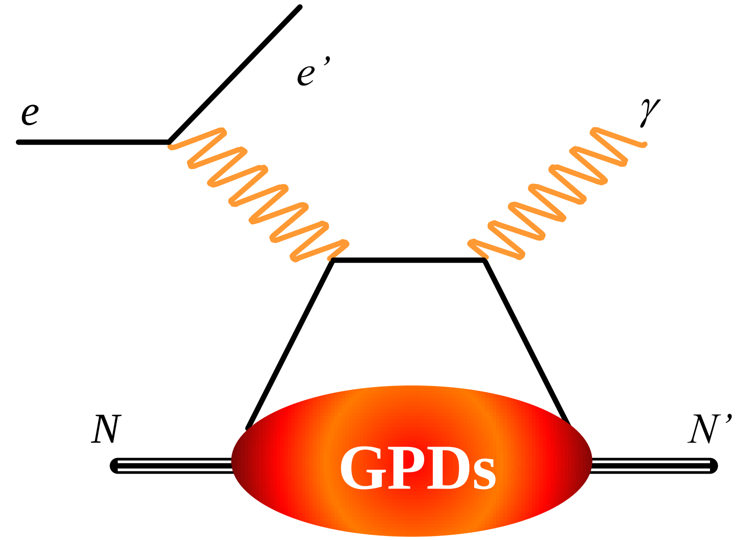
# Experimental overview of DVCS and GPDs at Jefferson Lab




*Silvia Niccolai, IPN Orsay*
*for the CLAS Collaboration*

DIS16 – Hamburg (Germany) 13/4/2016

DIS16
DESY, HAMBURG 11-15 APRIL 2016

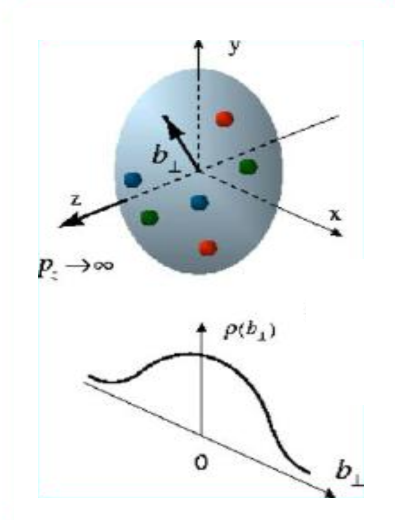
- **Interest of GPDs**
- **GPDs and Deeply Virtual Compton Scattering**
- **New DVCS results from Jefferson Lab**
- **The JLab 12 GeV upgrade**
- **Future JLab experiments on DVCS**

clas

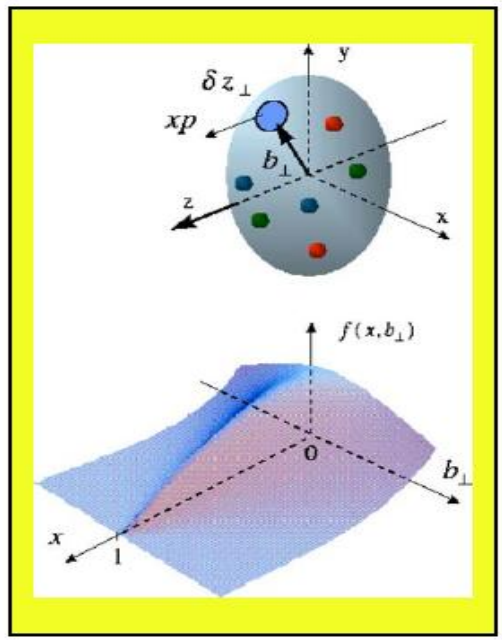
IPN ORSAY

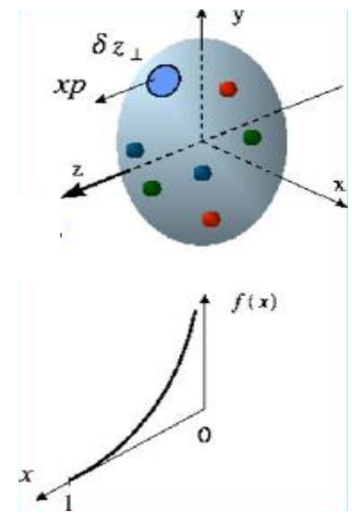
# Electron-proton scattering to study nucleon structure

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

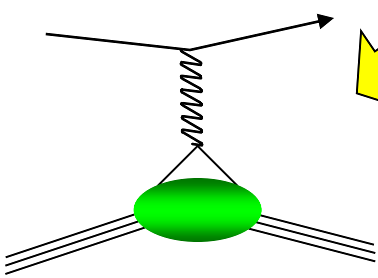



**Form factors:**
**transverse quark distribution in coordinate space**




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

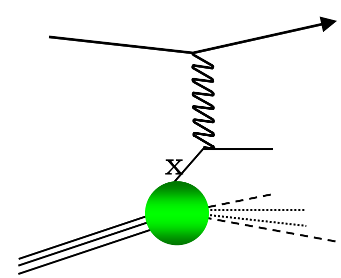


$\int H(x,\xi,t)dx = F_1(t)$ $(\forall\ \xi)$

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

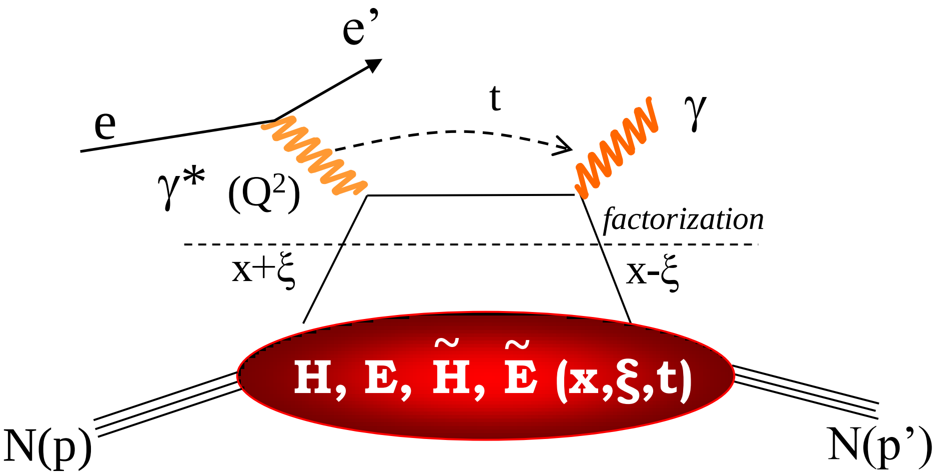
**Accessible in**
**hard exclusive processes**

High $Q^2$ Final state known



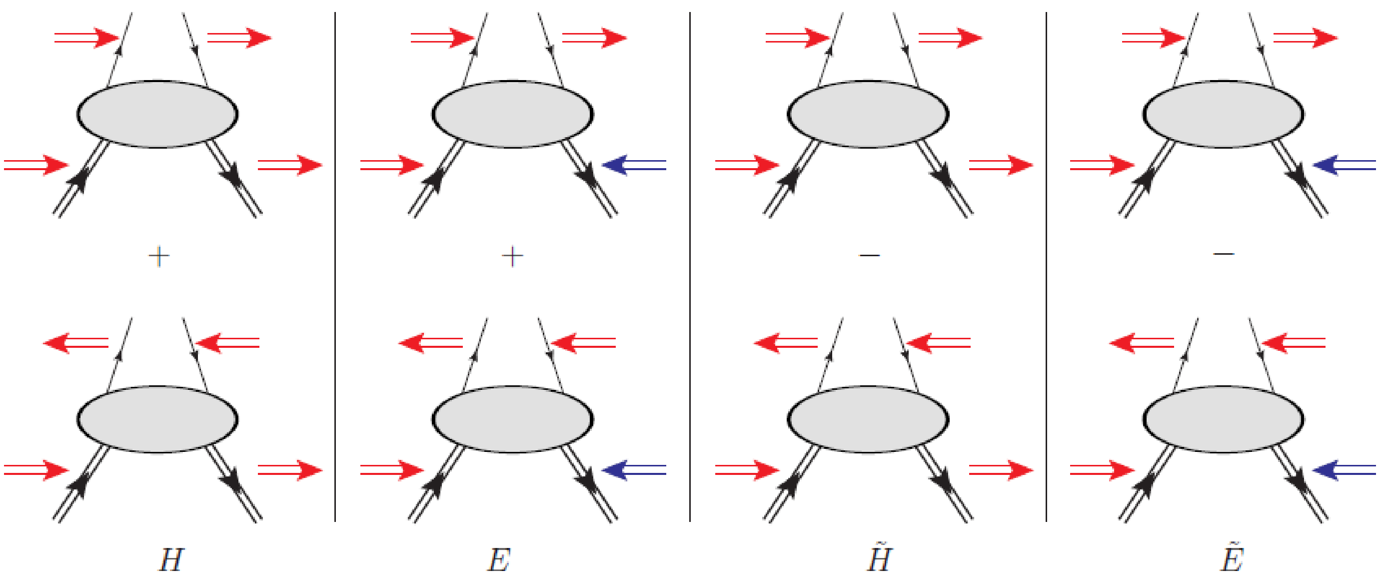

$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$

# 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 $Q^2$ and $\nu$, 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 $(x,\xi,t)$** | **Axial-Vector: $\tilde{H}$ $(x,\xi,t)$** |
| **flip nucleon spin** | **Tensor: E $(x,\xi,t)$** | **Pseudoscalar: $\tilde{E}$ $(x,\xi,t)$** |

# 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**

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

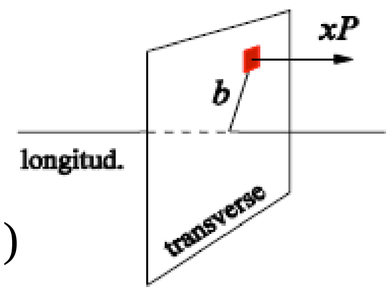
Forward limit: **PDFs**
(not for E, Ẽ)

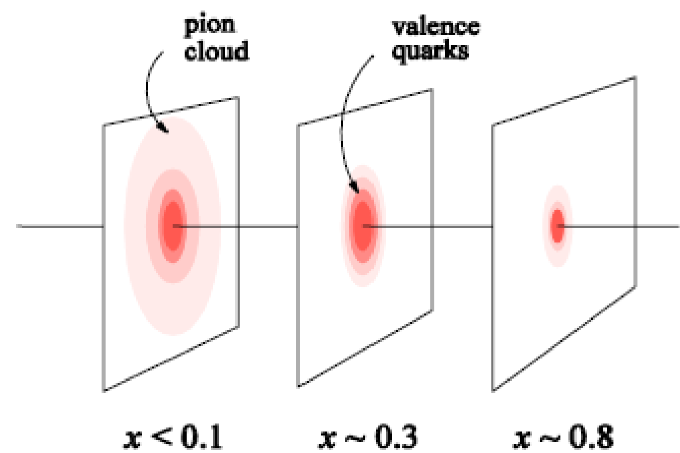
## Nucleon tomography

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

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

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 ≈ 30%**

**Intrinsic spin on the gluons ΔG ≈ 0-20%**

**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)**

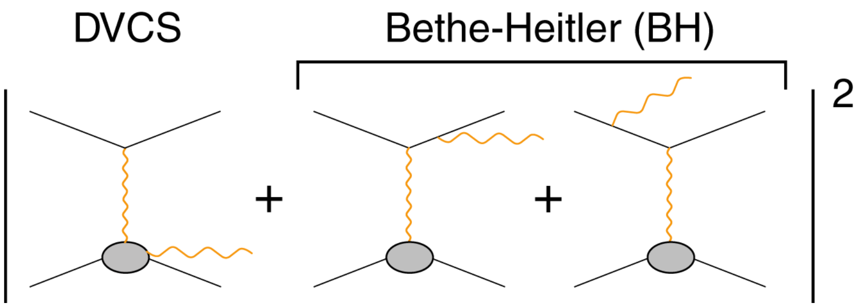
$$T^{DVCS} \sim P\int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi} dx \pm i\pi GPDs(\pm\xi,\xi,t) + \ldots$$

**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) =

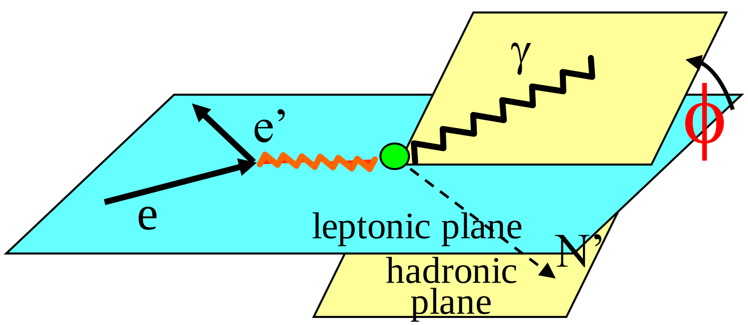



BH is calculable (electromagnetic FFs)

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

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

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



# 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 ($-t \ll Q^2$)

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

Proton Neutron

Polarized beam, unpolarized target:

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

Unpolarized beam, longitudinal target:

$s^I_{1,UL} \sim \sin\phi \mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2 \tilde{\mathcal{E}} + \ldots\}$ → $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

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

Unpolarized beam, transverse target:

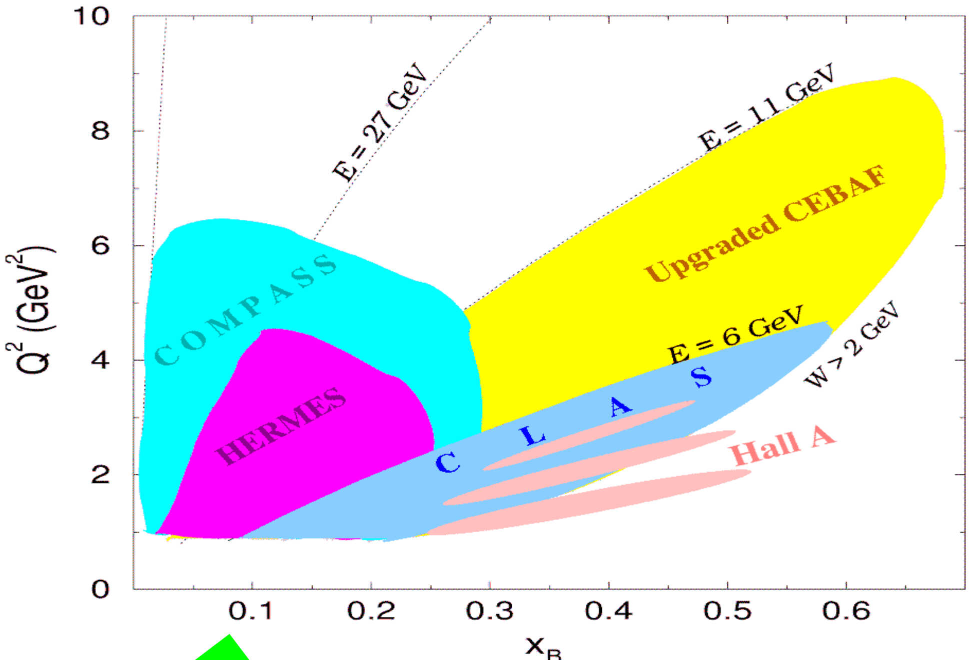
$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi) \mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ → $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

