COMPASS projections for GPDs

Andrzej Sandacz

Sołtan Institute for Nuclear Studies, Warsaw

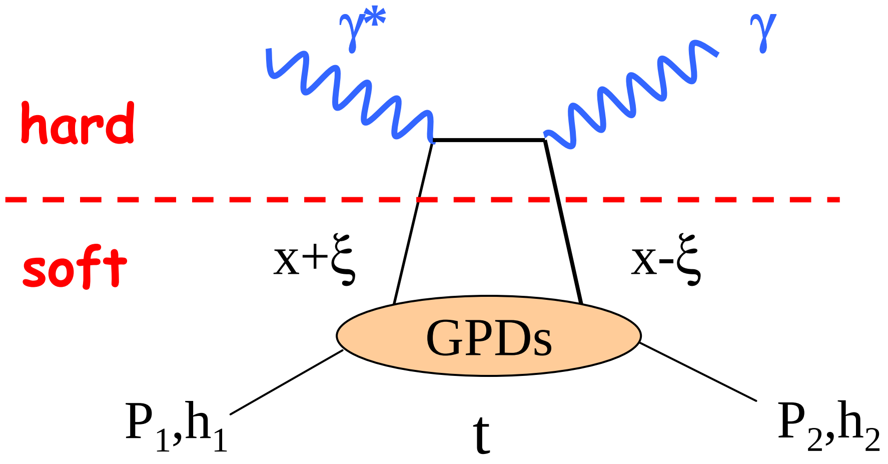
IWHSS10

International Workshop on Hadron Structure and Spectroscopy

at Venice International University, Italy

March 14 - 17, 2010

Generalized Parton Distributions and DVCS



Factorisation:

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

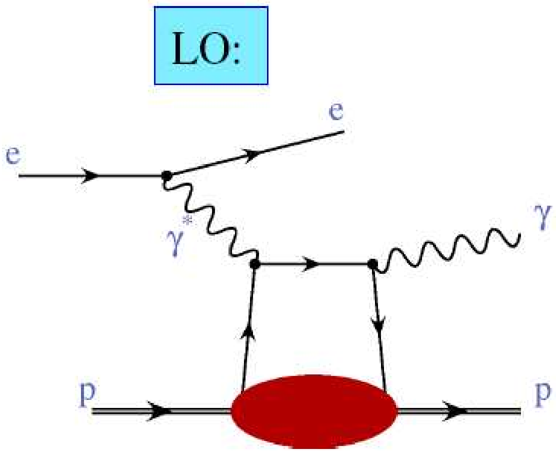
$$\xi = \frac{x_B}{2 - x_B}$$

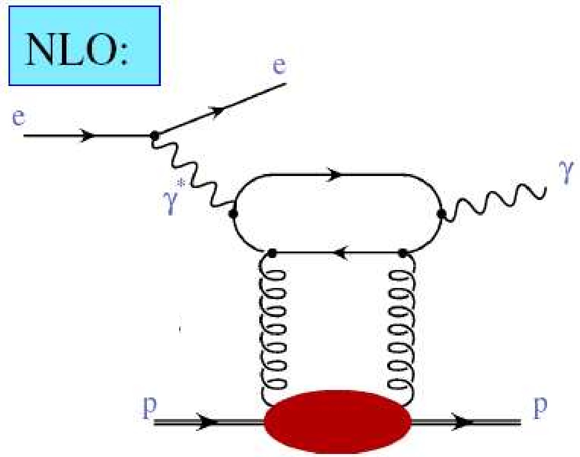
P_i, h_i – proton momentum and helicity

4 Generalised Parton Distributions : $H, E, \tilde{H}, \tilde{E}$ depending on 3 variables: x, ξ, t

for each quark flavour and for gluons

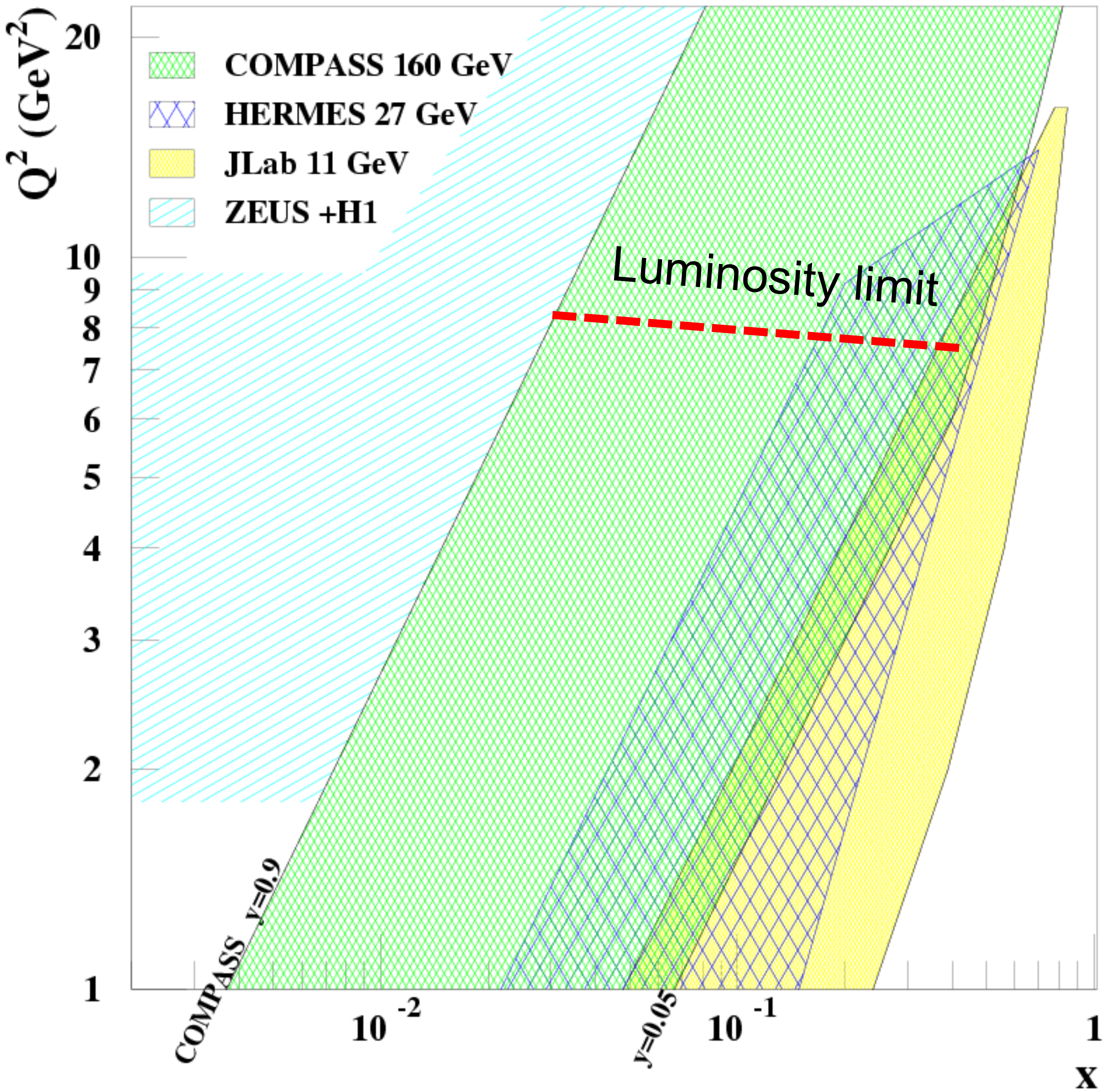
for DVCS gluons contribute at higher orders in α_s





COMPASS kinematical coverage for DVCS

CERN SPS high energy polarised muon beam 100/190 GeV



with a 2.5m long LH_2 target
$L = 10^{32}$ cm^{-2} s^{-1}

$Q^2 \rightarrow$ 8 GeV^2

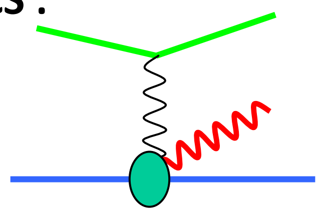
$\rightarrow$ 16 GeV^2 if luminosity increased by factor 4

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

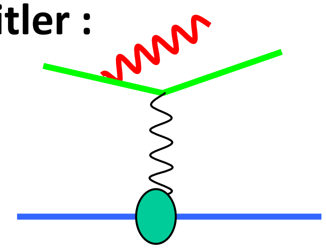
$x \rightarrow$ 0.20 with extension of present calorimetry

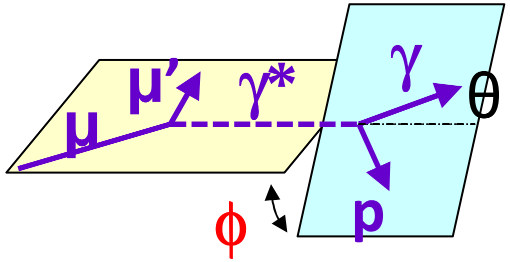
Comparison of BH and DVCS at 160 GeV

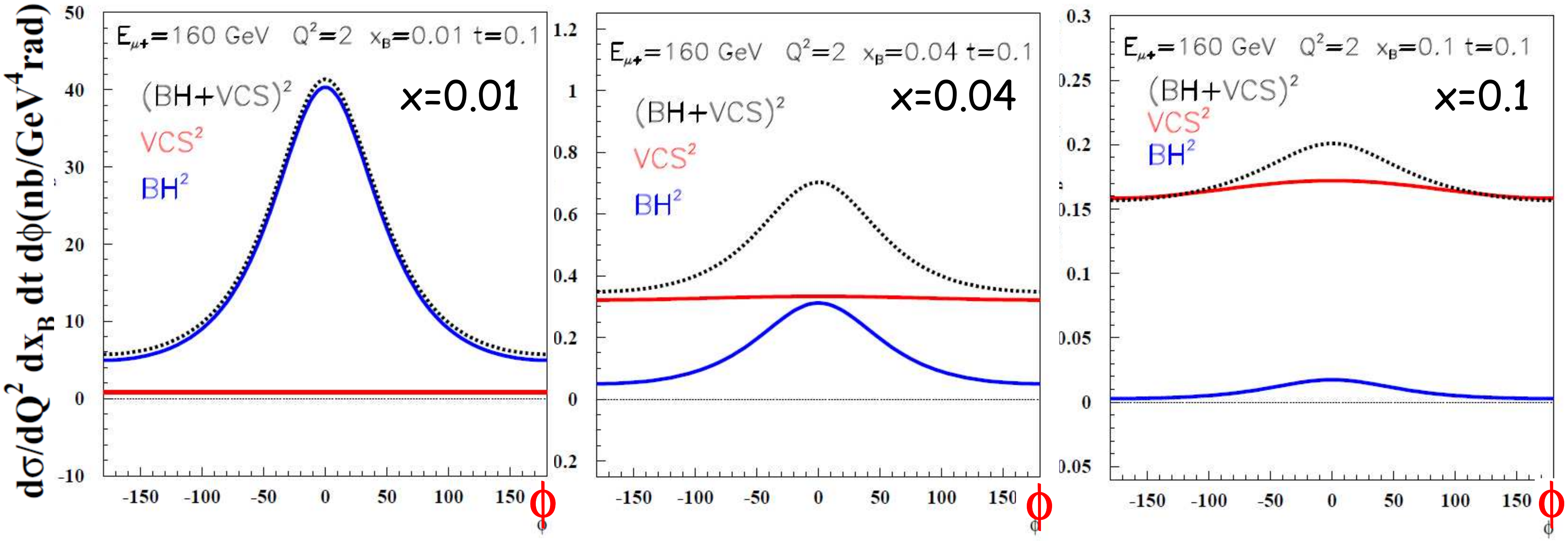
DVCS :



Bethe-Heitler :







BH dominates	BH and DVCS at the same level	DVCS dominates
excellent reference yield	access to DVCS amplitude through the interference	study of $d\sigma^{DVCS}/dt$

The GPDs in the next several years

- **H1, ZEUS, HERMES, JLab 6 GeV** are providing the first results
  significant increase of statistics expected after
  full data sets analysed

