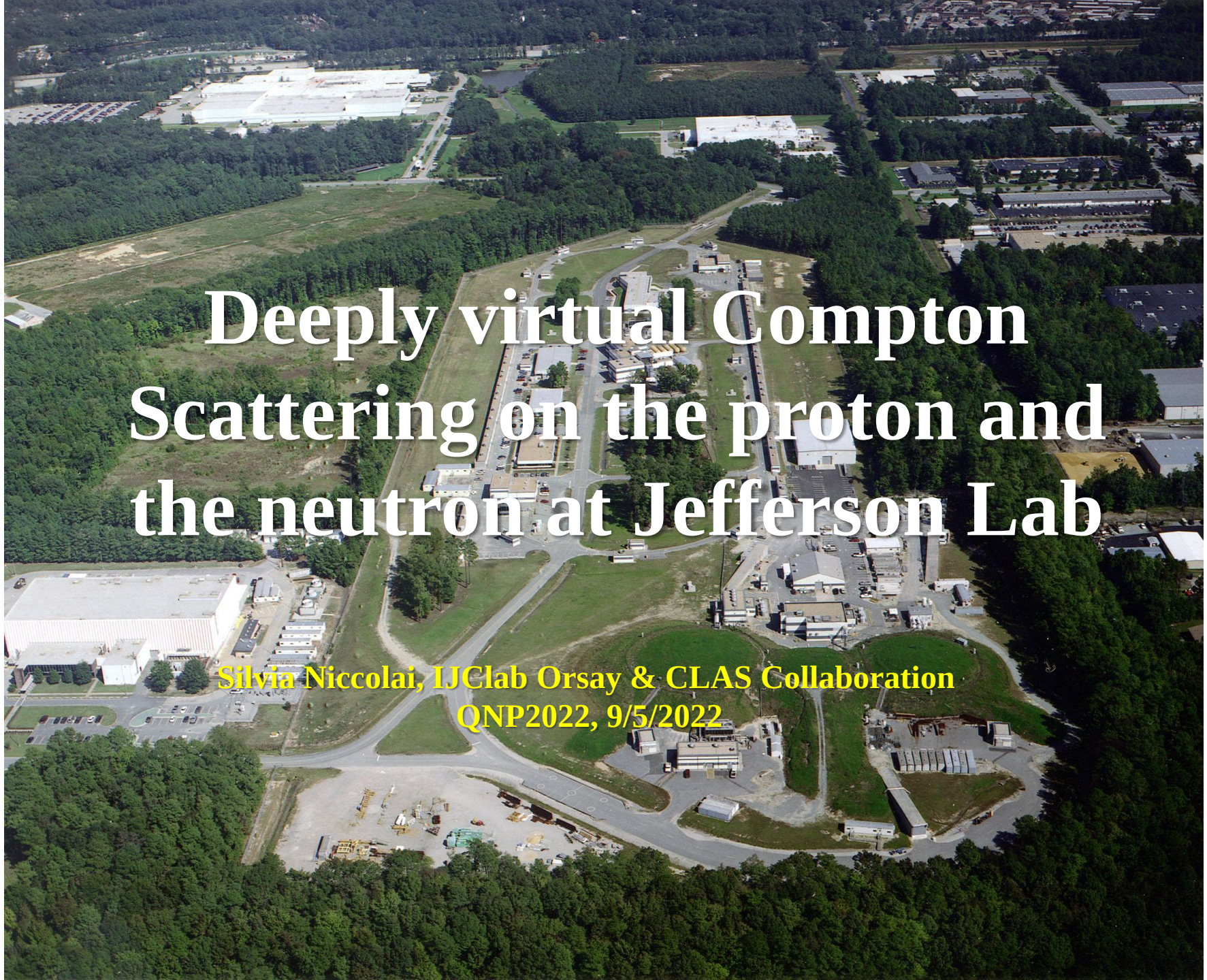


Deeply virtual Compton Scattering on the proton and the neutron at Jefferson Lab

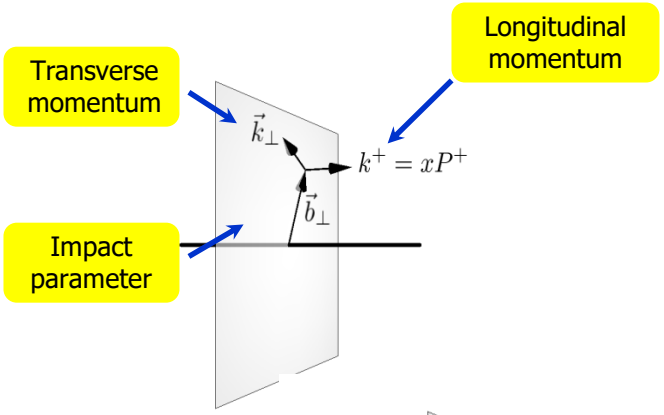
Silvia Niccolai, IJClab Orsay & CLAS Collaboration

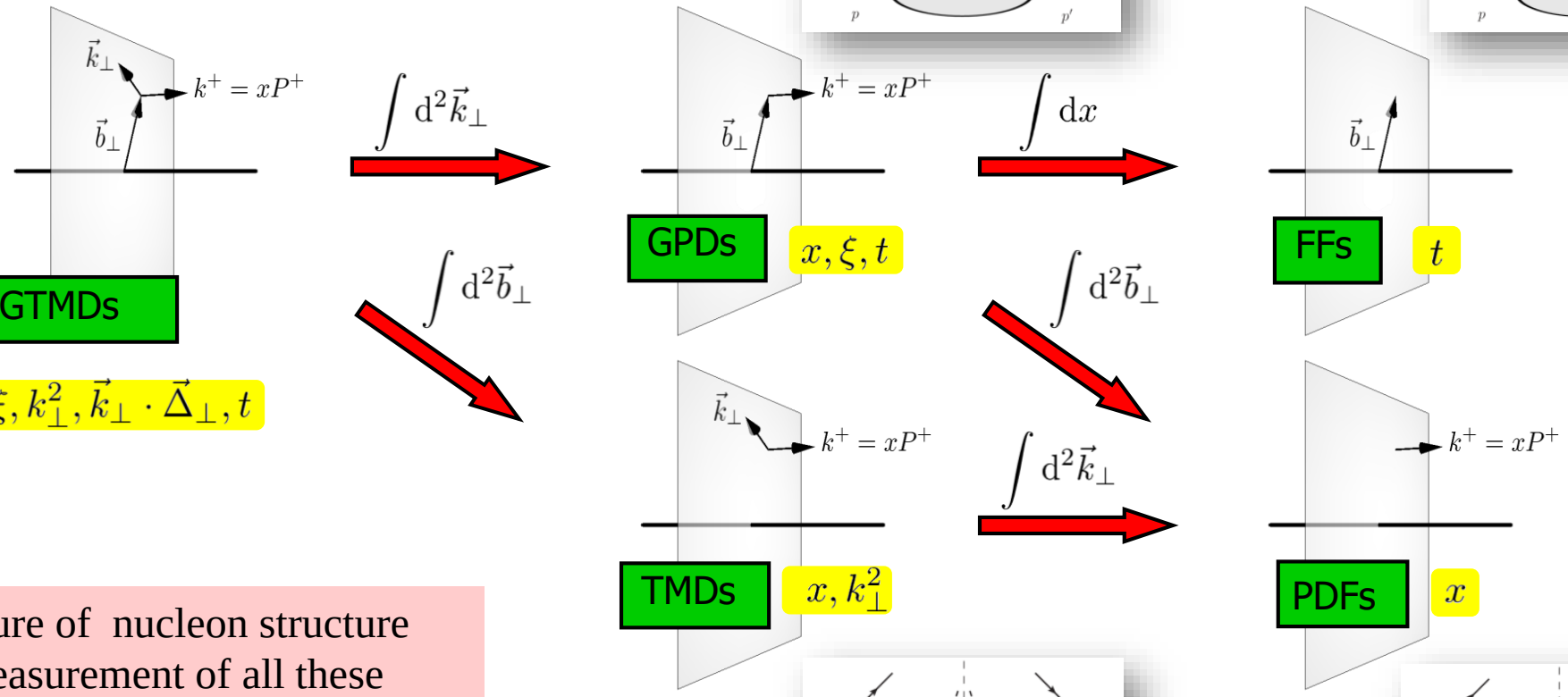
QNP2022, 9/5/2022

CEBAF Large Acceptance Spectrometer

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

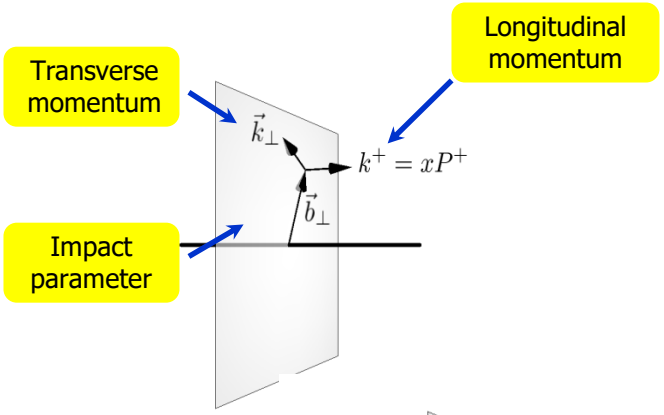
Multi-dimensional mapping of the nucleon

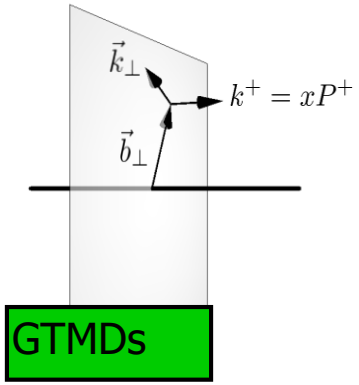




A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon

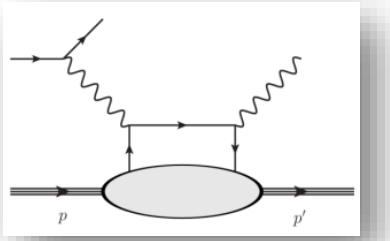


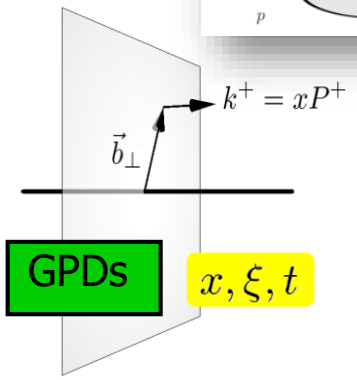


$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

$\int d^2\vec{k}_\perp$

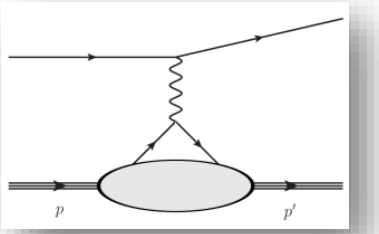
DVCS et al.

