The GPD program at COMPASS

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on behalf of the COMPASS collaboration

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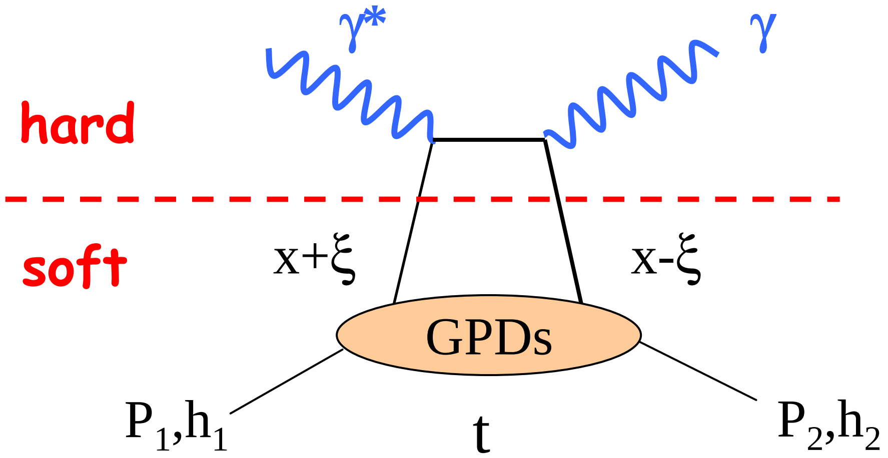
Generalized Parton Distributions and DVCS



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

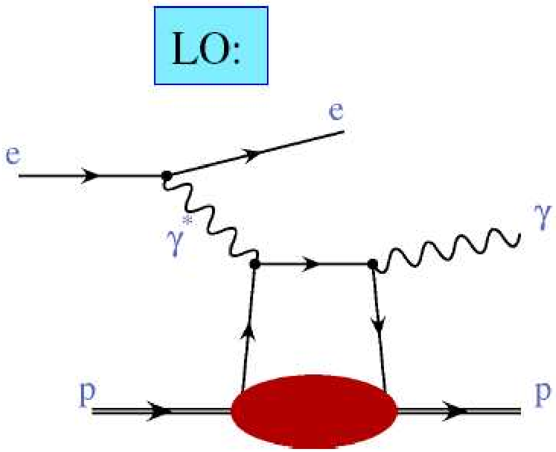
$$\xi = \frac{x_B}{2 - x_B}$$

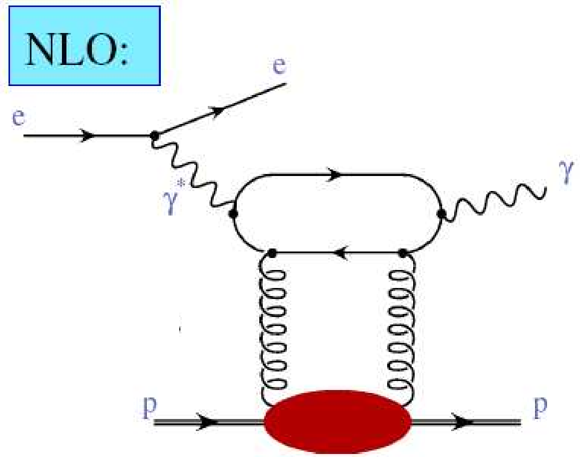
P_i, h_i – proton momentum and helicity

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

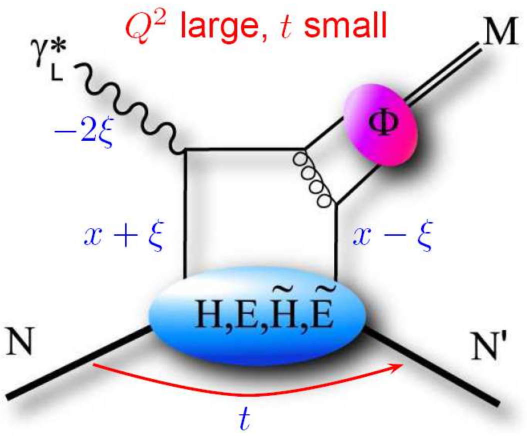
for each quark flavour and for gluons

for DVCS gluons contribute at higher orders in α_s





GPDs and Hard Exclusive Meson Production



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

- 4 Generalised Parton Distributions (GPDs)
  for each quark flavour and for gluons
- factorisation proven only for σ_L
  σ_T suppressed by $1/Q^2$
  necessary to extract longitudinal contribution to observables (σ_L , …)
- allows separation $(H,E) \leftrightarrow (\tilde{H},\tilde{E})$ and wrt quark flavours

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

  Vector mesons (ρ, ω, φ)

  Pseudoscalar mesons (π, η)
- 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

GPDs properties, links to DIS and form factors

$$H^q, \widetilde{H}^q \leftrightarrow h_1 = h_2$$ for $P_1 = P_2$ recover usual parton densities

$$H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x) \quad \text{for } x > 0$$
$$H^q(x,0,0) = -\bar{q}(-x), \quad \widetilde{H}^q(x,0,0) = \Delta\bar{q}(-x) \quad \text{for } x < 0$$

$$E^q, \widetilde{E}^q \leftrightarrow h_1 \neq h_2$$ no similar relations; these GPDs decouple for $P_1 = P_2$

$$E^q, \widetilde{E}^q \neq 0$$ **needs** orbital angular momentum between partons

$$\int dx\, H^q(x,\xi,t) = F_1^q(t)$$ **Dirac**

$$\int dx\, E^q(x,\xi,t) = F_2^q(t)$$ **Pauli**

$$\int dx\, \widetilde{H}^q(x,\xi,t) = g_A^q(t)$$ **axial**

$$\int dx\, \widetilde{E}^q(x,\xi,t) = g_P^q(t)$$ **pseudoscalar**

Ji's sum rule $$\frac{1}{2}\int dx\, x\,(H^q + E^q) = J^q(t)$$

$J^q(0)$ **total** angular momentum carried by quark flavour *q* (helicity and **orbital** part)

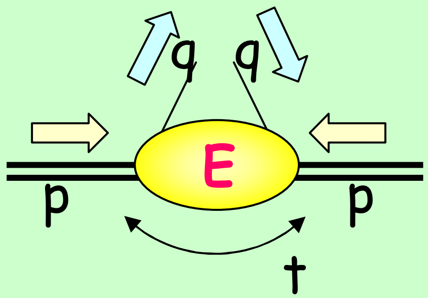
‘Holy Grails’ of the GPD quest

- Contribution to the nucleon spin puzzle

E related to the angular momentum

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

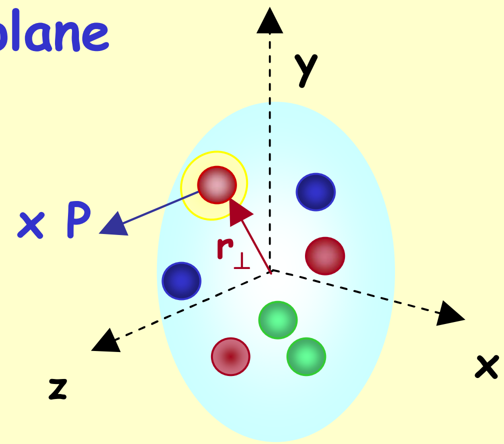
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$



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

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

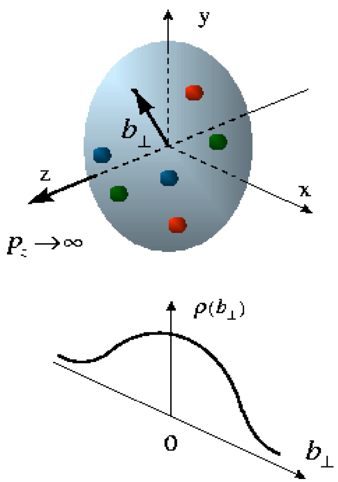
probability interpretation
Burkardt



Structure of the Nucleon

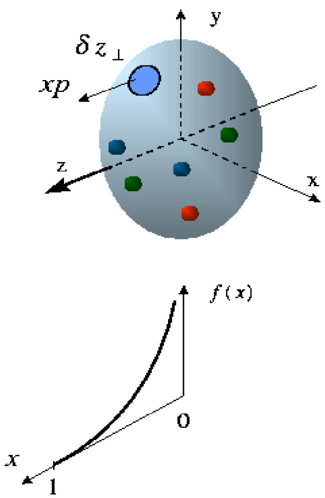
form factors

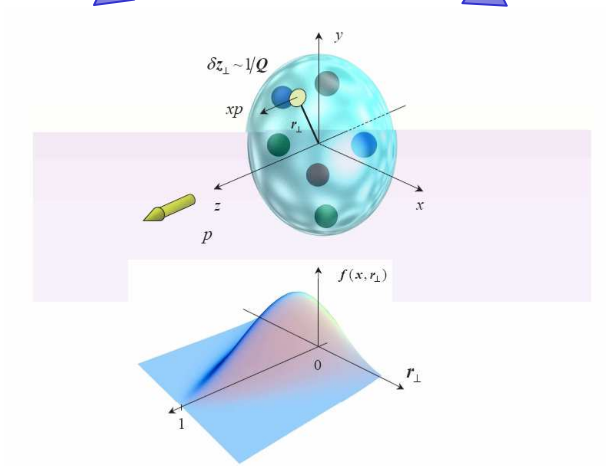
location of partons in nucleon



parton distributions

longitudinal momentum fraction x





generalised parton distributions (GPDs)