# DVCS experiments worldwide

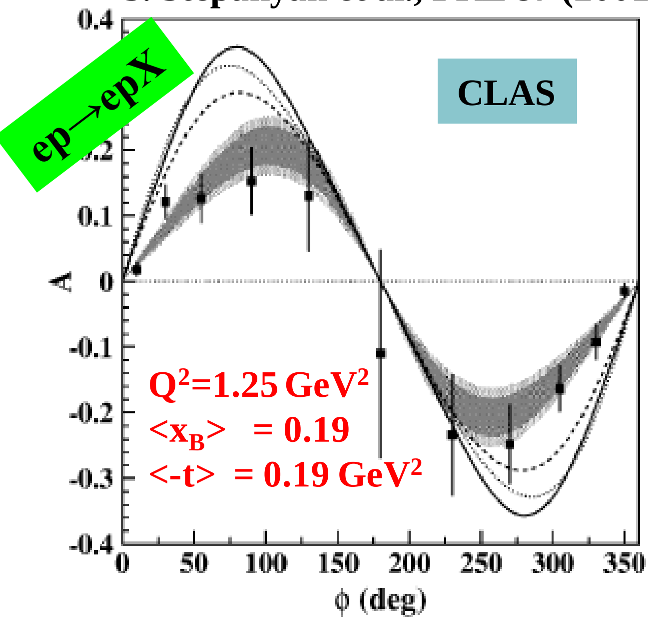
| JLAB | |
|---|---|
| *Hall A* | *CLAS (Hall B)* |
| p,n-DVCS<br>Beam-pol. CS | p-DVCS<br>BSA,lTSA,DSA,CS |

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

| CERN |
|---|
| *COMPASS* |
| p-DVCS<br>CS,BSA,BCA,<br>tTSA,lTSA,DSA |



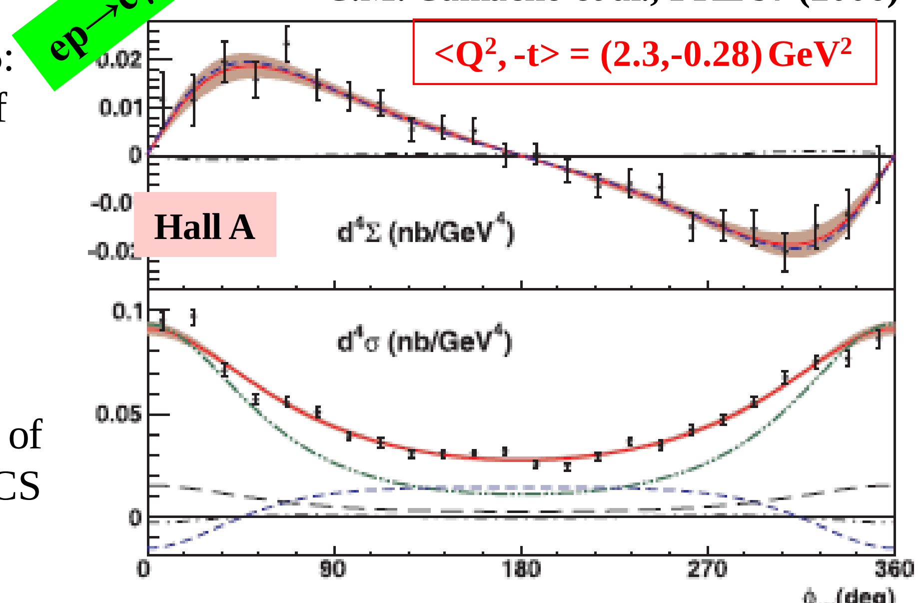

S. Stepanyan et al., PRL 87 (2001)



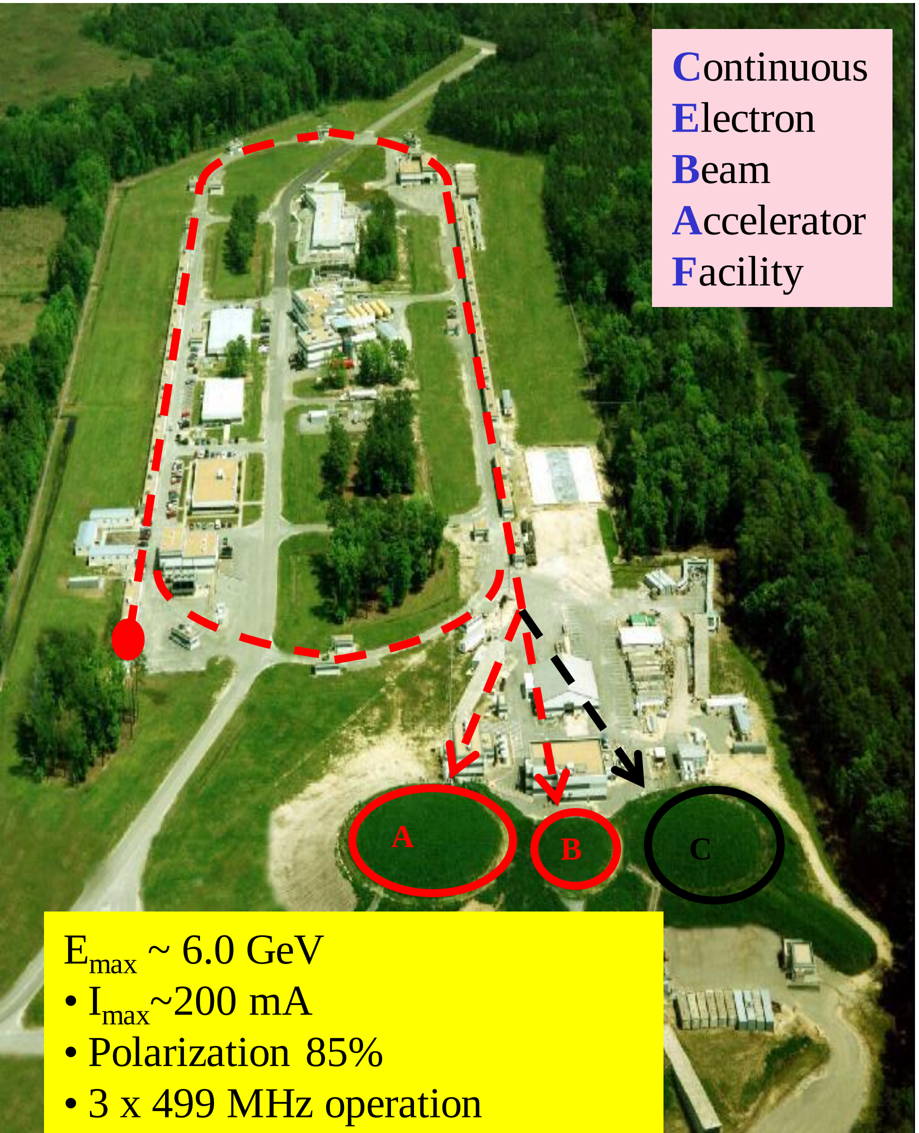

**CLAS, HERMES**: first observation of DVCS-BH interference

**Hall A**: proof of scaling for DVCS

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



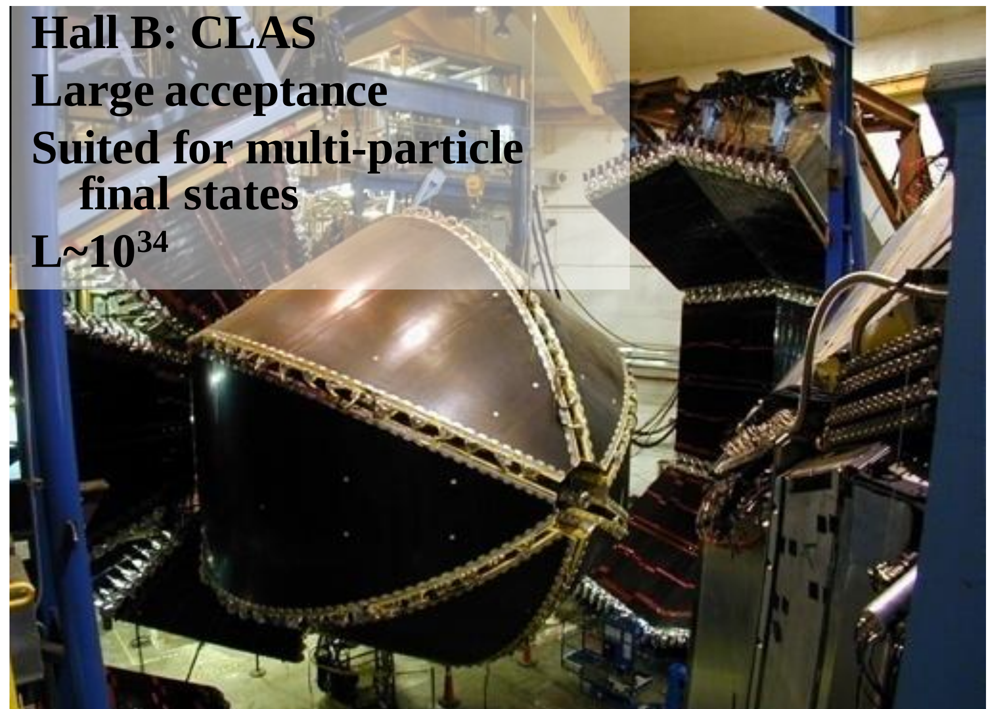
# JLab@6 GeV




**C**ontinuous
**E**lectron
**B**eam
**A**ccelerator
**F**acility

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

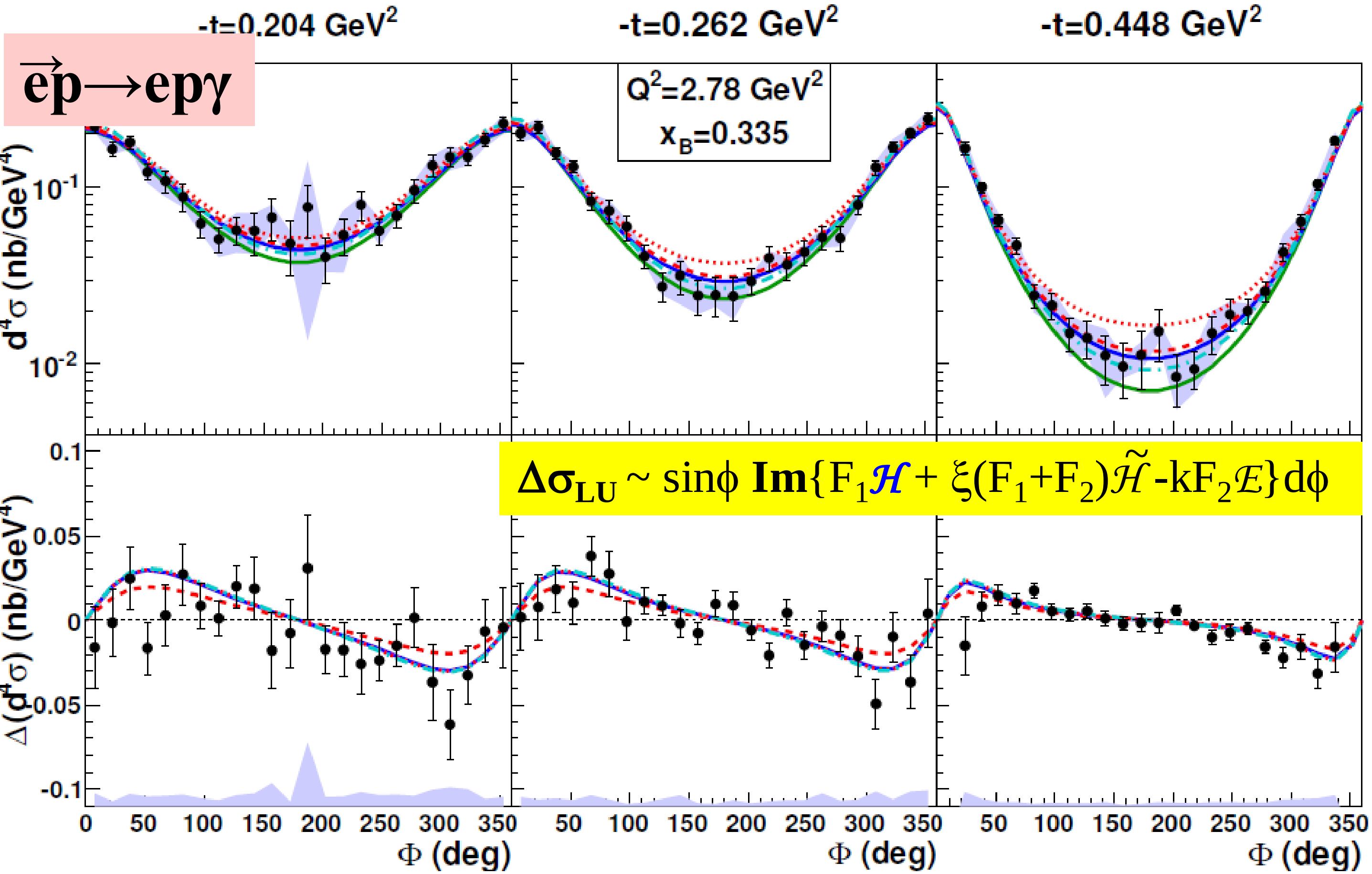
**Hall A: 2 HRS**
**High resolution**
**High luminosity ($L$~$10^{37}$)**
**Limited coverage**



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

# CLAS: unpolarized and beam-polarized cross sections

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




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

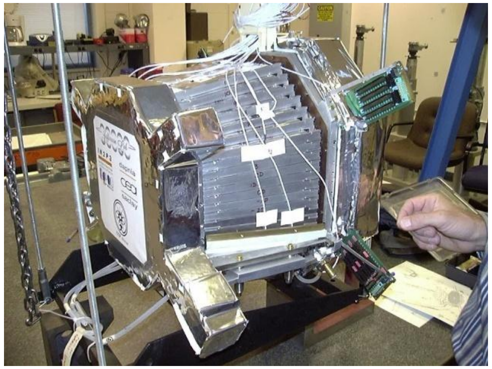
*H.S. Jo et al.*, PRL 115, 212003 (2015)

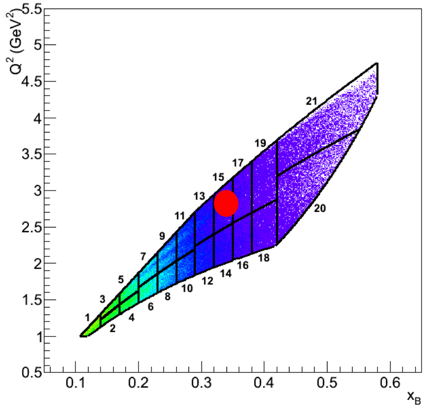
- **Largest kinematic ever covered**
- **Two observables extracted**

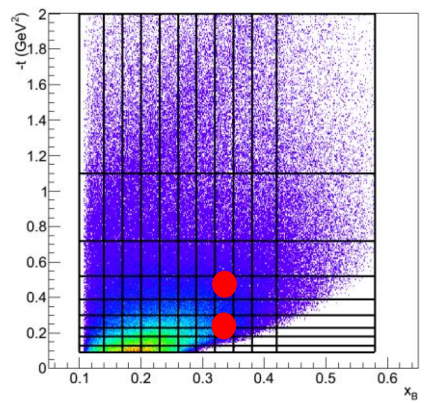
**KM10 model fits Hall A 2006 data using « anomalous » $\tilde{H}$**