- 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

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

‘Stage 1’ of COMPASS GPD program

DVCS and HEMP with unpolarised proton target

↓

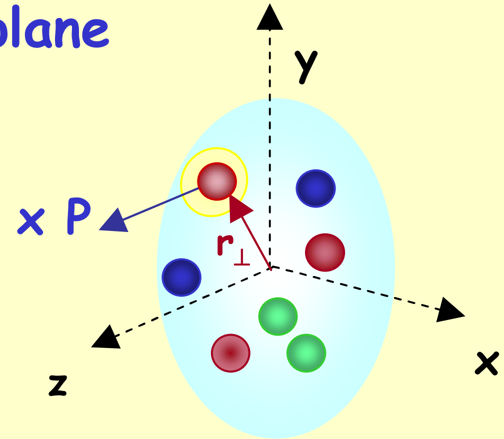
to constrain GPD H

- GPD - 3-dimensional picture of the partonic nucleon structure or spatial parton distribution in the transverse plane

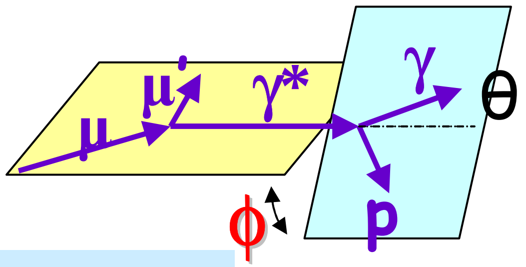
$$H(x, \xi=0, t) \rightarrow H(x, r_{x,y})$$

probability interpretation

Burkardt



DVCS + BH with μ+↓ and μ-↑ beams
and unpolarized proton target



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

Beam Charge & Spin Difference

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

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi$$

$$s_1^{DVCS}\sin\phi$$

Beam Charge & Spin Sum

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

$$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

$$s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi$$

Assumptions for the simulations

- polarised muon beam with 160 GeV energy
- 48 s SPS period with 9.6 s spill duration
- μ^+ beam intensity 4.6 x 10^8 muons / spill
- 3 times smaller intensity for μ^- beam
- running time 280 days (70 days with μ^+, 210 days with μ^-)
- a) 2.5 m LH target => $\mathcal{L} = 1. \times 10^{32}$ $cm^{-2}s^{-1}$ for μ^+ beam

  b) 1.2 m NH_3 target => $\mathcal{L} = 3.4 \times 10^{32}$ $cm^{-2}s^{-1}$ for μ^+ beam
- a new decoil proton detector(s) (RPD) surrounding the target(s)
- two existing electromagnetic calorimeters (ECAL1, ECAL2)

  as an option an additional new large angle calorimeter (ECAL0)
- an overall global efficiency $\varepsilon_{global} = 0.1$

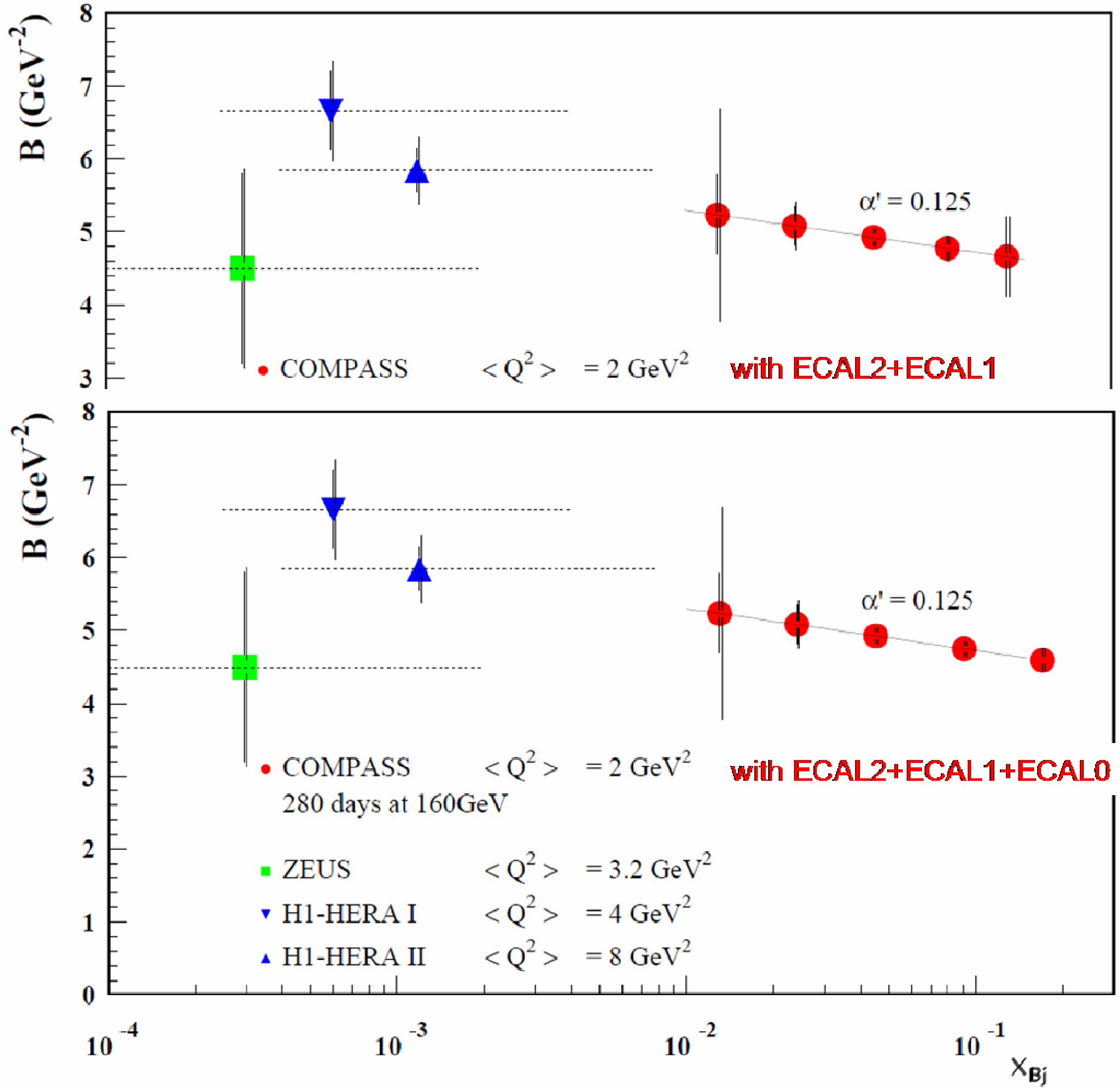
Generators for single photon production (BH+DVCS): for DVCS amplitude used

a) VGG code b) FFS model adapted for COMPASS (AS)

t-slope measurement; relevant for nucleon 'tomography'

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

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



FFS model

adapted for COMPASS (AS)

assumed

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

with $\alpha' = 0.125\ GeV^{-2}$

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

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

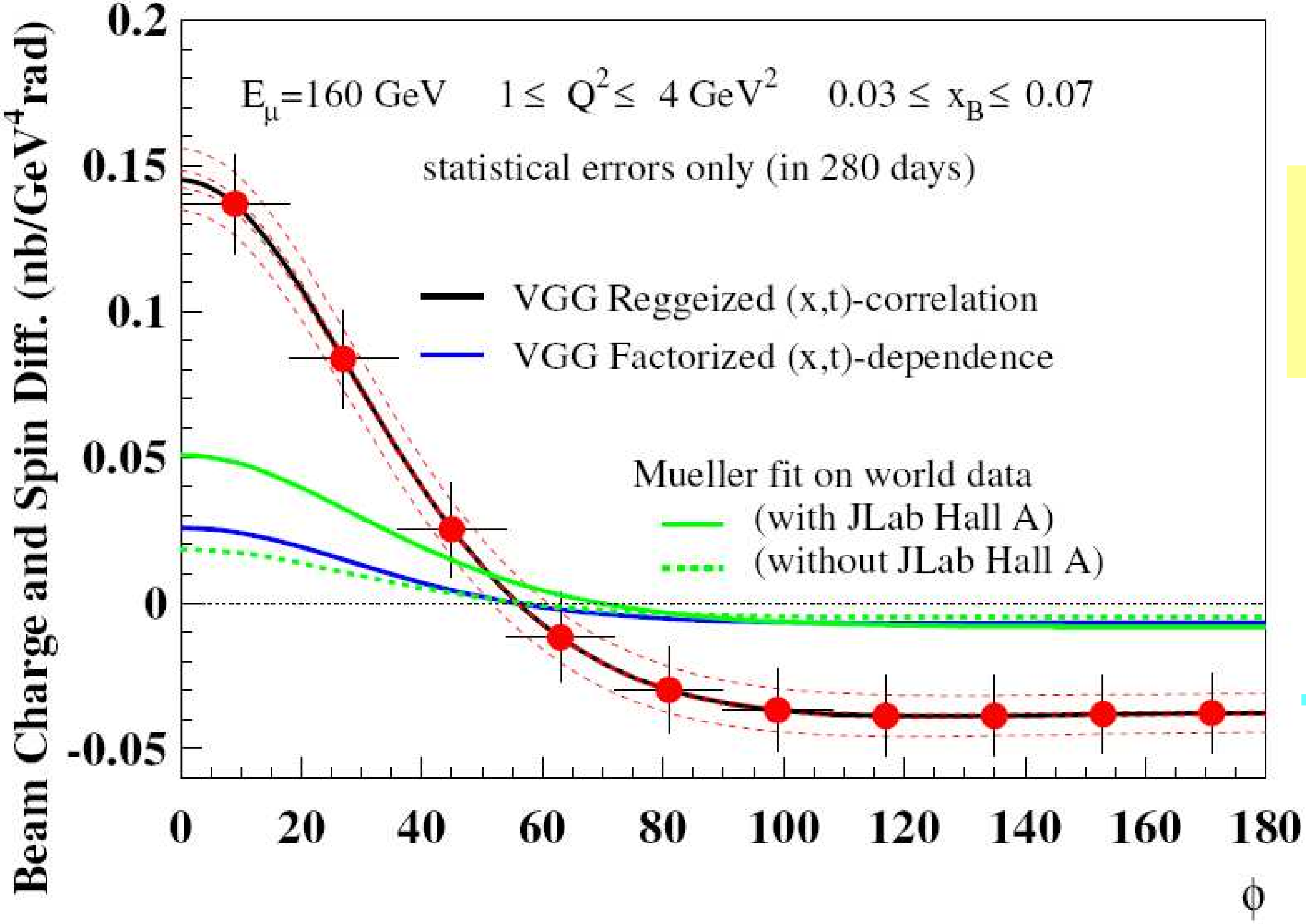
assumed 3% systematic error on extracted DVCS c.s.