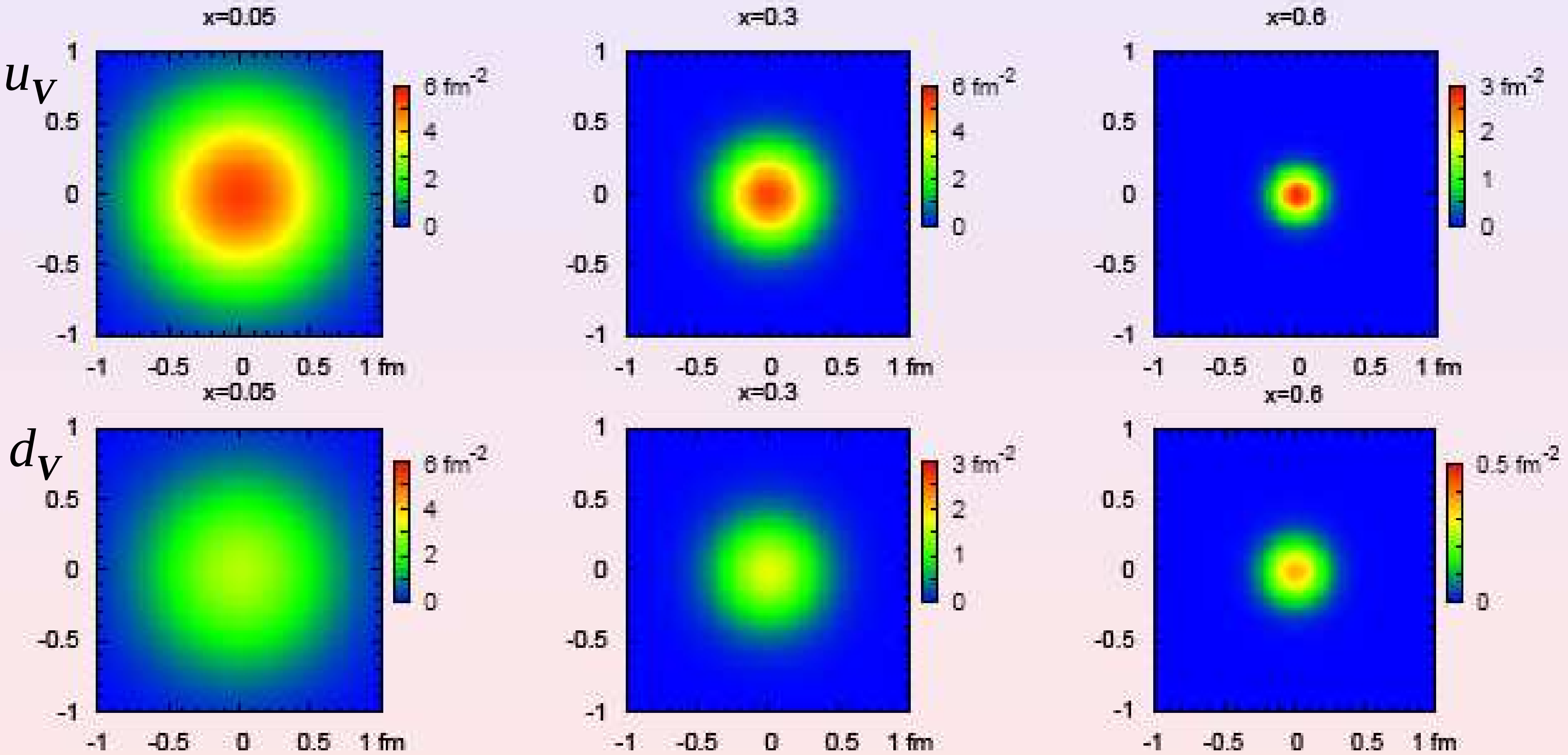
transverse location $b_\perp$ and longitudinal momentum fraction x

embody 3D picture of hadrons

Nucleon tomography from fits to elastic form factors

from GPD fits to $F_{1,2}^{p,n}$ Diehl, Feldmann, Jakob, Kroll – (2005)

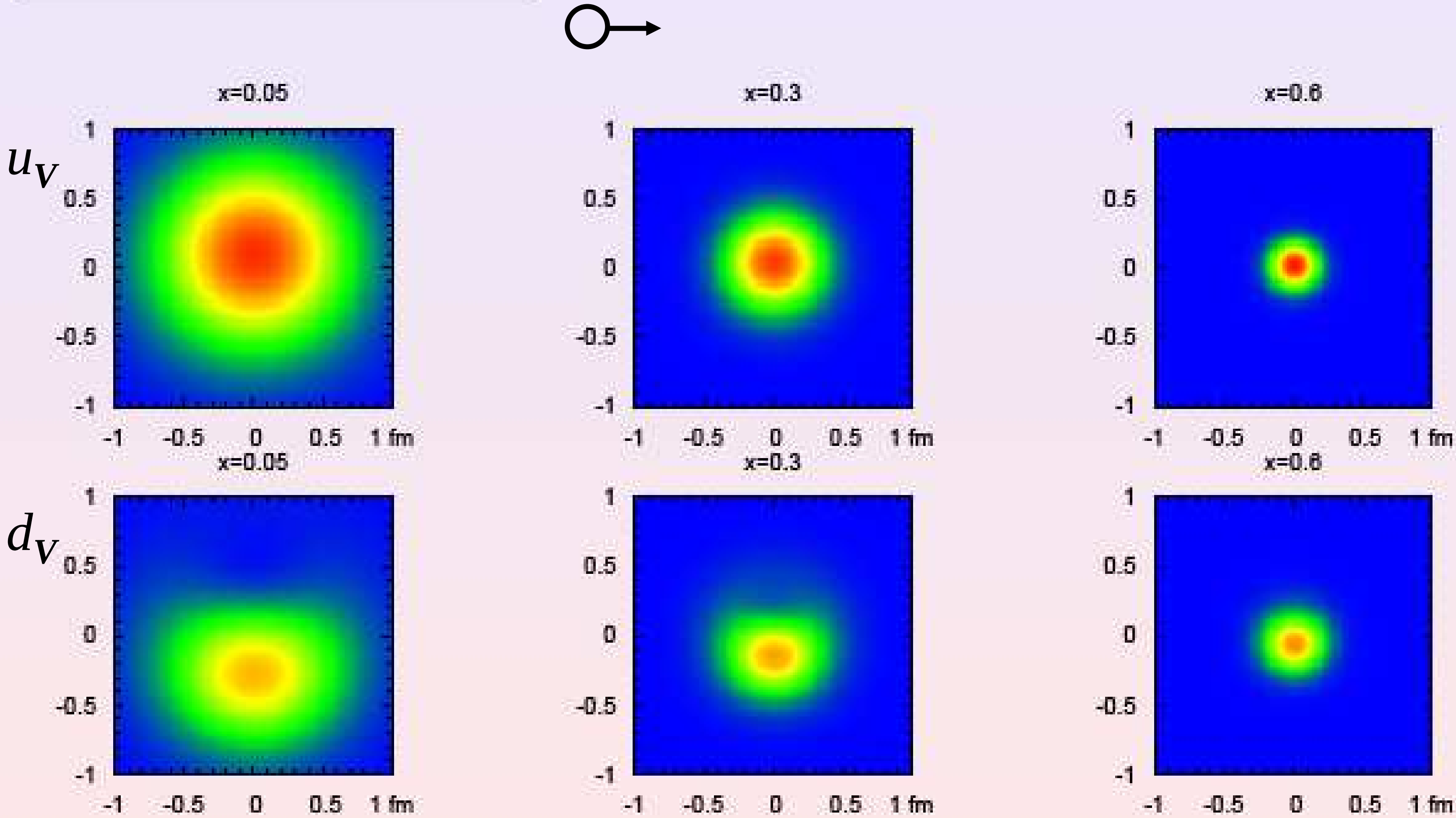
valence quarks unpolarized proton



Nucleon tomography from fits to elastic form factors

from GPD fits to $F_{1,2}^{p,n}$ Diehl, Feldmann, Jakob, Kroll – (2005)

valence quarks in ⊥ polarized proton (sizeable systematic uncertainties!)



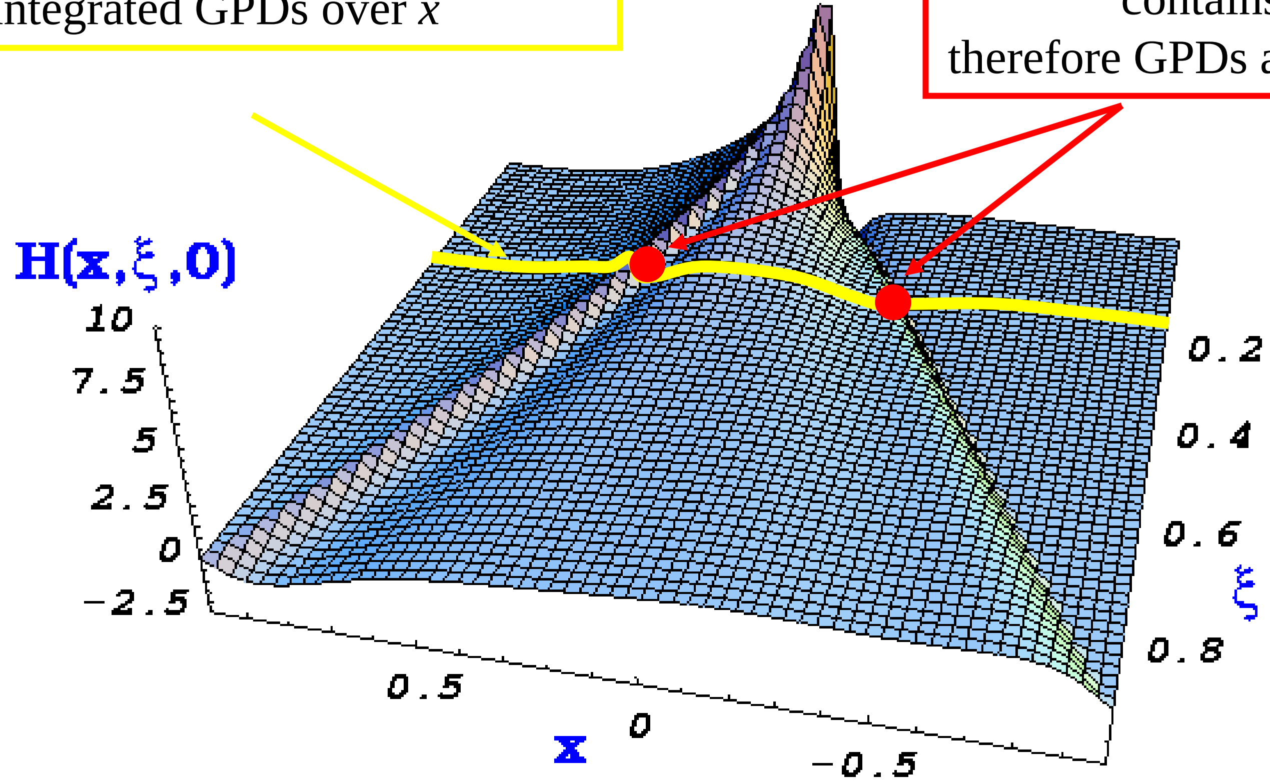
Observables and their relationship to GPDs

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon}\, dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi}\, dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Beam charge asymmetry contains ReT,
integrated GPDs over x

Beam or target spin asymmetry
contains ImT,
therefore GPDs at $x = \xi$ and $-\xi$



