

OAM measurements from DVCS at JLab



The nucleon is sensitive to all the interactions known so far

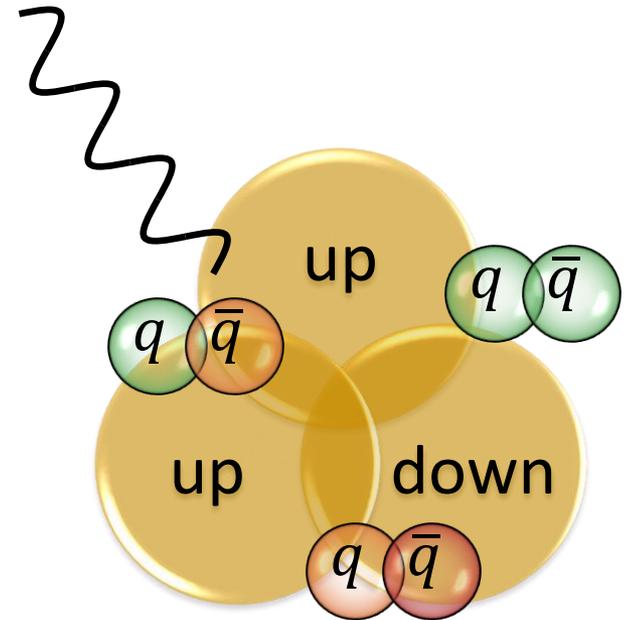
How the nucleon experiences a specific interactions is encoded in a **charge** → it depends on the nature of the operator describing the interaction

What is the spatial size of the nucleon?

How its charges are distributed in its bulk?

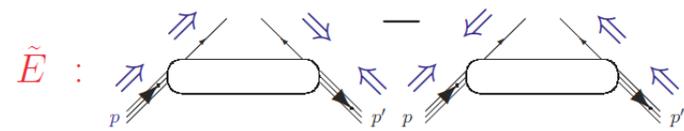
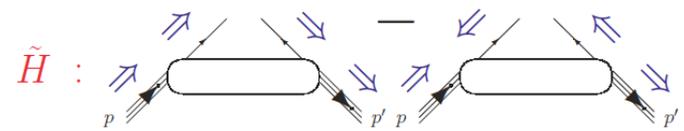
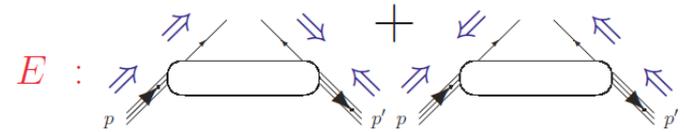
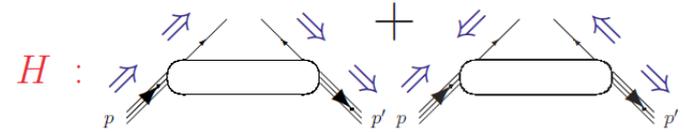
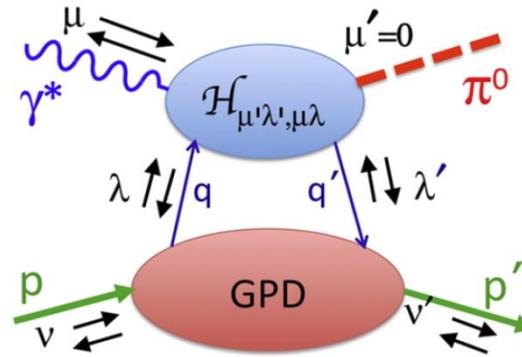
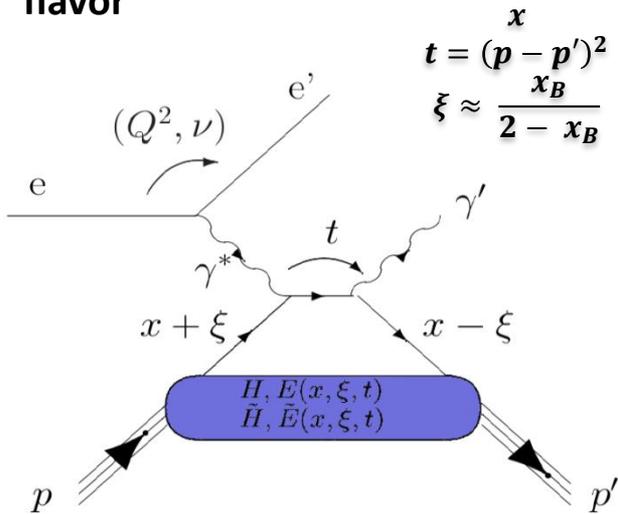
How nucleon description relates to the *first-principle-QCD* description encoded in lattice-based calculations?

→ **What is the orbital angular momentum of the nucleon constituents?**



Generalized Parton Distributions → transverse spatial images of quarks and gluons as a function of their longitudinal momentum fraction.

There are **4 chiral-even + 4 chiral-odd** GPDs for any quark flavor



$$\begin{aligned}
 H^q(x, 0, 0) &= f_1(x) \\
 \tilde{H}^q(x, 0, 0) &= g_1(x) \\
 H_T^q(x, 0, 0) &= h_1(x) \\
 &\text{(for } x > 0; \text{ antiquark for } x < 0)
 \end{aligned}$$

$$\begin{aligned}
 \int_{-1}^{+1} dx H^q(x, \xi, t) &= F_1^q(t), & \int_{-1}^{+1} dx E^q(x, \xi, t) &= F_2^q(t) \\
 \int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) &= G_A^q(t), & \int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) &= G_P^q(t)
 \end{aligned}$$

Only (ξ, t) are experimentally accessible, not x . GPDs will enter in the observables through

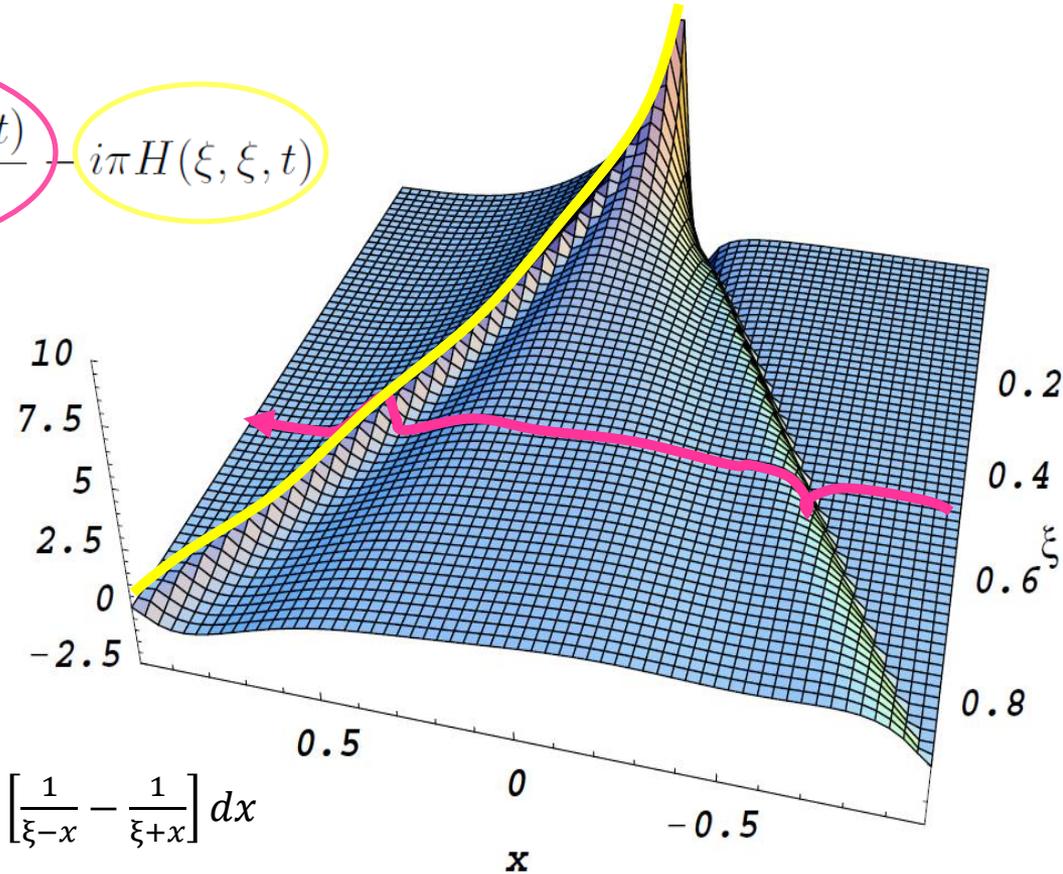
$$\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(\xi, \xi, t)$$

The two parts will be accessible through observables sensitive to the *imaginary* (A_{LU}, A_{UL}) or the *real part* ($A_{LL}, A_{BeamCharge}$) of the amplitude.

The following **Compton Form Factors** are introduced (experimentally observable):

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

$$Im\mathcal{H}_q = \pi e^2_q (H^q(\xi, \xi, t) - H^q(-\xi, \xi, t))$$



Different observables are sensitive to different combinations of Compton Form Factors and electromagnetic Form Factors:

1. Beam-Spin Asymmetry:

$$\Delta\sigma_{LU} \propto \sin\varphi \operatorname{Im}\{F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} + kF_2\mathcal{E}\}d\varphi$$

2. Target-Spin Asymmetry:

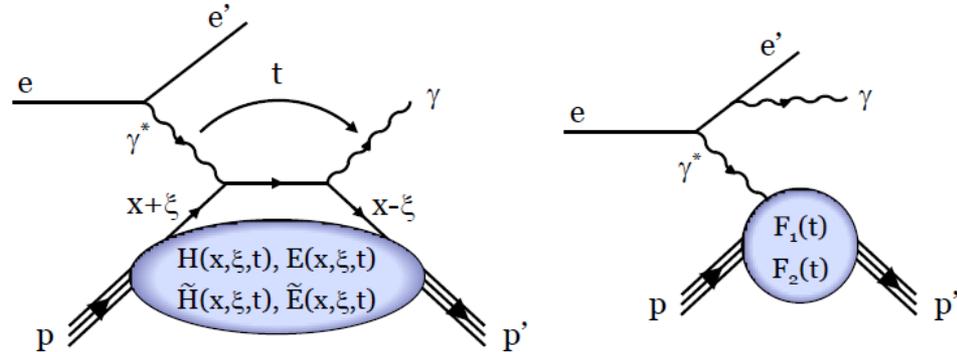
$$\Delta\sigma_{UL} \propto \sin\varphi \operatorname{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)\mathcal{H} + kF_2\mathcal{E}\}d\varphi$$

3. Double-Spin Asymmetry:

$$\Delta\sigma_{LL} \propto (A + B\cos\varphi) \operatorname{Re}\left\{F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right)\right\}d\varphi$$

4. Transverse Target-Spin Asymmetry:

$$\Delta\sigma_{UT} \propto \sin\varphi \operatorname{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \dots\}d\varphi$$



$$\sigma = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2$$

Access to LINEAR combinations of GPDs (instead of bilinear) thanks to the presence of Bethe-Heitler

Asymmetries identified as modulations in φ , the *angle between the leptonic and the hadronic plane*

Gauge-Invariant Decomposition of Nucleon Spin

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Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
and Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195
(Received 20 March 1996)*

I introduce a gauge-invariant decomposition of the nucleon spin into quark helicity, quark orbital, and gluon contributions. The total quark (and hence the quark orbital) contribution is shown to be measurable through virtual Compton scattering in a special kinematic region where single quark scattering dominates. This deeply virtual Compton scattering has much potential to unravel the quark and gluon structure of the nucleon. [S0031-9007(96)02221-1]

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

$$J_q = L_q + S_q$$

$S_q \rightarrow$ accessible through Inclusive Deep-Inelastic Scattering

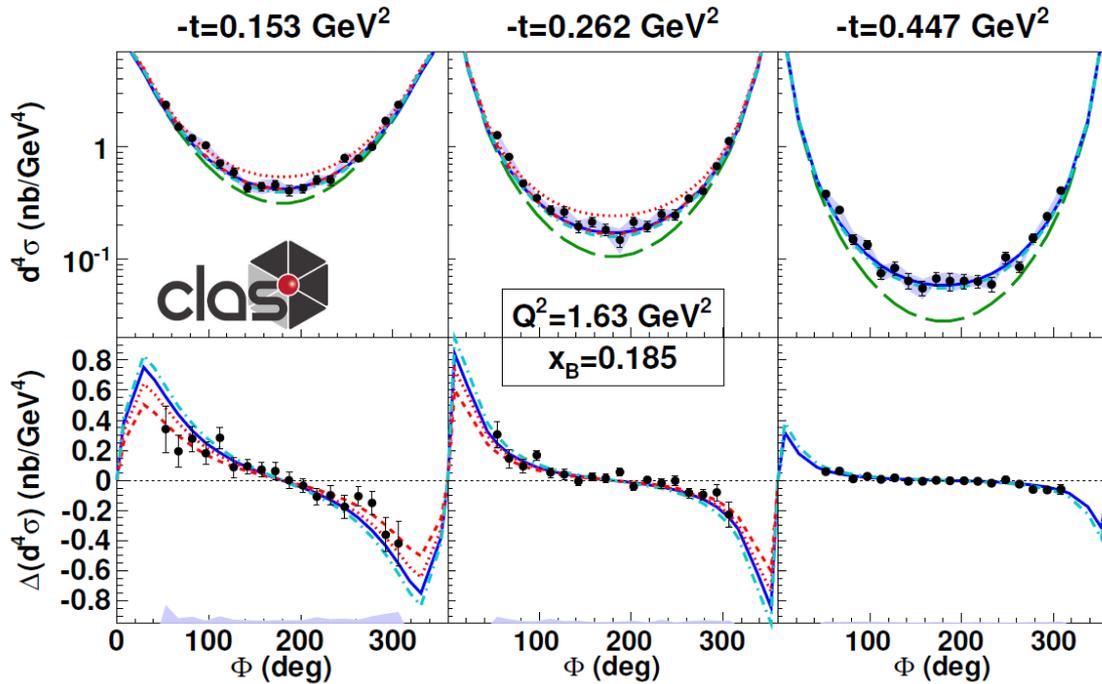
Quark Orbital Angular Momentum can be extracted

\mathcal{H}^p_{Im} : cross-section on the proton in Hall-B (E01-113)

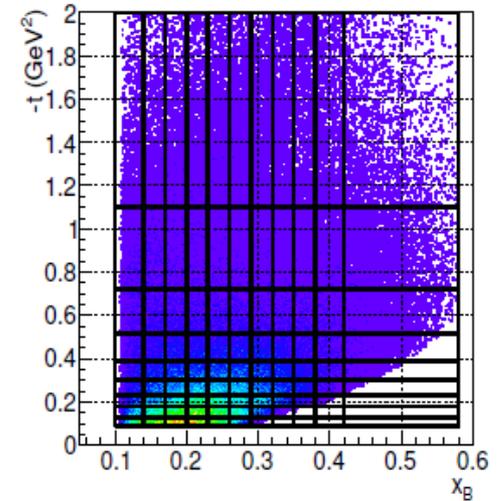
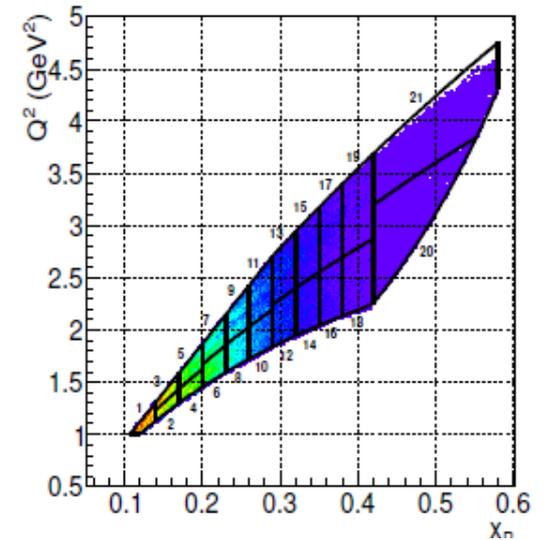
Extraction in a LARGE kinematic domain

$$\frac{d^4\sigma_{ep \rightarrow e'p\gamma}}{dQ^2 dx_B dt d\phi}$$

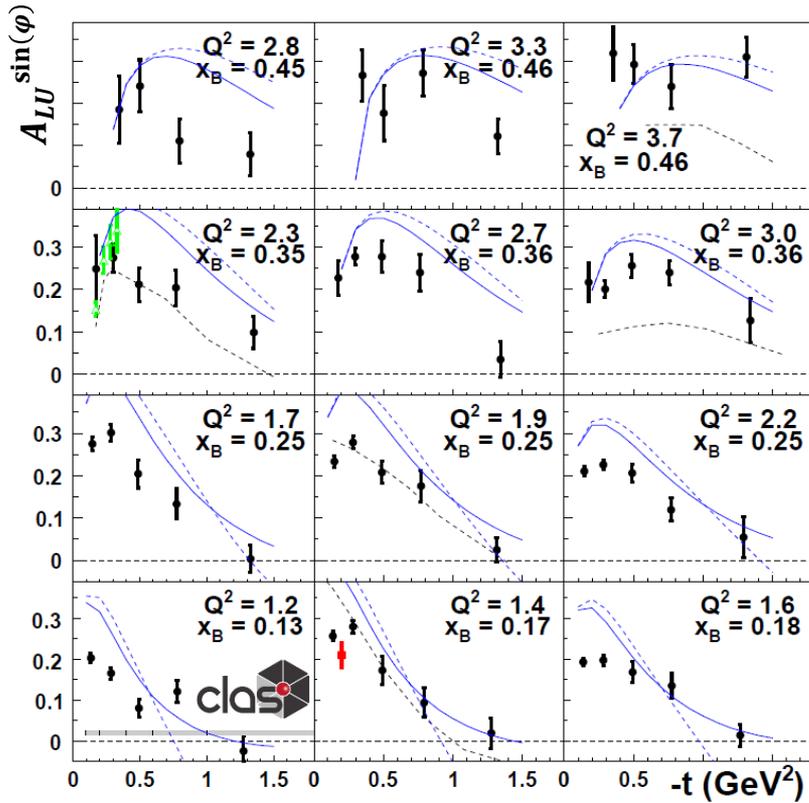
- BH only
- VGG (H only)
- ⋯ KM10 (Kumericki, Mueller)
- - - KM10a
- - - KMS



