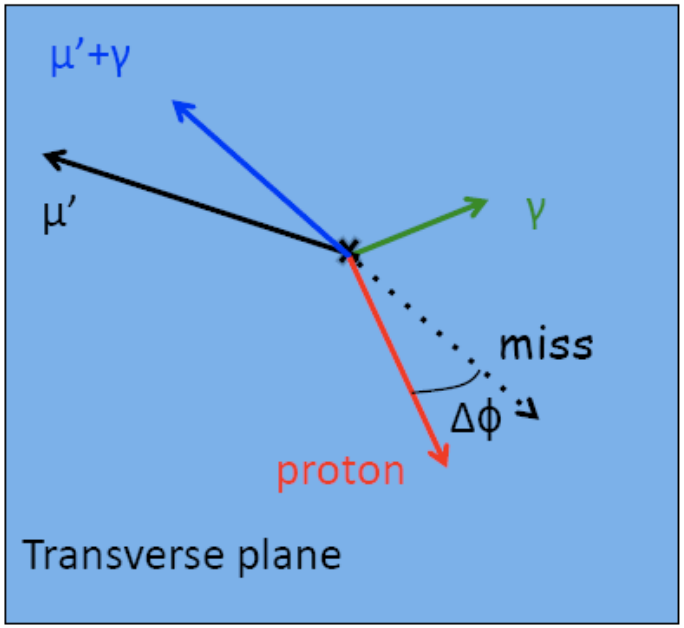
COMPASS 'hadron' set-up

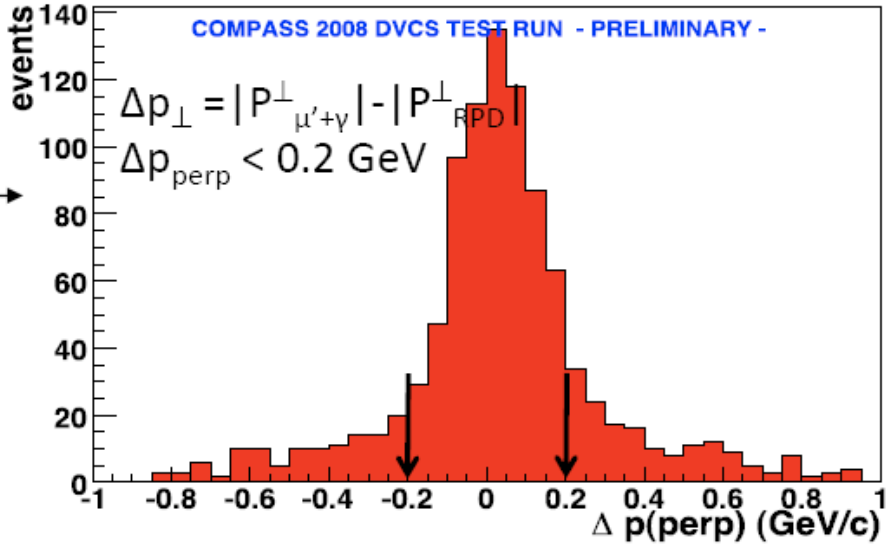


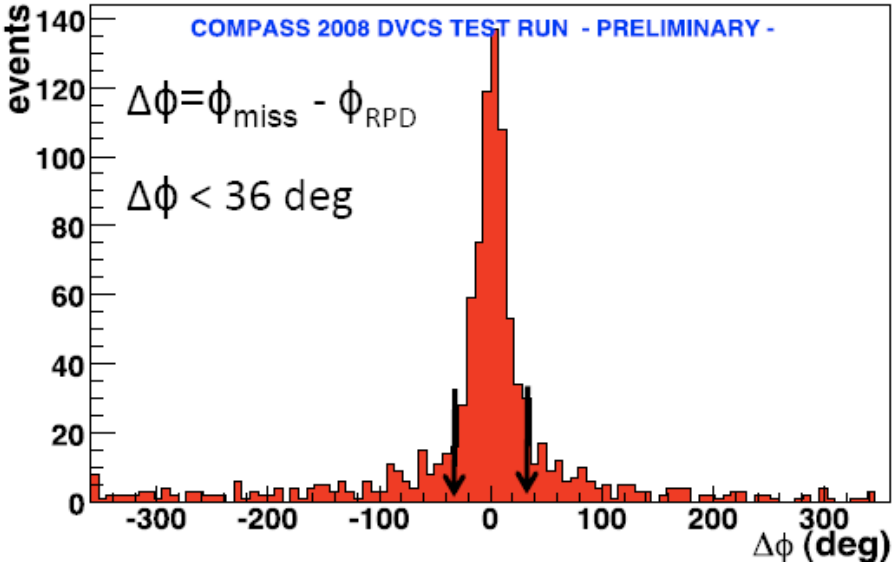
Short: 1.5 day in 2008 and 10 days in 2009 of 160 GeV muon beam (μ^+ and μ^-)

