GPDs in experiments

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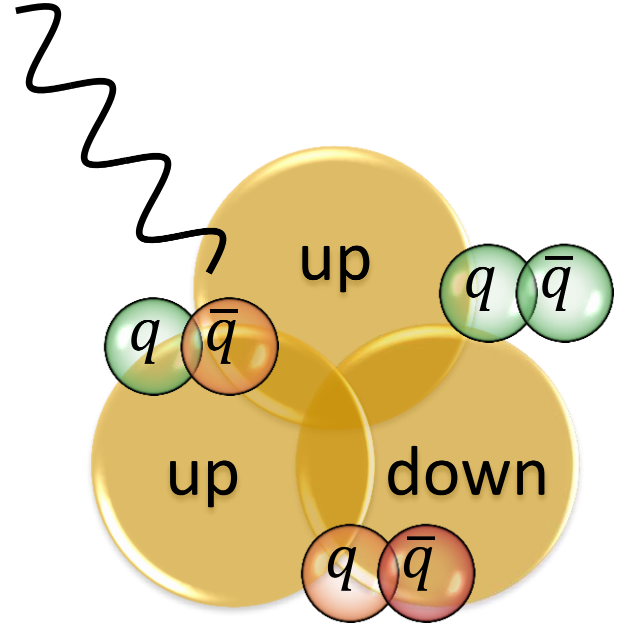
npQCD2015 – April 20th, 2015.

The interactions of the nucleon



The nucleon is sensitive to all the interactions known so far

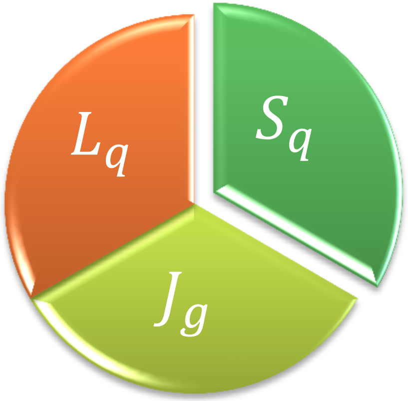
How the nucleon experiences a specific interactions is encoded in a ***charge*** → it depends on the nature of the operator describing the interaction

What is the spatial size of the nucleon?

And how its charges are distributed in its bulk?

What is the orbital angular momentum of the nucleon constituents?

And how its description relates to the full-QCD description encoded in lattice-based calculations?



GPDs & Deeply-Virtual Compton Scattering

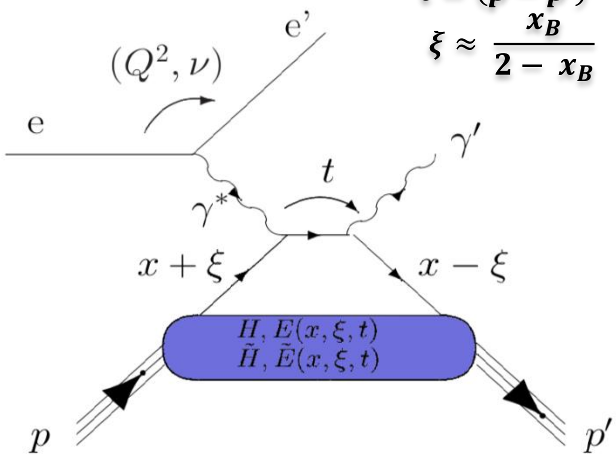
Generalized Parton Distributions → transverse spatial images of quarks and gluons as a function of their longitudinal momentum fraction.

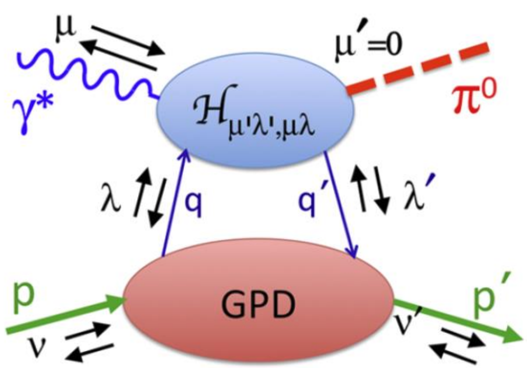
There are 4 *chiral-even* + 4 *chiral-odd* GPDs for any quark flavor

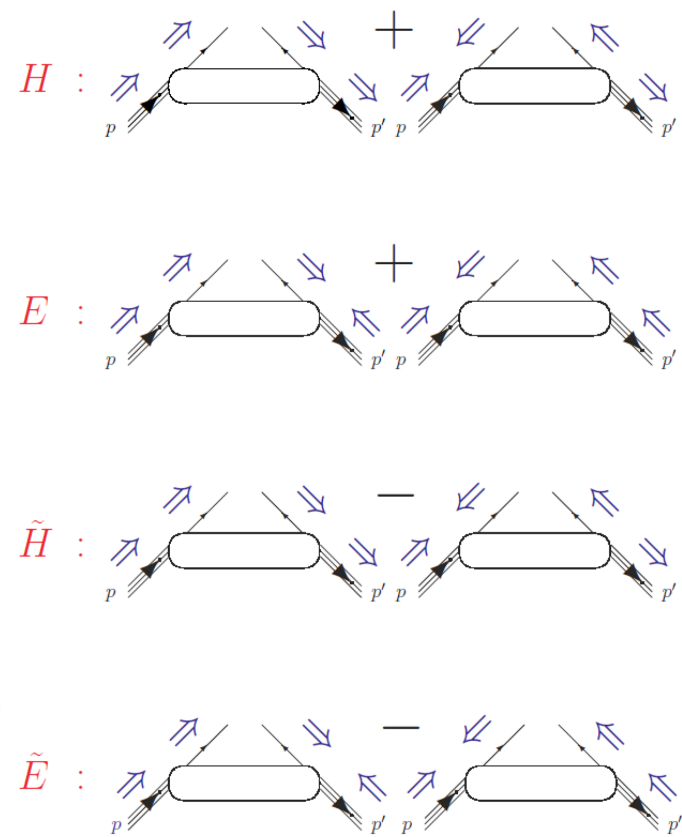
$\boldsymbol{x}$

$$t = (p - p')^2$$

$$\xi \approx \frac{x_B}{2 - x_B}$$







$$\boldsymbol{H^q(x,0,0) = f_1(x)}$$
$$\boldsymbol{\tilde{H}^q(x,0,0) = g_1(x)}$$
$$\boldsymbol{H_T{}^q(x,0,0) = h_1(x)}$$

(for x > 0; antiquark for x<0)

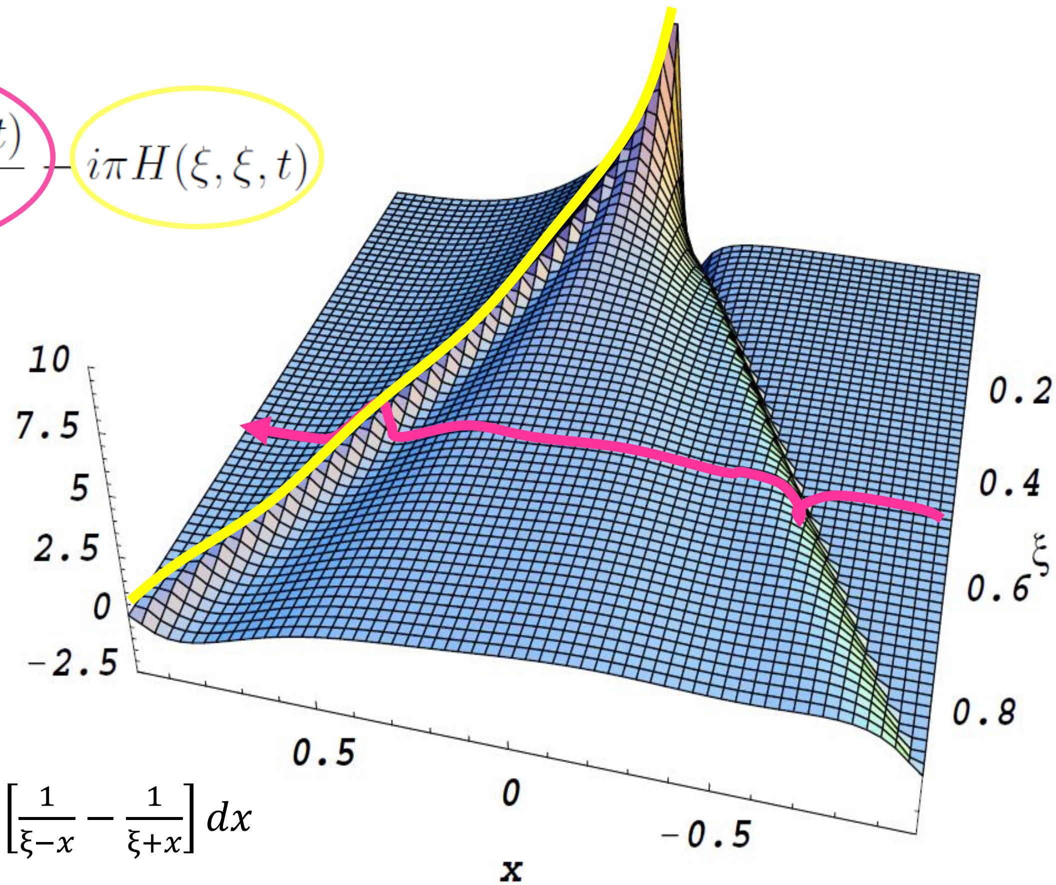
$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t)\,, \qquad \int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t)$$

$$\int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = G_A^q(t)\,, \qquad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = G_P^q(t)$$

Sensitivity to GPDs in observables - Compton Form Factors

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):

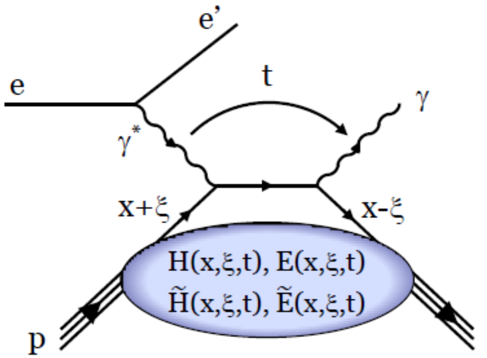
$$Re\mathcal{H}_q = e^2{}_q P\int_0^1 (H^q(x,\xi,t) - H^q(-x,\xi,t))\left[\frac{1}{\xi-x} - \frac{1}{\xi+x}\right]dx$$

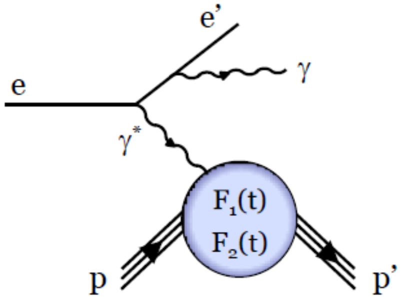
$$Im\mathcal{H}_q = \pi e^2{}_q (H^q(\xi,\xi,t) - H^q(-\xi,\xi,t))$$

see M. Guidal's talk on Tuesday

Accessing GPDs through DVCS observables

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





1. **Beam-Spin Asymmetry**:
   $$\Delta\sigma_{LU} \propto \sin\varphi \, Im\{F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} + kF_2\mathcal{E}\}d\varphi$$

2. **Target-Spin Asymmetry**:
   $$\Delta\sigma_{UL} \propto \sin\varphi \, Im\{F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)\mathcal{H} + kF_2\mathcal{E}\}d\varphi$$

3. **Double-Spin Asymmetry**:
   $$\Delta\sigma_{LL} \propto (A + B\cos\varphi) \, Re\left\{F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right)\right\} d\varphi$$

4. **Transverse Target-Spin Asymmetry**:
   $$\Delta\sigma_{UT} \propto \sin\varphi \, Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ \dots\}d\varphi$$

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

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*

Experiments and phase-space coverage

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

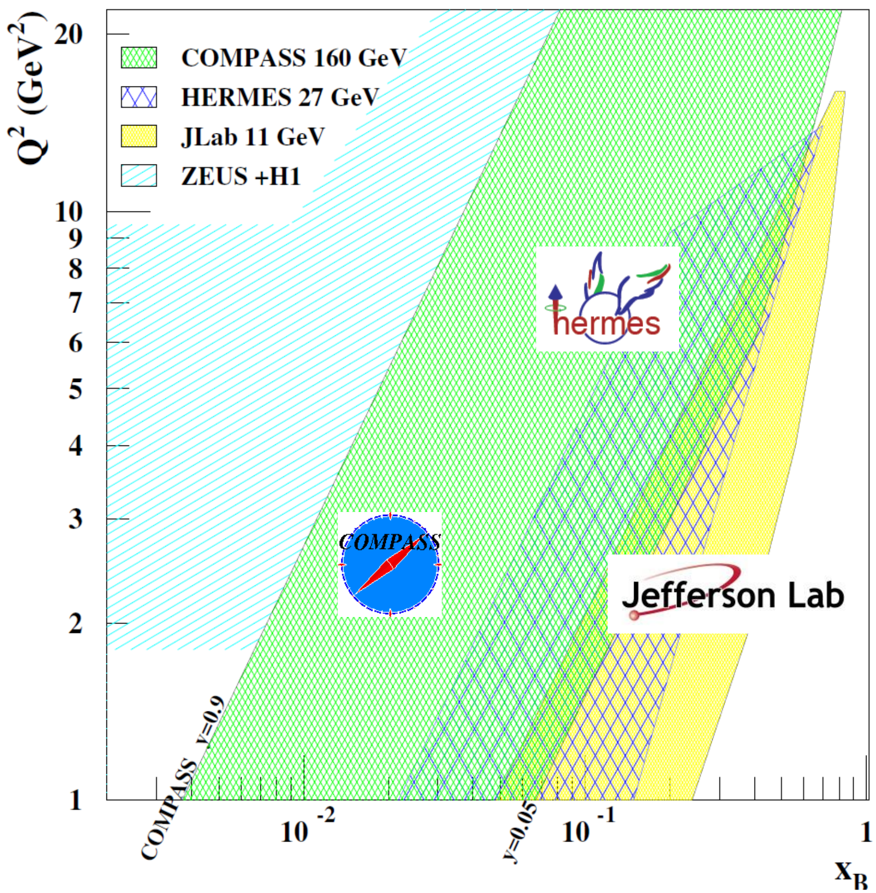
…ranging from the gluon-dominated domain of HERA to the quark valence region of JLab

Fixed-target experiments in the past:

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

Future experiments:

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

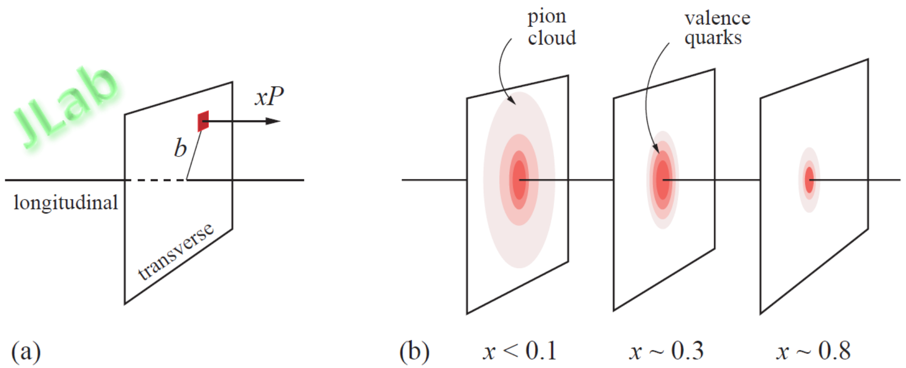


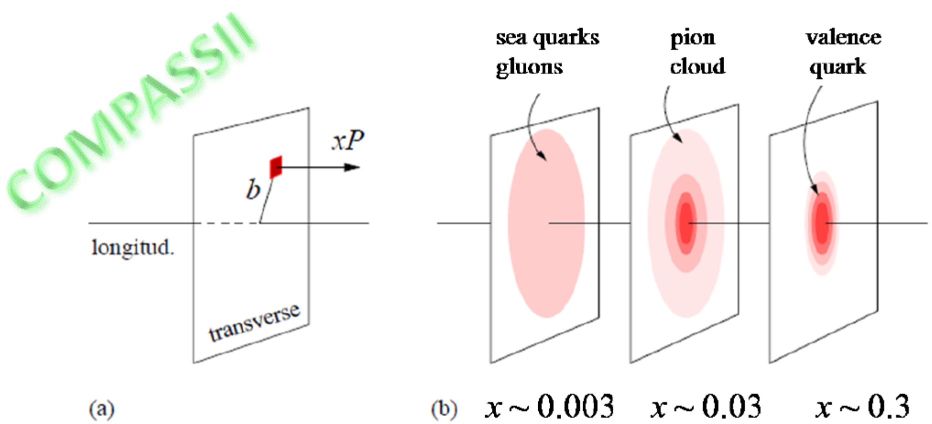
Nucleon transverse size

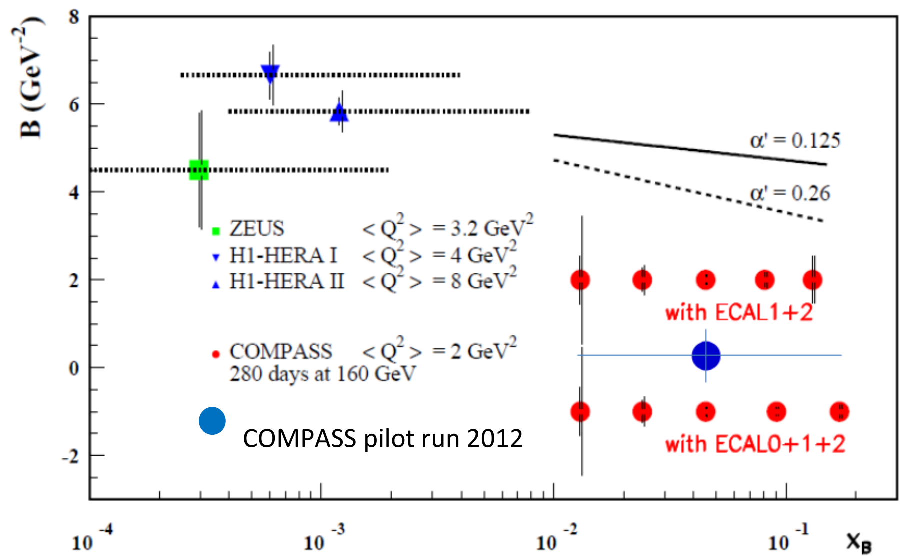
The distance $\langle r_\perp^2 \rangle$ between the struck quark and the spectator c.m. is given by the t-slope of the DVCS cross-section. Extracting it for different x_B values provides a tomographic picture of the nucleon, *i.e.* how its shape changes with x_B