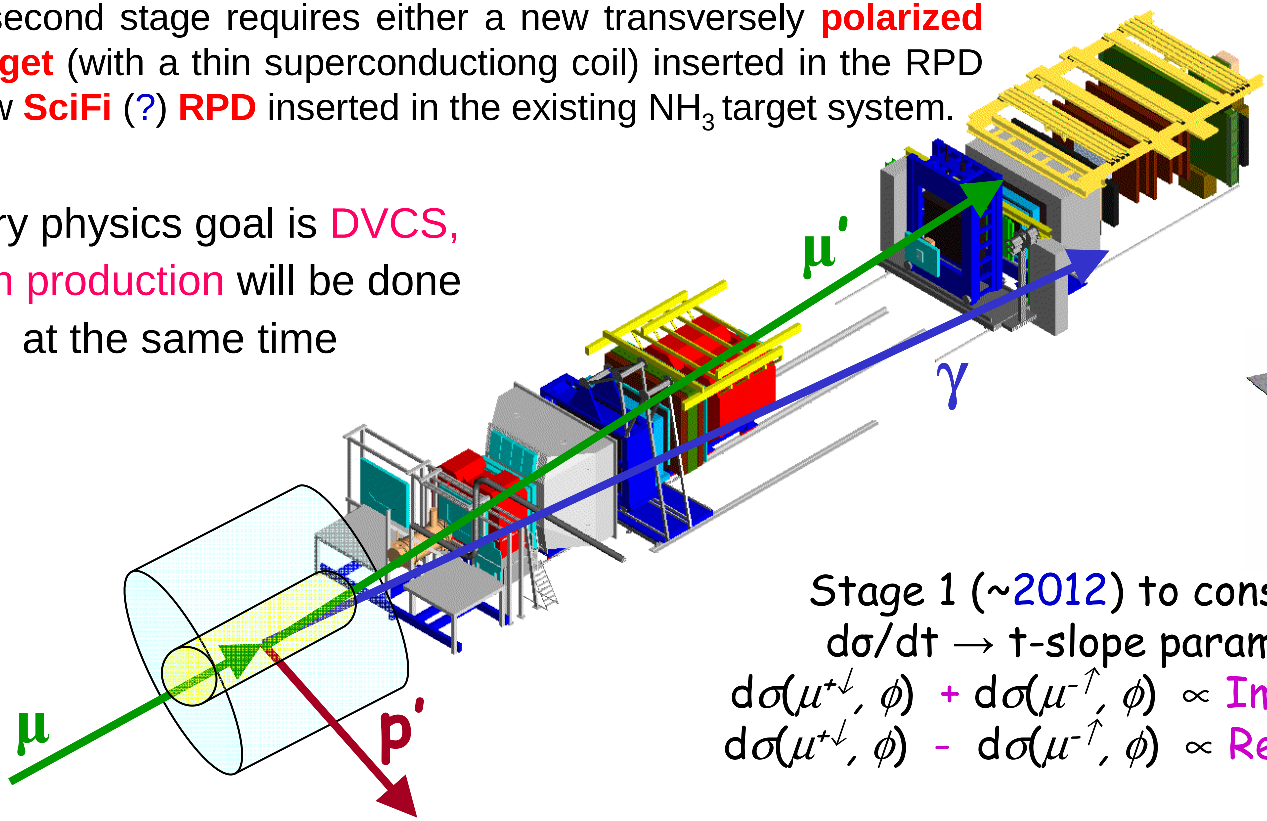
Future GPD program @ COMPASS

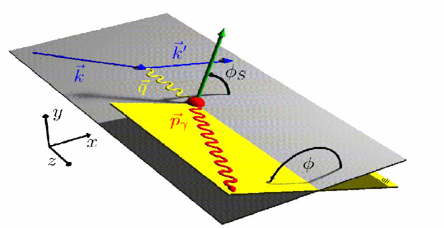
➢ The GPDs program is part of the **COMPASS Phase II** (2012-2016) proposal to be submitted to CERN in 2009.

➢ The first stage of this program requires a 4 m long recoil proton detector (**RPD**) together with a 2.5 m long **LH_2 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

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

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

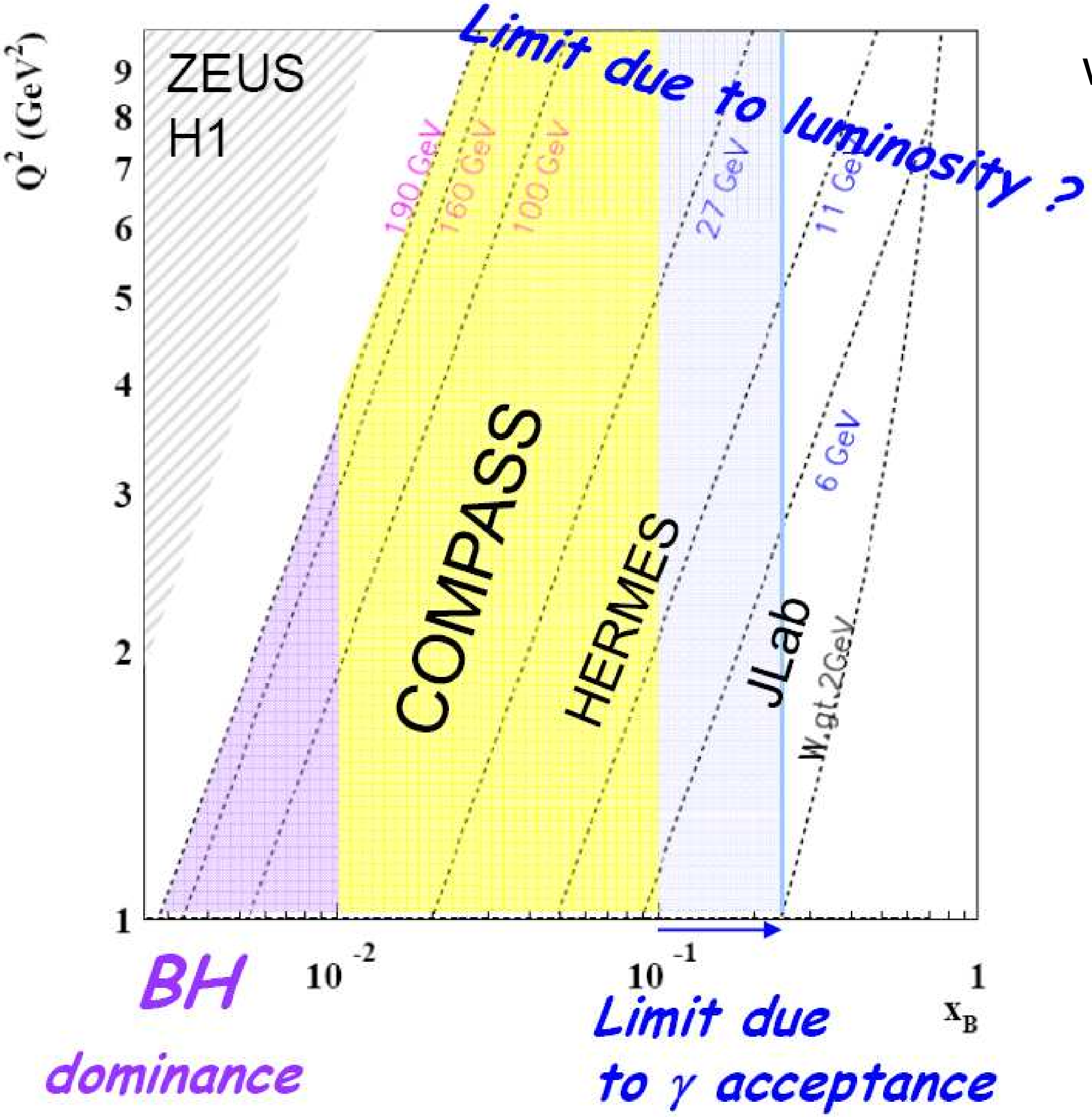
Stage 2 (~2014) to constrain **E**

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

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

COMPASS kinematical coverage for DVCS

CERN SPS high energy 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

$\rightarrow$ 12 GeV^2 if luminosity increased by factor 4

~10^{-2} < x < ~10^{-1}

x $\rightarrow$ 0.15 with upgrade of present calorimetry

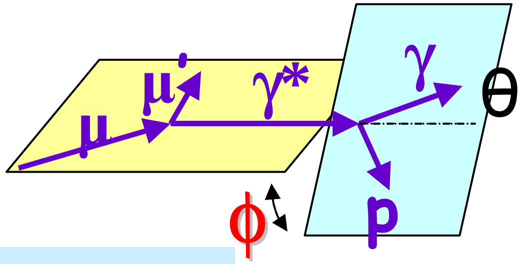
The GPDs in the next several years

- **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(12) GeV^2) range
  COMPASS will be **the only experiment in this range** before
  availability of new colliders

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



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

Beam Charge & Spin Difference

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

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

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

Beam Charge & Spin Sum

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

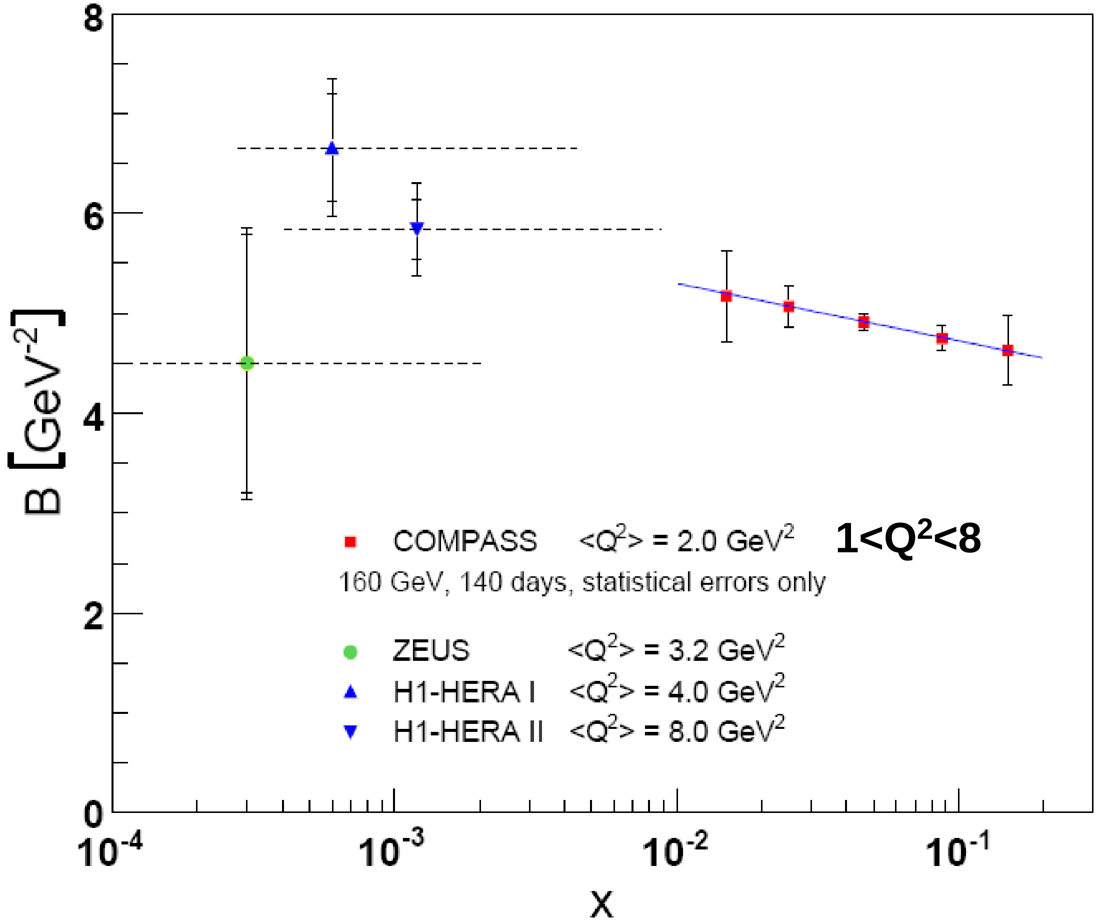
$$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

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

t-slope measurement; relevant for nucleon 'tomography'

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

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



FFS model

adapted for COMPASS by A.S.

assumed

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

with α' =0.125 GeV^{-2}

160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 140 days
L = $1222 pb^{-1}$

for gluons, from J/Ψ at HERA $\alpha' \sim 0.164\ GeV^{-2}$ - photoproduction ($Q^2 \approx 0$)