2008-2009 'DVCS test' runs: exclusivity cuts

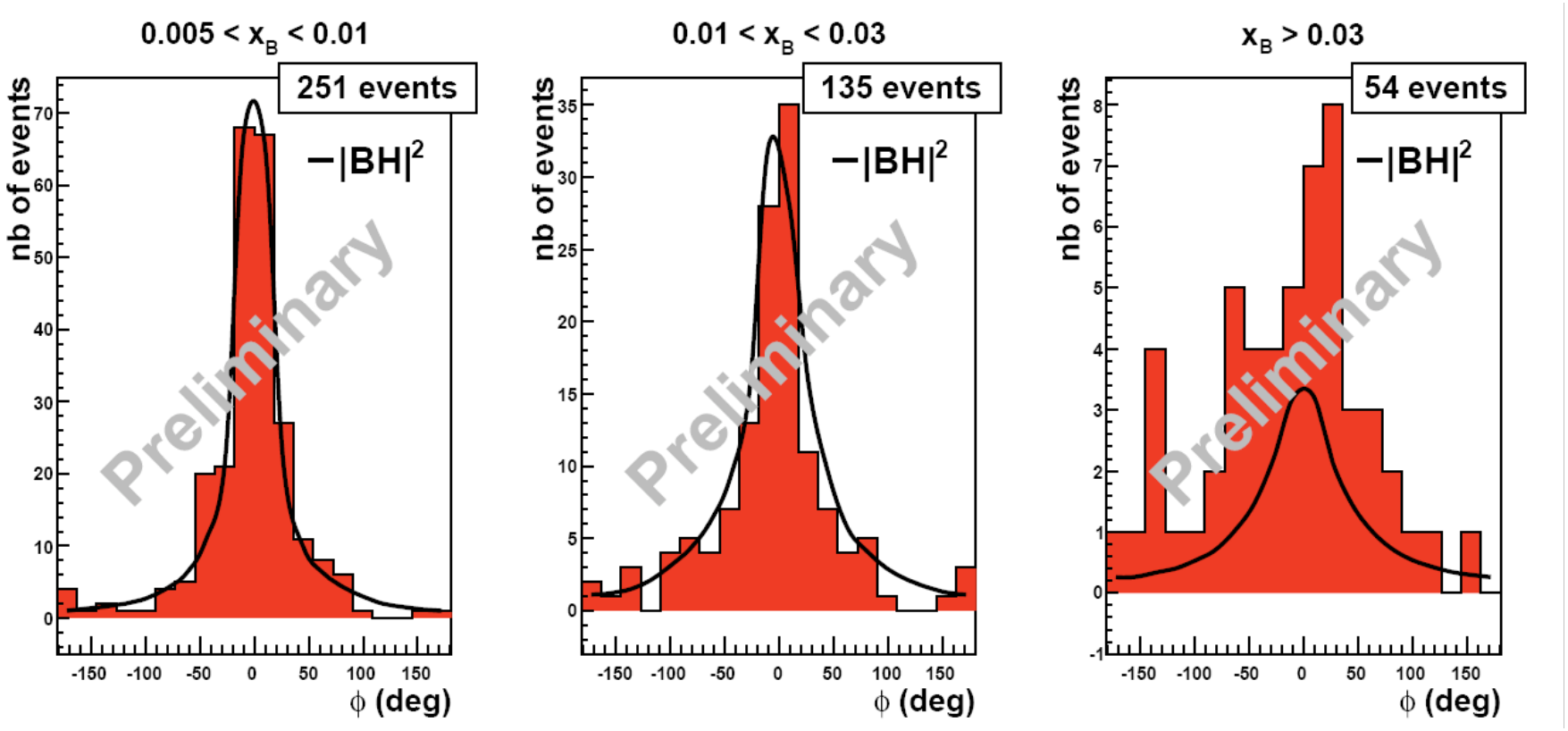








Exclusive γ production from 2009 DVCS test run



$\epsilon_{\mu p \to \mu' \gamma p} \approx 35\%$

× $(0.8)^4$ for SPS + COMPASS avail. + trigger eff + dead time

