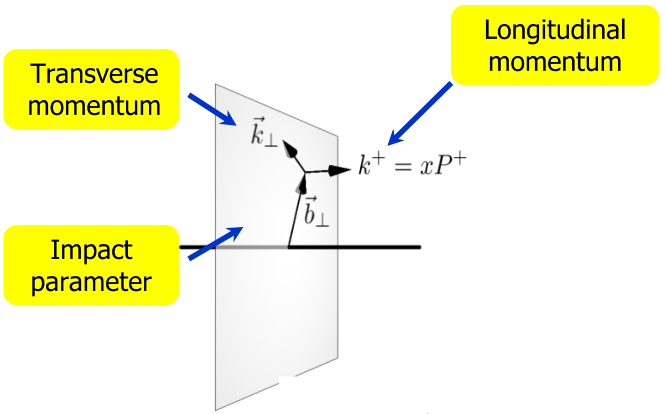
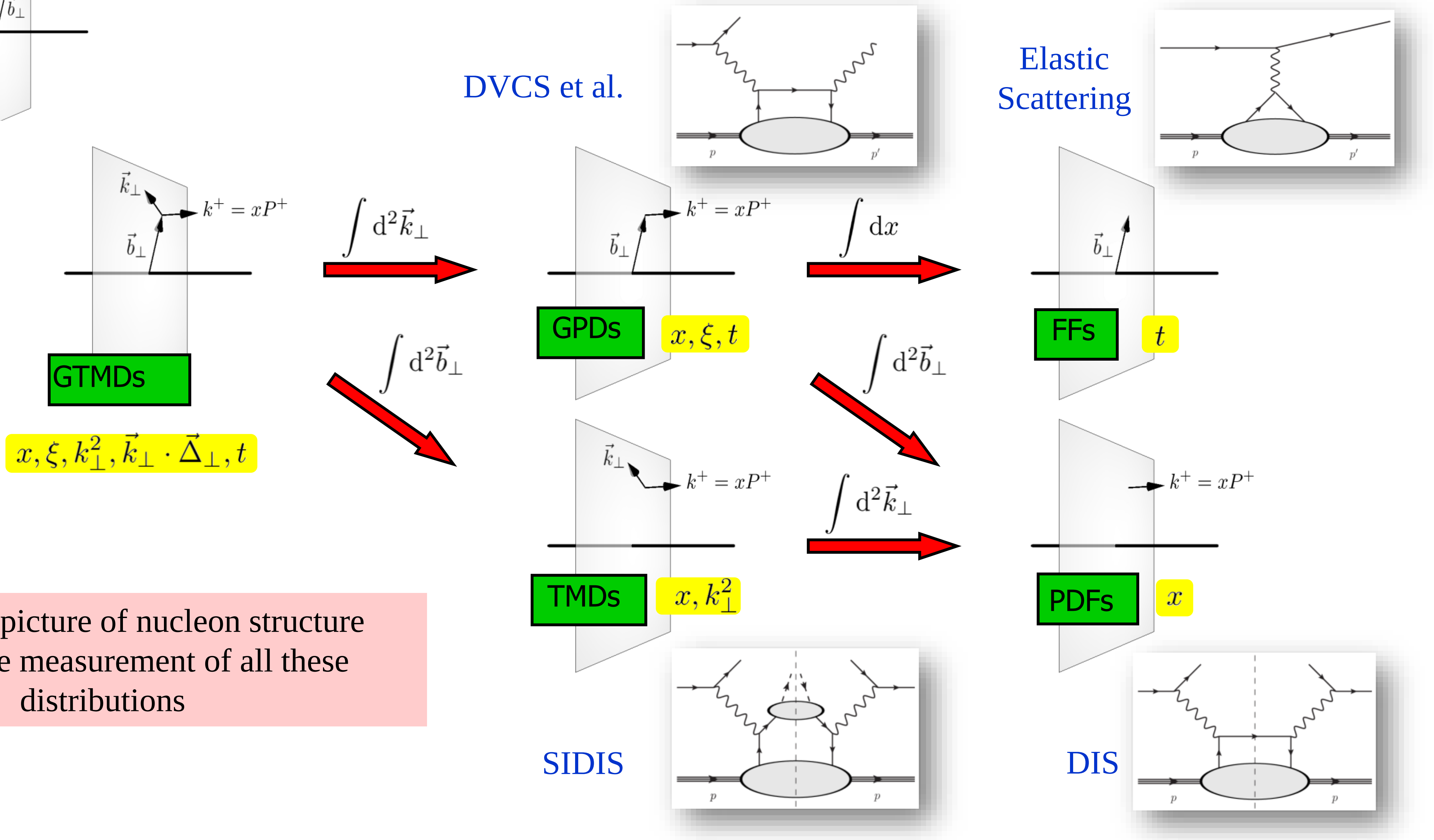
DVCS and TCS measurements at JLab

Silvia Niccolai, IJClab Orsay & CLAS Collaboration

Transversity 2024, Trieste (Italia), 6/6/2024

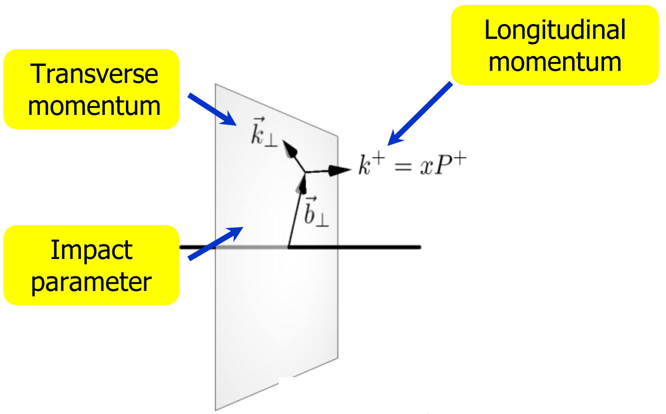
Multi-dimensional mapping of the nucleon



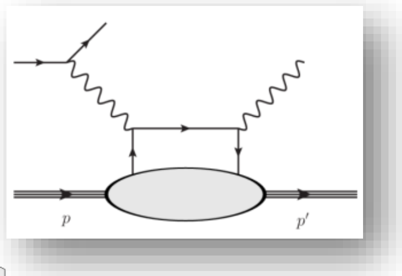


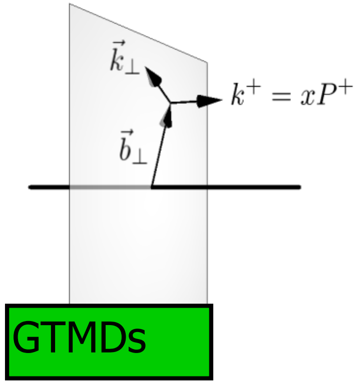
A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon

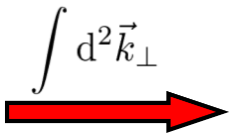


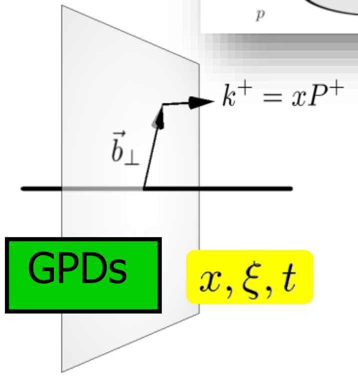
DVCS et al.





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





x, ξ, t

Nucleon tomography

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

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

Generalized Parton Distributions:

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

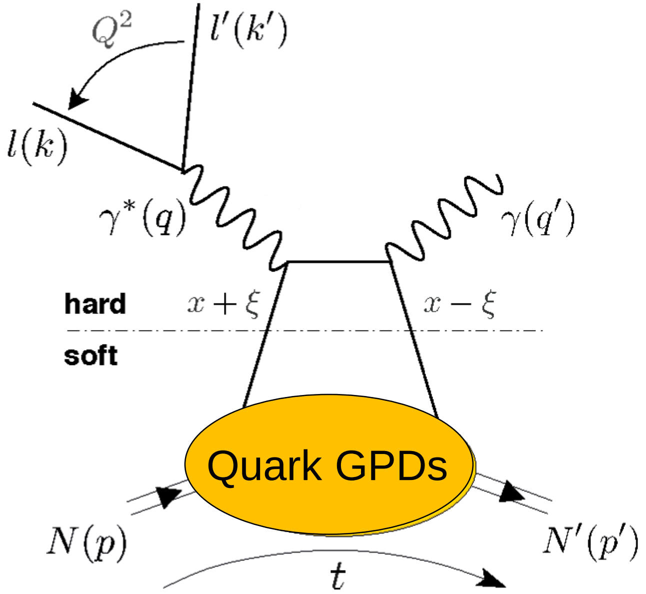
✓ linked to **FFs** and **PDFs**

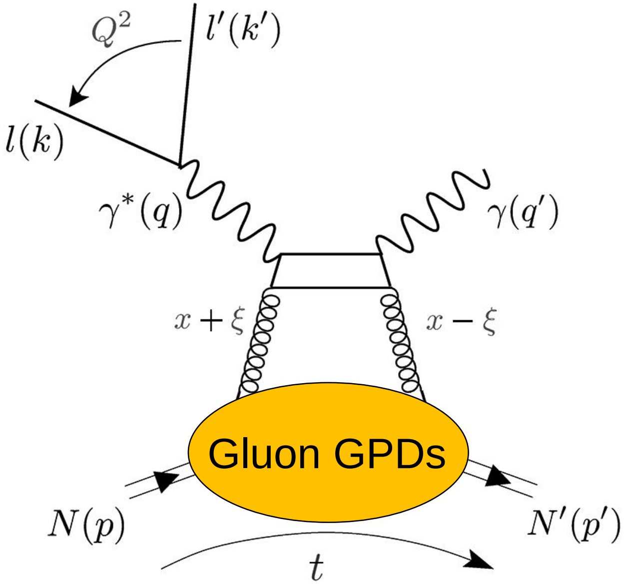
✓**Accessible in exclusive reactions**

Quark angular momentum (Ji's sum rule)

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

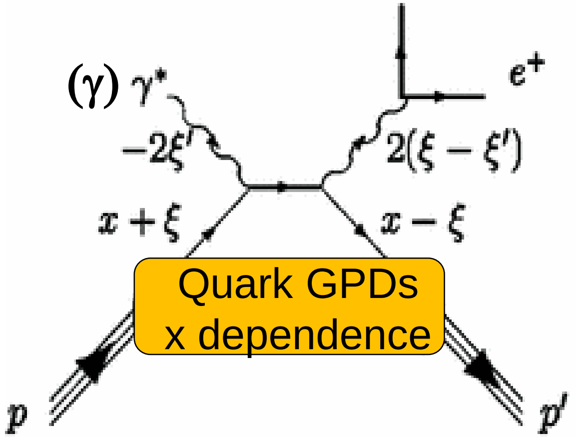
Exclusive reactions giving access to GPDs

