DVCS measurements with CLAS12

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Kyungpook National University

ECT*-APCTP Joint Workshop:
Exploring resonance structure with transition GPDs

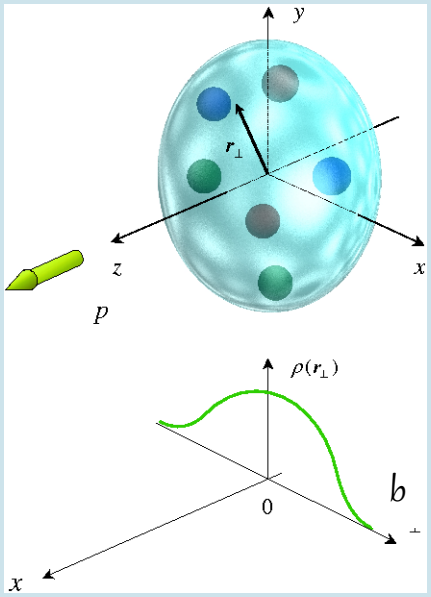
ECT*, Villazzano (Trento) - 2023.08.21

Outline

- GPDs and Deeply virtual Compton scattering (DVCS)
- Selected DVCS results from CLAS
- DVCS measurements with CLAS12
- Overview

Generalized parton distributions (GPDs)

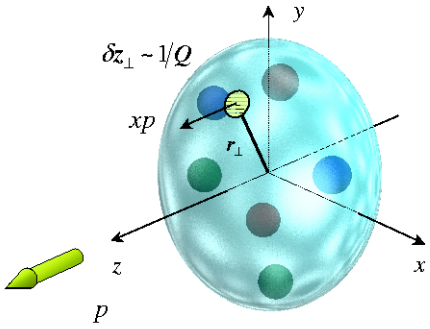
GPDs, accessible via exclusive reactions, provide a **correlation** between the transverse position and the longitudinal momentum of the partons (quarks and gluons) in the nucleon

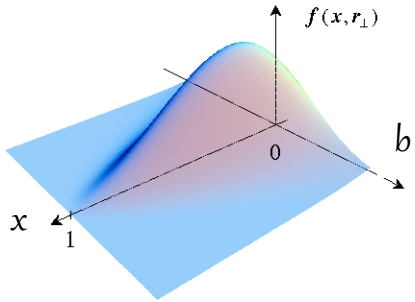


Form Factors (accessed via elastic scattering) :

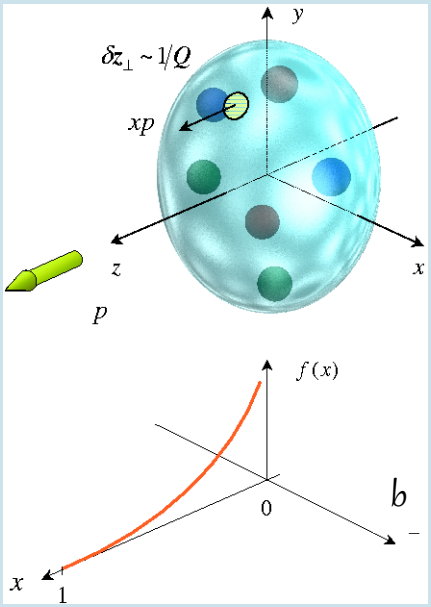
Transverse position of the partons in the nucleon

Nucleon tomography





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



Parton Distribution Functions (accessed via deep inelastic scattering) :

Longitudinal momentum of the partons in the nucleon

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:

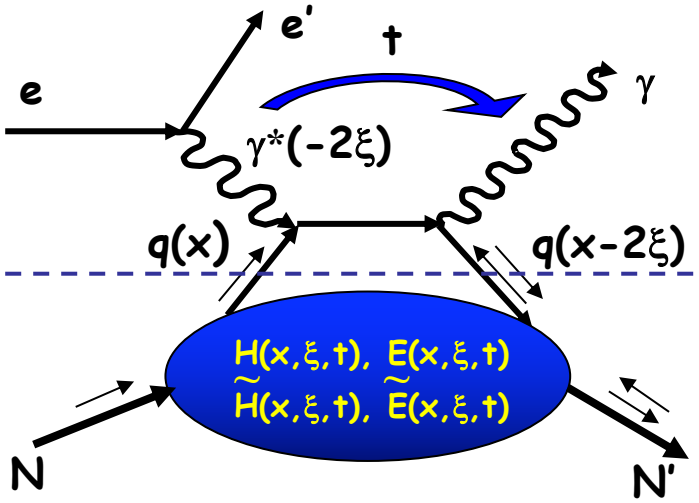
$$J^{q,g} = \frac{1}{2}\int_{-1}^{1} x dx \left(H^{q,g}(x,\xi,t=0) + E^{q,g}(x,\xi,t=0)\right)$$

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.

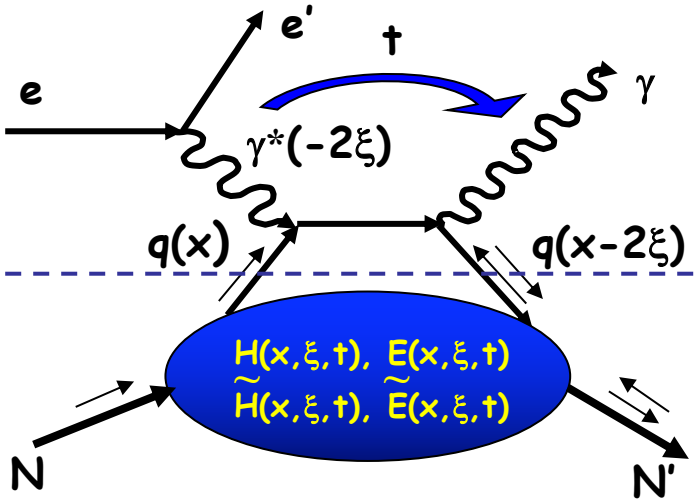
$t = (p' - p)^2$ squared momentum transfer to the nucleon.

Deeply Virtual Compton Scattering (DVCS) and GPDs

High Q^2, small t

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

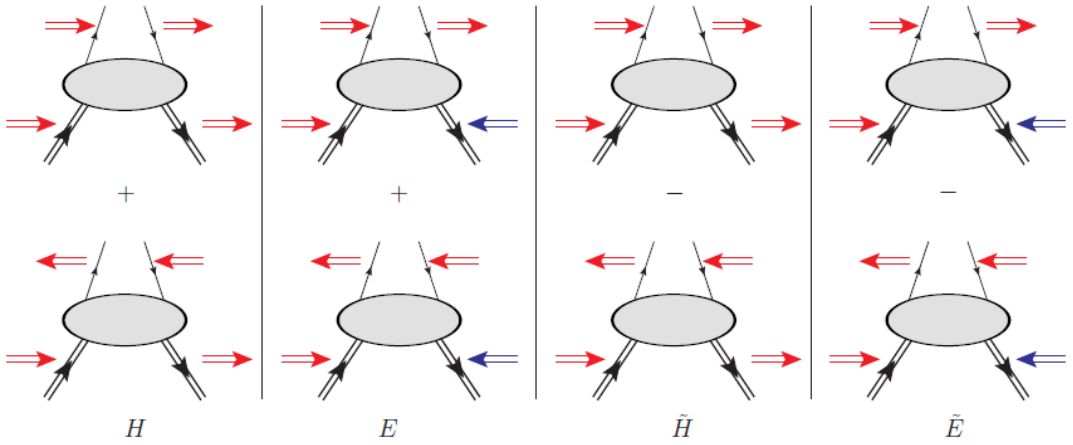
DVCS



e N ⟶ e' N' γ

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

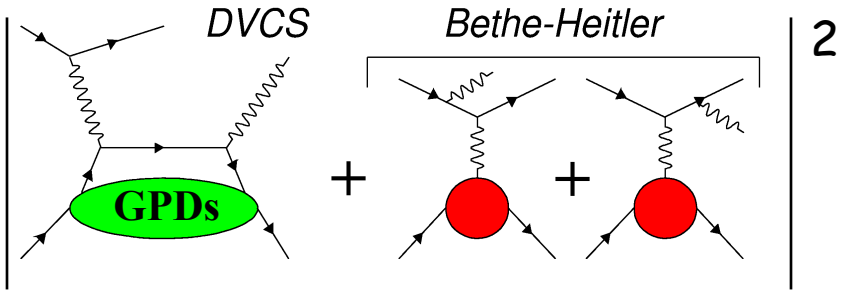
At leading-order QCD, there are 4 chiral-even (parton helicity is conserved) GPDs for each parton