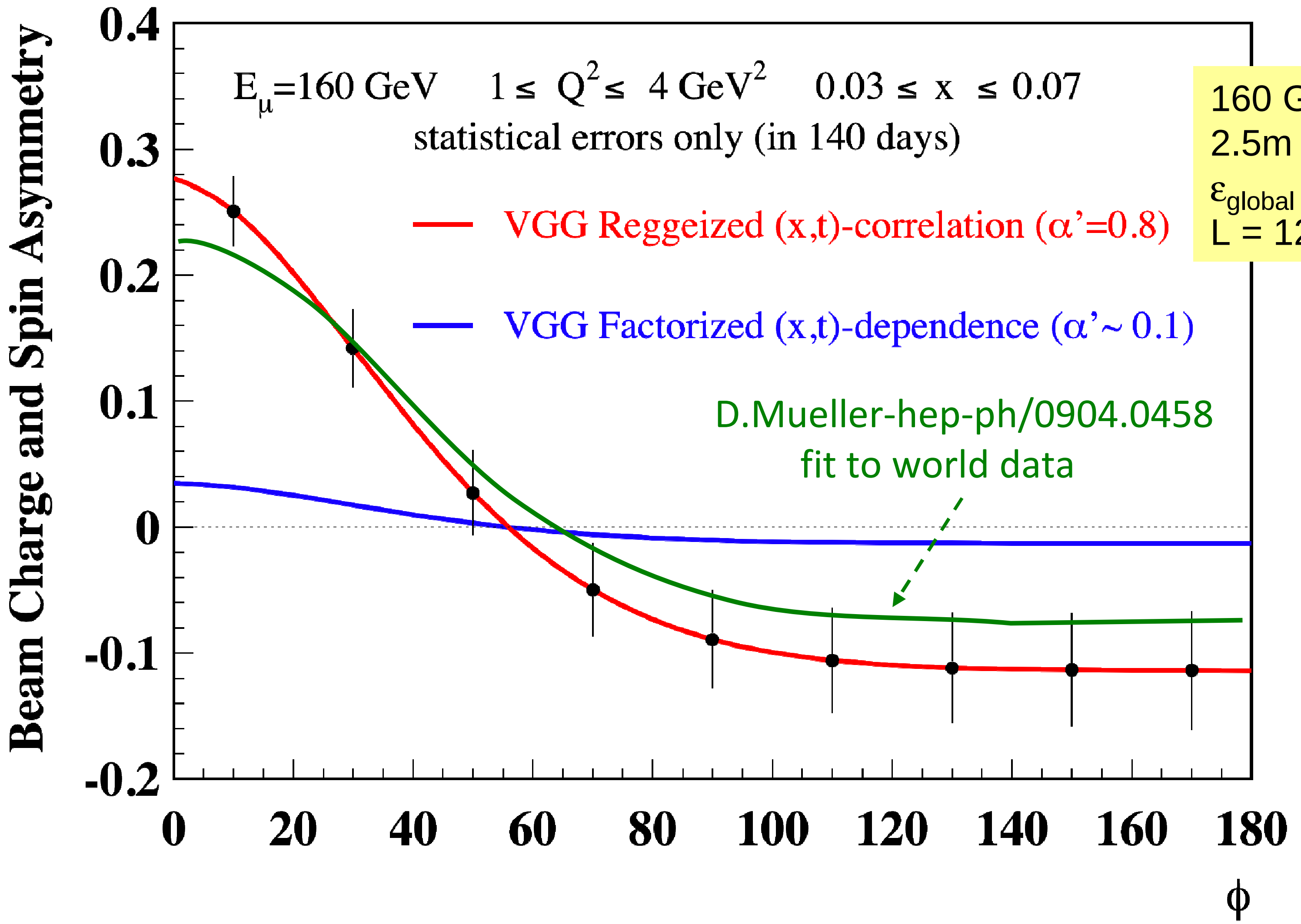
$\alpha' \sim 0.02\ GeV^{-2}$ - DIS (Q^2=2-80 GeV^2)

for valence quarks, from fits to FF $\alpha' \sim 1\ GeV^{-2}$

Beam Charge and Spin Asymmetry

from $\mathcal{D}_{U,CS} / \mathcal{S}_{U,CS}$:

Comparison to different models

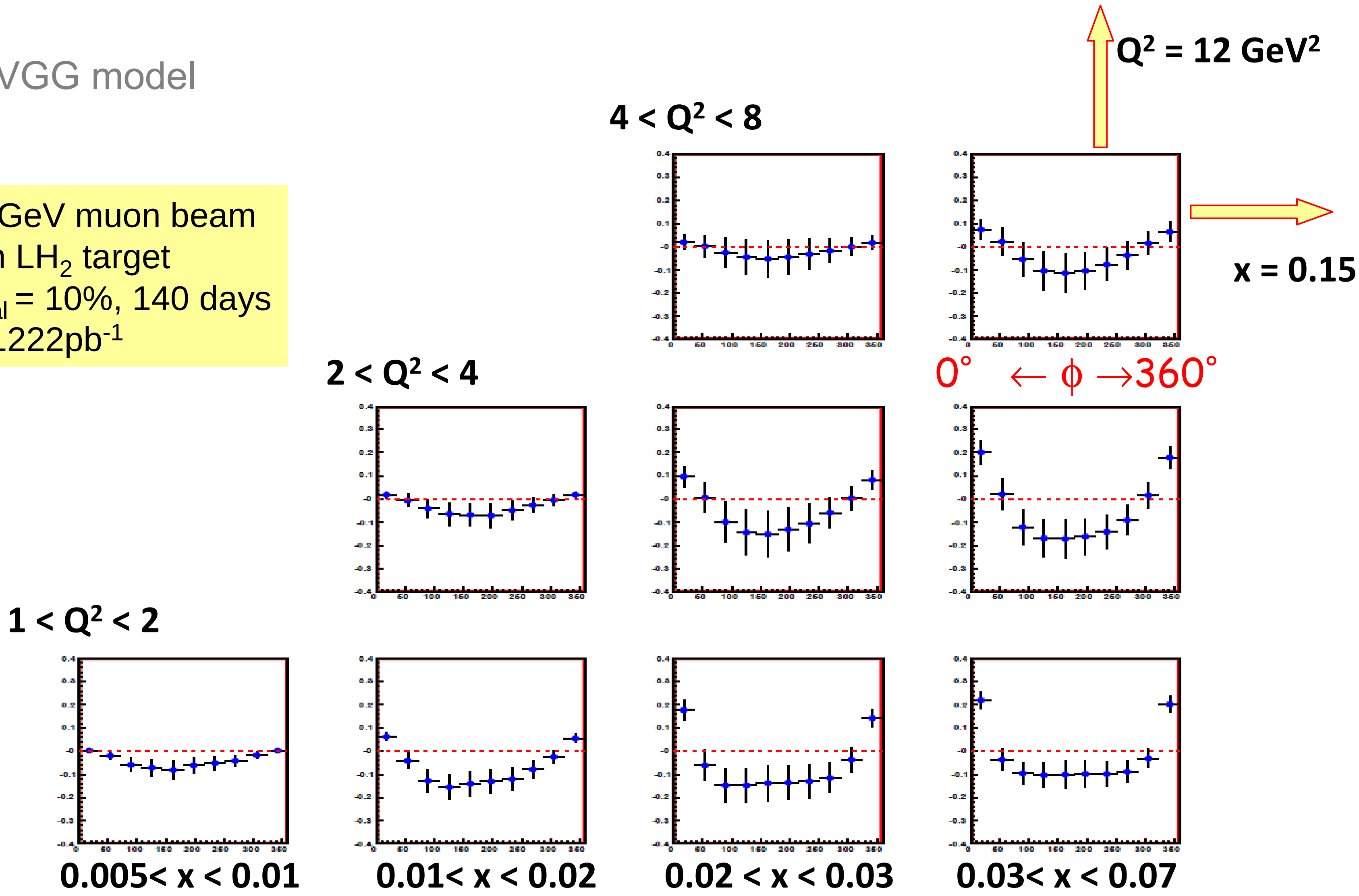


160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 140 days
L = $1222pb^{-1}$

Beam Charge and Spin Asymmetry in various kinematic bins

VGG model

160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 140 days
L = $1222 pb^{-1}$



If Lumi × 4 → more bins up to Q2 = 12 GeV2

Single γ production with transversely polarised target

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

unpolarized target — transversely polarized target

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

to isolate TTS part measurements at opposite target polarisations needed

$$d\sigma_T = \tfrac{1}{2}\,\{d\sigma\,(S_T=+P_T) - d\sigma(S_T=-P_T)\}$$

to disentangle DVCS and Interference terms having the same azimuthal dependence

both μ+↓ and μ-↑ beams needed

cf. the next slide

measure

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

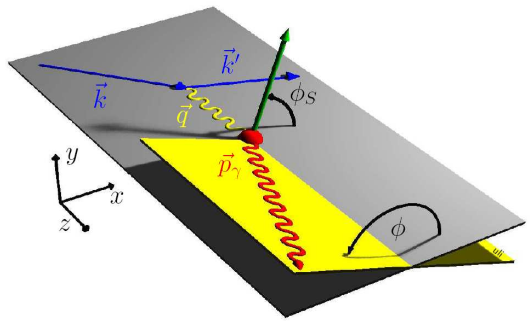
or/and

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

$d\sigma_0$ 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

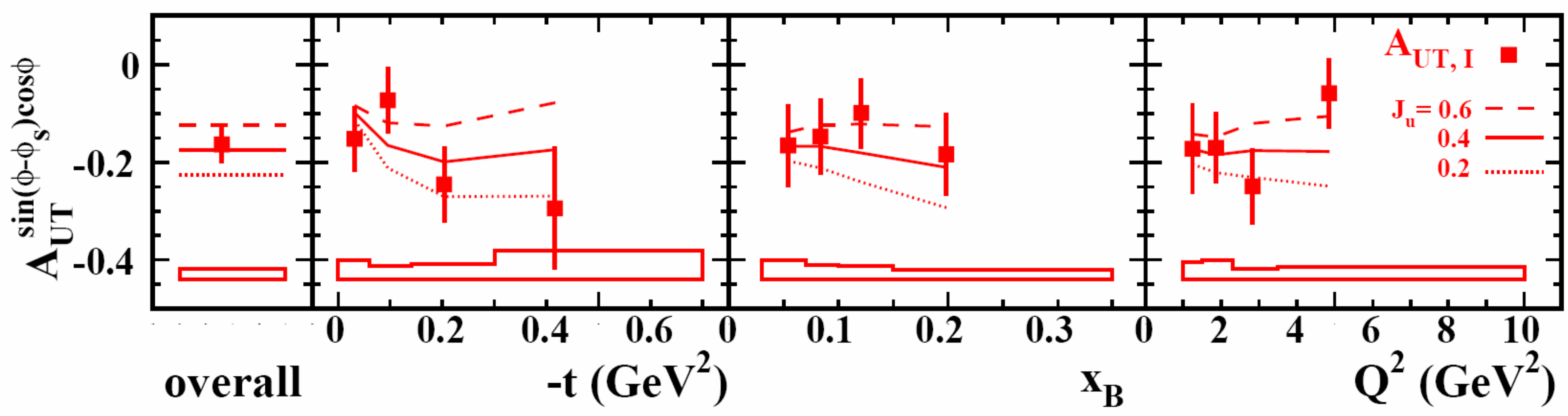
not shown are terms with sin(kφ) and cos(kφ) (k=2,3) dependence

those are twist-3 and NLO twist-2 gluon helicity flip terms

An 'appetizer' – HERMES measurements of DVCS

from Transverse Target Spin asymmetry $A_{UT}^{\sin(\phi-\phi s)\cos\phi} \longrightarrow c_{1,T-}^{Int}$

