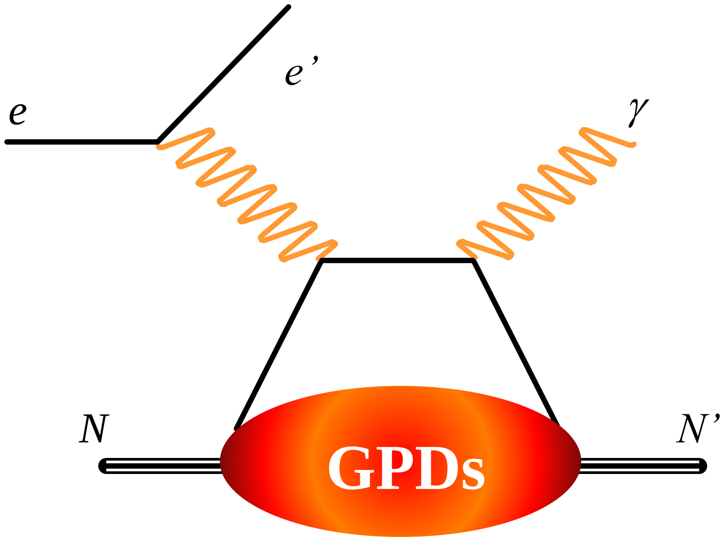
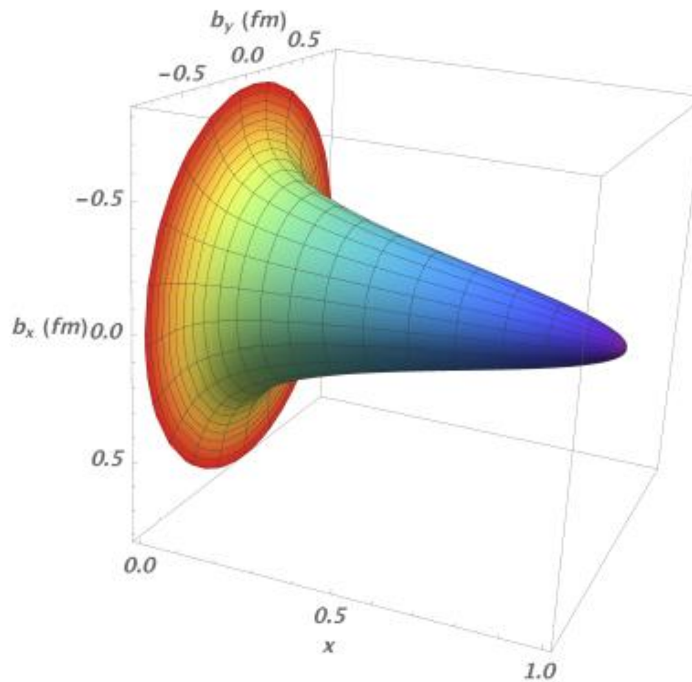
Multidimensional nucleon structure at Jefferson Lab





Silvia Niccolai, IPN Orsay

& CLAS Collaboration

clas IPN ORSAY

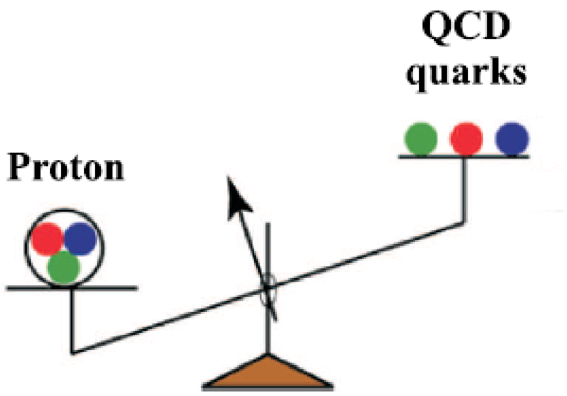
The nucleon: QCD at work!

What we know about the content of the proton:

- 2 *up* quarks ($q_u = 2/3\ e$) + 1 *down* quark ($q_d = -1/3\ e$)
- Any number of quark-antiquark pairs (sea)
- Any number of gluons

$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$

Fundamental questions:



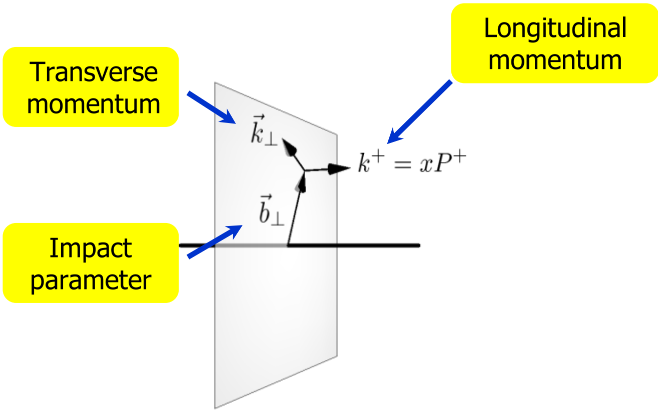
- Origin of proton **mass**?

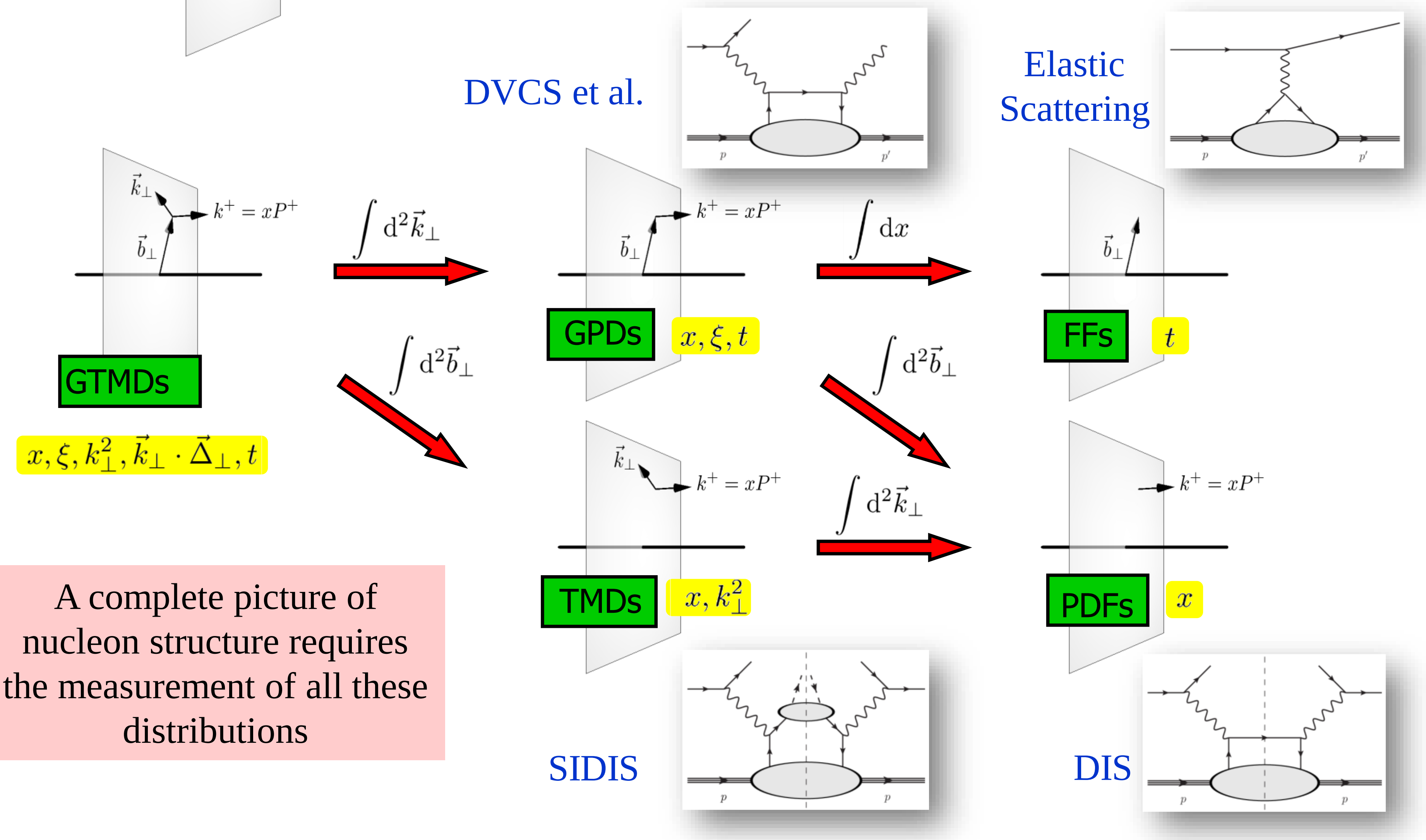
→ Only a **small fraction** of it comes from the actual quark masses
→ Most of it comes from the ***motion of quarks and gluons***

- Origin of proton **spin**?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