$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*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

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

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

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

Compton Form Factors (CFFs) and DVCS observables

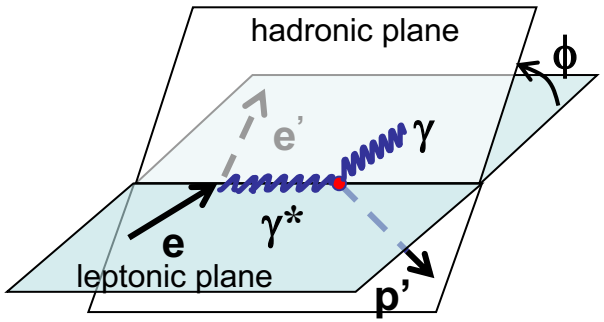
Compton Form Factors (CFFs)

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

← Integrals of GPDs over x

← GPDs at $x = \pm\xi$

Each DVCS observable is sensitive to a different combination of CFFs



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

Proton Neutron

Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \widetilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\widetilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

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

Unpolarized beam, transverse target:

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

Quark-flavor separation of GPDs

The extraction of the quark GPDs which requires a quark-flavor separation of GPDs can be done through a combined analysis of DVCS observables for the proton and the neutron (deuterium target)

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

Proton Neutron

Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \widetilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\widetilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

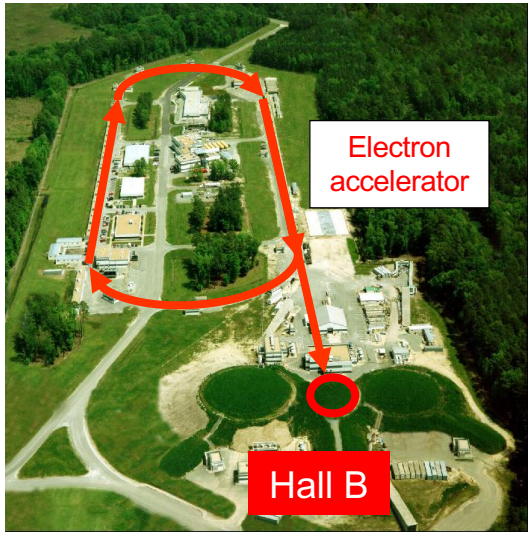
$\Delta\sigma_{LL} \sim (A+B\cos\phi)\mathrm{Re}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\}$ ⇒ $Re\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

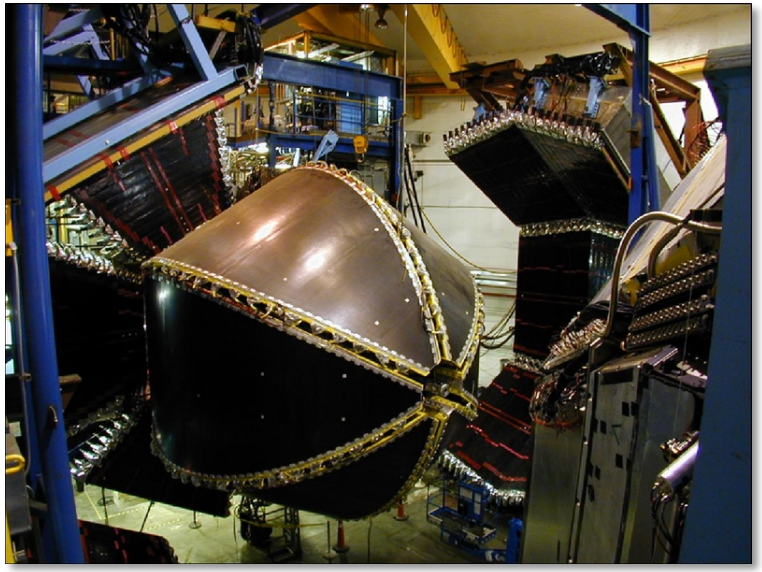
Unpolarized beam, transverse target:

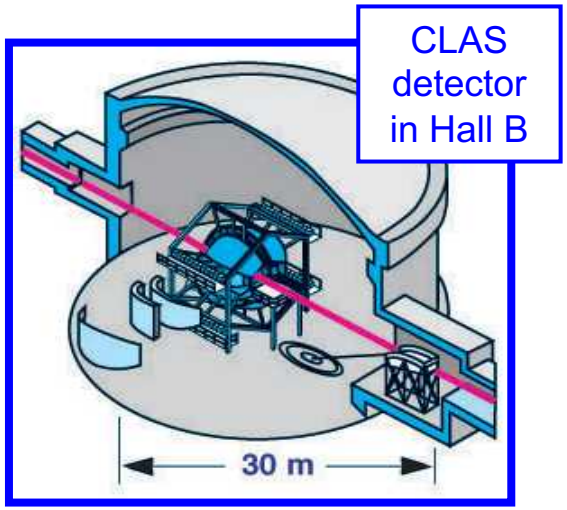
$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n\}$