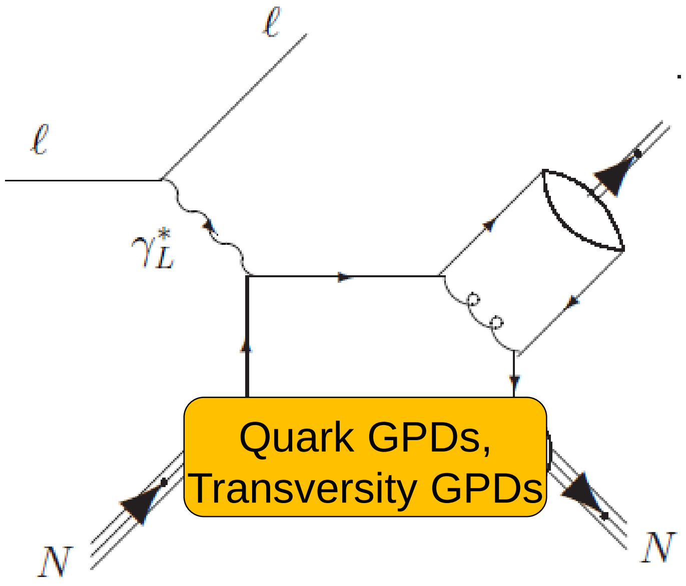




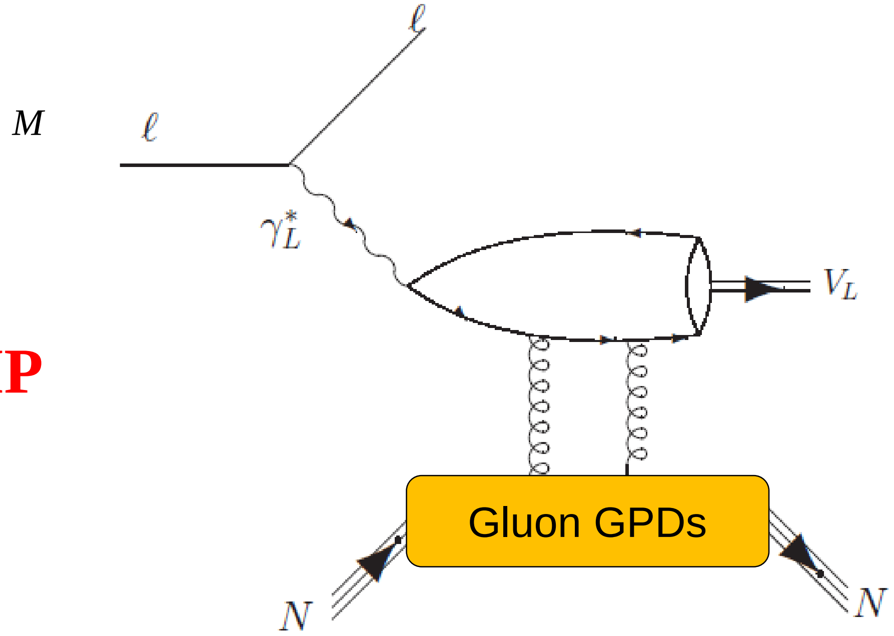
DVCS

(TCS), DDVCS



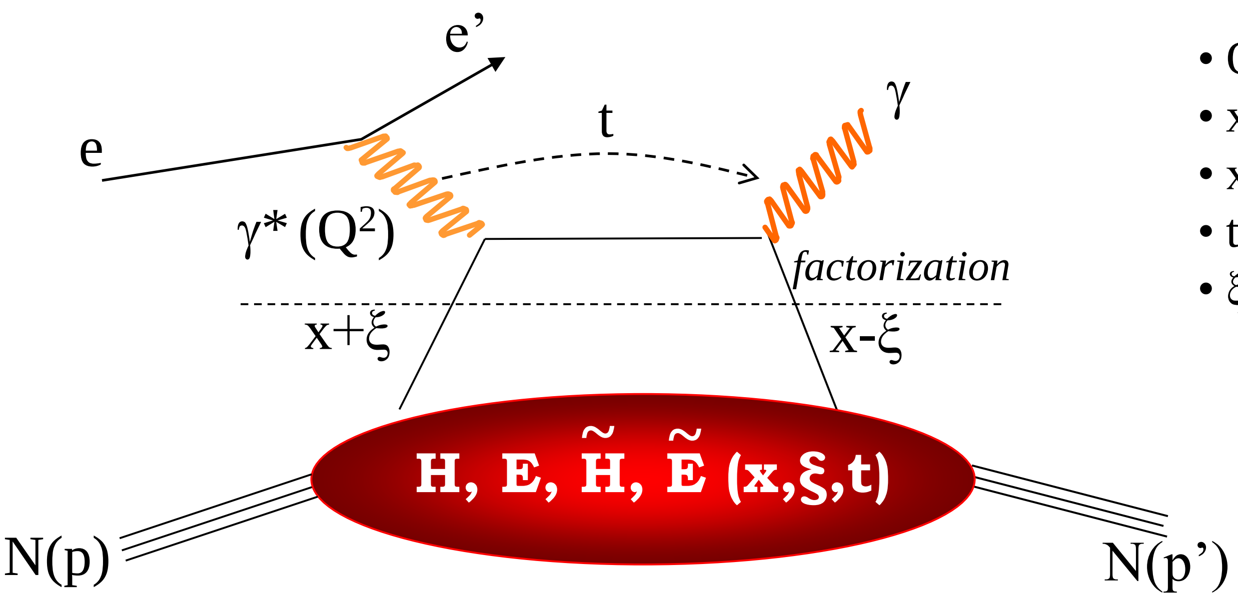


DVMP



See Kyungseon Joo's talk on Friday

Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

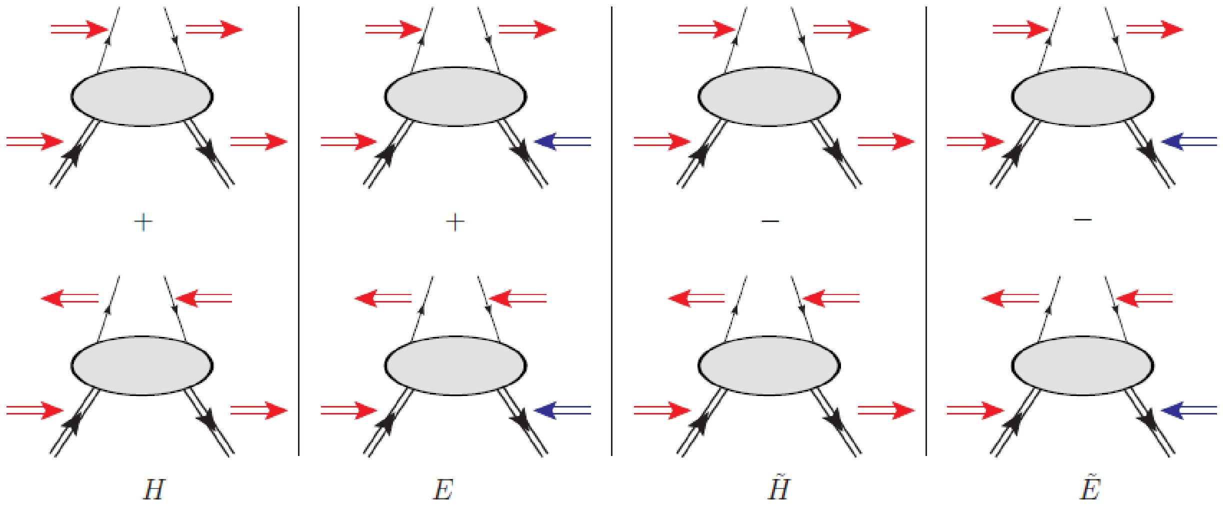
« **Handbag** » factorization, valid in the **Bjorken regime** (**high Q^2** and **ν**, fixed x_B), **$t \ll Q^2$**

*GPDs: Fourier transforms of **non-local**, **non-diagonal** QCD operators*

4 GPDs for each quark flavor
(leading-order, leading twist, quark-helicity conservation)

conserve nucleon spin

flip nucleon spin



Vector **Tensor** **Axial-vector** **Ps.scalar**

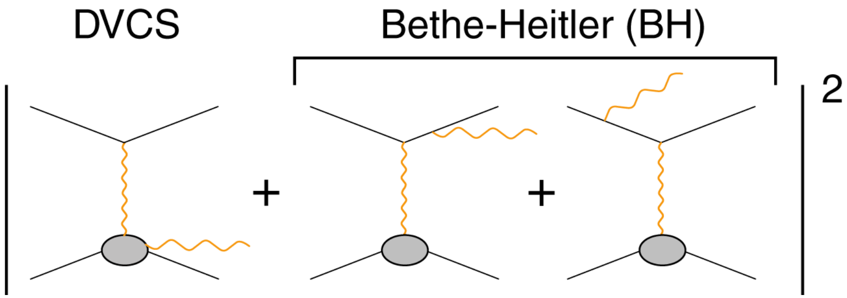
Accessing GPDs through DVCS

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

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

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

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



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:

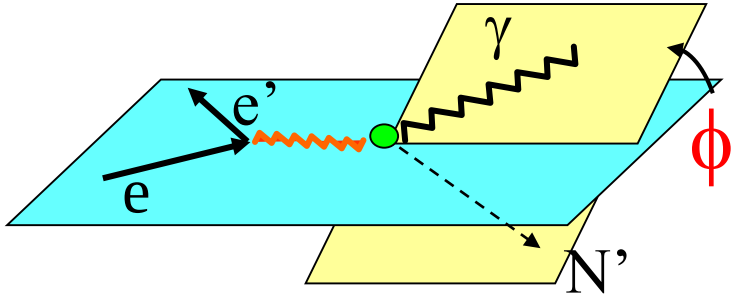
$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s-\phi)Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) +\ldots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n\}$

Unpolarized beam and target, different lepton charges:

$\Delta\sigma_C \sim \cos\phi\ Re\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}+\ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Re\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

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

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

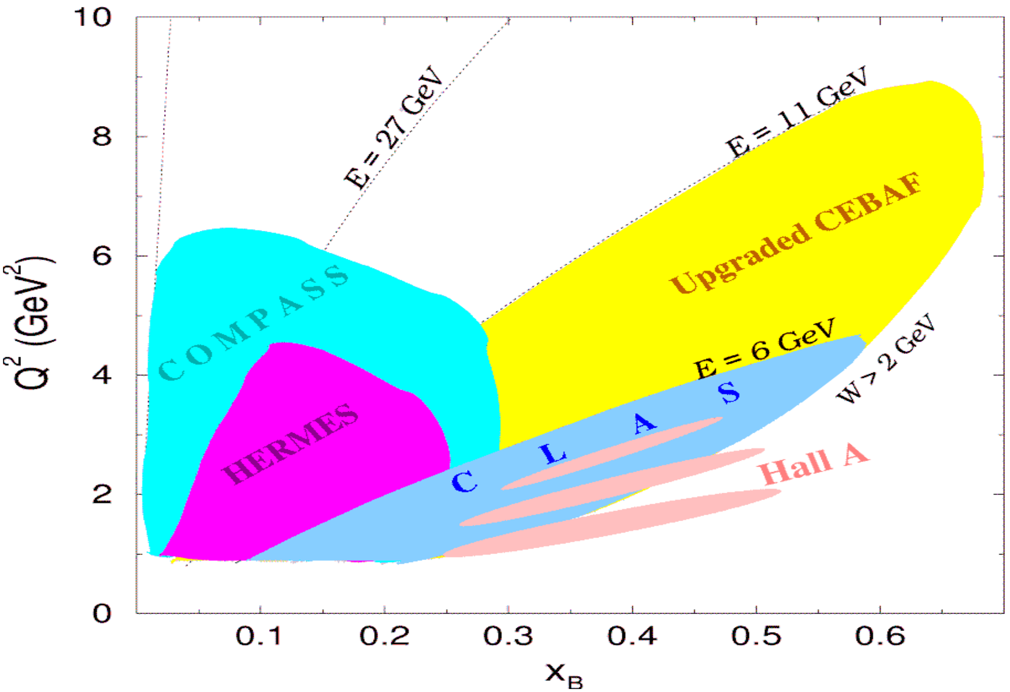


History of DVCS experiments worldwide

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

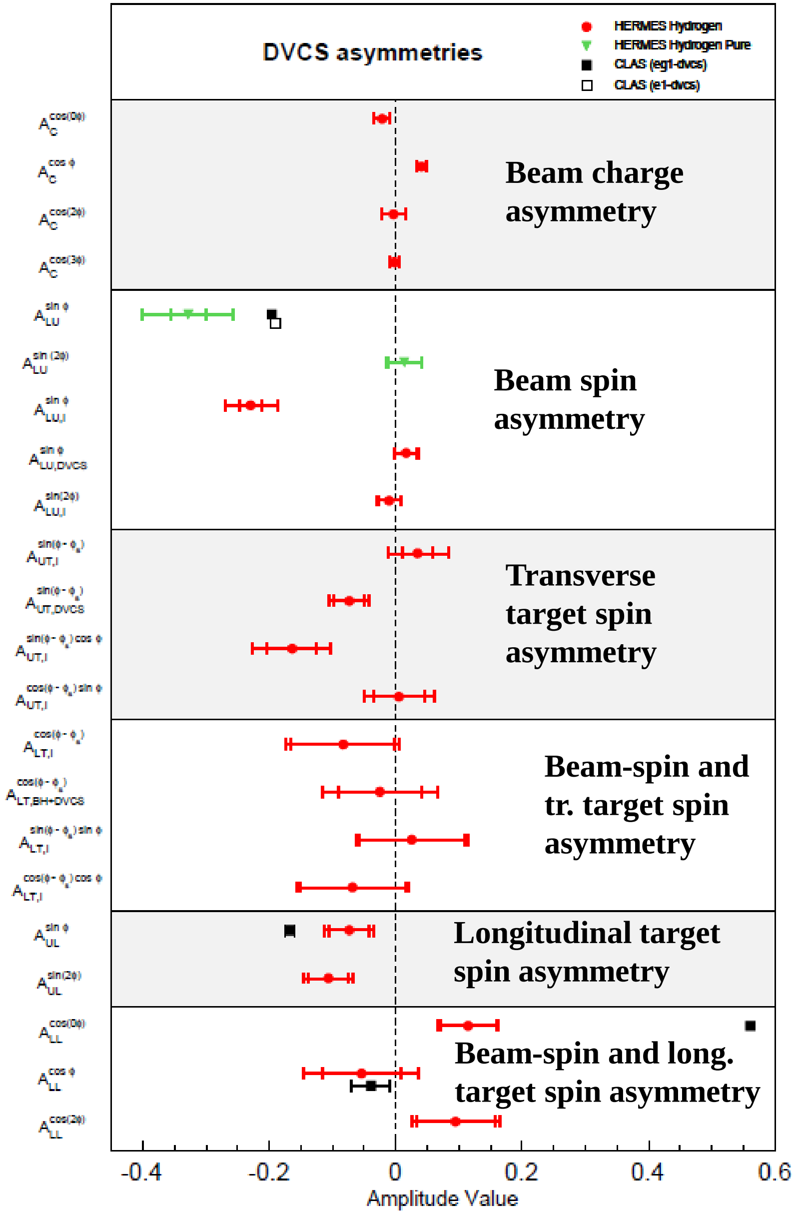
DESY	
HERMES	*H1/ZEUS*
p-DVCS,BSA,BCA, tTSA,lTSA,DSA	p-DVCS,CS,BCA

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



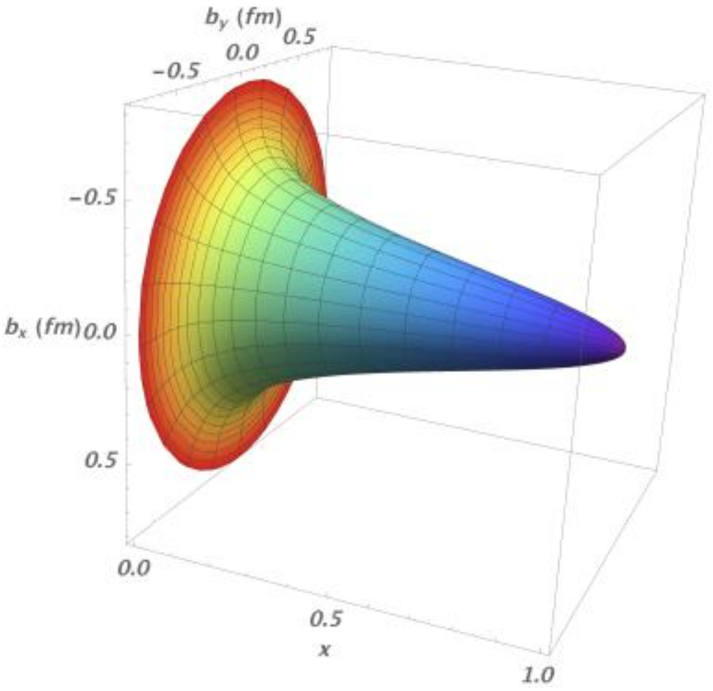
CLAS, HERMES: first observation of DVCS-BH interference in the beam-spin asymmetry (2001)

Hall A: test of scaling for DVCS (2006)



What have we learned from the first generation of DVCS results?

