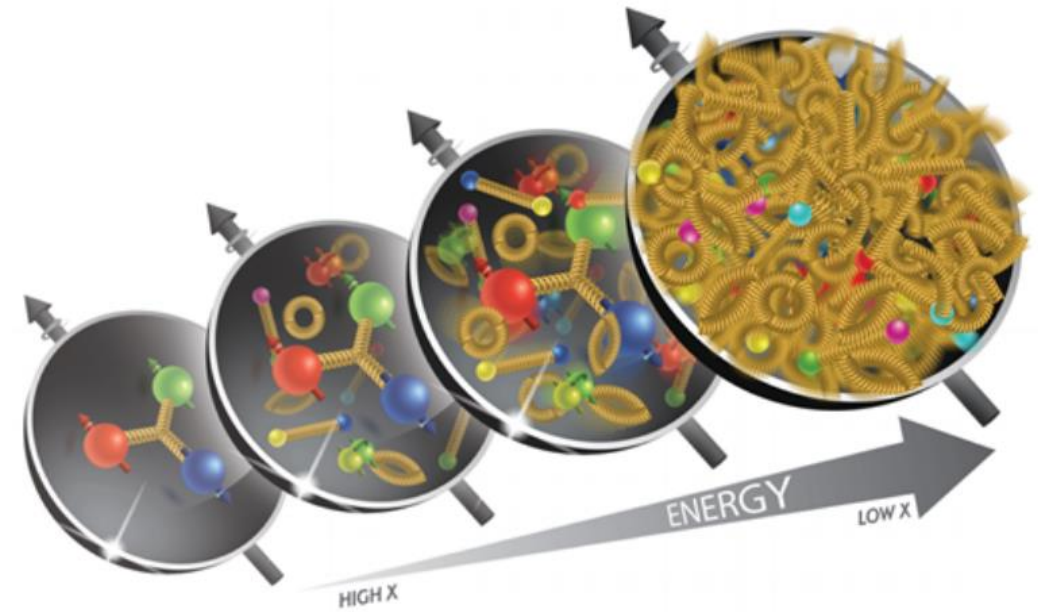
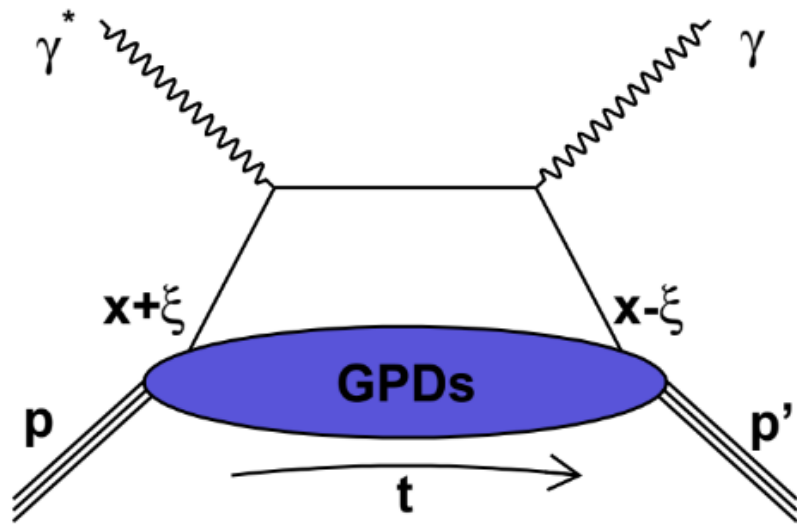


Deeply Virtual Compton Scattering and Spatial Imaging



Lecture 4

Carlos Muñoz Camacho
IJCLab-Orsay (CNRS/IN2P3, France)

Outline

□ Lecture 1: Introduction

- Elastic scattering, form factors (FFs)
- Deep Inelastic scattering, parton distribution functions (PDFs)
- Exclusive reactions, Generalized Parton Distributions (GPDs)

□ Lecture 2: Deeply Virtual Compton Scattering

- Experimental results on proton targets
- Flavor separation using quasi-free neutrons

□ Lecture 3: Deeply Virtual Meson Production & GPD models

- Rosenbluth separation
- Access to transversity GPDs
- GPD models and parametrizations

□ Lecture 4: GPDs at JLab12 and beyond

- Review of GPD programs in other facilities worldwide
- Future experiments at JLab at 12 GeV

□ Lecture 5: Electron-Ion Collider

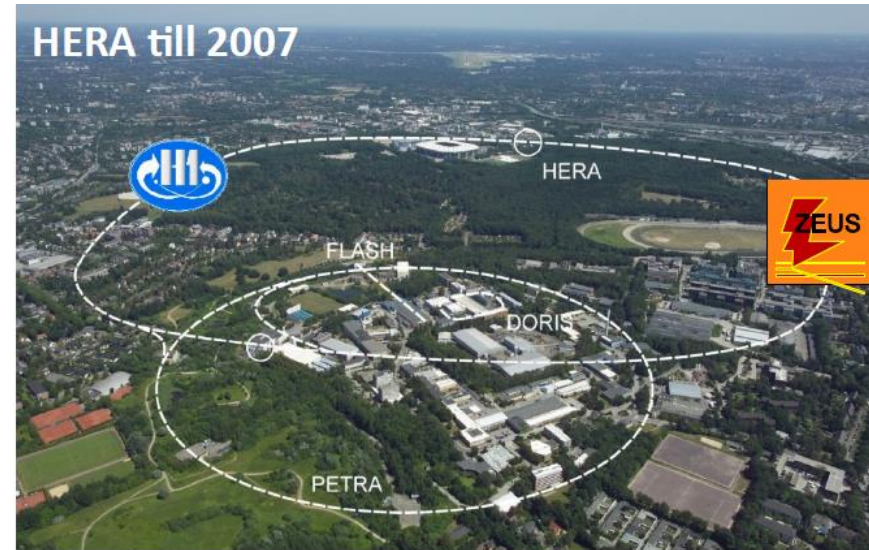
- Imaging gluons inside the nucleon
- The EIC project

Past and future experiments

Collider mode e-p forward fast proton



Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction



Past and future experiments

Collider mode e-p forward fast proton

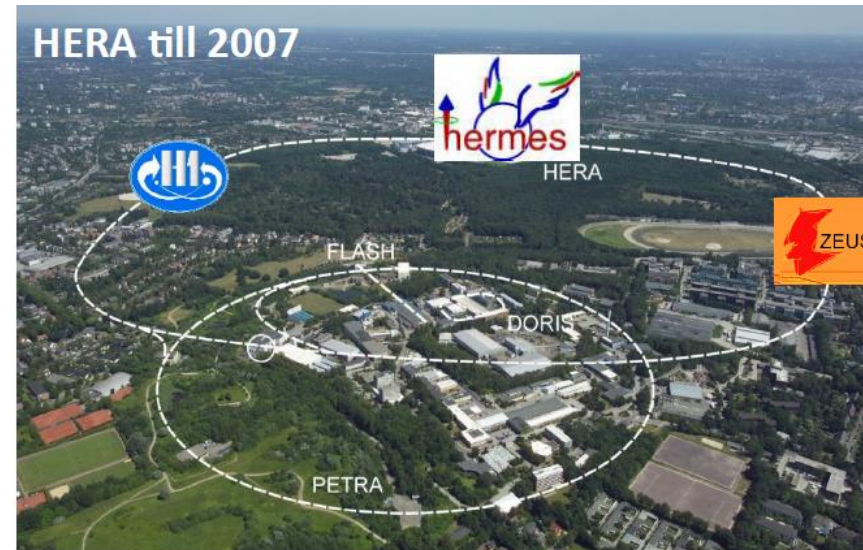


Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction

Fixed target mode slow recoil proton



Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector



Past and future experiments

Collider mode e-p forward fast proton



Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction



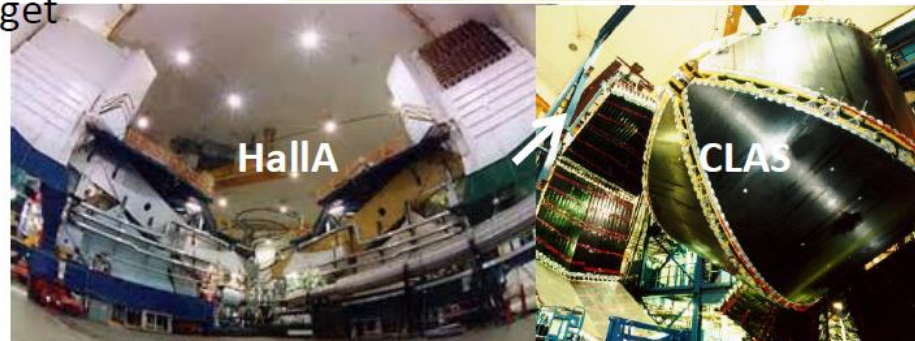
Fixed target mode slow recoil proton



Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector



High lumi, highly polar. 6 & 12 GeV e-
Long, (Trans) polarised p, d target
Missing mass technique



Past and future experiments

Collider mode e-p forward fast proton



Polarised 27 GeV e-/e+
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Fixed target mode slow recoil proton



Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector



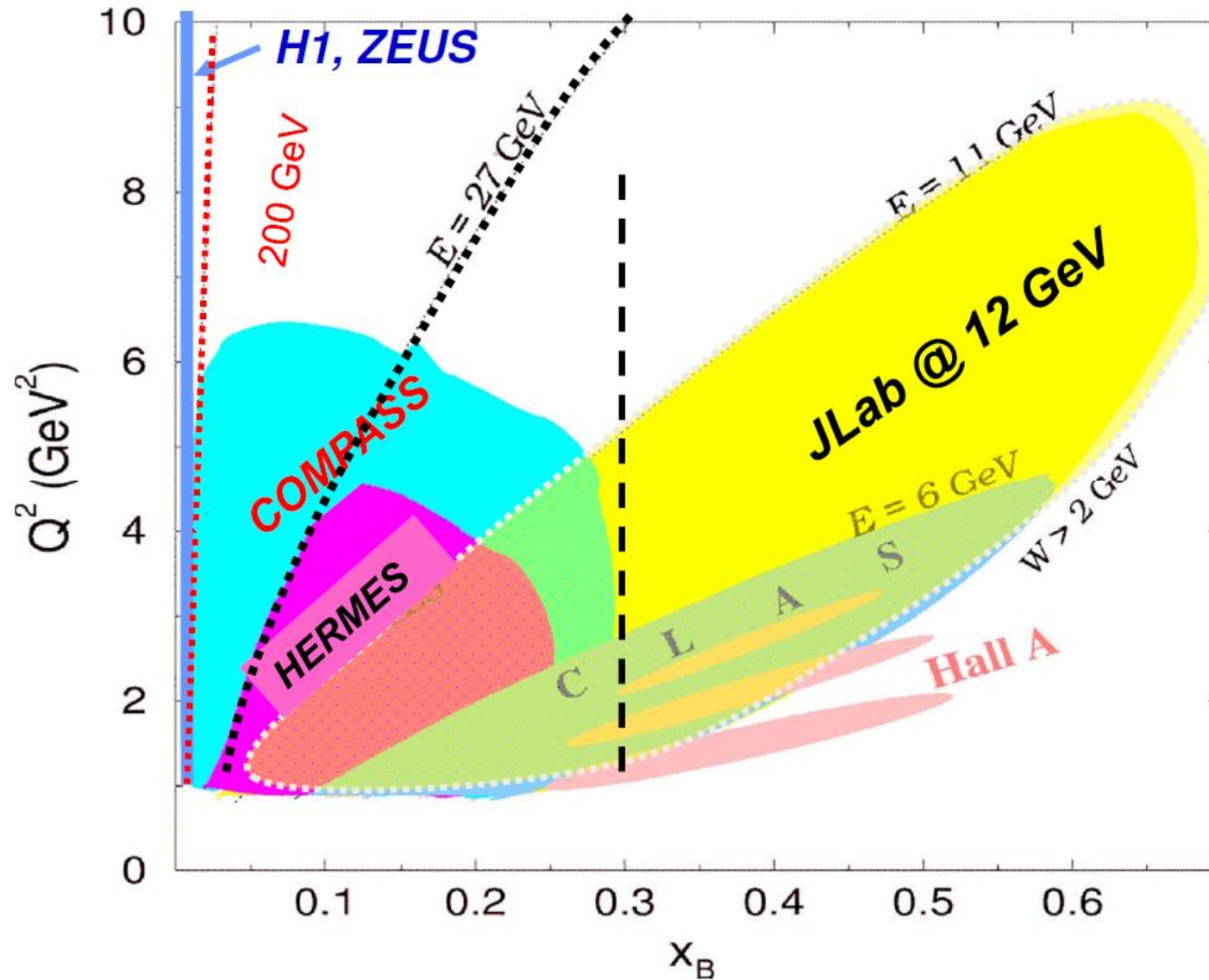
High lumi, highly polar. 6 & 12 GeV e-
Long, (Trans) polarised p, d target
Missing mass technique