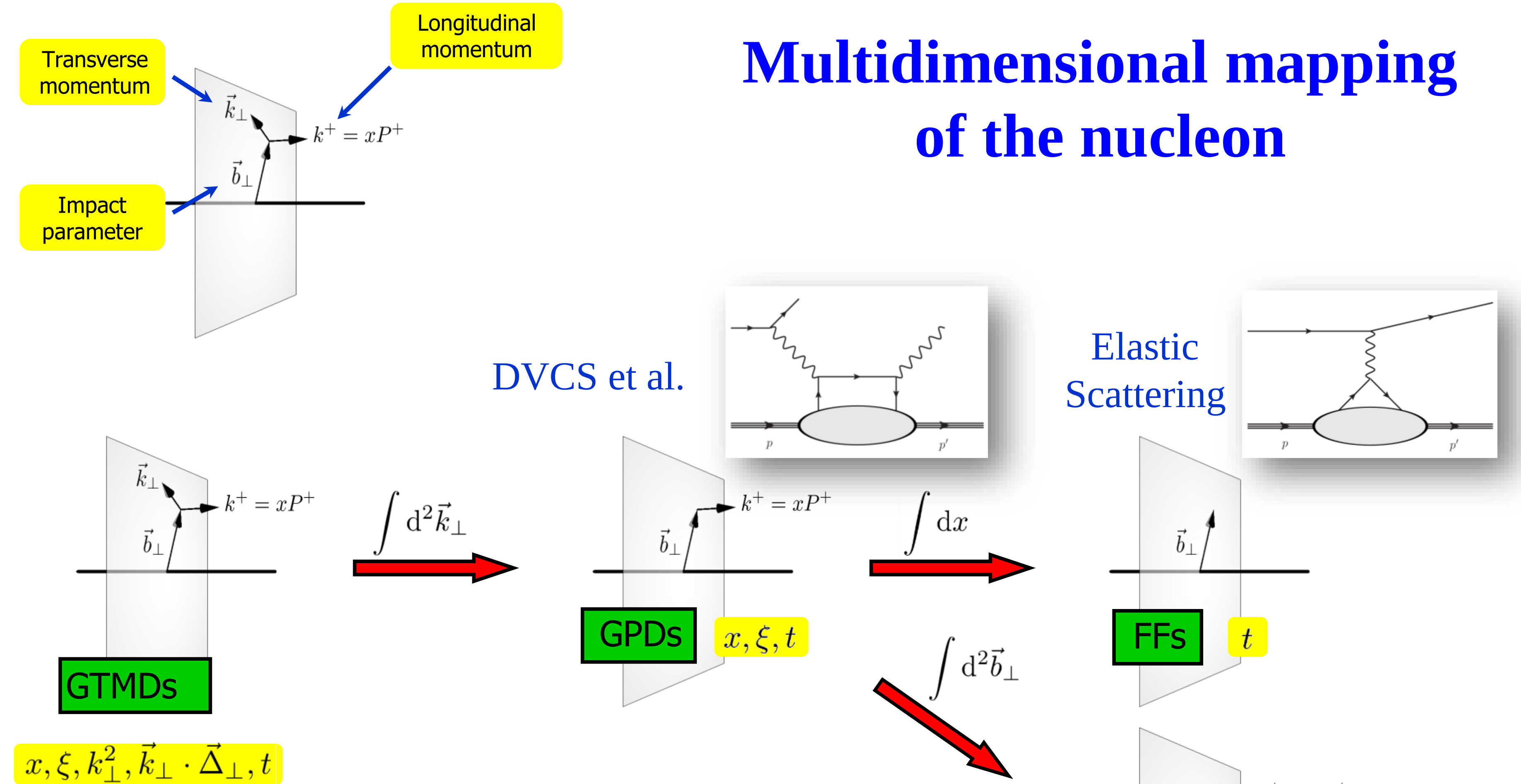
Multidimensional mapping of the nucleon

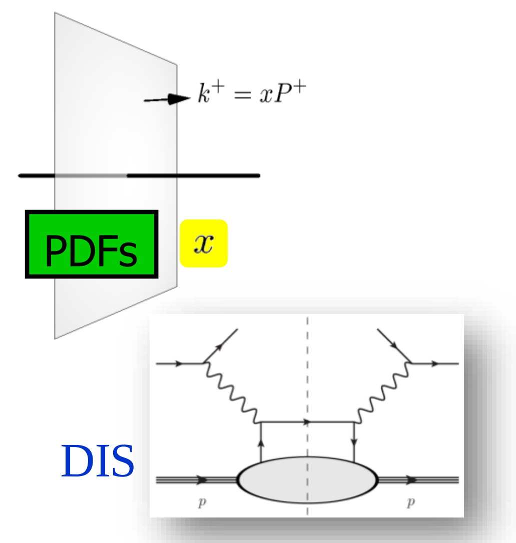




A complete picture of nucleon structure requires the measurement of all these distributions

Multidimensional mapping of the nucleon





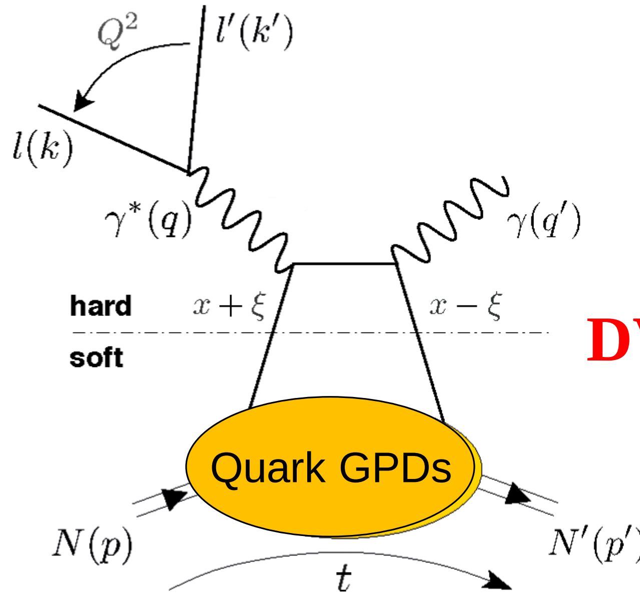
Generalized Parton Distributions:

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

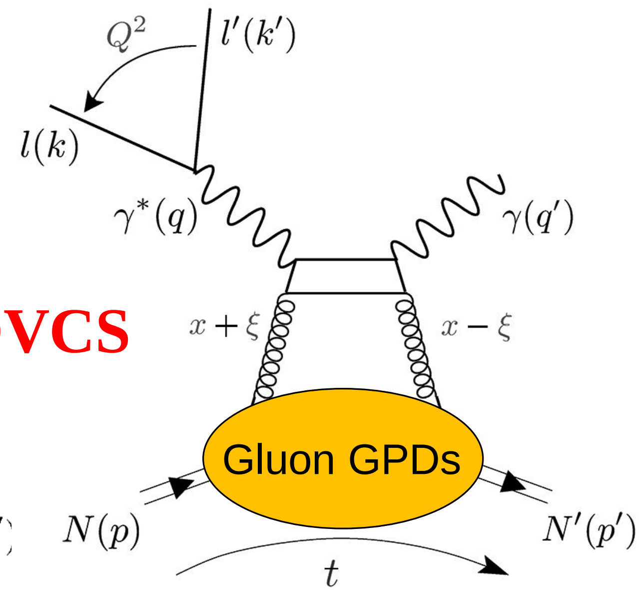
✓ linked to **FFs** and **PDFs**

✓ accessible in **hard exclusive** reactions (DVCS, DVMP,…)

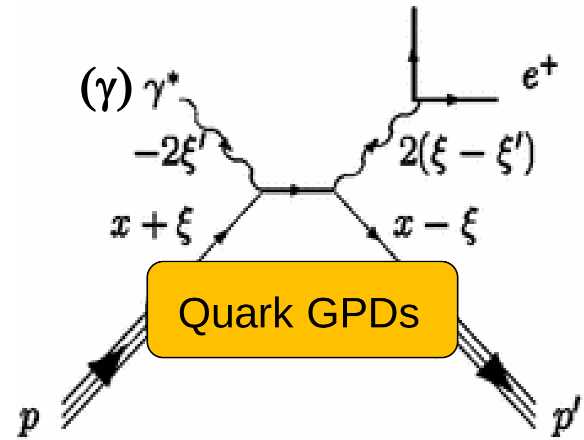
Exclusive reactions giving access to GPDs

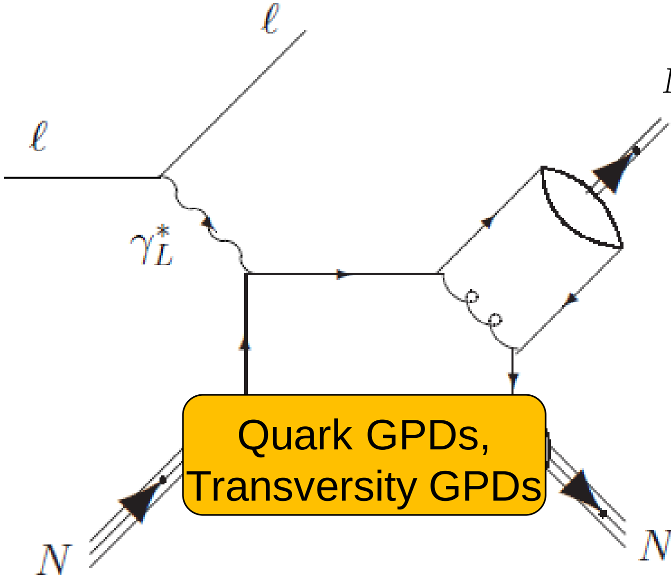


DVCS

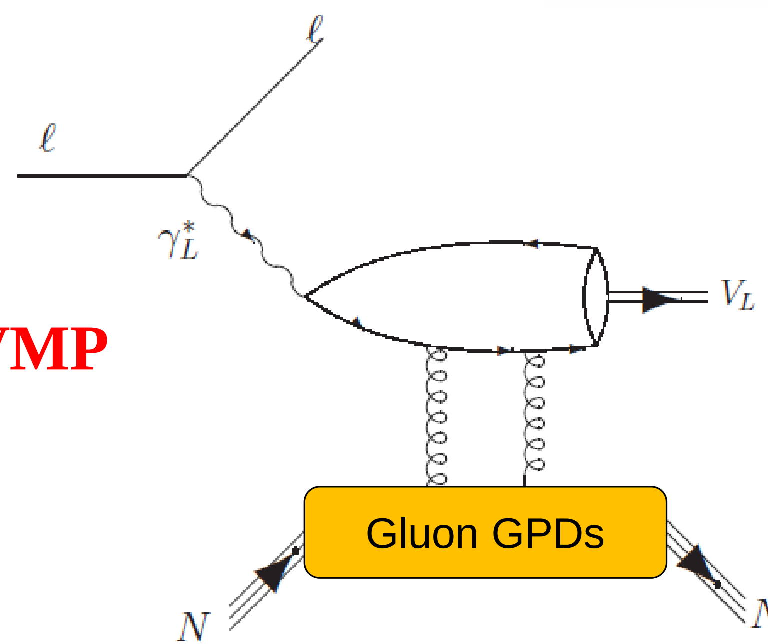


(TCS), DDVCS

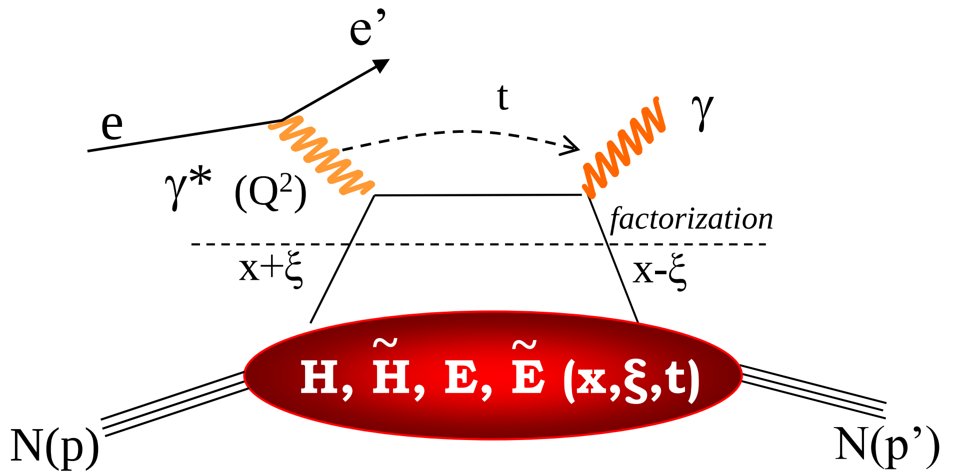




DVMP

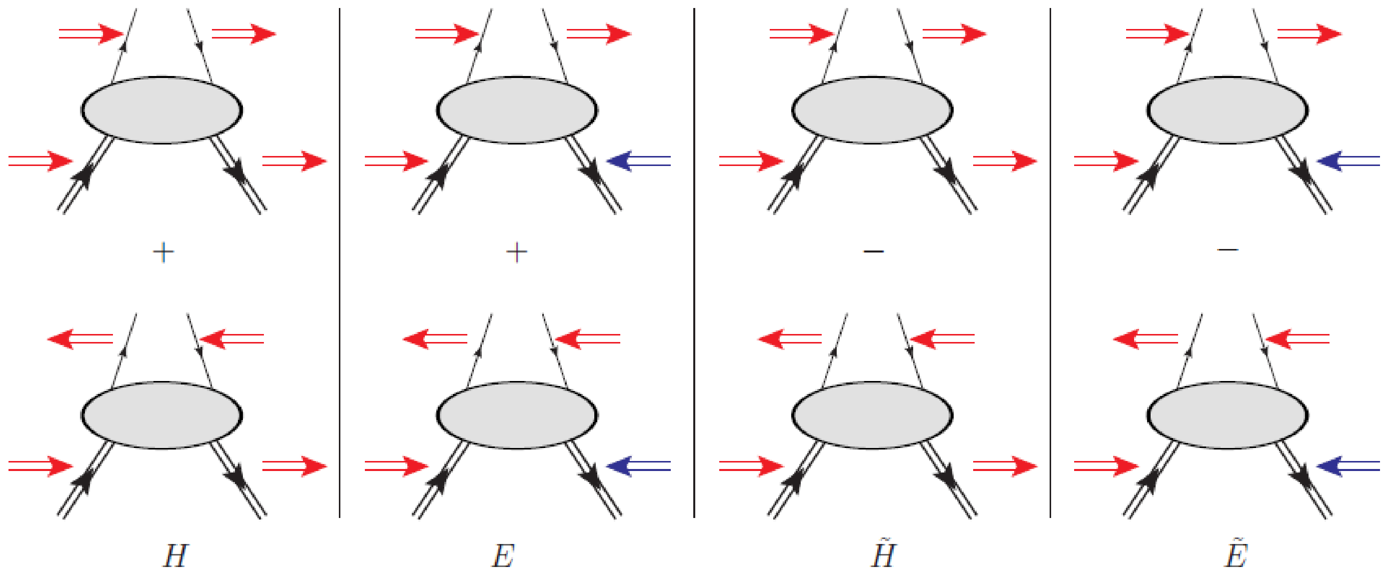


Deeply Virtual Compton Scattering and quark GPDs



- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

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



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**

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

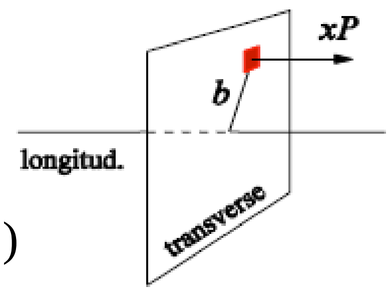
Forward limit: **PDFs** (not for E, Ẽ)