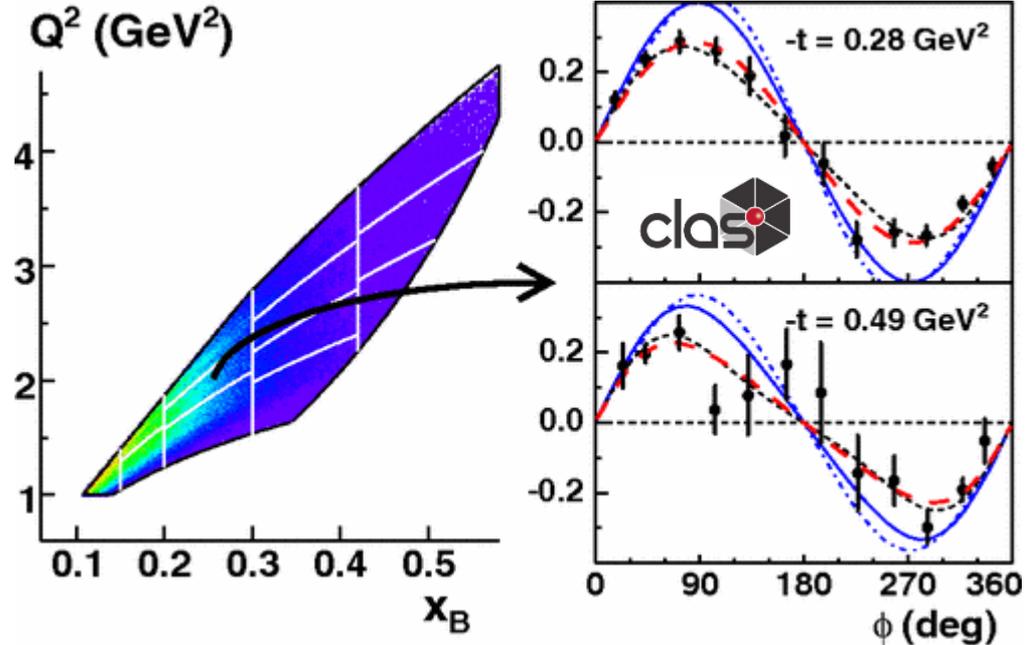
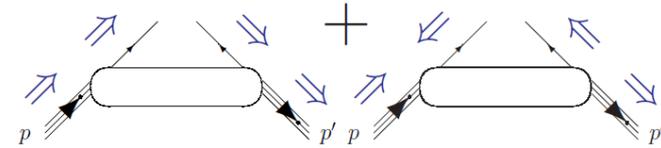
H. S. Jo et. al., hep-ex:1504.02009



First CLAS DVCS devoted experiment on unpolarized H_2



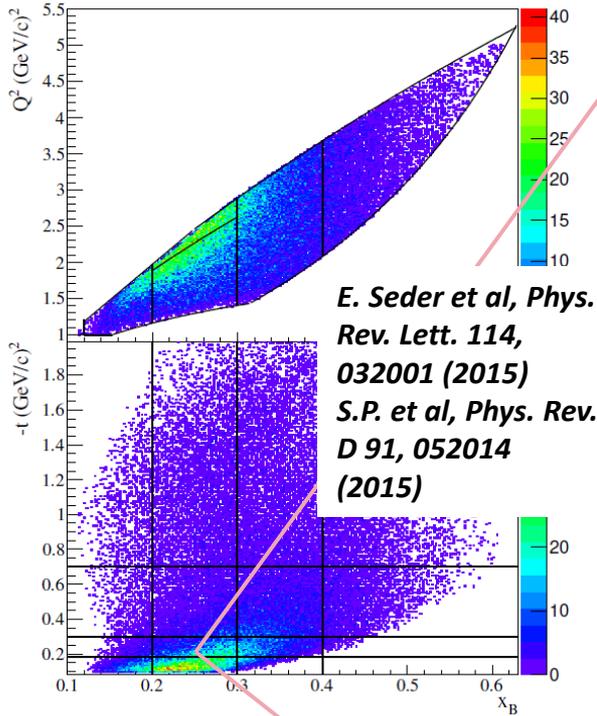
$---$ $f = \frac{a \sin \phi}{1 + b \cos \phi}$
 $---$ VGG twist-2
 $---$ VGG twist-3



- CLAS e1-dvcs
- ▲ Hall A
- CLAS @ 4.3 GeV²
- VGG(*) twist-2
- - - VGG(*) twist-2 and 3
- ⋯ Regge model (Laget)

F. X. Girod et al., Phys. Rev. Lett. 100, 162002 (2008).

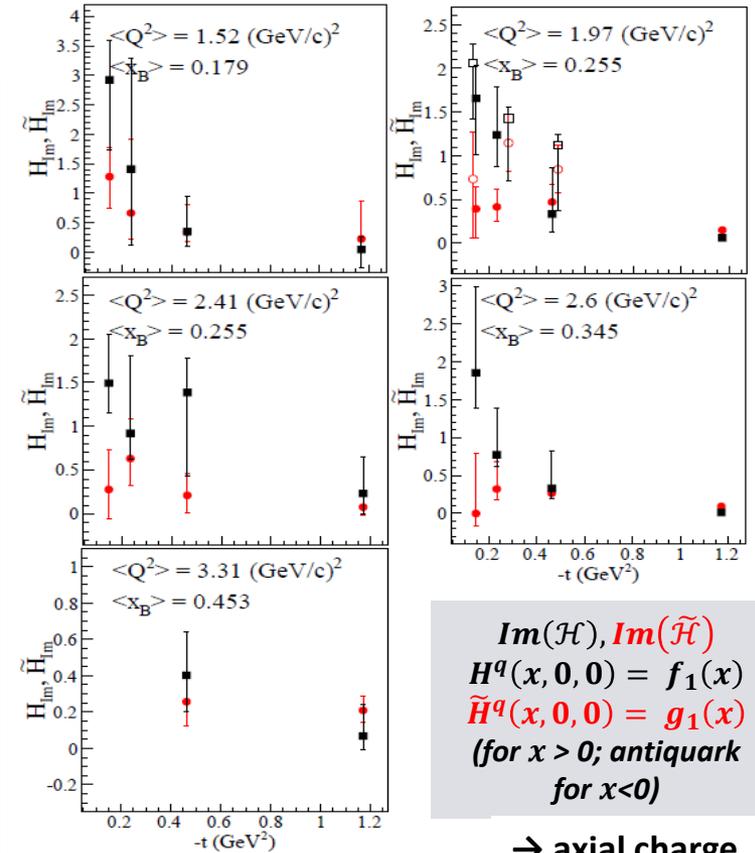
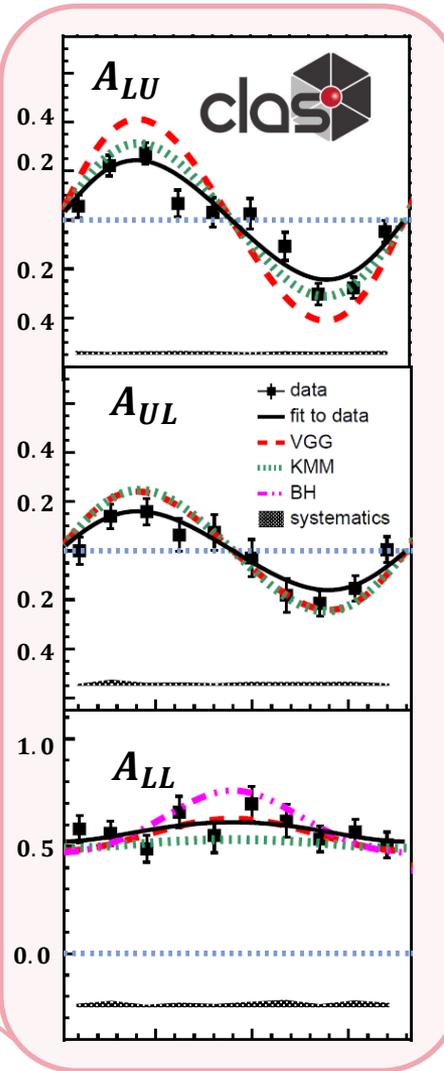
Comparing charge distributions: $A_{LU} \propto \mathcal{H}^p_{Im}$, $A_{UL} \propto \tilde{\mathcal{H}}^p_{Im}$



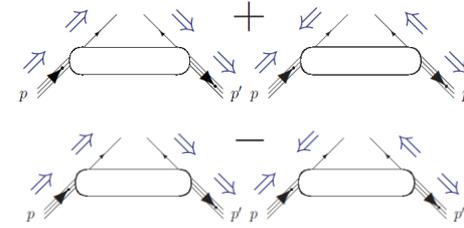
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)

High statistics extraction of Single and Double-Spin Asymmetries

→ simultaneous CFF extraction from three observables in a common kinematics



$Im(\mathcal{H}), Im(\tilde{\mathcal{H}})$
 $H^q(x, 0, 0) = f_1(x)$
 $\tilde{H}^q(x, 0, 0) = g_1(x)$
 (for $x > 0$; antiquark for $x < 0$)



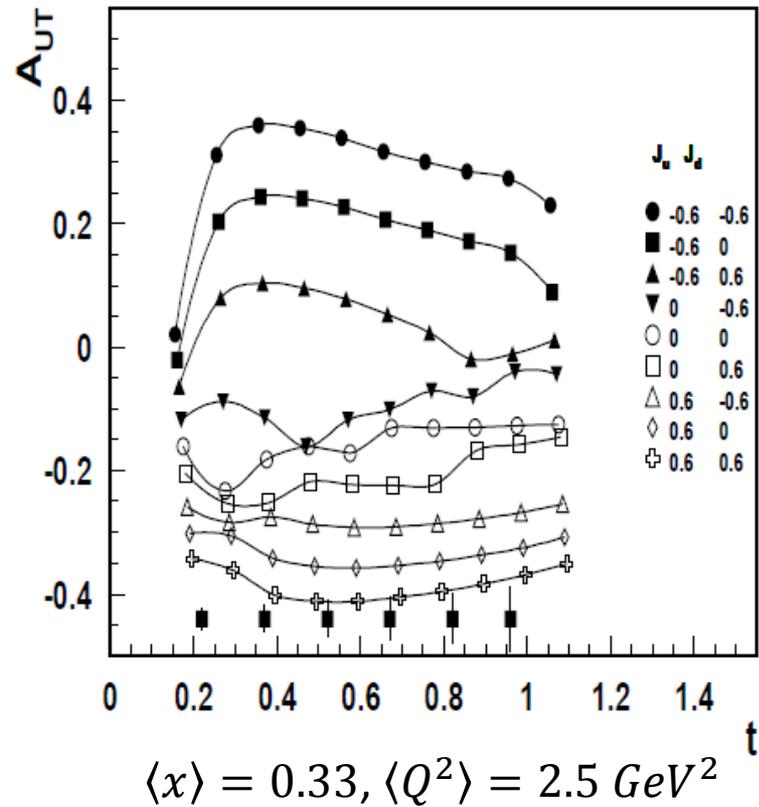
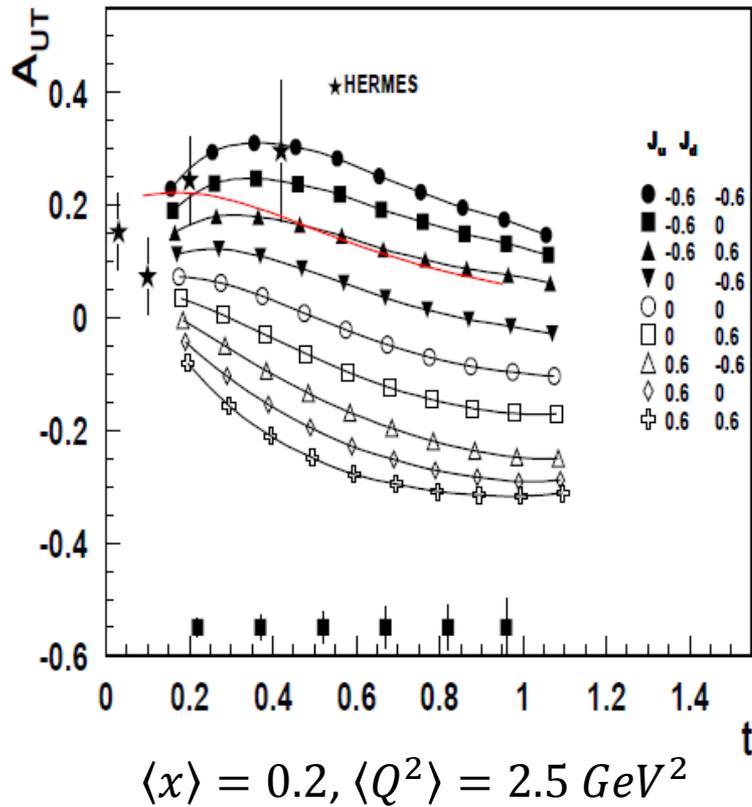
→ axial charge is more concentrated in the nucleon centre than the electric charge

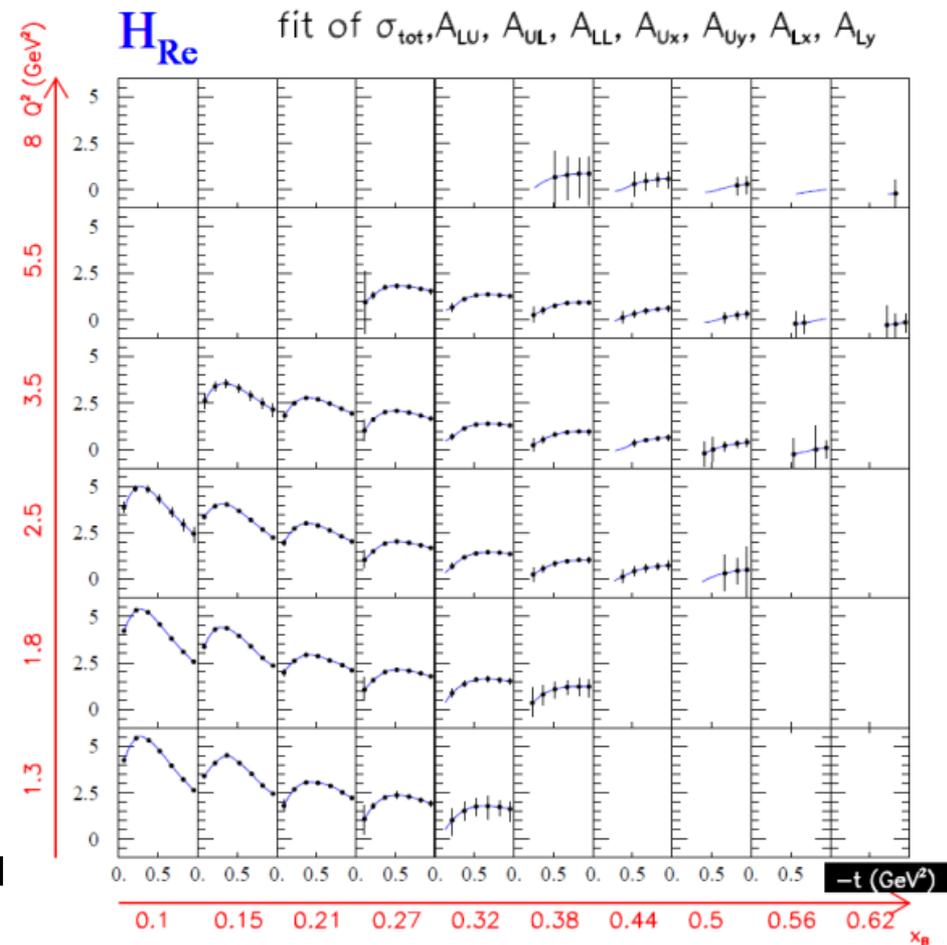
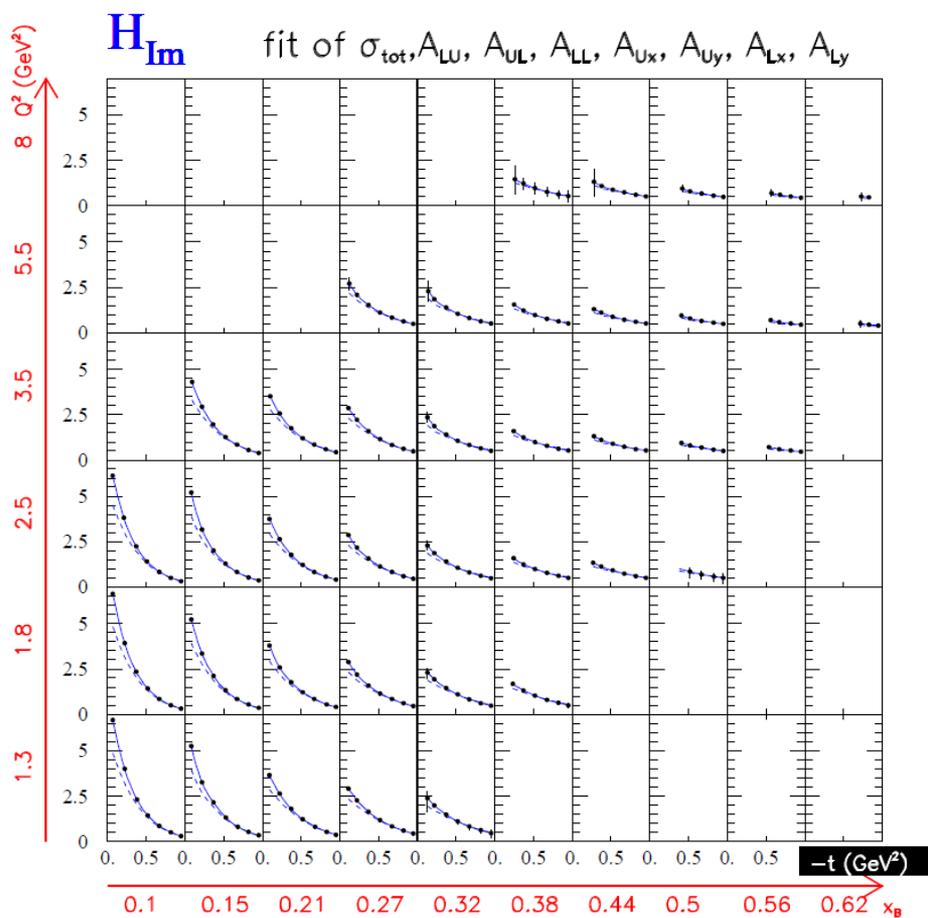
\mathcal{E}^p : transverse Target-Spin Asymmetry in the 12 GeV era



