Experimental studies of Generalized Parton Distributions

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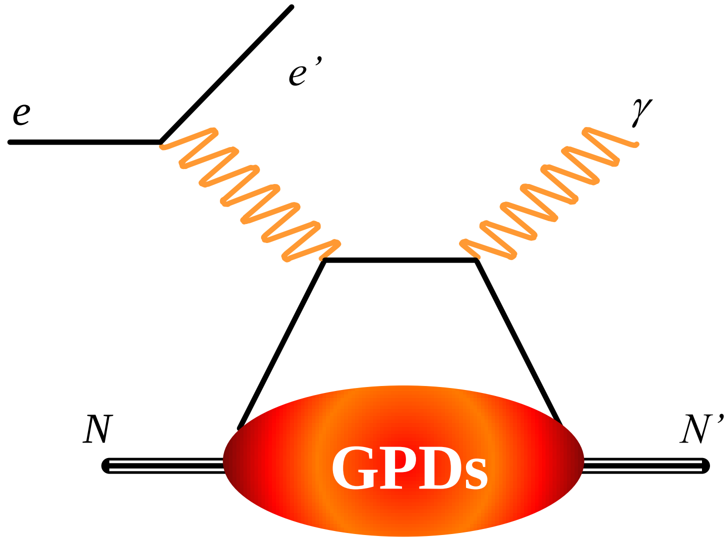
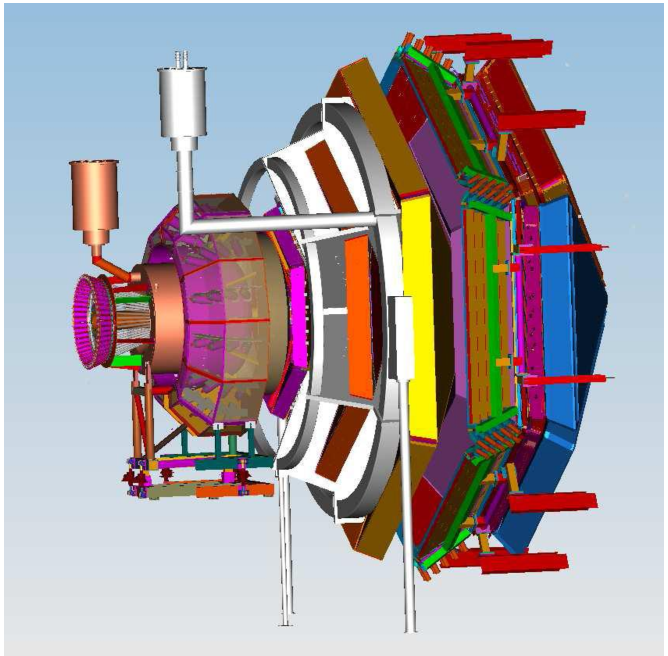
for the CLAS Collaboration

EUNPC2015
4/9/2015, Groningen



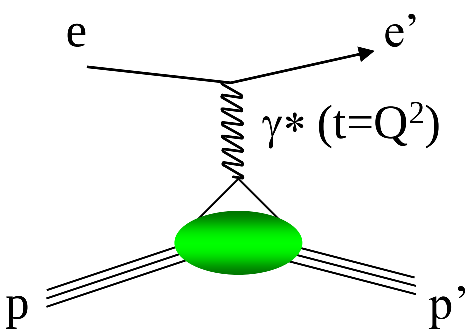


- **Interest of GPDs**
- **GPDs and Deeply Virtual Compton Scattering**
- **New DVCS results from Jefferson Lab**
- **The JLab 12 GeV upgrade**
- **Future JLab experiments on DVCS**

Electron-nucleon scattering to study nucleon structure

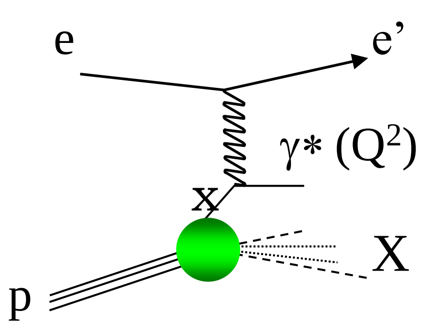
Electrons are **structureless** and interact only **electromagnetically**

- 1950: **Elastic scattering** ep→e'p' (Hofstadter, Nobel prize 1961)

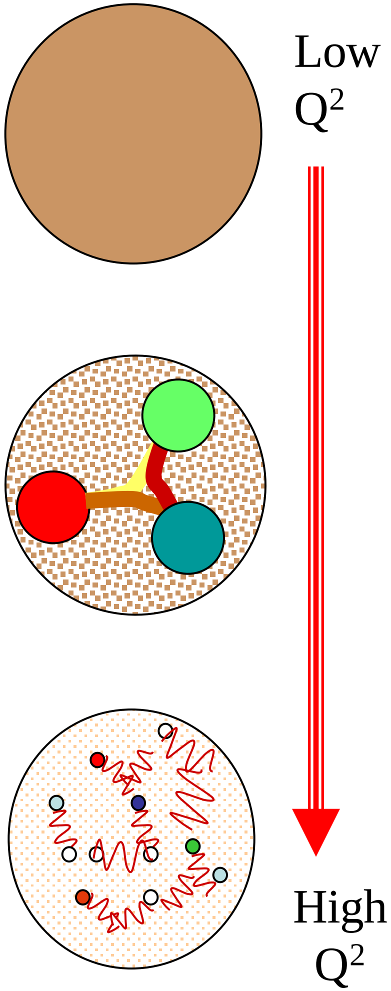


- The proton is **not a point-like object**
- Measurement of charge and current distributions of the proton: **form factors ($F_1(t)$, $F_2(t)$)**

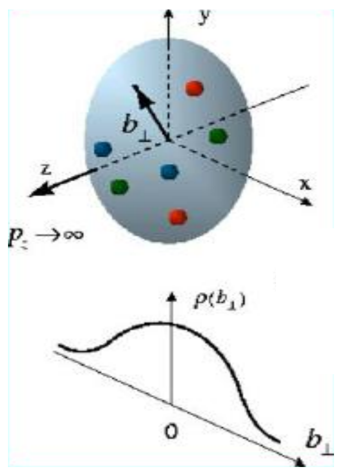
- 1967: **Deep inelastic scattering** (DIS) ep→e'X (Friedman, Kendall, Taylor, Nobel prize 1990)



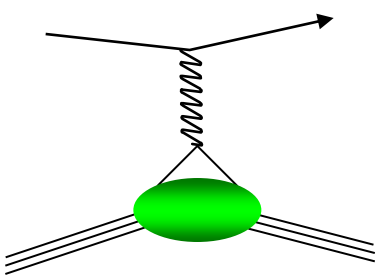
- Discovery of the **quarks** (or "partons")
- Measurement of the momentum and spin distributions of the partons: **q(x), Δq(x)**

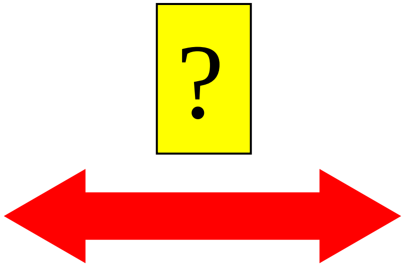


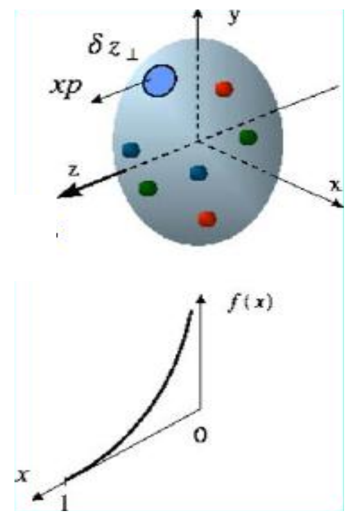
Electron-proton scattering: yesterday



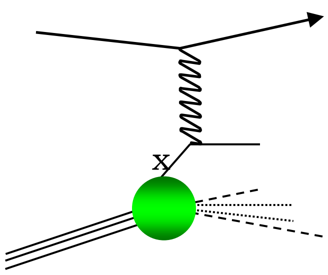
Form factors:
transverse quark distribution in coordinate space





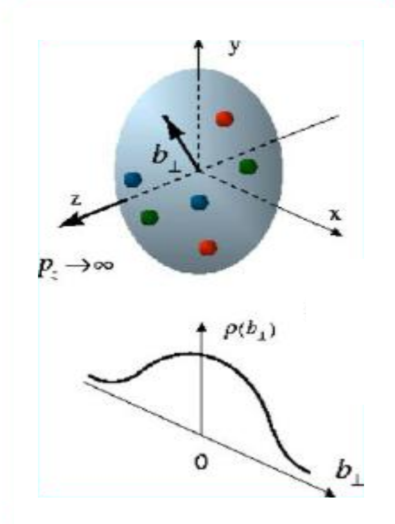


Parton distributions:
longitudinal quark distribution in momentum space

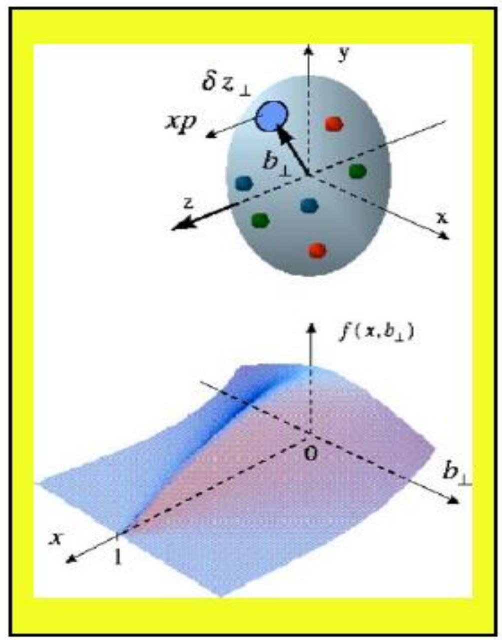


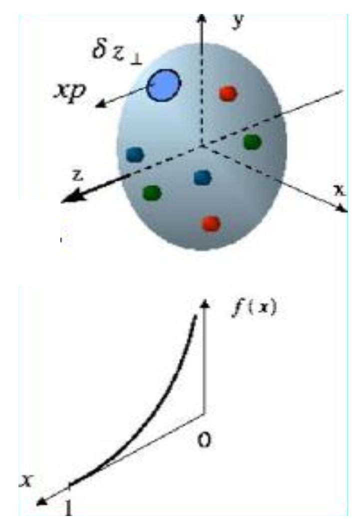
Electron-proton scattering: today

GPDs: H, E, $\tilde{H}$, $\tilde{E}$
Fully correlated quark distributions in both coordinate and momentum space

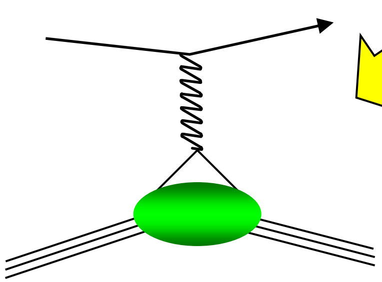


Form factors: **transverse quark distribution** **in coordinate space**





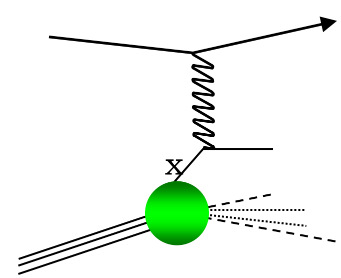
Parton distributions: **longitudinal quark distribution** **in momentum space**



$$\int H(x,\xi,t)dx = F_1(t) \ (\forall \ \xi)$$
$$\int E(x,\xi,t)dx = F_2(t) \ (\forall \ \xi)$$

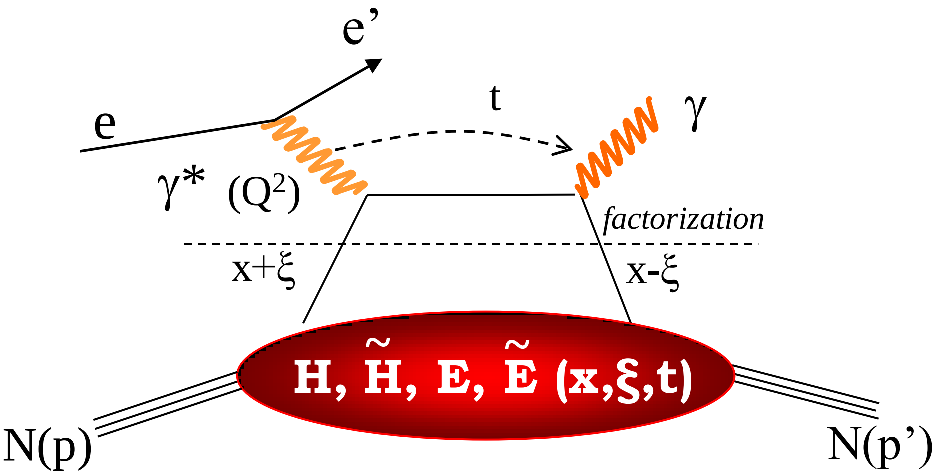
Accessible in hard exclusive processes

High Q^2 Final state known



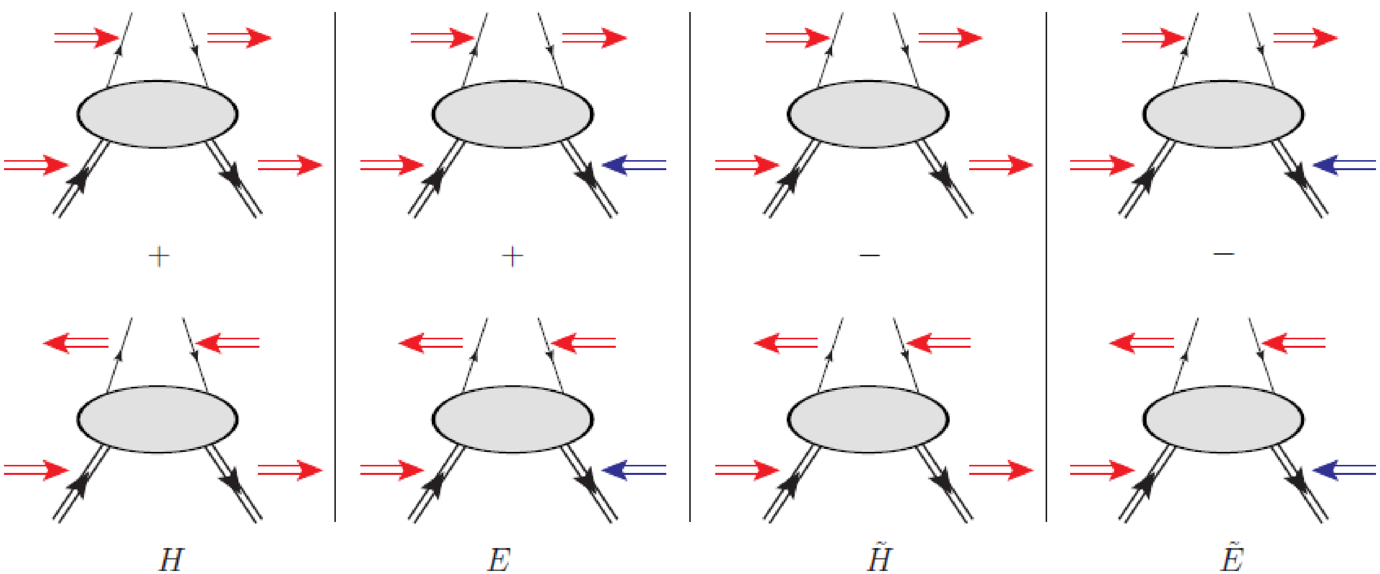
$$H(x,0,0) = q(x),$$
$$\tilde{H}(x,0,0) = \Delta q(x)$$

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, ν (fixed x_B), $t \ll Q^2$



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

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

conserve nucleon spin — **Vector: H (x,ξ,t)** — **Axial-Vector: H̃ (x,ξ,t)**

flip nucleon spin — **Tensor: E (x,ξ,t)** — **Pseudoscalar: Ẽ (x,ξ,t)**

Properties and "virtues" of GPDs

$$\int H(x,\xi,t)dx = F_1(t) \quad \forall \xi$$
$$\int E(x,\xi,t)dx = F_2(t) \quad \forall \xi$$
$$\int \tilde{H}(x,\xi,t)dx = G_A(t) \quad \forall \xi$$
$$\int \tilde{E}(x,\xi,t)dx = G_P(t) \quad \forall \xi$$

Link with **FFs**

$$H(x,0,0) = q(x)$$
$$\tilde{H}(x,0,0) = \Delta q(x)$$

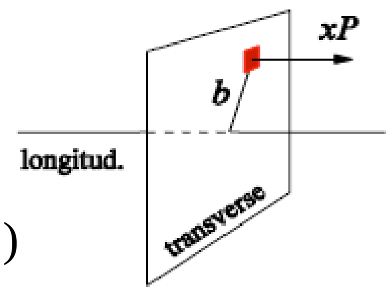
Forward limit: **PDFs** (not for E, Ẽ)

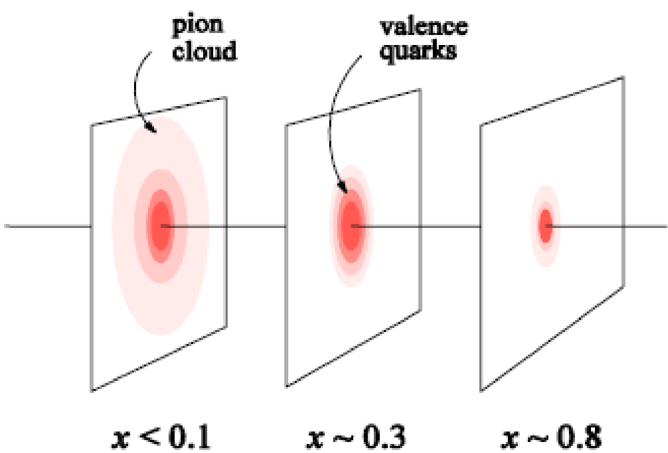
Nucleon tomography

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

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

M. Burkardt, PRD 62, 71503 (2000)





Quark angular momentum (Ji's sum rule)

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

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

Nucleon spin: ½ = ½ ΔΣ + ΔL + ΔG

(½ ΔΣ + ΔL = **J**)

Intrinsic spin of the quarks ΔΣ ≈ 25%

Intrinsic spin on the gluons ΔG ≈ 0 (??)