Beam Charge&Spin Difference of cross sections

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

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi$$

$$s_1^{DVCS}\sin\phi$$



160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
ECAL1+ECAL2 only

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

$\ldots + c_1^{Int}\cos\varphi + \ldots$

$\Rightarrow \mathcal{R}e(F_1\mathcal{H})$

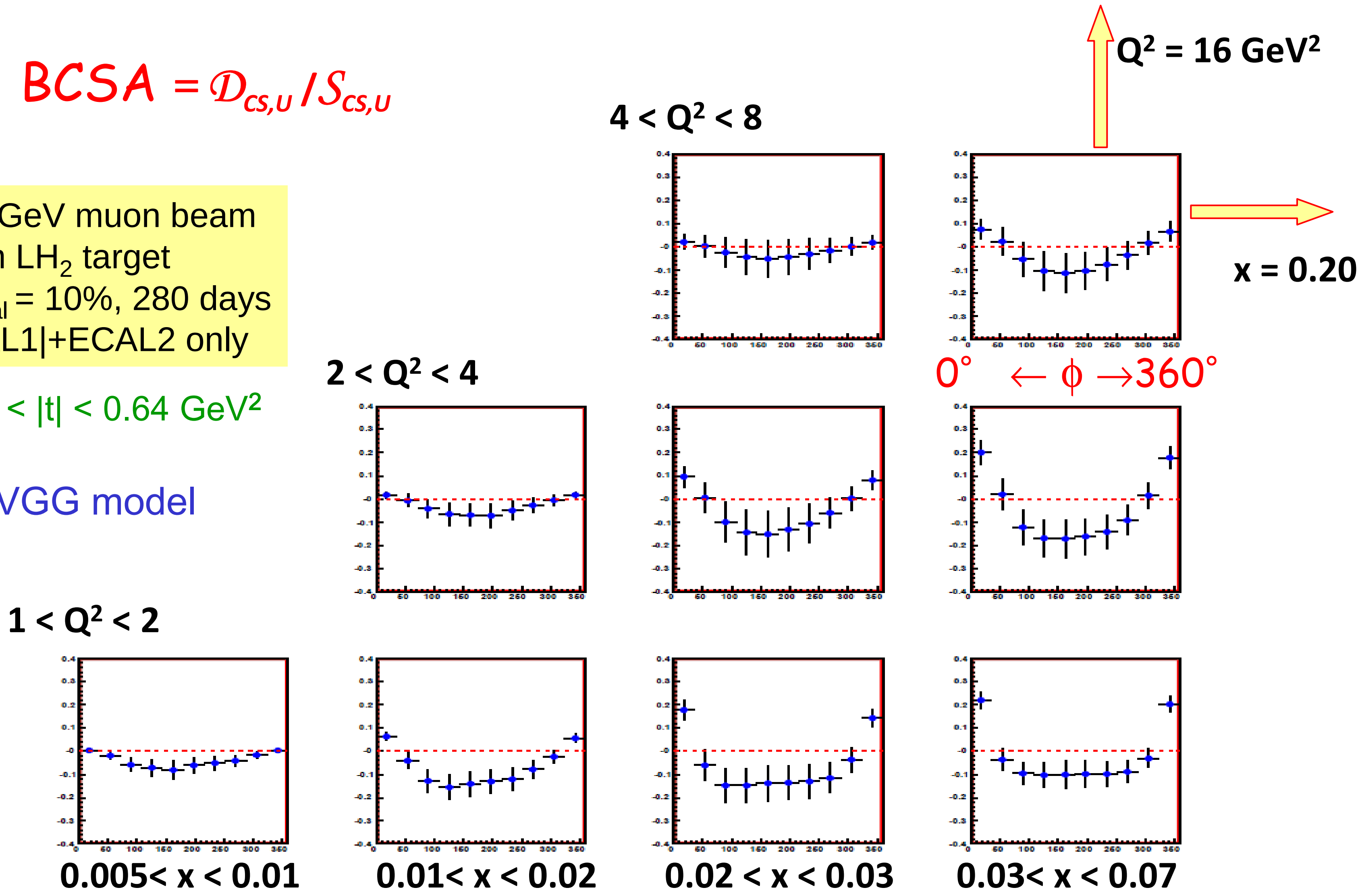
Beam Charge and Spin Asymmetry in various kinematic bins

$BCSA = \mathcal{D}_{cs,U} / \mathcal{S}_{cs,U}$

160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
ECAL1|+ECAL2 only

0.06 < |t| < 0.64 GeV^2

VGG model



If Lumi × 4 → more bins up to Q2 = 16 GeV2

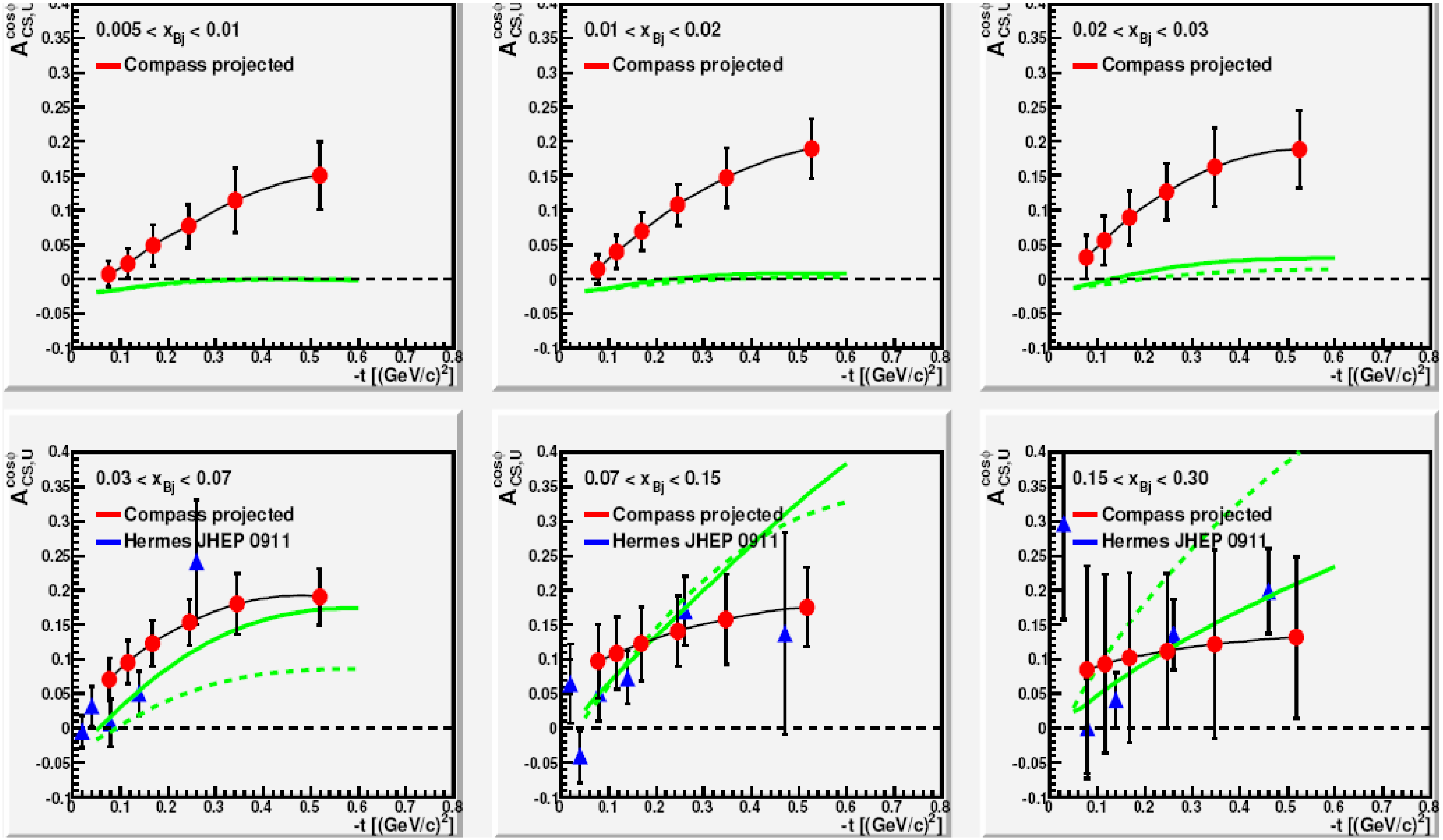
Statistical precision of cos ϕ modulation vs. (x_{Bj}, t)

$$BCSA = \mathcal{D}_{U,CS} / \mathcal{S}_{U,CS} = A_0 + A_{CS,U}\cos\phi + A_2 \cos 2\phi$$

160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 280 days
ECAL0+ECAL1+ECAL2

$A_{CS,U}$ => c_1^{Int} => $\mathcal{R}e(F_1\mathcal{H})$

Mueller's fit on world data'
(with JLab Hall A)
(without JLab Hall A)



‘Stage 2’ of COMPASS GPD program

DVCS and HEMP with transversely polarised proton target (NH_3)

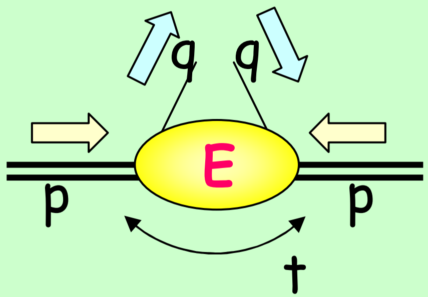
to constrain GPD E

- **Contribution to the nucleon spin puzzle**

E related to the angular momentum

$$2J_q = \int x \, (H^q(x,\xi,0) + E^q(x,\xi,0)) \, dx$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \sum_{q=u,d,s} L^q + J^g$$



Single γ production with transversely polarised target

$$d\sigma_{(\mu p\rightarrow\mu p\gamma)} = d\sigma_{U(\mu p\rightarrow\mu p\gamma)} + d\sigma_{T(\mu p\rightarrow\mu p\gamma)}$$

unpolarized target | transversely polarized target

to isolate TTS part measurements at opposite target polarisations needed

$$d\sigma_T = ½ \{d\sigma\,(S_T=+P_T)\ -\ d\sigma(S_T=-P_T)\}$$

$$d\sigma_{T(\mu p\rightarrow\mu p\gamma)} = S_T\,P_\mu\,d\sigma_T^{BH} + S_T\,d\sigma_T^{DVCS} + S_T\,P_\mu\,d\sigma_T^{DVCS}{}_{pol}$$

$$+\ S_T\,e_\mu\,a_T^{BH}\,T_T^{DVCS} \qquad +\ S_T\,e_\mu\,P_\mu\,a_T^{BH}\,T_T^{DVCS}{}_{pol}$$

to disentangle DVCS and Interference terms having the same azimuthal dependence

both μ+↓ and μ-↑ beams needed

cf. the next slide

measure

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

$$\mathcal{S}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) + d\sigma_T(\mu^{-\uparrow})$$

or/and

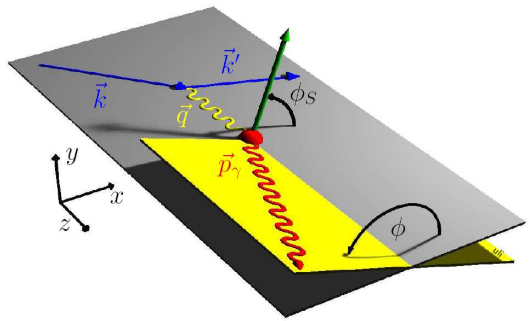
$$\mathcal{A}^{D}{}_{CS,T} \equiv \mathcal{D}_{CS,T}/d\sigma_0$$

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

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

Harmonics decomposition of TTS-dependent 1 γ production cross section

Belitsky, Müller, Kirchner



$S_T\, P_\mu \times$ $$d\sigma_T^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\phi)P_2(\phi)}\left(c_{0,T}^{BH}\cos(\phi-\phi_s) + c_{1,T}^{BH}\cos(\phi-\phi_s)\cos\phi + s_{1,T}^{BH}\sin(\phi-\phi_s)\sin\phi\right)$$

$S_T \times$ $$d\sigma_T^{DVCS} = \frac{e^6}{y^2Q^2}\left(c_{0,T-}^{DVCS}\sin(\phi-\phi_s) + c_{1,T-}^{DVCS}\sin(\phi-\phi_s)\cos\phi + s_{1,T+}^{DVCS}\cos(\phi-\phi_s)\sin\phi + \ldots\right)$$

$S_T\, P_\mu \times$ $$d\sigma_{T,pol}^{DVCS} = \frac{e^6}{y^2Q^2}\left(c_{0,T+}^{DVCS}\cos(\phi-\phi_s) + c_{1,T+}^{DVCS}\cos(\phi-\phi_s)\cos\phi + s_{1,T-}^{DVCS}\sin(\phi-\phi_s)\sin\phi + \ldots\right)$$

$S_T\, e_\mu \times$ $$a_T^{BH} T_T^{DVCS} = \frac{e^6}{xy^3tP_1(\phi)P_2(\phi)}\left(c_{0,T-}^{Int}\sin(\phi-\phi_s) + c_{1,T-}^{Int}\sin(\phi-\phi_s)\cos\phi + s_{1,T+}^{Int}\cos(\phi-\phi_s)\sin\phi + \ldots\right)$$

$S_T\, e_\mu\, P_\mu \times$ $$a_T^{BH} T_{T,pol}^{DVCS} = \frac{e^6}{xy^3tP_1(\phi)P_2(\phi)}\left(c_{0,T+}^{Int}\cos(\phi-\phi_s) + c_{1,T+}^{Int}\cos(\phi-\phi_s)\cos\phi + s_{1,T-}^{Int}\sin(\phi-\phi_s)\sin\phi + \ldots\right)$$

twist-2 terms

not shown are terms with sin(kφ) and cos(kφ) (k=2,3) dependence
those are twist-3 and NLO twist-2 gluon helicity flip terms

Sensitivity to GPD E

the most promissing Transverse Target Spin asymmetry

$$A^D_{CS,T} \text{ (or } A_{UT}) \; {}^{\sin(\phi-\phi s)\cos\phi} \longrightarrow c_{1,T-}^{Int}$$