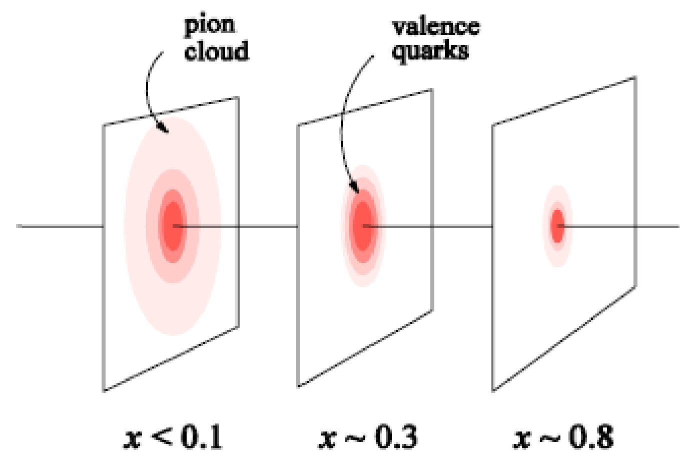
Nucleon tomography

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

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

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

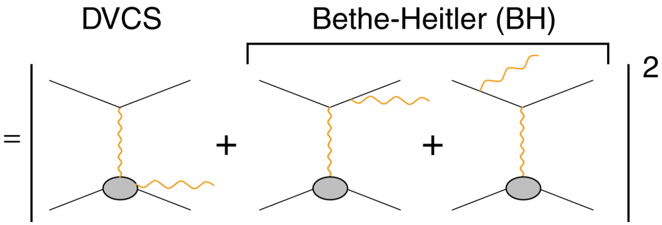
DVCS allows access to 4 complex GPDs-related quantities: **Compton Form Factors (ξ,t)**

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

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

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

σ(eN → eNγ) =



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

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

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:

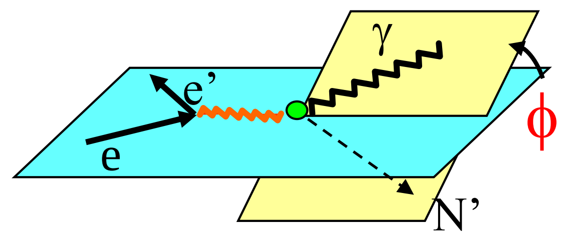
$\Delta\sigma_{UL} \sim \sin\phi\ Im\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

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:

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

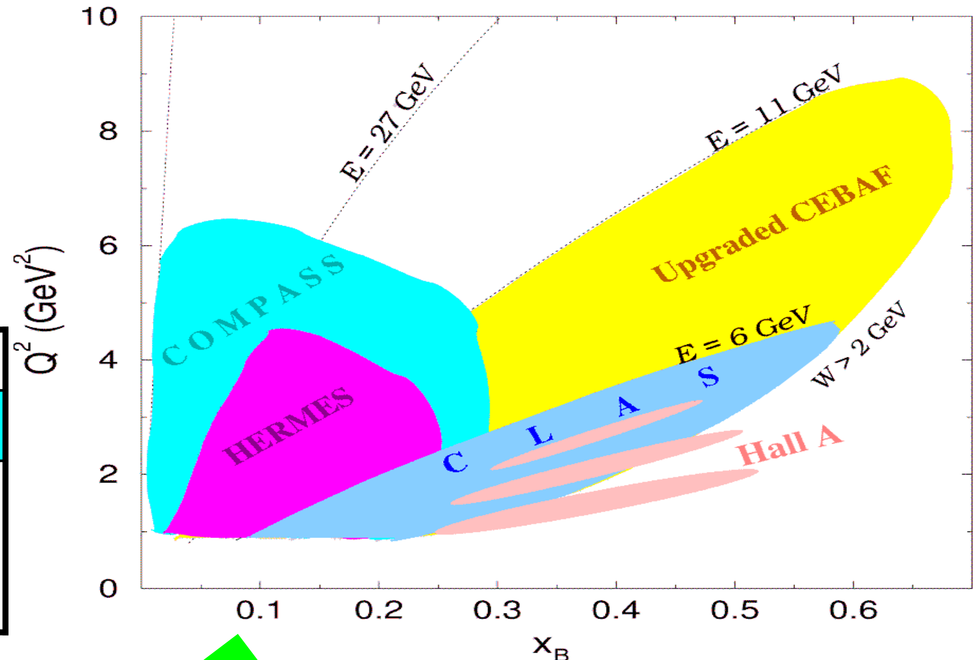


DVCS experiments worldwide

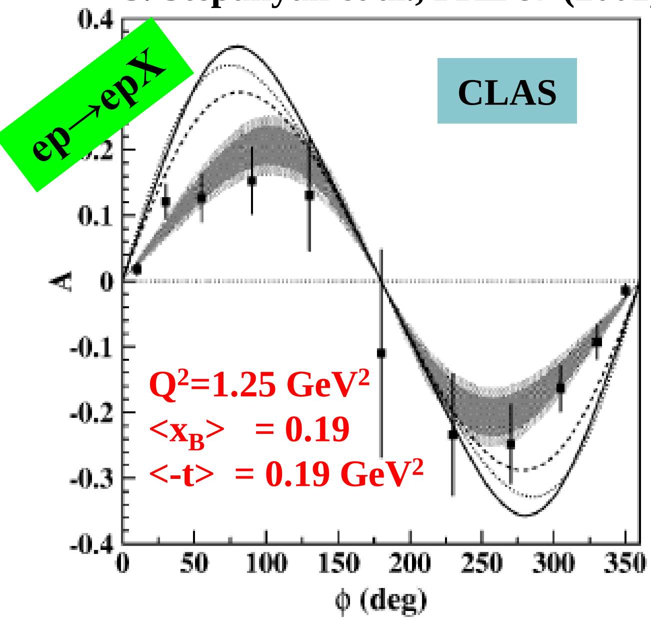
JLAB	
Hall A	*CLAS (Hall B)*
p,n-DVCS (Bpol.) CS	p-DVCS BSA,lTSA,DSA,CS

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



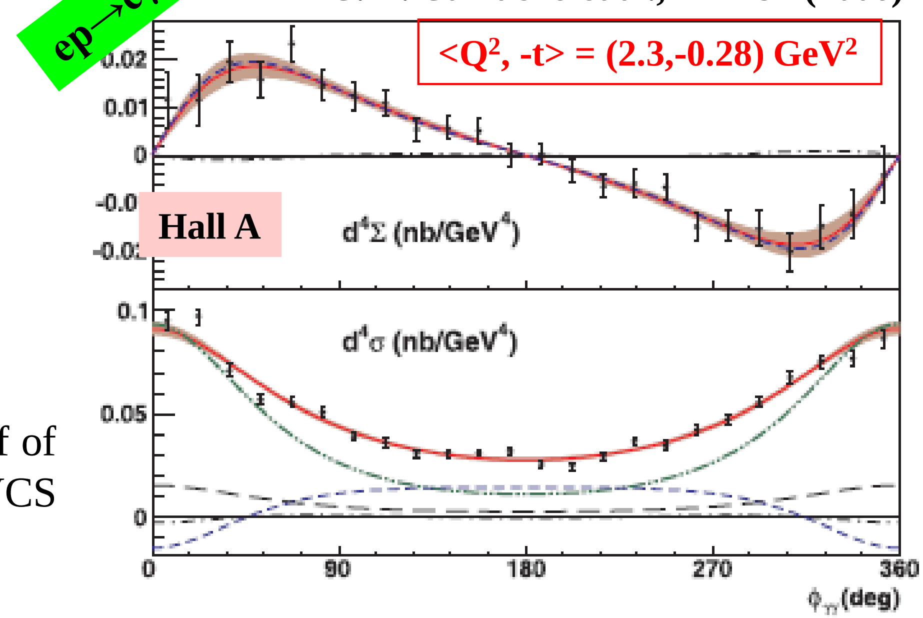
S. Stepanyan et al., PRL 87 (2001)



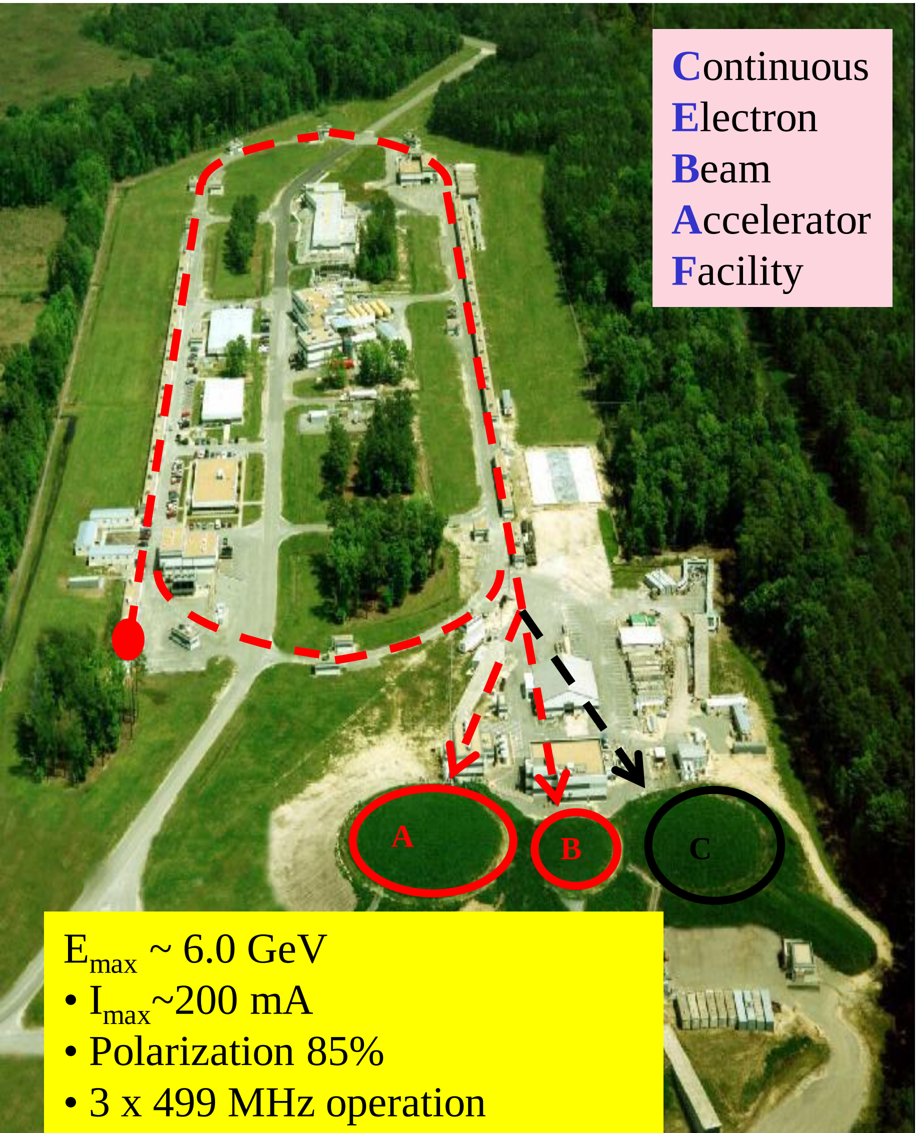
CLAS & HERMES: first observation of DVCS-BH interference