Orbital angular momentum of the quarks ΔL ?

Accessing GPDs through DVCS

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

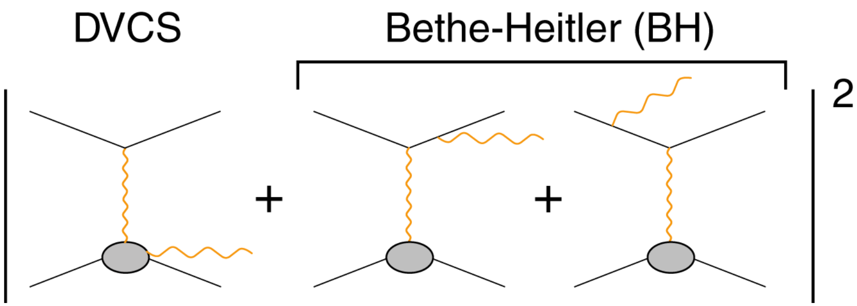
$$T^{DVCS} \sim P\int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi}dx \pm i\pi GPDs(\pm\xi,\xi,t) + \ldots$$

Only ξ and t are accessible experimentally

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

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

σ(eN ⟶ eNγ) =

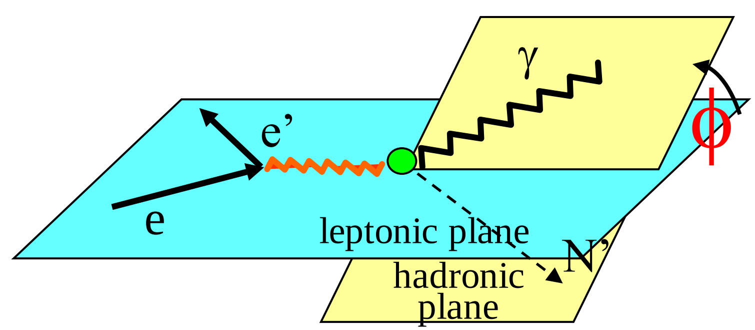


BH is calculable (electromagnetic FFs)

$$\sigma \sim \left|T^{DVCS} + T^{BH}\right|^2 \rightarrow \mathrm{Re}(CFFs) \quad (also\, DSA)$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I\left(DVCS \cdot BH\right) \rightarrow \mathrm{Im}(CFFs)$$

$$A = \frac{\Delta\sigma}{2\sigma} \propto \frac{I\left(DVCS \cdot BH\right)}{\left|BH\right|^2 + \left|DVCS\right|^2 + I}$$



Sensitivity to CFFs of DVCS spin observables

$$A_{LU(UL)} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \frac{s^I_{1,unp(UL)} \sin\phi}{c^{BH}_{0,unp} + c^I_{0,unp} + (c^{BH}_{1,unp} + c^I_{1,unp})\cos\phi}$$

$$A_{LL} = \frac{\sigma^{++} + \sigma^{+-} - \sigma^{+-} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-} + \sigma^{+-} + \sigma^{+-}} \propto \frac{c^{BH}_{0,LP} + c^I_{0,LP} + (c^{BH}_{1,LP} + c^I_{1,LP})\cos\phi}{c^{BH}_{0,unp} + c^I_{0,unp} + (c^{BH}_{1,unp} + c^I_{1,unp})\cos\phi}$$

Twist-2 approximation ($-t \ll Q^2$)

($\xi = x_B/(2-x_B)$ $k = -t/4M^2$)

Proton Neutron

Polarized beam, unpolarized target:

$s^I_{1,unp} \sim \sin\phi \; Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}$ → $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, longitudinal target:

$s^I_{1,UL} \sim \sin\phi Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \ldots\}$ → $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

$c^I_{1,LP} \sim (A + B\cos\phi) Re\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) \ldots\}$ → $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

Unpolarized beam, transverse target:

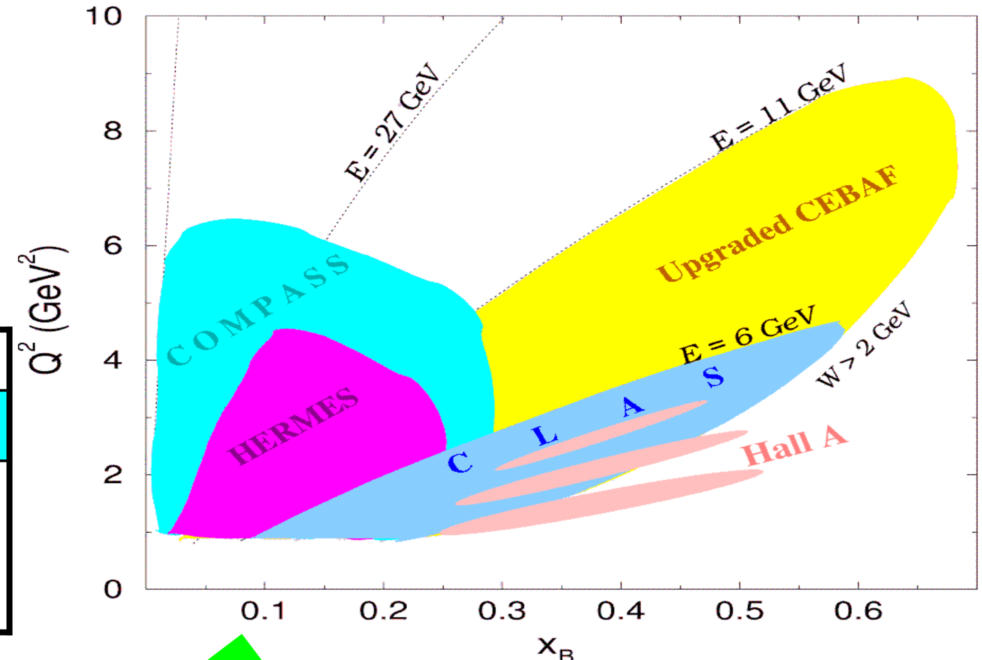
$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi) Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ → $Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n\}$

DVCS experiments worldwide

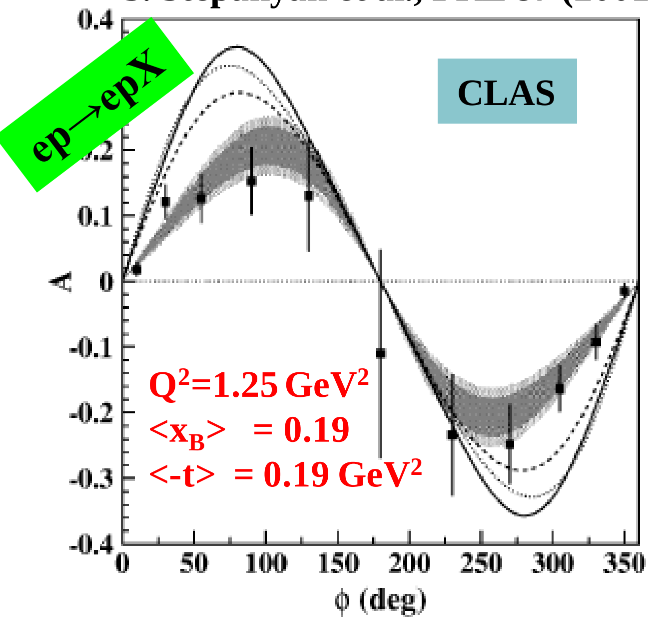
JLAB	
Hall A	*CLAS (Hall B)*
p,n-DVCS (Bpol.) CS	p-DVCS BSA,lTSA,DSA,CS

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

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



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

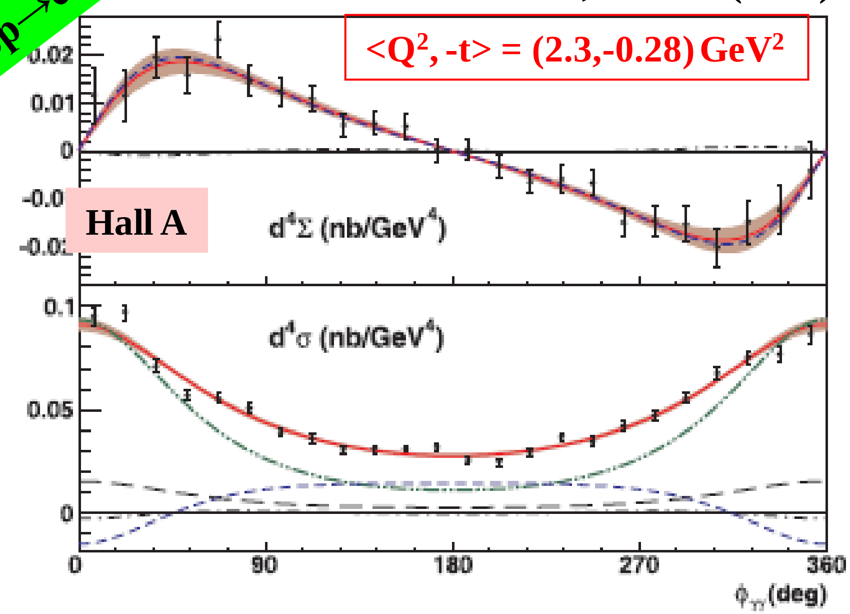


CLAS: first observation of DVCS-BH interference

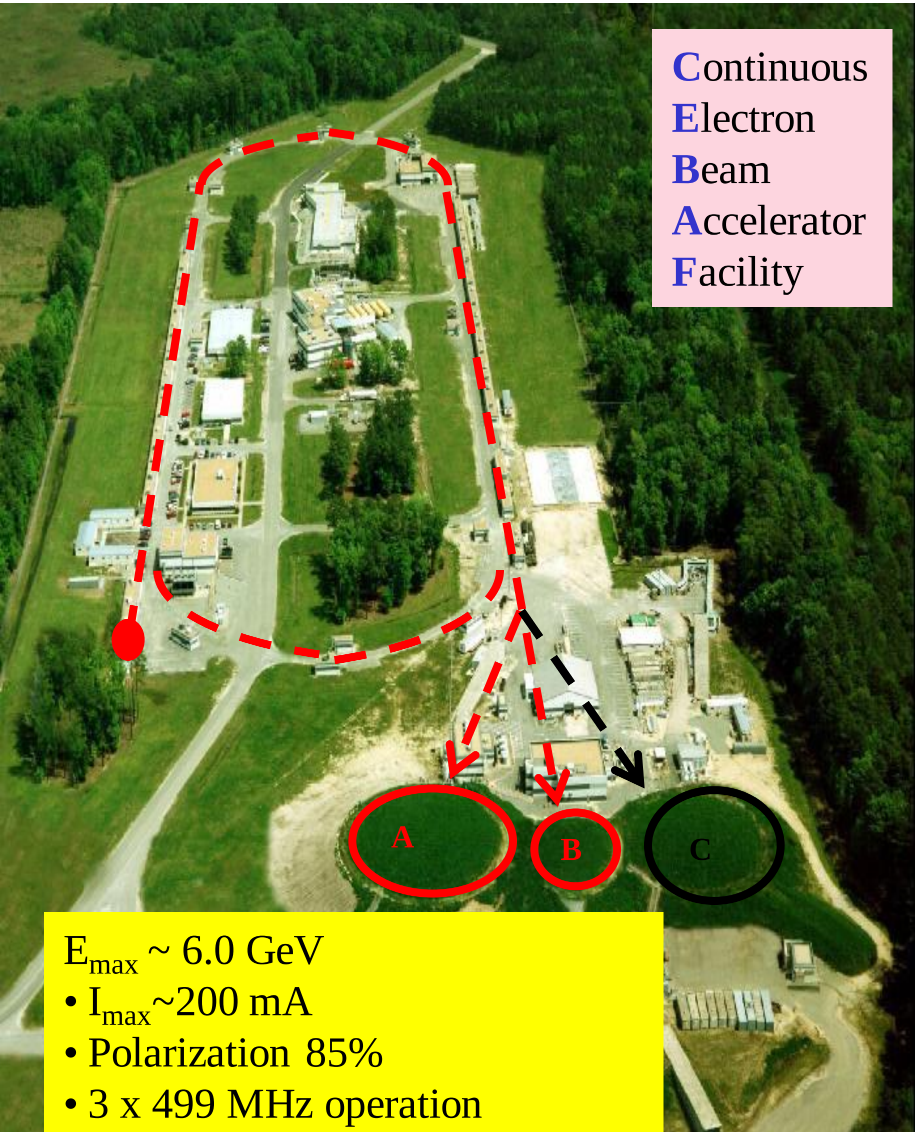
Hall A: proof of scaling for DVCS

ep→eγX

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



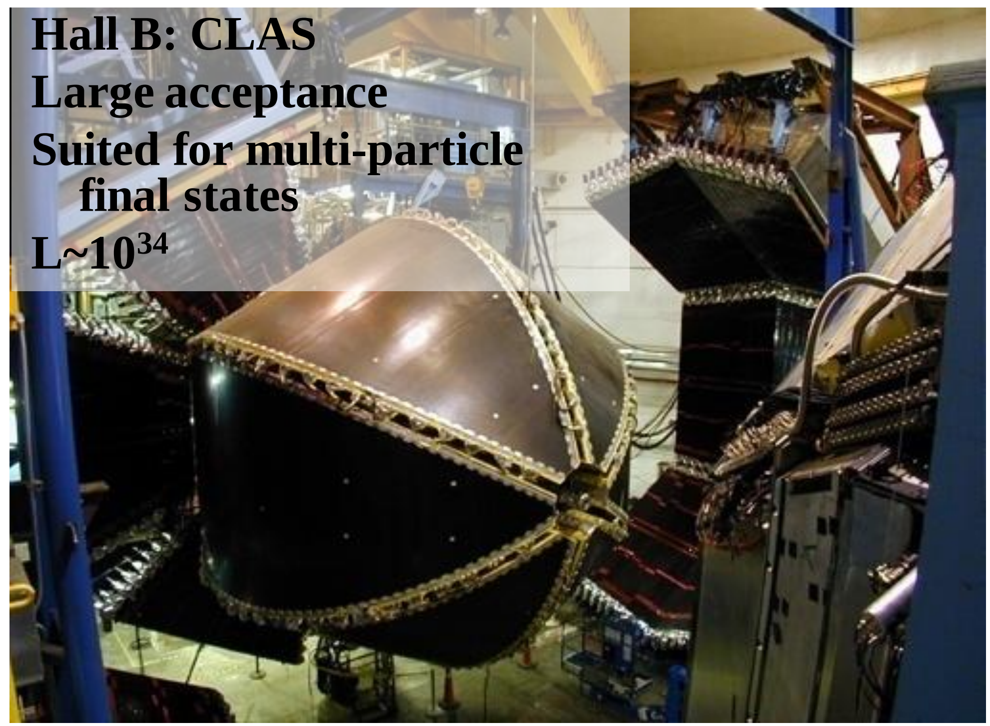
JLab@6 GeV



Continuous
Electron
Beam
Accelerator
Facility

E_{max} ~ 6.0 GeV
- I_{max}~200 mA
- Polarization 85%
- 3 x 499 MHz operation
- Simultaneous delivery to 3 halls
- Shutdown in May 2012

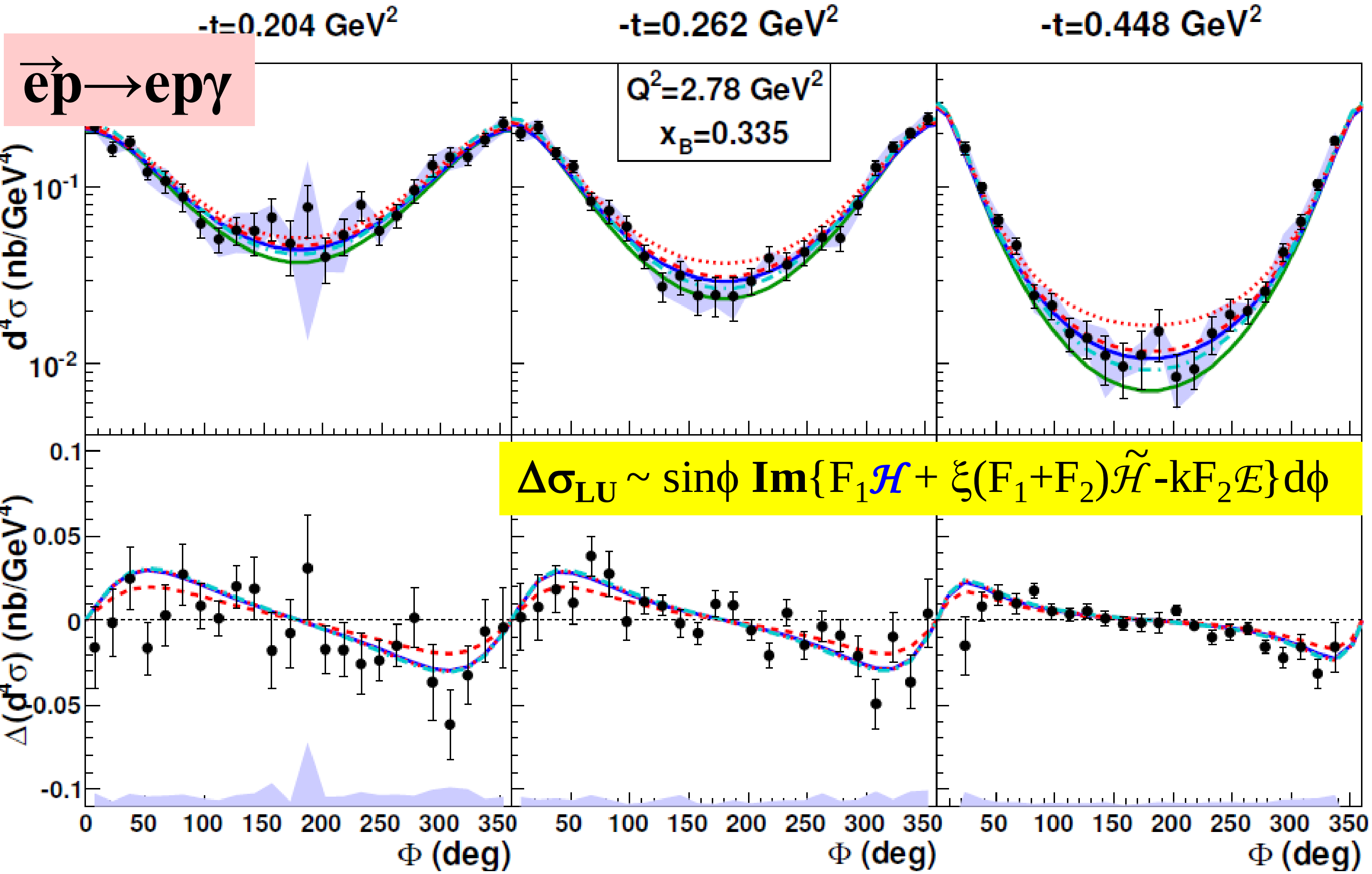
Hall A: 2 HRS
High resolution
High luminosity (L~10^{37})
Limited coverage