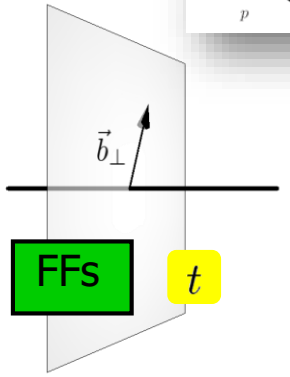




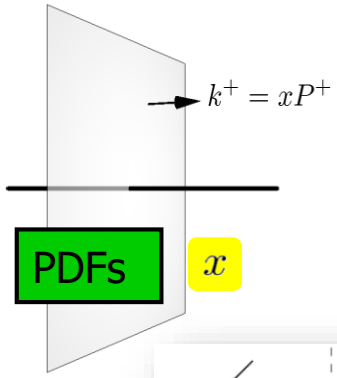
$\int dx$

Elastic Scattering

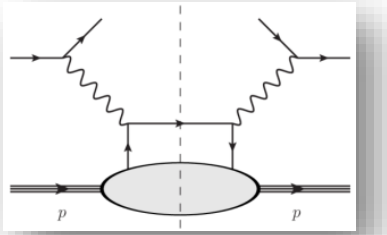




$\int d^2\vec{b}_\perp$



DIS



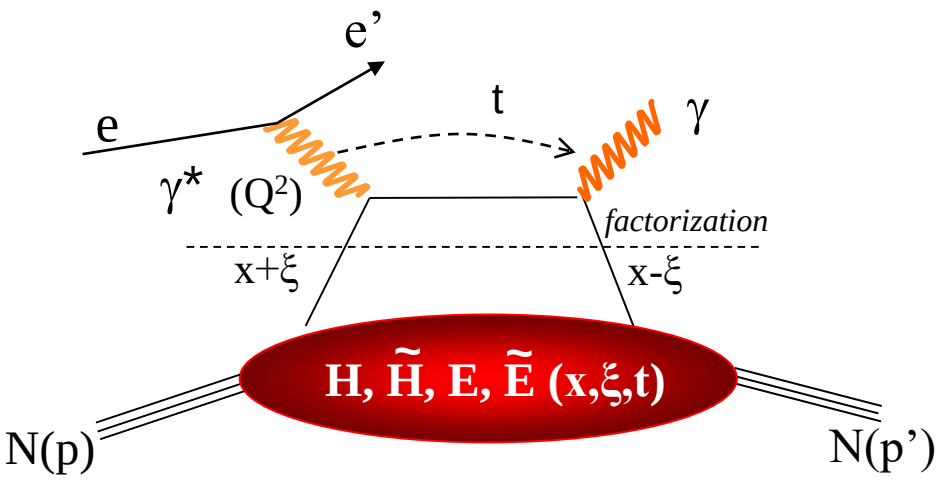
Generalized Parton Distributions:

✓fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space

✓ linked to **FFs** and **PDFs**

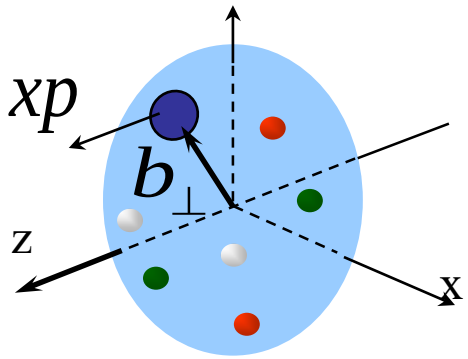
✓**Accessible in exclusive reactions**

Deeply Virtual Compton Scattering and quark GPDs



- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu$ $n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $x \cong x_B/(2-x_B)$

At leading order QCD, twist 2, chiral-even (quark helicity is conserved), quark sector
→ **4 GPDs for each quark flavor**



Quark angular momentum (Ji's sum rule)

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

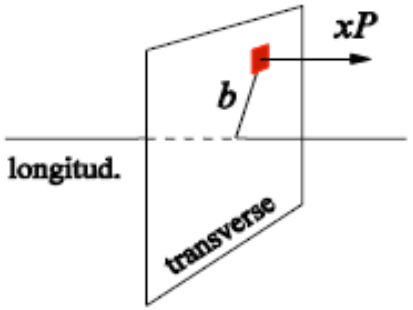
X. Ji, Phy.Rev.Lett.78,610(1997)

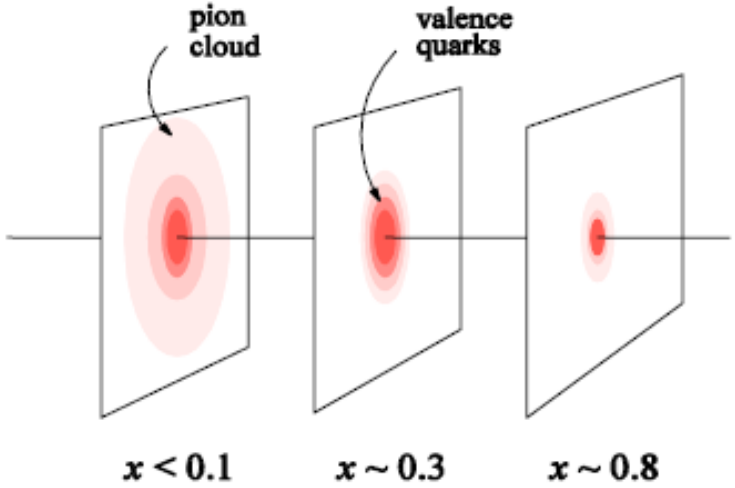
Nucleon tomography

$$q(x,\mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x,\mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} \tilde{H}(x,0,-\Delta_\perp^2)$$

M. Burkardt, PRD 62, 71503 (2000)



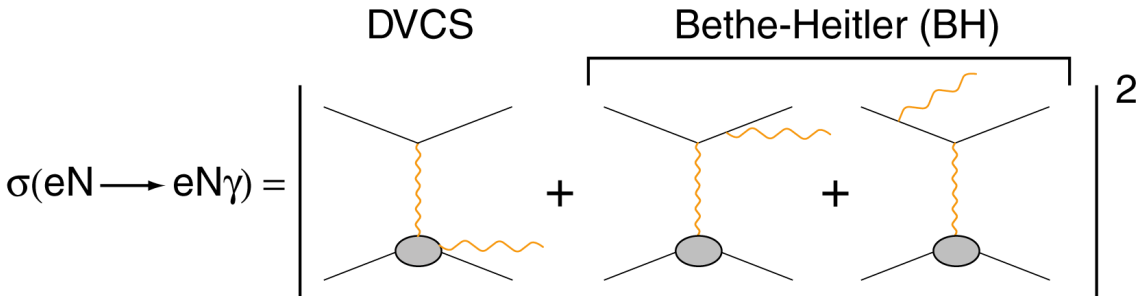


Accessing GPDs through DVCS

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

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

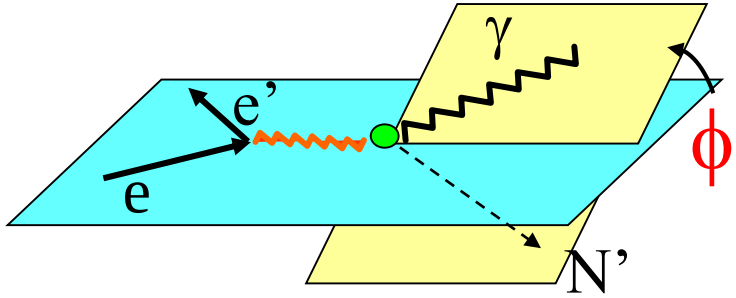
$$Im\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right]$$



	Proton	Neutron
Polarized beam, unpolarized target: $\Delta\sigma_{LU} \sim \sin\phi\, Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$	$Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$
Unpolarized beam, longitudinal target: $\Delta\sigma_{UL} \sim \sin\phi\, Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$	$Im\{\mathcal{H}_n, \mathcal{E}_n\}$
Polarized beam, longitudinal target: $\Delta\sigma_{LL} \sim (A + B\cos\phi) Re\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\}$	$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$	$Re\{\mathcal{H}_n, \mathcal{E}_n\}$
Unpolarized beam, transverse target: $\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi) Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$	$Im\{\mathcal{H}_p, \mathcal{E}_p\}$	$Im\{\mathcal{H}_n\}$
Unpolarized beam and target, different lepton charges: $\Delta\sigma_C \sim \cos\phi\, Re\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$	$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$	$Re\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

$$\sigma \sim \left|T^{DVCS} + T^{BH}\right|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I\left(DVCS \cdot BH\right)$$

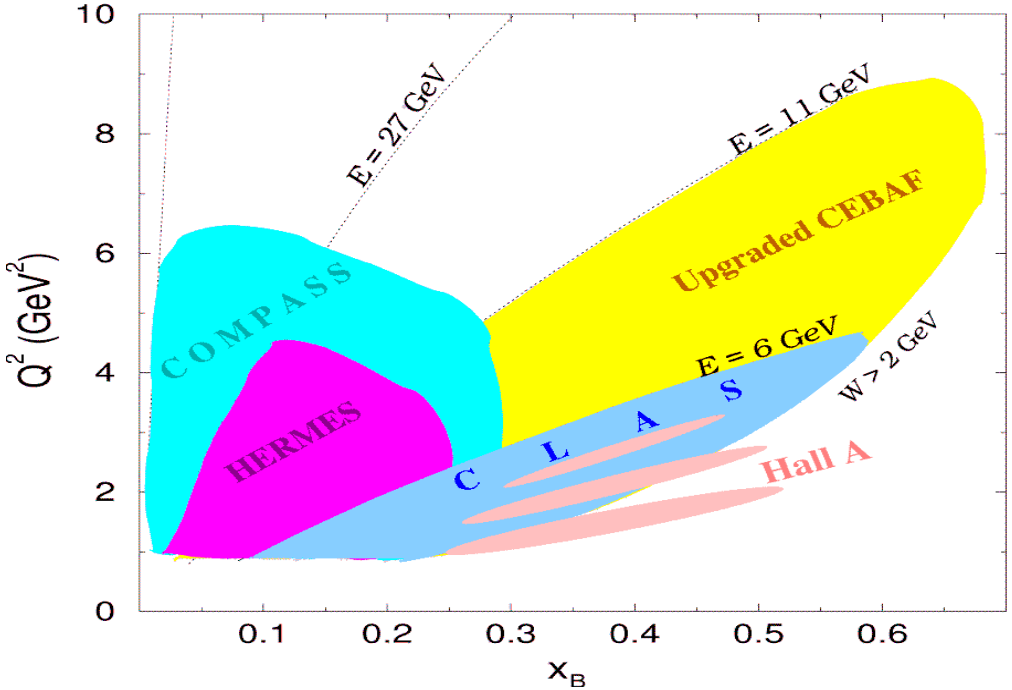


DVCS experiments worldwide

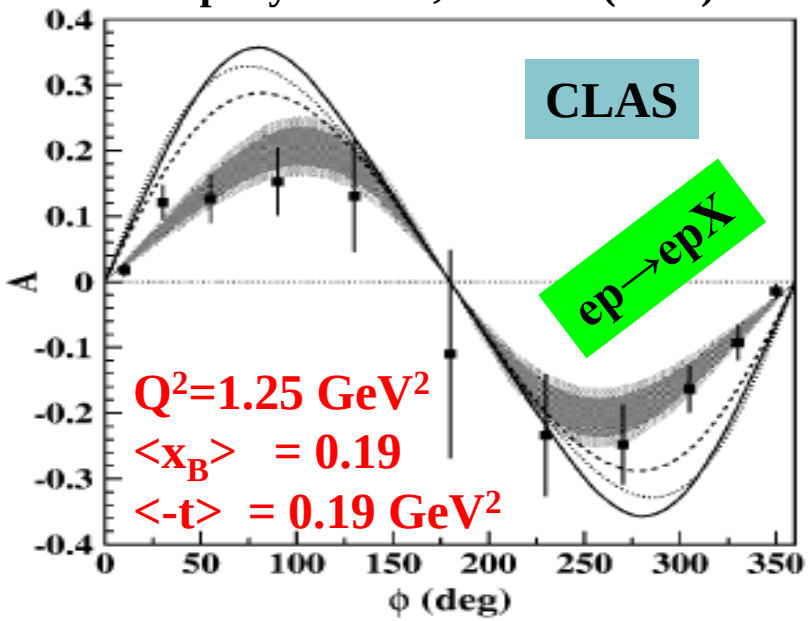
JLAB	
Hall A	***CLAS (Hall B)***
p,n-DVCS, Beam-pol. CS	p-DVCS, BSA,lTSA,DSA,CS

