CEBAF Large Acceptance Spectrometer

Nucleon structure and the Generalized Parton Distributions

Adam HOBART on behalf of the CLAS collaboration

Transversity 2022, 23 – 27 May

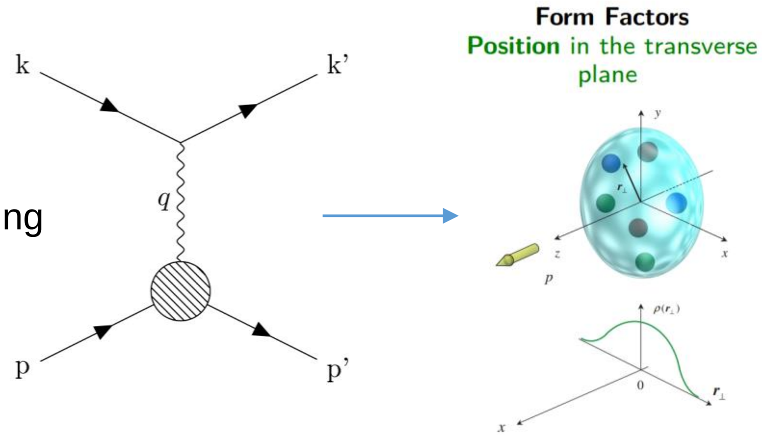
Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

cnrs

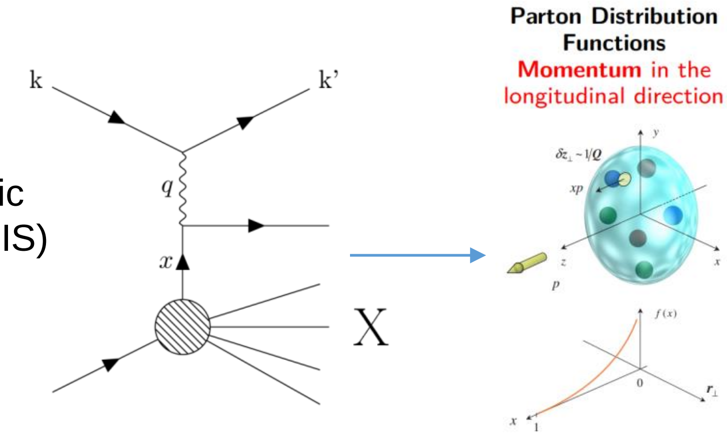
université PARIS-SACLAY

- QCD at low energies: non perturbative regime
  - Need structure functions to describe nucleon structure

Elastic scattering



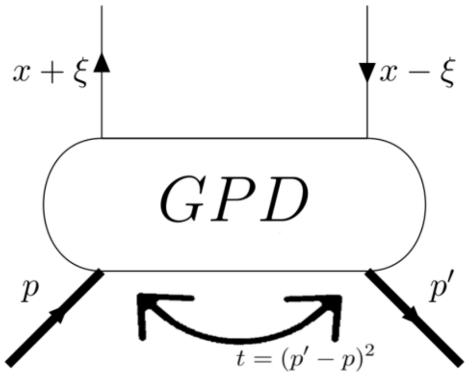
Deep inelastic scattering (DIS)

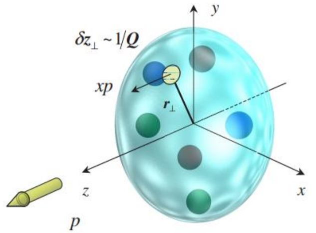


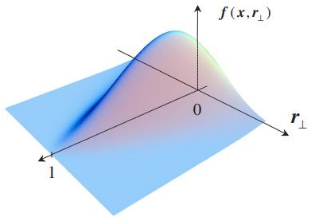
Uni-dimensional information on nucleon structure

Belitsky, Radyushkin, Physics Reports, 2005

- QCD at low energies: non perturbative regime
  - Need structure functions to describe nucleon structure



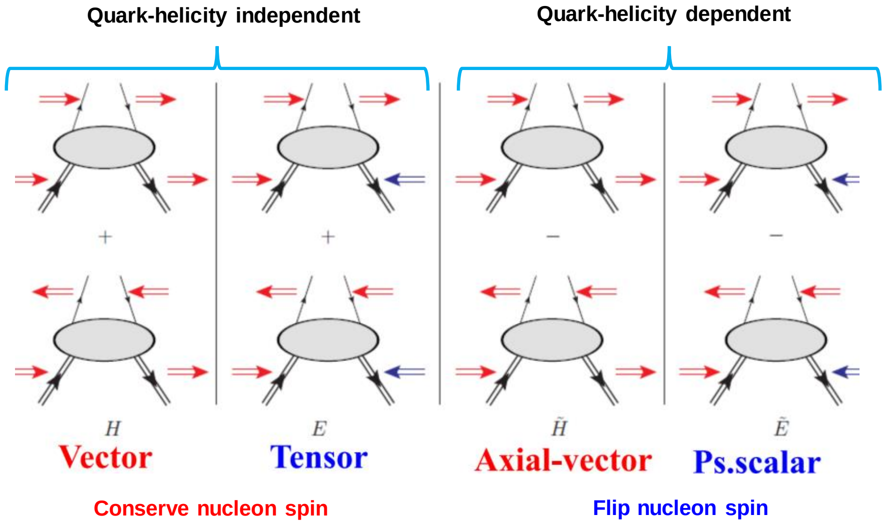




GPDs

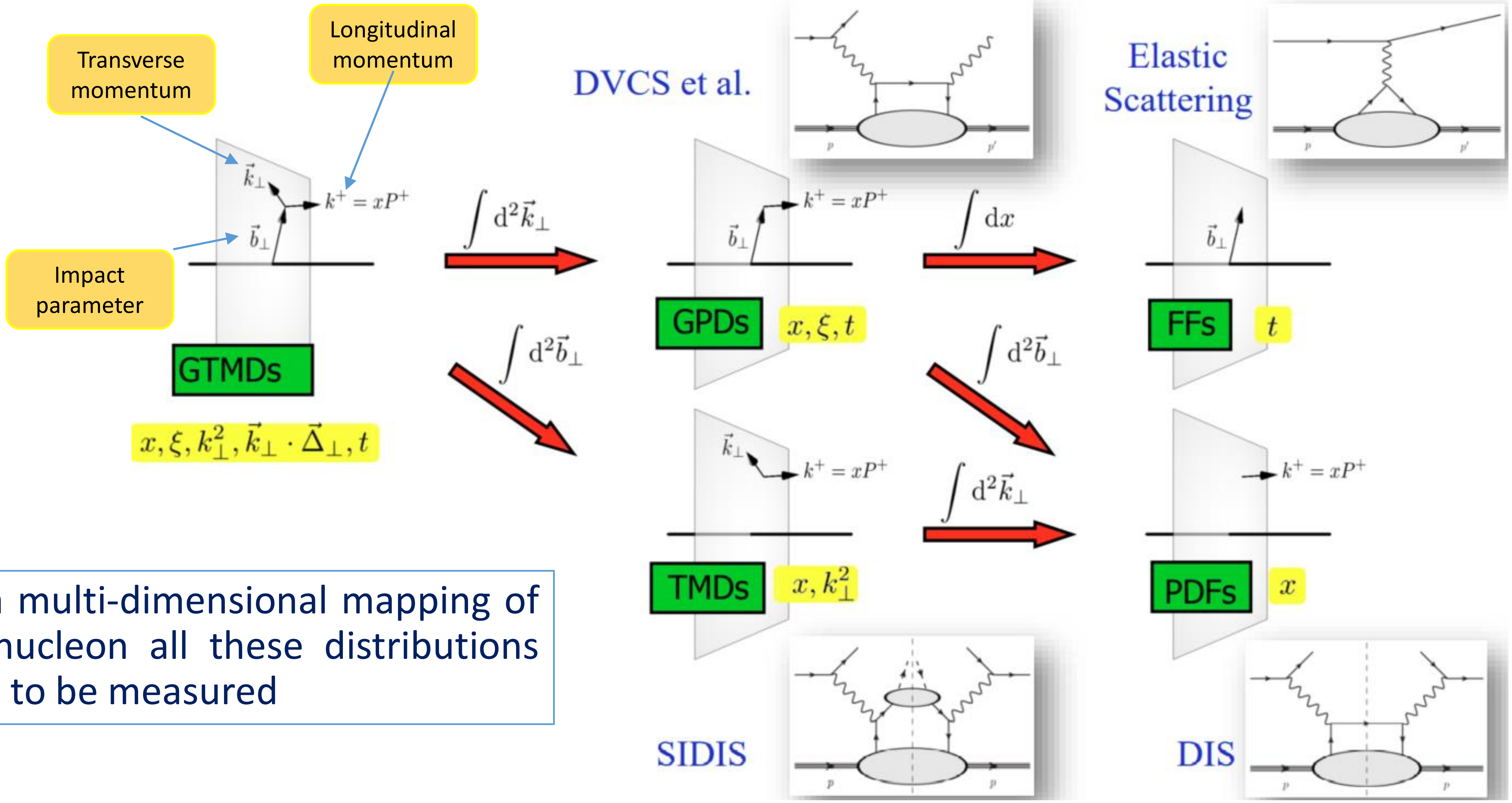
Correlation of transverse position and longitudinal momentum of partons in the nucleon & the spin structure

- GPDs can be accessed through exclusive leptoproduction reactions
- At leading order QCD, chiral-even (quark helicity is conserved), quark sector: 4 GPDs for each quark flavor $H, \widetilde{H}, E$ and $\tilde{E}$
- GPDs depend on x, ξ and t = (p' − p) 2



Belitsky, Radyushkin, Physics Reports, 2005

Multi-dimensional mapping of nucleon structure



For a multi-dimensional mapping of the nucleon all these distributions need to be measured

Why are GPDs important?