Hall B: CLAS
Large acceptance
Suited for multi-particle final states
L~10^{34}

CLAS: unpolarized and beam-polarized cross sections

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



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

H.S. Jo et al., arXiv:1504.02009, *submitted to PRL*

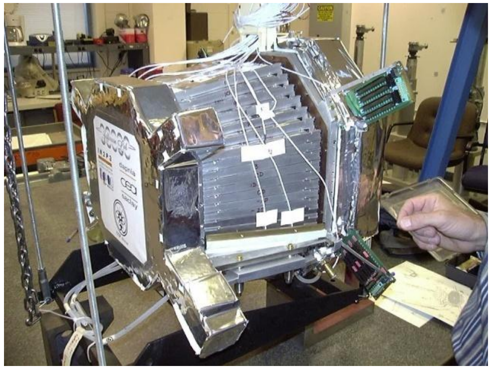
- Largest kinematic ever covered
- Two observables extracted

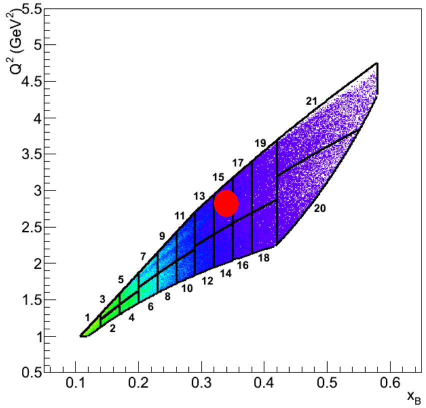
BH — VGG — KM10 ······ KM10a - - -

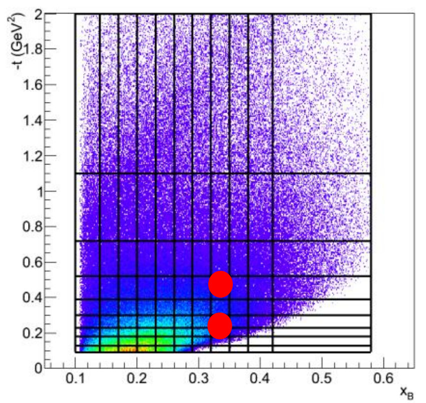
KM10a model fits Hall A 2006 data using « anomalous » $\tilde{H}$

- Data taken in **2005, e1-dvcs**
- Beam energy ~ **5.75 GeV**
- Beam polarization ~ **80%**
- Target **LH_2**
- **Inner Calorimeter (IC)**

21 Q^2-x_B bins, 9 t bins, 24 φ bins







Extraction of Compton Form Factors from DVCS observables

GPDs cannot directly be extracted from DVCS observables, one can access Compton Form Factors:

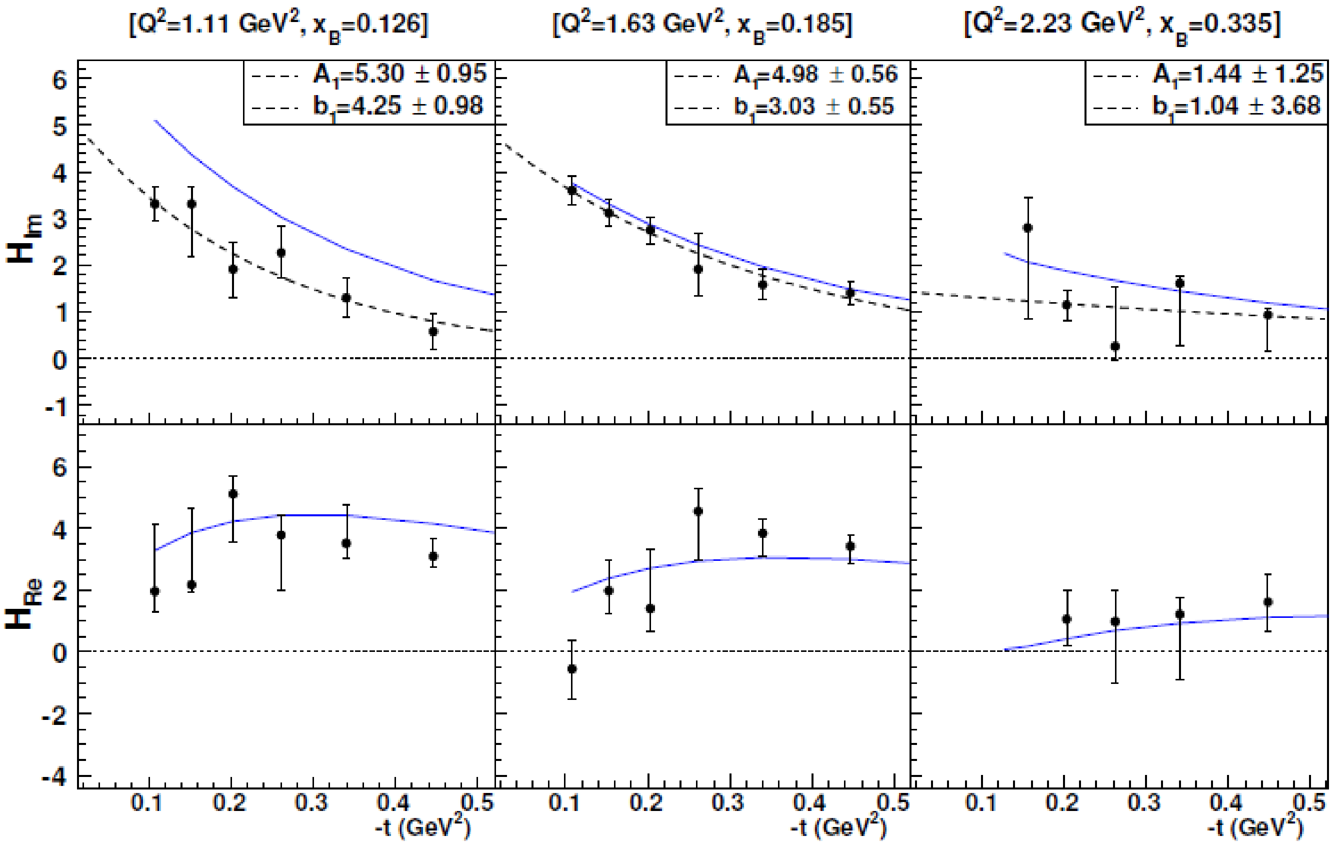
8 CFF

$$\left\{\begin{aligned}
&\mathrm{Re}(\mathcal{H}) = P\int_0^1 dx\left[H(x,\xi,t) - H(-x,\xi,t)\right]C^+(x,\xi)\\
&\mathrm{Re}(\mathcal{E}) = P\int_0^1 dx\left[E(x,\xi,t) - E(-x,\xi,t)\right]C^+(x,\xi)\\
&\mathrm{Re}(\tilde{\mathcal{H}}) = P\int_0^1 dx\left[\tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)\right]C^-(x,\xi)\\
&\mathrm{Re}(\tilde{\mathcal{E}}) = P\int_0^1 dx\left[\tilde{E}(x,\xi,t) + \tilde{E}(-x,\xi,t)\right]C^-(x,\xi)\\
&\mathrm{Im}(\mathcal{H}) = H(\xi,\xi,t) - H(-\xi,\xi,t)\\
&\mathrm{Im}(\mathcal{E}) = E(\xi,\xi,t) - E(-\xi,\xi,t)\\
&\mathrm{Im}(\tilde{\mathcal{H}}) = \tilde{H}(\xi,\xi,t) - \tilde{H}(-\xi,\xi,t)\\
&\mathrm{Im}(\tilde{\mathcal{E}}) = \tilde{E}(\xi,\xi,t) - \tilde{E}(-\xi,\xi,t)
\end{aligned}\right.$$

$$\text{with } C^{\pm}(x,\xi) = \frac{1}{x-\xi} \pm \frac{1}{x+\xi}$$

M. Guidal: **Model-independent fit**, at fixed Q^2, x_B and t of DVCS observables
8 parameters (the CFFs), loosely bound (+/- 5 x VGG prediction)
M. Guidal, Eur. Phys. J. A 37 (2008) 319 & many other papers…

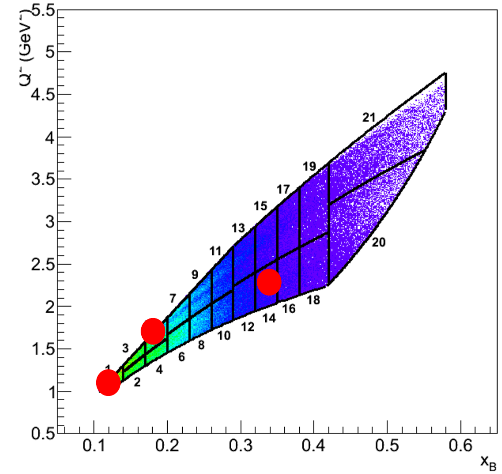
Extraction of CFFs from e1dvcs pol. and unpol. cross sections



CFF fits by M. Guidal
(H and $\tilde{H}$ only)

Ae^{-bt} fit

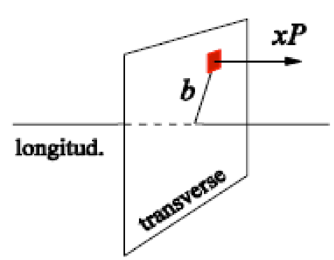
VGG predictions

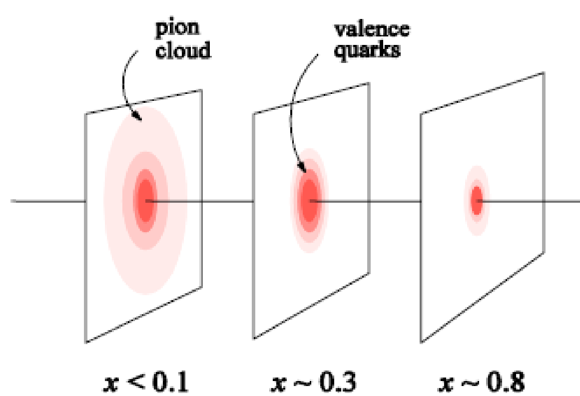


$$q(x,b_\perp)=\int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} H(x,0,-\Delta_\perp^2)$$

***Im($\mathcal{H}_p$)*, flatter t slope at high x_B: faster quarks (valence) at the core of the nucleon, slower quarks (sea) at its periphery**

→ PROTON TOMOGRAPHY



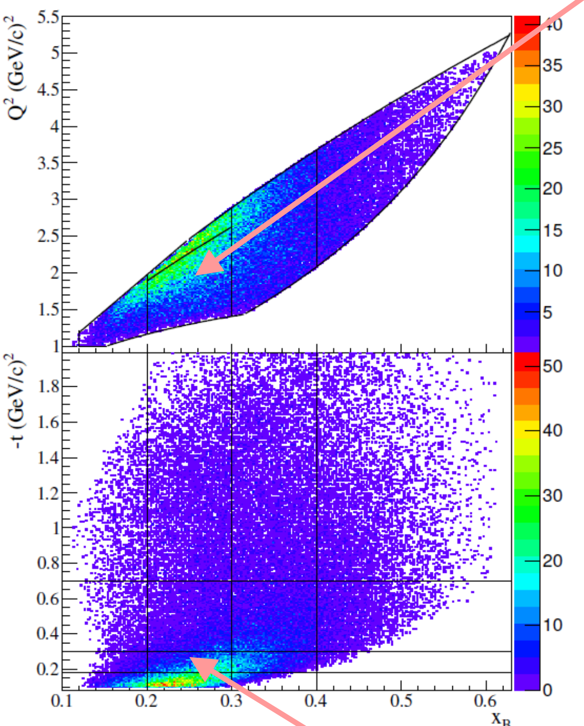


CLAS: DVCS on longitudinally polarized target

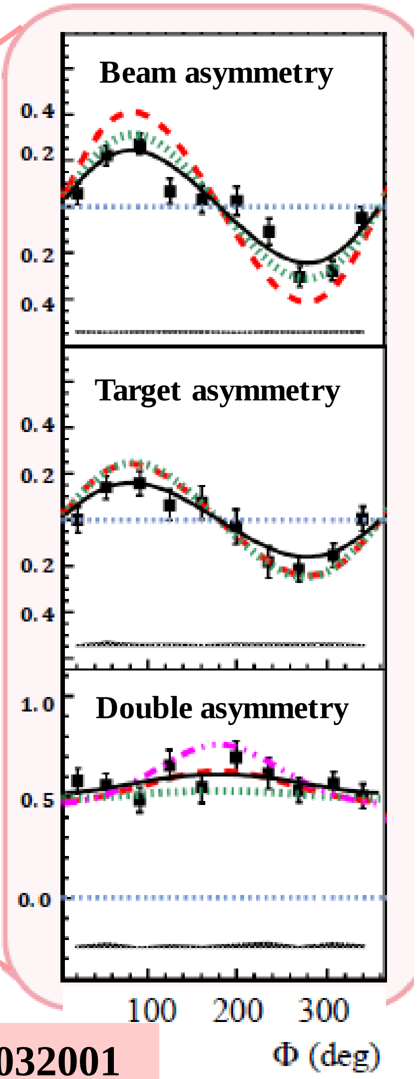
$\vec{e}\vec{p} \to e p \gamma$

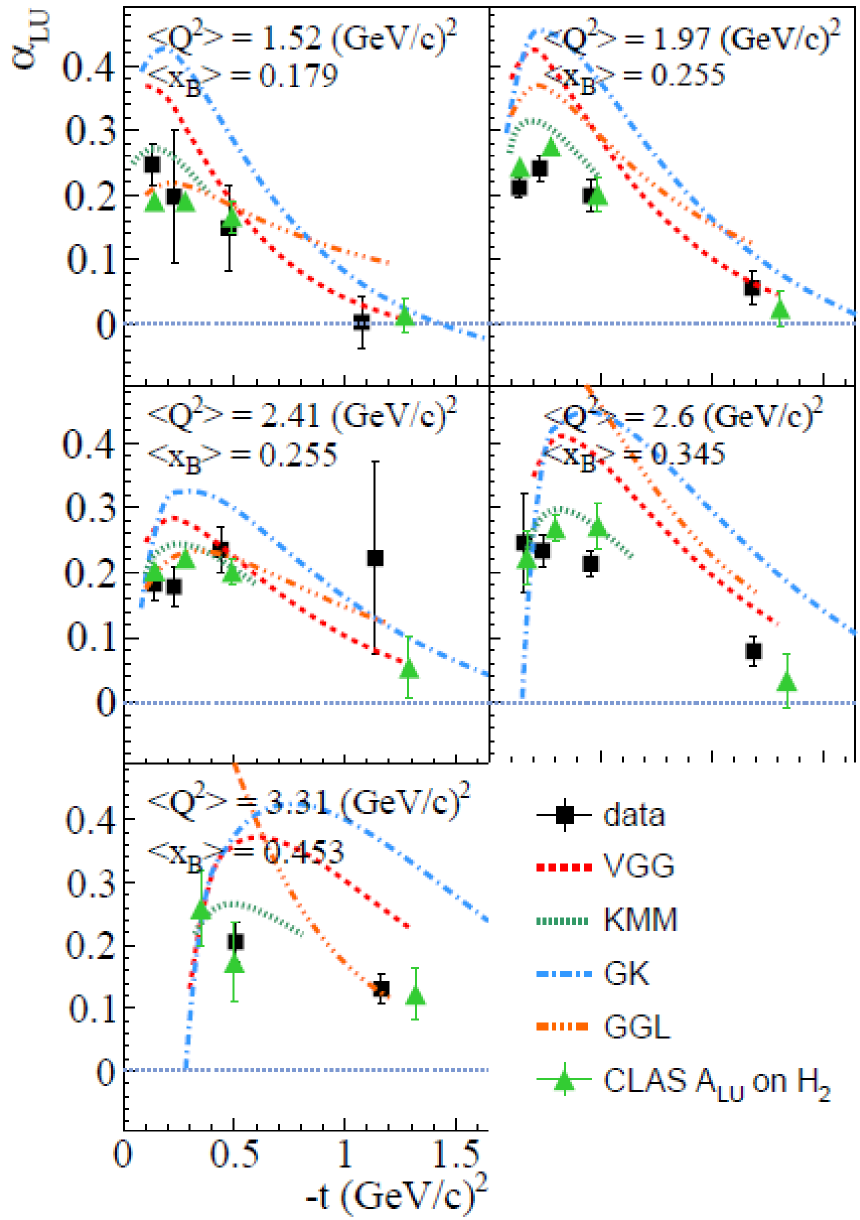
BSA ~ $Im\{\mathcal{H}_p\}$

- Data taken in **2009, eg1-dvcs**
- Beam energy **~5.9 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**