DVCS experiment at Jefferson Lab 6 GeV in Hall B with CLAS

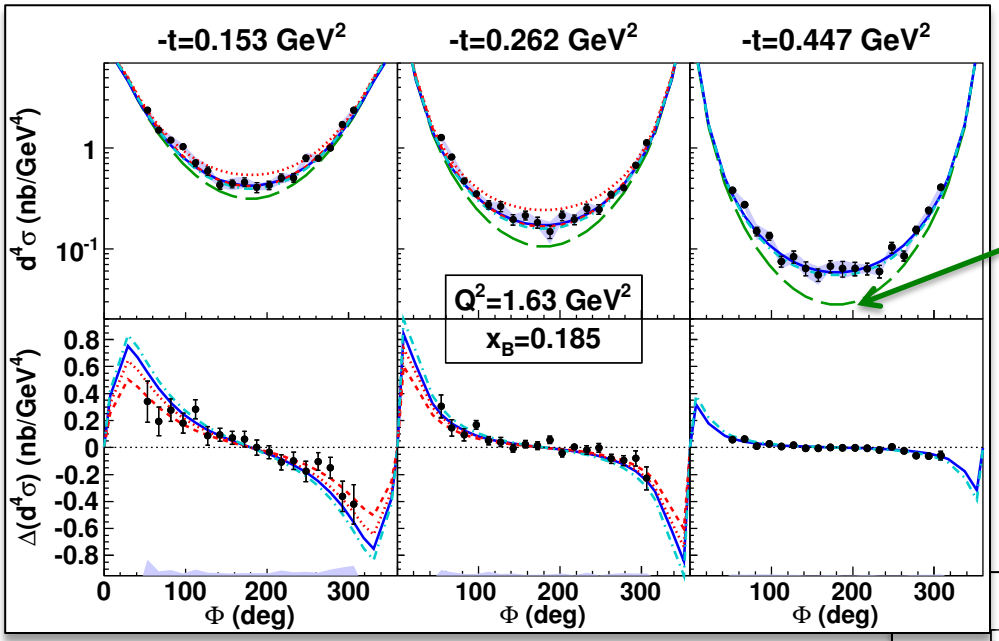
Jefferson Lab



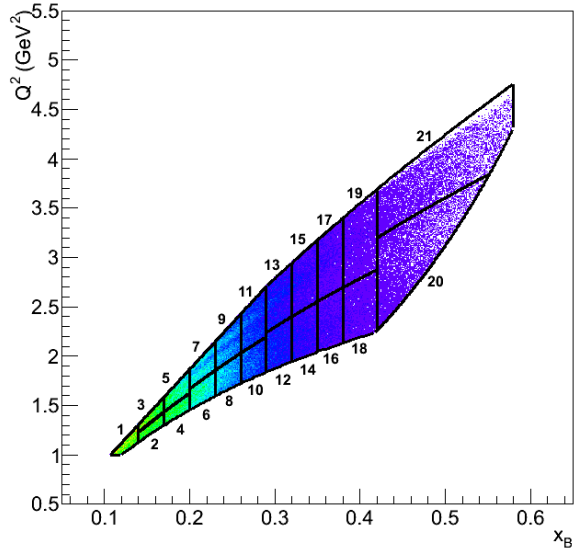




DVCS unpolarized and beam-polarized cross sections from CLAS data



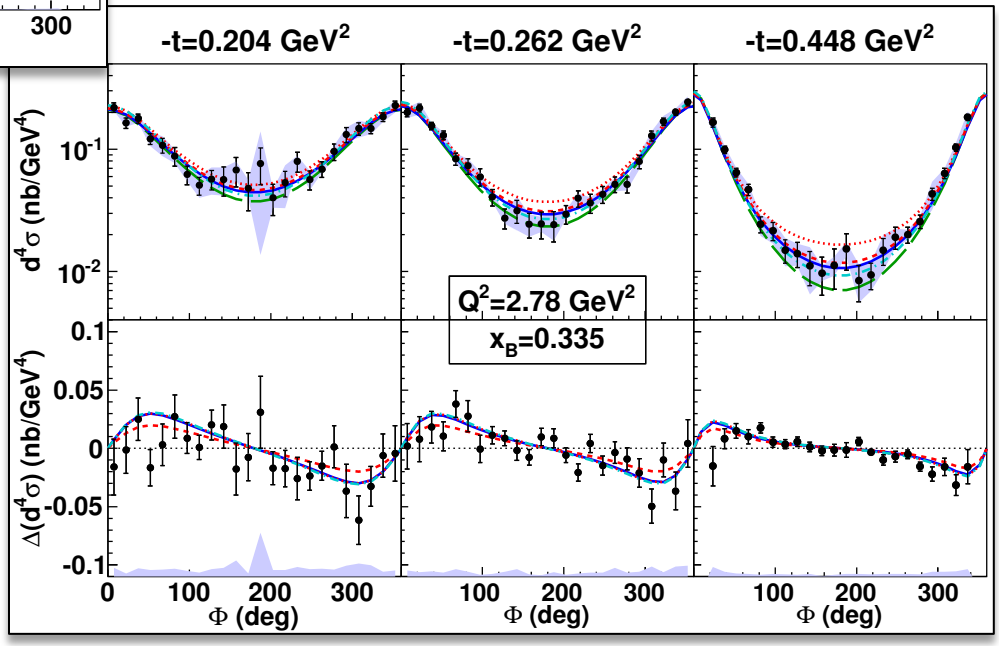
Bethe Heitler



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

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

Cross sections extracted for about **3000** (Q^2, x_B, t, ϕ) bins

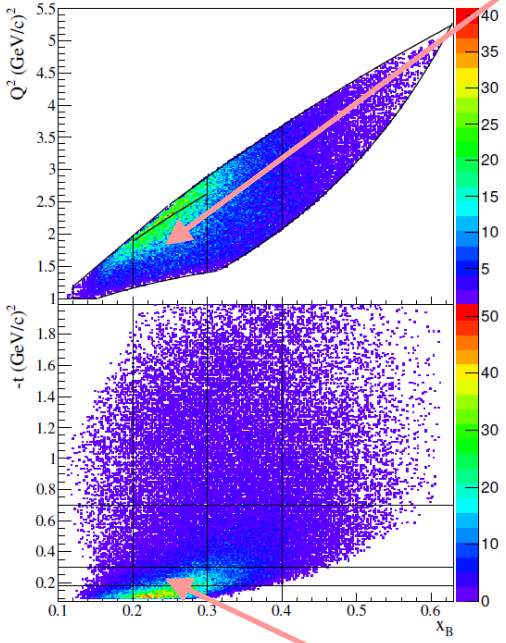


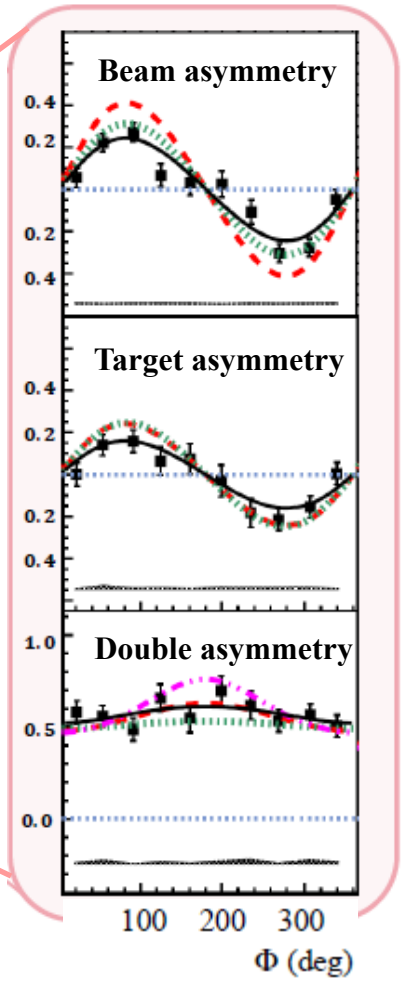
DVCS on longitudinally polarized target from CLAS 6 GeV data

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

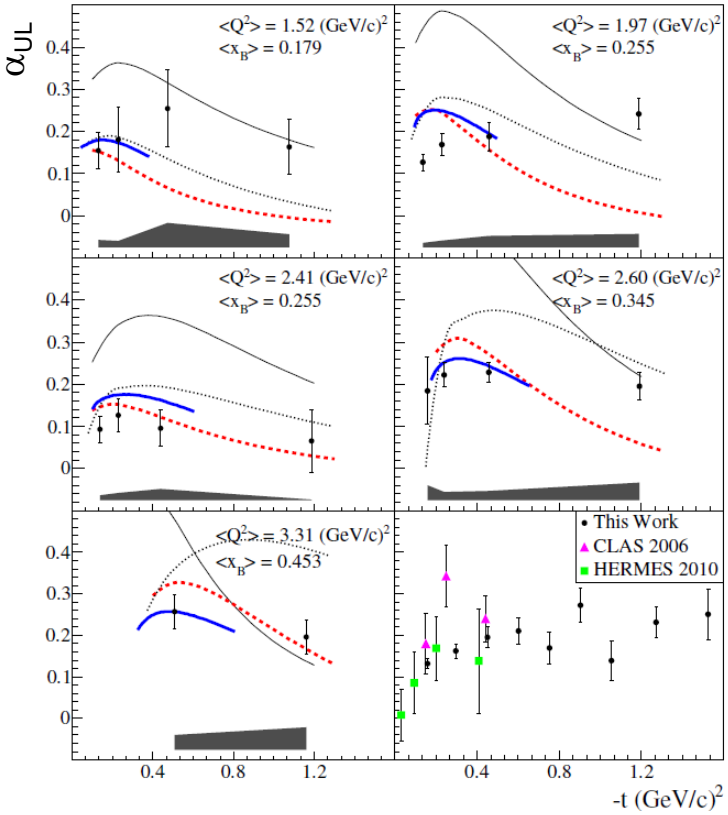
$\vec{e}\vec{p} \rightarrow ep\gamma$

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





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



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

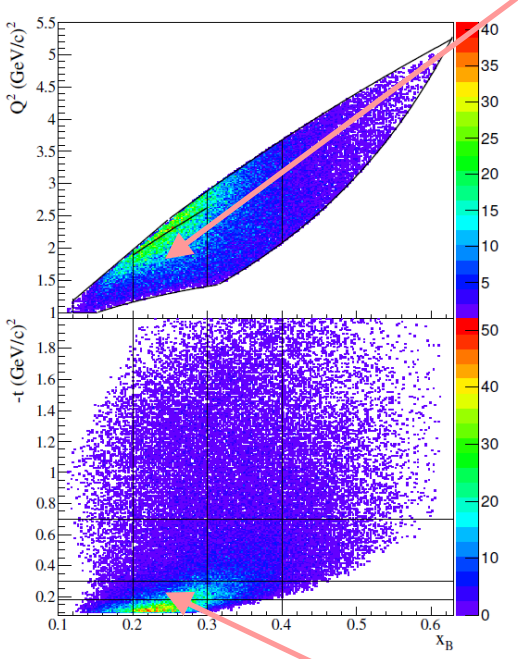
E. Seder *et al.* (CLAS Collaboration), Phys. Rev. Lett. 114, 032001 (2015)

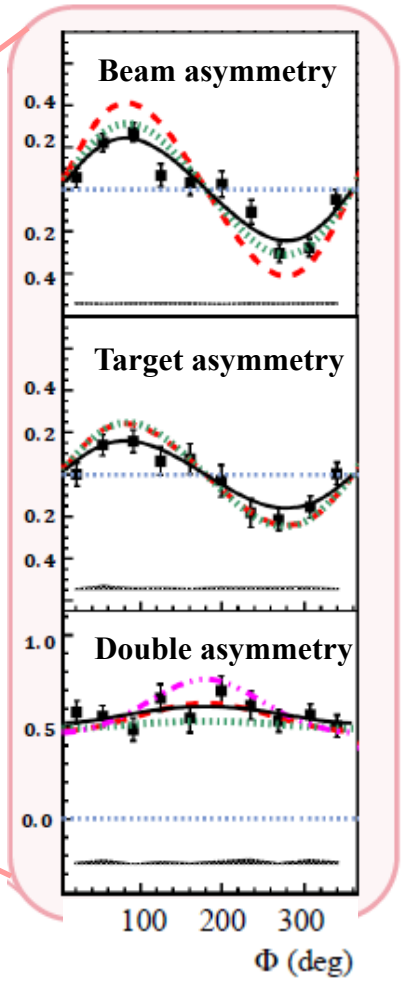
DVCS on longitudinally polarized target from CLAS 6 GeV data