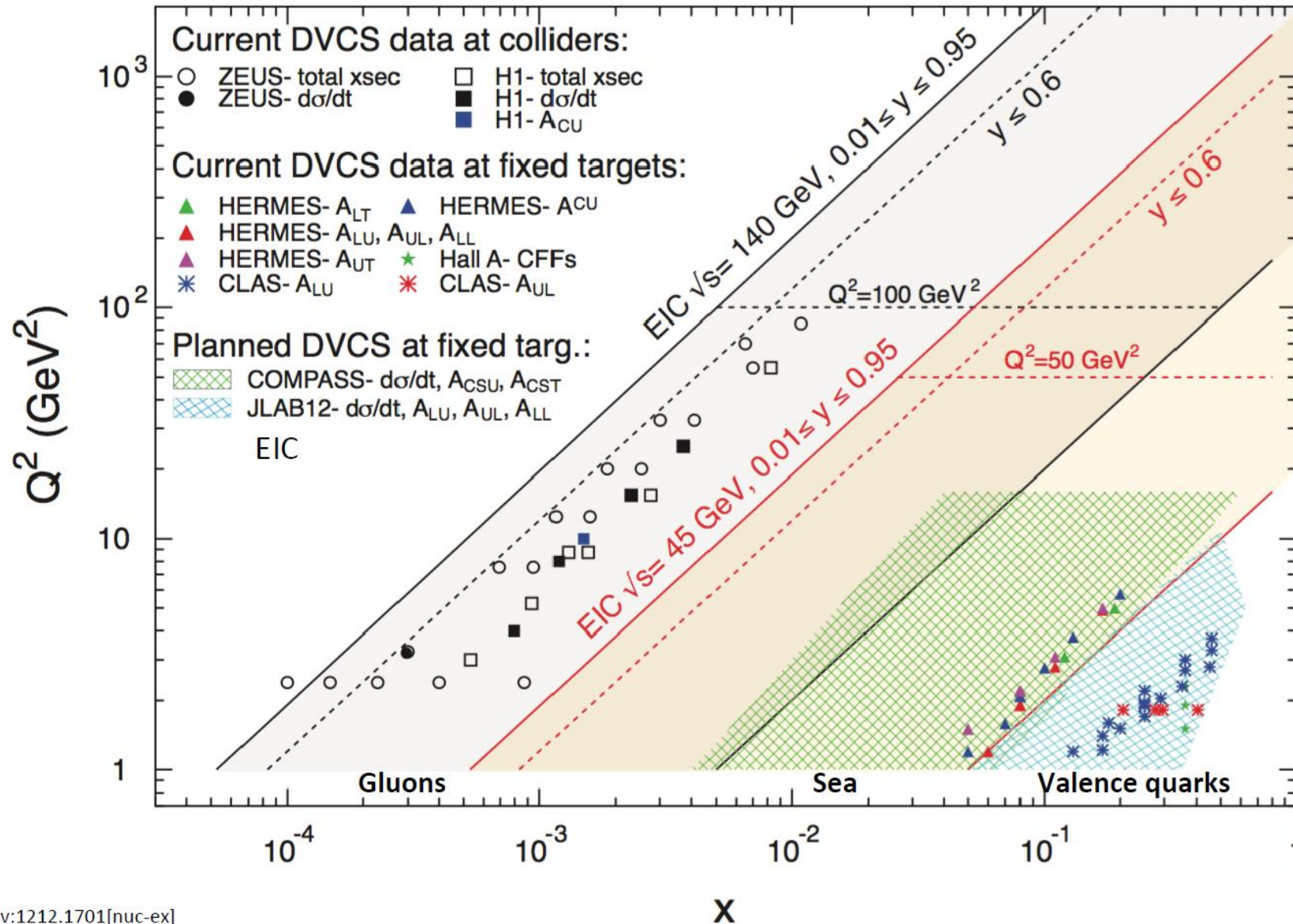
Highly polarised 160 GeV μ^+/μ^-
p target, (Trans) polarised target
with recoil detection



Kinematic coverage



Worldwide DVCS measurements existing and planned



arXiv:1212.1701[nuc-ex]

Cross-section measurements vs relative asymmetries

$$\sigma = \frac{d\sigma}{d\Omega} = \frac{N}{\mathcal{L} d\Omega} \epsilon$$

N : number of event detected

\mathcal{L} : luminosity

$d\Omega$: solid angle

ϵ : detector efficiency

P : polarization rate

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_{\text{total}}} = \frac{1}{P} \left(\frac{N_+ - N_-}{N_+ + N_-} \right)$$



Needs to understand the total cross-section to reliably interpret the data



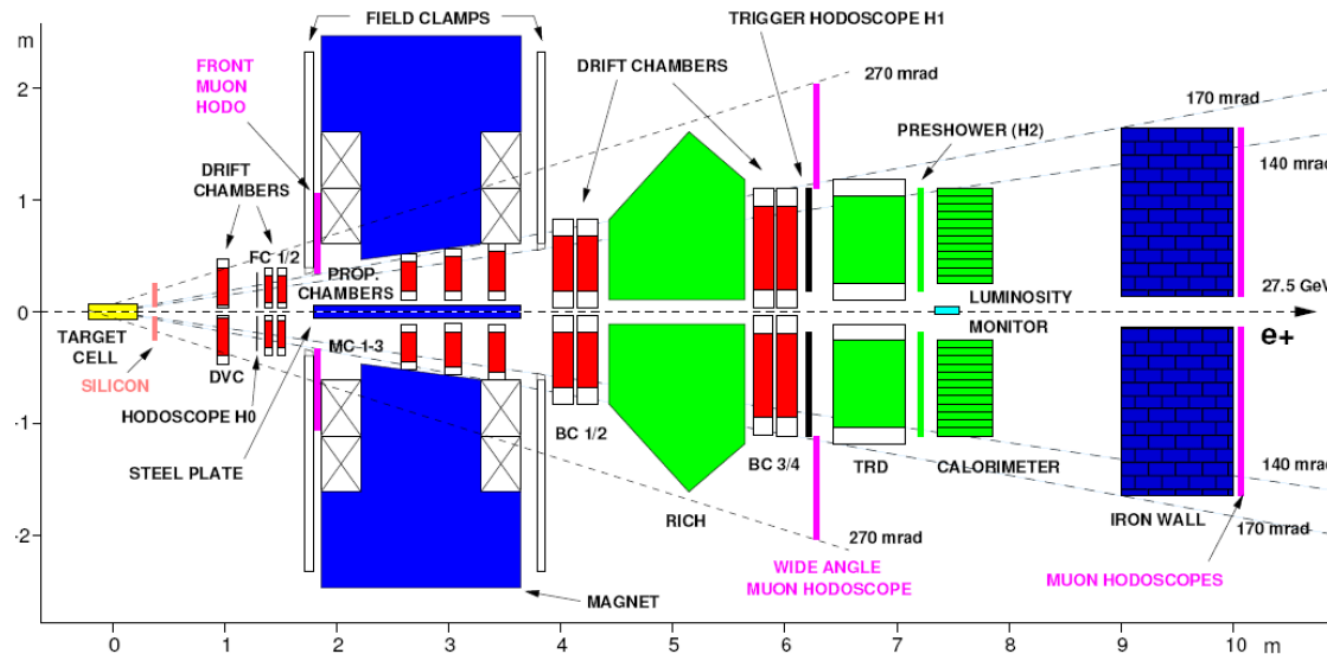
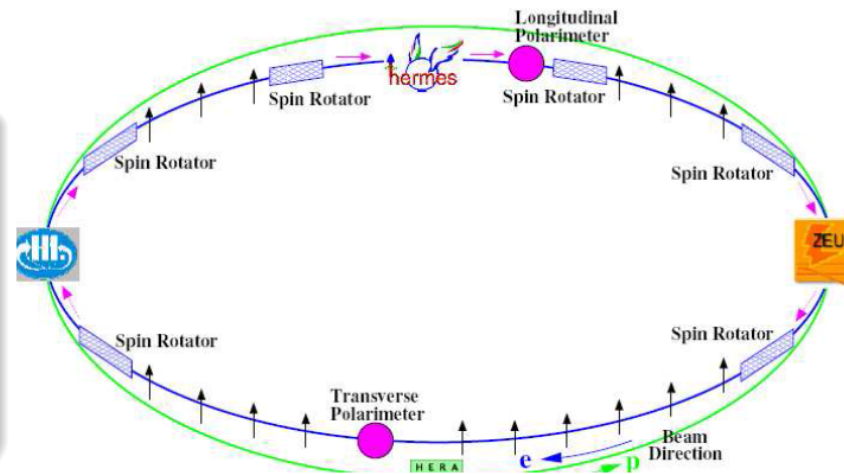
Experimentally “easy” to measure

