Nucleon tomography with GPDs at the EIC

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2020 KPS Fall Meeting

Focus Session : Cornerstone for future collider projects

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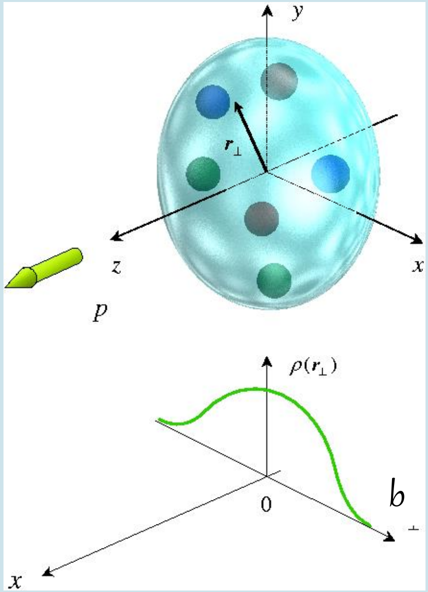
Generalized parton distributions (GPDs)

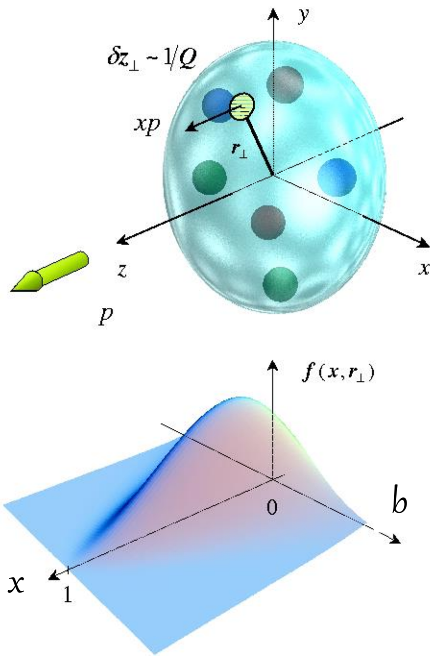
GPDs, accessible via exclusive reactions, provide a **correlation** between the transverse position and the longitudinal momentum of the quarks in the nucleon



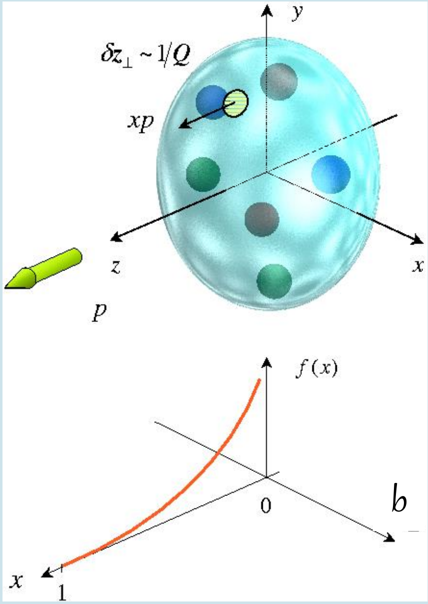
Form Factors (elastic scattering) :

Transverse position of the quarks in the nucleon

Nucleon tomography



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



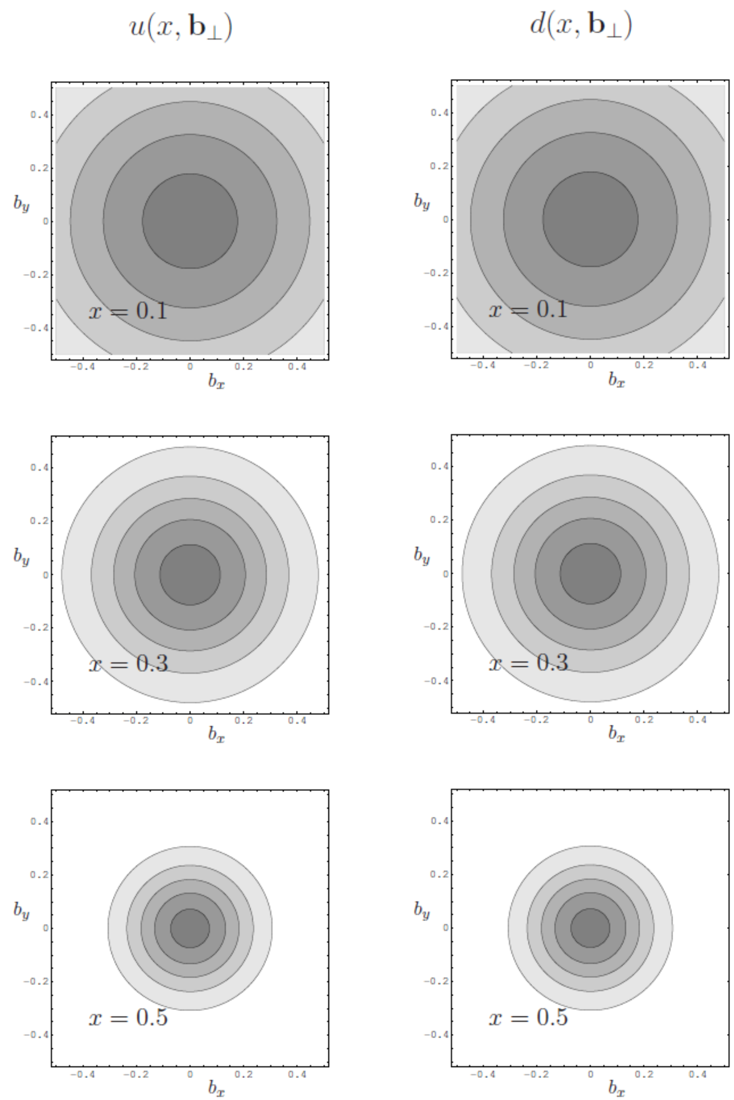
Parton Distribution Functions (deep inelastic scattering) :

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 partons inside the nucleon for different values of longitudinal momentum fraction x

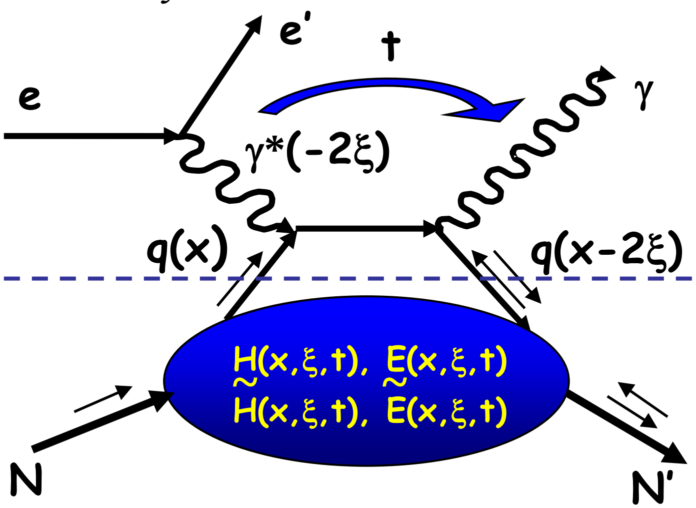


Deeply Virtual Compton Scattering (DVCS) and GPDs

high Q^2, small t, fixed x_B

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

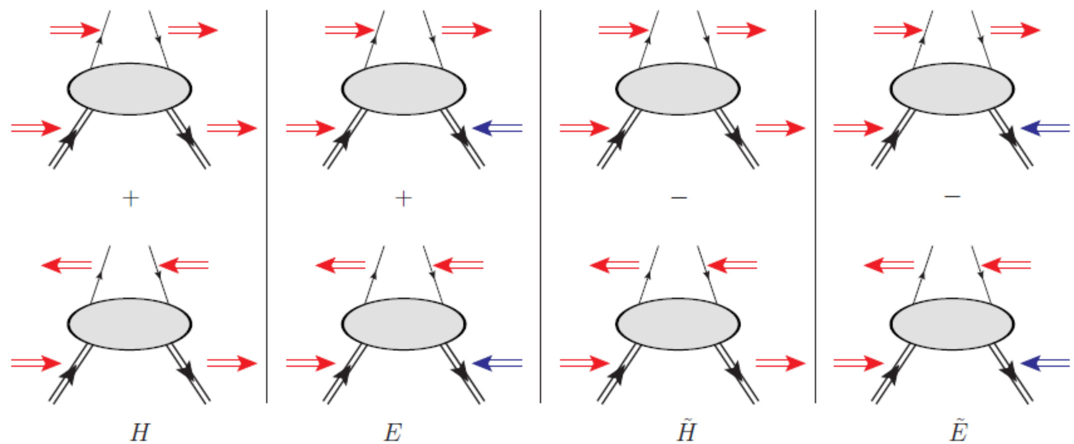
DVCS



e N ⟶ e' N' γ

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

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

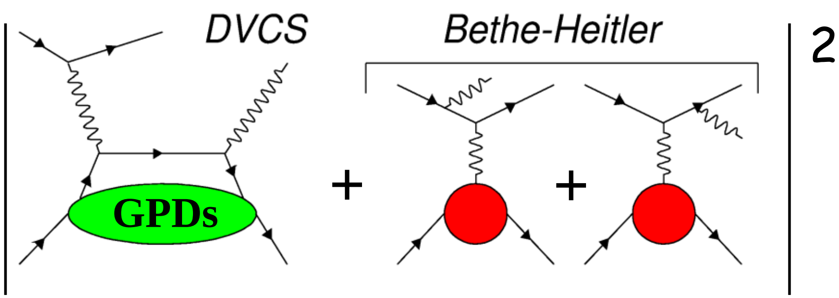


$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

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

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

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

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

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

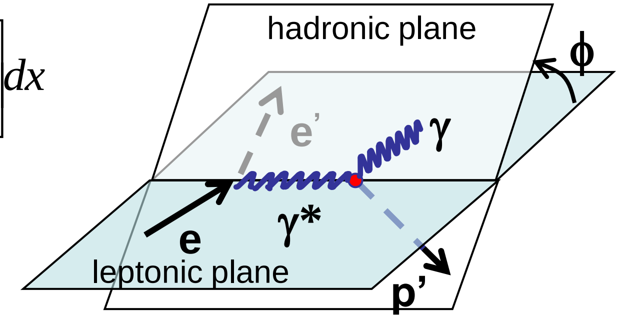
Ji's angular momentum sum rule:

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

Compton Form Factors (CFFs) and DVCS observables

Compton Form Factors (CFFs)

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



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

Each DVCS observable is sensitive to a different combination of GPDs

Proton Neutron

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

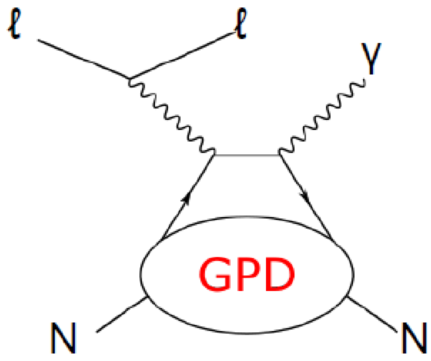
Unpolarized beam, longitudinal target:
$\Delta\sigma_{UL} \sim \sin\phi \mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2 \widetilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

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

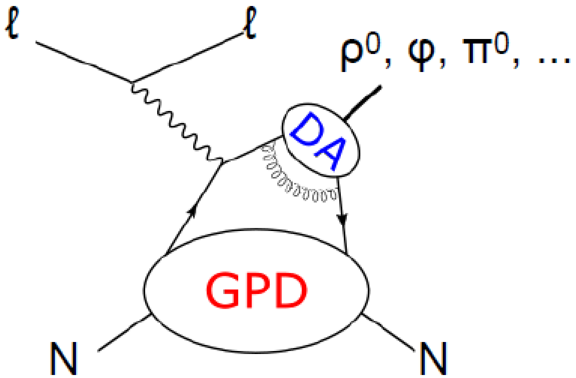
Unpolarized beam, transverse target:
$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \dots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

Quark-flavor separation of GPDs

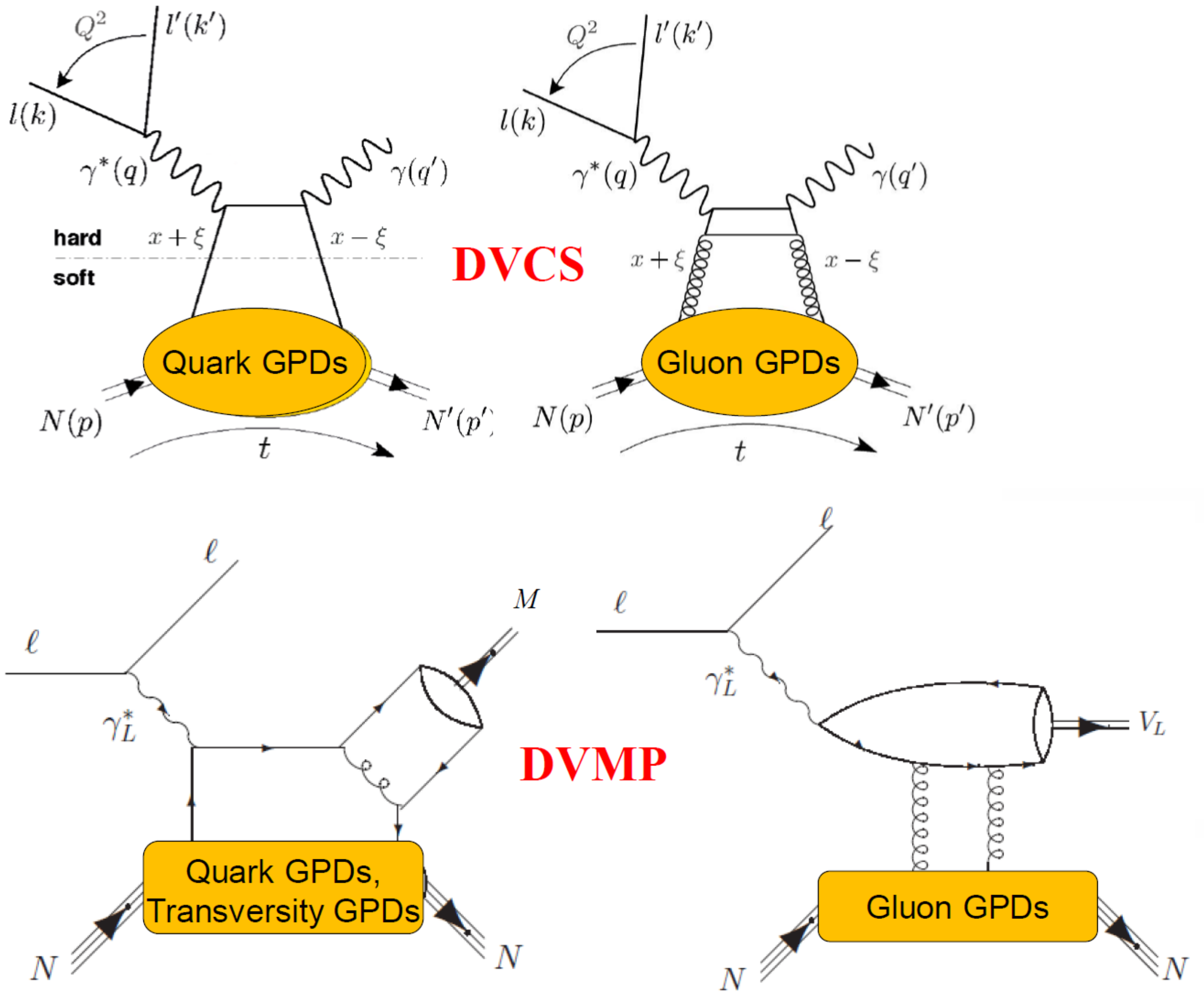
- 1st method : Neutron DVCS
  - A combined analysis of DVCS observables for proton and neutron (deuterium) targets is needed to perform a quark-flavor separation of the GPDs
  - High sensitivity to GPD E with a polarized beam



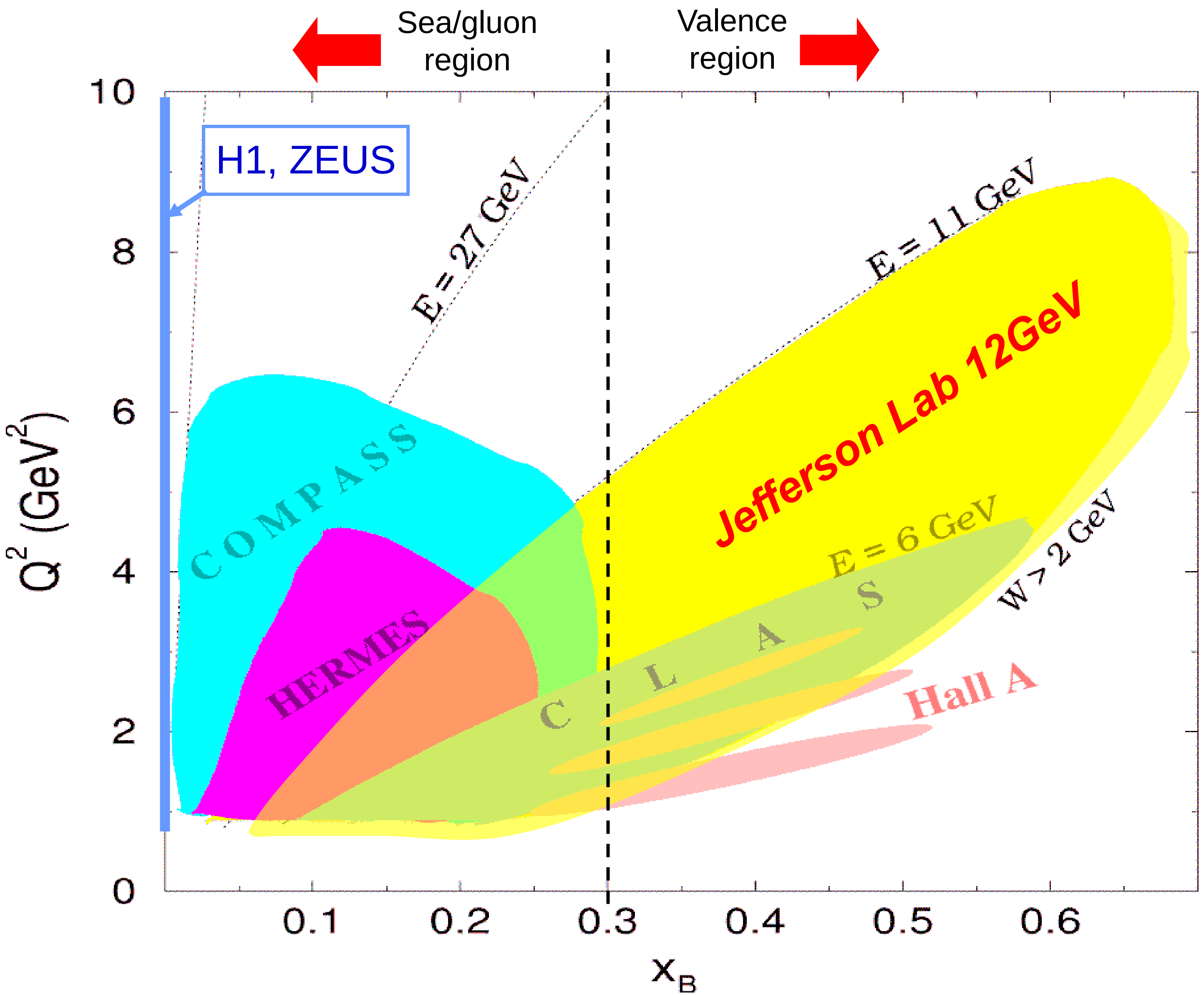
- 2nd method : Deeply virtual meson production (DVMP)
  - DVMP cross-section measurements are another way to access quark-flavor separation of GPDs
  - Gives also access to transversity GPDs (chiral-odd GPDs, where parton helicity is changed)