DESY	
HERMES	***H1/ZEUS***
p-DVCS,BSA,BCA, tTSA,lTSA,DSA	p-DVCS,CS,BCA

CERN
COMPASS
p-DVCS CS,BSA,BCA, tTSA,lTSA,DSA



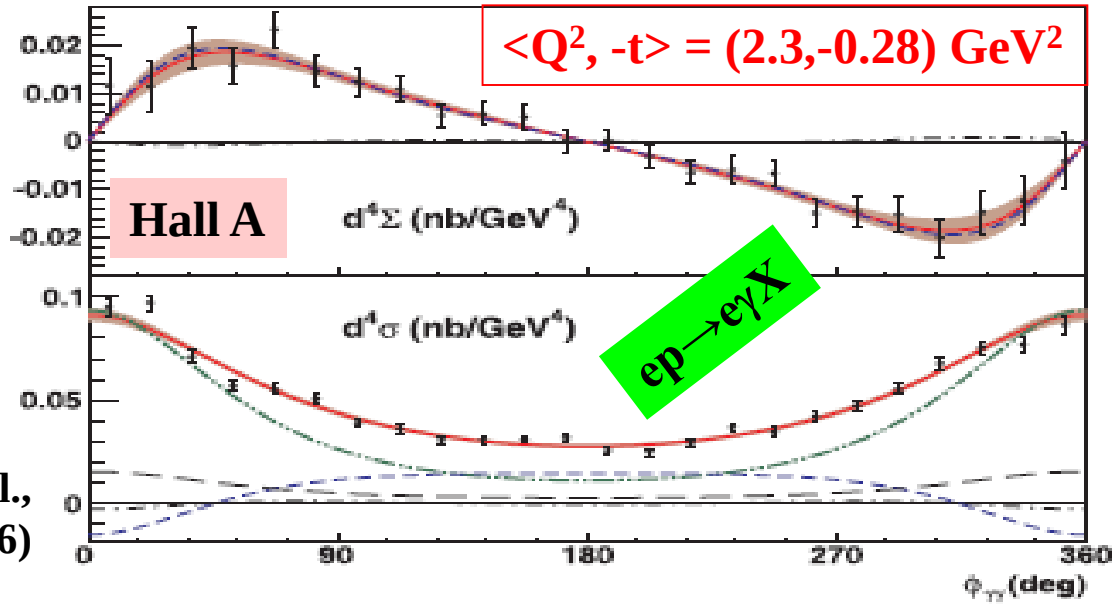
S. Stepanyan et al., PRL 87 (2001)



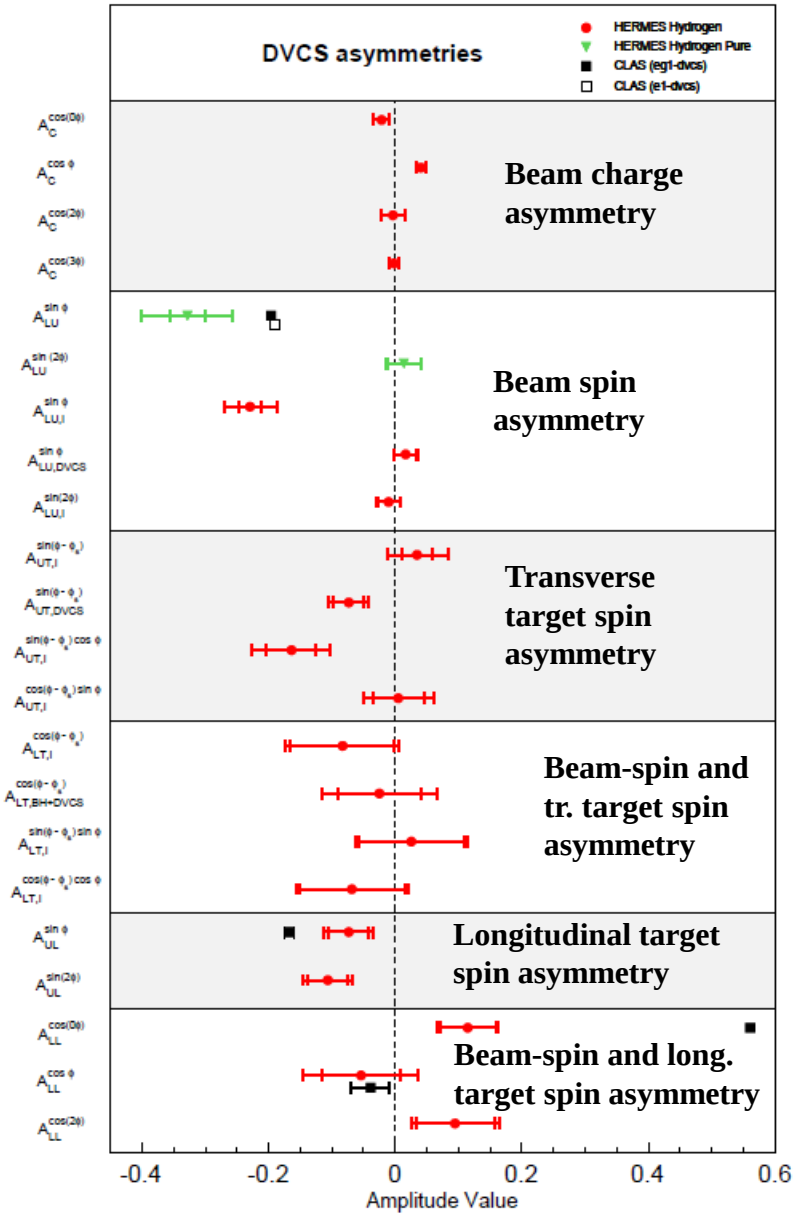
CLAS, HERMES: first observation of DVCS-BH interference

Hall A: proof of scaling for DVCS

C.M. Camacho et al., PRL 97 (2006)



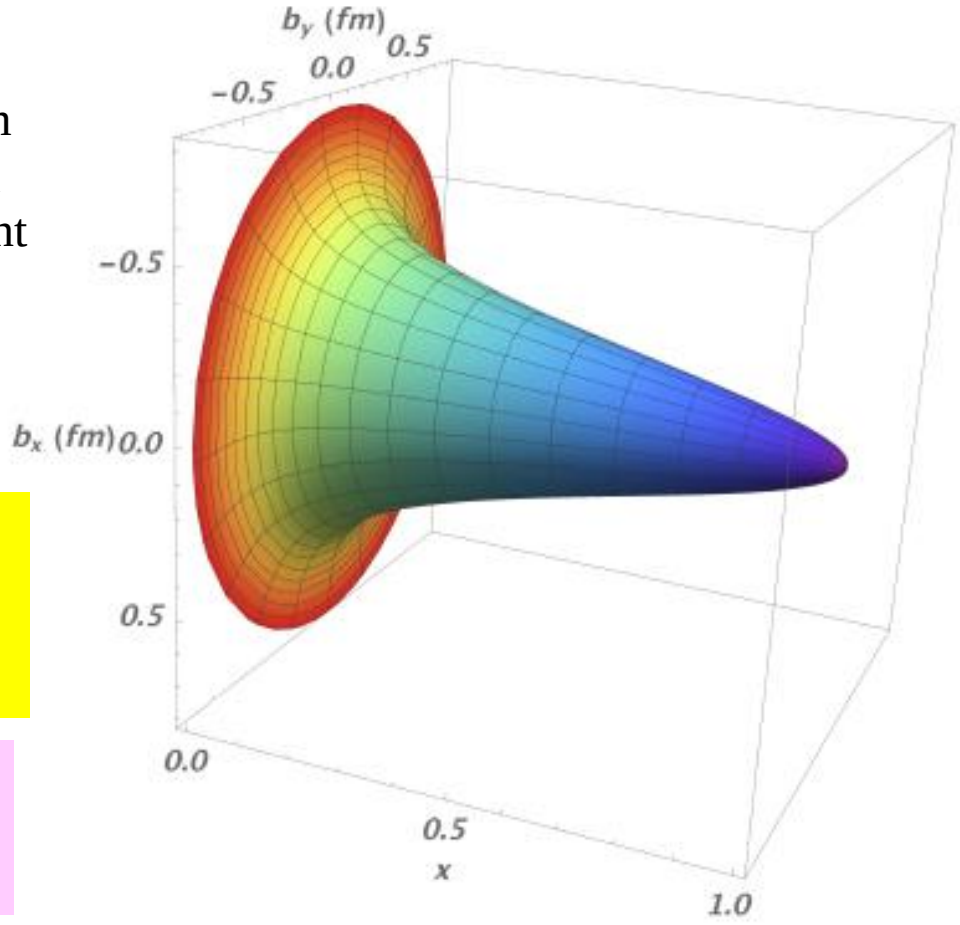
Measured p-DVCS observables and proton properties



Proton tomography obtained from *local fits* to HERMES, CLAS, and Hall-A data (Im$\mathcal{H}$ + model dependent assumptions for x dependence)

High-momentum quarks (valence) are at the core of the nucleon, low-momentum quarks (sea) are at its periphery

YouTube video on proton structure: https://www.youtube.com/watch?v=G-9I0buDi4s



R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)

GPDs also give an insight in the **sheer forces and pressure** distribution in the proton