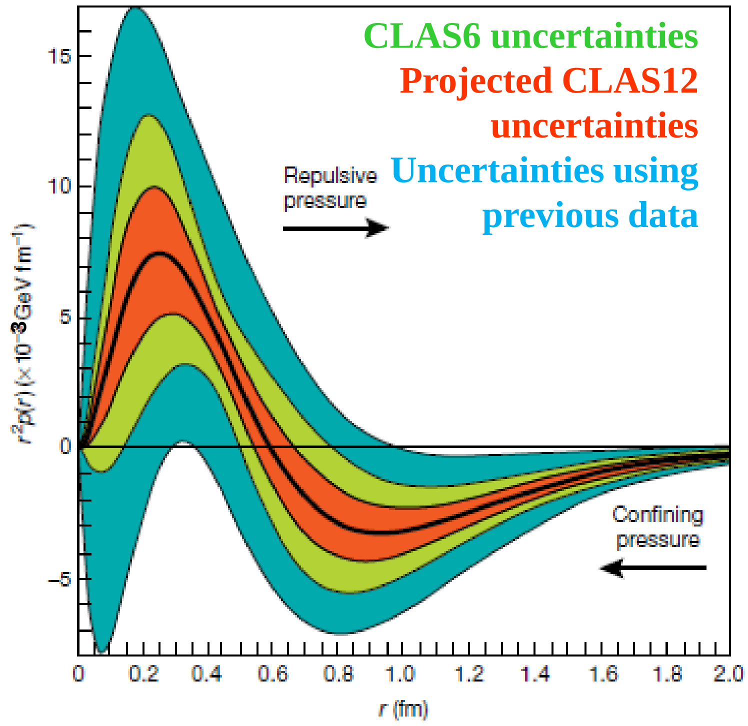
Proton tomography from *local fits* to HERMES, CLAS, and Hall-A data (**Im$\mathcal{H}$** + **model dependent** assumptions for x dependence)



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

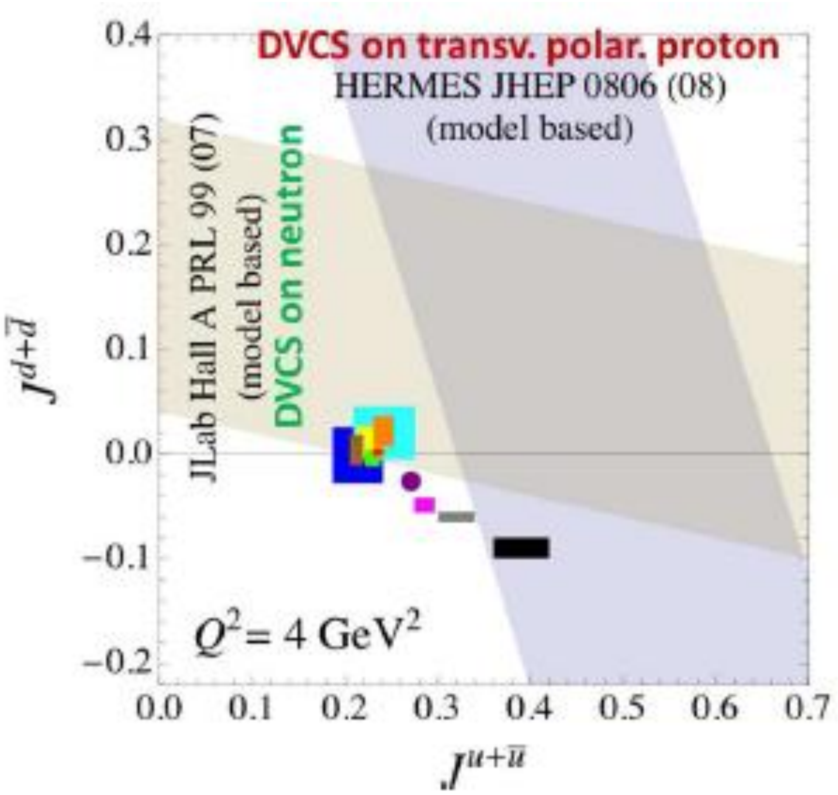
R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95 (2017)

From **$\mathcal{H}$-only fit** of DVCS BSA and cross section from CLAS@6 GeV **(model dependent)**: **an insight in the pressure distribution in the proton**



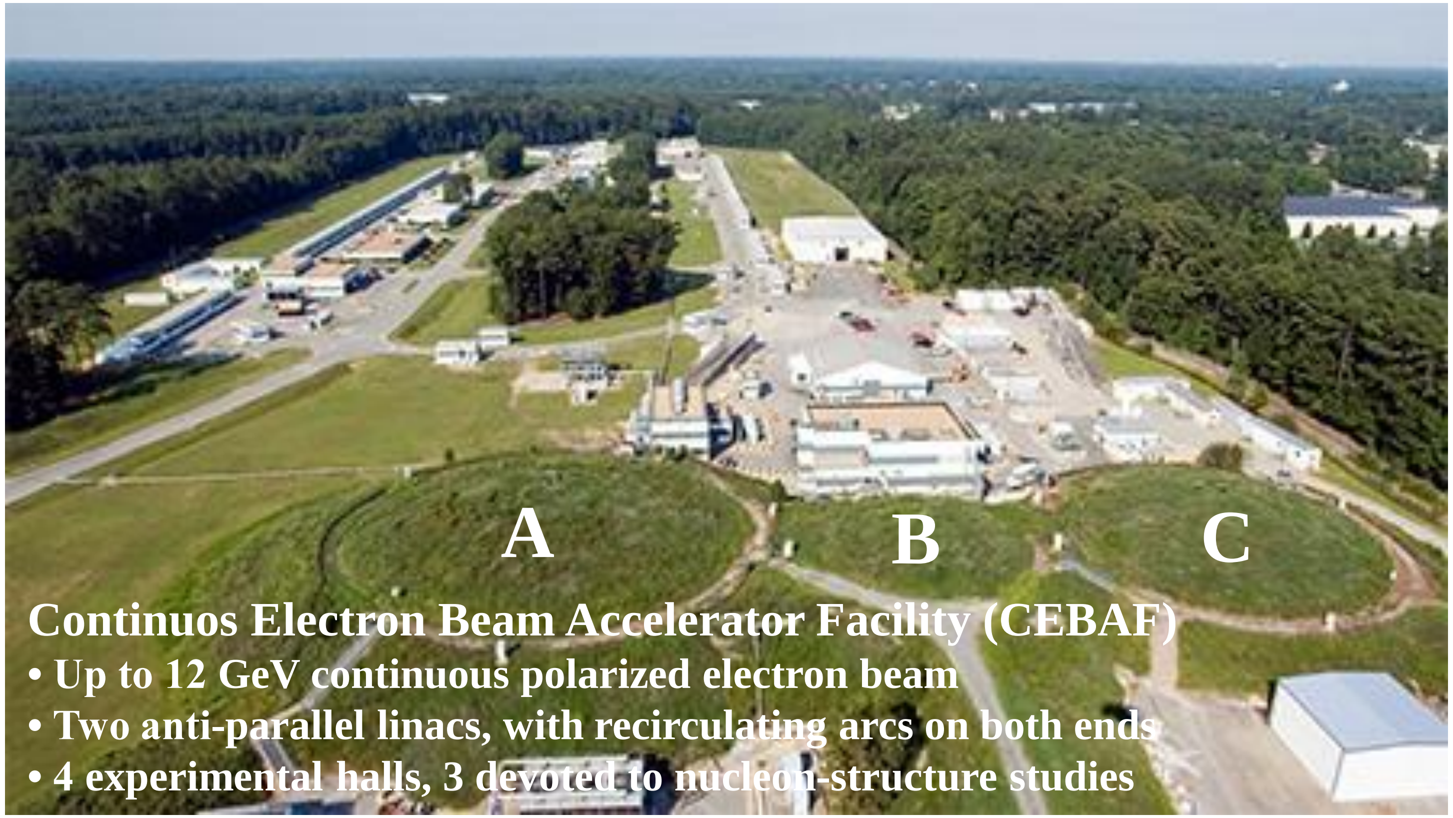
V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

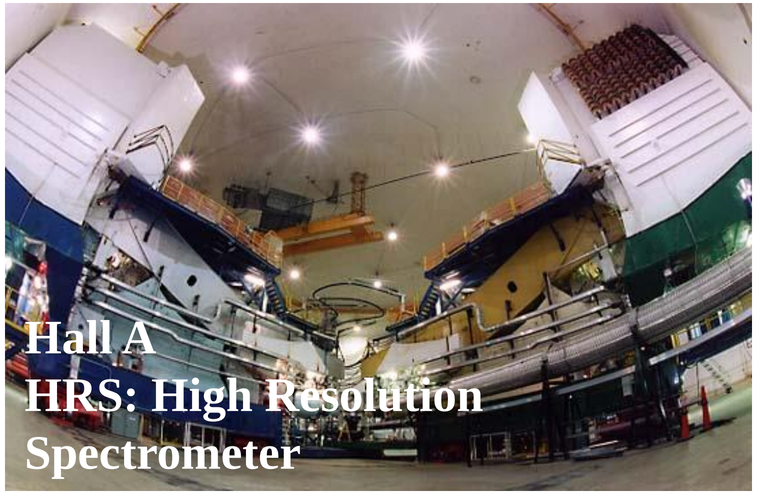
Importance of **neutron-DVCS** and **transversely-polarized proton-DVCS** to **constrain J_u and J_d**



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

Jefferson Lab at 12 GeV





Complementarity of the setups in the 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

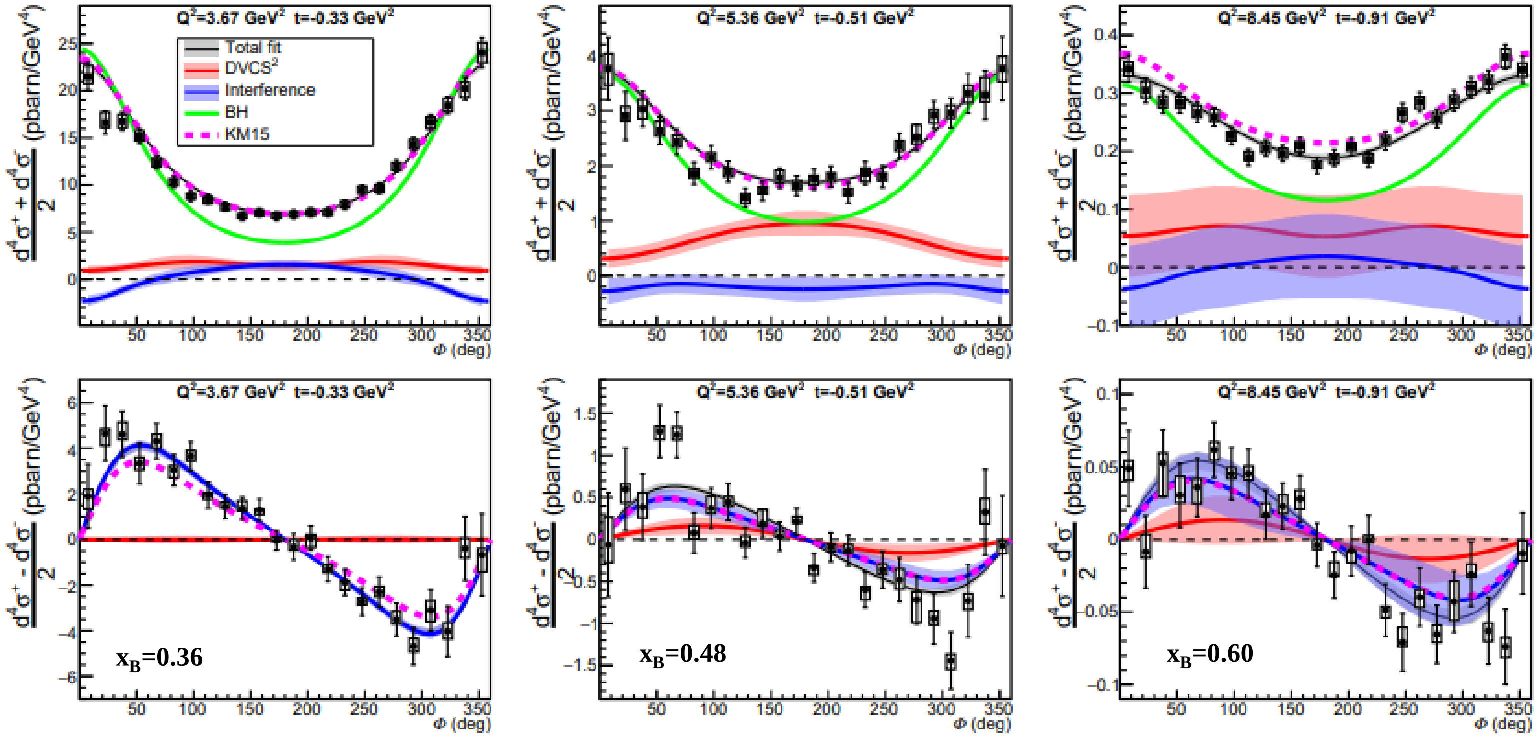
An extensive experimental program focused on DVCS and GPDs is underway

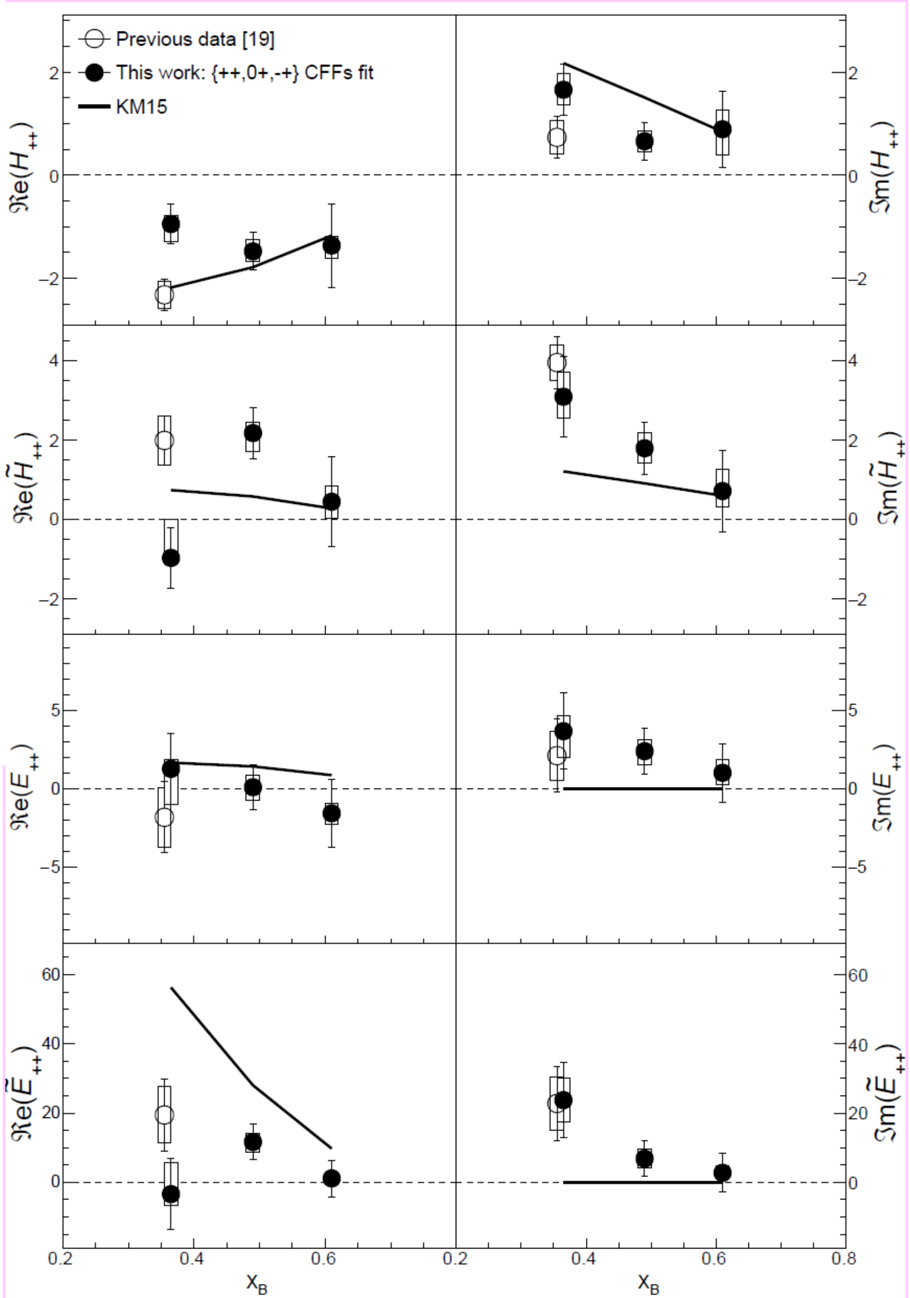
JLab@12 GeV DVCS program

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)	Data taken in 2016; Phys. Rev. Lett. 128 (2022) Data taken in 2018-2019; CS analysis under review Experiment just finished
BSA(p) + **TCS**	CLAS12	Im$\mathcal{H}$(p)	Data taken in 2018-2019; Phys. Rev. Lett. 130 (2023) Phys. Rev. Lett. 127 (2021)
lTSA(p), lDSA(p)	CLAS12	Im$\tilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p), Re$\tilde{\mathcal{H}}$(p), Re$\mathcal{H}$(p)	Experiment completed in March 2023
tTSA(p)	CLAS12	Im$\mathcal{H}$(p), Im$\mathcal{E}$(p)	Experiment foreseen for > 2027
BSA(n)	CLAS12	Im$\mathcal{E}$(n)	Data taken in 2019-2020; BSA paper ready for release
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}$(n), Re$\mathcal{H}$(n)	Experiment completed in March 2023