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



$A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ for proton sensitive to J_u (not to J_d) => allows model dependent constraints

study of azimuthal asymmetries from transversely polarized NH_3 target is a part of Phase 2 of COMPASS proposal, simulations are in progress

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

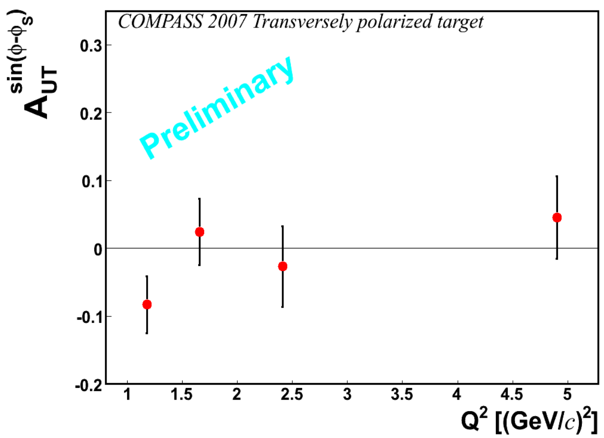
$$\frac{1}{\Gamma'}\,\mathrm{Im}\,\frac{d\sigma_{00}^{+-}}{dt} = -\sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\mathrm{Im}\,(\mathcal{E}_M^*\mathcal{H}_M)$$

access to GPD E
related to orbital momentum

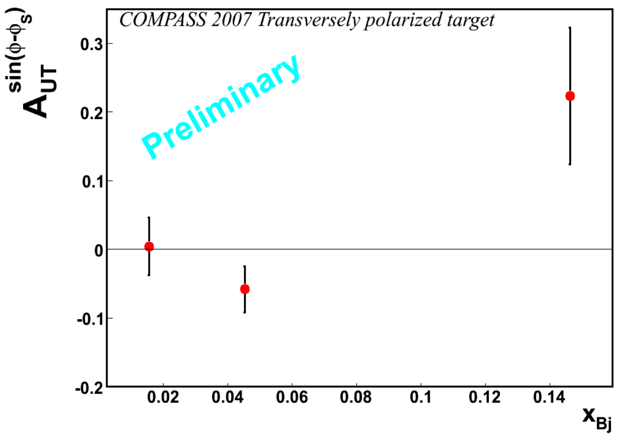
$$\Gamma' = \frac{\alpha_{\rm em}}{Q^6}\,\frac{x_B^2}{1-x_B} \qquad -t_0 = \frac{4\xi^2 M_p^2}{1-\xi^2}$$

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

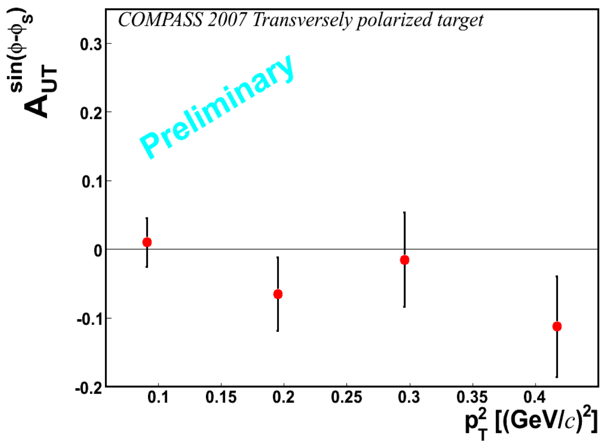
$< Q^2 > \approx 2.2\ (\mathrm{GeV}/c)^2$



$< x_{Bj} > \approx 0.04$



$< p_t^2 > \approx 0.18\ (\mathrm{GeV}/c)^2$



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

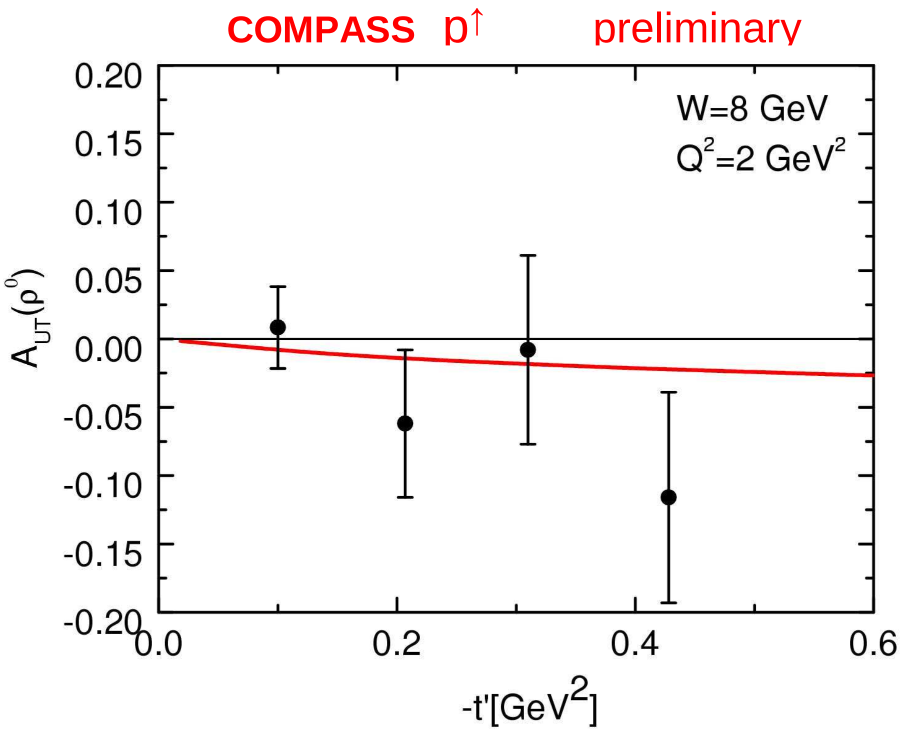
in progress: L/T γ^* separation (using ρ^0 decay angular distribution)

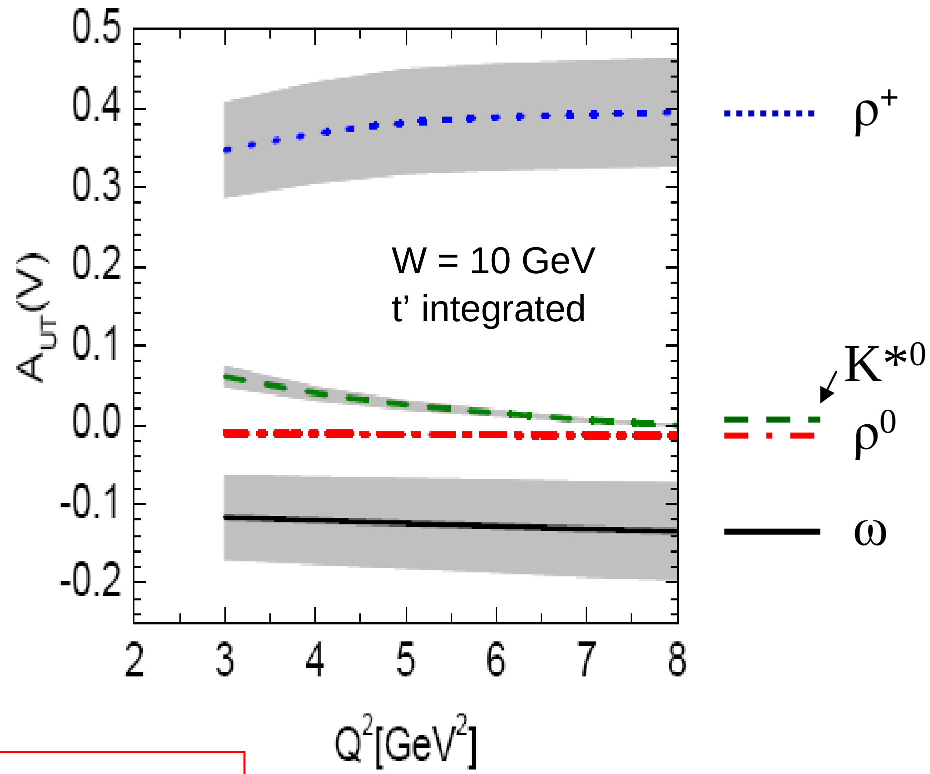
Comparison to a GPD model

- 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



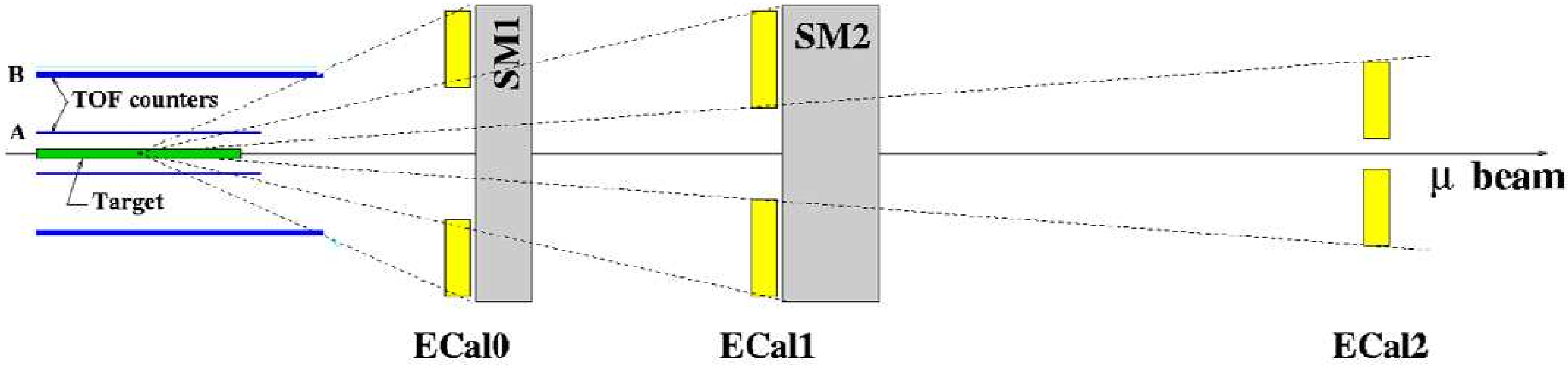


predictions for protons

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

Detectors to be built

- Large Proton Recoil Detector and a long LH_2 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

