Deeply virtual Compton scattering with CLAS and CLAS12

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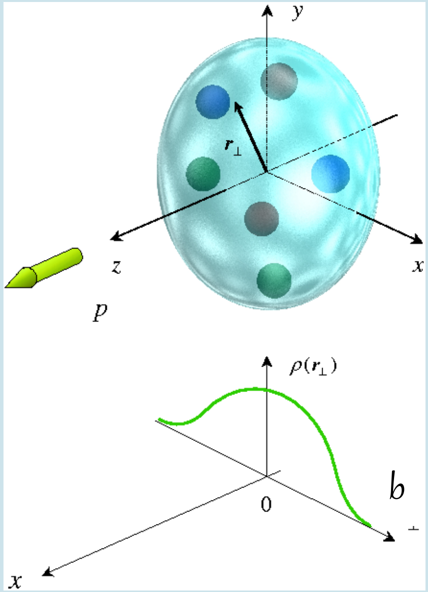
Inha HTG workshop: Modern issues in Hadronic Physics

Inha University - 2022.07.08

Outline

- Generalized parton distributions (GPDs)
- Deeply virtual Compton scattering (DVCS)
- DVCS with CLAS
- DVCS with CLAS12
- Overview

Generalized parton distributions (GPDs)

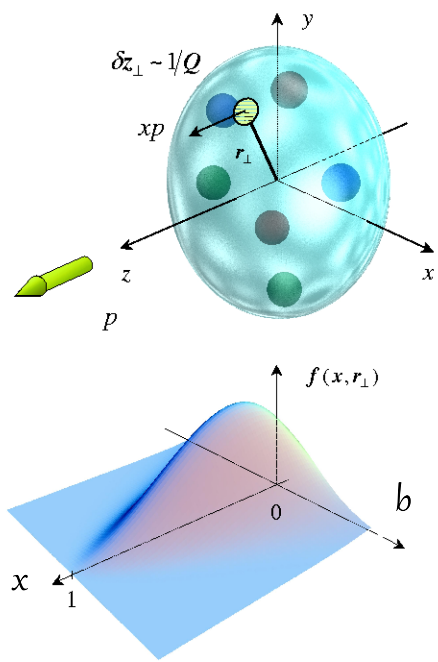


Form Factors (elastic scattering) :

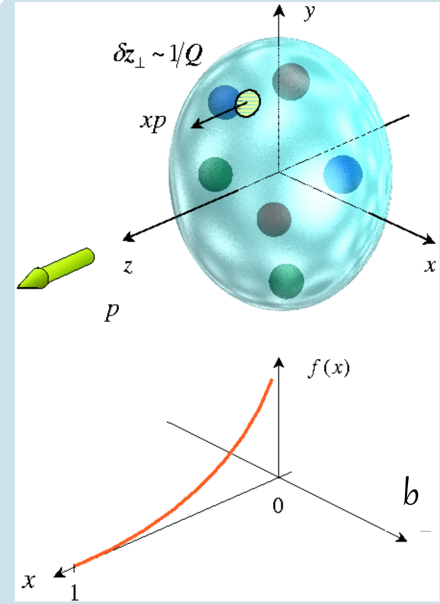
Transverse position of the quarks in the nucleon

GPDs, accessible via exclusive reactions, provide a **correlation** between the transverse position and the longitudinal momentum of the quarks in the nucleon

Nucleon tomography



Transverse position (b) as a function of longitudinal momentum fraction (x)



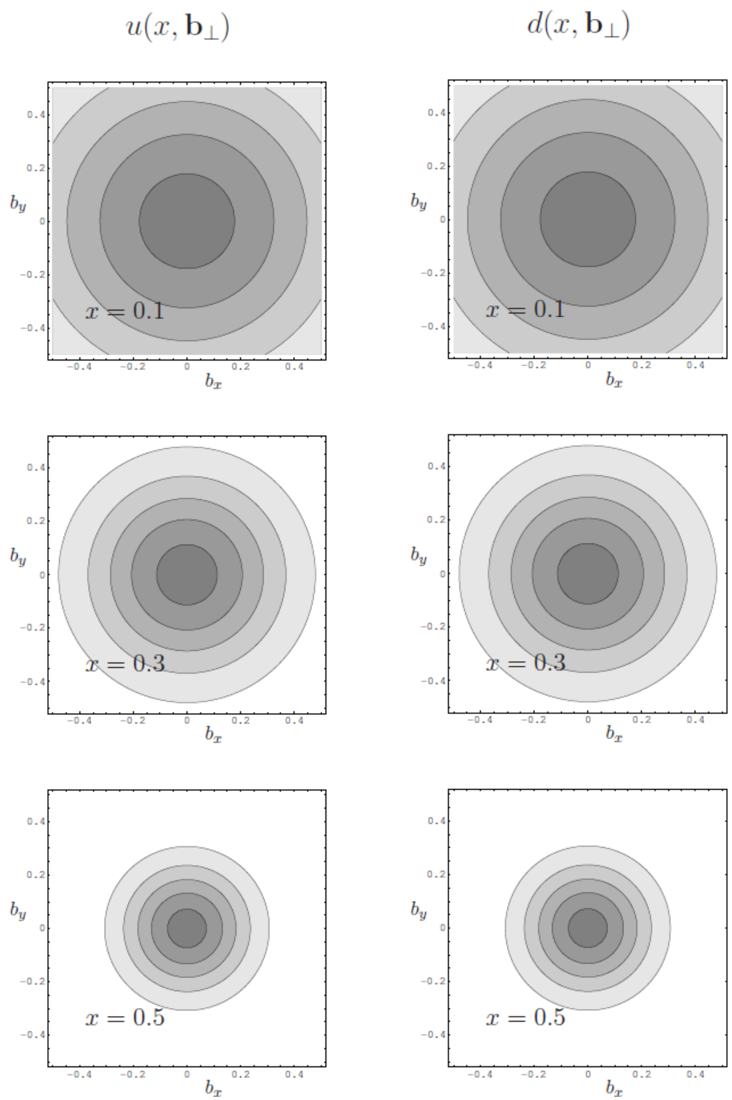
Parton Distribution Functions (deep inelastic scattering) :

Longitudinal momentum of the quarks in the nucleon

In this model, valence quarks (high x) are at the heart of the nucleon and sea quarks (low x) extend to its periphery

Interpretation of GPDs : impact parameter $b_\perp$ as a function of x

Transverse position $b_\perp$ of the quarks inside the nucleon for different values of longitudinal momentum fraction x

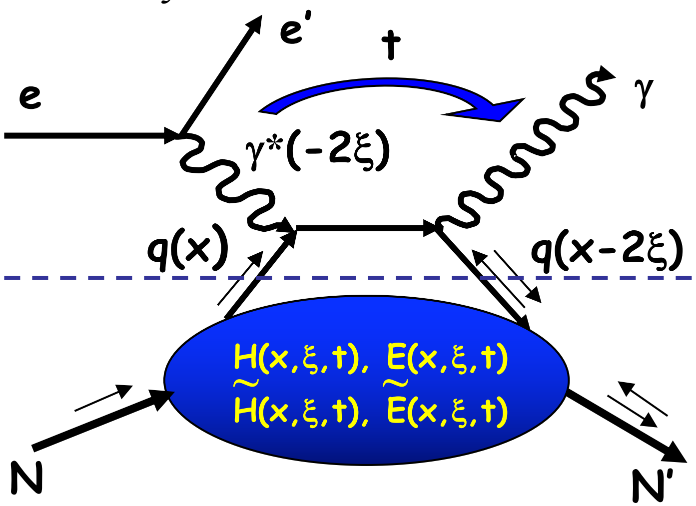


Deeply Virtual Compton Scattering (DVCS) and GPDs

High Q^2, small t

$$x_B = \frac{2\xi}{1+\xi}$$

DVCS



e N ⟶ e' N' γ

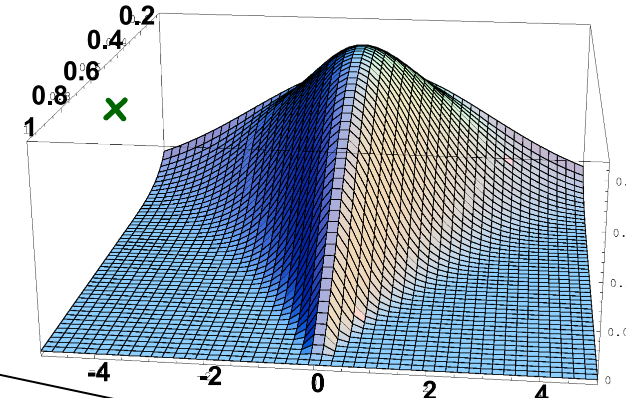
DVCS is the key reaction to access the GPDs as it offers the simplest interpretation in terms of GPDs

x longitudinal momentum fraction carried by the active quark.

$\xi \sim \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.

$t = (p' - p)^2$ squared momentum transfer to the nucleon.

GPD(x,ξ,t)



$b_\perp$: Fourier conjugate of t

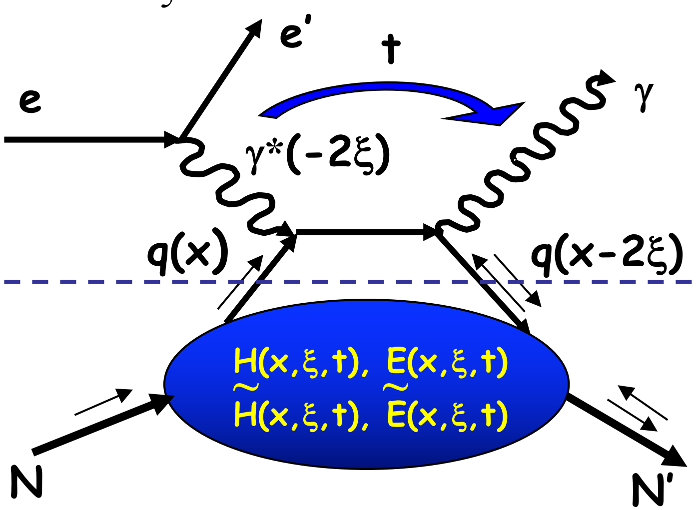
$$H^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H^q(x, \xi = 0, -\mathbf{\Delta}_\perp{}^2)$$

Deeply Virtual Compton Scattering (DVCS) and GPDs

High Q^2, small t

$$x_B = \frac{2\xi}{1+\xi}$$

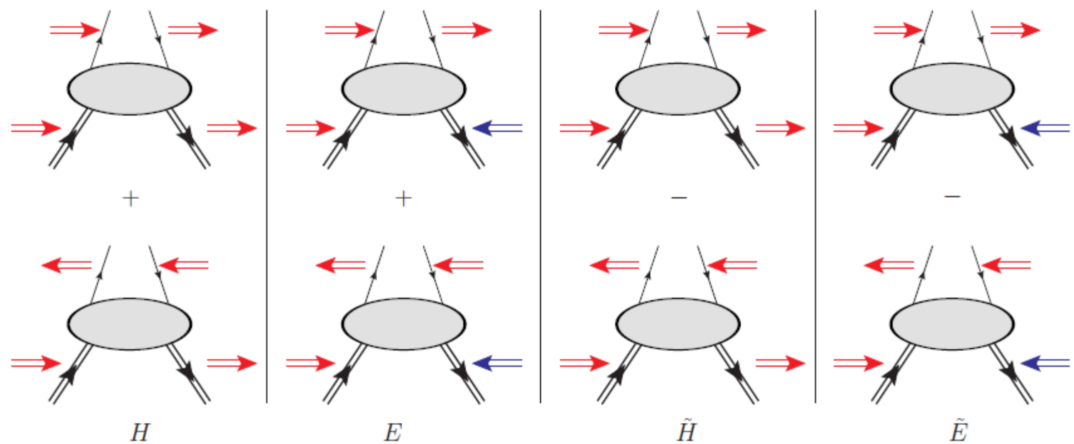
DVCS



$e\,N \longrightarrow e'\,N'\,\gamma$

DVCS is the key reaction to access the GPDs as it offers the simplest interpretation in terms of GPDs

At leading-order QCD, leading twist, there are 4 chiral-even (parton helicity is conserved) GPDs for each parton



$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

GPDs and proton spin puzzle

Proton spin puzzle :
The origin of the proton spin is still unknown

$$\frac{1}{2} = J^q + J^g = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Orbital angular momentum

GPDs H and E provide access to the total angular momentum of the partons in the nucleon

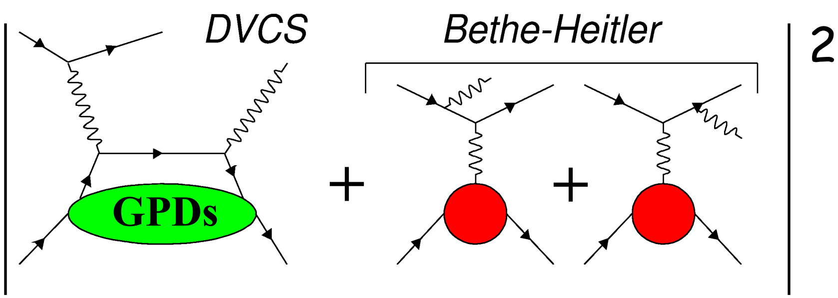
Ji's angular momentum sum rule:

$$J^{q,g} = \frac{1}{2}\int_{-1}^{1} x dx \left(H^{q,g}(x,\xi,t=0) + E^{q,g}(x,\xi,t=0)\right)$$