HERMES

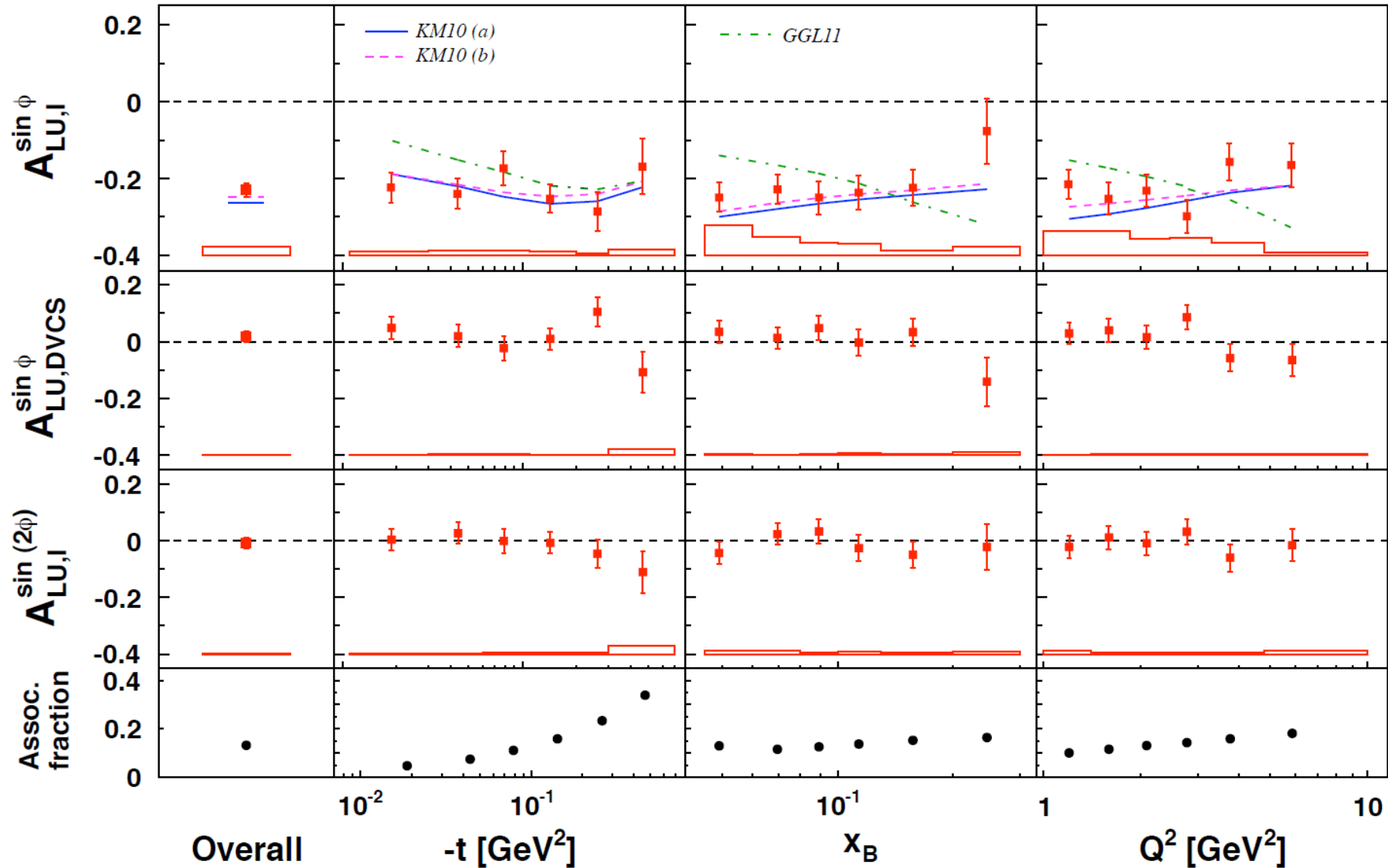
27.5 GeV polarised e^+/e^- beam of HERA

Data taking 95–07

- 96–00 (H/D) Lpol + Upol
- 02–05 (H) Tpol+ Upol
- 06–07 (H/D) Upol+Recoil

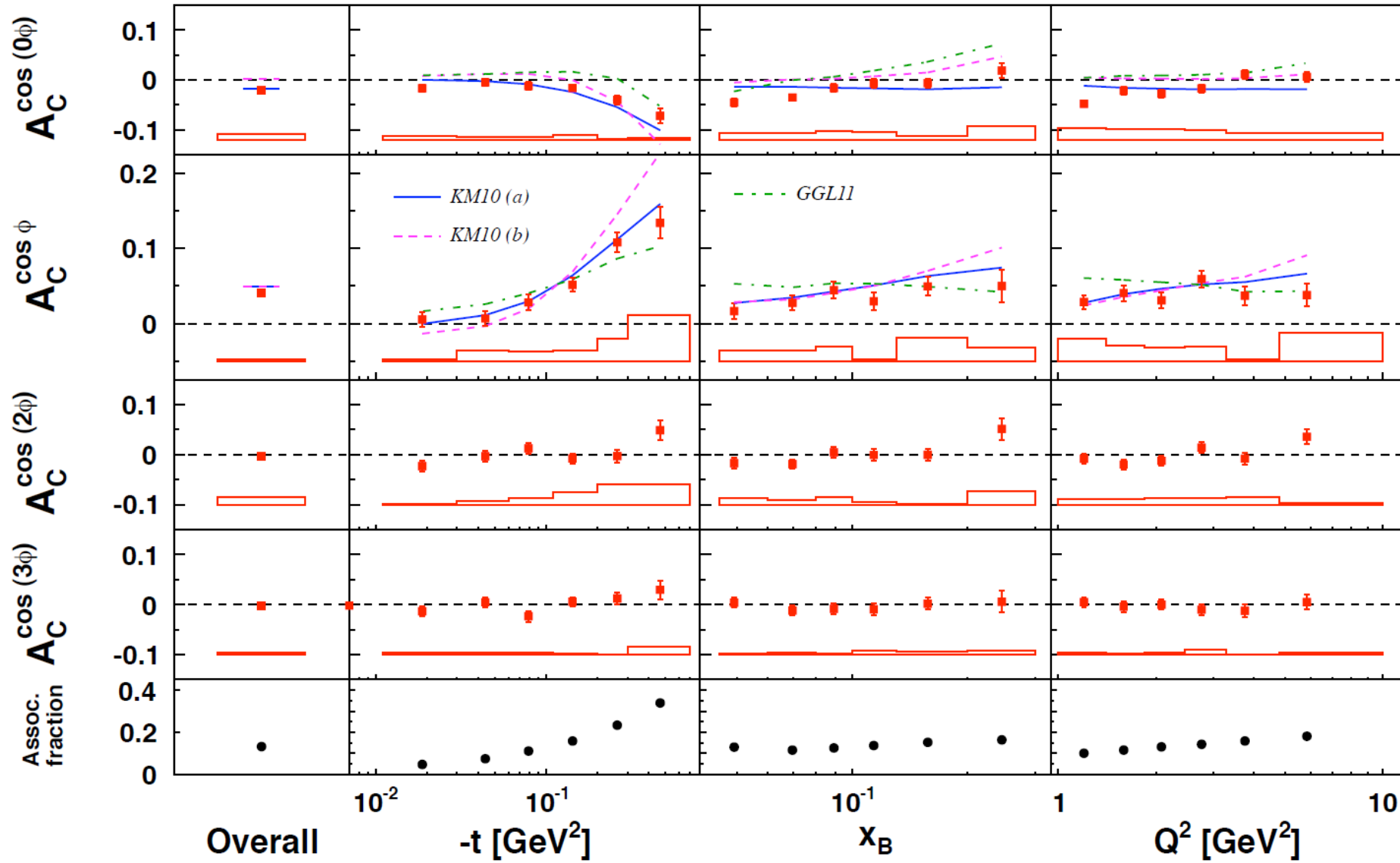


HERMES: Beam Spin Asymmetry



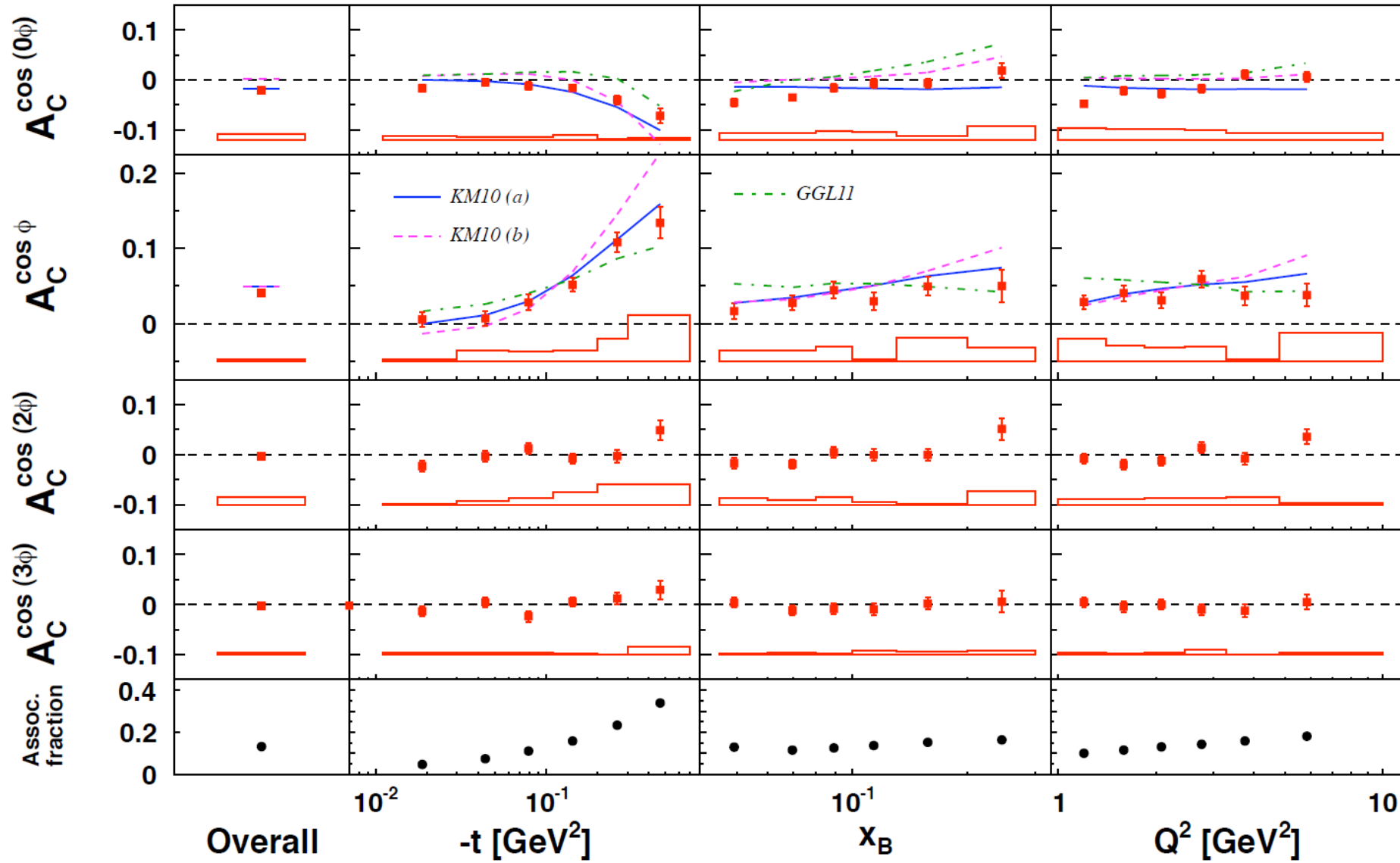
arXiv: 1203.6287

HERMES: Beam Charge Asymmetry



arXiv: 1203.6287

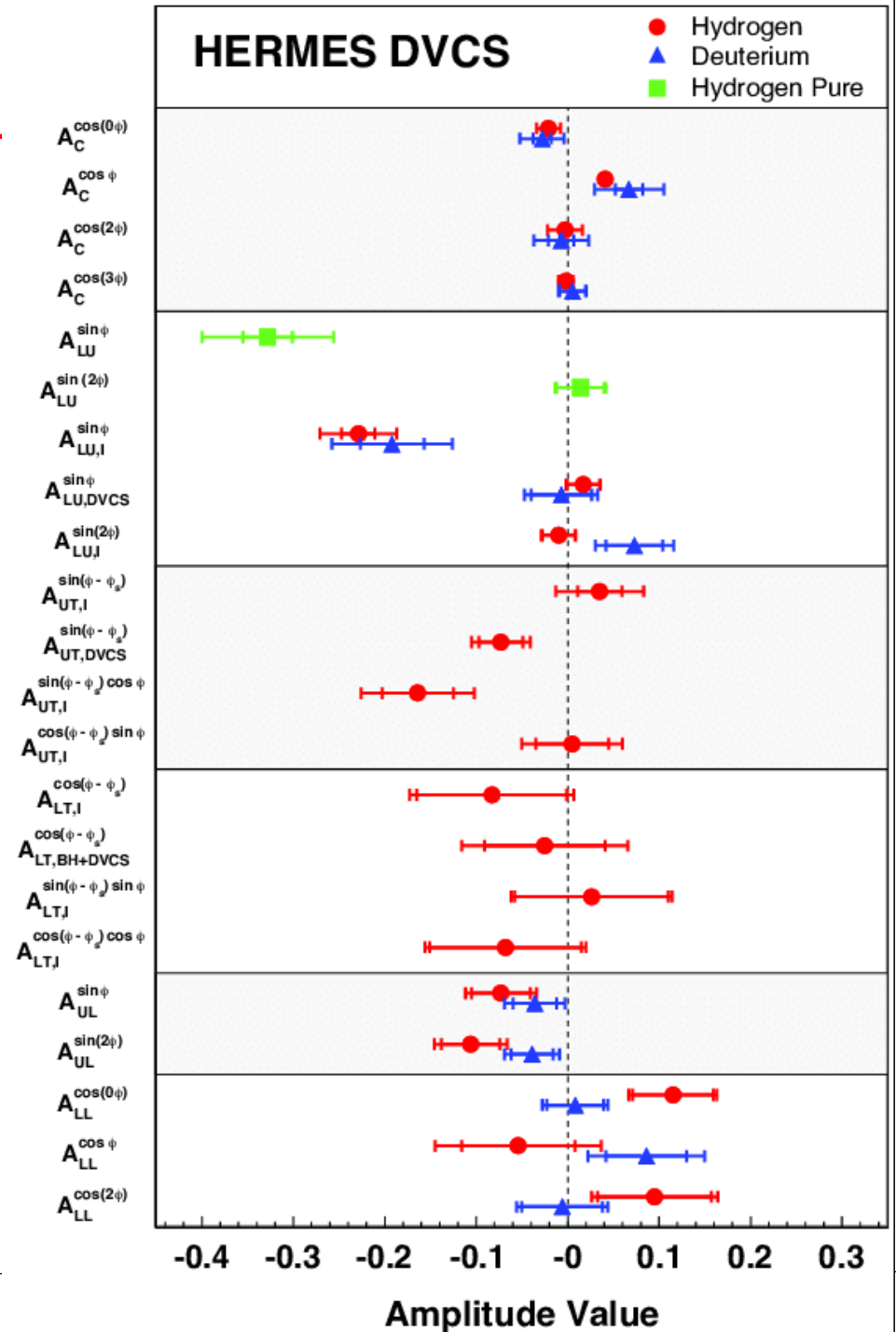
HERMES: Beam Charge Asymmetry



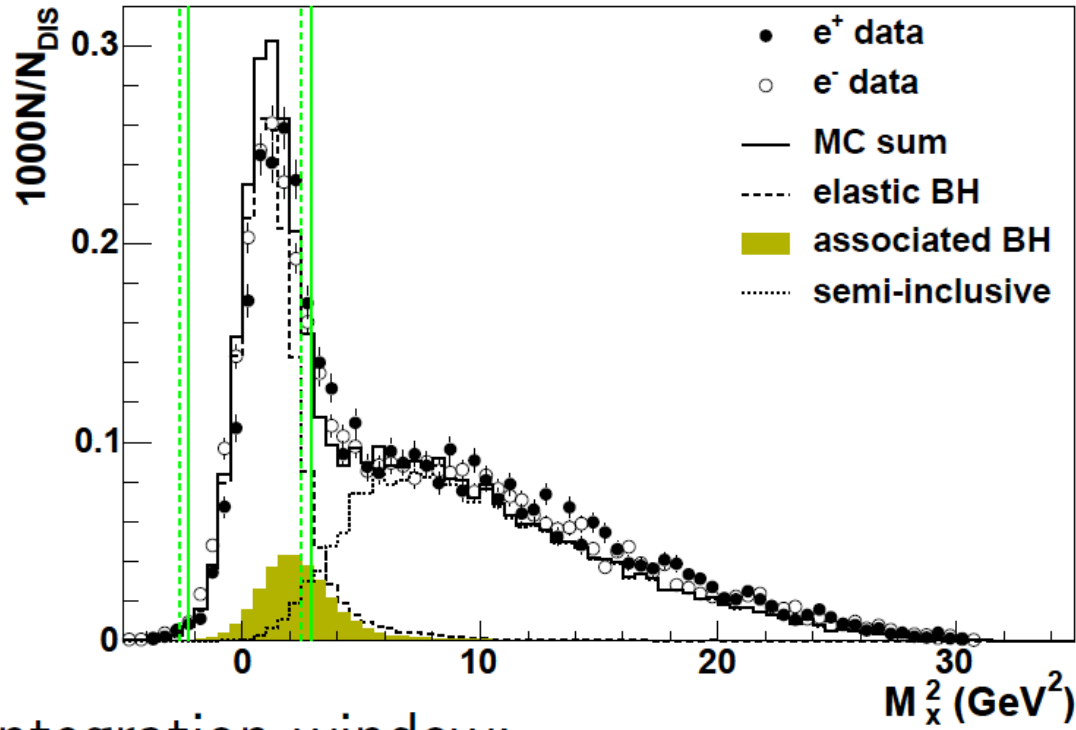
arXiv: 1203.6287

HERMES DVCS summary

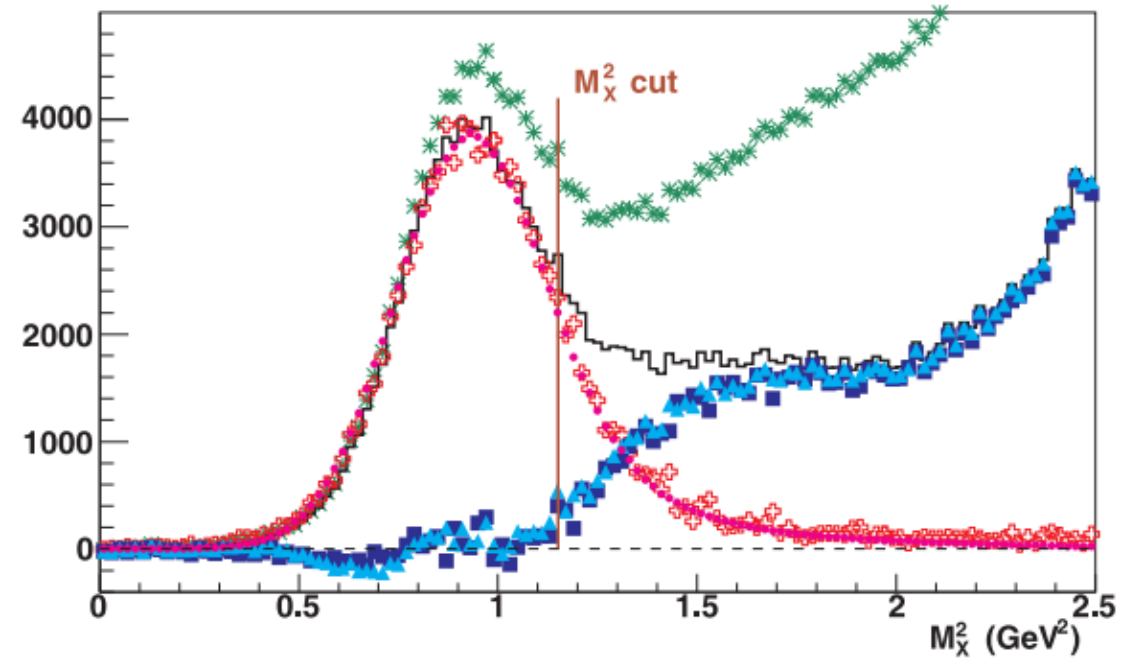
- Very complete set of measurements on DVCS
- Only relative asymmetries
- Limited statistics
- Limited exclusivity