Hall-A@10.6 GeV: high-precision cross sections for DVCS on the proton

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





- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Separation of Interference, BH, and DVCS^2 terms
- Sensitivity to all 4 Compton Form Factors
- BMMP (Braun-Manashov-Muller-Pirnay) formalism
- Kinematical power corrections (~t/Q^2, ~M/Q^2) included in the analysis

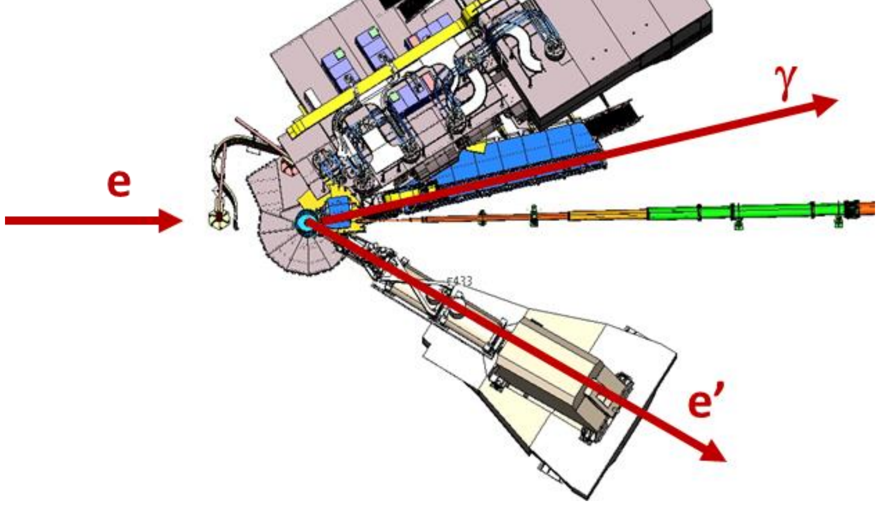
F. Georges et al., Phys. Rev. Lett. 128 (2022)

NPS experiment in Hall C

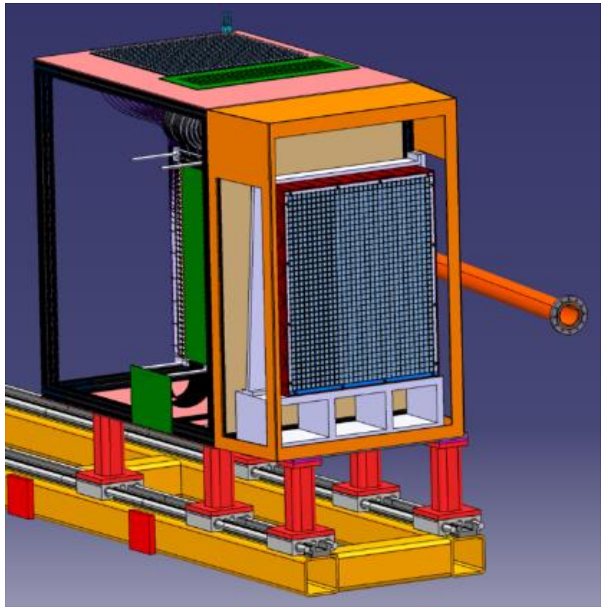
$\vec{e}p \to e\gamma(p)$

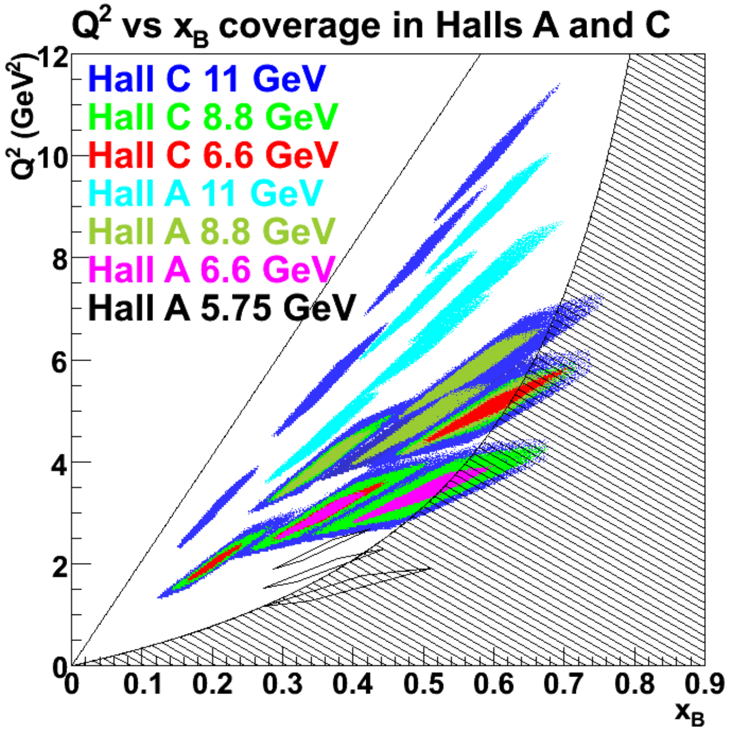
- Experiment **just completed**:
  Sep 15 (2023) – May 20 (2024)
- LH2 and LD2 targets
- Energy separation of the DVCS cross section
- Low-x_B coverage

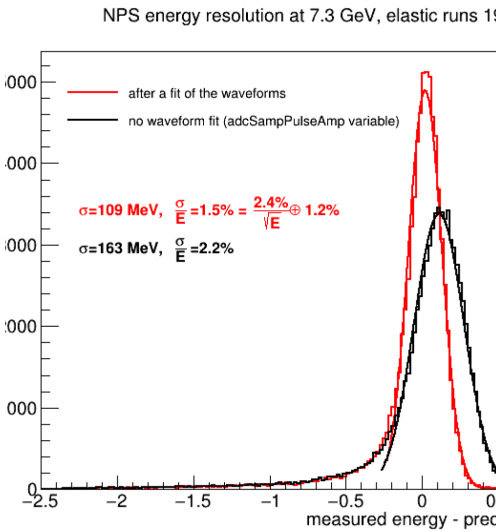
Experimental setup



Neutral Particle Spectrometer



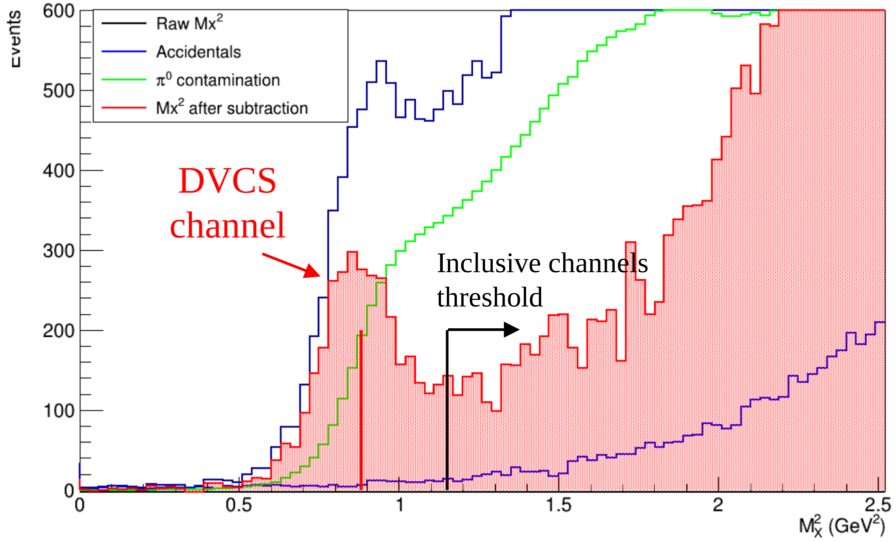




Measured energy resolution (online):

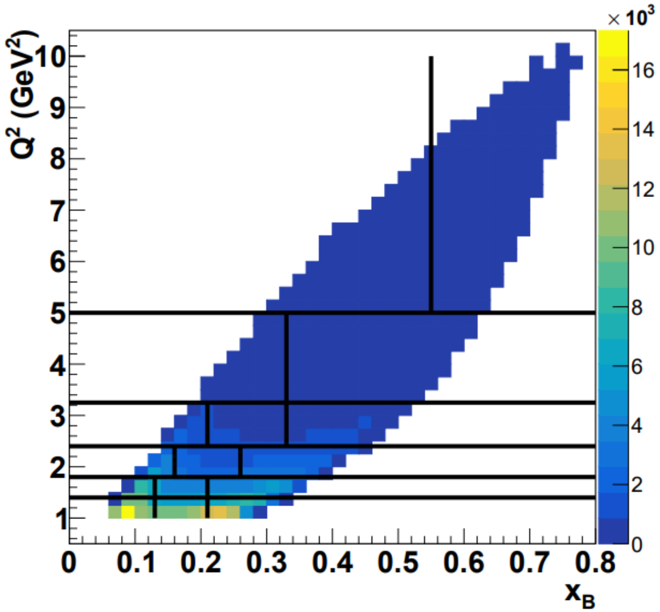
$$\frac{2.4\%}{\sqrt{E}} \oplus 1.2\%$$

DVCS missing mass squared

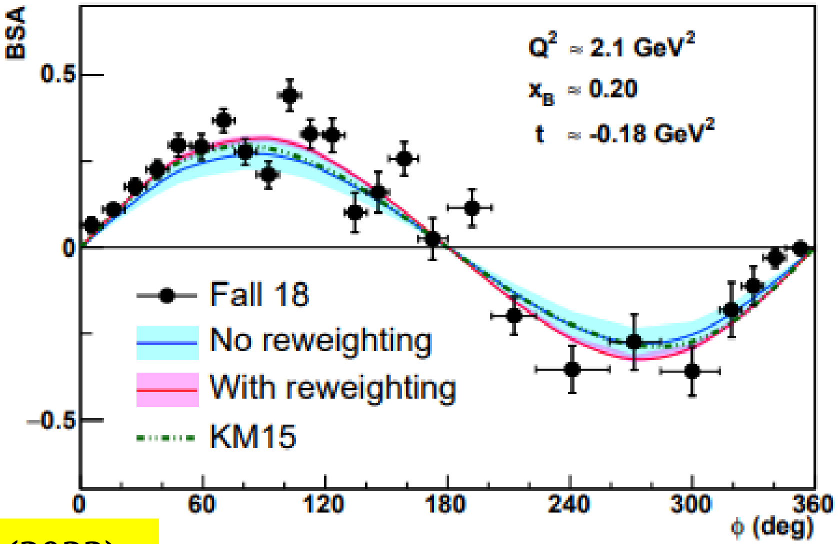


CLAS12: beam spin asymmetry for DVCS on the proton

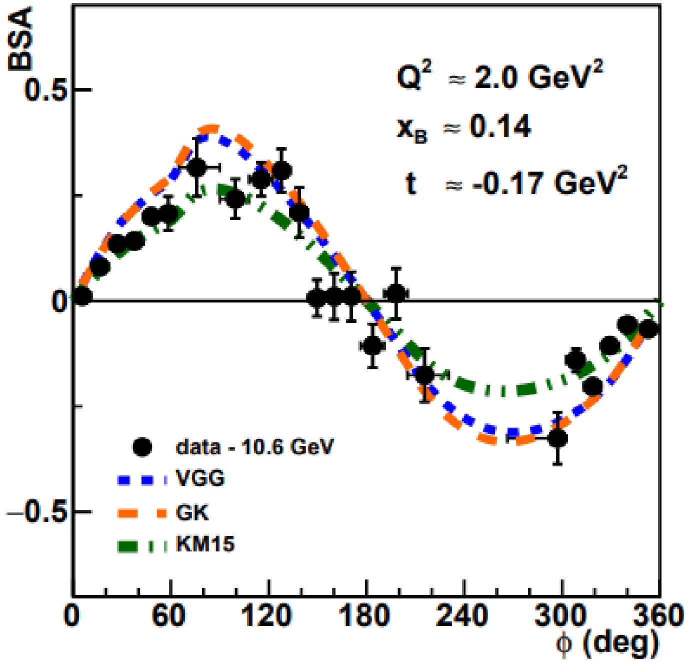
$\vec{e}p \rightarrow ep\gamma$

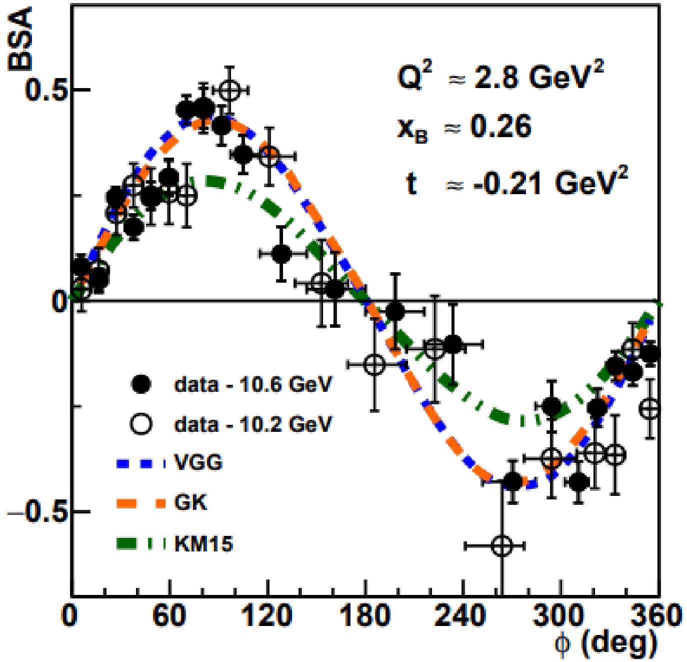


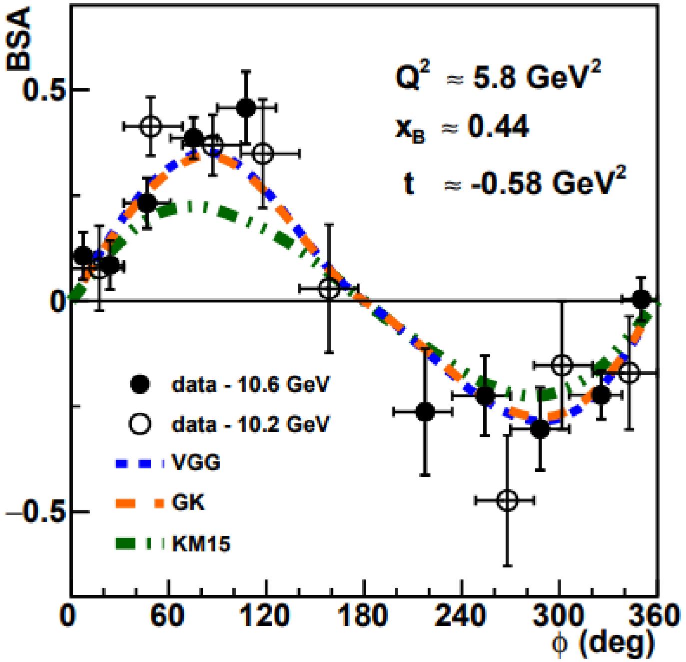
- Polarized beam (86%) with energy 10.6 GeV
- Unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many **kinematics never covered before**
- In **previously measured kinematics**, the new data are in good agreement with existing data and **improve the precision of GPD fits**