Hall A: proof of scaling for DVCS

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



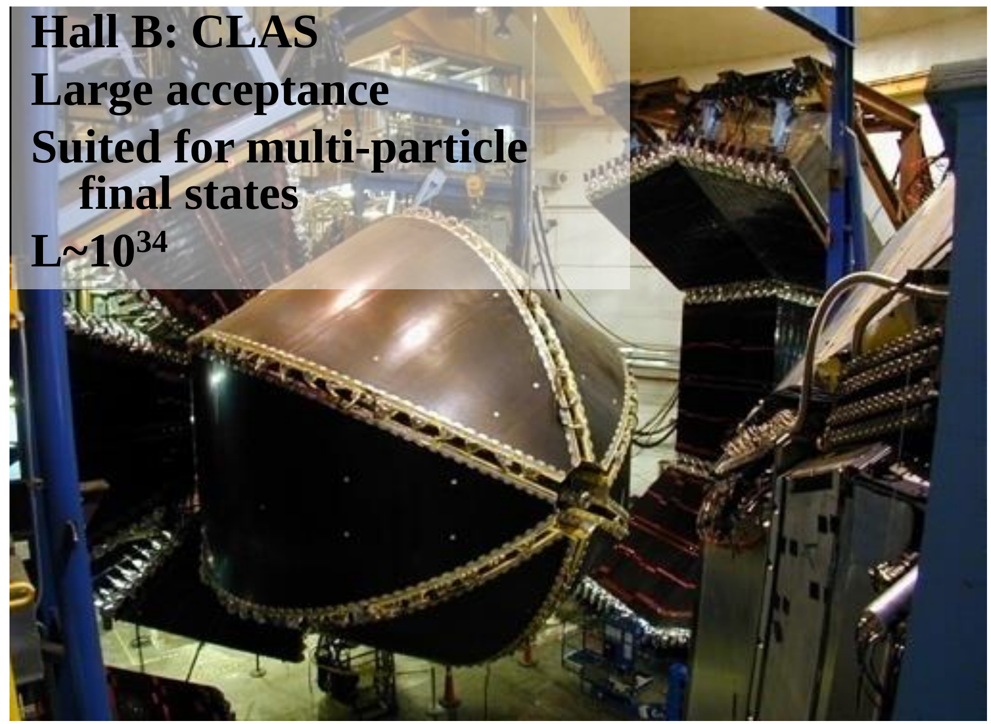
JLab@6 GeV



Continuous
Electron
Beam
Accelerator
Facility

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

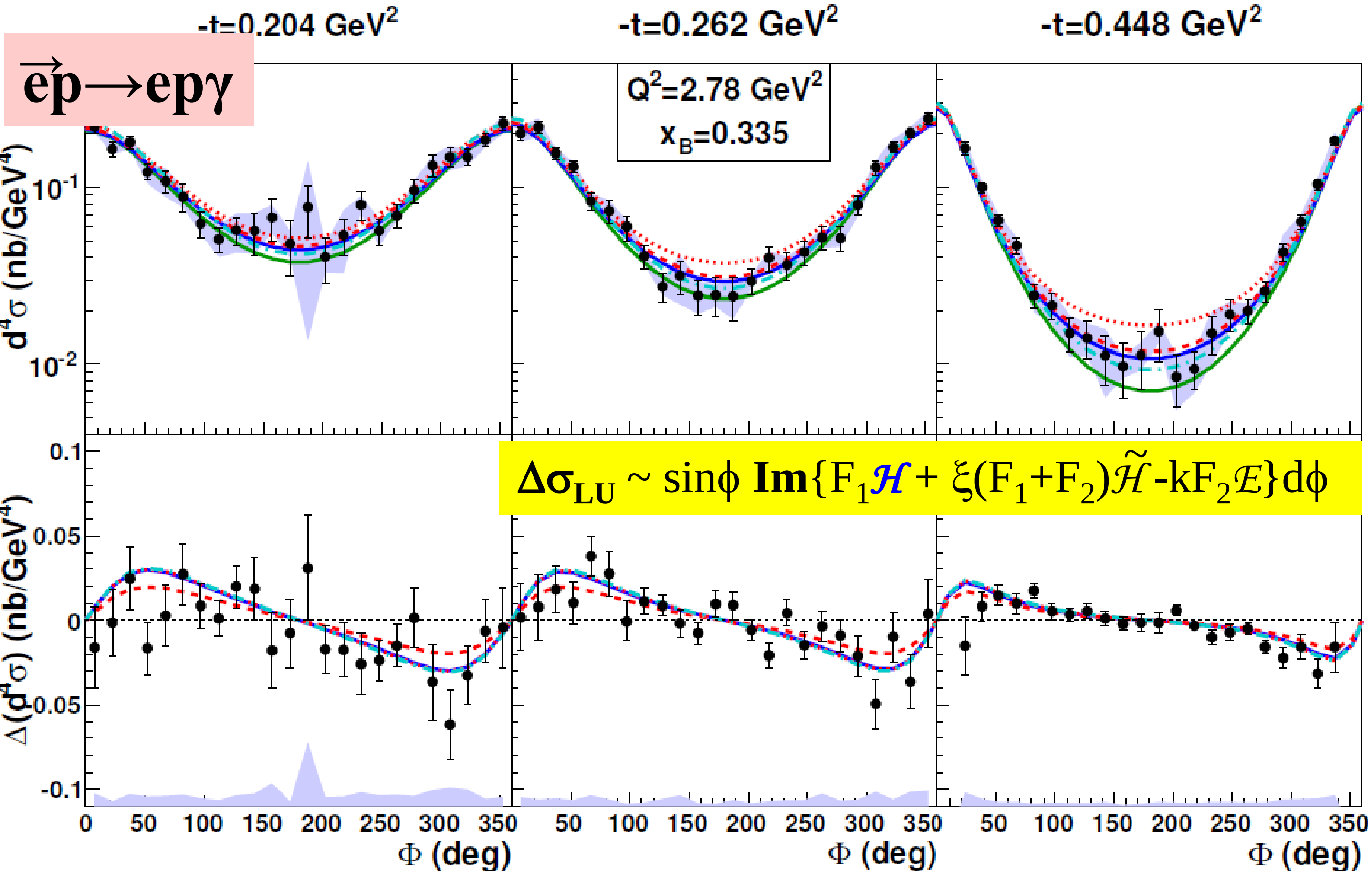
Hall A: 2 HRS
High resolution
High luminosity (L~10^{37})
Limited coverage



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

CLAS: unpolarized and beam-polarized cross sections

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



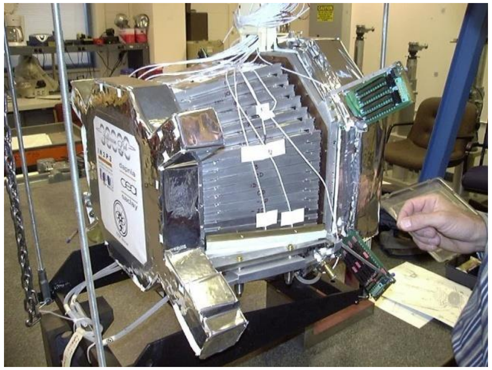
$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$

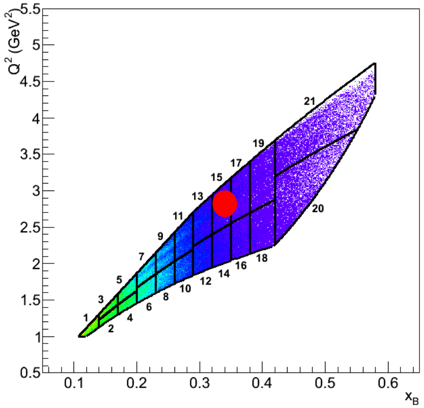
H.S. Jo et al., PRL 115, 212003 (2015)

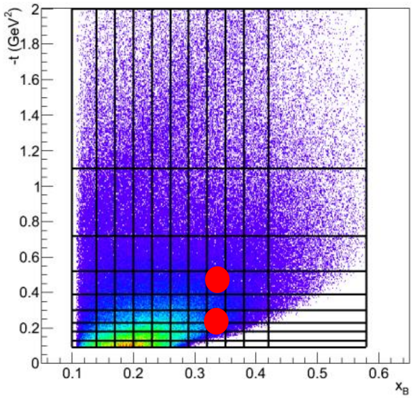
- **Largest kinematic ever covered for DVCS**
- **Two observables extracted**

BH — VGG
KM10 KM10a

- Beam energy ~ **5.75 GeV**
- Beam polarization ~ **80%**
- Target **LH_2**
- **Inner Calorimeter (IC)**

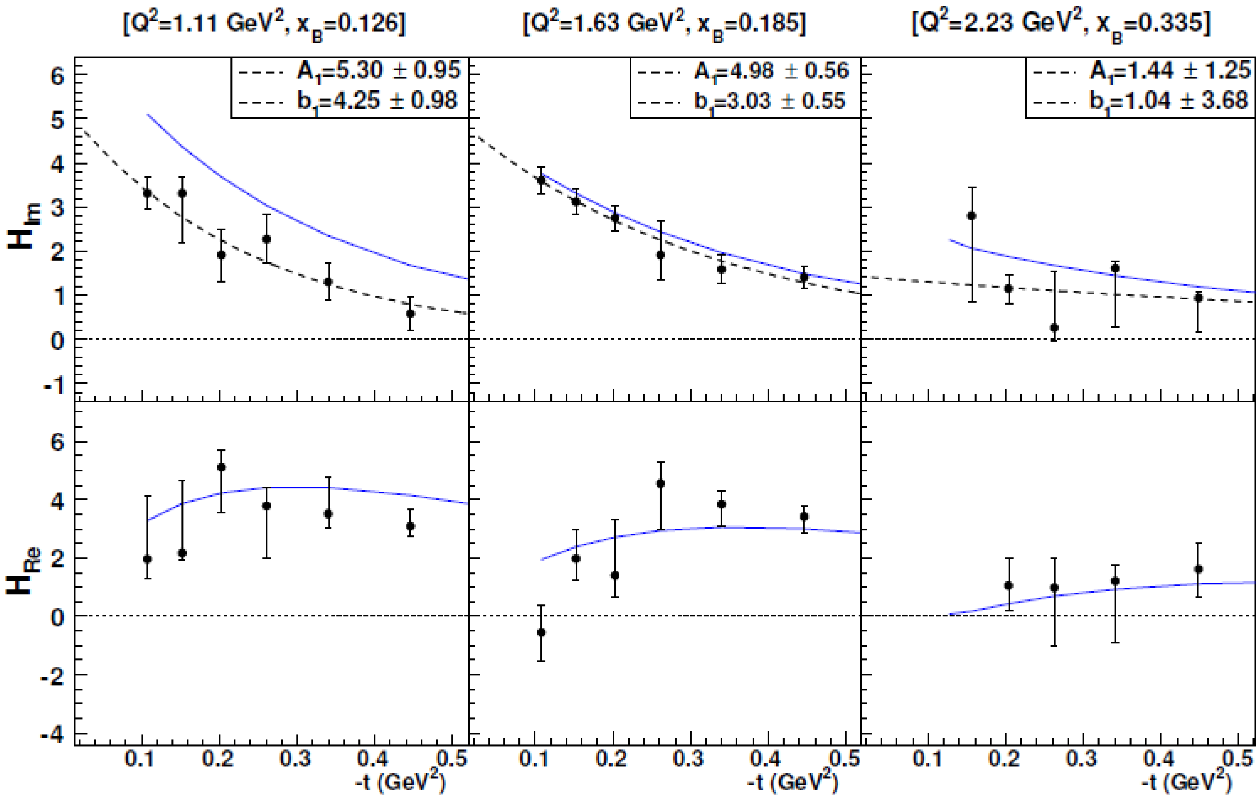






21 Q^2-x_B bins, 9 t bins, 24 φ bins

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



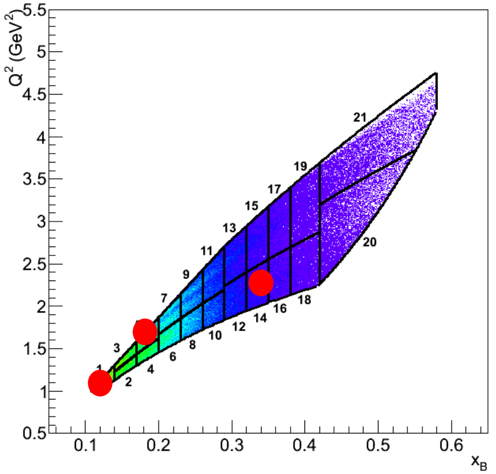
CFF fits

(H and H̃ only)

