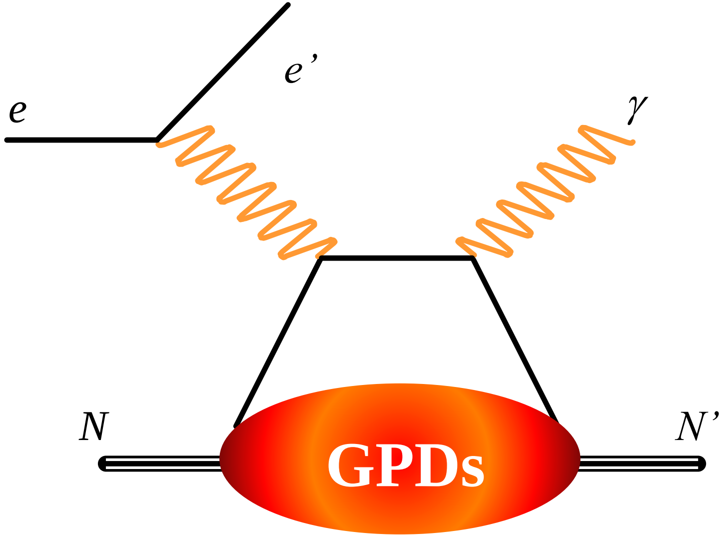
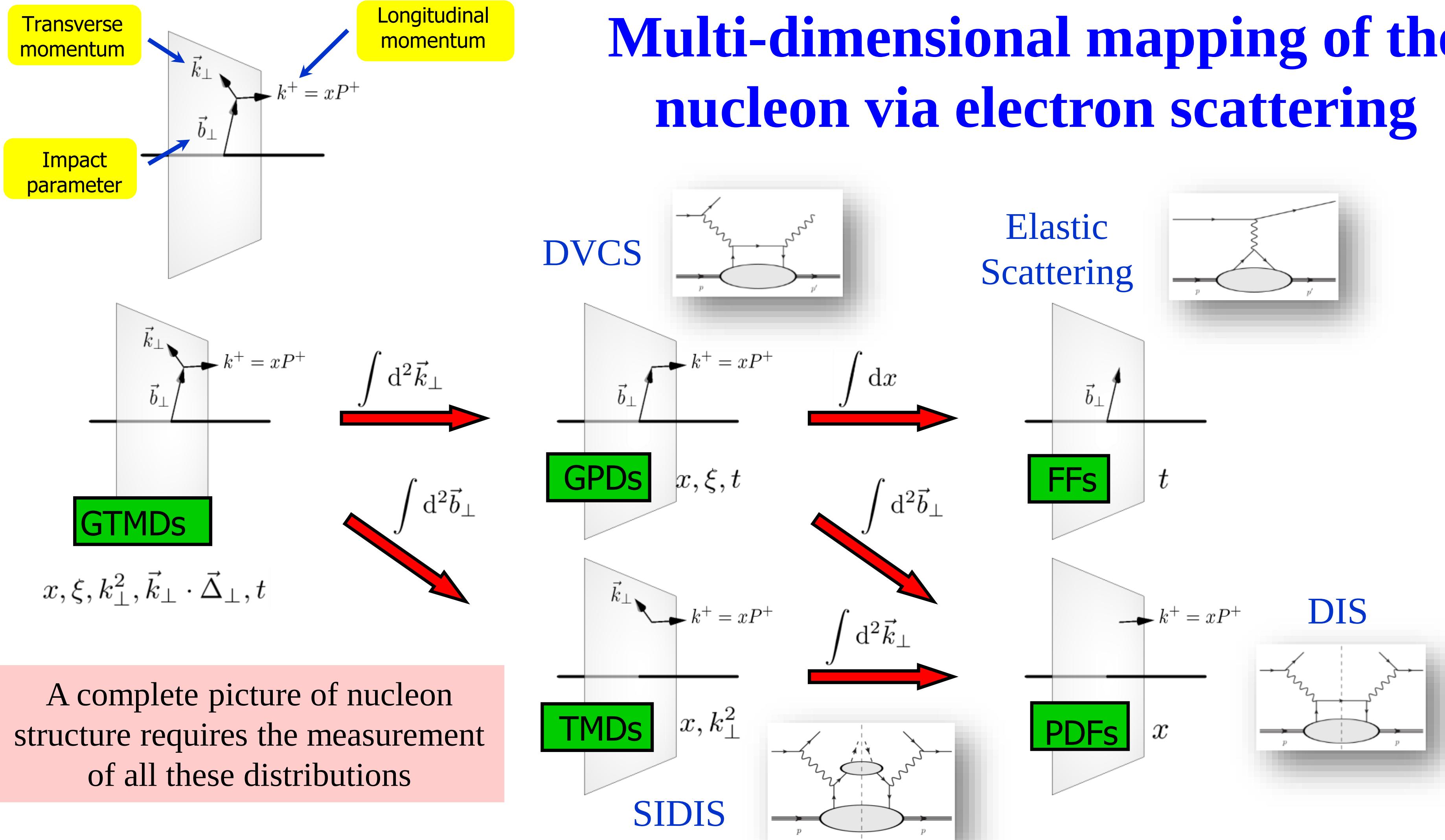
Results on Generalized Parton Distributions

Silvia Niccolai, IPN Orsay & CLAS Collaboration



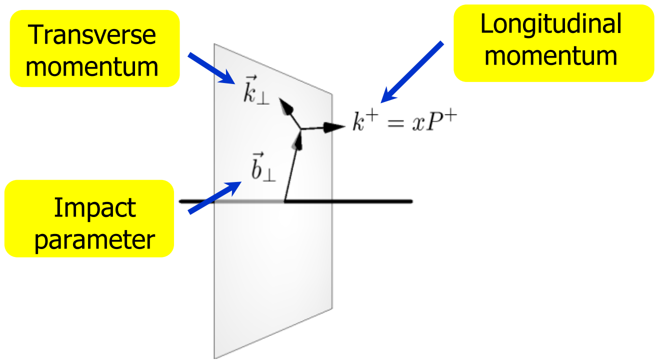
- Interest of GPDs
- GPDs and Deeply Virtual Compton Scattering
- Recent DVCS results from Jefferson Lab
- Nucleon tomography
- The JLab 12 GeV GPD program

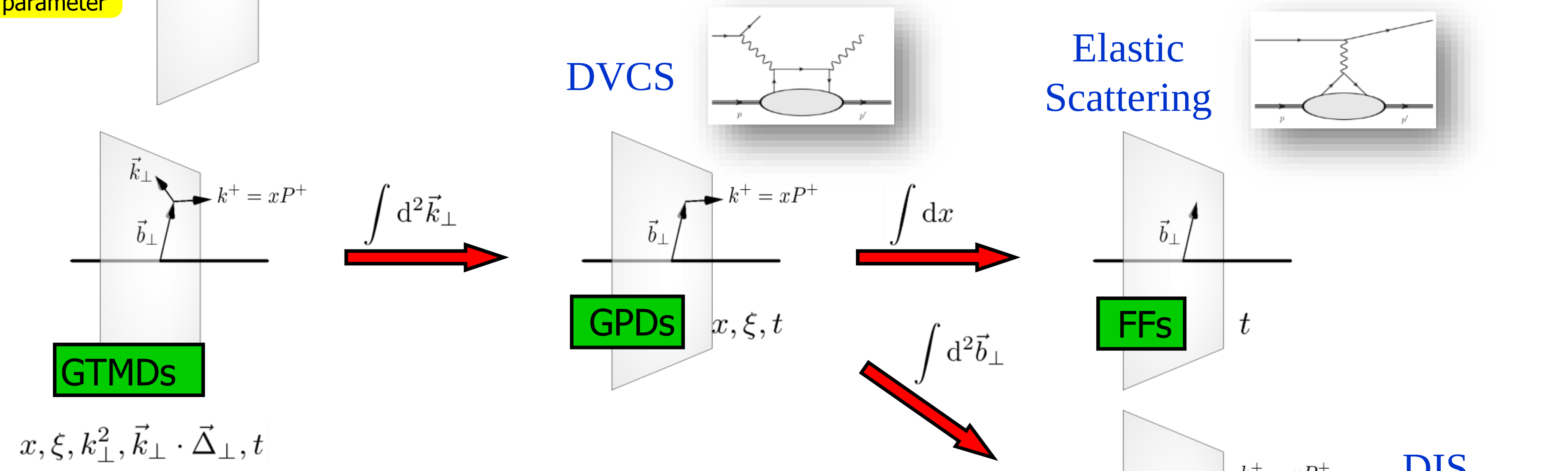
Multi-dimensional mapping of the nucleon via electron scattering

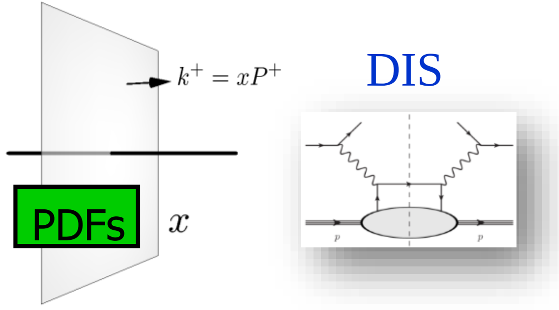


A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon via electron scattering







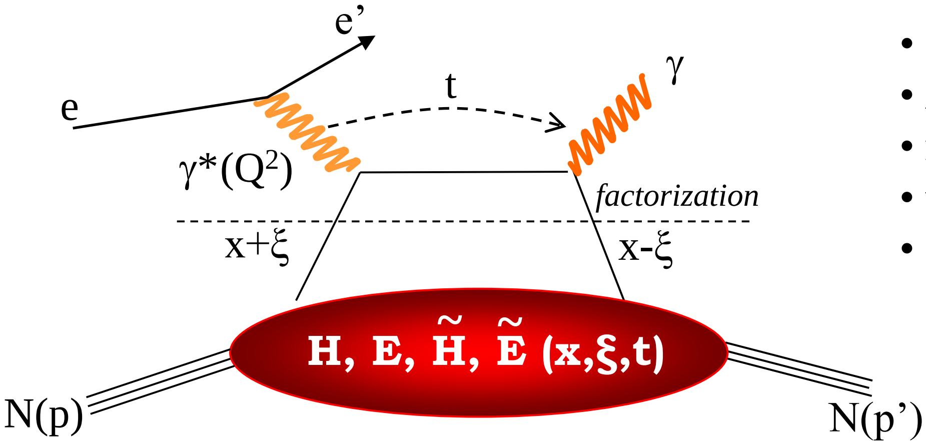
Generalized Parton Distributions:

✓fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space

✓ linked to **FFs** and **PDFs**

✓ accessible in **hard exclusive** reactions (DVCS, meson production)

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
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

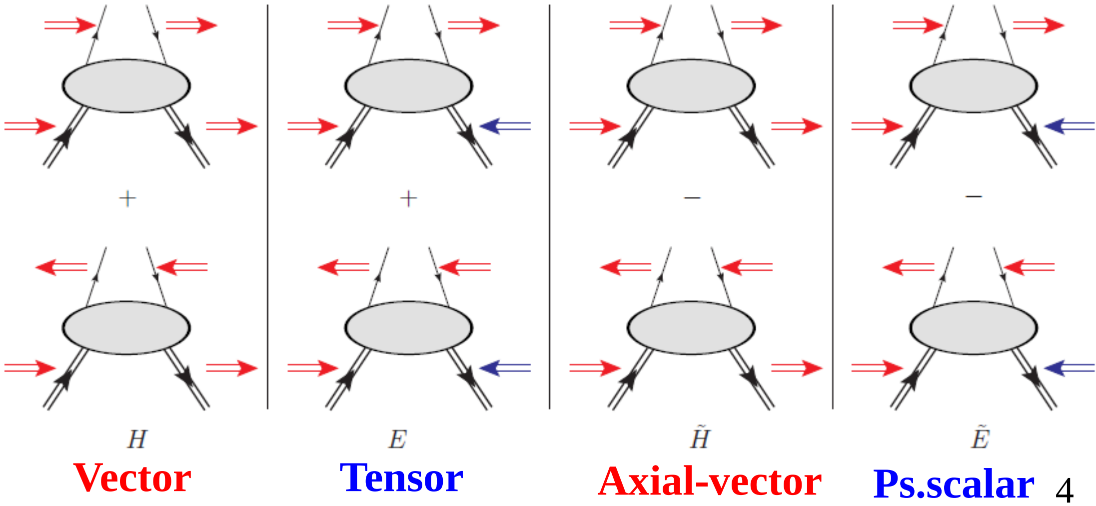
« **Handbag** » factorization, valid in the **Bjorken regime** (**high Q^2** and **ν**, fixed x_B), **$t \ll Q^2$**

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

4 GPDs for each quark flavor
(leading-order, leading twist)

conserve nucleon spin

flip nucleon spin



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, $\tilde{\mathrm{E}}$)

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: $\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + \Delta L}_{J} + \Delta G$

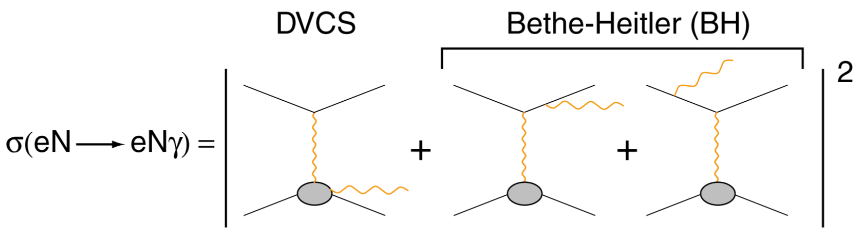
Intrinsic spin of the quarks $\Delta\Sigma \approx 30\%$

Intrinsic spin on the gluons $\Delta G \approx 20\%$

Orbital angular momentum of the quarks ΔL ?

Accessing GPDs through DVCS

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



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

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

$$\sigma \sim \left|T^{DVCS} + T^{BH}\right|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I\left(DVCS \cdot BH\right)$$

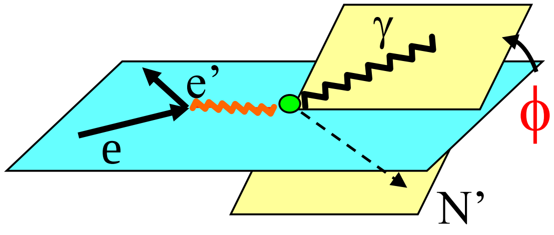
Proton Neutron

Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$



Polarized beam, longitudinal target:

$\Delta\sigma_{LL} \sim (A+B\cos\phi)Re\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

Unpolarized beam, transverse target:

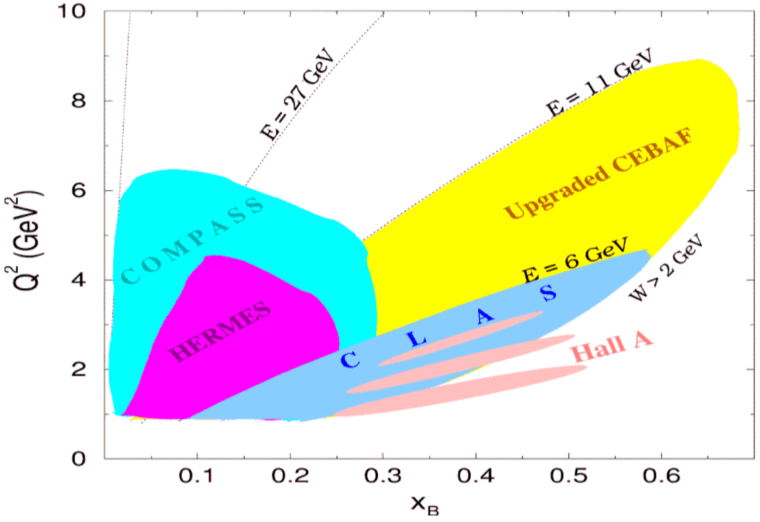
$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

DVCS experiments worldwide

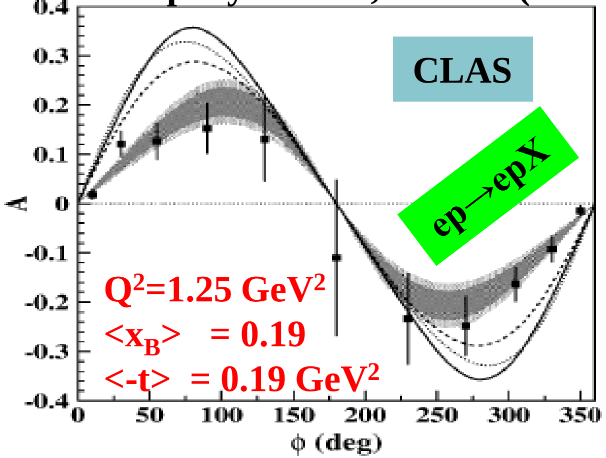
JLAB	
Hall A	***CLAS (Hall B)***
p,n-DVCS, Beam-pol. CS	p-DVCS, BSA,lTSA,DSA,CS