DVCS and Bethe-Heitler processes

BH fully calculable in QED

$\sigma(eN \rightarrow eN\gamma)$ =



DVCS and Bethe-Heitler (BH) experimentally undistinguishable

interference between the 2 processes

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

Unpolarized Cross Section

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \approx \left|T^{DVCS} + T^{BH}\right|^2 = \left|T^{DVCS}\right|^2 + \left|T^{BH}\right|^2 + I$$

Beam-polarized Cross-Section difference

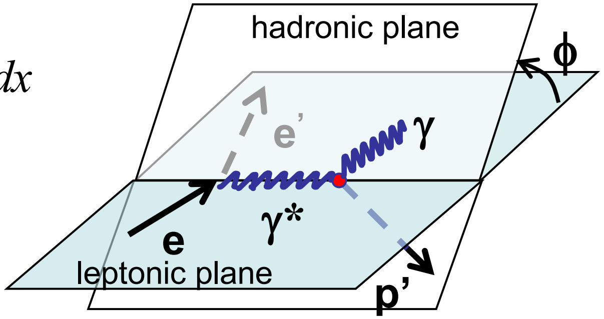
$$\frac{d^4\overrightarrow{\sigma}}{dQ^2 dx_B dt d\phi} - \frac{d^4\overleftarrow{\sigma}}{dQ^2 dx_B dt d\phi} \propto \mathrm{Im}(T_{DVCS}) \times T_{BH}$$

Compton Form Factors (CFFs) and DVCS observables

Compton Form Factors (CFFs)

$$\begin{cases} Re\mathcal{H}_q = e_q^2 P\int_0^{+1}\left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right]dx \\ Im\mathcal{H}_q = \pi e_q^2\left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right] \end{cases}$$

$\xi = x_B/(2-x_B)$ $k = t/4M^2$



ep ⟶ epγ

Each DVCS observable is sensitive to a different combination of GPDs

Proton Neutron

Polarized beam, unpolarized target:
$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$ ⟹ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, longitudinal target:
$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⟹ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

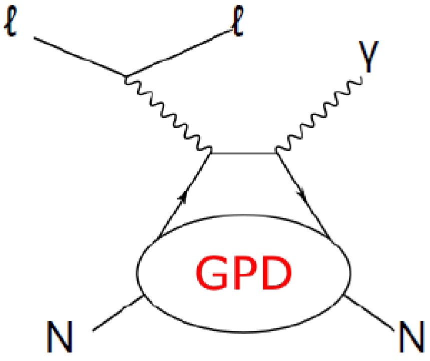
Polarized beam, longitudinal target:
$\Delta\sigma_{LL} \sim (A+B\cos\phi)\mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) + \ldots\}$ ⟹ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

Unpolarized beam, transverse target:
$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ ⟹ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

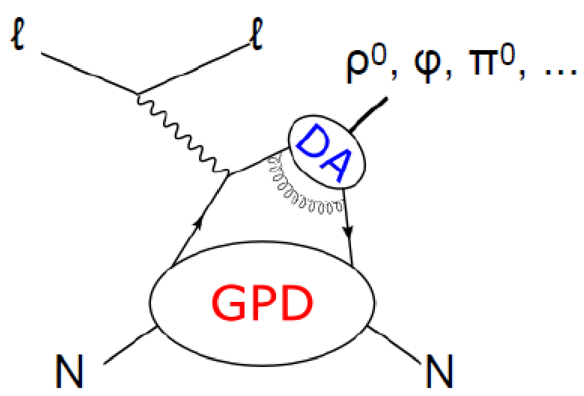
Quark-flavor separation of GPDs

- 1st method : Neutron DVCS
  - A combined analysis of DVCS observables for proton and neutron (deuterium) targets is needed to perform a quark-flavor separation of the GPDs
  - High sensitivity to GPD E with a polarized beam

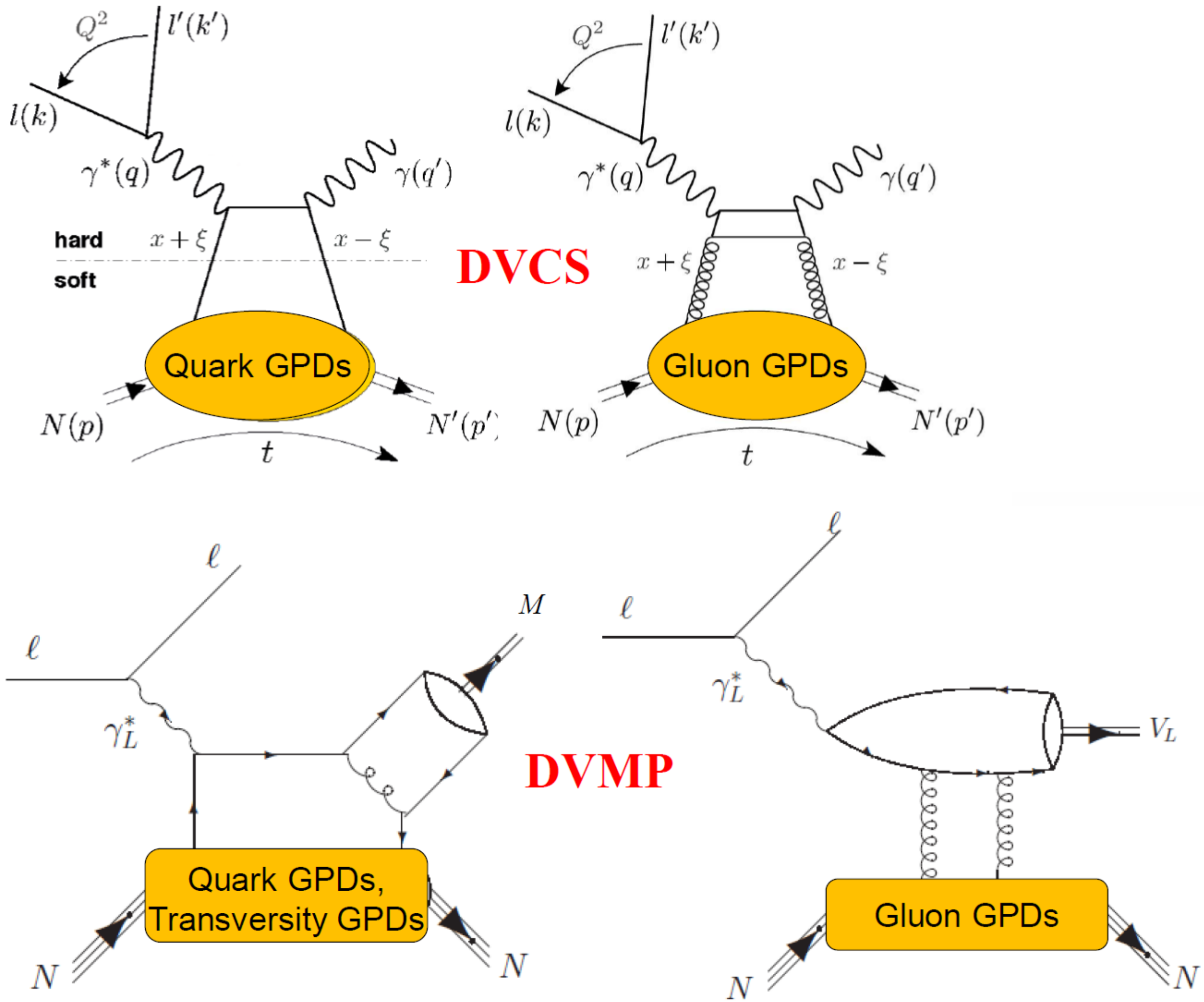
$$(H,E)_u(\xi,\xi,t) = {}^9\!/_{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$
$$(H,E)_d(\xi,\xi,t) = {}^9\!/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$



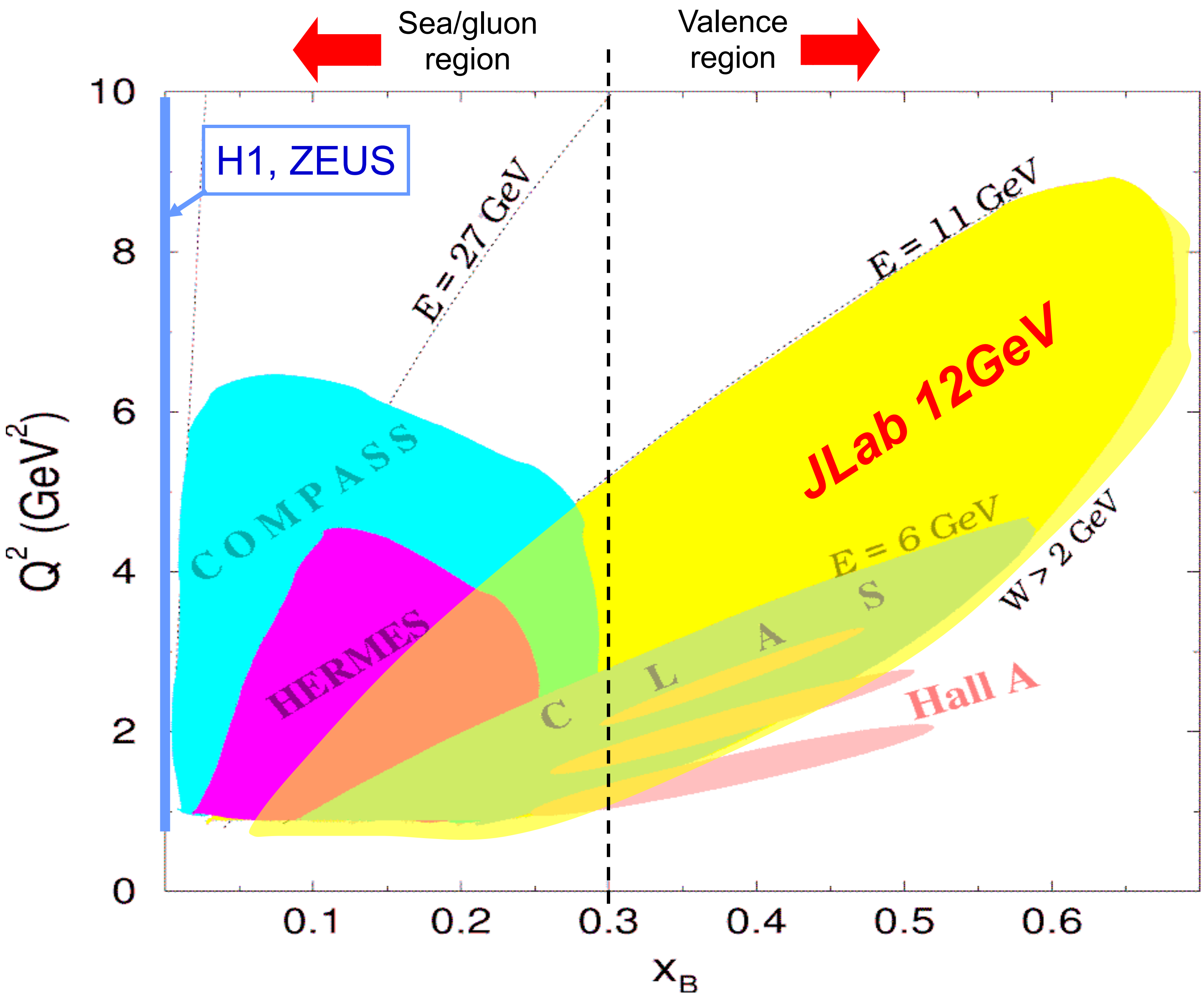
- 2nd method : Deeply virtual meson production (DVMP)
  - DVMP cross-section measurements are another way to access quark-flavor separation of GPDs
  - Gives also access to transversity GPDs (chiral-odd GPDs, where parton helicity is changed)