2008 DVCS test run

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

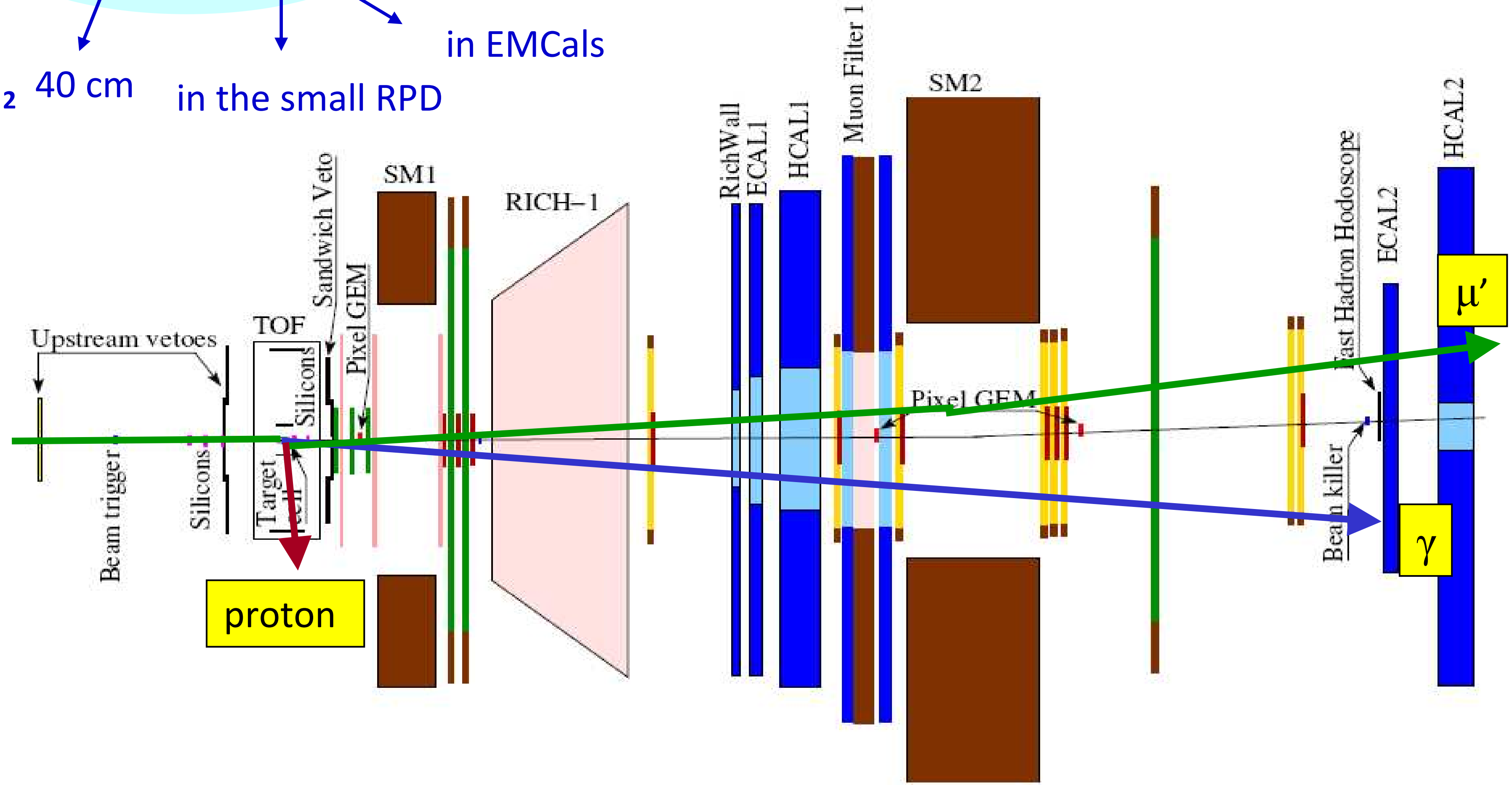
$\mu\, p \rightarrow \mu\, p\, \gamma$

LH_2 40 cm

in the small RPD

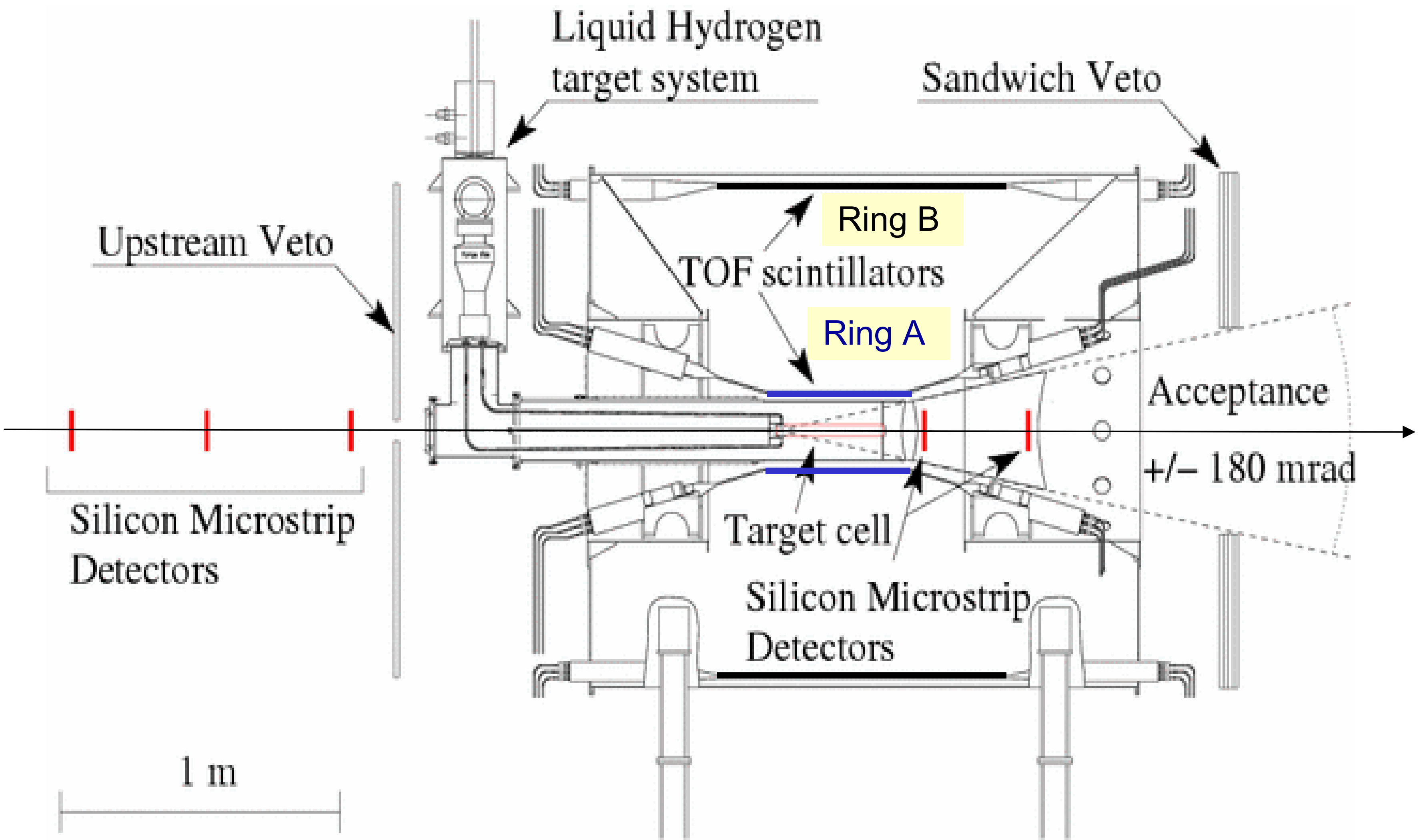
in EMCals

Use COMPASS 'hadron' set-up



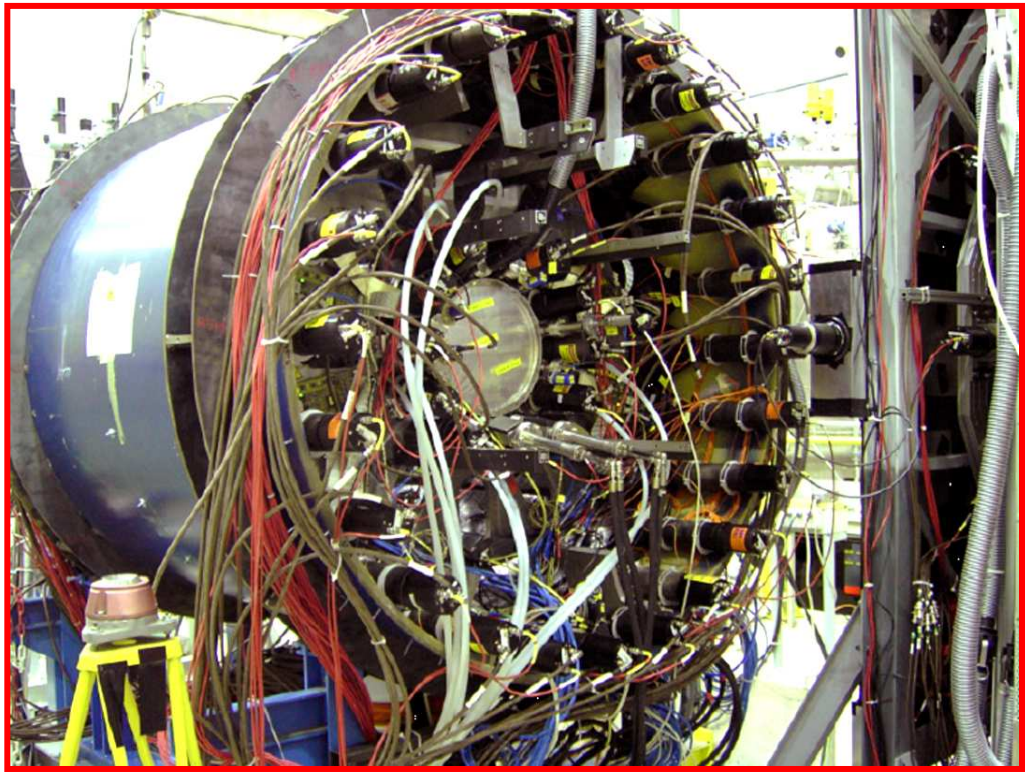
1.5 days of 160 GeV muon beam (μ^+ and μ^-)

LH target region in 2008 DVCS test run

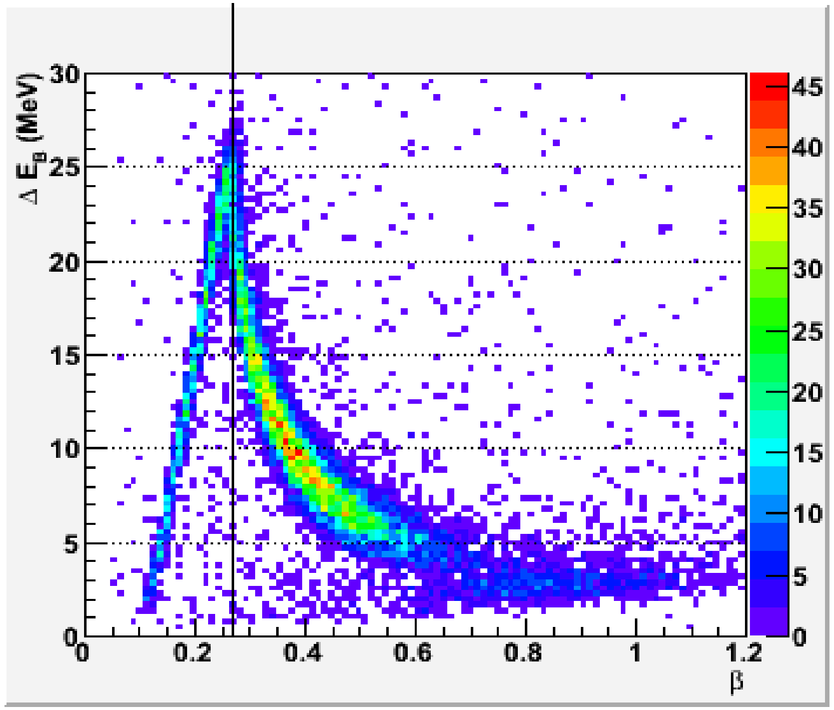


Recoil Proton Detector

Small 1 m long Recoil Proton Detector
and a 40cm LH2 target available in 2008/2009