- **5 Q^2-x_B bins**
- **4 t bins**
- **10 ϕ bins**





E. Seder et al., PRL 114 (2015) 032001

CLAS: DVCS on longitudinally polarized target

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

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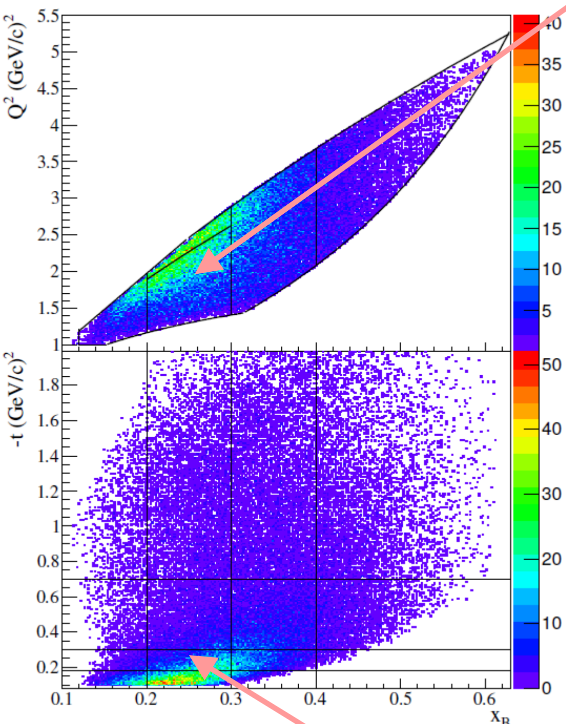

- **5 Q^2-x_B bins**
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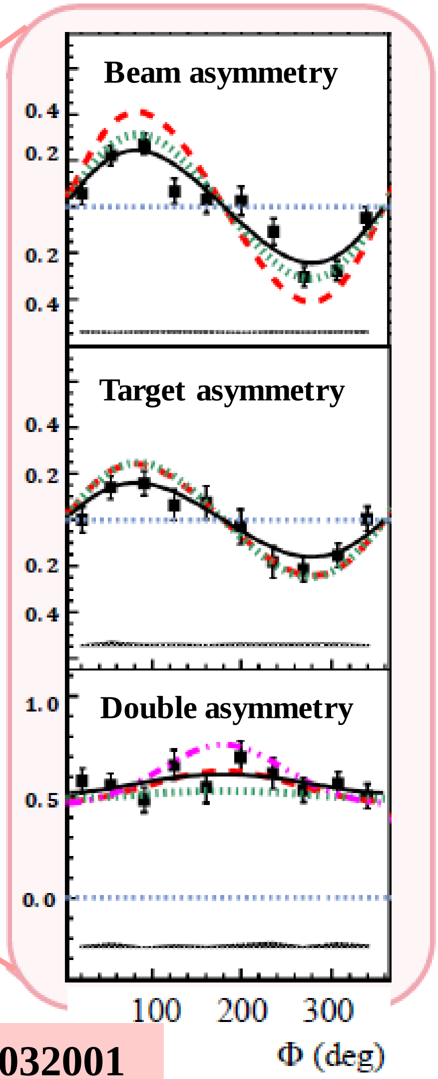
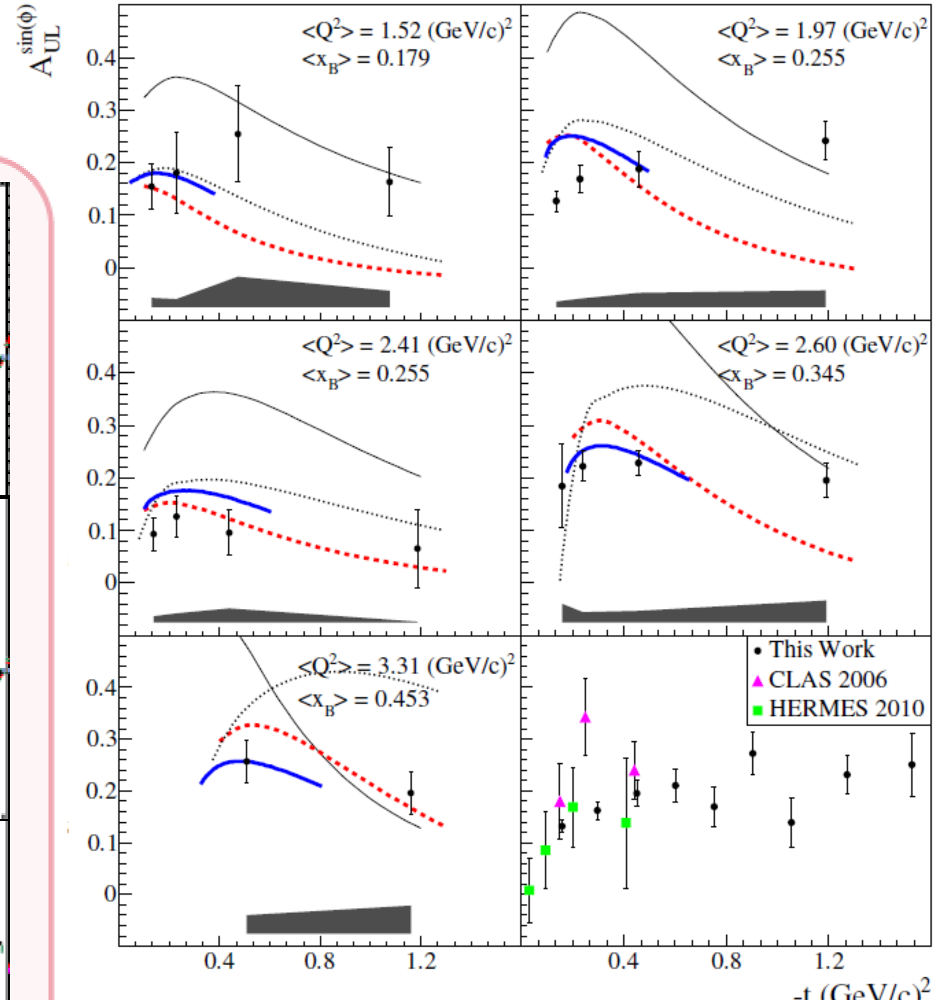


TSA ~ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$



CLAS: $\langle Q^2\rangle$= 2.4 (GeV/c)^2, $\langle x_B\rangle$= 0.31
HERMES: $\langle Q^2\rangle$= 2.459 (GeV/c)^2, $\langle x_B\rangle$= 0.096
CLAS2006: $\langle Q^2\rangle$= 1.82 (GeV/c)^2, $\langle x_B\rangle$= 0.28

- **Improved statistics x10 at low *–t***
- **Extended kinematic coverage**

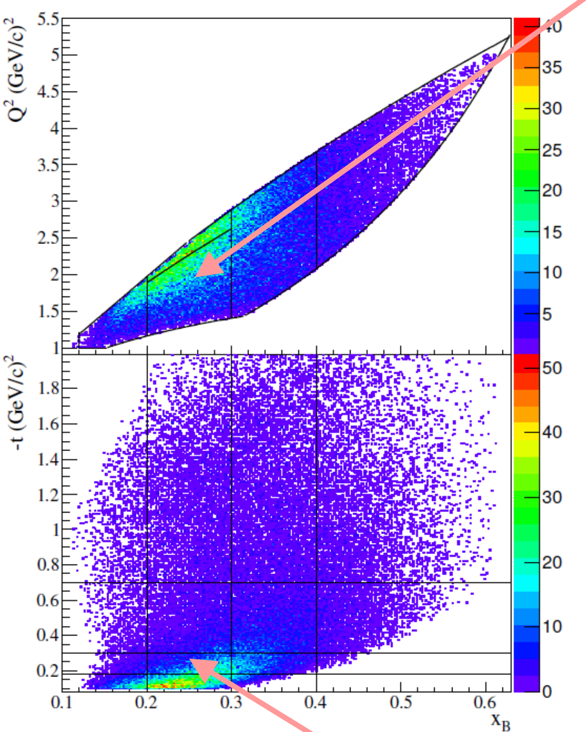
E. Seder et al., PRL 114 (2015) 032001

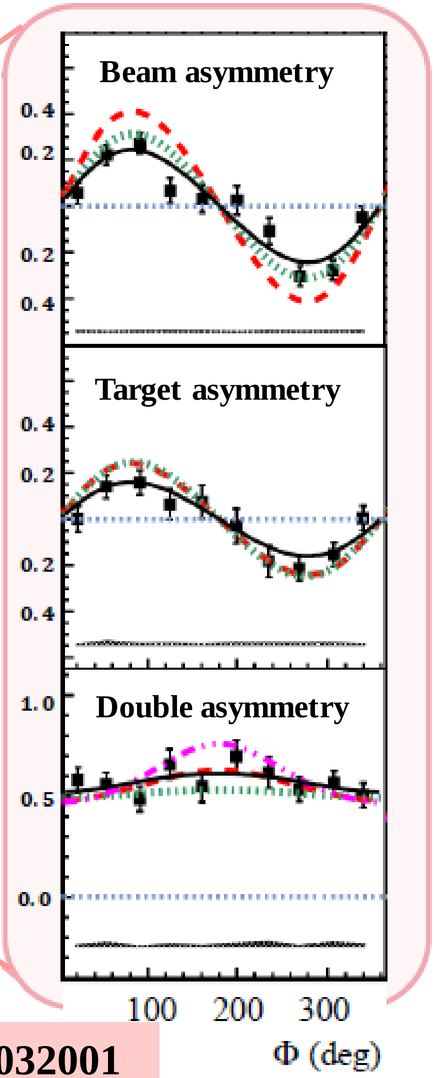
CLAS: DVCS on longitudinally polarized target

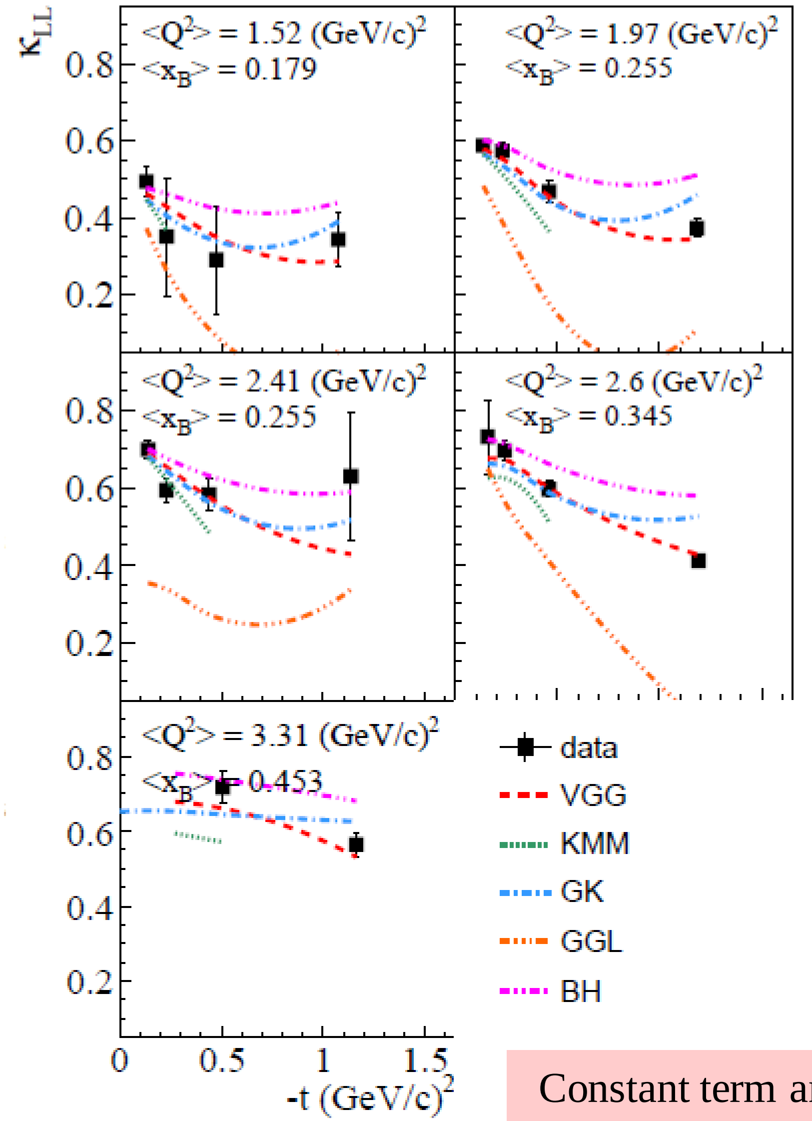
$\vec{e}\vec{p} \to ep\gamma$

DSA ~ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

- Data taken in **2009, eg1-dvcs**
- Beam energy **~5.9 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**







- **5 Q^2-x_B bins**
- **4 t bins**
- **10 ϕ bins**

E. Seder et al., PRL 114 (2015) 032001

Constant term and cosϕ term are dominated by **BH**

Extraction of CFFs from eg1-dvcs TSA, BSA, DSA

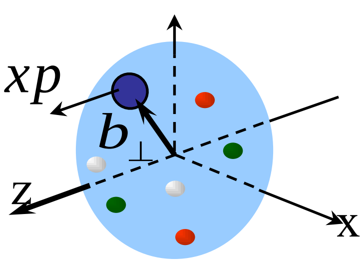
CFFs fitting code by M. Guidal
(7 CFFs included in the fit)

$Im\mathcal{H}$ has steeper t-slope than $Im\widetilde{\mathcal{H}}$: is axial charge more "concentrated" than the electromagnetic charge?
→ PROTON TOMOGRAPHY

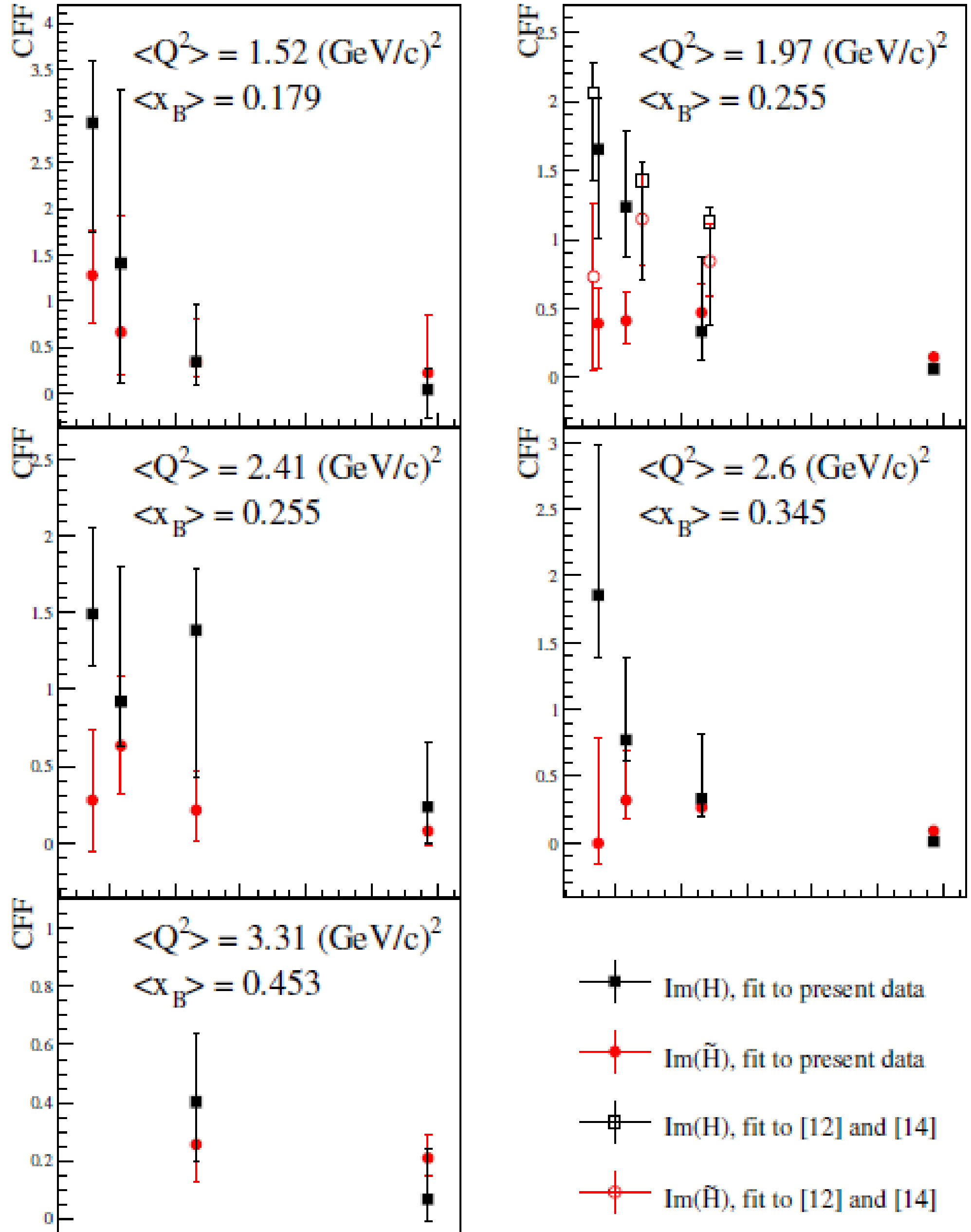
$$\Delta q(x, \mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} \widetilde{H}(x, 0, -\Delta_\perp^2)$$

$$\int H(x,\xi,t)dx = F_1(t)$$

$$\int \widetilde{H}(x,\xi,t)dx = G_A(t)$$



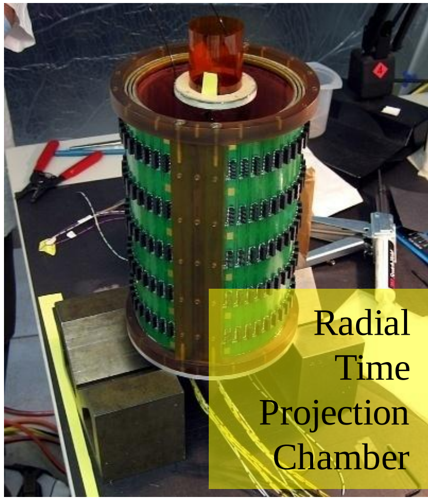
S. Pisano et al., PRD 91, 052014 (2015)