M. Guidal, Eur. Phys. J. A 37 (2008) 319, etc…

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

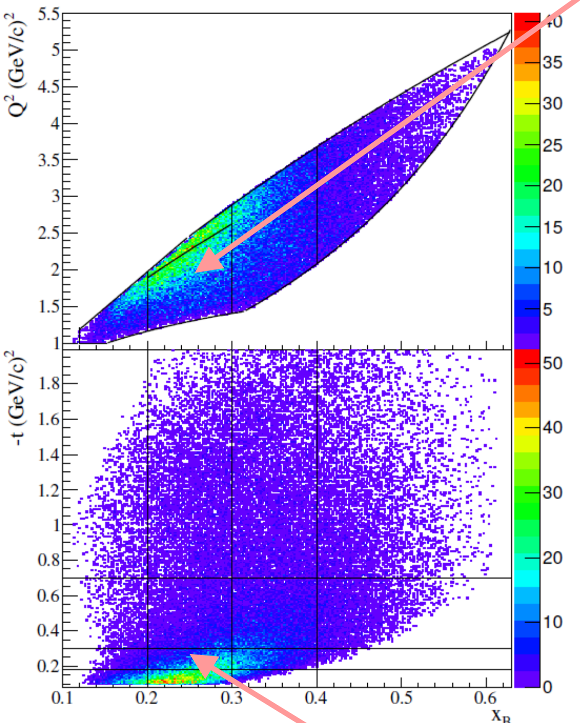
CLAS: DVCS on longitudinally polarized target

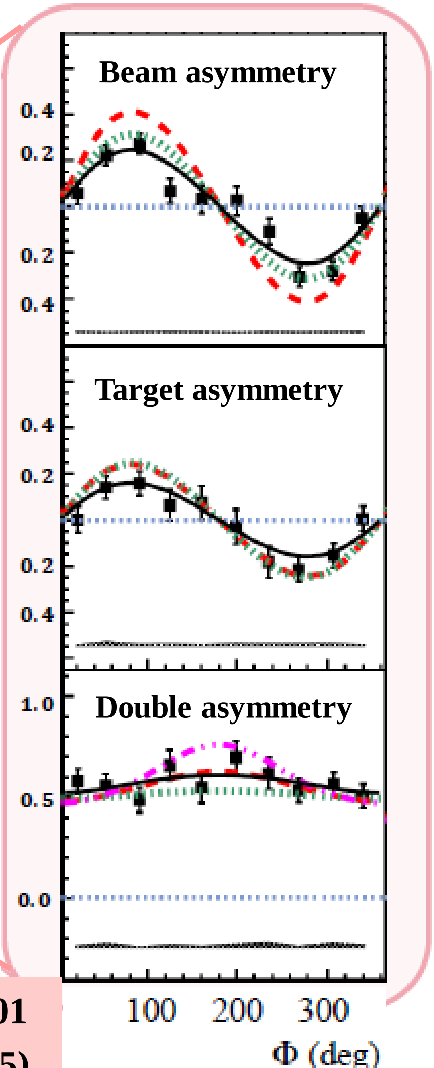
$\vec{e}\vec{p} \rightarrow ep\gamma$

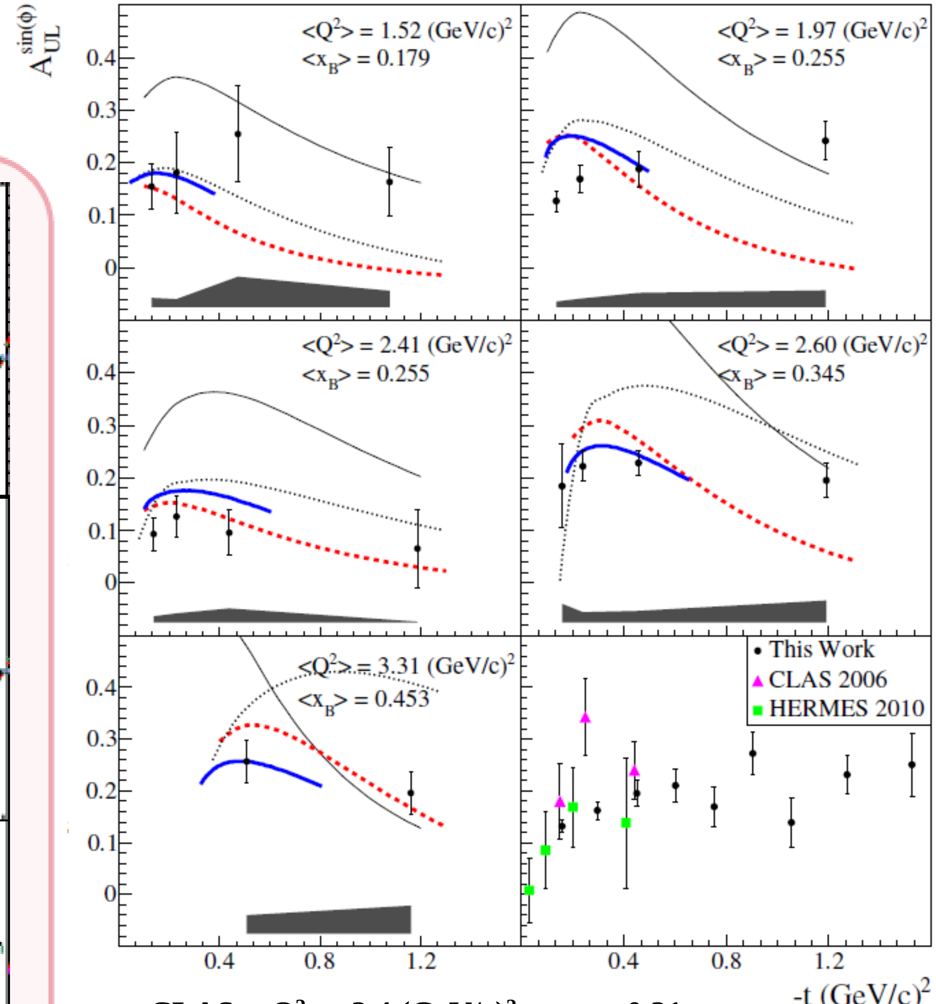
- Beam energy **~5.9 GeV**
- **CLAS + IC** to detect forward photons

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

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







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

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

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

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

Extraction of CFFs from CLAS TSA, BSA, DSA

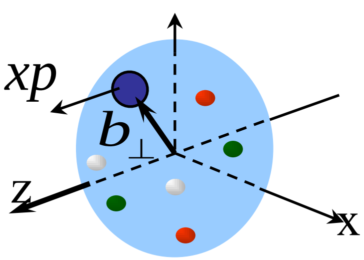
CFFs fitting code
M. Guidal, Eur. Phys. J. A 37 (2008) 319, etc…

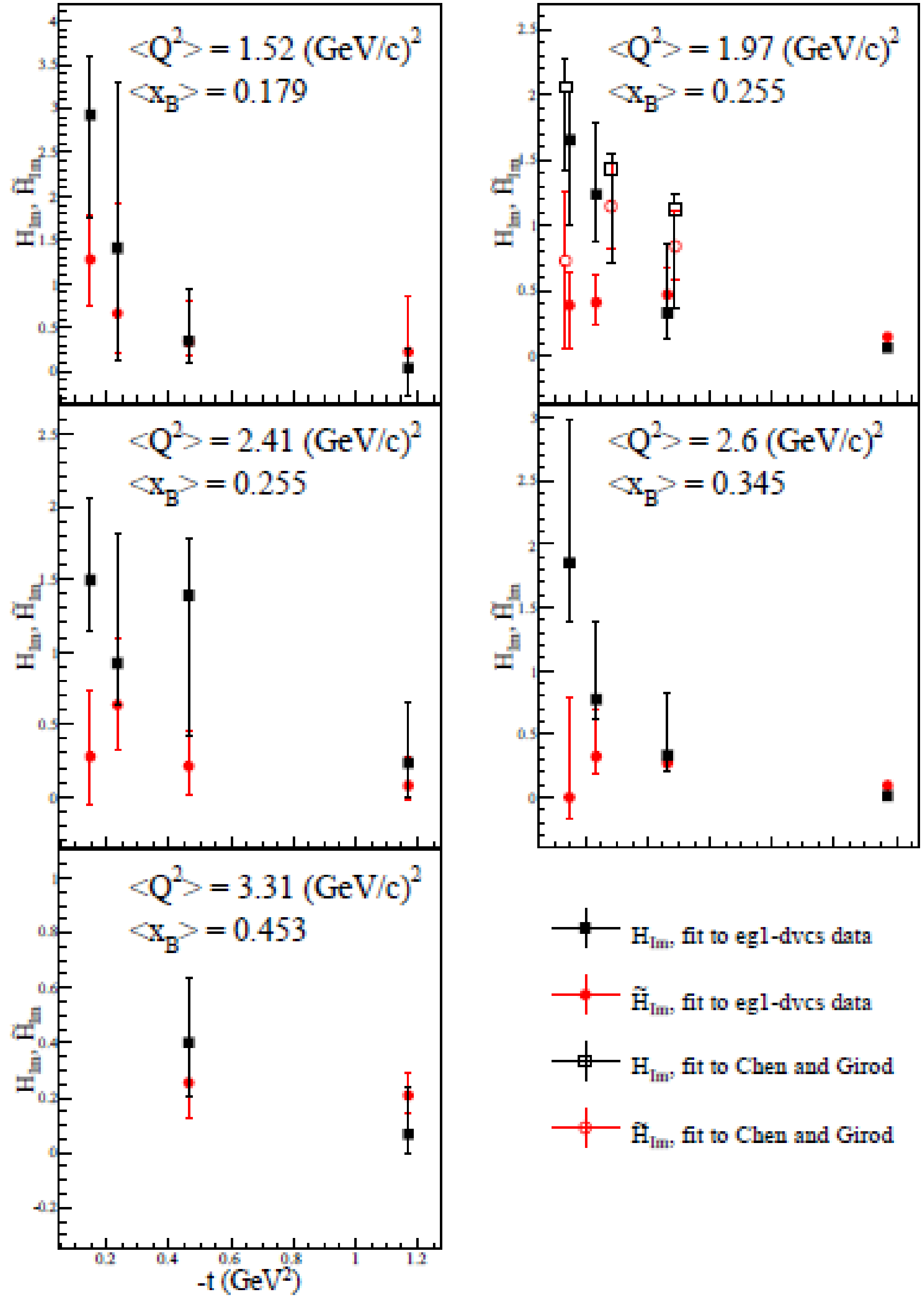
***Im$\mathcal{H}$* has steeper t-slope than *Im$\widetilde{\mathcal{H}}$*:**
the axial charge is more "concentrated" than the electric charge
→ PROTON TOMOGRAPHY