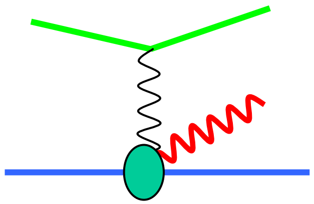


Proton identification in RPD

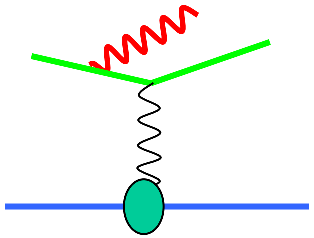


Elastic scattering with pion beam (2008)

Selection of exclusive single γ events



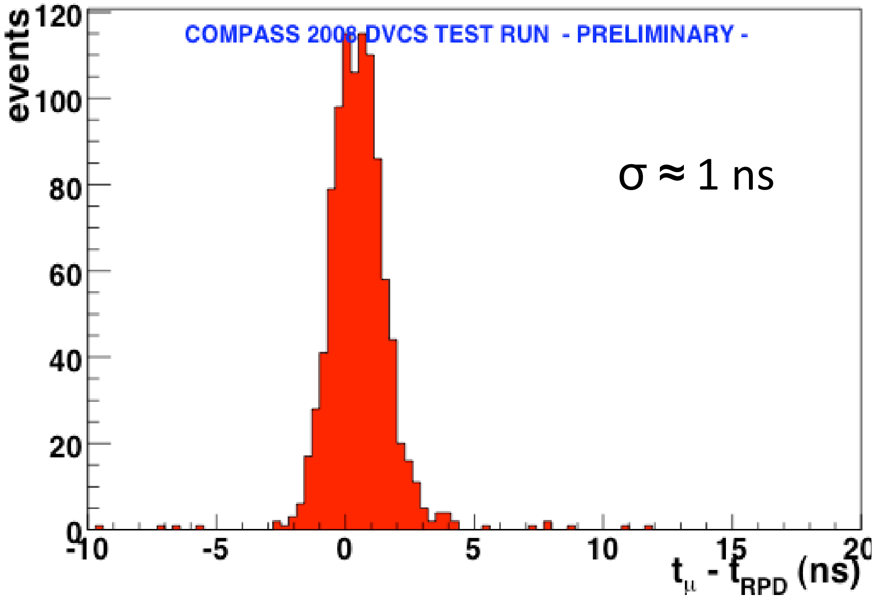
DVCS



Bethe-Heitler

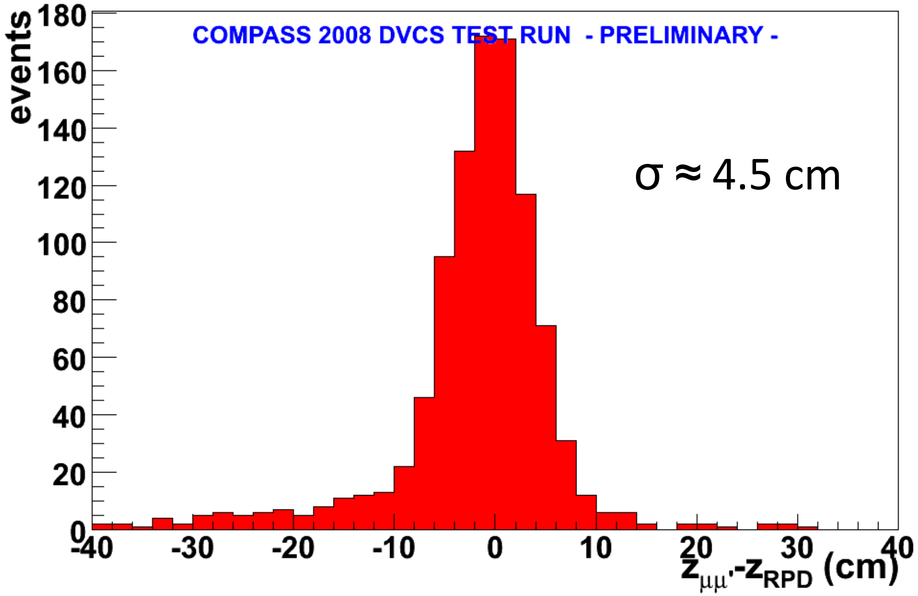
Selection of events :

- 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 :

$t_\mu - t_{RPD}$

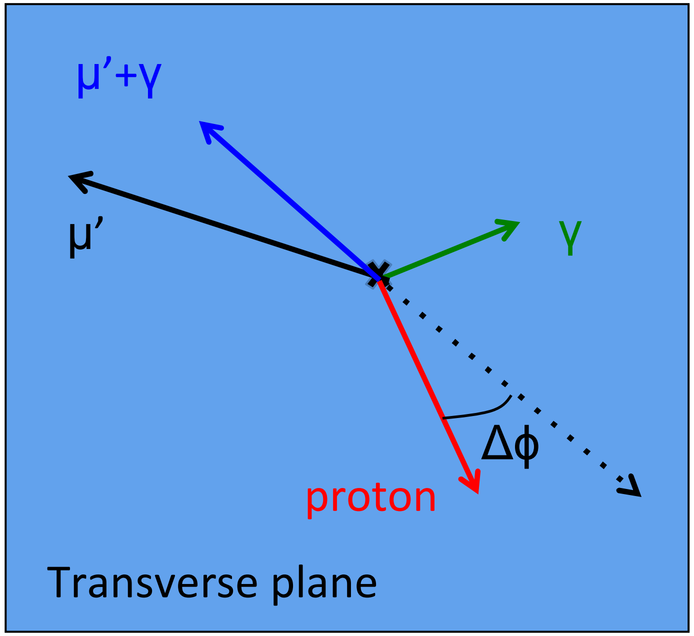


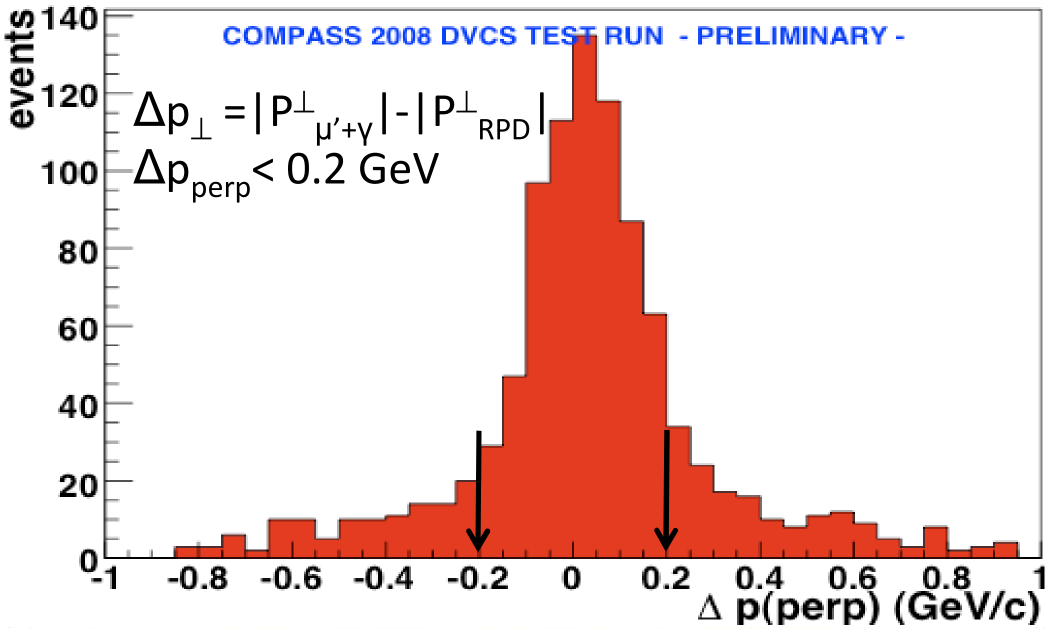
Z position difference :

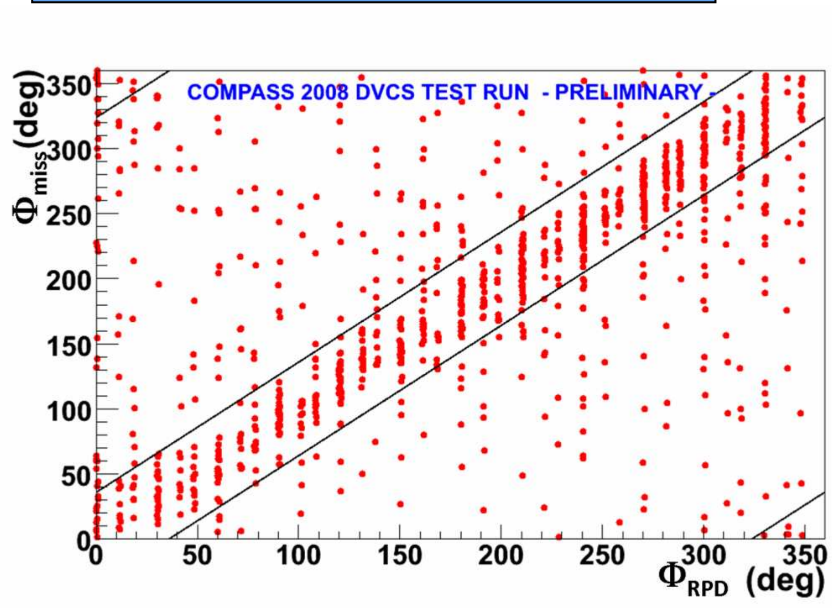
$z_{\mu\mu'} - z_{RPD}$

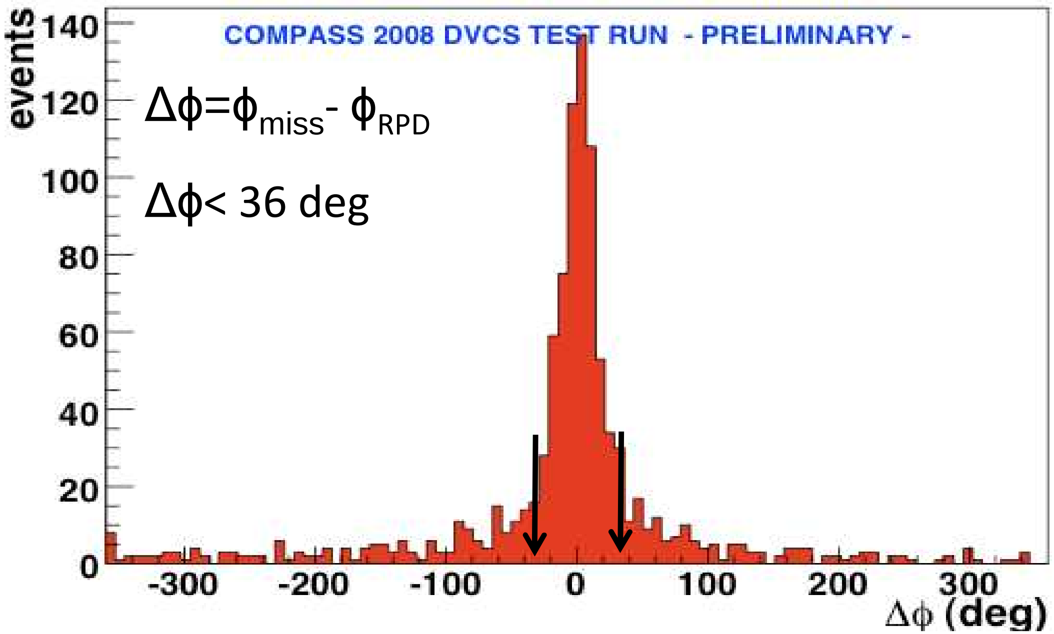
Kinematic constraints in the transverse plane