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

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



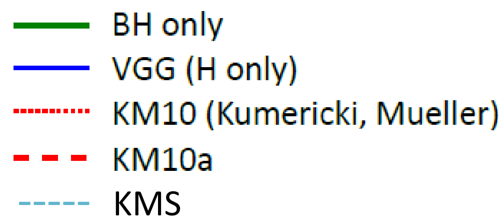


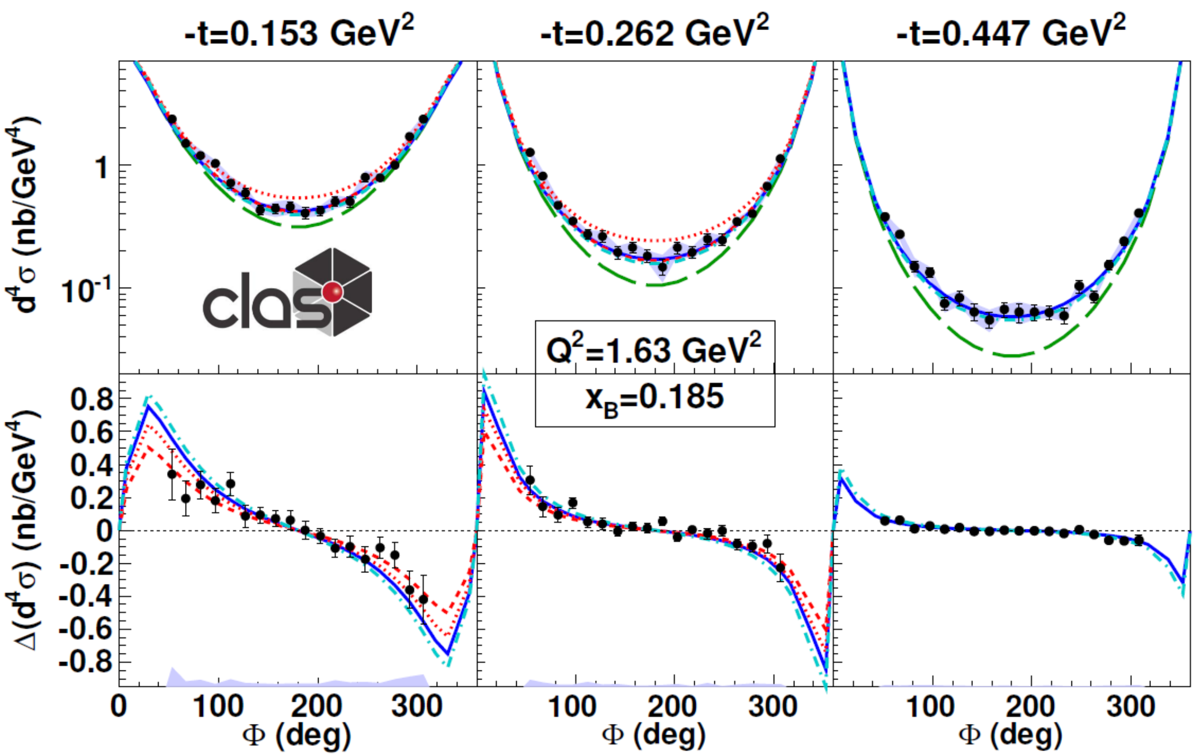


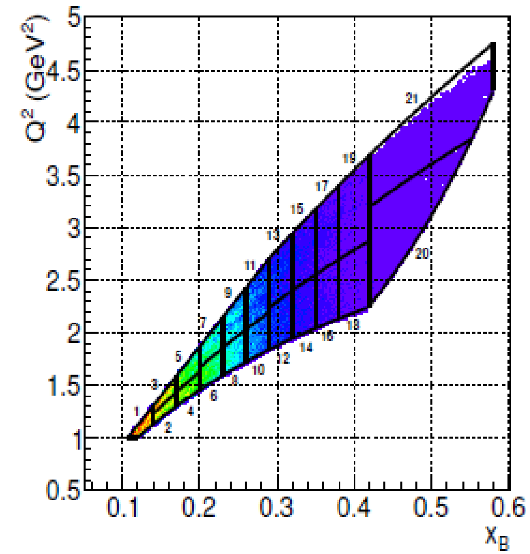
Hall-B: DVCS cross-section on the proton in Hall-B (E01-113)

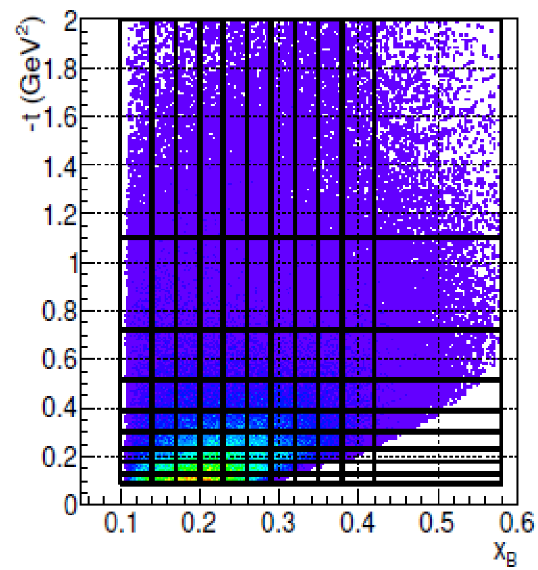
Extraction in a LARGE kinematic domain

$$\frac{d^4\sigma_{ep\to e'p'\gamma}}{dQ^2\,dx_B\,dt\,d\varphi}$$



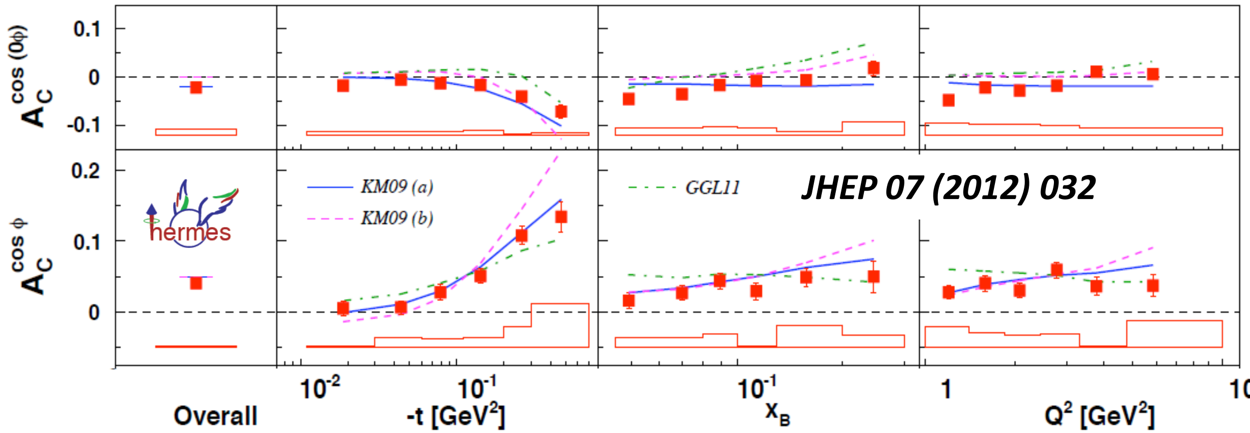


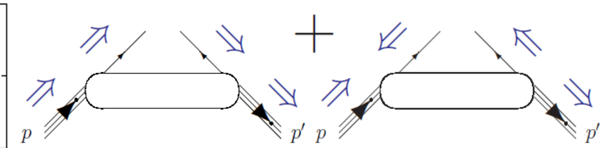




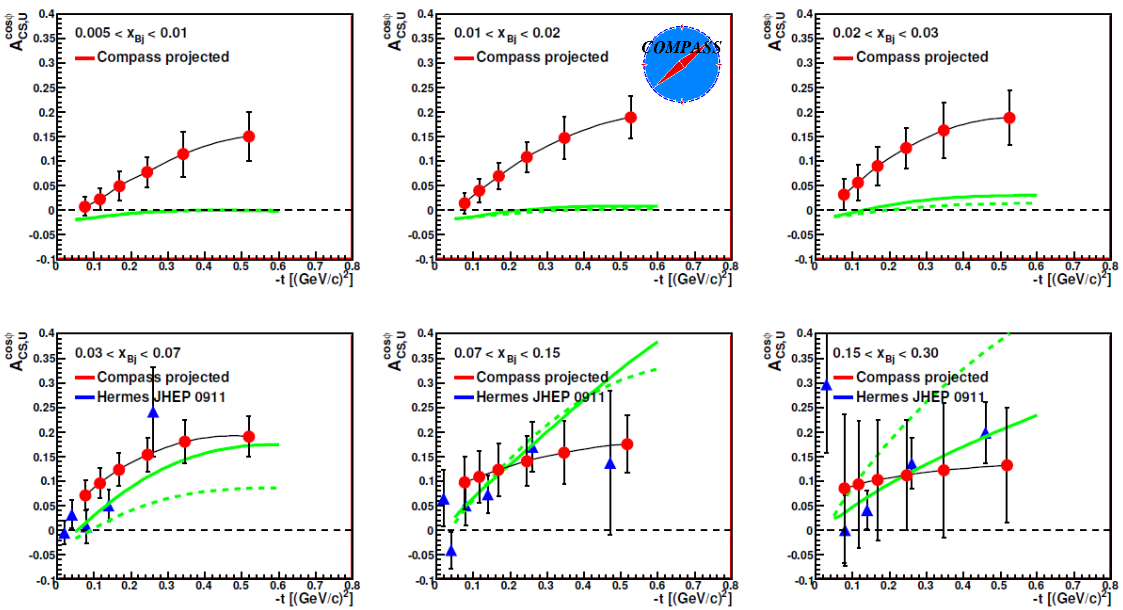
H. S. Jo et. al., hep-ex:1504.02009

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





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



Asymmetry found significantly non zero in HERMES

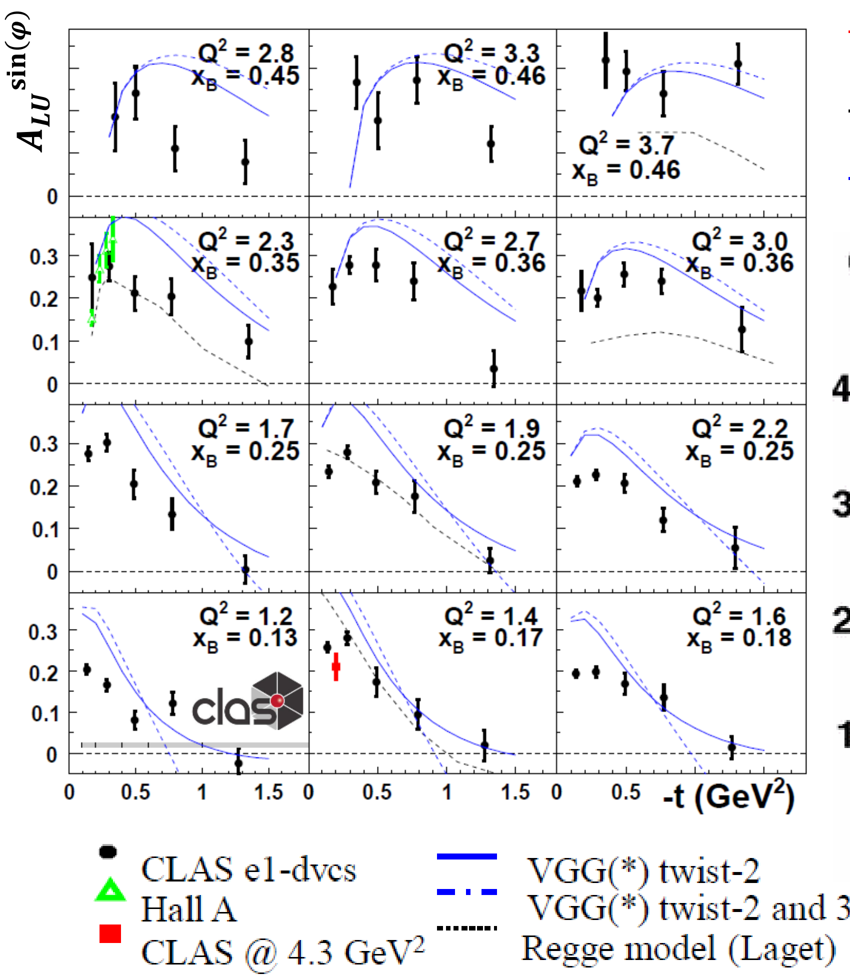
Strong dependence on *-t*

COMPASSII measurement will extend HERMES measurement to lower-x_B

---- Fits by Kumericki, Mueller

Mapping GPDs: Beam-spin asymmetries - $\mathcal{H}_{Im}$

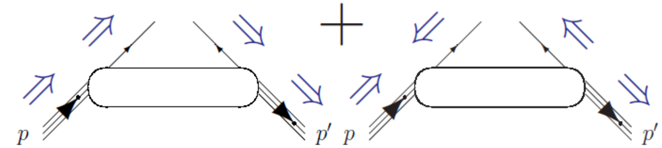
First CLAS DVCS devoted experiment on unpolarized H_2

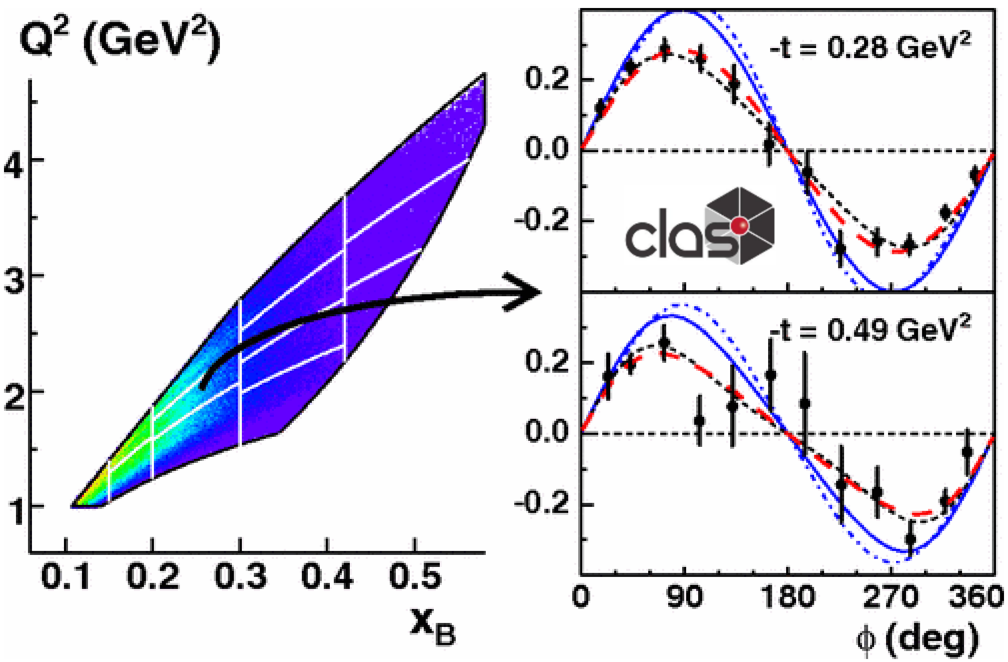


$f = \frac{a \sin\phi}{1 + b\cos\phi}$

VGG twist-2

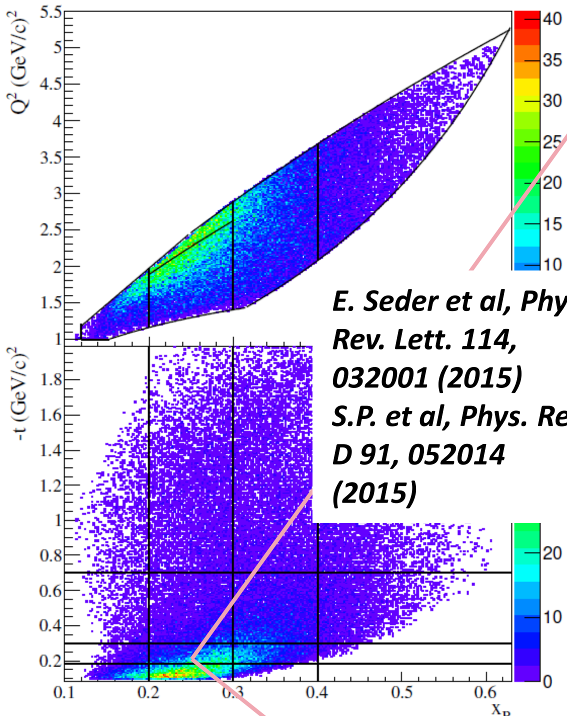
VGG twist-3



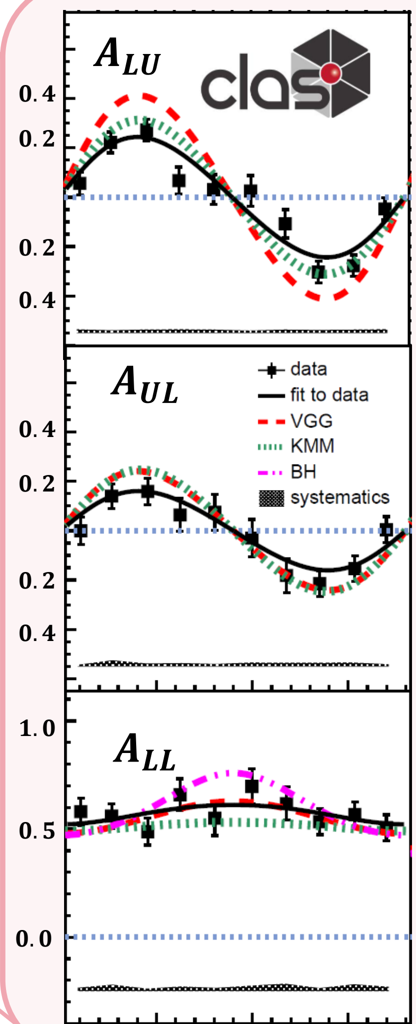


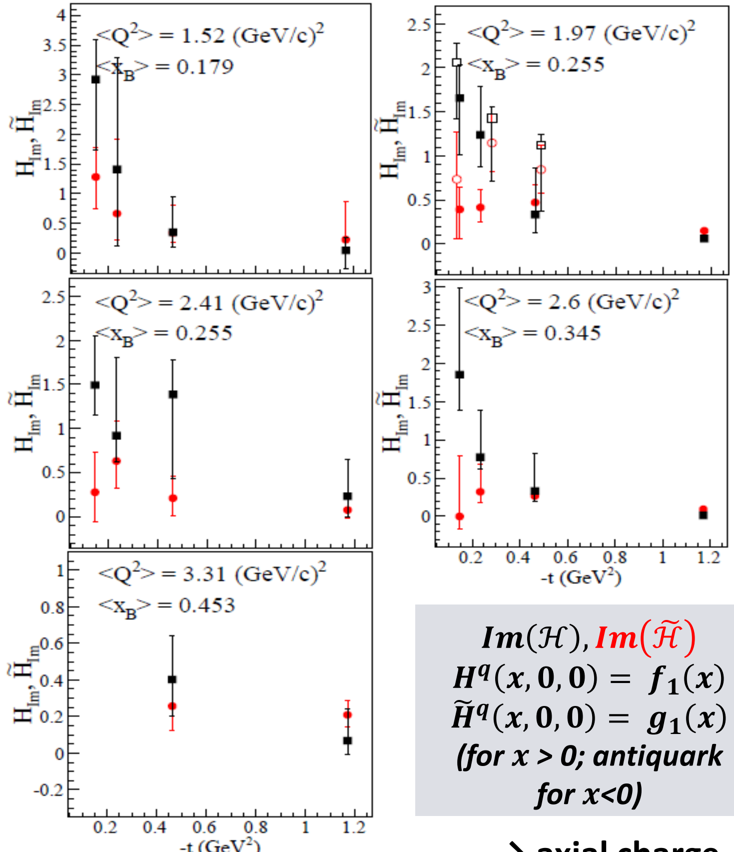
F. X. Girod et al., Phys. Rev. Lett. 100, 162002 (2008).

