Simulations of exclusive processes at EIC and COMPASS

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- Simulations of DVCS for EIC
  - ✓ generator - FFS
  - ✓ projections for eRHIC
  - ✓ experimental requirements for exclusive program at EIC

- GPD program for COMPASS
  - ✓ modified FFS generator
  - ✓ program and projections for GPDs at COMPASS

Frankfurt, Freund and Strikman (FFS) model invented (1998) to make predictions for DVCS at small x_B (~ 10^{-3})

main features of the original model:

- only contribution of GPD H to the DVCS amplitude considered
- $\mathcal{Im}$(CFF $\mathcal{H}$(t=0)) related to structure function F_2

  $R := \mathrm{Im}\, A(\gamma^* p \rightarrow \gamma^* p) / \mathrm{Re}\, A(\gamma^* p \rightarrow \gamma\, p)$
- $\mathcal{Re}$(CFF $\mathcal{H}$(t=0)) from $\mathcal{Im}$(CFF $\mathcal{H}$(t=0)) using derivative dispersion relation

  $\eta := \mathrm{Re}\, A(\gamma^* p \rightarrow \gamma\, p) / \mathrm{Im}\, A(\gamma^* p \rightarrow \gamma\, p)$
- factorised t-dependence, the same for $\mathcal{Im}$ and $\mathcal{Re}$ parts

  t-slope b from measured dσ/dt for DVCS (H1, ZEUS)
- LO pQCD
- Twist-2, but only terms leading in $1/Q$ kept
- Kinematic approximations: $x_B << 1$, $t/Q^2 << 1$, $Q^2 >> 1$

  reasonable for HERA, but not OK for COMPASS and other FT experiments

  with approximations of original FFS => no φ-dependence of pure BH term !

FFS model (cont.d)

original FFS describes HERA data on DVCS cross sections at 30% accuracy

FFS in NLO by Freund and McDermott (2001)
used by Laurent Schoeffel to describe H1 and ZEUS data

NLO in good agreement with the HERA data on DVCS cross sections

A criticism on a rigorous theoretical ground;
in this model the GPD does not obey the feauture of polynomiality

Simulations of DVCS at eRHIC

HE setup: $e^{+/-}$ (10 GeV) + p (250 GeV) $\mathcal{L} = 4.4 \cdot 10^{32}\ cm^{-2}s^{-1}$ 38 pb^{-1}/day

LE setup: $e^{+/-}$ (5 GeV) + p (50 GeV) $\mathcal{L} = 1.5 \cdot 10^{32}\ cm^{-2}s^{-1}$ 13 pb^{-1}/day

diam. of the pipe - 20 cm, space for Central Detector: ≈ +/- 280 cm from IP

→ acceptance of Central Detector (improved ZDR) **$2° < \theta_{lab} < 178°$**

event generator: FFS (1998) parameterization with **R=0.5, η = 0.4** and **b = 6.2 GeV^{-2}**

→ DVCS + BH + INT cross section

acceptance simulated by kinematical cuts

$2° < \theta_{e'} < 178°$	$2° < \theta_{\gamma} < 178°$
$E_{e'} > E_{min}$ GeV	$E_{\gamma} > 0.5$ GeV

E_{min} = 2 GeV (HE) or 1 GeV (LE)

kinematical **smearing**: parameterization of resolutions of H1 (SPACAL, LArCal) + ZEUS (θ_γ, φ_γ) + expected for LHC ($\theta_{e'}$, $\varphi_{e'}$)

acceptance and 'reasonable' balance between DVCS and BH motivate **kinematical ranges** →

HE setup	LE setup
$1 < Q^2 < 50$ GeV²	**$1 < Q^2 < 50$ GeV²**
$10 < W < 90$ GeV	**$2.5 < W < 28$ GeV**
$0.05 < \|t\| < 1.0$ GeV²	**$0.05 < \|t\| < 1.0$ GeV²**

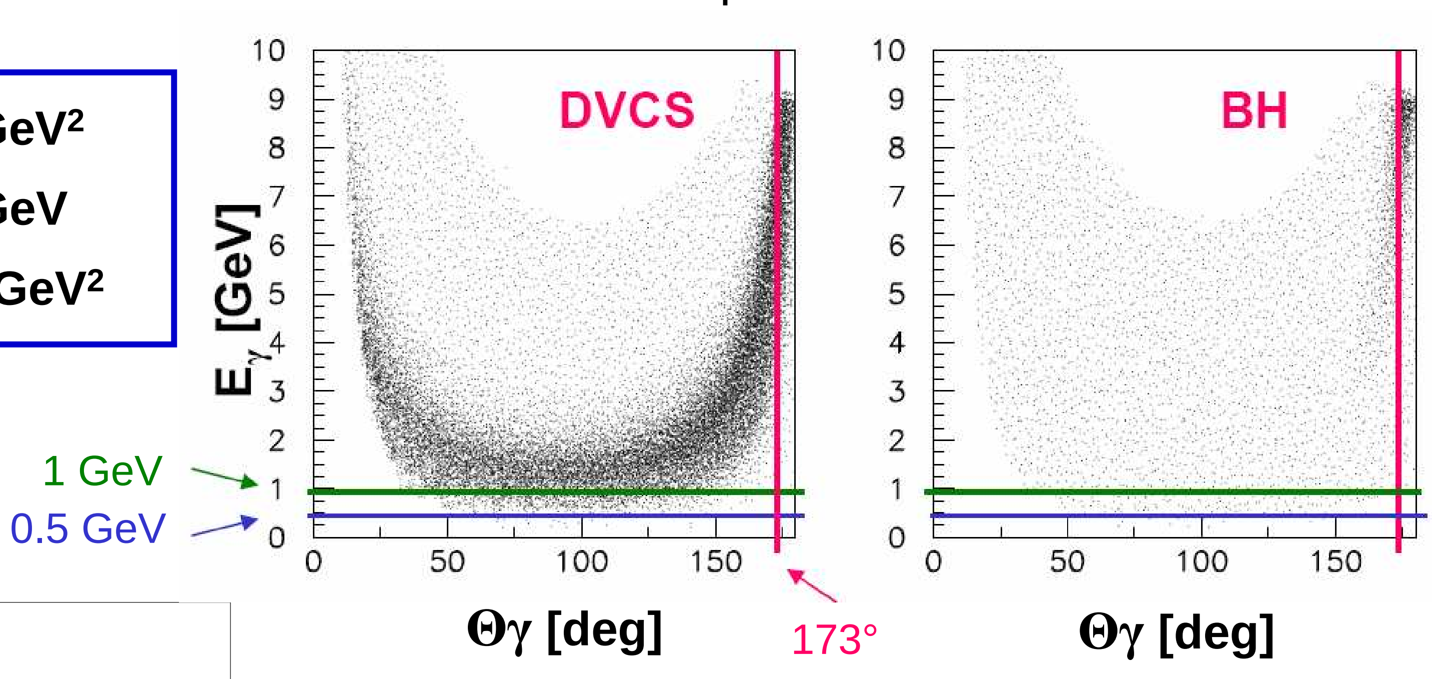
Photon and scattered electron kinematics

ep → e'p'γ E_e = 10 GeV E_p=250 GeV

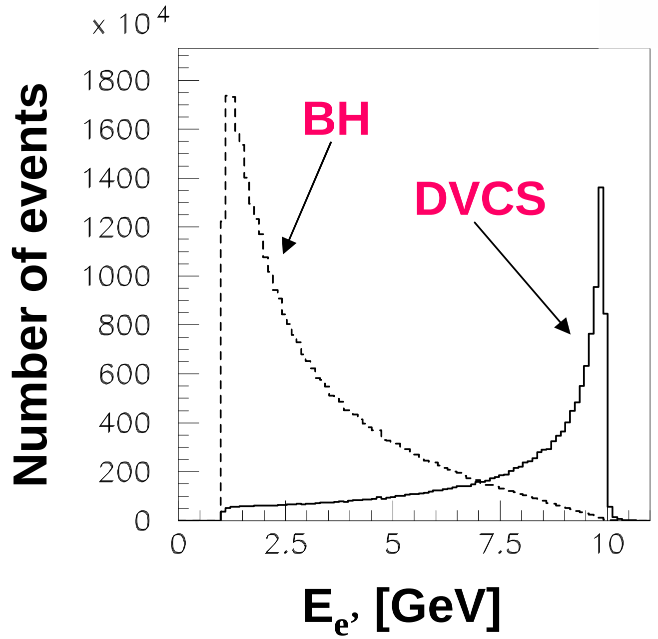
1 < Q^2 < 50 GeV²

10 < W < 90 GeV

0.05 < |t| < 1.0 GeV²



(arbitrary relative normalisation between plots)