$\epsilon_{global} \approx 0.14$ confirmed $\epsilon_{global} = 0.1$

assumed for COMPASS-II projections

54 evts ≈ 20 BH

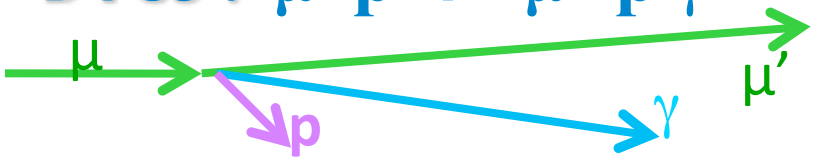
+ 22 DVCS

+ about 12 γ from π^0

upper limit

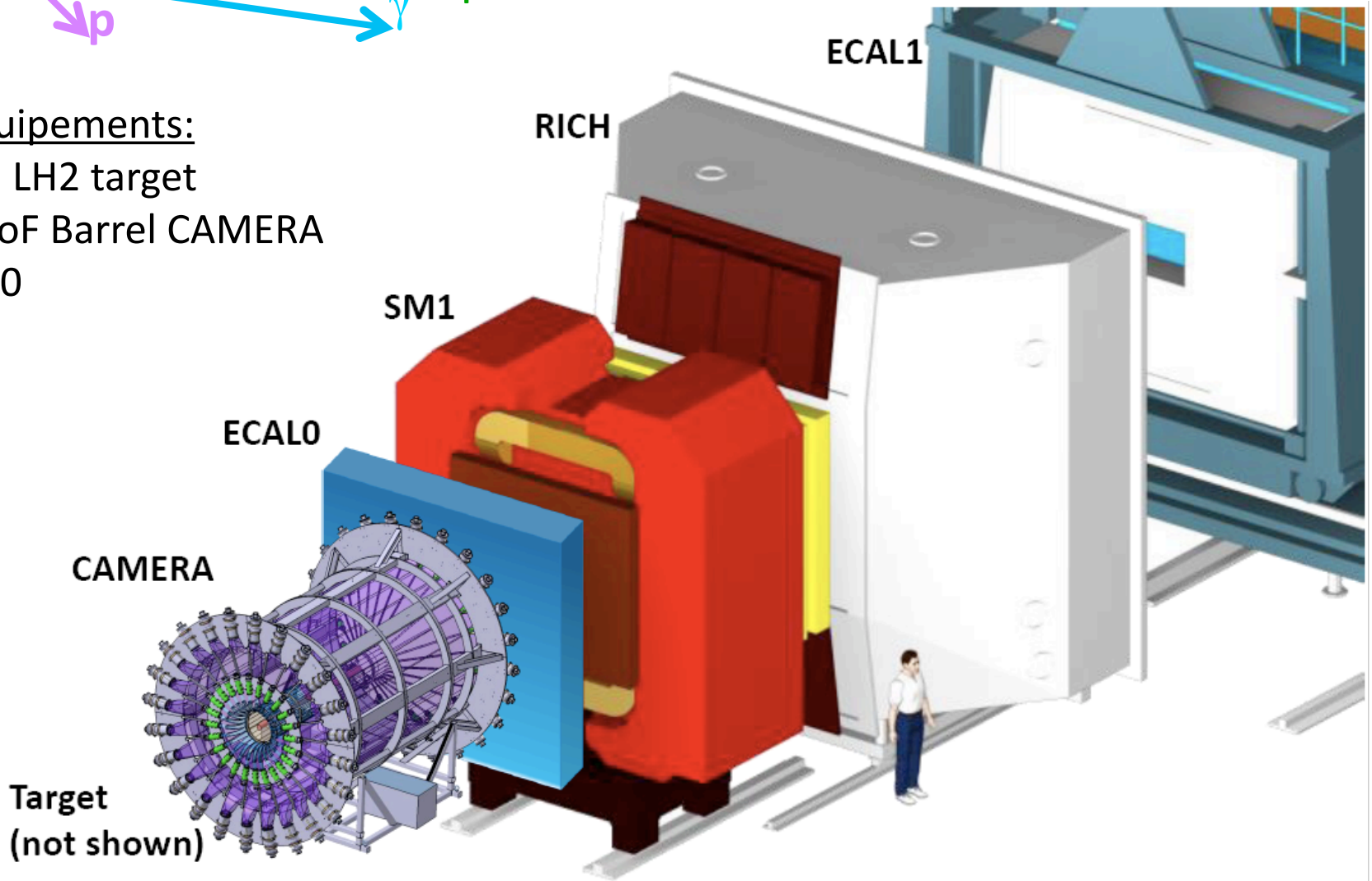
Upgrades of COMPASS spectrometer

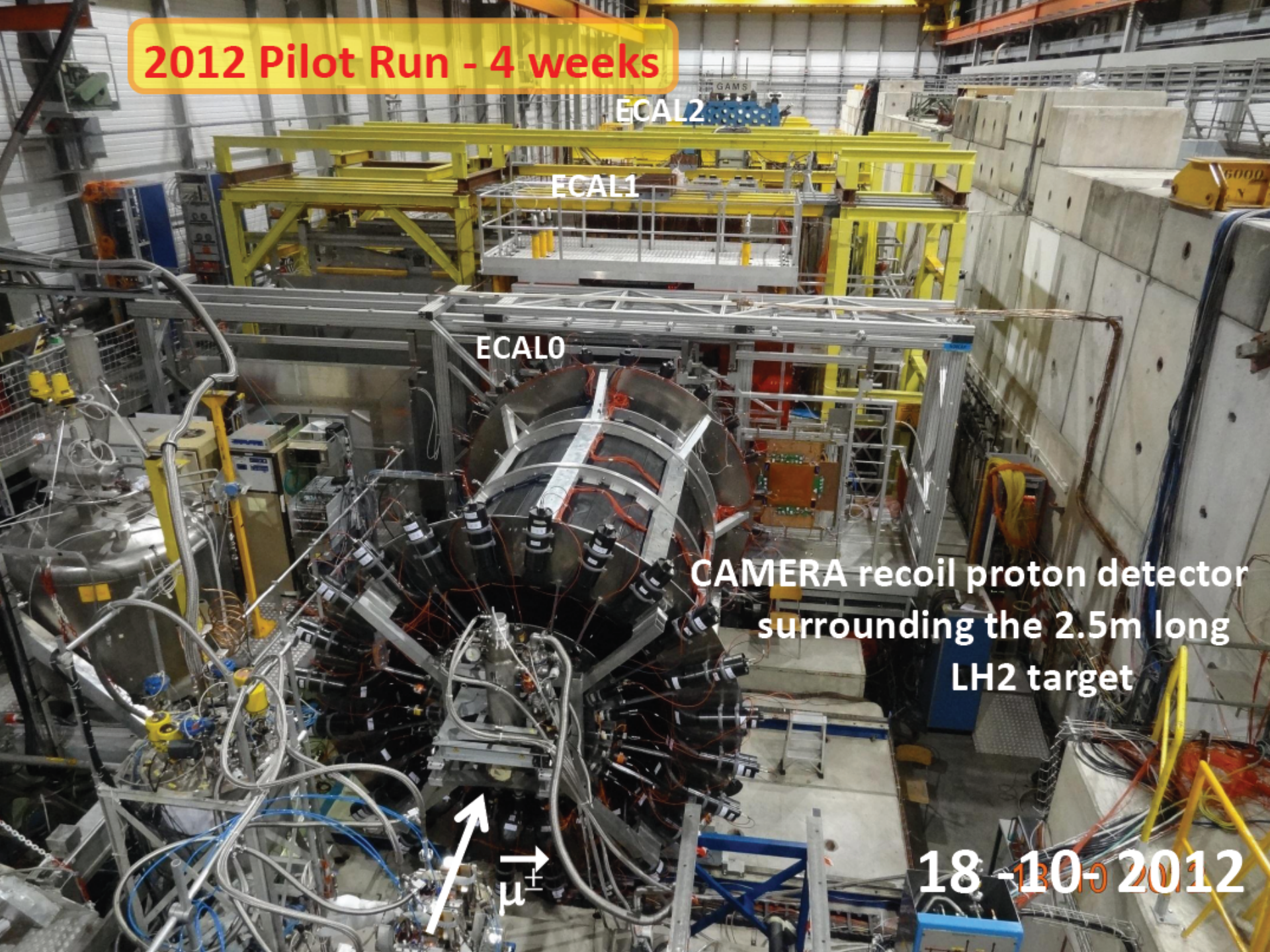
DVCS : μ p → μ' p γ



New equipements:

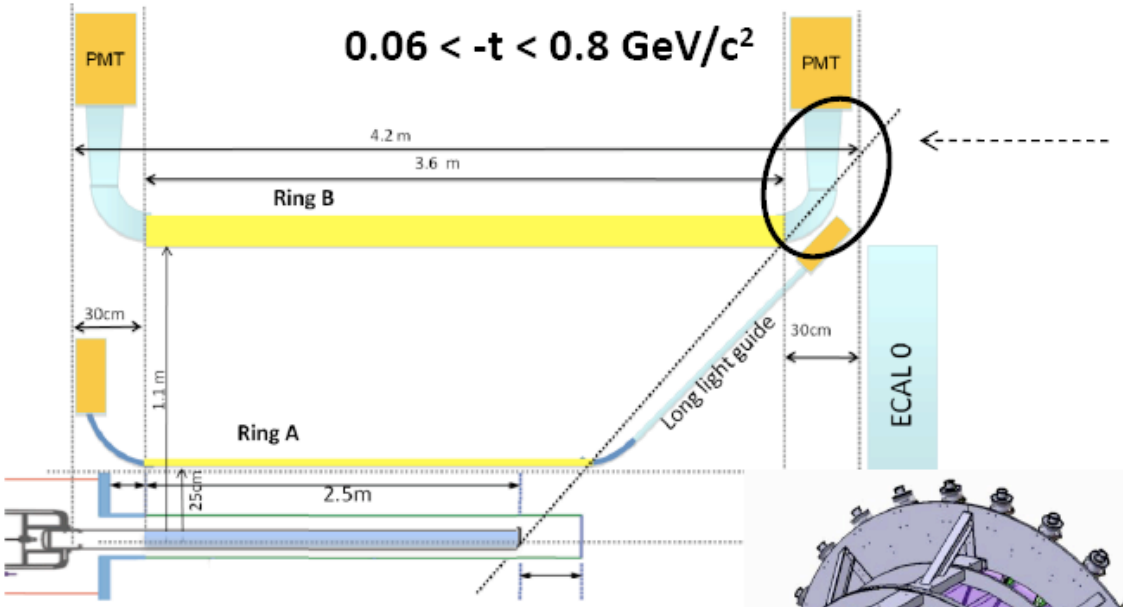
- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0