DVCS and DVMP diagrams for gluons GPDs

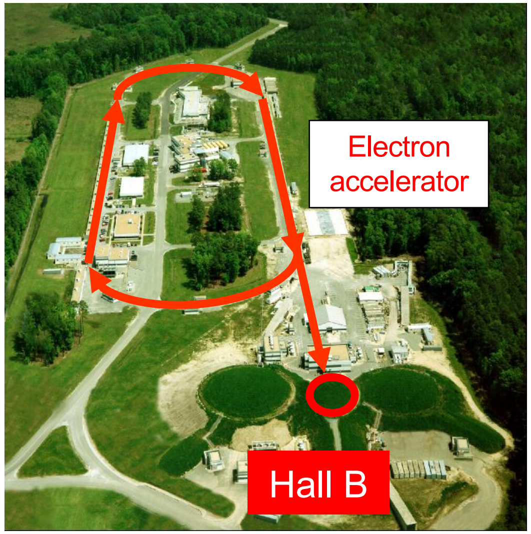


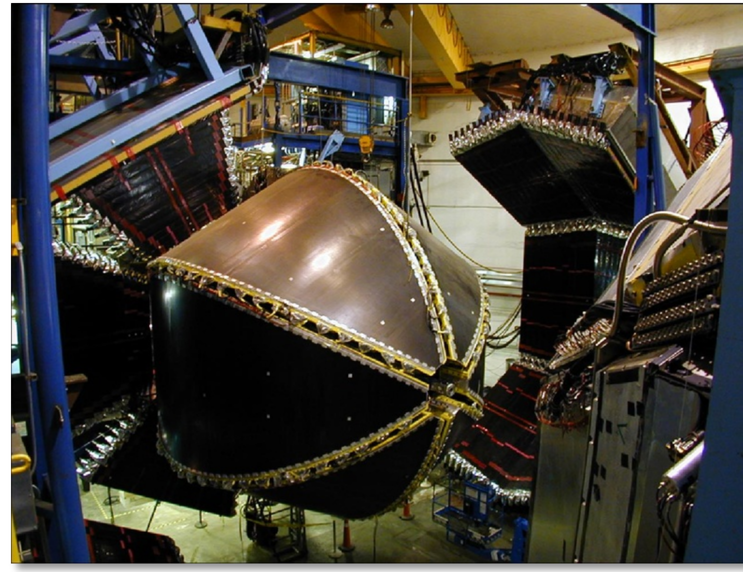
Kinematic coverage of the different experiments

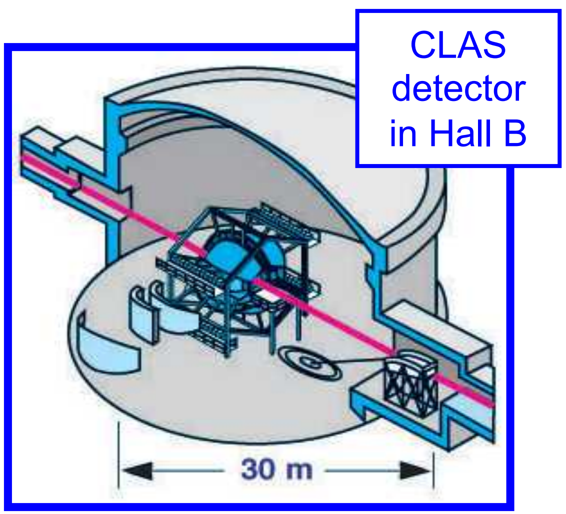


Jefferson Lab 6 GeV and the CLAS detector

Jefferson Lab

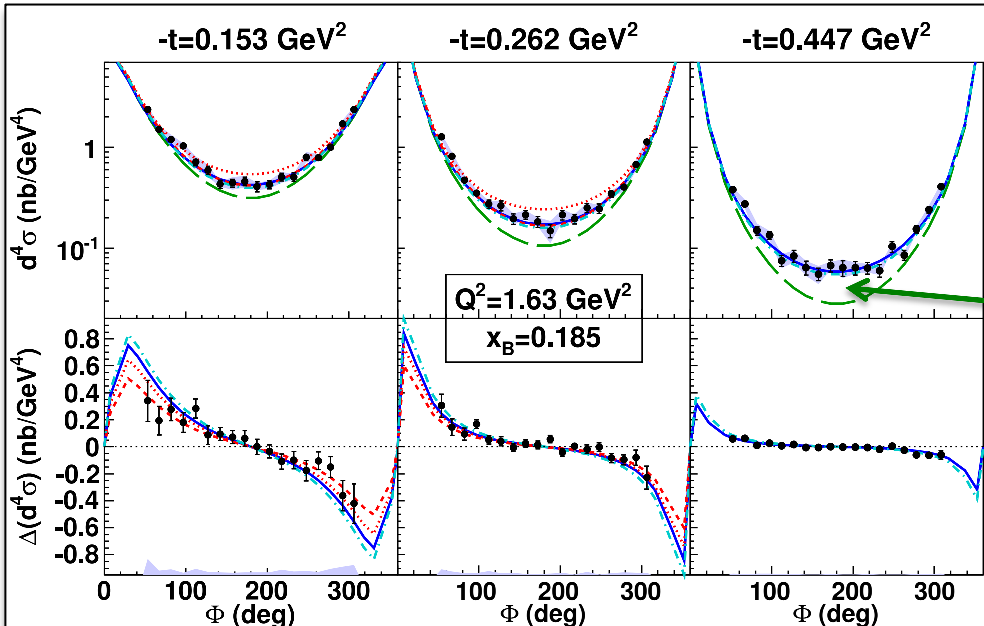






DVCS unpolarized and beam-polarized cross sections from CLAS data

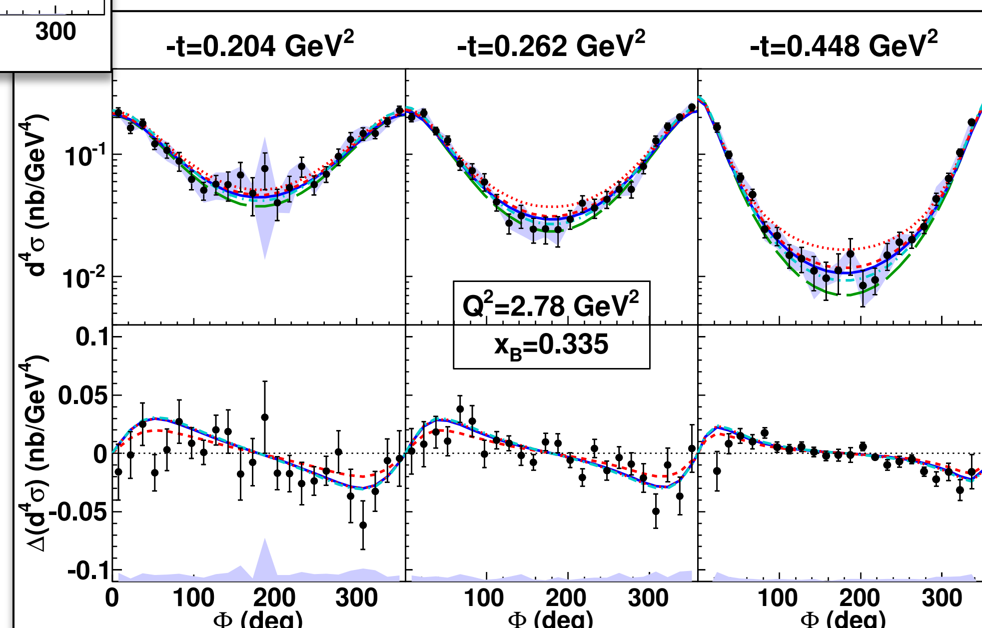
H.S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)



$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}(nb/GeV^4)$$

DVCS + interference

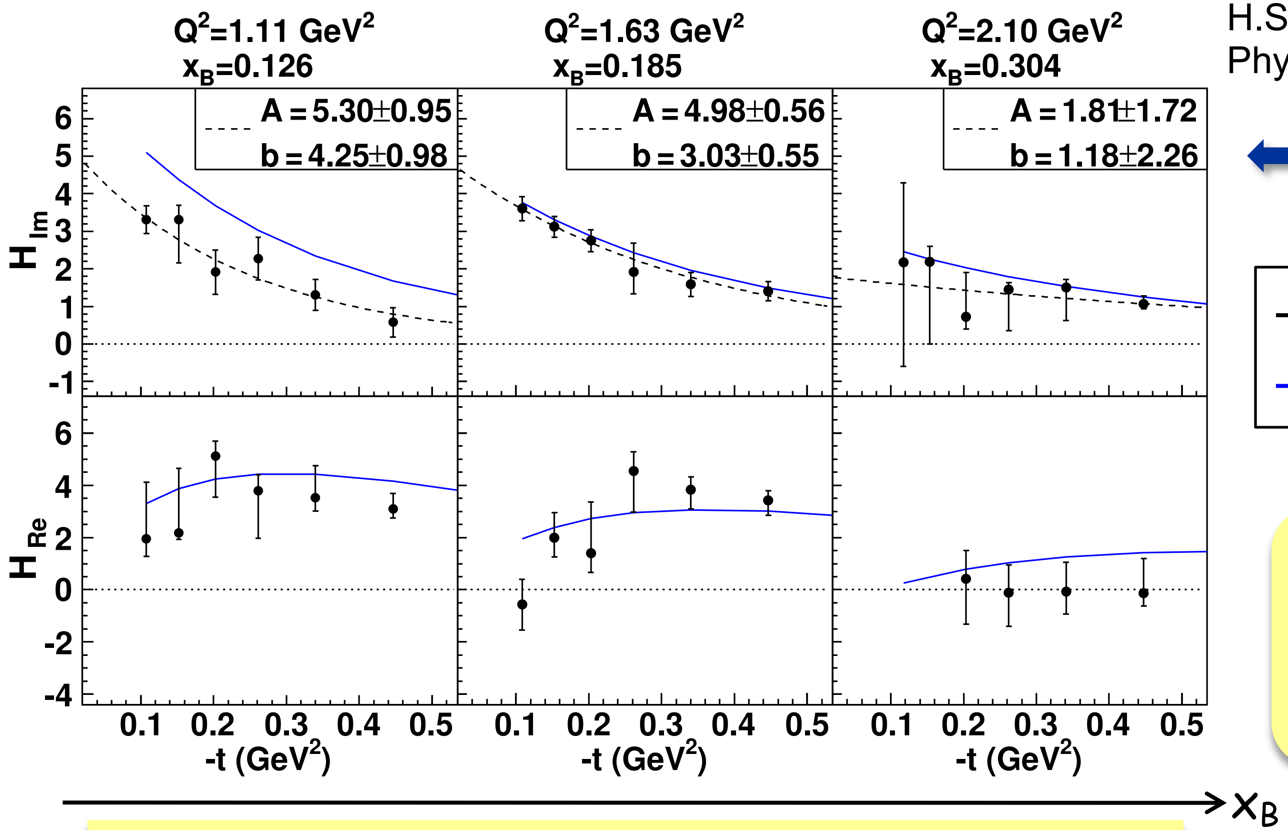
$$\frac{1}{2}\left(\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}-\frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}\right)(nb/GeV^4)$$



- Bethe Heitler
- VGG
- KMS
- KM10
- KM10a

- Jefferson Lab's polarized electron beam (energy ~ 6 GeV, polarization ~ 80%) + LH_2 target
- Luminosity L = 2.10^{34} cm^{-2}s^{-1}

Interpretation of fit results obtained from the cross sections



H.S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)

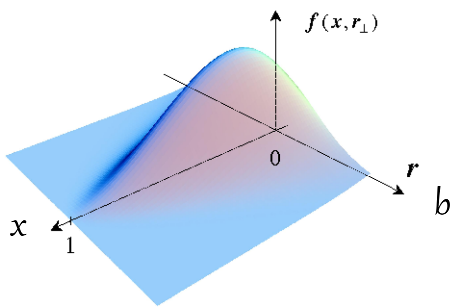
b : transverse position of the quarks in the nucleon

- - - *Fits with function Ae^{bt}*

—— *VGG predictions*

The results tend to show that valence quarks (high x) are at the heart of the nucleon and sea quarks (low x) extend to its periphery

The transverse position *b* decreases with increasing x_B



The results suggest that the nucleon size decreases at higher parton-momentum values, thus revealing from the experiment a **first tomographic image of the nucleon**

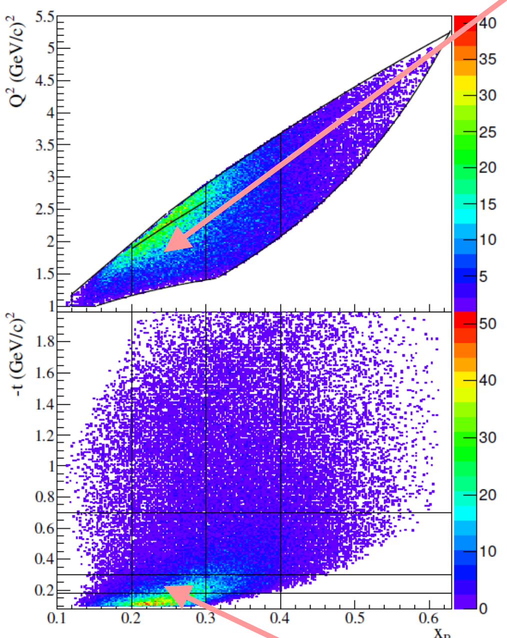
DVCS on longitudinally polarized target from CLAS data