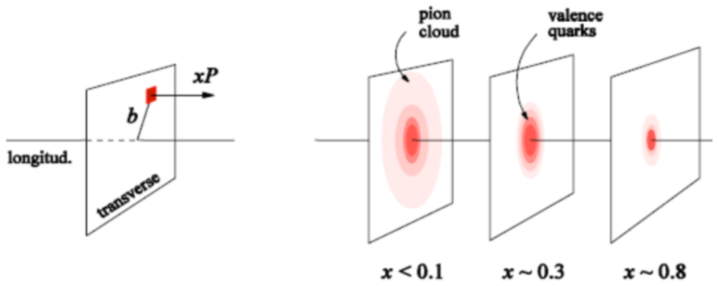
- GPDs: Fourier transforms of non-local, non-diagonal QCD operators

Nucleon tomography

M. Burkardt, PRD 62, 71503 (2000)

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

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



Quark angular momentum

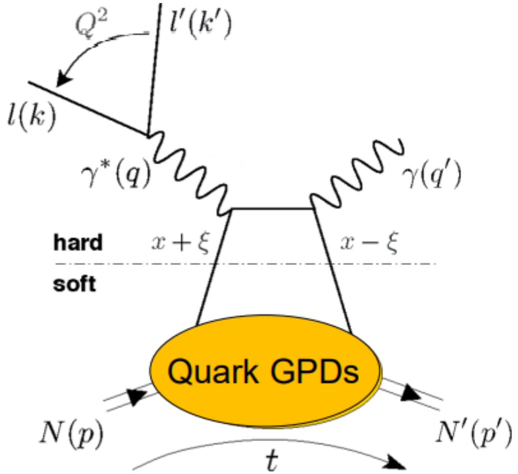
X. Ji, Phy.Rev.Lett.78,610(1997)

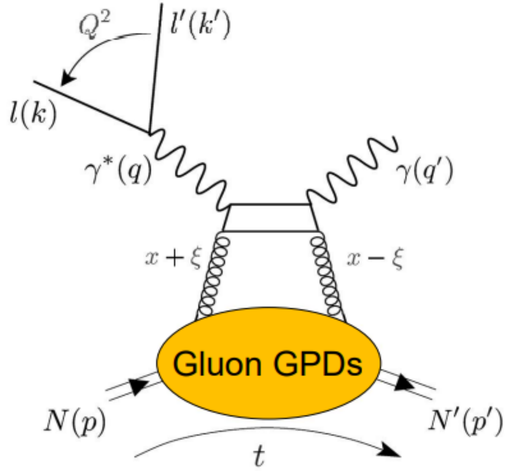
$$\frac{1}{2}\int_{-1}^{1}xdx(H(x,\xi,t=0)+E(x,\xi,t=0))=J=\frac{1}{2}\Delta\Sigma+\Delta L$$

Nucleon spin: $\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta L+\Delta G$

- The intrinsic spin of the quarks can not explain the origin of the spin of the nucleon **(nucleon Spin Crisis)**
- **Intrinsic spin of the gluons??**
- GPDs: quantify the contribution of orbital angular momentum of quarks to the nucleon spin

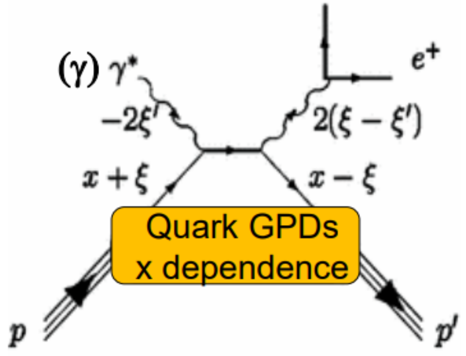
Exclusive reactions giving access to GPDs

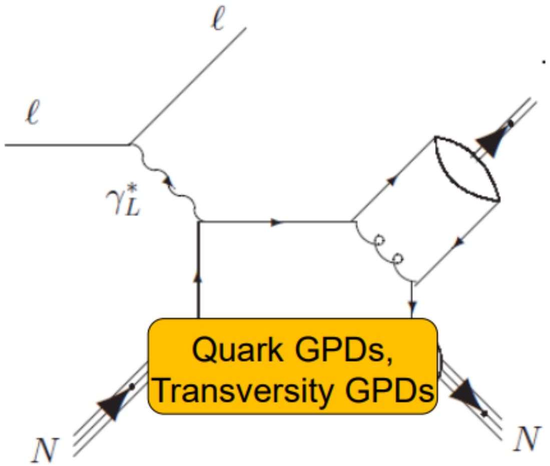




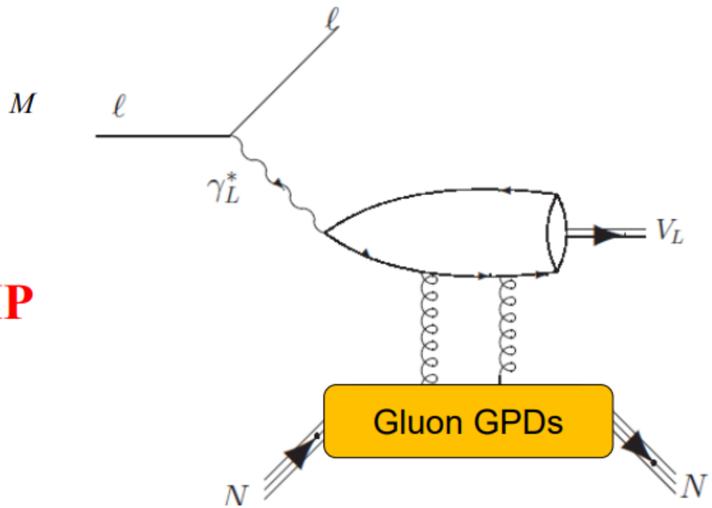
DVCS

(TCS), DDVCS

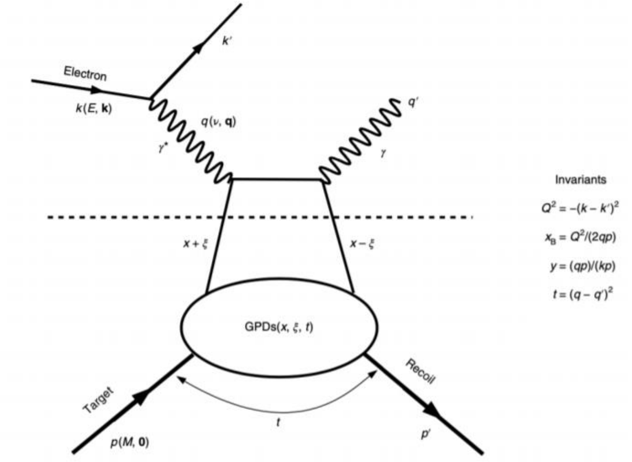


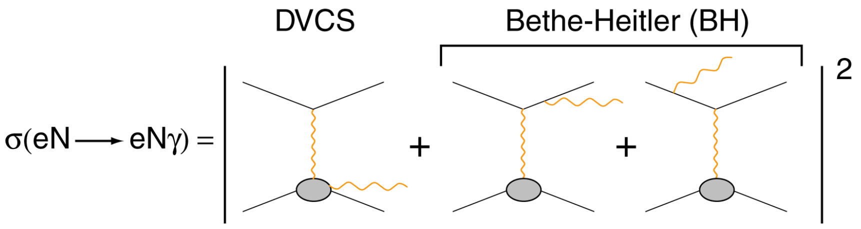


DVMP



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





BH is purely electromagnetic and parametrised by FFs

- DVCS allows access to 4 complex GPDs-related quantities: Compton Form Factors (ξ,t) (CFFs)

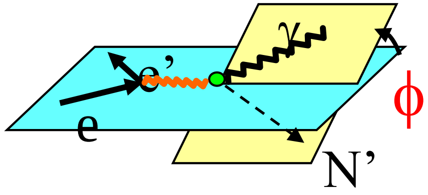
$$\mathcal{H} = \sum_q e_q^2 \left\{ i\,\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t) \right] + \mathcal{P} \int_{-1}^{1} dx H^q(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] \right\}$$

- x can not be accessed experimentally by DVCS: Models needed to map the x dependence

- Experimentally measured observables:
  - Contribution from both the DVCS and BH amplitudes
  - In order to be sensitive to the DVCS-BH interference part (linear in CFFs) we should have:
    - Beam polarized and/or target polarized
  - Each measured asymmetry gives access to combinations of CFFs
  - The separation of CFFs requires the measurement of several observables
  - Depending on the target (proton or neutron): different sensitivity to the CFFs (GPDs)
  - The flavor separation of GPDs requires measurements on both nucleons

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

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



Polarized beam, unpolarized taget

$$\Delta\sigma_{LU} \sim \sin(\phi)\,\Im\{F_1 \boldsymbol{H} + \xi(F_1 + F_2)\widetilde{\boldsymbol{H}} - k\,F_2 \boldsymbol{E} + \ldots\}$$

Unpolarized beam, polarized target

$$\Delta\sigma_{UL} \sim \sin(\phi)\,\Im\left\{F_1\,\widetilde{\boldsymbol{H}} + \xi(F_1 + F_2)\left(\boldsymbol{H} + \frac{x_b}{2}\boldsymbol{E}\right) - \xi k\,F_2 \widetilde{\boldsymbol{E}}\right\}$$

polarized beam, longitudinal polarized target

$$\Delta\sigma_{LL} \sim (A + B\cos(\phi))\,\Re\{F_1\,\widetilde{\boldsymbol{H}} + \xi(F_1 + F_2)\left(\boldsymbol{H} + \frac{x_b}{2}\boldsymbol{E}\right) + \ldots\}$$

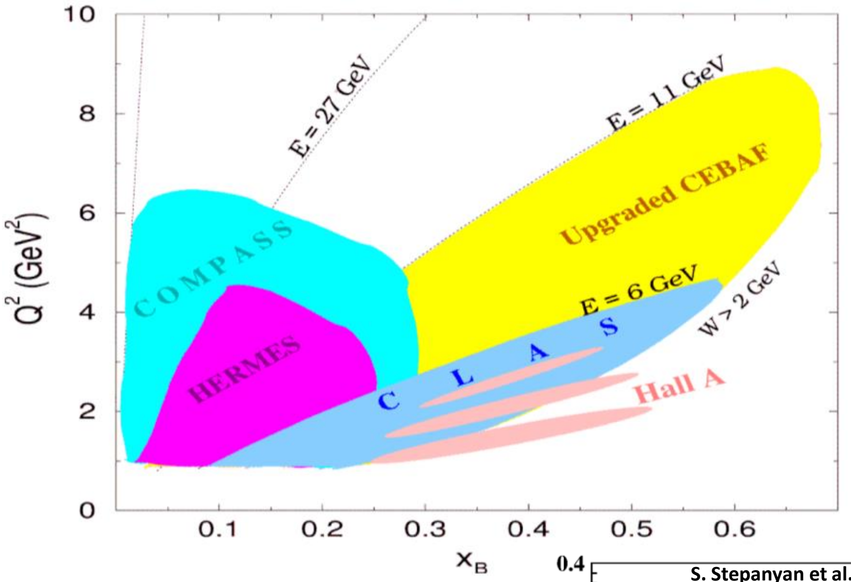
unpolarized beam, transverse polarized target