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

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

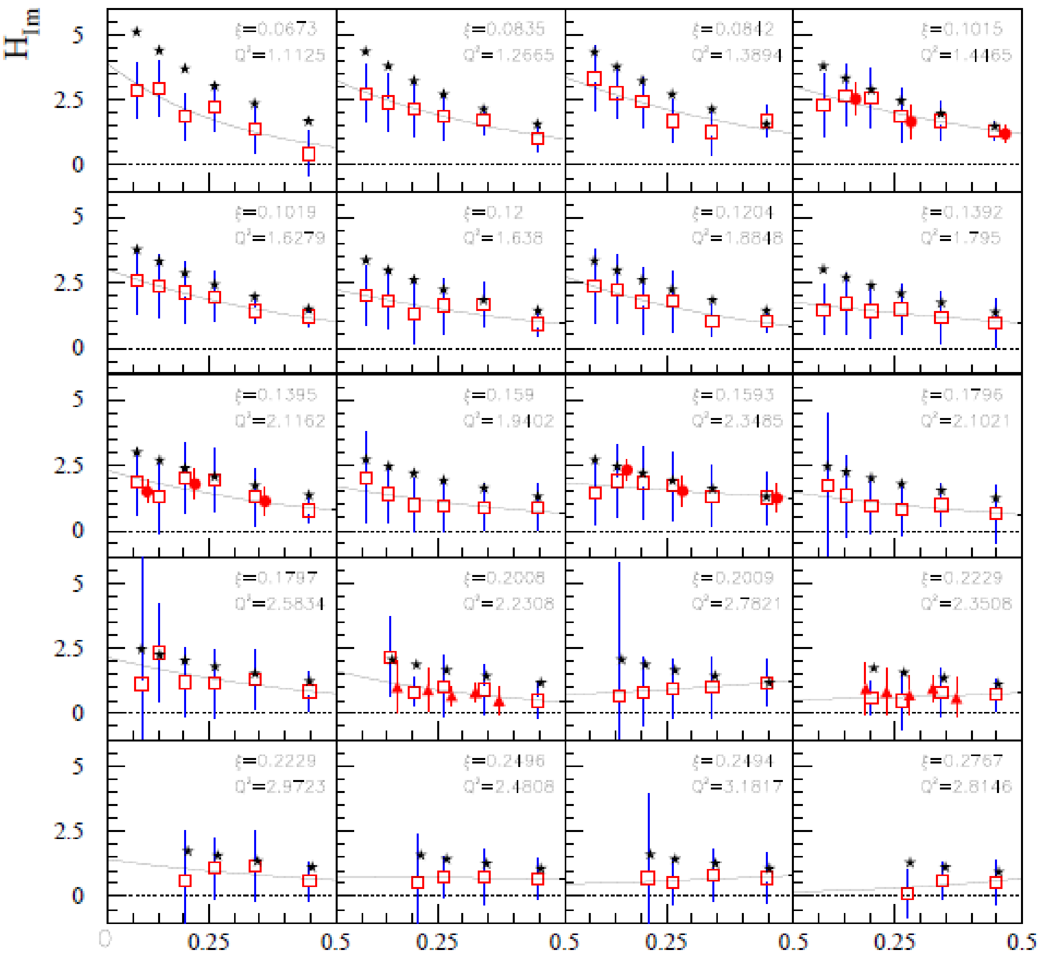
$$\int \widetilde{H}(x,\xi,t)dx = G_A(t)$$





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

From CFFs to proton charge radius



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

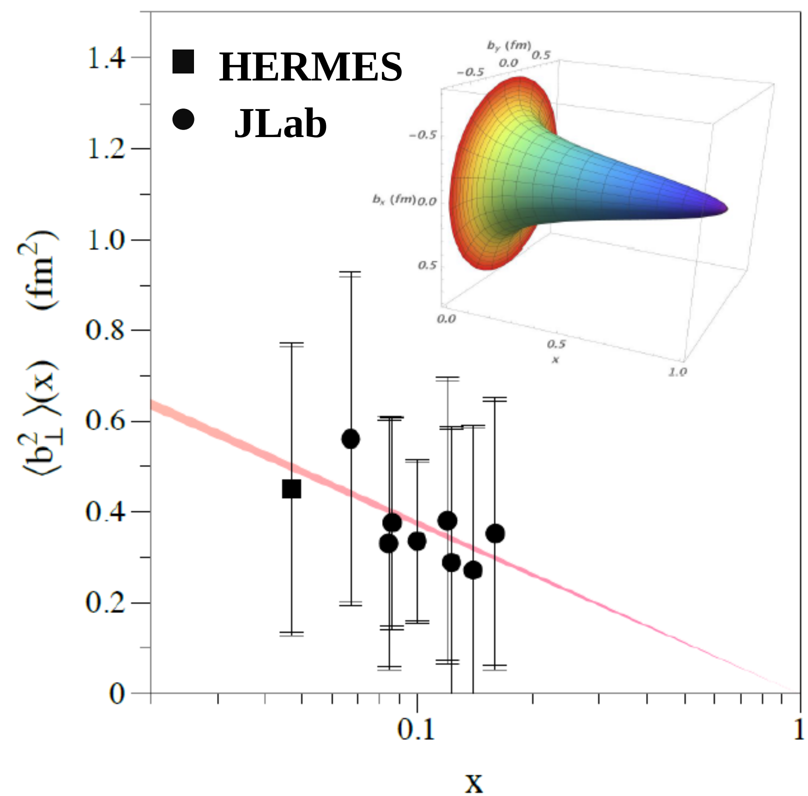
$$\mathcal{H}_{Im}(\xi,t) = A(\xi)e^{B(\xi)t}$$

$$A(\xi) = a_A(1-\xi)/\xi \qquad a_A = 0.36 \pm 0.06$$

$$B(\xi) = a_B \ln(1/\xi) \qquad a_B = 1.07 \pm 0.26 \text{ GeV}^{-2}$$

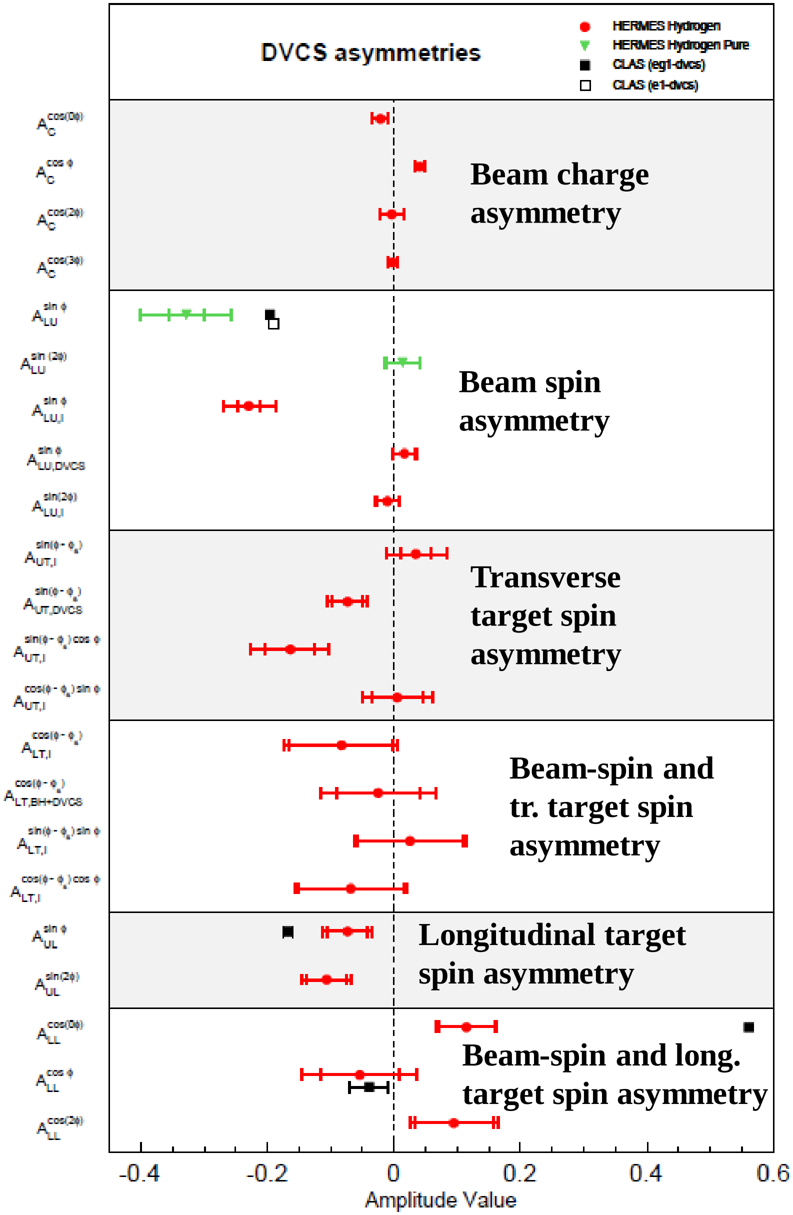
$$\langle b_\perp^2 \rangle^q(x) = -4\frac{\partial}{\partial \boldsymbol{\Delta}_\perp^2} \ln H_-^q(x,0,-\boldsymbol{\Delta}_\perp{}^2)\Big|_{\boldsymbol{\Delta}_\perp=0}$$

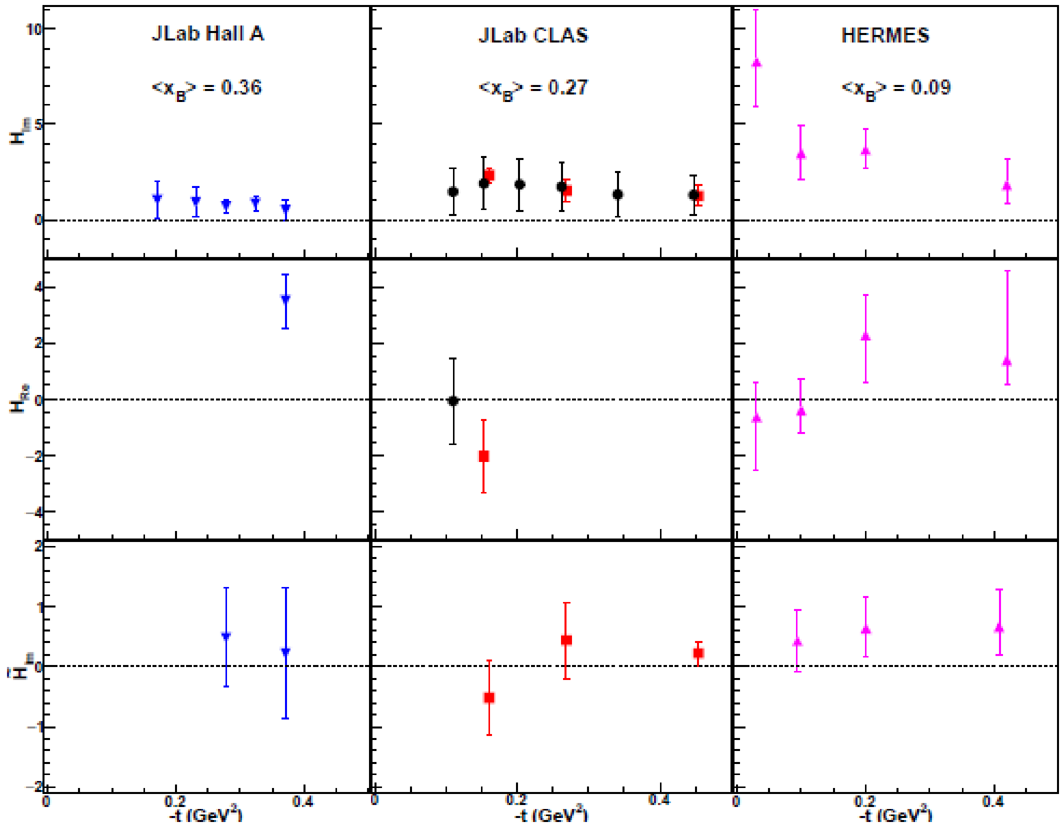
Model-dependent « **deskewing** » factor: $\dfrac{H(\xi,0,t)}{H(\xi,\xi,t)}$



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

Summary of proton-DVCS spin observables and GPDs extraction





Hall A (2015)

CLAS C.S.