Comparing charge distributions: $A_{LU} \propto \mathcal{H}_{Im}$, $A_{UL} \propto \widetilde{\mathcal{H}}_{Im}$



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

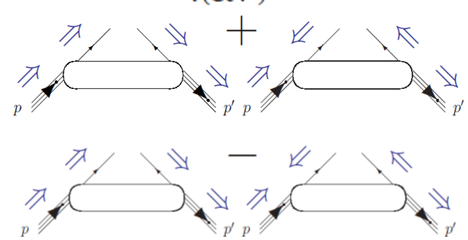




$Im(\mathcal{H}), Im(\widetilde{\mathcal{H}})$
$H^q(x,0,0) = f_1(x)$
$\widetilde{H}^q(x,0,0) = g_1(x)$
(for x > 0; antiquark for x<0)

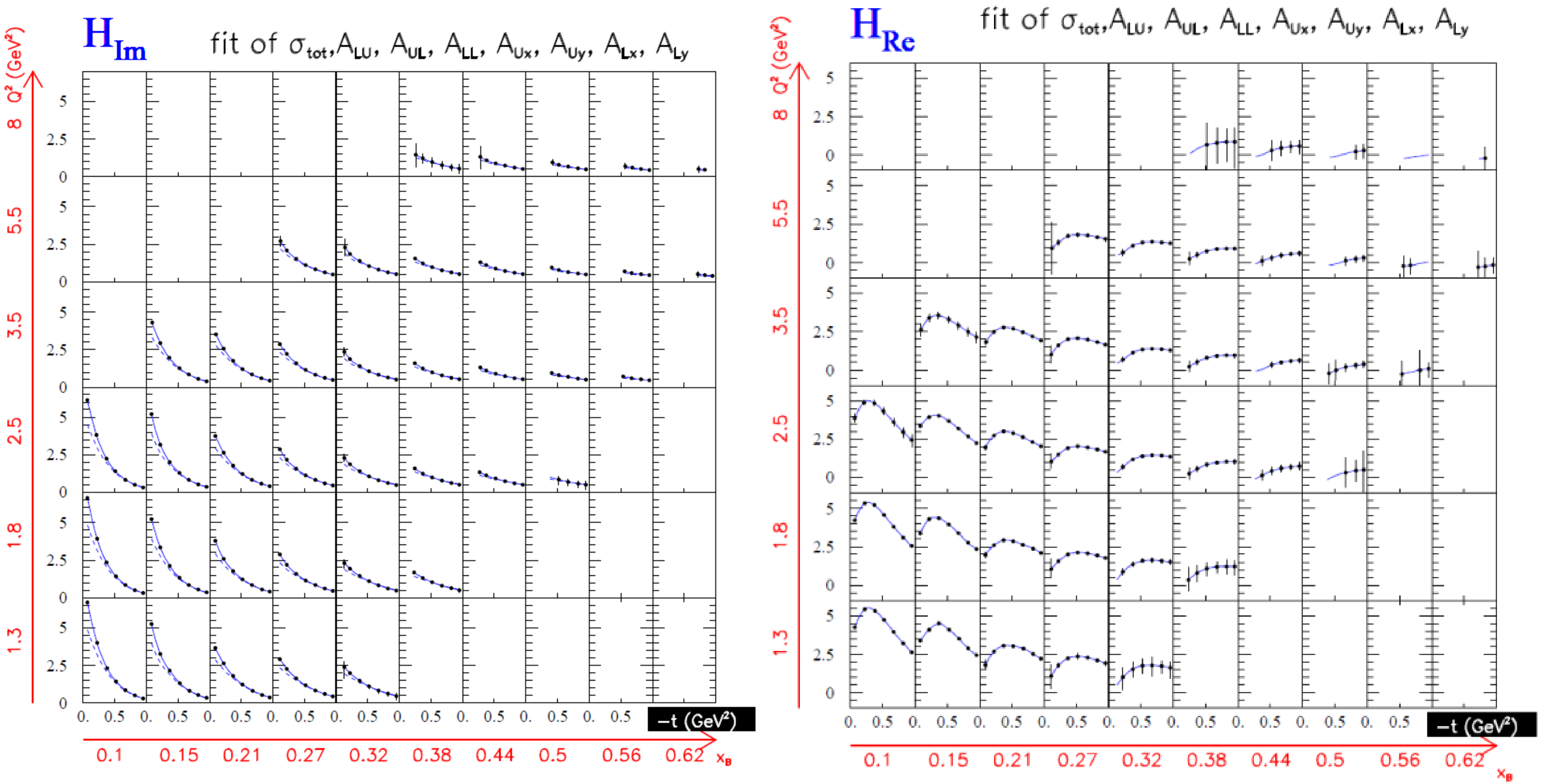
High statistics extraction of Single and Double-Spin Asymmetries

→ *simultaneous CFF extraction from three observables in a common kinematics*
see M.Guidal's talk on Tuesday



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

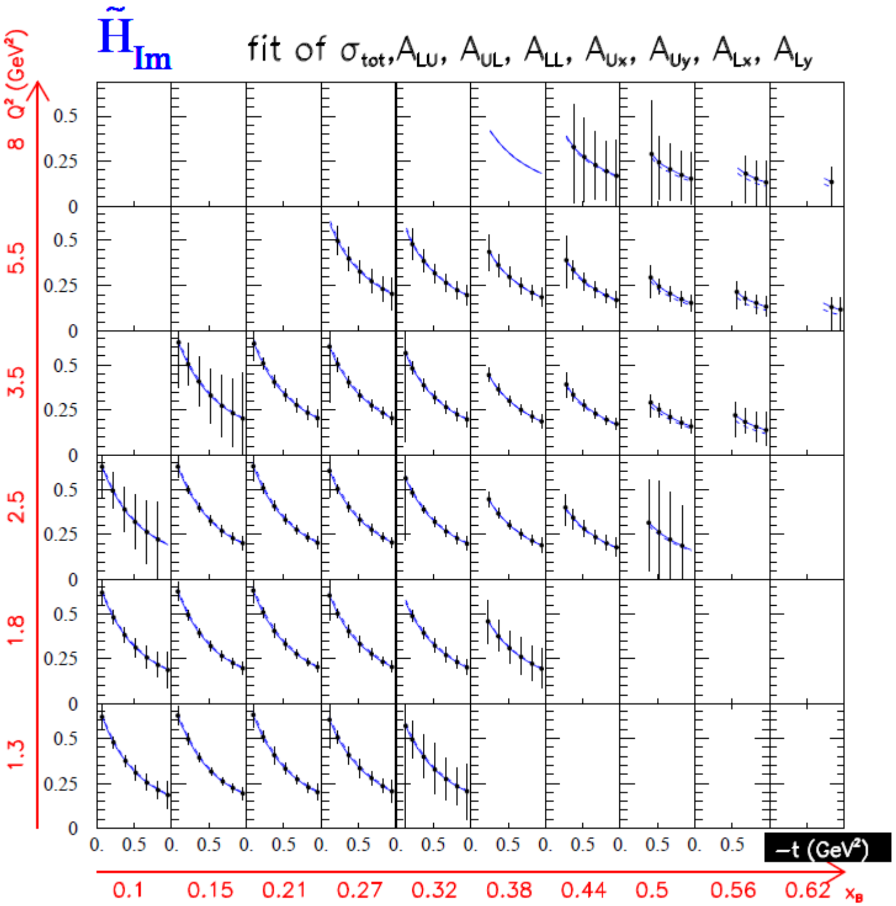
JLab 12 GeV data: impact on $\mathcal{H}$

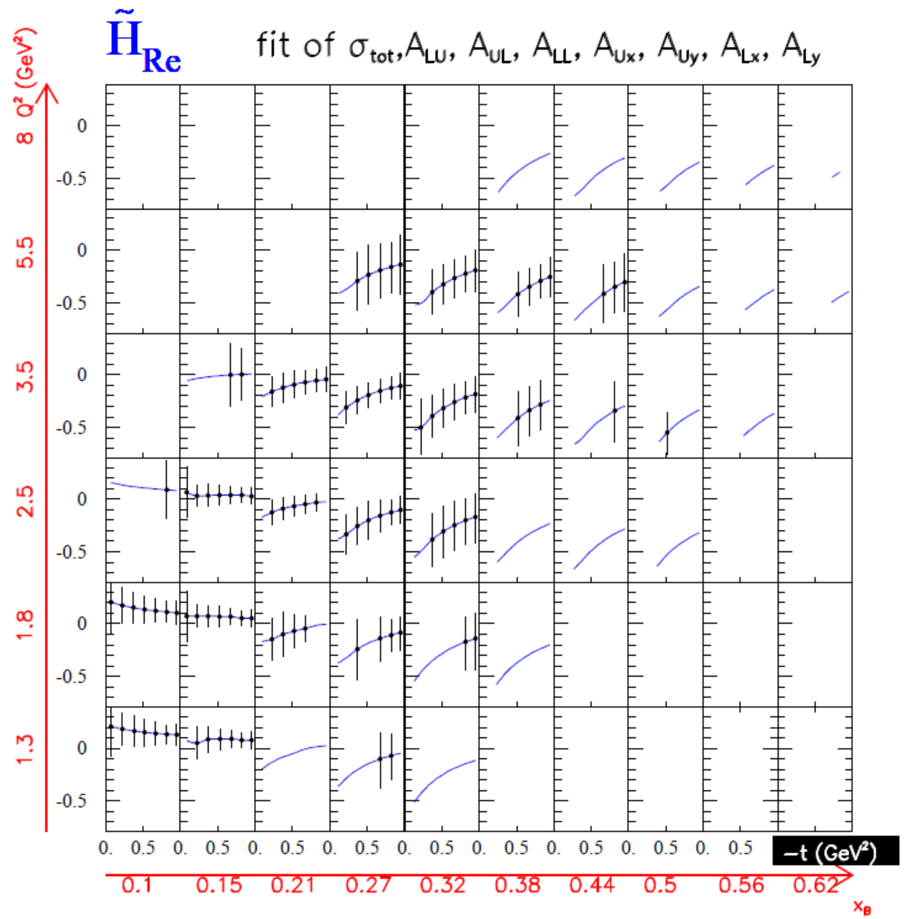


M. Guidal, H. Moutarde, M. Vanderhaeghen:
hep-ph > arXiv:1303.6600

see M.Guidal's talk on Tuesday

JLab 12 GeV data: impact on $\widetilde{\mathcal{H}}$

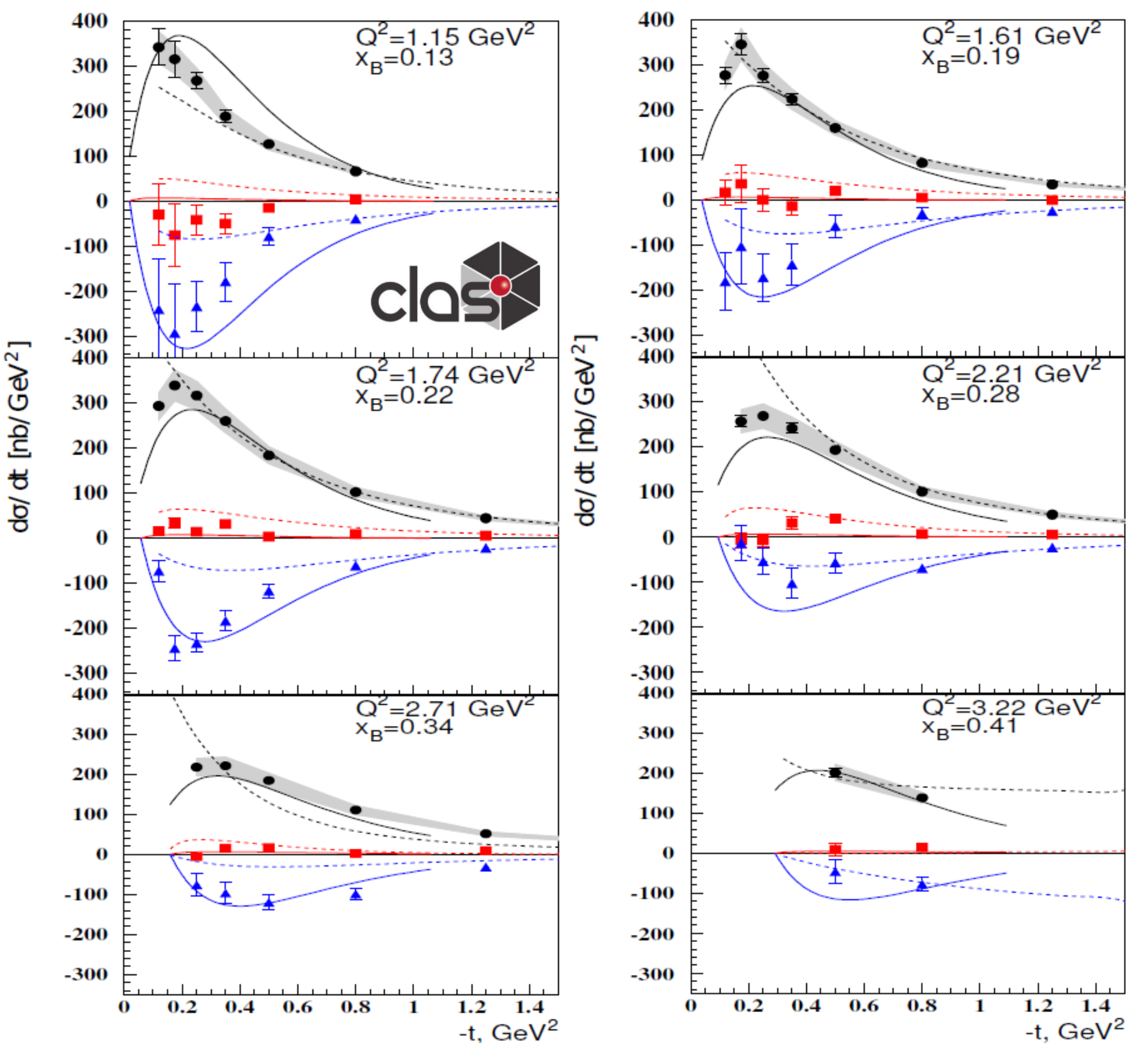




M. Guidal, H. Moutarde, M. Vanderhaeghen: hep-ph > arXiv:1303.6600

see M.Guidal's talk on Tuesday

DVπ^0P cross-section in Hall-B@JLab – tensor charge



π^0 electroproduction → sensitivity to *transversity* GPDs

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

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

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

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

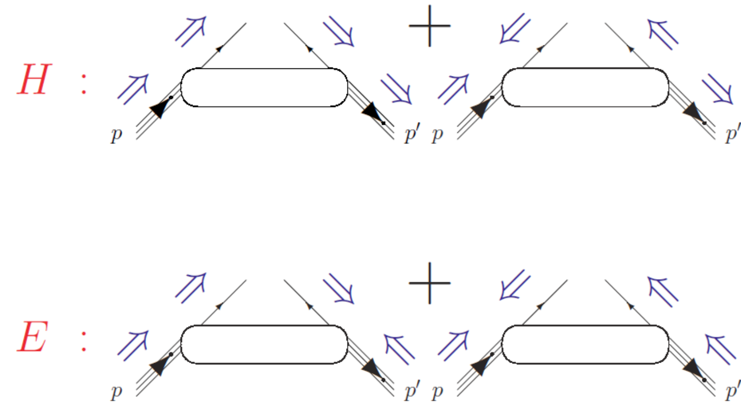
$$\boldsymbol{\sigma_{TT} \sim \frac{t'}{8m^2}|\bar{E}_T|^2}$$

solid: P.Kroll & S.Goloskokov
dashed: G.R. Goldstein, J.O. Gonzalez & S.Liuti

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

Quark orbital angular momentum

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



$$J_q = L_q + S_q$$

S_q → accessible through Inclusive Deep-Inelastic Scattering

Quark Orbital Angular Momentum can be extracted

To access $E_u \& E_d$ both $E_p \& E_n$ are needed so to perform a *flavor separation*

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

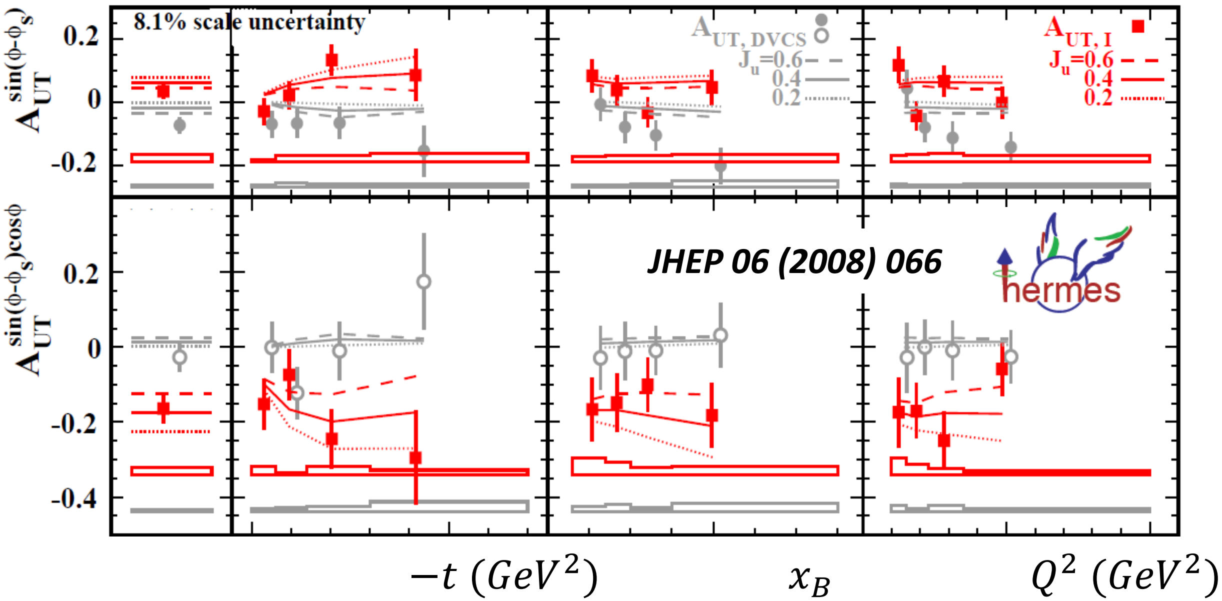
$$(H,E)_d(\xi,\xi,t) = {}^{9}/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