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

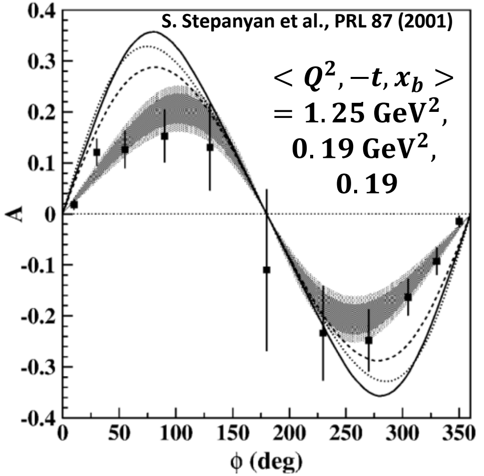
Observable	Proton	Neutron
$\Delta\sigma_{LU}$	$\Im\{\boldsymbol{H_p}, \widetilde{H}_p, E_p\}$	$\Im\{H_n, \widetilde{H}_n, \boldsymbol{E_n}\}$
$\Delta\sigma_{UL}$	$\Im\{\boldsymbol{H_p}, \widetilde{\boldsymbol{H}}_{\boldsymbol{p}}\}$	$\Im\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{LL}$	$\Re\{\boldsymbol{H_p}, \widetilde{\boldsymbol{H}}_{\boldsymbol{p}}\}$	$\Re\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{UT}$	$\Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$	$\Im\{\boldsymbol{H_n}\}$

GPD-aimed experiments worldwide

- JLAB
  - Hall A: cross sections and beam-polarised cross section differences measurements
  - Hall B (CLAS/CLAS12): beam and target spin asymmetries + cross section measurements over large phase-space acceptance
- DESY
  - HERMES: low-x_b low-Q^2 moments of spin asymmetries measurements
  - ZEUS: cross section measurements
- CERN
  - COMPASS: low-x_b high-Q^2 cross section measurements

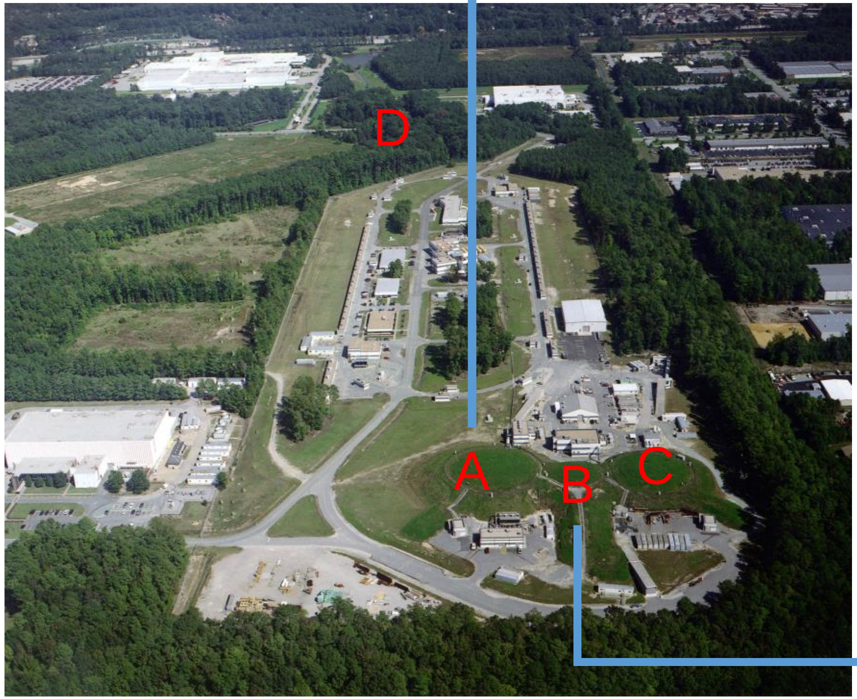


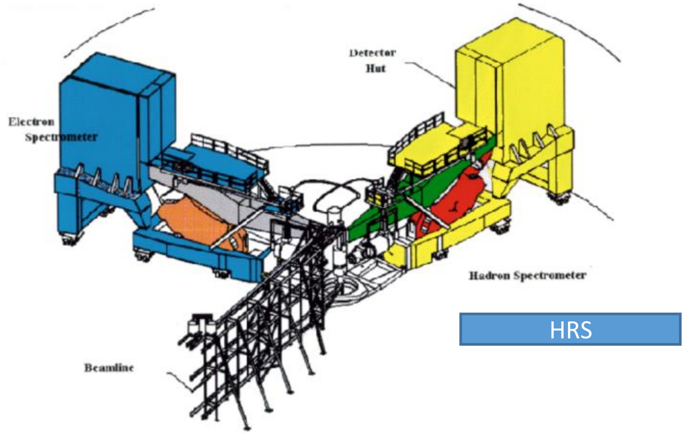
$ep \to epX$, from CLAS data: First observation of DVCS-BH interference

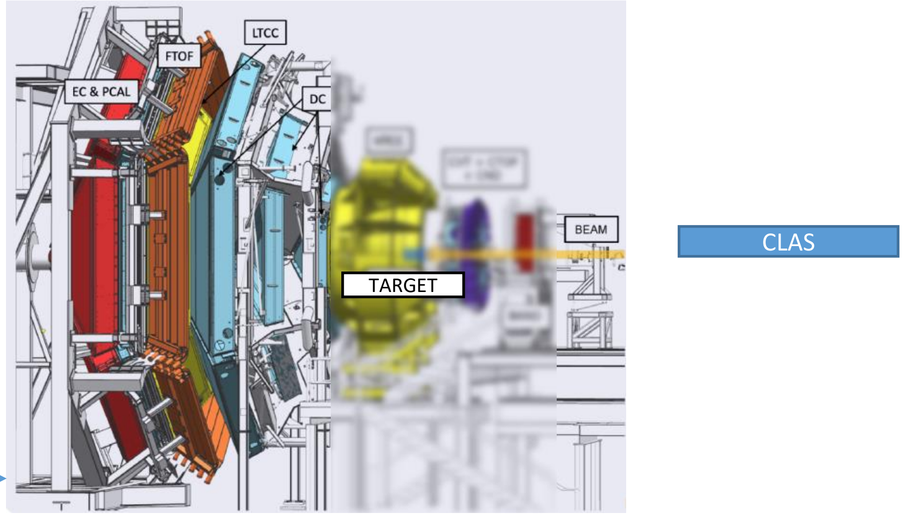


Continuos Electron Beam Accelerator Facility

- Up to 12 GeV electrons
- Two anti-parallel linacs, with recirculating arcs on both ends
- 4 experimental halls



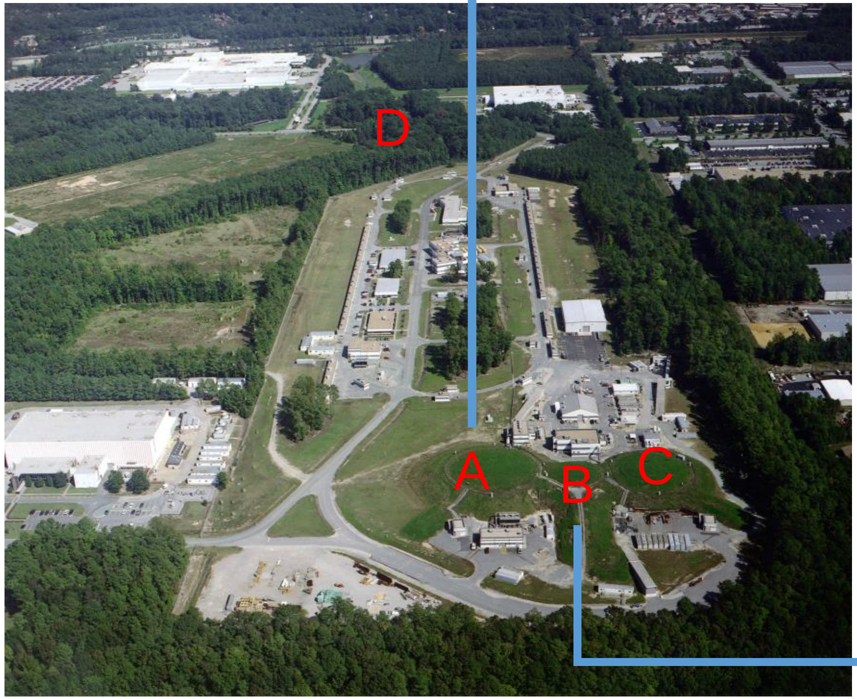


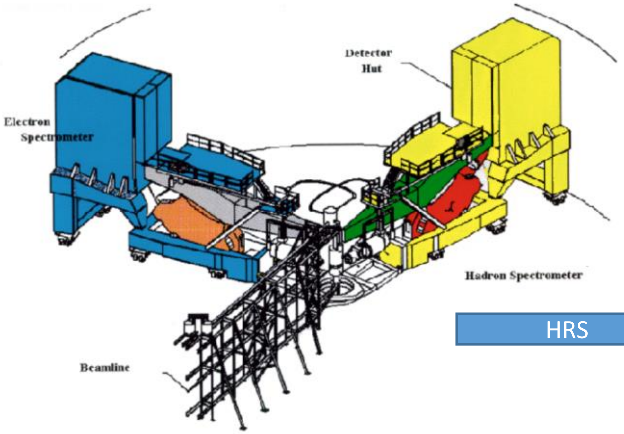


The CEBAF at Jefferson Laboratory

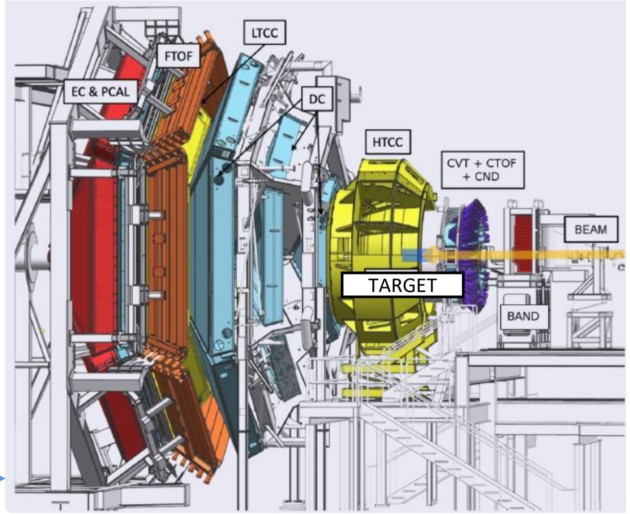
Continuos Electron Beam Accelerator Facility