CLAS C.S. +TSA+DSA

HERMES

Beam Charge Asymmetry: strong constraint for H_{Re}

N. d'Hose, S.N., A. Rostomyan, EPJA 52, 151 (2016)

Distribution of forces in the proton

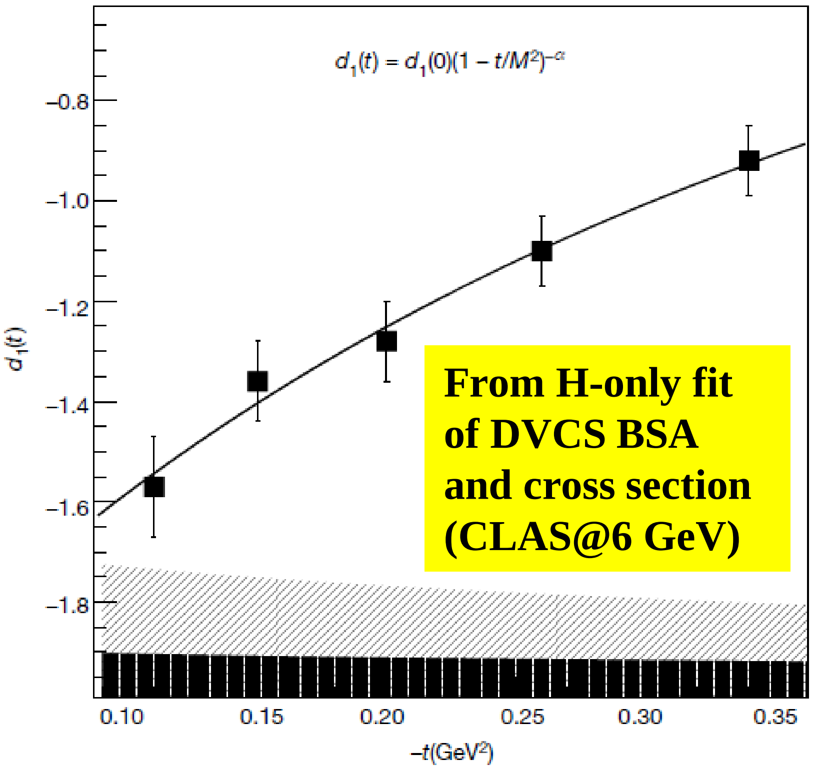
$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

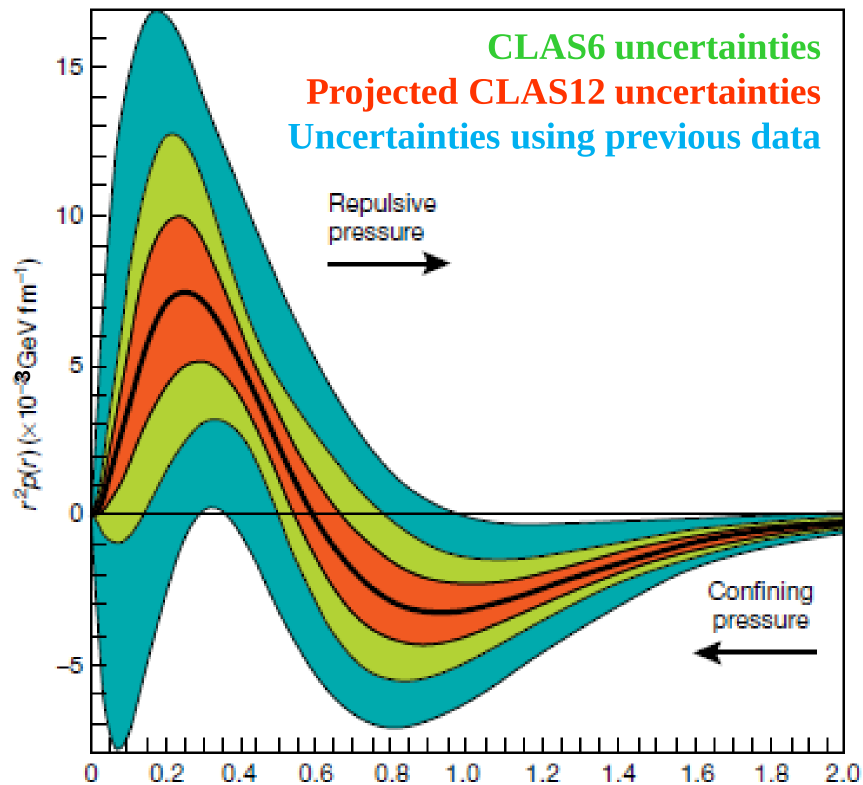
Gravitational form factor → shear forces and pressure

$$\mathrm{Re}\mathcal{H}(\xi,t) + i\mathrm{Im}\mathcal{H}(\xi,t) = \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right) H(x,\xi,t) \quad (1)$$

$$\mathrm{Re}\mathcal{H}(\xi,t) \stackrel{\mathrm{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(x,t)$$

$$D(t) = \frac{1}{2}\int_{-1}^{1} \frac{D(z,t)}{1-z}\mathrm{d}z \qquad D(z,t) = (1-z^2)[d_1(t)C_1^{3/2}(z) + \cdots] \qquad d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r)\mathrm{d}^3 r$$

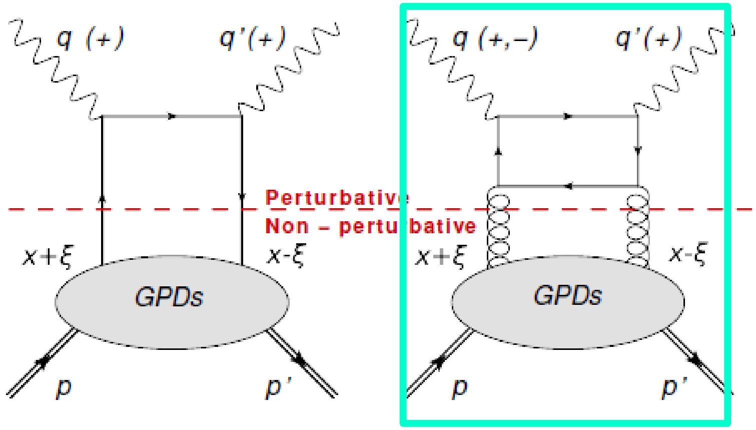


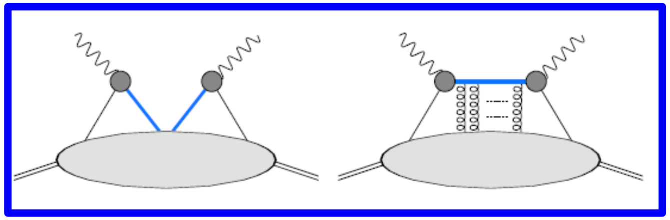


V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

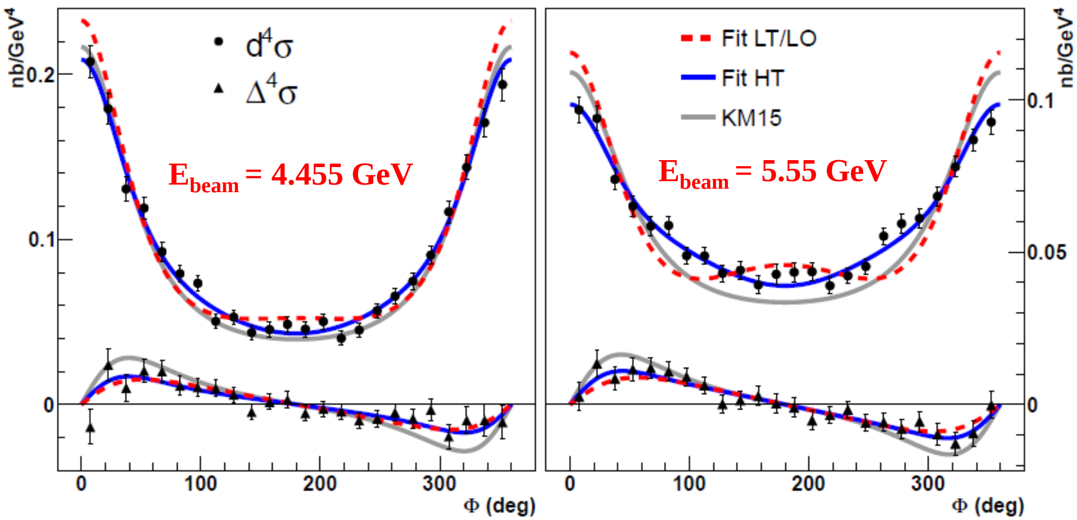
High-precision DVCS: JLab Hall A at 6 GeV