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

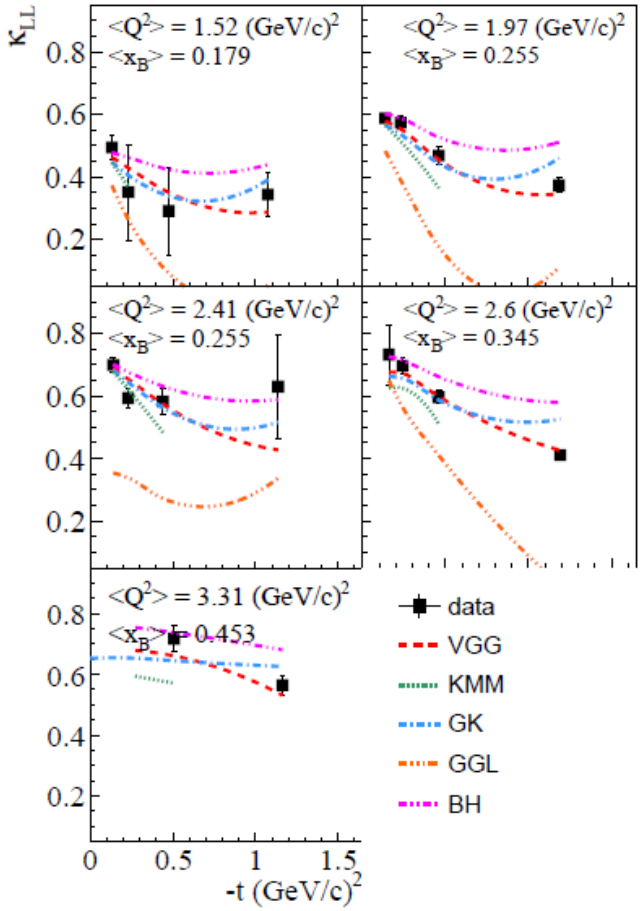
$\vec{e}\vec{p} \rightarrow ep\gamma$

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





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



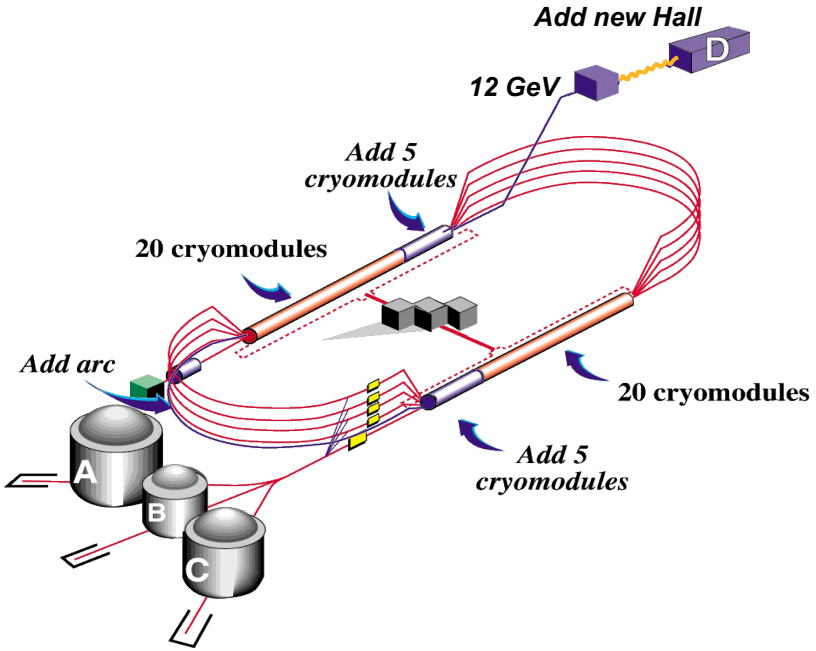
S. Pisano *et al.* (CLAS Collaboration), Phys. Rev. D 91, 052014 (2015)

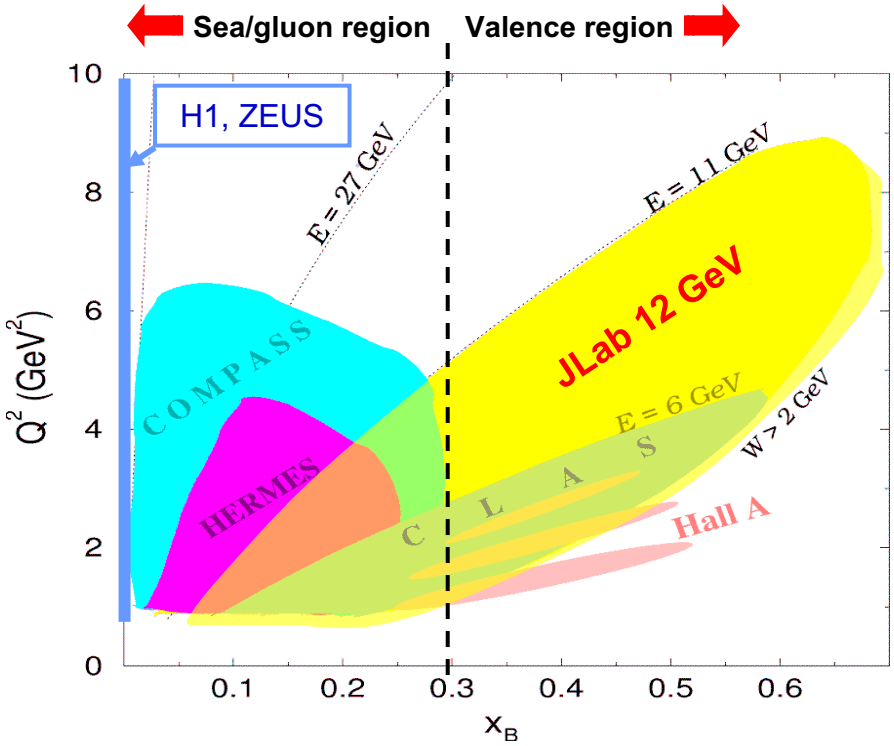
Jefferson Lab upgrade to 12 GeV

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

Beam polarization > 80%

Accelerator 12 GeV upgrade



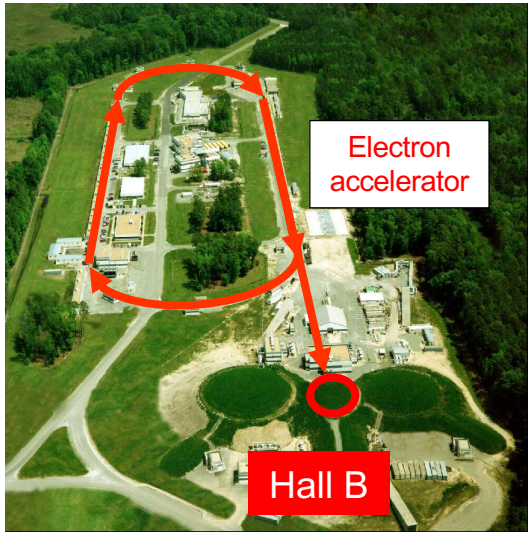


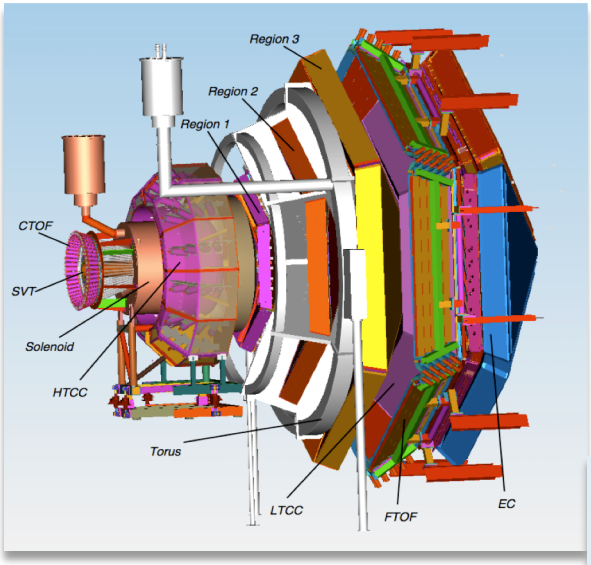
Study of high x_B domain requires high luminosity