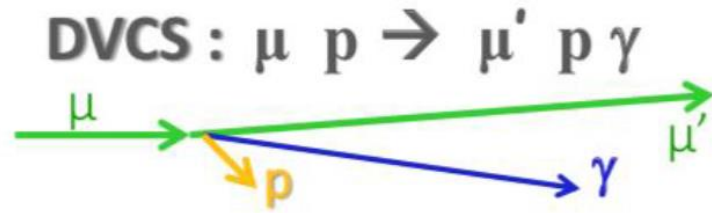
HERMES: limited exclusivity



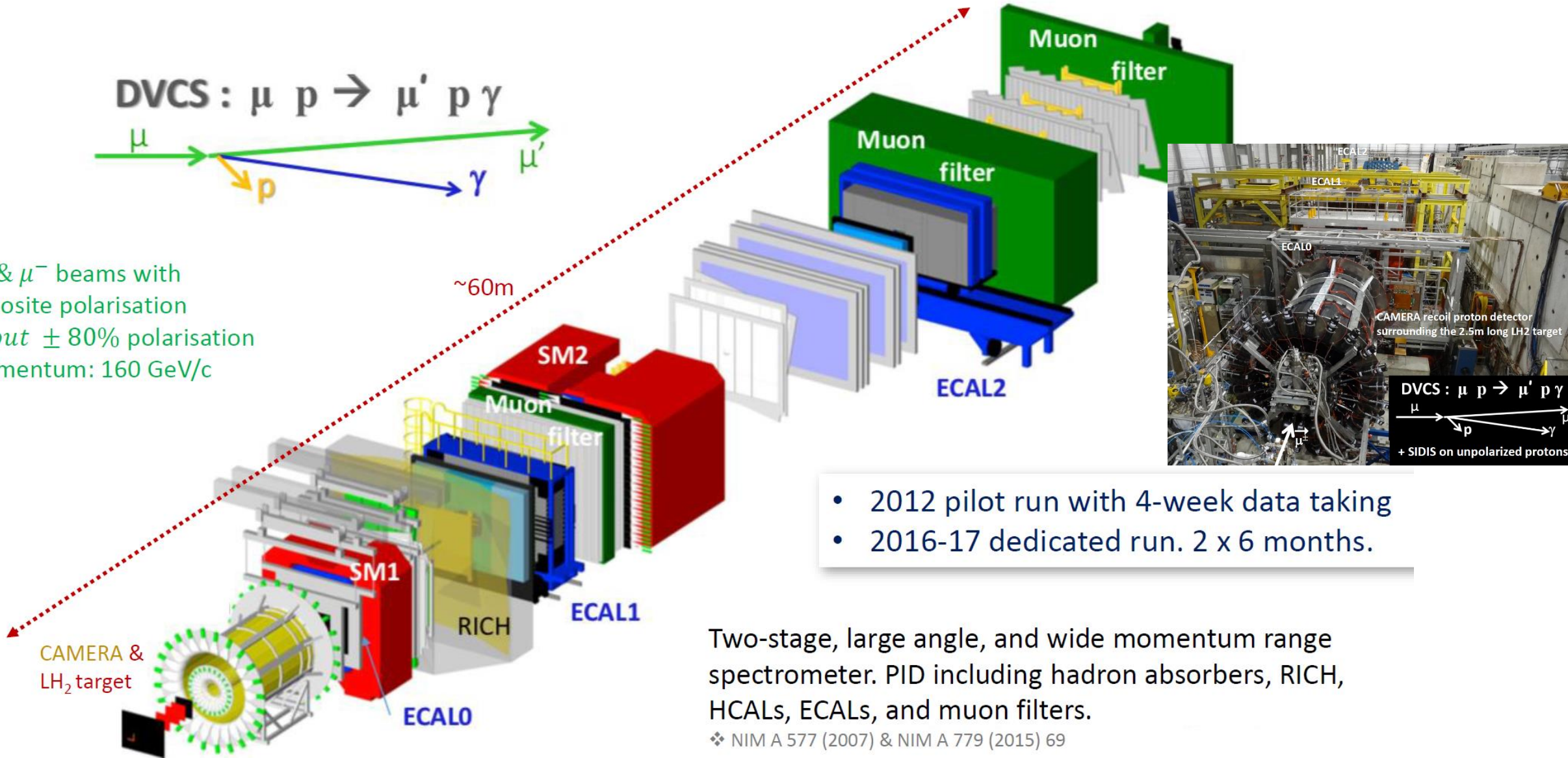
Integration window:
 $-2.25 \text{ GeV}^2 < M_x^2 < 2.89 \text{ GeV}^2$



COMPASS experiment (CERN)



- μ^+ & μ^- beams with opposite polarisation
- About $\pm 80\%$ polarisation
- Momentum: 160 GeV/c



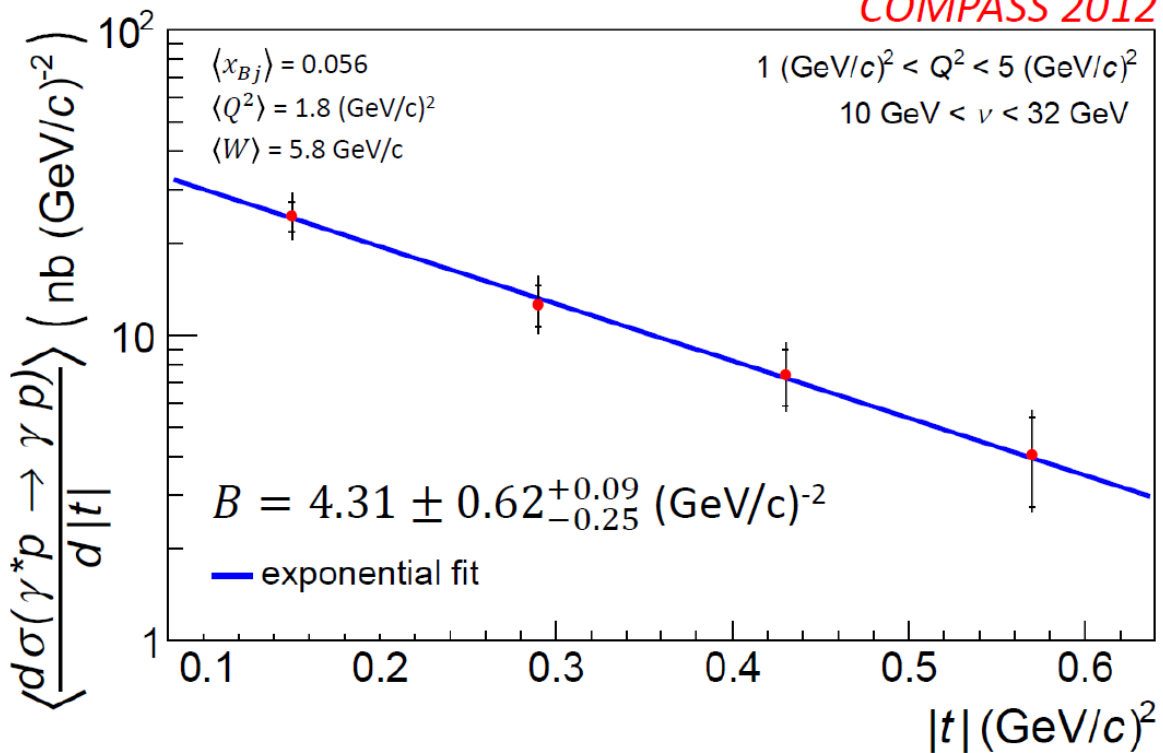
- 2012 pilot run with 4-week data taking
- 2016-17 dedicated run. 2 x 6 months.

Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

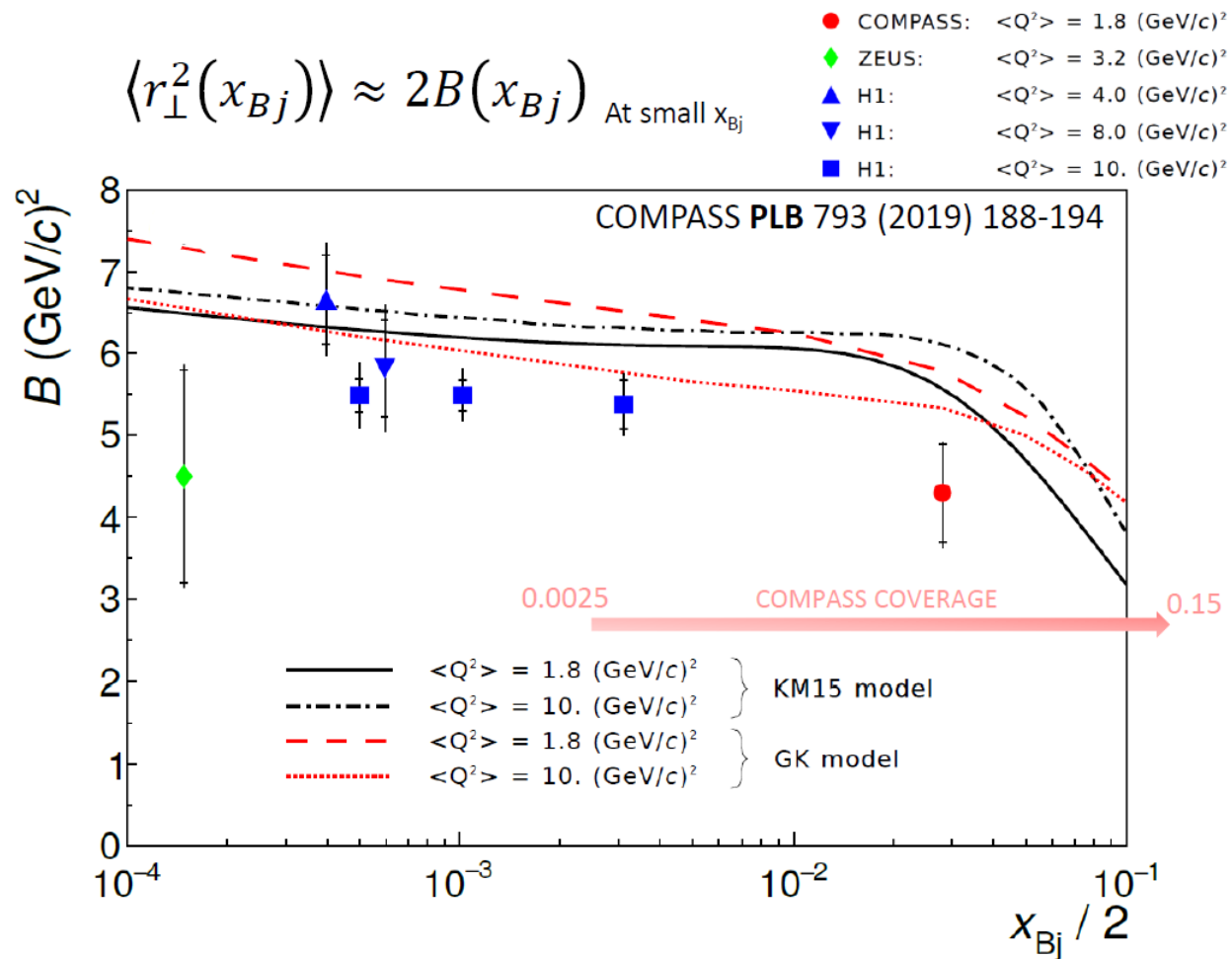
❖ NIM A 577 (2007) & NIM A 779 (2015) 69

Transverse extension of partons

$$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$$



$$\langle r_{\perp}^2(x_{Bj}) \rangle \approx 2B(x_{Bj}) \quad \text{At small } x_{Bj}$$

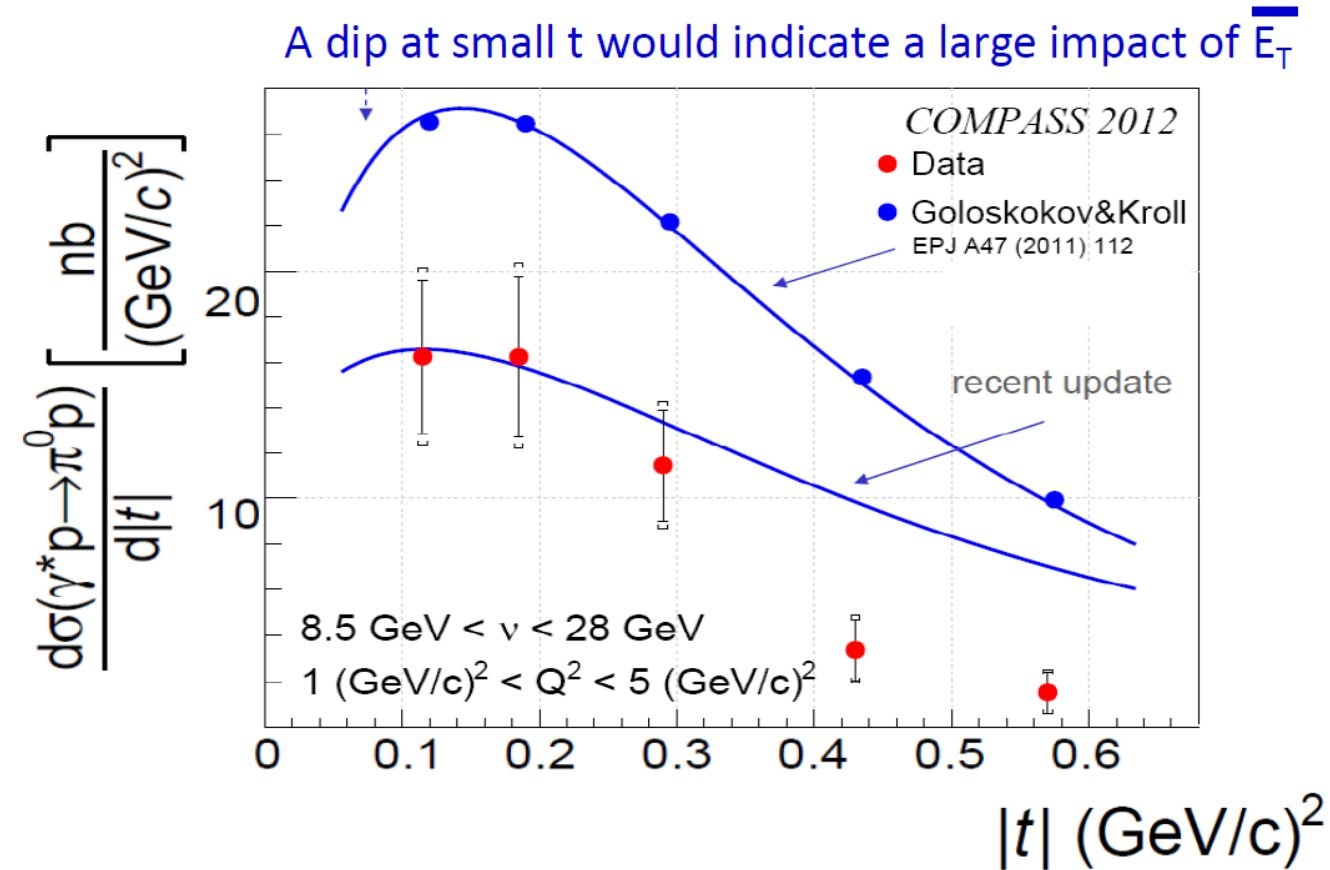
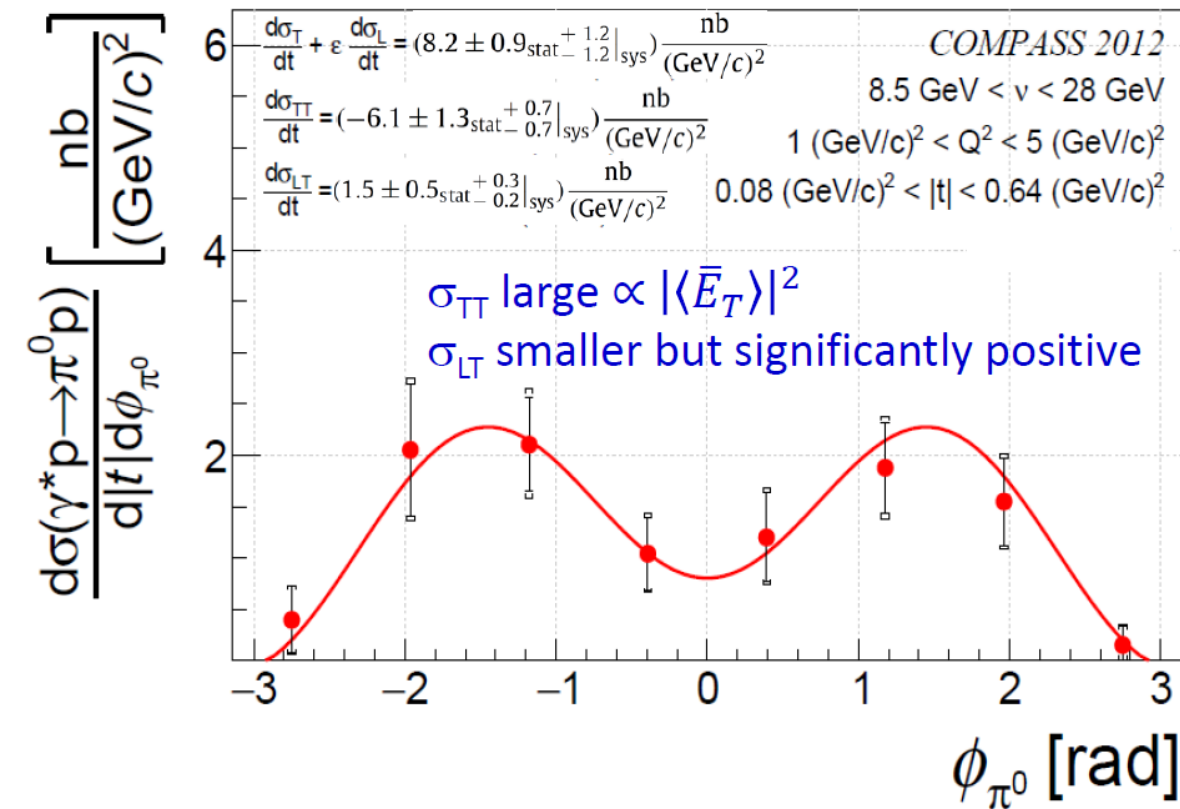