COMPASS HERMES

$$c^{Int}_{1,T-} \propto -\frac{M}{Q}\mathrm{Im}\left\{\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right] + x_B\xi\left[F_1(\mathcal{H}+\mathcal{E}) - (F_1+F_2)(\widetilde{\mathcal{H}} + \frac{t}{4M^2}\widetilde{\mathcal{E}})\right]\right\}$$

Study of azimuthal asymmetries from transversely polarized NH_3 target is a part of Phase 2 of COMPASS GPD program

example: COMPASS projections for

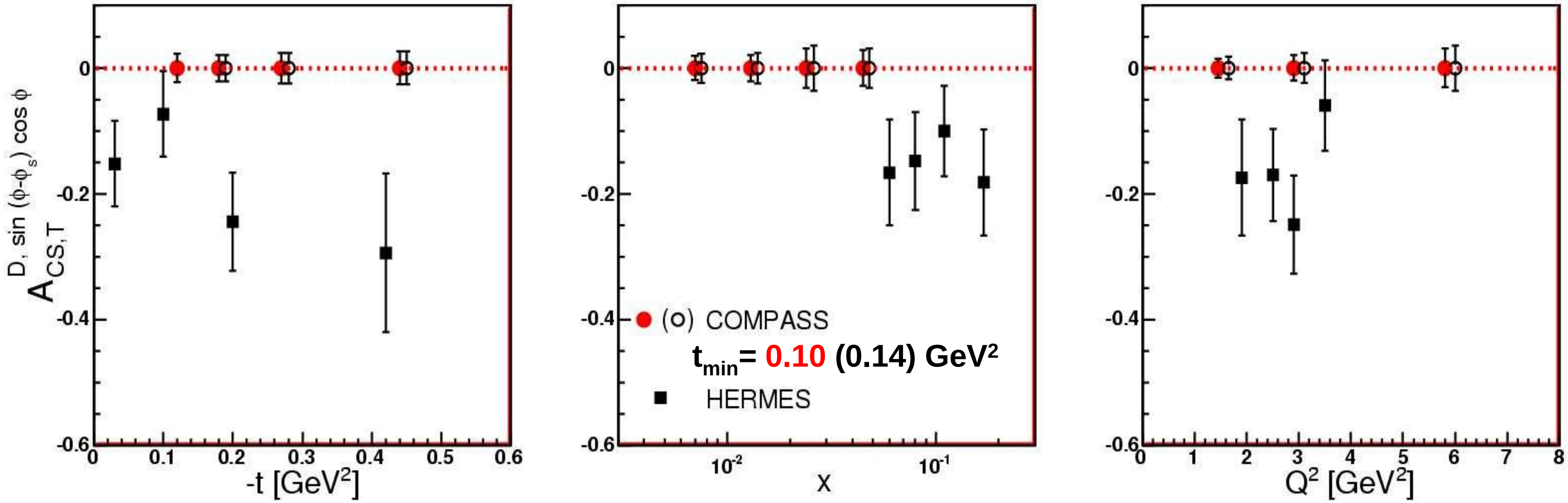
$$A^{D}_{CS,T}{}^{\sin(\phi-\phi s)\cos\phi}$$

160 GeV muon beam
1.2m NH_3 target
ε_{global} = 10%, 280 days
ECAL1+ECAL2 only

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

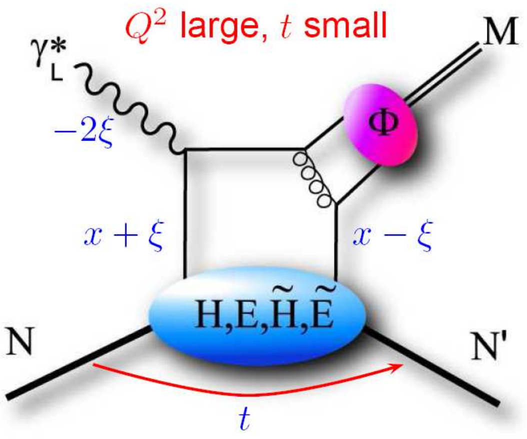
FFS model
adapted for COMPASS (AS)

0.10 (0.14) < |t| < 0.64 GeV²



Typical statistical errors of TTS azimuthal asymmetries:
projections for COMPASS ≈ 0.03
for HERMES ≈ 0.08

GPDs and Hard Exclusive Meson Production



- factorisation proven only for σ_L

  σ_T suppressed by $1/Q^2$

  desirable to extract longitudinal contribution to observables (σ_L , …)

- allows separation $(H,E) \leftrightarrow (\tilde{H},\tilde{E})$ and wrt quark flavours

  H, E — Vector mesons (ρ, ω, φ)

  $\tilde{H}$, $\tilde{E}$ — Pseudoscalar mesons (π, η)

  H, $\tilde{H}$: conserve; E, $\tilde{E}$: flip nucleon helicity

Flavour sensitivity of HEMP on the proton

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

- quarks and gluons enter at the same order of α_S

- at $Q^2 \approx$ few GeV² power corrections/higher order pQCD terms are essential

- wave function of meson (DA Φ) additional input

Analyses of exclusive channels in leptoproduction with present setup

without recoil detector

- Analyses for ρ^0 and φ channels

❖ transverse target spin asymmetry	ρ^0	on	p, d	$Q^2 > 1$ GeV^2
❖ cross sections, R($=\sigma_L/\sigma_T$), t-slopes	ρ^0, φ	on	p, d	$Q^2 > 1$ GeV^2
❖ SDMEs	ρ^0, φ	on	p, d	all Q^2
❖ longitudinal double spin asymmetry	ρ^0, φ	on	d	all Q^2

- Searches for signals of exclusive $J/\psi(\rightarrow\mu^+\mu^-)$, ω^0, π^0 production

TTS asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ for ρ^0 production on protons from COMPASS

2007 data from transversely polarised NH_3 COMPASS target

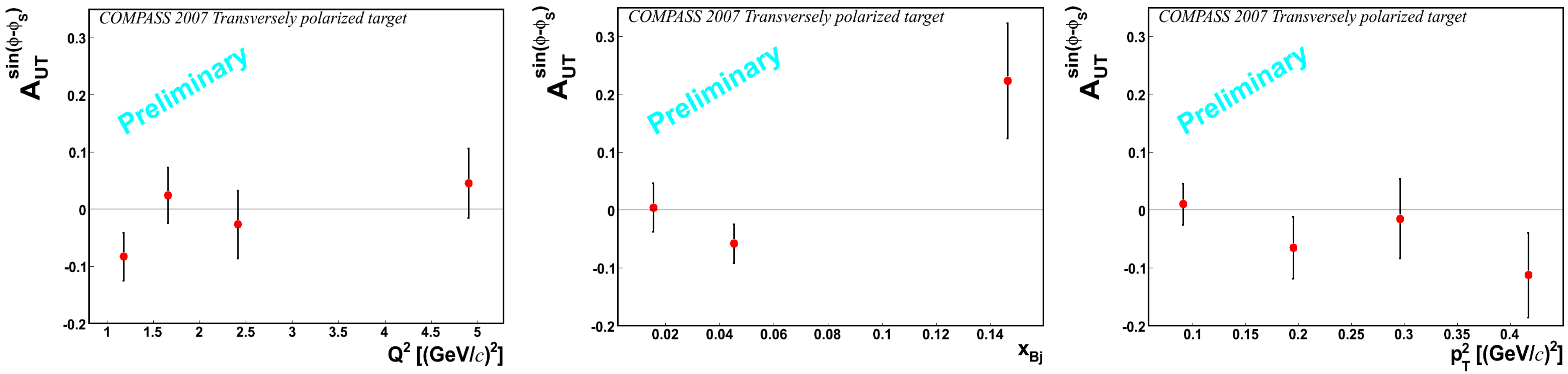
transverse spin dep. VM cross section $\frac{1}{\Gamma'} \mathrm{Im} \frac{d\sigma_{00}^{+-}}{dt} = -\sqrt{1-\xi^2} \frac{\sqrt{t_0 - t}}{M_p} \mathrm{Im}(\mathcal{E}_M^* \mathcal{H}_M)$ ⟸ **access to GPD E**

related to orbital momentum

$$\Gamma' = \frac{\alpha_{em}}{Q^6} \frac{x_B^2}{1-x_B} \qquad -t_0 = \frac{4\xi^2 M_p^2}{1-\xi^2}$$

$\mathcal{H}_M, \mathcal{E}_M$ are weighted sums of integrals of the GPDs $H_{q,g}, E_{q,g}$

$< Q^2 > \approx 2.2\ (\mathrm{GeV}/c)^2$ $< x_{Bj} > \approx 0.04$ $< p_t^2 > \approx 0.18\ (\mathrm{GeV}/c)^2$



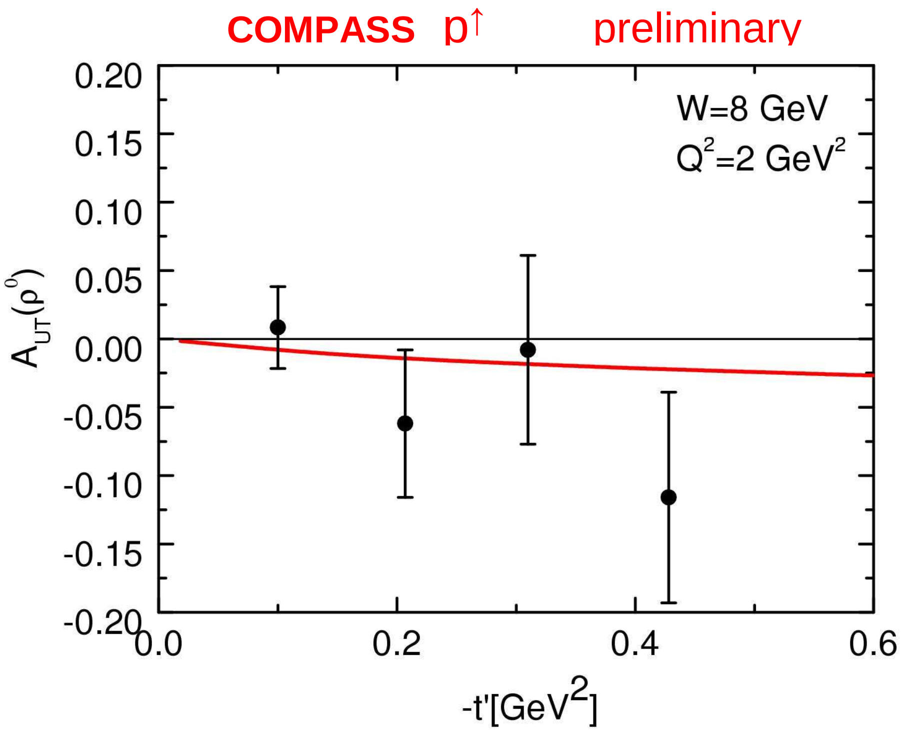
$A_{UT}^{\sin(\phi-\phi_S)}$ compatible with 0

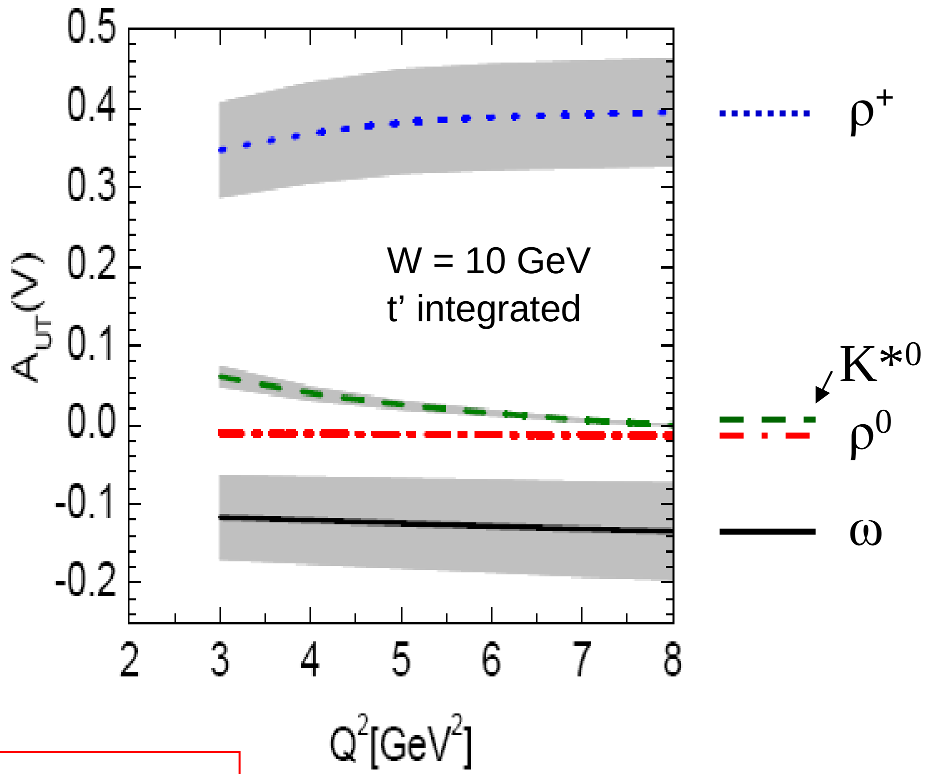
in progress: L/T γ^* separation (using ρ^0 decay angular distribution)