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







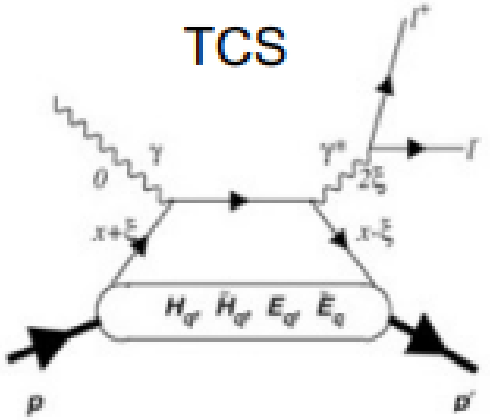
Examples of kinematics only accessible with ~10.6-GeV beam

Beyond DVCS: Timelike Compton Scattering

$\gamma p \to \gamma^* p$

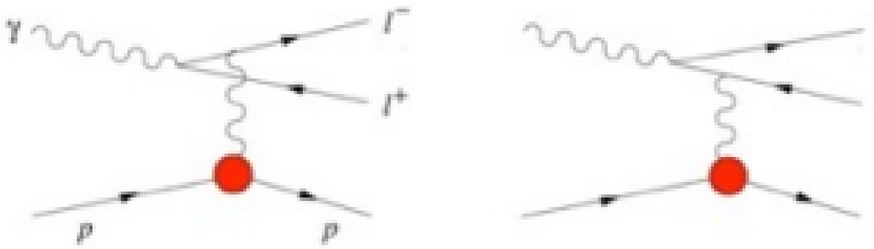
TCS is the time-reversal symmetric process to DVCS:
The incoming photon is real, the outgoing photon is highly virtual and decays in a pair of leptons

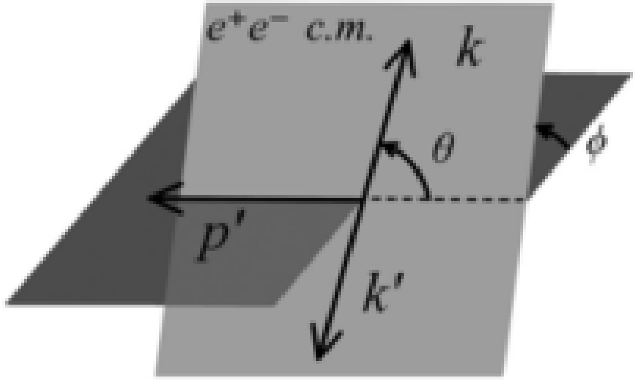
TCS



+

Bethe-Heitler (BH)





$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\cos\varphi\frac{1+\cos^2\theta}{\sin\theta}\mathrm{Re}\tilde{M}^{--} - \cos 2\varphi\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\tilde{M}^{+-} + O\Big(\frac{1}{Q'}\Big)\Big]$$

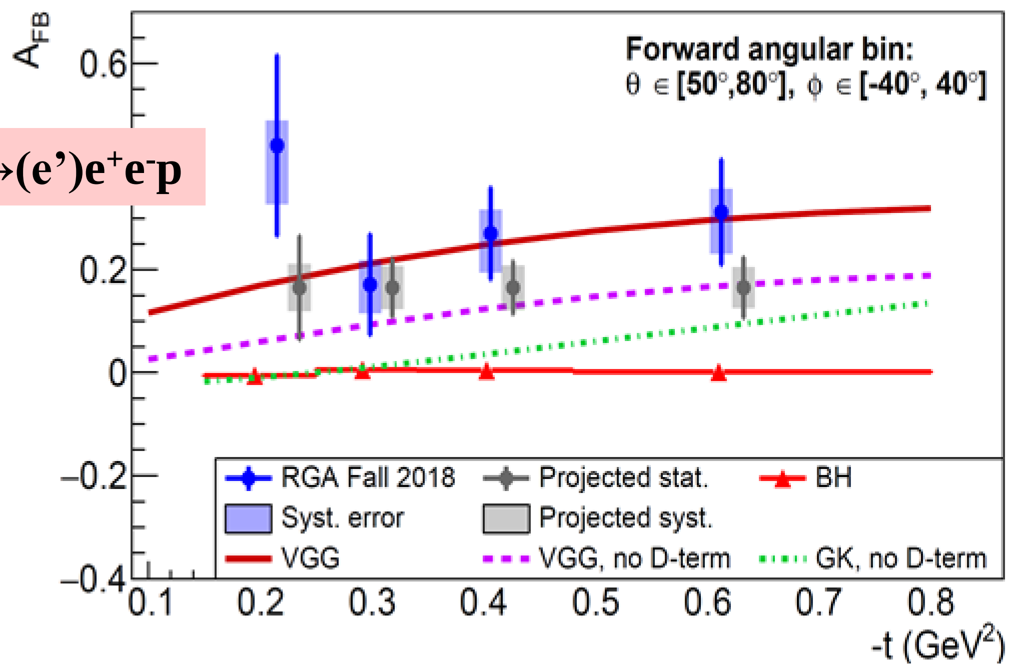
$$-\lambda\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\sin\varphi\frac{1+\cos^2\theta}{\sin\theta}\mathrm{Im}\tilde{M}^{--} - \sin 2\varphi\sqrt{2}\cos\theta\,\mathrm{Im}\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\tilde{M}^{+-} + O\Big(\frac{1}{Q'}\Big)\Big].$$

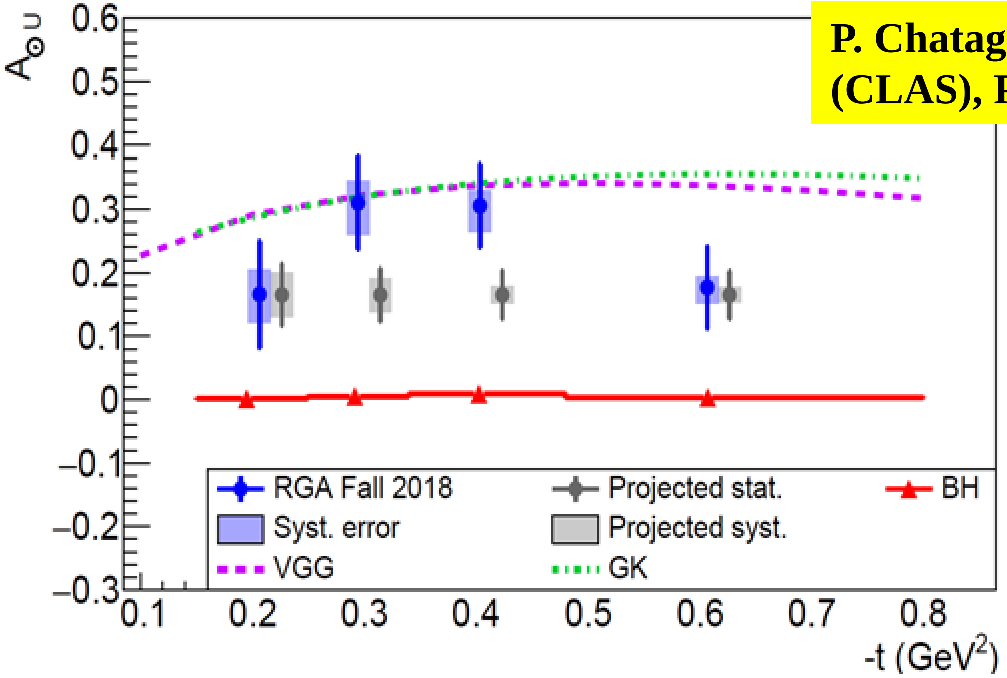
Incoming photon polarization

First-ever measurement of Timelike Compton Scattering (CLAS12)

P. Chatagnon et al. (CLAS), PRL 127 (2021)

$\gamma p \rightarrow \gamma^* p \rightarrow (e')e^+e^-p$





$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$

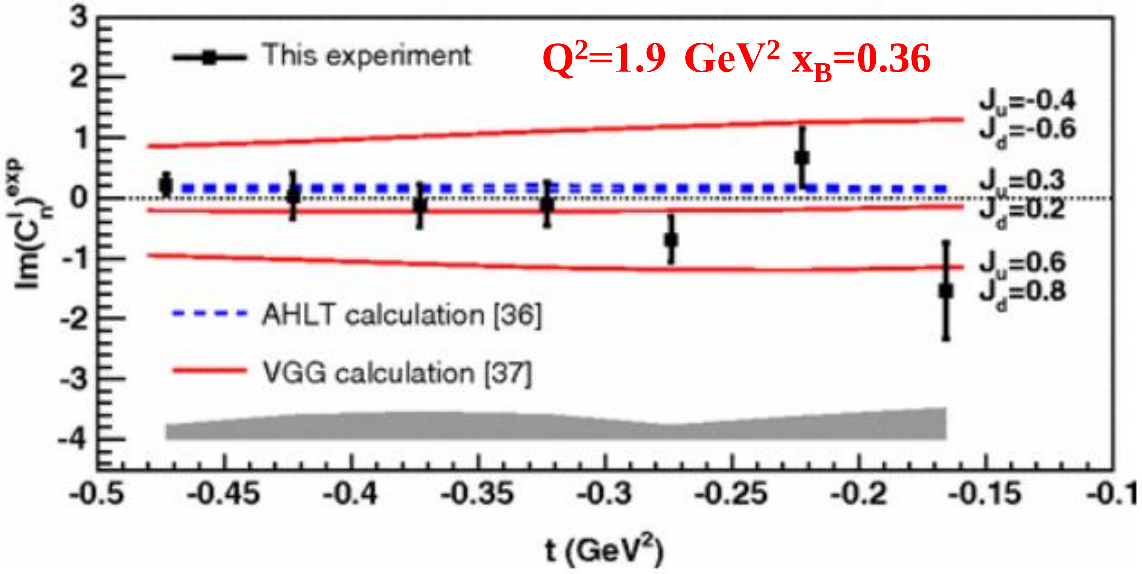
$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

- Quasi-real photo-production ($Q^2 \sim 0$)
- The beam helicity asymmetry of TCS accesses the **imaginary part of the CFF** in the same way as in DVCS and probes the **universality of GPDs**
- The forward-backward asymmetry is sensitive to the **real part of the CFF** → direct access to the Energy-Momentum Form Factor $d_q(t)$ (linked to the D-term) that relates to the **mechanical properties of the nucleon** (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.
- Limits: **very small cross section** → high luminosity is necessary for a more precise measurement
- **Imminent doubling of statistics thanks to data reprocessing with improved reconstruction (projections: gray points)**

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

Interest of DVCS on the neutron: Hall A at 6 GeV

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



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

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

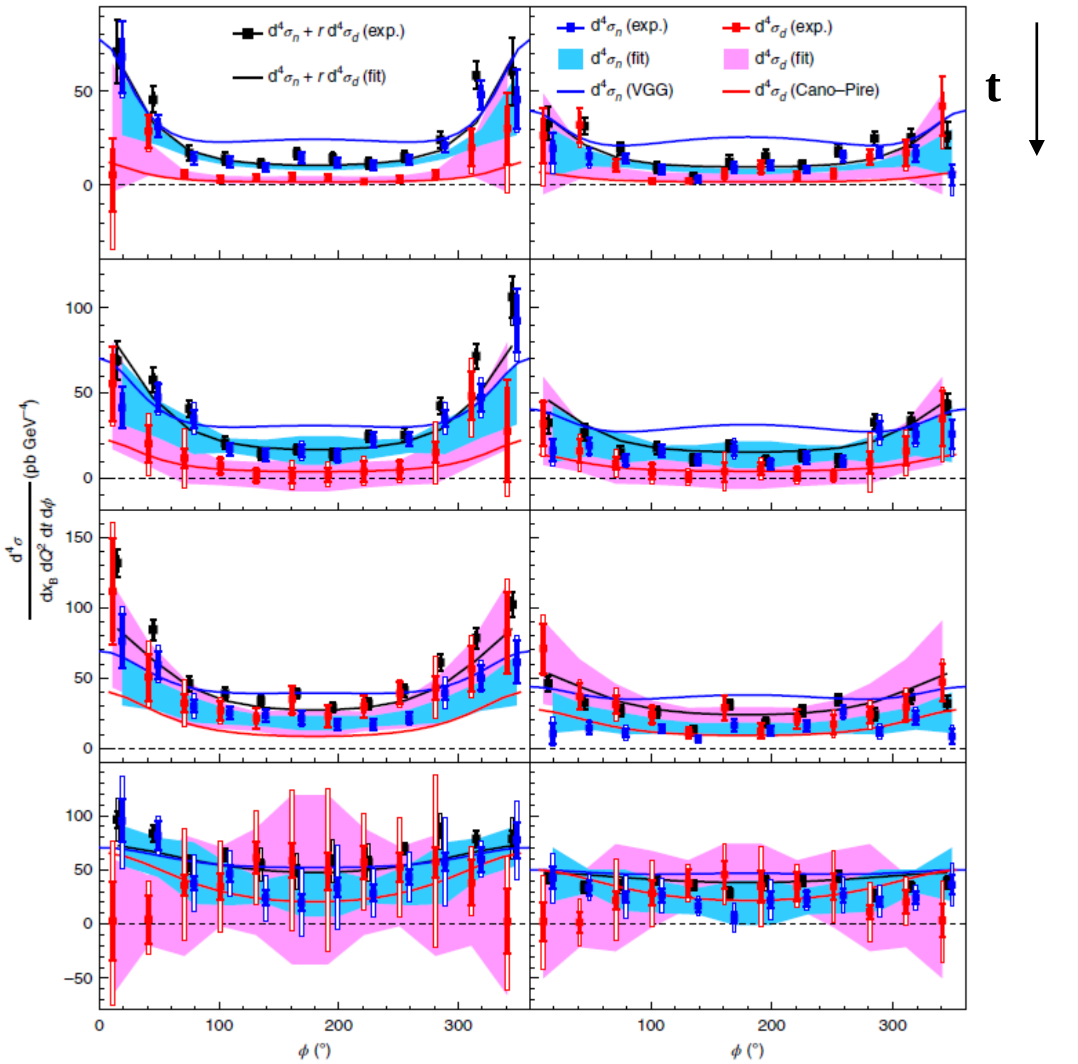
nDVCS and coherent **dDVCS** separated through MM^2_X shift:

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

Hall-A experiment E08-025 (2010)

- Two beam-energies: « Rosenbluth » separation of nDVCS CS
- First observation of non-zero nDVCS CS

M. Benali et al., Nature 16 (2020)

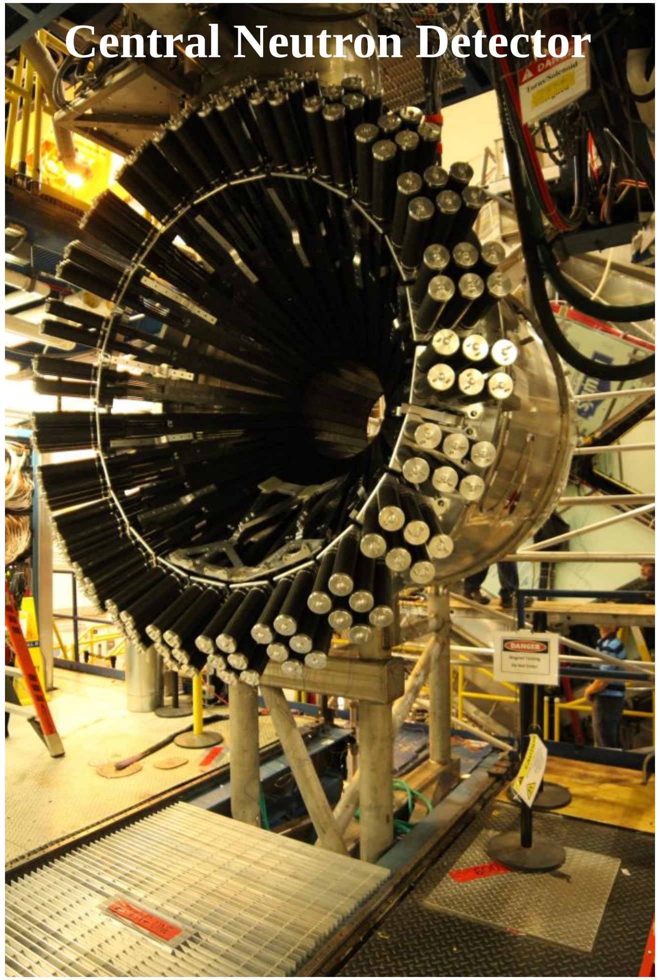


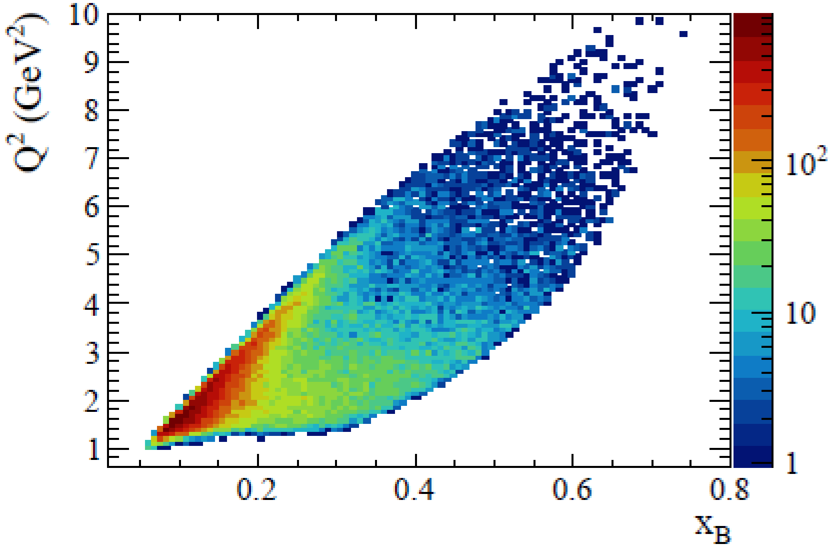
New CLAS12 results: Beam Spin Asymmetry for neutron DVCS

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

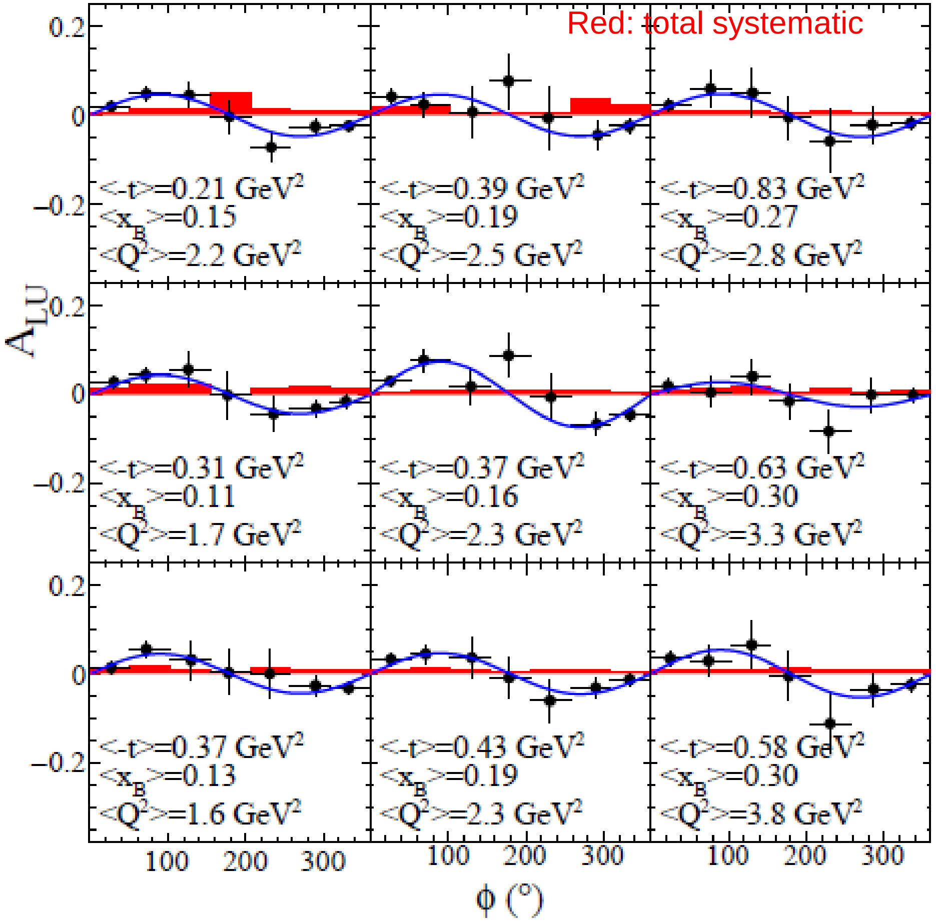
First-time measurement of nDVCS with detection of the active neutron

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





- Liquid deuterium target
- Beam energy ~10.4 GeV
- Scan of the BSA of nDVCS on a wide phase space
- Exclusive measurement with the detection of the active neutron → small systematics
- Results of ed→epγ(n) to be released soon

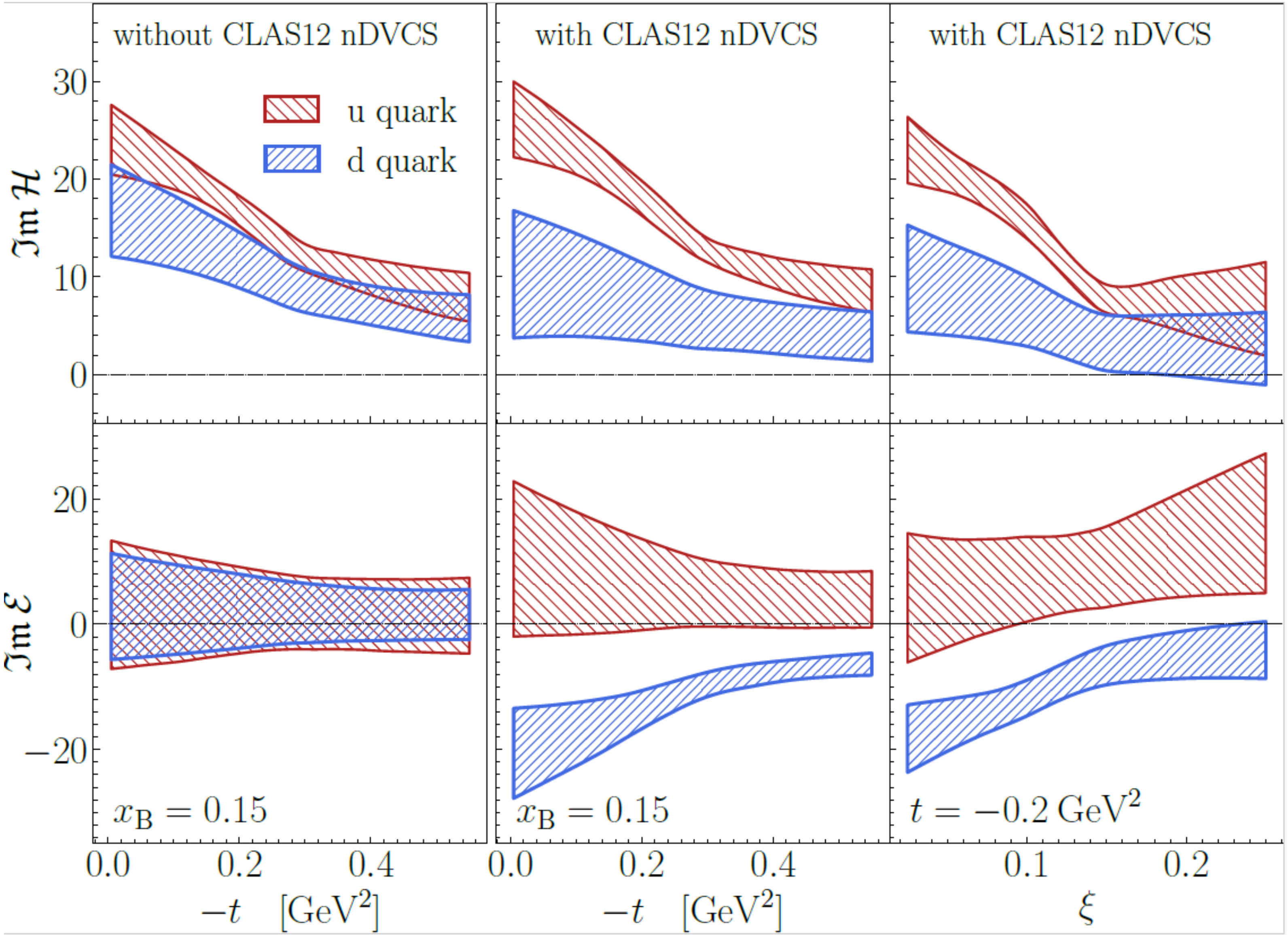


A. Hobart, S.N. et al (CLAS), about to be submitted to PRL

Flavor separation of CFFs using the Hall A and CLAS12 p,n DVCS data

- **Global fits of CFF** using **neural networks** (**K. Kumericki et al., JHEP 07, 073531 (2011); M. Cuic, K. Kumericki, et al., Phys. Rev. Lett. 533 125, 232005 (2020)**).
- Data used: CLAS6 and HERMES pDVCS observables, CLAS12 pDVCS BSA and nDVCS BSA
- Same extraction method applied to nDVCS Hall-A data, only separation for Im$\mathcal{H}$

The CLAS12 nDVCS data allow the quark-flavor separation of both Im$\mathcal{H}$ and Im$\mathcal{E}$



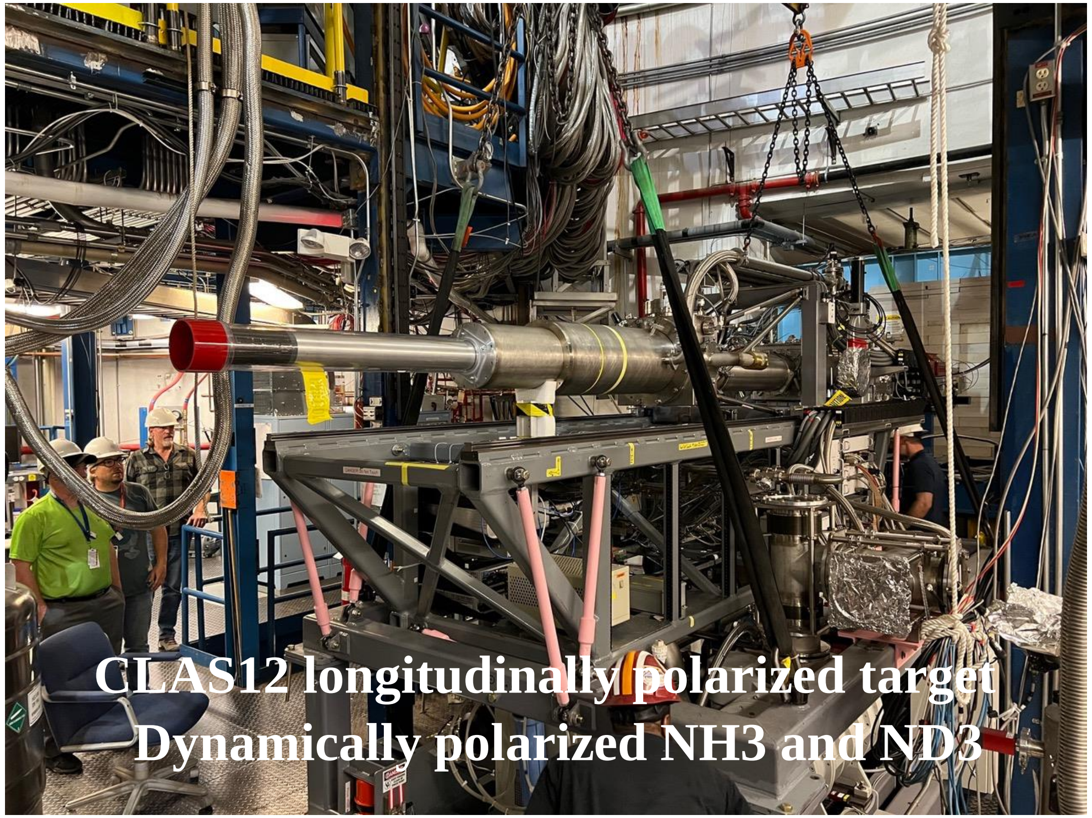
Recently run with CLAS12: DVCS (p, n) on longitudinally polarized target