DVCS and DVMP diagrams for gluons GPDs

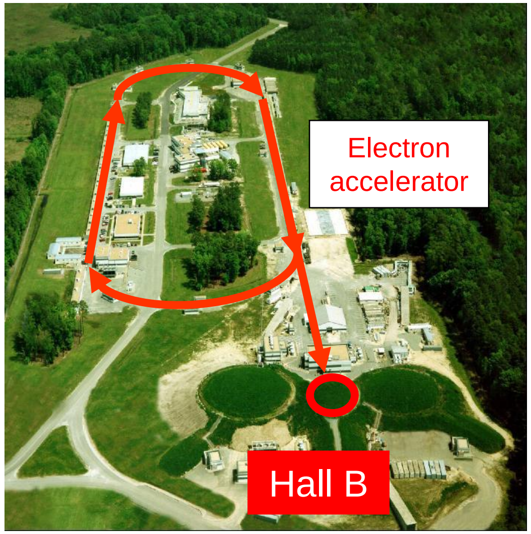


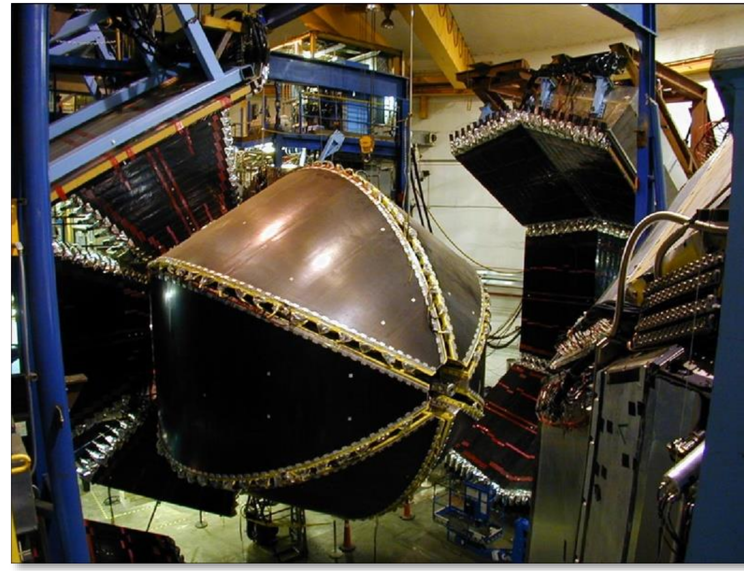
Kinematic coverage of past and current DVCS experiments

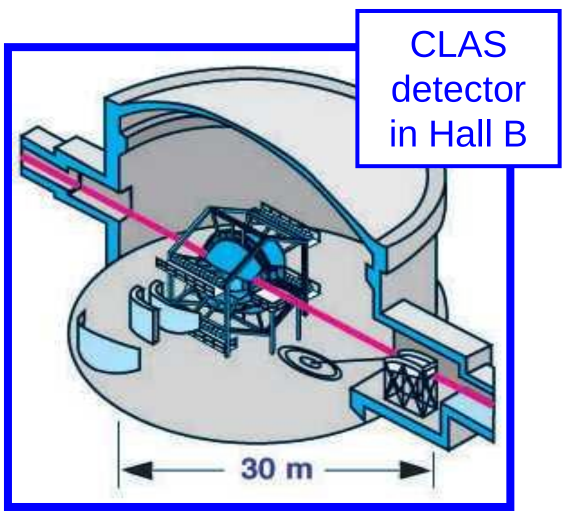


Jefferson Lab 6 GeV and the CLAS detector

Jefferson Lab

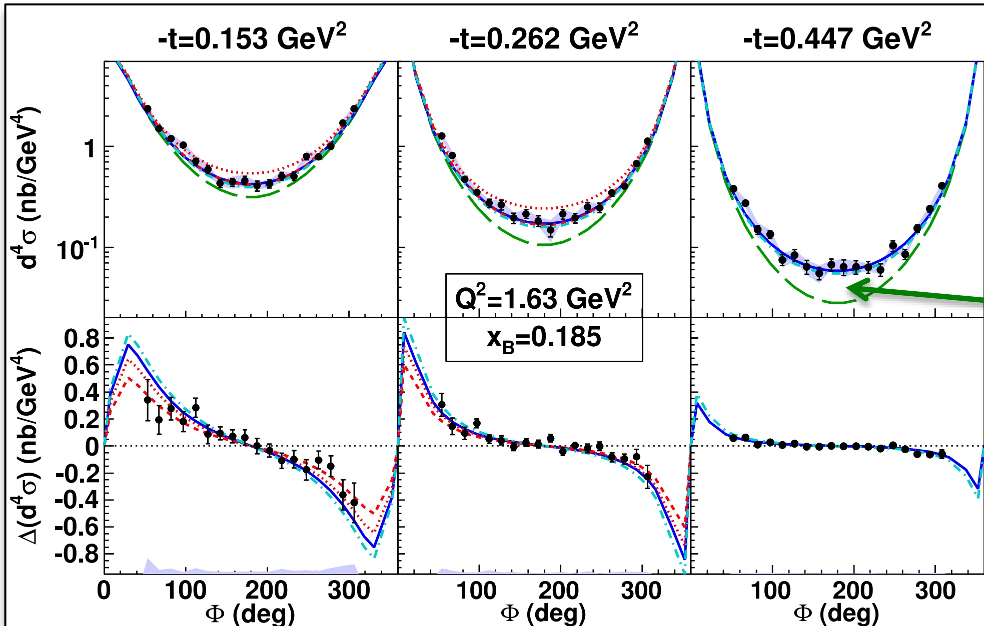






DVCS unpolarized and beam-polarized cross sections from CLAS data

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

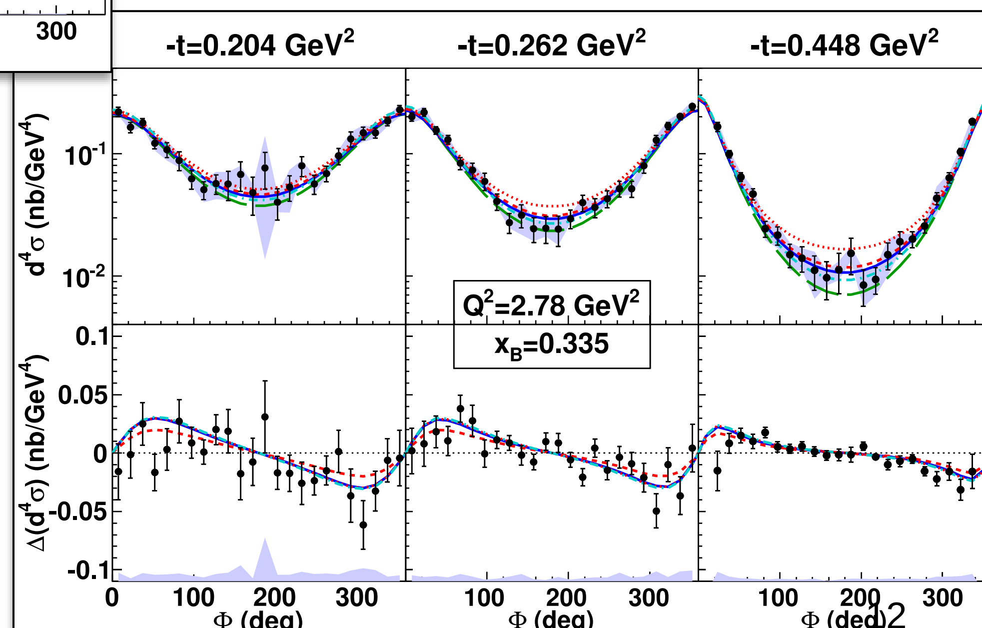


$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}(nb/GeV^4)$$

DVCS + interference

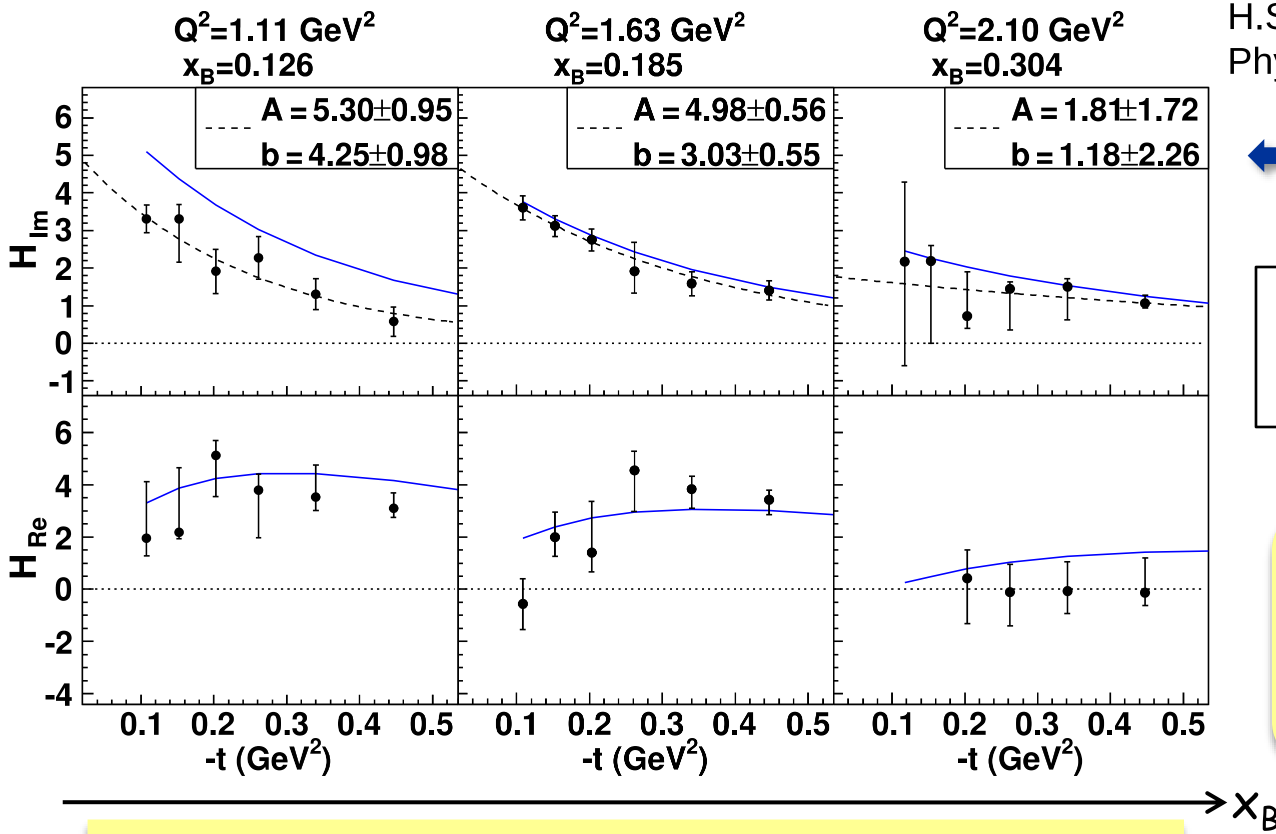
$$\frac{1}{2}\left(\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}-\frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}\right)(nb/GeV^4)$$