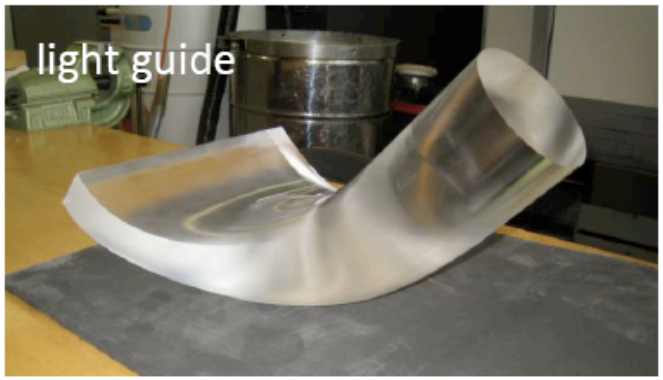


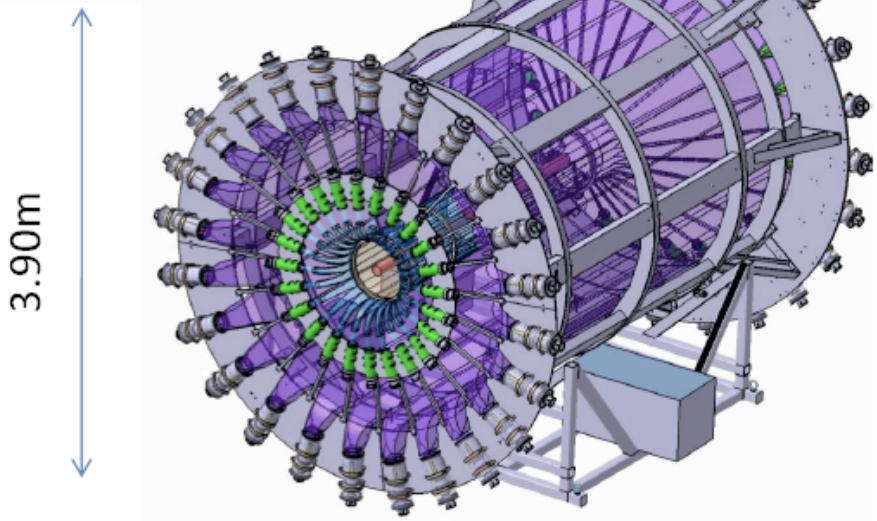

2012 Pilot Run - 4 weeks
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\mu^{\pm}$
18 -10- 2012

Recoil proton detector - CAMERA

ToF between 2 rings of plastic scintillators σ(ToF) < 350ps







Specifications

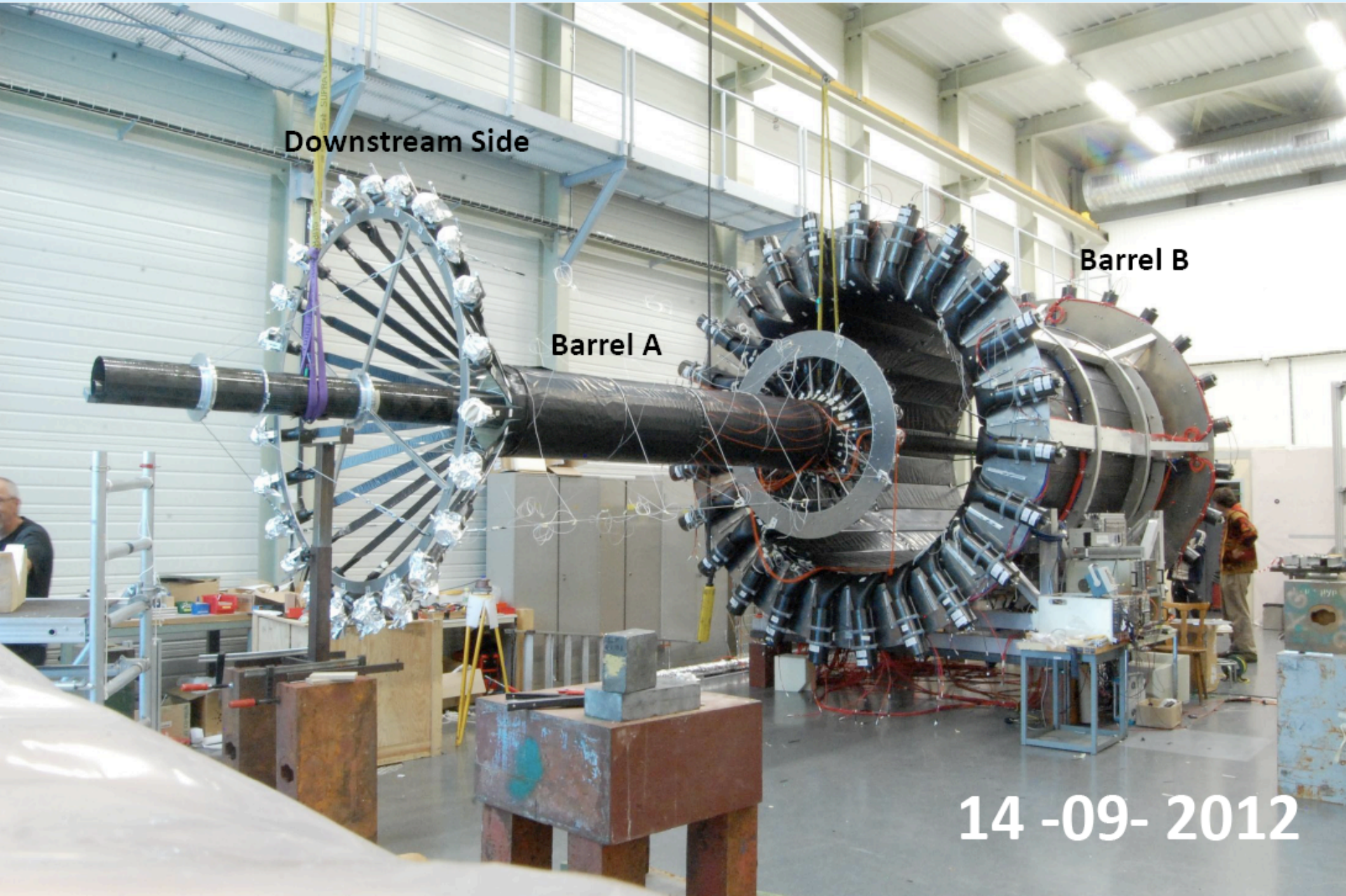
Ring A :

- 4mm thick, 280 cm long
- 310 ps
- Light holding structure

Ring B :