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**



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

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

CLAS12 + Longitudinally polarized target + CND

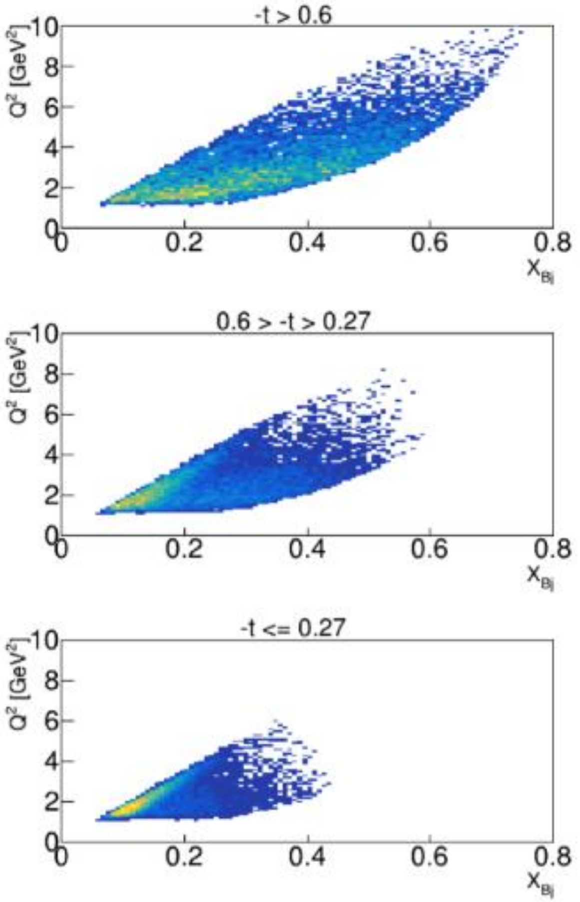
Ran from June 2022 to March 2023

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

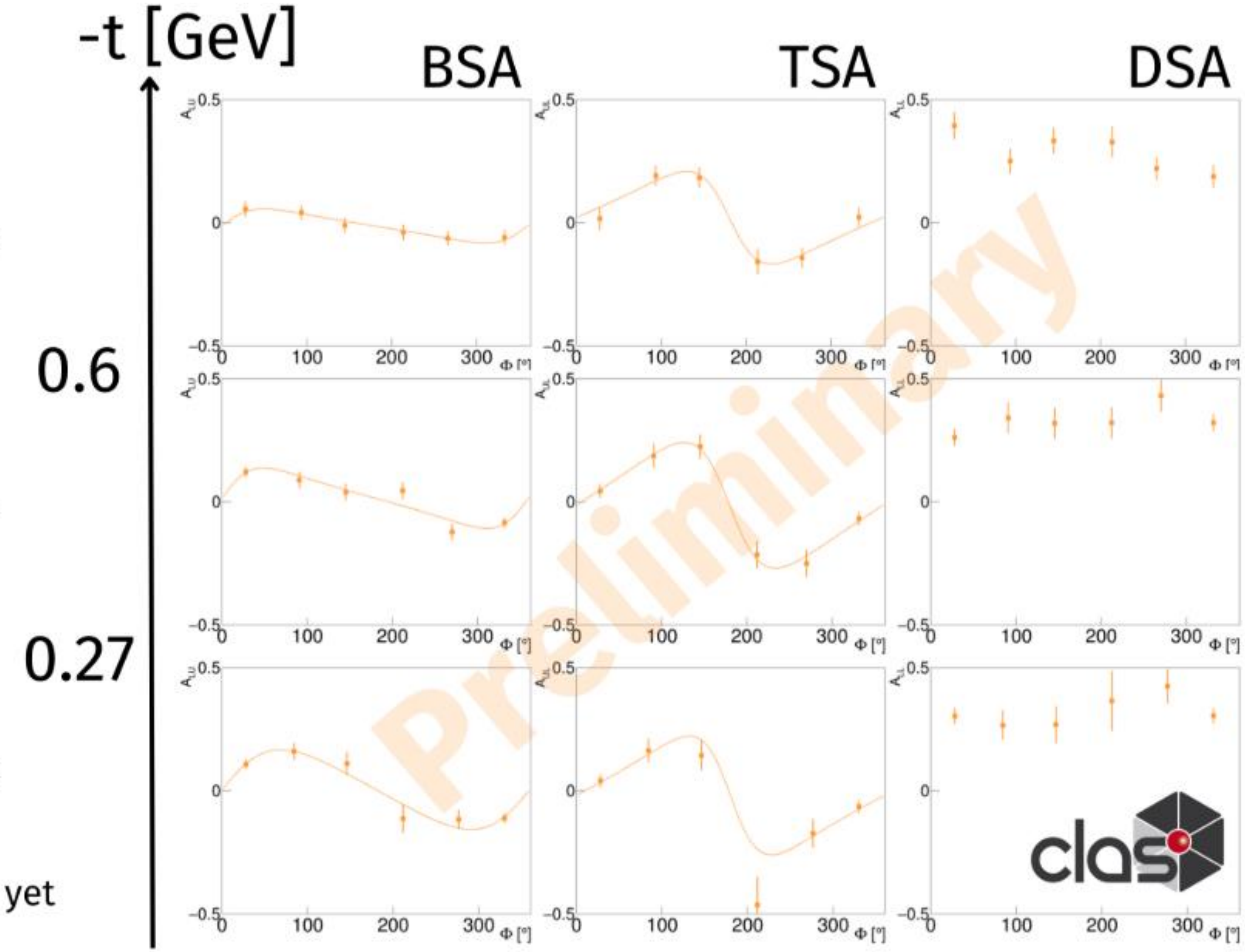
Thanks to the JLab Target Group

Recently run with CLAS12: DVCS (p, n) on longitudinally polarized target

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



Raw asymmetries
No background subtraction yet

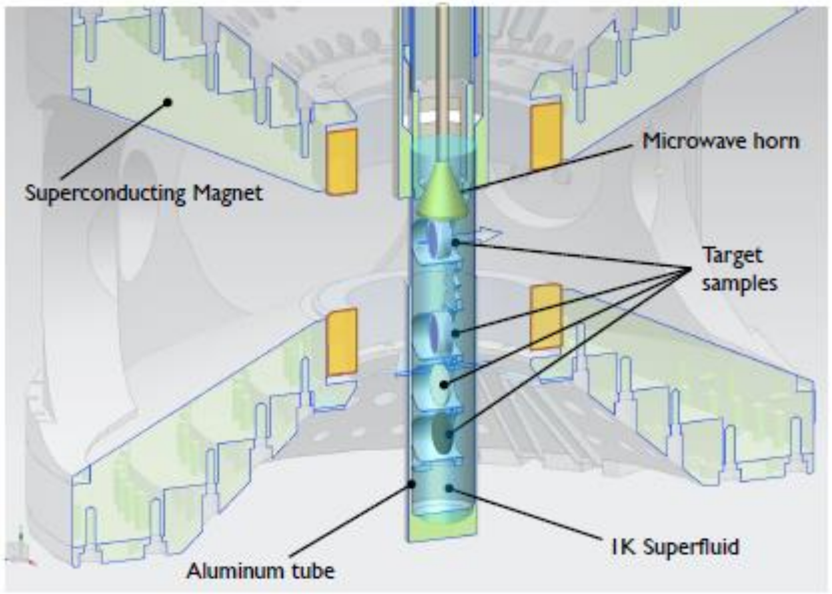


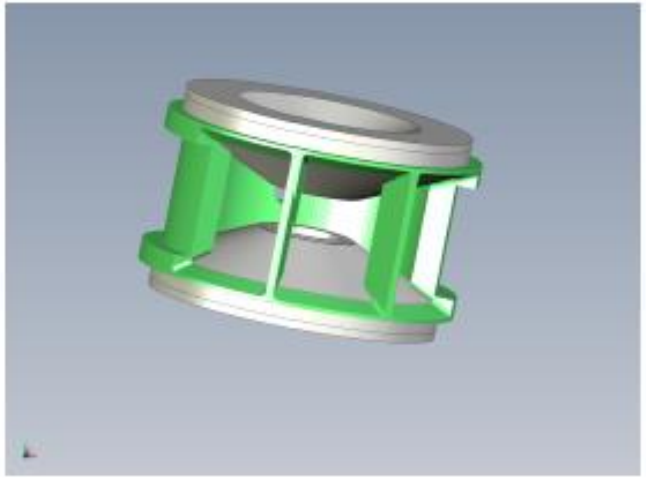
- **Very preliminary** analysis on **NH3**, done on a **subset** (~5%) of the data, with **non-final calibrations.**
- The calibrations and reconstruction for the first 1/3 of the data were recently completed, updated preliminary results will be released soon.

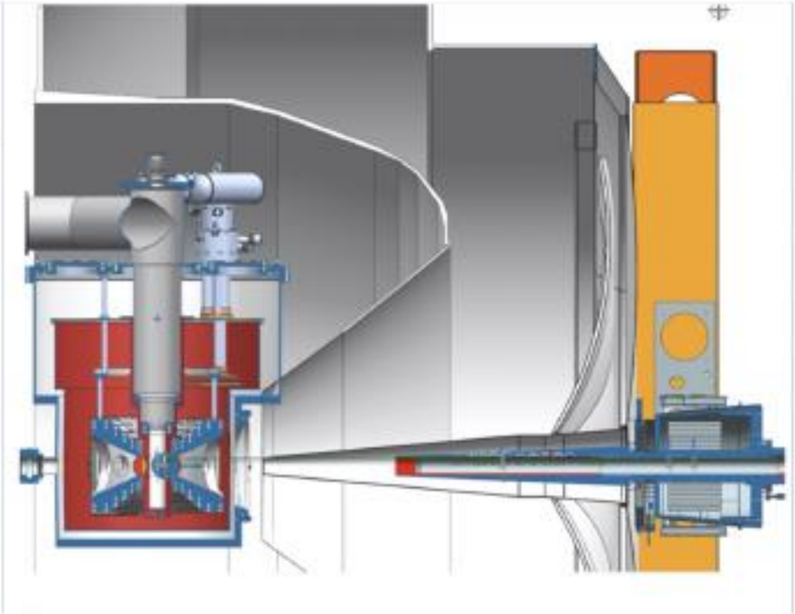
Work by N. Pilleux

In preparation: pDVCS on transversely polarized target with CLAS12

Transversely polarized target for CLAS12 under development







- The original idea to use a frozen-spin polarized target will not work (beam-induced depolarization)
- An alternative approach, dynamically polarized NH3 at 5T/1K is expected to work well
- A new magnet design is being studied, to maximize the acceptance and to properly fit in CLAS12
- A chicane of magnets will be necessary to compensate the bending of the beam electrons by the holding magnet
- A recoil detector to compensate the lack of Central Detector is being designed

Thanks to the JLab Target Group

In preparation: pDVCS on transversely polarized target with CLAS12

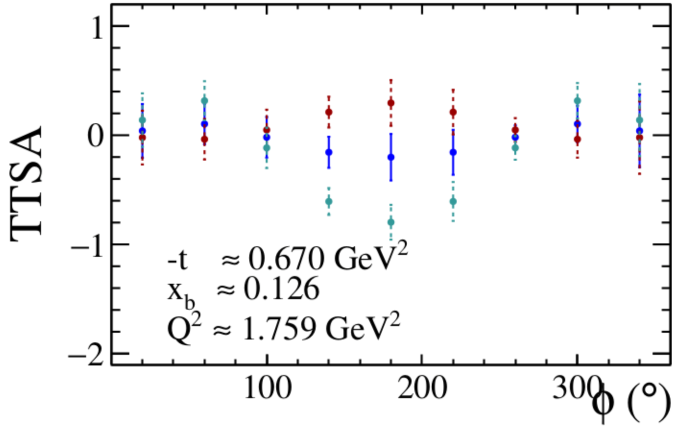
$\vec{e}p^{\uparrow} \rightarrow ep\gamma$

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

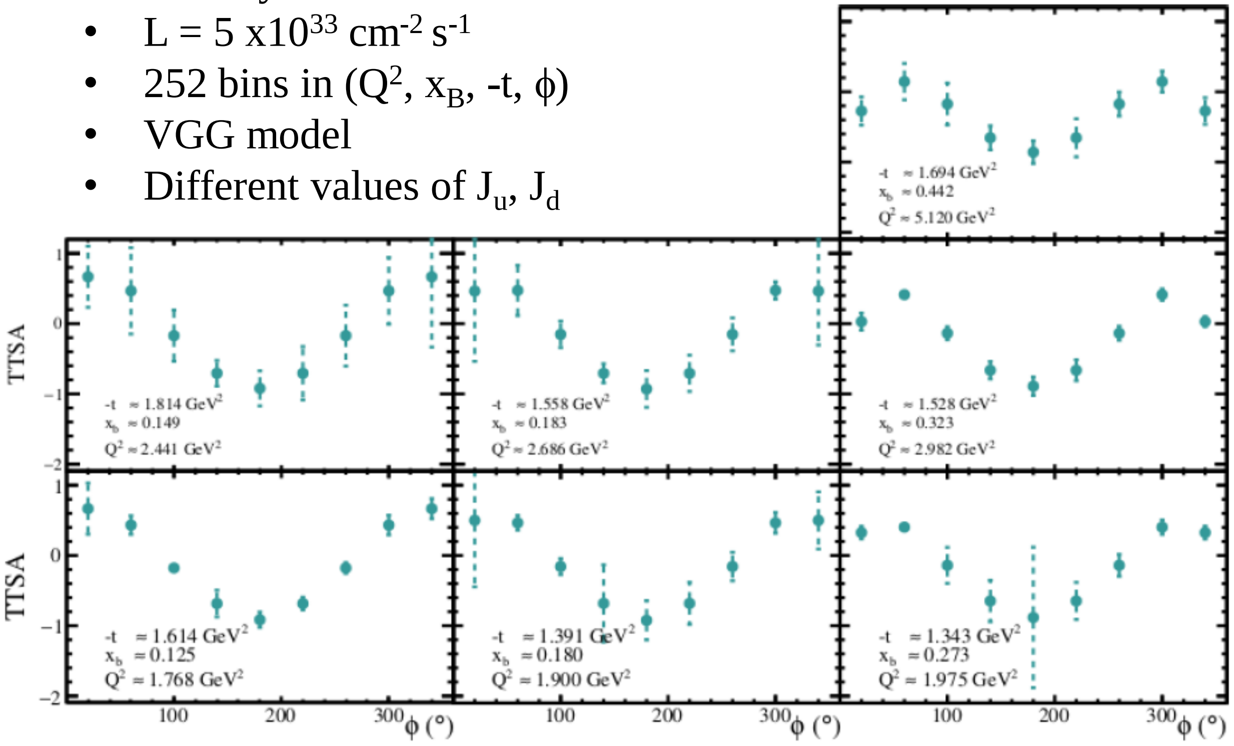
pDVCS on a transverse target is complementary to nDVCS for its sensitivity to the GPD E