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)

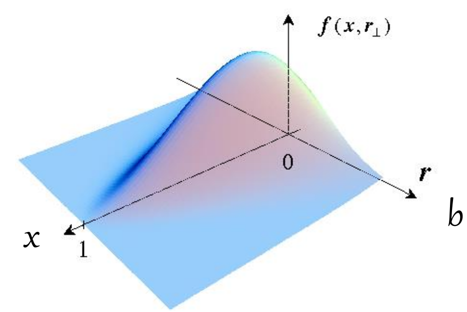
b : transverse position of the quarks in the nucleon

- - - *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**

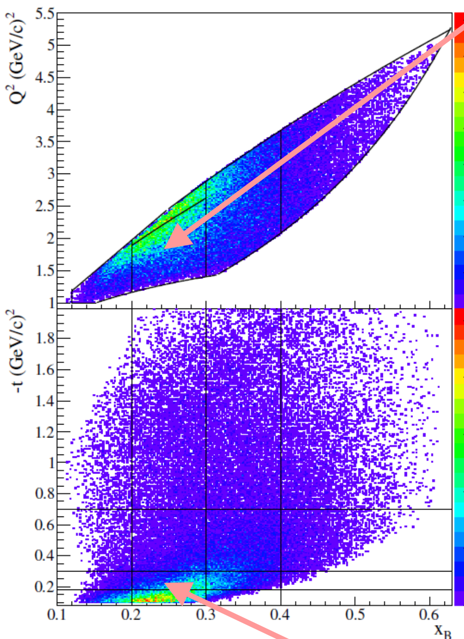
DVCS on longitudinally polarized target from CLAS data

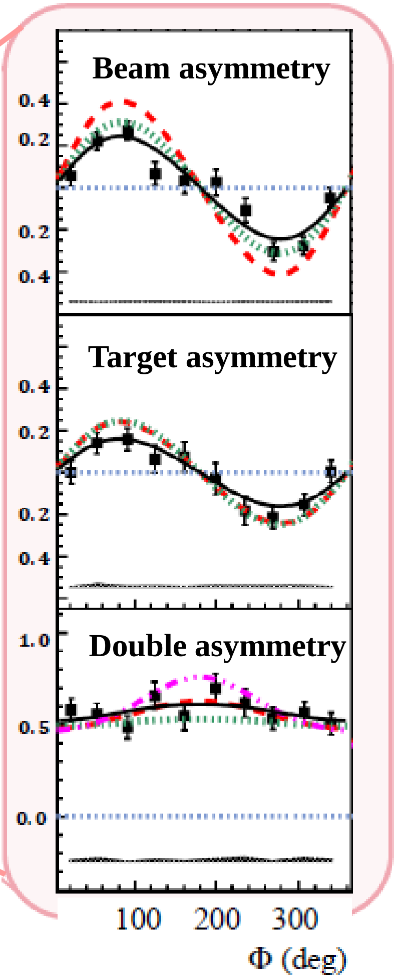
- **eg1-dvcs experiment**
- Beam energy **~6 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**

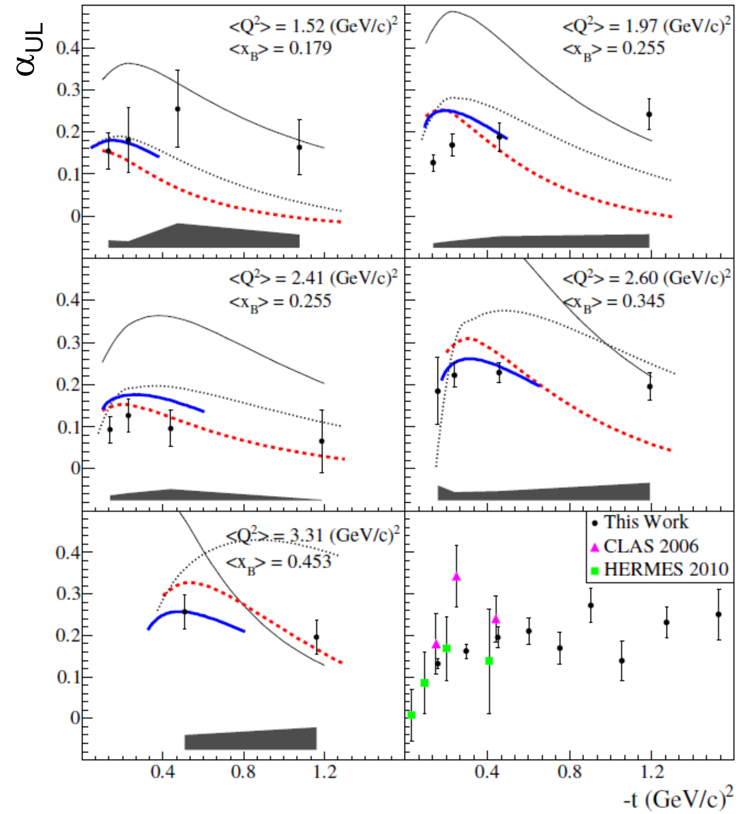
$\vec{e}\vec{p} \rightarrow ep\gamma$

$A_{UL} \sim Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

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







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

- Improved statistics ×10 at low *–t*
- Extended kinematic coverage

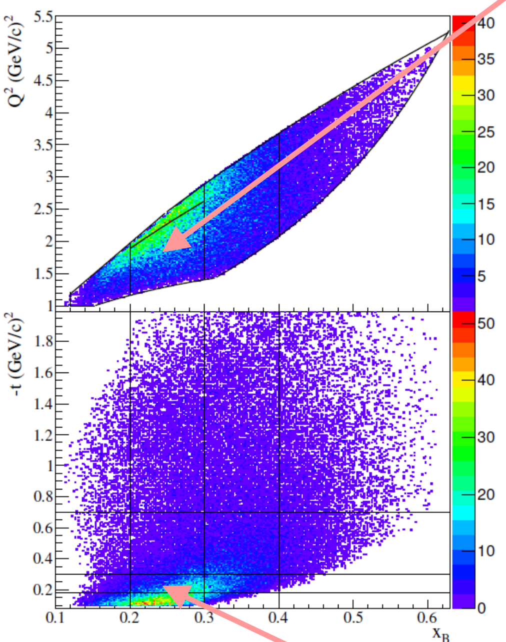
E. Seder *et al.* (CLAS Collaboration), Phys. Rev. Lett. 114, 032001 (2015)

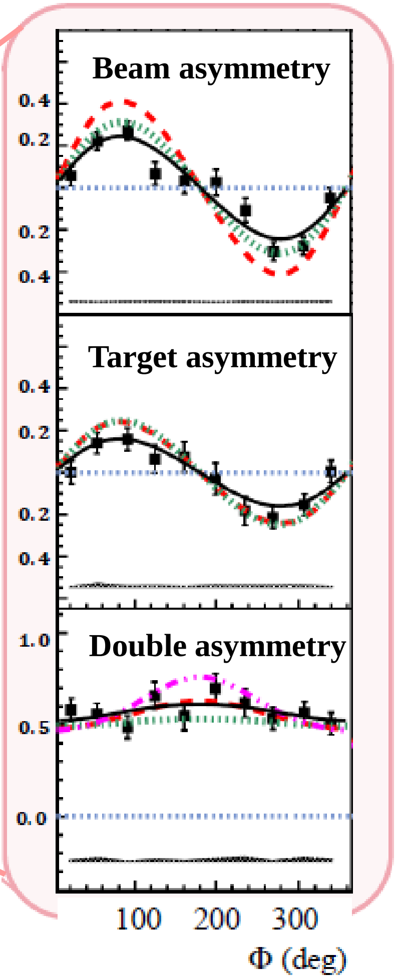
DVCS on longitudinally polarized target from CLAS data