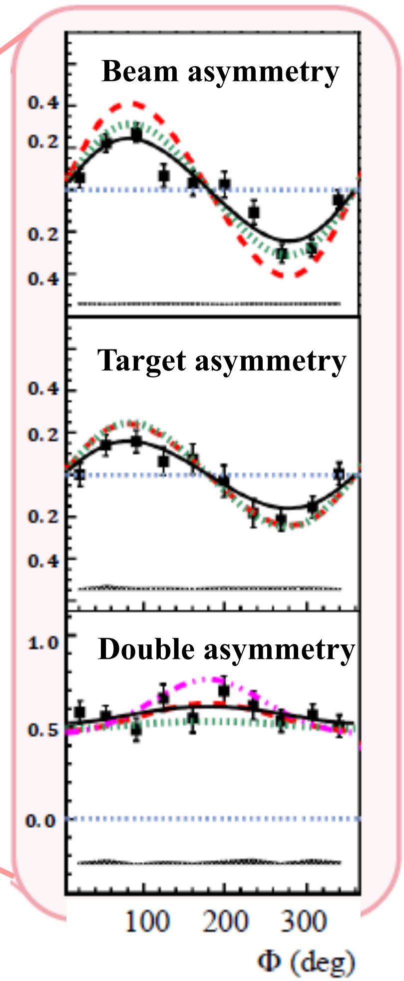
- **eg1-dvcs experiment**
- Beam energy **~6 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**

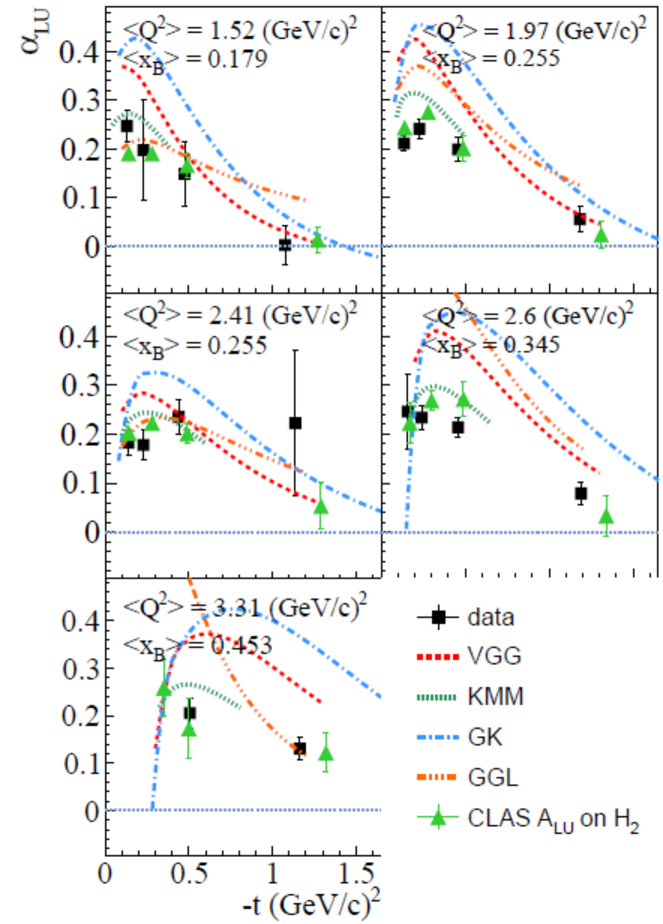
$\vec{e}\vec{p} \rightarrow ep\gamma$

$A_{LU} \sim Im\{\mathcal{H}_p\}$

$$A_{LU} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$







- **5 (Q^2-x_B) bins**
- **4 t bins**
- **10 φ bins**

S. Pisano *et al.* (CLAS Collaboration), Phys. Rev. D 91, 052014 (2015)

DVCS on longitudinally polarized target from CLAS data

- **eg1-dvcs experiment**
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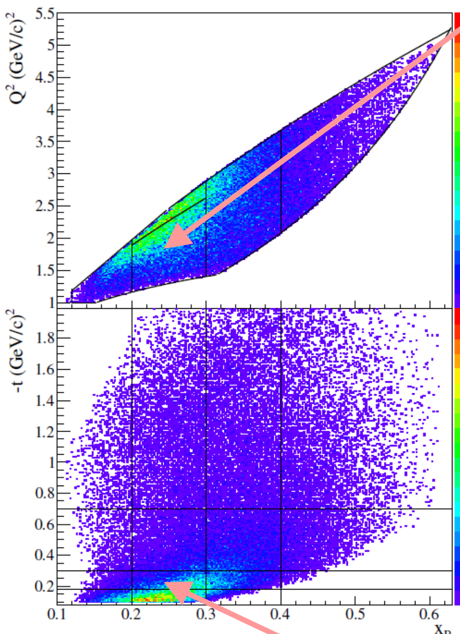
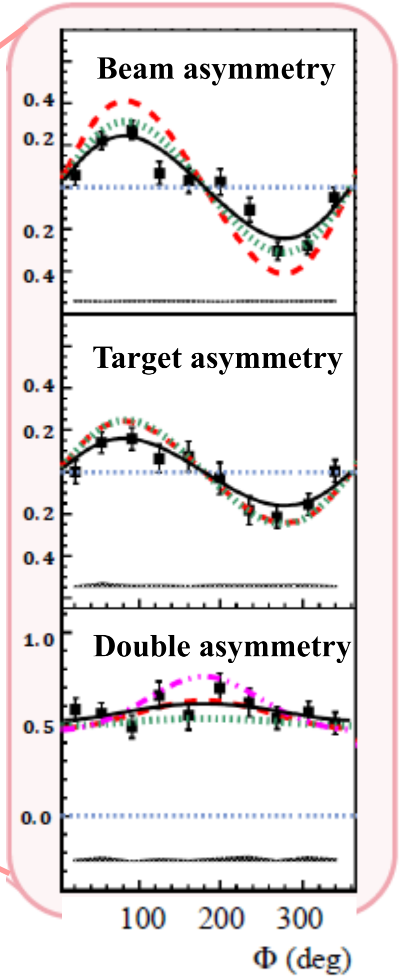
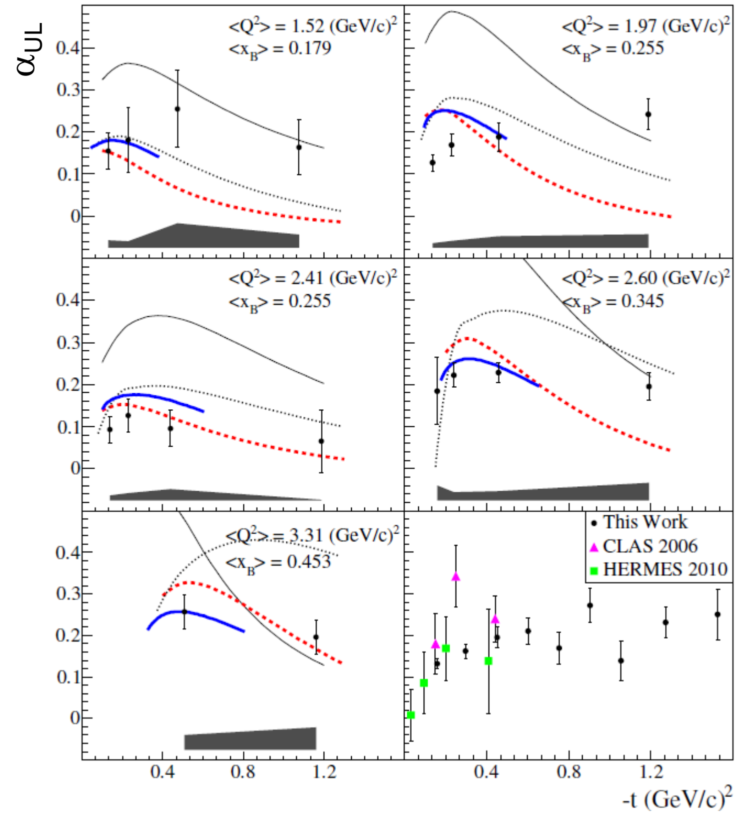
$A_{UL} \sim Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$







- **5 (Q^2-x_B) bins**
- **4 t bins**
- **10 ϕ bins**

- Improved statistics ×10 at low $-t$
- Extended kinematic coverage

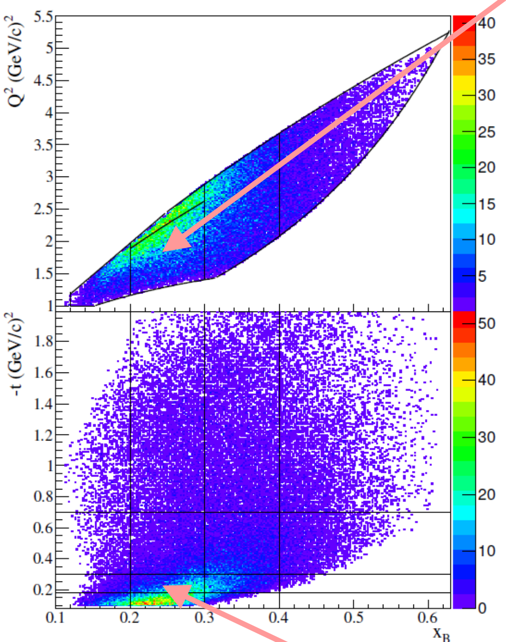
E. Seder *et al.* (CLAS Collaboration), Phys. Rev. Lett. 114, 032001 (2015)

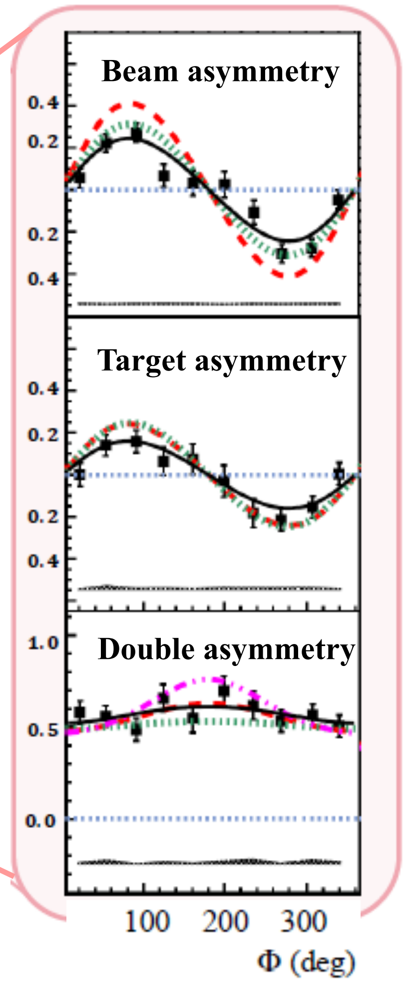
DVCS on longitudinally polarized target from CLAS data

- **eg1-dvcs experiment**
- Beam energy **~6 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**