V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

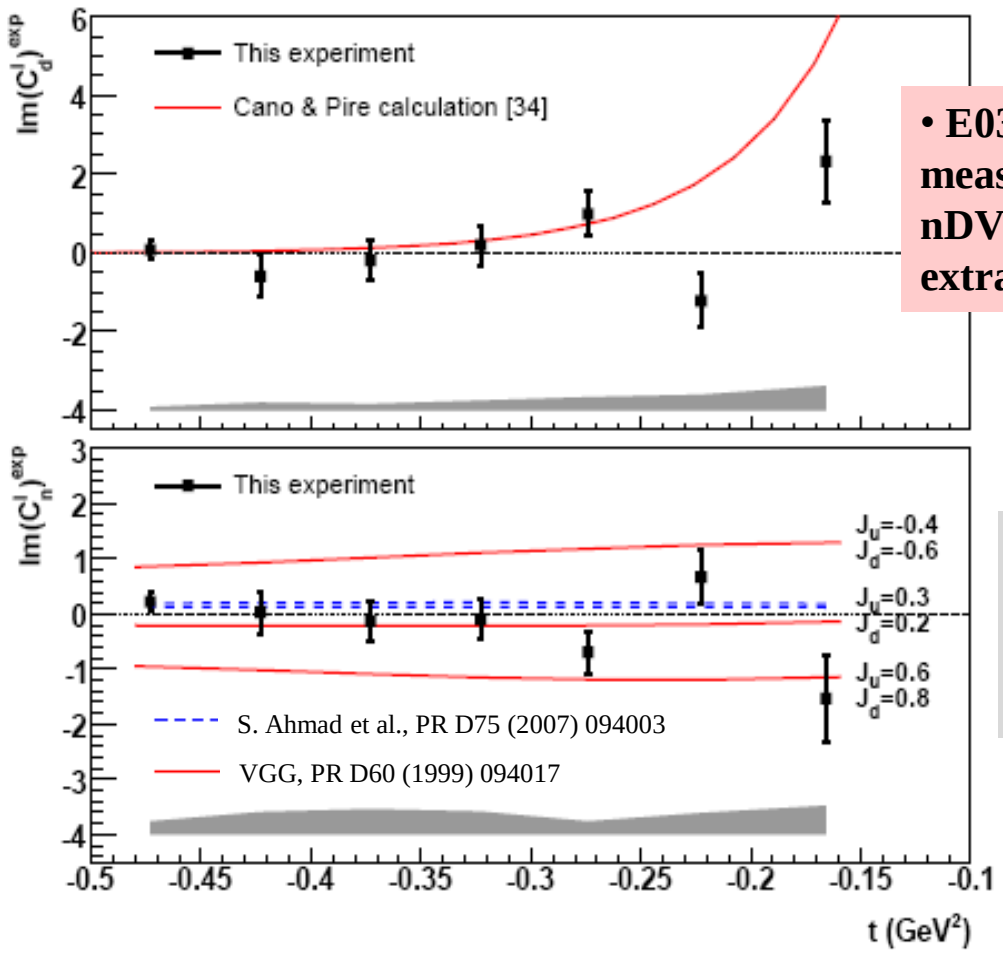
DVCS on the neutron in Hall A at 6 GeV

$\vec{e}d \to e\gamma(np)$

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

Q^2=1.9 GeV^2 x_B=0.36

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

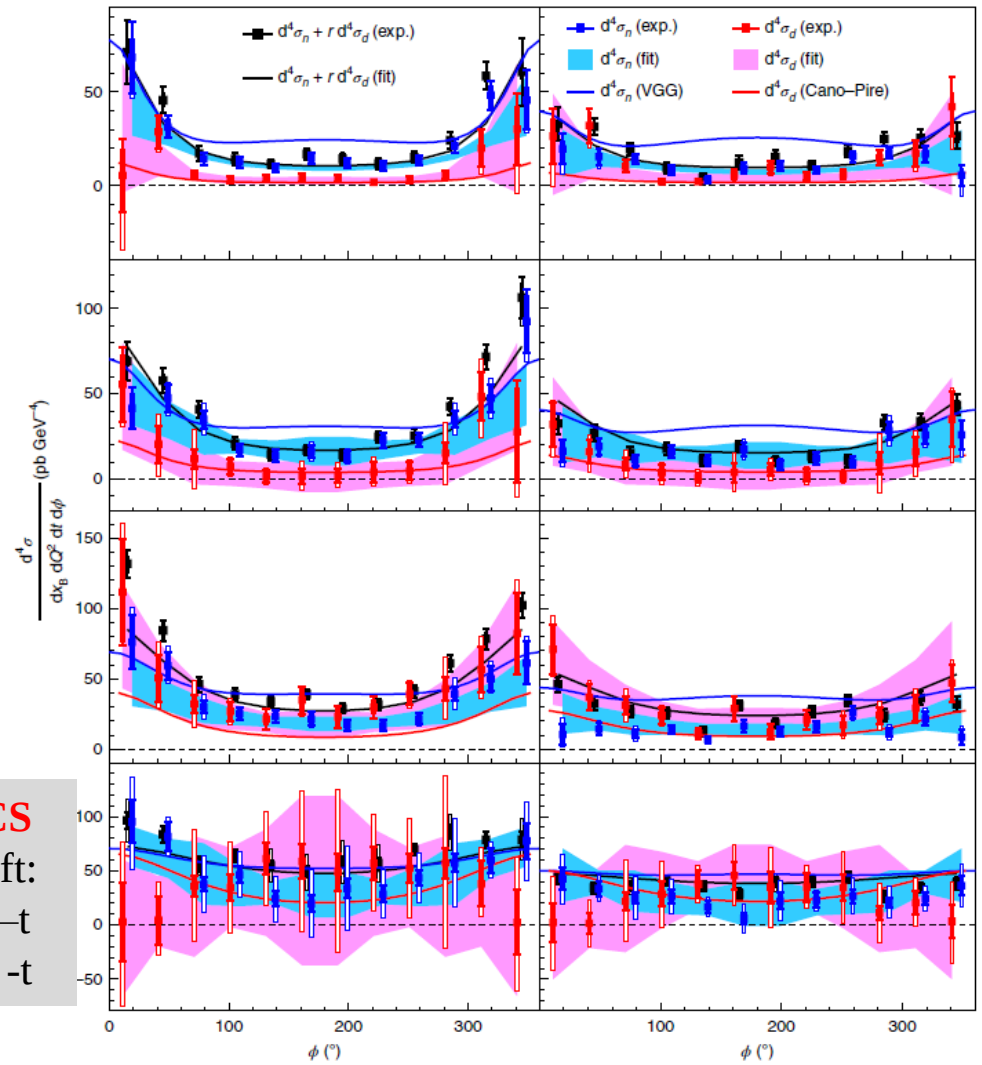


M. Mazouz et al., PRL 99 (2007) 242501

- **E03-106: First-time measurement of $\Delta\sigma_{LU}$ for nDVCS, model-dependent extraction of J_u, J_d**

nDVCS and coherent **dDVCS** separated through MM^2_X shift:

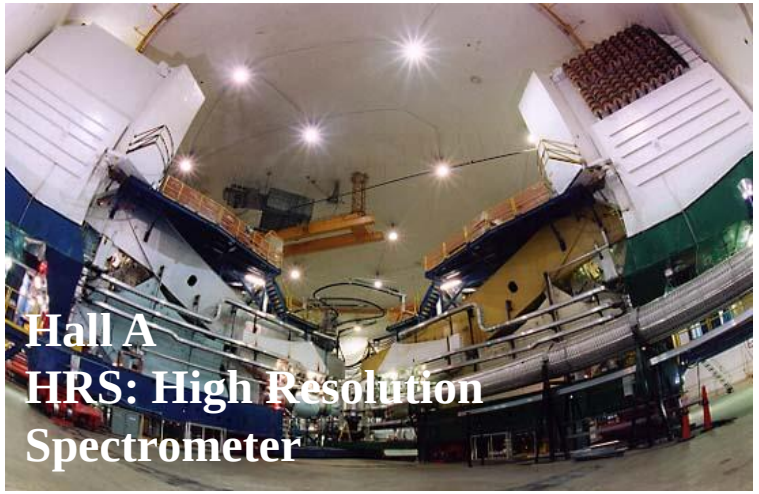
- large correlations at low –t
- good separation at larger -t

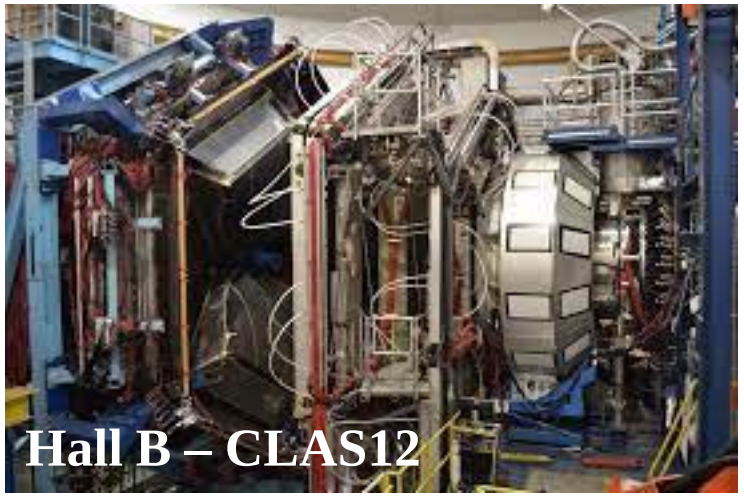


Hall-A experiment E08-025 (2010)

- Beam-energy « Rosenbluth » separation of nDVCS CS (two beam energies)
- First observation of non-zero nDVCS CS
- **M. Benali et al., Nature 16 (2020)**

Jefferson Lab at 12 GeV





Continuos Electron Beam Accelerator Facility (CEBAF)

- Up to 12 GeV continuous polarized electron beam
- Two anti-parallel linacs, with recirculating arcs on both ends
- 4 experimental halls, 3 devoted to nucleon-structure studies