- **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**
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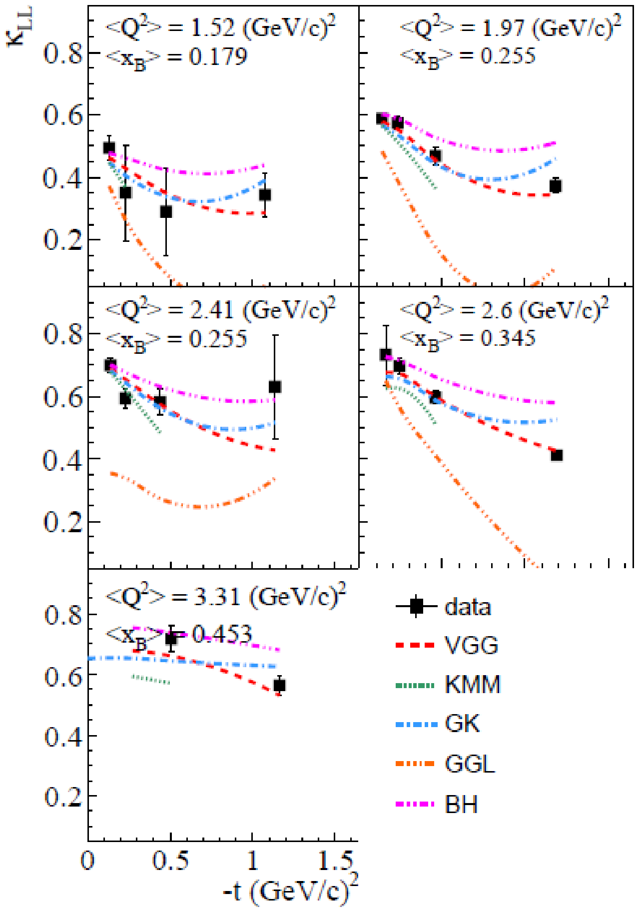
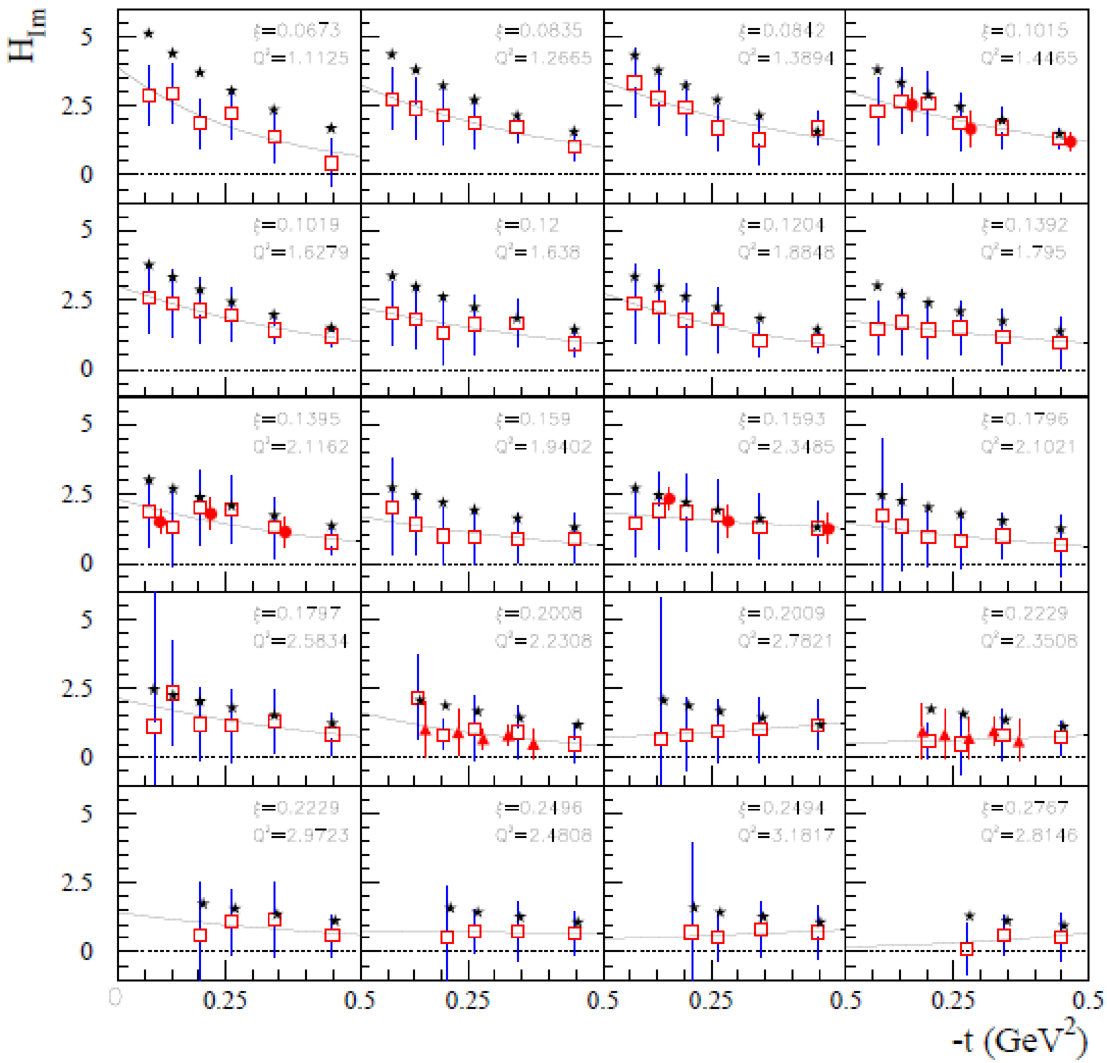


S. Pisano *et al.* (CLAS Collaboration), Phys. Rev. D 91, 052014 (2015)

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

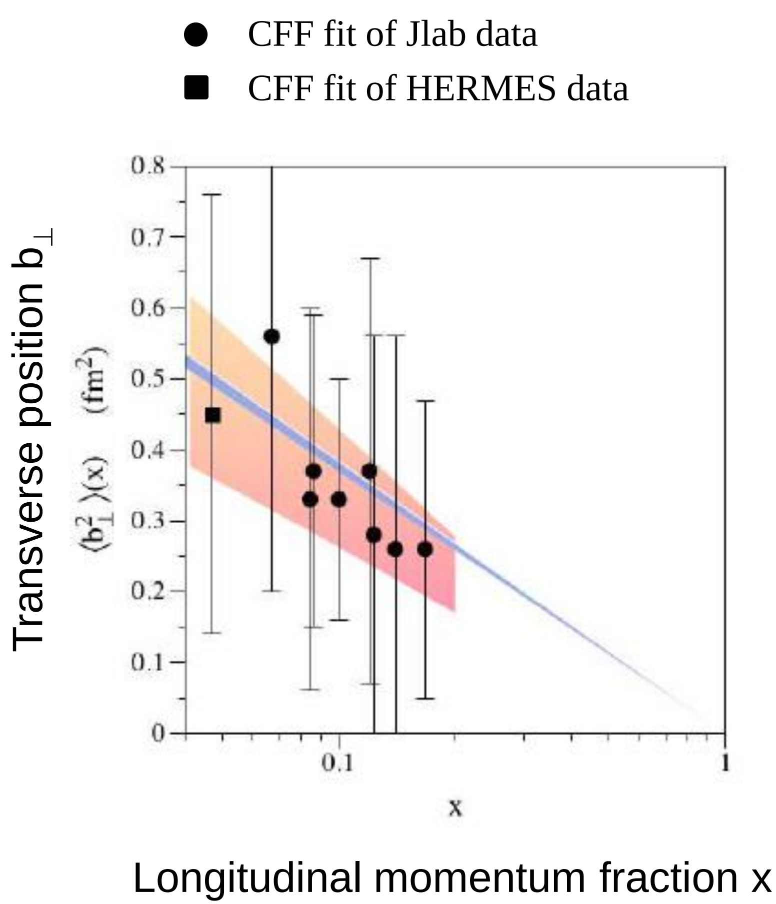
Fits in each (Q^2, x_B, t) bin of data

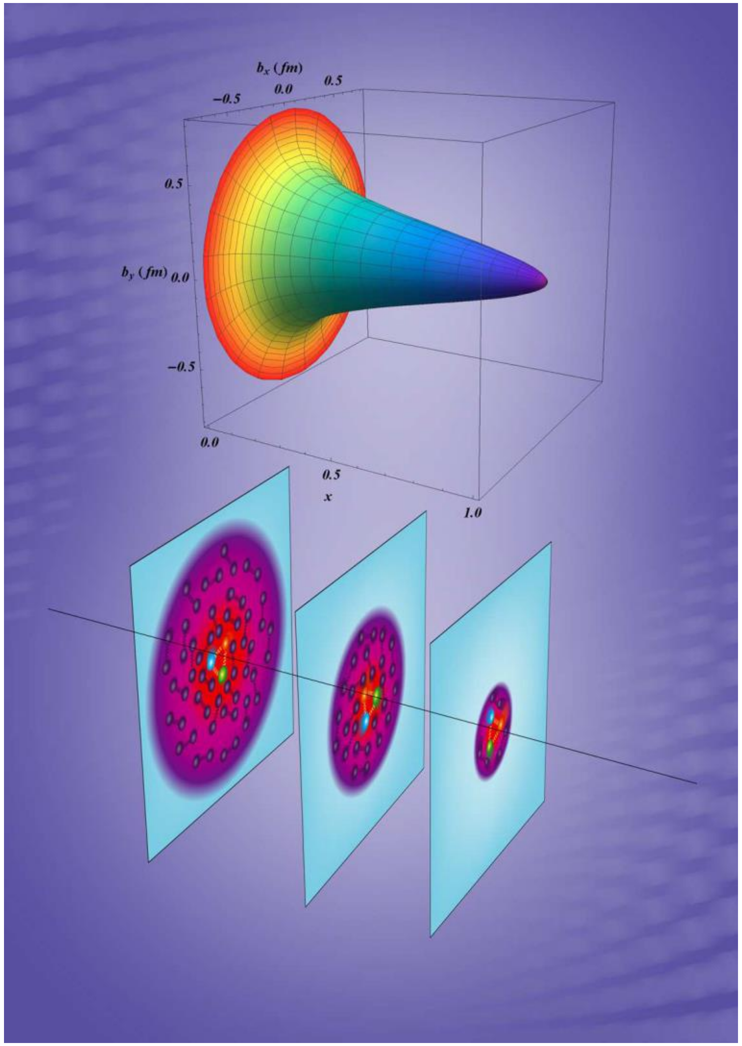
$$H_{Im}(\xi,t) = A(\xi)e^{b(\xi)t}$$

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

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

From CFFs to proton tomography





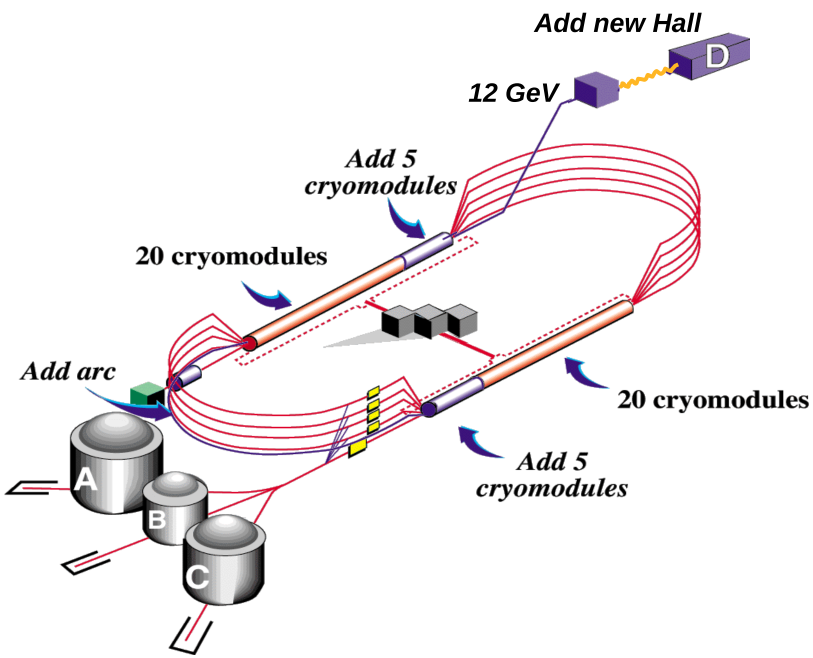
R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen,
Eur. Phys. J. A 53, 171 (2017)