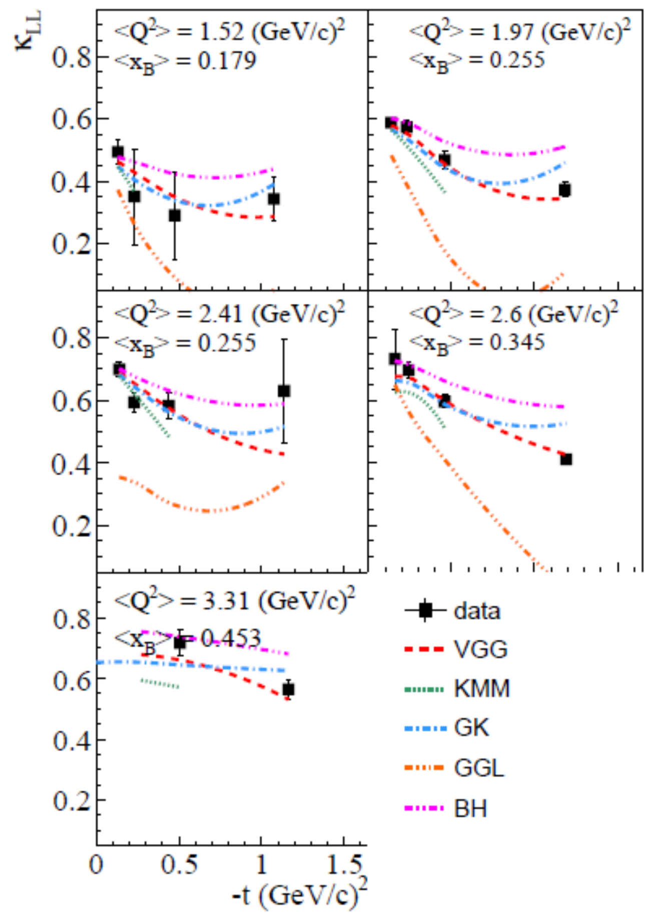
$\vec{e}\vec{p} \rightarrow ep\gamma$

$A_{LL} \sim Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$



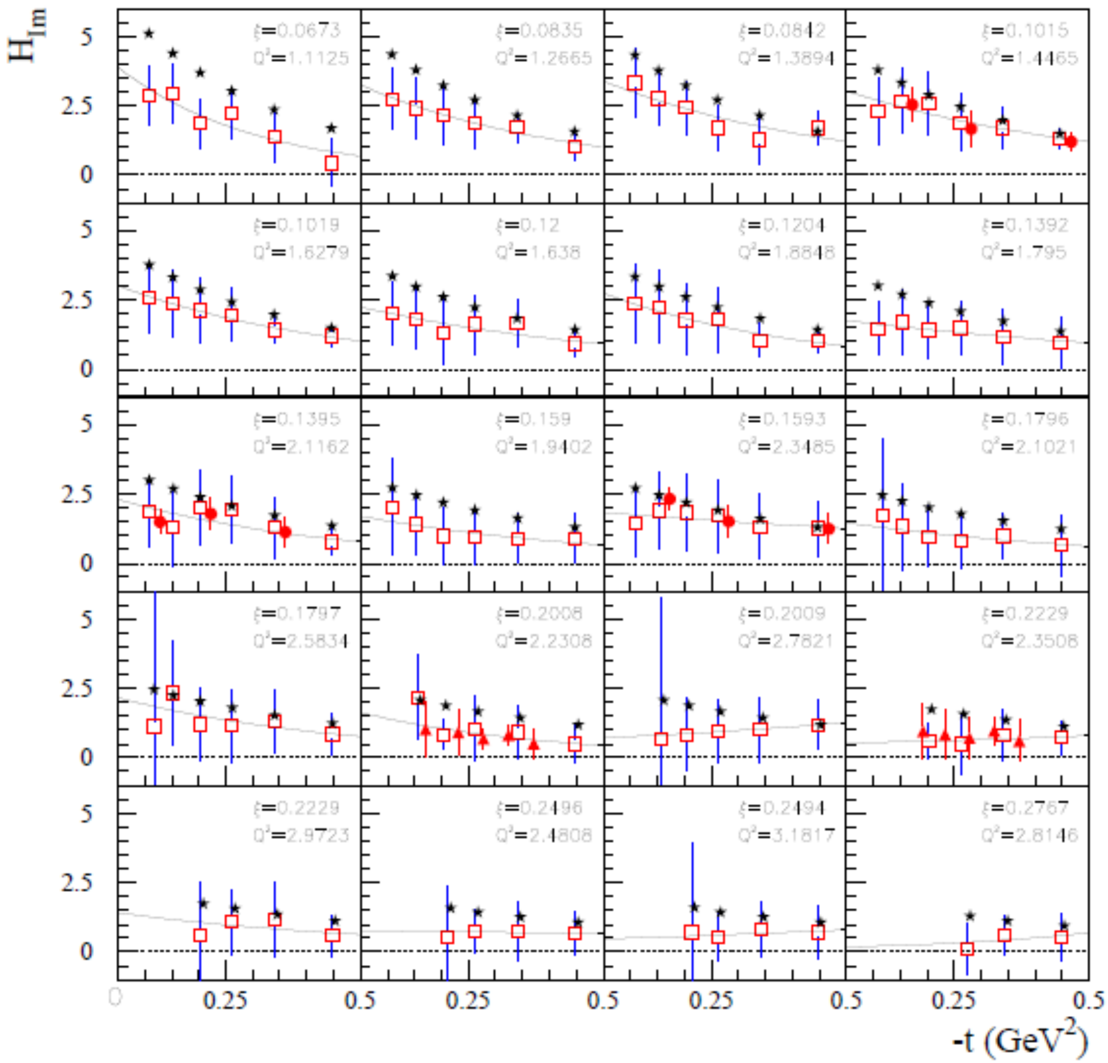


- **5 (Q^2-x_B) bins**
- **4 t bins**
- **10 ϕ bins**



S. Pisano *et al.* (CLAS Collaboration), Phys. Rev. D 91, 052014 (2015)

Extraction of H_{Im} from the fits of Jefferson Lab 6 GeV data



- □ Fit to CLAS σ and Δσ
- ● Fit to CLAS σ, Δσ, A_{UL}, A_{LL}
- ▲ Fit to Hall A σ and Δσ
- ★ VGG model

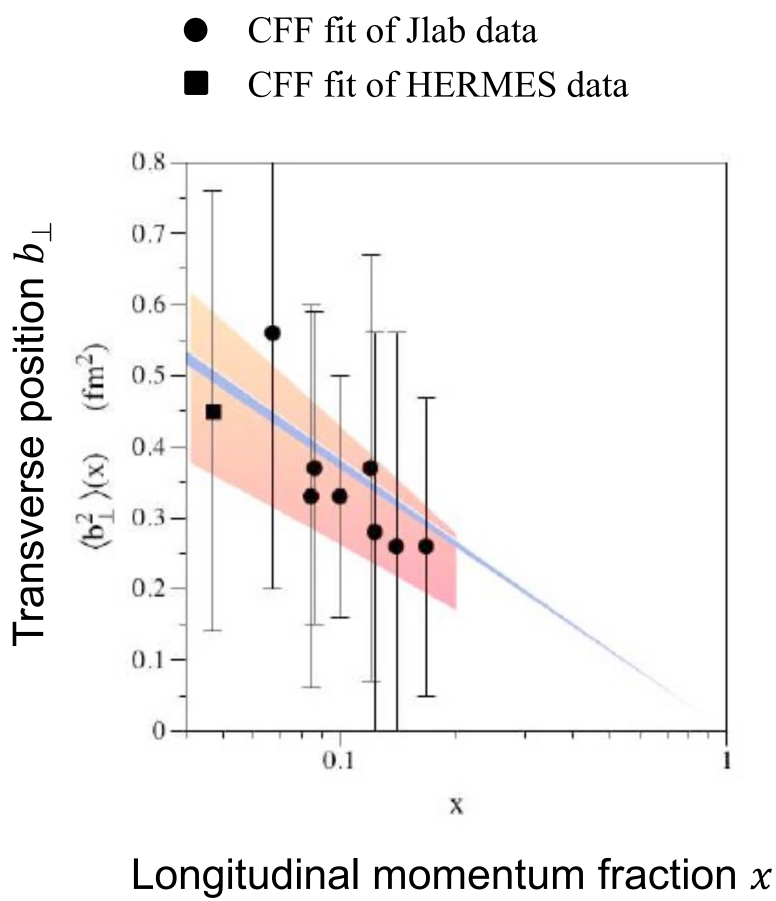
Fits in each (Q^2, x_B, t) bin of data

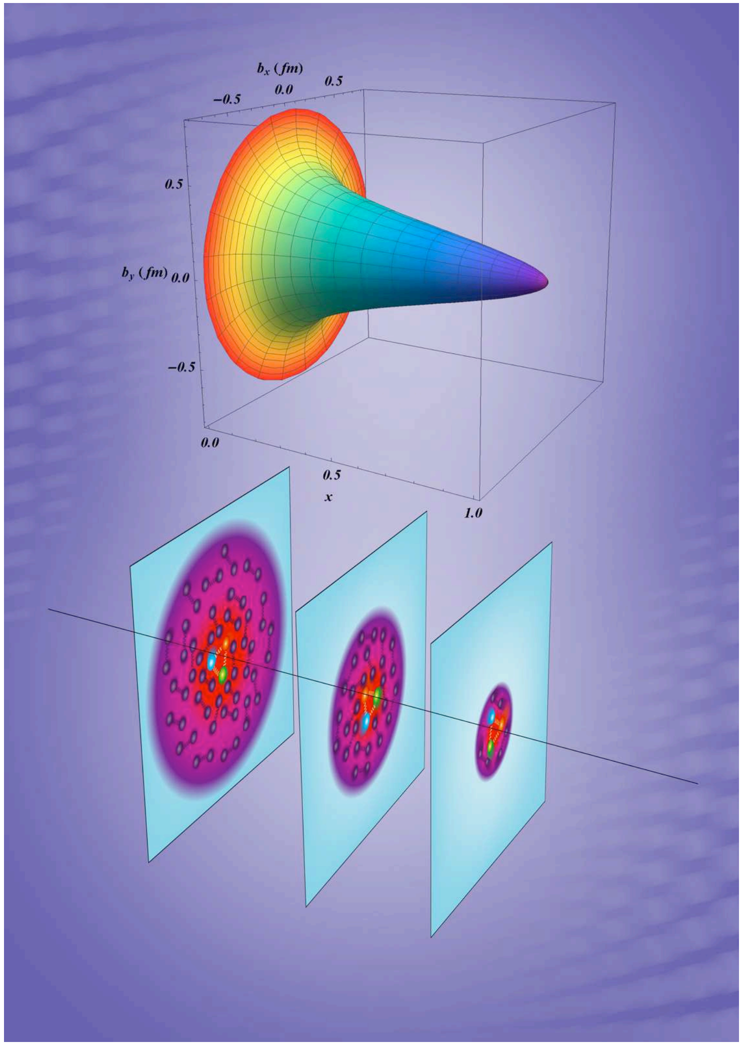
$$H_{Im}(\xi,t) = A(\xi)e^{b(\xi)t}$$

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

R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen, Eur. Phys. J. A 53, 171 (2017)

From CFFs to proton tomography





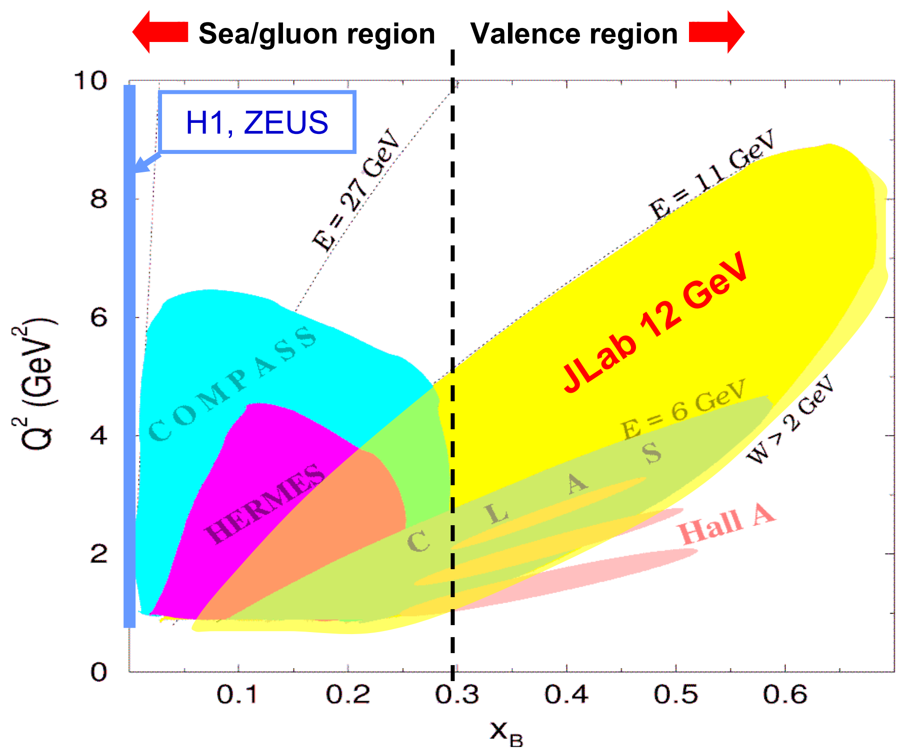
R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen,
Eur. Phys. J. A 53, 171 (2017)