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

Jefferson Lab 12 GeV and the CLAS12 detector

Jefferson Lab

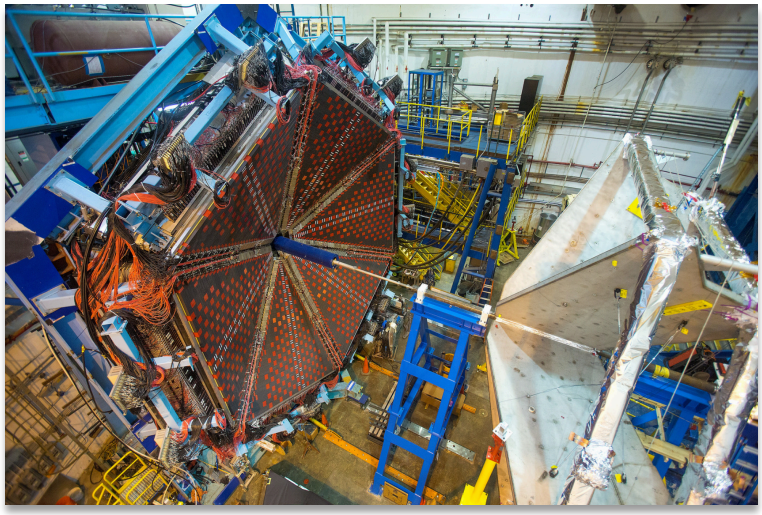


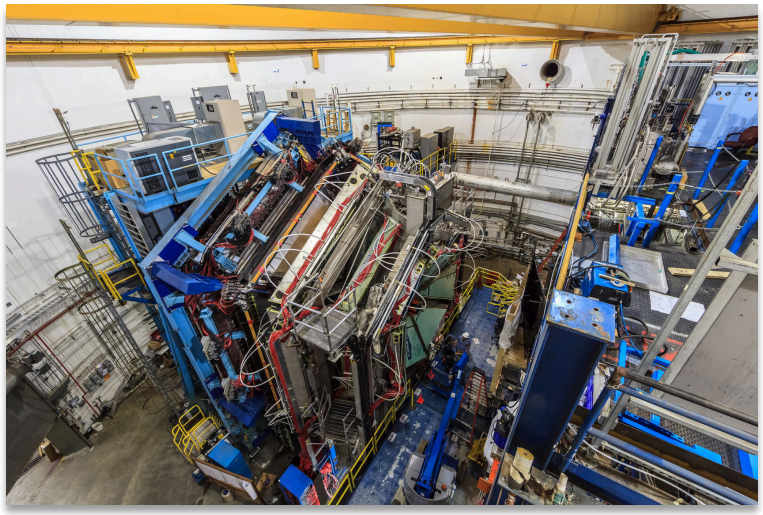


CLAS12 detector in Hall B

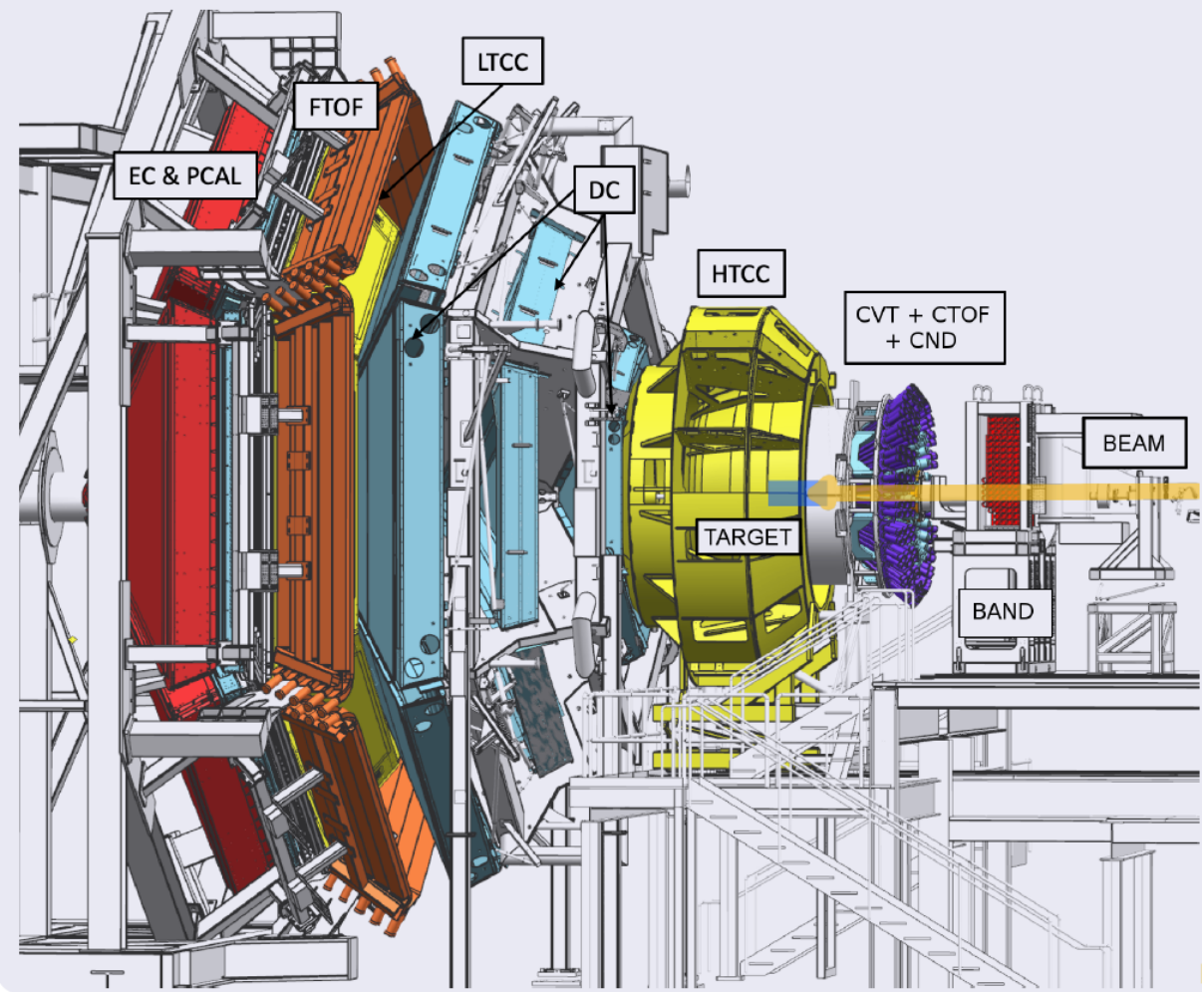
Max luminosity
$L \sim 10^{35}\ cm^{-2}s^{-1}$