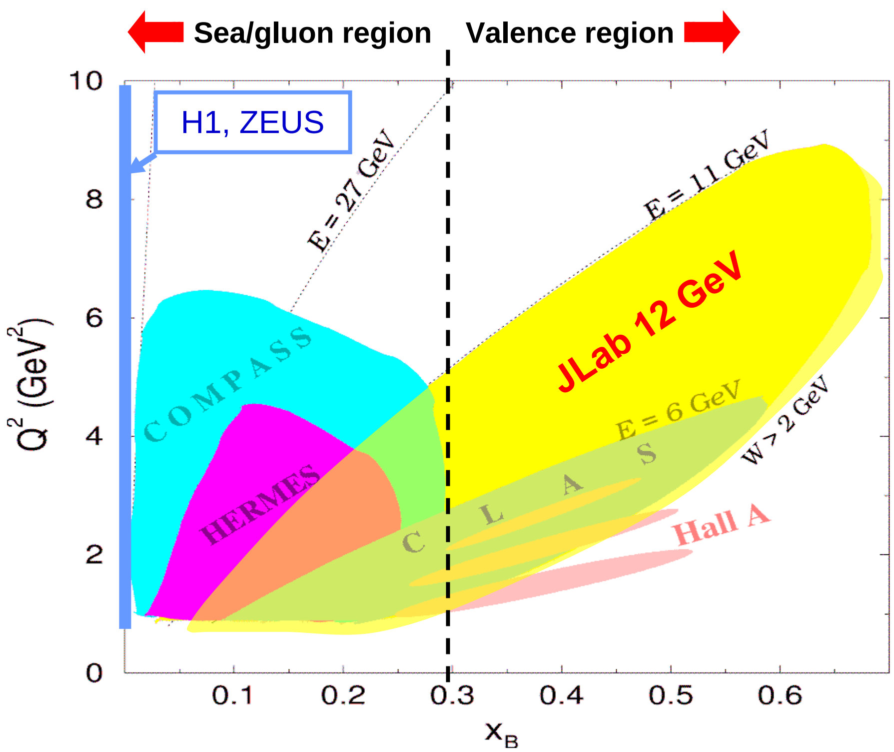
Jefferson Lab upgrade to 12 GeV

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

Beam polarization > 80%

Accelerator 12 GeV upgrade



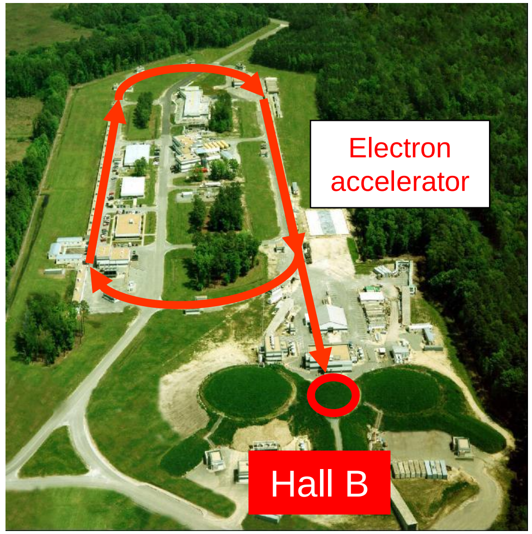


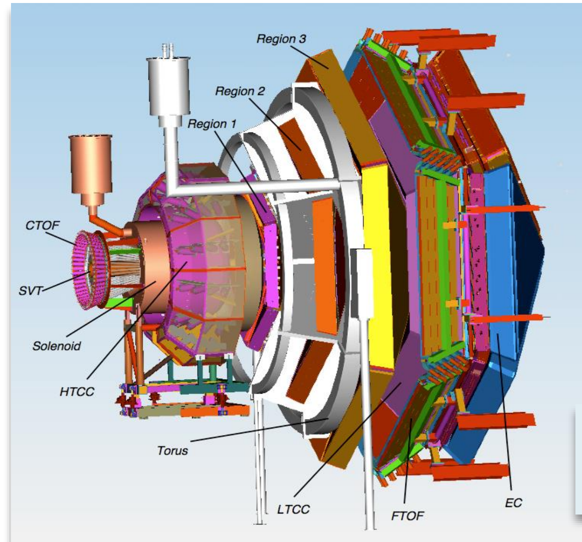
Study of high x_B domain requires high luminosity

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

Jefferson Lab 12 GeV and the new CLAS12 detector

Jefferson Lab

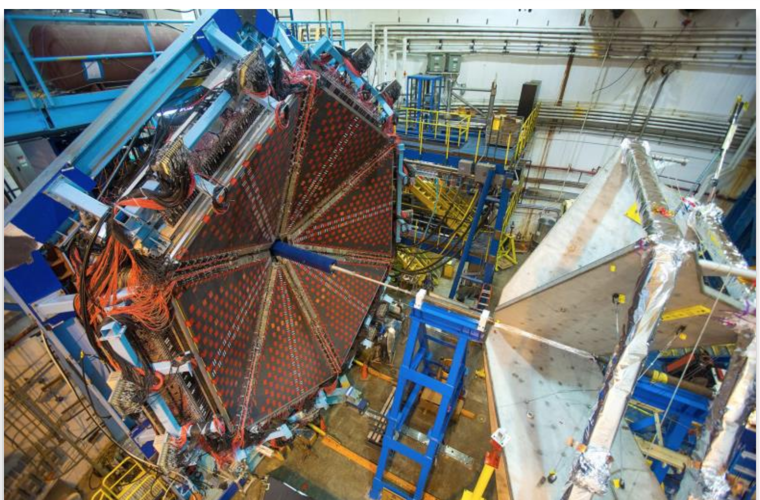




CLAS12 detector in Hall B

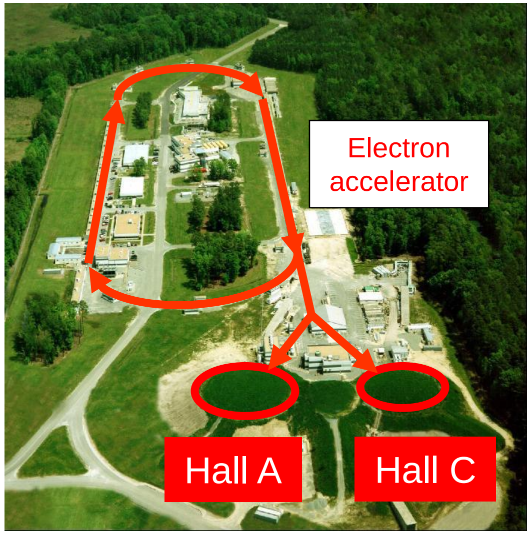
Design luminosity $L \sim 10^{35}\ cm^{-2}s^{-1}$

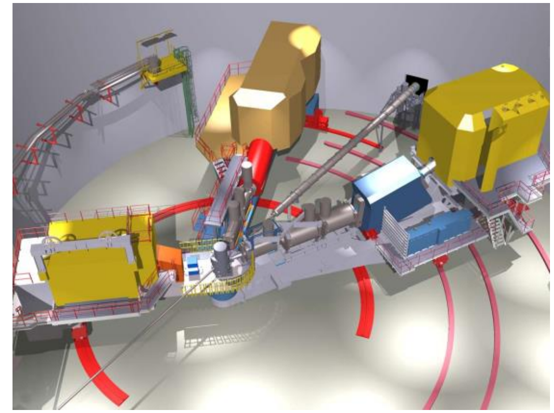
Data taking with the new CLAS12 detector started in 2018



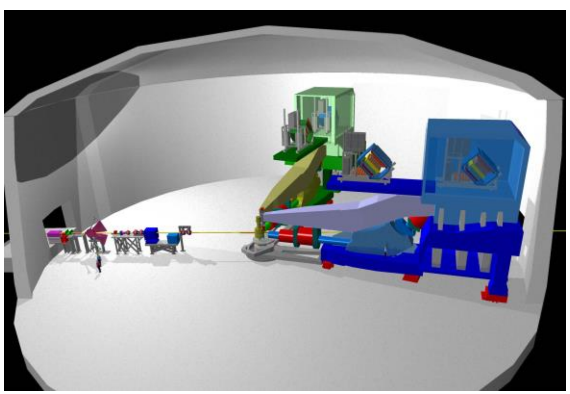
DVCS experiments in Hall A and Hall C of Jefferson Lab