JLab@12 GeV DVCS program

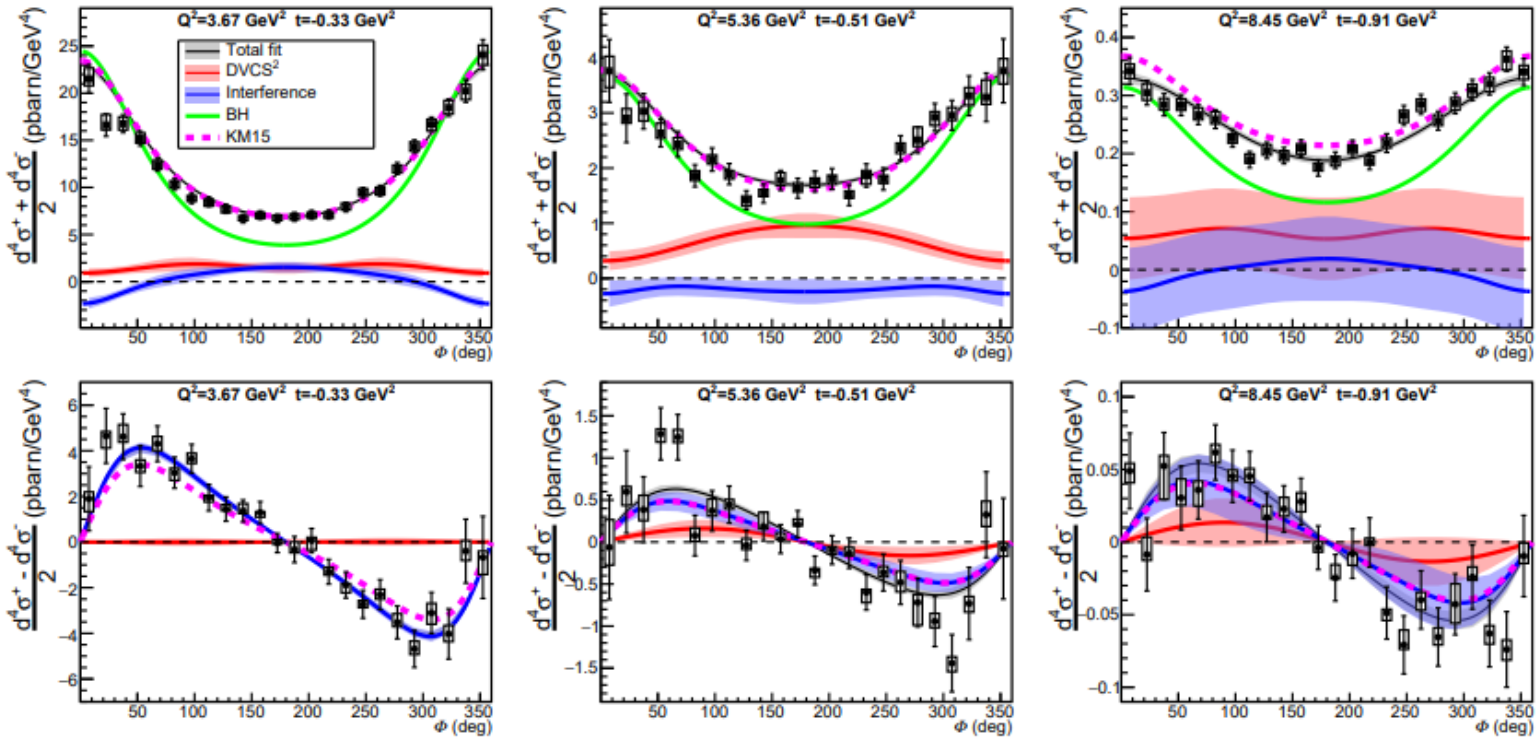
Observable (target)	12-GeV experiments	CFF sensitivity	Status
σ, $\Delta\sigma_{beam}(p)$	Hall A CLAS12 Hall C	Re$\mathcal{H}$(p), Im$\mathcal{H}$(p)	Hall A: data taken in 2014 and 2016; **Phys. Rev. Lett. 128, 252002 (2022)** CLAS12: data taken in 2018-2019; BSA paper under final review steps; CS analysis in progress Hall C: experiment planned for 2023-2024
BSA(p)	CLAS12	Im$\mathcal{H}$(p)	BSA publication in Ad Hoc review stage
lTSA(p), lDSA(p)	CLAS12	Im$\mathcal{H}$(p), Im$\mathcal{H}$(p), Re$\tilde{\mathcal{H}}$(p), Re$\mathcal{H}$(p)	Experiment just started! (will last 6 months)
tTSA(p)	CLAS12	Im$\mathcal{H}$(p), Im$\mathcal{E}$(p)	Experiment foreseen for ~2025
BSA(n)	CLAS12	Im$\mathcal{E}$(n)	Data taken in 2019-2020, BSA analysis undergoing CLAS review
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}$(n), Re$\mathcal{H}$(n)	Experiment just started! (will last 6 months)

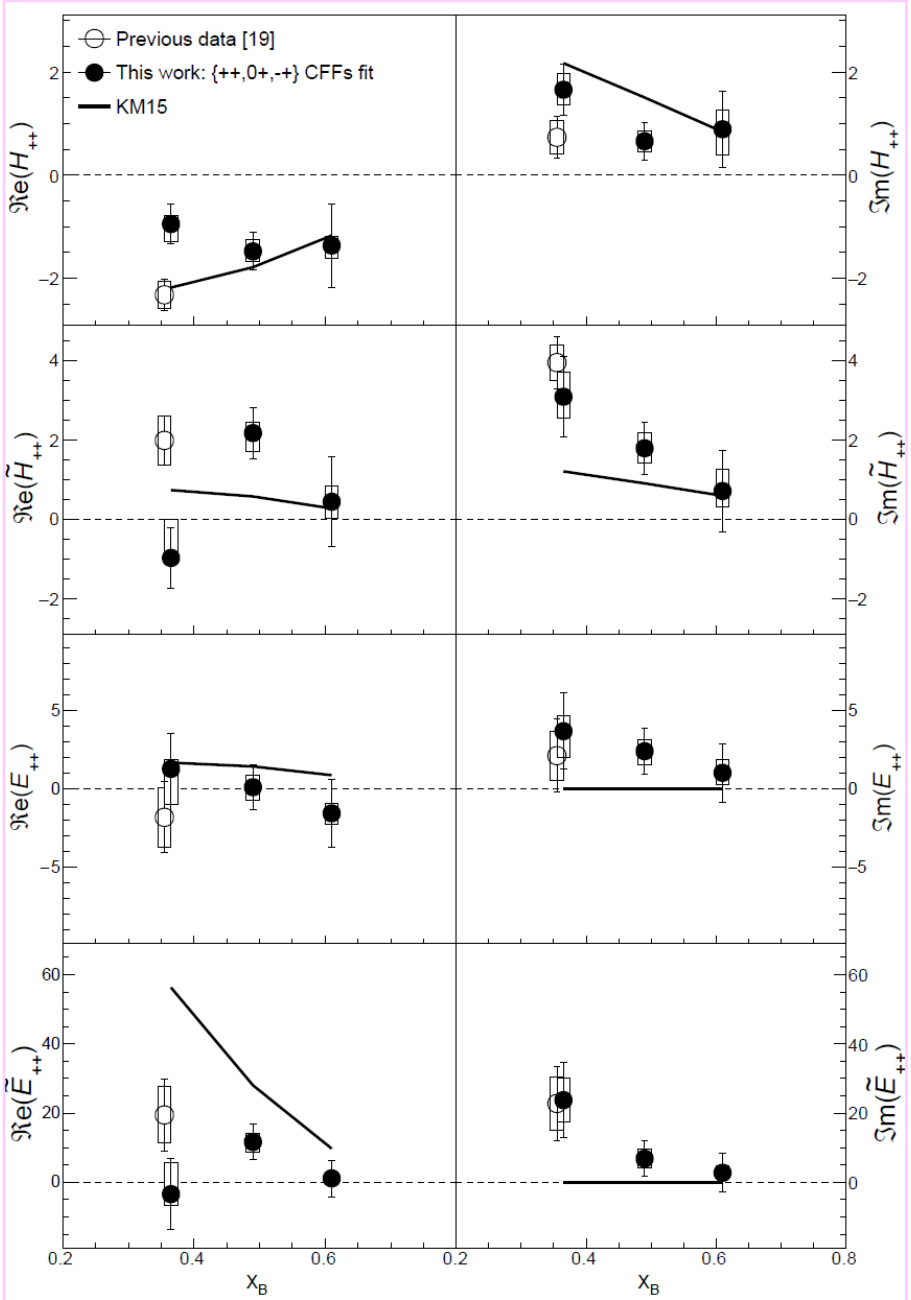
Complementarity of the experimental setups in the JLab Halls A/C and B

- Hall A/C: high luminosity → precision, small kinematic coverage, eγ topology
- Hall B (CLAS12): lower luminosity, large kinematic coverage, fully exclusive final state

Hall-A@11 GeV: high-precision cross sections for DVCS on the proton

$\vec{e}p \to e\gamma(p)$



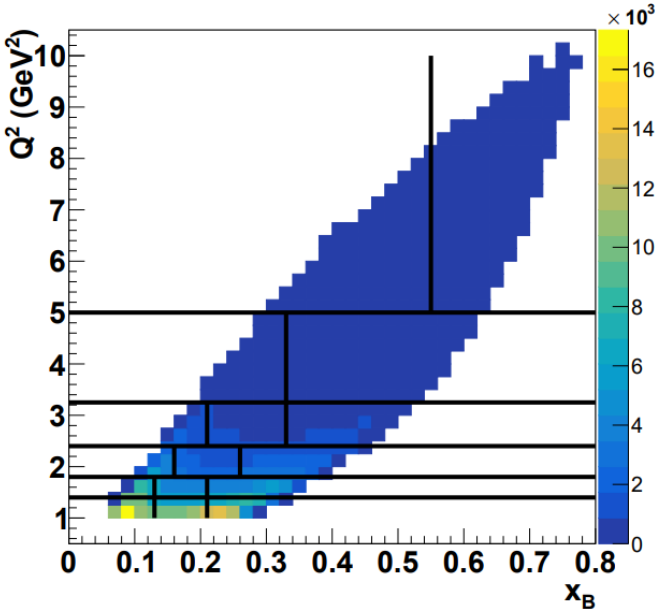


- Data taken in 2014 and 2016
- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Sensitivity to all 4 Compton form factors
- Kinematical power corrections (~t/Q^2, ~M/Q^2) included in the analysis

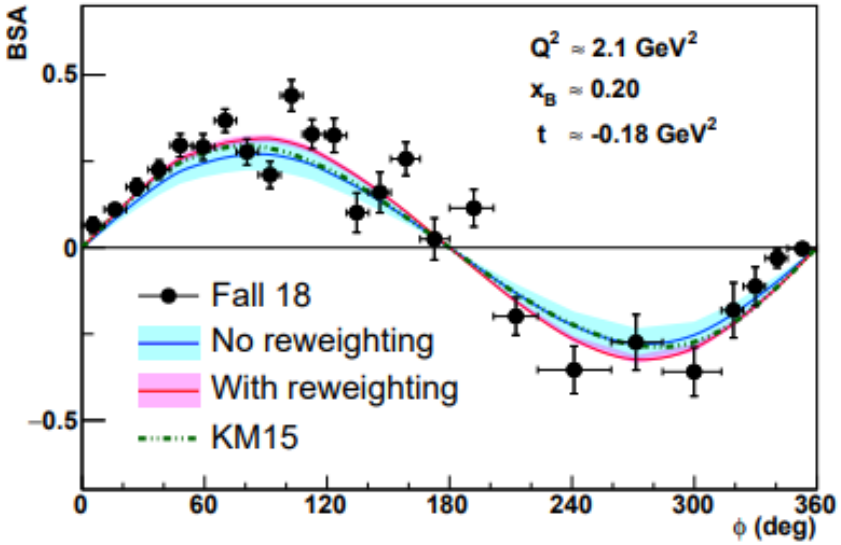
F. Georges et al., Phys. Rev. Lett. 128, 252002 (2022)

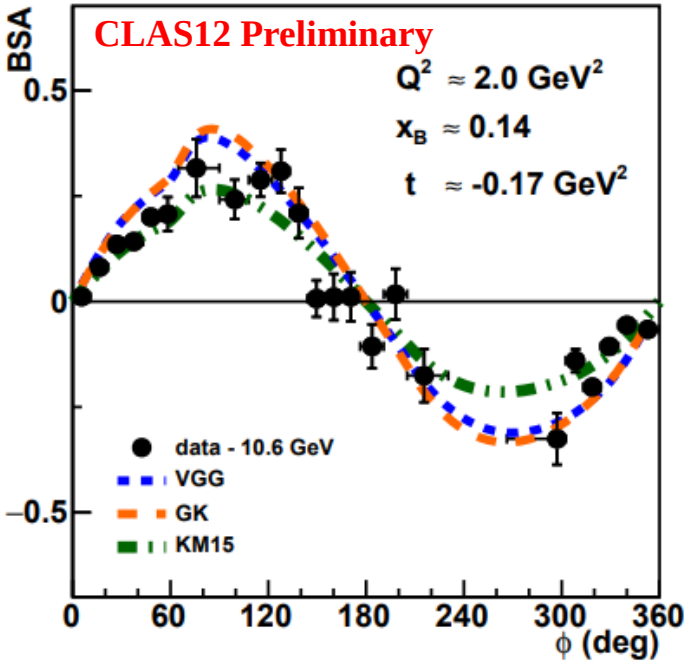
CLAS12: preliminary beam spin asymmetry for DVCS on the proton