Data taking with the new CLAS12 detector started in 2018



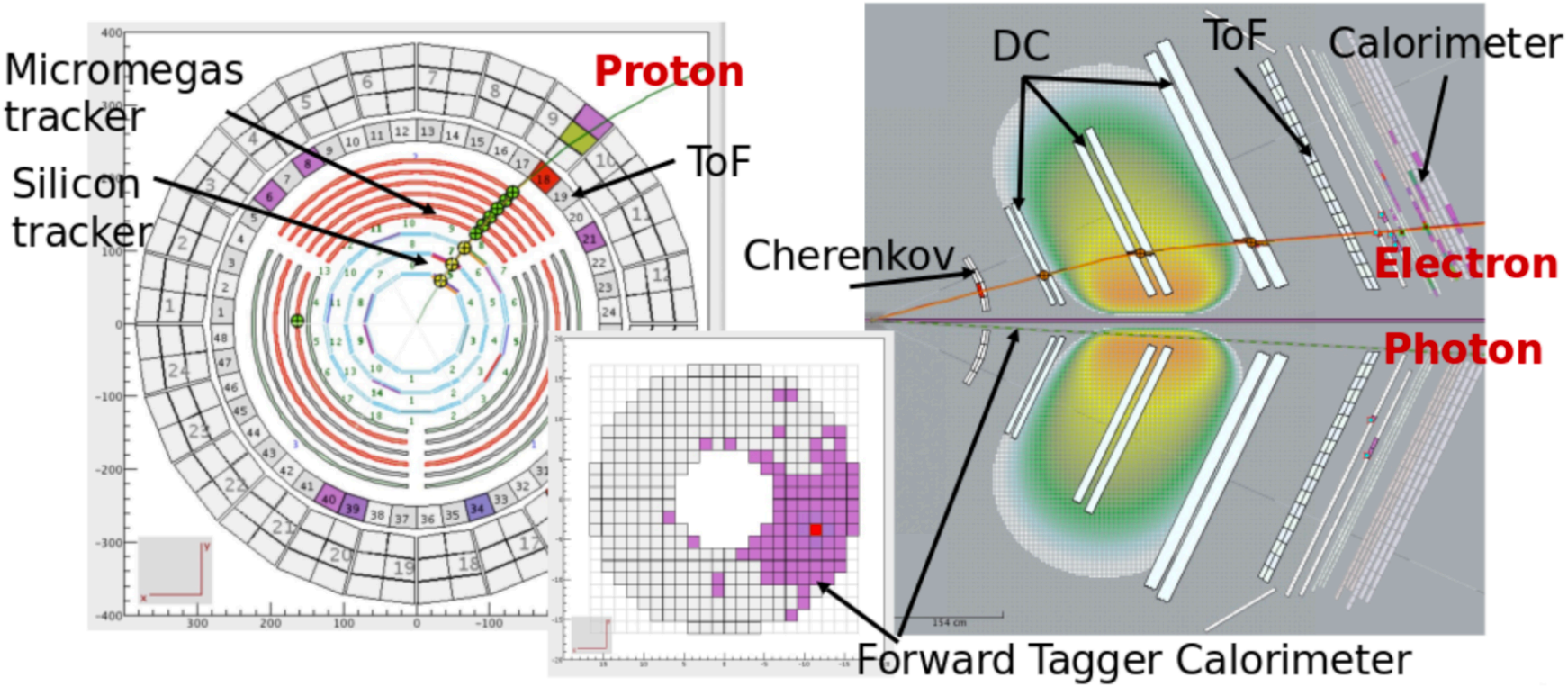


The CLAS12 detector in Hall B



Typical DVCS event in CLAS12

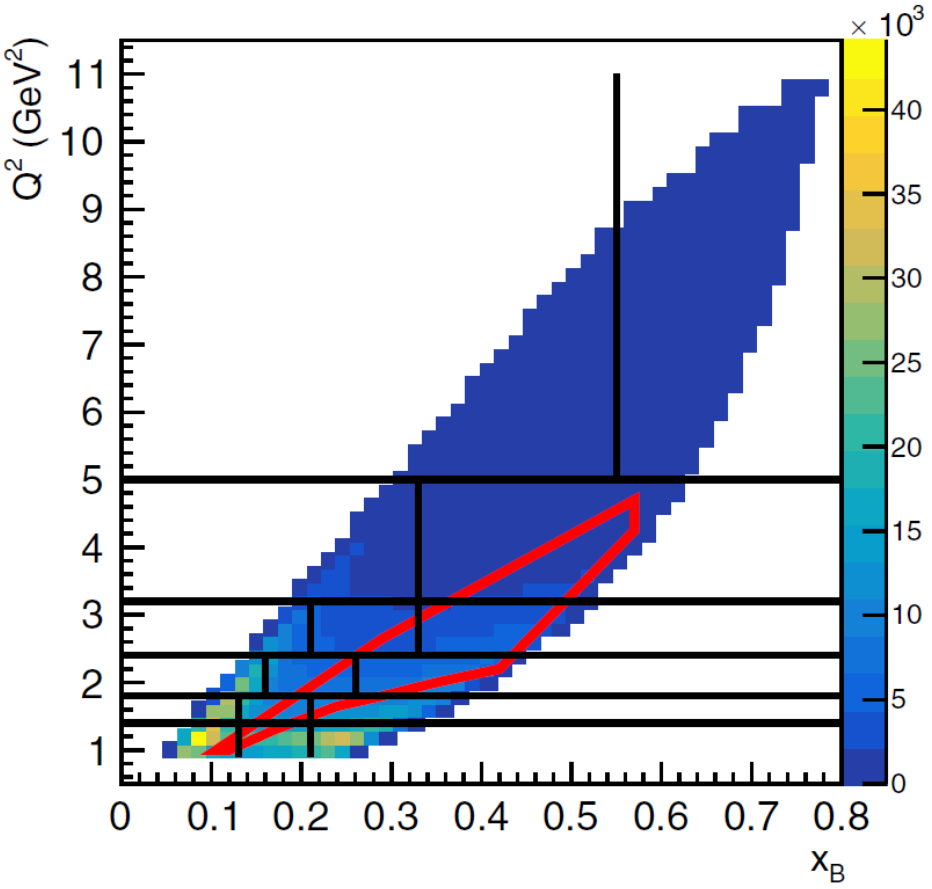
- Electron: measured in the Forward Detector or in the Forward Calorimeter
- Photon: in the FT (or FD) calorimeter
- Proton: most often in the Central Detector



Proton DVCS A_{LU} with CLAS12

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

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



- Beam spin asymmetry extracted in a much wider phase space than at 6 GeV with CLAS
- Based on 25% of the total beam time allocated to CLAS12 DVCS experiment on unpolarized proton

G. Christiaens *et al.* (CLAS Collaboration)
Phys. Rev. Lett. 130, 211902 (2023)

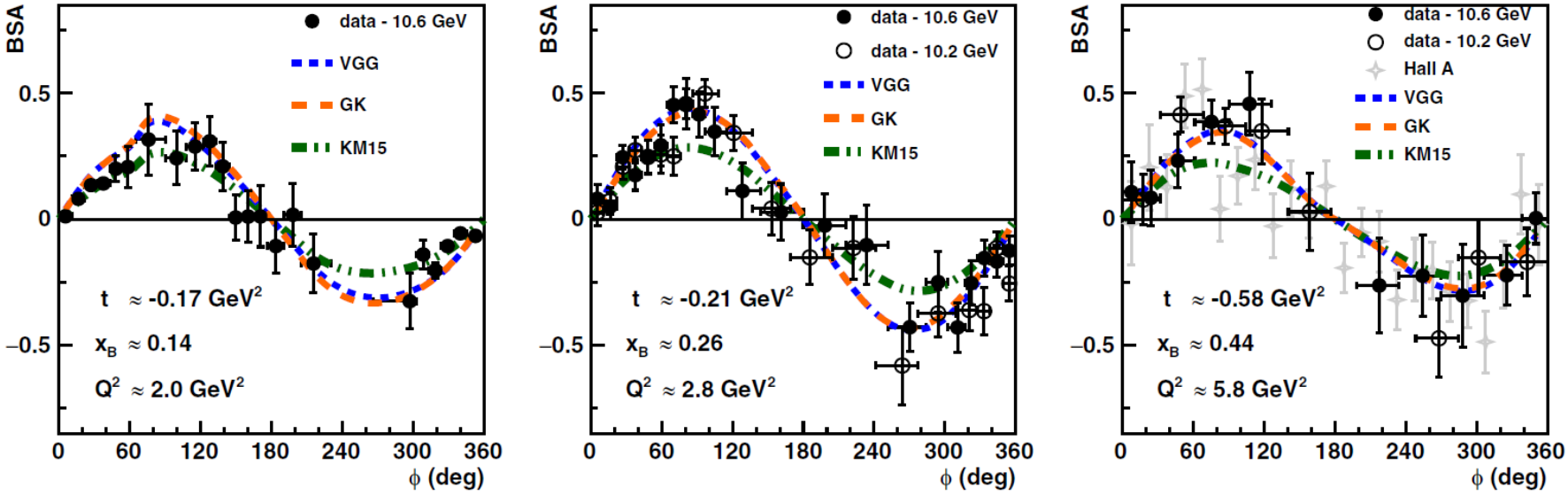
Proton DVCS A_{LU} with CLAS12

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

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

Small sample of the numerous results

Results compared with VGG, GK, KM15 models



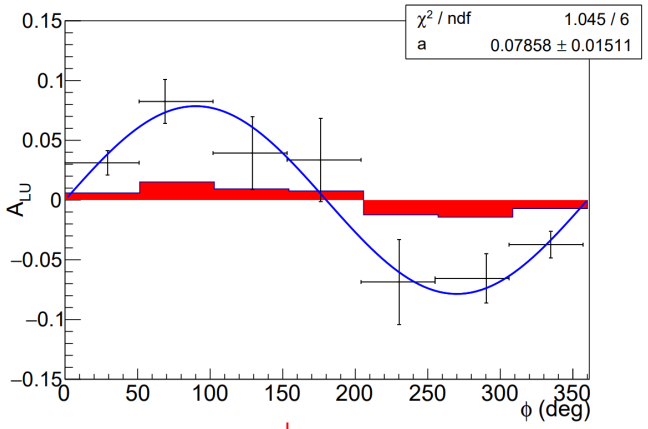
G. Christiaens *et al.* (CLAS Collaboration)
Phys. Rev. Lett. 130, 211902 (2023)