- Up to 12 GeV electrons
- Two anti-parallel linacs, with recirculating arcs on both ends
- 4 experimental halls





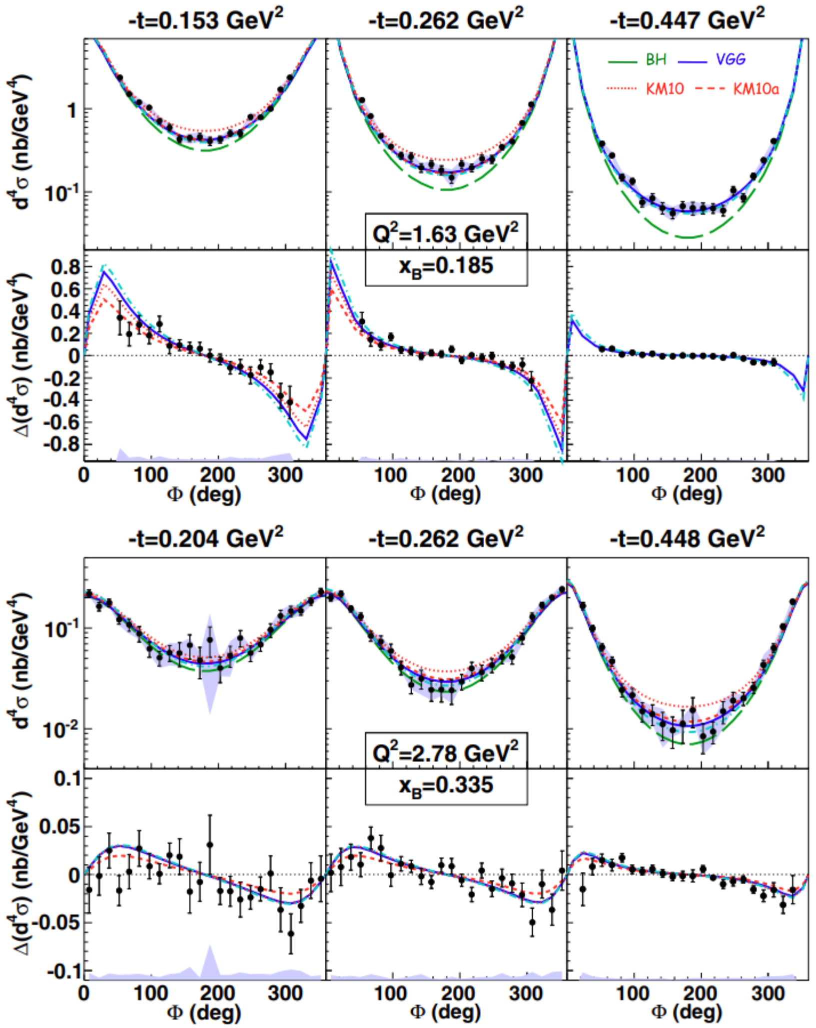
HRS

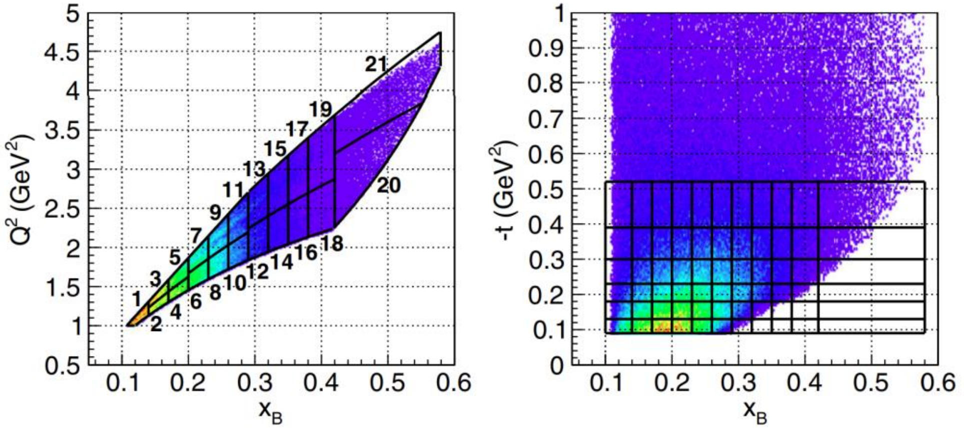


CLAS12

CLAS: unpolarized and beam-polarized cross sections at ~6 GeV

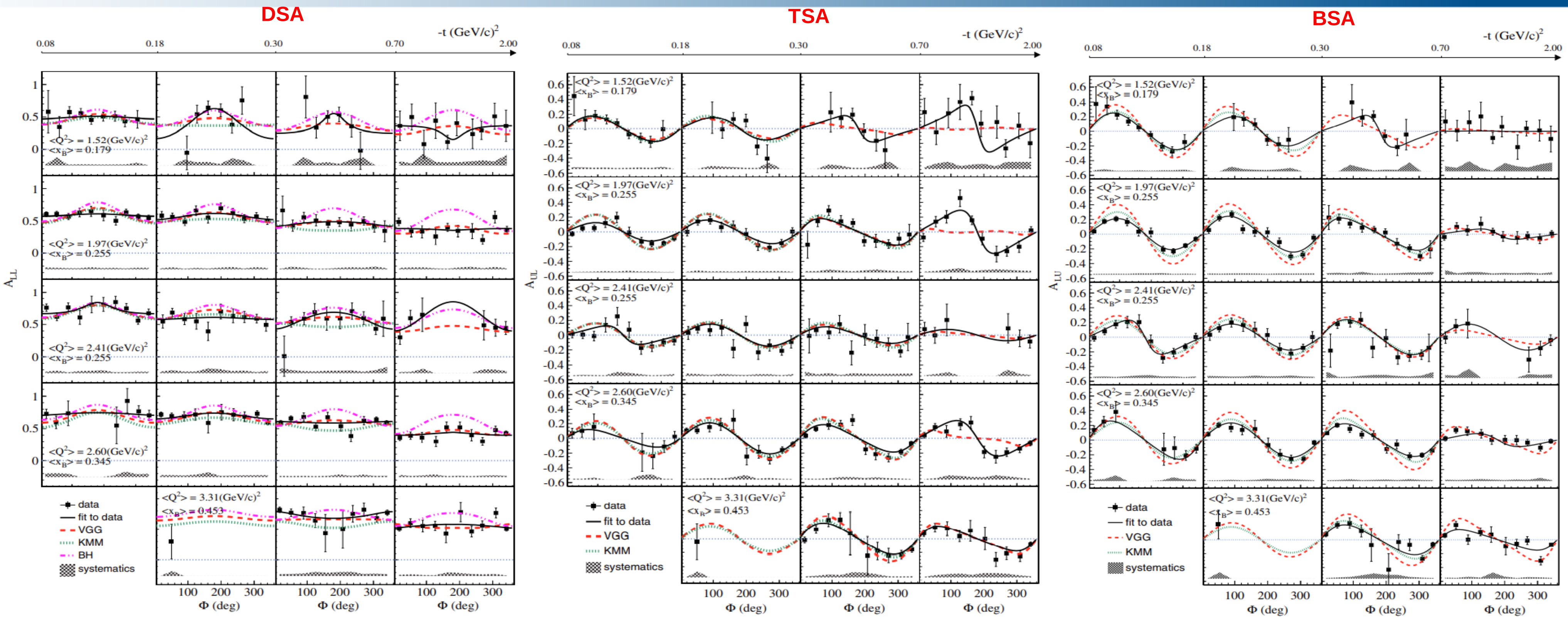
- Beam energy ~ 5.75 GeV
- Beam polarization ~ 80%
- Target LH2
- 110 (Q^2, x_b, t) kinematical bins in total





H.S. Jo et al., PRL 115, 212003 (2015)

CLAS: DVCS on longitudinally polarized target at ~6 GeV



- Beam energy ~5.9 GeV and longitudinally polarized NH3 (P~80%)
- Observables: Beam, Target and double Spin Asymmetries
- Bins: 5 $Q^2 - x_b$ bins, 4 t bins and 10 Φ bins

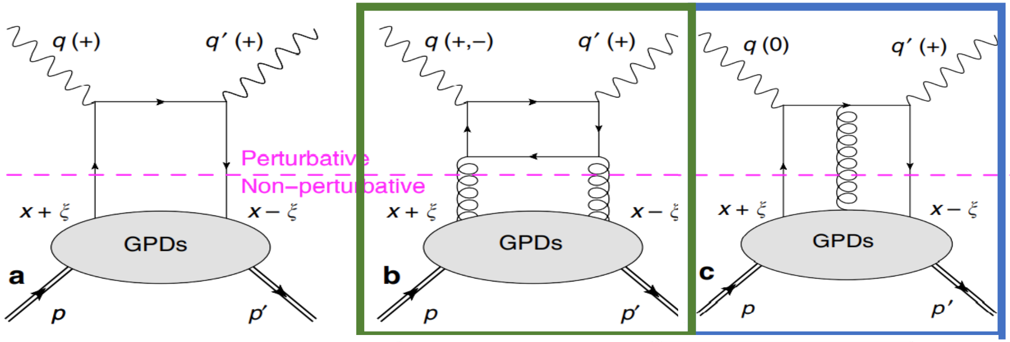
w.r.t previous pioneering CLAS6 data
Improved statistics x10 at low –t
Extended kinematic coverage