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



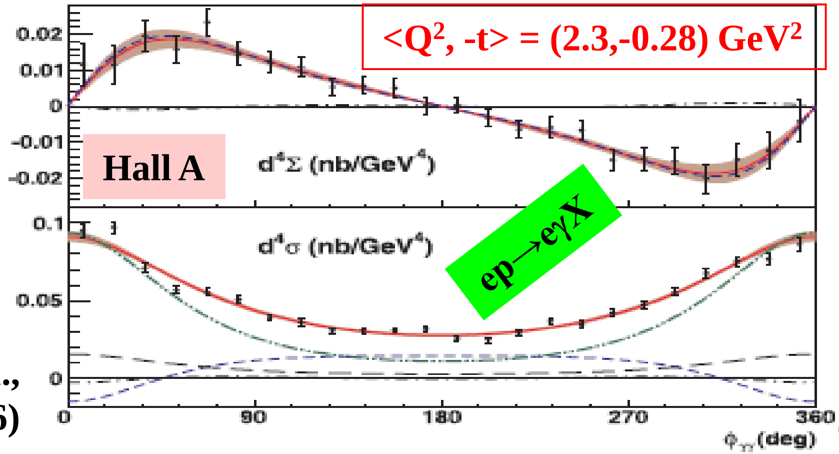
S. Stepanyan et al., PRL 87 (2001)



CLAS, HERMES: first observation of DVCS-BH interference

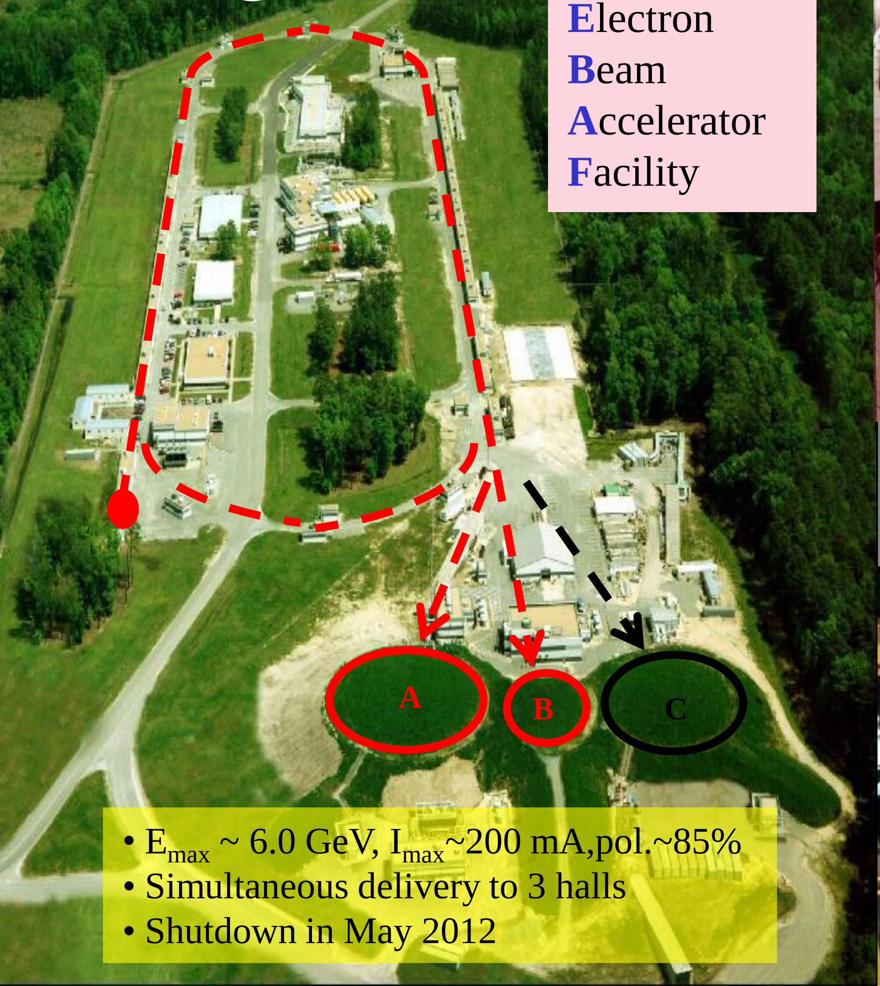
Hall A: proof of scaling for DVCS

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



JLab@6 GeV

Continuous
Electron
Beam
Accelerator
Facility



- E_{max} ~ 6.0 GeV, I_{max}~200 mA,pol.~85%
- Simultaneous delivery to 3 halls
- Shutdown in May 2012

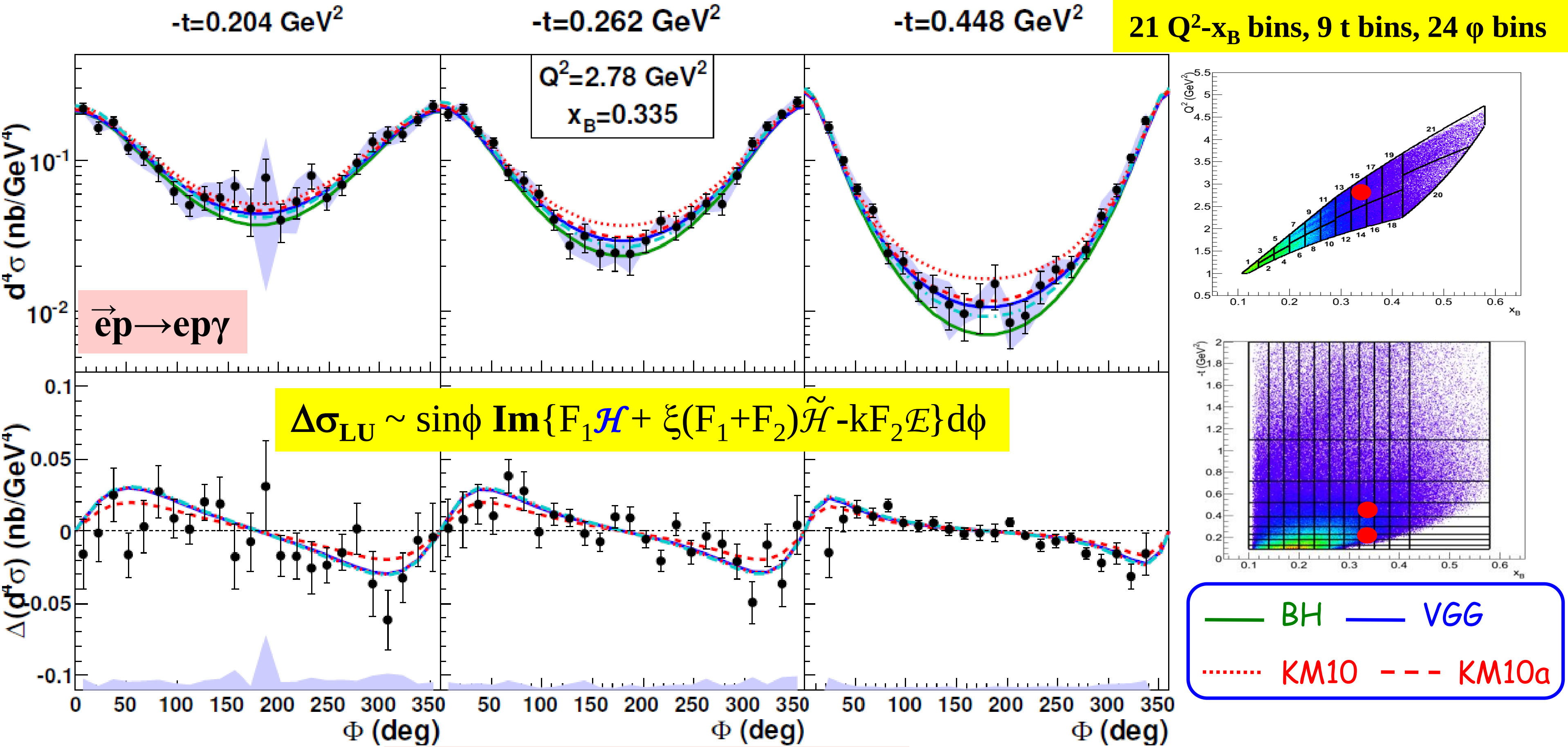
Hall A: 2 HRS
High luminosity (L~10^{37})
Limited coverage

Hall B: CLAS
Large acceptance
L~10^{34}

+ dedicated **calorimeters** to detect forward-emitted **DVCS-BH photons**

CLAS: unpolarized and beam-polarized cross sections

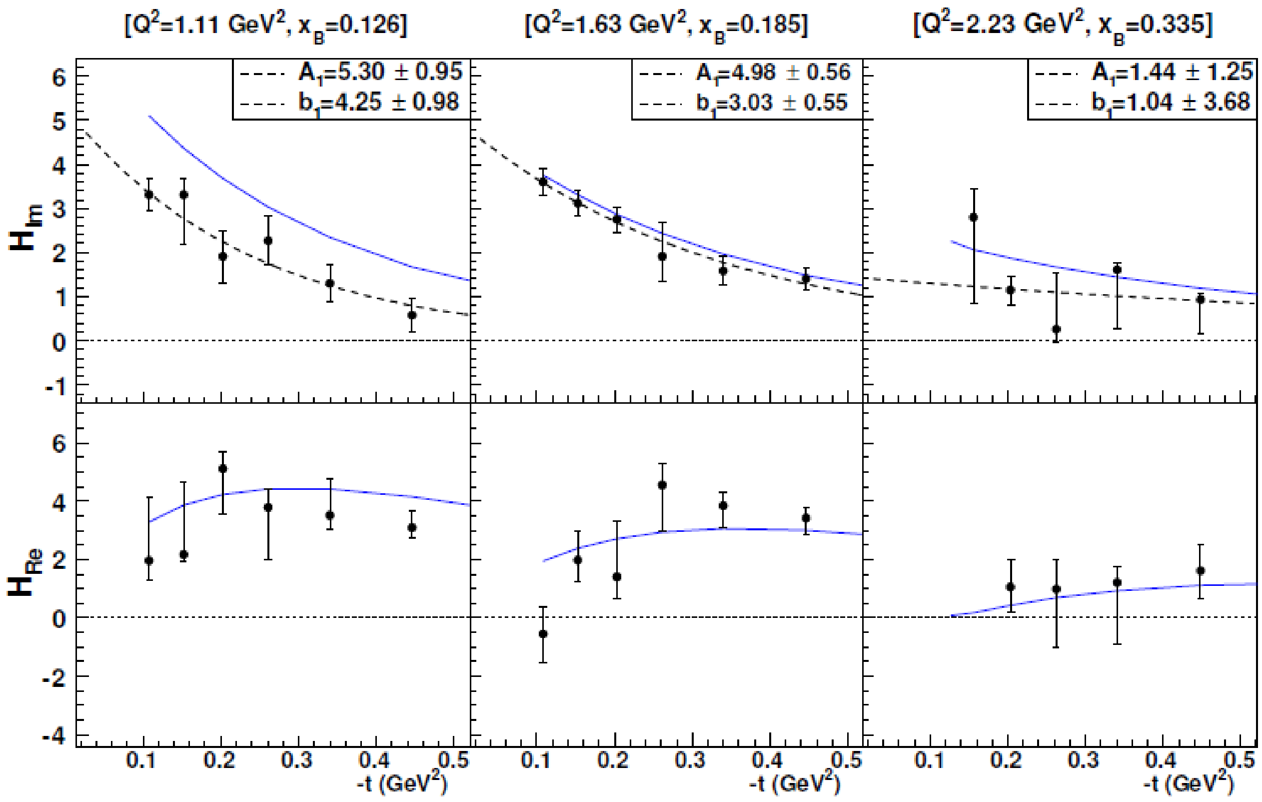
21 Q^2-x_B bins, 9 t bins, 24 φ bins



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

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

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

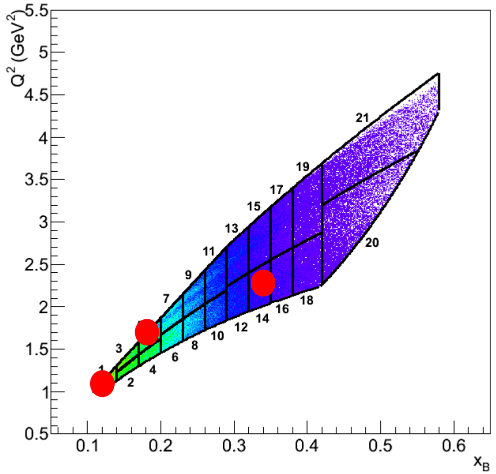


CFF fits by M. Guidal

(*H and H̃ only*)

Ae^{-bt} fit

VGG predictions



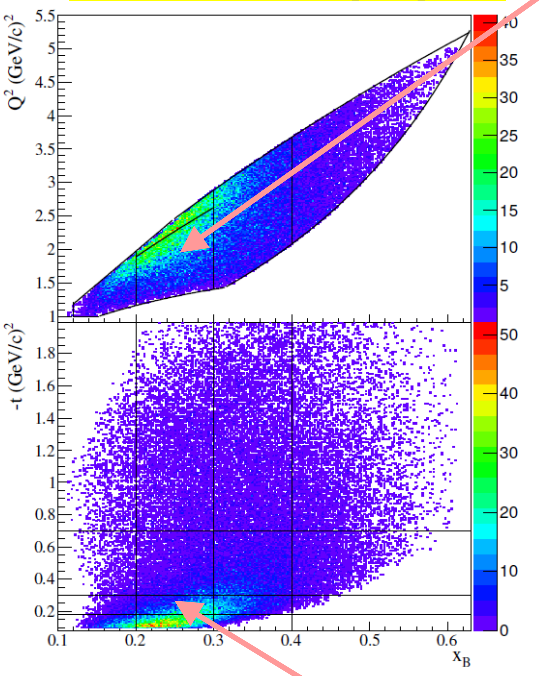
$$q(x, \mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} H(x, 0, -\Delta_\perp^2)$$

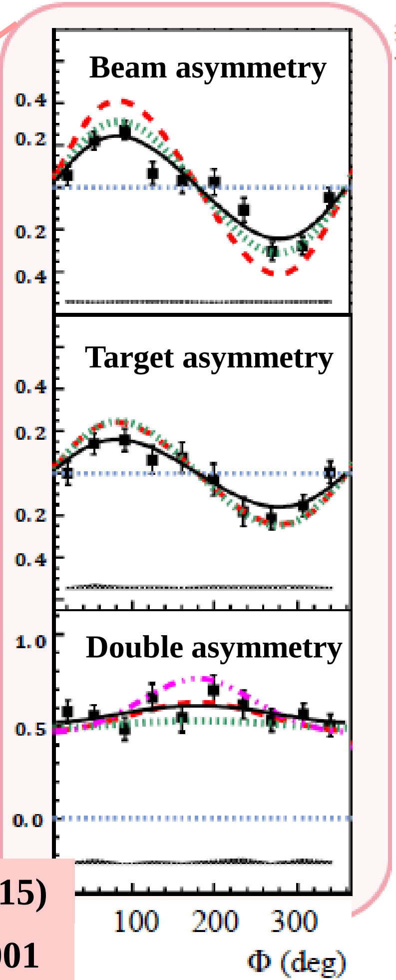
***Im*($\mathcal{H}_p$), flatter t slope at high x_B: faster quarks (valence) at the core of the nucleon, slower quarks (sea) at its periphery → PROTON TOMOGRAPHY**

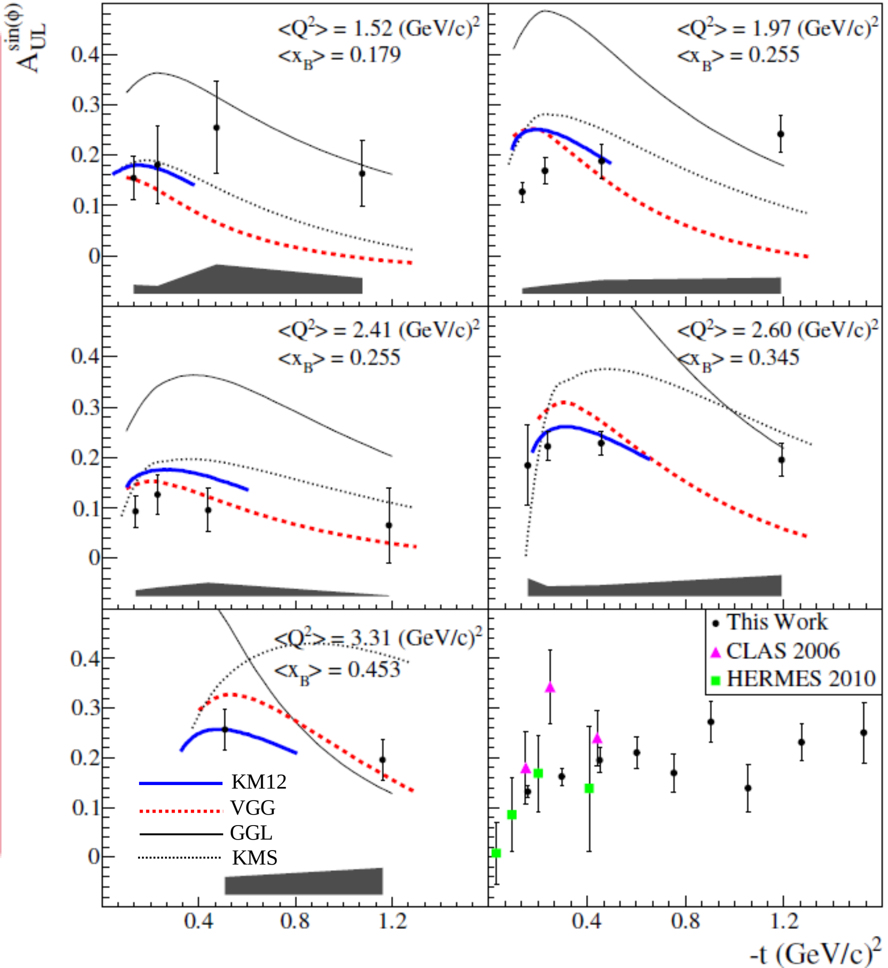
CLAS: DVCS on longitudinally polarized target