Comparison to a GPD model

- Goloskokov-Kroll
  [EPJ C53 (2008) 367]

'Hand-bag model'; GPDs from DD using CTEQ6
power corrections due to k_t of quarks included
→ both contributions of γ^*_L and γ^*_T included





predictions for protons

$A_{UT}(\rho) \approx -0.02$
$A_{UT}(\omega) \approx -0.10$

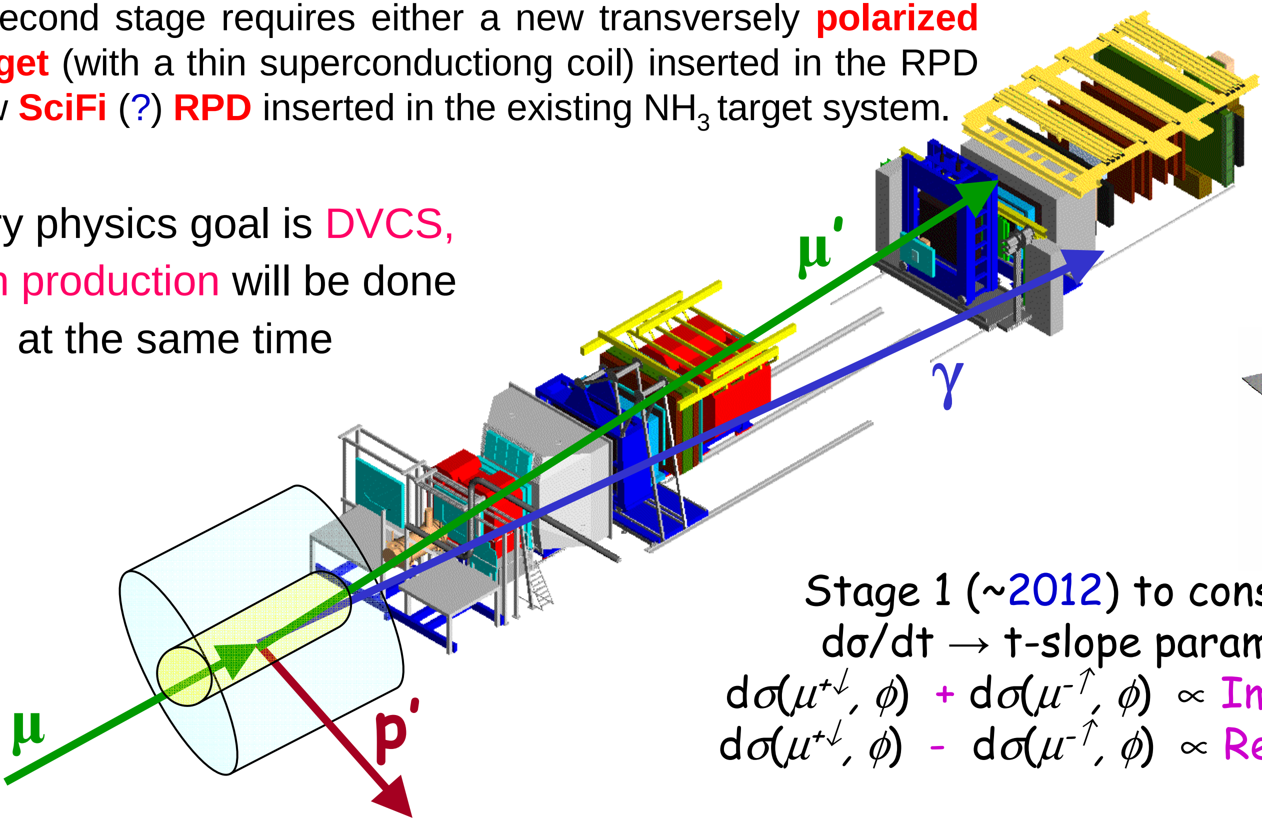
Future GPD program @ COMPASS in a nutshell

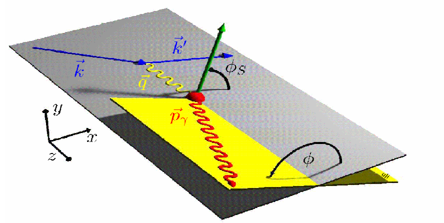
- The GPDs program is part of the **COMPASS Phase II** (2012-2016) proposal to be submitted to CERN in 2010.

- The first stage of this program requires a 4 m long recoil proton detector (**RPD**) together with a 2.5 m long **LH target**. Upgrades of electromagnetic calorimeters to enlarge coverage at large x_B and reduce bkg.

- The second stage requires either a new transversely **polarized NH_3 target** (with a thin superconductiong coil) inserted in the RPD or a new **SciFi** (?) **RPD** inserted in the existing NH_3 target system.

primary physics goal is DVCS, meson production will be done at the same time





Stage 1 (~2012) to constrain **H**

$d\sigma/dt \rightarrow$ t-slope parameter b

$$d\sigma(\mu^{+\downarrow}, \phi) + d\sigma(\mu^{-\uparrow}, \phi) \propto \mathrm{Im}(F_1\, H) \sin\phi$$

$$d\sigma(\mu^{+\downarrow}, \phi) - d\sigma(\mu^{-\uparrow}, \phi) \propto \mathrm{Re}(F_1\, H) \cos\phi$$

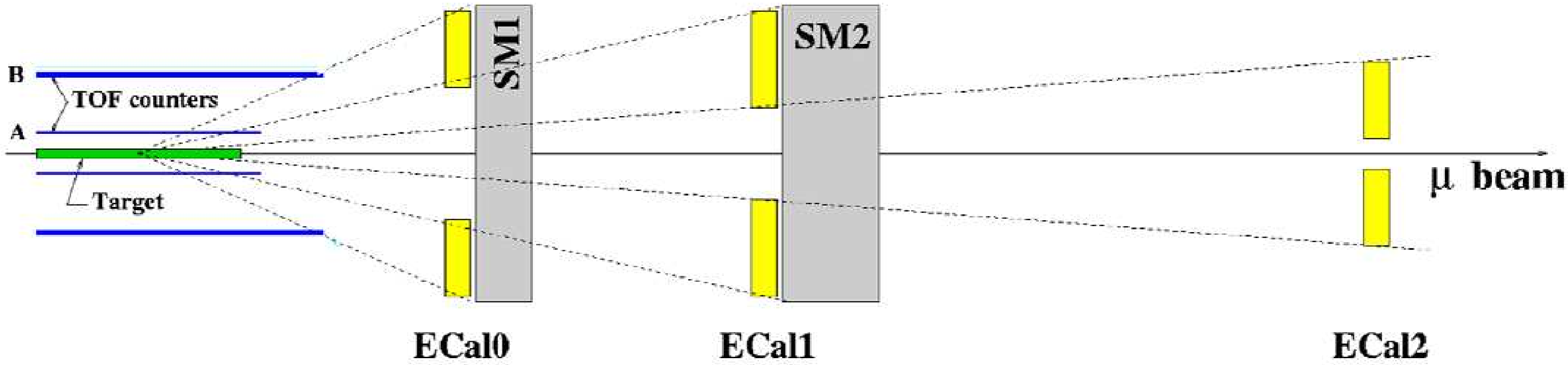
Stage 2 (later) to constrain **E**

$$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S+\pi) \propto \mathrm{Im}(F_2\, H - F_1\, E) \sin(\phi - \phi_S) \cos\phi$$

100 – 190 GeV $\mu^{+\downarrow,-\uparrow}$ 80%

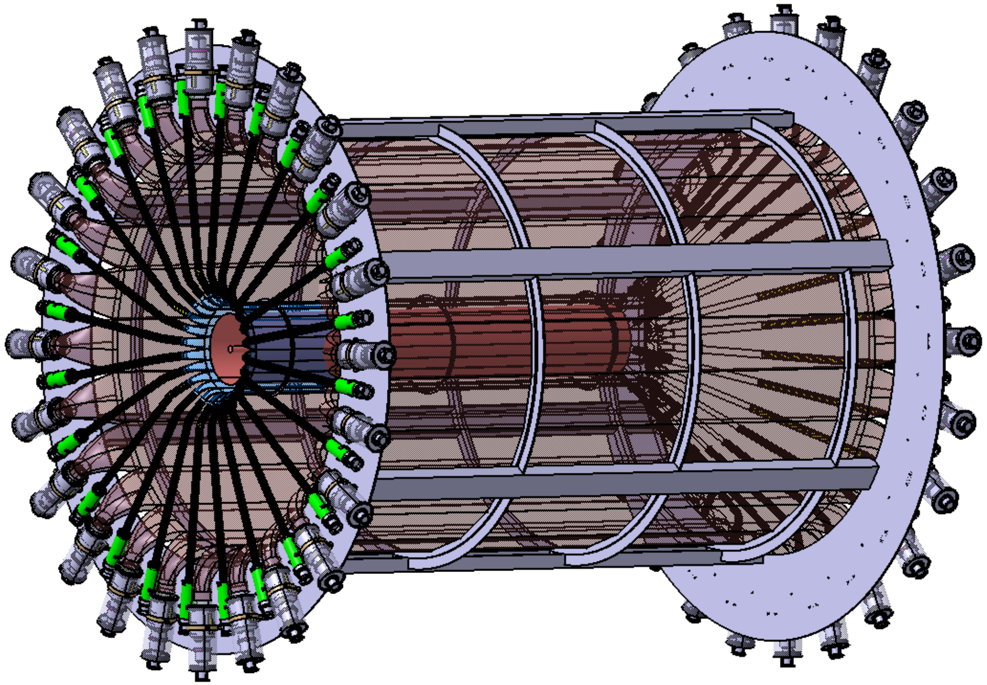
Detectors to be built

- Large Proton Recoil Detector and a long LH target (Phase 1)
  with dedicated read out electronics with 1 GHz sampling
- Proton Recoil Detector for a transversely polarized ammonia target (Phase 2)
- Large Q^2 trigger
- Monitoring of muon flux
- ECAL1 and ECAL2 to be extended and upgraded
- ECAL0 to be designed and build to increase range in x_{Bj}
  and to reduce background