Jefferson Lab

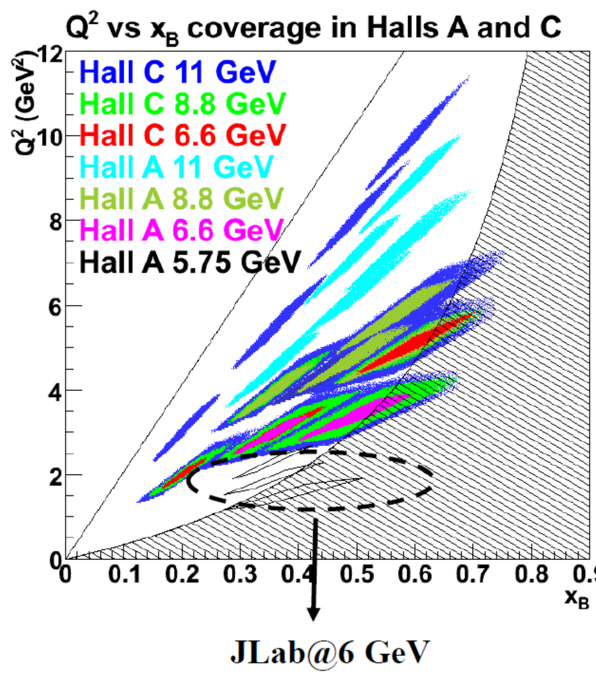




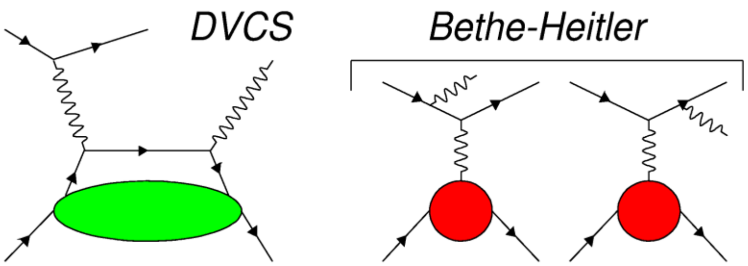
Hall C

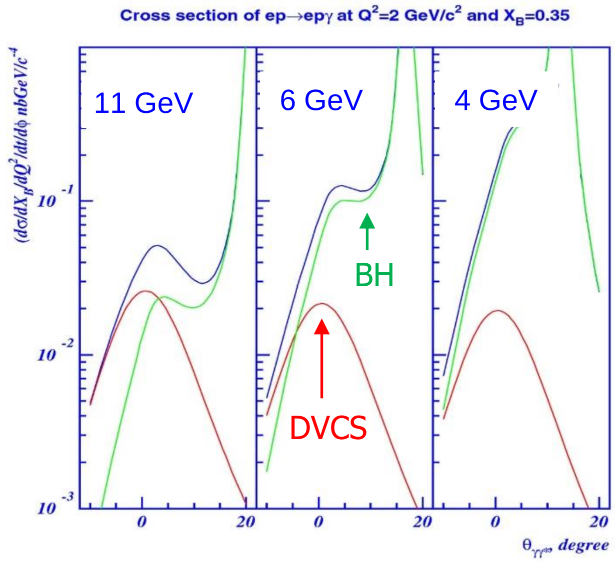


Hall A



Projected results for CFFs with CLAS12



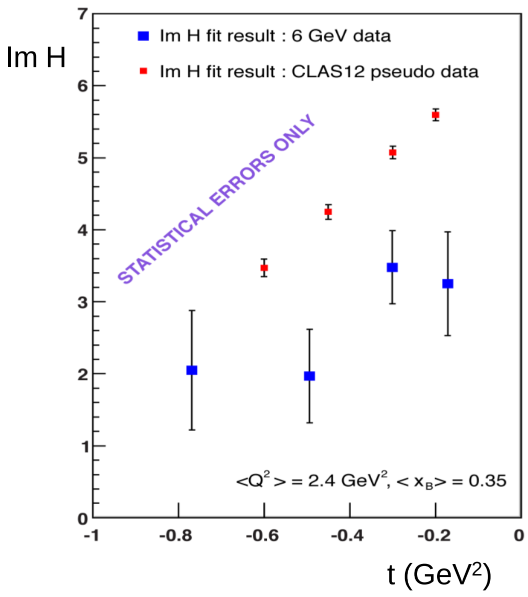


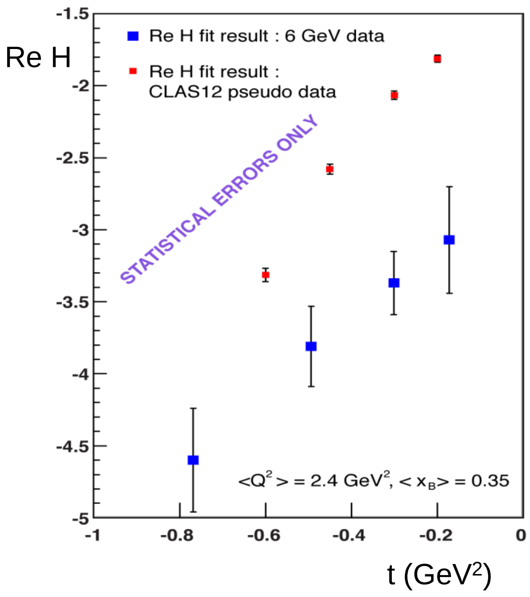
The contribution ratio from BH and DVCS to the ep→epγ cross section changes with the electron beam energy

Impact of CLAS12 DVCS pseudo data on CFF fit

CLAS 6 GeV data

CLAS12 pseudo data





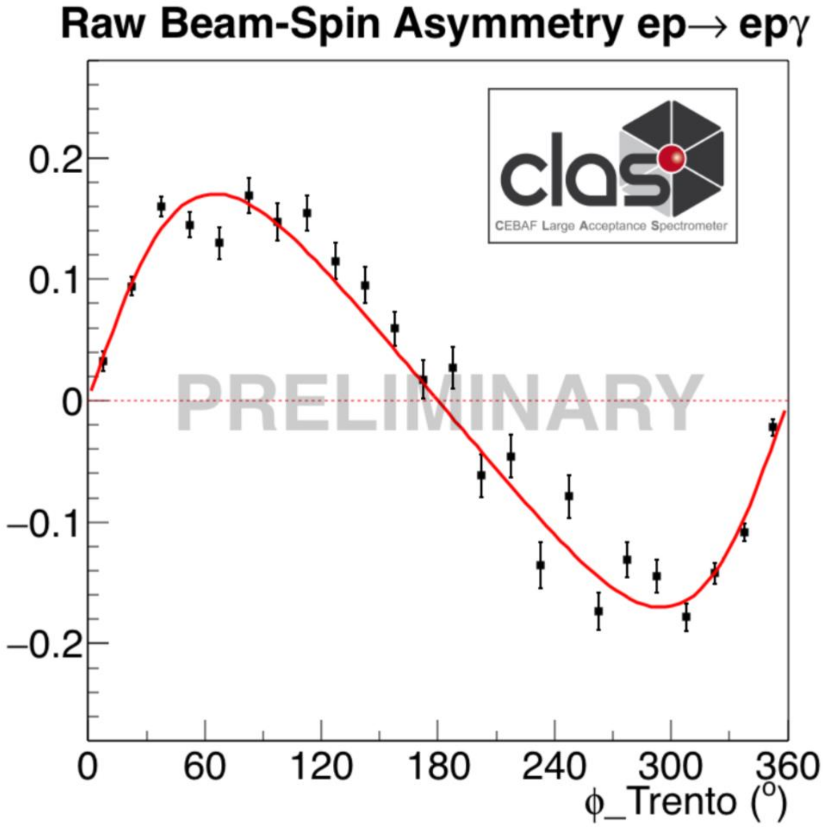
First look at DVCS A_{LU} with CLAS12 preliminary data

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

Beam spin asymmetry

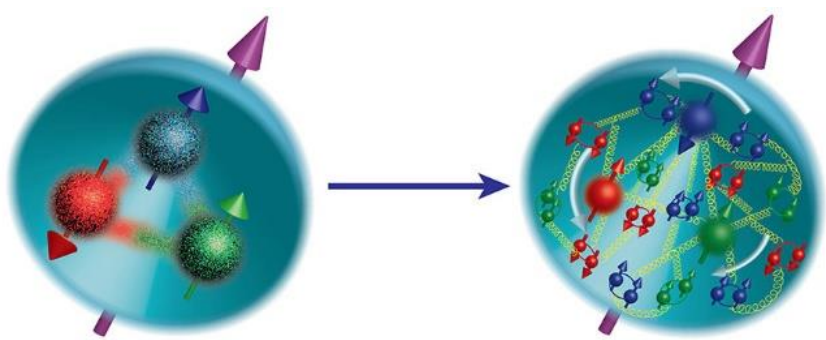
$$A_{LU} = \frac{1}{P} \frac{N^+(\phi_{Trento}) - N^-(\phi_{Trento})}{N^+(\phi_{Trento}) + N^-(\phi_{Trento})}$$

- P: electron polarization
- $N^{+(-)}$: number of photon electroproduction candidates with beam helicity +(-)
- Analysis based on 2% of approved beam time

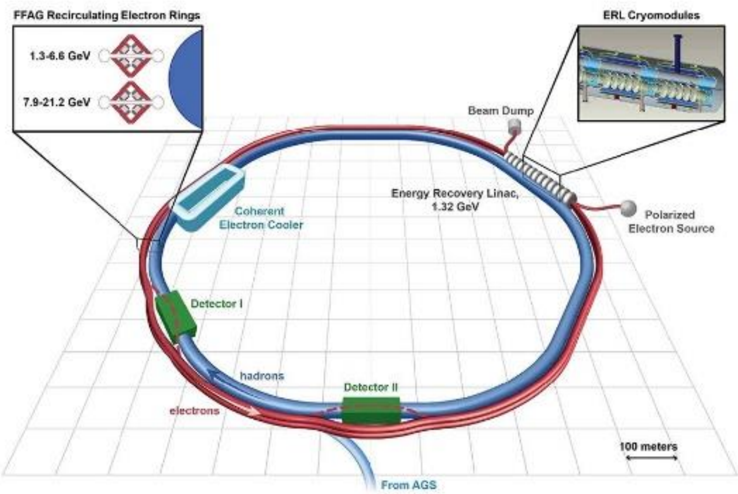


DVCS at the Electron-Ion Collider (EIC)