$$\sqrt{\langle r_{\perp}^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}} \pm 0.04_{\text{model}}) \text{ fm}$$

With $\langle x_{Bj} \rangle = 0.056$

Exclusive π^0 electroproduction

$$\mu p \rightarrow \mu \pi^0 p$$



PLB 805 (2020) 135454

JLab 12 GeV program on GPDs

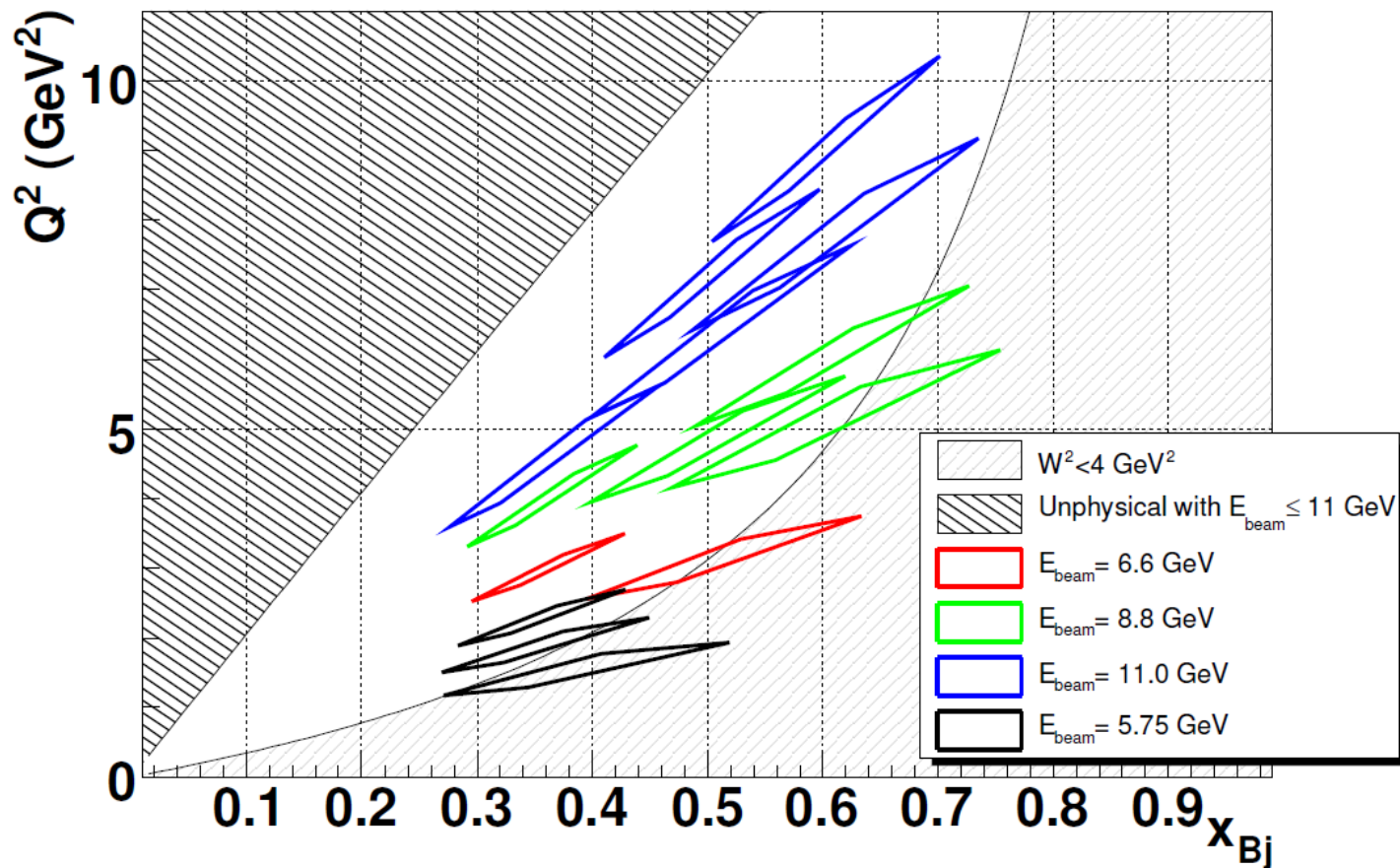
- Multiple experiments planned in all three experimental Halls: A, B and C
- Large combination of observables:
polarized beam and targets, proton/neutron, meson production, etc
- Expanded kinematical range compared to 6 GeV experiments
- Program expands over 10+ years (and beyond with the possibility of a positron beam)

Hall A program

JLab12 with 3, 4, 5 pass beam

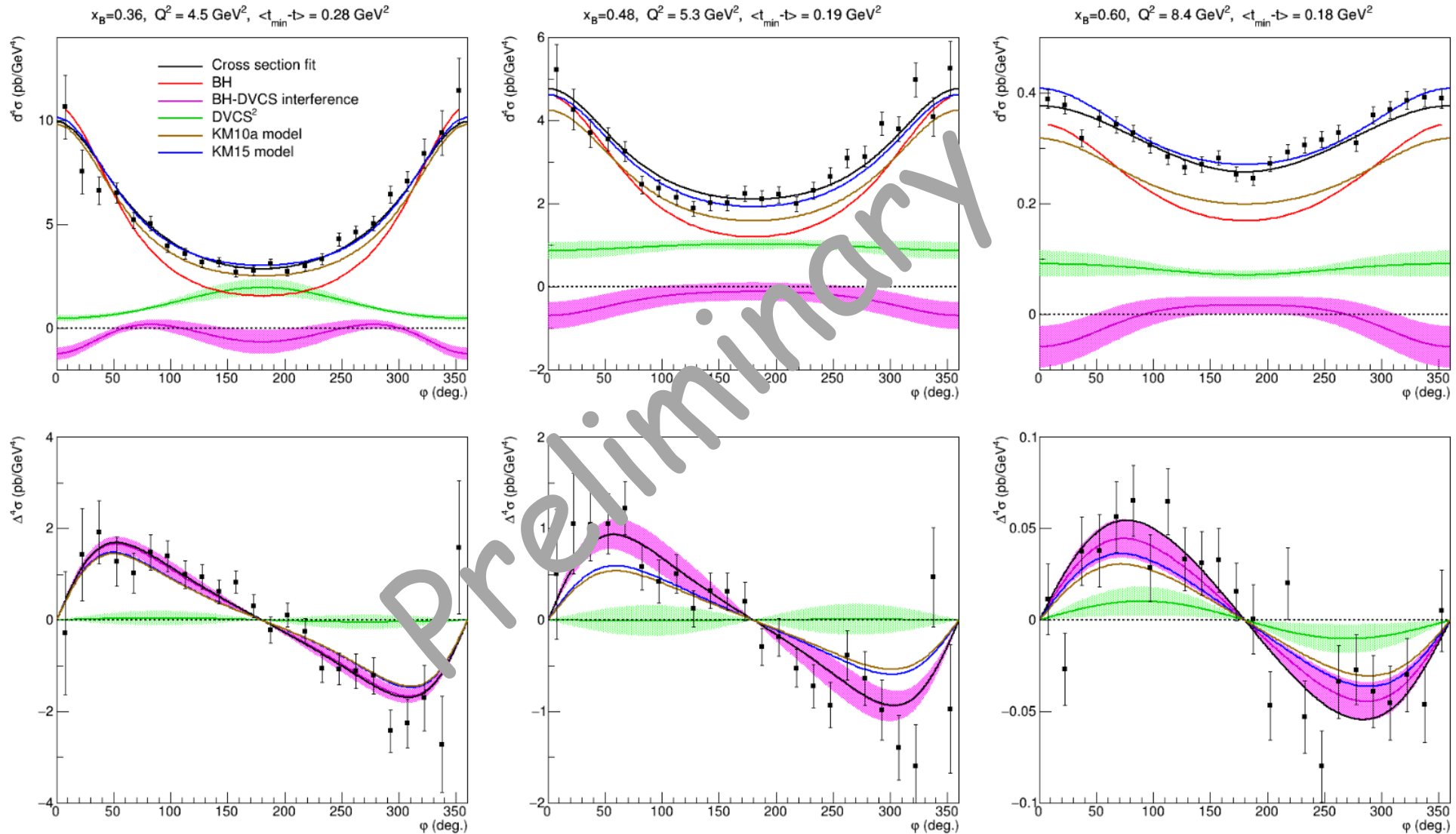
(6.6, 8.8, 11.0 GeV beam energy)