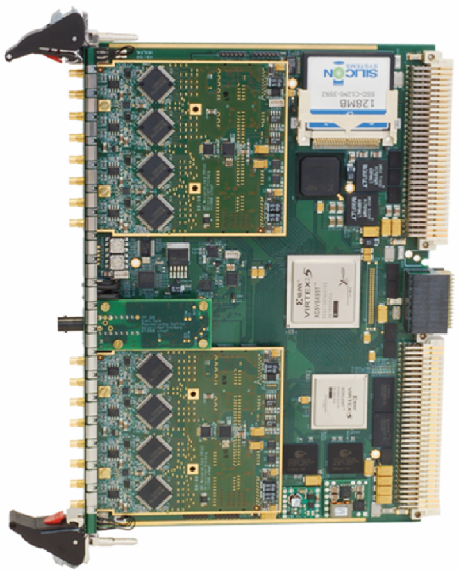
sketch, not to the scale

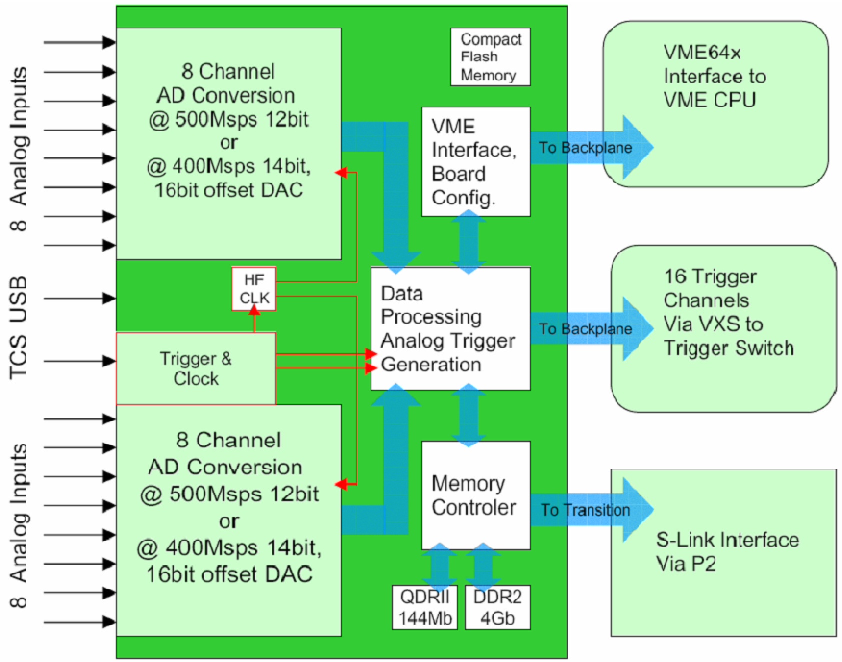
Recoil proton detector for 2.5 m long LH target



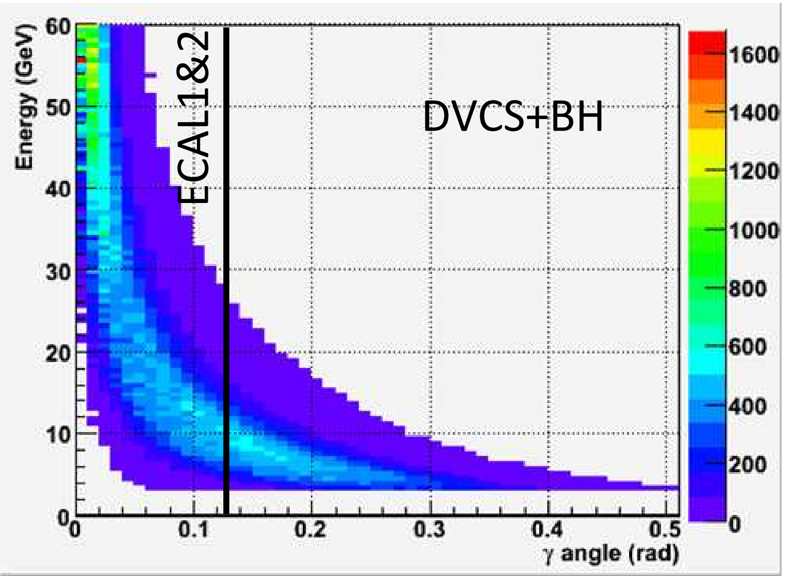
- 4 m long scintillator slabs
- ~ 300ps timing resolution
- 30º prototype tested successfully

Gandalf Project:
1 GHz digitalisation of the PMT signal to cope with high rate





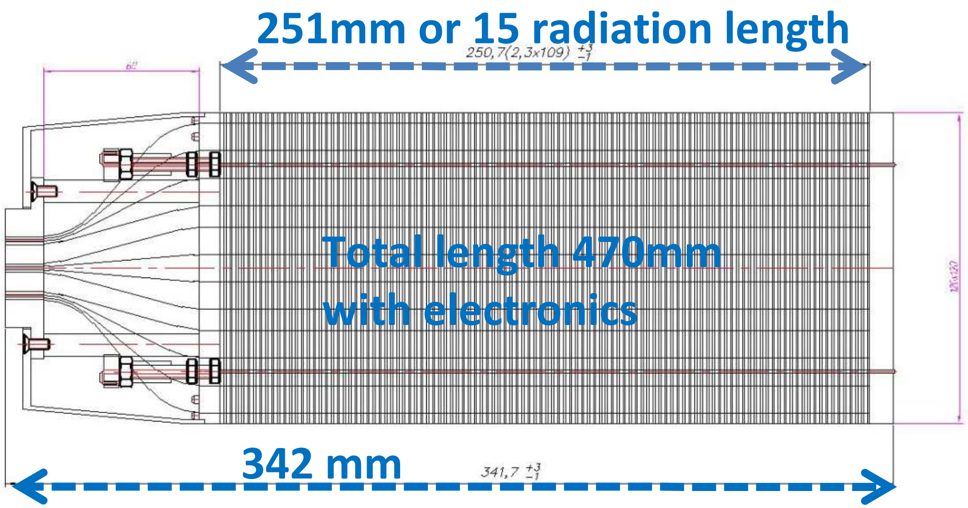
New large-angle electromagnetic calorimeter ECAL0



Requirements
- Photon energy range 0.2- 30 GeV
- Size: 360cm x 360cm ;
- Granularity 4x4 – 6x6 cm²
- Energy resolution < 10.0%/√E (GeV)
- Thickness < 50 cm,
- Insensitive to the magnetic field.

Prototype under studies
Shaschlyk module with AMPD readout

new shashlyk modules for tests in 2011
109 plates made of Sc 0.8 mm /Pb 1.5 mm



Avalanche Micropixel Photo Diodes
3 x 3 mm², density of pixels 40 000/mm²

2008 DVCS test run

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

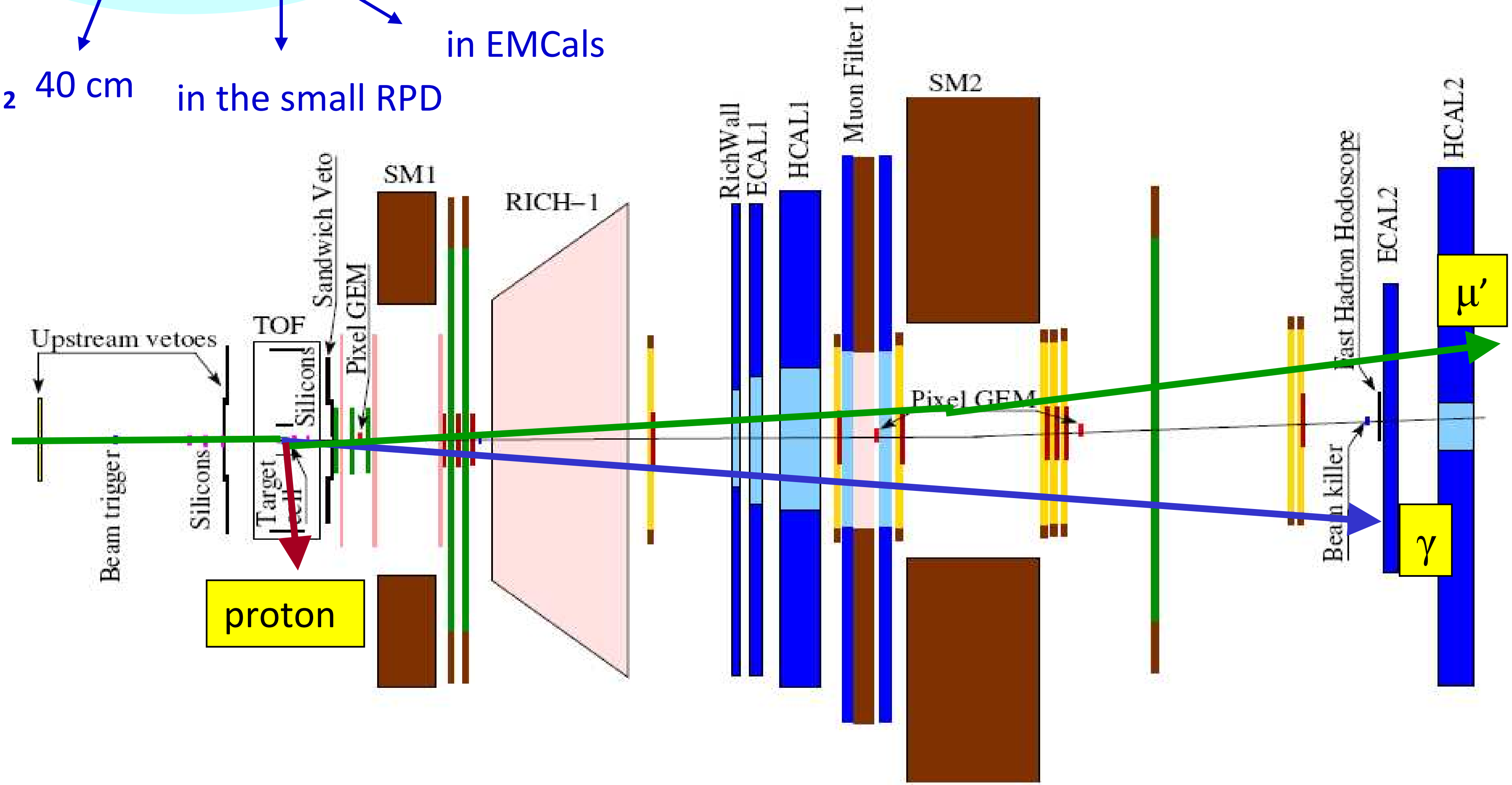
$\mu\, p \rightarrow \mu\, p\, \gamma$

LH_2 40 cm

in the small RPD

in EMCals

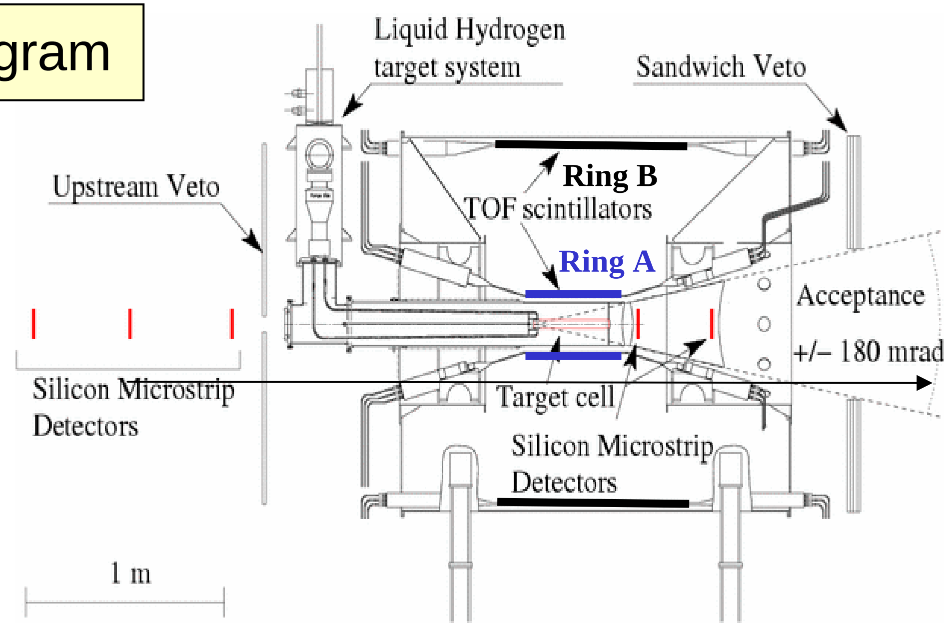
Use COMPASS 'hadron' set-up



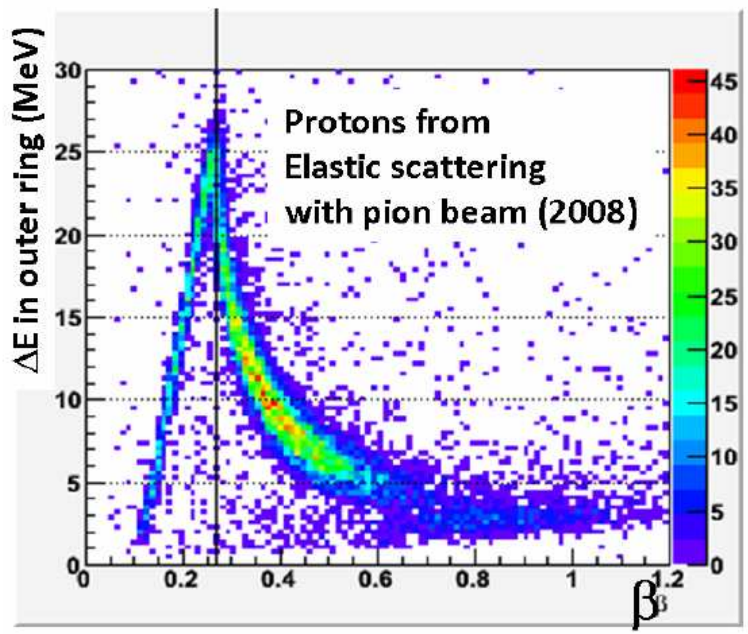
1.5 days of 160 GeV muon beam (μ^+ and μ^-)