[12] CLAS BSA (Girod *et al.*)
[14] CLAS TSA (Chen *et al.*)

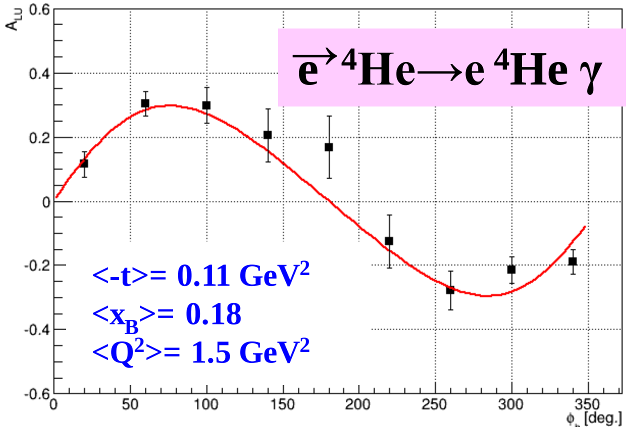
DVCS on nuclei: the CLAS eg6 experiment

- Data taken in the fall 2009
- CLAS+IC+**RTPC**+^{4}He target; E~**6.065 GeV**
- **Coherent and incoherent DVCS: nuclear GPDs, EMC effect**



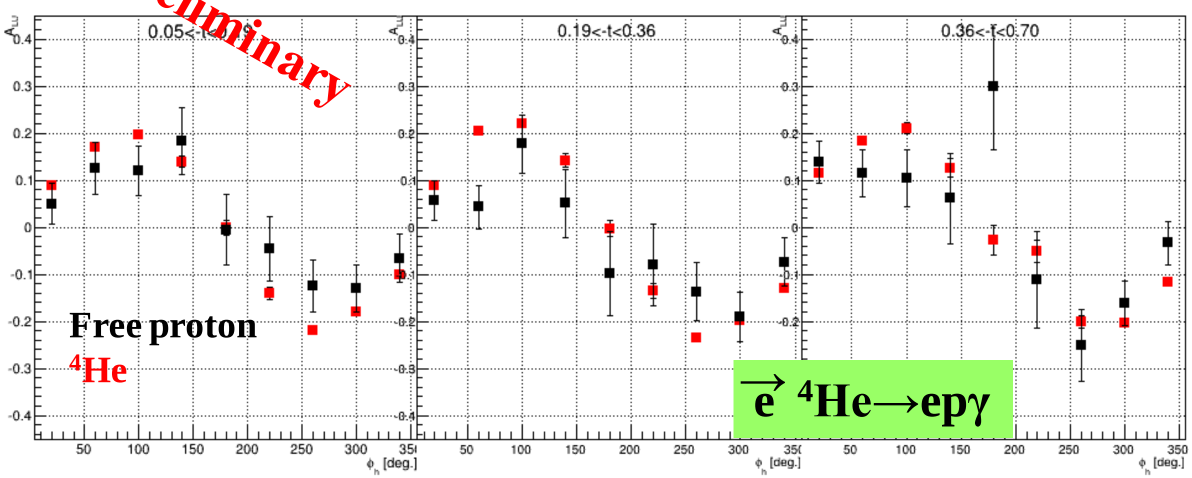
^{4}He is a spin-0 nucleus: at twist-2 **only one CFF** in DVCS BSA

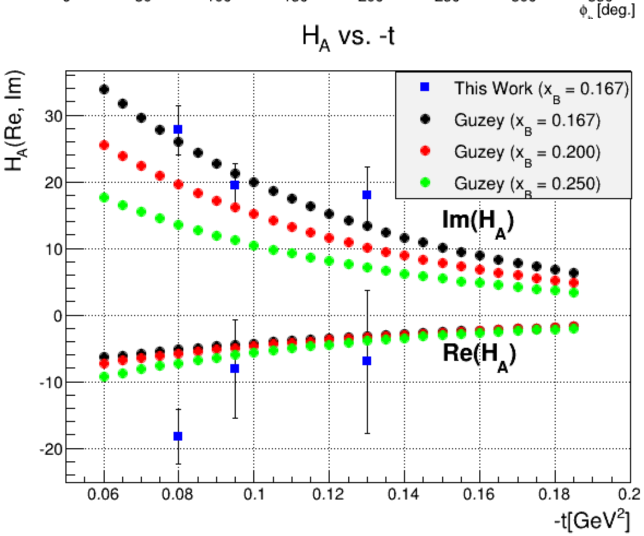
$$A_{LU}^{^4He}(\varphi) = \frac{\alpha_0(\varphi) F_A(t) \Im m[\mathcal{H}_A]}{\alpha_1(\varphi) F_A^2(t) + \alpha_2(\varphi) F_A(t) \Re e[\mathcal{H}_A] + \alpha_3(\varphi) \Re e[\mathcal{H}_A]^2 + \alpha_3(\varphi) \Im m[\mathcal{H}_A]^2}$$



Work by M. Hattaway, IPNO

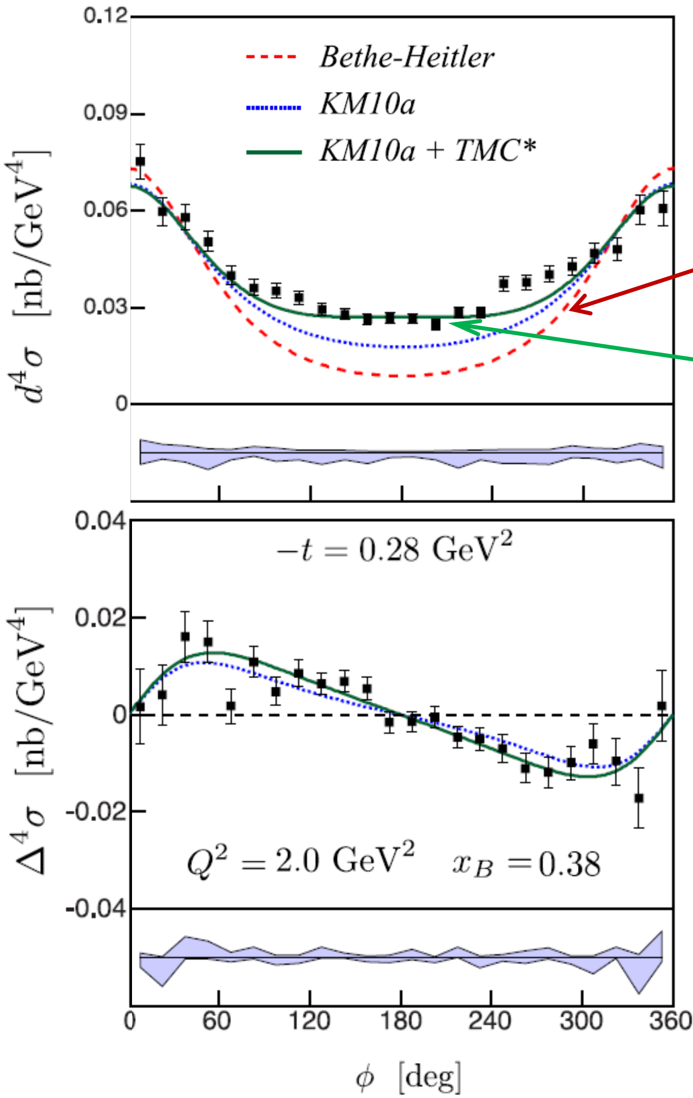
CLAS preliminary





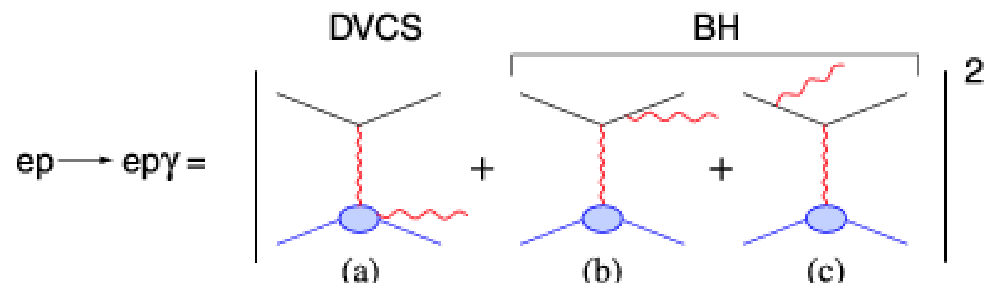
- ➢ **Small –t**: asymmetry for bound proton lower than the ^{4}He one
- ➢ **High –t**: the two asymmetries tend to become compatible

DVCS on the proton in Hall A



Results from E00-110
M. Defurne et. al., arXiv 1504.05453 (2015)

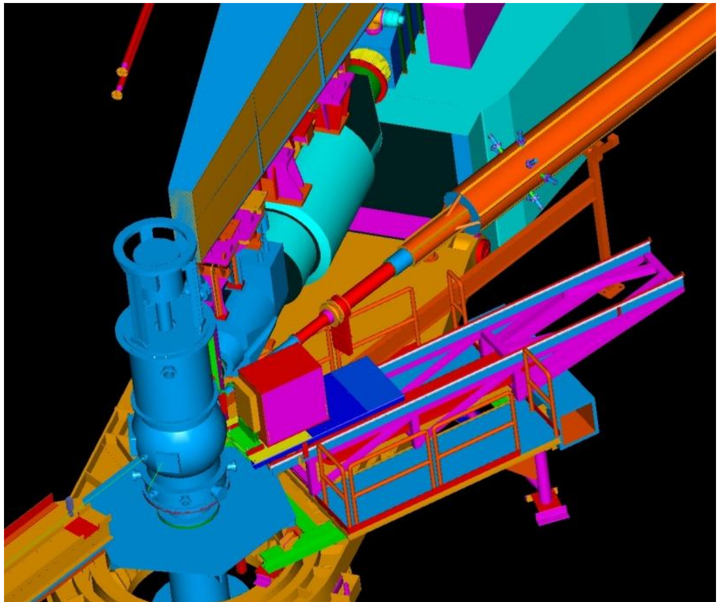
- Significant deviation from Bethe-Heitler (BH)
- Both I(BH·DVCS) and DVCS^2 contribute to the cross section
- Twist-4 corrections (TMC) may be necessary to fully describe data



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

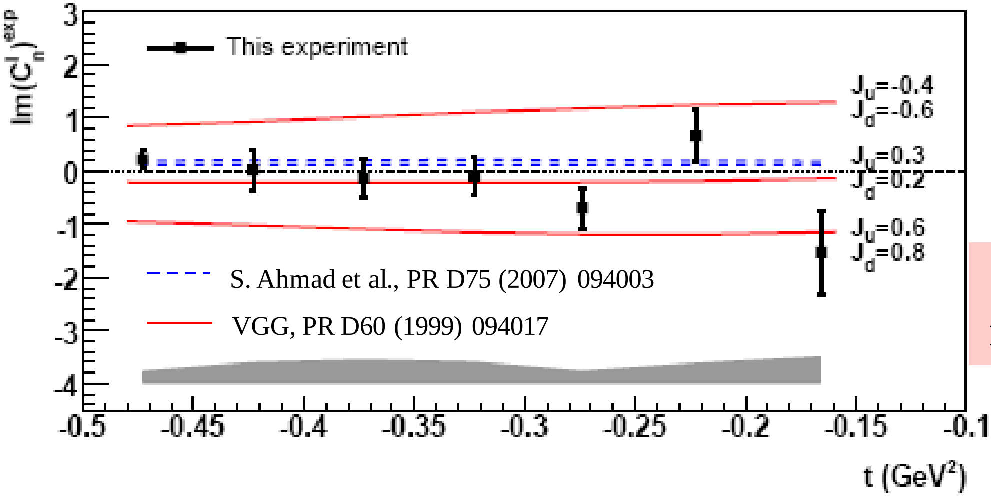
$\sim E_b^3$ $\sim E_b^2$

Beam-energy separation at constant Q^2, x_B and t:
experiment E07-007
(Analysis ongoing)



DVCS on the neutron in Hall A

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



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

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

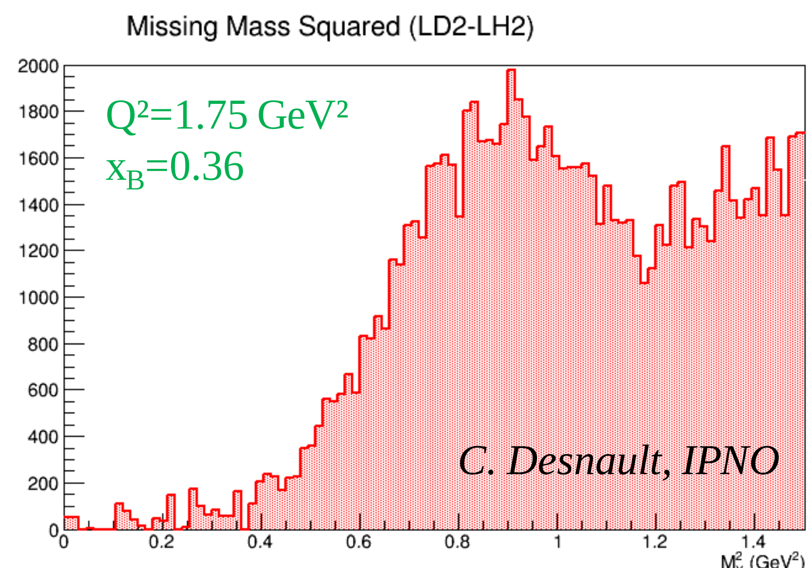
- **E03-106**: **First-time measurement of $\Delta\sigma_{LU}$ for nDVCS, model-dependent extraction of J_u, J_d**

- **E08-025**: Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target
- Data taken in fall 2010 concurrently with E07-007, **analysis ongoing**

Proton and neutron GPDs (and CFFs) are **linear combinations** of quark GPDs

$$\mathcal{H}_p(\xi,t) = \frac{4}{9}\mathcal{H}_u(\xi,t) + \frac{1}{9}\mathcal{H}_d(\xi,t)$$

$$\mathcal{H}_n(\xi,t) = \frac{1}{9}\mathcal{H}_u(\xi,t) + \frac{4}{9}\mathcal{H}_d(\xi,t)$$



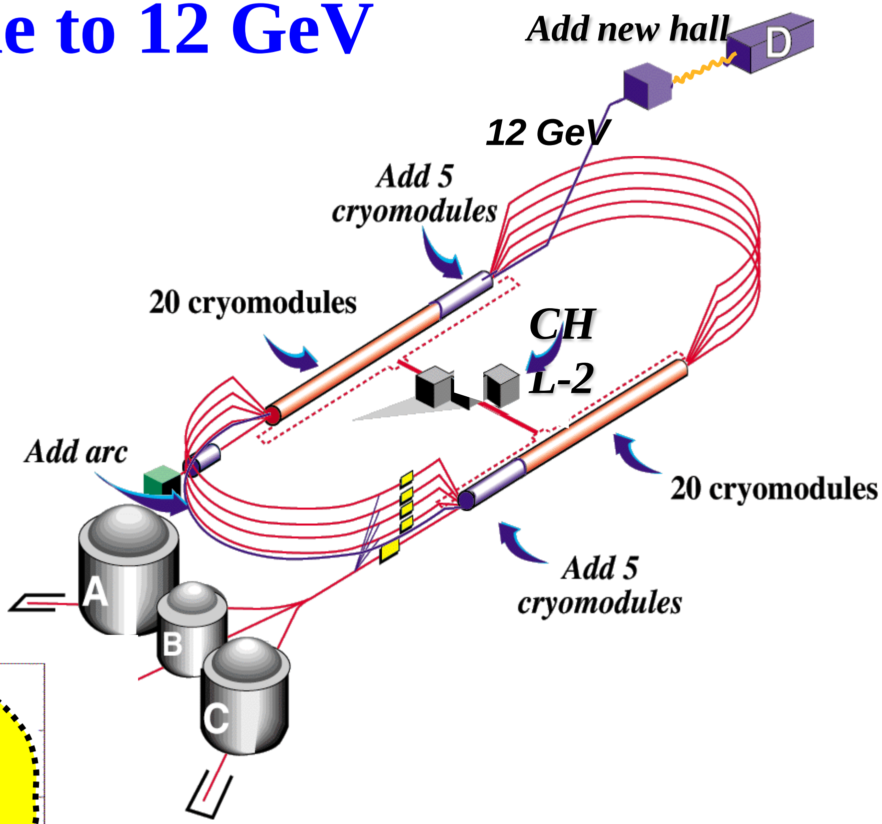
A **combined analysis** of **DVCS observables for proton and neutron targets** is necessary to perform a **quark-flavor separation** of the GPDs