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

$\Delta\sigma_{UL} \sim Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$







5 Q^2-x_B bins, 4 t bins, 10 ϕ bins

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

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

Extraction of CFFs from CLAS TSA, BSA, DSA

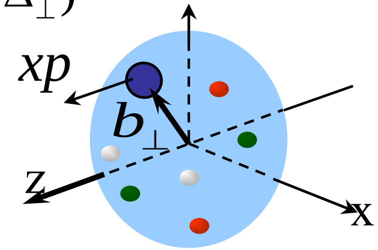
CFFs fitting code by M. Guidal (7 CFFs)

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

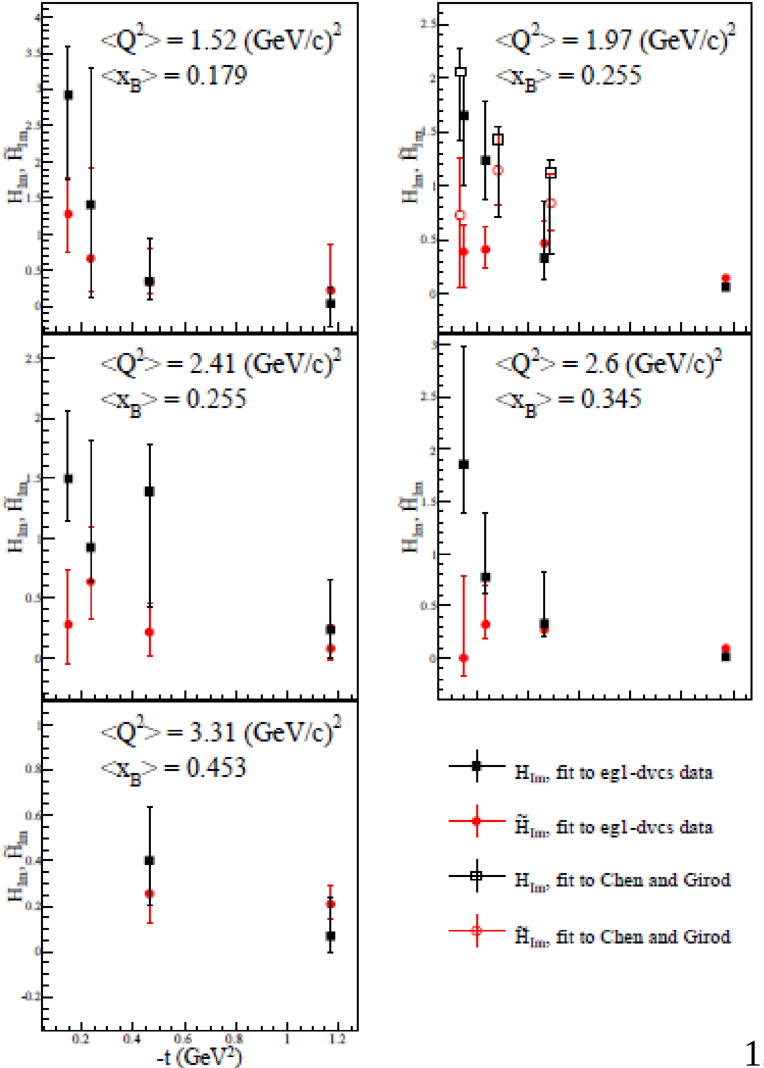
$$\Delta q(x, b_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} \tilde{H}(x, 0, -\Delta_\perp^2)$$

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

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



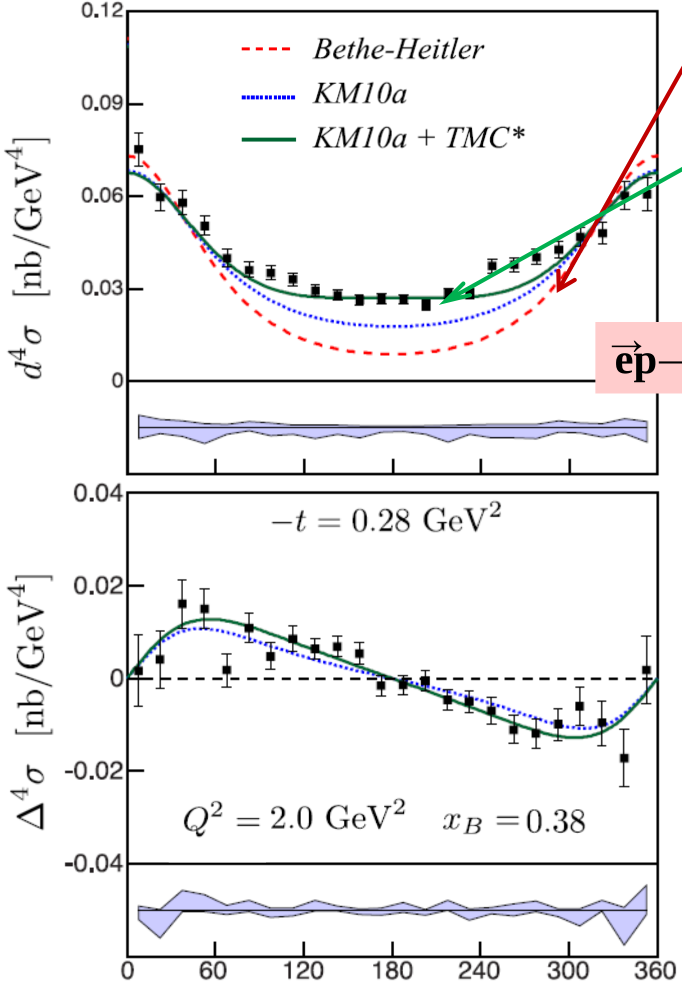
S. Pisano et al., PRD 91, 052014 (2015)



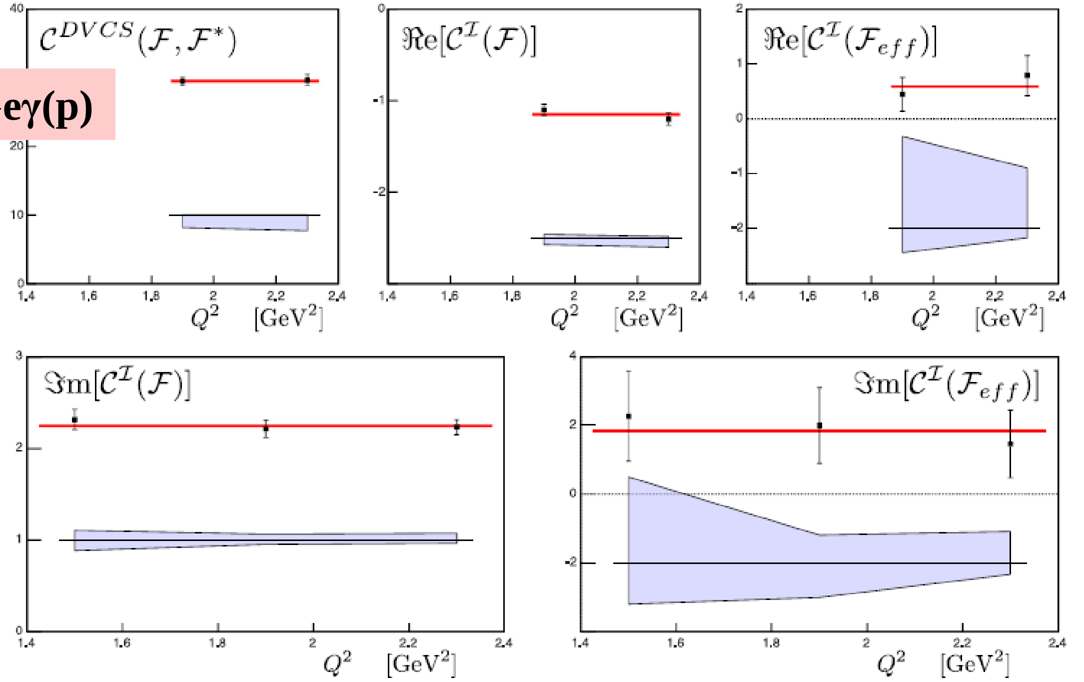
DVCS on the proton in Hall A

M. Defurne et. al., PRC 92, 055202 (2015)

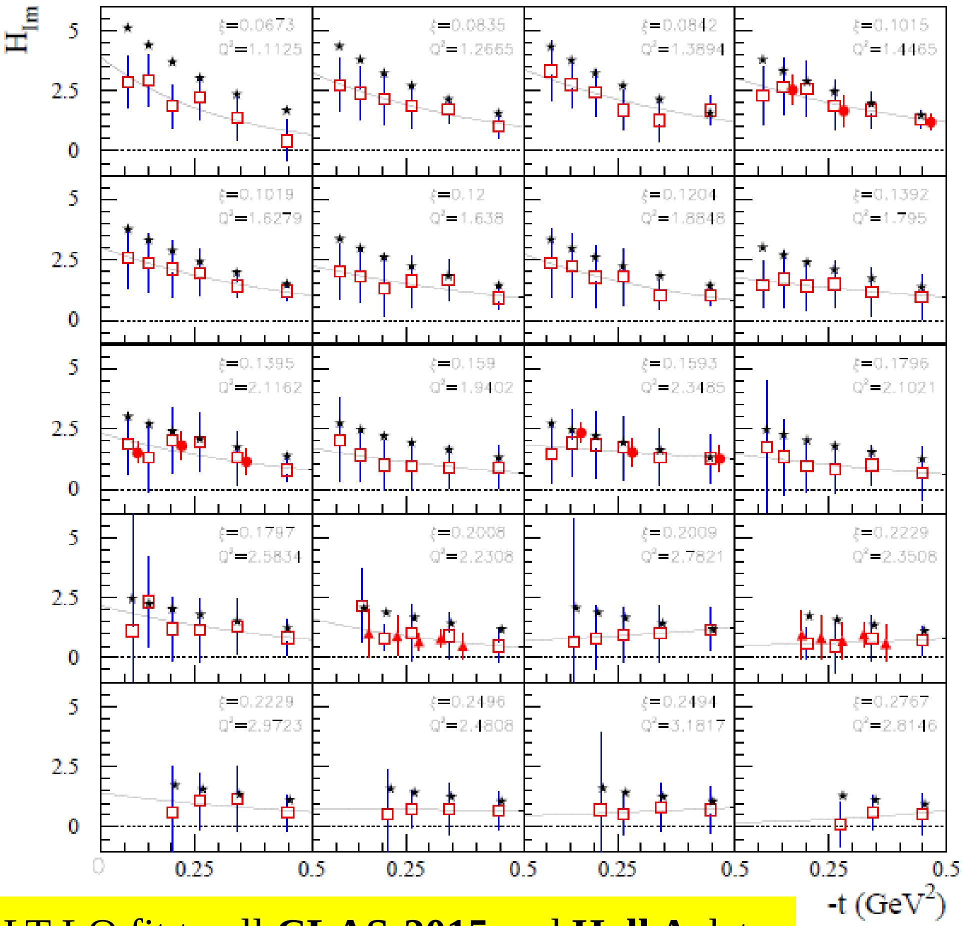
- Significant deviation from Bethe-Heitler
- Both $\mathcal{I}$(BH·DVCS) and DVCS^2 contribute to the cross section
- Twist-4 corrections (TMC) may be necessary to describe the data



$\vec{e}p \rightarrow e\gamma(p)$

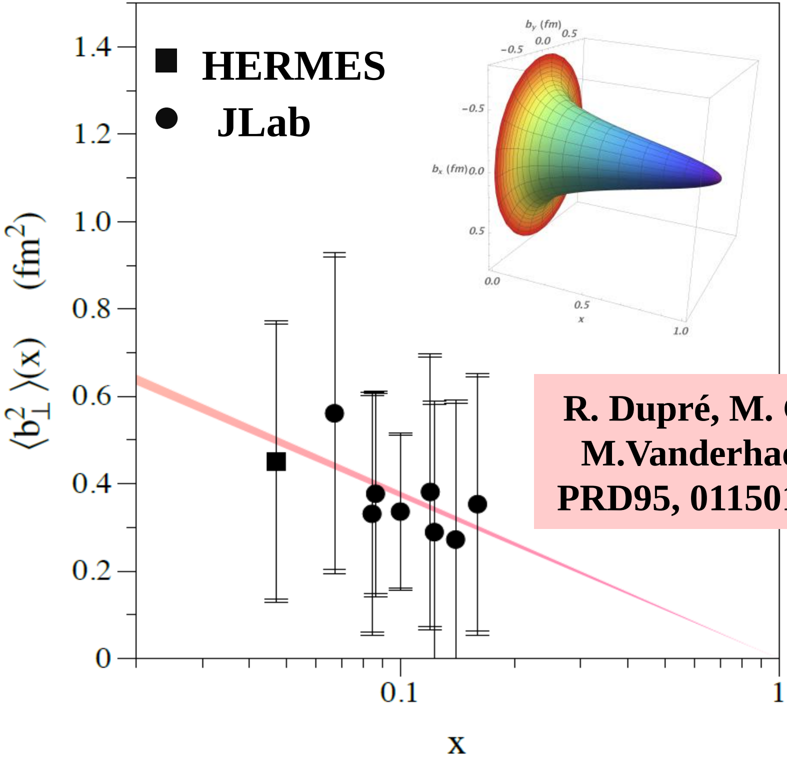


From CFFs to proton transverse size vs x



$$\langle b_\perp^2 \rangle^q(x) = -4 \frac{\partial}{\partial \mathbf{\Delta}_\perp^2} \ln H_-^q(x, 0, -\mathbf{\Delta}_\perp{}^2) \Big|_{\mathbf{\Delta}_\perp = 0}$$

Model-dependent « **deskewing** » factor: $\dfrac{H(\xi, 0, t)}{H(\xi, \xi, t)}$

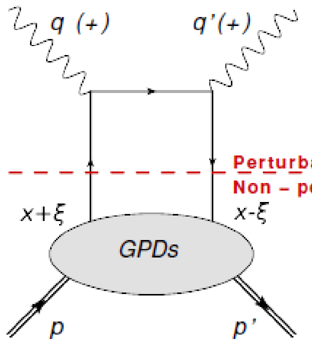


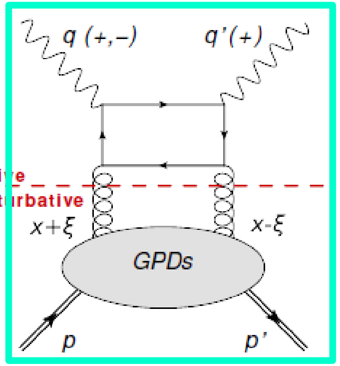
R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)

LT-LO fit to all **CLAS-2015** and **Hall A** data

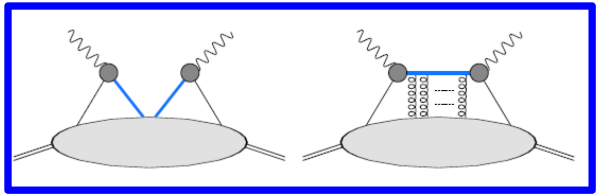
DVCS: new results from JLab Hall A at 6 GeV

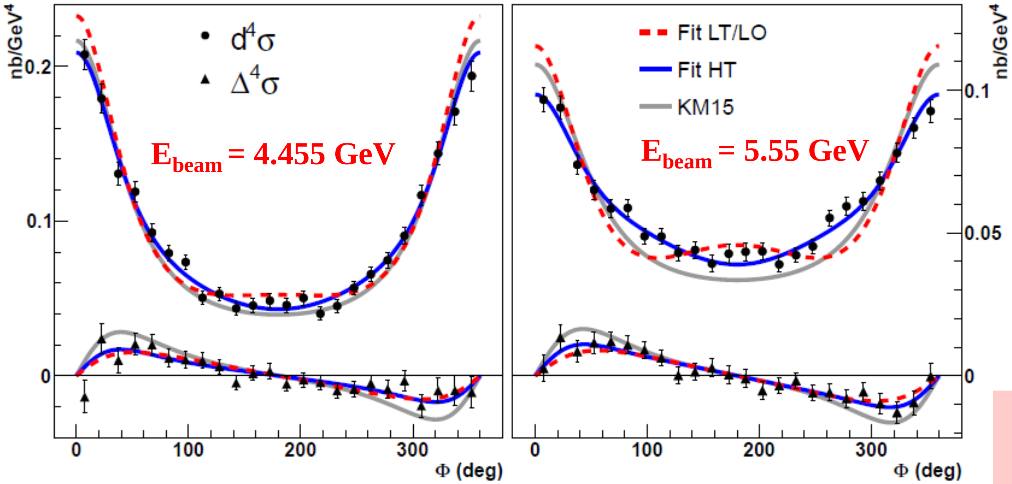
$\vec{e}p \rightarrow e\gamma(p)$

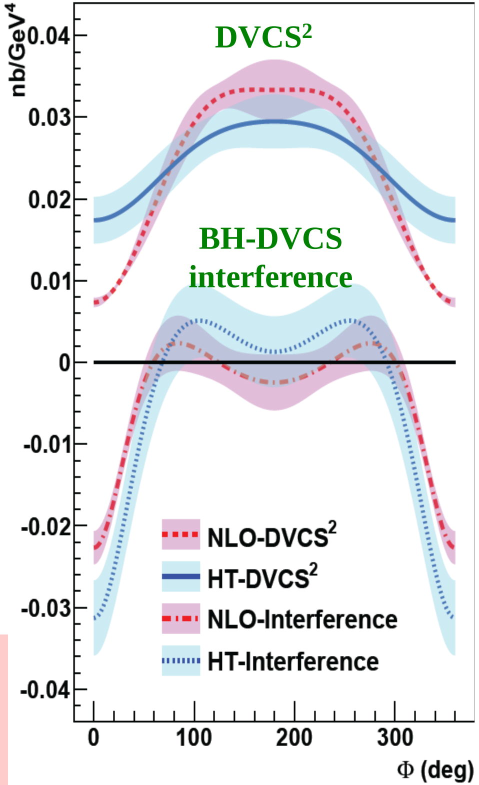




High precision DVCS cross sections from Hall A (E07-007):
sensitivity to **higher twist** (HT) or **LT-NLO** contributions (gluon exchange)