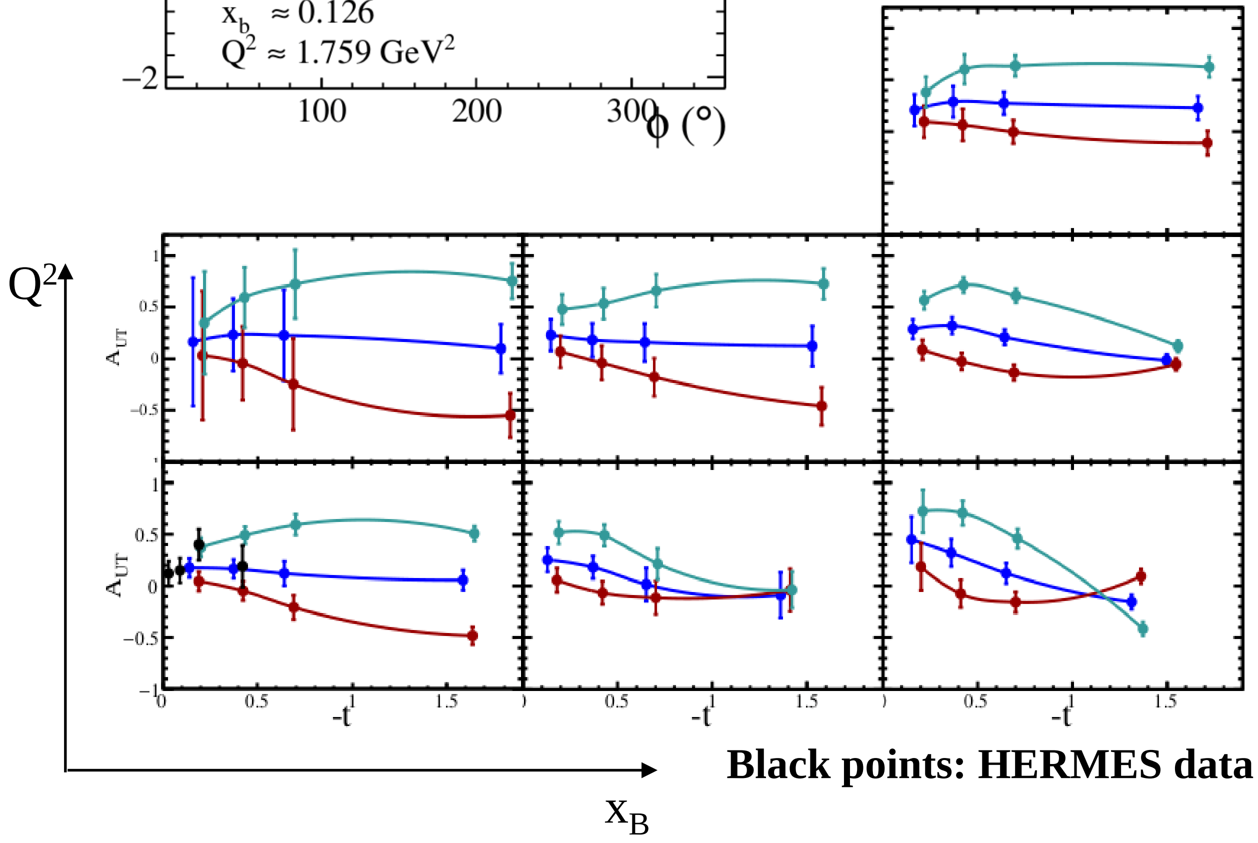
Projections for pDVCS

- 100 days of beam time
- $L = 5 \times 10^{33}\ cm^{-2}\ s^{-1}$
- 252 bins in (Q^2, x_B, -t, ϕ)
- VGG model
- Different values of J_u, J_d



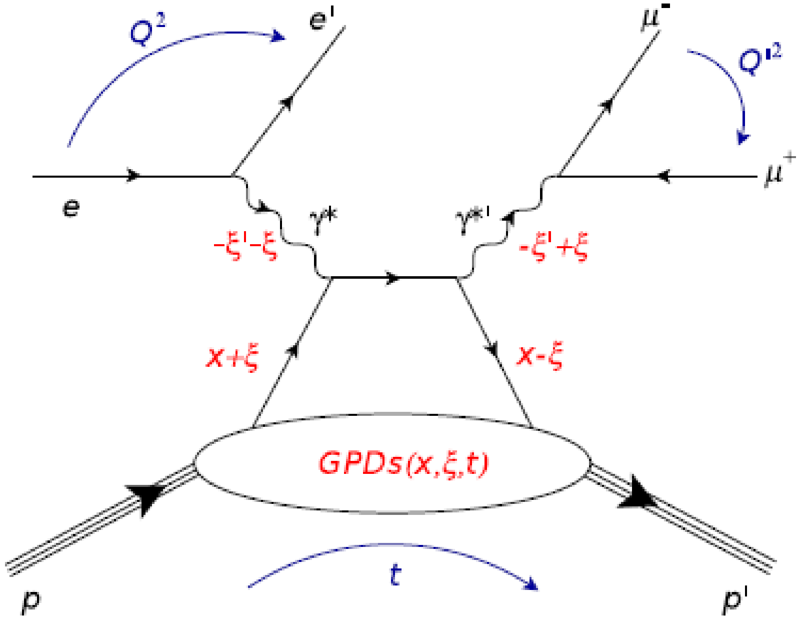
- $J_u = 0.5, J_d = 0.1$
- $J_u = -0.5, J_d = -0.1$
- $J_u = 0.2, J_d = 0$

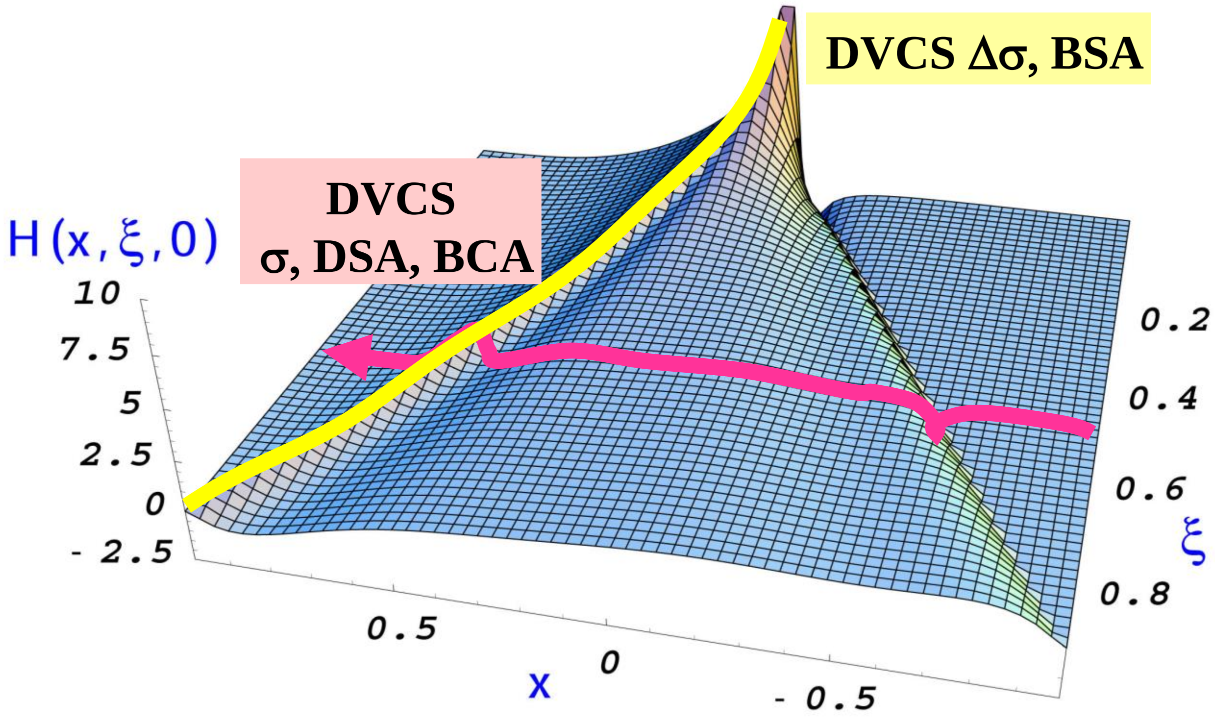




Black points: HERMES data

DDVCS: the gateway to the full kinematic mapping of GPDs





Thanks to the virtuality of the final photon, Q'², **DDVCS** allows a unique direct access to GPDs at **$x \neq \pm\xi$**, which is fundamental for their modeling

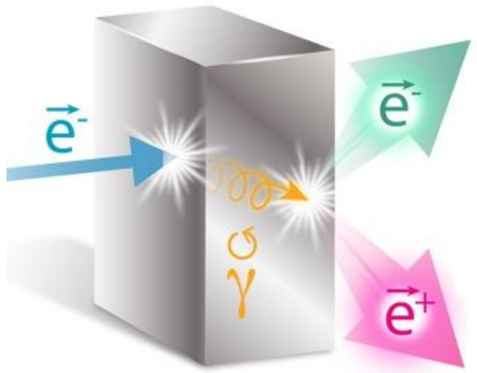
Experimental challenges:

- Small cross section (300 times less than DVCS)
- Need to detect muons

- **Possible CLAS12 upgrade (LOI): "μCLAS12" for DDVCS and J/ψ ep→e'p'μ+μ- at L~10^{37} $cm^{-2}s^{-1}$ New tracker, calorimeter, shielding**
- **Possible DDVCS experiment with SOLID@HallA (LOI)**

Perspectives: polarized positrons beam for Jefferson Lab

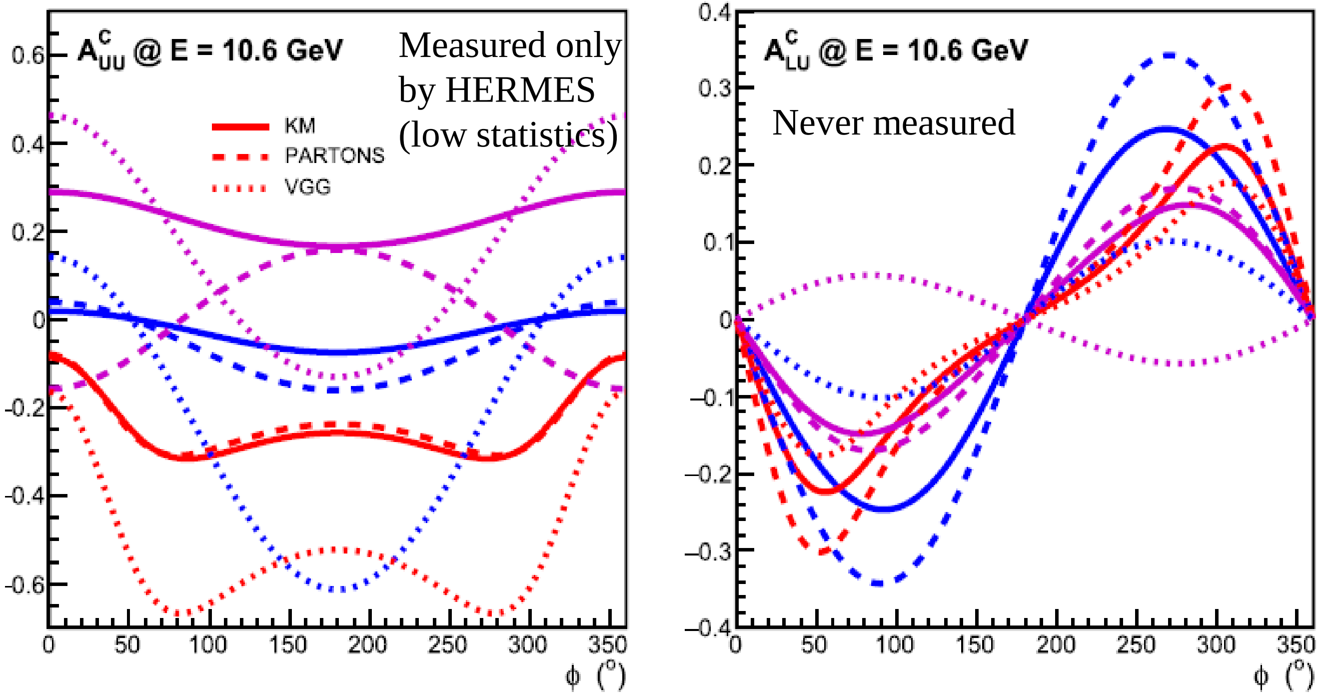
Physics Motivations:
- Two-photon physics
- **Generalized parton distributions**
- Neutral and charged current DIS
- Charm production
- Neutral electroweak coupling
- Light Dark Matter search
- Charged Lepton Flavor Violation



PePPO: proof-of-principle for a polarized positron beam PRL 116 (2016) 214801

R&D ongoing
Possible timeline: >2030

- Publication of the **EPJ A Topical Issue about "An experimental program with positron beams at Jefferson lab", Eur. Phys. J. A 58 (2022) 3, 45**
- 5 positron-based proposals, two of which on DVCS (CLAS12, Hall C) recently Conditionally Approved by JLab PAC51



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

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 **results** on proton-DVCS observables were obtained from **HERMES**, **CLAS** and **Hall-A** at 6 GeV

→ First **tomographic interpretations** of the quarks in the **proton** from DVCS

→ Insight in the **pressure distribution** in the proton

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

✓ DVCS and DVMP experiments on both **proton** and **neutron** (polarized and unpolarized) are ongoing in **3 of the 4 Halls at JLab@12 GeV**, and **a wealth of results** are being released**:**

→ **GPD extraction, quarks' spatial densities, GPD flavor separation, <u>quarks' orbital angular momentum</u>**, chiral-odd GPDs, transition GPDs,…

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