Preliminary neutron DVCS A_{LU} with CLAS12

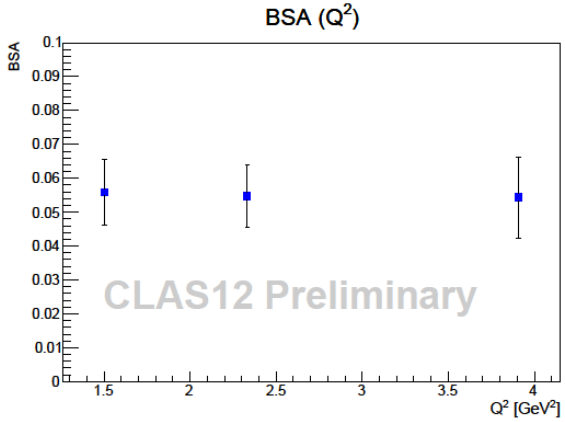
$$A_{LU} \sim Im\{\mathcal{E}_n\}$$

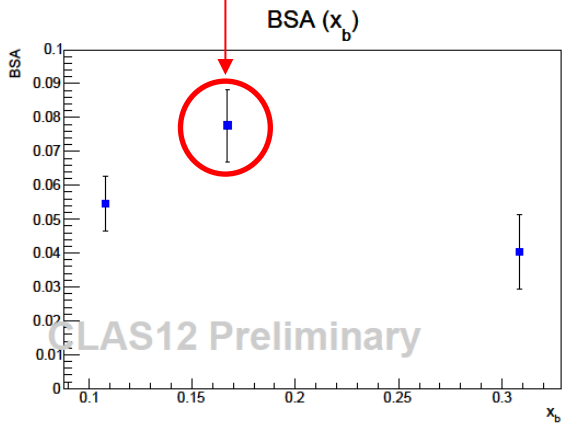
Neutron DVCS BSA with an unpolarized deuterium target

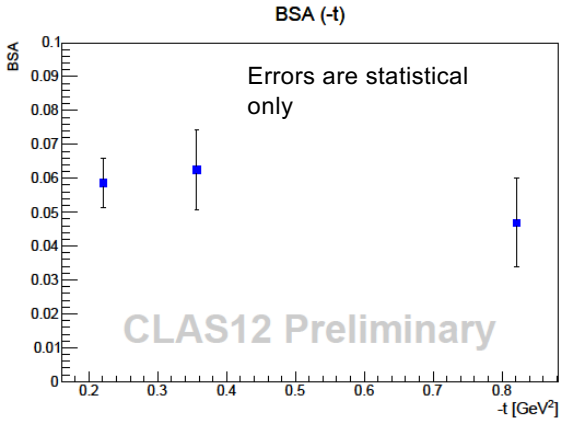
Lead analyzers:
A. Hobart / S. Niccolai
(IJCLab Orsay)



First-time measurement of neutron DVCS with detection of the active neutron





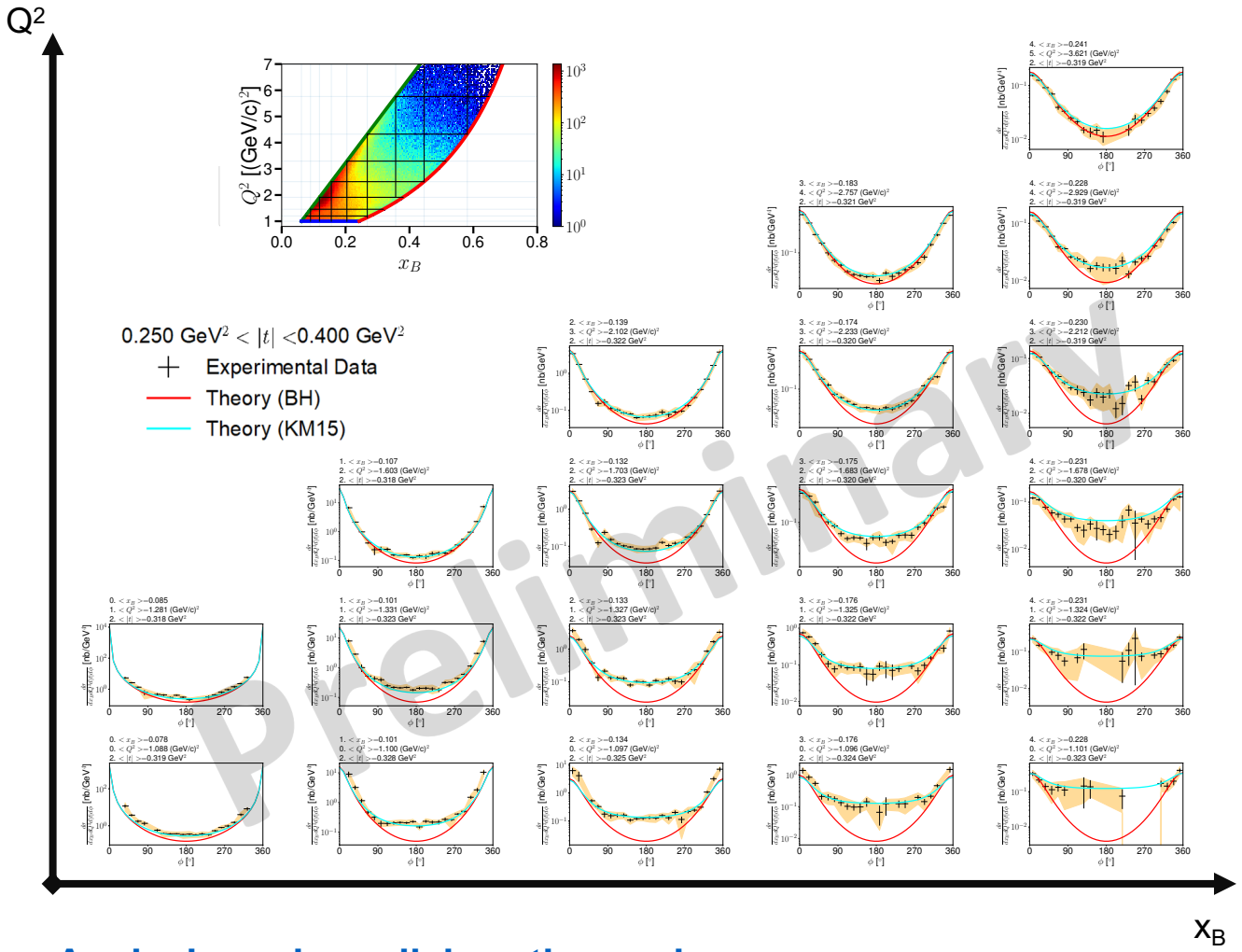


Analysis under collaboration review

Preliminary DVCS cross sections on the proton with CLAS12

Lead analyzer:
S. Lee (ANL)

Small sample of the numerous unpolarized cross-sections



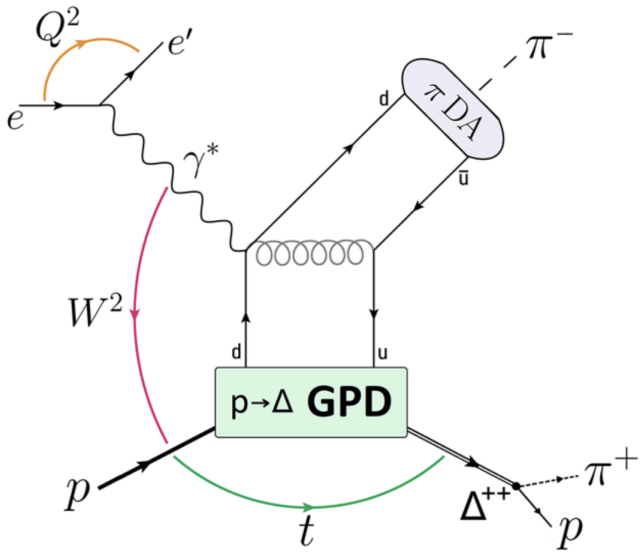
Analysis under collaboration review

Transition GPDs with CLAS12

First measurement of hard exclusive $\pi^-\Delta^{++}$ electroproduction beam-spin asymmetries off the proton