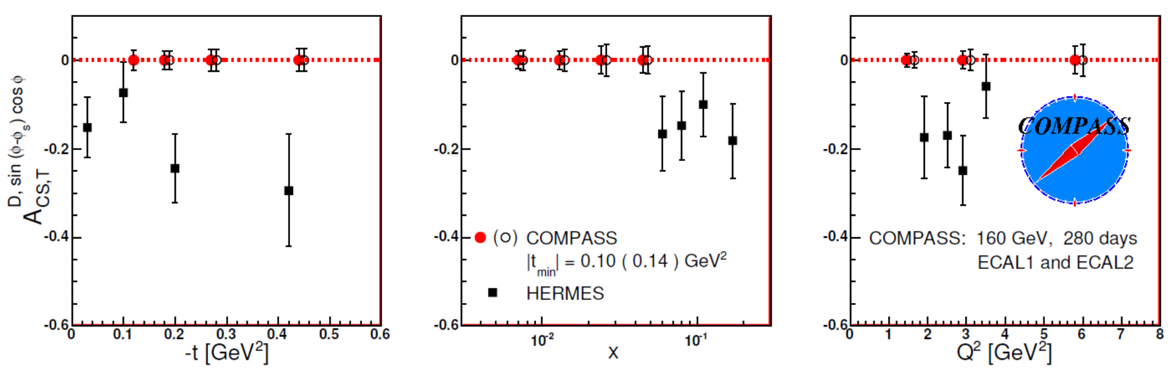
Neutron GPD E_n: A_{LU} on the neutron

Proton GPD E_p: $\cos\varphi$ modulation in σ_{UT} on proton

cfr. B.Pasquini's talk this morning

Exploring E_p in a wide kinematic range

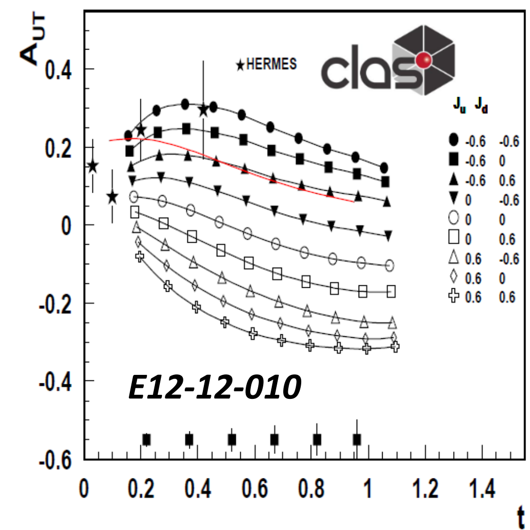




Coefficient accessible through A_{UT} modulations sensitive to E_p

→ observed significantly non-zero @HERMES

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

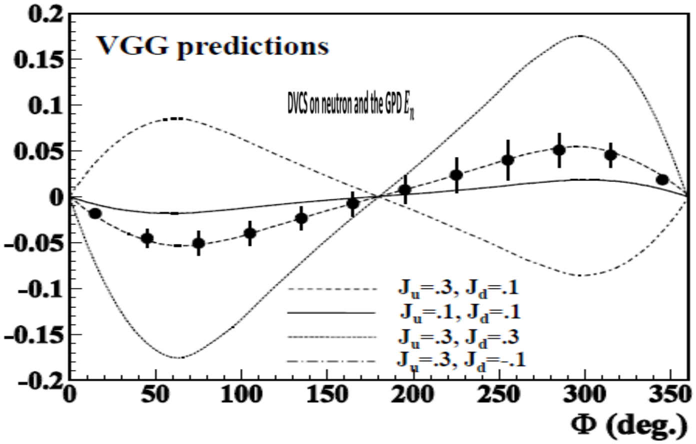


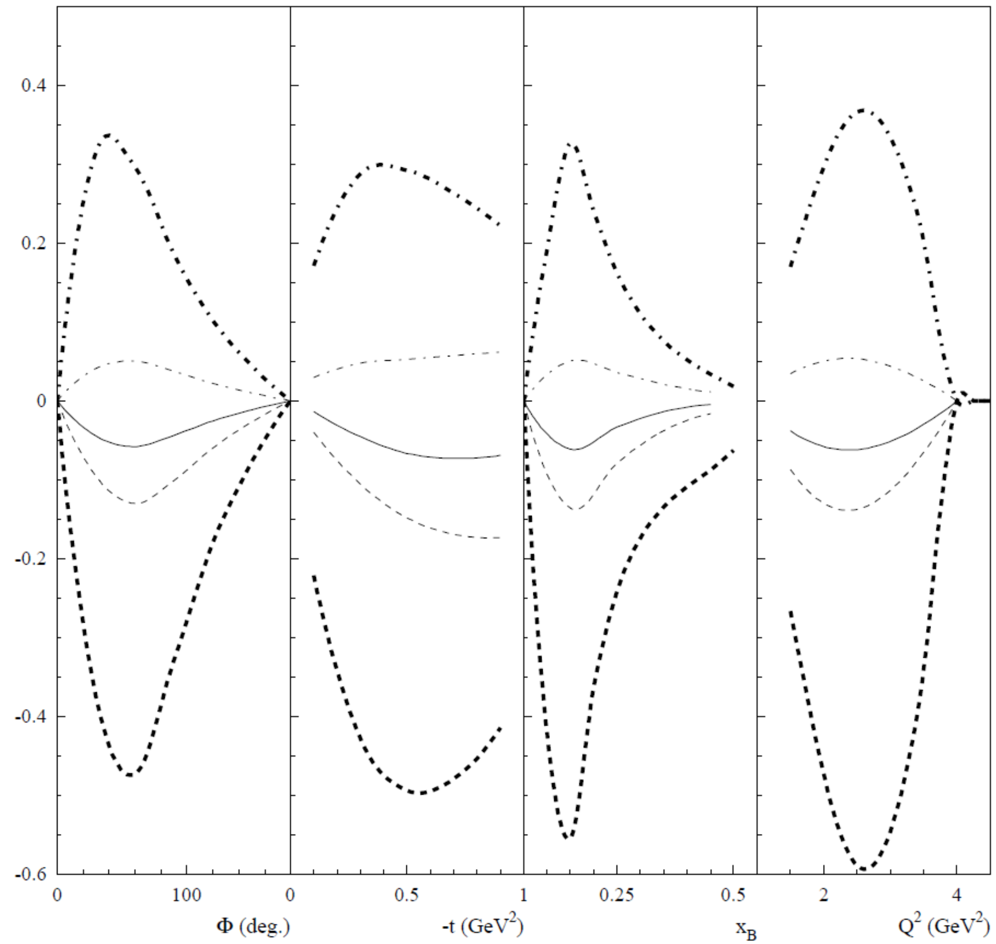
DVCS on neutron and the GPD E_n

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

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

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





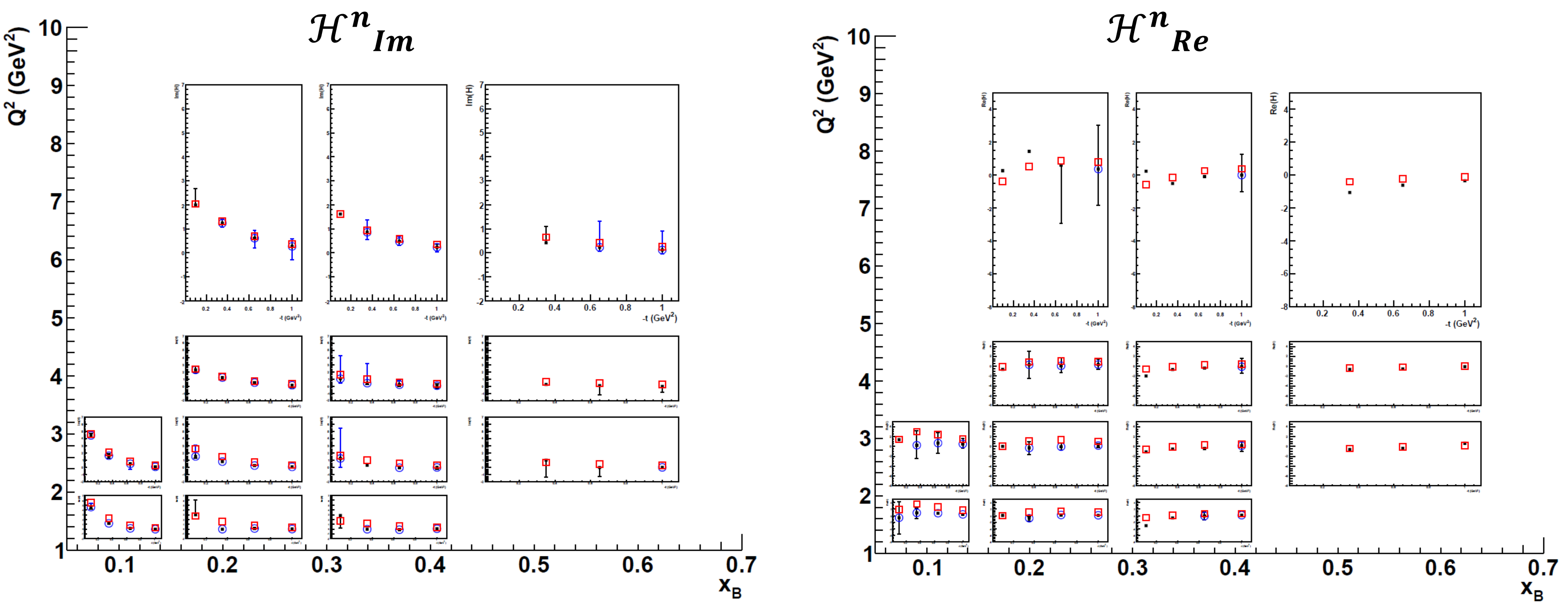
E12-11-003, A_{LU} on neutron

Exploring H_n in the valence region

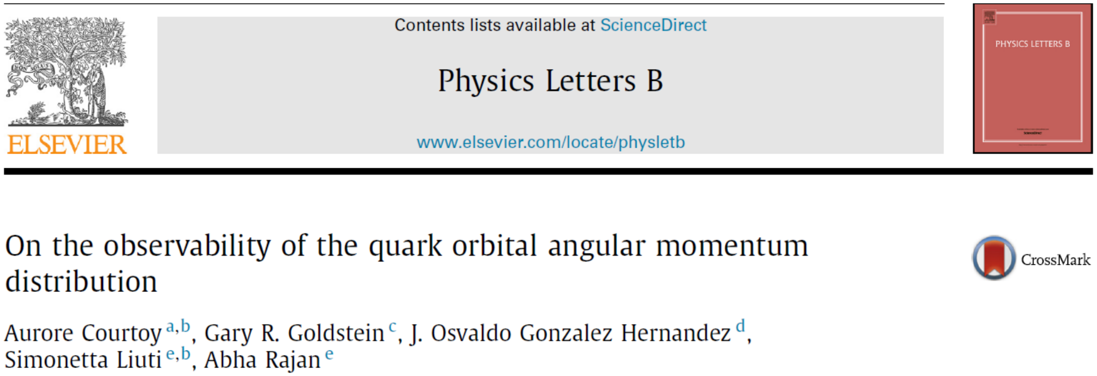
New Research Proposal to Jefferson Lab PAC 43

→ to be submitted on June to **PAC43**

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



Higher-twist GPDs: $A_{UL}^{\sin 2\varphi}$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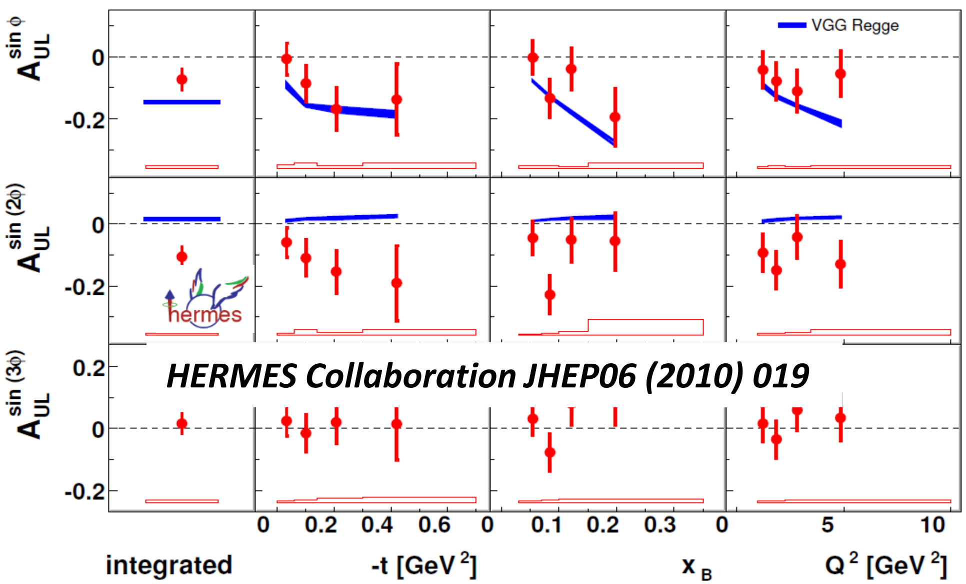
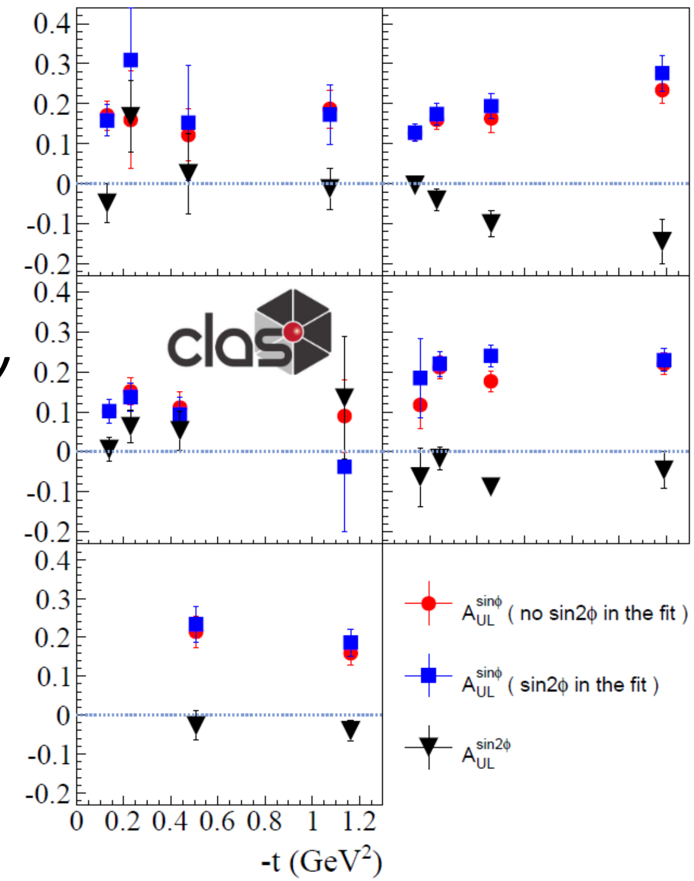
On the observability of the quark orbital angular momentum distribution

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

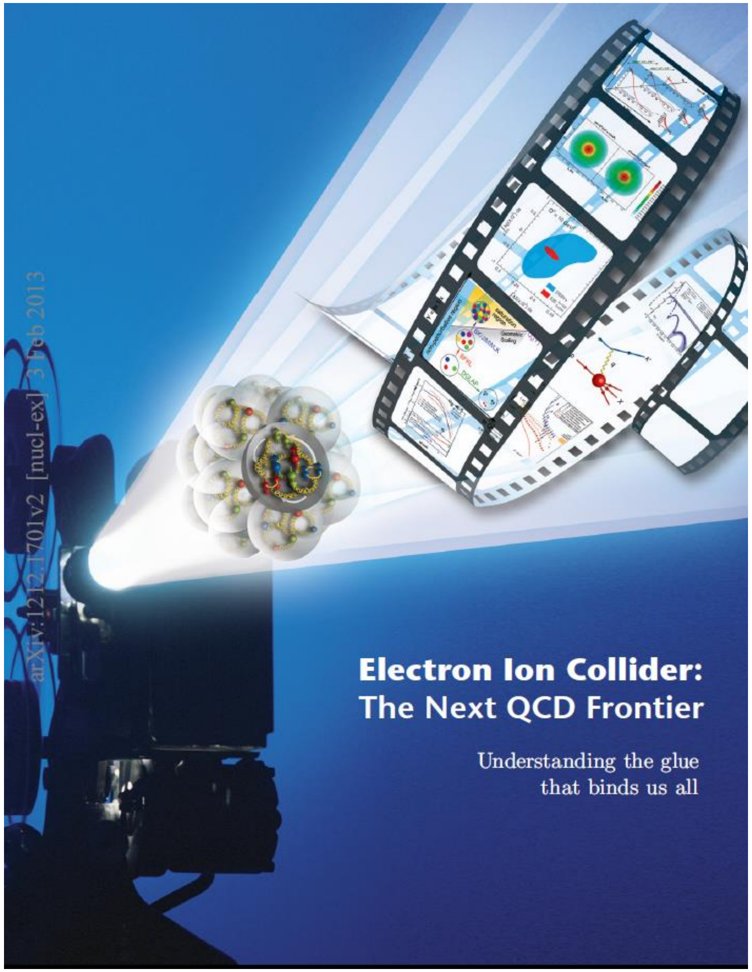


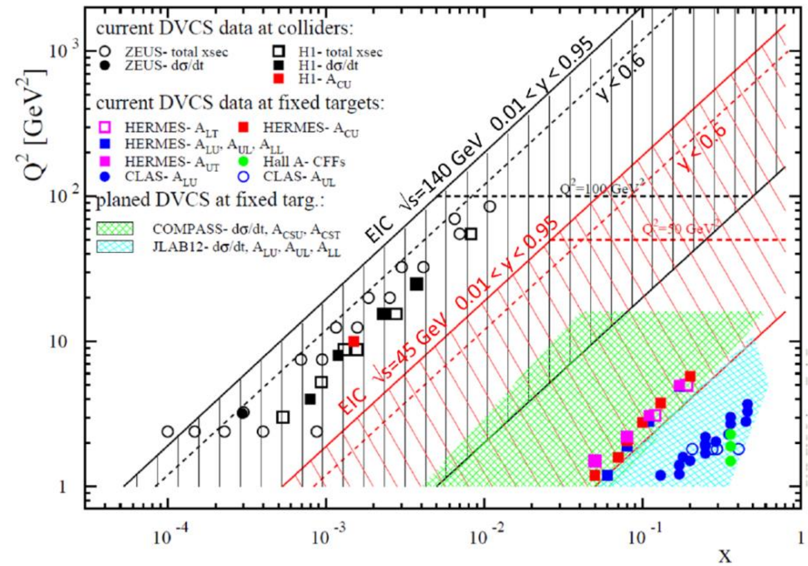
HERMES Collaboration JHEP06 (2010) 019



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

Electron-Ion Collider





- A collider is needed to reach the gluon-saturated domain
- electron probe will provide the unmatched precision of the electromagnetic probes
- dynamical interplay between sea quarks & gluons through their distributions
- change of distributions when going from small to large x, to relate sea and valence quarks

Conclusions

- Past experiments, both fixed target (JLab, HERMES, COMPASS) or active in colliders (ZEUS, H1), played a crucial role in proving the feasibility of a nucleon tomography through the formalism of the Generalized Parton Distributions

- Deeply-Virtual Compton Scattering emerged as the cleanest process to access GPDs (CFFs) through specific observables

- First constraints of the CFFs $\mathcal{H}, \widetilde{\mathcal{H}}$ through DVCS A_{LU}, A_{UL}, A_{LL} and cross-sections

- A good mapping of GPDs will describe how the different charges describing nucleon interactions are distributed inside its volume

- The observables can be compared to Lattice results → connection to pure QCD

- The (bright?) future will see a wide investigation ranging from the gluon/sea regime explored at COMPASSII to the valence region explored at JLab12

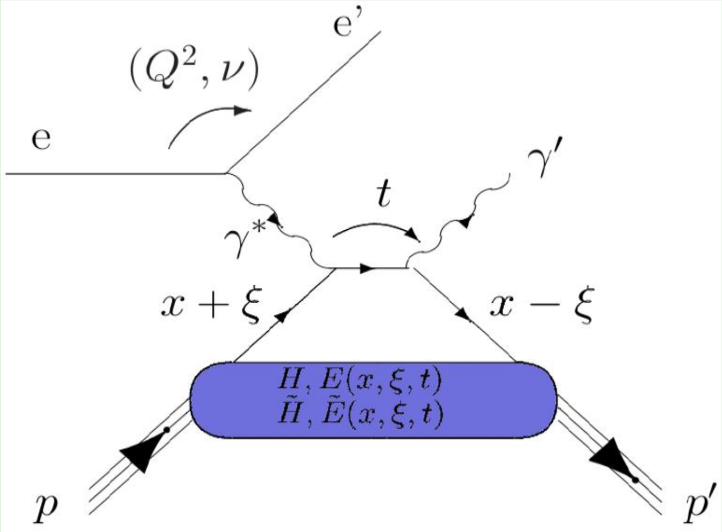
→ final goal (together with the TMDs): wide-coverage, high-statistics mapping of the 5D nucleon structure

Thanks to A. Martin, M. Chiosso and A. Movsisyan for the material!