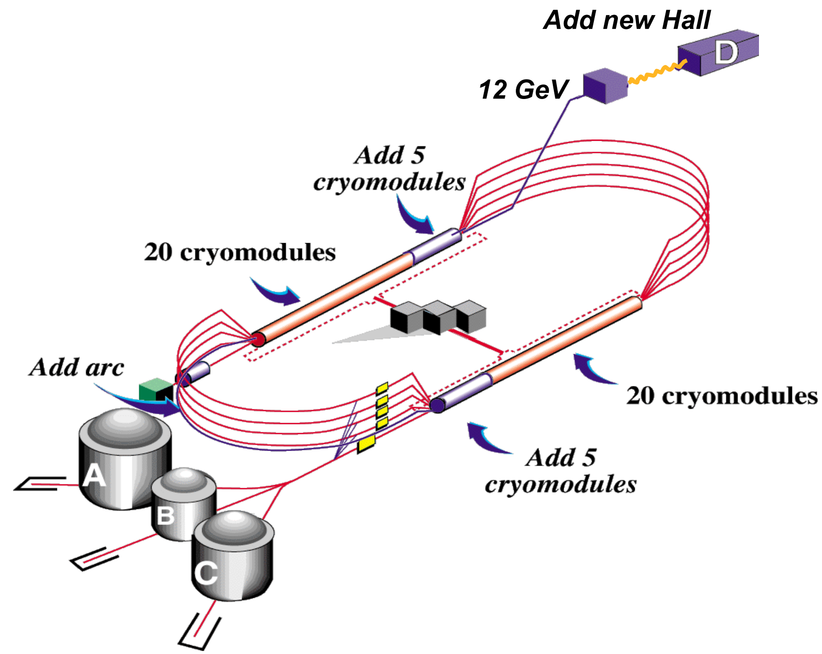
Jefferson Lab upgrade to 12 GeV

E= 2.2, 4.4, 6.6, 8.8, 11 GeV
for the Halls A, B, C

Beam polarization > 80%

Accelerator 12 GeV upgrade



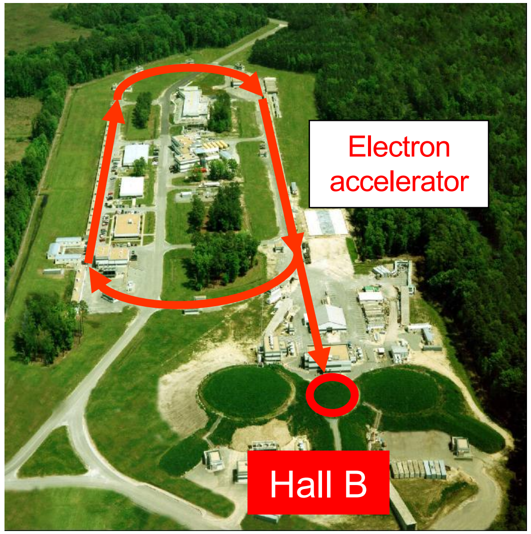


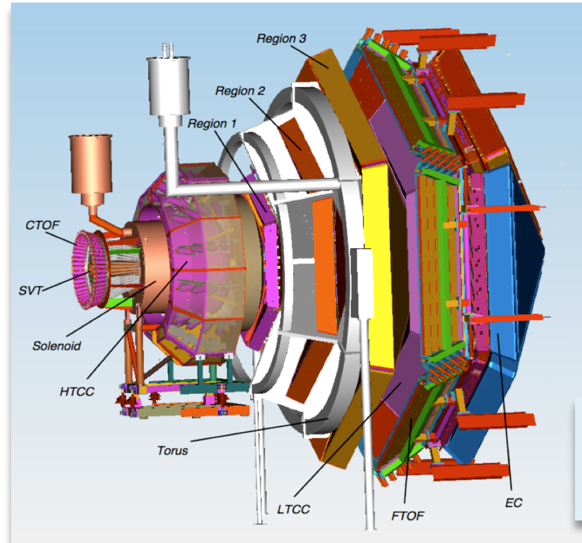
Study of high x_B domain requires high luminosity

The 12-GeV upgrade is well matched to studies in the valence-quark regime

Jefferson Lab 12 GeV and the CLAS12 detector

Jefferson Lab

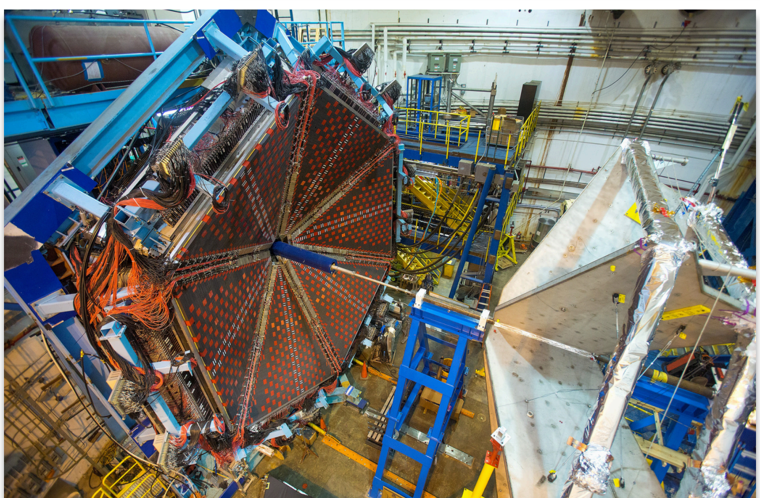


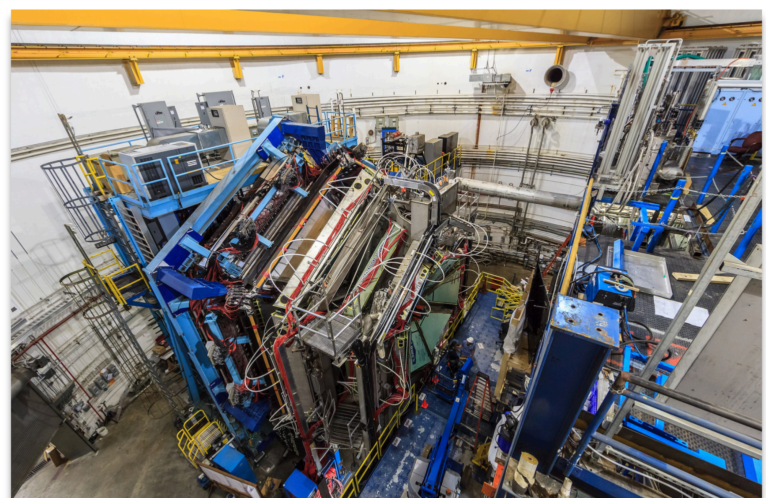


CLAS12 detector in Hall B

Luminosity
$L \sim 10^{35}\ cm^{-2}s^{-1}$

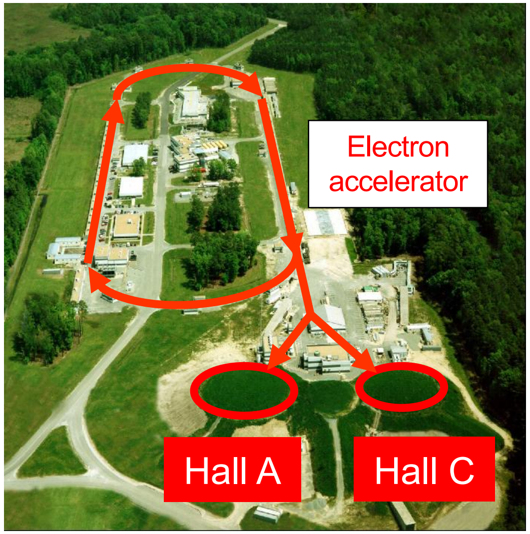
Data taking with the new CLAS12 detector started in 2018

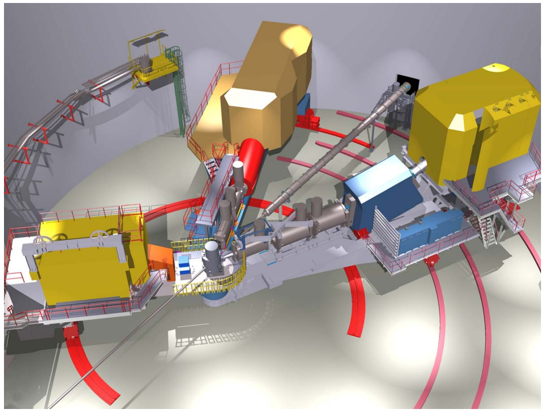




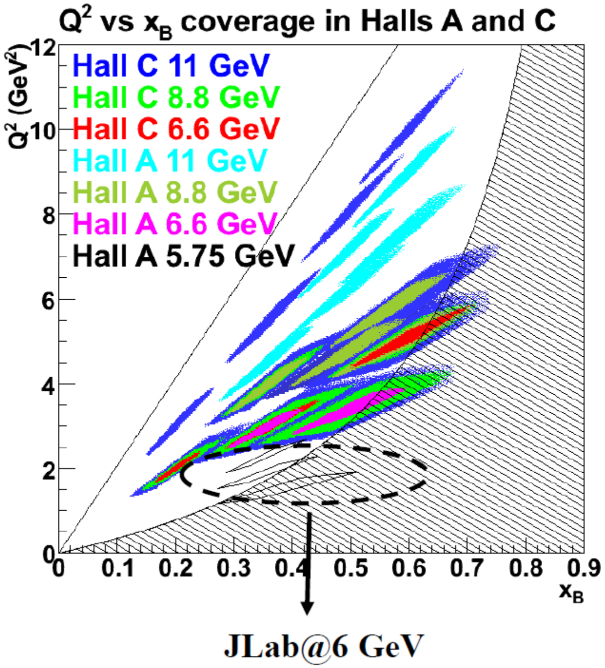
DVCS experiments in Hall A and Hall C of Jefferson Lab

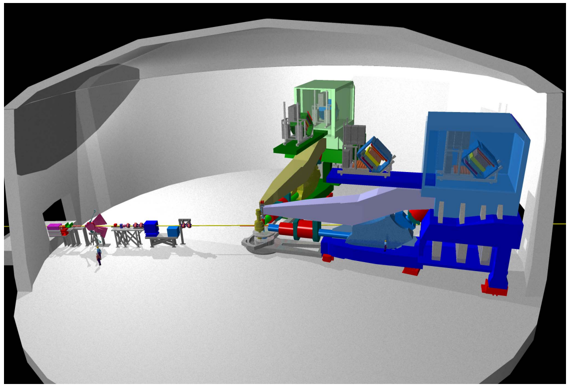
Jefferson Lab





Hall C

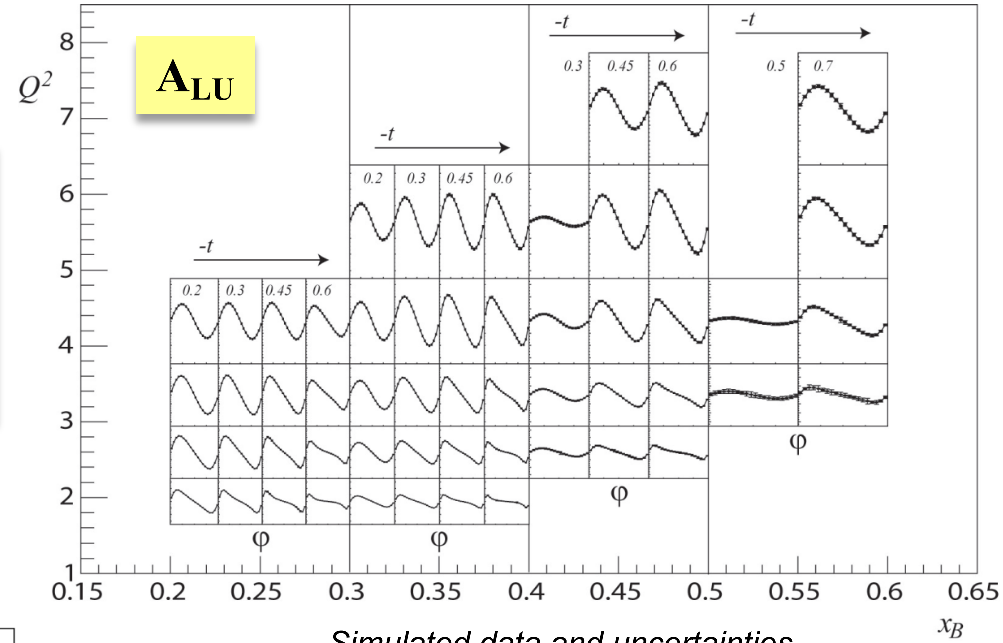




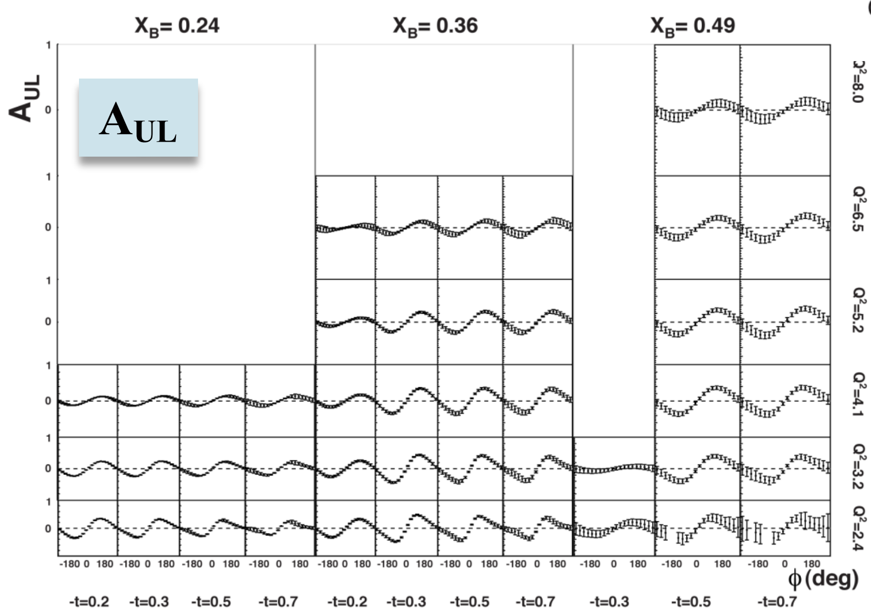
Hall A

Projected results for DVCS A_{LU} and A_{UL} with CLAS12

80 days of beam time
$P_{beam} = 85\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
Statistical error: 1% to 10% on sinϕ moments
Systematic uncertainties: ~6-8%