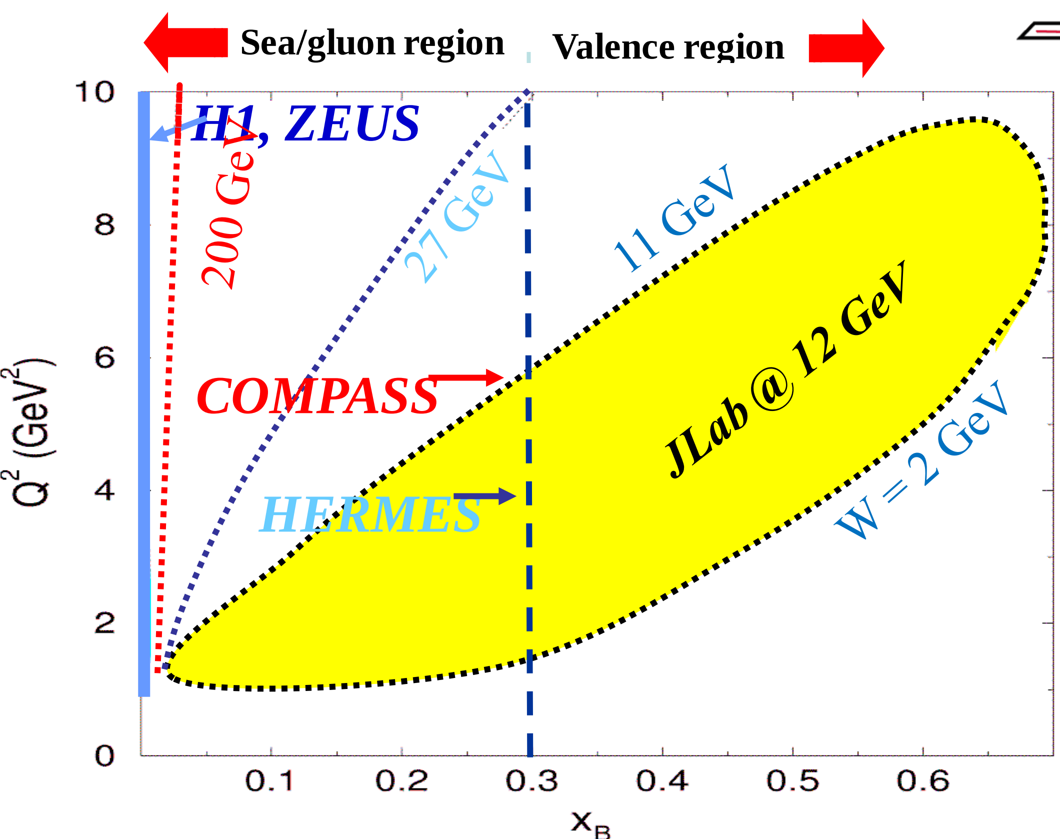
JLab upgrade to 12 GeV

E= 2.2, 4.4, 6.6, 8.8, 11 GeV
for the Halls A, B, C

Beam polarization > 80%

Upgrade completed in 2014

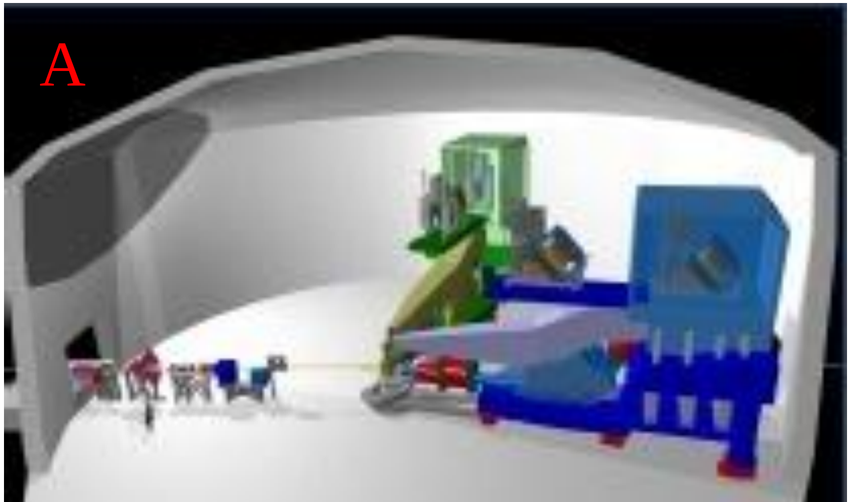




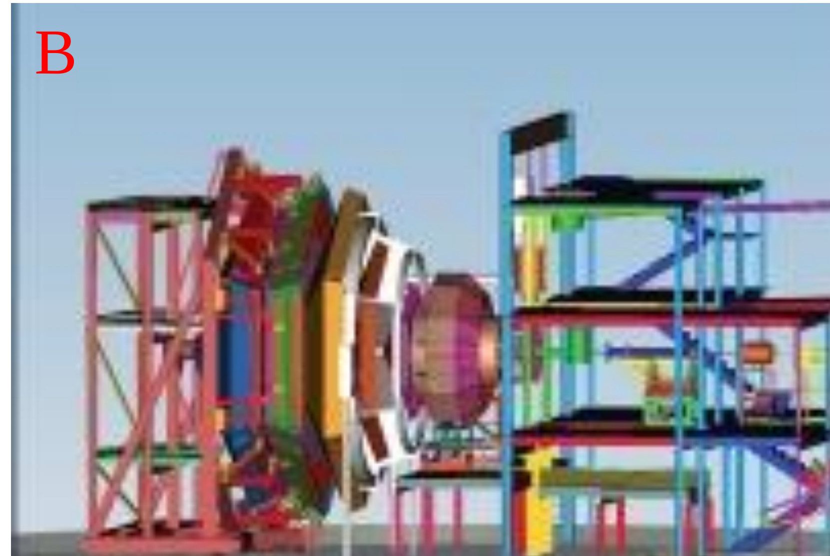
Study of high x_B domain requires high luminosity

The 12-GeV upgrade is well matched to studies in the valence-quark regime

New capabilities in Halls A, B & C



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

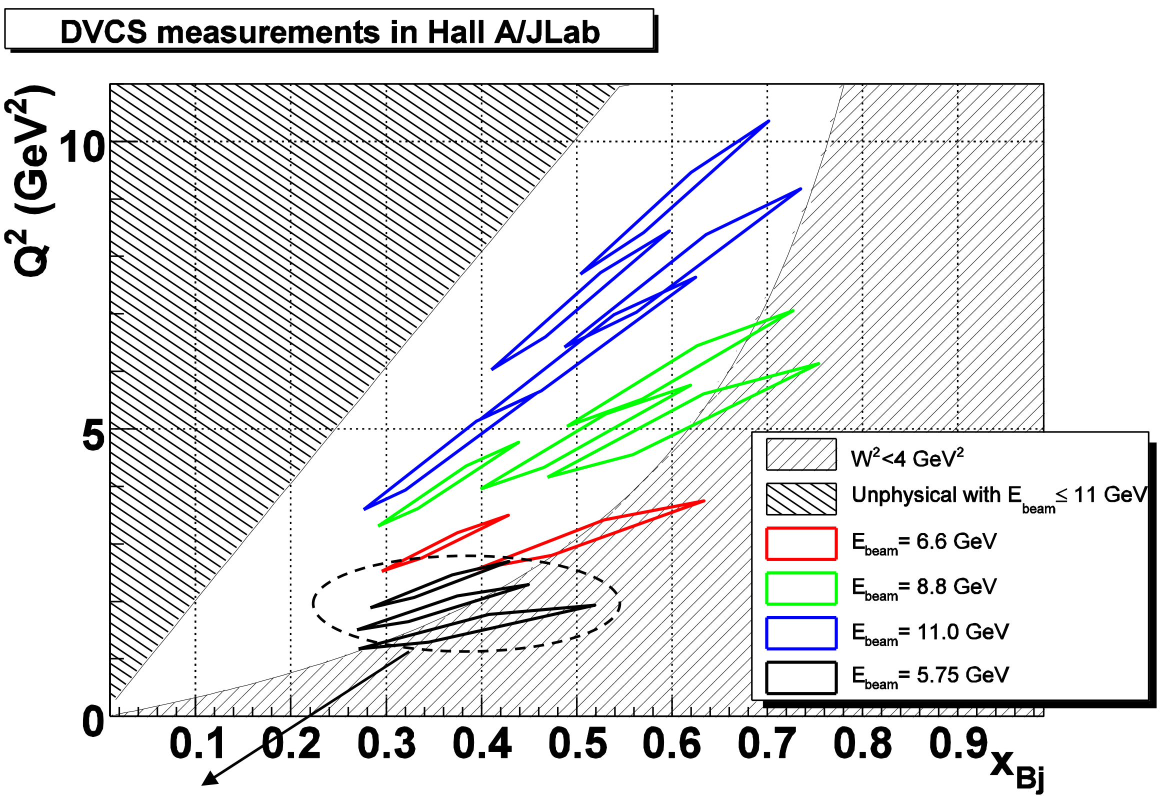
DVCS experiments at 11 GeV have been approved for each of these **three halls**.
Complementary programs:

- different kinematic coverage
- different precisions/resolutions
- focus on different observables

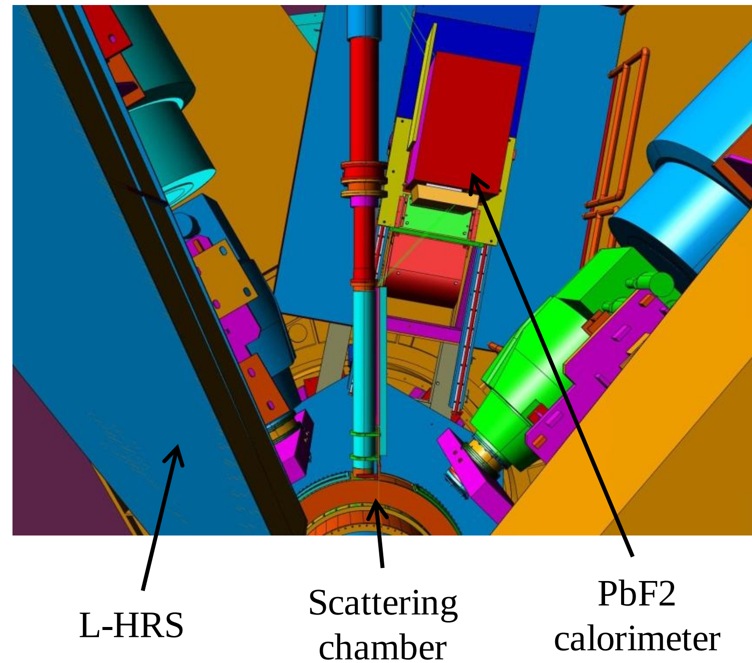
E12-06-114: DVCS at 11 GeV in Hall A

- Absolute cross-section measurements
- Test of scaling: Q^2 dependence of dσ at fixed x_{Bj}
- Increased kinematical coverage

JLab12 with 3, 4, 5 pass beam (6.6, 8.8, 11.0 GeV)



JLab @ 6 GeV

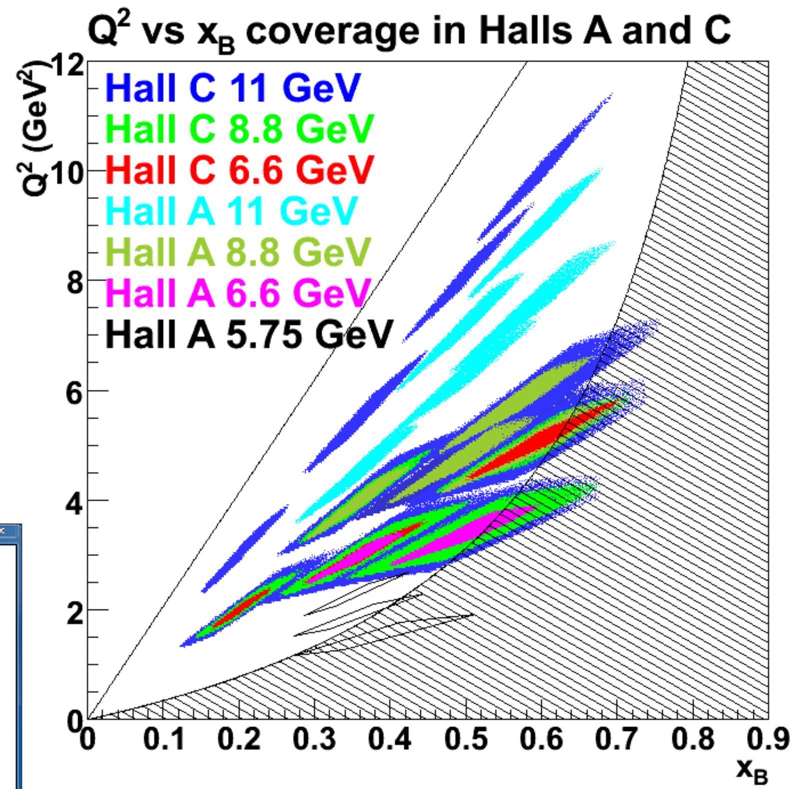


1st experiment to run after the 12-GeV upgrade

Started in fall 2014, to be continued in 2015-2016

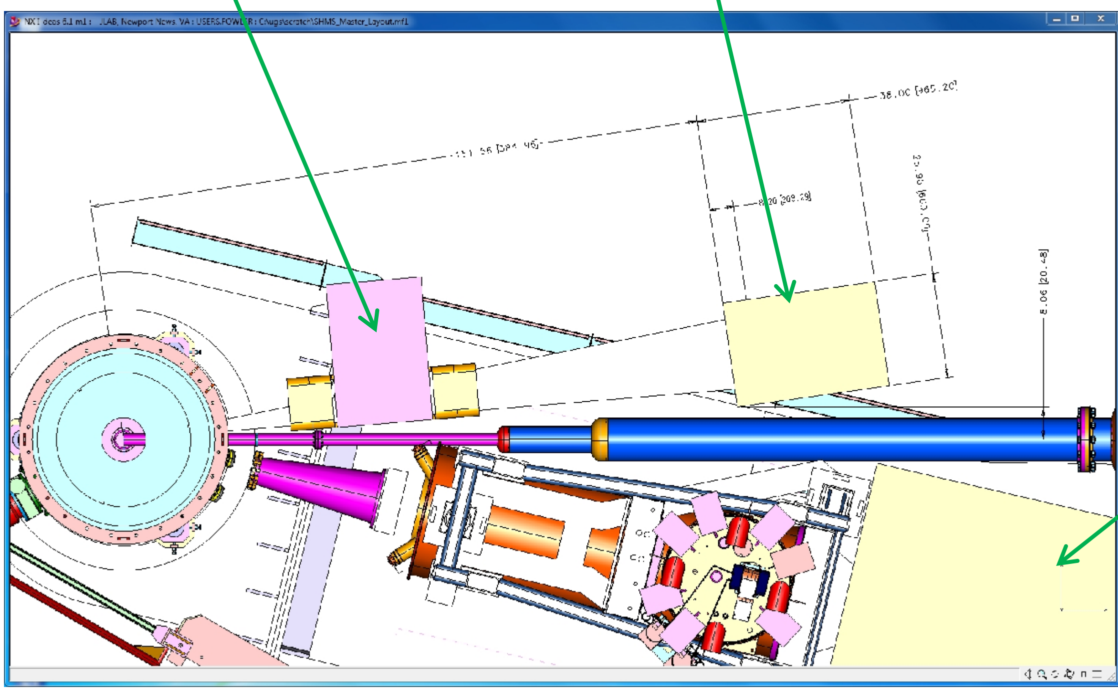
E12-13-010: DVCS at 11 GeV in Hall C

- Energy separation of the DVCS cross section
- Higher Q^2: measurement of higher twist contributions
- Low-x_B extension (thanks to sweeping magnet)



Sweeping magnet

1116-block $PbWO_4$ calorimeter

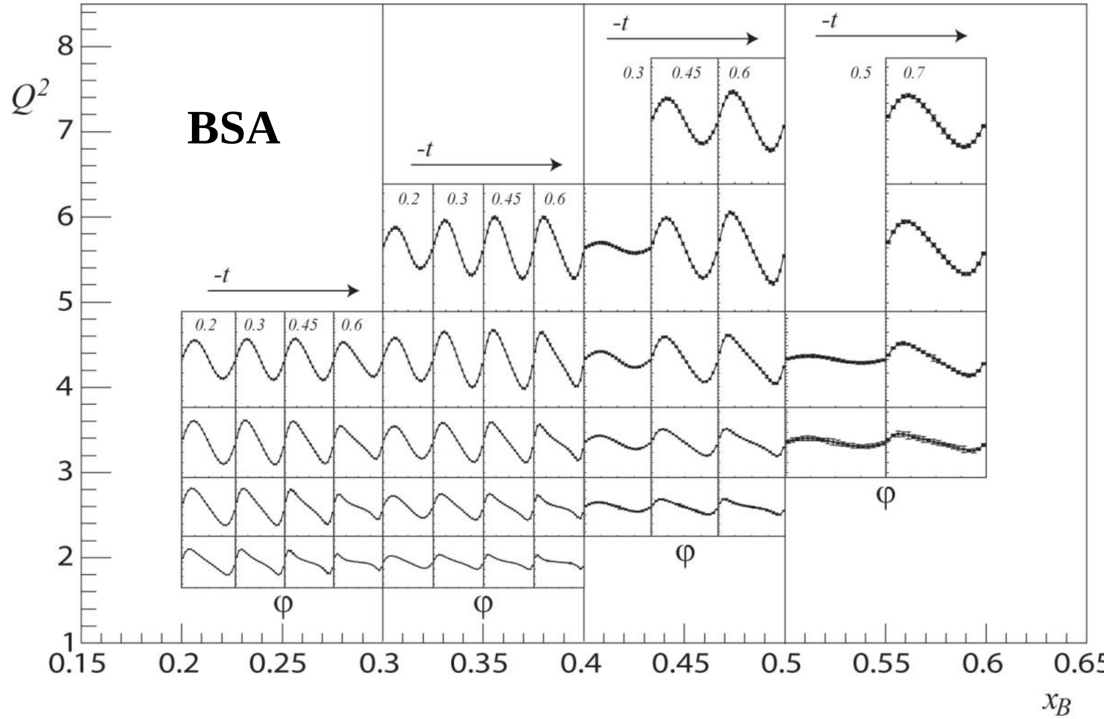


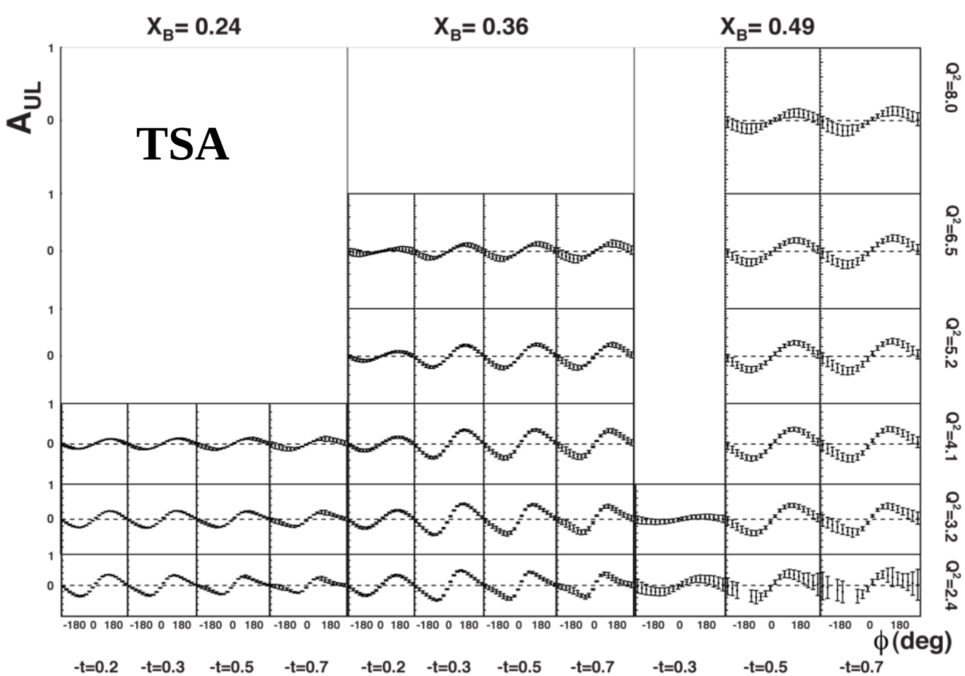
Hall C HMS

Tentative running:
~ 2019-20

DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
$P_{beam} = 85\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$
$0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$
Statistical error: 1% to 10%
on sinϕ moments
Systematic uncertainties: ~6-8%