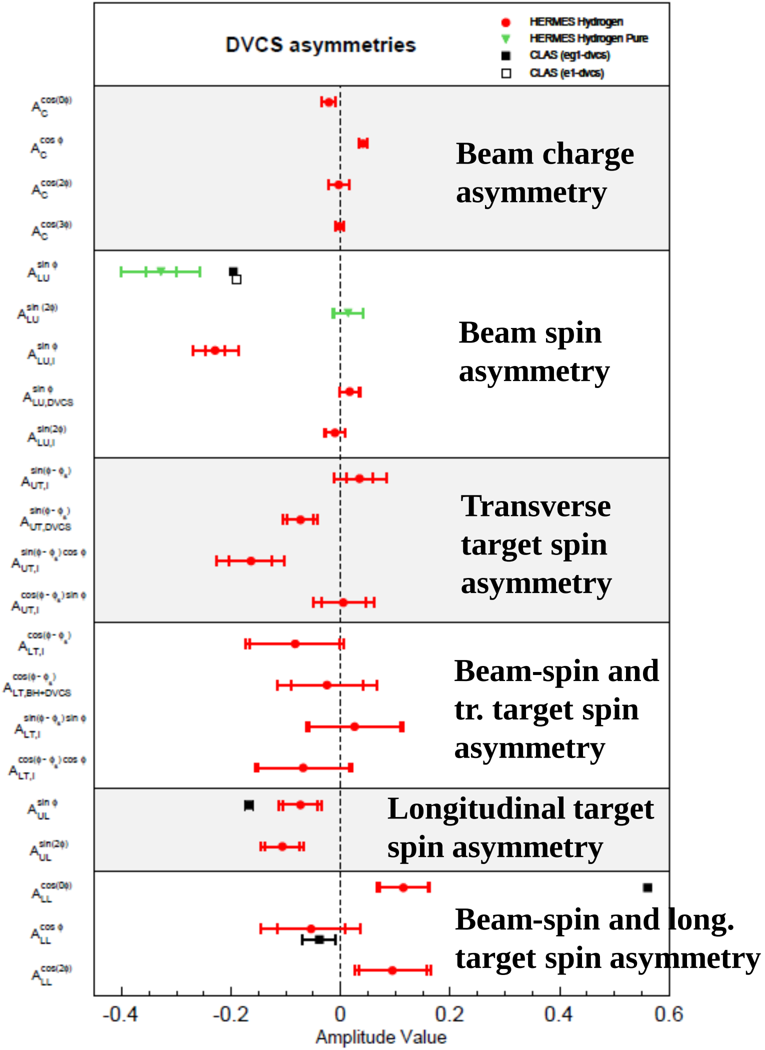


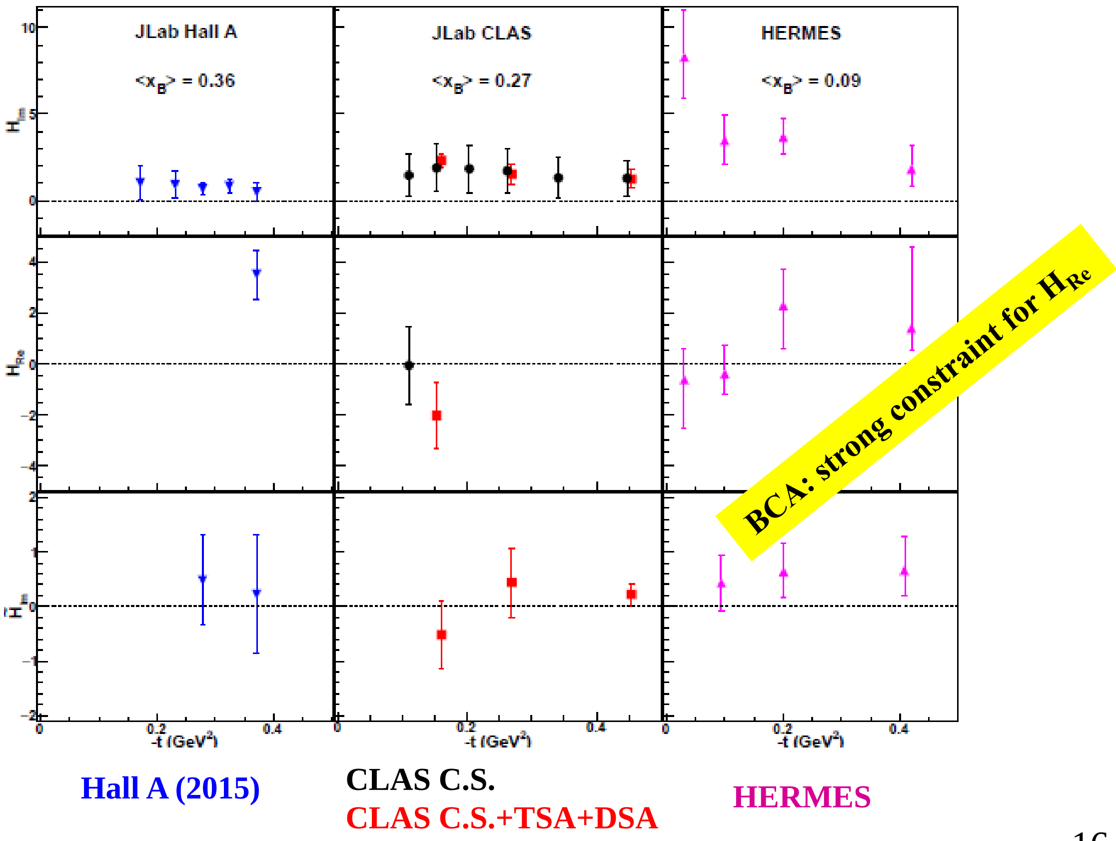


Different beam energies used to separate **BH-DVCS interference ($\sim E_b^3$)** and **DVCS² ($\sim E_b^2$)** contributions

M. Defurne *et al.*, arXiv:1703.00942 (Mar 28,2017)

Summary on proton-DVCS spin observables and GPDs extraction



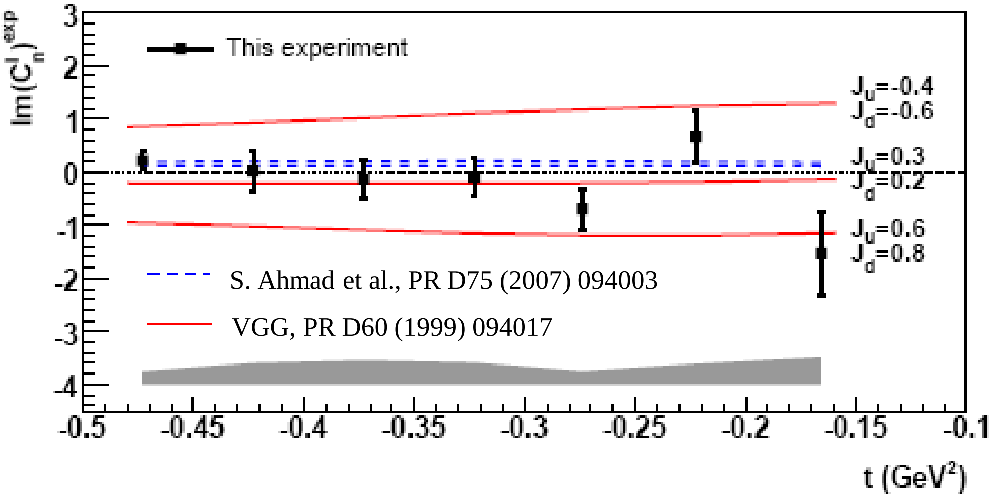


DVCS on the *neutron* in Hall A

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

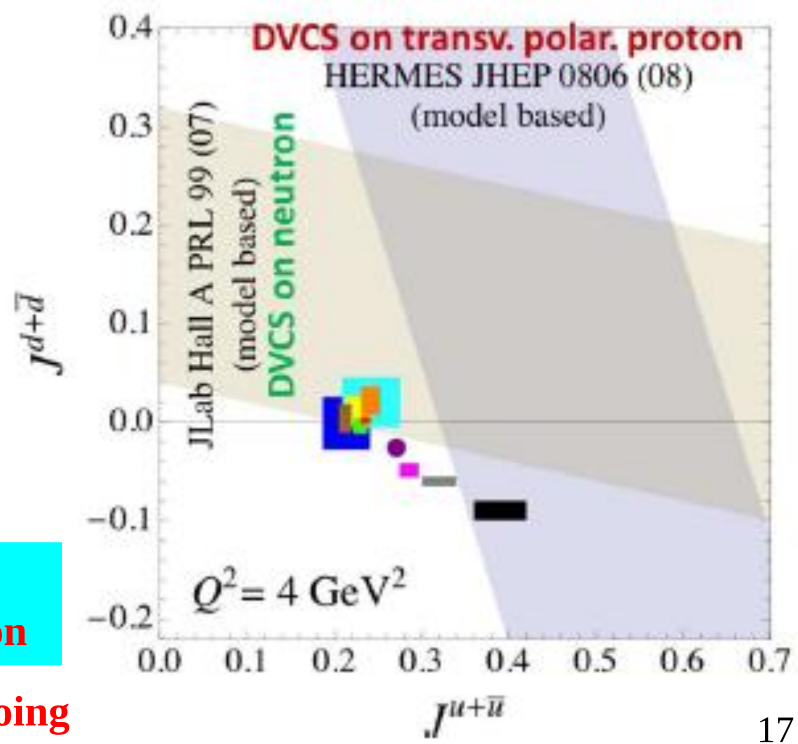
$$\frac{1}{2}\int_{-1}^{1} xdx\left(H^q(x,\xi,t=0)+E^q(x,\xi,t=0)\right)=J^q$$

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



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

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

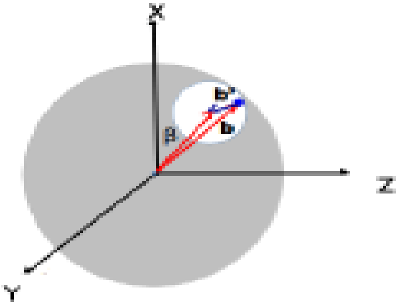


A **combined analysis** of **DVCS observables for proton and neutron targets** is necessary for GPD **quark-flavor separation**

E08-025: Beam-energy separation of nDVCS CS, **analysis ongoing**

DVCS on nuclei: the CLAS eg6 experiment

Work by M. Hattawy

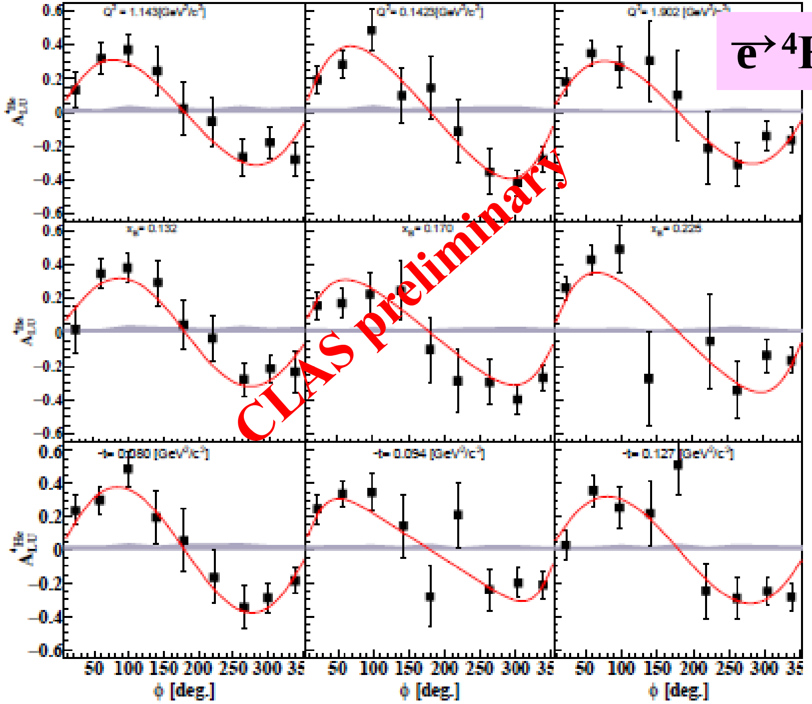


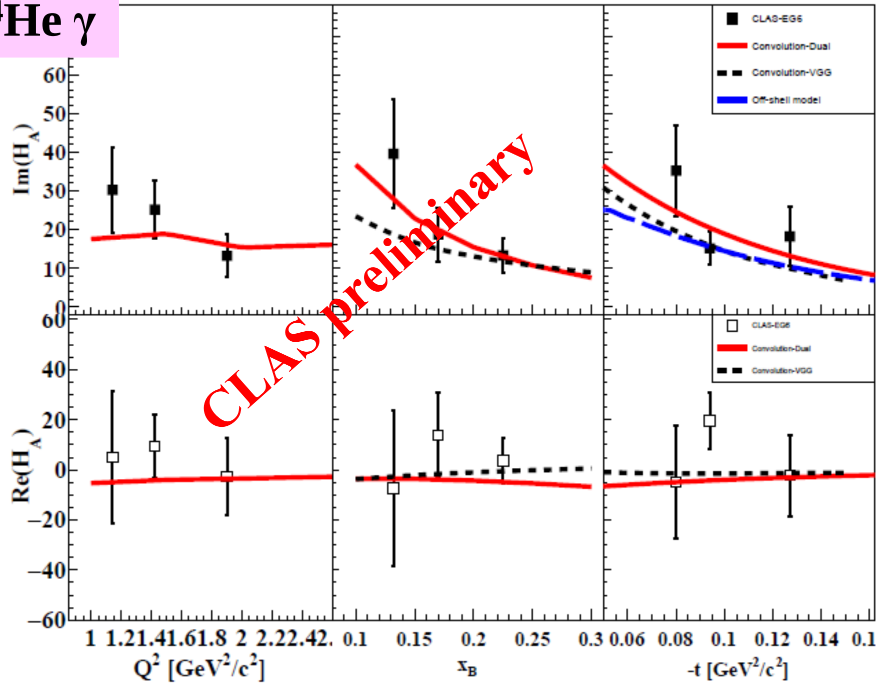
- CLAS+IC+**RTPC**+^{4}He target; E**~6.065 GeV**
- **Coherent** and **incoherent DVCS: nuclear GPDs, EMC effect**

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

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

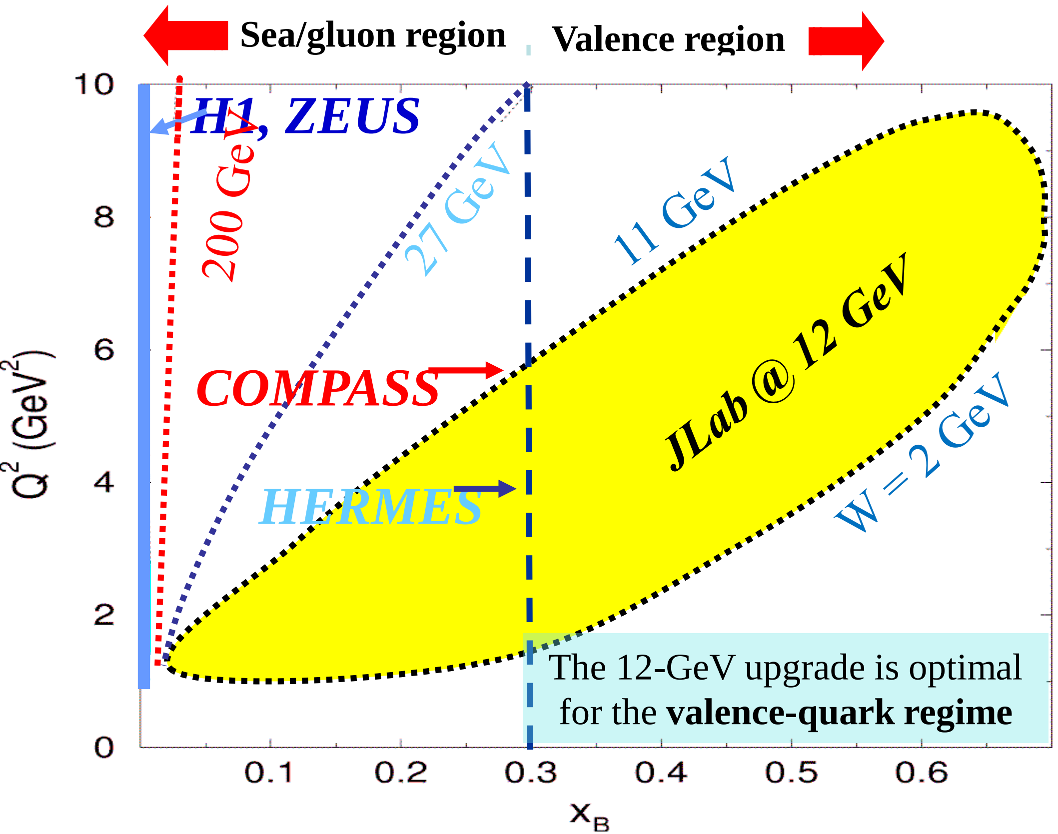
$\vec{e}\ ^4He \rightarrow e\ ^4He\ \gamma$