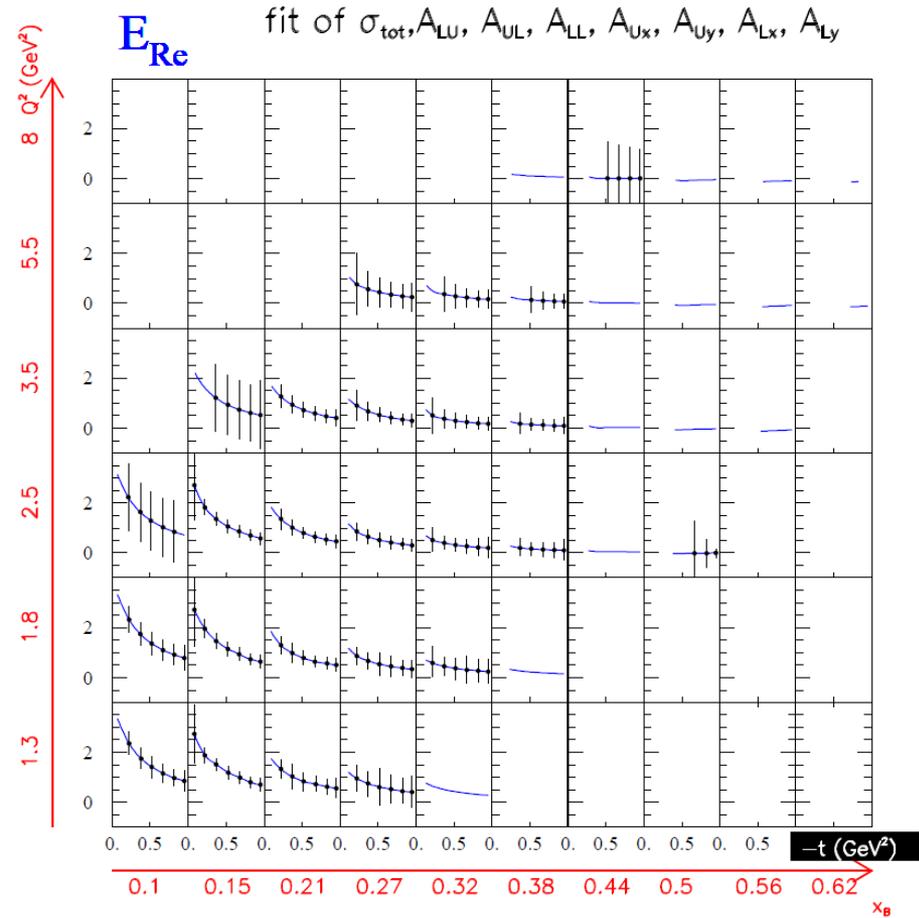
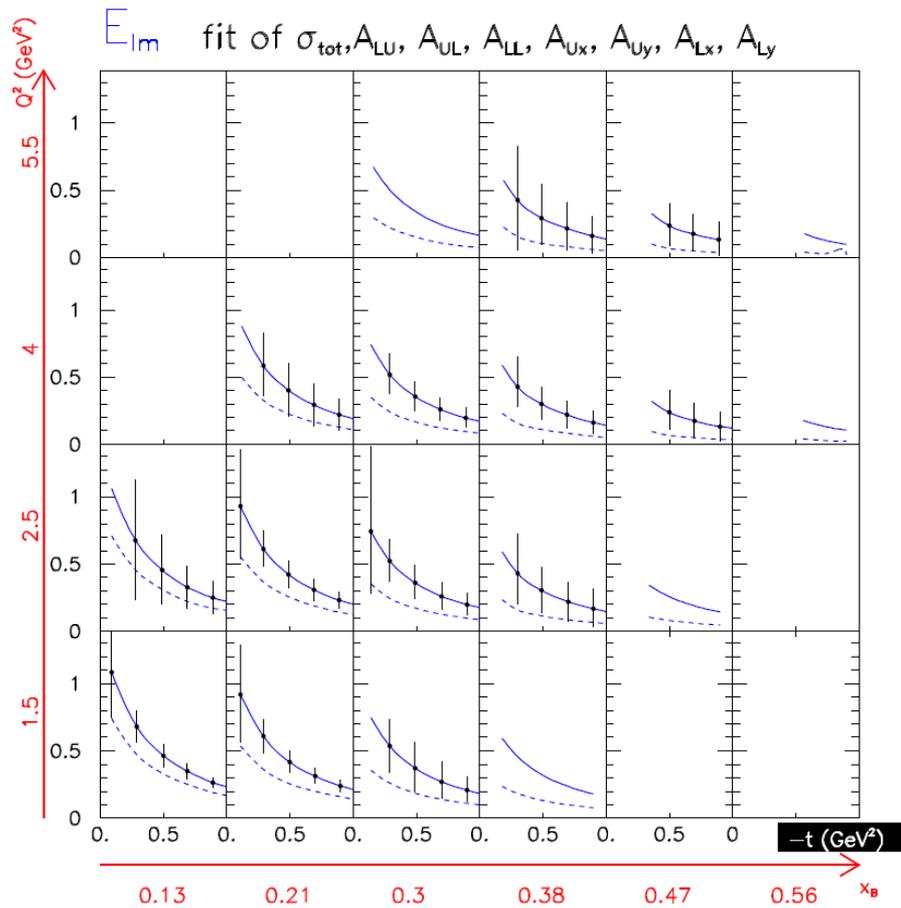
Transversely polarized observables for proton are mostly sensitive to Compton Form Factor \mathcal{E}^p

→ *asymmetries on a transversely polarized proton target (E12-12-010 in Hall-B)*





M. Guidal, H. Moutarde, M. Vanderhaeghen: *hep-ph* > arXiv:1303.6600



M. Guidal, H. Moutarde, M. Vanderhaeghen: hep-ph > arXiv:1303.6600

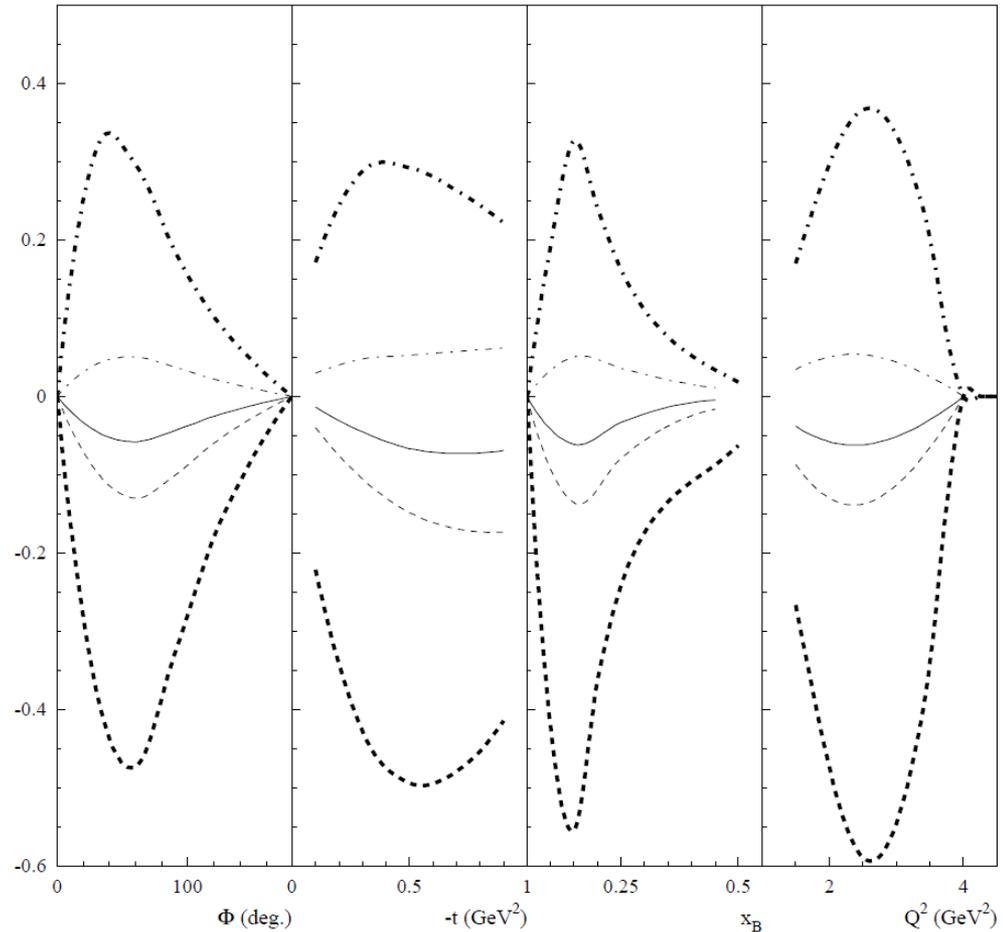
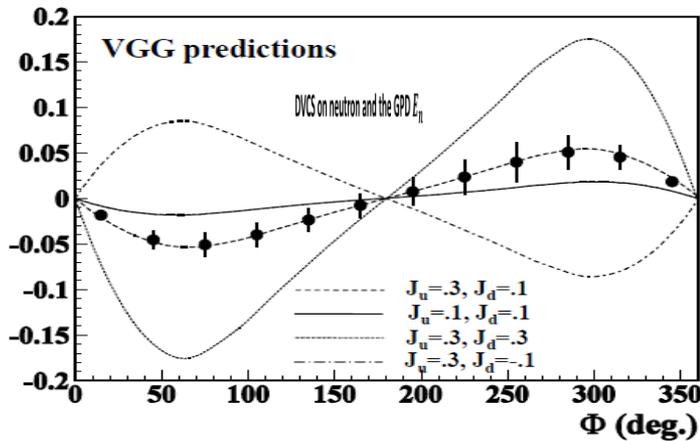
\mathcal{E}^n : neutron DVCS Beam-Spin Asymmetry at 12-GeV JLab



Beam-Spin Asymmetry on the neutron highly sensitive to quark angular momentum

Different curves: VGG at $E_e = 11 \text{ GeV}, x_B = 0.17, Q^2 = 2 \text{ GeV}^2, -t = 0.4 \text{ GeV}^2$ for

- $J_u = 0.3, J_d = 0.1$
- - - $J_u = -0.5, J_d = 0.1$
- · - $J_u = 0.3, J_d = 0.8$
- - - $J_u = 0.3, J_d = -0.5$



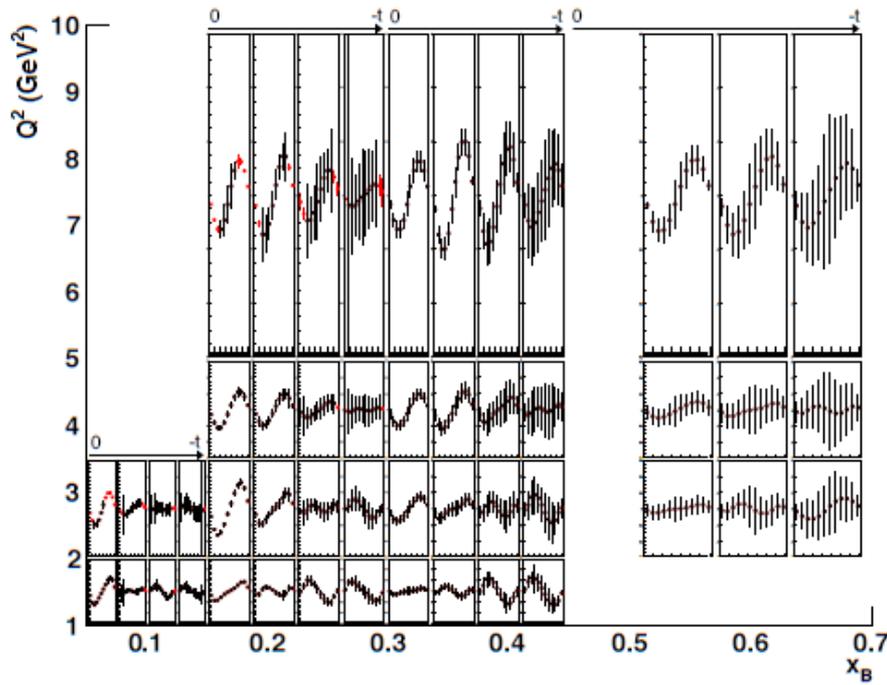
E12-11-003, A_{LU} on neutron

New Research Proposal to Jefferson Lab PAC 43

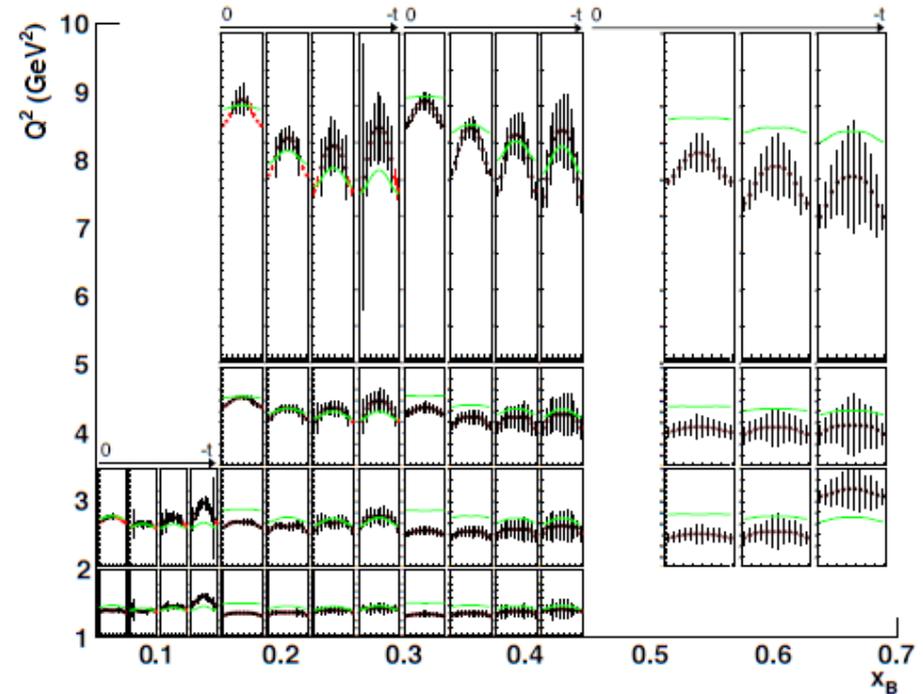
→ to be (re-)submitted on
2016 to **PAC44**

Deeply virtual Compton scattering on the neutron
at 11 GeV with CLAS12 and a longitudinally polarized deuterium target

A_{UL}^n

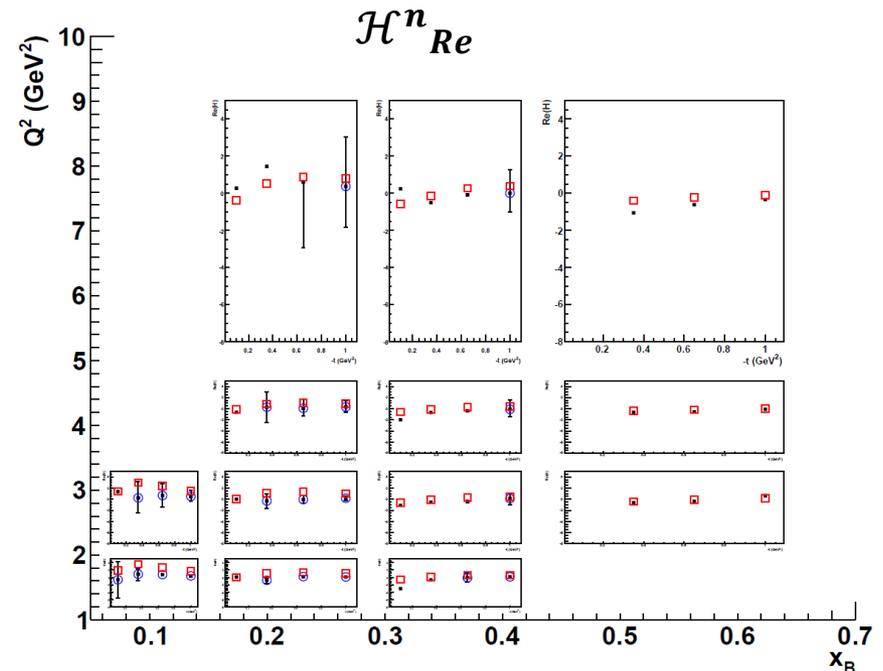
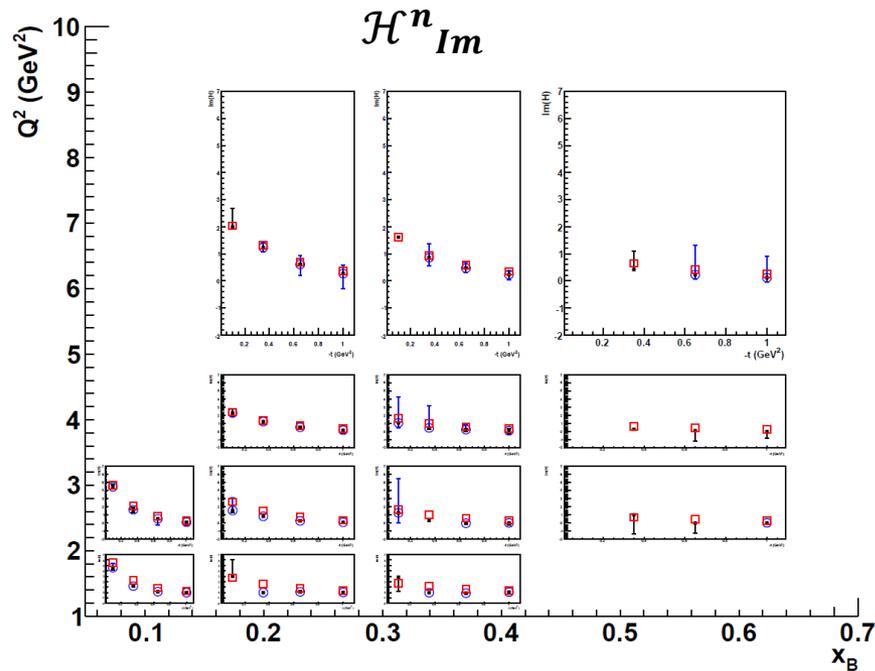


A_{LL}^n



New Research Proposal to Jefferson Lab PAC 43

Deeply virtual Compton scattering on the neutron at 11 GeV with CLAS12 and a longitudinally polarized deuterium target