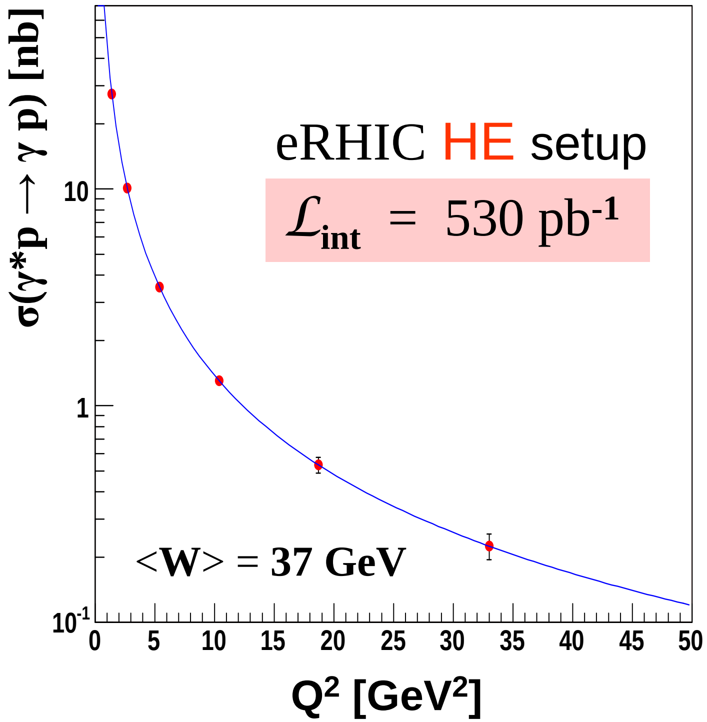


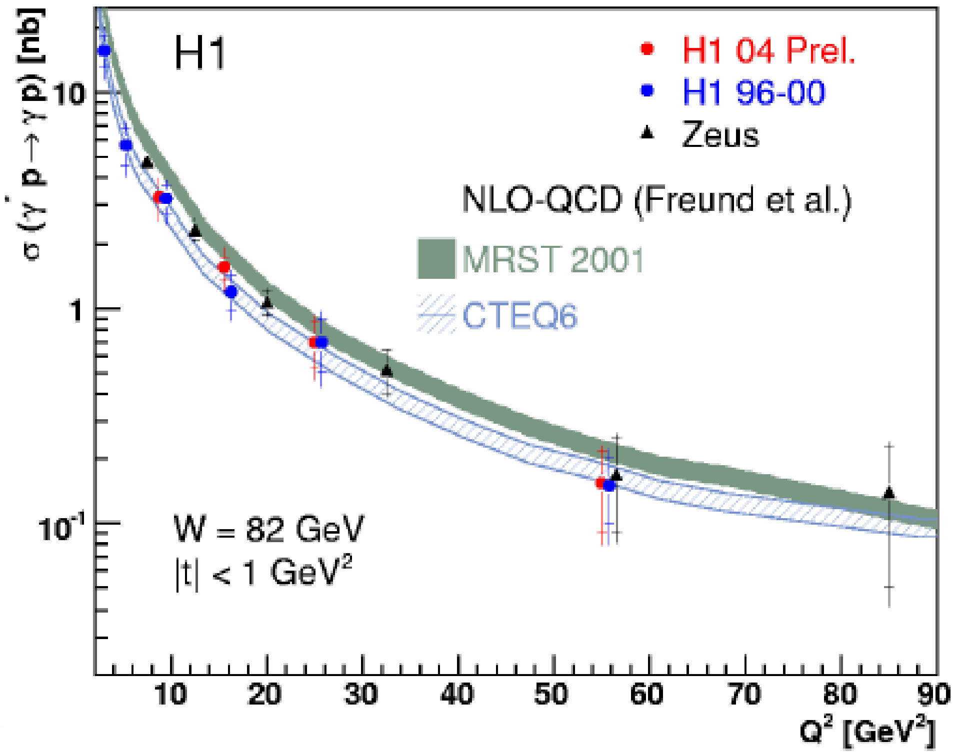
- **polar angle coverage affects acceptance at Q^2 < 2 GeV² and at both low and the highest W**
- **low energy photons correlate with low W**
- **increase of lower cut on electron energy allows to diminish fraction of BH, but reduces range at large W**

Precision of DVCS unpolarized cross sections at eRHIC (1)

HE setup: $e^{+/-}$ (10 GeV) + p (250 GeV) $\mathcal{L}$ = 4.4 · 10^{32} $cm^{-2}s^{-1}$ 38 pb^{-1}/day

For one out of 6 W intervals (30 < W < 45 GeV)





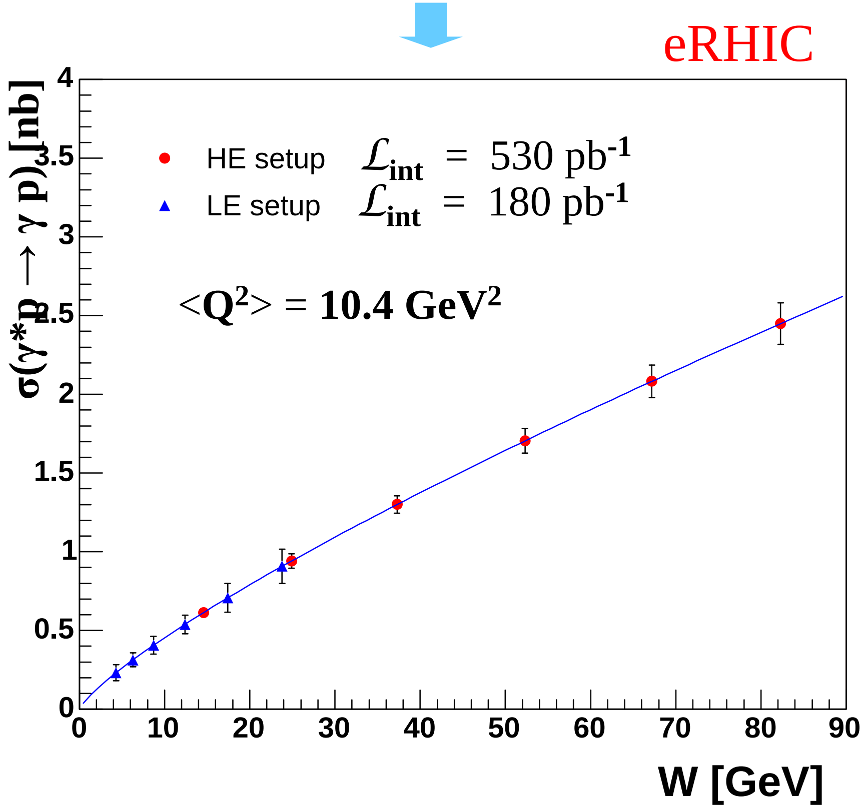
❖ **eRHIC measurements of cross section will provide significant constraints**