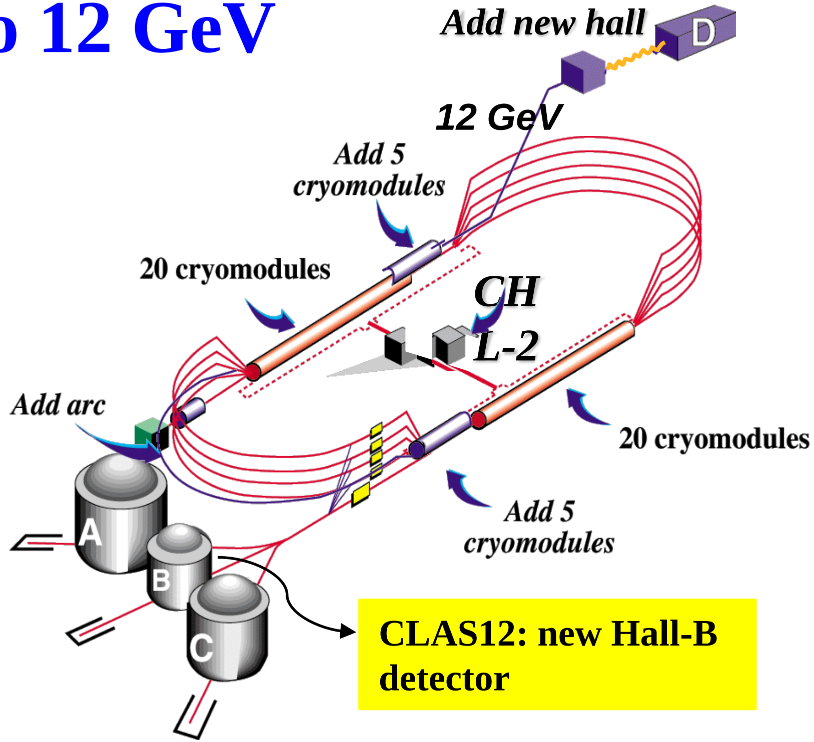




JLab upgrade to 12 GeV

Upgrade of CEBAF completed





CLAS12: new Hall-B detector

GPD experiments at 11 GeV have been approved for each of the **three halls A, B, C**
Complementary programs:
- different kinematic coverage
- different precisions/resolutions
- focus on different observables

pDVCS at 11 GeV in the Halls A and C

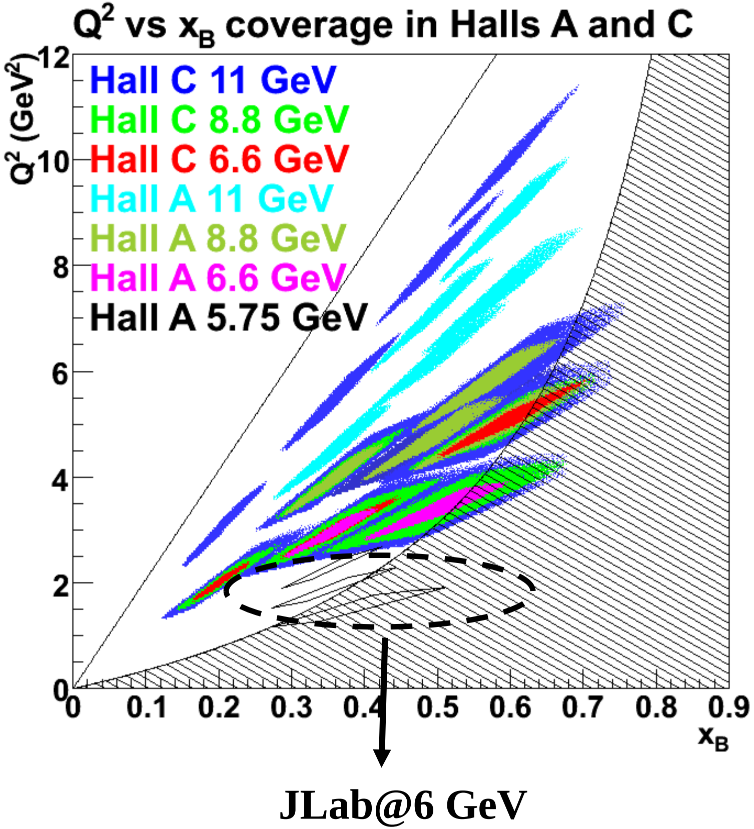
$\vec{e}p \to e\gamma(p)$

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

Hall A:
- Absolute cross section measurements
- Test of scaling: Q^2 dependence of $d\sigma$ at fixed x_B
- Increased kinematical coverage

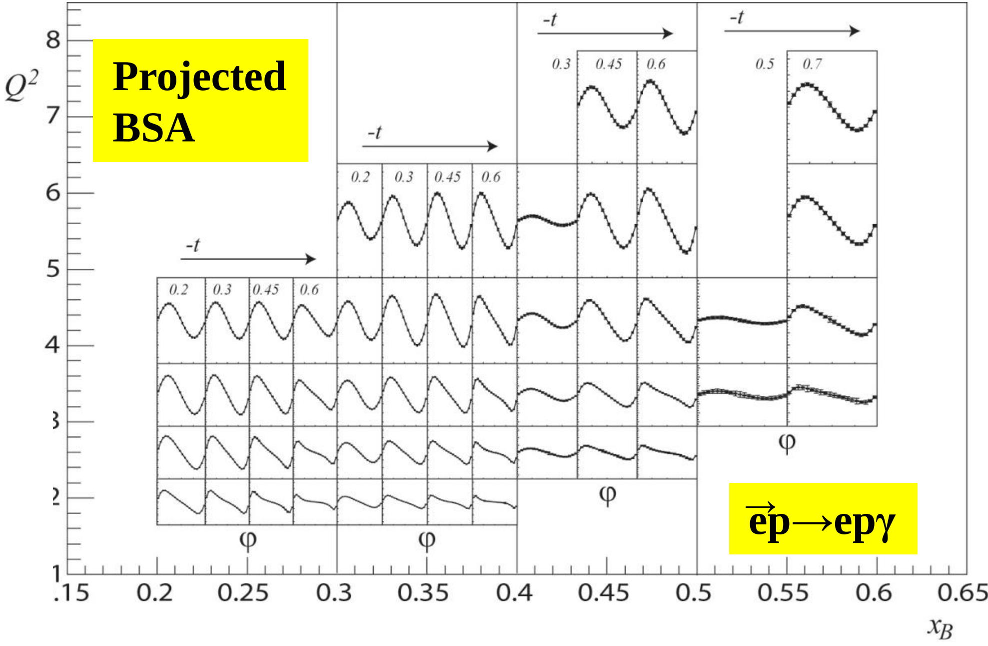
Hall A: 1st JLab experiment after the 12-GeV upgrade
Data taking finished 12/2016, analysis ongoing

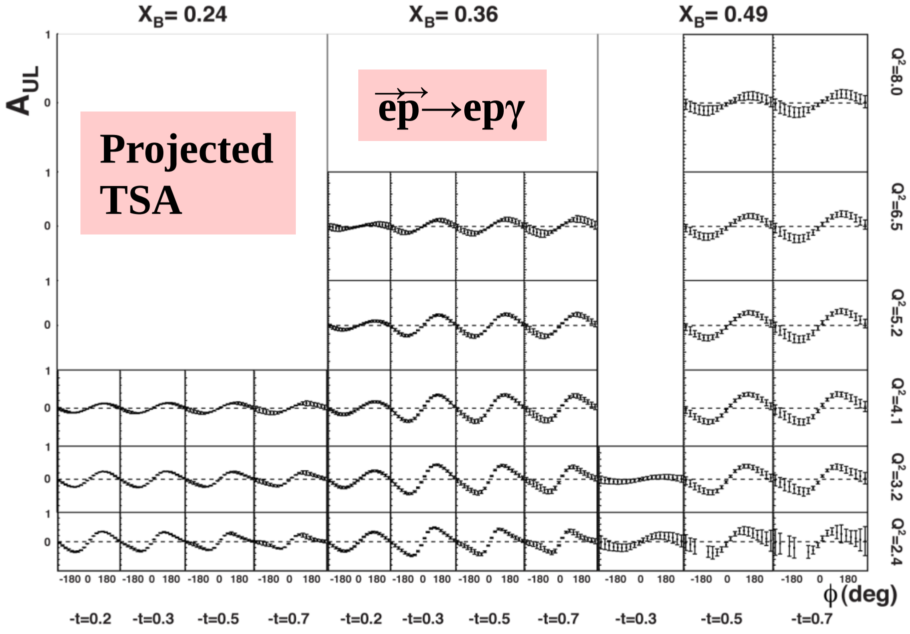
Hall C:
- Energy separation of the DVCS cross section
- Higher Q^2: measurement of higher twist contributions
- Low-x_B extension (thanks to sweeping magnet)



DVCS BSA and TSA with CLAS12 & 11 GeV beam

Liquid hydrogen target
P_{beam} = 85%, L = 10^{35} $cm^{-2}s^{-1}$
First CLAS12 experiment (2017)

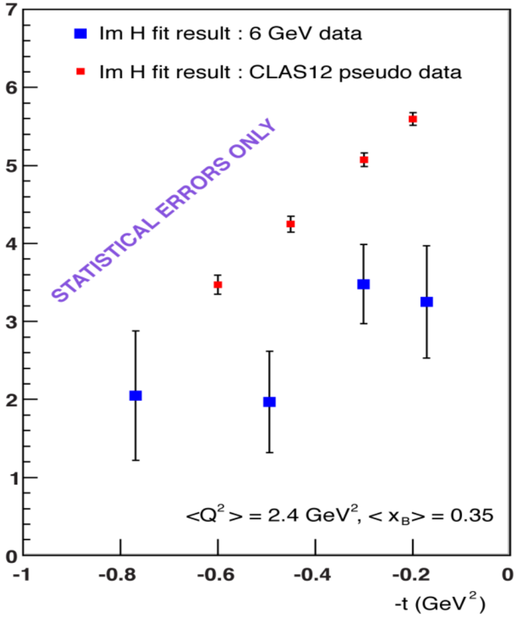




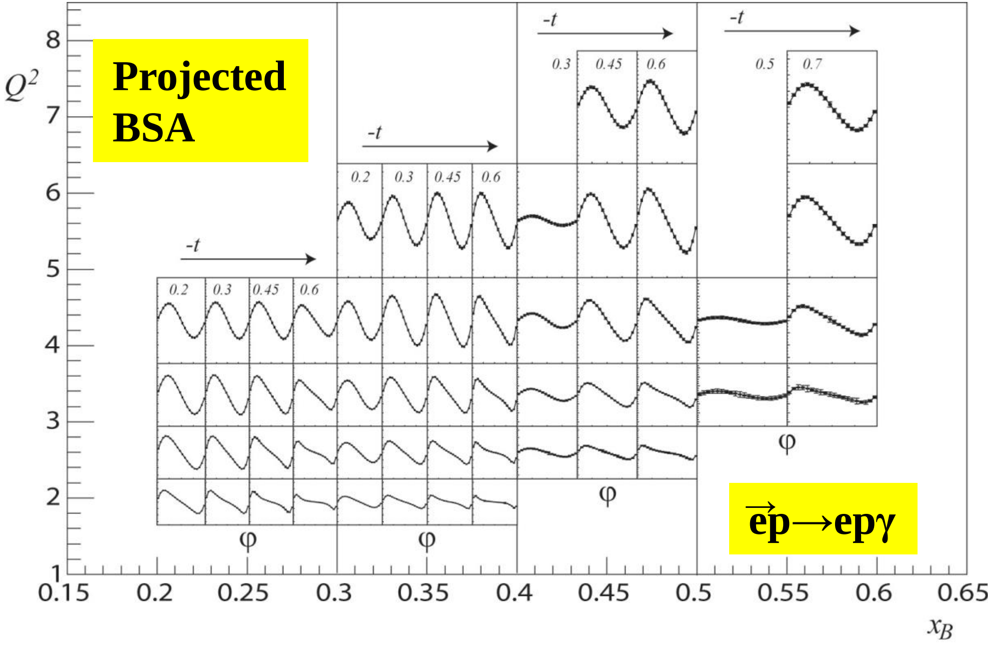
NH_3 longitudinally polarized target
P_{target} = 80%, L = 2.10^{35} $cm^{-2}s^{-1}$
Expected to run in ~2019

DVCS BSA and TSA with CLAS12 & 11 GeV beam

Liquid hydrogen target
P_{beam} = 85%, L = 10^{35} $cm^{-2}s^{-1}$
First CLAS12 experiment (2017)



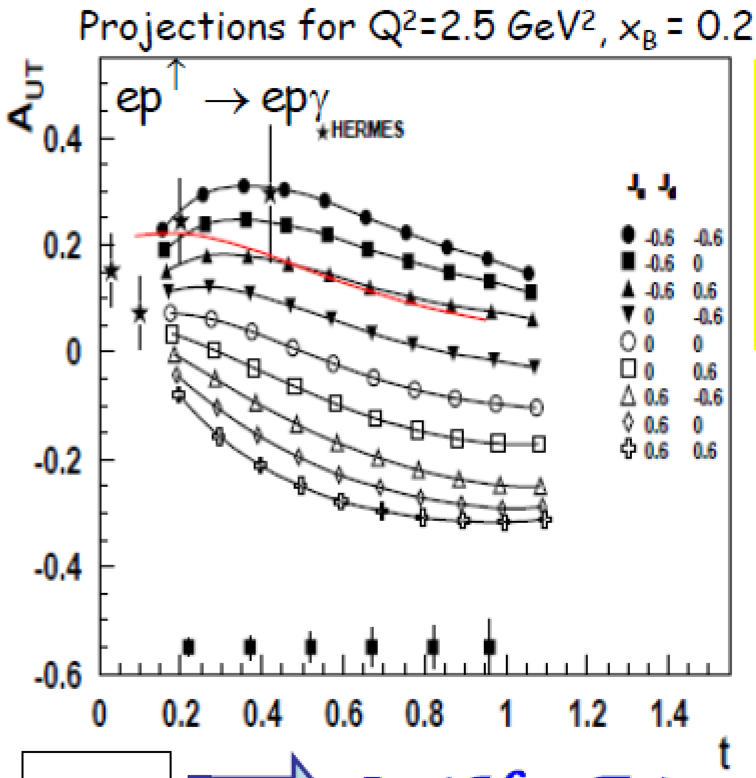
Impact of CLAS12 DVCS-BSA data on fit to extract Im(H)



NH_3 longitudinally polarized target
P_{target} = 80%, L = 2.10^{35} $cm^{-2}s^{-1}$
Expected to run in ~2019

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

100 days of beam time; Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = 5×10^{33} $cm^{-2}s^{-1}$

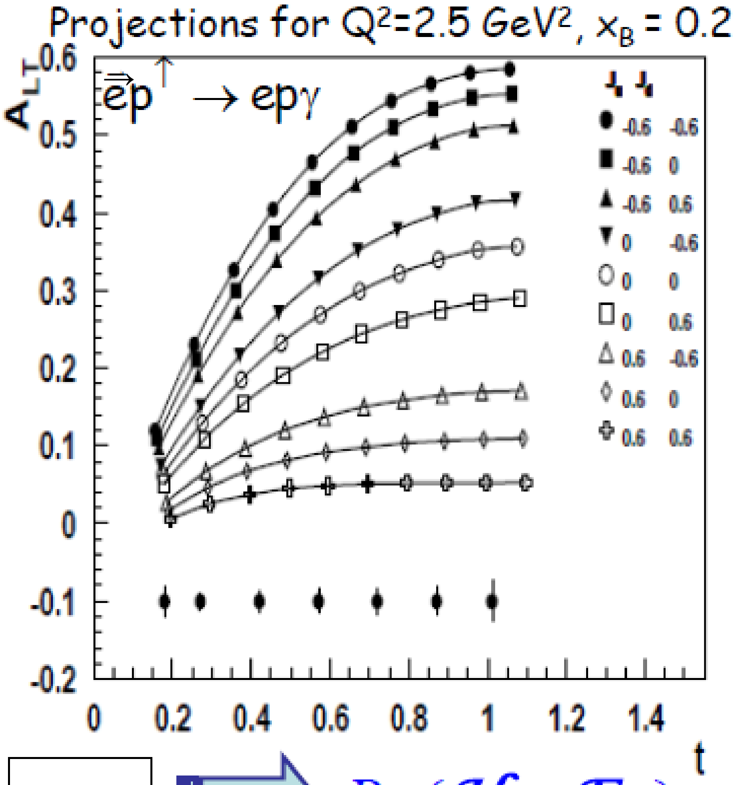


$\Delta\sigma_{UT}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$

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

JLab PAC:
high-impact experiment

Conditionally approved by PAC39
Tests on HDIce target are ongoing



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

BSA for DVCS on the *neutron* with CLAS12

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

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

$\vec{e}d \rightarrow e\gamma n(p)$

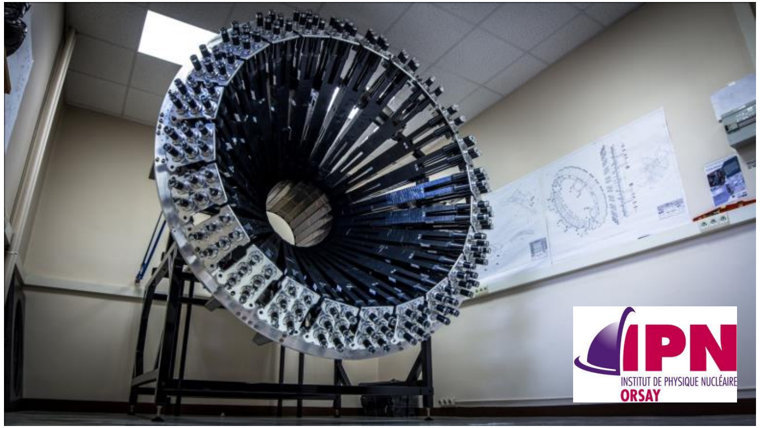
- **The most sensitive observable to E**