Simulated data and uncertainties

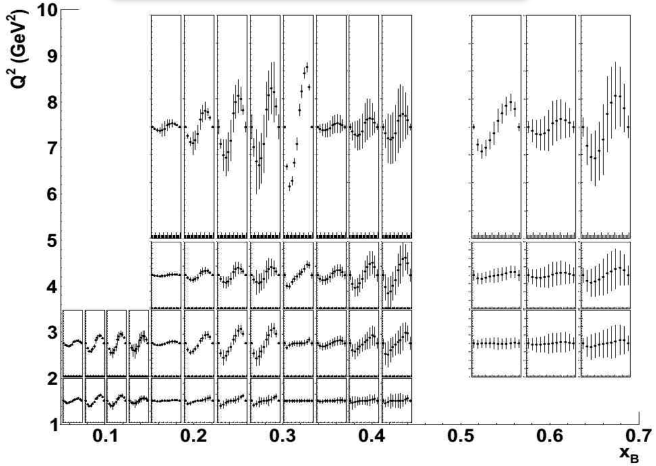


120 days of beam time
$P_{beam} = 85\%$, $P_{target} = 80\%$
$L = 2.10^{35}\ cm^{-2}s^{-1}$
Statistical error: 2% to 15% on sinϕ moments
Systematic uncertainties: ~6-8%

Simulated data and uncertainties

Projected results for other DVCS observables with CLAS12

A_{LU} on the neutron

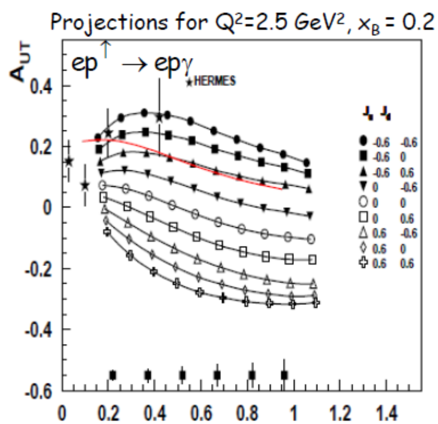


$\Delta\sigma_{LU}$ → $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

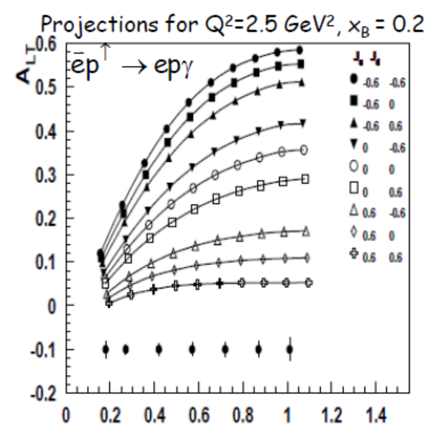
The most sensitive observable to the GPD E

+ also A_{UL} and A_{LL} on the neutron

A_{UT} and A_{LT} on the proton



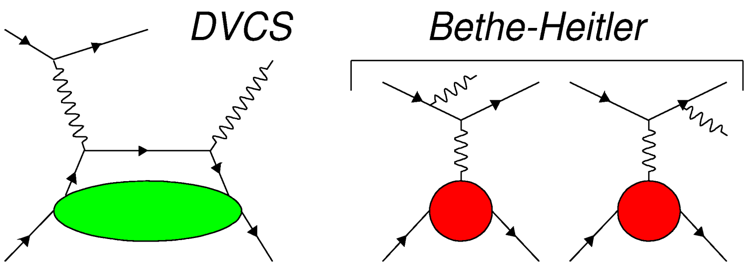
$\Delta\sigma_{UT}$ → $Im\{\mathcal{H}_p, \mathcal{E}_p\}$



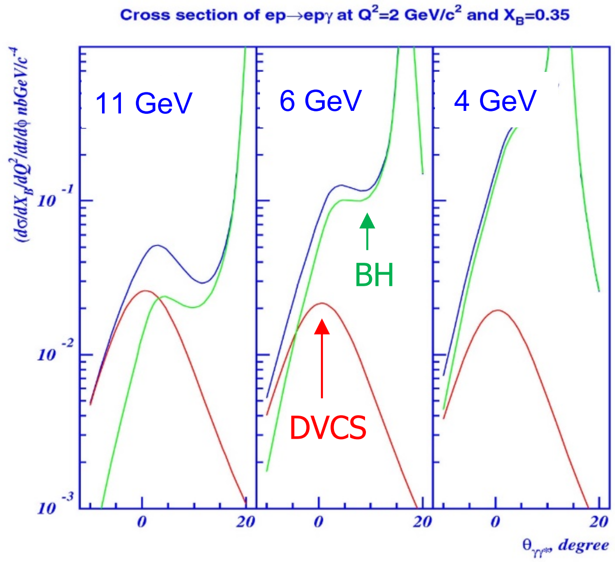
$\Delta\sigma_{LT}$ → $Re\{\mathcal{H}_p, \mathcal{E}_p\}$

and also exclusive electroproduction of mesons, etc…

Projected results for CFFs with CLAS12



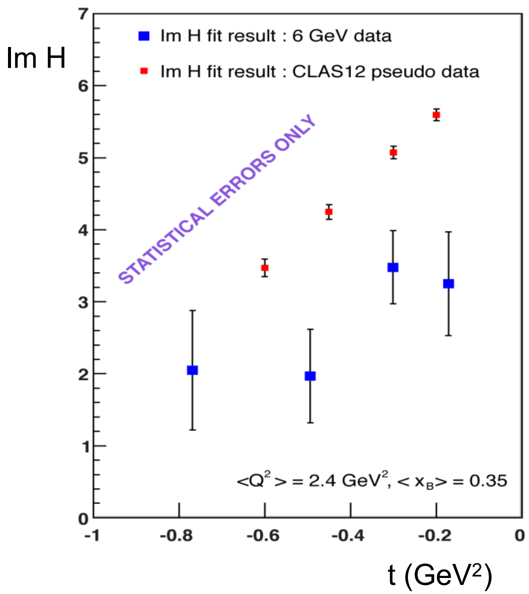
The contribution ratio from BH and DVCS to the ep→epγ cross section changes with the electron beam energy

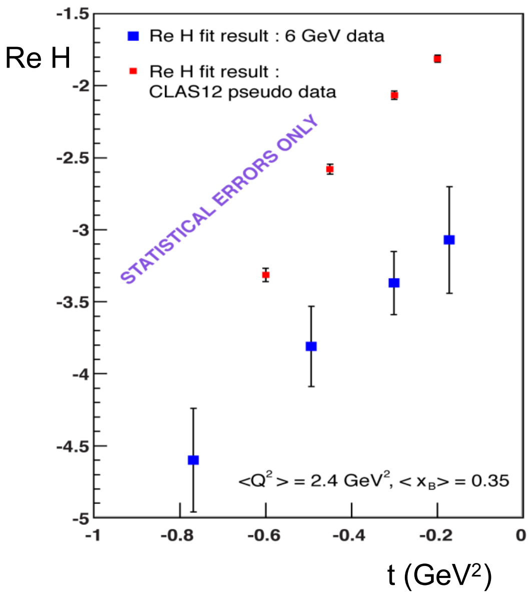


Impact of CLAS12 DVCS pseudo data on CFF fit

CLAS 6 GeV data

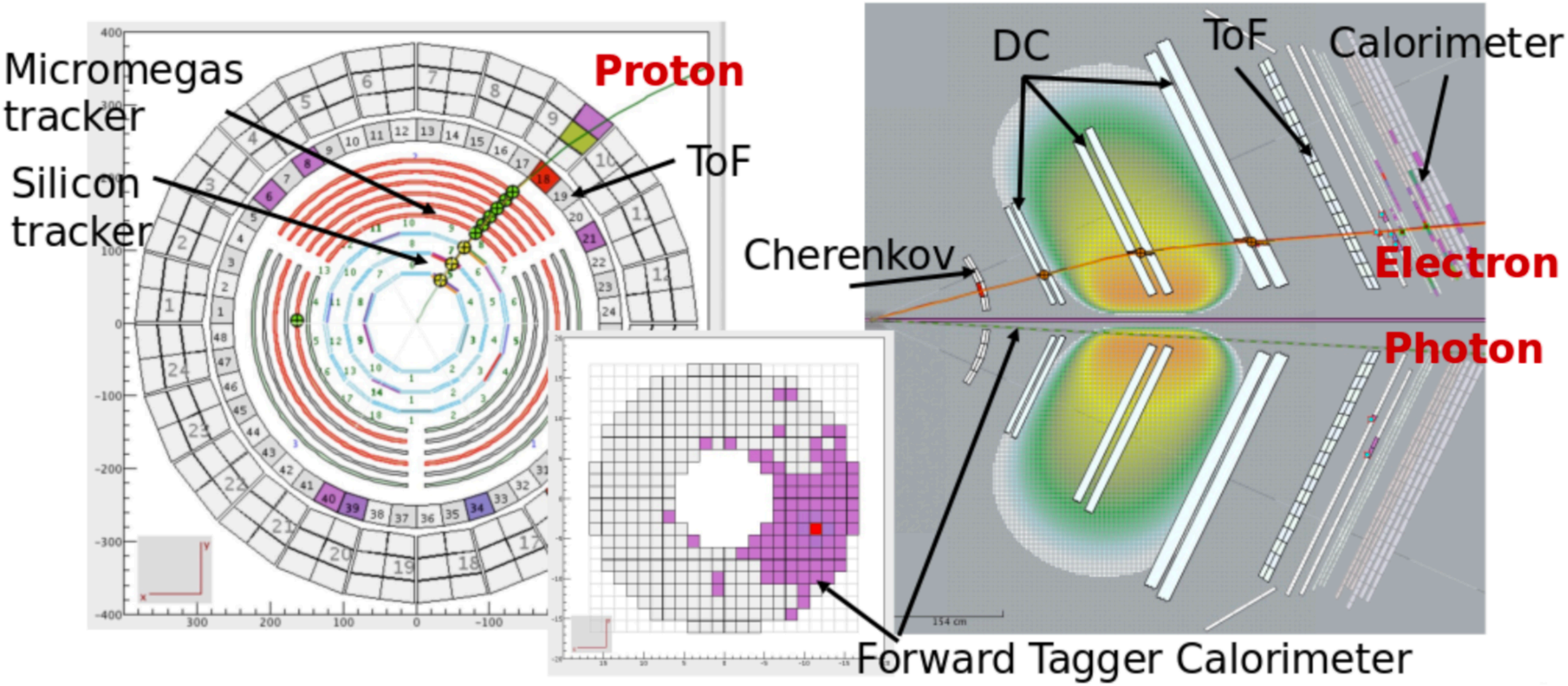
CLAS12 pseudo data





Typical DVCS event in CLAS12

- Electron: measured in the Forward Detector or in the Forward Calorimeter
- Photon: in the FT (or FD) calorimeter
- Proton: most often in the Central Detector



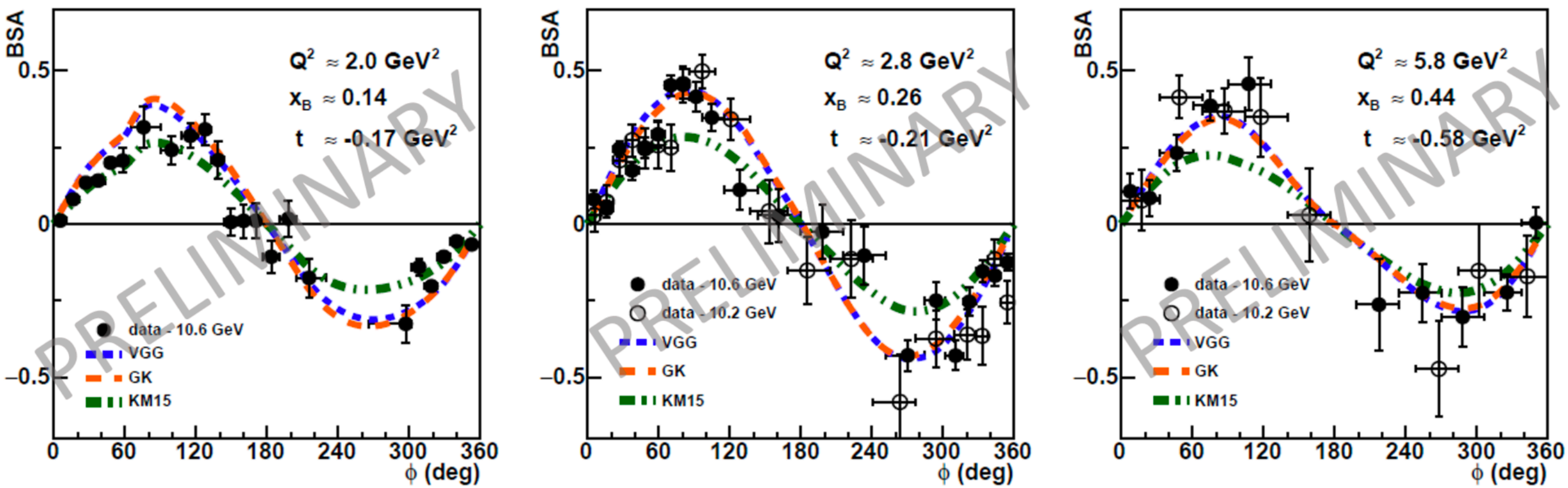
Preliminary proton DVCS A_{LU} with CLAS12