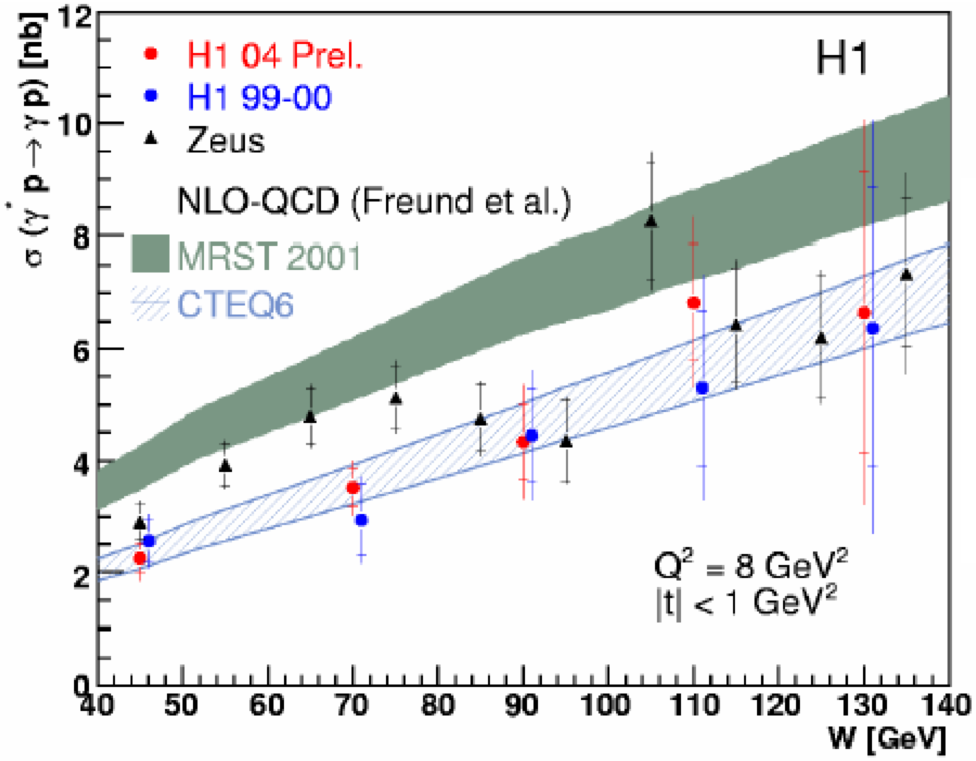
Precision of DVCS unpolarized cross sections at eRHIC (2)

HE setup: $e^{+/-}$ (10 GeV) + p (250 GeV) $\mathcal{L}$ = $4.4 \cdot 10^{32}$ $cm^{-2}s^{-1}$ 38 pb^{-1}/day

LE setup: $e^{+/-}$ (5 GeV) + p (50 GeV) $\mathcal{L}$ = $1.5 \cdot 10^{32}$ $cm^{-2}s^{-1}$ 13 pb^{-1}/day

For one out of 6 Q^2 intervals ($8 < Q^2 < 15$ GeV^2)

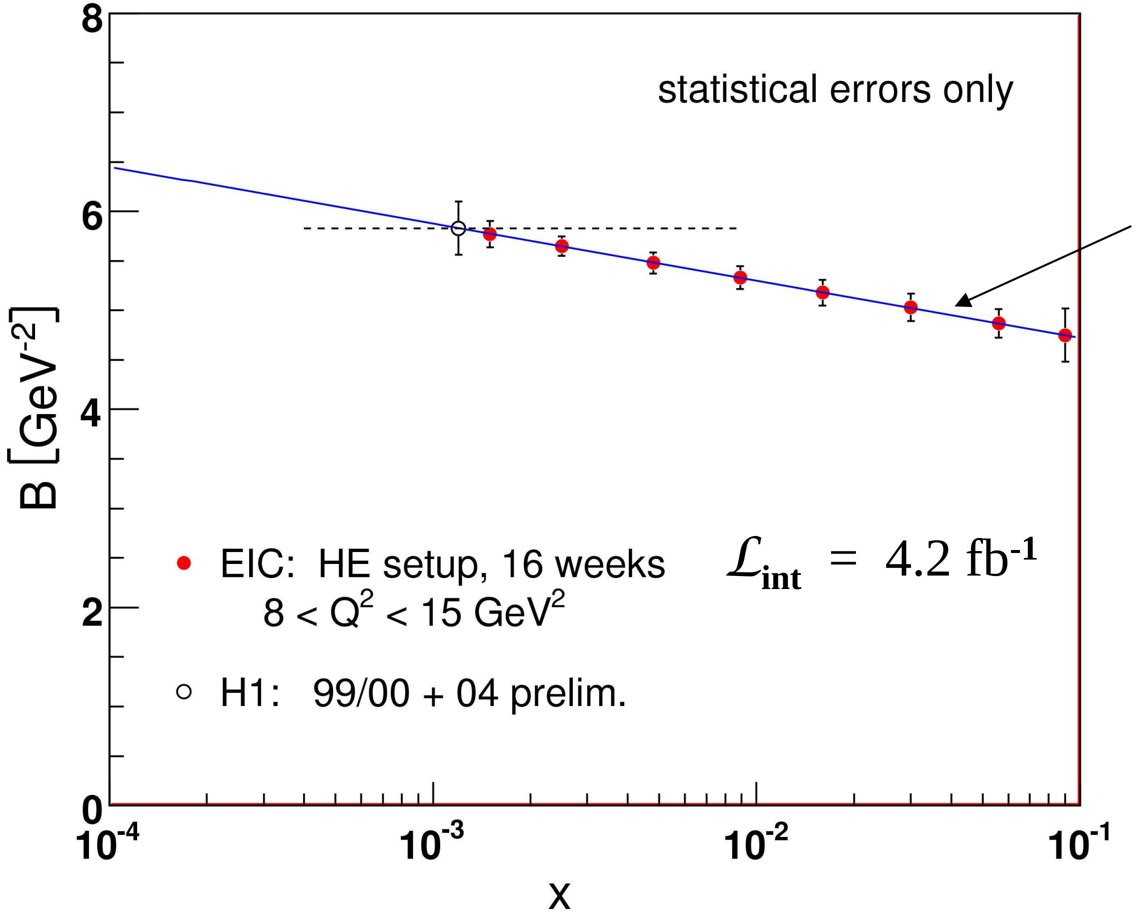




❖ **EIC measurements of cross section will provide significant constraints also significantly extend the range towards small W**

Towards 3D mapping of parton structure of the nucleon at EIC

$$d\sigma/dt(\gamma^* p \to \gamma\, p) \propto \exp(-B|t|)$$

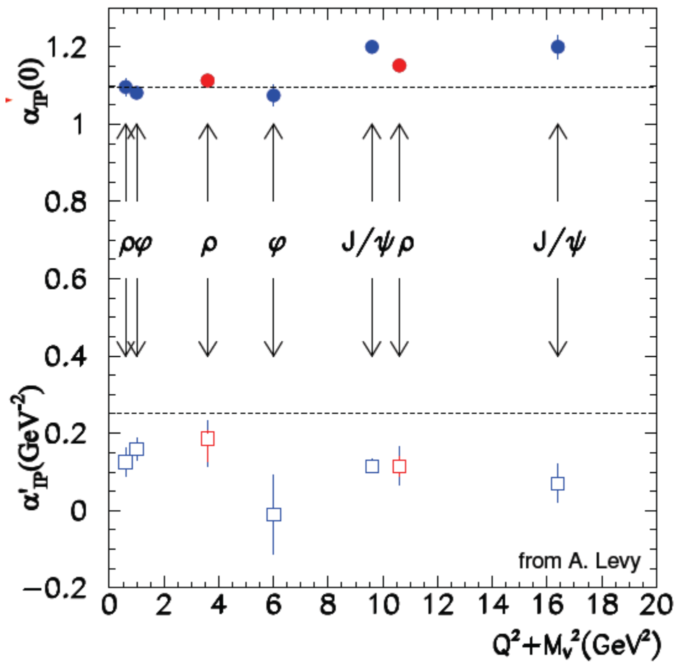


simultaneous data in several (6) Q^2 bins

(assumed for illustration)