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

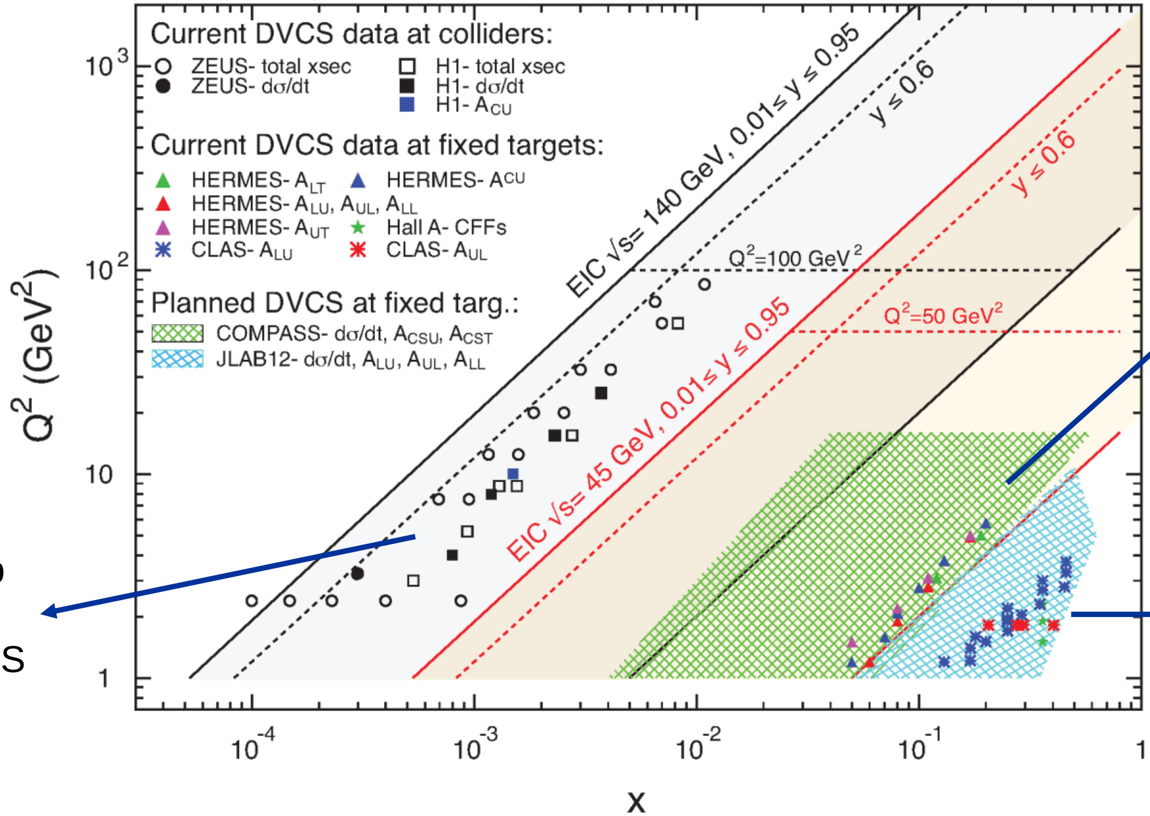


The Electron-Ion Collider (EIC) will be constructed at BNL



eRHIC design (BNL)

DVCS at the EIC : gluons and sea quarks



Overlap with H1 and ZEUS

Overlap with HERMES and COMPASS

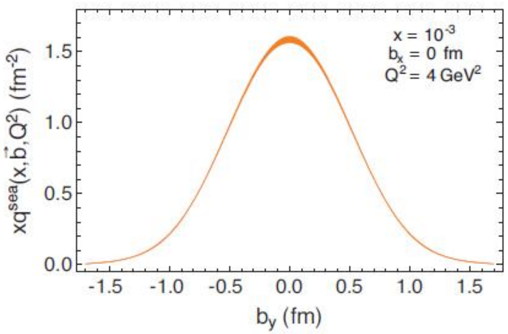
Overlap with JLab 6 GeV and JLab 12 GeV

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

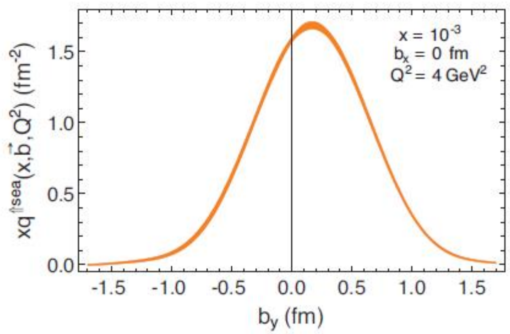
Spatial distributions of sea quarks from EIC DVCS pseudo data

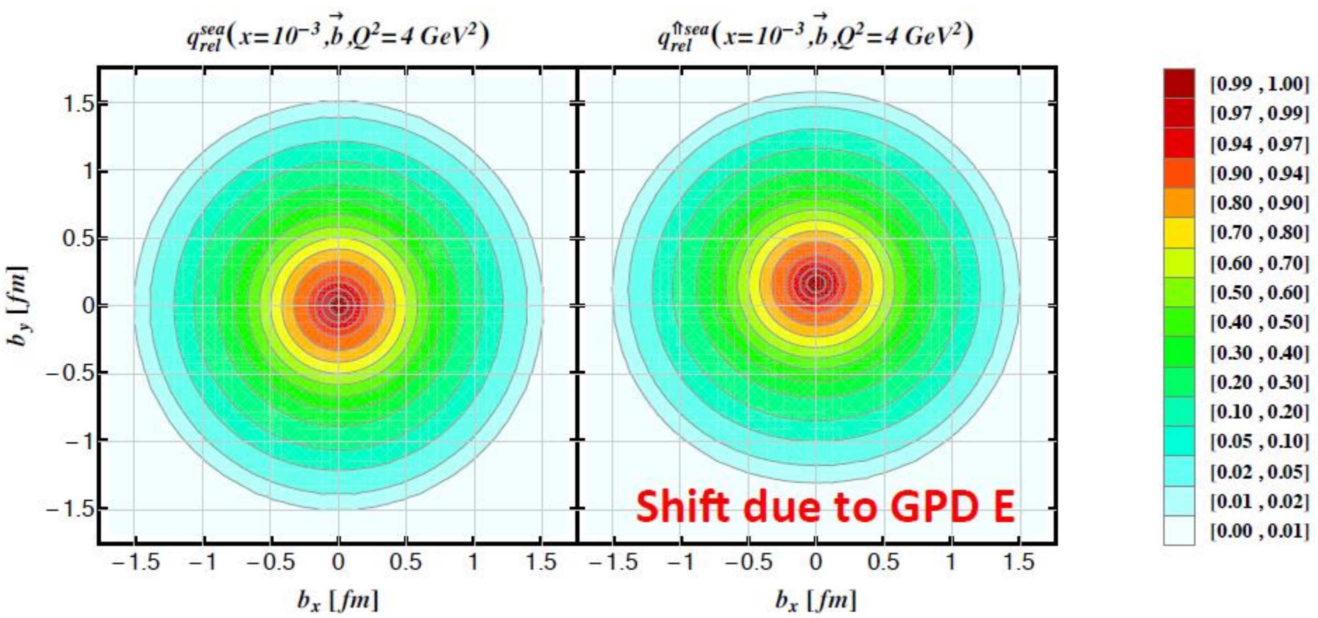
Spatial distributions obtained from GPD fits to EIC simulated DVCS data

Unpolarized proton



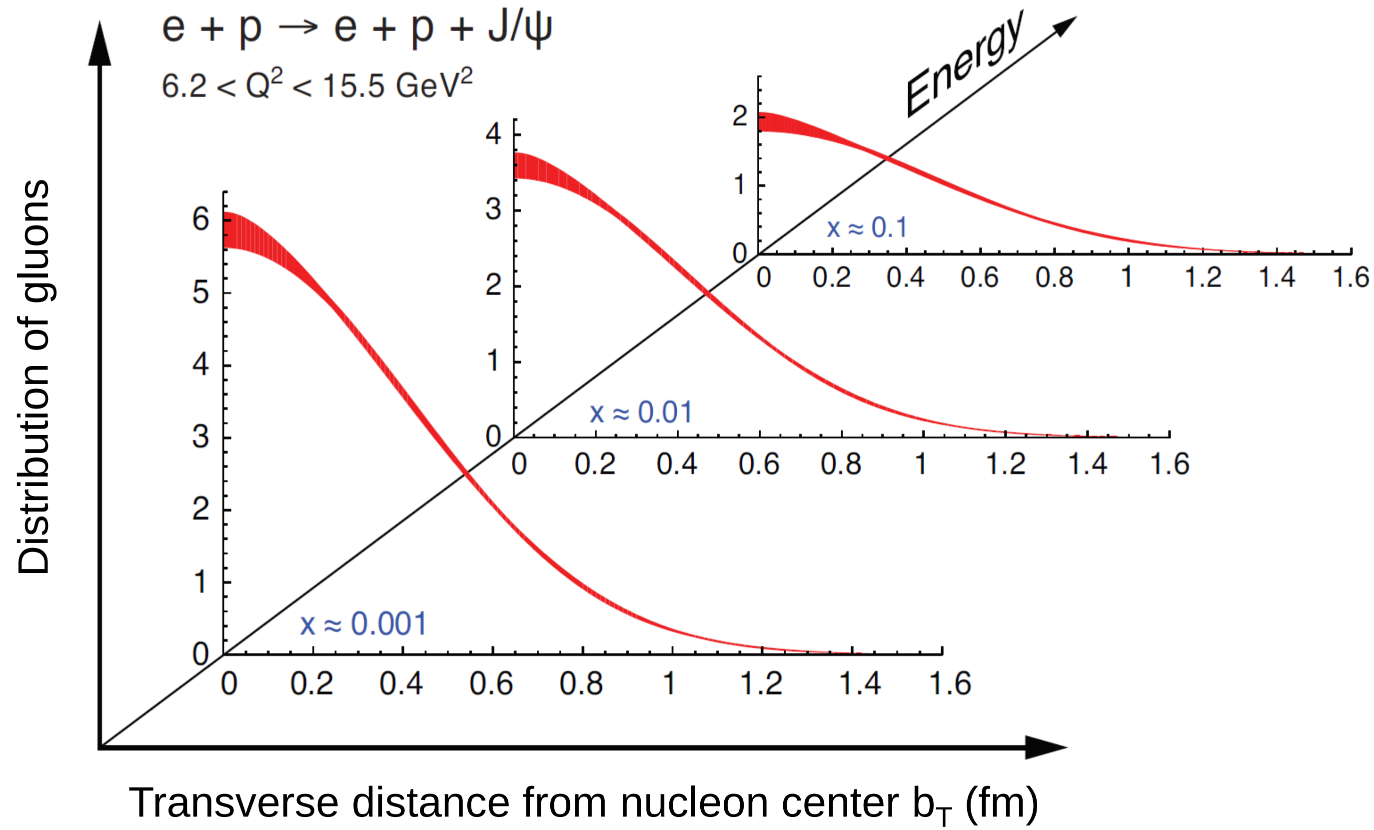
Transversely polarized proton





Gluon distributions from EIC J/ψ pseudo-data

Projected gluon distributions vs transverse distance from the center of the nucleon from EIC pseudo-data of J/ψ production cross section



Overview

- DVCS data from Jefferson Lab 6 GeV were used to extract a first experimental result of nucleon tomography.
- Jefferson Lab 12 GeV will provide high-precision data 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