E. Seder et al., PRL 114 (2015) 032001
S. Pisano et al., PRD 91, 052014 (2015)

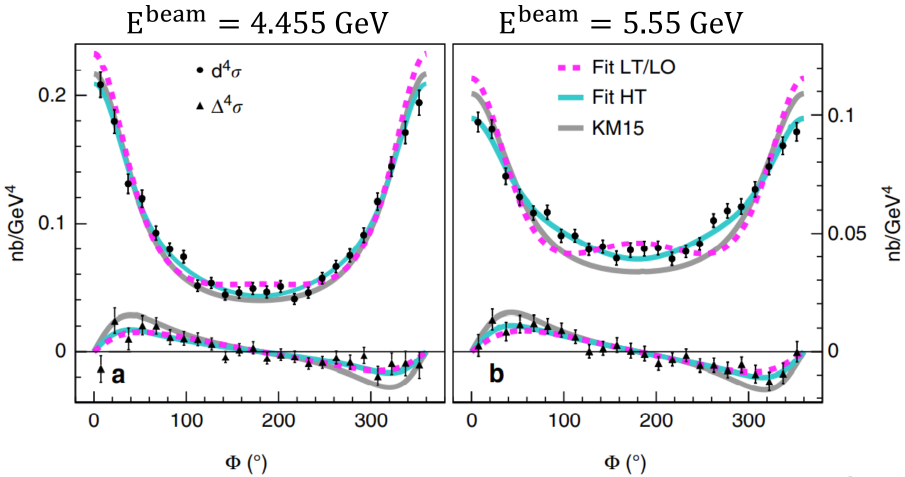
Hall A: High-precision DVCS at 6 GeV

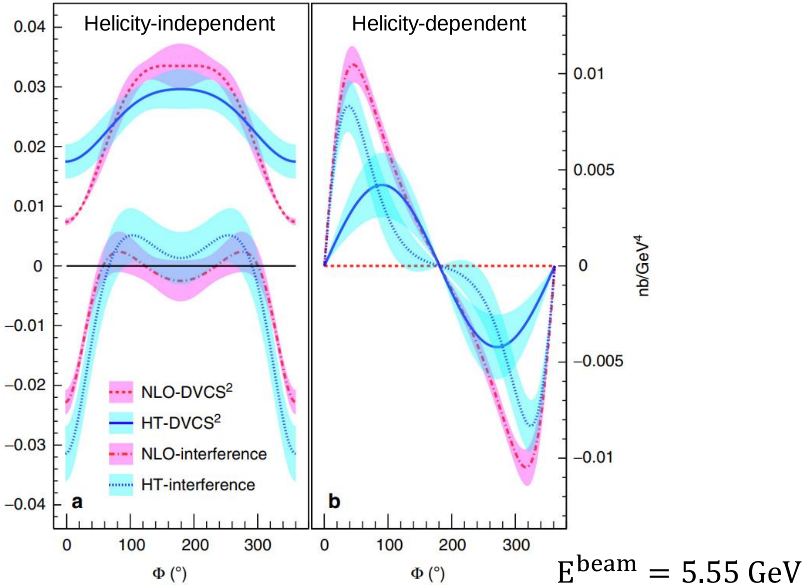
M. Defurne et al., Nature Communications 8, 1408 (2017)

- Quantify the sensitivity to LT-NLO contributions or higher twist (HT) (gluon exchange)



- Different beam energies used to separate BH-DVCS interference and $DVCS^2$ contributions





$Q^2 = 1.75\ \text{GeV}^2$, $x_B = 0.36$, and $t = -0.30\ \text{GeV}^2$

Hall A: nDVCS with an unpolarized deuterium target at ~6 GeV

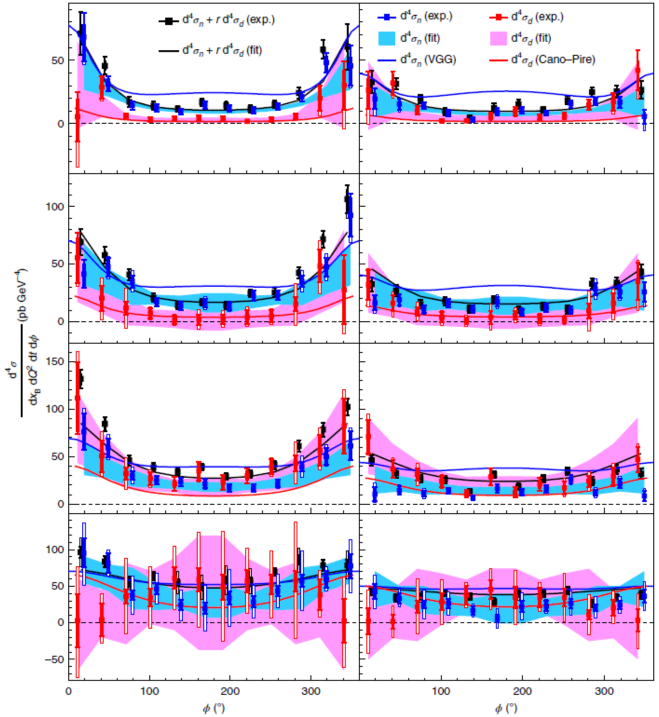
- nDVCS
  - Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target and two different beam energies
  - First observation of non-zero nDVCS CS

- No neutron detection $D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$

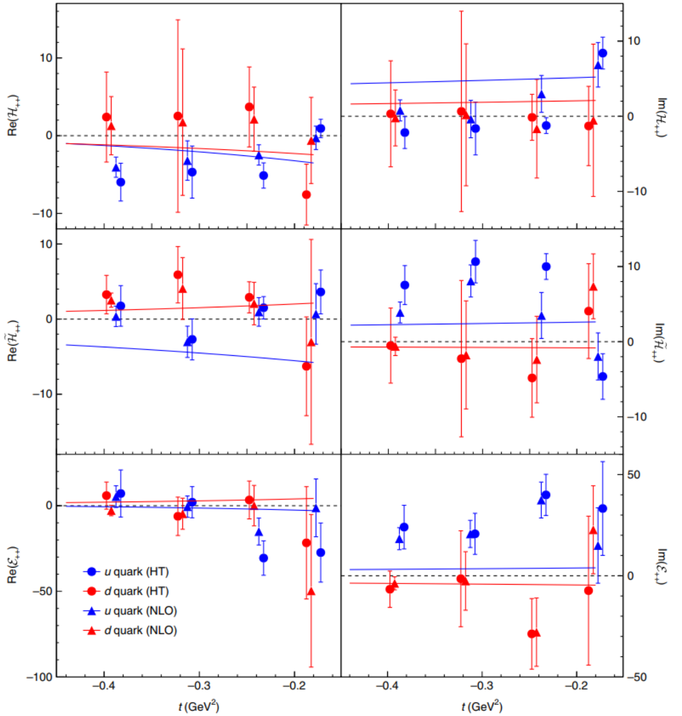
+data from: Mazouz, M. et al. Phys. Rev. Lett. 99, 242501 (2007).

- Scattering off neutron (nDVCS): GPD E
  - Determination of the **Ji sum rule**: Contribution of the orbital angular momentum of quarks to the nucleon spin

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



One measured kinematical point: Q^2=1.9 GeV^2 and x_B=0.36

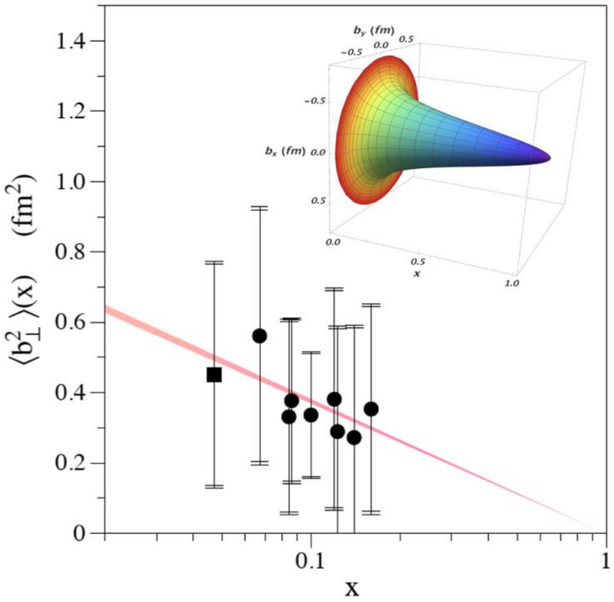


Benali, M., Desnault, C., Mazouz, M. *et al. Nat. Phys.* 16, 191–198 (2020)

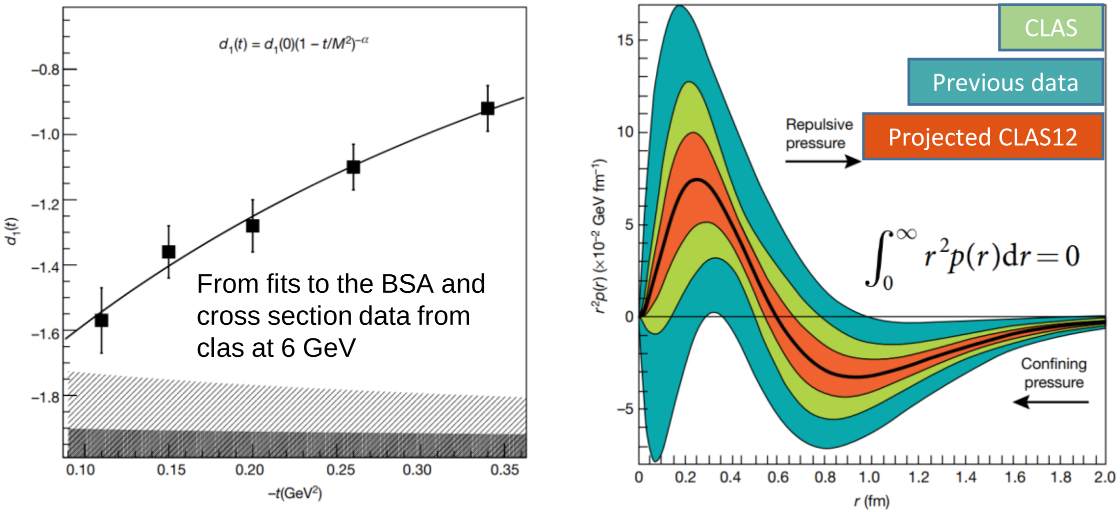
What did we learn from JLAB data at ~6 GeV?