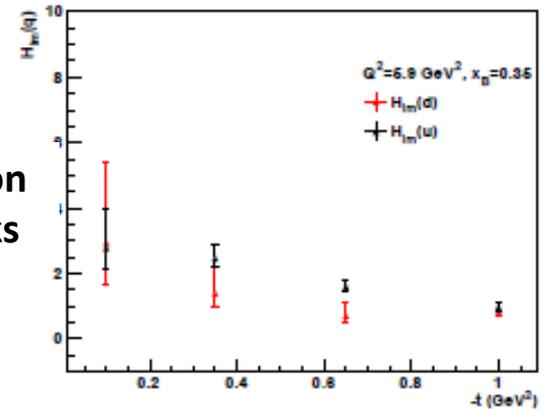
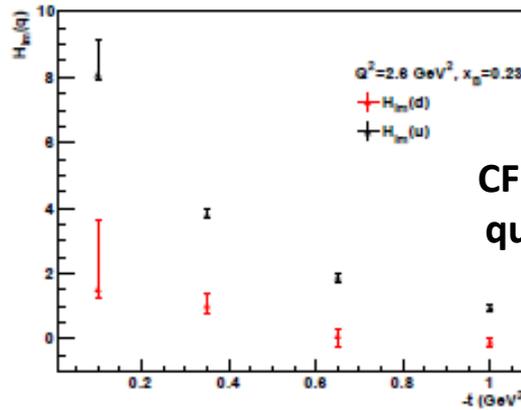
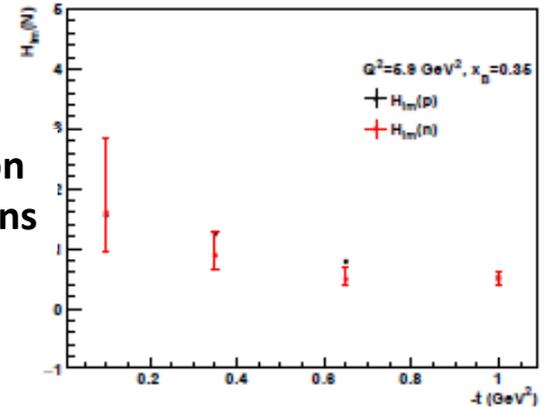
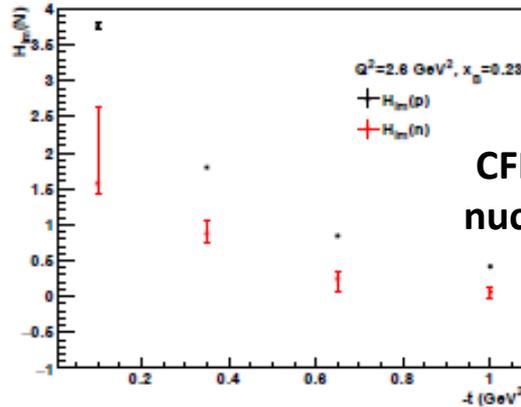


Eventually, proton and neutron data collected in Hall-B will be combined to get to the single flavor CFF

$$(H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]$$

$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

$\mathcal{H}_u, \mathcal{H}_d, \mathcal{E}_u$ and \mathcal{E}_d will provide the final ingredients entering the J_i 's relation



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

- Our knowledge of the nucleon structure has become richer in the last years thanks to GPD formalism and the experimental results of DVCS
- **combined measurement of several DVCS observables** in a vast kinematic space *to* disentangle the contributions of the various GPDs and their complex kinematic dependences
- Extracting both proton and neutron data is paramount if we want to ultimately perform a flavor decomposition of the GPDs
- Such a flavor separation is critical to access the elementary degrees of freedom of QCD and to connect them to macroscopic hadron properties such as mass or orbital angular momentum

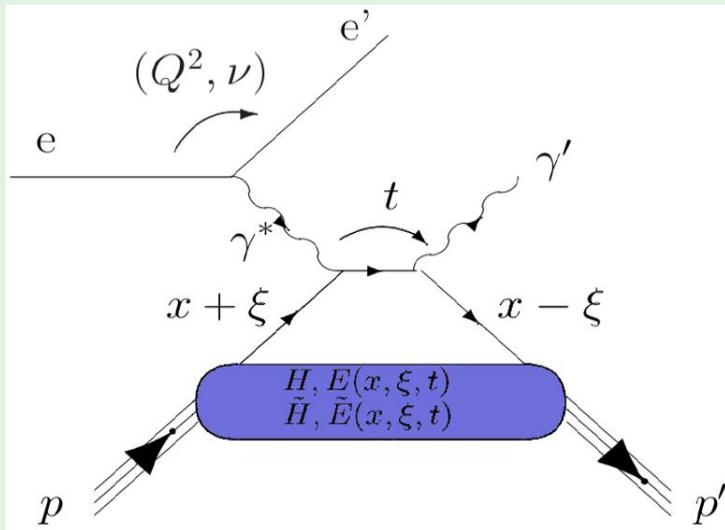
It is important to comment on practical aspects of the experiment. First of all, from the cross section, one finds that E and H can be measured either in unpolarized scattering, or in electron single-spin asymmetry through interference with the Bethe-Heitler amplitude [12], or in polarized electron scattering on a transversely polarized target. A detailed examination of various possibilities, together with some numerical estimates will be published elsewhere [13]. Second, the DVCS cross section is down by an order of α_{em} compared with the deep-inelastic cross section, but has the same scaling behavior. So the cross section is appreciable, but statistics would be a challenging requirement. The ideal accelerator for the experiment is ~~ELFE~~ [14]. Finally, the extrapolation of Δ^2 from order M^2 to 0 requires an extensive study of the form factors of the tensor \langle

X. Ji Phys. Rev. Lett. 78 (1997) 610

JLab

backup

Generalized Parton Distributions through DVCS & DVMP



Hall-A: feasibility test at JLab kinematics & handbag description

PRL97: 262002 (2006), C. Munoz Camacho et al. (Hall A collaboration), E12-06-114

Hall-B: Pioneering single-spin asymmetry observations

A_{LU}: S. Stepanyan et al., Phys. Rev. Lett. 87, 182002 (2001)

A_{UL}: S. Chen et al., Phys. Rev. Lett. 97, 072002 (2006)

Hall-B: DVCS & DVMP cross-section measurements in a large kinematic domain

*E01-113, H. Jo et al., soon to be published
I. Bedlinskiy et al., PRL109:112001 (2012)*

Hall-B: High-statistics extraction of Single- and Double Spin Asymmetries

A_{LU} for π⁰ on H₂: R. de Masi et al., PRC77:042201 (2008)

A_{LU} on H₂: PRL100: 162002 (2008) F.X. Girod et al., E12-06-119

DVCS & DVπ⁰P A_{LU}, A_{UL}, A_{LL} on NH₃: soon to be published

Hall-B Orbital Angular Momentum through GPDs

E12-12-010, A_{UT} on proton

E12-11-003, A_{LU} on neutron



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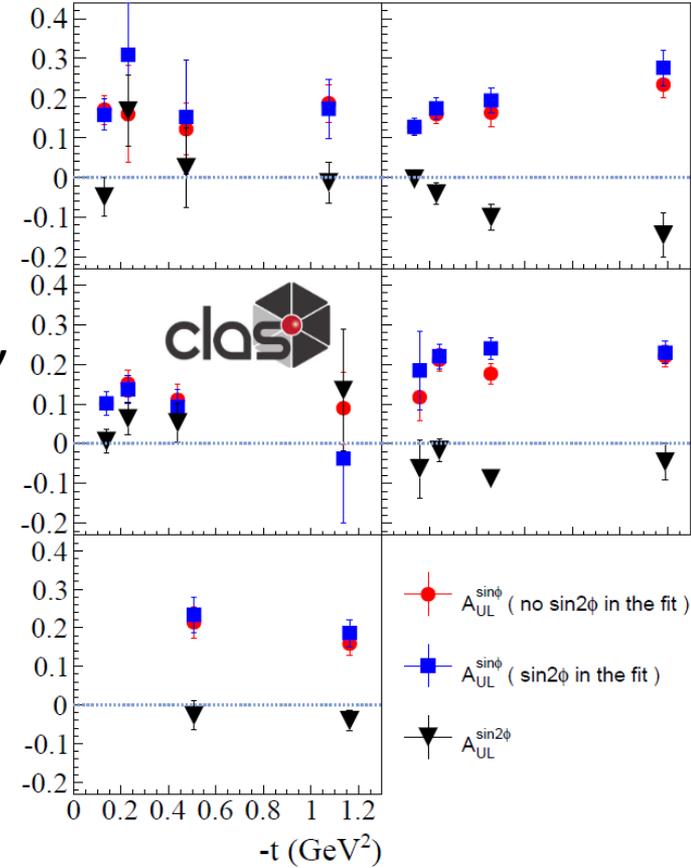
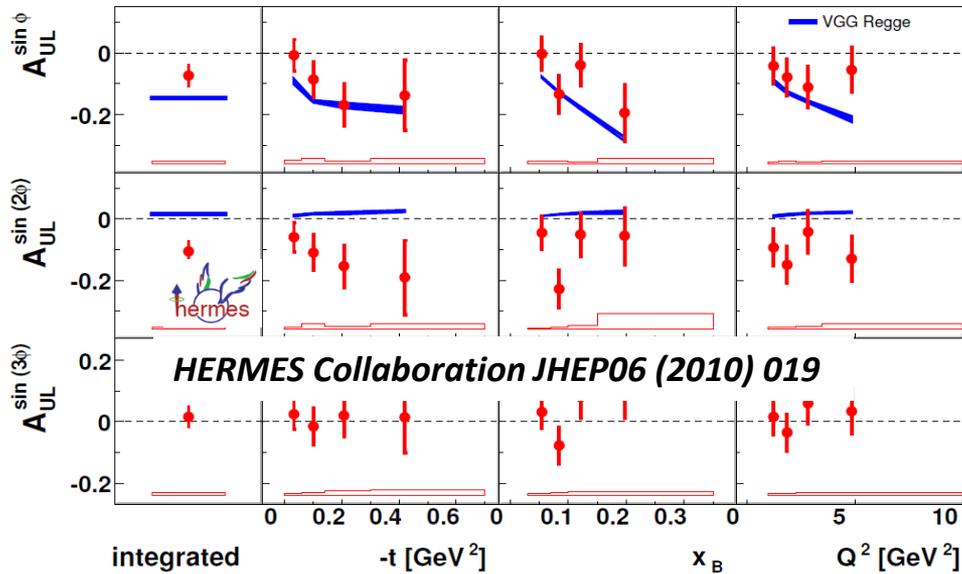


On the observability of the quark orbital angular momentum distribution

Aurore Courtoy^{a,b}, Gary R. Goldstein^c, J. Osvaldo Gonzalez Hernandez^d,
Simonetta Liuti^{e,b}, Abha Rajan^e



Higher-twist modulations of the **longitudinal Target-Spin Asymmetry** could provide access to the quark orbital angular momentum



red: S.P. et al, PRD 91 052014 (2015)
black: $\sin 2\phi$ CLAS preliminary

Different experiments (will) explore (-ed) different regions of the phase space

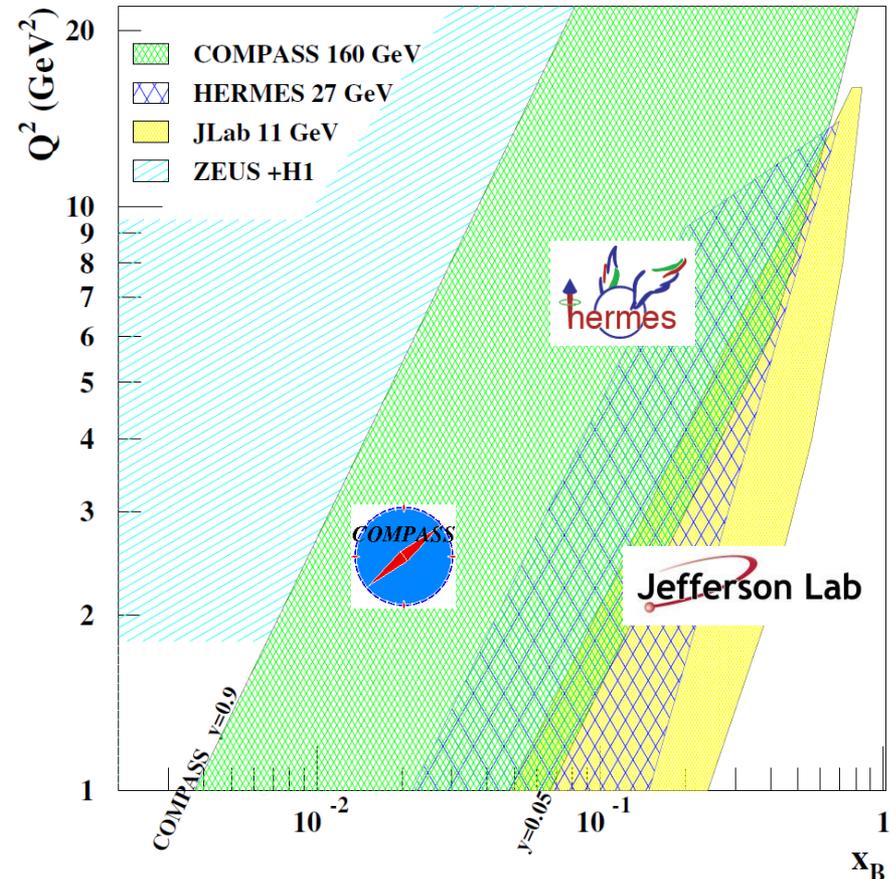
...ranging from the gluon-dominated domain of HERA to the quark valence region of JLab

Fixed-target experiments in the past:

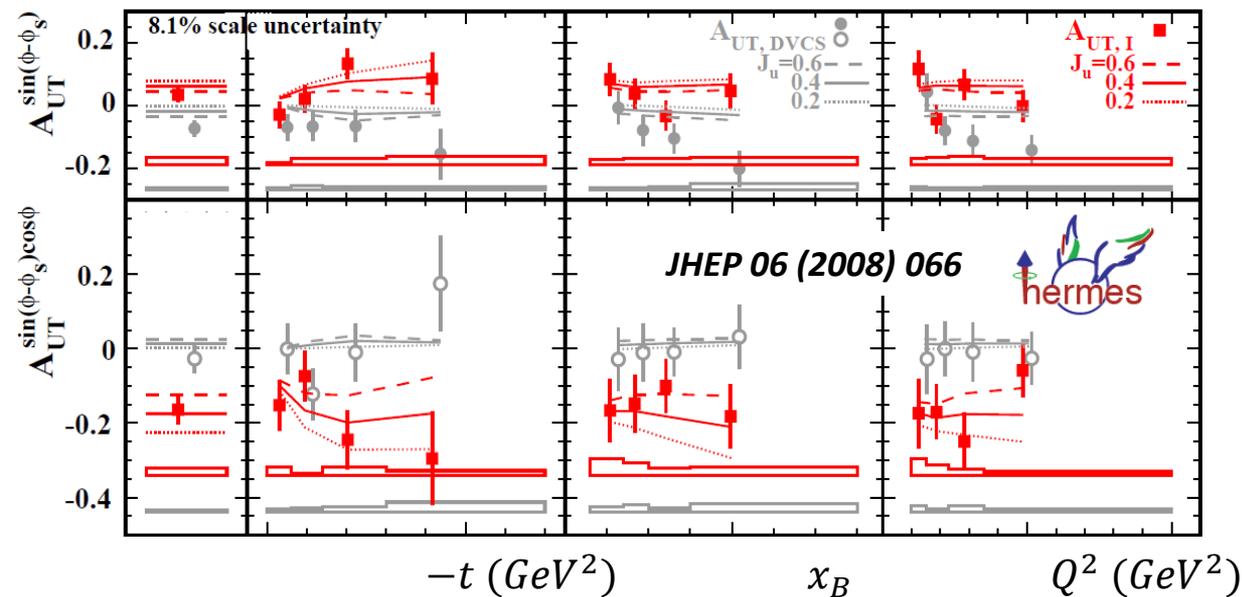
- HERMES@Desy: e^\pm beam ($E_e = 27\text{GeV}$)
- Hall-A, CLAS@JLab: e^- beam ($E_e = 6\text{GeV}$)

Future experiments:

- Hall-A, CLAS12@JLab12: e^- beam ($E_e = 12\text{GeV}$)
- COMPASSII@CERN: μ^\pm beam ($E_e = 160\text{GeV}$)



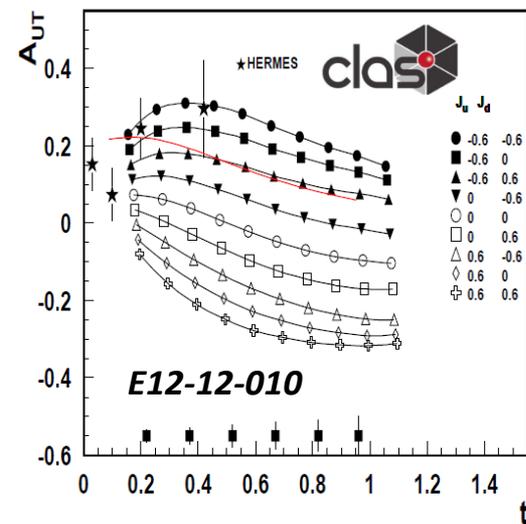
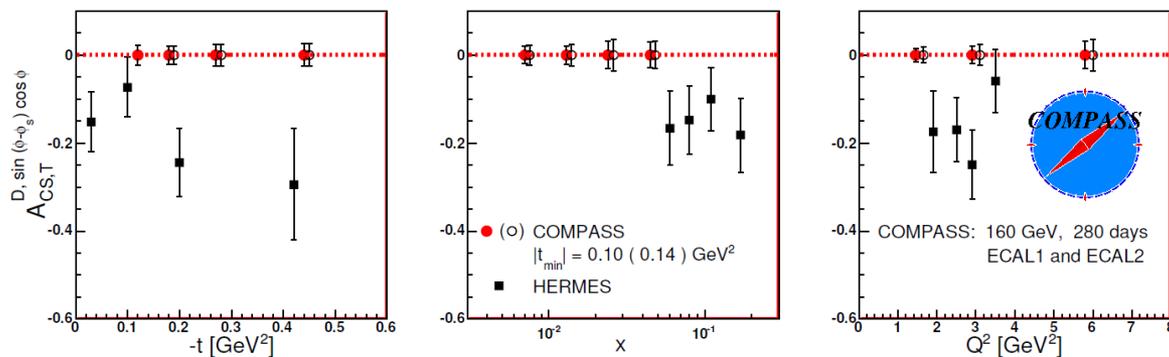
Exploring E_p in a wide kinematic range



Coefficient accessible through A_{UT} modulations sensitive to E_p

→ observed significantly non-zero @HERMES

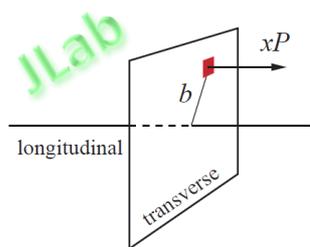
Different J_u values tested (with $J_d = 0$)