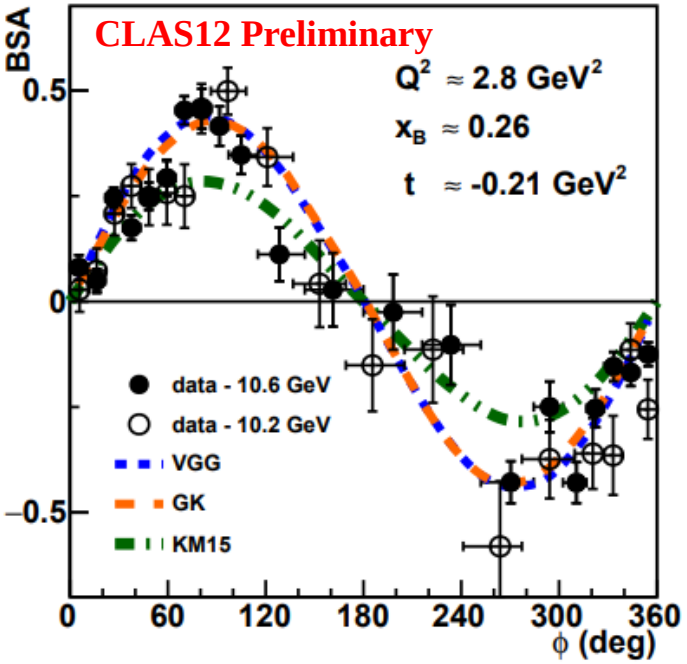
$\vec{e}p \rightarrow e\gamma p$

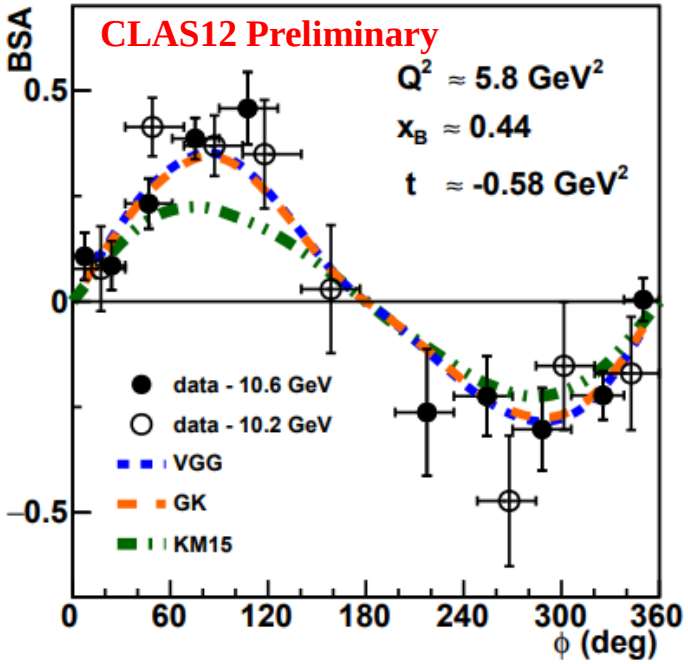


- Data taken 2018/2019
- Polarized beam (86%) with energy 10.6 GeV
- Unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits







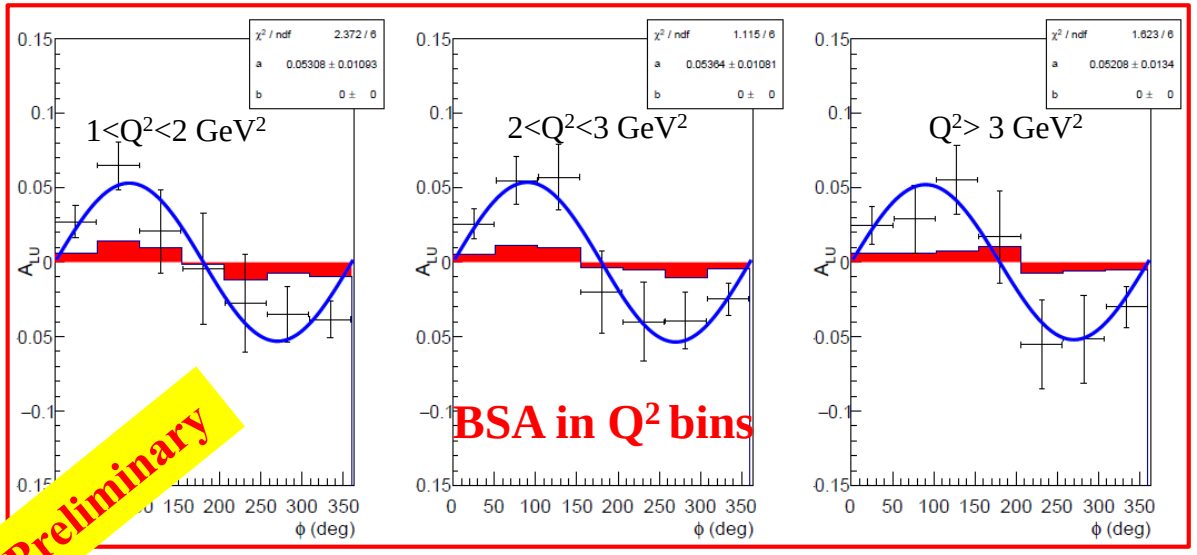


Examples of kinematics only accessible with ~10.6-GeV beam

Preliminary CLAS12 results: Beam Spin Asymmetry for neutron DVCS

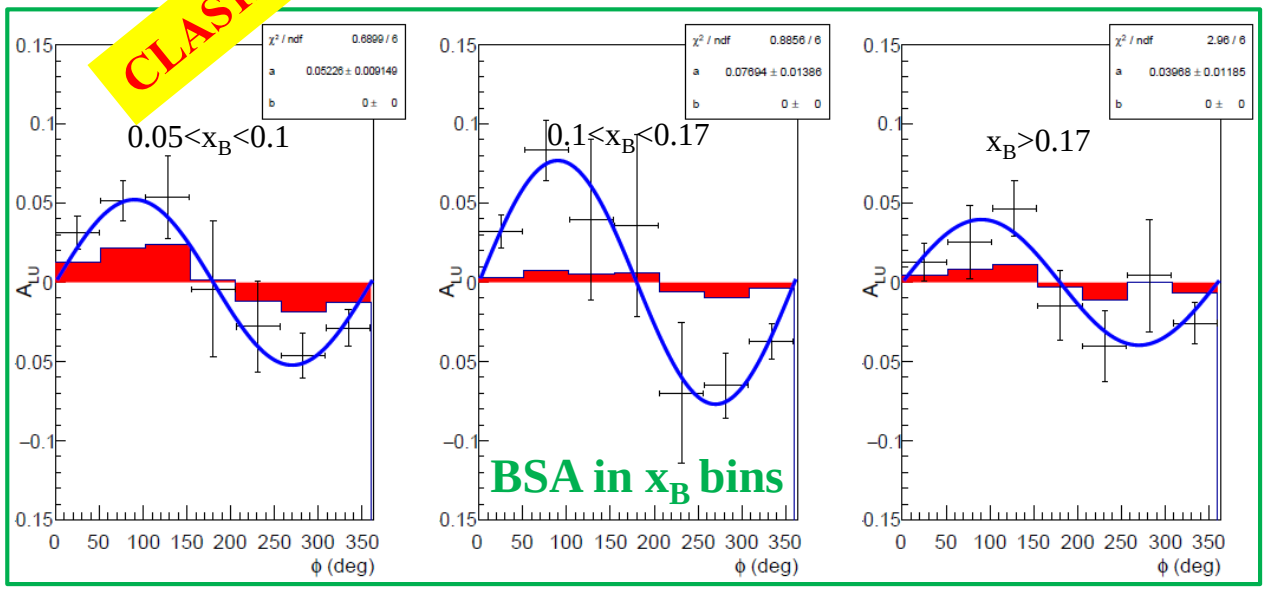
$\vec{e}d \rightarrow e\gamma n(p)$

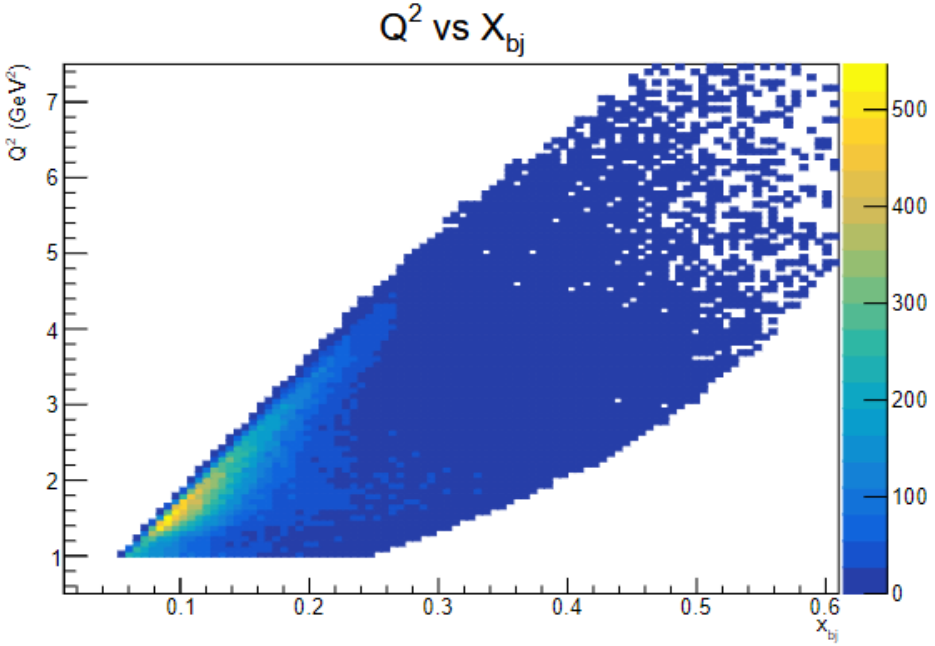
First-time measurement of nDVCS with detection of the active neutron (Central Neutron Detector)



- Data taken in 2019/2020
- LD2 target, ~10.4 GeV beam energy
- Scan of the BSA on a wide phase space
- Reaching the high Q^2- high x_B region
- Exclusivity thanks to detection of the active neutron → small systematics