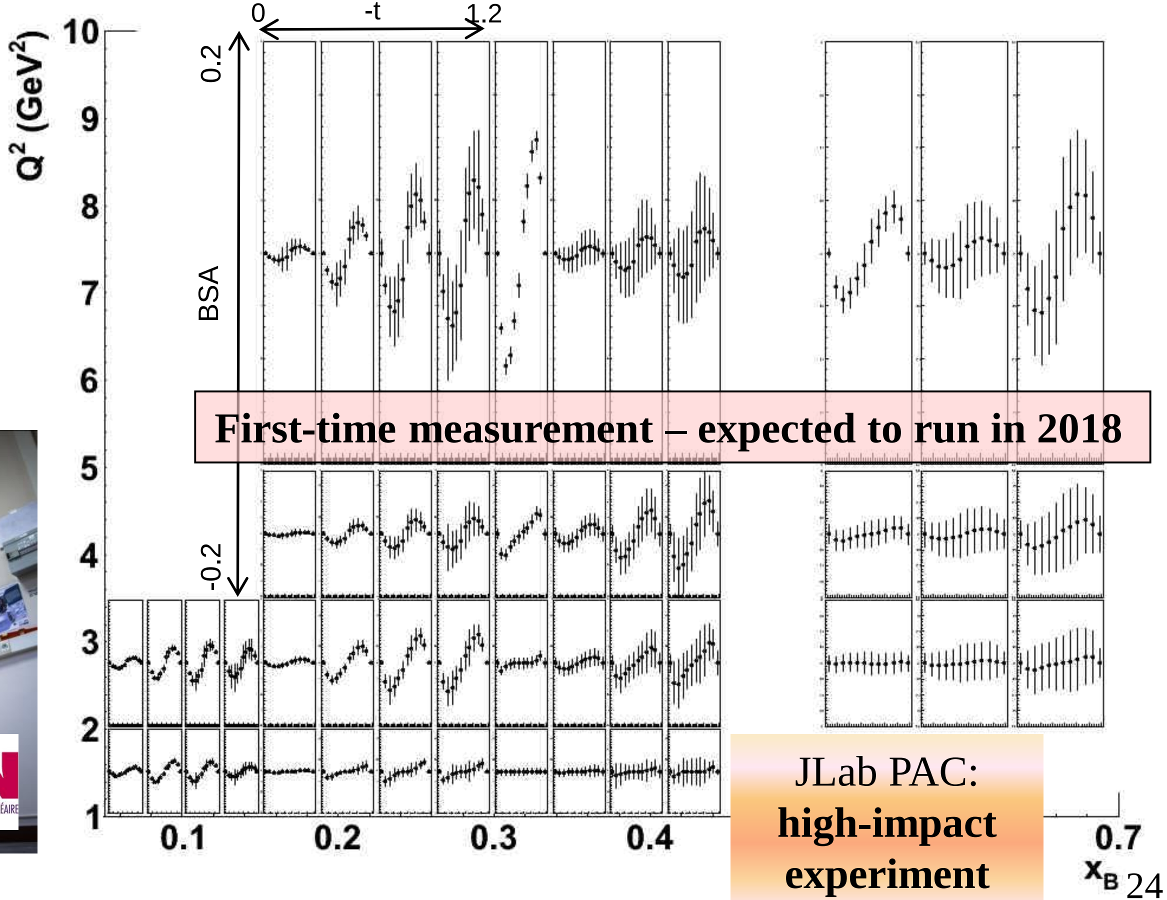
$$(H,E)_u(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

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

- **Flavor separation of CFFs**

Central Neutron Detector





First-time measurement – expected to run in 2018

JLab PAC:
high-impact experiment

BSA for DVCS on the *neutron* with CLAS12

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

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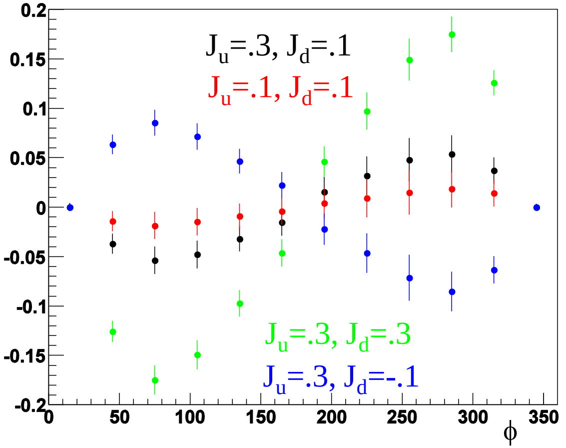
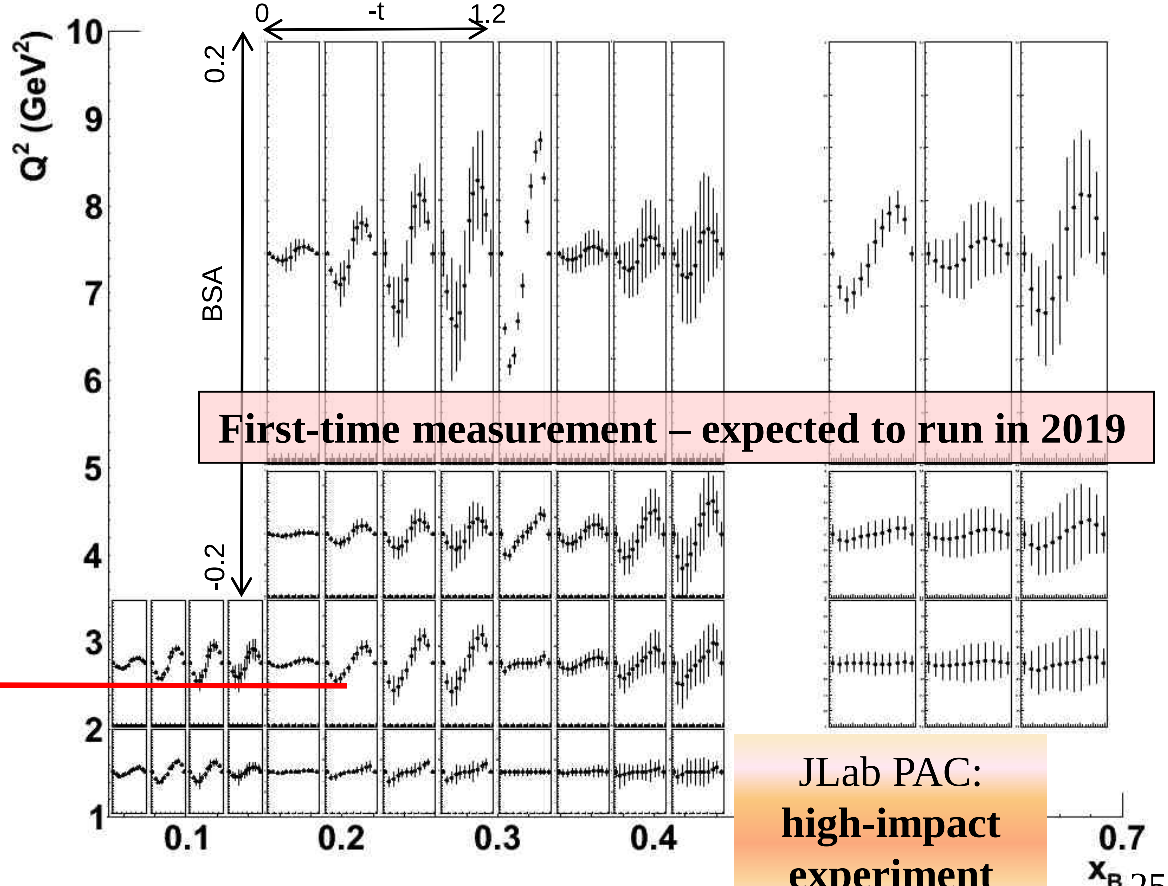
- **Flavor separation of CFFs**

Model predictions (VGG) for different values of quarks' OAM





First-time measurement – expected to run in 2019

JLab PAC: **high-impact experiment**

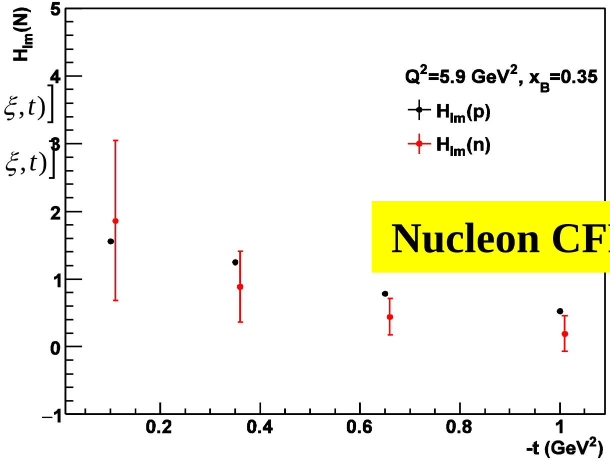
CLAS12: projections for flavor separation ($Im\mathcal{H}$, $Im\mathcal{E}$)

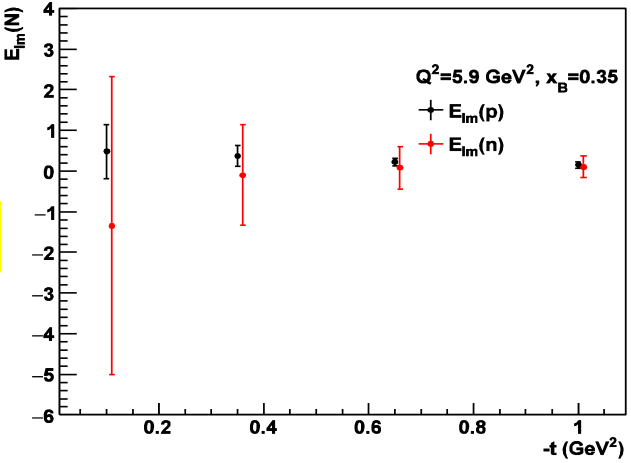
$$(H,E)_u(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

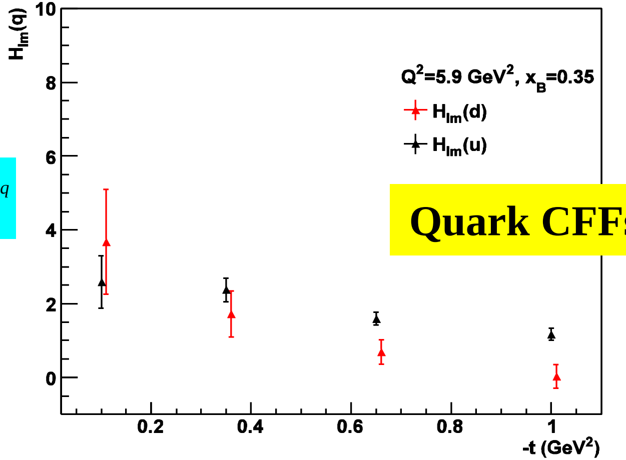
$$(H,E)_d(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

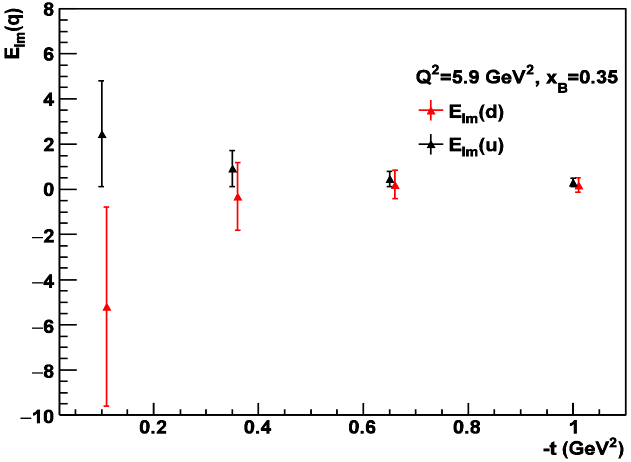
Fits done to all the projected observables for **pDVCS** (BSA, lTSA, lDSA, tTSA, CS, ΔCS) and **nDVCS** (BSA,lTSA, lDSA) of the CLAS12 program

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

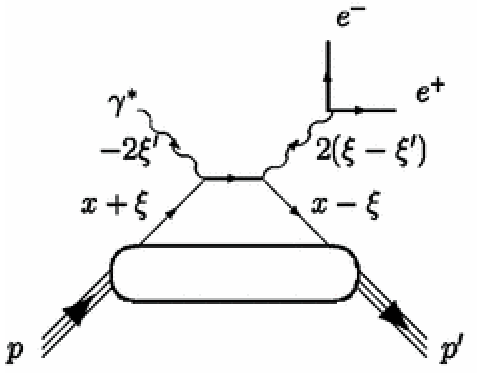




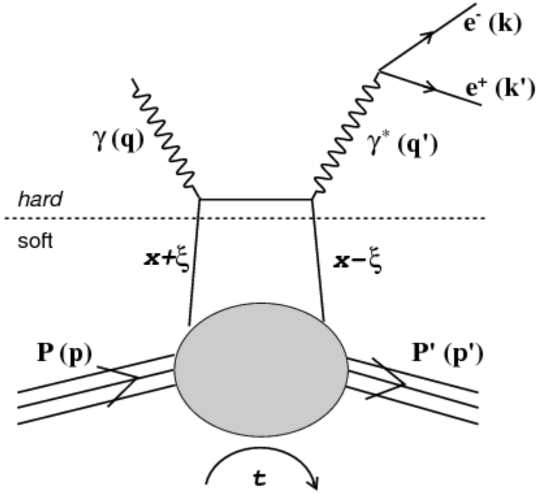




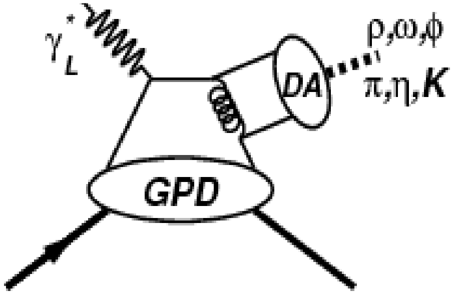
GPDs: beyond DVCS



Double DVCS: $\gamma^* p \to p \gamma^* \to p l^+ l^-$
- Access to **x dependence** of GPDs, decorrelated from ξ
- LOI for SOLID (Hall A), and plans for CLAS12



Time-like Compton Scattering: $\gamma p \to p \gamma^* \to p l^+ l^-$
- Sensitive to **real part** of CFFs, test of **universality** of GPDs
- CLAS12 experiment running in 2017, with pDVCS



Deeply virtual meson production: $\gamma^* p \to p M$
- **Flavor separation** of GPDs, **universality**
- **Transversity GPDs** (pseudoscalars mesons)
- Experiments in Hall A, CLAS12

Summary

✓ 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

✓ 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 JLab (**CLAS** and **Hall-A**) experiments at 6 GeV (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**