- Tomography of the proton
  - Obtained from local fits to HERMES, CLAS, and Hall-A data ($\Im H$ + model dependent assumptions for x dependence)

- The pressure distribution inside the proton
  - Gravitational form factor
    - $\int xH(x,\xi,t)dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$
    - $d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t}\rho(r)d^3r$



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



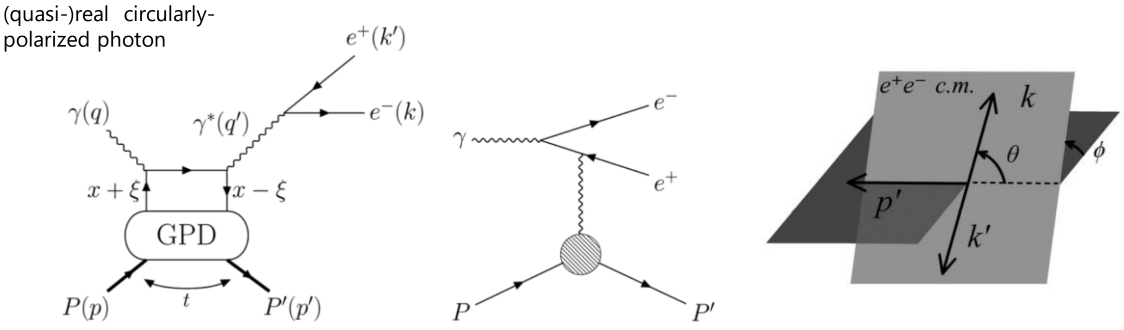
V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

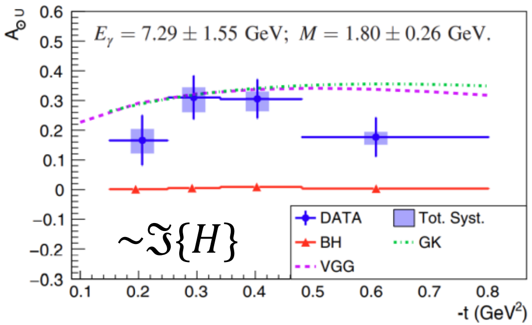
P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127, 262501 (2021)

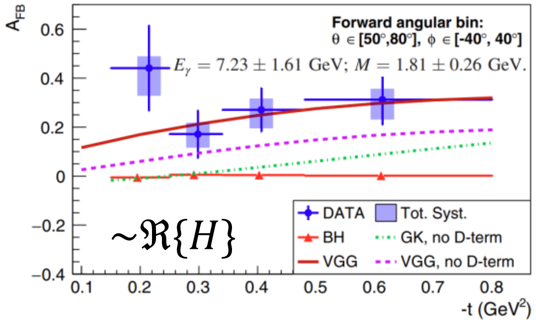
- Test of universality of GPDs: direct comparison between DVCS and TCS results
- Real part of CFFs and D-term: TCS unpolarized cross section is sensitive to $\Re\{H\}$
- D-term can be related to the mechanical properties of the nucleon.

$$\mathrm{Re}\mathcal{H}(\xi,t) \overset{\mathrm{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right) \mathrm{Im}\mathcal{H}(x,t)$$

$$D(t) = \frac{1}{2}\int_{-1}^{1} \frac{D(z,t)}{1-z}\mathrm{d}z \qquad D(z,t) = (1-z^2)[d_1(t)C_1^{3/2}(z) + \cdots]$$



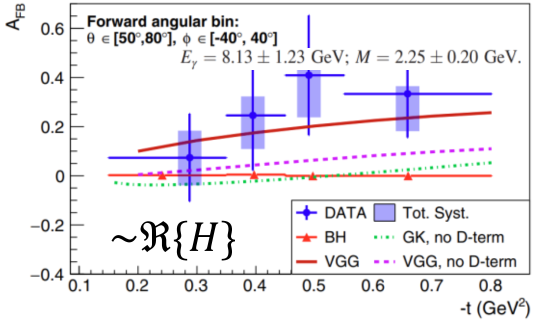




Measured observables:

- Beam helicity asymmetry: $\Im\{H\}$
- Forward-backward asymmetry: $\Re\{H\}$

- GPDs are universal functions
- Data compatible with model including D-term: understand the internal pressure of proton



CLAS12: DVCS off proton

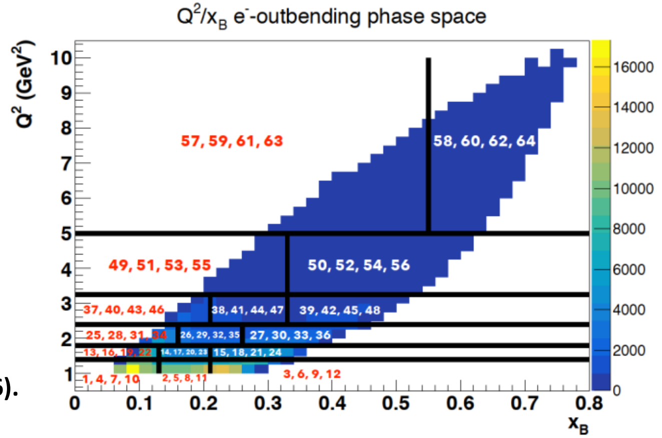
G. Christiaens, M. Defurne, D. Sokhan to be published soon

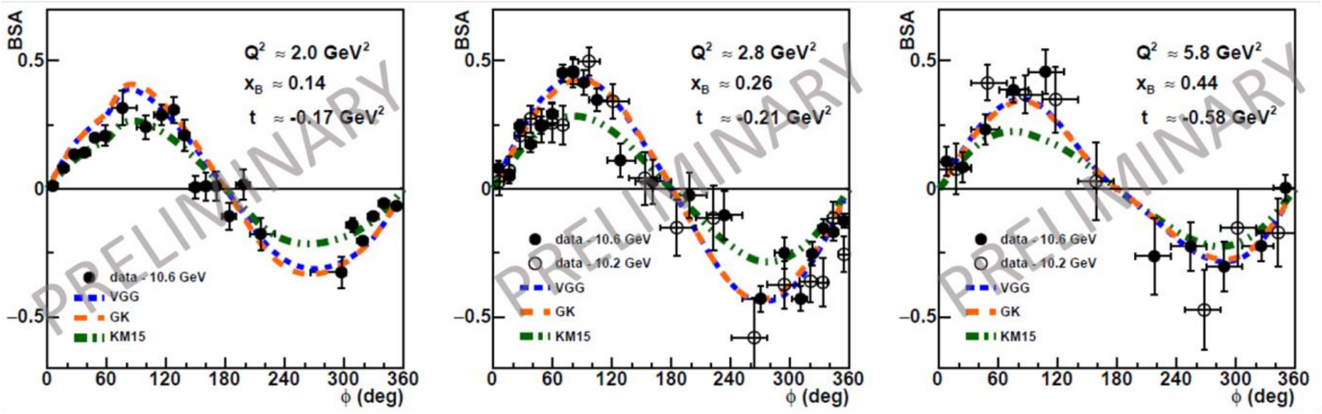
- Polarised beam (86%) with energy 10.6 GeV
- Unpolarised LH2 target
- 64 (Q^2, x_b, t) kinematical bins

Comparisons with KM15 and VGG/GK models

Kumericki, Kresimir and M uller, Dieter, EPJ Web of Conferences 112, 01012 (2016).
S. V. Goloskokov and P. Kroll, EPJC 65, 10.1140 (2009)
M. Vanderhaeghen, P. A. Guichon, and M. Guidal, Phys.Rev. D60, 094017 (1999)

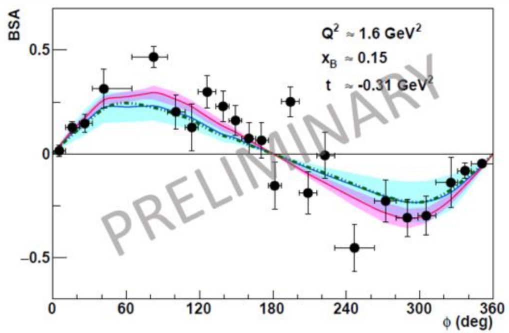
Extended kinematical coverage

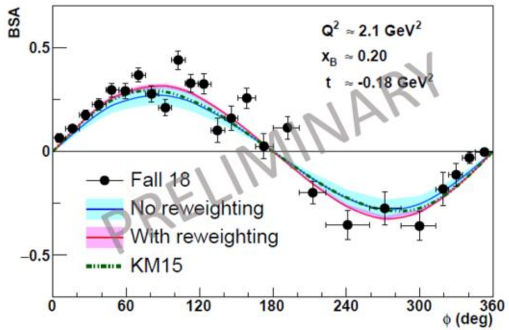




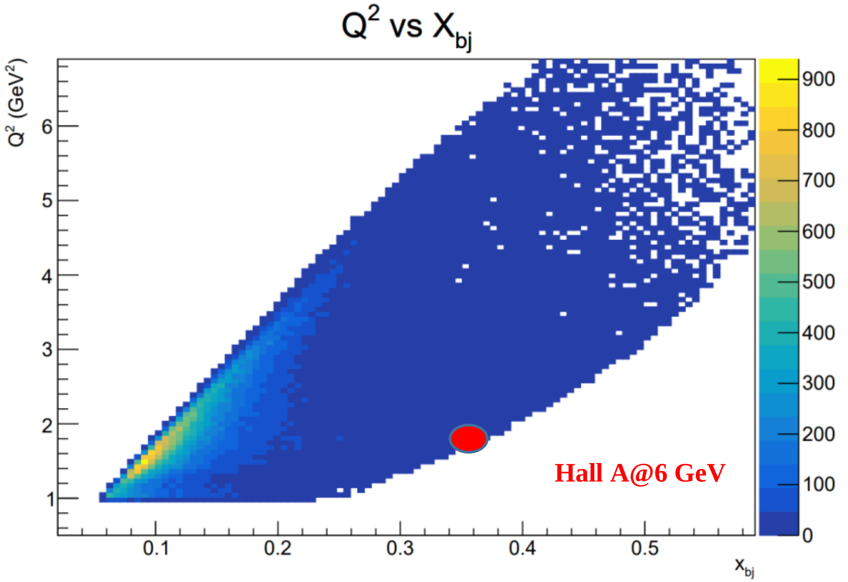
H. Moutarde, P. Sznajder, and J. Wagner, EPJC 79, 614 (2019)

- Deriving the mean and standard deviation of a 100 ANN-predictions produced by a global fit (PARTONS)
- The new data are shown to be in good agreement