- 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:**

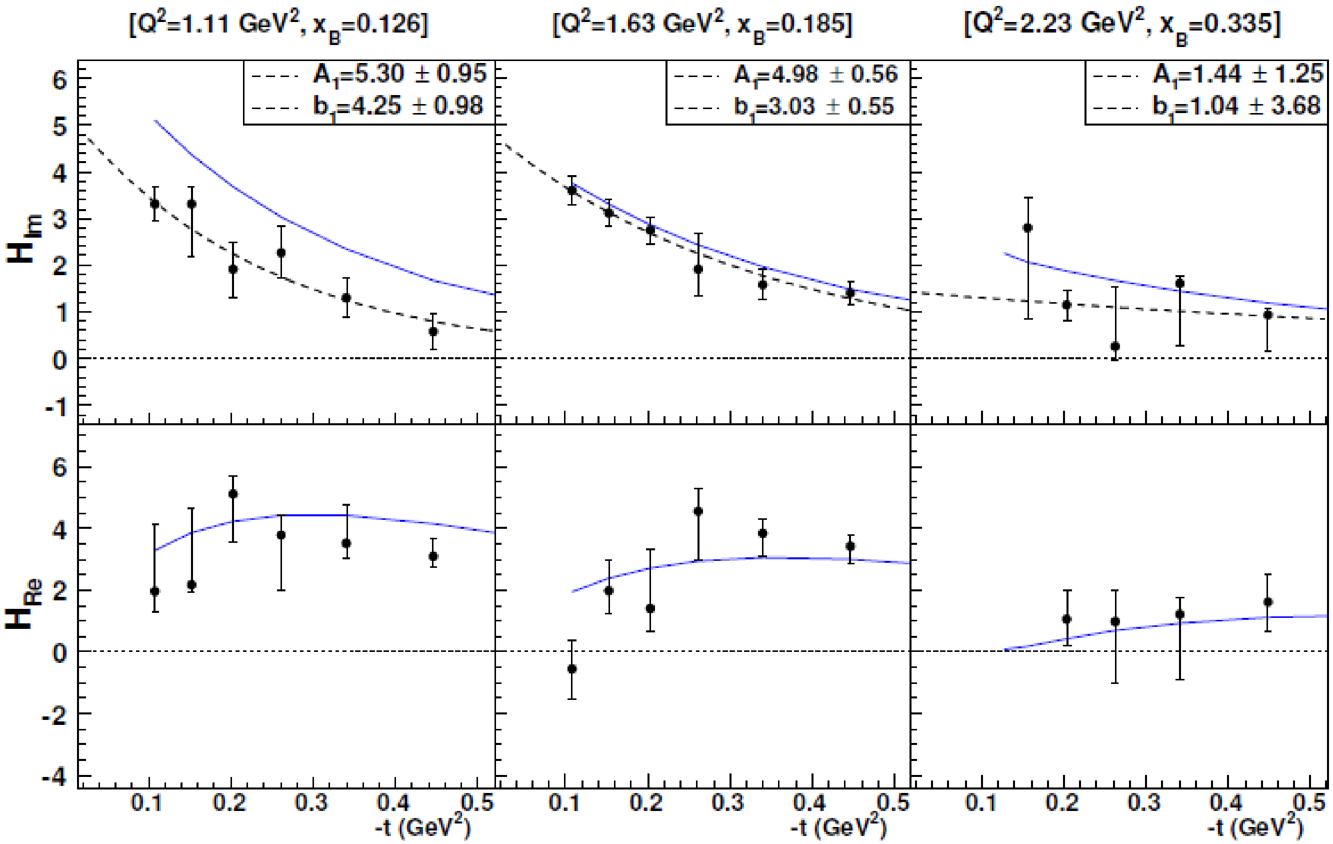
**8 CFF**

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

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

**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…*

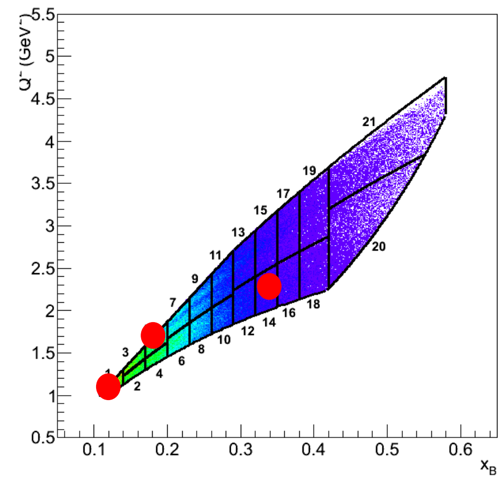
# Extraction of CFFs from e1dvcs pol. and unpol. cross sections



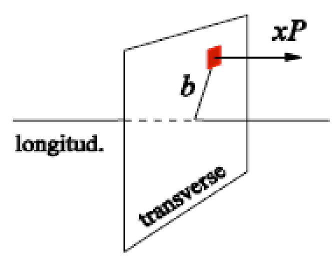

*CFF fits by M. Guidal*
*(H and $\tilde{H}$ only)*

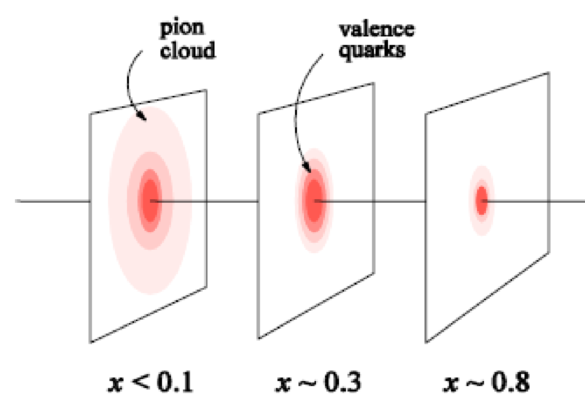
$Ae^{-bt}$ fit

VGG predictions




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



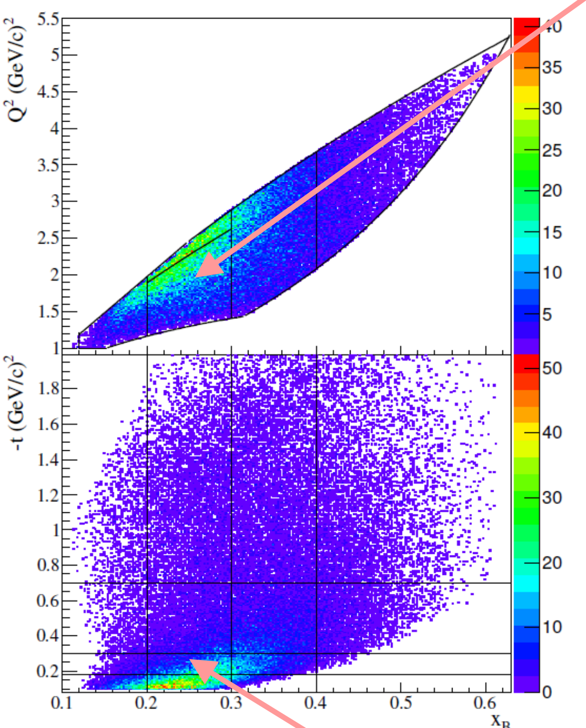

**$Im(\mathcal{H}_p)$, flatter t slope at high $x_B$: faster quarks (valence) at the core of the nucleon, slower quarks (sea) at its periphery**

**→ PROTON TOMOGRAPHY**

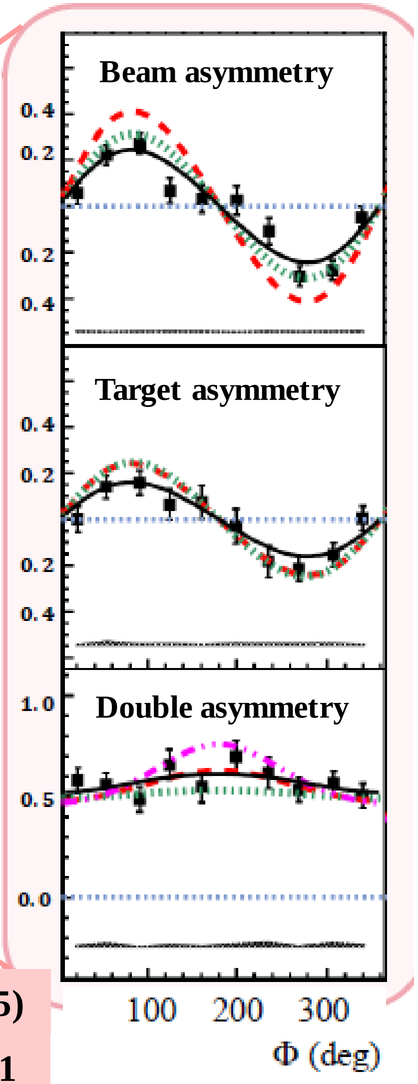
# CLAS: DVCS on longitudinally polarized target

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

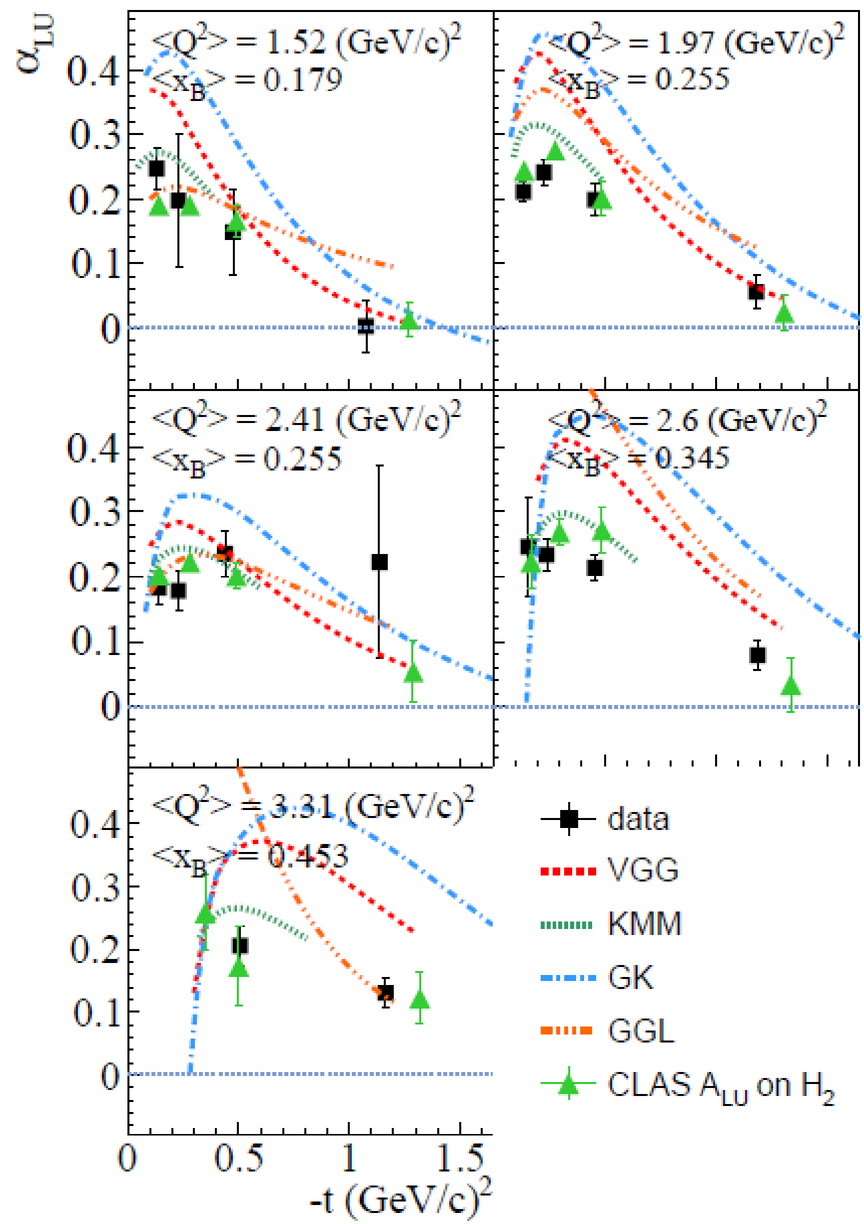
- Data taken in **2009, eg1-dvcs**
- Beam energy **~5.9 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized $NH_3$** (P~80%)
- **3 DVCS observables**




**5 $Q^2$-$x_B$ bins, 4 t bins, 10 $\phi$ bins**




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




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

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

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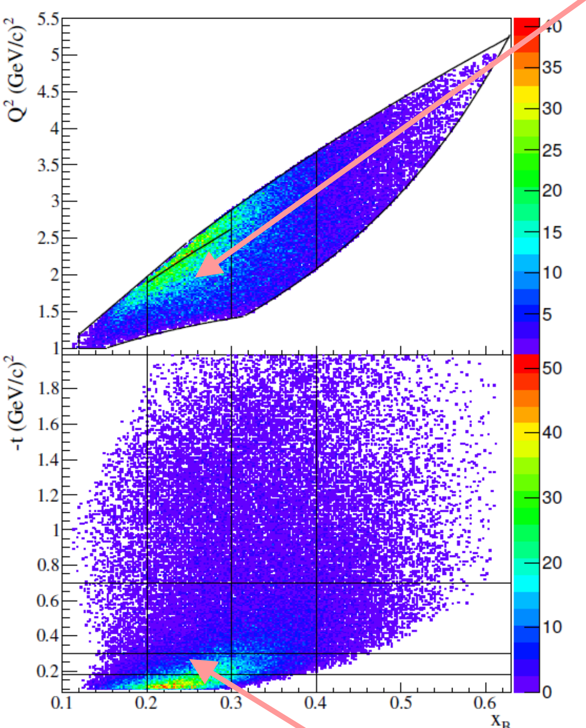


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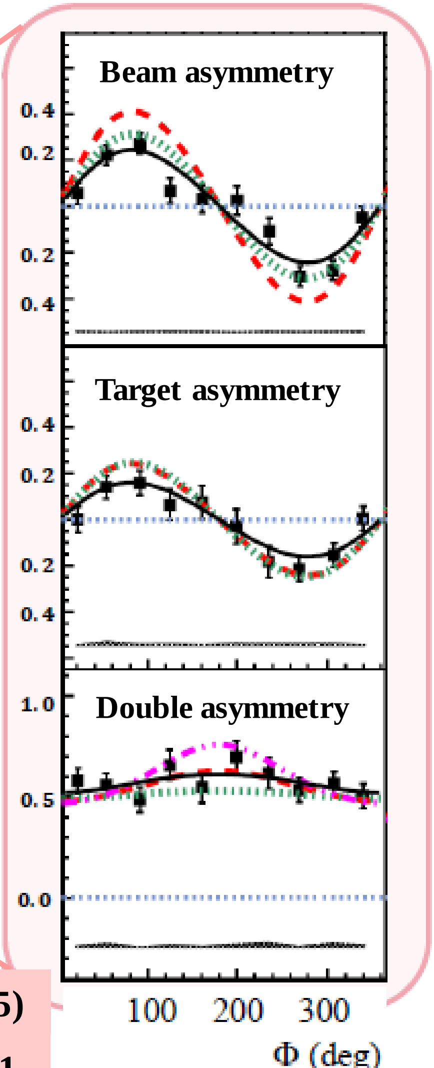
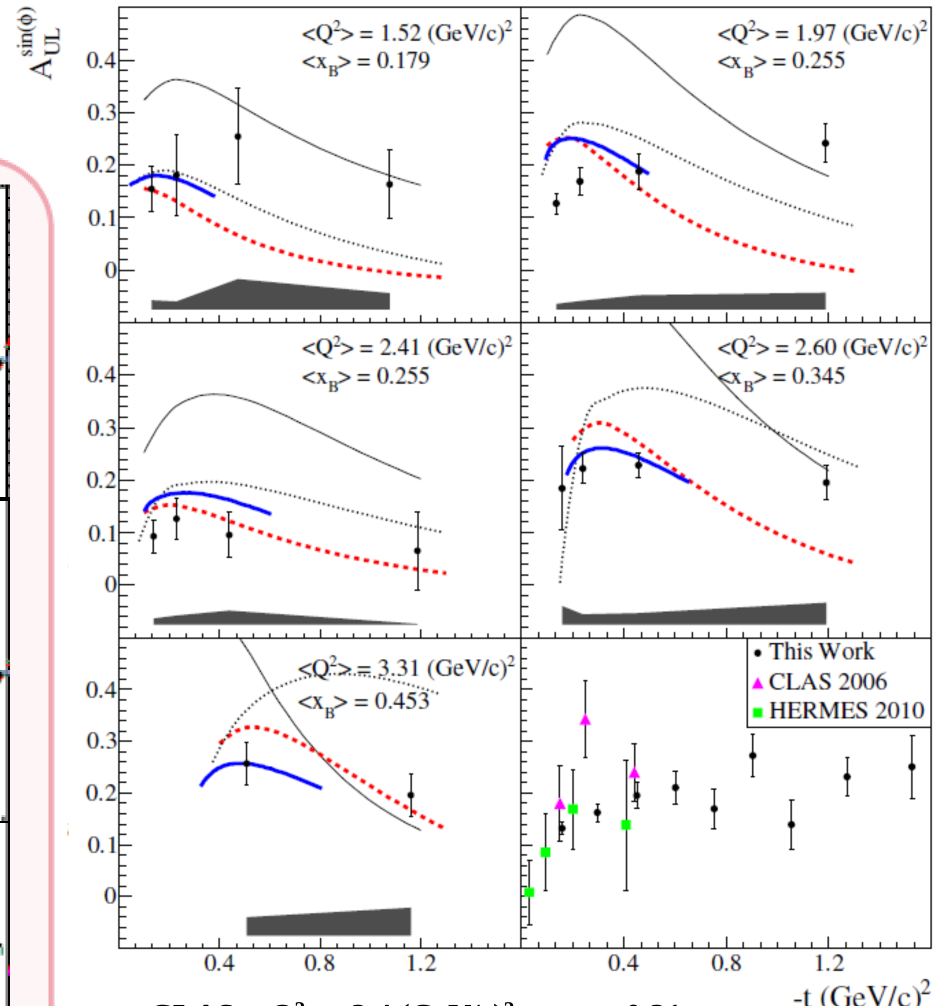