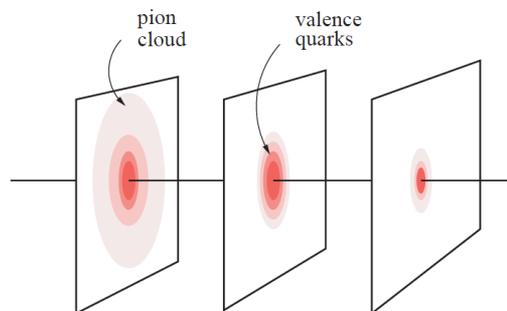
The distance $\langle r_{\perp}^2 \rangle$ between the struck quark and the spectator c.m. is given by the t -slope of the DVCS cross-section. Extracting it for different x_B values provides a tomographic picture of the nucleon, *i.e.* how its shape changes with x_B

$$\frac{d\sigma_0^{DVCS}}{dt} \propto \exp(-B(x_B)|t|)$$

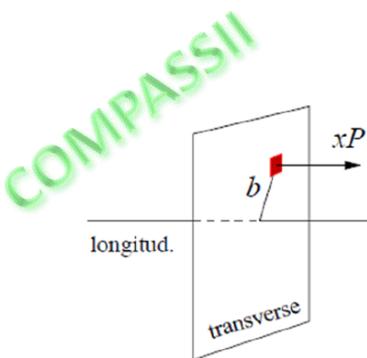
$$B(x_B) = B_0 + 2\alpha' \log\left(\frac{x_0}{x_B}\right)$$



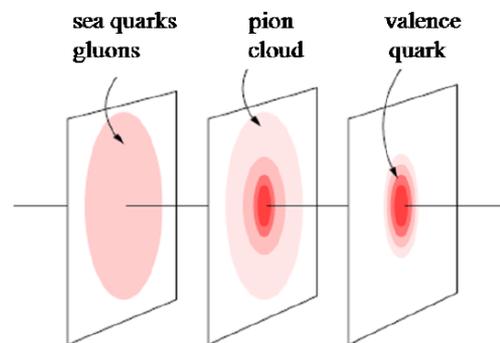
(a)



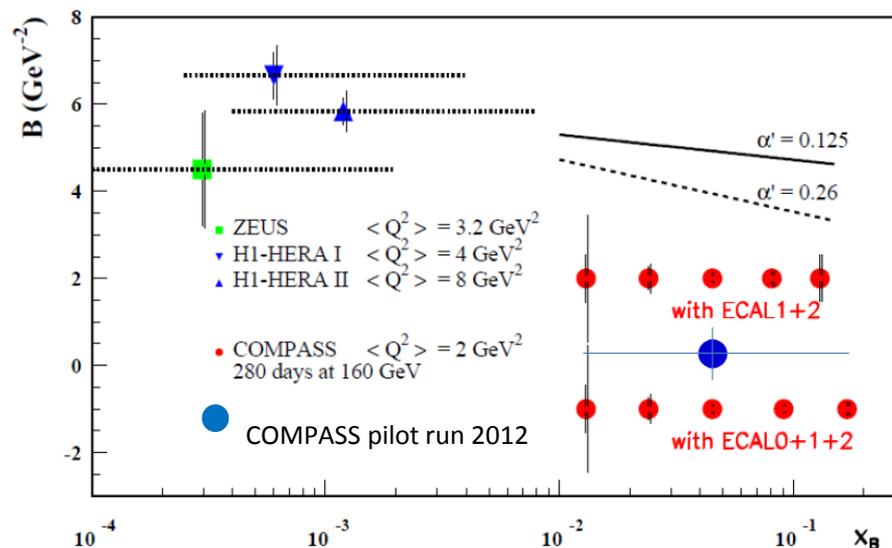
(b) $x < 0.1$ $x \sim 0.3$ $x \sim 0.8$



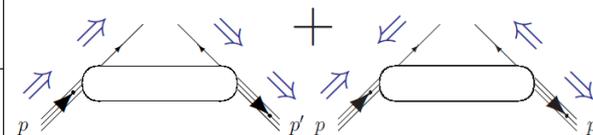
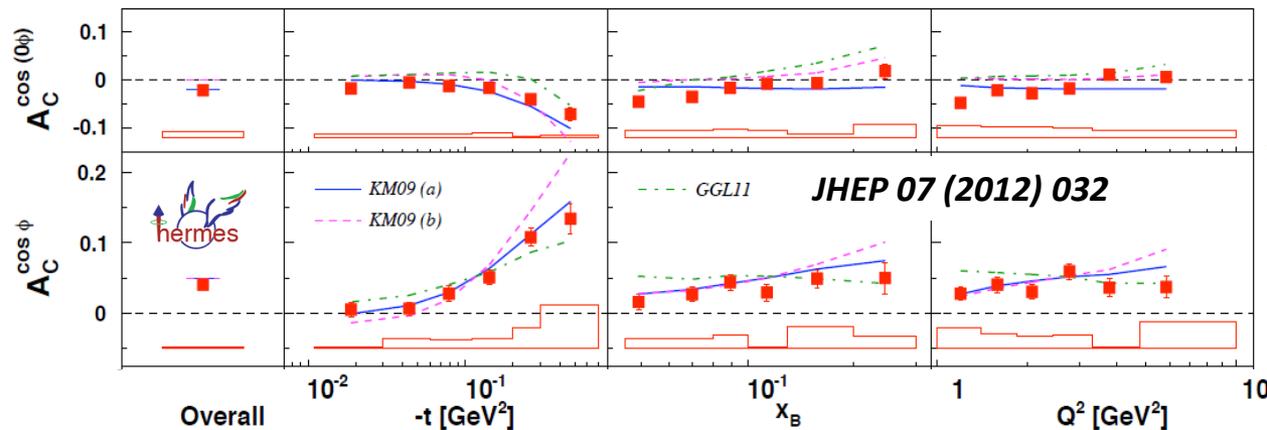
(a)



(b) $x \sim 0.003$ $x \sim 0.03$ $x \sim 0.3$



Mapping GPDs: Beam-charge asymmetries - \mathcal{H}_{Re}



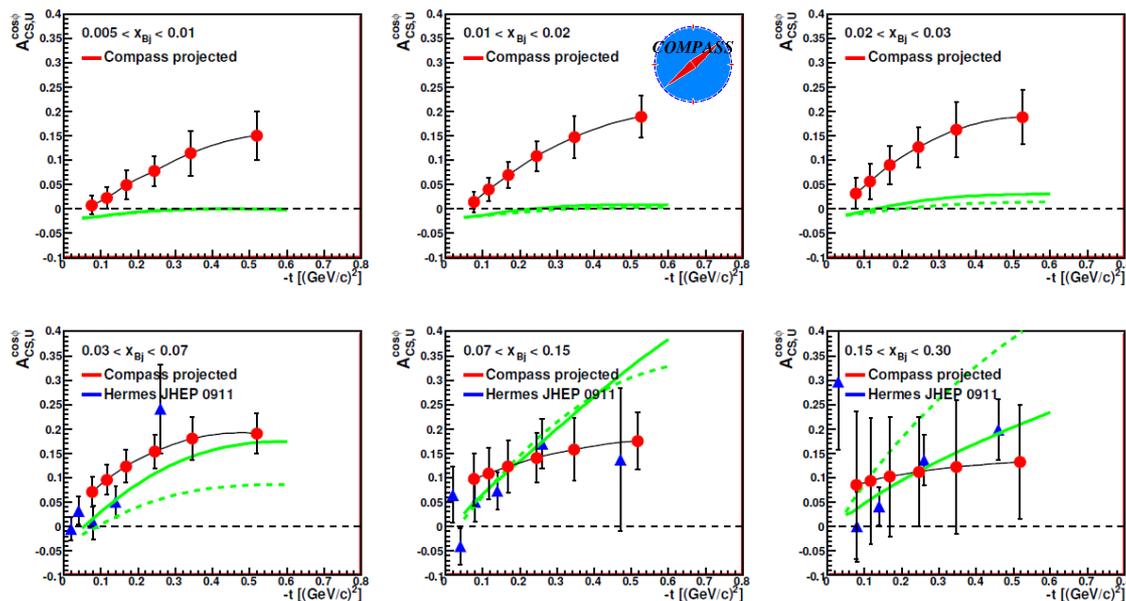
Different beam charge in COMPASS and HERMES provides access to the Beam-Charge Asymmetry \rightarrow mostly sensitive to the *real part* of \mathcal{H}

Asymmetry found significantly non zero in HERMES

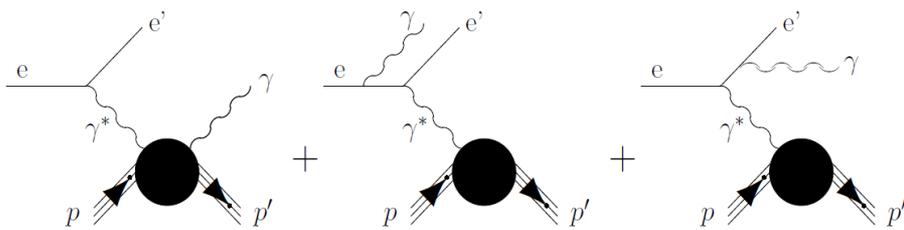
Strong dependence on $-t$

COMPASSII measurement will extend HERMES measurement to lower- x_B

--- Fits by Kumericki, Mueller



Two processes contribute to the same (e, p, γ) final state: Bethe-Heitler and Deeply-Virtual Compton Scattering.

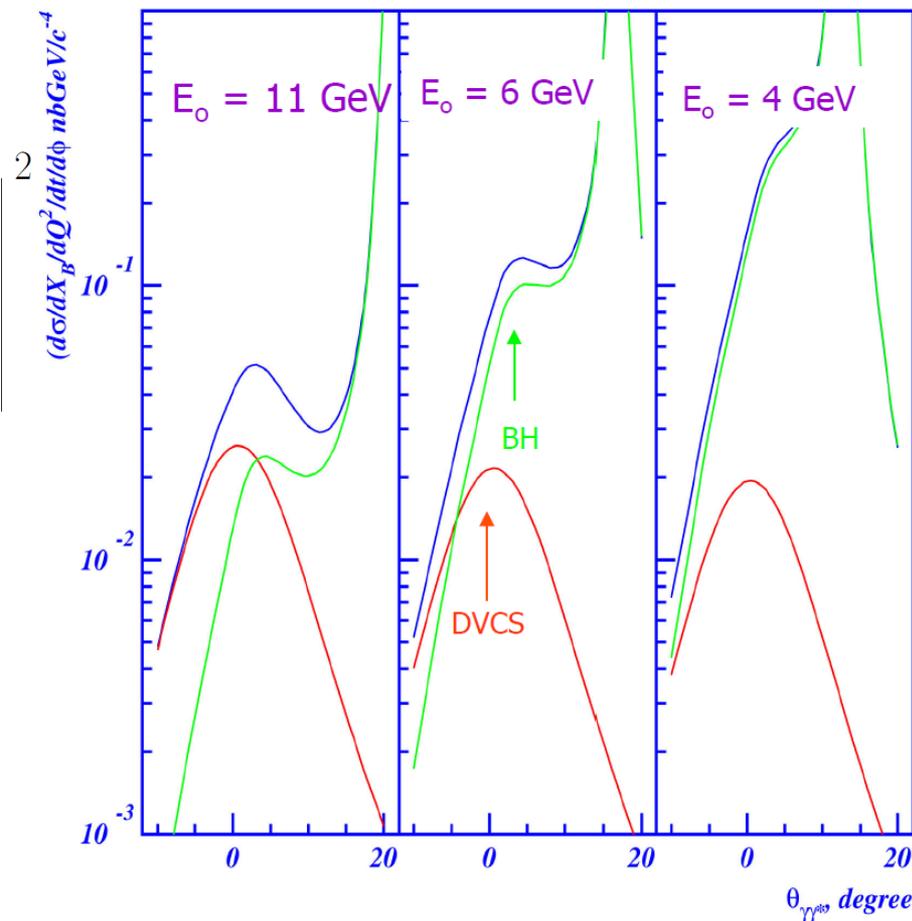


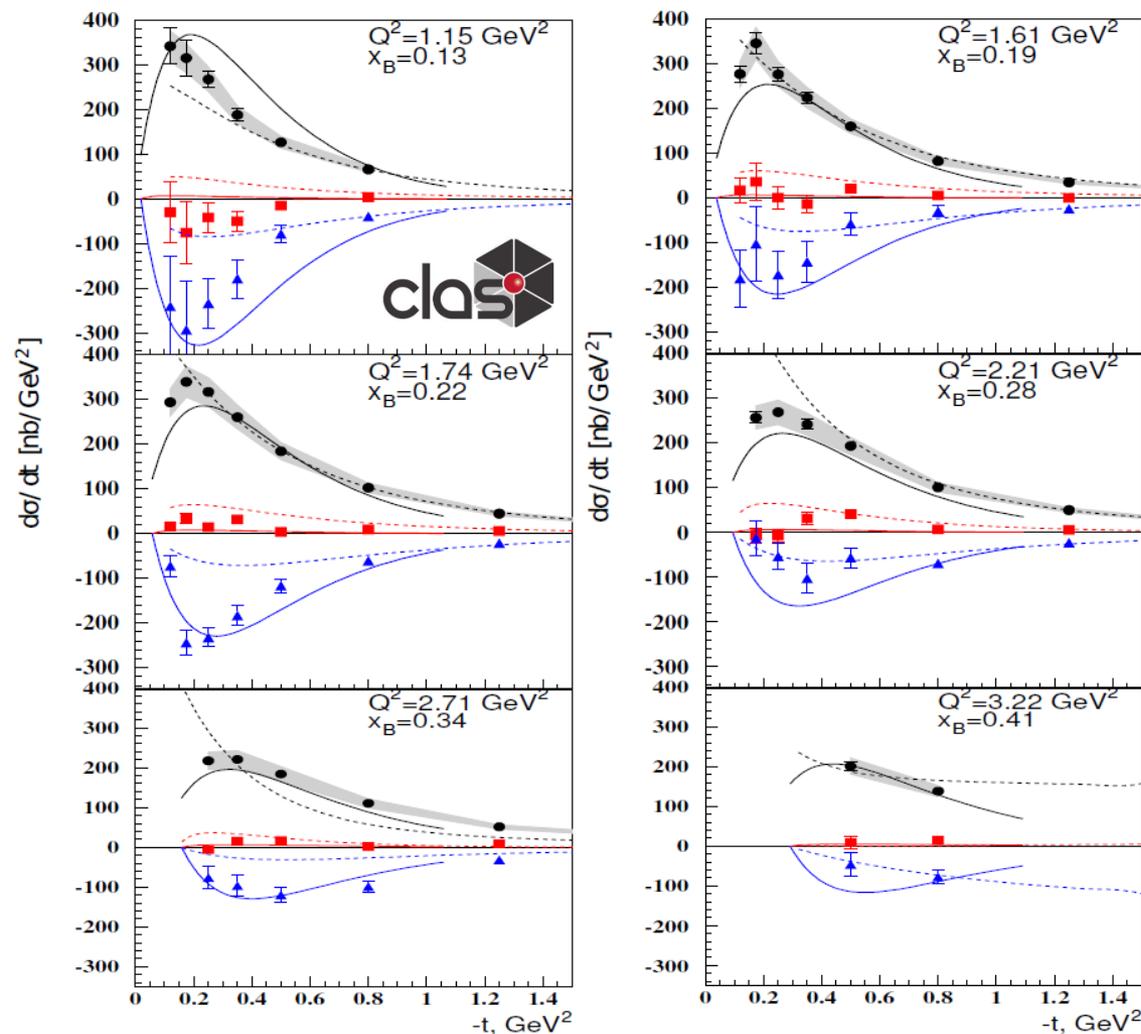
$$\sigma = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2$$



$I(BH \cdot DVCS)$ gives rise to spin asymmetries, which can be connected to combinations of GPDs

Cross section of $ep \rightarrow ep\gamma$ at $Q^2=2 \text{ GeV}/c^2$ and $X_B=0.35$





π^0 electroproduction \rightarrow sensitivity to *transversity* GPDs

$h_1(x)$ is related to the nucleon tensor charge \rightarrow possible test of beyond-SM interactions of the nucleon (effects on beta decay)

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E) \frac{1}{2\pi} (\sigma_T + \epsilon\sigma_L + \epsilon \cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_\pi \sigma_{LT}).$$

$$\sigma_T \sim (1 - \xi^2) |H_T|^2 - \frac{t'}{8m^2} |\bar{E}_T|^2$$

$$\sigma_{TT} \sim \frac{t'}{8m^2} |\bar{E}_T|^2$$

— $\sigma_0 = \sigma_T + \epsilon\sigma_L$
 — σ_{TT}
 — σ_{LT}

solid: P.Kroll & S.Goloskokov

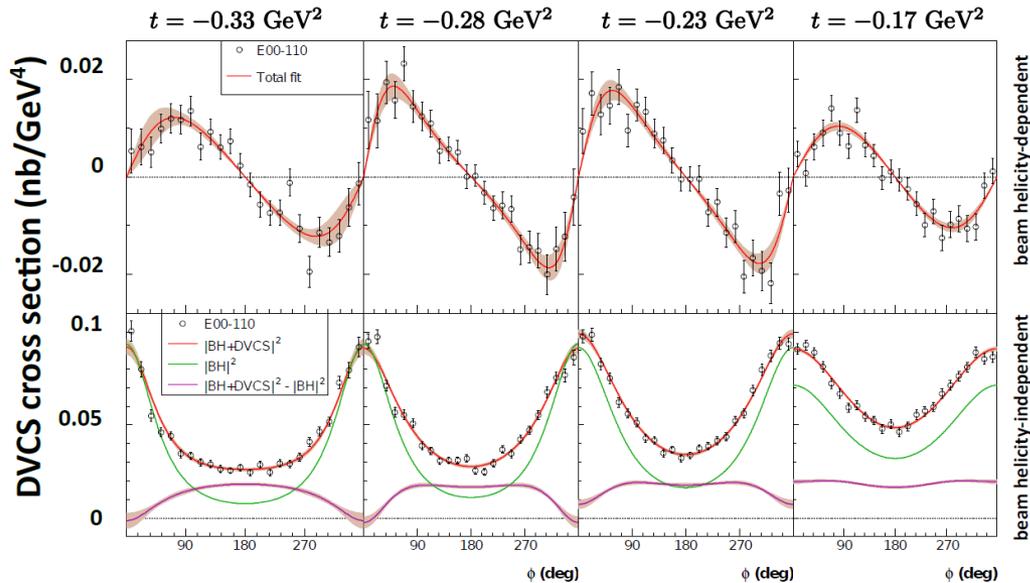
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