Beam spin asymmetry

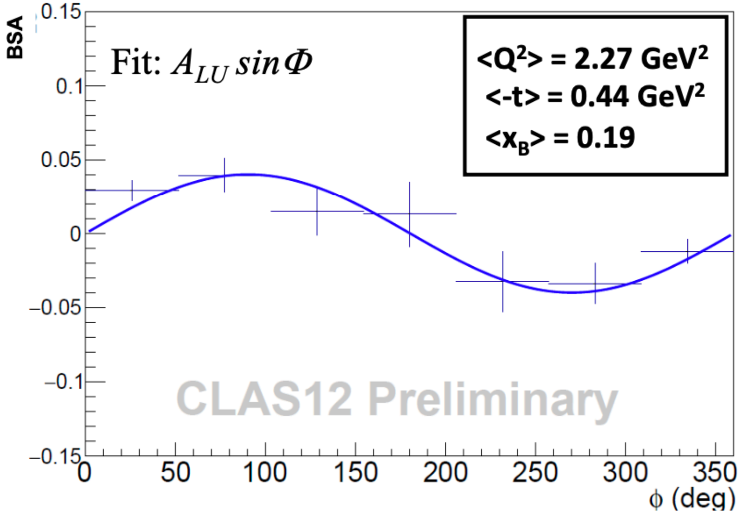
$$A_{LU} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_{LU} = \frac{1}{P}\frac{N^+(\phi_{Trento}) - N^-(\phi_{Trento})}{N^+(\phi_{Trento}) + N^-(\phi_{Trento})}$$

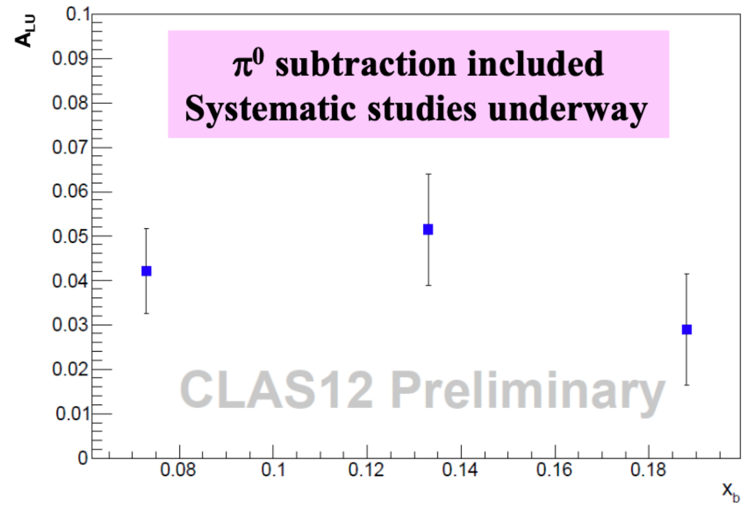
- P: electron polarization
- $N^{+(-)}$: number of photon electroproduction candidates with beam helicity +(-)



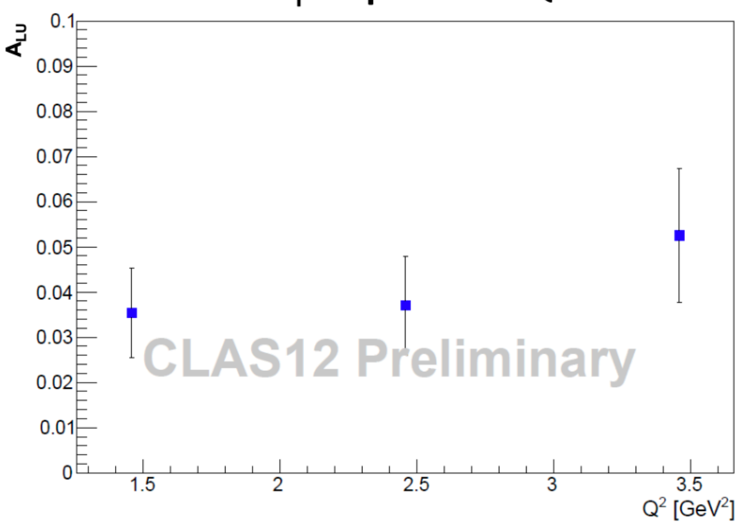
Preliminary neutron DVCS A_{LU} with CLAS12



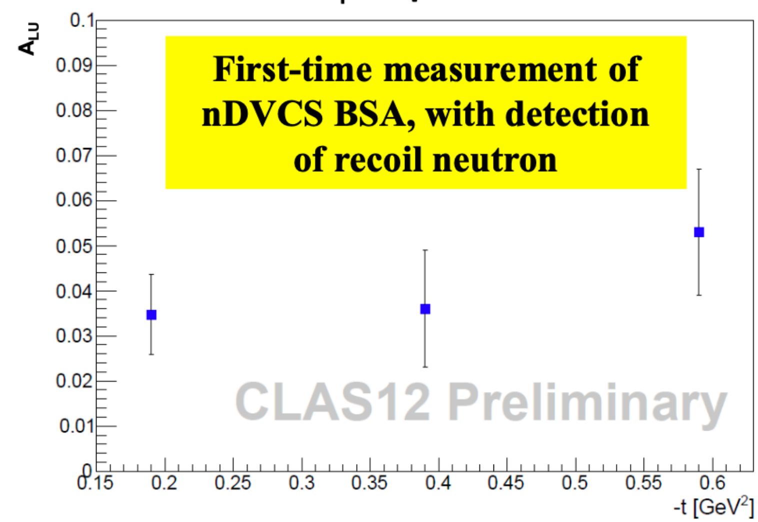
sinϕ amplitude vs x_B



sinϕ amplitude vs Q^2

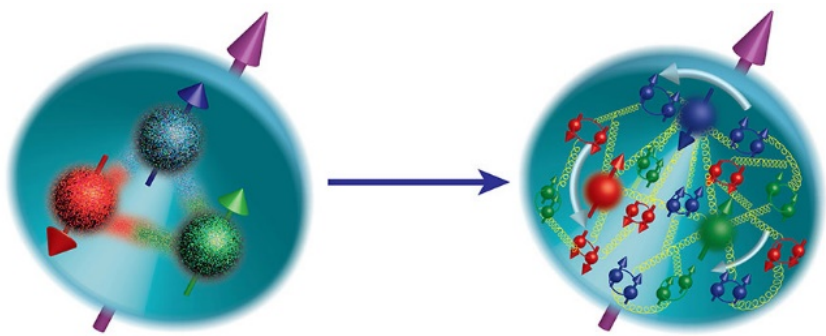


sinϕ amplitude vs -t

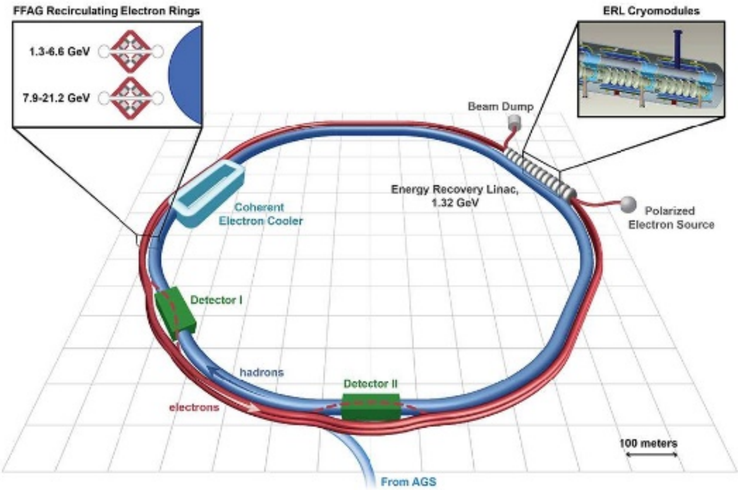


DVCS at the Electron-Ion Collider (EIC)

Nucleon tomography of the gluons and sea quarks (low momentum fraction x)

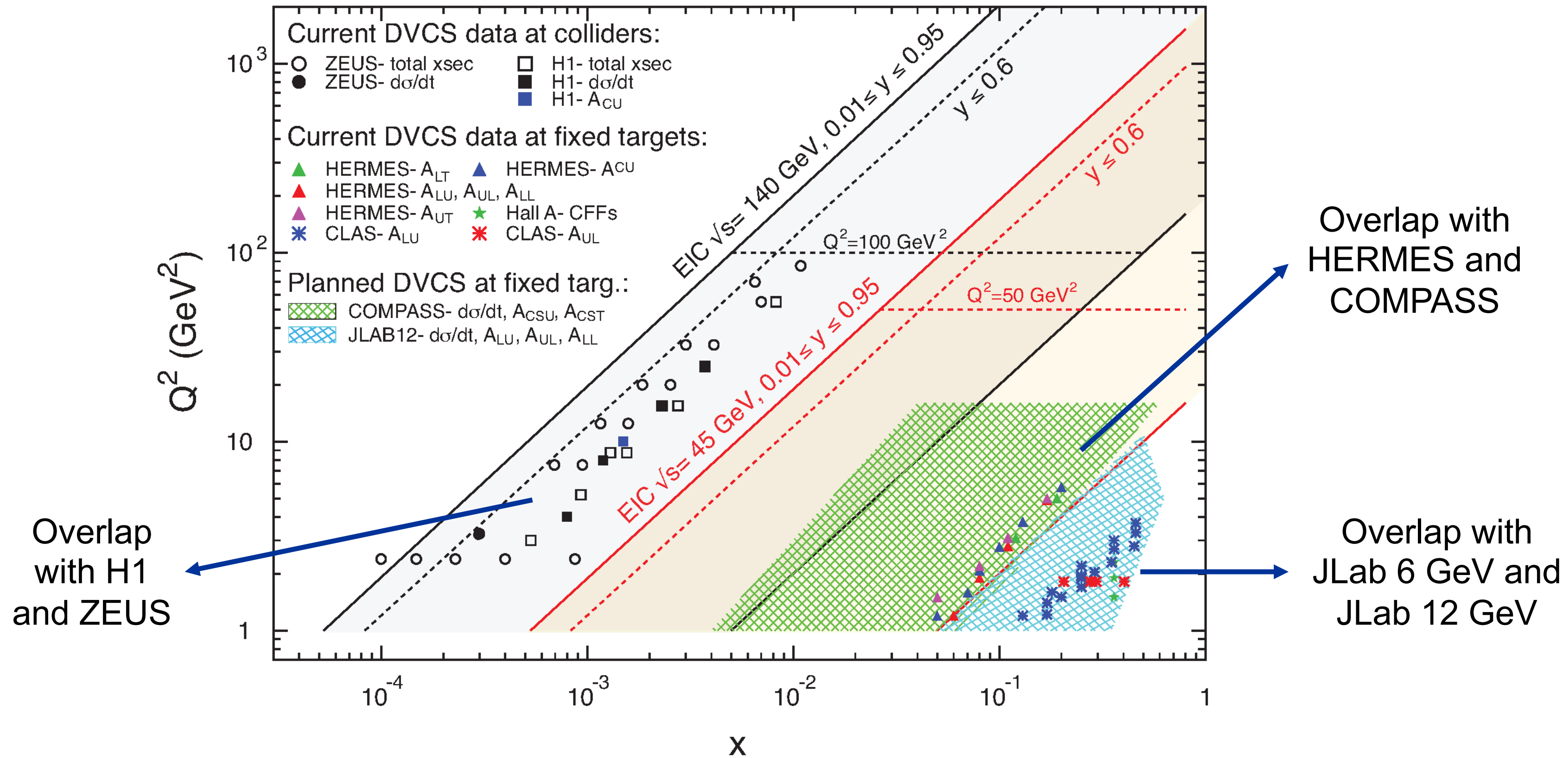


The Electron-Ion Collider (EIC) will be constructed at BNL



eRHIC design (BNL)

DVCS at the EIC : gluons and sea quarks



- Collision of polarized electrons with polarized protons, light and heavy nuclei
- High Luminosity : $L_{ep} \geq 10^{33\text{-}34}$ cm^{-2} s^{-1} (100-1000 times HERA)

Overview

- DVCS 6 GeV CLAS data were used to extract a first experimental result of nucleon tomography.

- Jefferson 12 GeV data will provide high-precision measurements covering a large unexplored kinematic domain at high x.

- While Jefferson Lab is a unique facility to study the valence quarks, the future Electron-Ion Collider (EIC) will provide high-precision GPD measurements at low x, allowing us to perform nucleon tomography of the gluons and sea quarks.

Thank you