**TSA ~ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$**




**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**

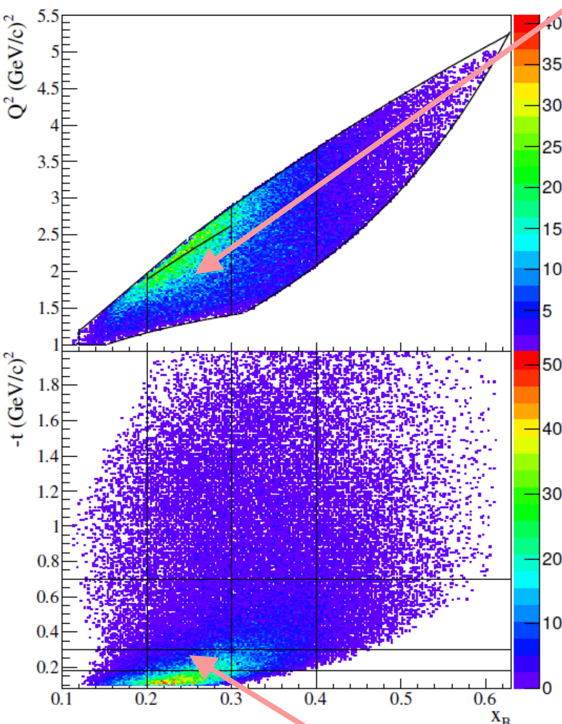
**S. Pisano et al., PRD 91, 052014 (2015)**
**E. Seder et al., PRL 114 (2015) 032001**

# CLAS: DVCS on longitudinally polarized target

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

**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**

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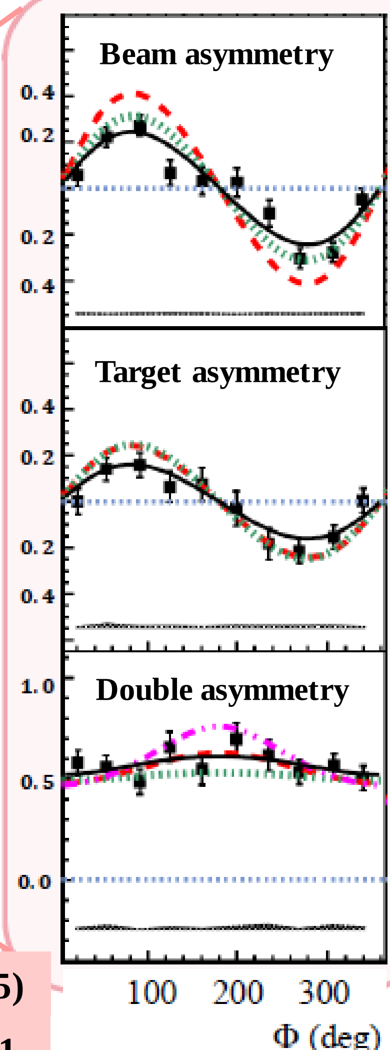
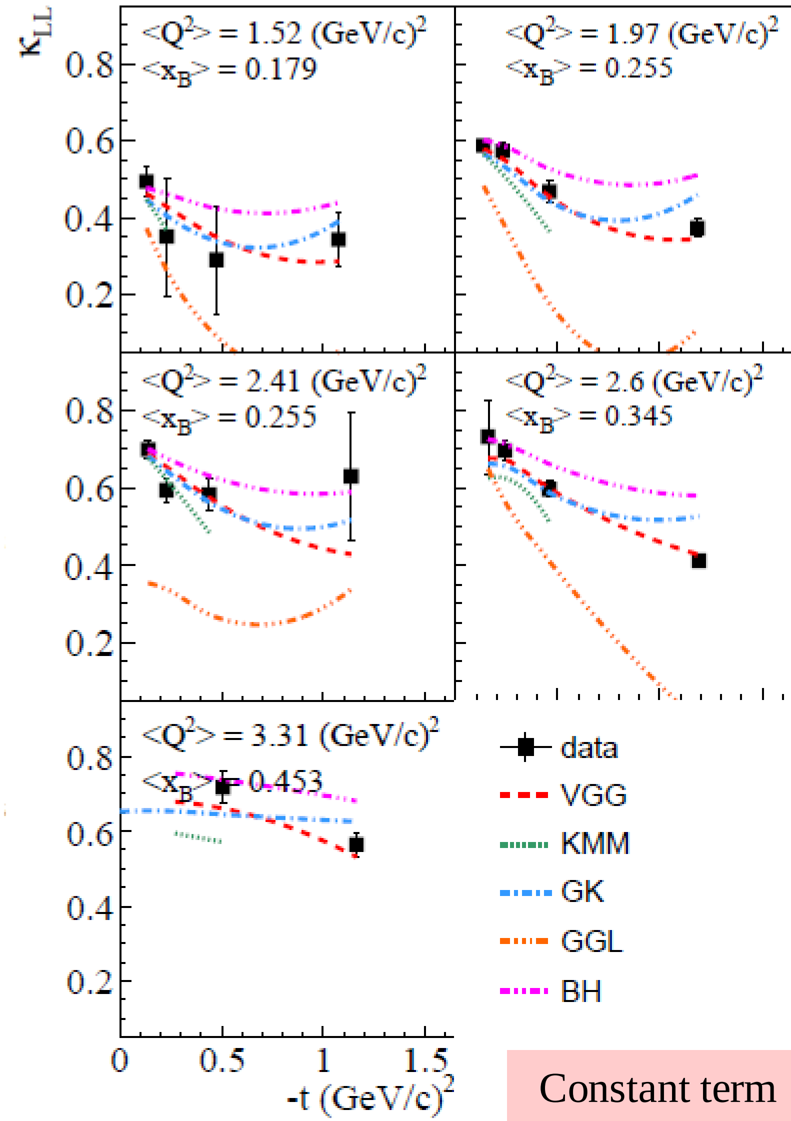



Constant term and cosϕ term are dominated by **BH**

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

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

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

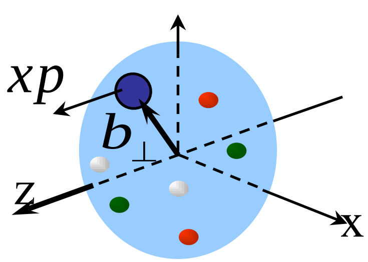
***CFFs fitting code by M. Guidal***
***(7 CFFs included in the fit)***

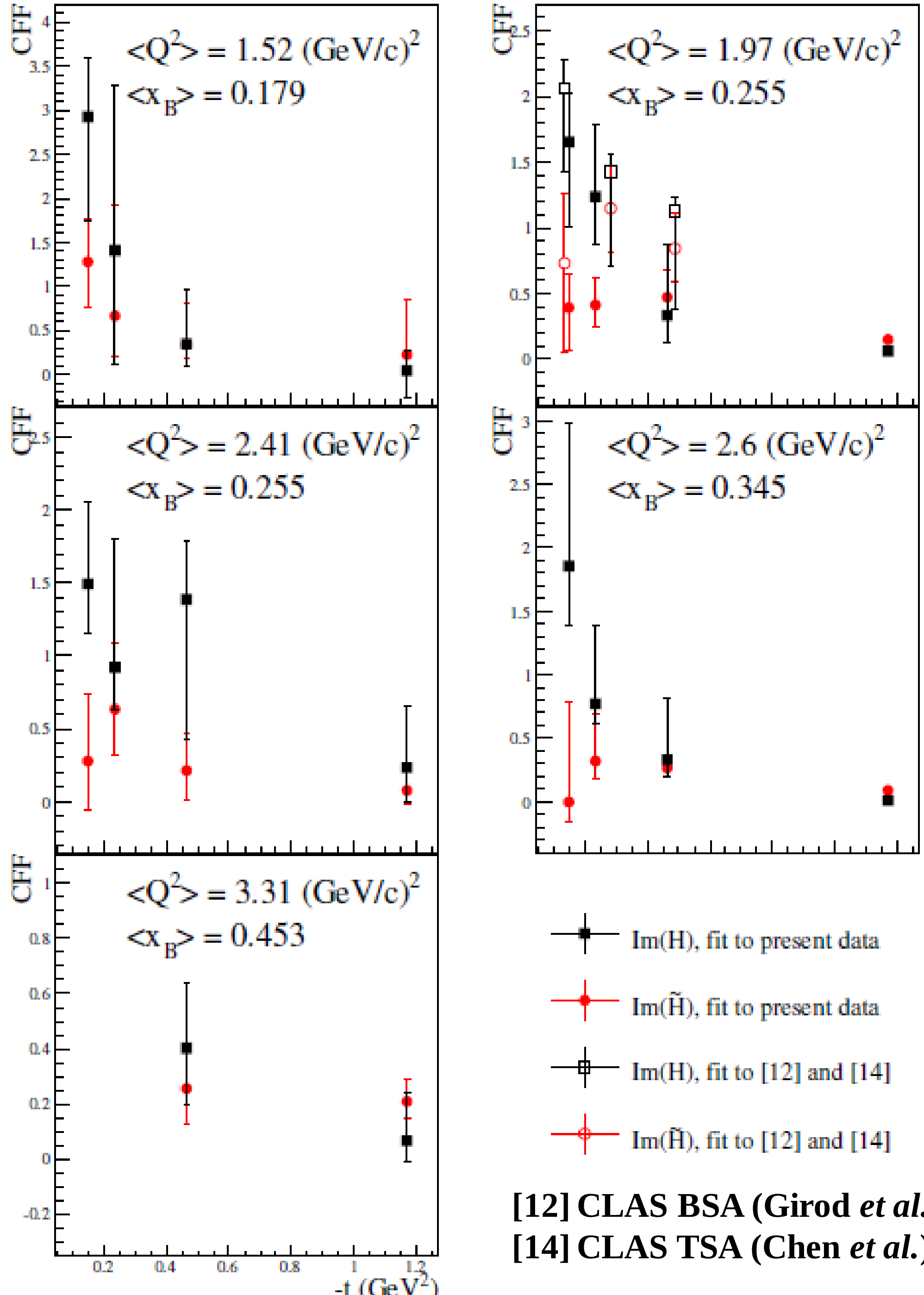
**$Im\mathcal{H}$ has steeper t-slope than**
**$Im\tilde{\mathcal{H}}$: is axial charge more "concentrated" than the electromagnetic charge?**
**→ PROTON TOMOGRAPHY**

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

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

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



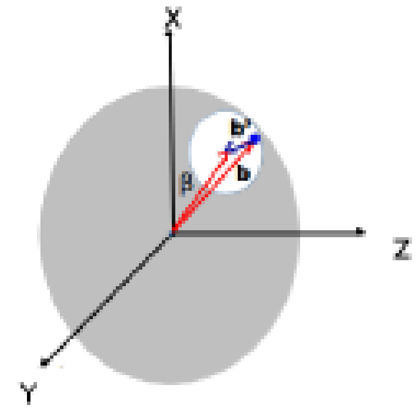




**[12] CLAS BSA (Girod *et al.*)**
**[14] CLAS TSA (Chen *et al.*)**

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

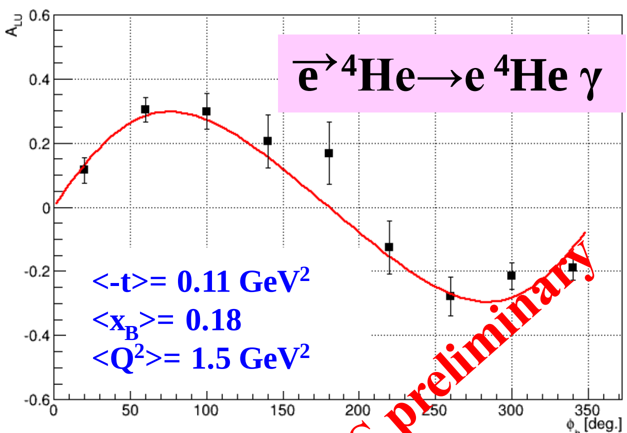
# DVCS on nuclei: the CLAS eg6 experiment

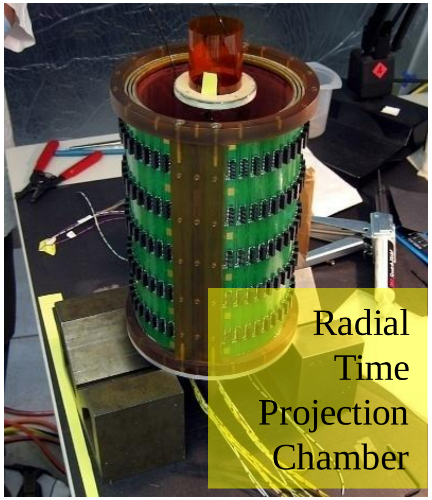
- Data taken in the fall 2009
- CLAS+IC+**RTPC**+$^4$He target; E~**6.065 GeV**
- **Coherent** and **incoherent DVCS: nuclear GPDs, EMC effect**