I. Bedlinskiy et al., PRL109:112001 (2012)

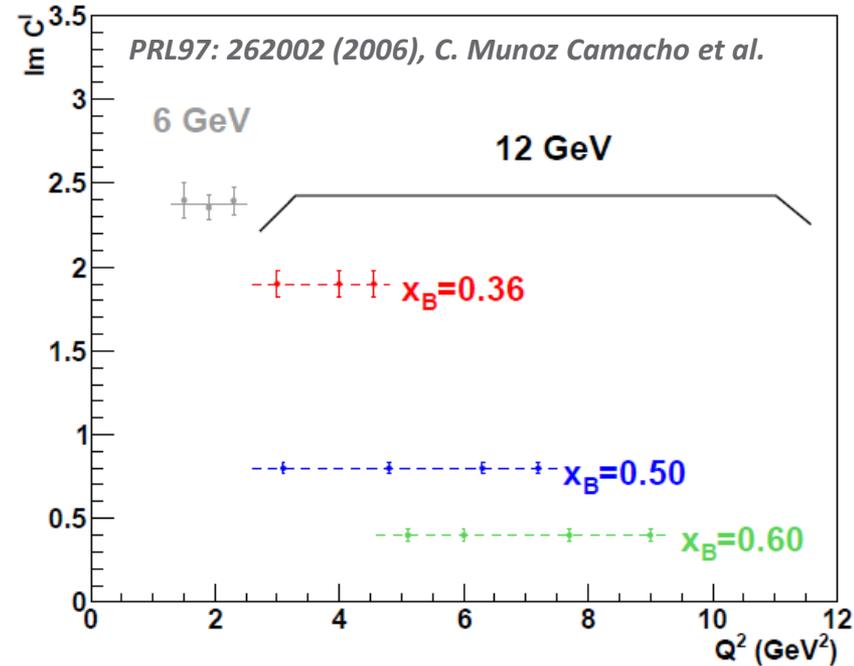
Test of the formalism: scaling in JLab/Hall-A (E00-110)



4-fold extraction at $x_B = 0.36$ of σ ($\langle Q^2 \rangle = 2.3 \text{ GeV}^2$) & $\sigma^+ - \sigma^-$ ($\langle Q^2 \rangle = 1.5, 1.9, 2.3 \text{ GeV}^2$) in 4 $-t$ bins



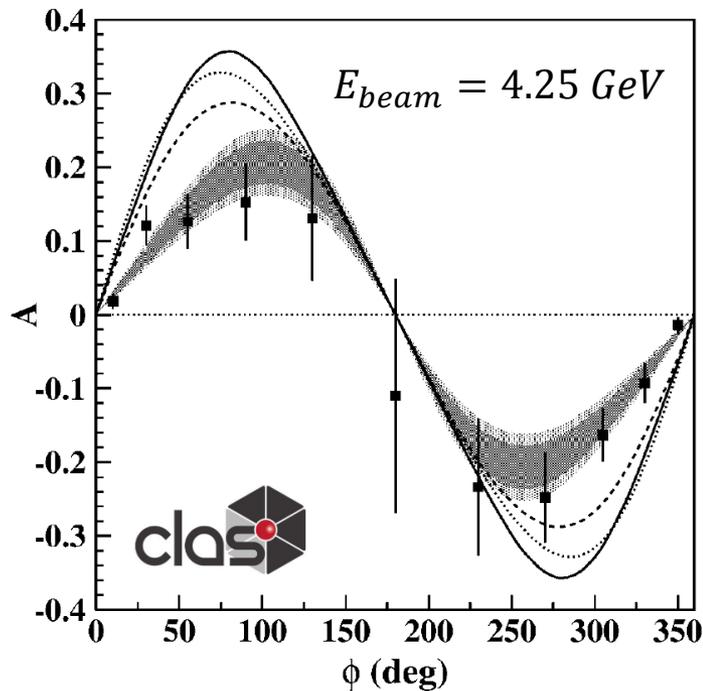
Significant deviation from pure BH \rightarrow DVCS contribution to the cross section not negligible



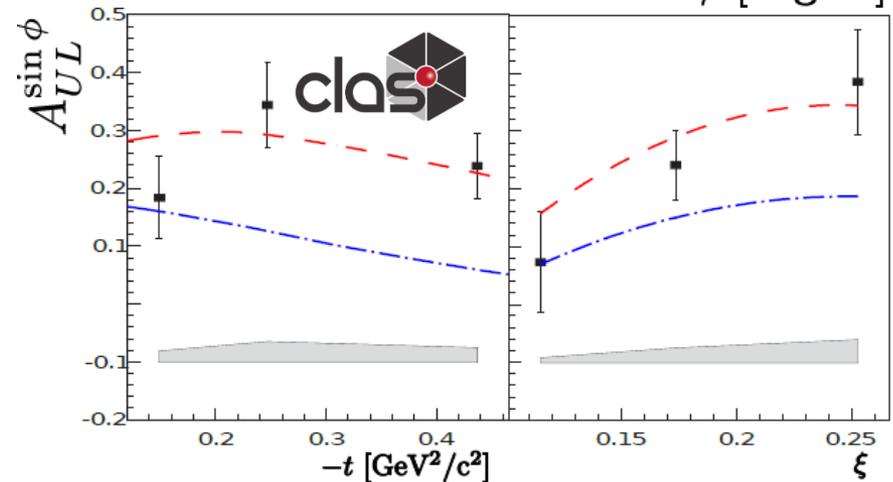
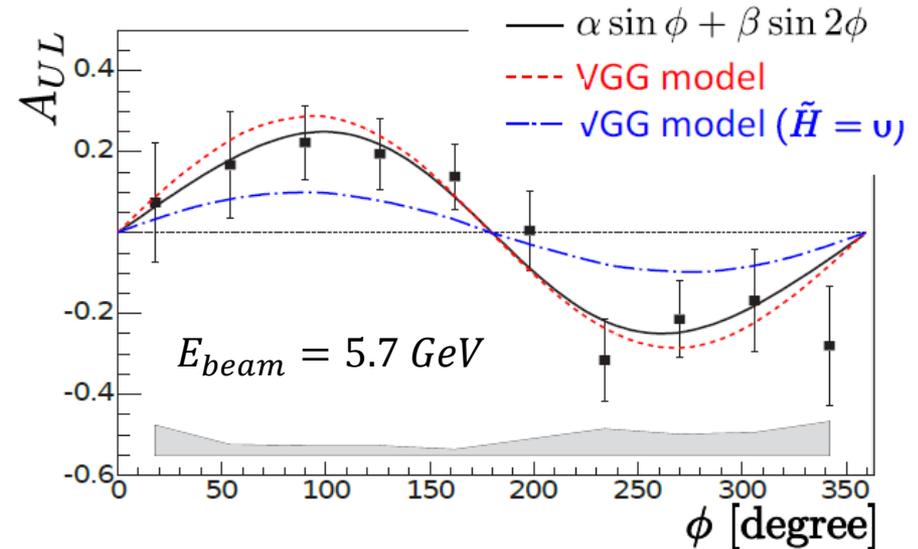
$\rightarrow \text{Im}(\mathcal{C}^I(\mathcal{F}))$ independent of Q^2 : no higher-order corrections enter \rightarrow **perturbative QCD scaling in DVCS**

Hall-B/CLAS: First observations of A_{LU} & A_{UL}

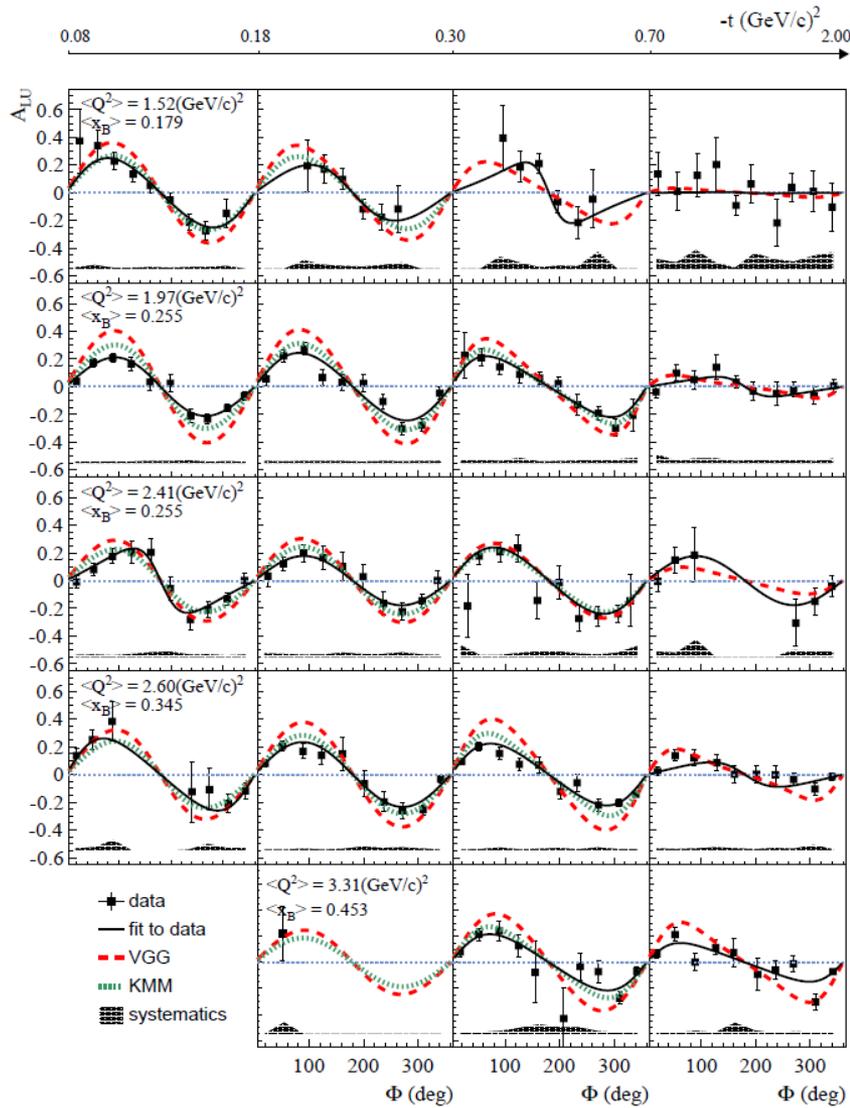
→ signal of the Bethe-Heitler and DVCS interference observed already at CLAS6 kinematics.



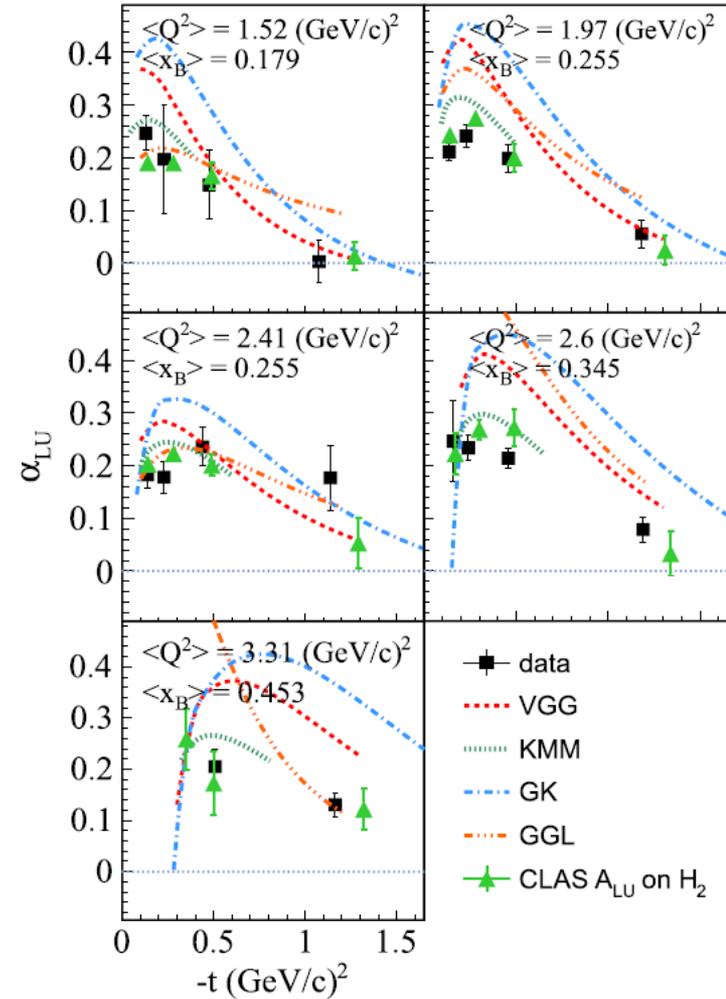
S. Stepanyan et al., Phys. Rev. Lett. 87, 182002 (2001).

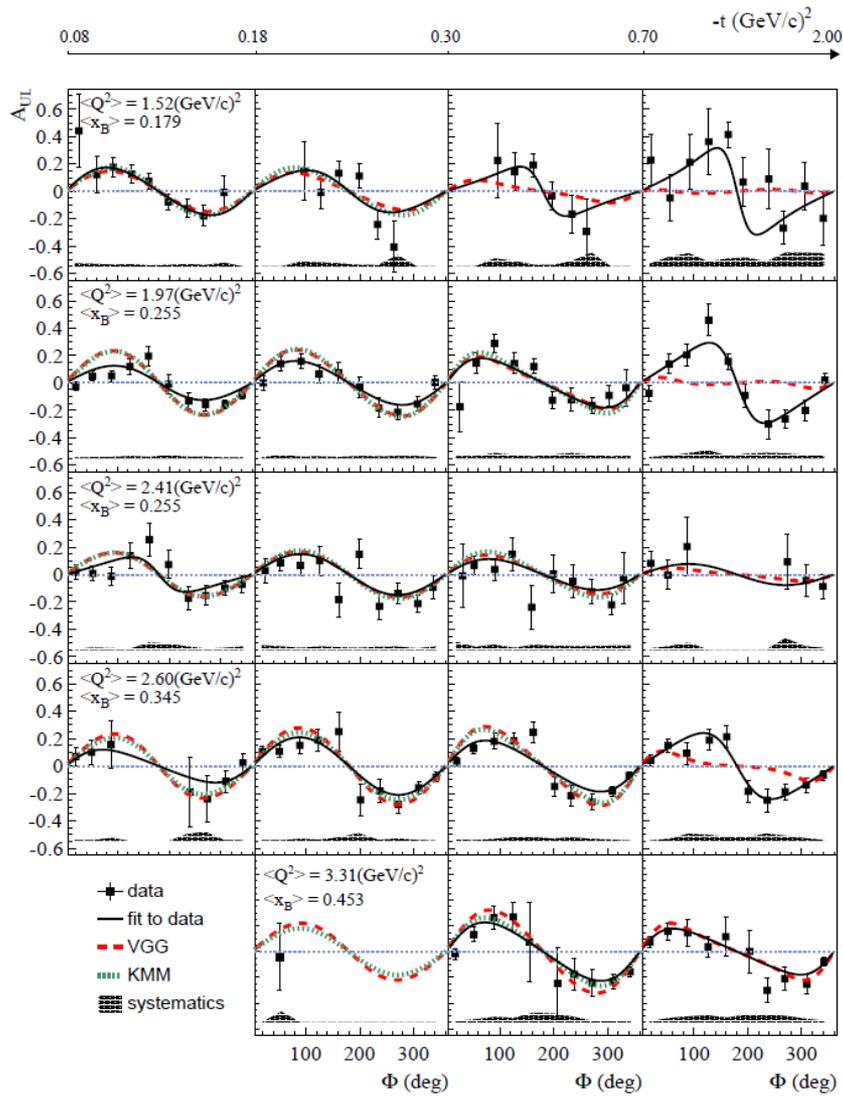


S. Chen et al., Phys. Rev. Lett. 97, 072002 (2006).

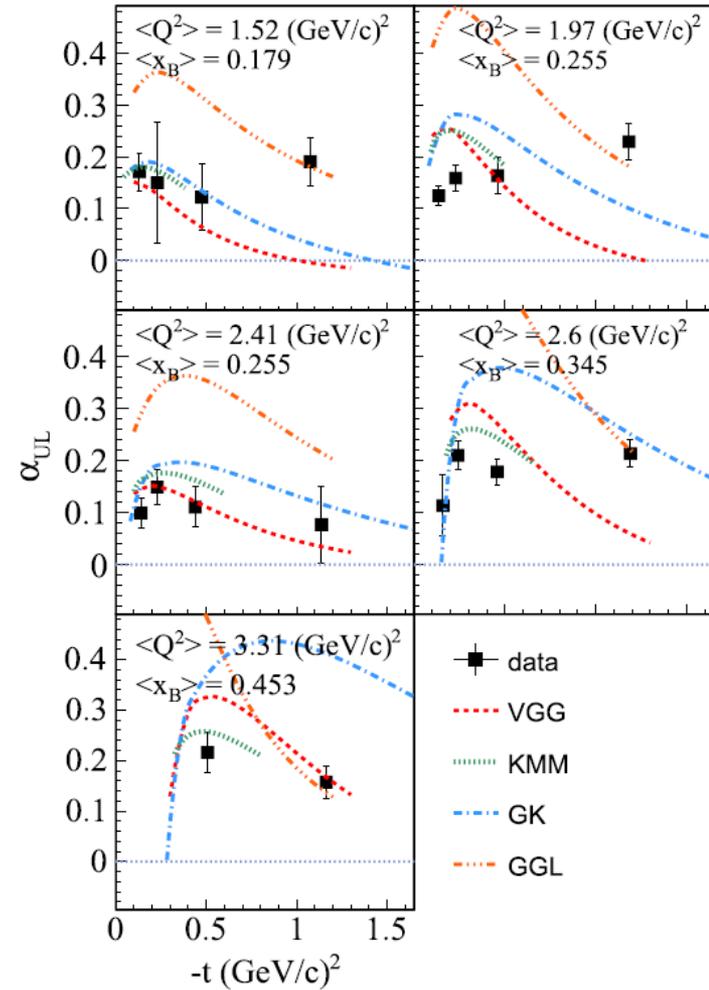


E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)