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

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



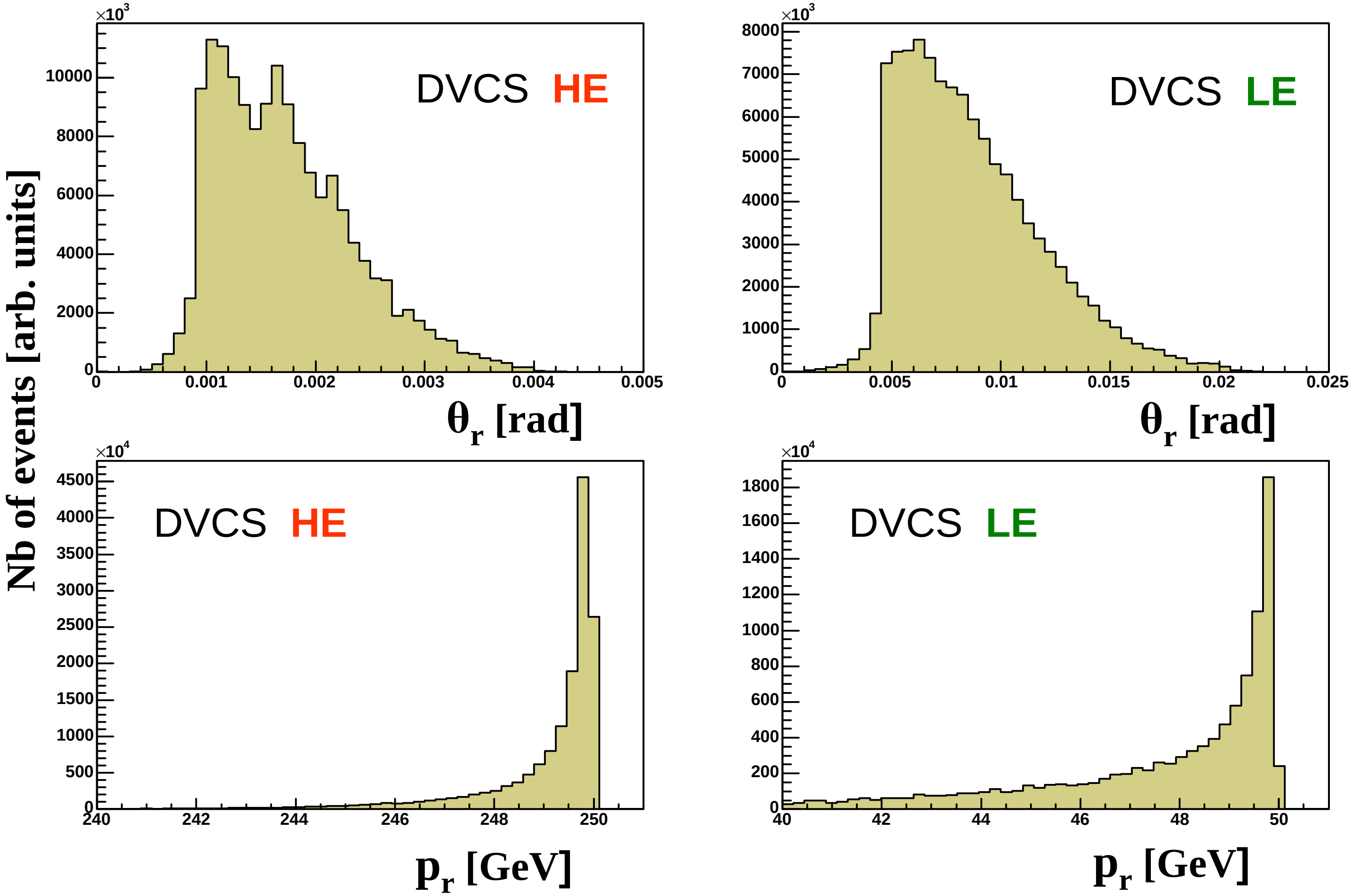
Sufficient luminosity to do triple-differential measurements in x, Q^2, t at EIC!

Detection of scattered fast protons ('recoils')

Aim: **clean subsample of exclusive events** => increased precision of t and φ determination + systematics due to DD background in the main sample

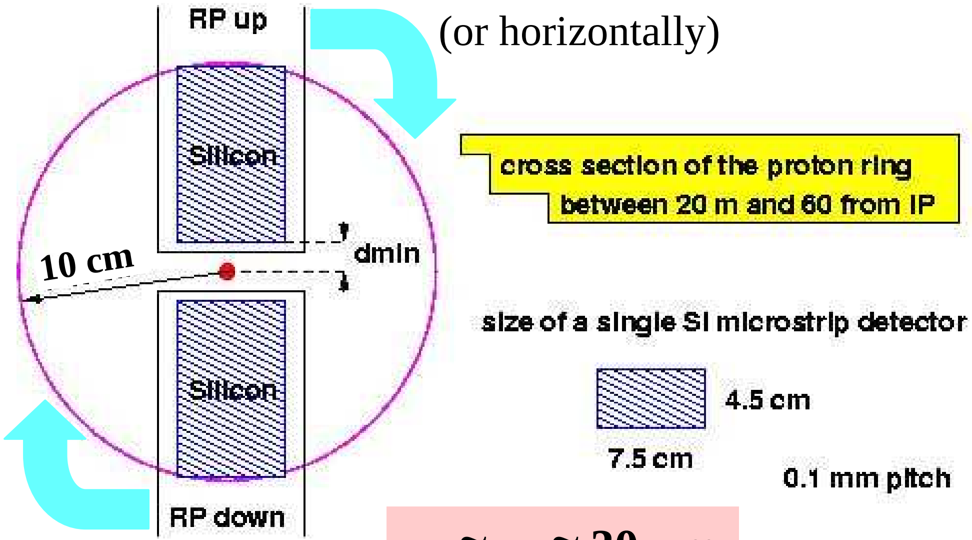
Since scattering angles of **fast protons** are small they **stay within the beam pipe** and follow trajectories determined by the magnetic field of accelarator

Note different θ_r scales for HE and LE setups



A method for detection of recoil protons

Roman Pot Station



$\sigma_x \approx \sigma_y \approx 30\ \mu m$

Beam transport matrix

$$\begin{pmatrix} x_D \\ \Theta_D^x \\ y_D \\ \Theta_D^y \end{pmatrix} = \begin{pmatrix} a_{11} & L_{eff}^x & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 \\ 0 & 0 & a_{33} & L_{eff}^y \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ \Theta_x^* \\ y_0 \\ \Theta_y^* \end{pmatrix}$$

↑ at the detector   at the IP ↑

Elements of TM depend on distance L from IP and on $\delta = (p_r - p_b)/p_b$

Requirements

- Distance from the nominal beam orbit > 12 σ beam envelope
- High sensitivity to the angles at the IP
- No strong dependence of TM elements on δ