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

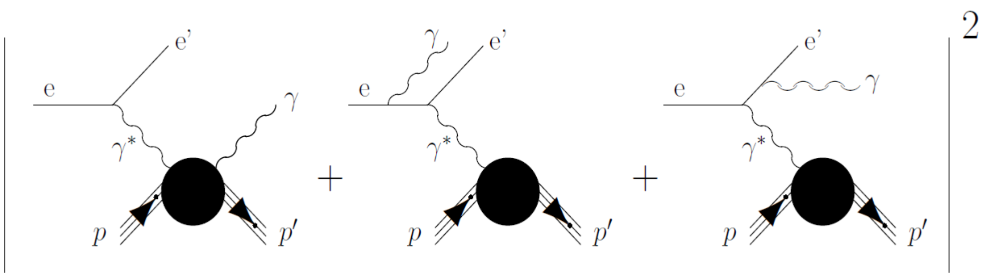
A_{LU} for π^0 on H_2: R. de Masi *et al.*, PRC77:042201 (2008)
A_{LU} on H_2: PRL100: 162002 (2008) F.X. Girod *et al.*, E12-06-119
DVCS & DVπ^0P A_{LU}, A_{UL}, A_{LL} on NH_3: soon to be published

Hall-B Orbital Angular Momentum through GPDs

E12-12-010, A_{UT} on proton
E12-11-003, A_{LU} on neutron

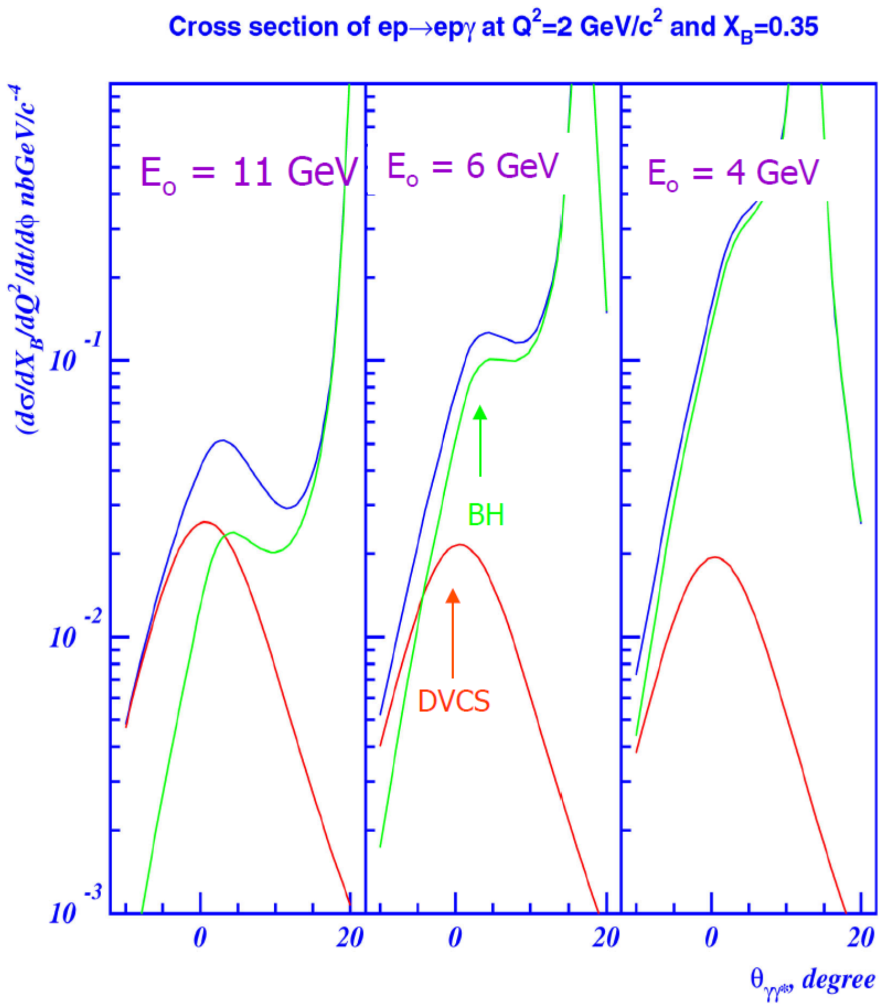
Experimental access to GPDs

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



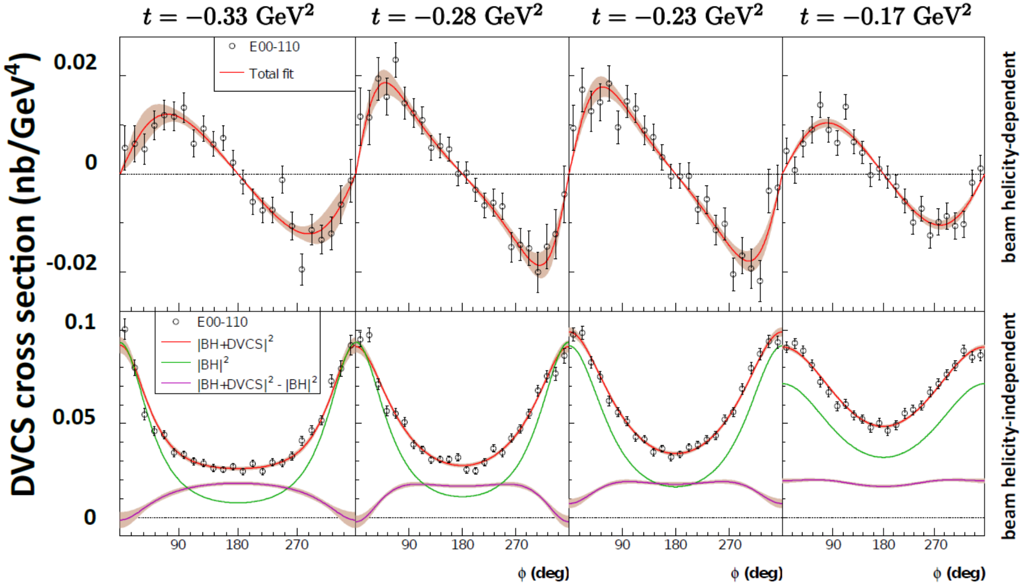
$$\sigma = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2$$

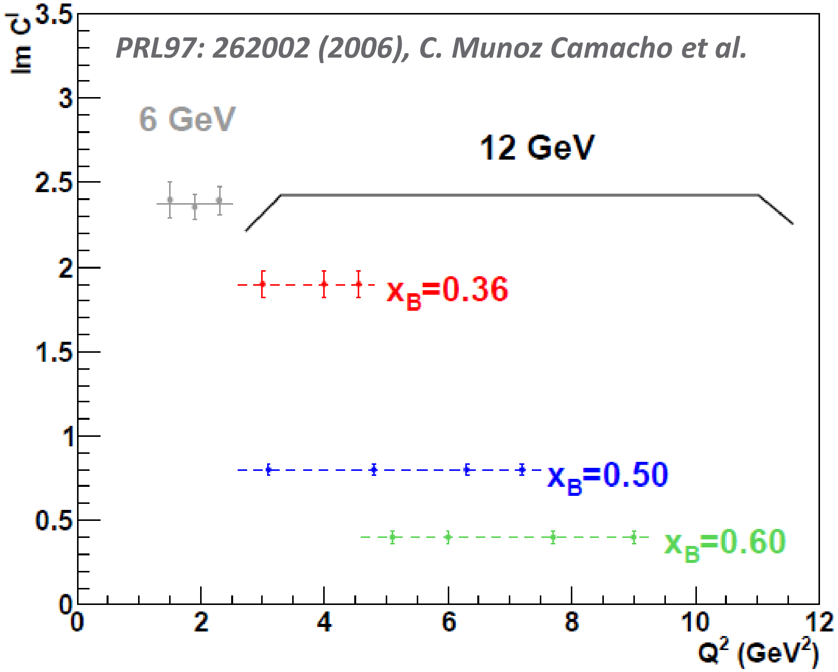
$I(BH \cdot DVCS)$ gives rise to spin asymmetries, which can be connected to combinations of GPDs



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

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



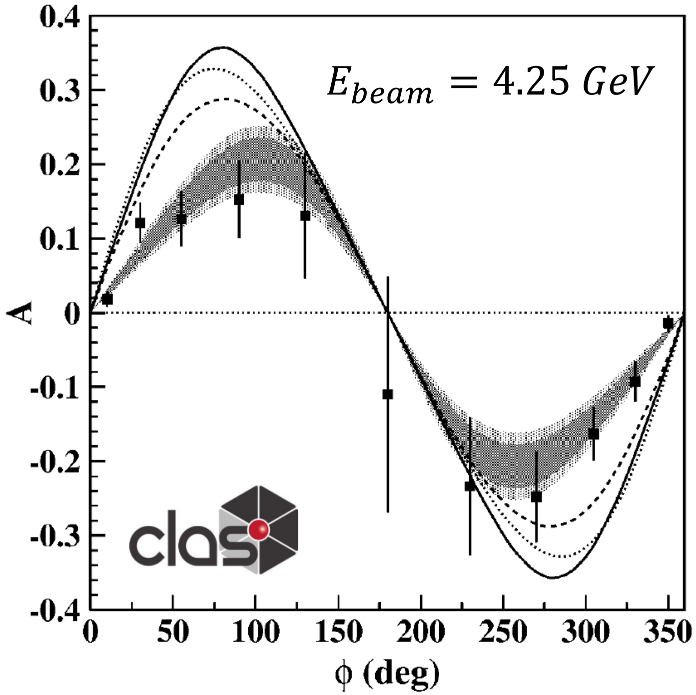


Significant deviation from pure BH → DVCS contribution to the cross section not negligible

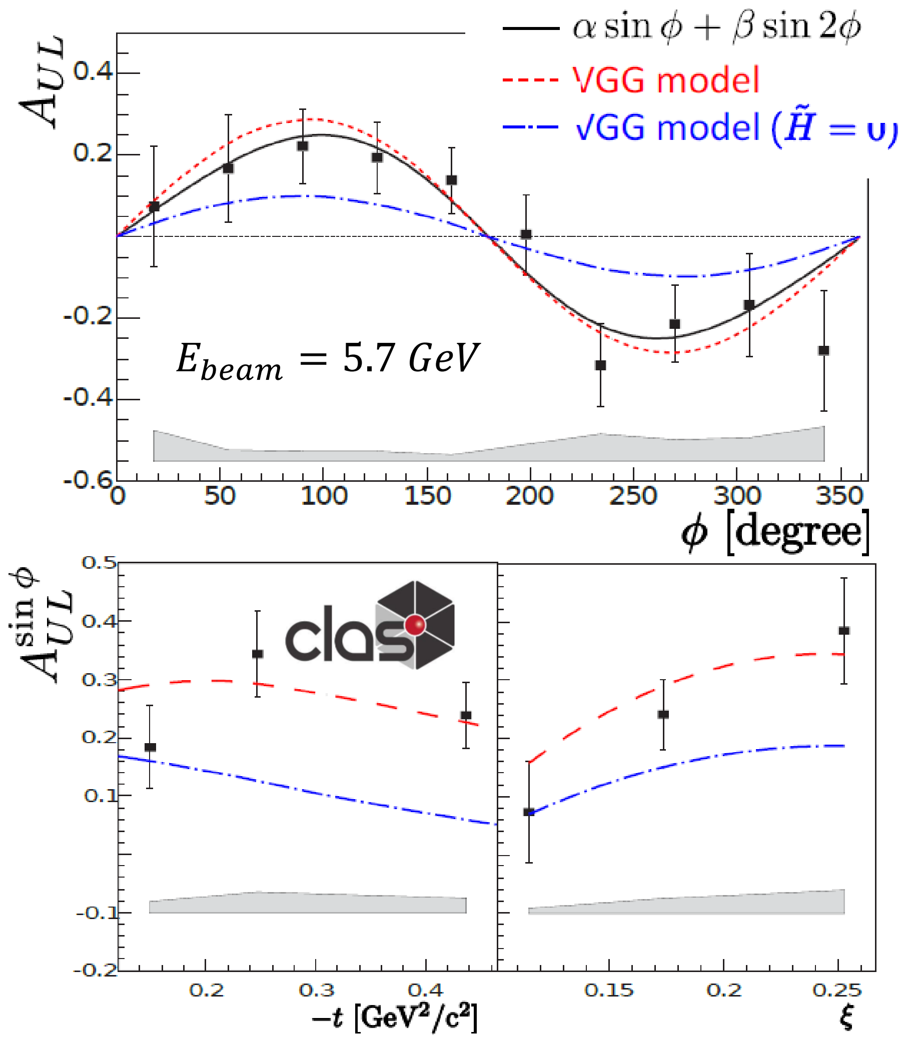
→ $\boldsymbol{Im(\mathcal{C}^I(\mathcal{F}))}$ independent of Q^2: no higher-order corrections enter → **perturbative QCD scaling in DVCS**