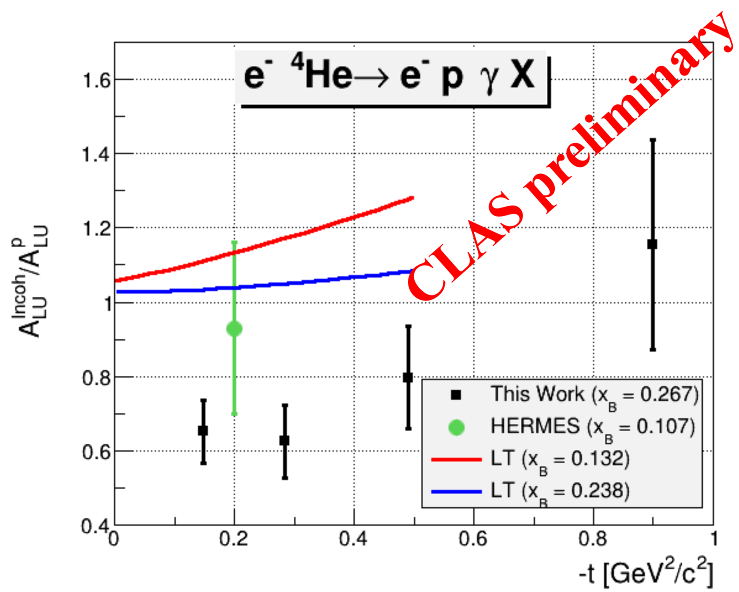


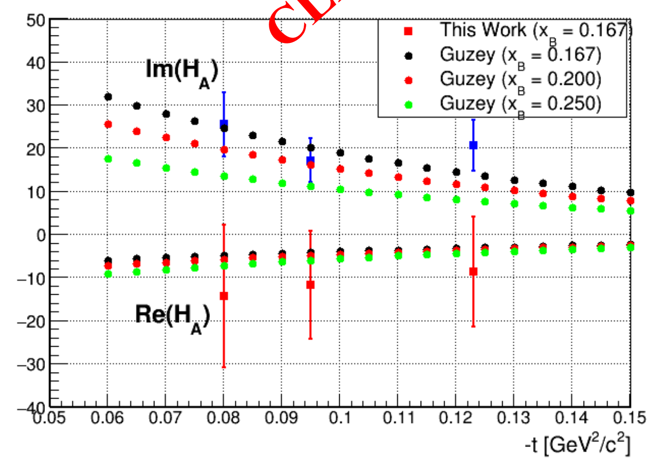

$^4$He is a spin-0 nucleus: at twist-2 **only one CFF** in DVCS BSA

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



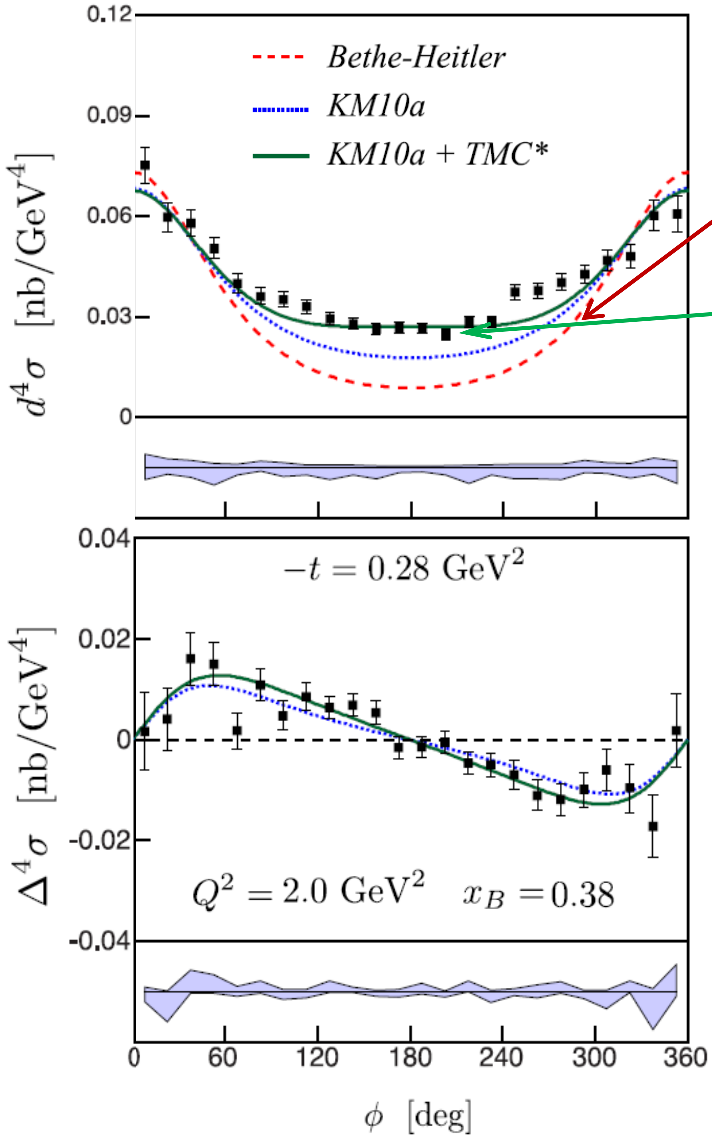




- **Small –t**: asymmetry for $^4$He lower than the bound proton one
- **High –t**: the two asymmetries tend to become compatible

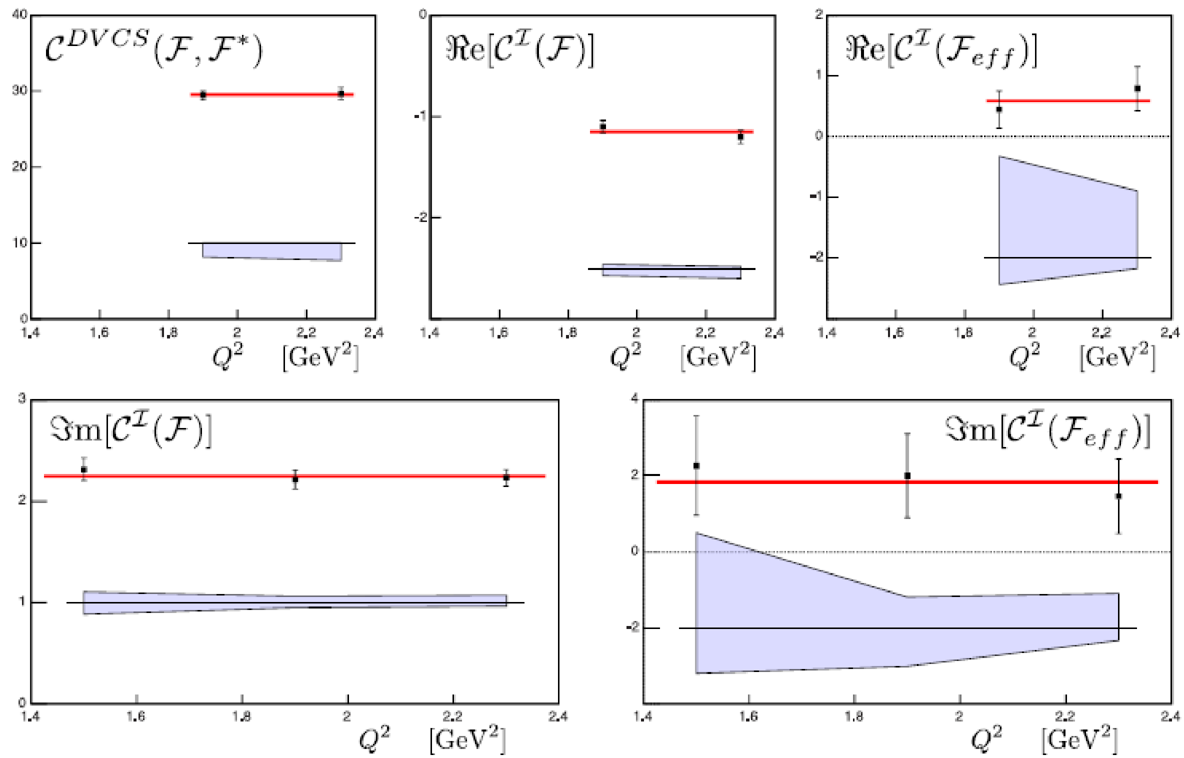
*Work by M. Hattawy, IPNO & ANL*

# DVCS on the proton in Hall A




**Re-analysis of E00-110 (2001)**
**M. Defurne et. al., Phys. Rev. C92, 055202 (2015)**

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



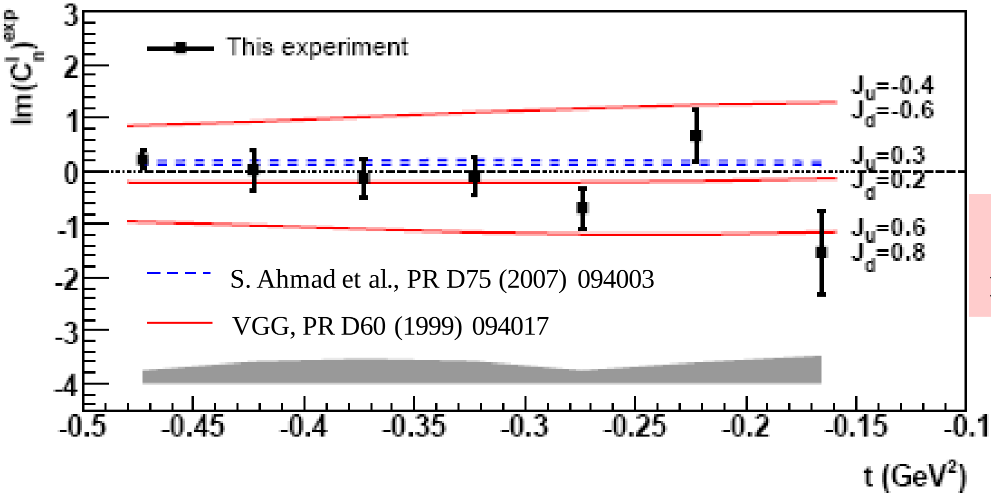

Beam-energy separation at constant $Q^2$, $x_B$ and $t$:
**experiment E07-007 (Analysis ongoing)**

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

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

# DVCS on the neutron in Hall A

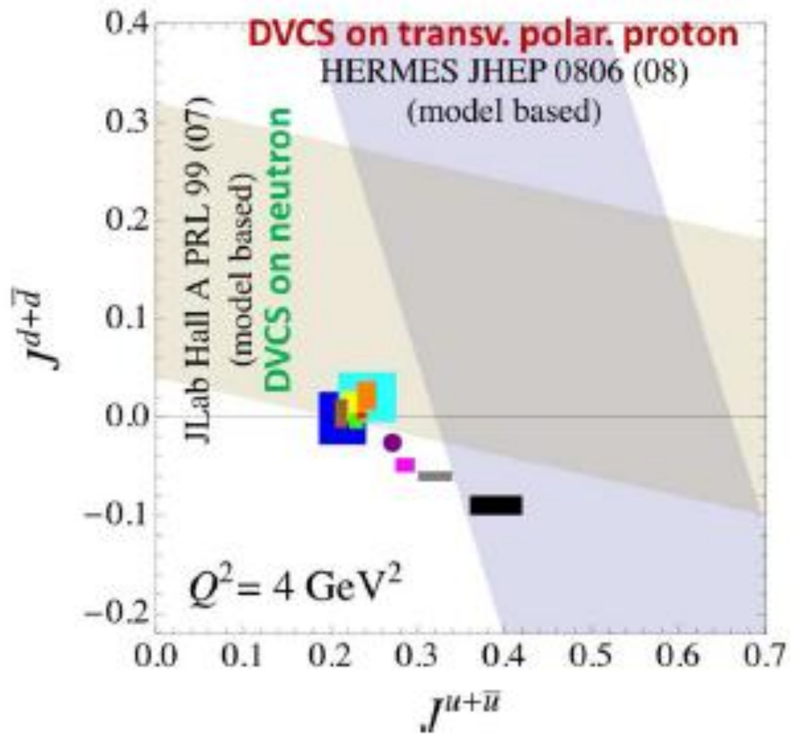
**M. Mazouz et al., PRL 99 (2007) 242501**




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

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

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




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

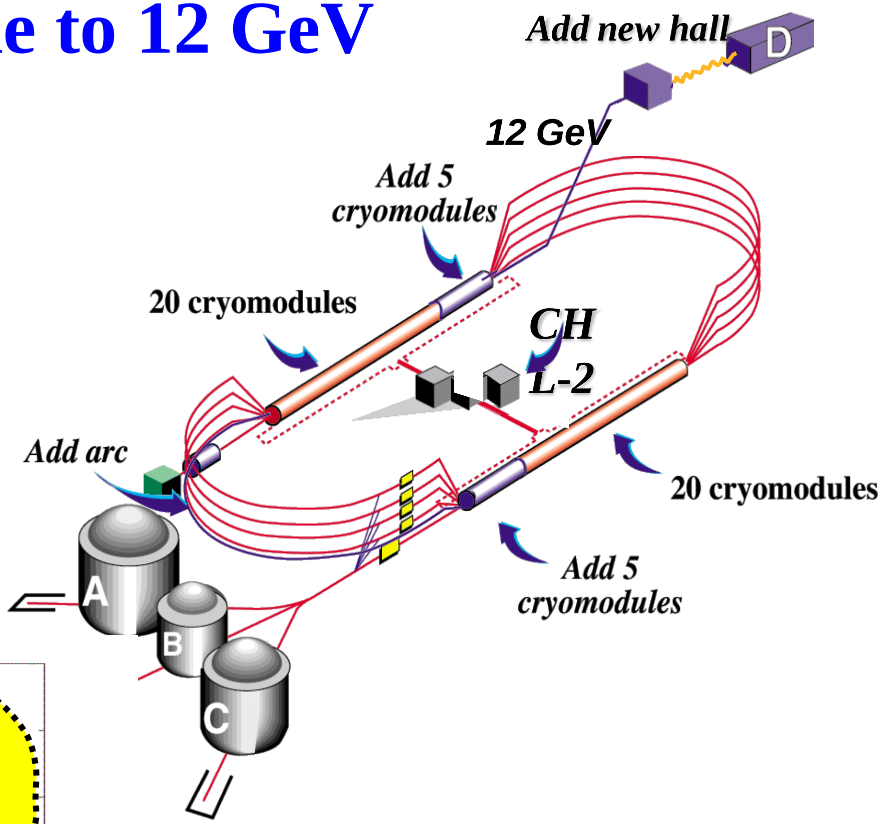
• **E08-025**: Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target
• Data taken in fall 2010, **analysis ongoing**