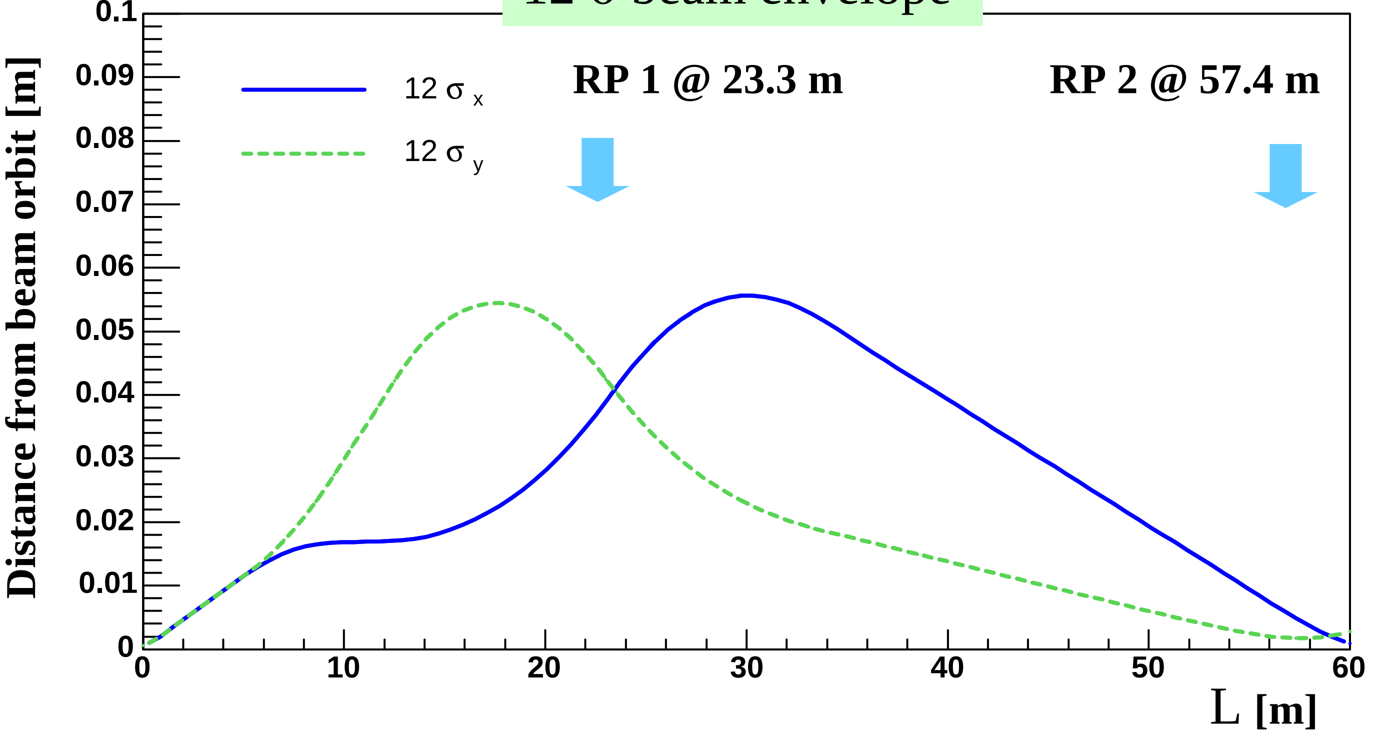
Beams characteristics and transport

Considered option: **linac-ring** for **10 GeV e + 250 GeV** p

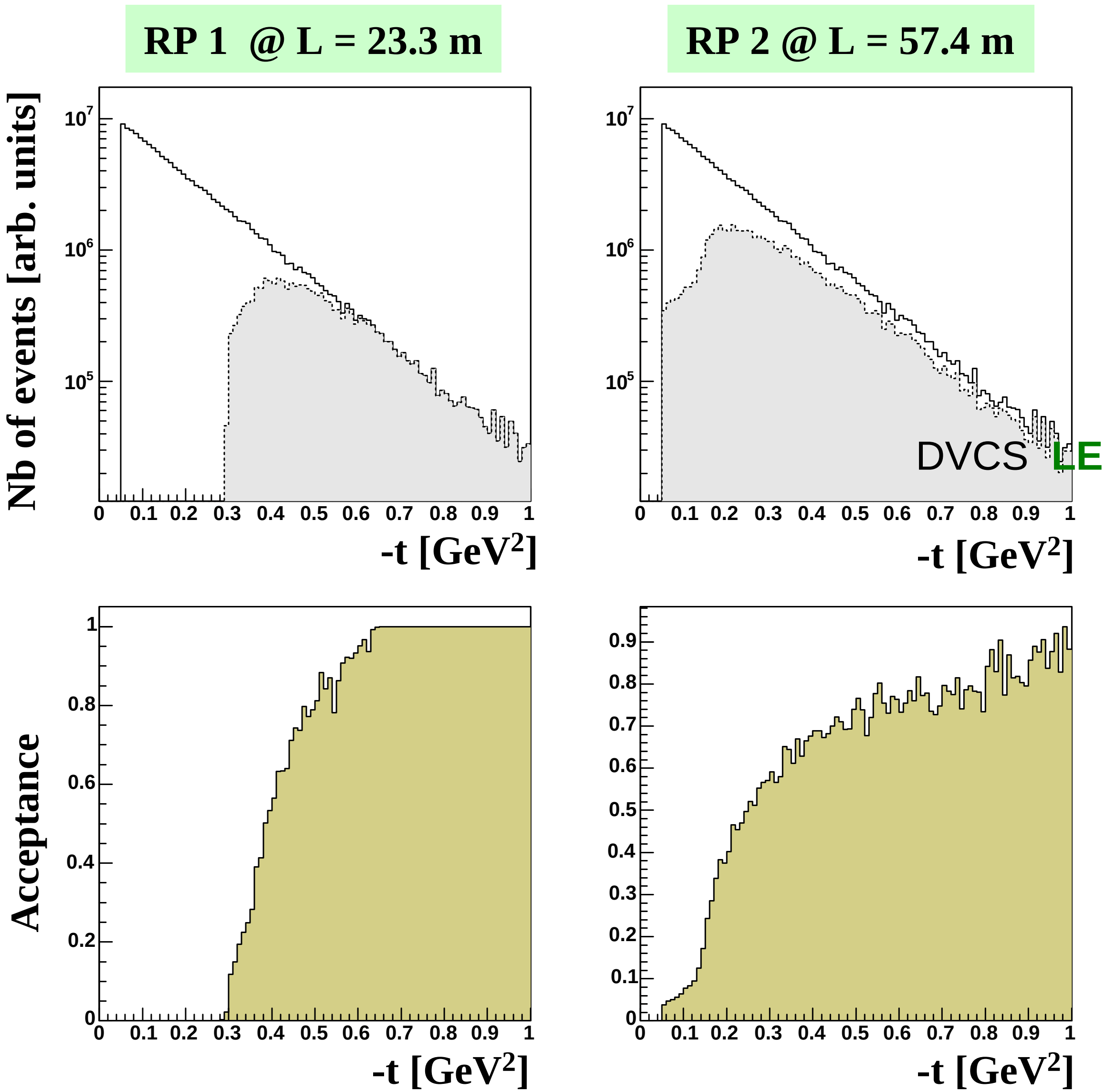
transport program written by **Christoph Montag** (CAD-BNL)

protons	$\varepsilon^* = 9.5$ nm	$\beta^*_{x/y} = 0.26$ m	$\sigma^0_{x/y} = 50$ µm	$\sigma^0_{\theta x/y} = 191$ µrad
electrons	$\varepsilon^* = 2.5$ nm	$\beta^*_{x/y} = 1$ m	$\sigma^0_{x/y} = 50$ µm	$\sigma^0_{\theta x/y} = 50$ µrad

12 σ beam envelope



Full acceptance including Roman Pots



—— generated

········ accepted (CD + RP)

reasonable acceptance for

$|t| > 0.35$ GeV^2 for RP 1
$|t| > 0.15$ GeV^2 for RP 2

average acceptance for $0.05 < |t| < 1.0$ GeV^2

12% for RP 1
25% for RP 2

For RP 2 t-range with reasonable acceptance wider , but …

At RP1 significantly higher (≈ 10 x) sensitivity to scattering angle

Detector requirements for exclusive processes

small cross sections
a challenge → { • large luminosity
• effective suppression of non-exclusive background }

- **Hermeticity** wide kinematical range and suppression of non-exclusive bkg.
  - angular acceptance of Central Detector strongly affects small x region
    $2^{o} \div 178^{o}$ ('improved ZDR')
  - importance of coverage of low E_γ region (both π^0 bkg. and accept. at small W)
    E_γ > 0.5 GeV (?)
  - Leading Proton Detector - suppression of bkg. from proton diff. dissociation

    acceptance and t-range strongly dependent

    on beam-line design and on beam tune (β^*)

- **Particle Identification** necessary minimum - e/μ/h separation

  with Calorimetry and Muon Detector

Detector requirements for exclusive processes

- Resolutions

  - in particular important for $d\sigma/dt$
    and angular distributions (DVCS and L/T separation for VM)

  - affect choice of exclusivity cuts ➡ background rejection

Conservative estimates of the resolutions (based on existing experience)

Central Detector

- scattered electrons $\frac{\sigma_E}{E} = \frac{0.071}{\sqrt{E}} \oplus .025$ (H1 SPACAL), $\sigma_\theta = \sigma_\varphi$ = 0.3 mrad (LHC)
- photons $\frac{\sigma_E}{E} = \frac{0.11}{\sqrt{E}}$ (H1 LAr), $\sigma_\theta = \sigma_\varphi$ = 5 mrad (ZEUS)
- charged particles $\frac{\sigma_{p_t}}{p_t} = 0.0058 p_t \oplus 0.0065 \oplus 0.0014 / p_t$, $\sigma_\eta = 0.0015 \oplus 0.0017 / p_t$, $\sigma_\varphi = 0.0006 \oplus 0.002 / p_t$ (ZEUS)

Leading Proton Detector

- silicon 100μm microstrip detectors $\sigma_x = \sigma_y$ = 30 μm (PP2PP)

example: for DVCS and 0.1 < t < 0.2 GeV^2 expected resolution in t is 0.06 GeV^2 when determined from CD or 0.02 GeV^2 from LPD

Summary for DVCS and HEPM at an EIC

- Wide kinematical range, overlap with HERA and COMPASS
  - $1.5 \cdot 10^{-4} < x_B < 0.15$ - sensitivity to gluons and sea quarks
  - $1 < Q^2 < 50\ GeV^2$ - sensitivity to QCD evolution

- Significant improvement of precision wrt HERA

- Sufficient luminosity to do tripple-differential measurements in x_B, Q^2, t

- Measurements at both high and low beam energy settings

  will provide kinematical overlap with existing data
  and L/T separation for pseudoscalar meson production

- Full exploratory potential for DVCS at amplitude level with
  - longitudinaly and transversely polarized protons
  - both e^+ and e^- beams

Modifications to FFS model for COMPASS kinematics   A. S.