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

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

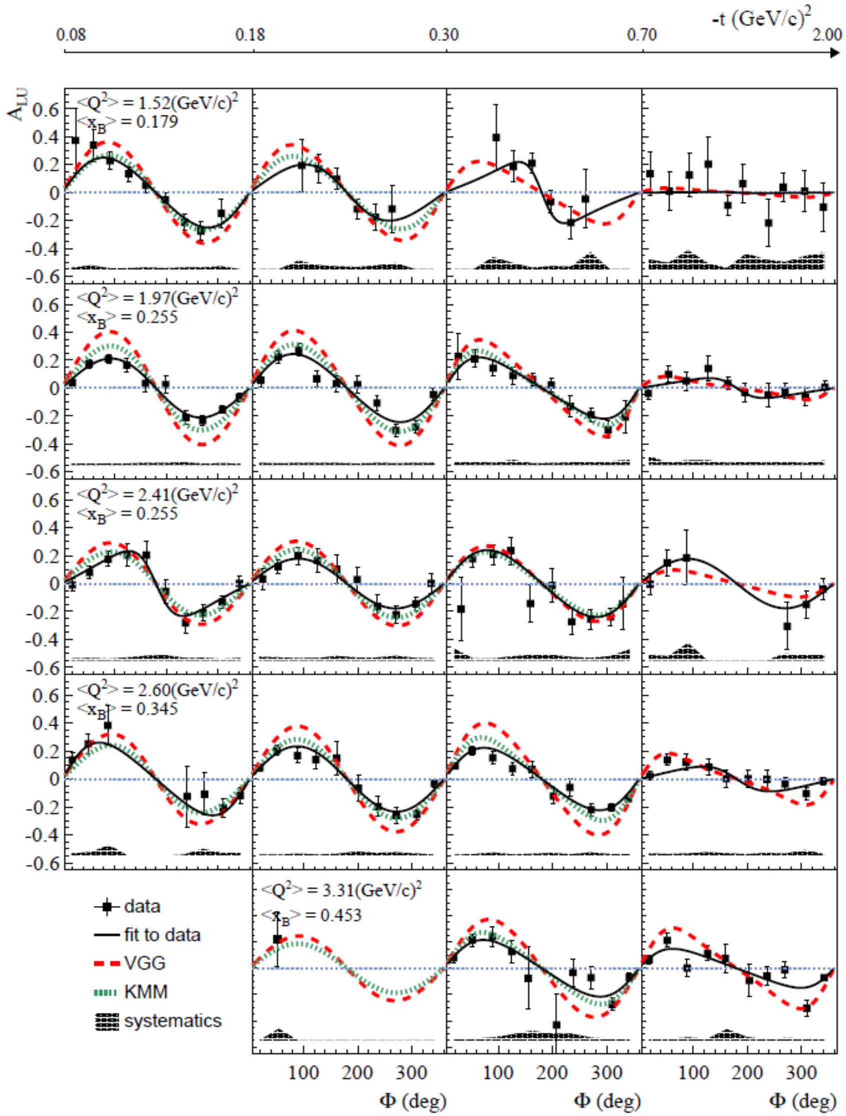


S. Stepanyan et al., Phys. Rev. Lett. 87, 182002 (2001).

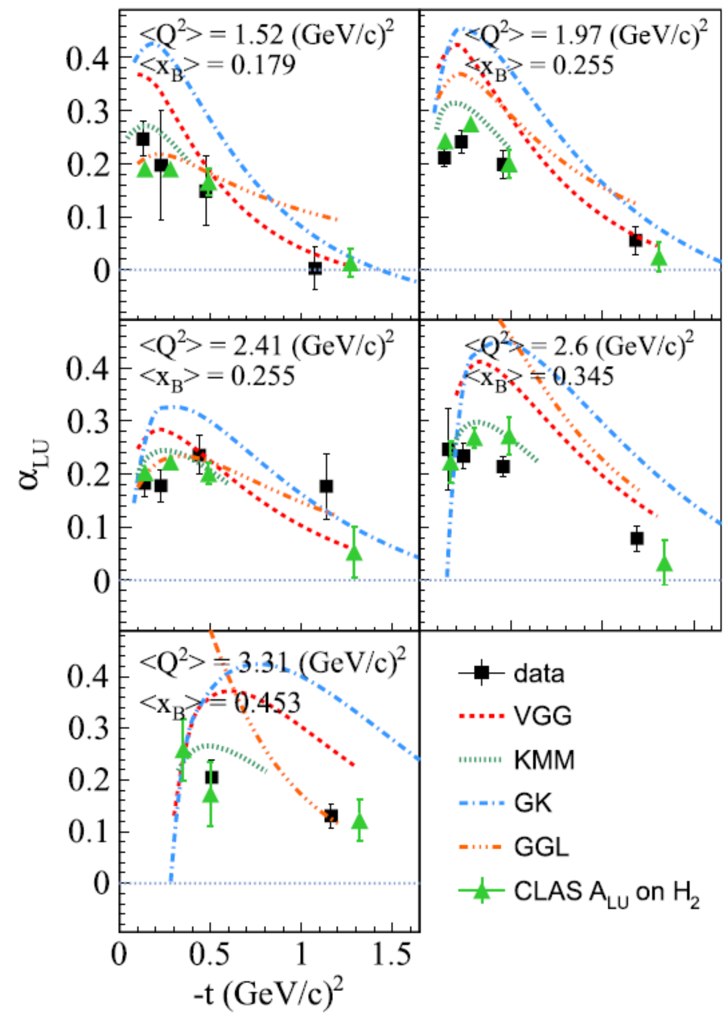


S. Chen et al., Phys. Rev. Lett. 97, 072002 (2006).

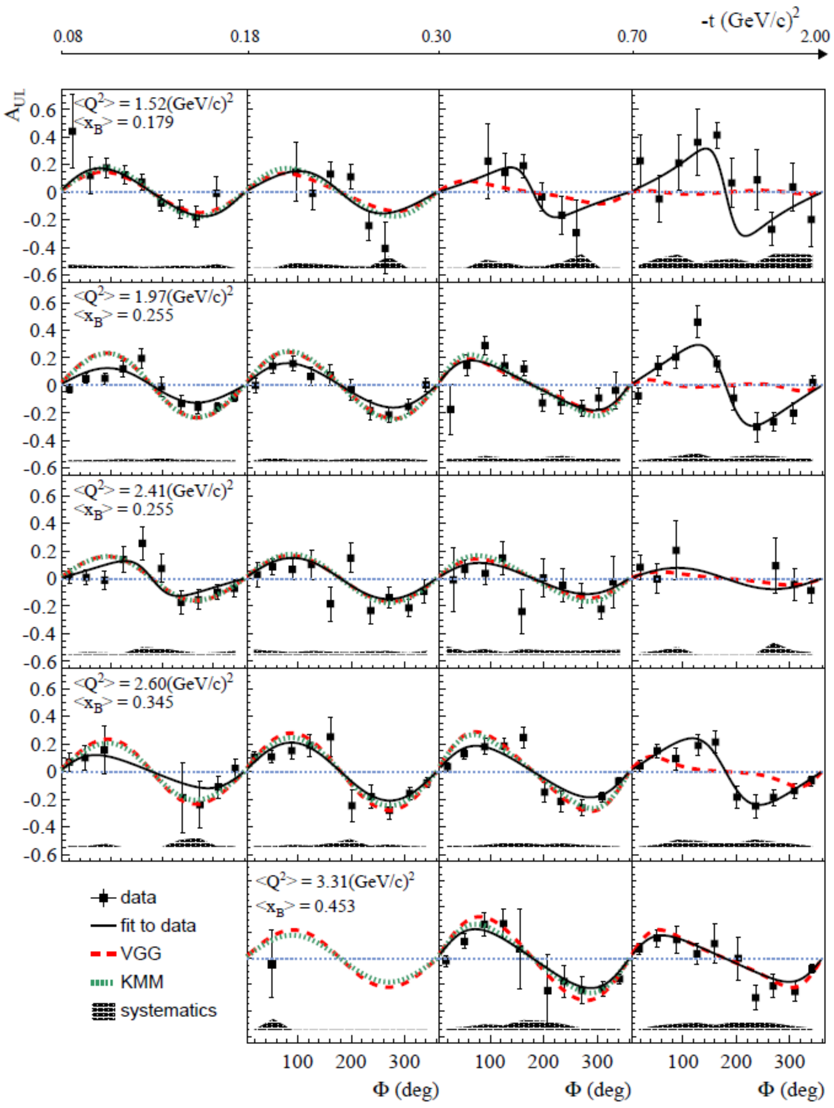
A_{LU} on NH_3



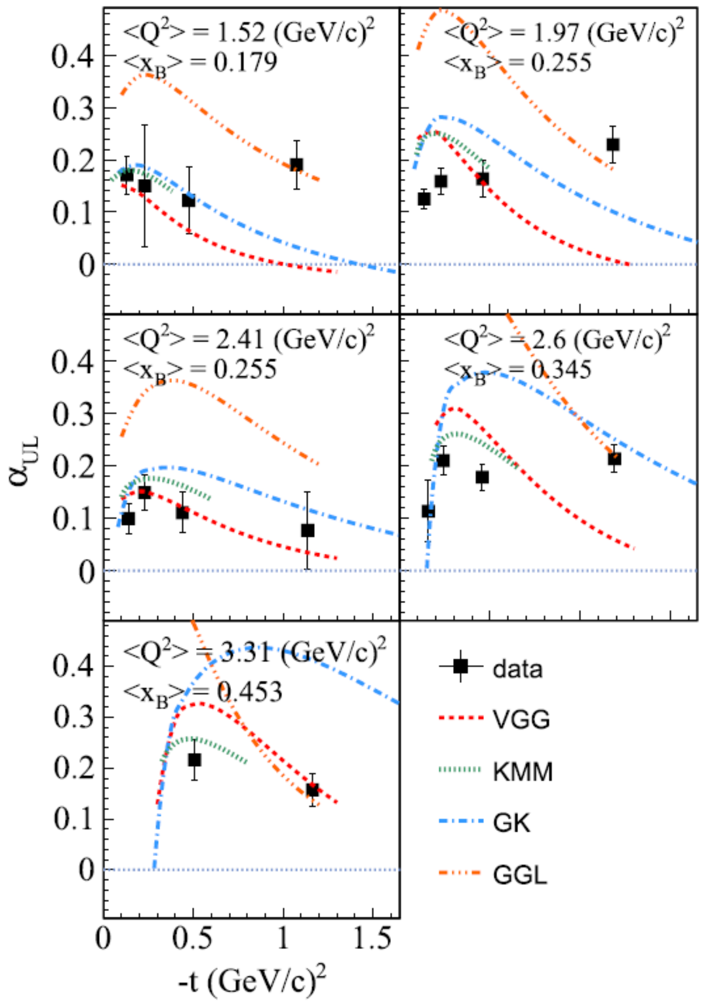
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)



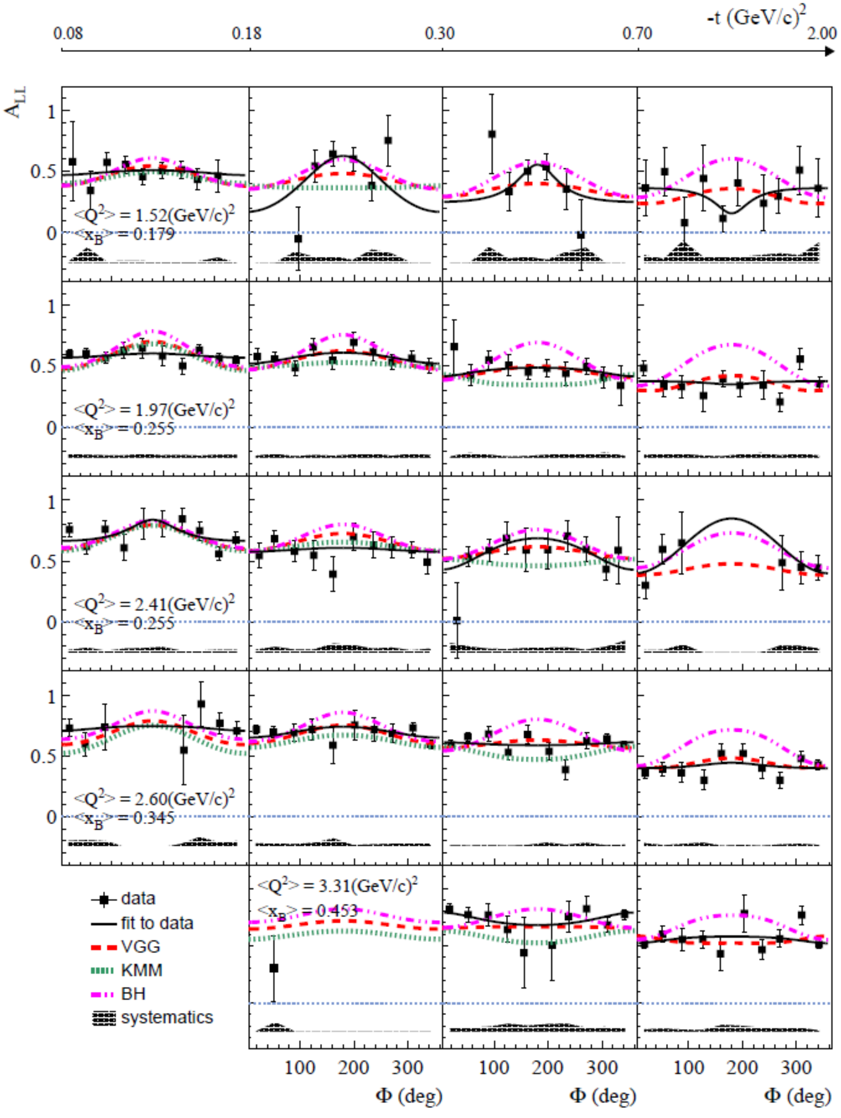
A_{UL} on NH_3



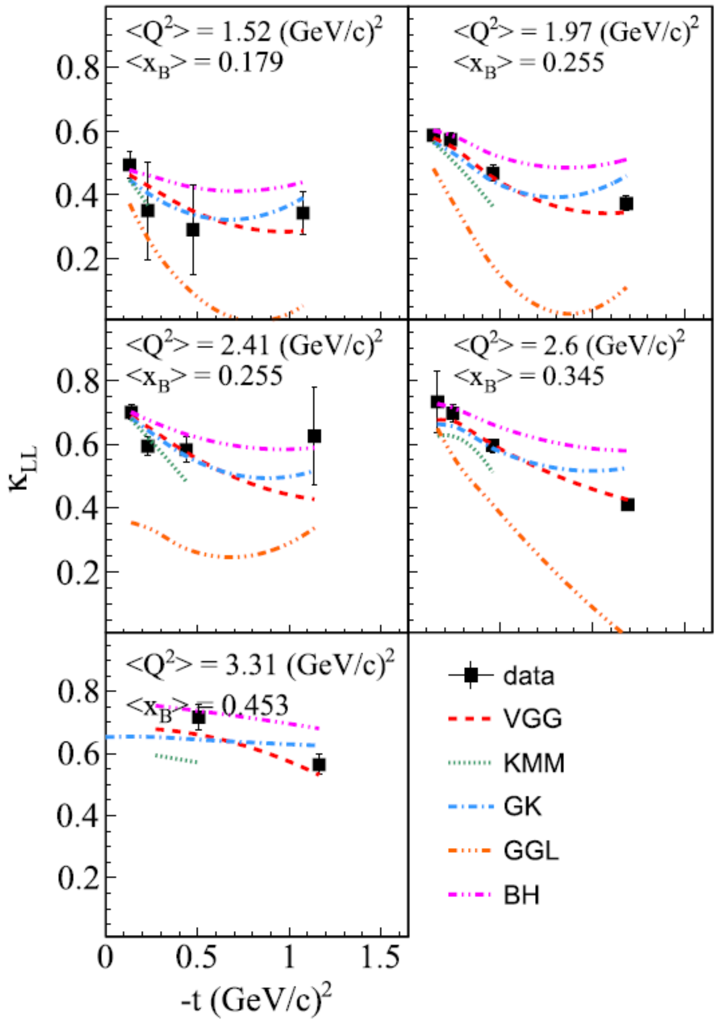
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)



A_{LL} on NH_3



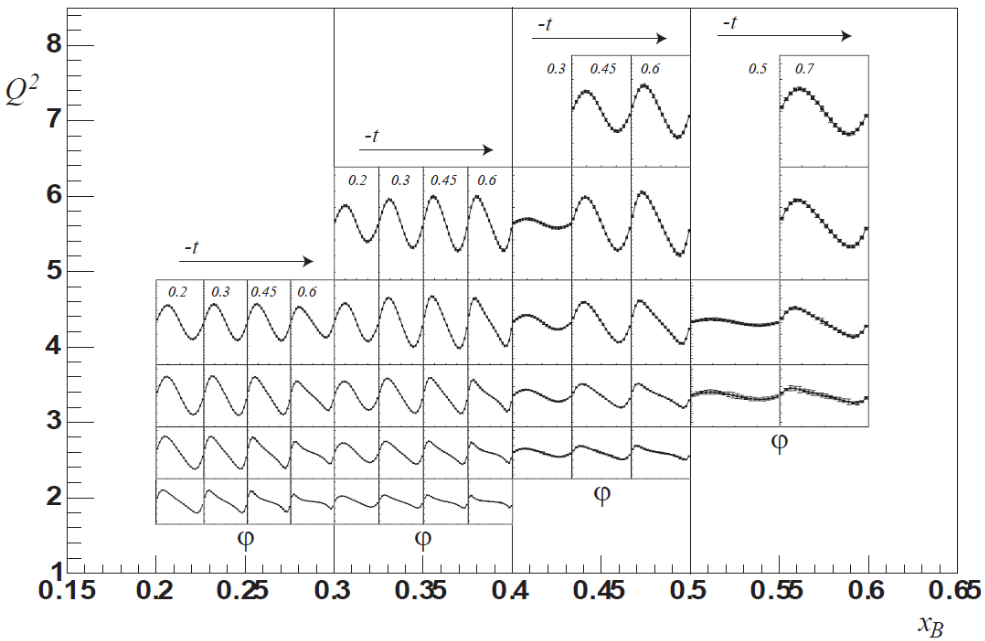
E. Seder et al, Phys. Rev. Lett. 114, 032001 (2015)
S.P. et al, Phys. Rev. D 91, 052014 (2015)

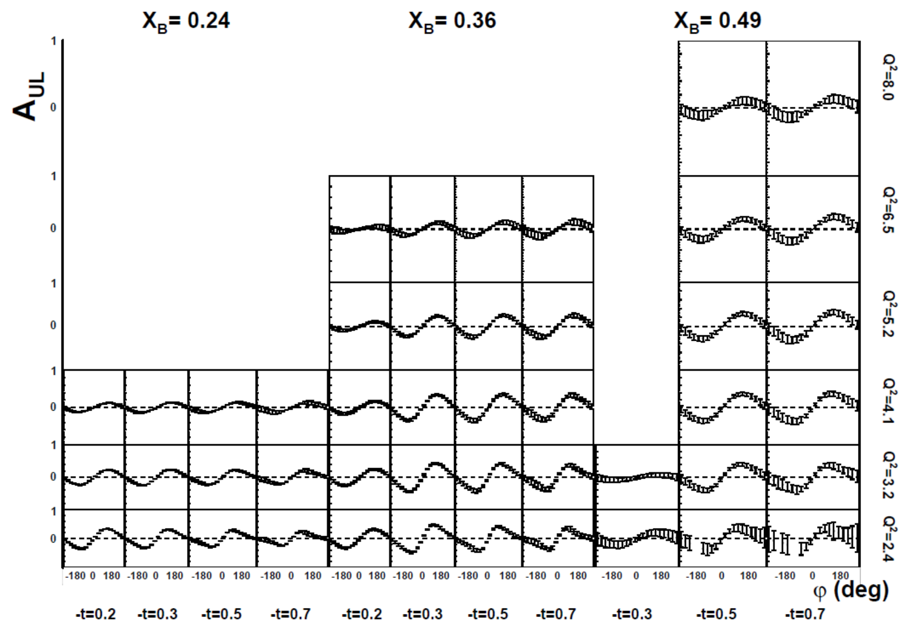


Hall-B/CLAS@12 GeV: High-statistics A_{LU}&A_{UL}- E12-06-119

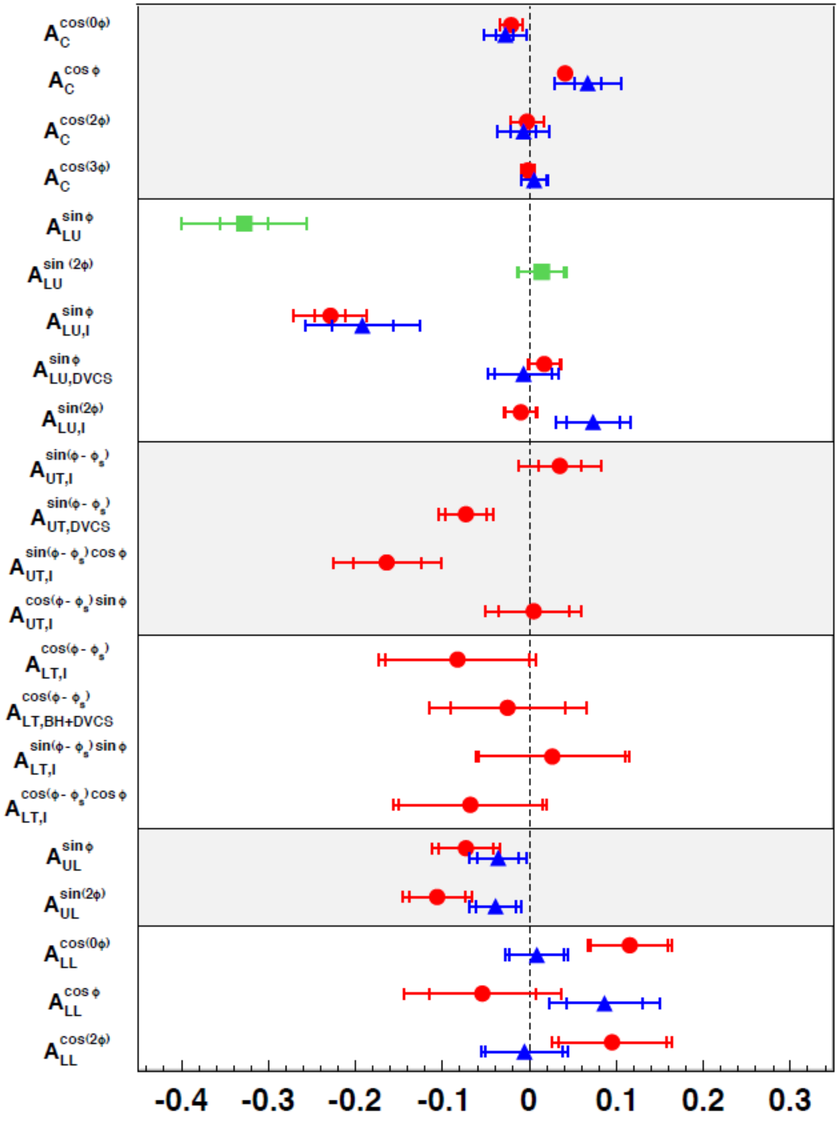
$$\Delta\sigma_{LU} \propto \sin\varphi\, Im\{F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} + kF_2\mathcal{E}\}d\varphi$$