See Stefan Diehl's talk

$$ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$$

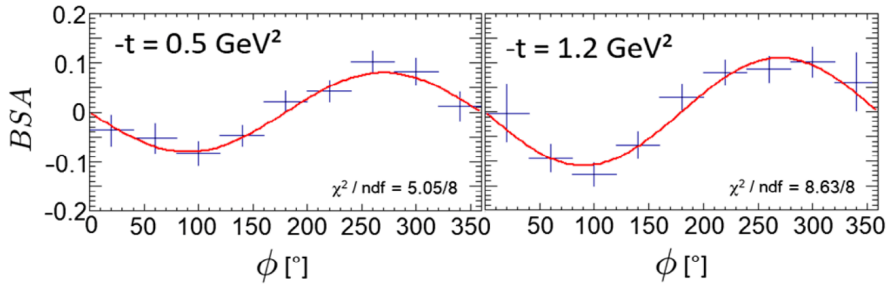


Access to p-Δ transition GPDs

- Data taken with CLAS12 in 2018 and 2019
- Electron beam energy : 10.6 GeV / 10.2 GeV
- Electron beam polarization : ~86%
- Target : LH_2 target

S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. 131, 021901 (2023)

Published last month (July 2023)

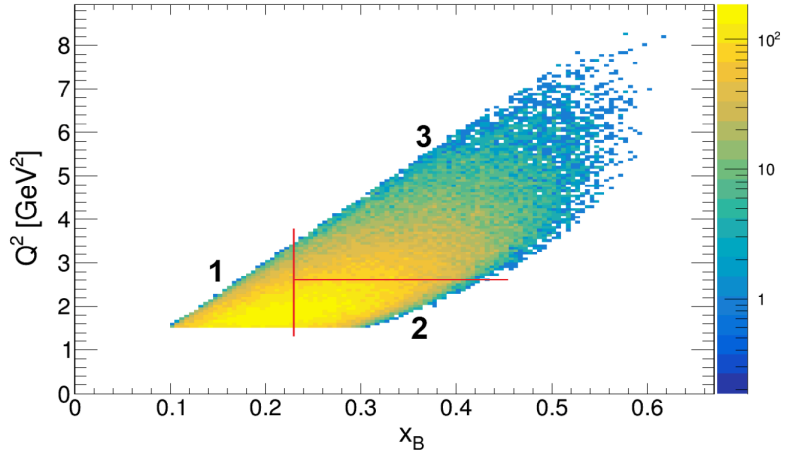


$$\mathrm{BSA} = \frac{\sqrt{2\epsilon(1-\epsilon)}\,\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\,\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\,\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

Transition GPDs with CLAS12

First measurement of hard exclusive $\pi^- \Delta^{++}$ electroproduction beam-spin asymmetries off the proton

See Stefan Diehl's talk



S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. 131, 021901 (2023)

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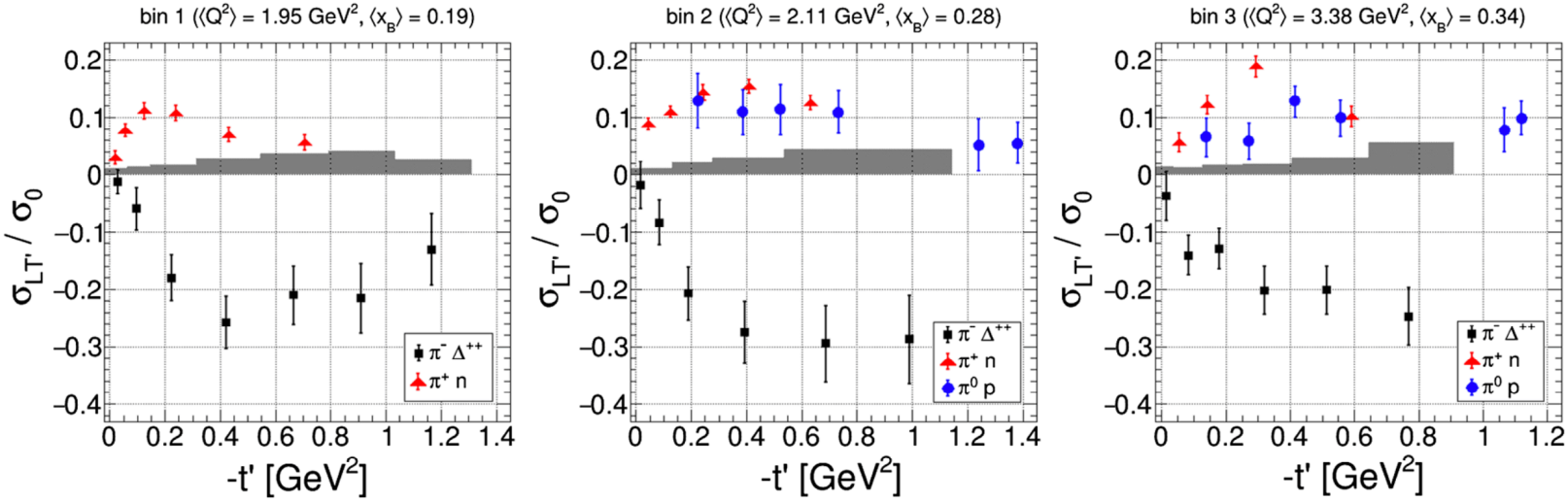
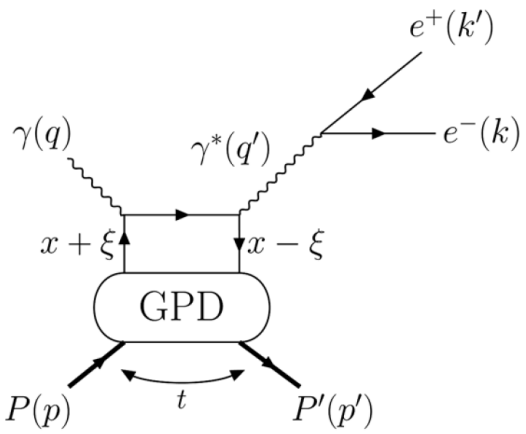
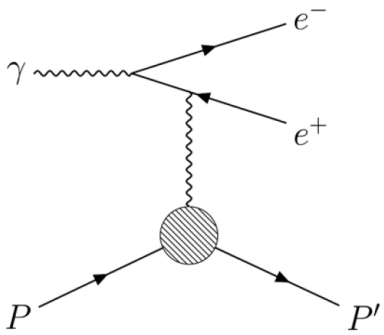
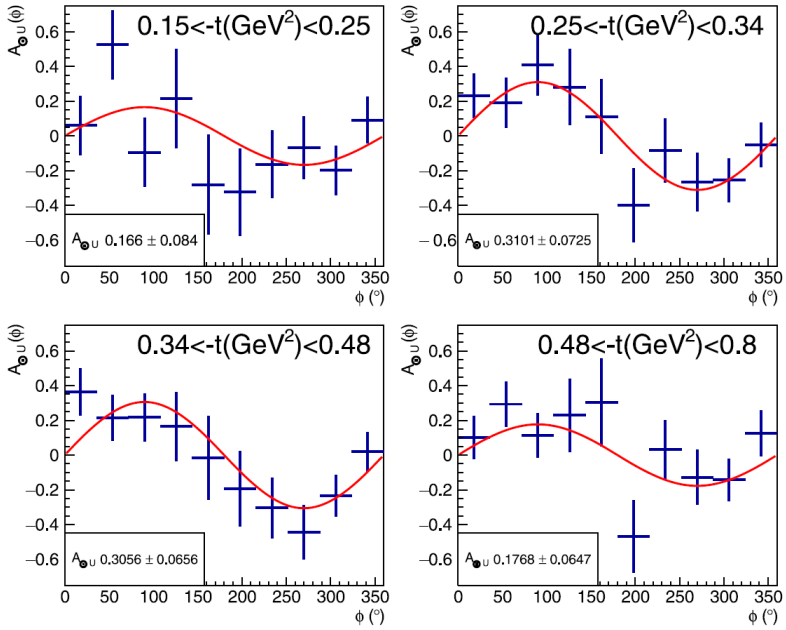


Timelike Compton scattering (TCS) with CLAS12





See Pierre Chatagnon's talk on Wednesday



P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

…And many other DVCS analyses ongoing with CLAS12 data

- Proton and neutron DVCS beam-spin asymmetries (BSA) and target-spin asymmetries (TSA) on a longitudinally polarized target
- DVCS on deuterium
- DVMP beam-spin asymmetries ⟶ See Andrey Kim's talk on Thursday
- DVMP cross sections
- Etc…

Overview

- CLAS12 offers the possibility to measure a large range of exclusive reactions using different experimental configurations (different beam energies and different targets) over a large kinematic range with its large acceptance.

- Several high-impact results have already been published (DVCS BSA on the proton, TCS, Transition GPDs).

- Stay tuned for many more exciting results !

Thank you