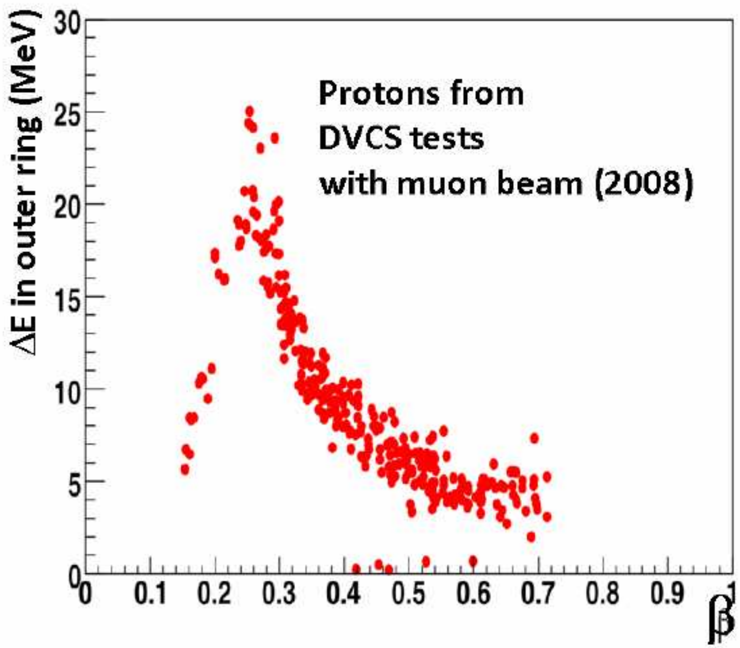
Recoil proton detector for hadron program

Small 1 m long Recoil Proton Detector
and a 40cm LH target in 2008/2009

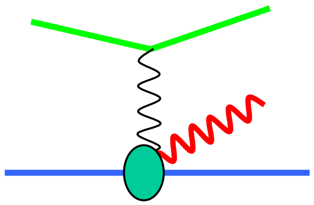


Proton identification in RPD

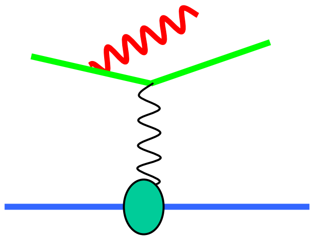




Selection of exclusive single γ events



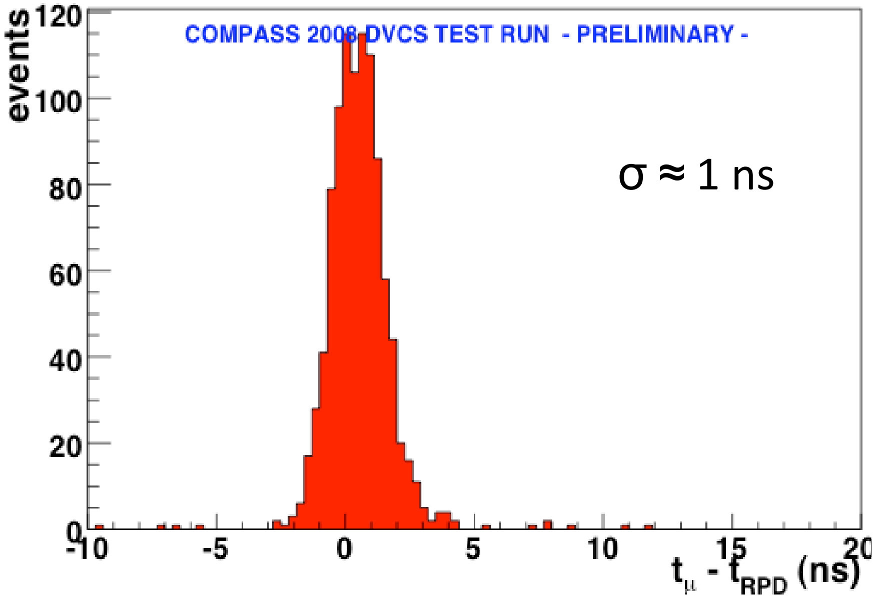
DVCS



Bethe-Heitler

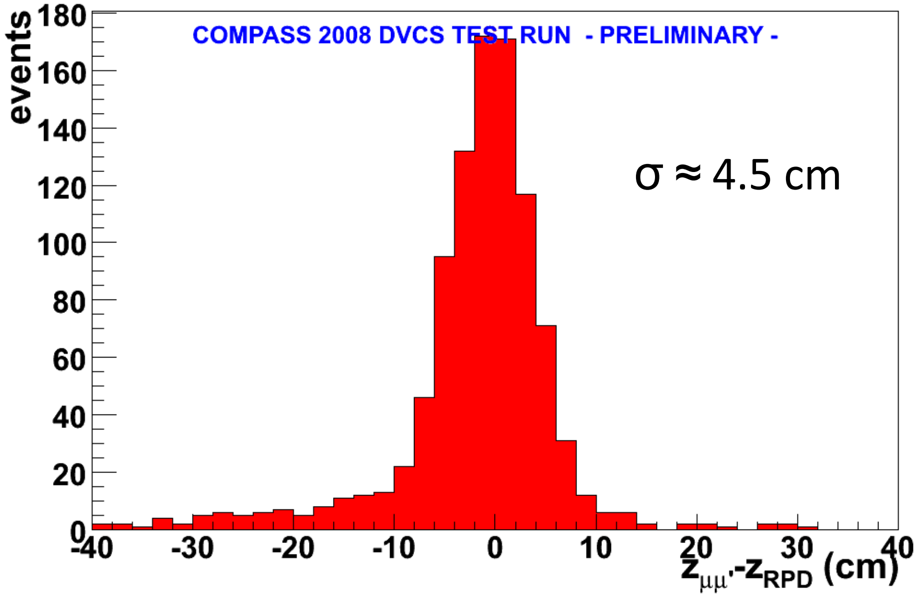
Selection of events :

- one vertex with μ and μ'
- no other charged tracks
- only 1 high energy photon
- 1 proton in RPD with p< 1. GeV/c



Timing difference :

$t_\mu - t_{RPD}$

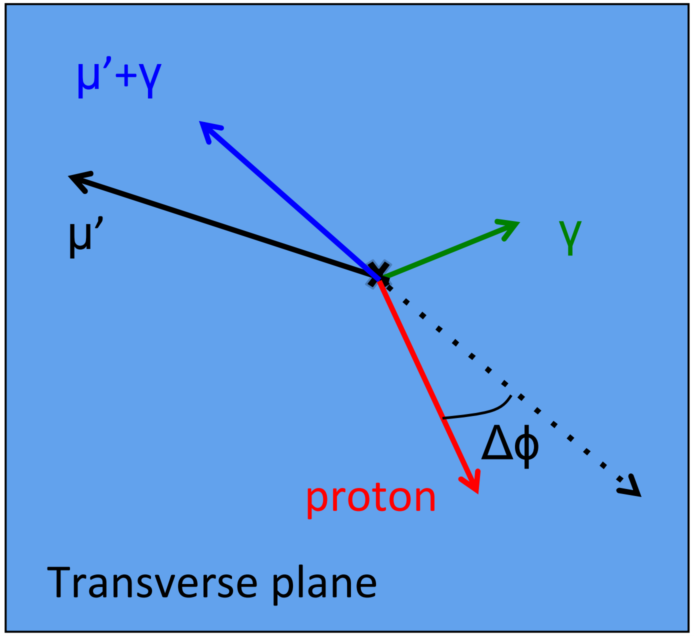


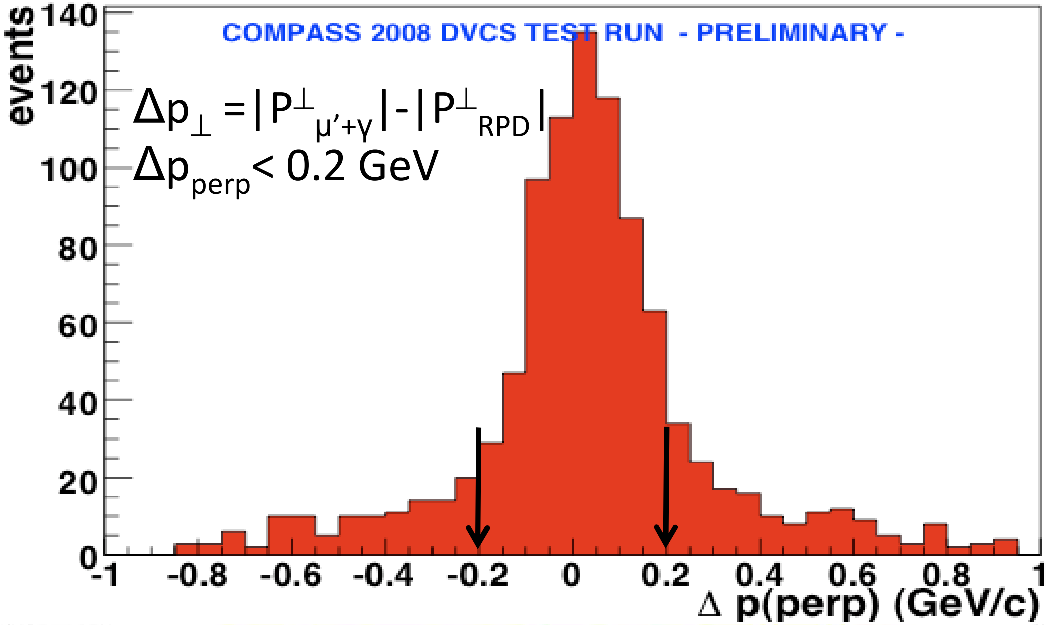
Z position difference :

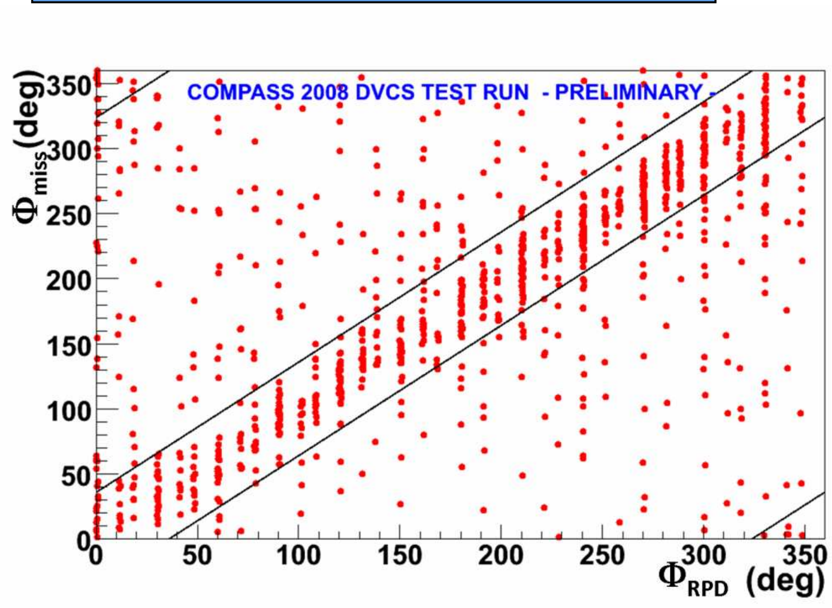
$z_{\mu\mu'} - z_{RPD}$

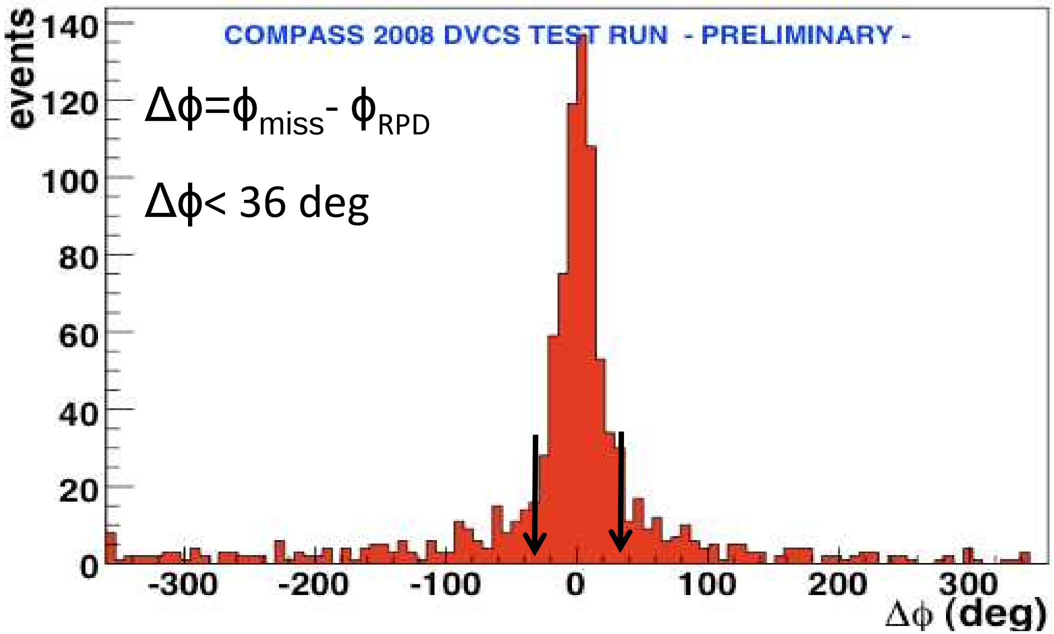
Kinematic constraints in the transverse plane