- no kinematic approximations

  formalism of Belitsky, Mueller and Kirchner (2002) used with

  a) complete BH terms

  b) all twist-2 terms included for DVCS and Interference terms

- *Im* part of *H* :

$$\mathrm{Im}\, H = \frac{\pi}{x} \frac{F_2(x,Q^2)}{R} \exp(-\frac{B(x)}{2} |\, t\,|)$$

where

- NMC parameterisation used for structure function F_2
- for skewing factor $R = \frac{\mathrm{Im}\, A(\gamma^* p \to \gamma^* p)_{t=0}}{\mathrm{Im}\, A(\gamma^* p \to \gamma\, p)_{t=0}}$ value R = 0.5 used
- t-slope $B(x) = B_0 + 2\,\alpha' \ln(x_0/x)$

two versions for simulations:

a) non-factorisable (Reggeized); $\alpha' = 0.8$, $B_0 = 4.94$ GeV^{-2}, $x_0 = 0.042$

b) factorisable ; $\alpha' = 0$, $B_0 = 5.0$ GeV^{-2}

Modifications to FFS model (cont.d)

- *Re* part of *H* :

integral dispersive relation $\mathrm{Re}\,H(x,t) \overset{\mathrm{LO}}{=} P\frac{1}{\pi}\int_{-1}^{1}\mathrm{Im}\,H(x',t)\left[\frac{1}{x-x'}-\frac{1}{x+x'}\right]dx' + D(t)$

need to know H in the full x range

and subtraction constant $D(t)$, „D-term", to be determined independently

instead, used the derivative dispersive relation $\eta = \frac{\mathrm{Re}\,H}{\mathrm{Im}\,H} \approx \frac{\pi}{2}\frac{d\ln(x\,\mathrm{Im}\,H)}{d\ln(1/x)}$

and assumption D=0

- in factorisable model $\eta = \eta_0$, where η_0 determined only by x-dependence of F_2
- in non-factorisable model $\eta = \eta_0 + \Delta\eta = \eta_0 + \pi/2\ \alpha'\ t$

real part becomes more negative with increase of α' and/or t

- LO pQCD

- all Twist-2 terms included

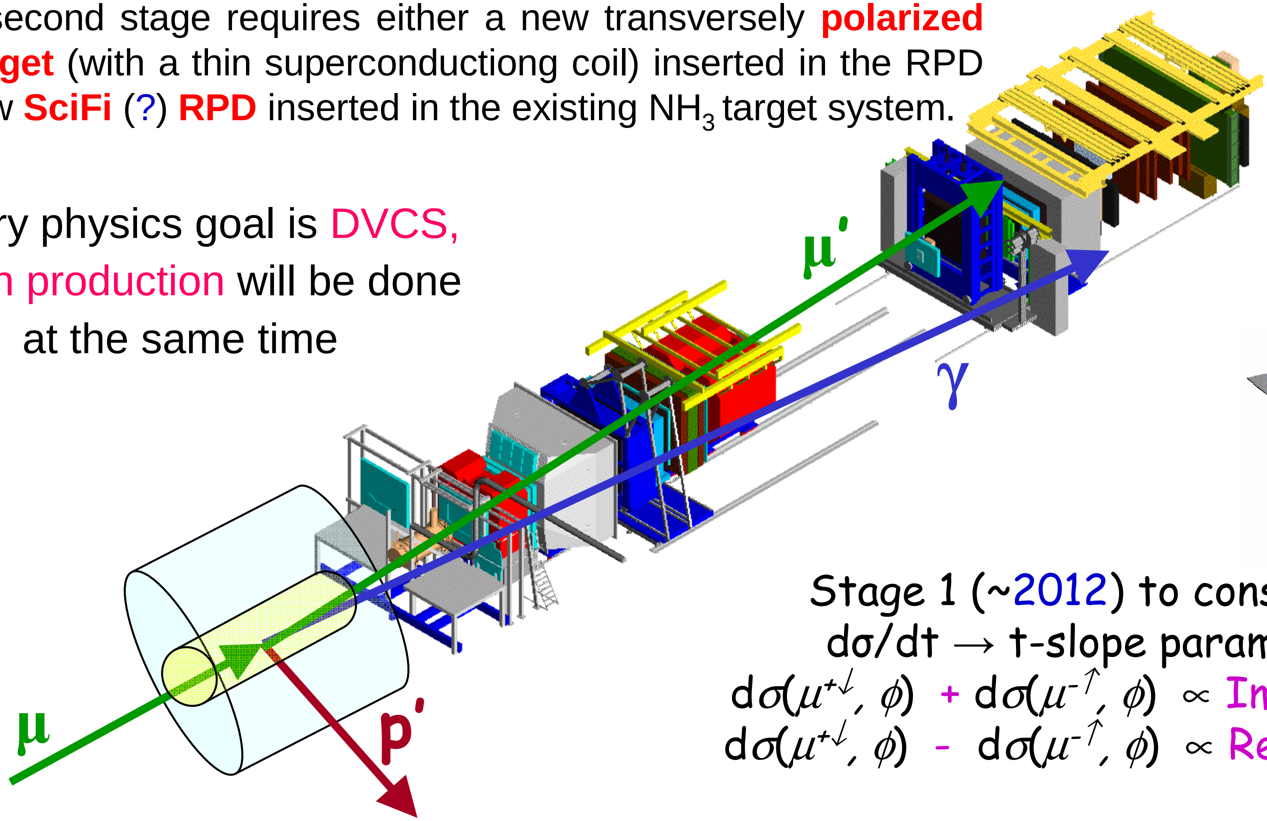
Future GPD program @ COMPASS

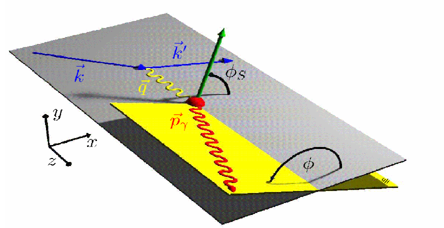
- The GPDs program is part of the **COMPASS Phase II** (2012-2016) proposal to be submitted to CERN in 2010.

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





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

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

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

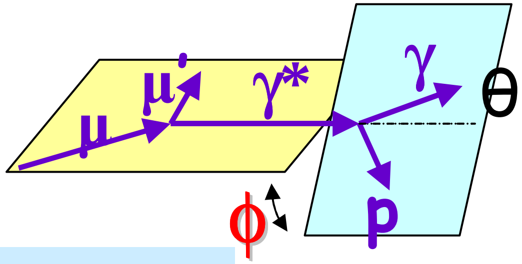
$d\sigma(\mu^{+\downarrow}, \phi) + d\sigma(\mu^{-\uparrow}, \phi) \propto \mathrm{Im}(F_1 H) \sin \phi$