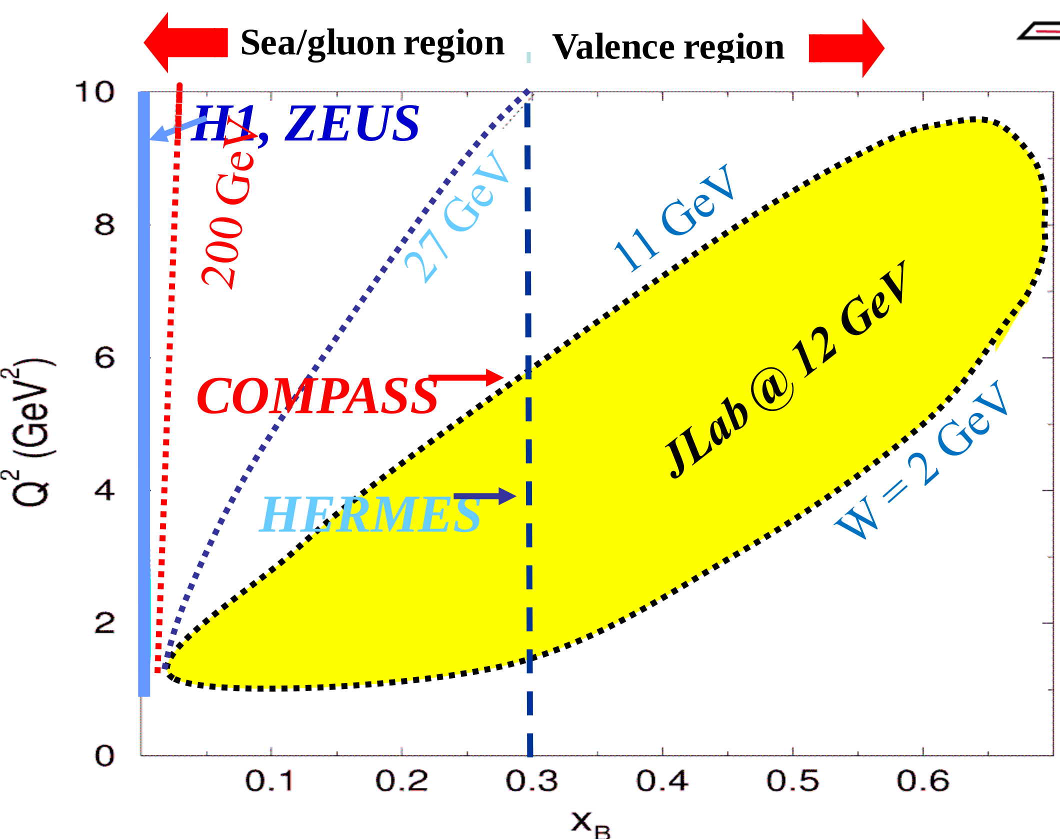
# JLab upgrade to 12 GeV

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

Beam polarization > 80%

**Upgrade completed in 2014**

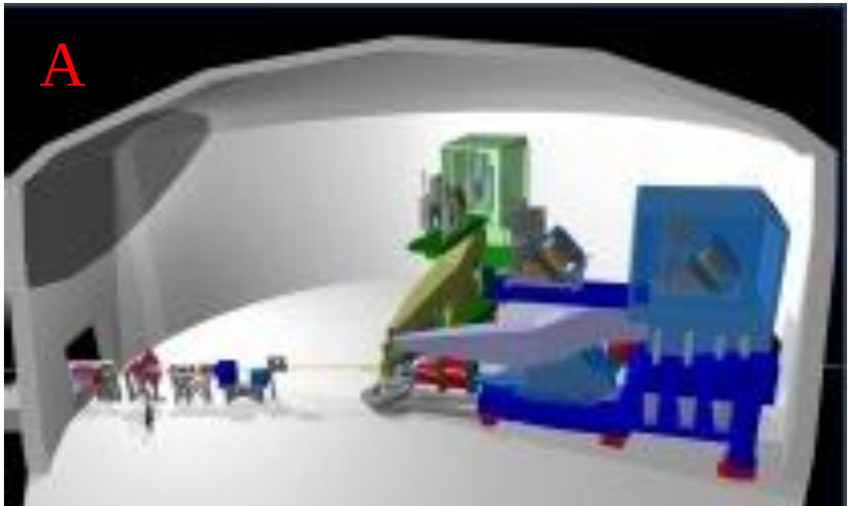


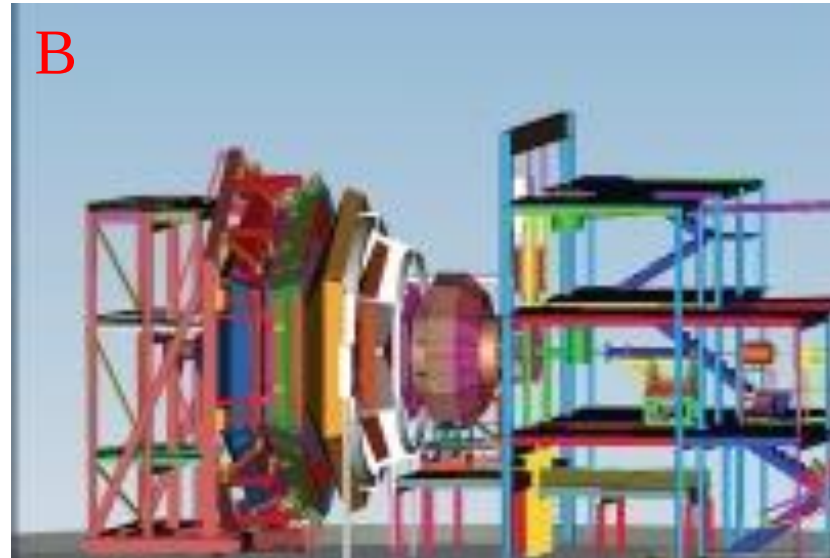

Study of high $x_B$ domain requires high luminosity

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

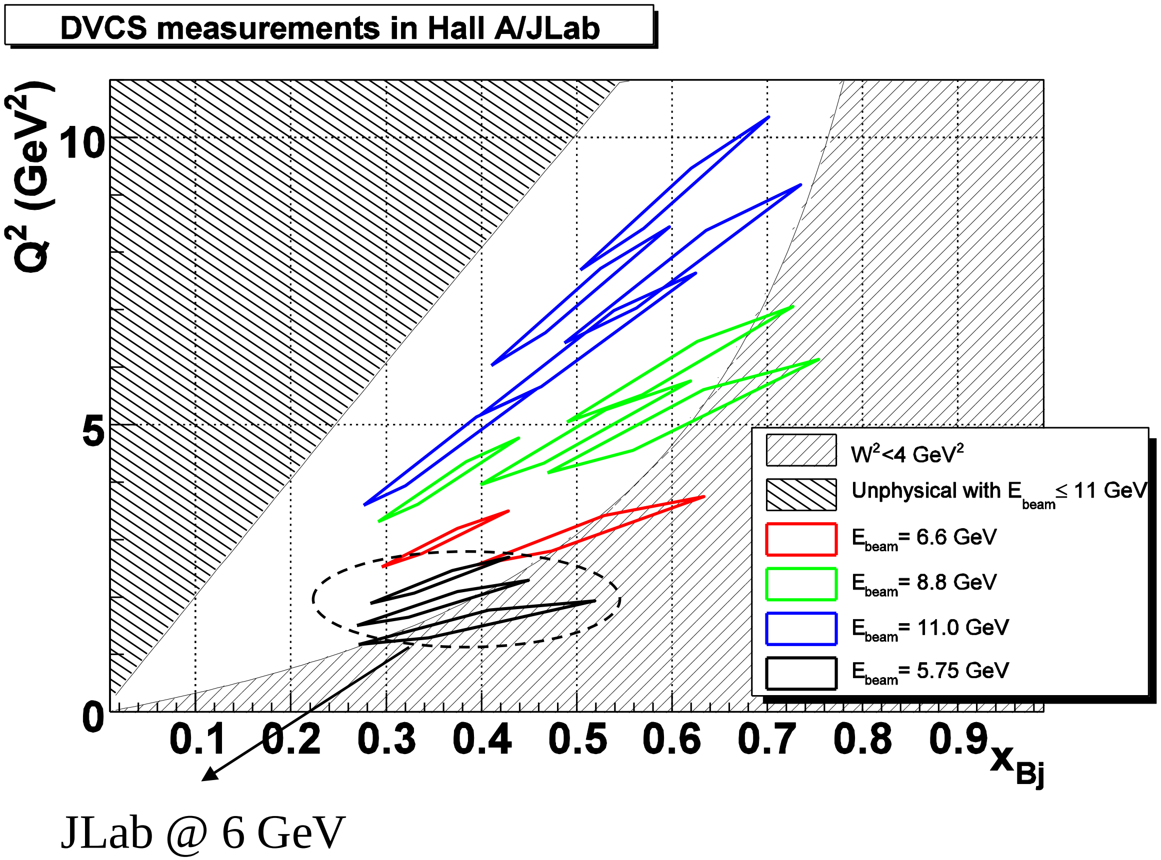

Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles

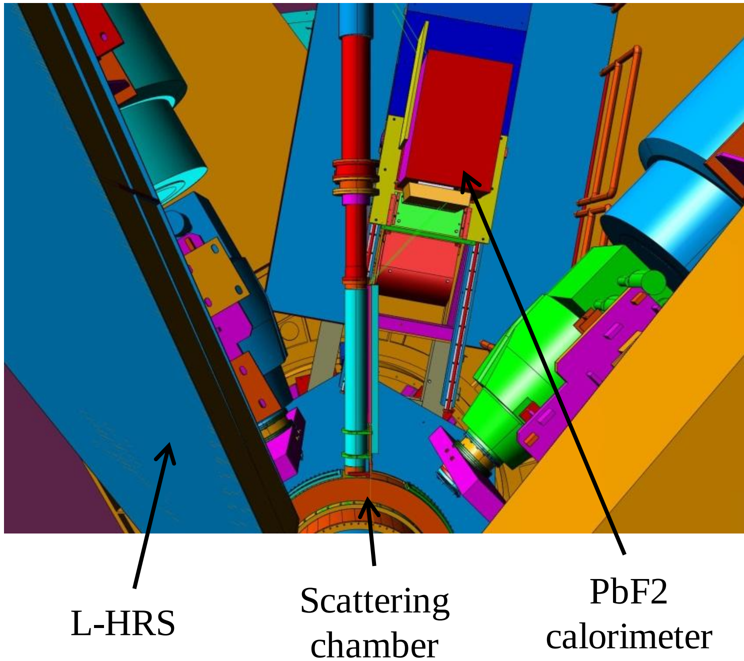
DVCS experiments at 11 GeV have been approved for each of these **three halls**.
**Complementary programs**:
- different kinematic coverage
- different precisions/resolutions
- focus on different observables

# E12-06-114: pDVCS at 11 GeV in Hall A

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

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



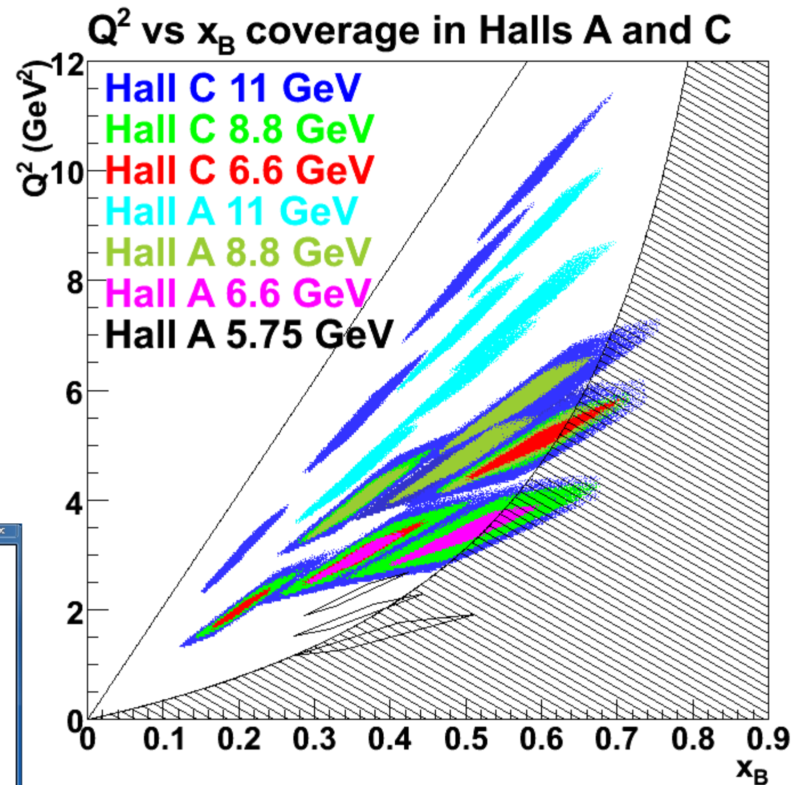



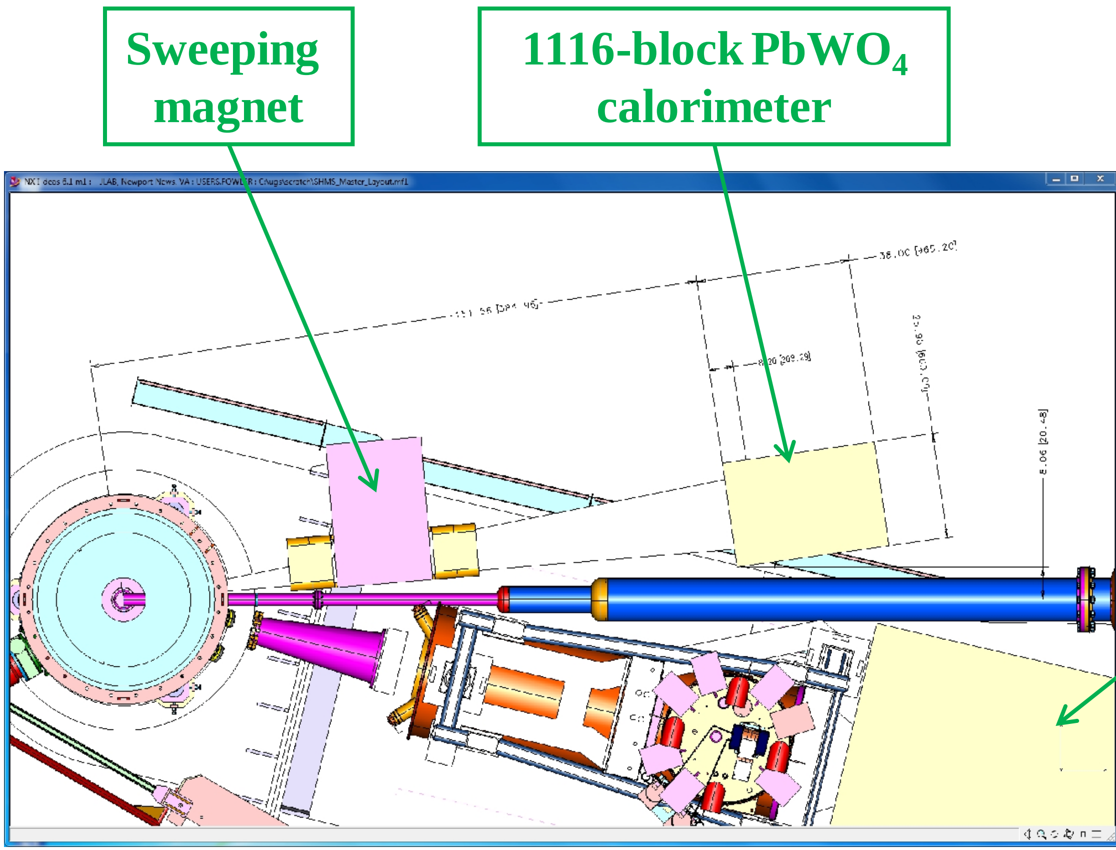

**1st experiment to run after the 12-GeV upgrade**

**Started in fall 2014, continuing in 2016**

# E12-13-010: pDVCS at 11 GeV in Hall C

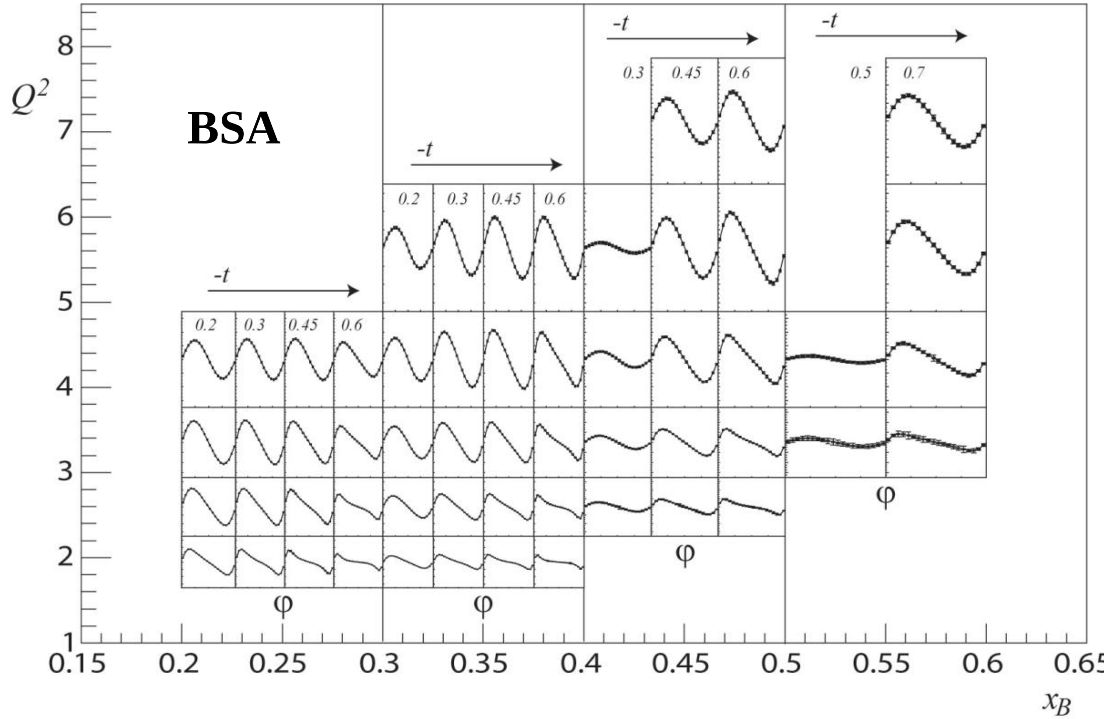
- Energy separation of the DVCS cross section
- Higher $Q^2$: measurement of higher twist contributions
- Low-$x_B$ extension (thanks to sweeping magnet)