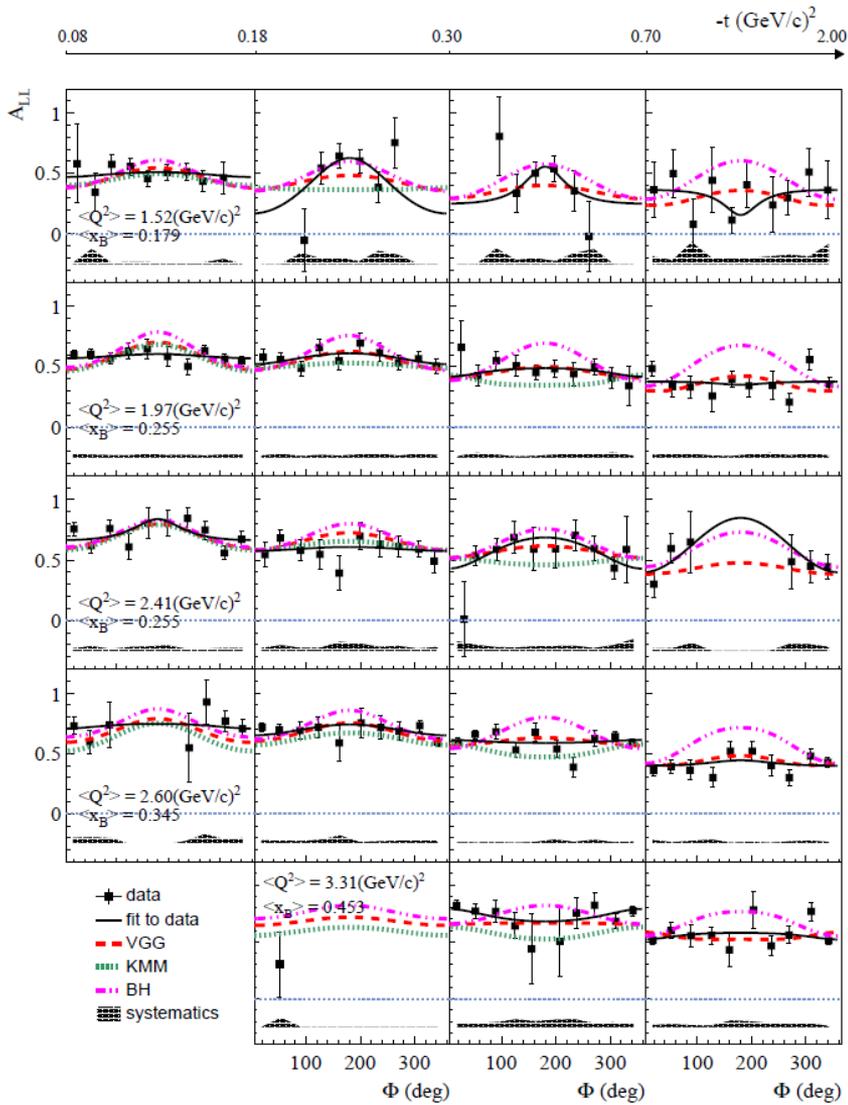




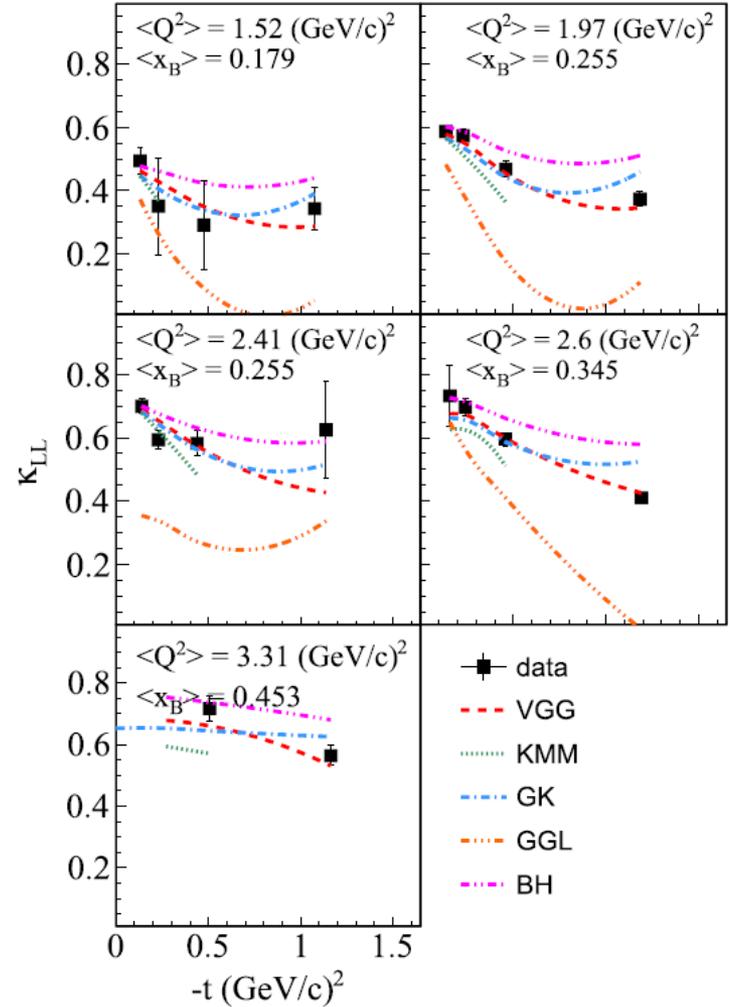
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)



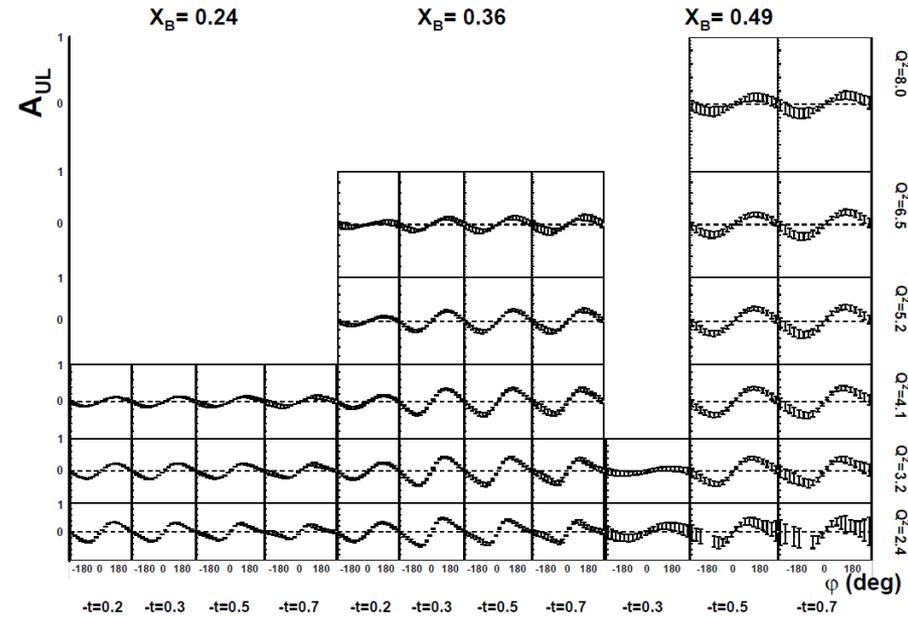
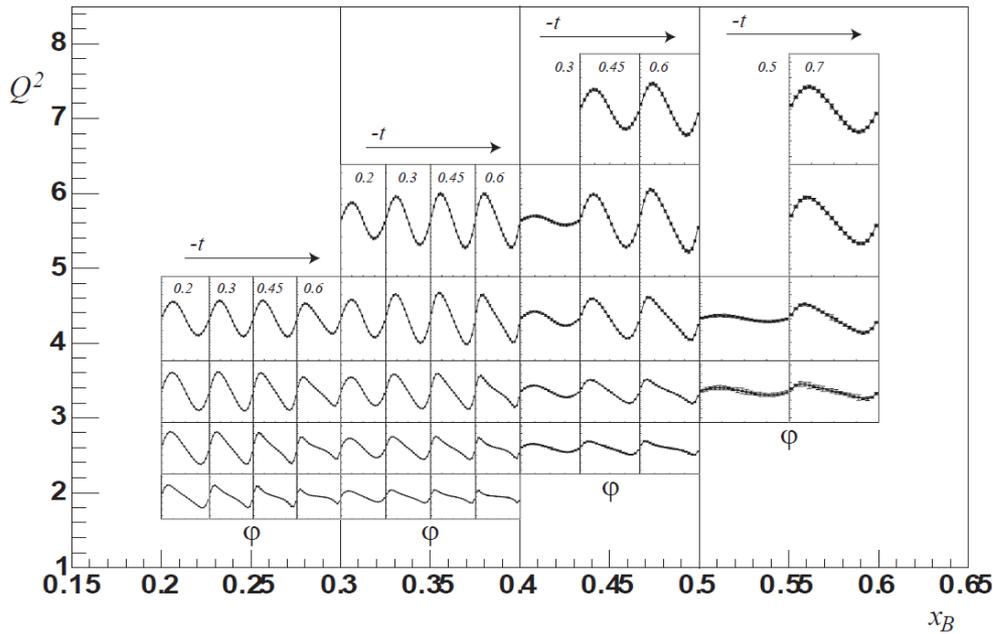
■ data
 - - - VGG
 KMM
 - · - GK
 - · - GGL



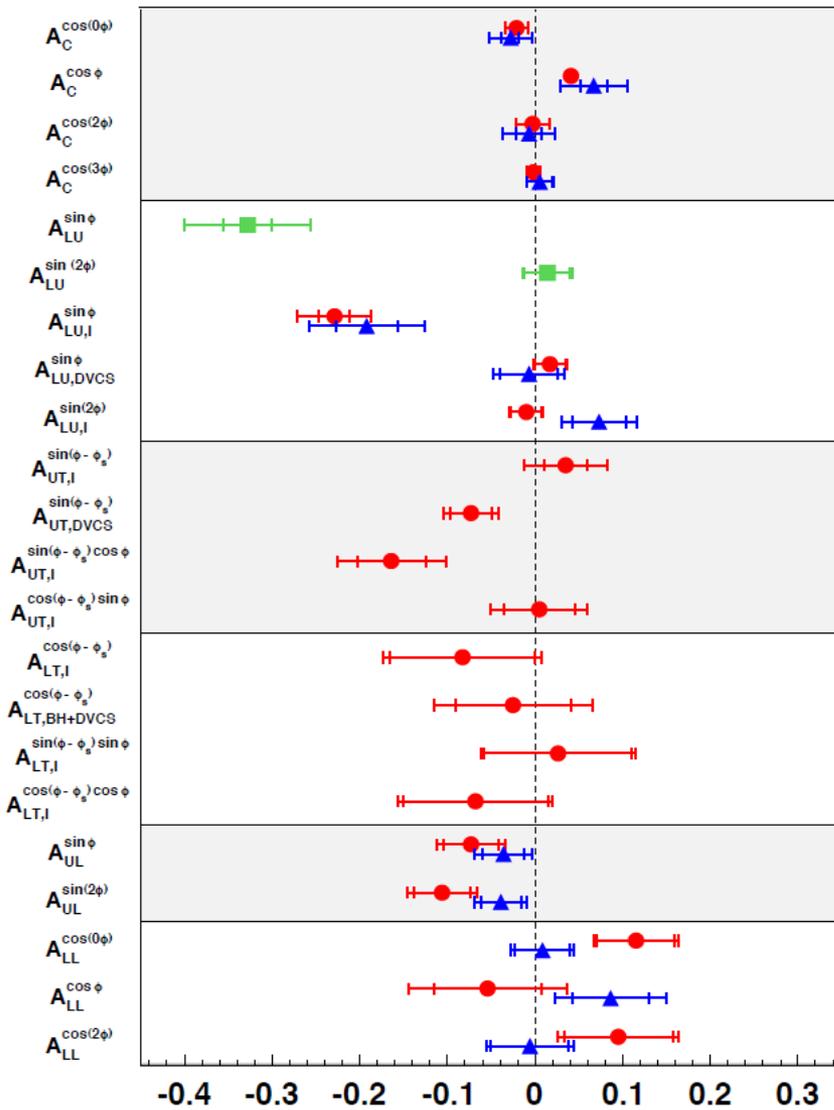
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)



$$\Delta\sigma_{LU} \propto \sin\varphi \operatorname{Im}\{F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} + kF_2\mathcal{E}\}d\varphi \quad \Delta\sigma_{UL} \propto \sin\varphi \operatorname{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)\mathcal{H} + kF_2\mathcal{E}\}d\varphi$$



HERMES measurements

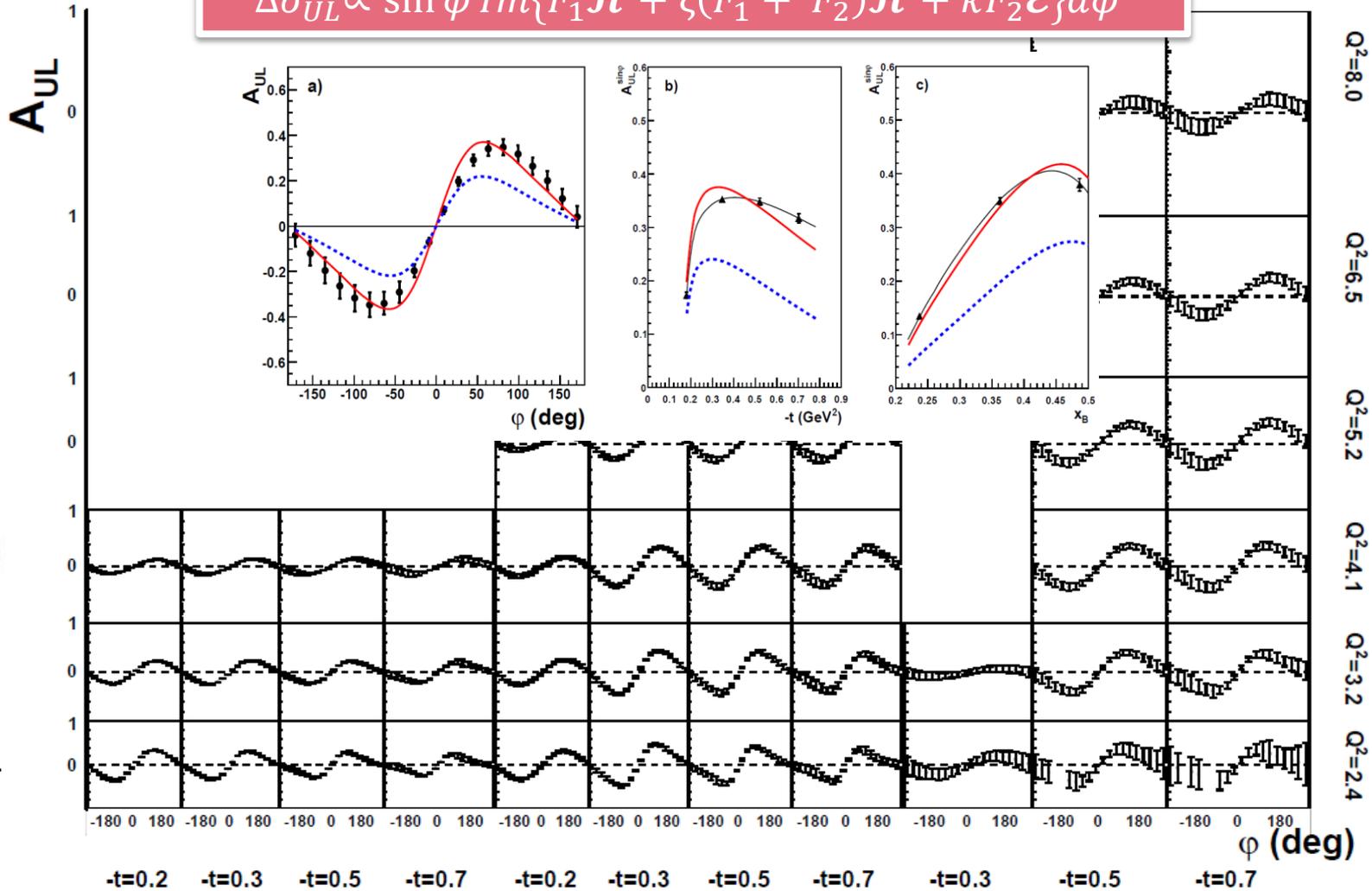


hydrogen
deuterium
hydrogen pure

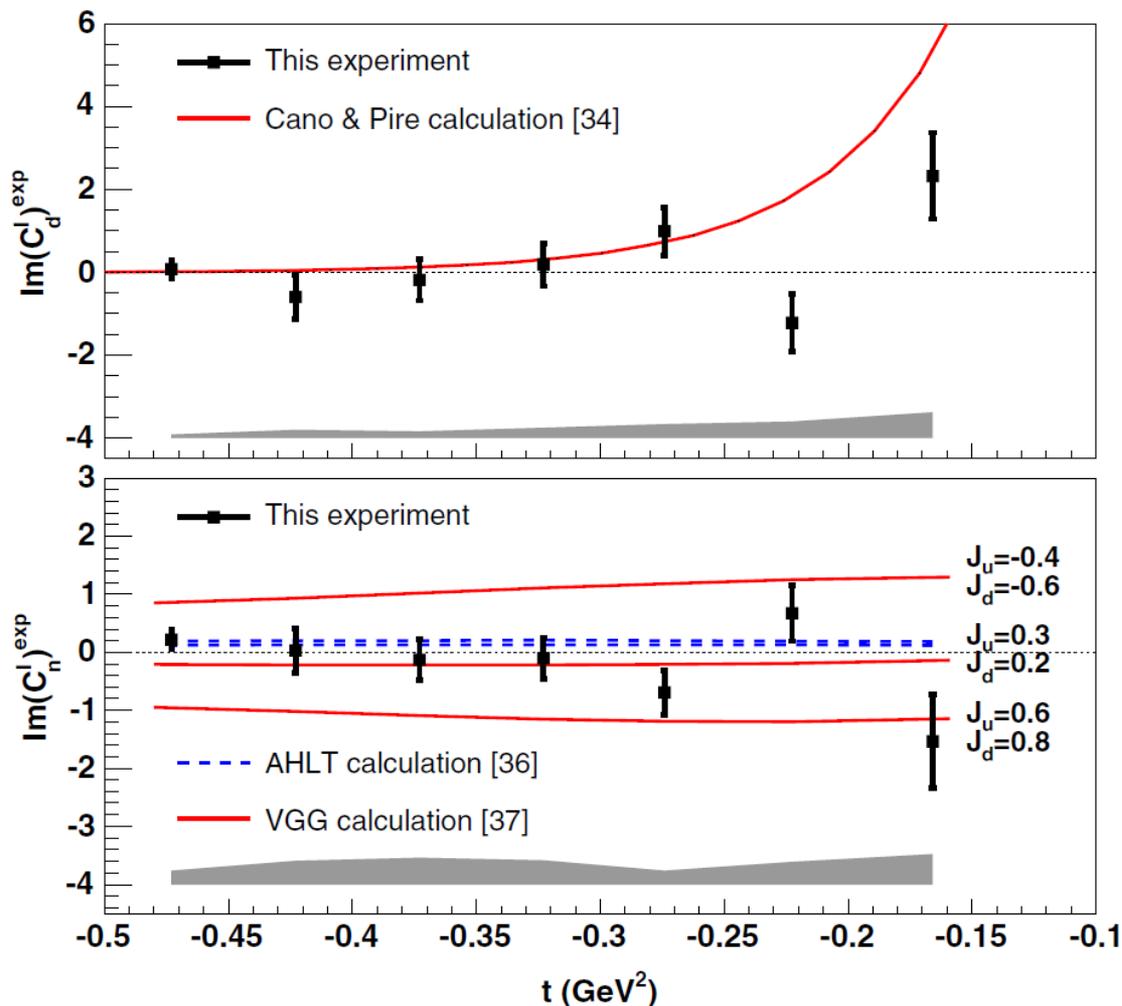
$$\Delta\sigma_{UL} \propto \sin\varphi \operatorname{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1 + F_2)\mathcal{H} + kF_2\mathcal{E}\}d\varphi$$