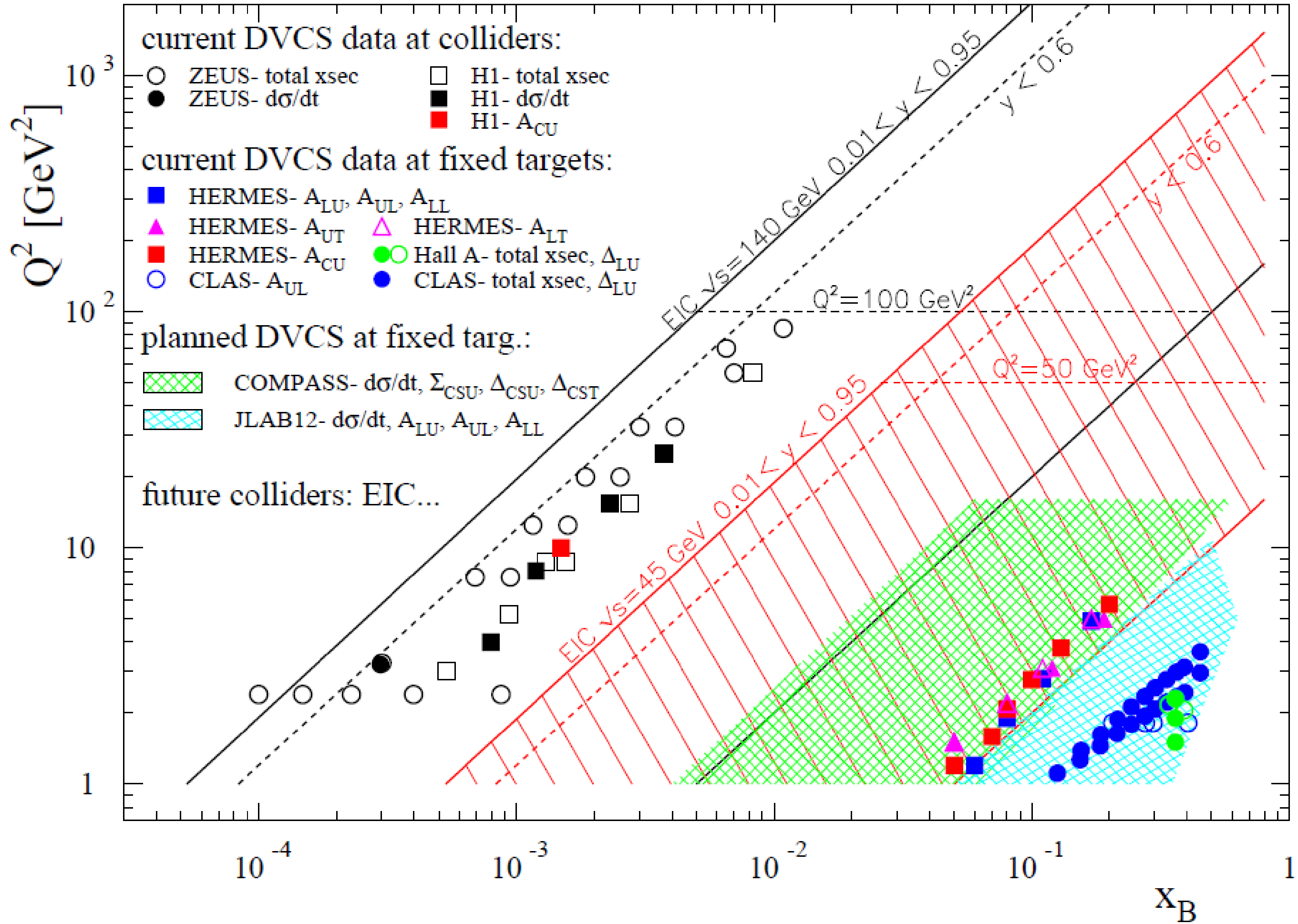
✓ **axial charge** more concentrated than the **electric** one

→ The 12-GeV-upgraded JLab will be **the optimal facility** to perform DVCS experiments **in the valence region**, for Q^2 up to ~10 GeV

→ DVCS experiments on both **proton** and **deuterium** targets 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, …**

Global outlook: DVCS past, present and future



Back-up slides

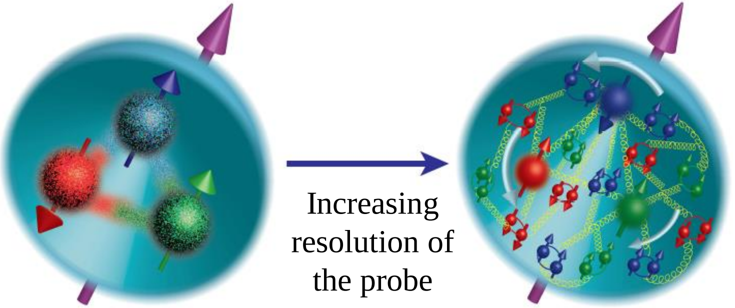
Exploring the partonic structure of the nucleon

Protons and neutrons are the building blocks of atomic **nuclei**.

Nucleons provide **~99% of the mass** of the visible universe.

~99% of nucleon mass arises from the **interactions** between its constituents (**quarks** and **gluons**).

The **structure of the nucleons** determines their **fundamental properties**, which affect the properties of **nuclei**.

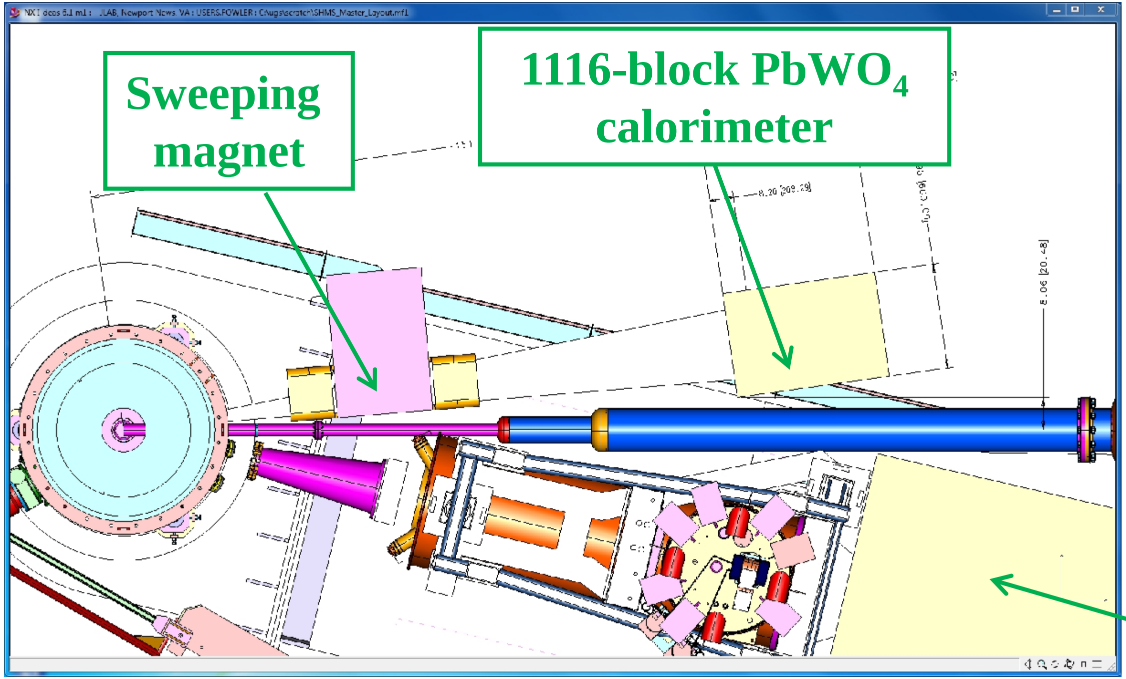


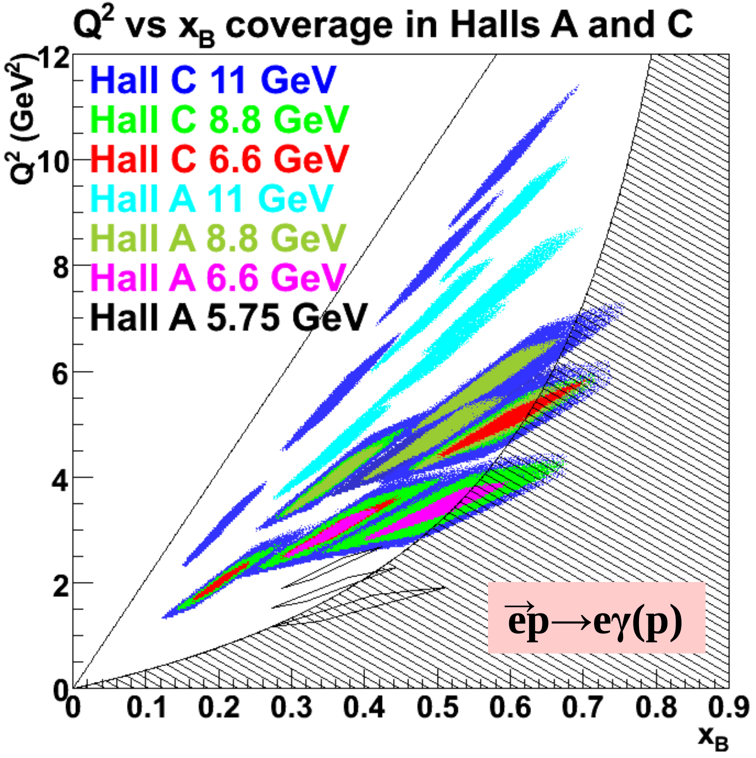
- How do the **QCD** Lagrangian degrees of freedom relate to the **hadrons** we observe?
- How do the **spin** and the **mass** of the nucleon emerge from the dynamics of its constituents?
- How do the parton dynamics **evolve with the resolution** of the hard probe?

Understanding how the nucleon is built in terms of its underlying quark and gluon degrees of freedom is an important and challenging issue in nuclear physics nowadays
→ **electron-nucleon scattering** is a precious tool to address it

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)

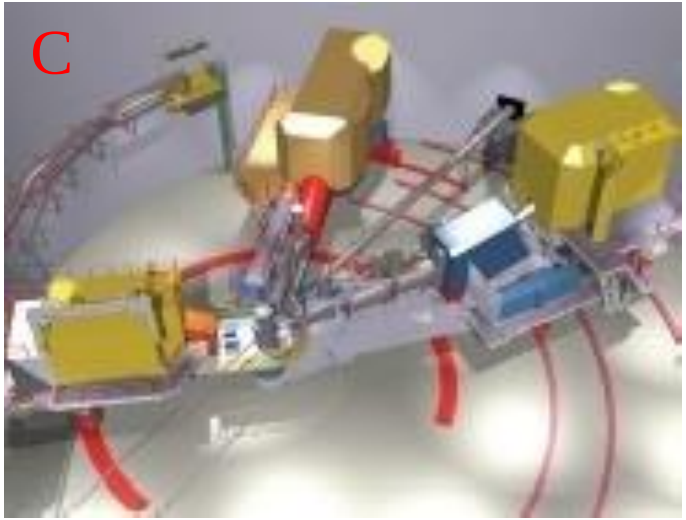




Tentative running: ~ 2019-20

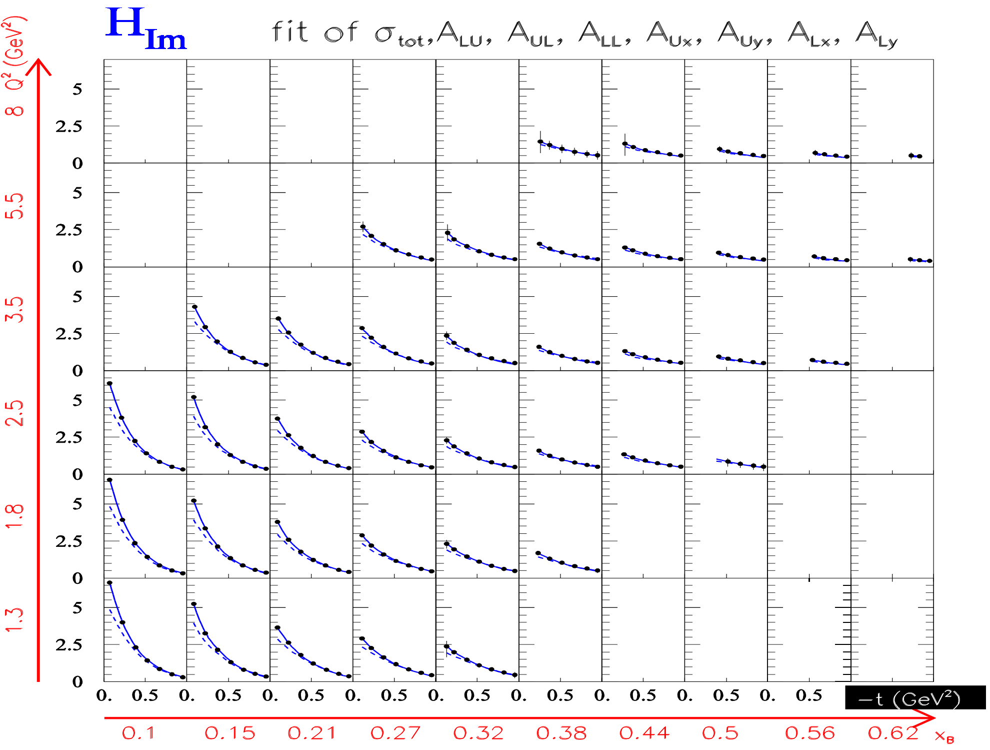
New capabilities in Halls A, B & C

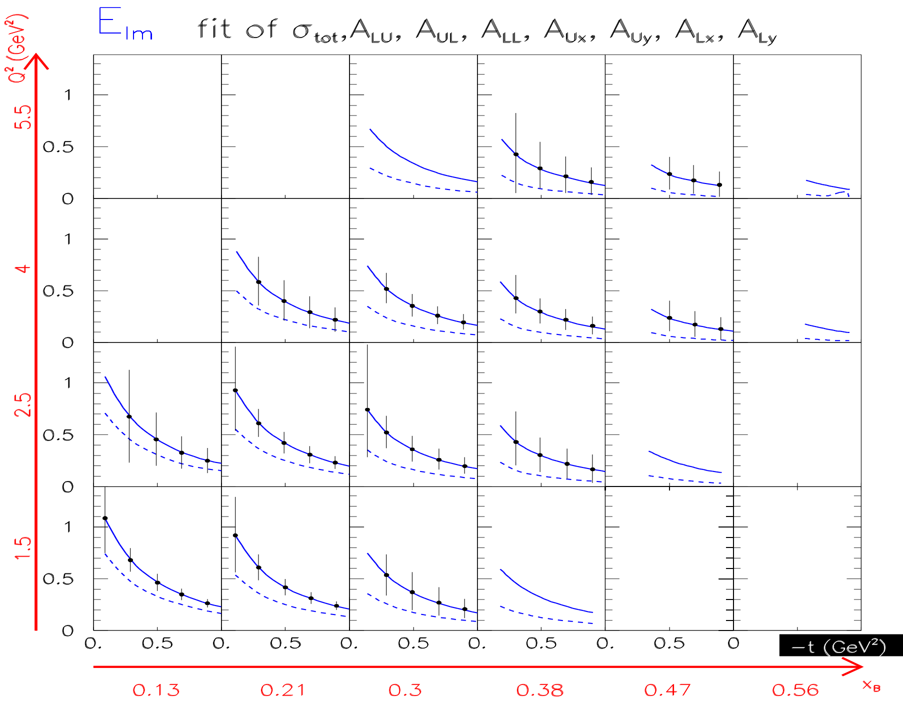
DVCS experiments at 11 GeV have been approved for each of these **three halls**.
Complementary programs:
- different kinematic coverage
- different precisions/resolutions
- focus on different observables



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

Projections for CLAS12 for $H_{im}(p)$ and $E_{im}(p)$





Work by M. Guidal

Extraction of Compton Form Factors from DVCS observables

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

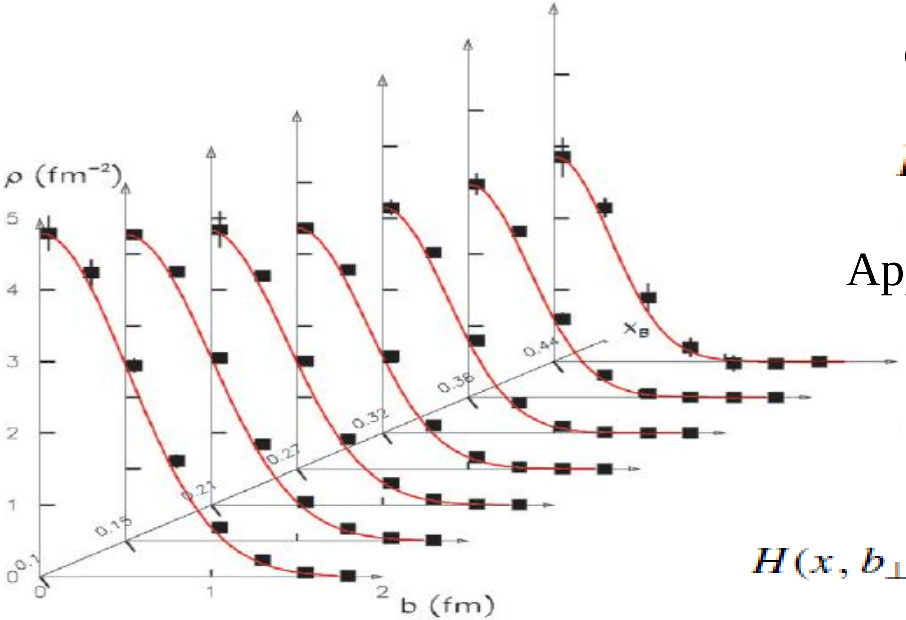
8 CFF

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

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

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…

From CFFs to spatial densities



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

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

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

Applying a model-dependent “deskewing” factor:

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

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

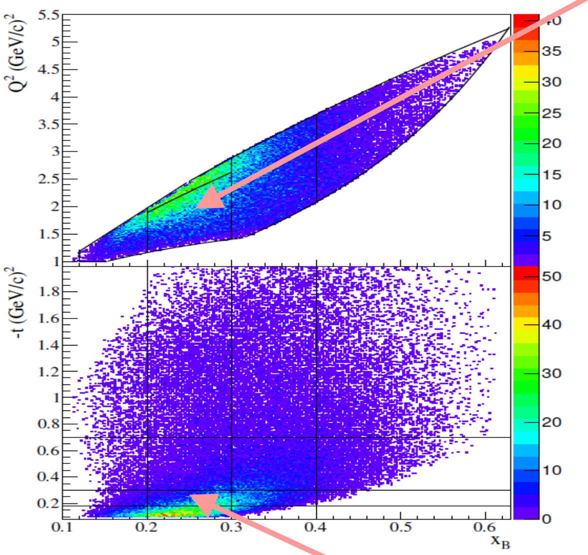
Burkardt (2000)