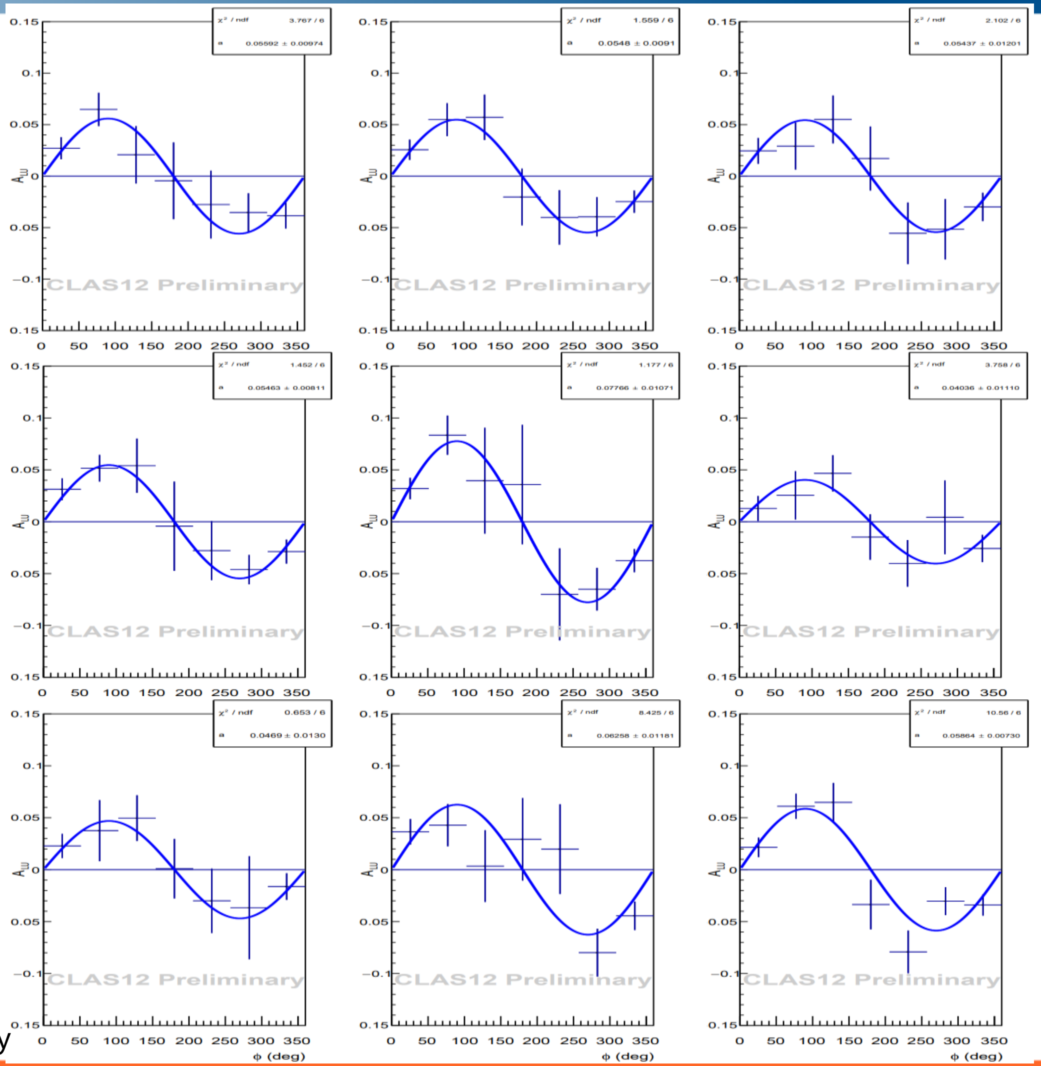
First-time measurement of nDVCS with detection of the active neutron



Q^2 bins

x_b bins

t bins

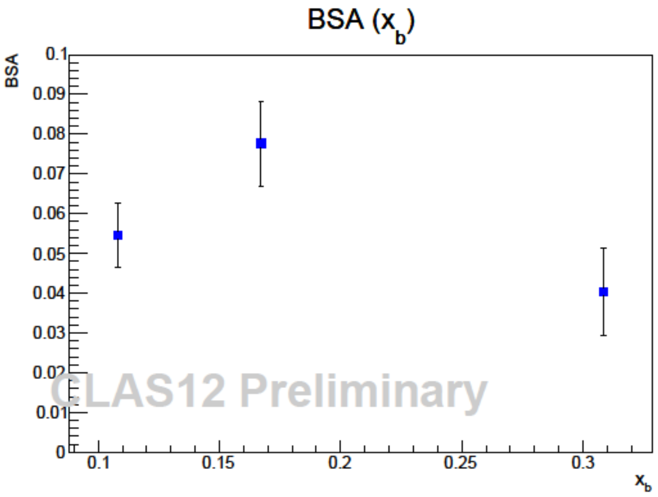


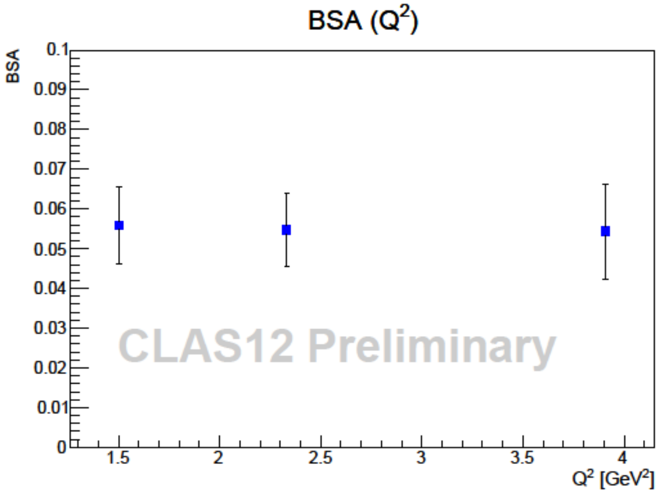
- Compared to the previous experiment, CLAS12 provides :
  - The possibility to scan the BSA of nDVCS on a wide phase space
  - The possibility to reach the high Q^2 high x_b region of the phase space
  - Exclusive measurement with the detection of the active neutron

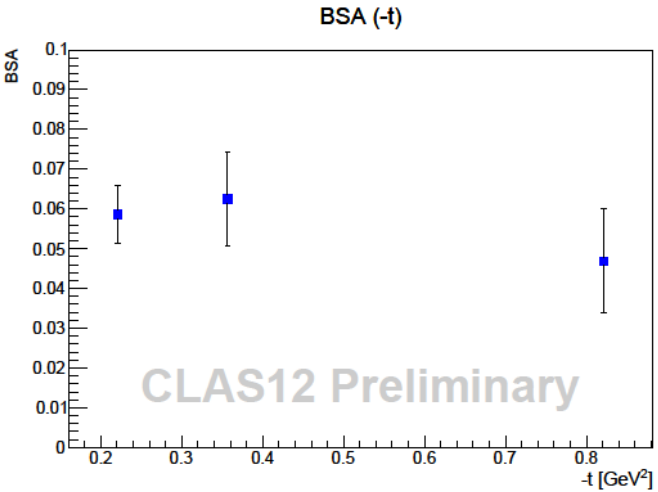
Errors are statistical only

CLAS12: nDVCS with an unpolarized deuterium target

$$\Delta\sigma_{LU} \sim \sin(\phi)\, \Im\{F_1 \boldsymbol{H} + \xi(F_1 + F_2)\widetilde{\boldsymbol{H}} - k\, F_2 \boldsymbol{E} + \ \dots\}$$







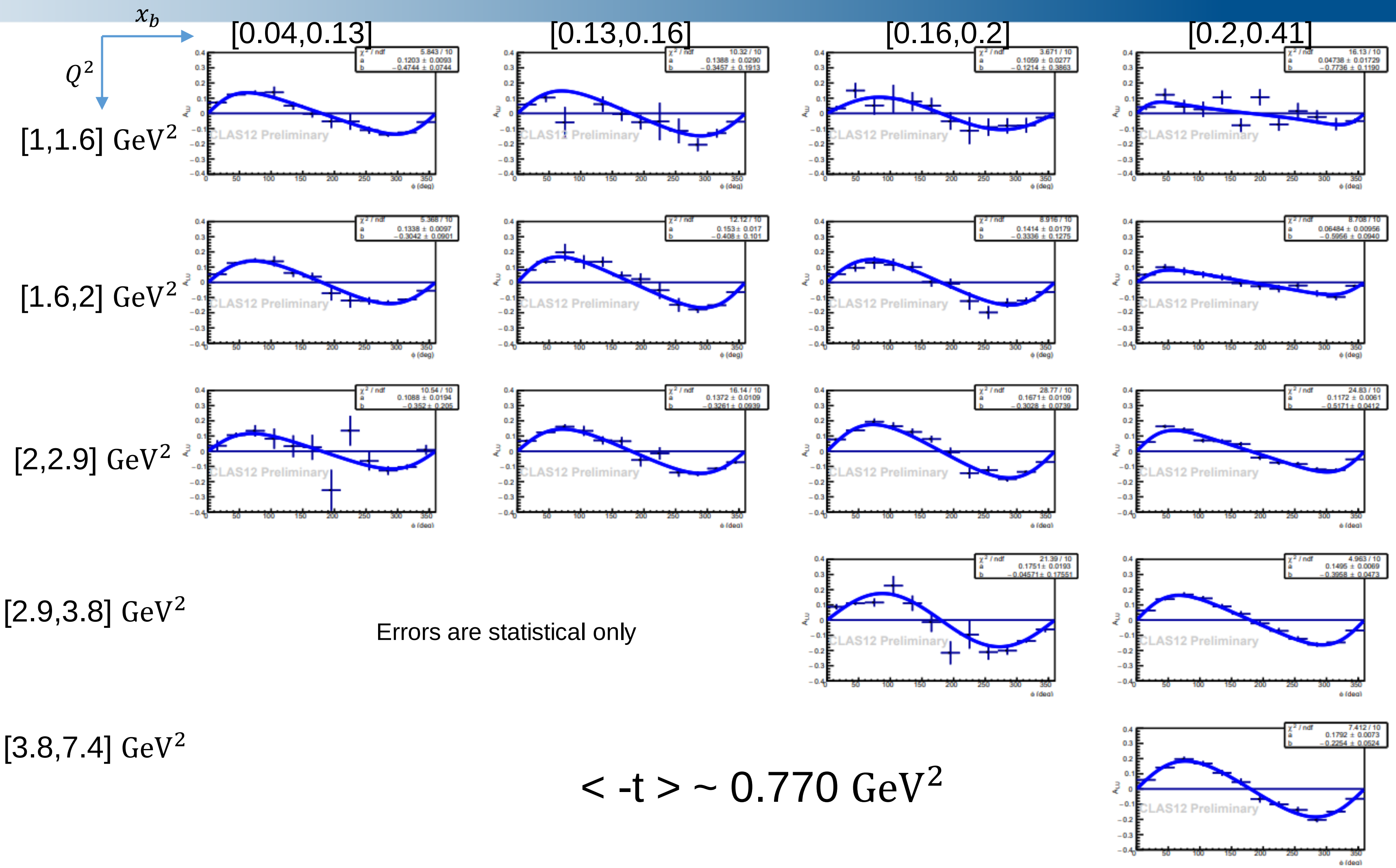
Errors are statistical only

CLAS12: pDVCS with an unpolarized deuterium target

First-time measurement of incoherent pDVCS on deuteron

Scattering off proton (pDVCS): GPD H

Quantify medium effects: Essential for the extraction of BSA of a “free” neutron (de-convoluting medium effect via comparison with DVCS on hydrogen target)