DVCS measurements in Hall A/JLab



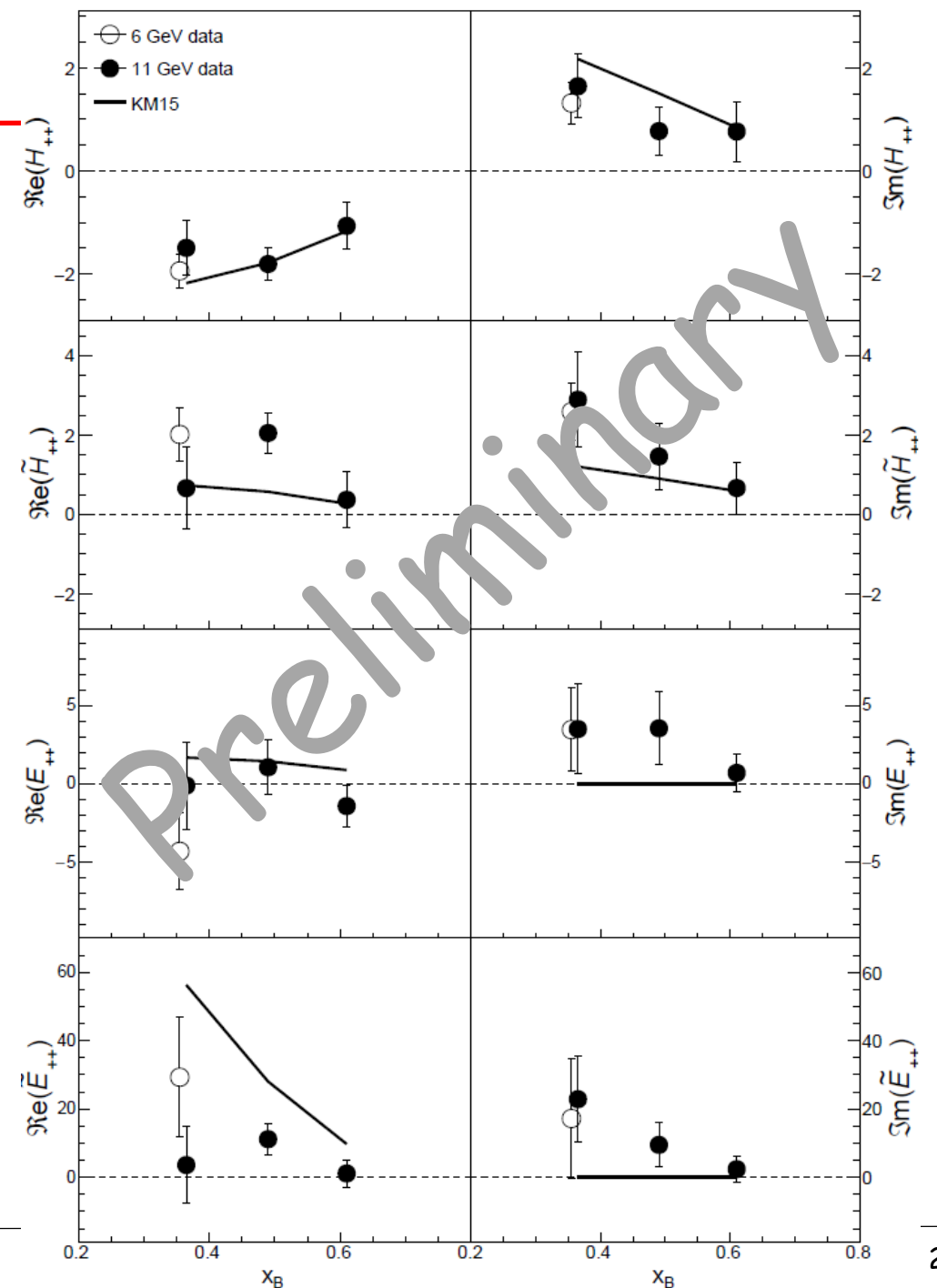
88 days
250k events/setting

Hall A program: cross sections



Hall A program: CFFs extraction

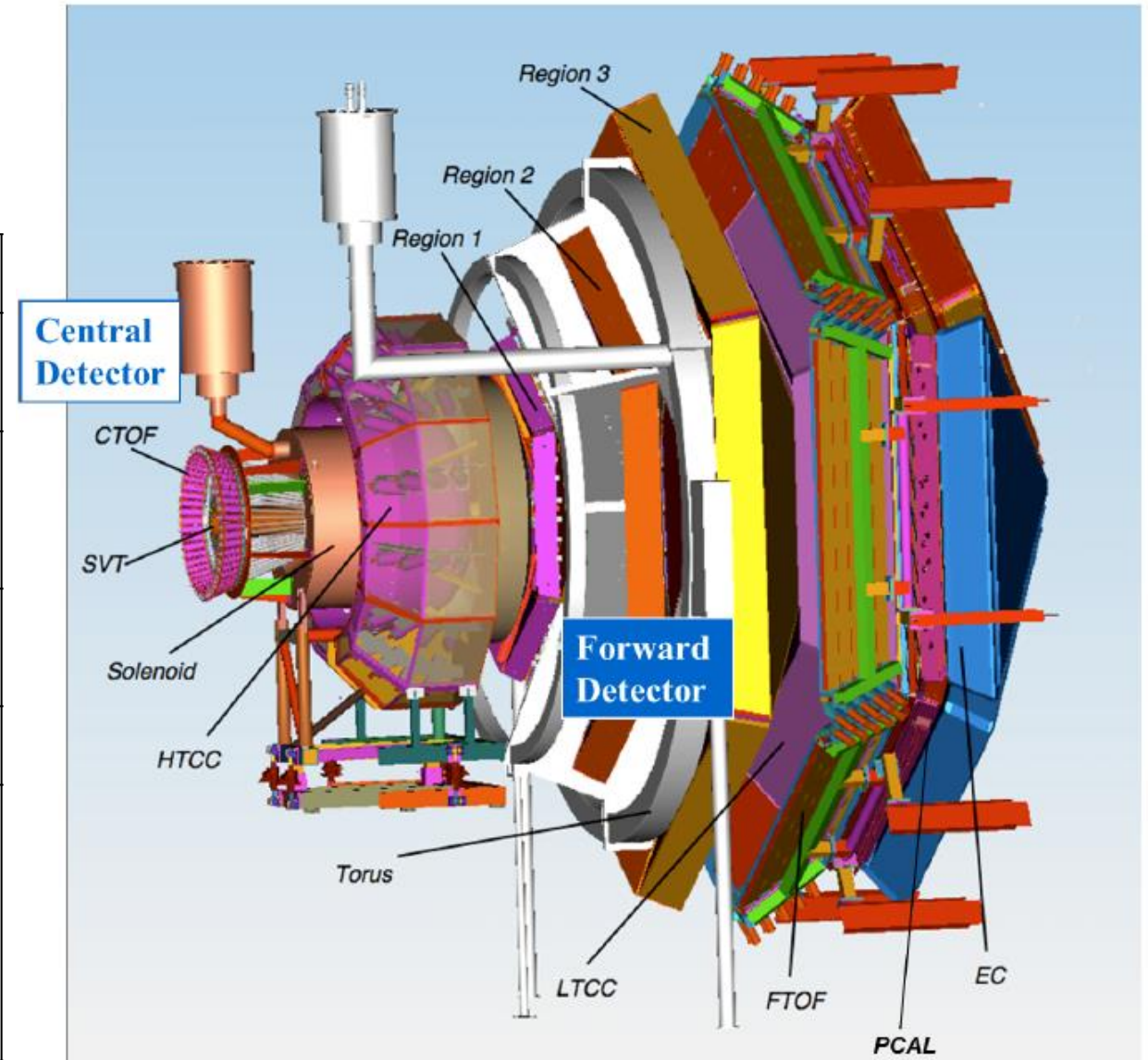
- Accurate data allows extraction of all CFFs as a function of x_B
- Extended coverage to very large values of x_B



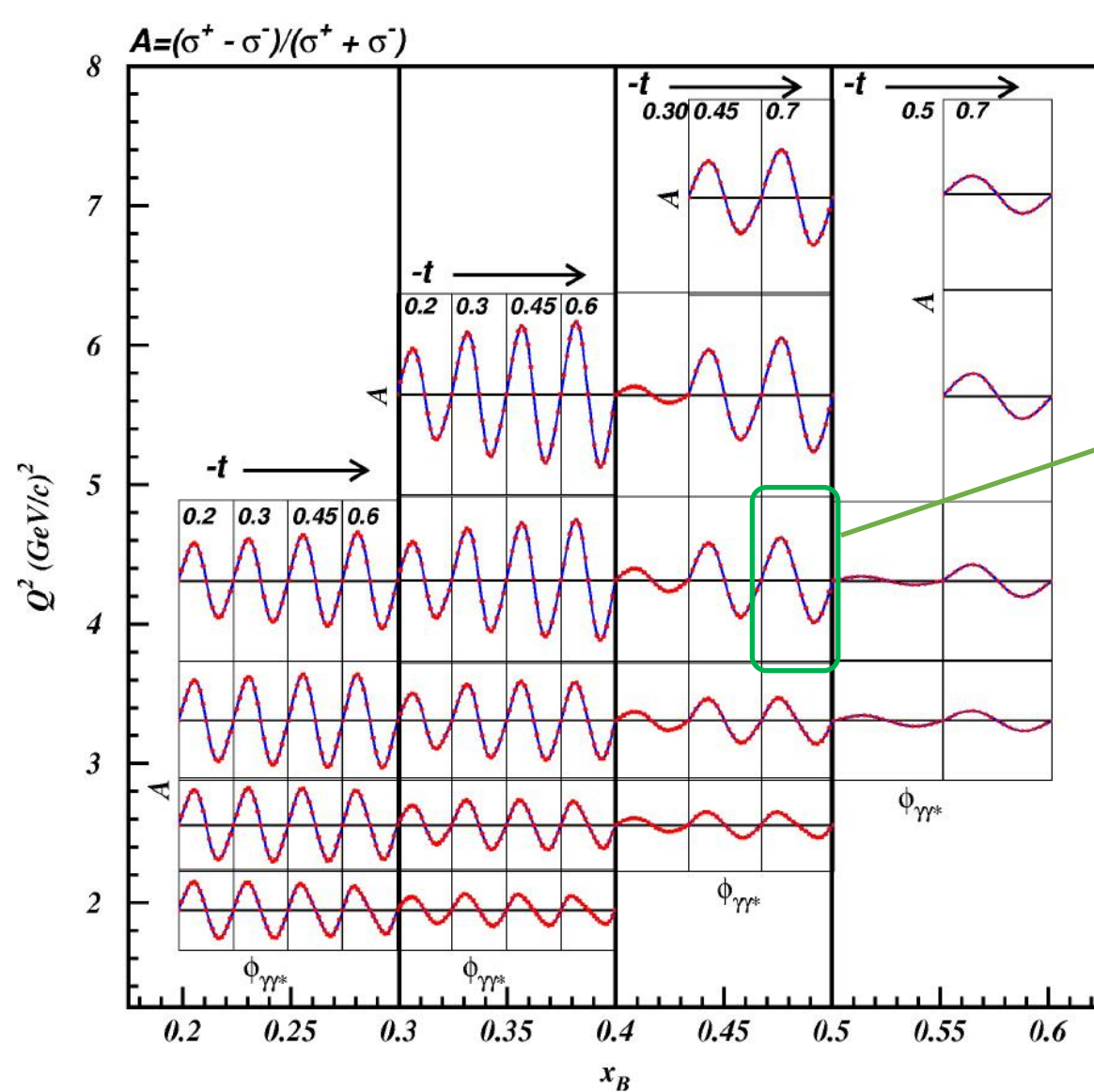
Hall B program

- Large acceptance detector
- Many channels measured simultaneously
- Wide kinematic coverage
- Limited luminosity

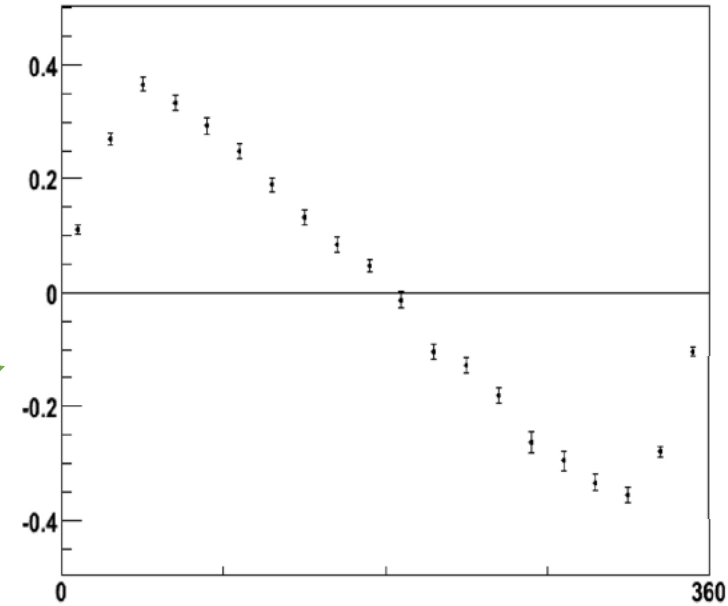
	Forward detector	Central detector
Angular range		
Tracks	5 – 40°	35 – 125°
Photons	2.5 – 40°	n.a.
Resolution		
$\delta p/p$	< 1% @ 5 GeV/c	5% @ 1.5 GeV/c
$\delta\theta$	< 1 mr	< 10-20 mr
$\delta\phi$	< 3 mr	< 5 mr
Photon detection		
Energy	> 0.15 GeV	n.a.
$\delta\theta$	4 mr @ 1 GeV	n.a.
Neutron detection		
Efficiency	< 0.7	under dev.
Particle ID		
e/ π	Full range	n.a.
π/p	Full range	< 1.25 GeV/c
π/K	Full range	< 0.65 GeV/c
K/p	< 4 GeV/c	< 1 GeV/c
$\pi \rightarrow \gamma\gamma$	Full range	n.a.
$\eta \rightarrow \gamma\gamma$	Full range	n.a.