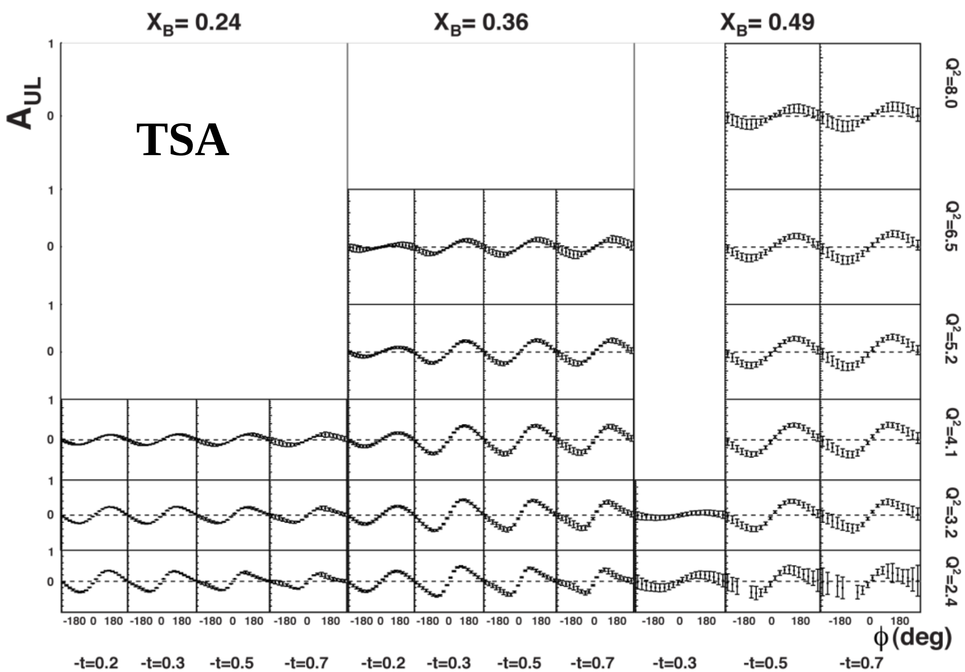




Tentative running:
~ 2019-20

# DVCS BSA and TSA with CLAS12 & 11 GeV beam



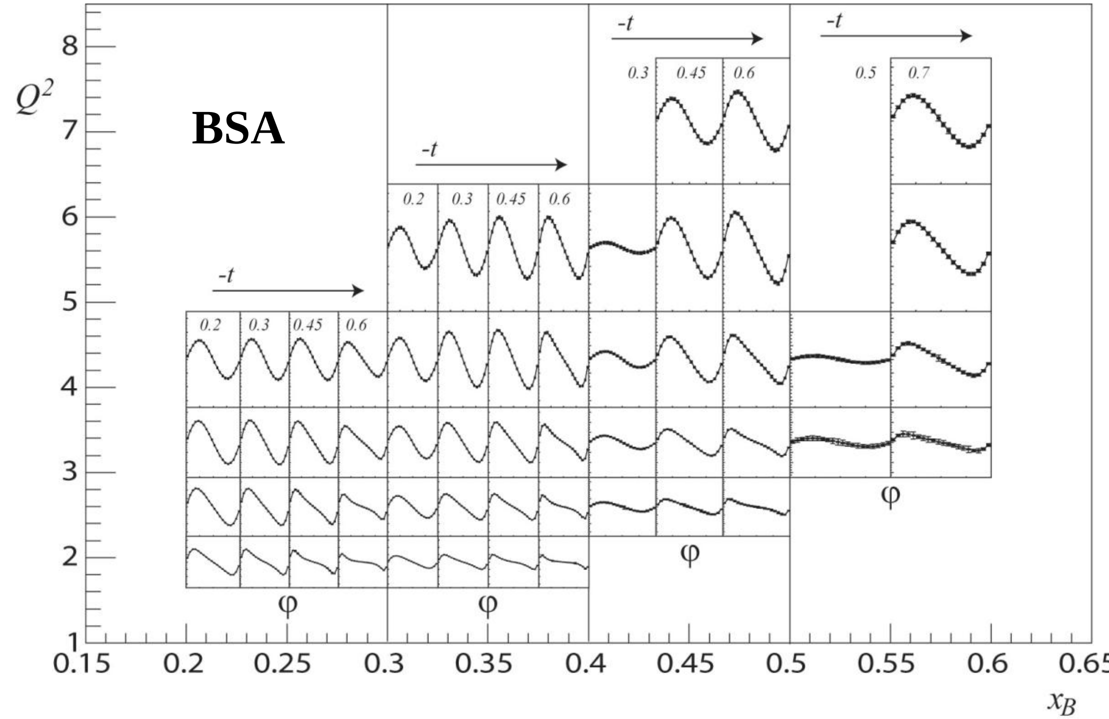

**85 days of beam time**
Liquid hydrogen target
$P_{beam} = 85\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$, $0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$
Statistical error: 1% to 10%
on $\sin\phi$ moments
Systematic uncertainties: ~6-8%

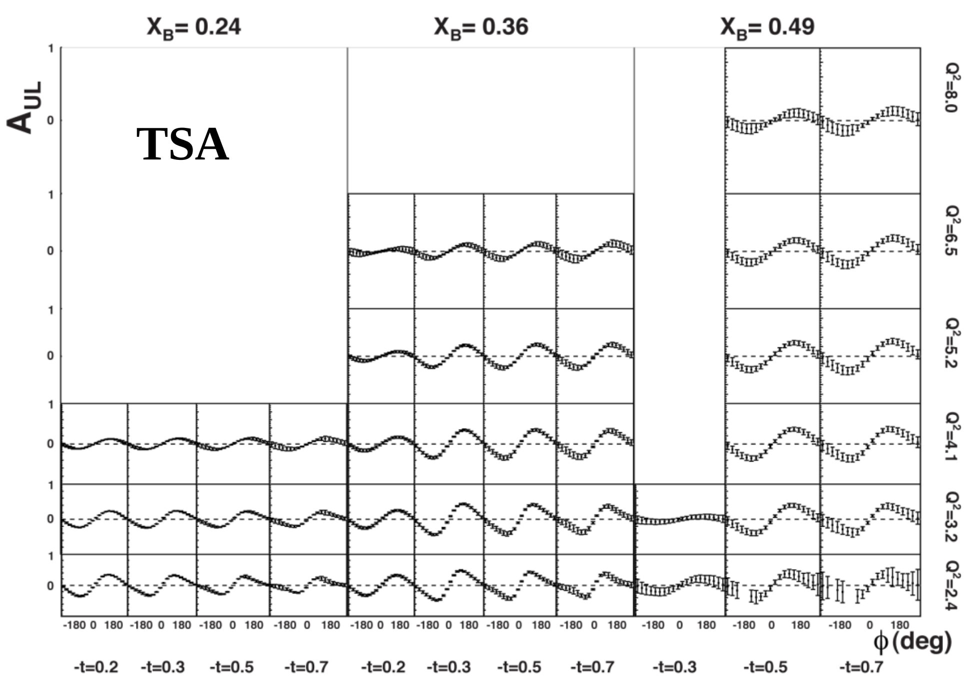



**120 days of beam time**
$NH_3$ long. polarized target
$P_{beam} = 85\%$, $P_{target} = 80\%$
$L = 2.10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$, $0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$
Statistical error: 2% to 15%
on $\sin\phi$ moments
Systematic uncertainties: ~6-8%

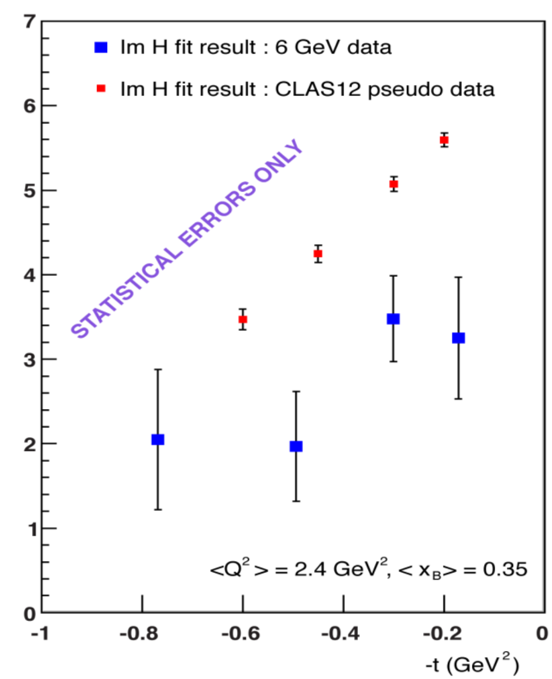
# DVCS BSA and TSA with CLAS12 & 11 GeV beam

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



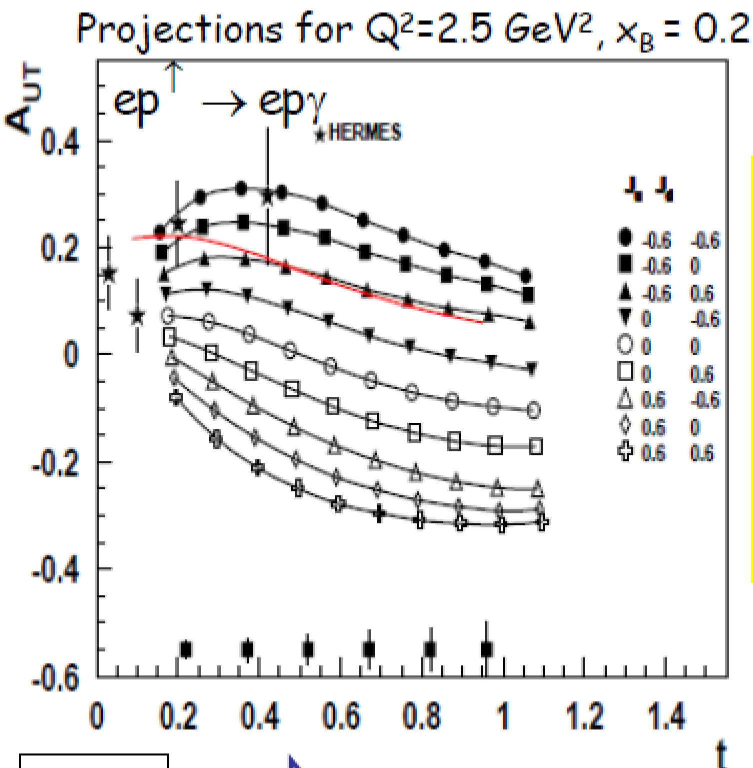




**Impact of CLAS12 DVCS-BSA data on model-independent fit to extract Im(H)**



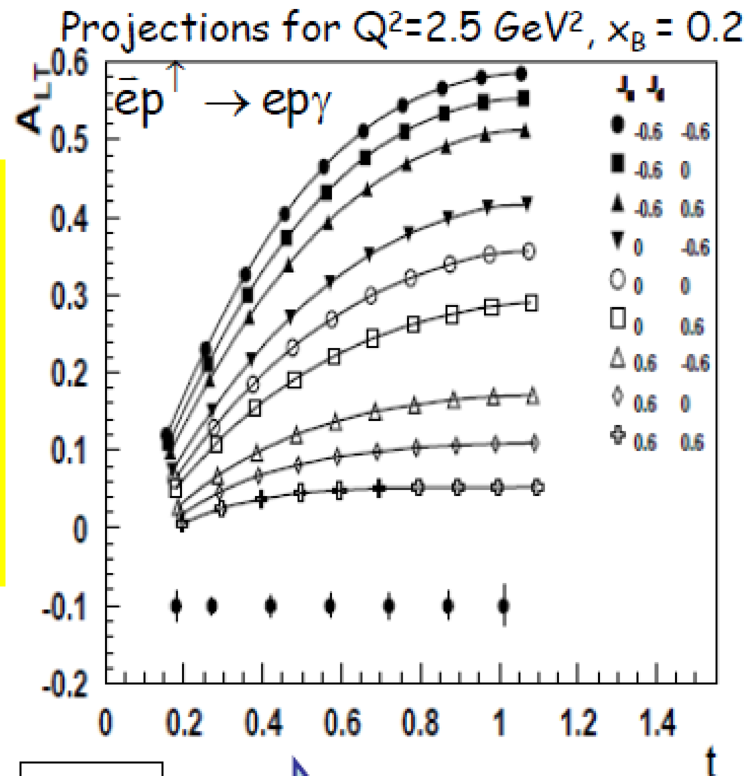
# CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time
Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = $5\times10^{33}$ $cm^{-2}s^{-1}$
$1 < Q^2 < 10$ $GeV^2$, $0.06 < x_B < 0.66$, $-t_{min} < -t < 1.5$ $GeV^2$