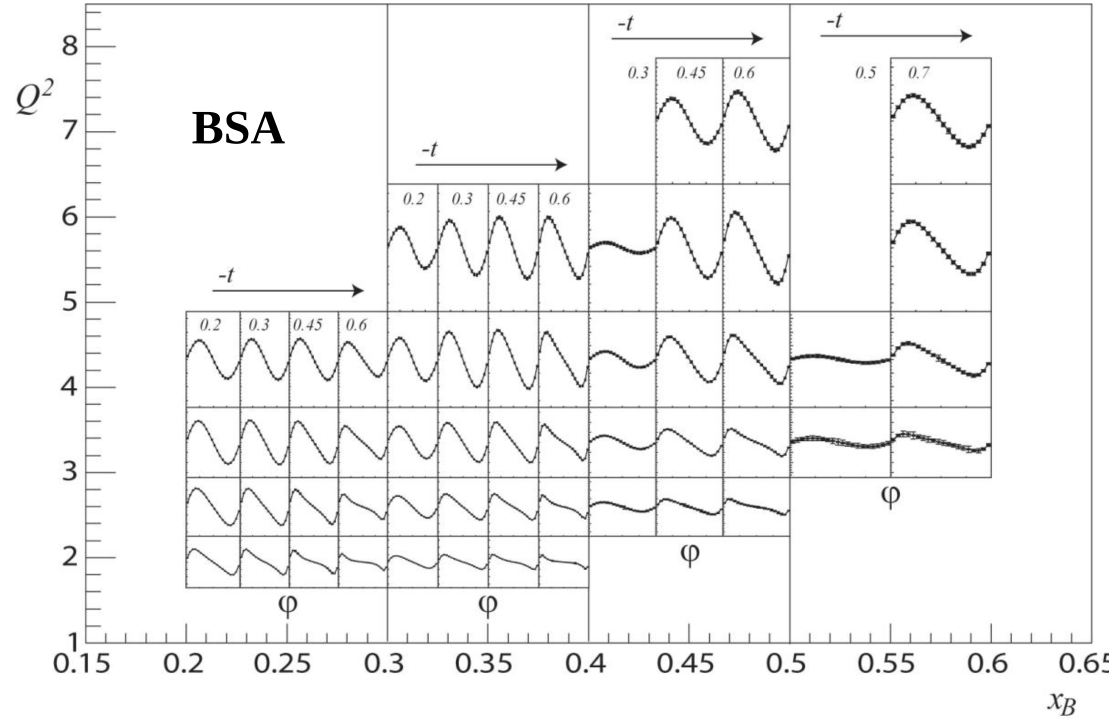


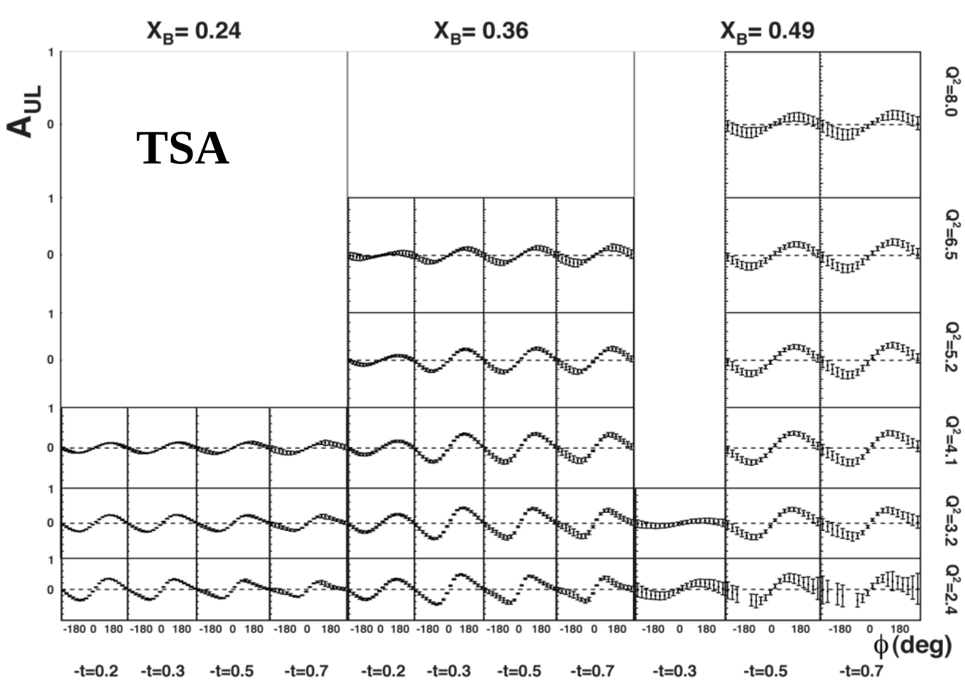


120 days of beam time
$P_{beam} = 85\%$, $P_{target} = 80\%$
$L = 2.10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$
$0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$
Statistical error: 2% to 15%
on sinϕ moments
Systematic uncertainties: ~6-8%

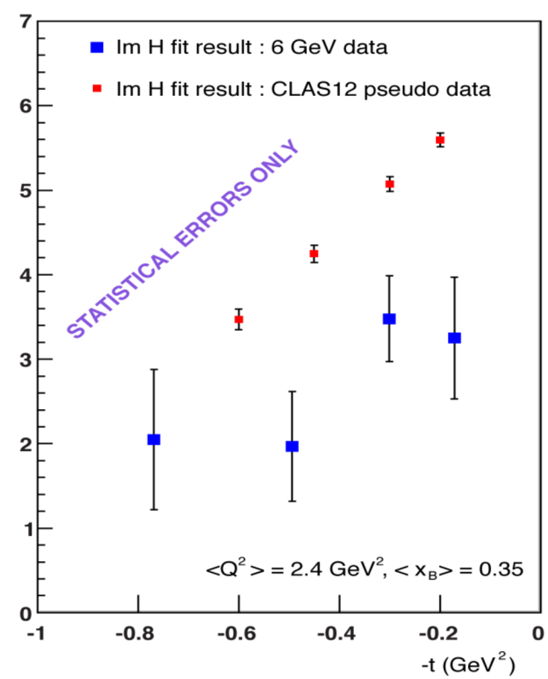
DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
$P_{beam} = 85\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$
$0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$
Statistical error: 1% to 10%
on $\sin\phi$ moments
Systematic uncertainties: ~6-8%





Impact of CLAS12 DVCS-BSA data on model-independent fit to extract Im(H)

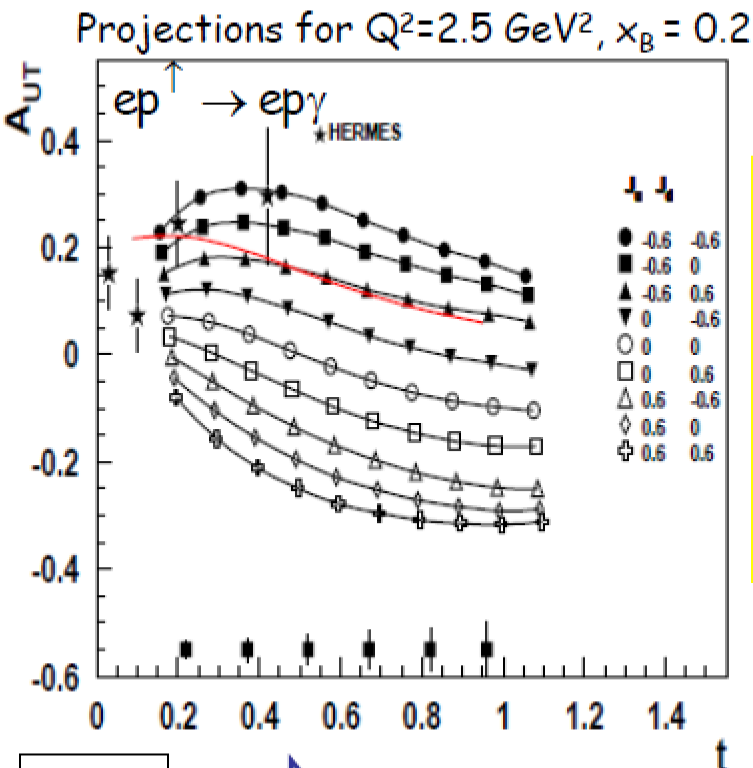


CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time

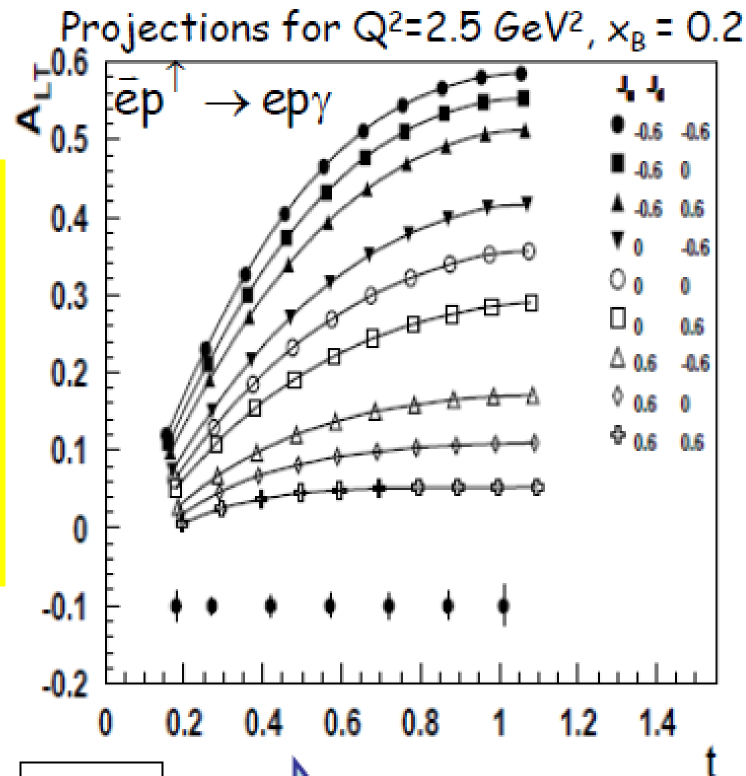
Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = $5\mathrm{x}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$1 < Q^2 < 10\ \mathrm{GeV}^2$, $0.06 < x_B < 0.66$, $-t_{min} < -t < 1.5\ \mathrm{GeV}^2$



$\Delta\sigma_{UT}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$

Transverse-target spin asymmetry for p-DVCS is **highly sensitive** to the **u-quark contributions** to proton spin.

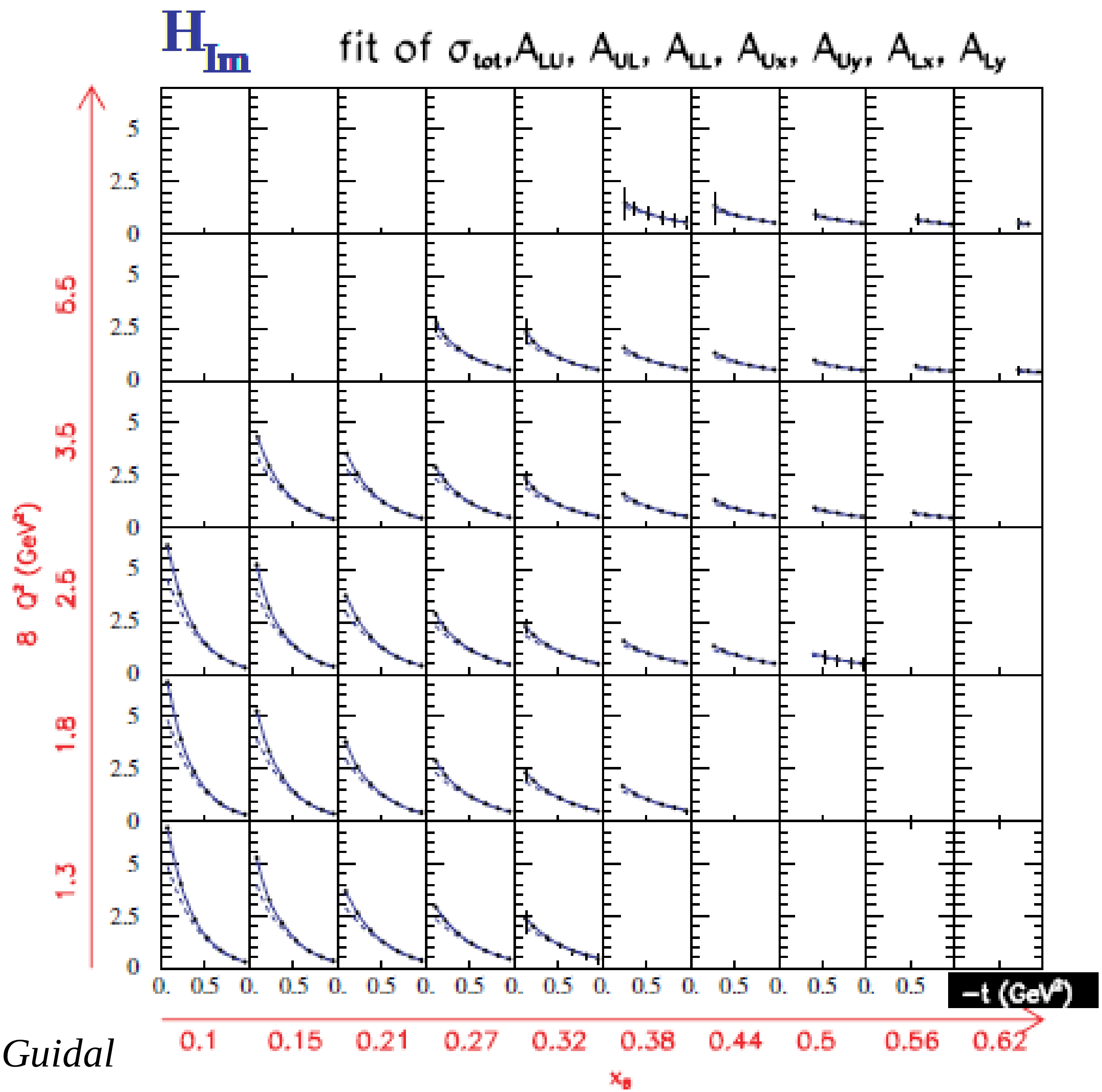


$\Delta\sigma_{LT}$ ⇒ $Re\{\mathcal{H}_p, \mathcal{E}_p\}$

JLab PAC:
high-impact experiment

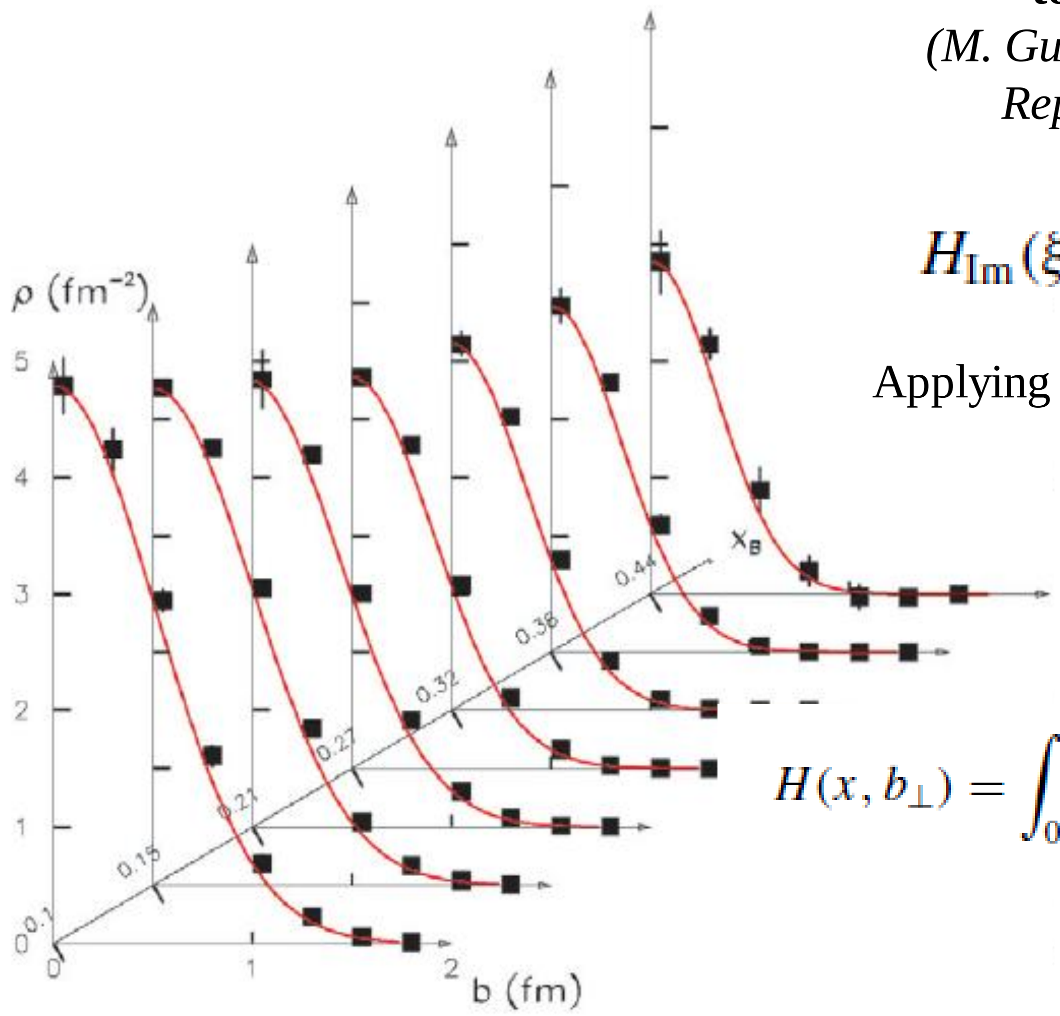
Proposal conditionally approved by PAC39

Projections for CLAS12 for H_{Im}



Work by M. Guidal

From CFFs to spatial densities



Projections for CLAS12

How to go from momentum coordinates (t) to space-time coordinates (b) ?