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





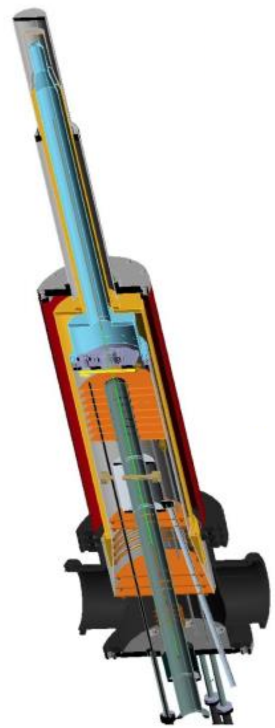
HERMES measurements



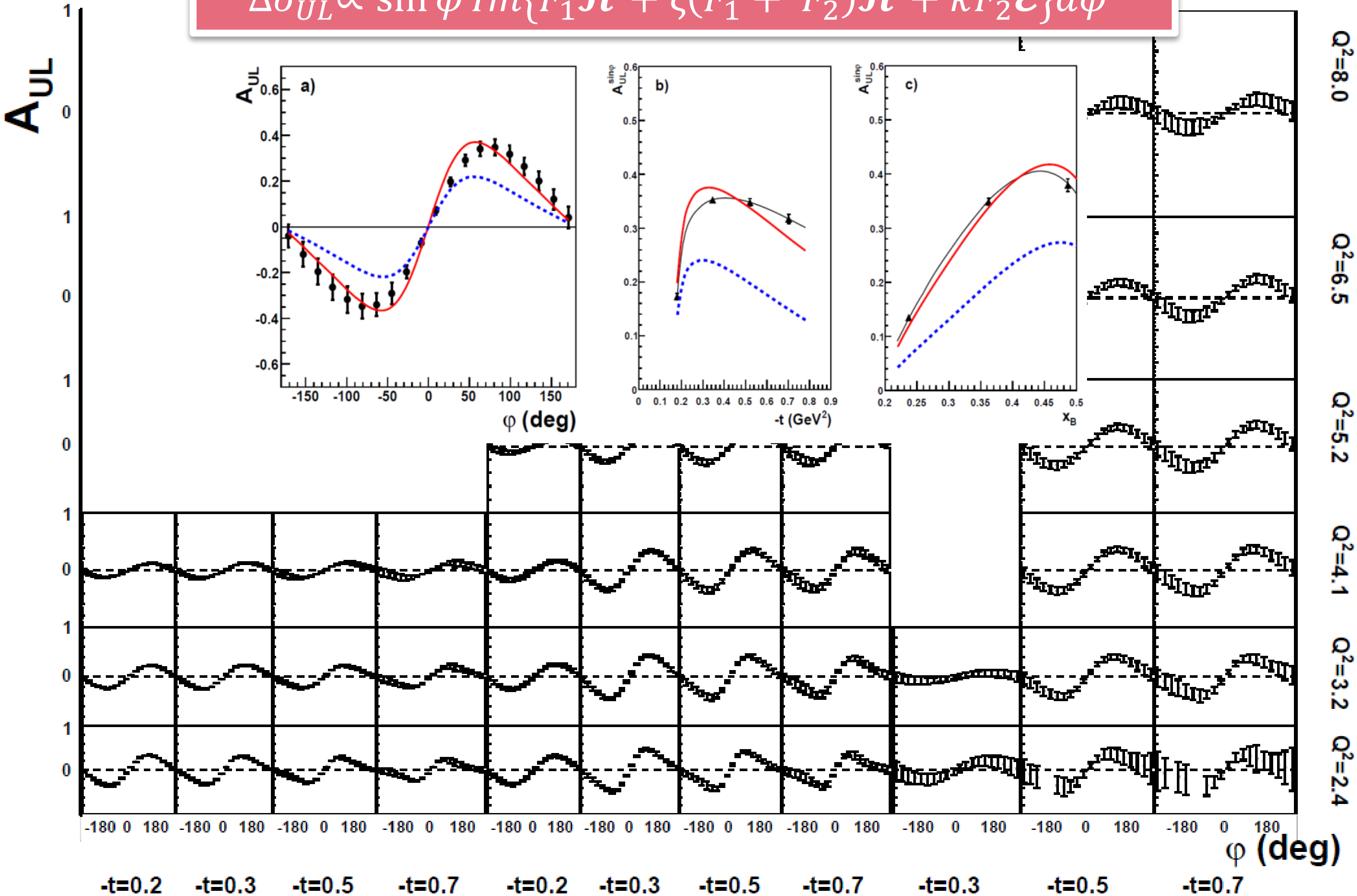
hydrogen
deuterium
hydrogen pure

Longitudinal Target-Spin Asymmetry: E12-06-119

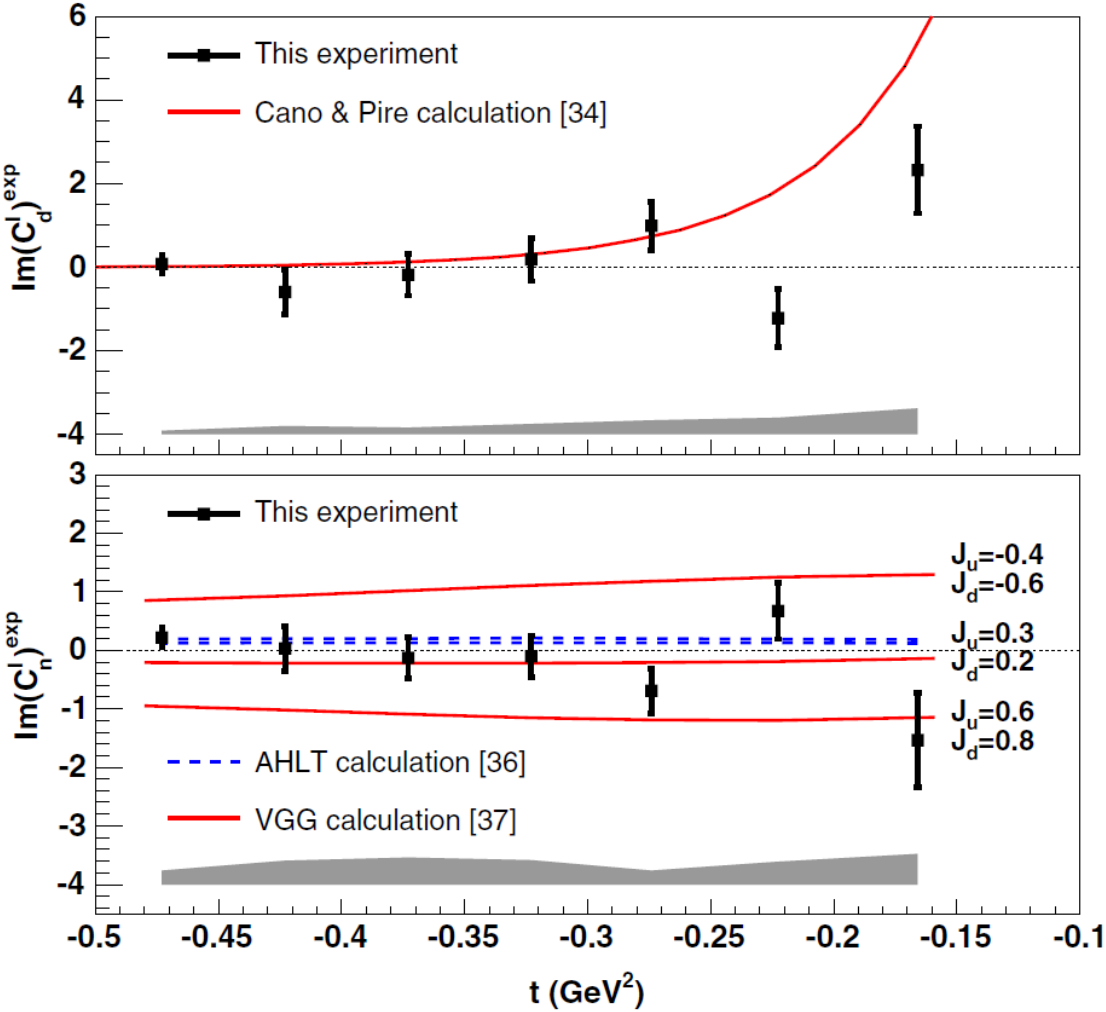
$$\Delta\sigma_{UL} \propto \sin\varphi \, Im\{F_1\widetilde{\mathcal{H}} + \xi(F_1 + F_2)\mathcal{H} + kF_2\mathcal{E}\}d\varphi$$



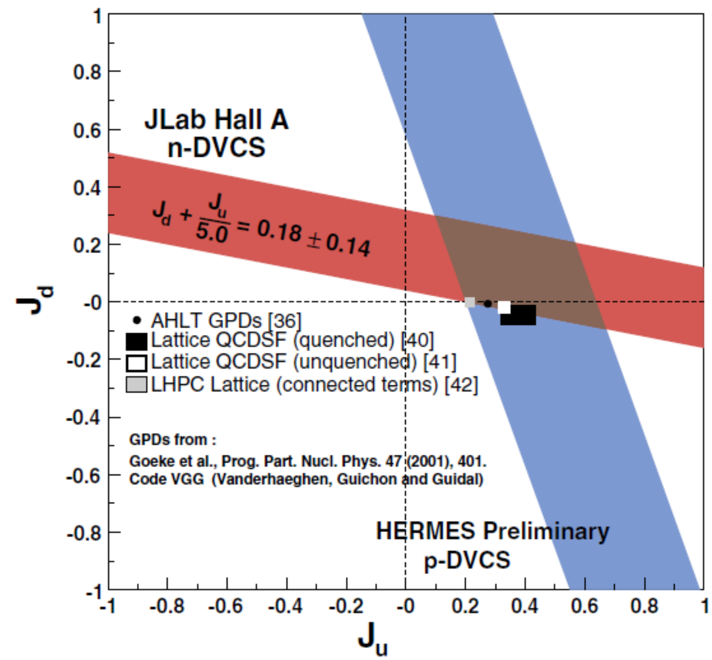
Dynamically-polarized NH_3 target



DVCS on the neutron in Hall-A - results



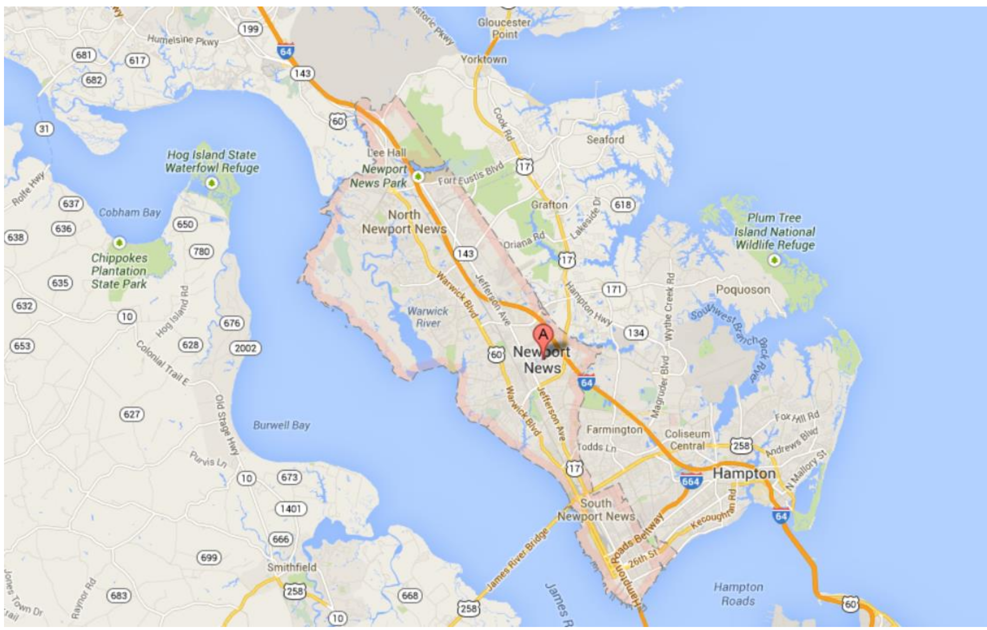
First experimental constraint on the parametrization of $E^q \rightarrow$ it is translated, whitin a model, in a constraint on the quark orbital angular momentum



Thomas Jefferson National Accelerator Facility

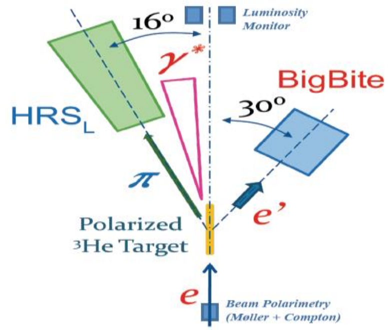
The ***CEBAF (Continuous Electron Beams Accelerator Facility)*** operates in the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA). The Cebaf:

- provides a continuous electron beam with a duty factor ~ 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 ~ 85%



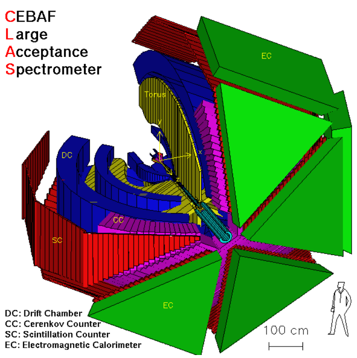
The three experimental Halls@JLab

The CEBAF provides longitudinally-polarized electrons to 3 experimental Halls, characterized by different and complementary characteristics.



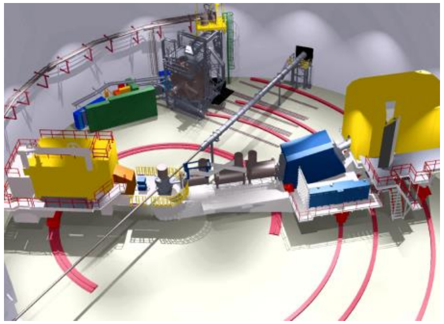
Hall-A: High-resolution spectrometers ($^{\delta p}/_{p} \sim 10^{-4}$), measurements with well-defined kinematics at very-high luminosity

NIM A 522, 294 (2004)



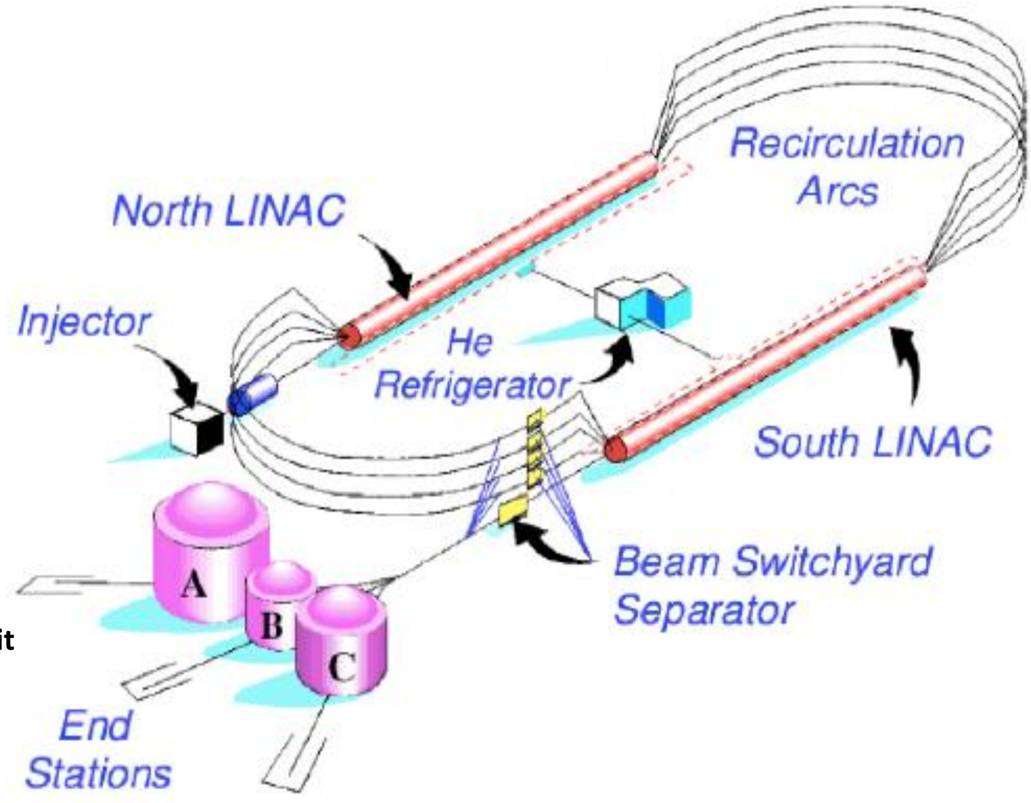
Hall-B: high luminosity, Large acceptance, Multi-particle final state measurements

NIM A 503, 513 (2003)

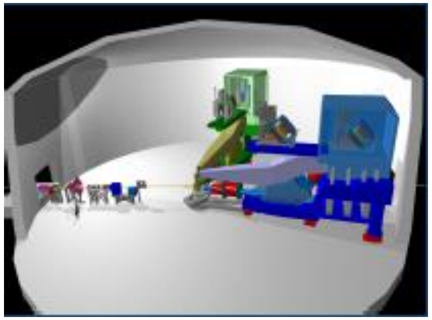


Hall C: High momentum spectromer and Short Orbit Spectrometer—well-controlled acceptance for precise cross section measurements

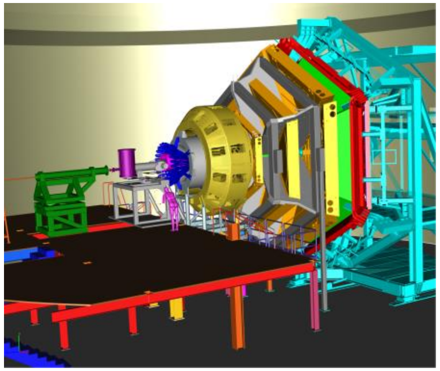
PRC 78, 045202 (2008)