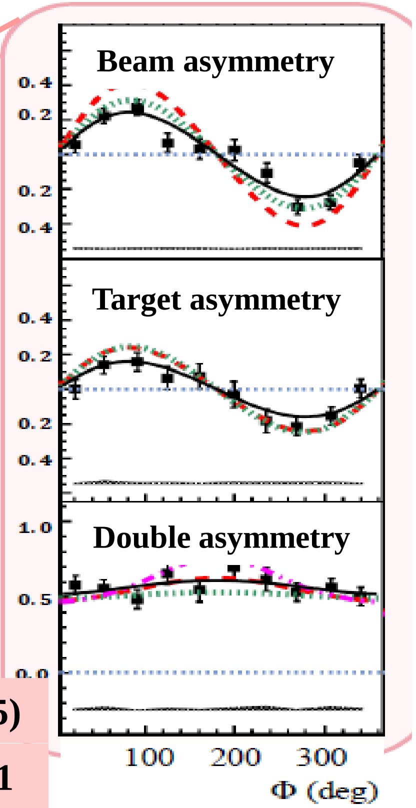
CLAS: DVCS on longitudinally polarized target

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

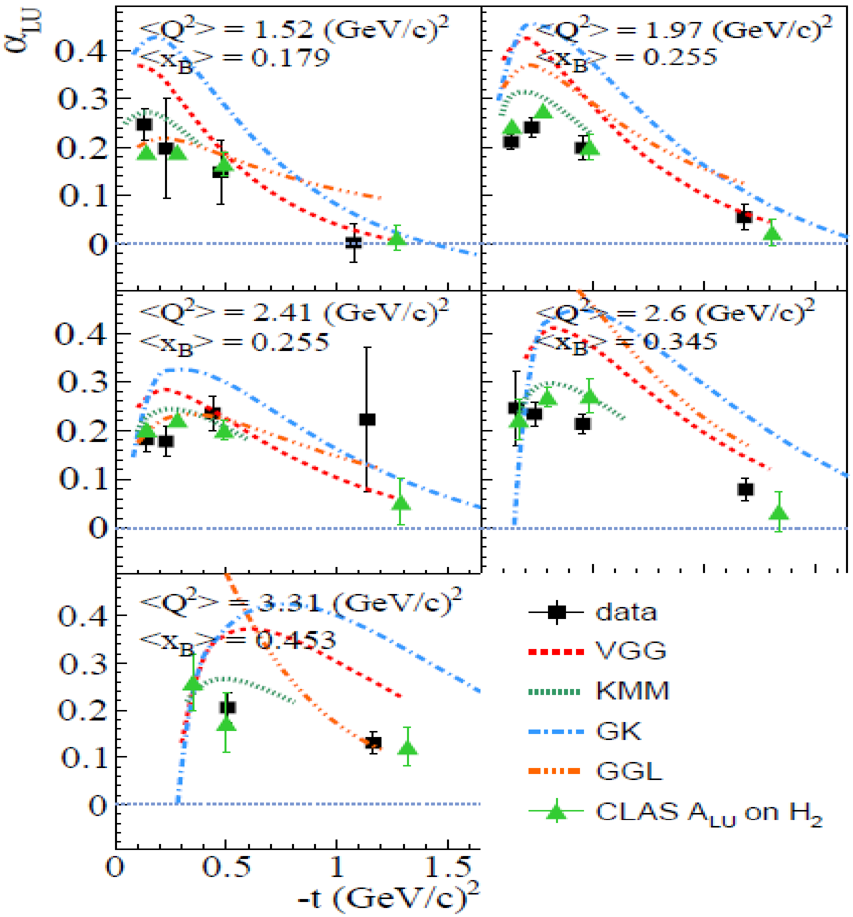
BSA ~ $Im\{\mathcal{H}_p\}$

- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**





5 Q^2-x_B bins, 4 t bins, 10 ϕ bins



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

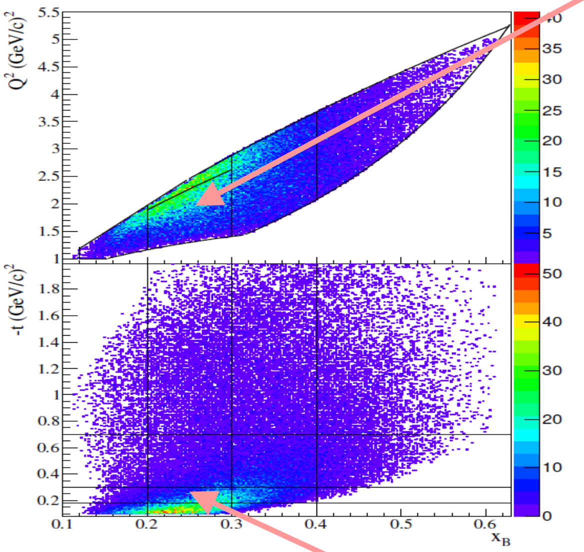
E. Seder et al., PRL 114 (2015) 032001

CLAS: DVCS on longitudinally polarized target

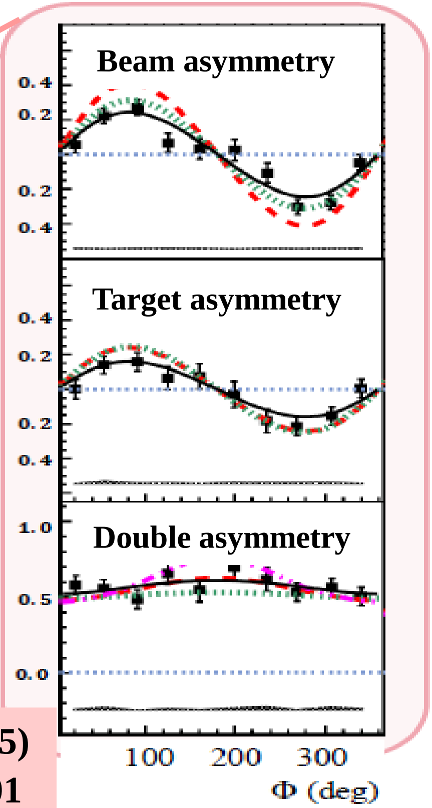
$\vec{e}\vec{p} \rightarrow ep\gamma$

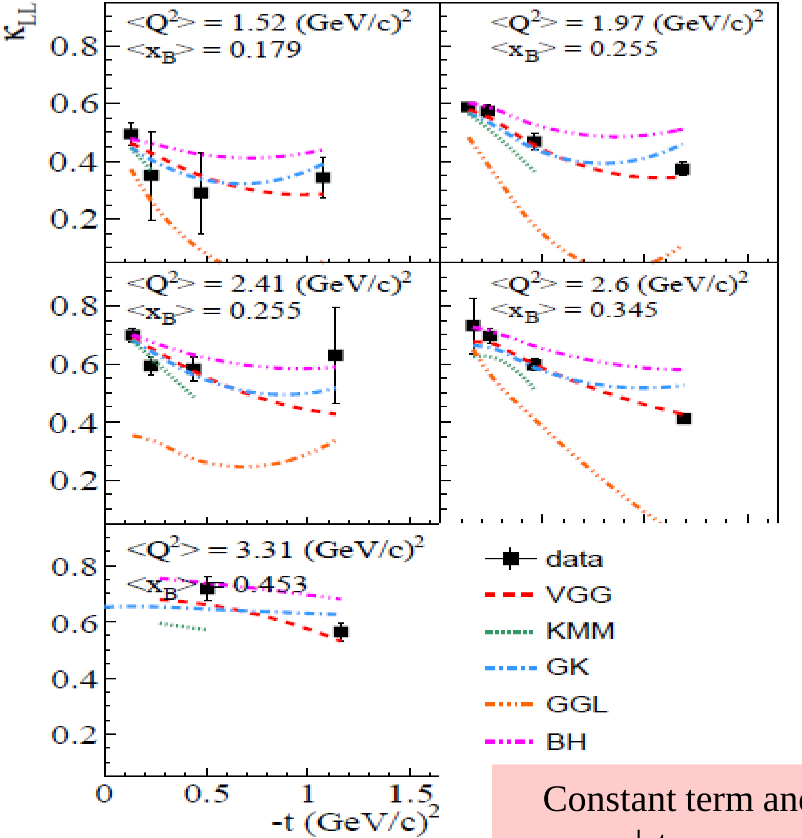
DSA ~ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**



5 Q^2-x_B bins, 4 t bins, 10 ϕ bins





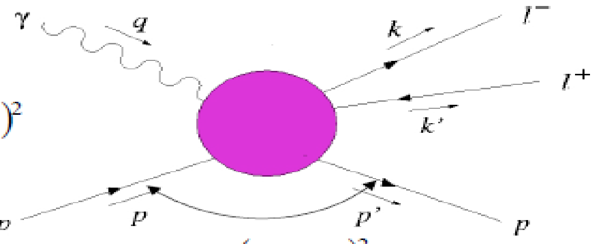
S. Pisano et al., PRD 91, 052014 (2015)
E. Seder et al., PRL 114 (2015) 032001

Constant term and $\cos\phi$ term are dominated by **BH**

Timelike Compton Scattering with CLAS12

$\gamma p \to p\gamma^* (\to e^+e^-)$

$s = (q+p)^2$

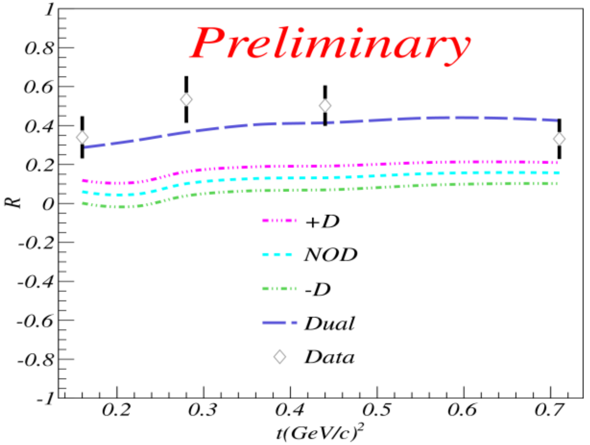


$t = (p - p')^2$

$$Q'^2 = M^2_{l^+l^-} = (k+k')^2$$

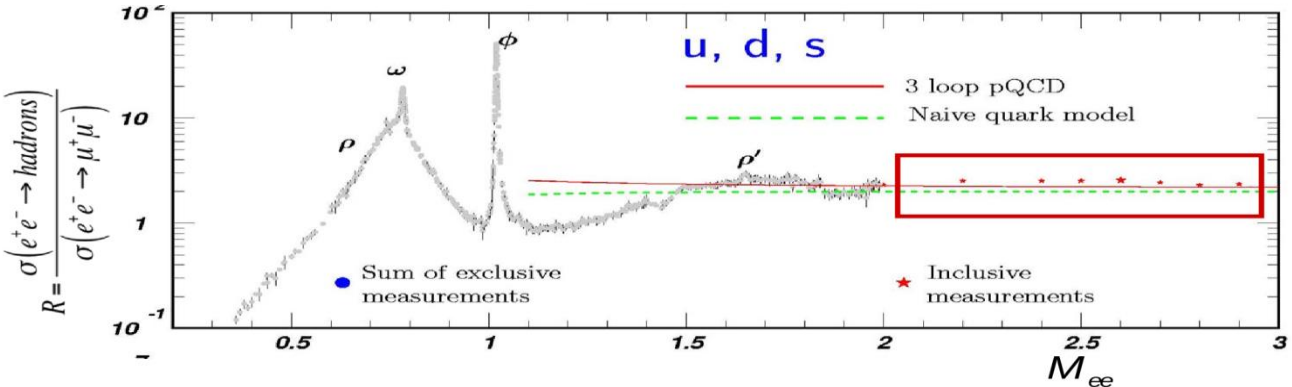
$$\eta = \frac{Q'^2}{2s - Q'^2}$$

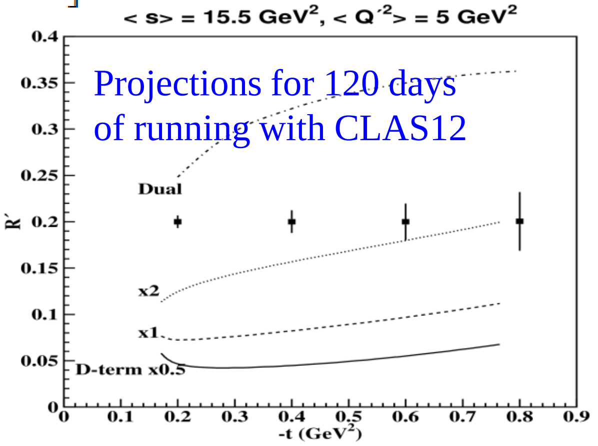
Exploratory measurement with CLAS@6 GeV (*R. Paremuzyan, IPNO & Yerevan*)



TCS: sensitivity to the **real part** of CFFs

$$R = \frac{2\int_0^{2\pi} d\phi \cos\phi \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \propto \tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{m}\frac{1-\eta}{1+\eta}\left[F_1\mathcal{H} - \eta(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right]$$

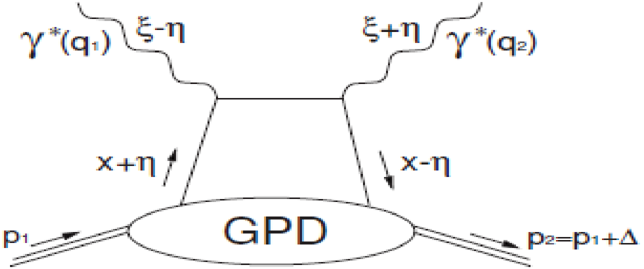


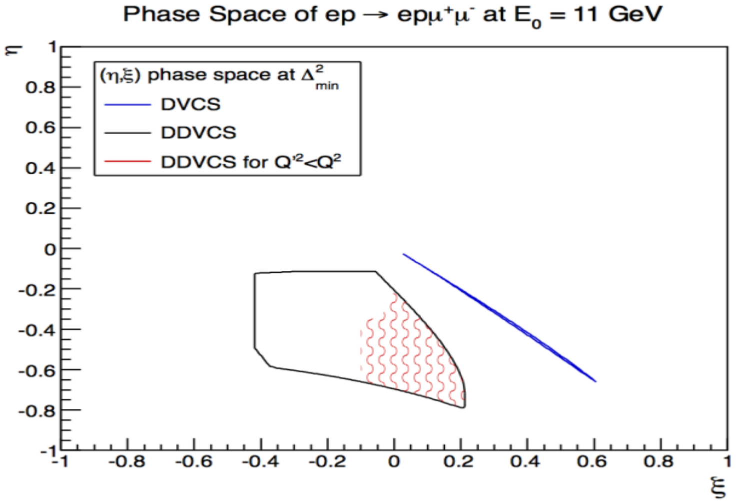


Double DVCS at SoLID (Hall A)

$ep \to ep\gamma^*(\to \mu^+\mu^-)$

LOI12-15-005, endorsed by PAC43

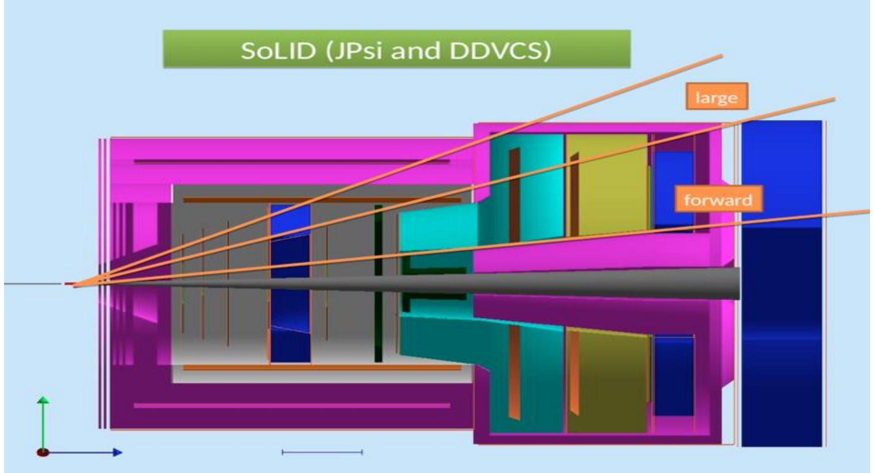


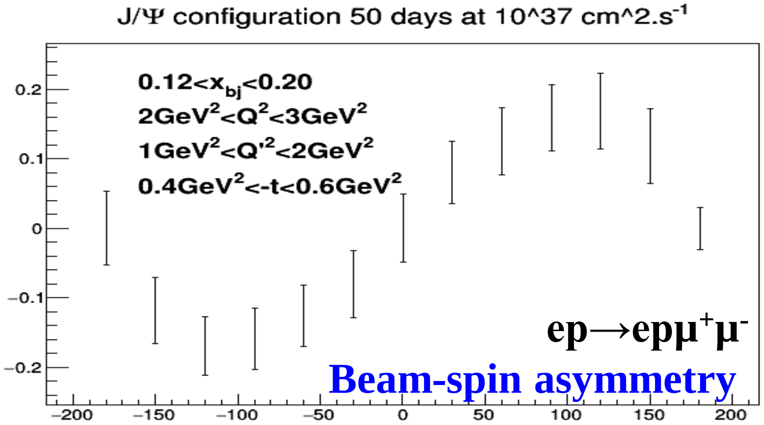


The virtuality of the emitted photon allows to investigate the **x and ξ dependence** of the GPDs in an **uncorrelated** way

Experimental setup, **Hall A**:

SoLID detector + **muon detection chambers**





$ep \to ep\mu^+\mu^-$

Beam-spin asymmetry