(M. Guidal, H. Moutarde, M. Vanderhagen, Rept.Prog.Phys. 76 (2013) 066202)

$$H_{\mathrm{Im}}(\xi,t) \equiv H(\xi,\xi,t) - H(-\xi,\xi,t)$$

Applying a model-dependent "deskewing" factor**:**

$$\frac{H(\xi,0,t)}{H(\xi,\xi,t)}$$

$$H(x,b_\perp) = \int_0^\infty \frac{d\Delta_\perp}{2\pi}\,\Delta_\perp\,J_0(b_\perp\Delta_\perp)\,H(x,0,-\Delta_\perp^2)$$

Burkardt (2000)

E12-11-003: BSA for DVCS *on the neutron* with CLAS12

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

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

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

The most sensitive observable to the GPD E

ed→ e(p)nγ

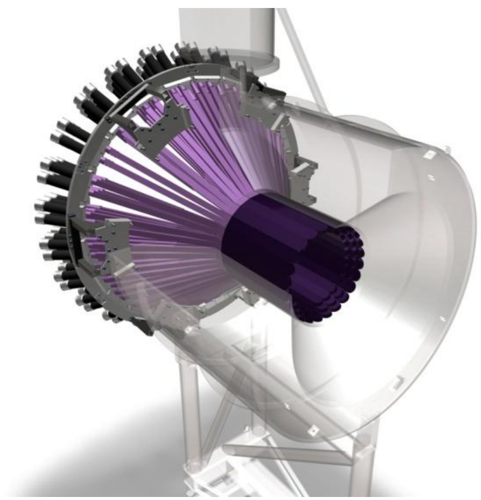
CLAS12 +

Forward Calorimeter +

Neutron Detector

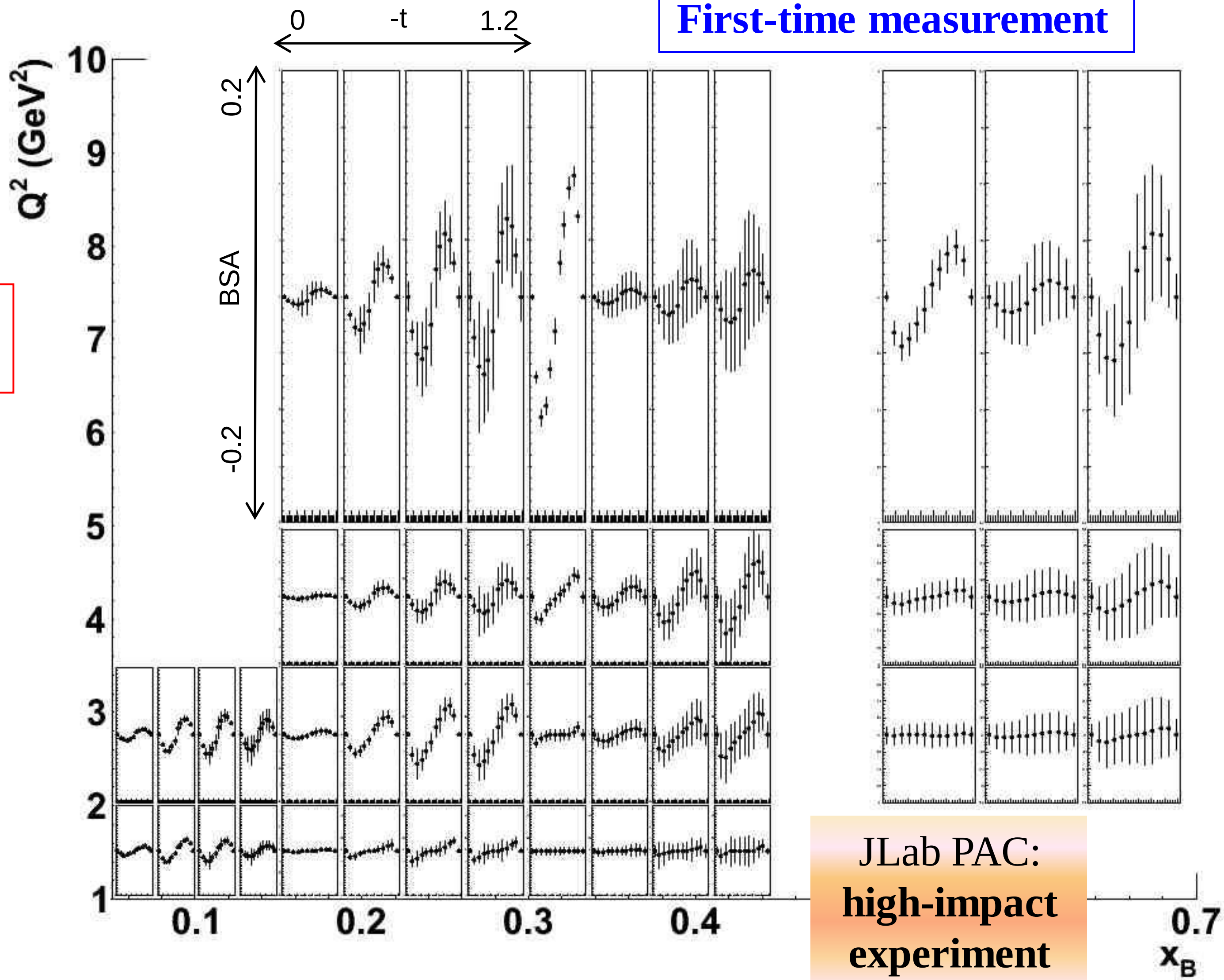
80 days of data taking

$L = 10^{35}$ cm^{-2}s^{-1}/nucleon



Construction completed (IPN Orsay)

First-time measurement



JLab PAC:
high-impact experiment

E12-11-003: BSA for DVCS *on the neutron* with CLAS12

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

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

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

The most sensitive observable to the GPD E

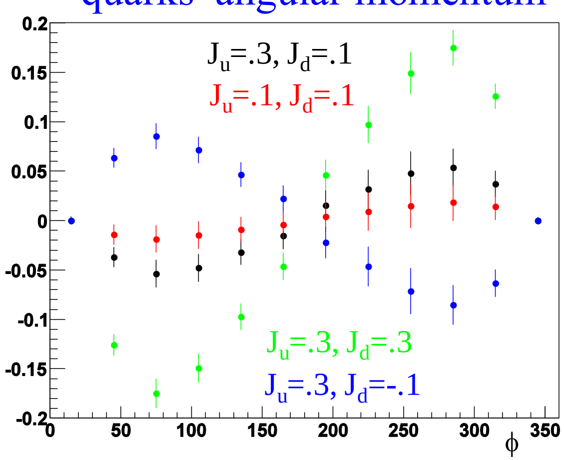
First-time measurement

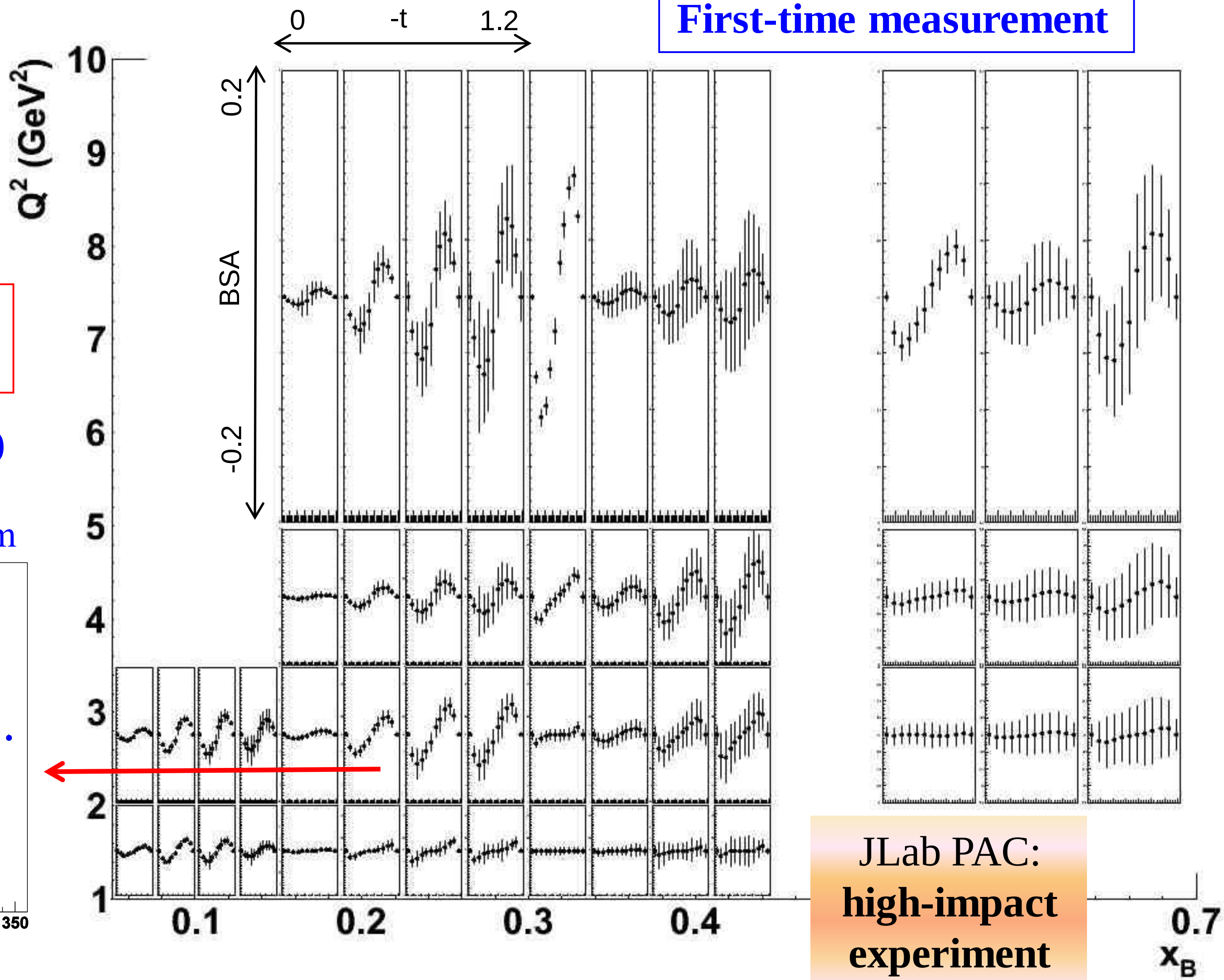
ed→ e(p)nγ

CLAS12 +
Forward Calorimeter +
Neutron Detector

80 days of data taking
L = 10^{35} $cm^{-2}s^{-1}$/nucleon

Model predictions (VGG)
for different values of
quarks' angular momentum





JLab PAC:
high-impact experiment

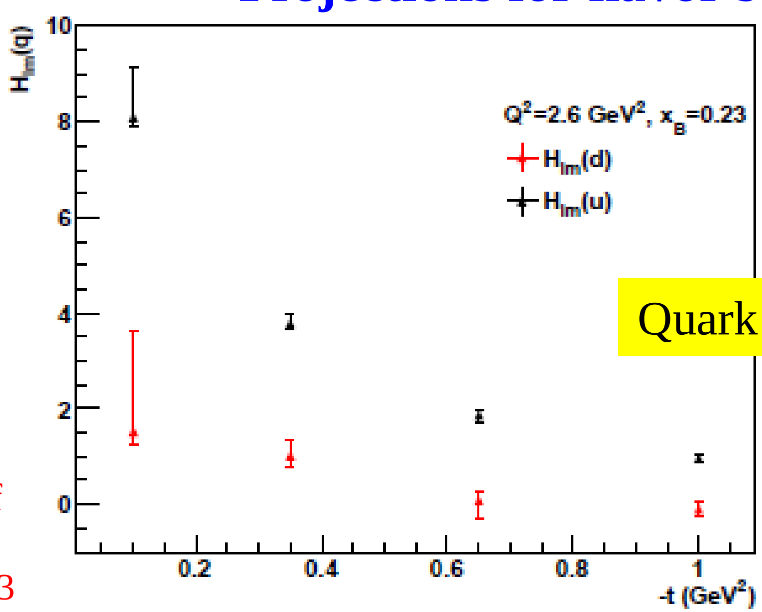
DVCS: global view

Observable (target)	Target	Sensitivity to CFFs	Completed experiments	12-GeV experiments
$\Delta\sigma_{beam}$(p)	Unpolarized hydrogen	$\Im m\mathcal{H}_p$	Hall A, CLAS	Hall A, CLAS12,Hall C
BSA(p)	Unpolarized hydrogen	$\Im m\mathcal{H}_p$	HERMES, CLAS	CLAS12
TSA(p)	Long. pol. NH3	$\Im m\tilde{\mathcal{H}}_p$, $\Im m\mathcal{H}_p$,	HERMES, CLAS	CLAS12
DSA(p)	Long. pol. NH3	$\Re e\tilde{\mathcal{H}}_p$, $\Re e\mathcal{H}_p$	HERMES, CLAS	CLAS12
tTSA(p)	Transv. pol. protons	$\Im m\mathcal{H}_p$, $\Im m\mathcal{E}_p$	HERMES	CLAS12
$\Delta\sigma_{beam}$(n)	Unpolarized deuterium	$\Im m\mathcal{E}_n$	Hall A	
BSA(n)	Unpolarized deuterium	$\Im m\mathcal{E}_n$		CLAS12
TSA(n)	**Long. pol. ND3**	$\Im m\mathcal{H}_n$		**PR12-15-004**
DSA(n)	**Long. pol. ND3**	$\Re e\mathcal{H}_n$		**PR12-15-004**

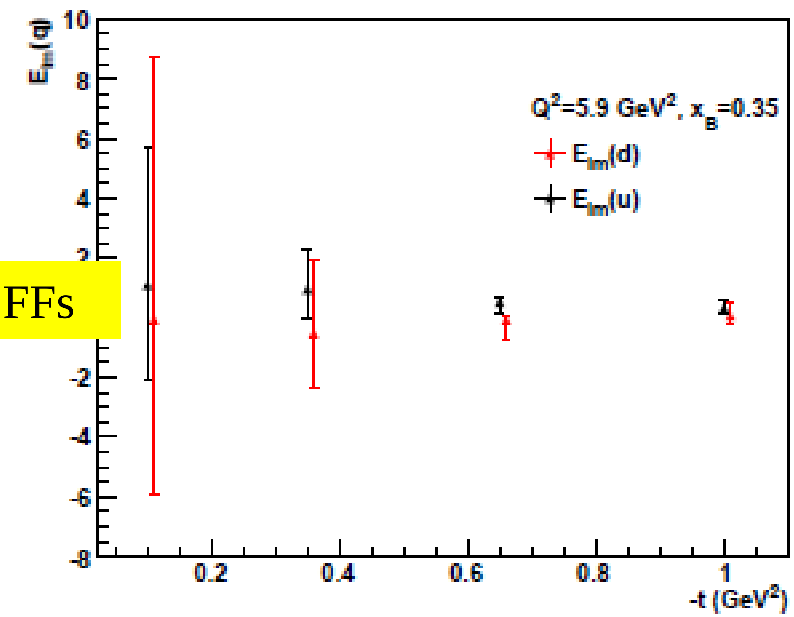
Projections for flavor separation (*Im*$\mathcal{H}$, *Im*$\mathcal{E}$)

Fit using all the projected pDVCS asymmetries of the CLAS12 program

Fit using the projected nDVCS asymmetries of PR12-15-004 and E12-11-003



Quark CFFs



Conclusions

- ➢ GPDs are a unique tool to explore the **internal dynamics of the nucleon**:
  - **3D** quark/gluon **imaging** of the nucleon
  - **orbital angular** momentum carried by quarks
- ➢ Their extraction from experimental data is **very difficult**:
  - there are **4 GPDs for each quark flavor**
  - they depend on **3 variables**, only two (ξ, t) experimentally accessible via DVCS

✓ Recently-developed fitting methods allow to **extract CFFs from DVCS observables.** Need to measure several **p-DVCS** and **n-DVCS observables** over a **wide phase space**

✓A wealth of **new results** on various DVCS observables is coming from recent **CLAS and Hall-A experiments** (on the proton, deuterium and ^{4}He targets)

✓ First **tomographic interpretations** of the quarks in the **proton**:
- ✓ **valence quarks** are concentrated in its **center**, **sea quarks** at its **perifery**
- ✓ **axial charge** more concentrated than the **electric** one

→ The 12-GeV-upgraded JLab will be **the only facility** to perform DVCS experiments **in the valence region**, for Q^2 up to 11 GeV

→ DVCS experiments on both **proton** and **deuterium** targets (polarized and unpolarized) are planned for **3 of the 4 Halls at JLab@12 GeV: quarks' spatial densities, quark-flavor separation, quarks' orbital angular momentum…**

→ **Beyond DVCS: double DVCS (x dependence), TCS, exclusive meson production, …**