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

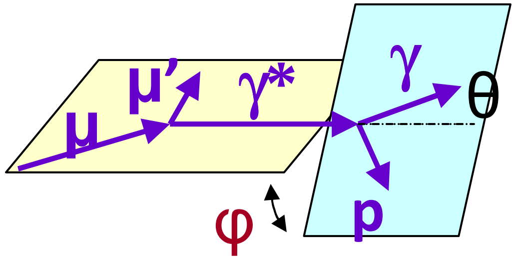


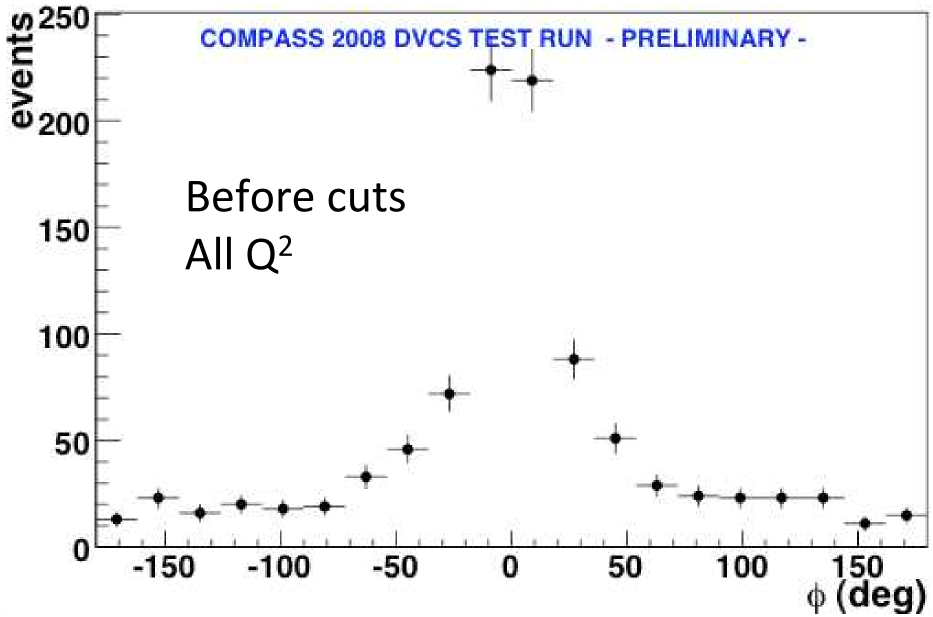


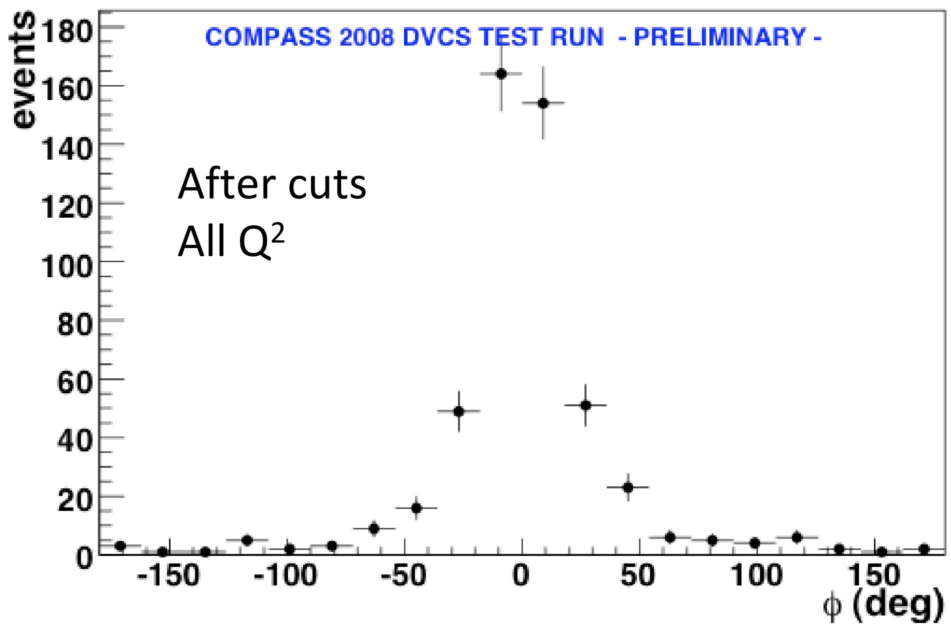




Azimuthal distribution for single photon events

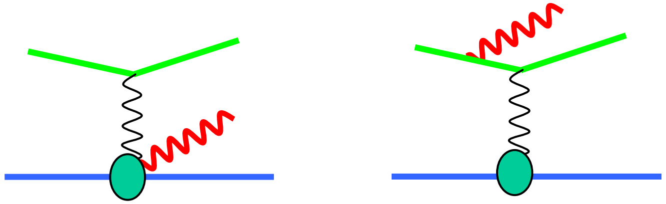




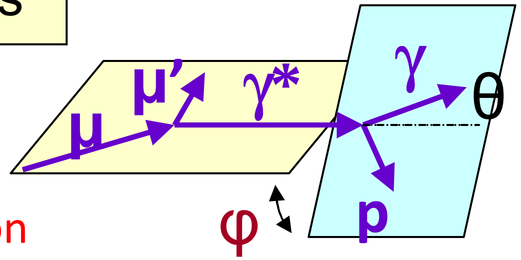


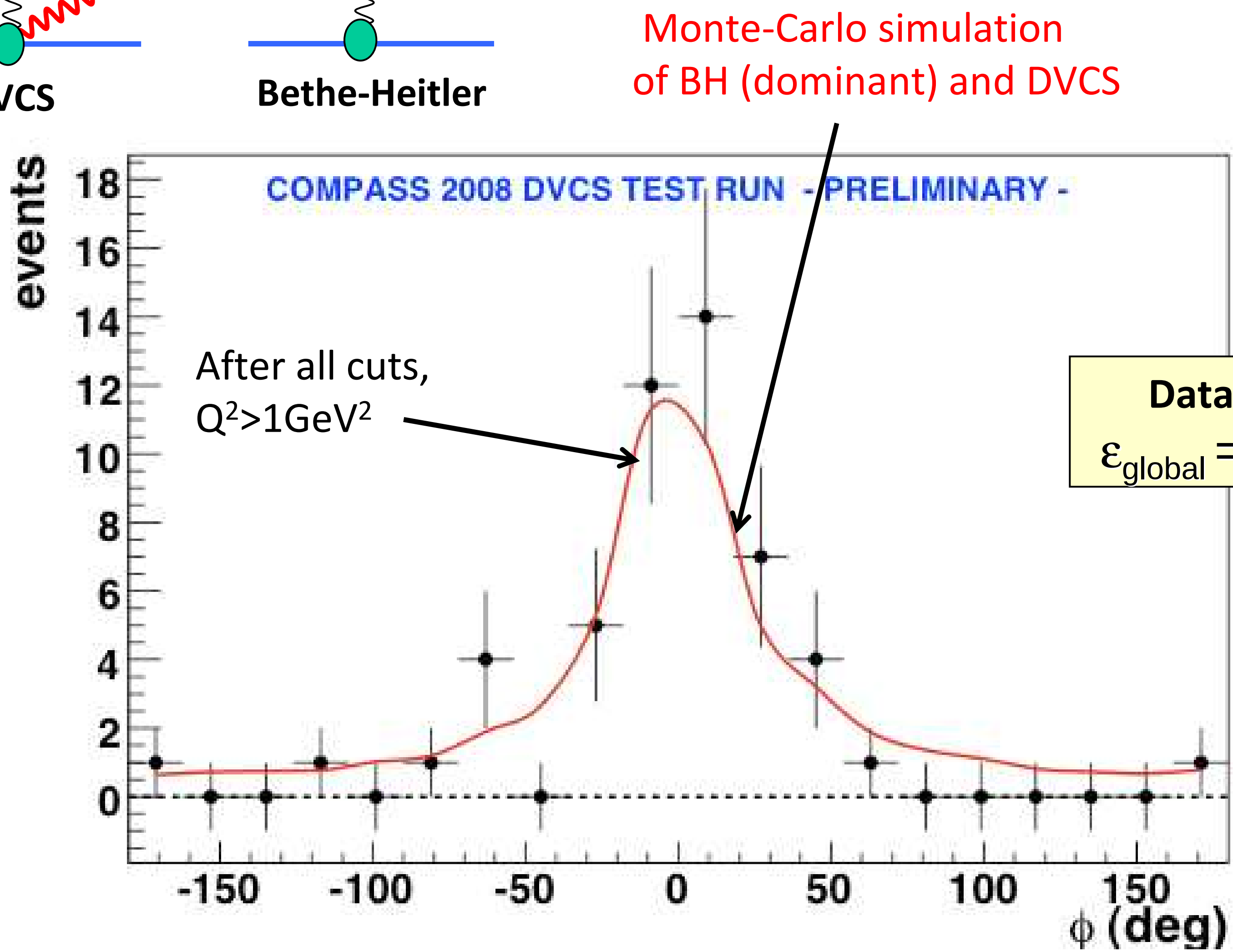
A flat background contribution in φ suppressed
The peak at φ=0 remains =>identified as BH

Azimuthal distribution for exclusive single photon events



DVCS   Bethe-Heitler





Data & MC =>

ε_{global} = 13%±5%

Clear signature of dominant BH events

2009 DVCS pilot run

2 weeks of DVCS pilot run in 2009 approved by SPSC
to start September 17

'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 $\mu+$ and $\mu-$ 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 or polarized target
  - Good calorimetry and Extension at larger angles

- Roadmap
  - A global COMPASS proposal for the period 2012-2016/2017 including GPD will be submitted to SPSC in 2009
  - 2008-9: The small RPD and liquid H_2 target are available for the hadron program → tests of DVCS feasibility
  - from 2012: The complete GPD program at COMPASS with a long RPD
    + liquid H_2 target (2012)
    + transversely polarized ammonia target (2014)