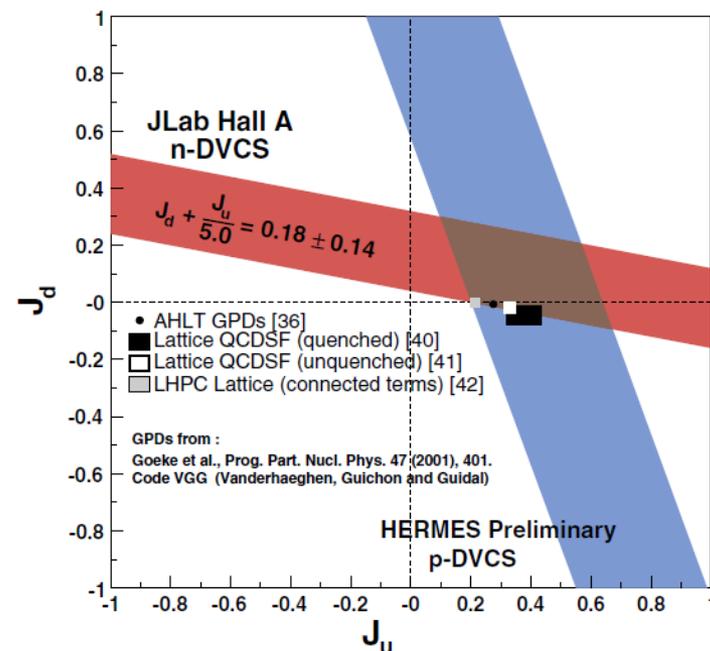
Dynamically-polarized NH_3 target



DVCS on the neutron in Hall-A - results



First experimental constraint on the parametrization of $E^q \rightarrow$ it is translated, within a model, in a constraint on the quark orbital angular momentum

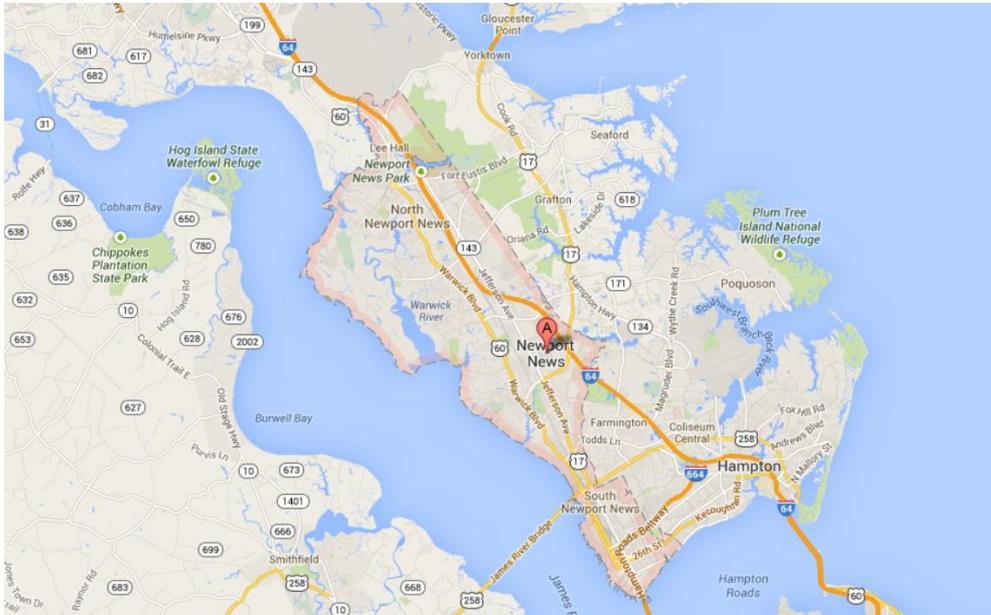


Thomas Jefferson National Accelerator Facility



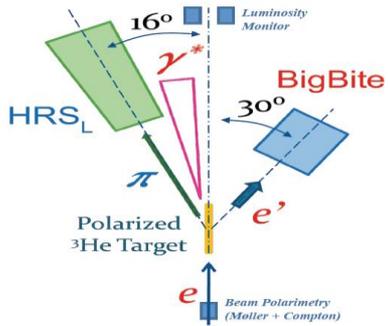
The **CEBAF (Continuous Electron Beams Accelerator Facility)** operates in the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA). The Cebaf:

- provides a continuous electron beam with a duty factor $\sim 100\%$;
- with a beam energy up to 6 GeV;
- has a good energy resolution ($\frac{\sigma_E}{E} \sim 10^{-5}$);
- and the beam has a polarization $\sim 85\%$

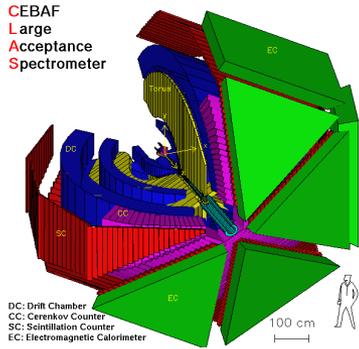


36

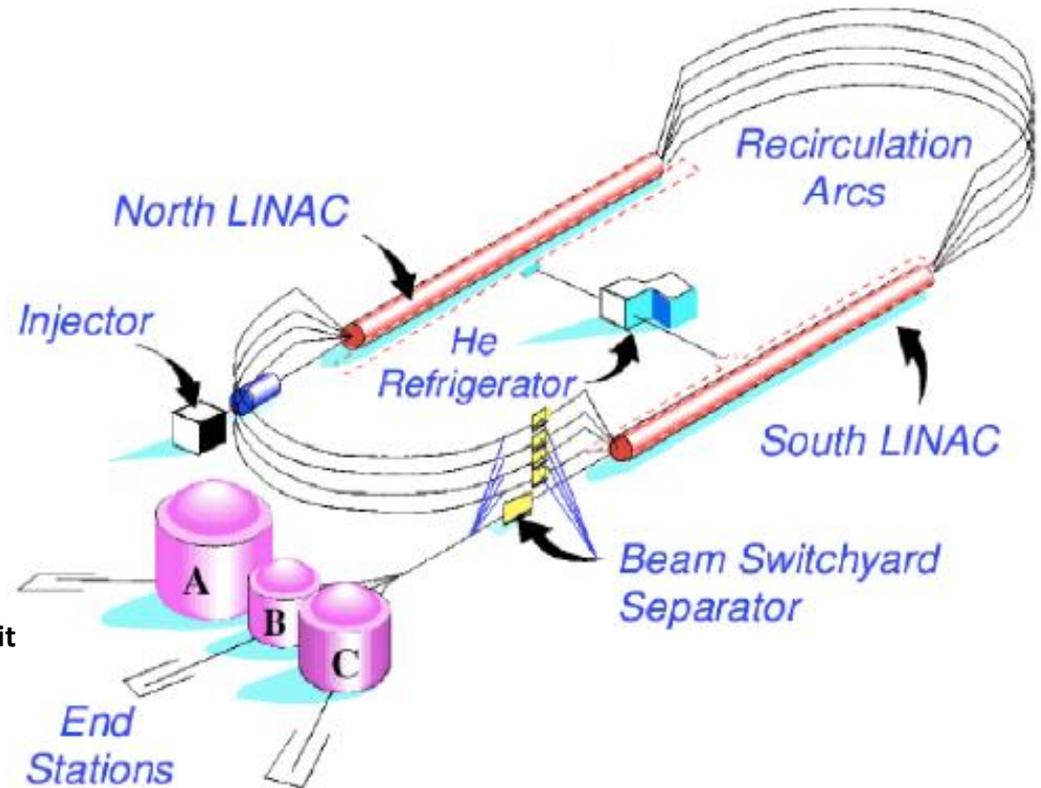
The three experimental Halls@JLab



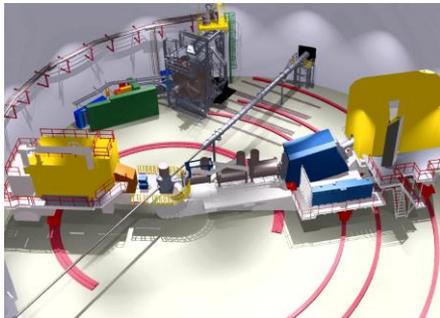
Hall-A: High-resolution spectrometers ($\delta p/p \sim 10^{-4}$), measurements with well-defined kinematics at very-high luminosity
NIM A 522, 294 (2004)



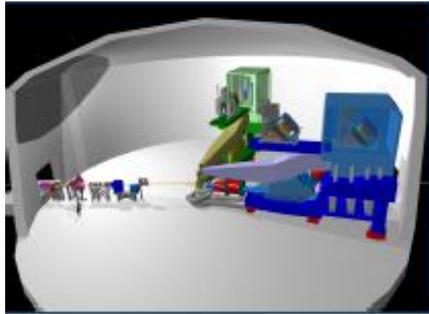
Hall-B: high luminosity, Large acceptance, Multi-particle final state measurements
NIM A 503, 513 (2003)



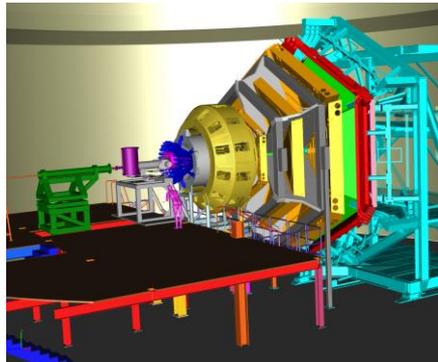
Hall C: High momentum spectrometer and Short Orbit Spectrometer—well-controlled acceptance for precise cross section measurements
PRC 78, 045202 (2008)



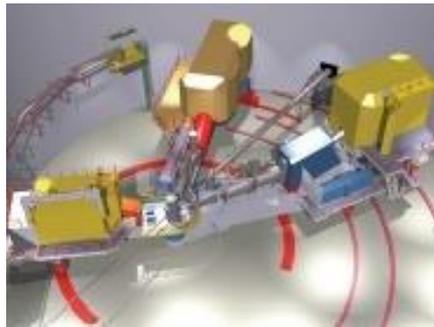
The 12-GeV upgrade



High Resolution Spectrometer (HRS) pair and specialized large installation experiments

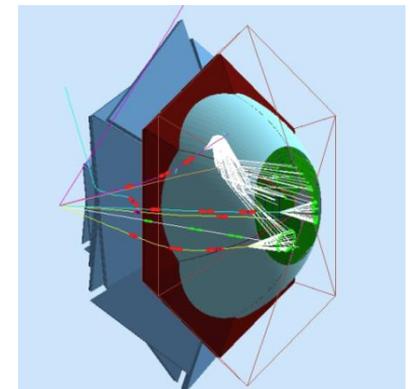
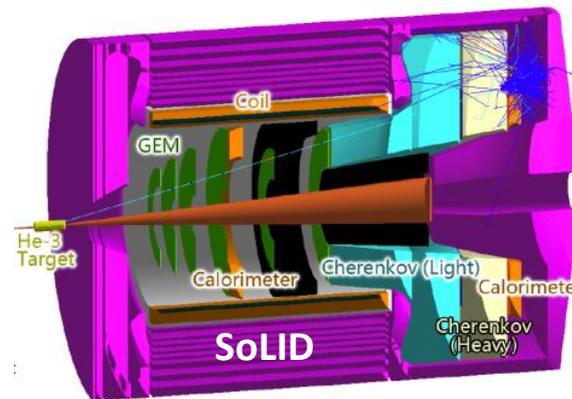
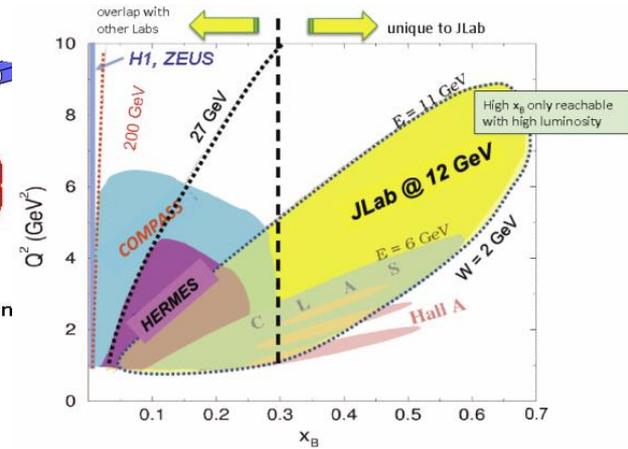
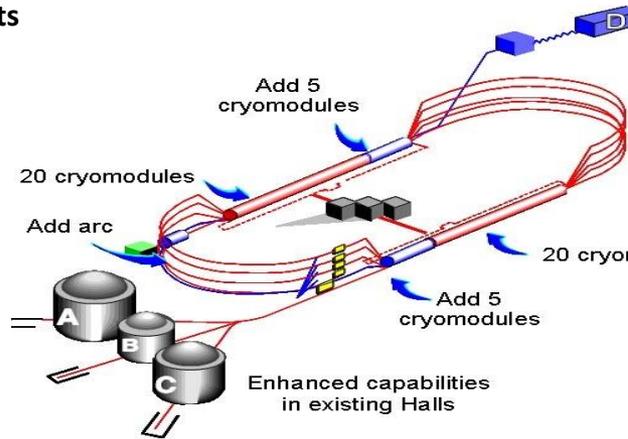


CLAS12: large acceptance, high luminosity

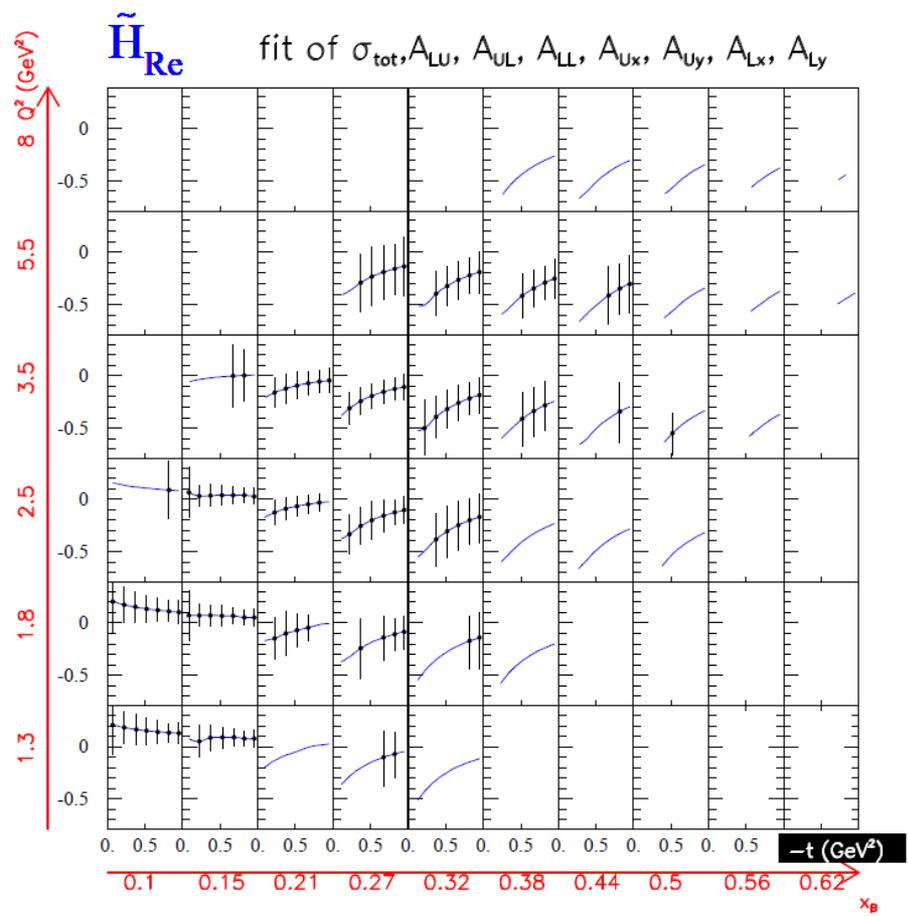
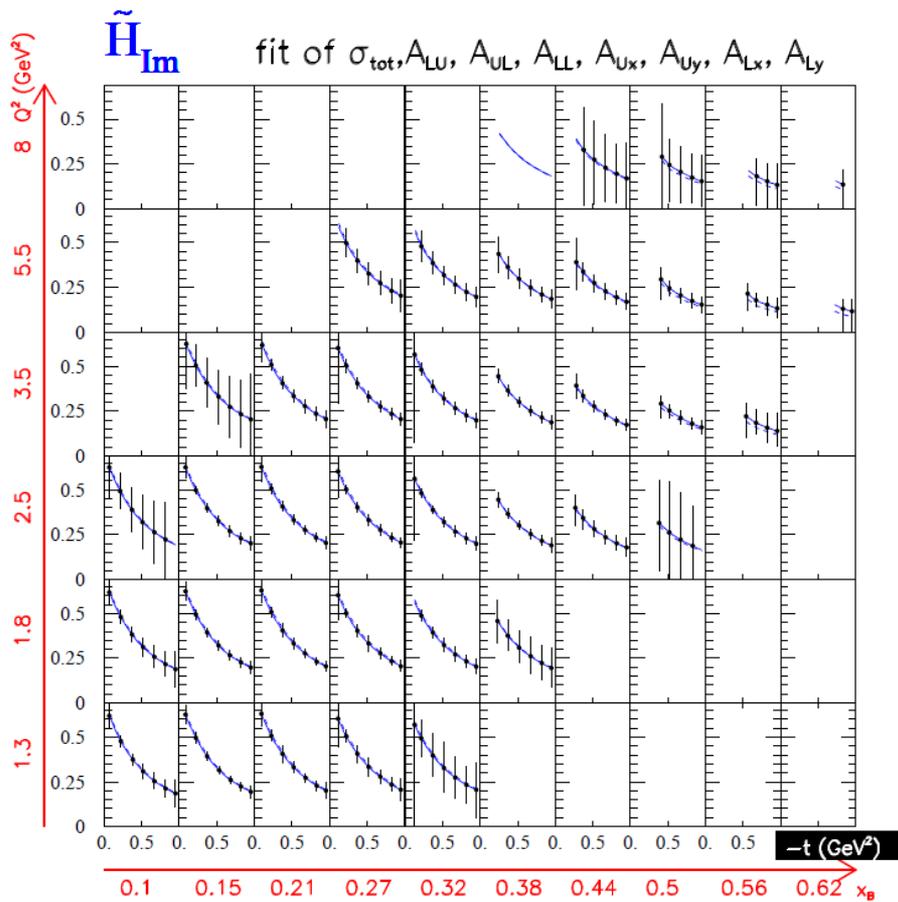


Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles

4 experimental halls with a longitudinally-polarized electron beam of E_{e^-} up to 12 GeV.



RICH for CLAS12



M. Guidal, H. Moutarde, M. Vanderhaeghen:
hep-ph > arXiv:1303.6600

***New measurement in Hall-A:
M. Defourne et al 1504.05453***