- 5cm thick, 360 cm long
- 180ps

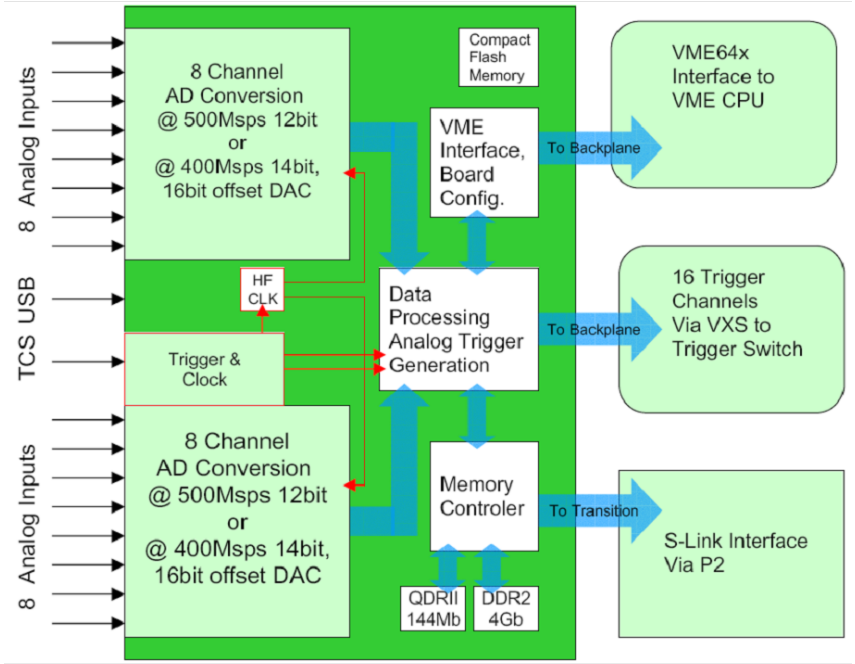
Mounting in clean area at CERN

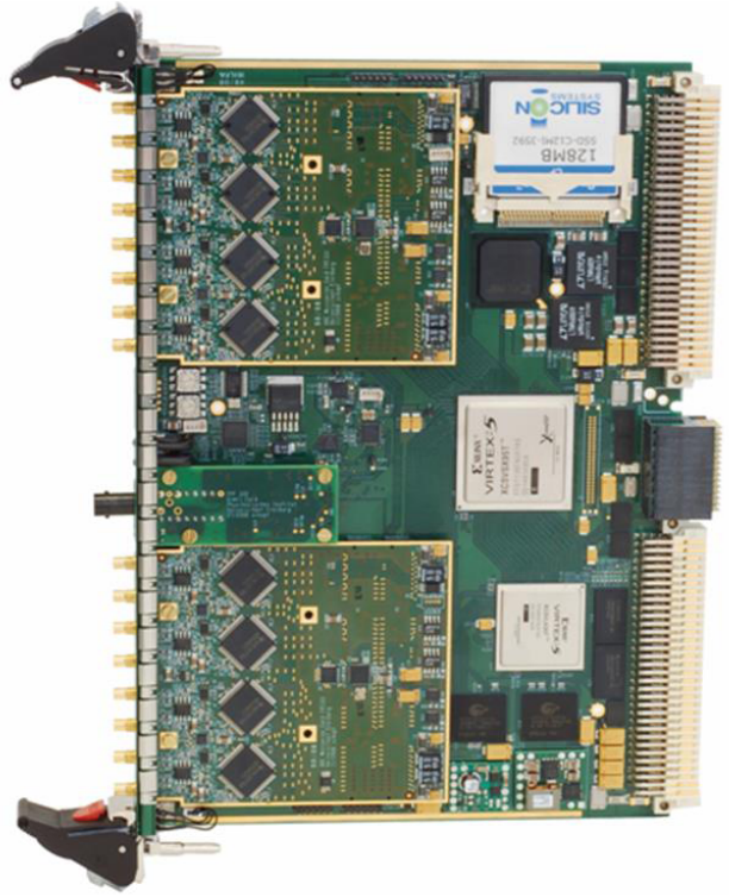


CAMERA read out: Gandalf boards

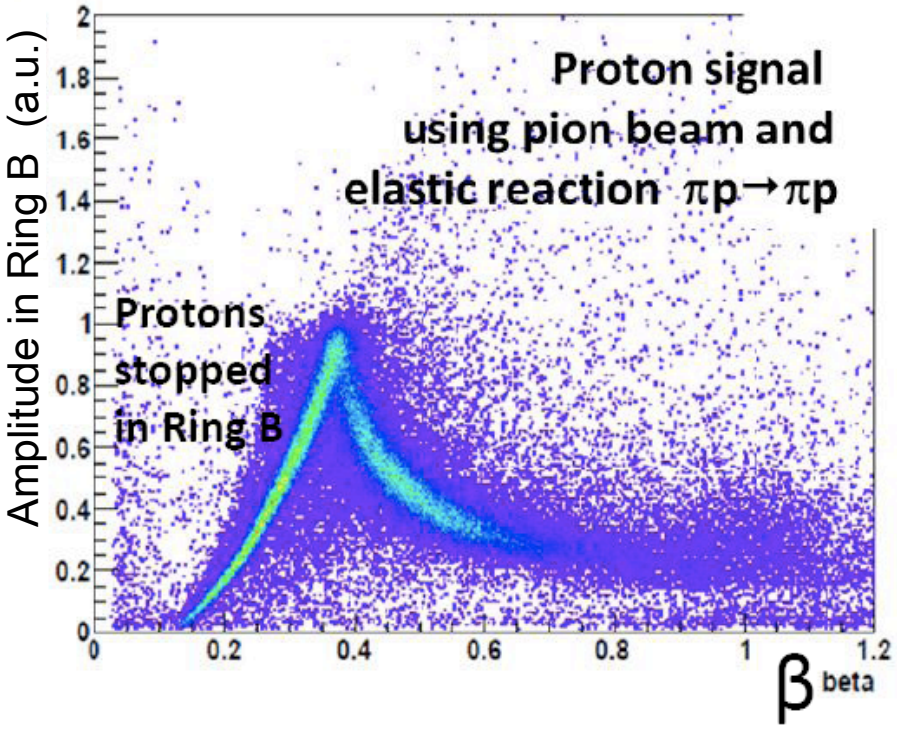
To cope with CAMERA high occupancy due to δ rays