CLAS12 Preliminary

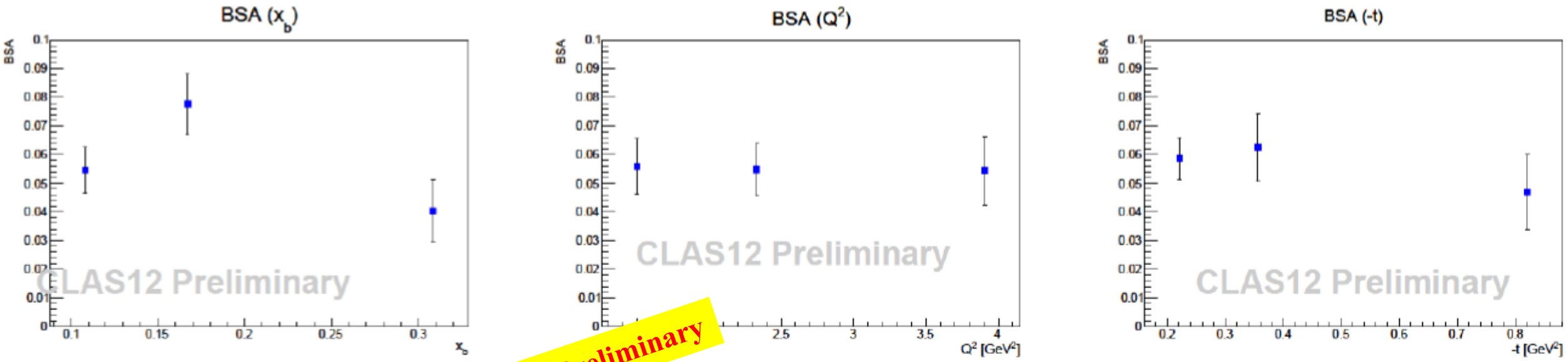




Preliminary CLAS12 results: Beam Spin Asymmetry for neutron DVCS

$\vec{e}d \rightarrow e\gamma n(p)$

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

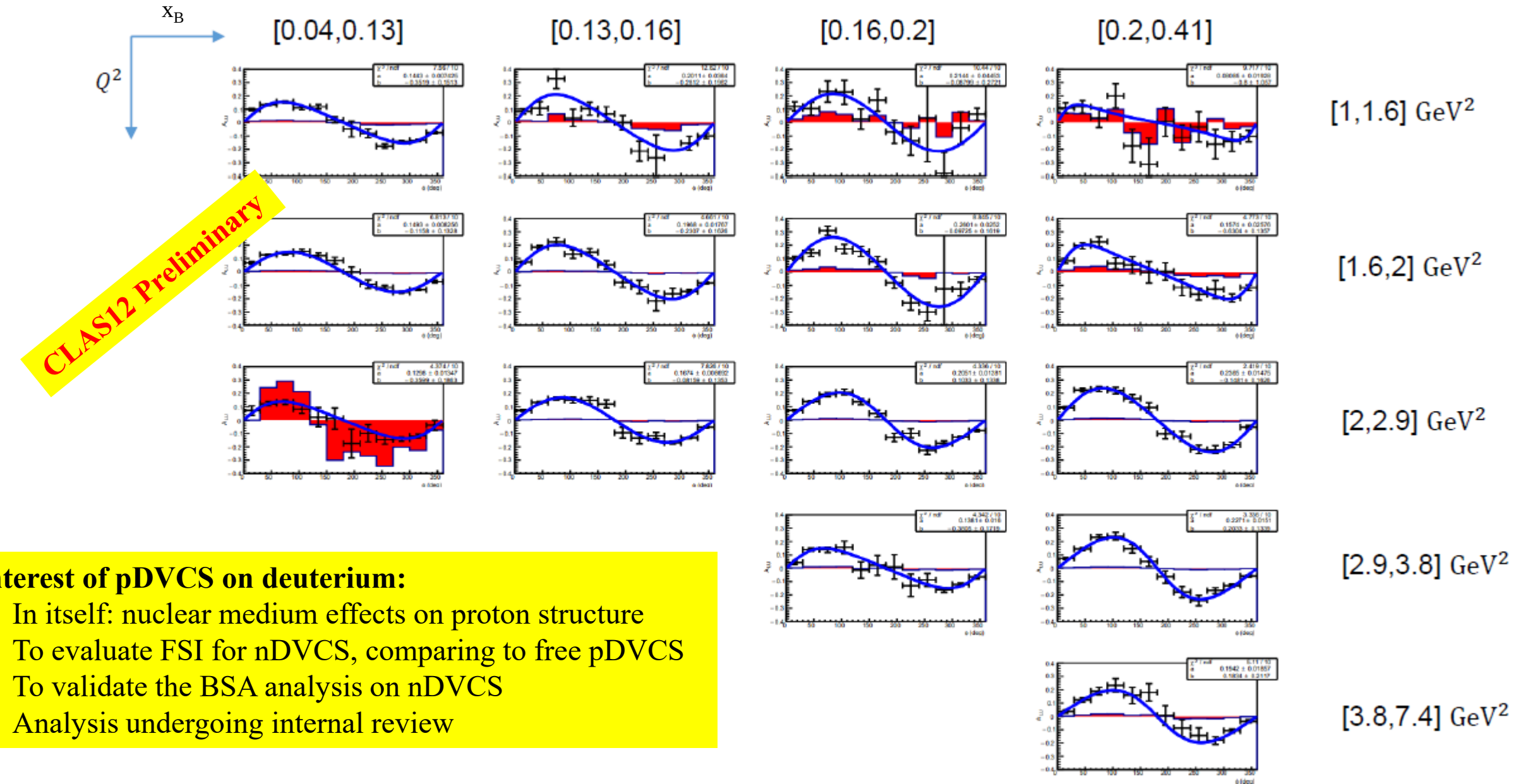


CLAS12 Preliminary

- Analysis review in the final stages
- Publication within a few months

Preliminary CLAS12 results: Beam Spin Asymmetry for proton DVCS in deuterium

$\vec{e}d \rightarrow ep\gamma(n)$

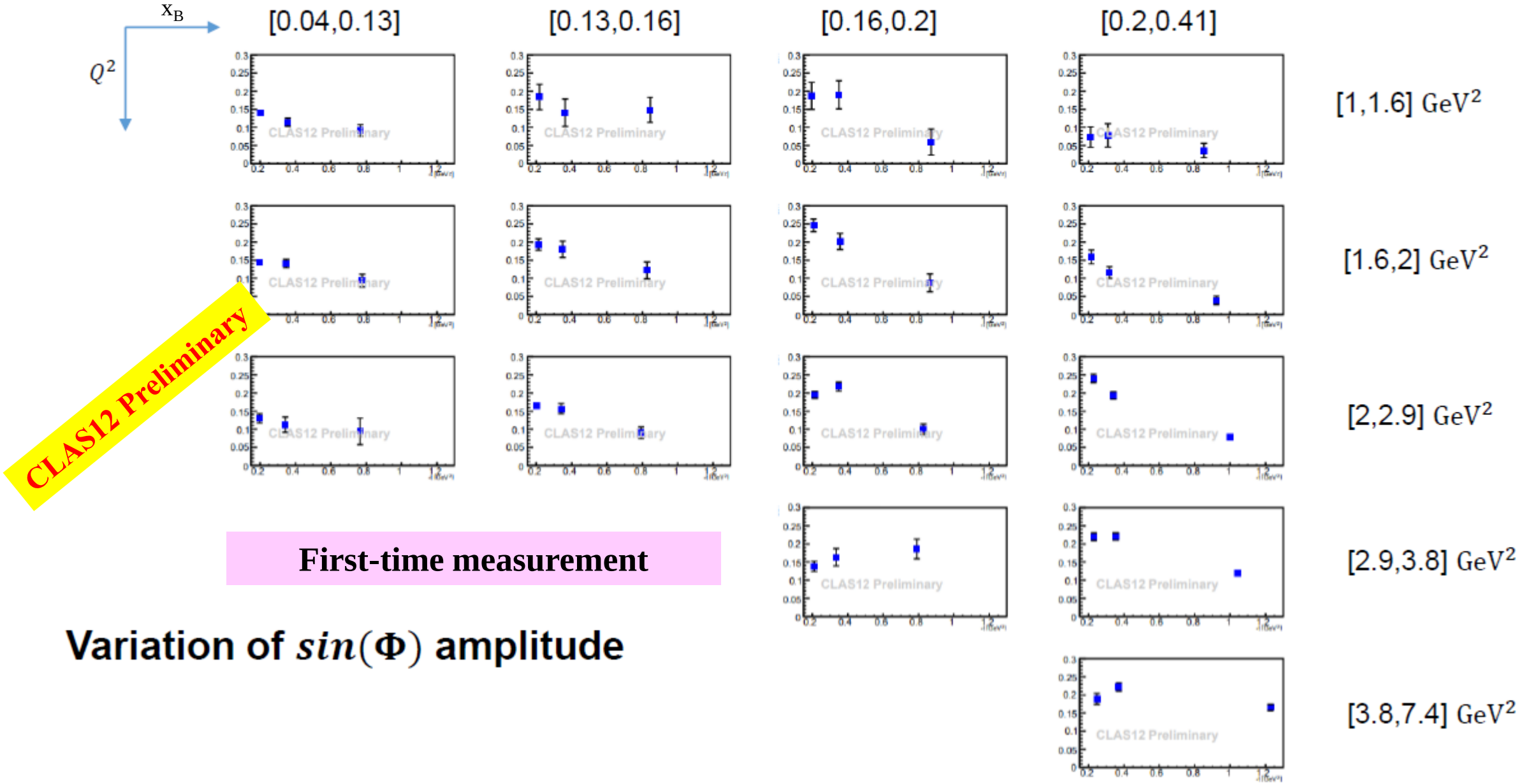


Interest of pDVCS on deuterium:

- In itself: nuclear medium effects on proton structure
- To evaluate FSI for nDVCS, comparing to free pDVCS
- To validate the BSA analysis on nDVCS
- Analysis undergoing internal review

Preliminary CLAS12 results: Beam Spin Asymmetry for proton DVCS in deuterium

$\vec{e}d \rightarrow ep\gamma(n)$



First-time measurement

Variation of $sin(\Phi)$ amplitude

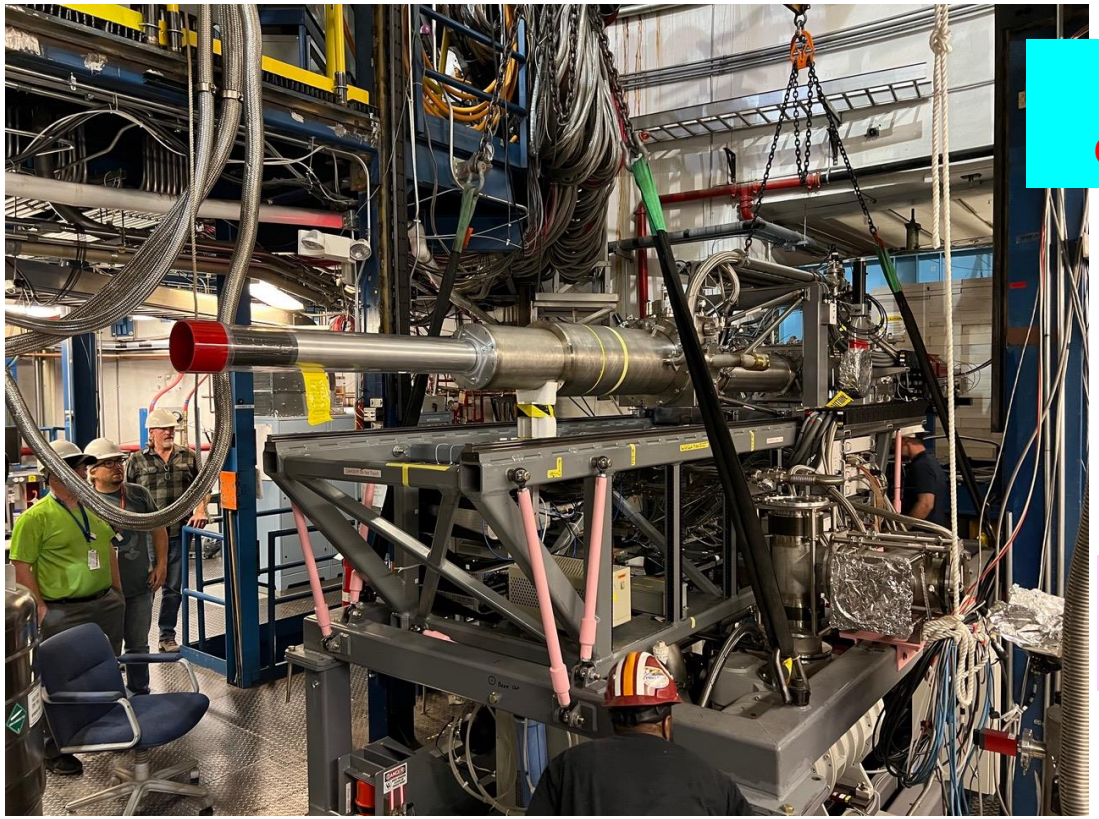
Ongoing: proton and neutron DVCS on longitudinally polarized target