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

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

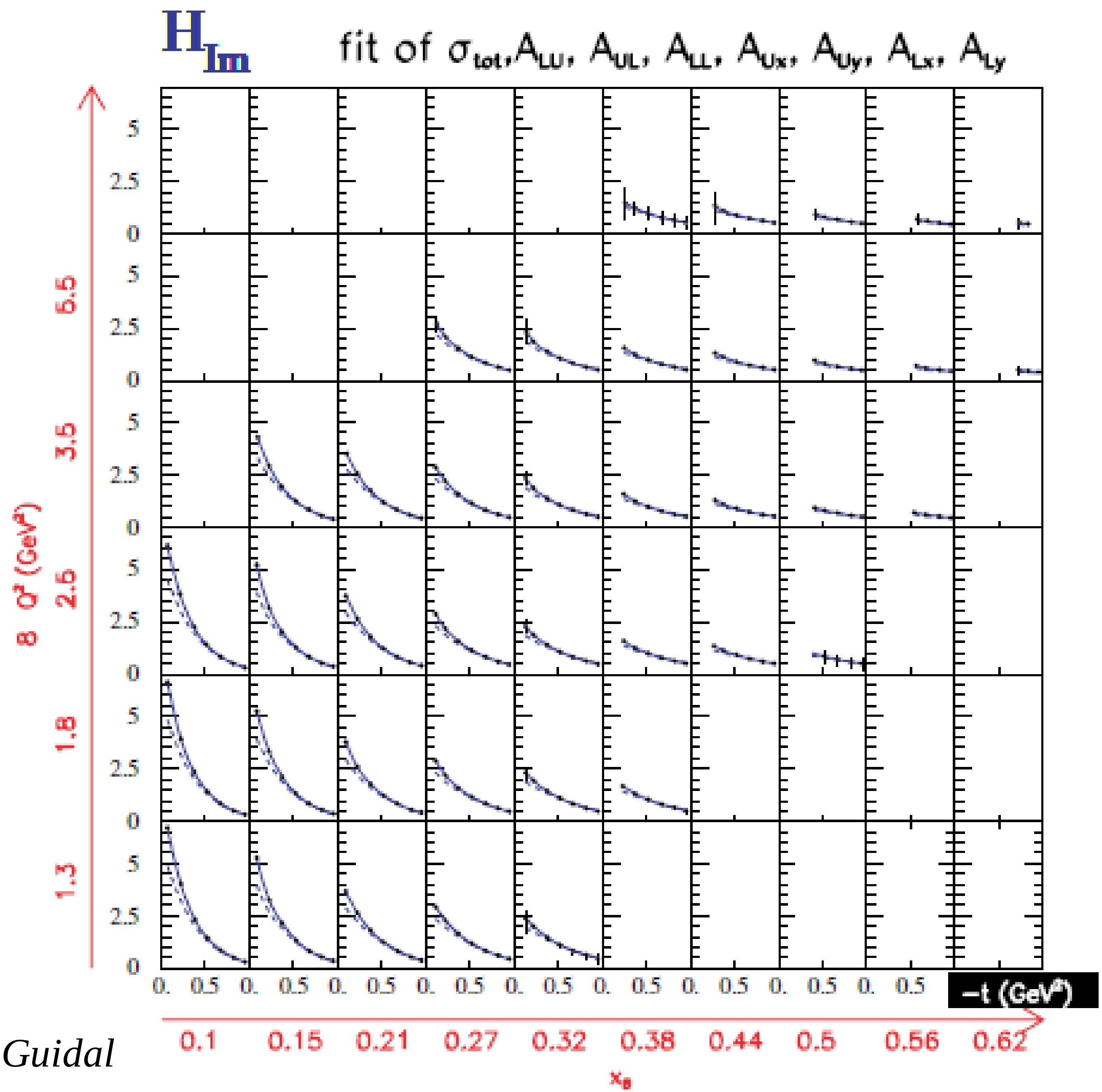



$\Delta\sigma_{LT}$ ⇒ $Re\{\mathcal{H}_p, \mathcal{E}_p\}$

JLab PAC: **high-impact experiment**

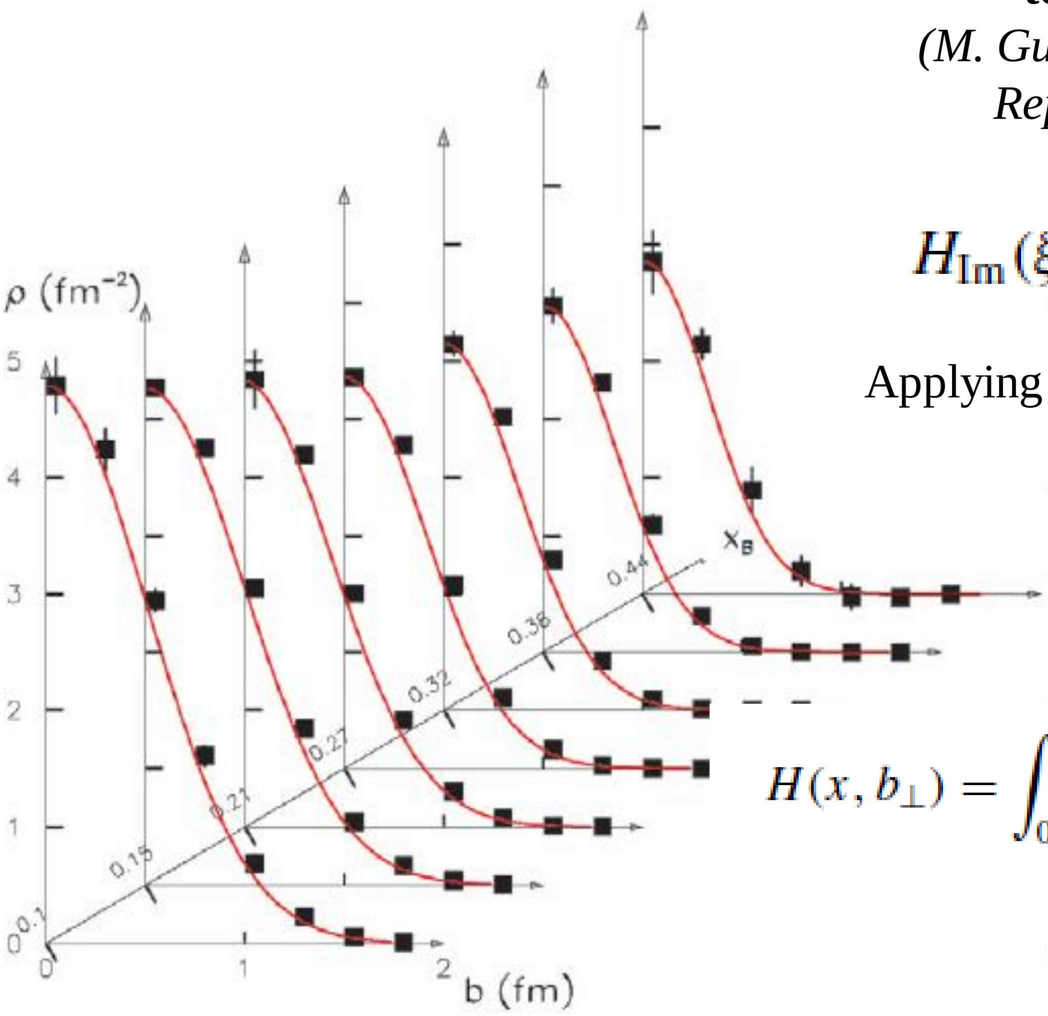
***Proposal conditionally approved by PAC39***

# 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

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

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

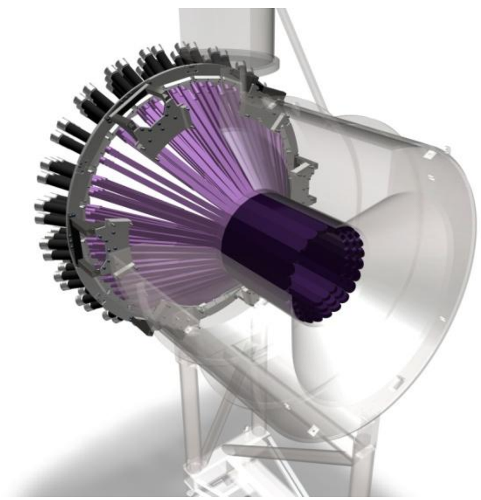
$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$

**The most sensitive observable to the GPD E**

*ed→ e(p)nγ*

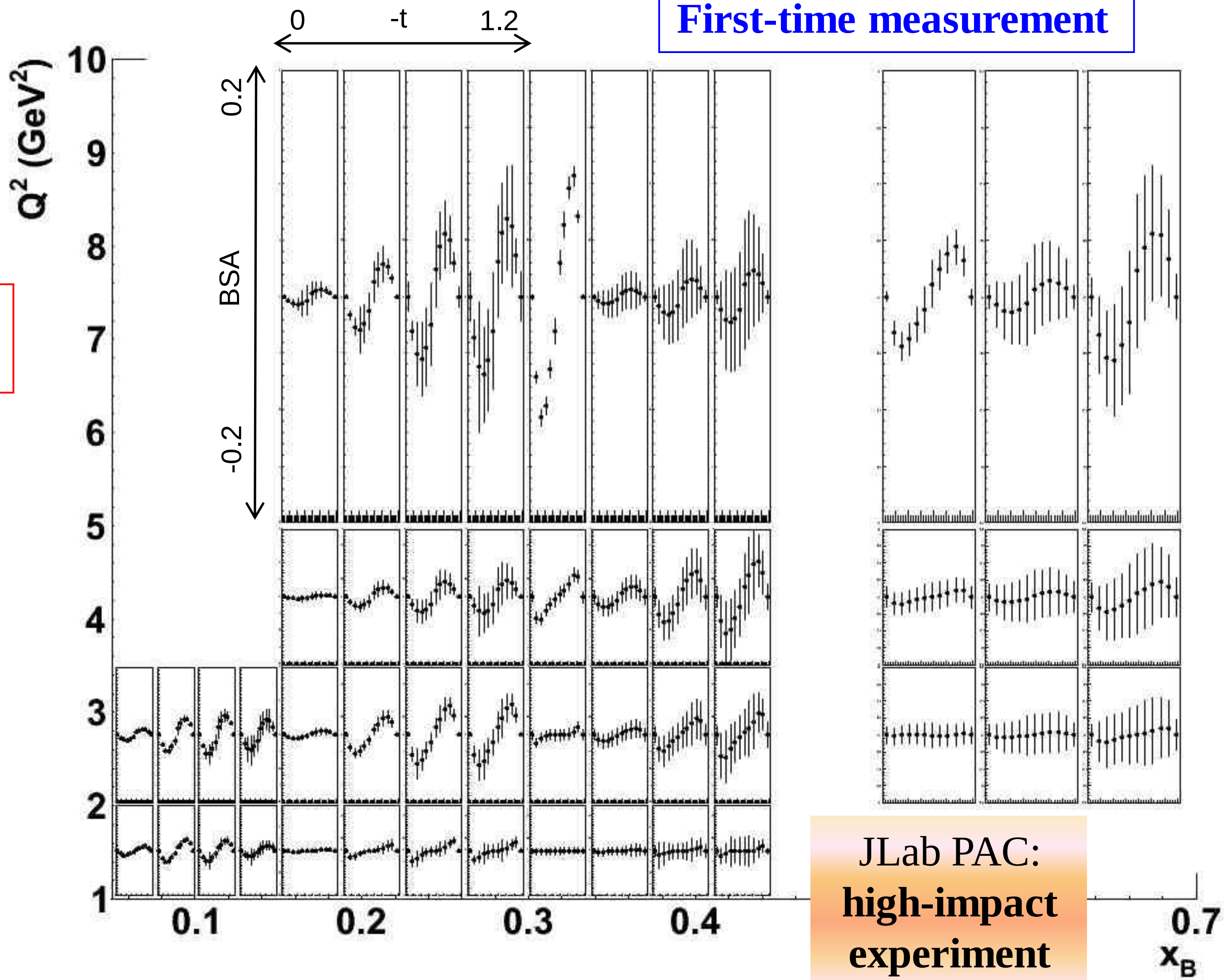
CLAS12 +
Forward Calorimeter +
**Neutron Detector**

**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

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

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

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

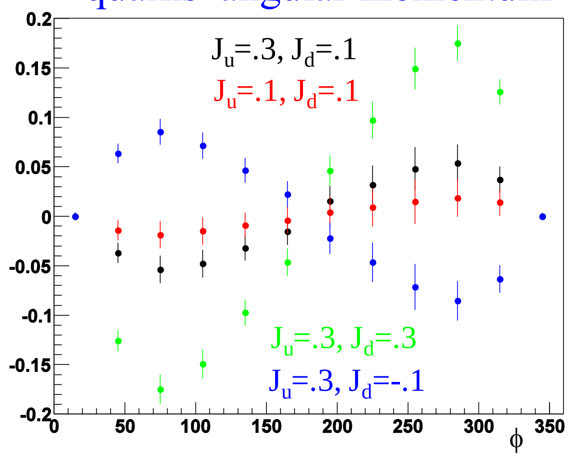
**The most sensitive observable to the GPD E**

*ed→ e(p)nγ*

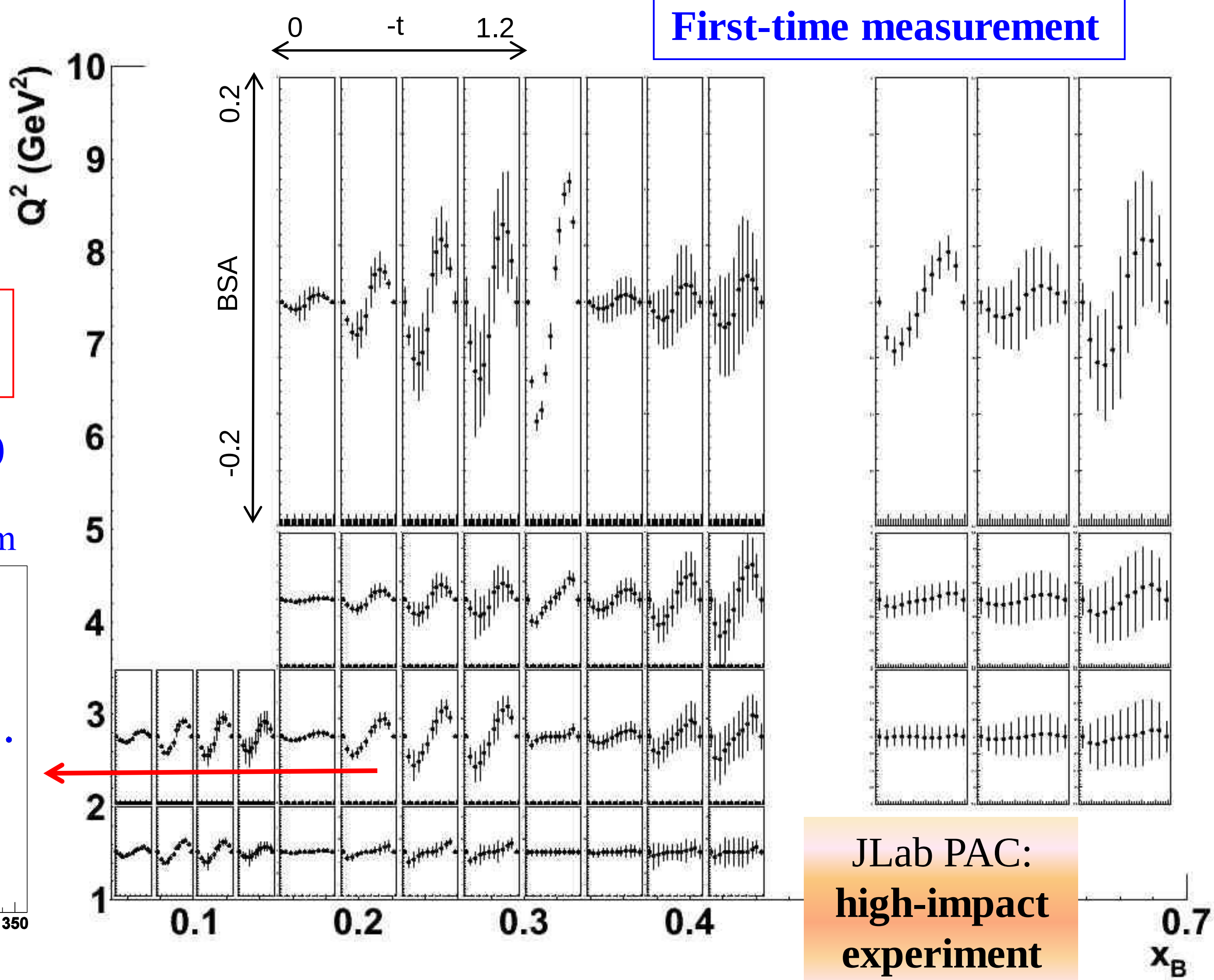
CLAS12 +
Forward Calorimeter +
**Neutron Detector**

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

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




**First-time measurement**




JLab PAC:
**high-impact experiment**

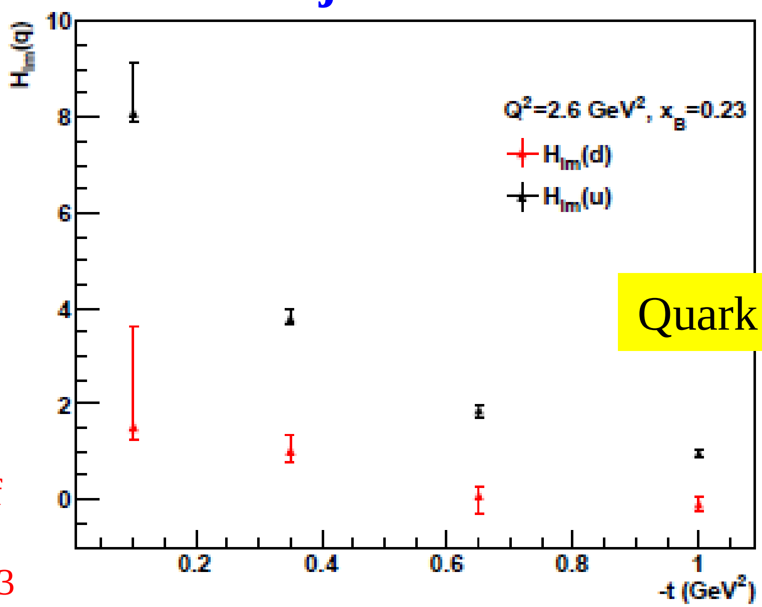
# DVCS: global view

| 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** |

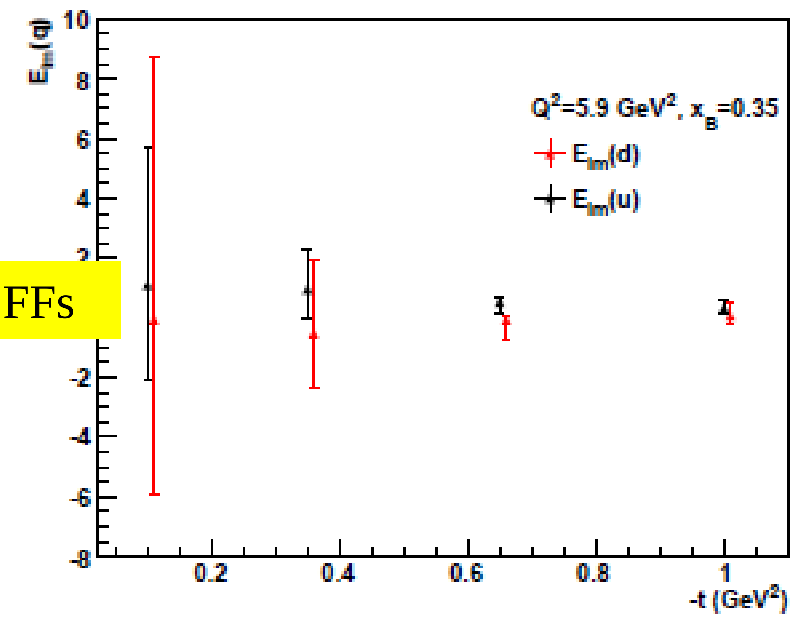
## Projections for flavor separation (*Im$\mathcal{H}$, Im$\mathcal{E}$*)

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, …**