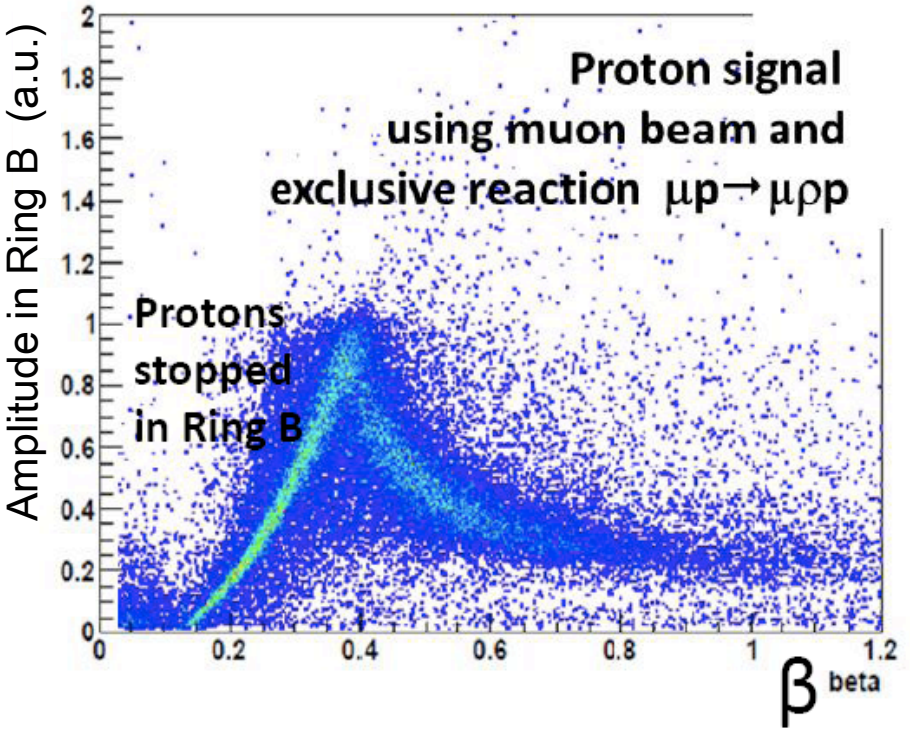
1 GHz digitization of the 96 PMT signals
Waveform treatment performed and the board
Data sent to 2 logic units (VXS backplane) : TIGER boards
⇒ One board for data concentration and DAQ
⇒ One board for level 1 trigger





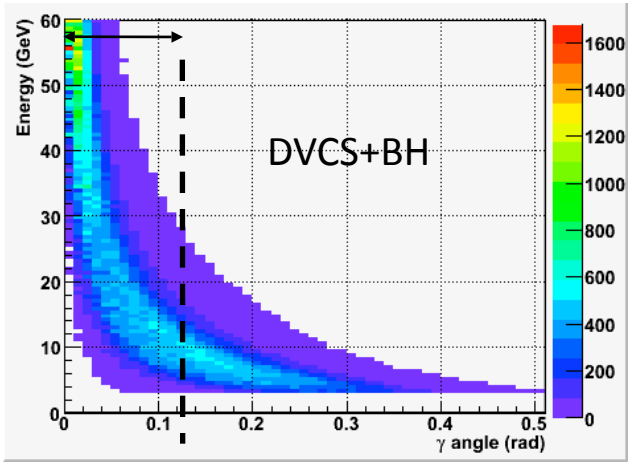
CAMERA performance

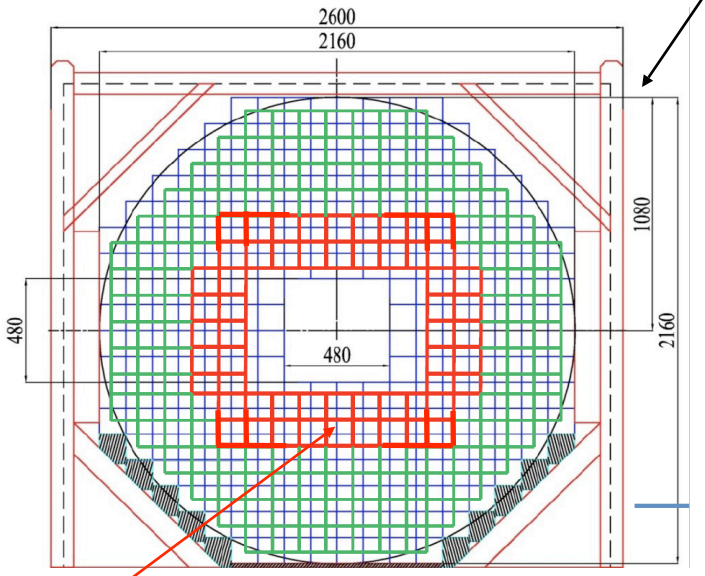




Large-angle electromagnetic calorimeter ECAL0

existing
ECAL1&2





central part of ECAL0 operating in 2012

ECAL0 specifications

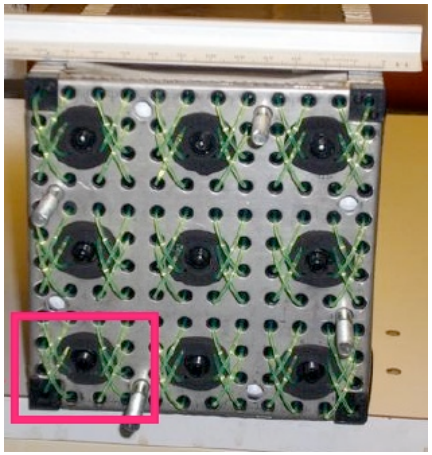
- located downstream of CAMERA
- transverse dimensions ~ 216x216 cm^2
- hole size 84x60 cm^2
- granularity 4x4 cm^2
- energy range 0.1 - 30 GeV
- polar angle range 0.15-0.6 rad.
- energy resolution ~ (5-7)%/sqrt(E)
- time resolution 0.5-0.6 ns
- thickness $\lesssim$ 50 cm
- insensitive to magnetic field