First-time measurement of longitidunal target-spin asymmetry and double (beam-target) spin asymmetry for nDVCS

$$\Delta\sigma_{UL} \sim \sin\phi\ \mathrm{Im}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})-\xi k F_2\,\tilde{\mathcal{E}}+\ldots\}$$

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

→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

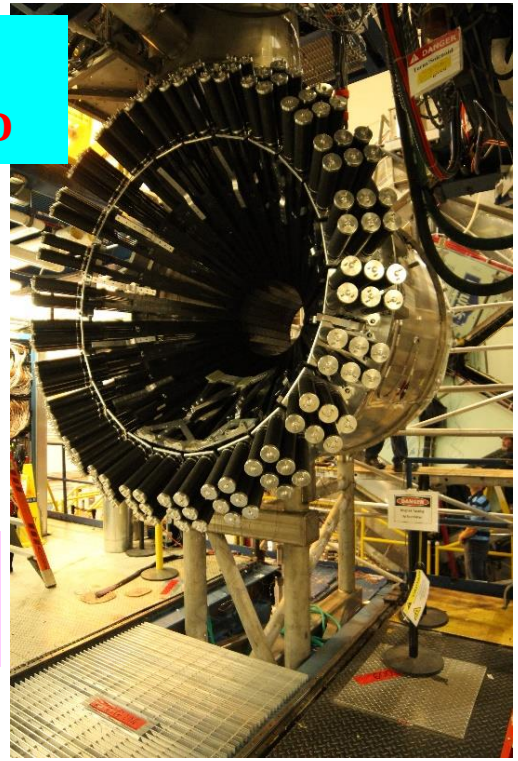


$eND_3 \rightarrow e(p)n\gamma$

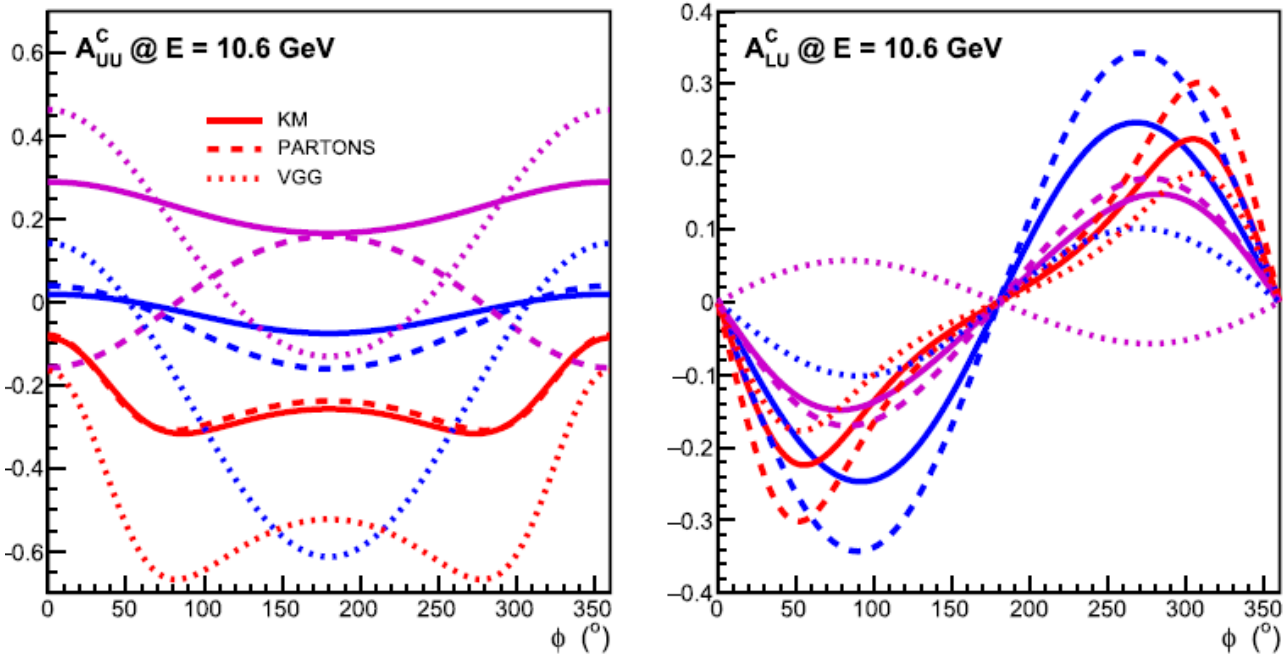
CLAS12 + Longitudinally polarized target + CND

Running between June 2022-March 2023

Ultimate goals: flavor separation of CFFs & Ji's sum rule



Perspectives: pDVCS and nDVCS with polarized positrons beam at CLAS



Model predictions for 2 out of the 3 proposed pDVCS observables

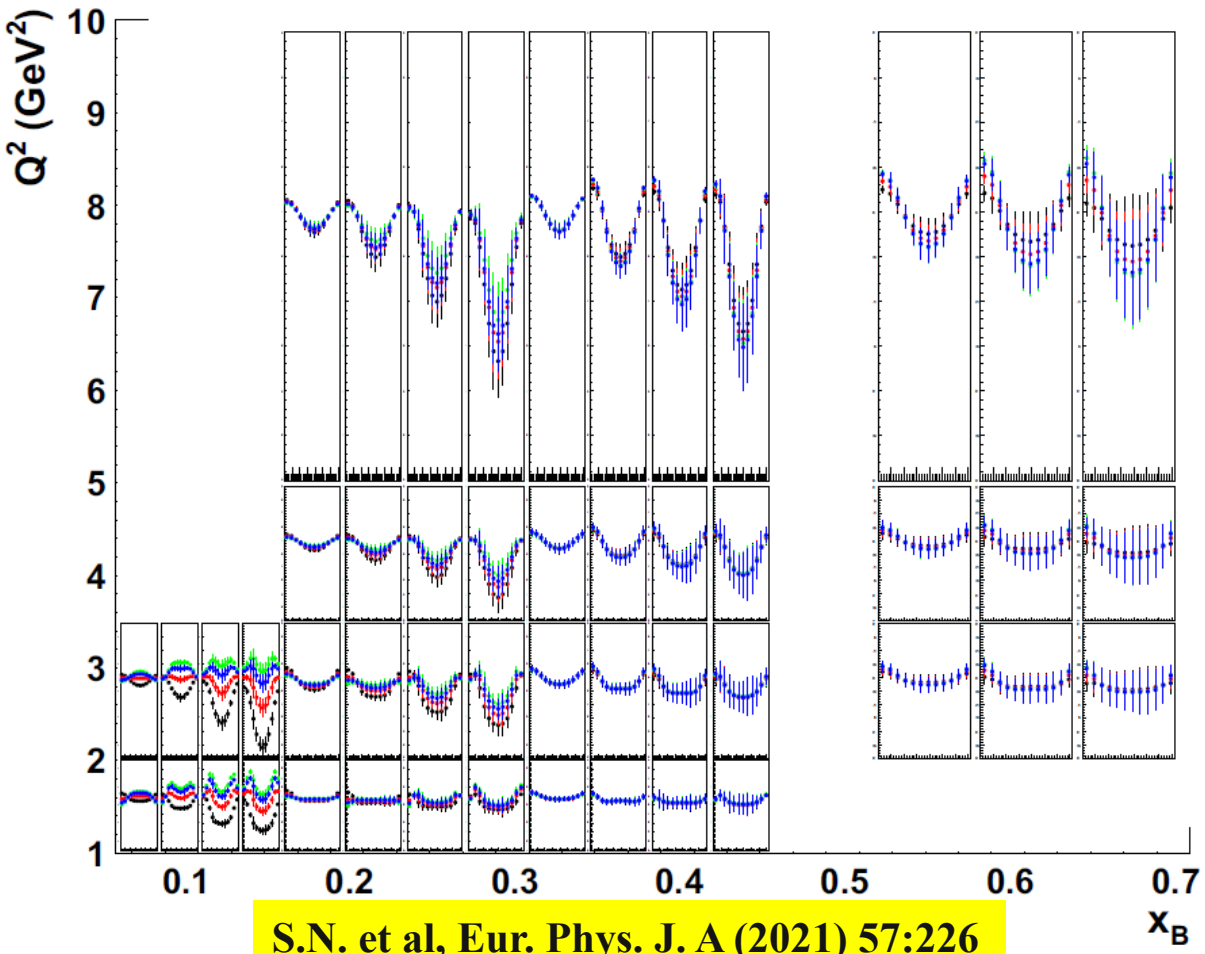
Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties, especially at low -t

V. Burkert et al., Eur. Phys. J. A (2021) 57

nDVCS Beam-charge asymmetry (BCA):
This observables has a strong impact on the extraction of Re$\mathcal{E}$. This was verified via local fits to the projections of approved CLAS12 nDVCS measurements with and without BCA

Projections (VGG) for the BCA, for various values of J_u, J_d

0.3, 0.1; 0.2/0.0; 0.1/−0.1; 0.3/−0.1



S.N. et al, Eur. Phys. J. A (2021) 57:226

Conclusions/outlook

✓ GPDs are a unique tool to explore **the structure of the nucleon**:

- **3D** quark/gluon **imaging** of the nucleon
- **orbital angular** momentum carried by quarks
- **pressure** distribution

✓ Fitting methods allow to **extract CFFs (→ GPDs) from DVCS** observables → several **p-DVCS** and **n-DVCS observables** are needed, covering a **wide phase space**

✓A lot of **recent results** on DVCS observables were obtained from **CLAS** and **Hall-A** at 6 GeV

→ First **tomographic interpretations** of the quarks in the **proton** from DVCS
→ Potential to understand the pressure and forces distributions in the proton

✓ JLab@12 GeV is **the optimal facility** to perform GPD experiments **in the valence region**

→ DVCS experiments on both **proton** and **neutron** (pol. and unpol.) are ongoing in **3 of the 4 Halls at JLab@12 GeV: quarks' spatial densities, flavor separation, quarks' orbital angular momentum, …**

→ JLab upgrade perspectives (positron beam, higher luminosity and energy) pave the road to the completion of the GPD program in the valence regime

Don't miss the presentation on the brand new CLAS12 results on Timelike Compton Scattering, P. Chatagnon, 9/7/2022, 13:20