Projections of DVCS Beam Spin Asymmetries off the proton

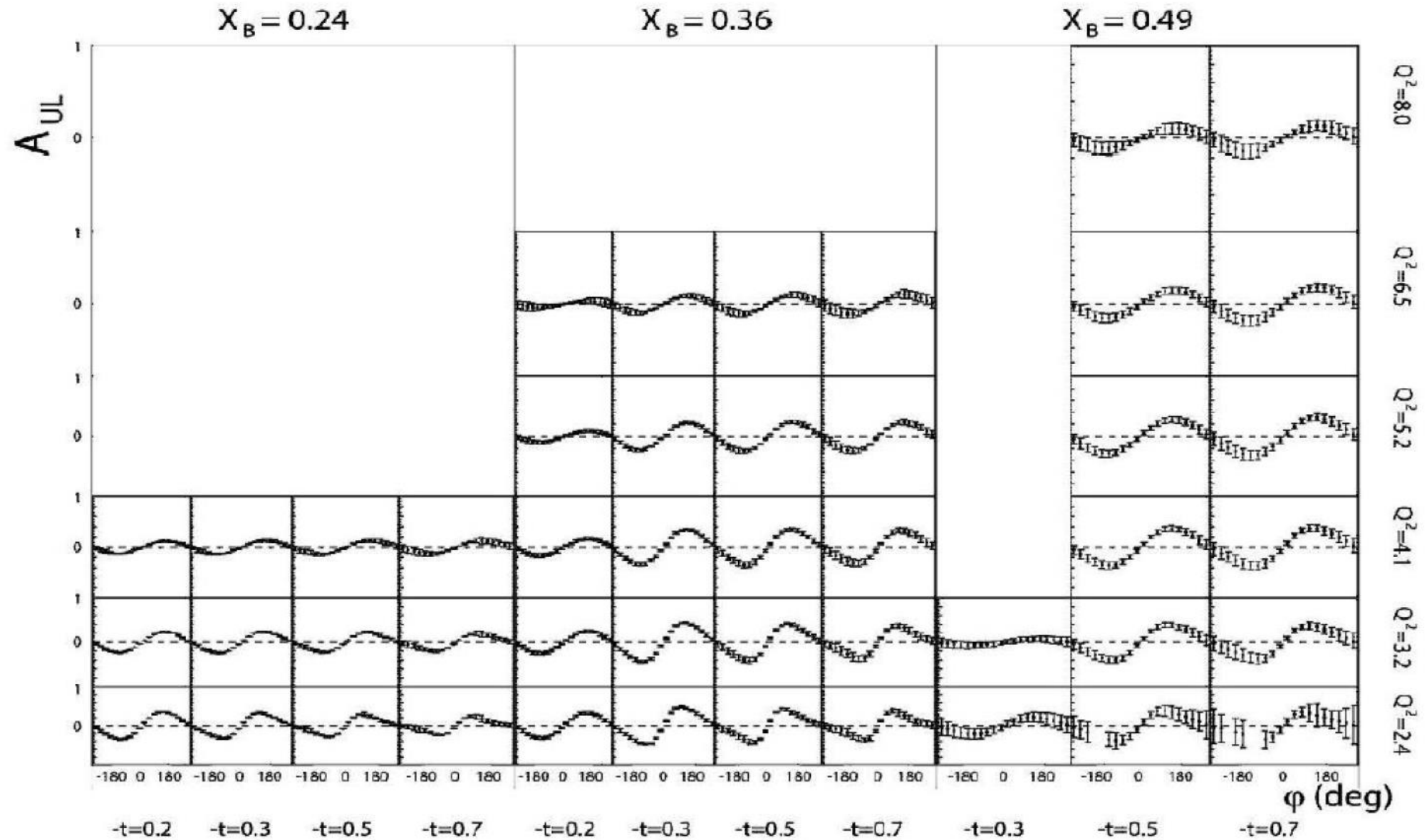


$$A_{LU} \propto F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$



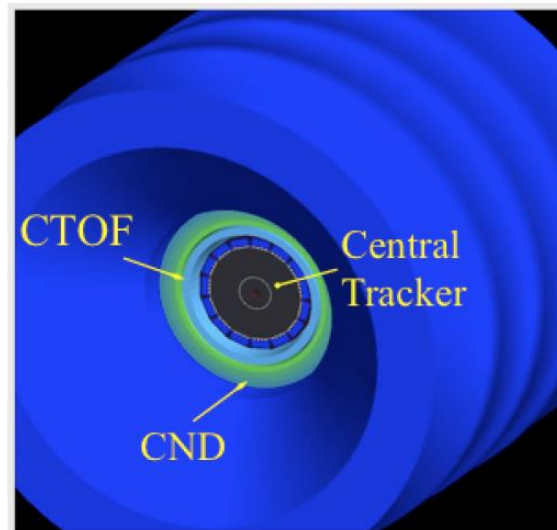
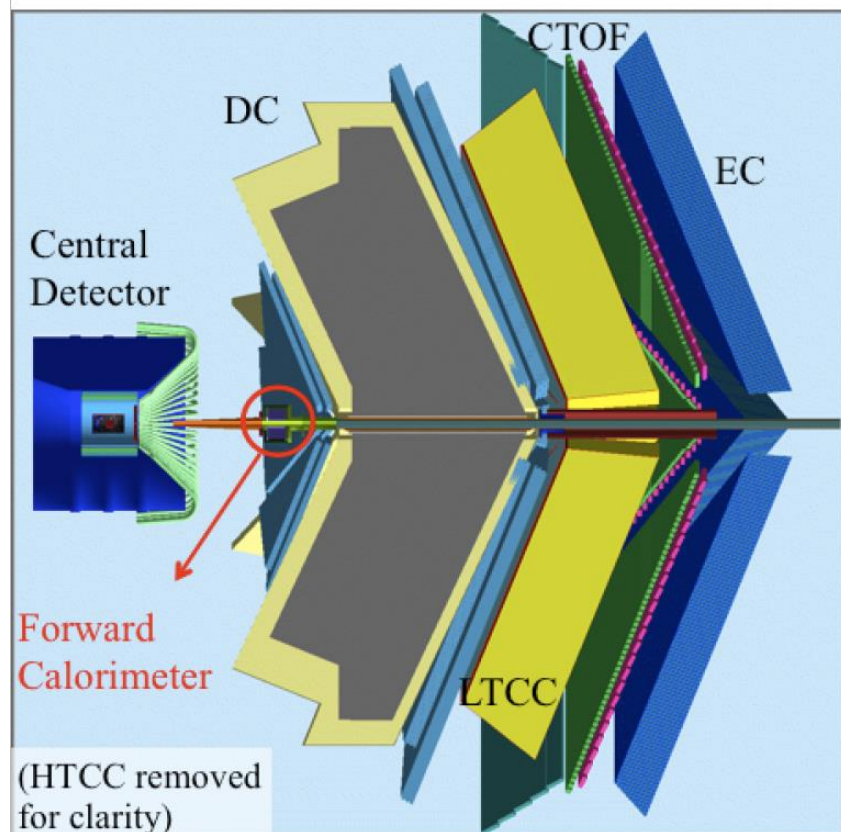
- Statistical uncertainties from 1% (low Q^2) to 10% (high Q^2)
- Unprecedented statistics over the full ϕ range up to high $x_B=0.6$

Unpolarized beam and longitudinally polarized proton target

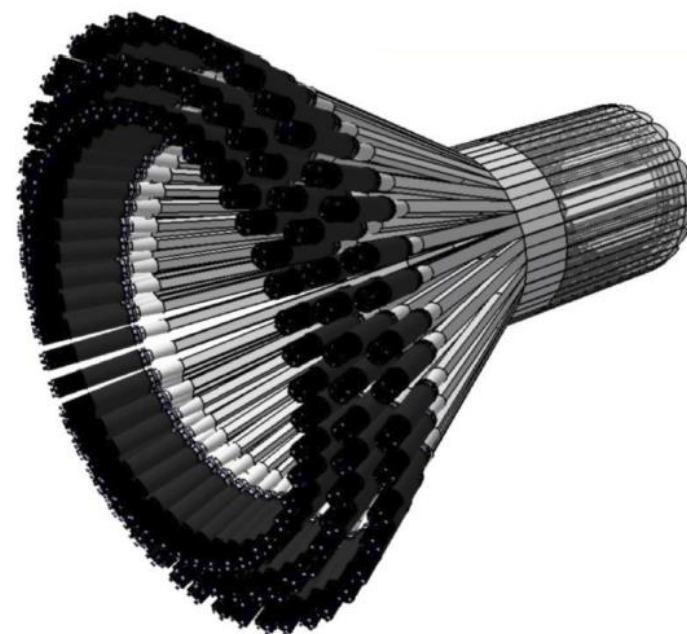


Neutron DVCS setup

For the detection of the scattered electron and of the DVCS photon: CLAS12 + Forward Calorimeter



Neutron detector for CLAS12



For the detection of the recoil neutron:
Central Neutron Detector (CND)

Detection efficiency : 7 to 10 %

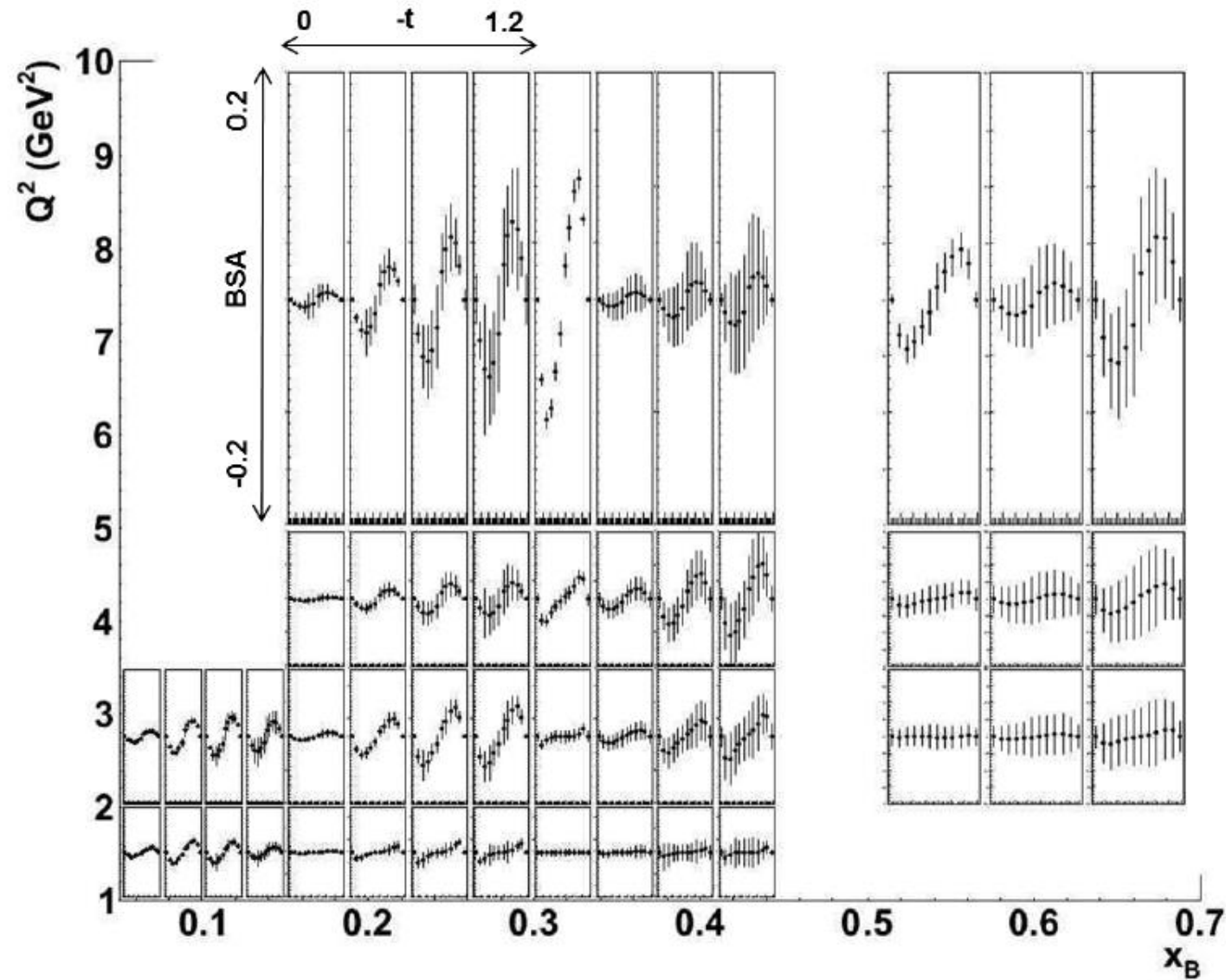
Acceptance for charged particles:

- Central (CD), $40^\circ < \theta < 135^\circ$
- Forward (FD), $5^\circ < \theta < 40^\circ$

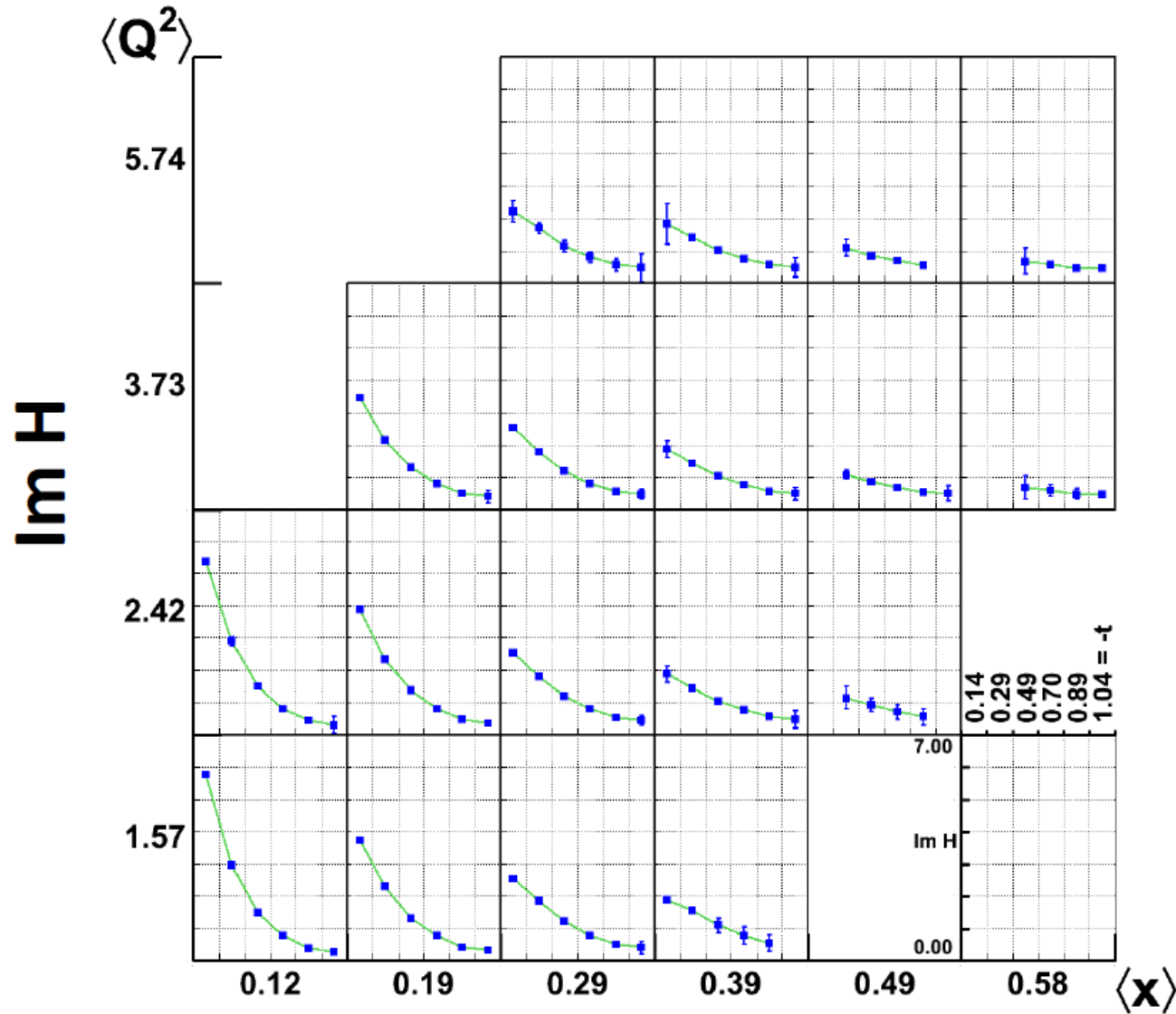
Acceptance for photons:

- FC $2.5^\circ < \theta < 5^\circ$
- EC, $5^\circ < \theta < 40^\circ$

Projections of DVCS Beam Spin Asymmetries off the neutron



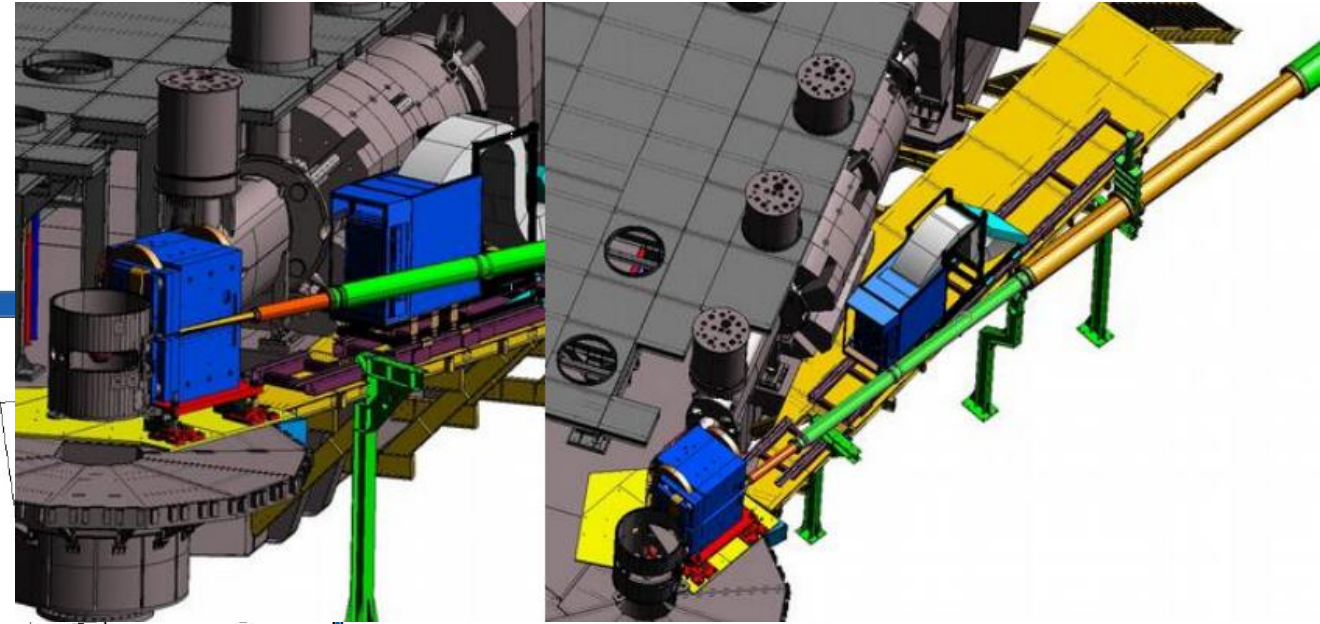
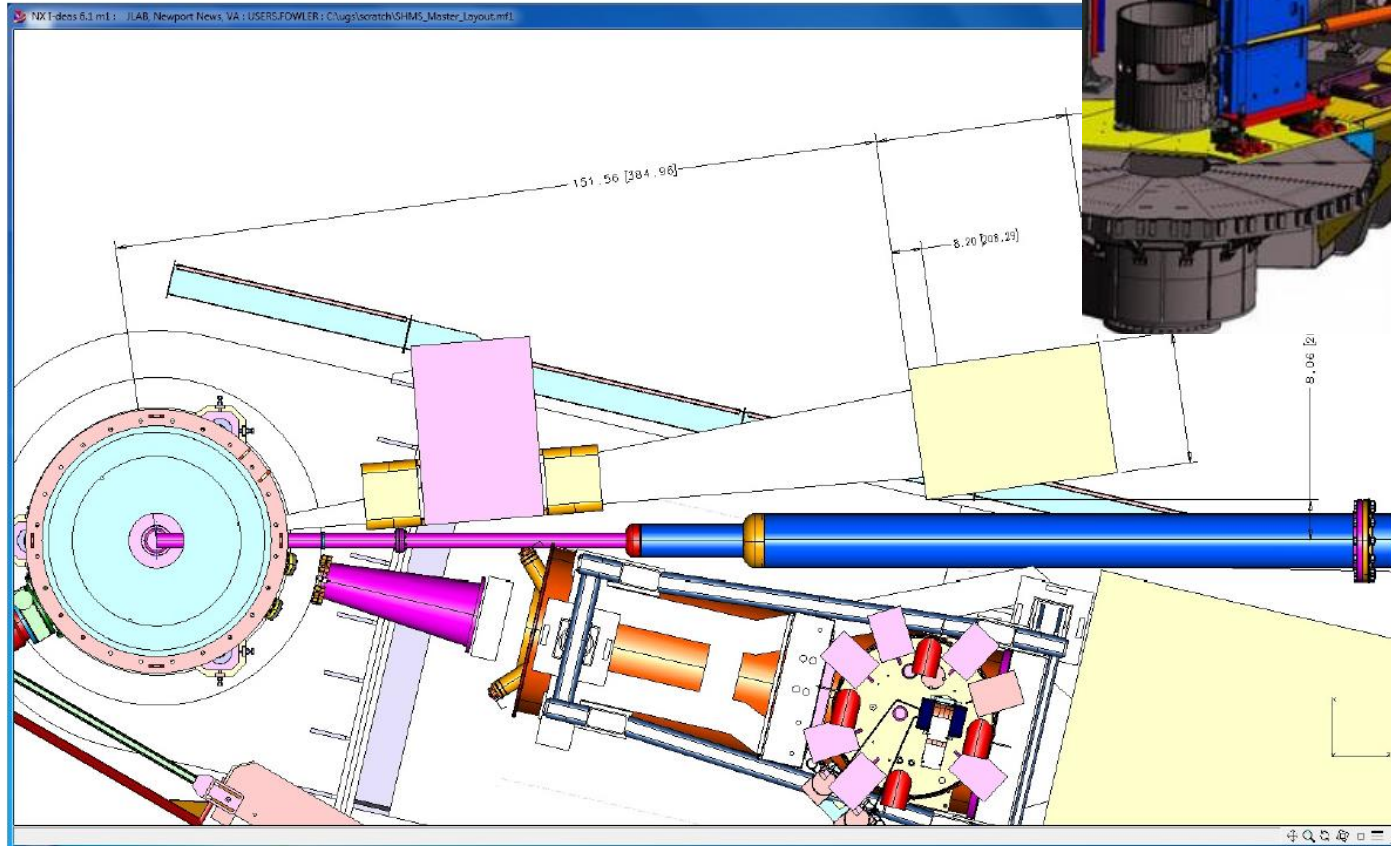
CFF extraction



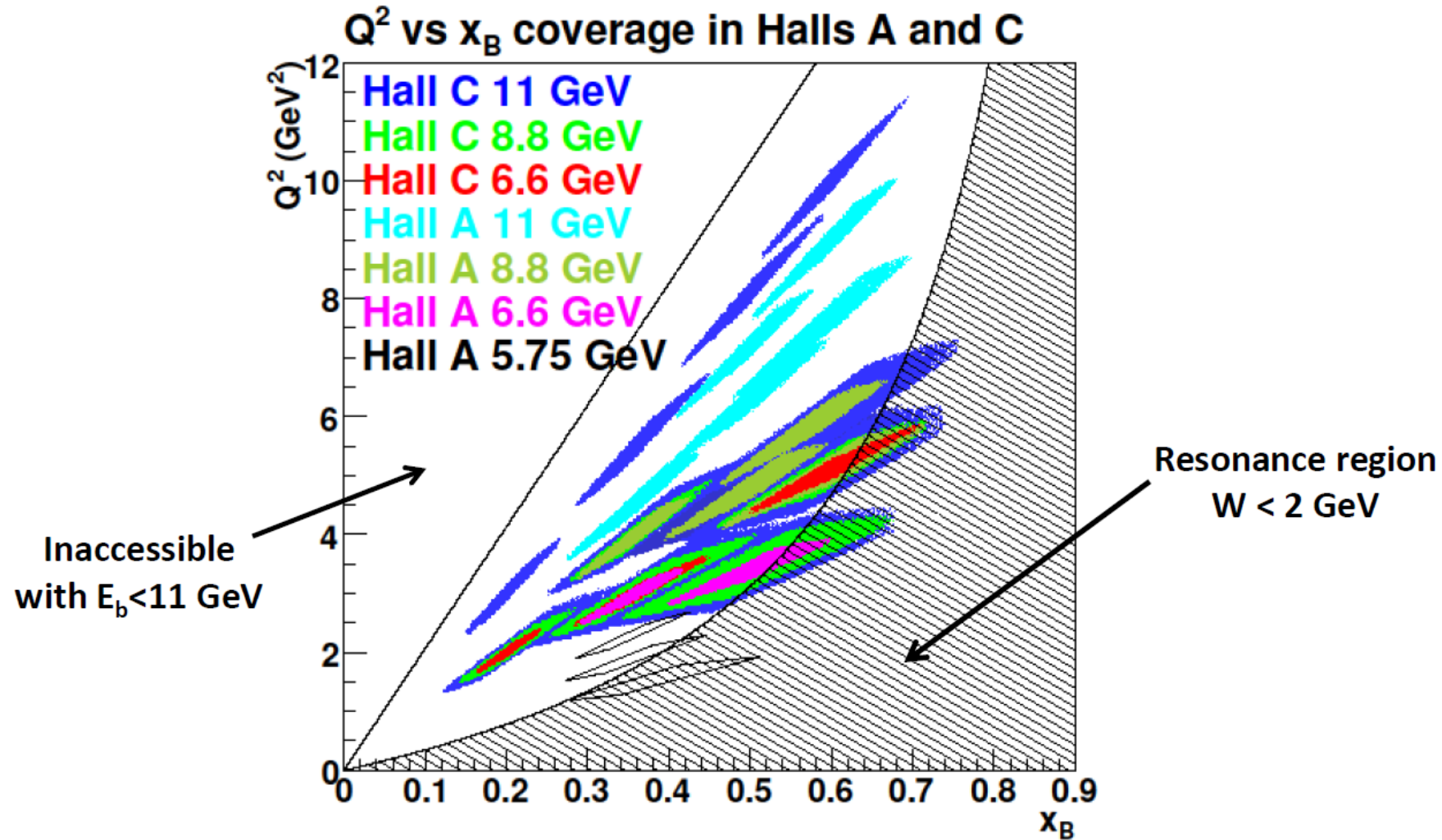
Example of projected CFF extracted from CLAS12 DVCS data on beam-spin and target-spin asymmetries

Hall C program

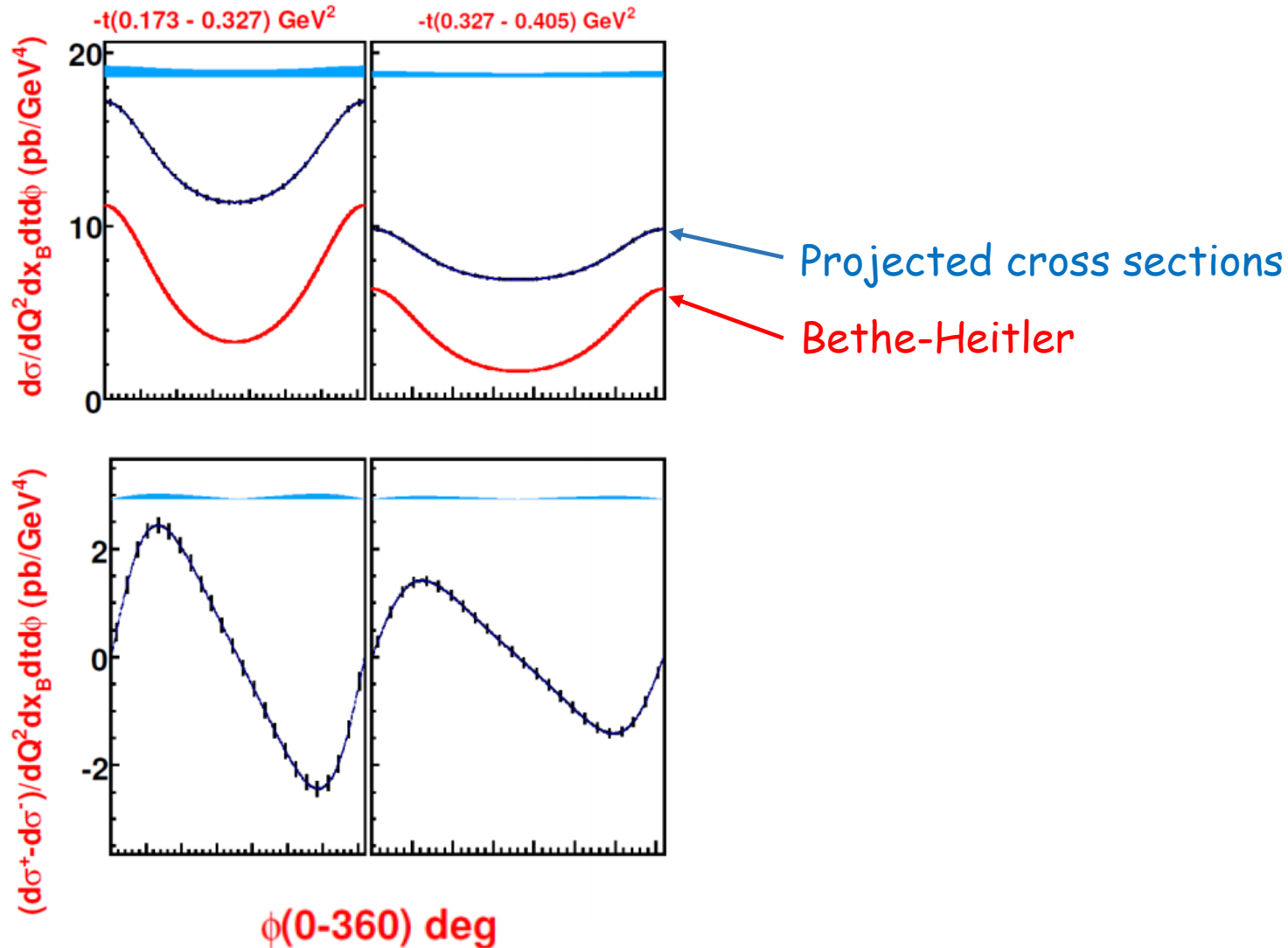
- HMS ($p < 7.3\text{GeV}$): scattered electron
- PbWO_4 calorimeter: γ/π^0 detection
- Sweeping magnet



Hall C program: kinematic coverage



Hall C program: projected results



- Very accurate cross section measurements
- Will constraint Interference and DVCS2 contributions
- Deep virtual π^0 production will be taken concurrently with the same setup

Summary lecture 4

- DVCS and GPD experimental program started in the early 2000s with non-dedicated experiments in low luminosity facilities (HERA: H1, ZEUS, HERMES)
- Jefferson Lab provides a high luminosity facility to study the large x_B region
- The GPD program is at the heart of the scientific motivation that drove the upgrade of JLab to 12 GeV
- An extensive program of high precision GPD measurements is currently planned in Halls A, B and C
- In parallel, COMPASS at CERN studies the intermediate x_B region
- Low x_B region will be extensively study with the future high-luminosity Electron-Ion Collider (*lecture 5*)