Total: 194 9-cell modules
1746 MAPDs
the weight about 5 tons

ECAL0 module

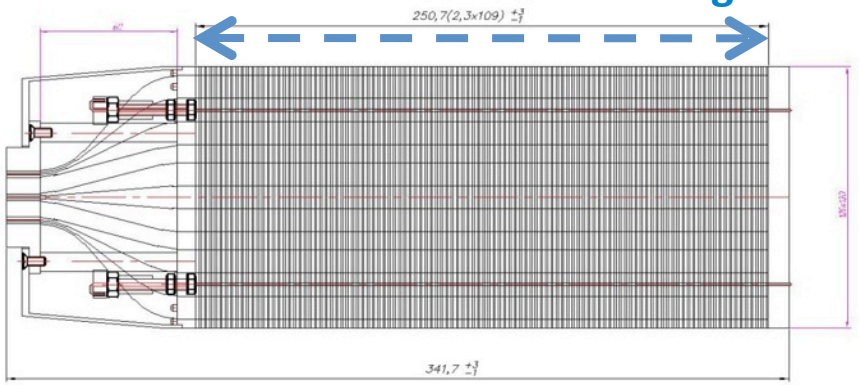
Single module:

- size is 12x12 cm^2
- 9 cells, size is 4x4 cm^2
- 9 light collection systems
- read out by 9 MAPDs
- 9 MSADC channels
- Temperature stabilization system (Peltier element, electronics)
- 9 Amplifiers
- Control system (LED, Laser)



ECAL0 cell

252mm or 15 radiation length



shashlyk technology

109 plates made of Sc 1.5 mm /Pb 0.8 mm

Micropixel Avalanche Photo Diodes

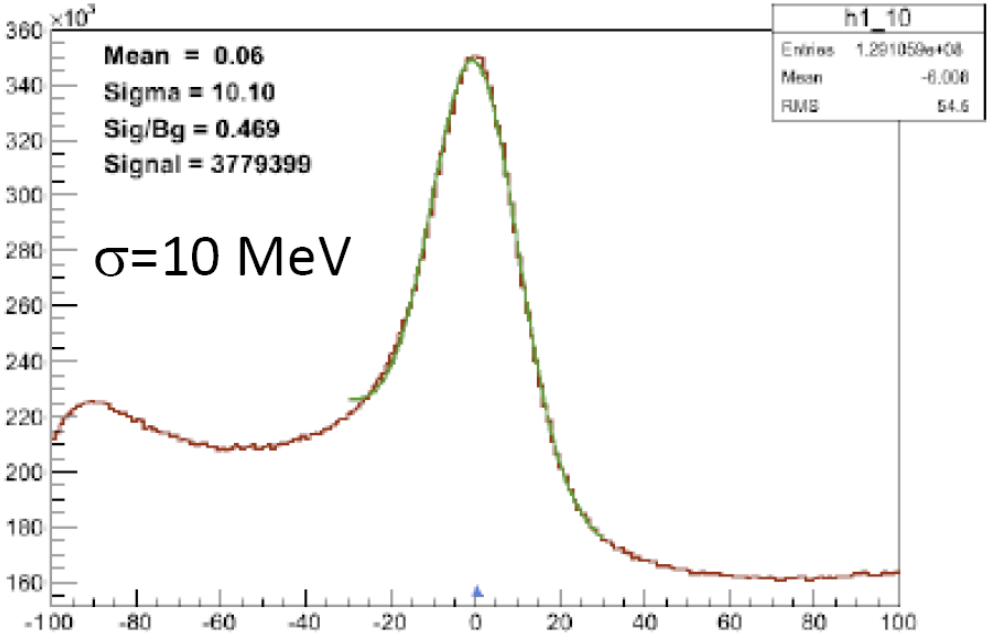
3 x 3 mm^2, number of pixels ~ 135 000

ECAL0 in 2012 DVCS pilot run

56 modules (~1/4 of total) availale for 2012 run
(calibrated with beam on Oct 24, 2012)

Reduced setup in 2012 (1/4 of total)

Invariant $\gamma\gamma$ mass spectra for π^0 production using pion beam



Complete GPD program of Stage 1 with complete ECAL0 is scheduled for 2016-2017

Summary

- COMPASS has a great potential for GPD physics
  - ✓ unique polarised μ^+ and μ^- beams
  - ✓ favourable kinematic domain (x_{Bj})
- Large projects for new apparatus
  - ✓ 4m RPD + large angle ECAL0 (phase 1)
  - ✓ recoil proton detector incorporated into a large polarised target (phase 2)
- Investigation of GPDs with both DVCS and HEMP on unpolarised nucleons
  - ✓ t-slope of DVCS and HEMP cross section as a function of x_{Bj}
    → transverse distribution of partons
  - ✓ Beam Charge&Spin sum and difference of DVCS cross sections
    → $\mathcal{R}e\, T^{DVCS}$ and $Im\, T^{DVCS}$ for the GPD H determination
  - ✓ Production of vector mesons ρ^0, ω, φ … → flavour separation for GPD H
  - ✓ Production of π^0 → sensitivity to GPDs $\tilde{E}$ and $\bar{E}_T$ ($\equiv 2\tilde{H}_T + E_T$)
- Transverse Target Spin Asymmetries for DVCS and hard exclusive meson production
  - → GPD E and angular momentum of partons
  - → also for mesons investigation of chiral-odd GPDs