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

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

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

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

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

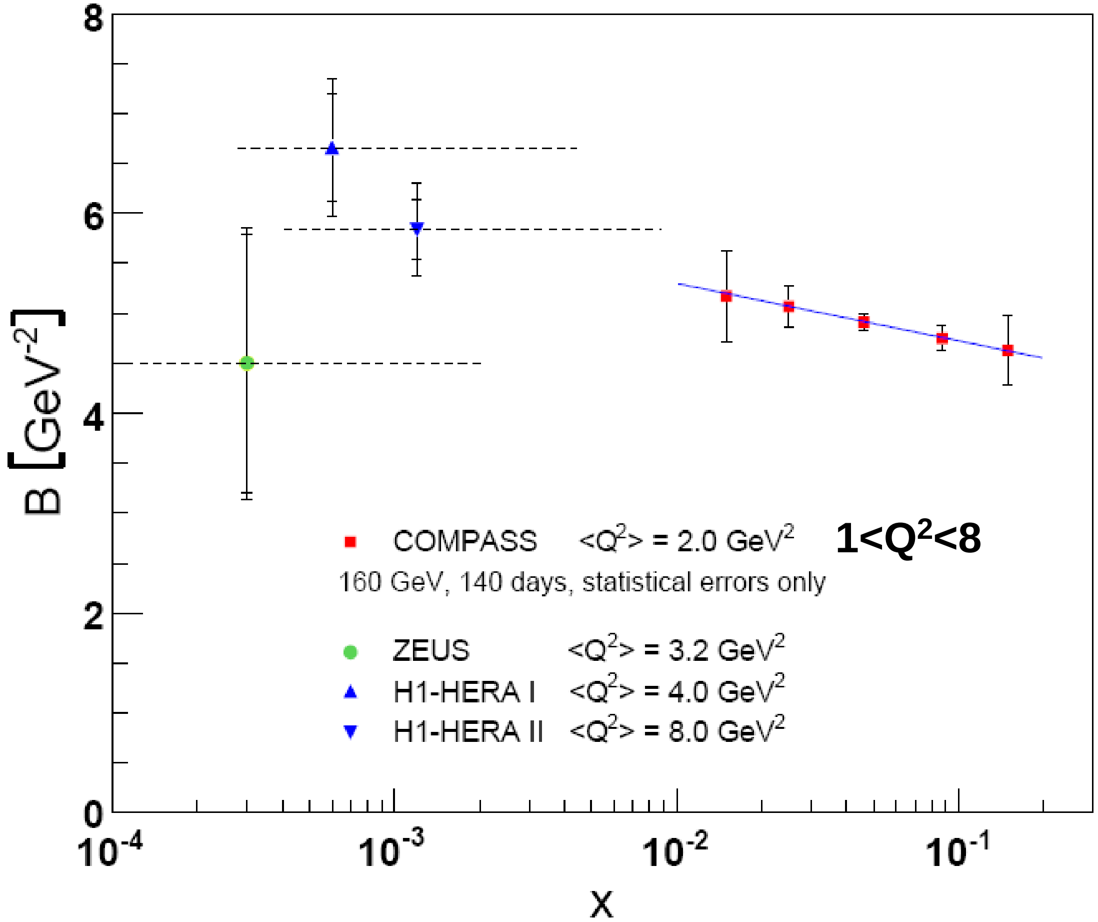
$$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

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

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

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 ($Q^2 \approx 0$)

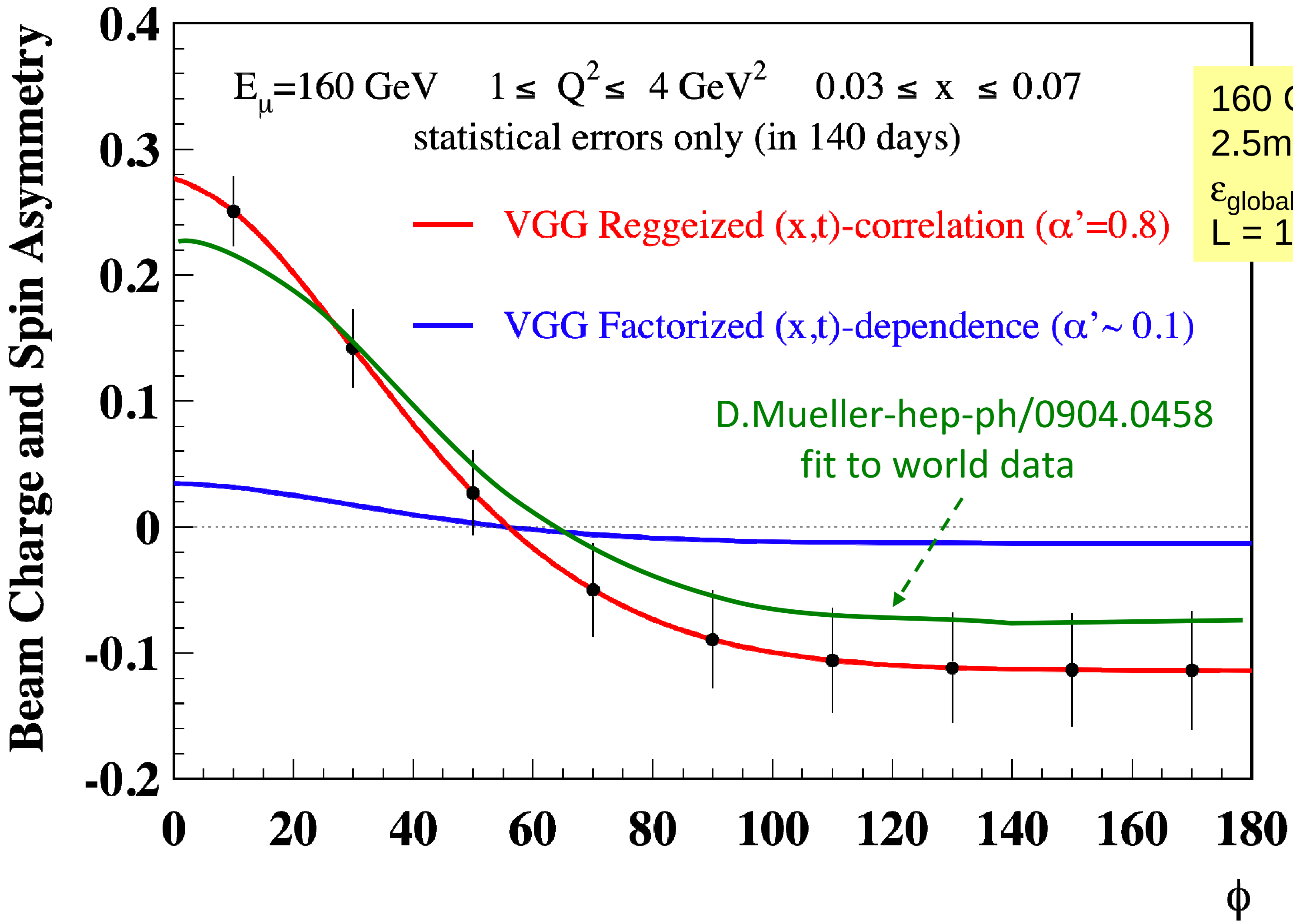
$\alpha' \sim 0.02\ GeV^{-2}$ - DIS (Q^2=2-80 GeV^2)