$$\vec{p}_{miss} = \vec{p}_{\mu} - \vec{p}_{\mu'} - \vec{p}_{\gamma}$$

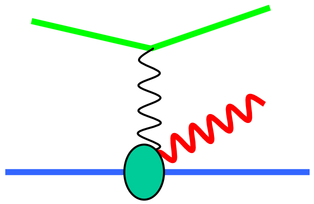




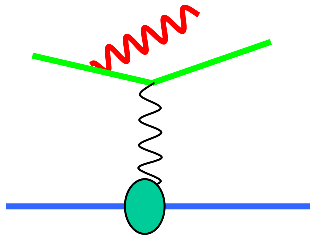




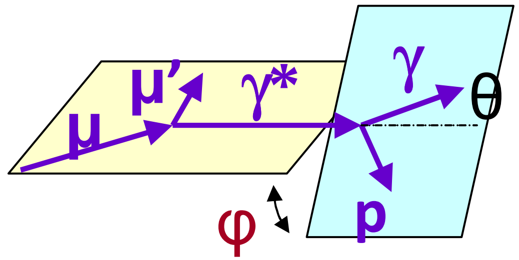
Azimuthal distribution for single photon events

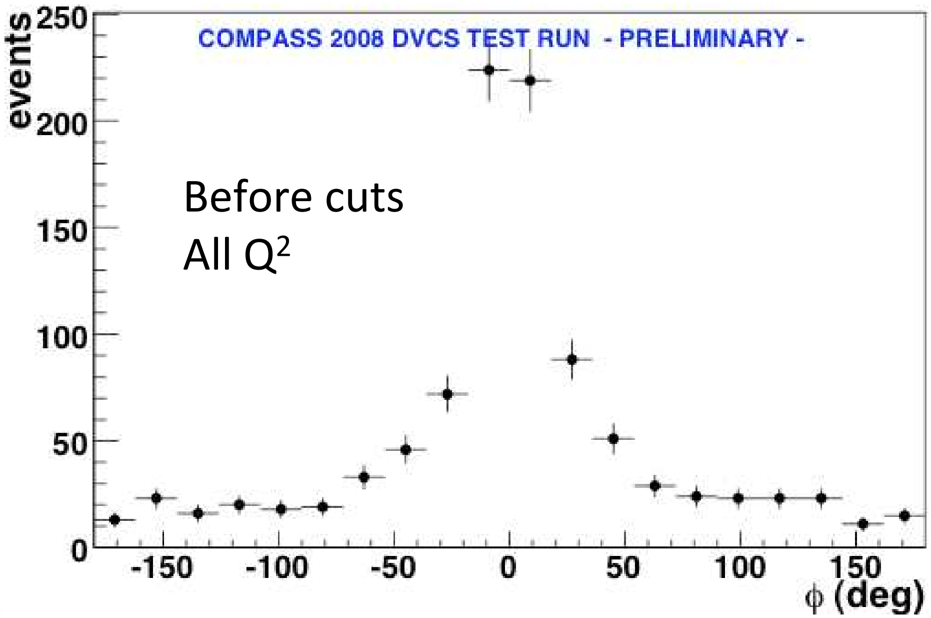


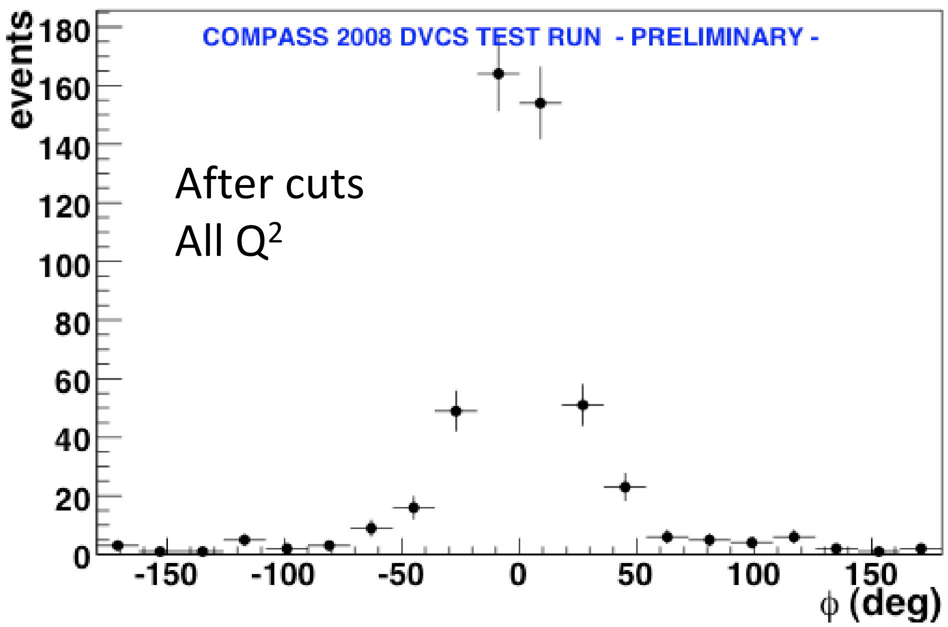
DVCS



Bethe-Heitler





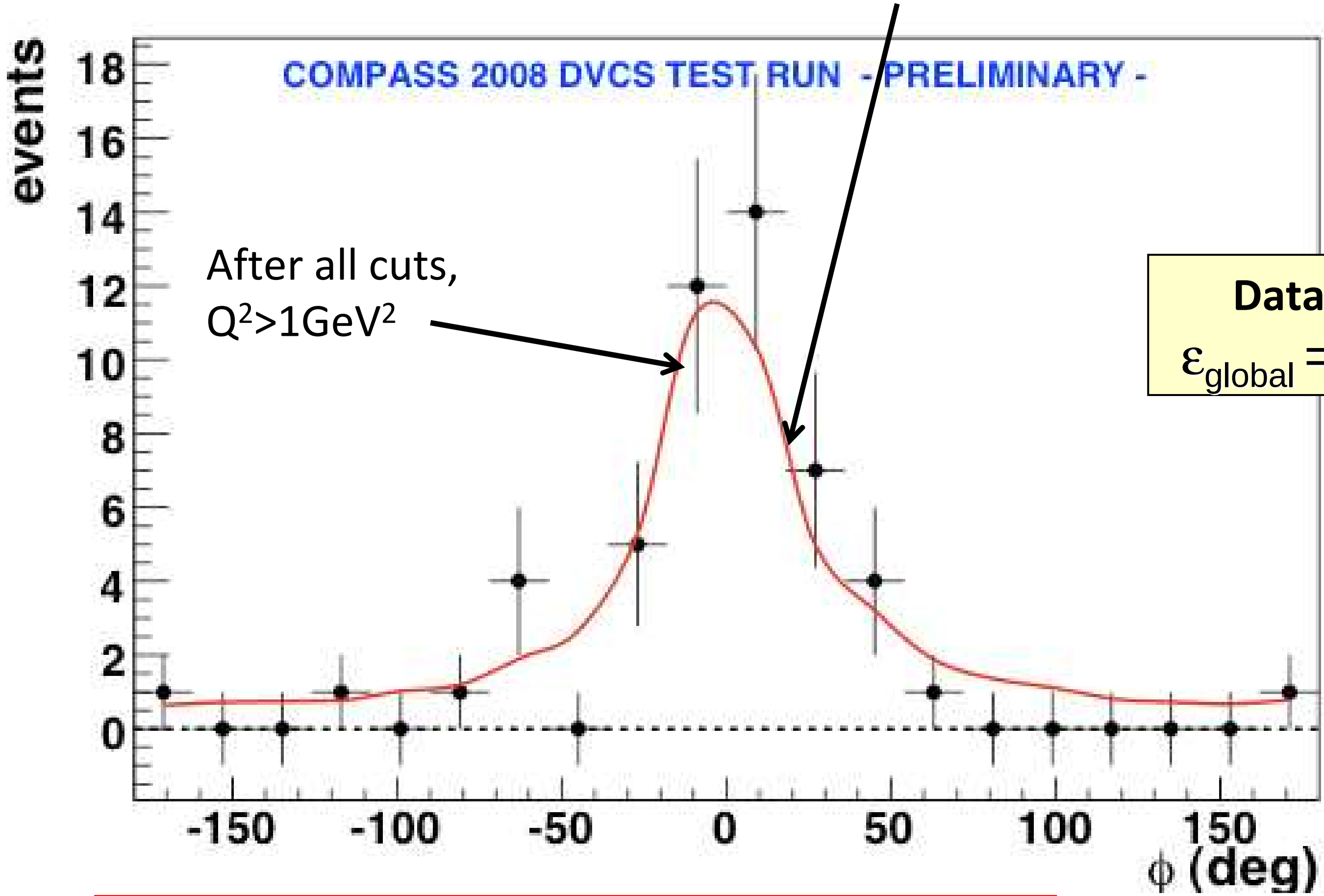


A flat background contribution in φ suppressed
The peak at φ=0 remains =>identified as BH

Azimuthal distribution for exclusive single photon events

COMPASS Note 2009-4

Monte-Carlo simulation
of BH (dominant) and DVCS



Data & MC =>
ε_{global} = 13%±5%

Clear signature of dominant BH events

confirmed by a refined analysis using ECAL timing information
and improved cluster reconstruction - COMPASS Note 2009-11

2009 DVCS pilot run

2 weeks of DVCS pilot run in September 2009

'Hadron setup' as in 2008 with the small RPD and 40 cm LH target
+ operational BMS for momentum measurements of beam μ's
+ beam flux measurement

Both μ+ and μ- beams

Goals : observe DVCS (~100 ev.)
measure BH (~1000 ev.) to precisely verify global efficiency
observe exclusive π^0 events, estimate background to DVCS
demonstrate feasibility of beam flux measurements at a few % level
measure other channels of exclusive meson prod. (ρ^0)

Conclusion & prospects

- Possible physics ouput
  - Sensitivity to transverse size of parton distributions inside the nucleon
  - Sensitivity to the GPD E and total angular momentum
  - Working on a variety of models to quantify the physics impact of GPD measurements at COMPASS

- Experimental requirements
  - Recoil detection with long LH target and polarized target
  - Good calorimetry with extension at larger angles

- Roadmap
  - A global COMPASS proposal for the period 2012-2016 including GPD will be submitted to SPSC in 2010
  - 2008-9: The small RPD and liquid H_2 target are available for the hadron program → tests of DVCS feasibility
  - from 2012: Start of GPD program at COMPASS with a long RPD
    + liquid H_2 target (2012)
    + transversely polarized ammonia target (later)