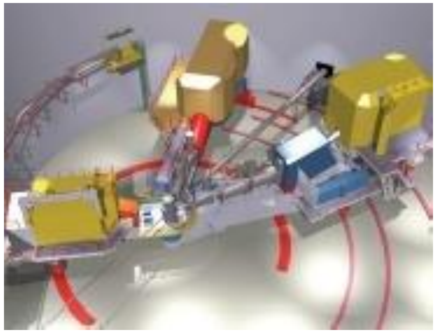
The 12-GeV upgrade



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

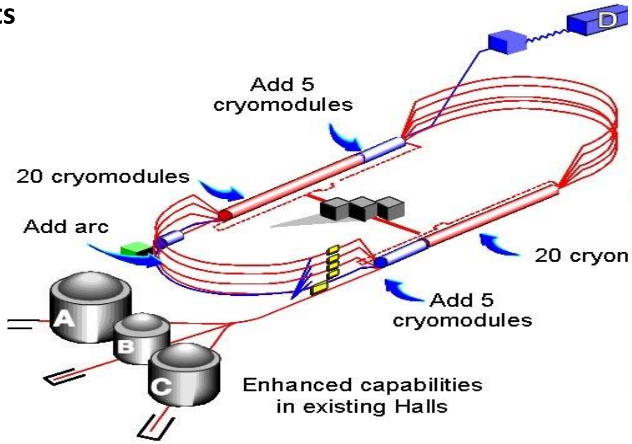


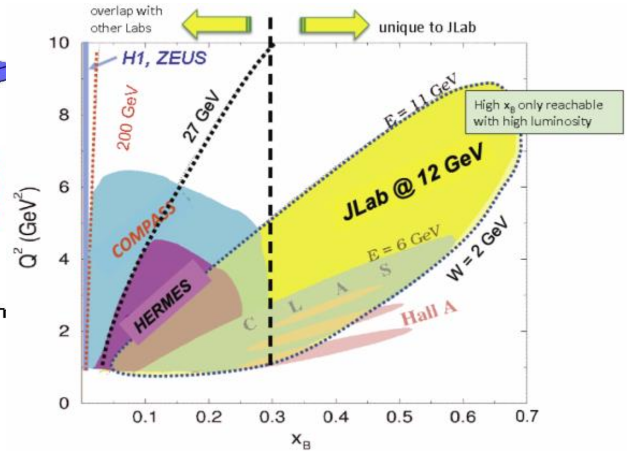
CLAS12: large acceptance, high luminosity

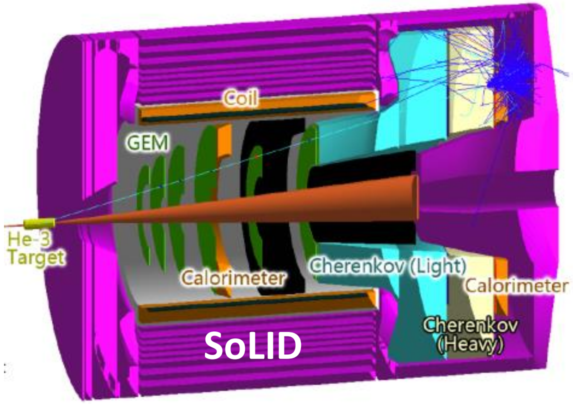


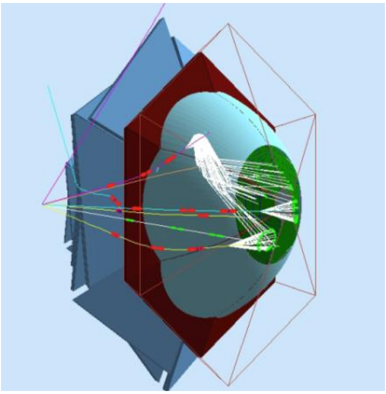
Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles

4 experimental halls with a longitudinally-polarized electron beam of E_e– up to 12 GeV.



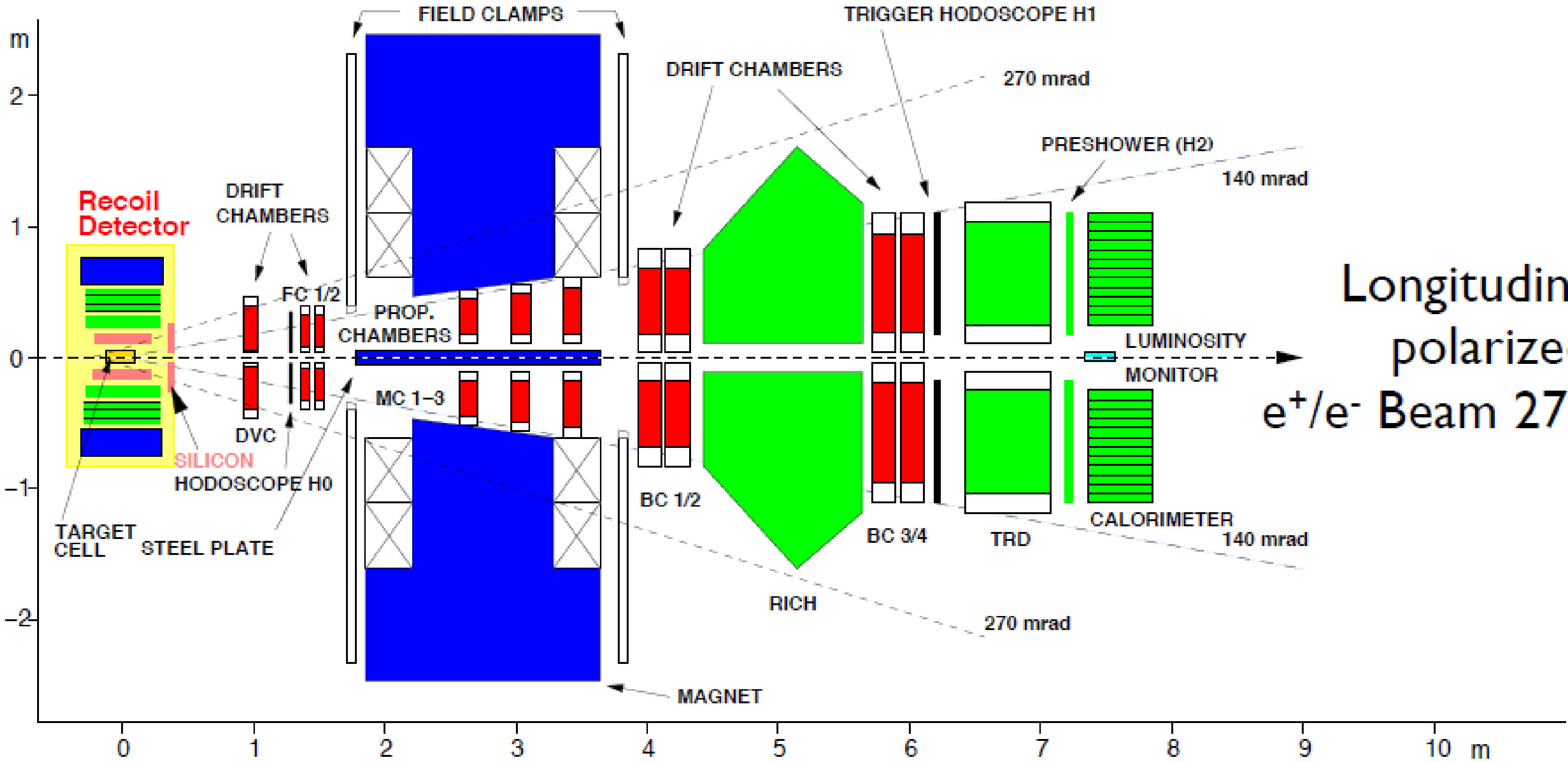






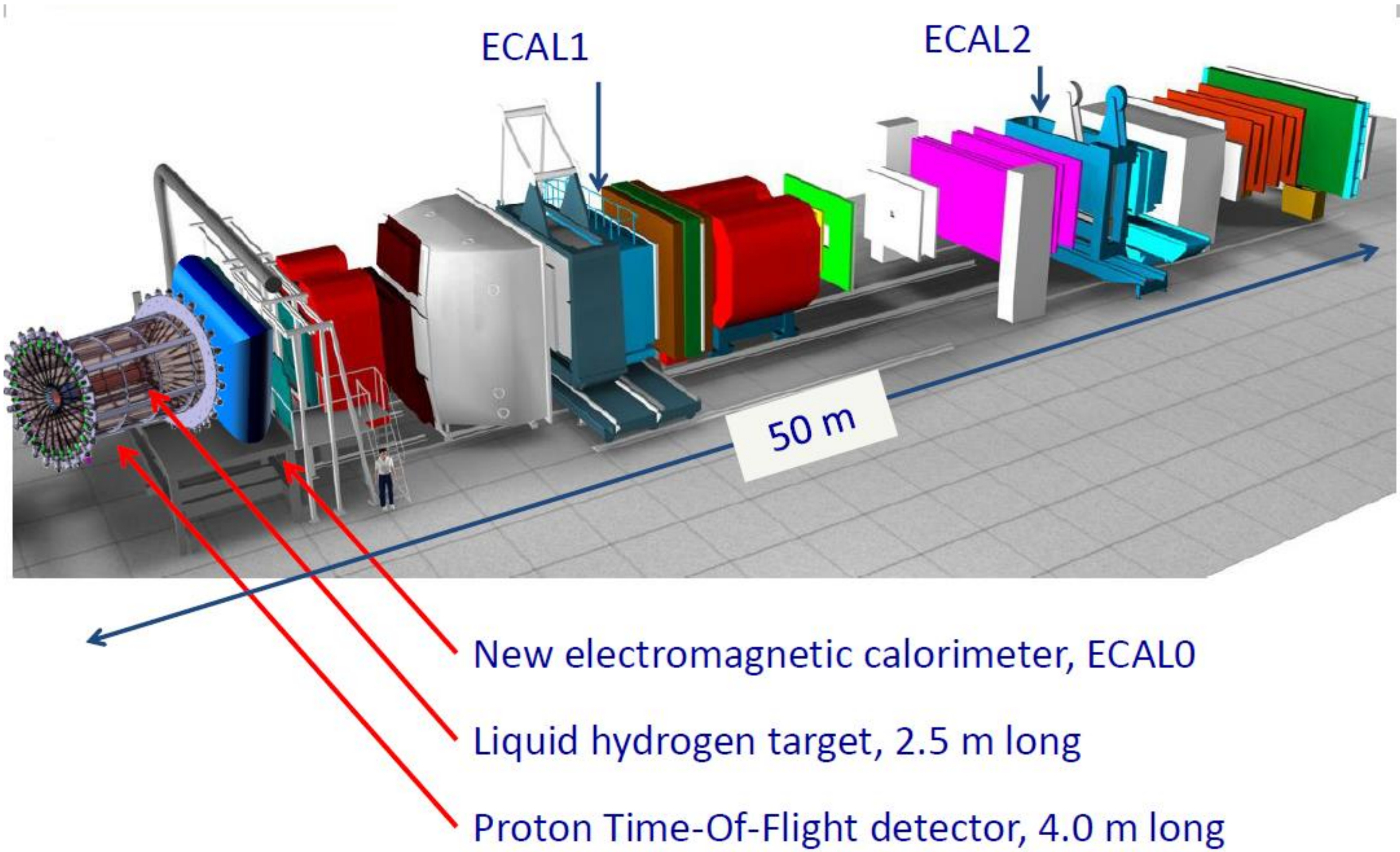
RICH for CLAS12

Hermes setup



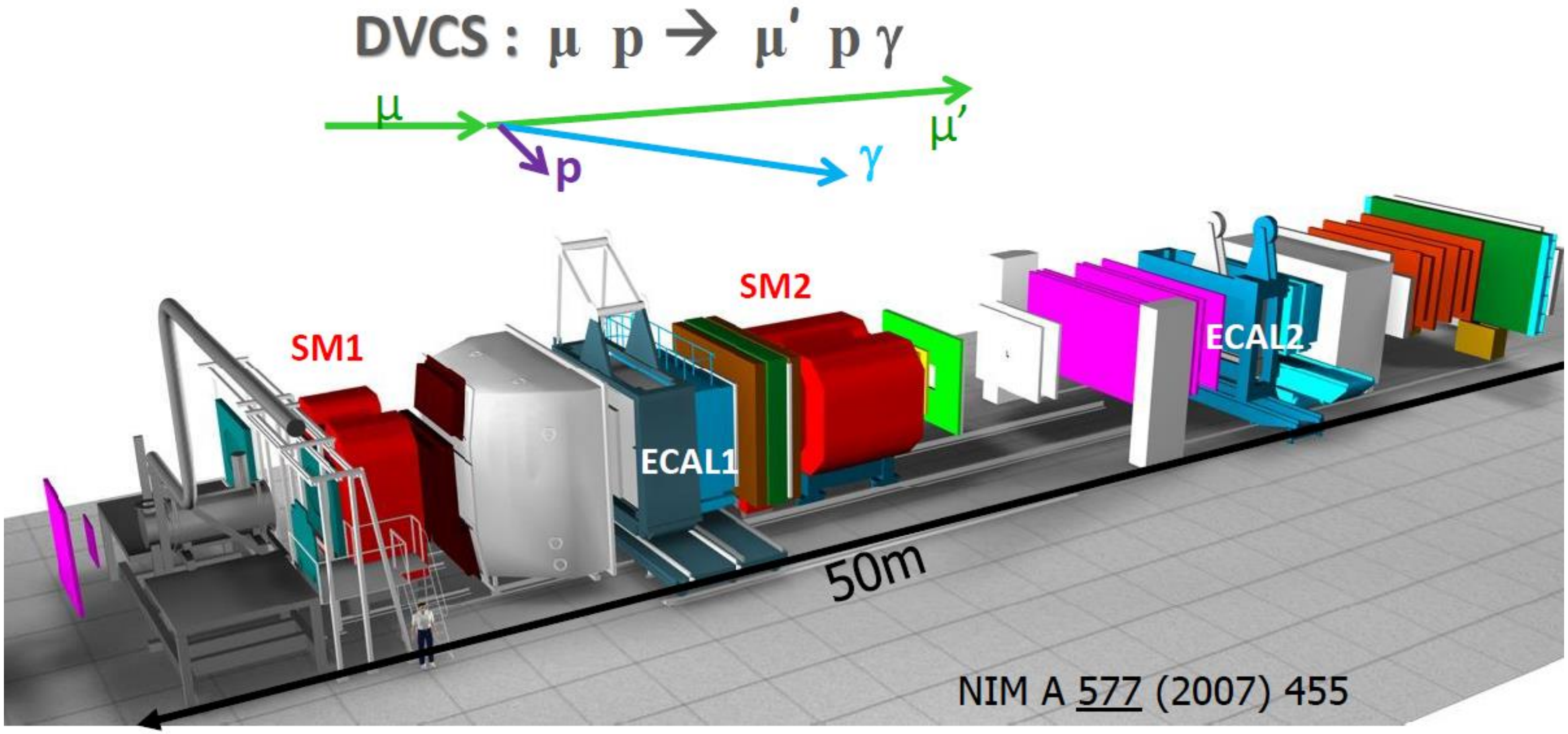
Longitudinally polarized e^+/e^- Beam 27.6 GeV

COMPASS(II)



slide from G.K. Mallot

COMPASS



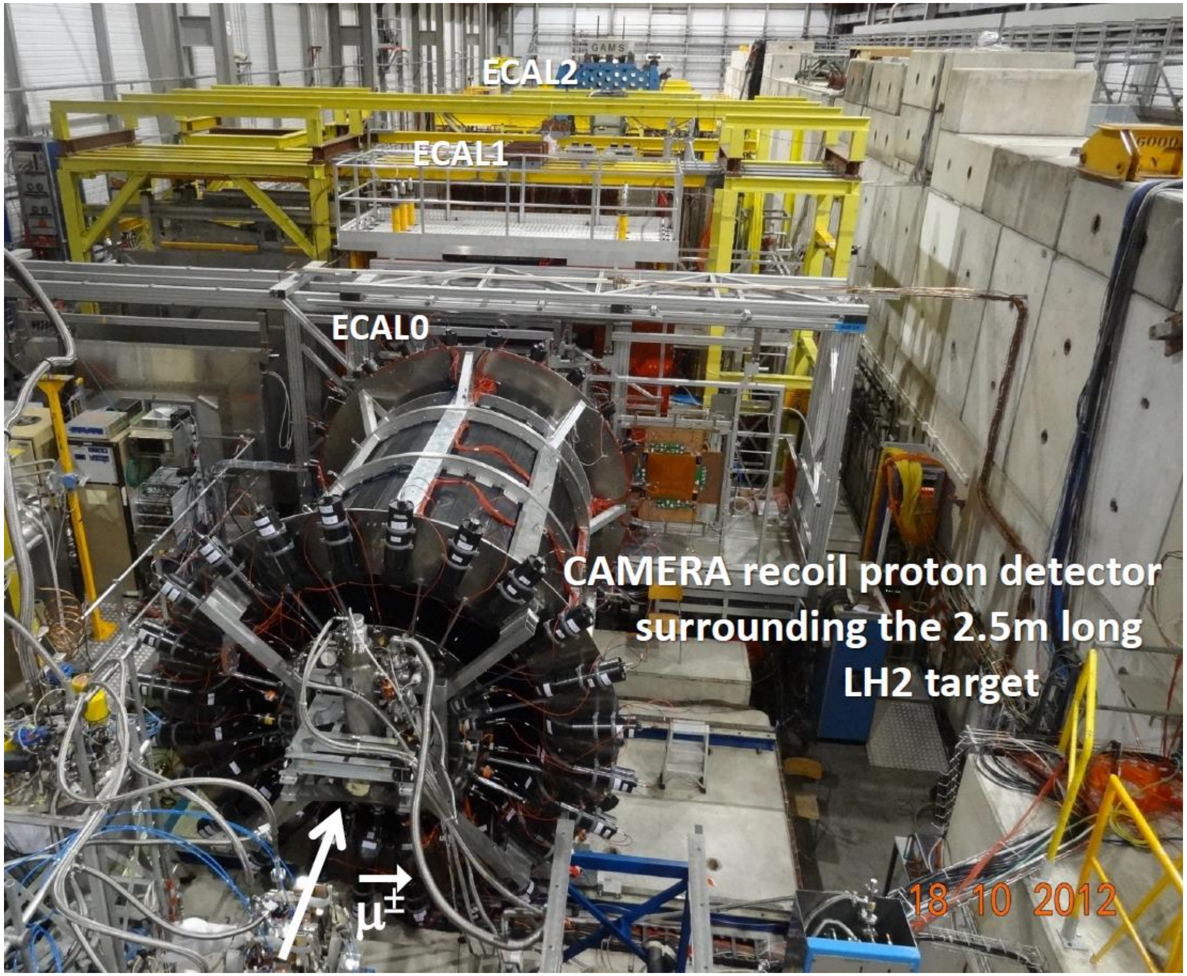
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

- Ring Imaging Cerenkov Counter
- Electromagnetic calorimeters (**ECAL1** and **ECAL2**)
- Hadronic calorimeters
- Hadron absorbers

slide from N. D'Hose

COMPASSII setup



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