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

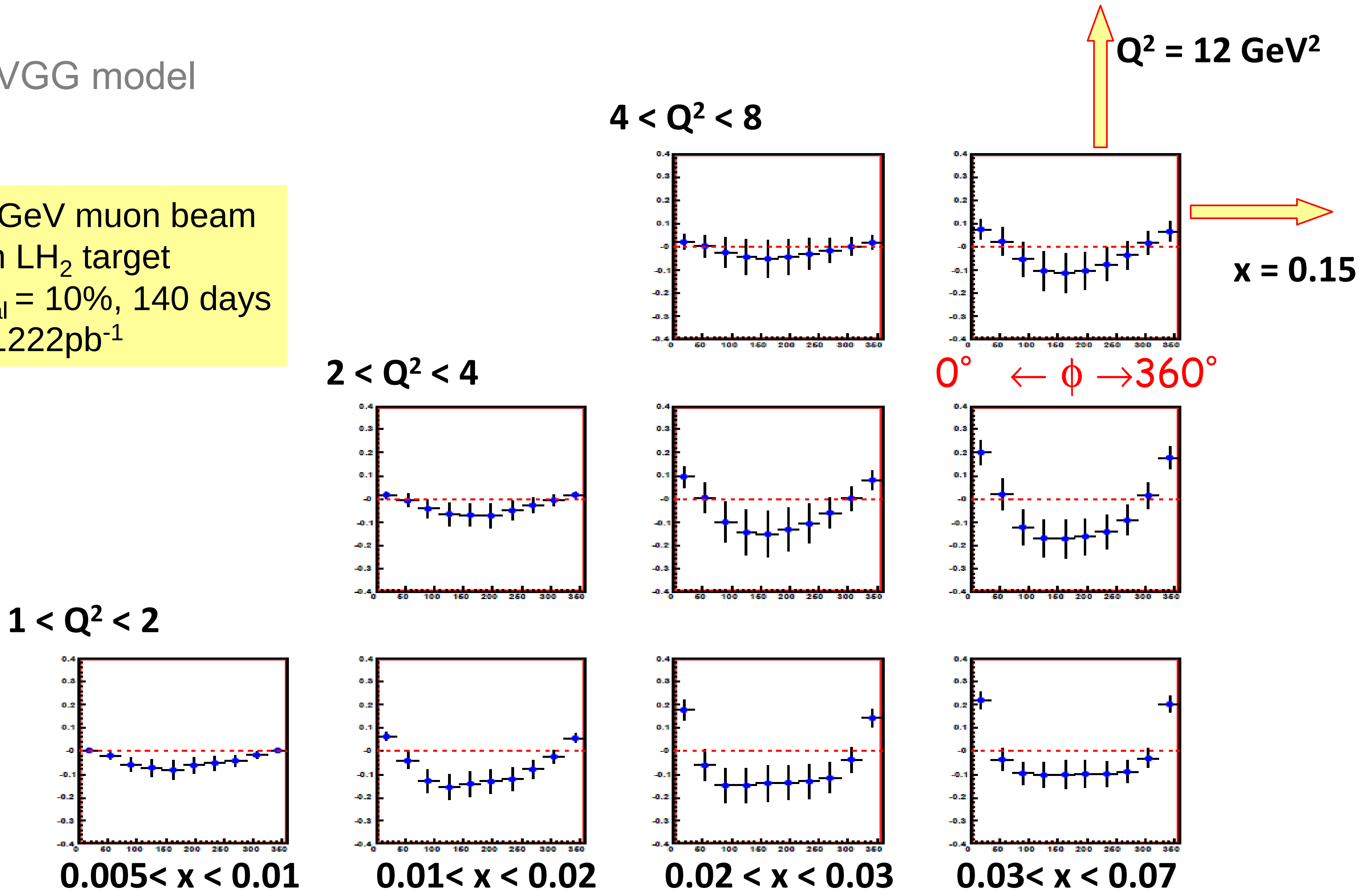


160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 140 days
L = 1222pb^{-1}

Beam Charge and Spin Asymmetry in various kinematic bins

VGG model

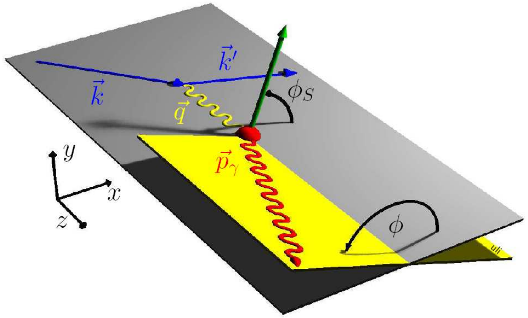
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%, 140 days
L = $1222 pb^{-1}$



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

Single γ production with transversely polarised target

Harmonics decomposition of TTS-dependent 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

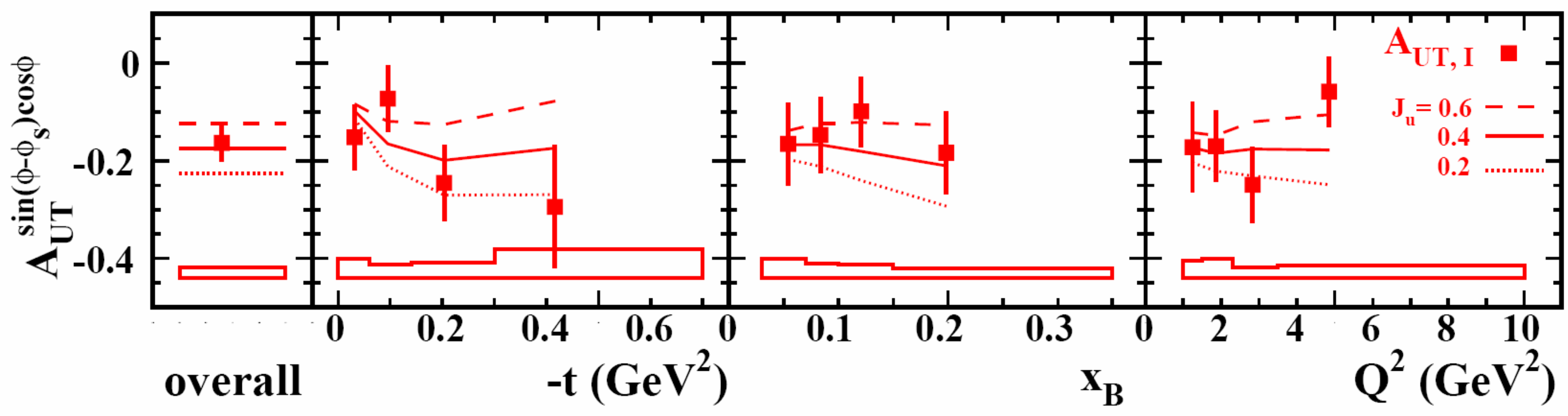
not shown are terms with sin(kφ) and cos(kφ) (k=2,3) dependence

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

An 'appetizer' – HERMES measurements of DVCS

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

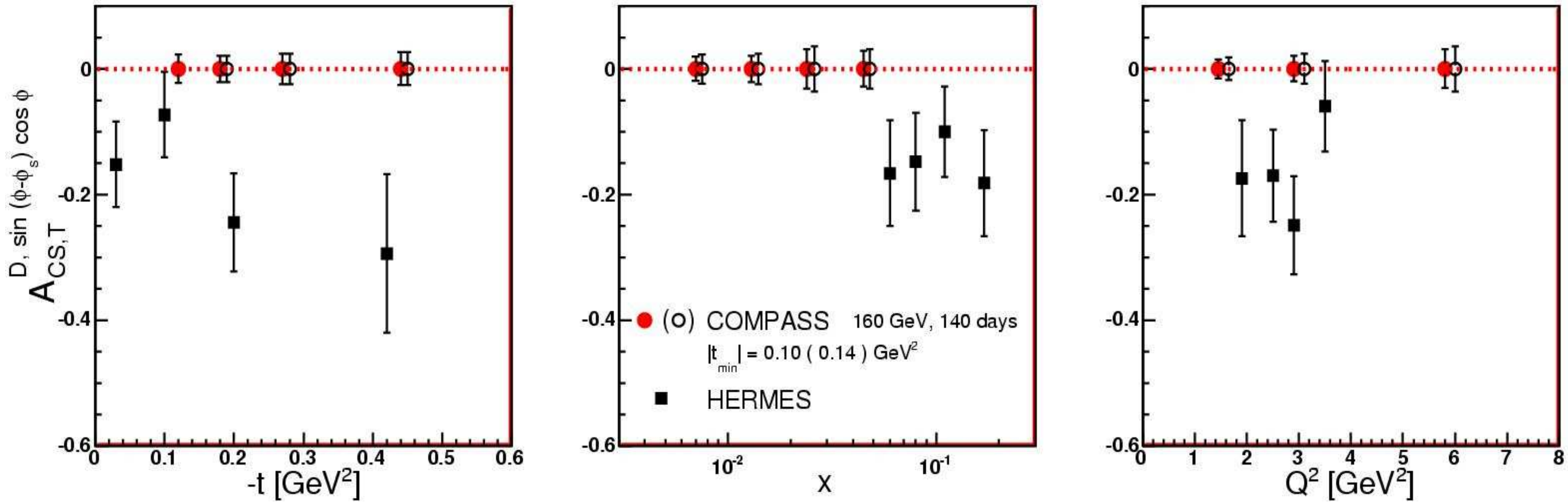
$$c_{1,T-}^{Int} \propto -\frac{M}{Q}\mathrm{Im}\left\{\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right] + x_B\xi\left[F_1(\mathcal{H}+\mathcal{E}) - (F_1+F_2)(\widetilde{\mathcal{H}} + \frac{t}{4M^2}\widetilde{\mathcal{E}})\right]\right\}$$



$A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ 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

$$A_{CS,T}^{D,\sin(\phi-\phi_s)\cos\phi} \quad (A_{UT}^{\sin(\phi-\phi_s)\cos\phi})$$

↑ COMPASS ↑ HERMES



Typical statistical errors of TTS azimuthal asymmetries:

projections for COMPASS ≈ 0.03

for HERMES ≈ 0.08

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 2010
  - 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)