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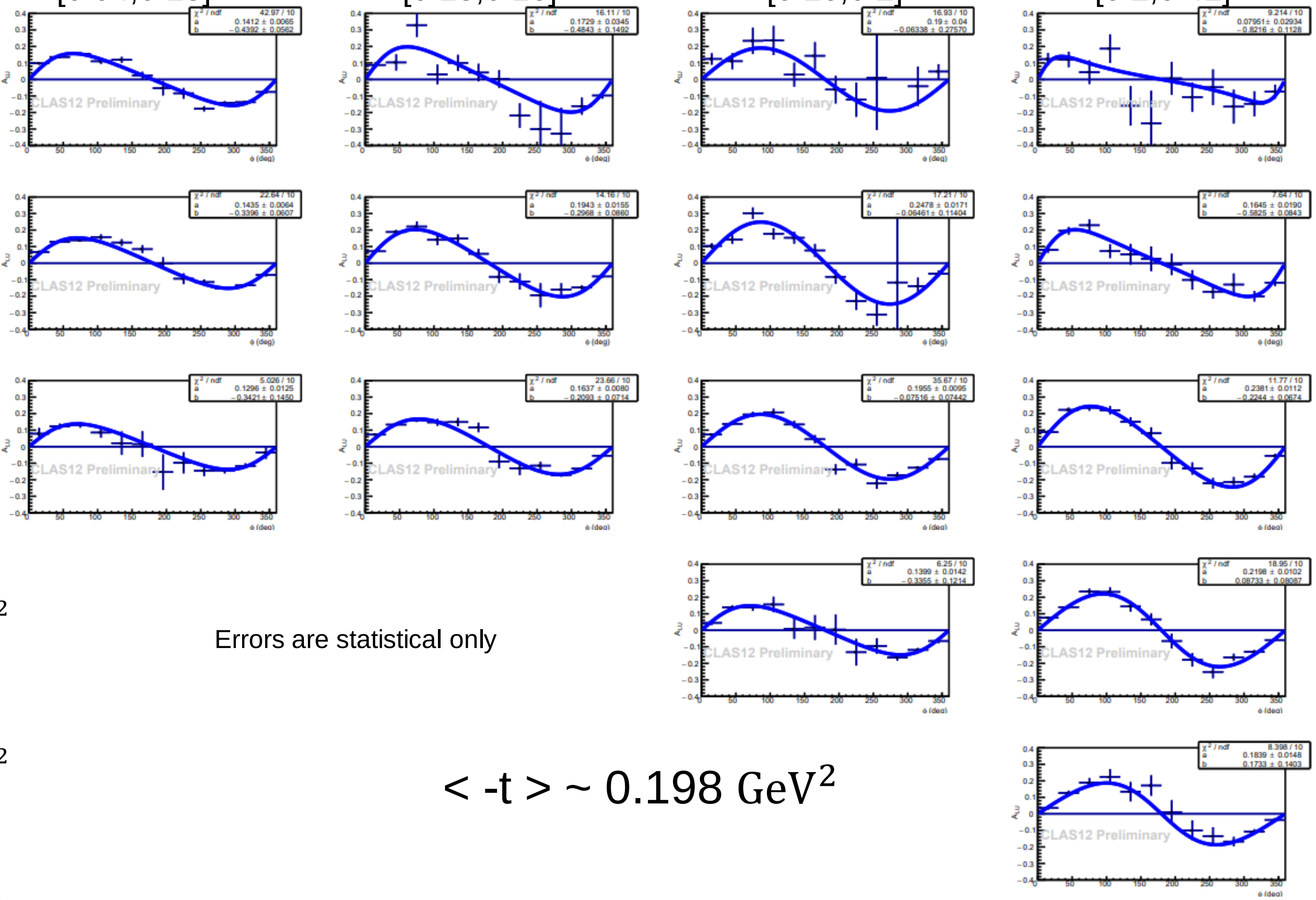
x_b: [0.04,0.13] [0.13,0.16] [0.16,0.2] [0.2,0.41]

Q^2: [1,1.6] GeV^2, [1.6,2] GeV^2, [2,2.9] GeV^2, [2.9,3.8] GeV^2, [3.8,7.4] GeV^2



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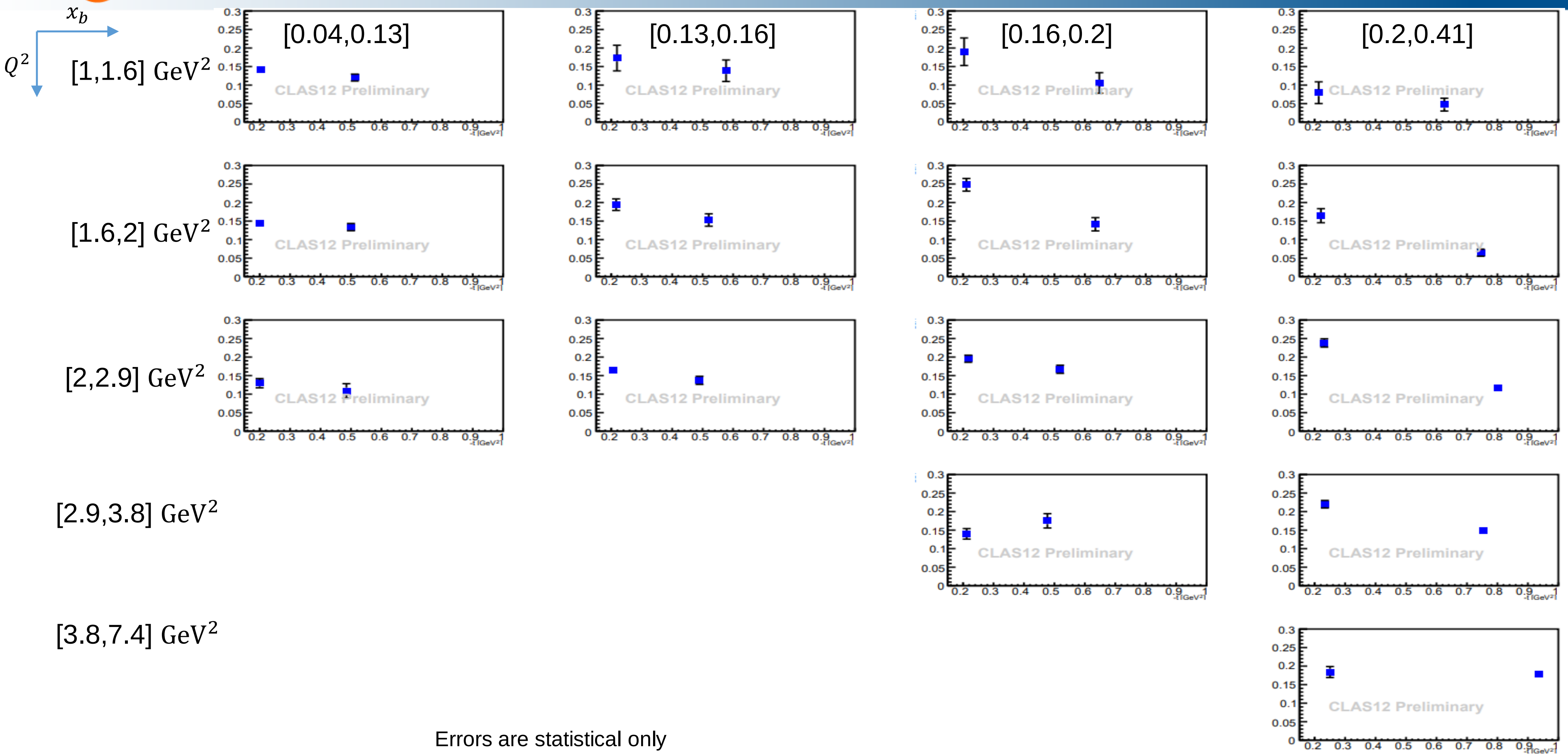
< -t > ~ 0.198 GeV^2

CLAS12: pDVCS with an unpolarized deuterium target



Errors are statistical only

CLAS12: upcoming

- Deuteron DVCS: Phyisics observable to extract is Beam Spin Asymmetry (BSA)

$$\Delta\sigma_{LU} \sim \sin(\phi)\,\Im\left\{\frac{2G_1\boldsymbol{H_1} + (G_1 - \tau G_3)(\boldsymbol{H_1} - 2\tau\boldsymbol{H_3}) + \frac{2}{3}\tau G_3\boldsymbol{H_5}}{2G_1^2 + (G_1 - 2\tau G_3)^2}\right\}$$

  - Spin 1: 9 GPDs for each quark flavor
    - BSA of DVCS off deuterium is sensitive to 3 of them
- + DVπ^0P of deuterium (BSA- soon)
- + longitudinally polarized target (lTSA(p), lDSA(p) – data to be collected starting this summer)
- + transversally polarized target (tTSA, complementary to nDVCS-data for the GPD E extraction; expected data taking in ~2025
- + … … …

Conclusions

- GPDs are powerful tool to explore the structure of the nucleons and nuclei
  - Nucleon tomography, quark angular momentum, distribution of forces in the nucleon
- Exclusive reactions can provide important information on nucleon structure via the extraction of GPDs
- GPDs require complex extraction from data
- JLAB (Hall A/CLAS) data: rich information about the nucleon structure
  - First tomographic image of the proton
  - Quarks shear forces and pressure distribution inside the proton
- CLAS12 offers a wide kinematical reach over which the GPDs dependence on different kinematical variables can be scanned
  - New data to add constraints on GPDs in unexplored regions of the phase space
  - Possibilities to measure new observables using different experimental configurations
    - Flavor separation of GPDs