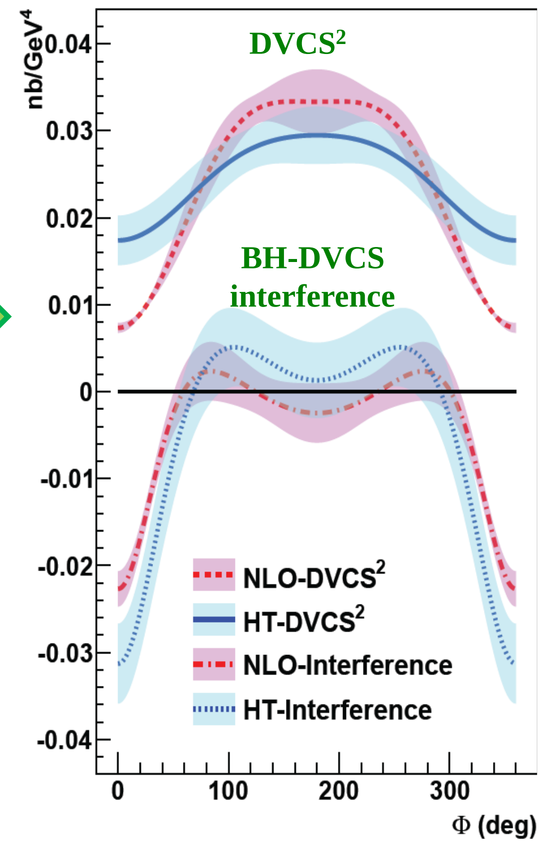
$\vec{e}p \rightarrow e\gamma(p)$





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





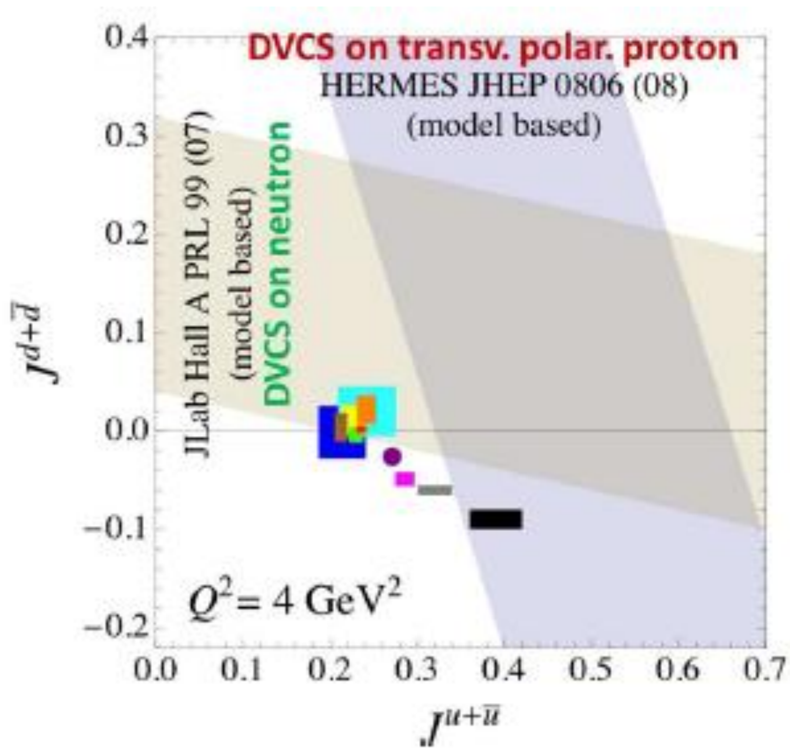
Different beam energies used to separate **BH-DVCS interference ($\sim E_b^3$)** and **DVCS² ($\sim E_b^2$)** contributions

M. Defurne *et al.*, Nature Communications 8, 1408 (2017)

$\vec{e}d \to e\gamma(np)$

DVCS on the neutron in Hall A

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



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

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

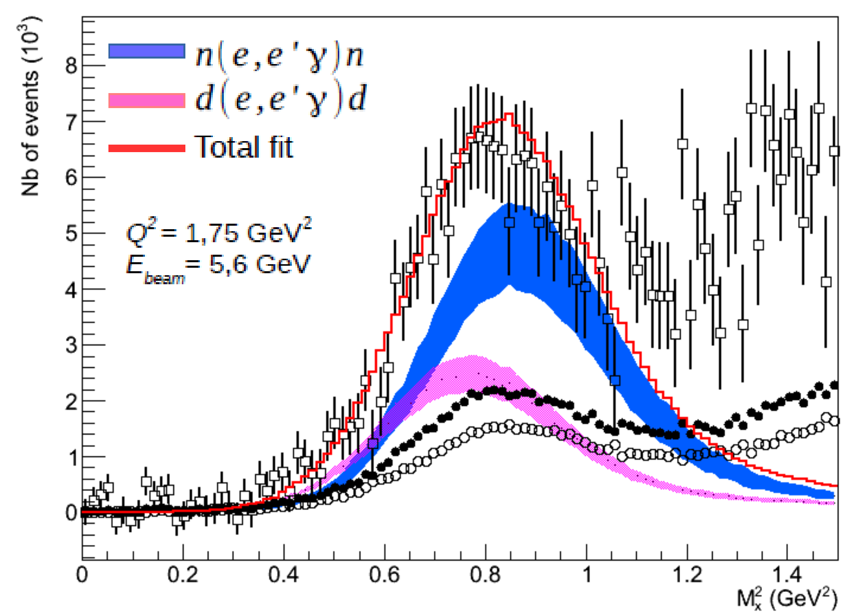
M. Mazouz et al., PRL 99 (2007) 242501

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

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

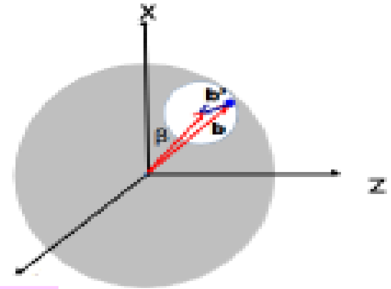
$$\mathcal{H}_n(\xi,t) = \frac{1}{9}\mathcal{H}_u(\xi,t) + \frac{4}{9}\mathcal{H}_d(\xi,t)$$

Hall A 2010 data - PRELIMINARY



DVCS on nuclei: the CLAS eg6 experiment

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

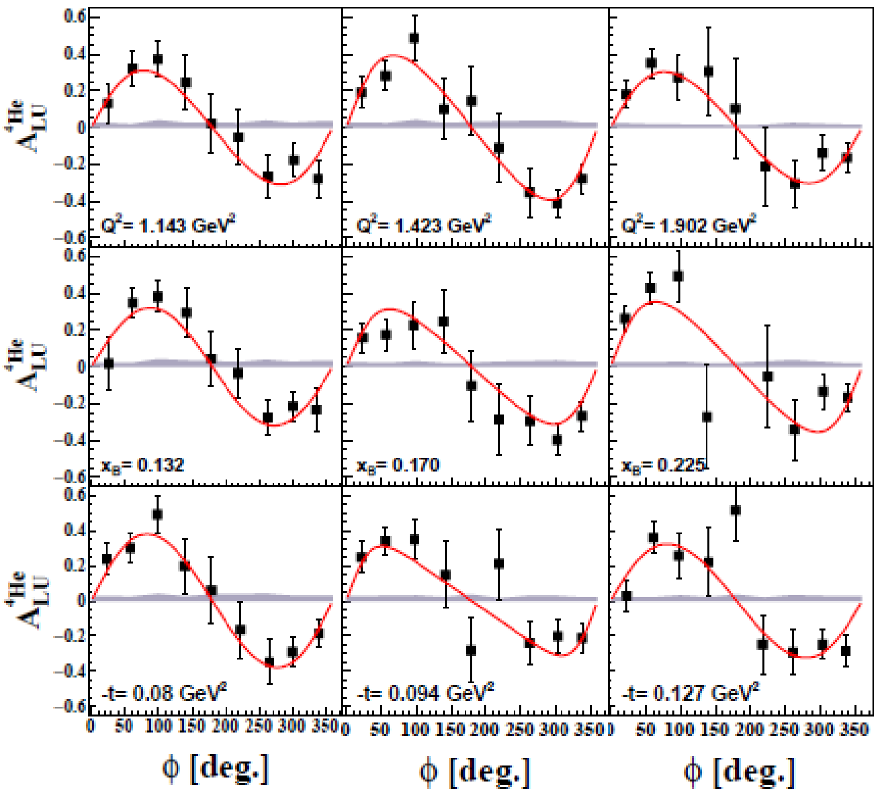


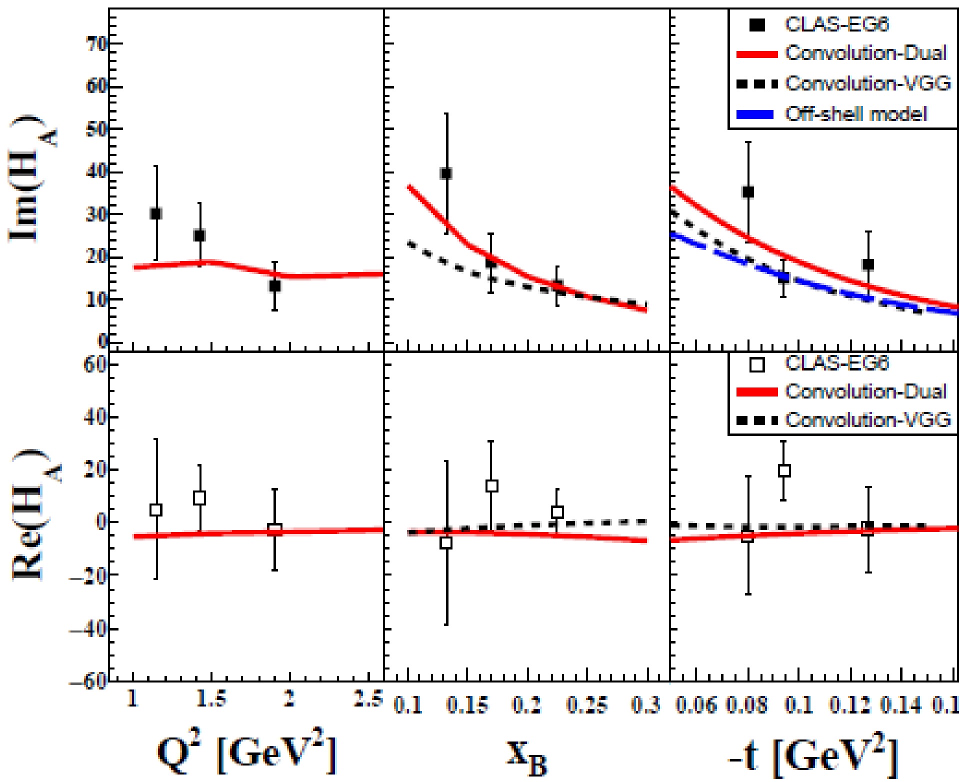
^{4}He is a spin-0 nucleus: at twist-2 **only one CFF** in DVCS BSA

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

$\vec{e}\,^4He \to e\,^4He\,\gamma$

M. Hattawy et al. PRL 119, 202004 (2017)



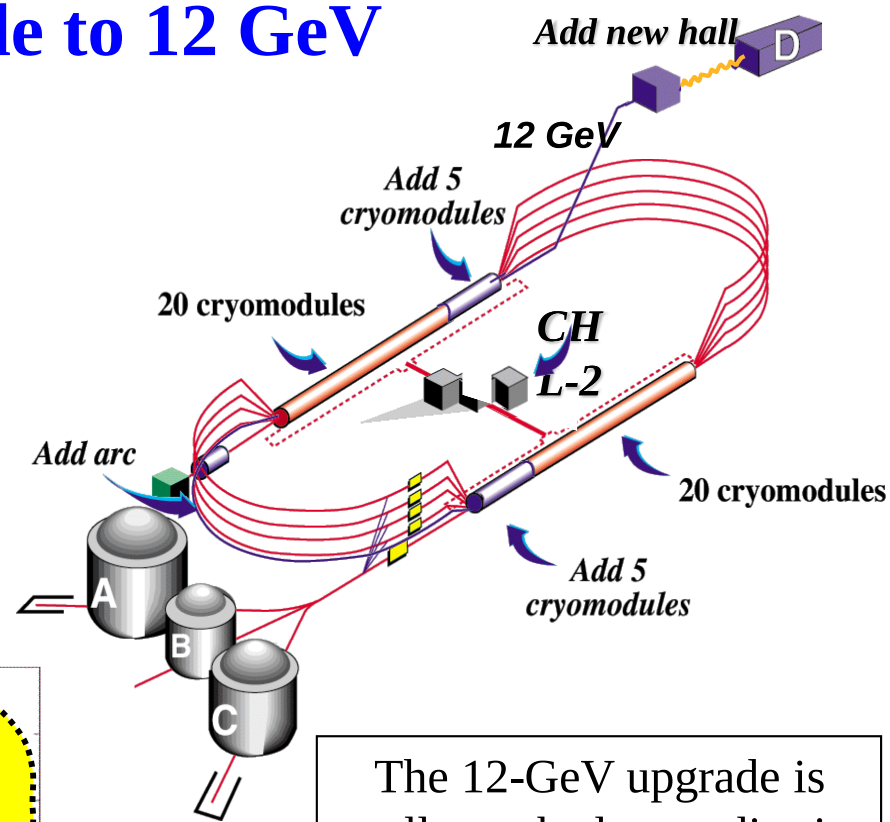


JLab upgrade to 12 GeV

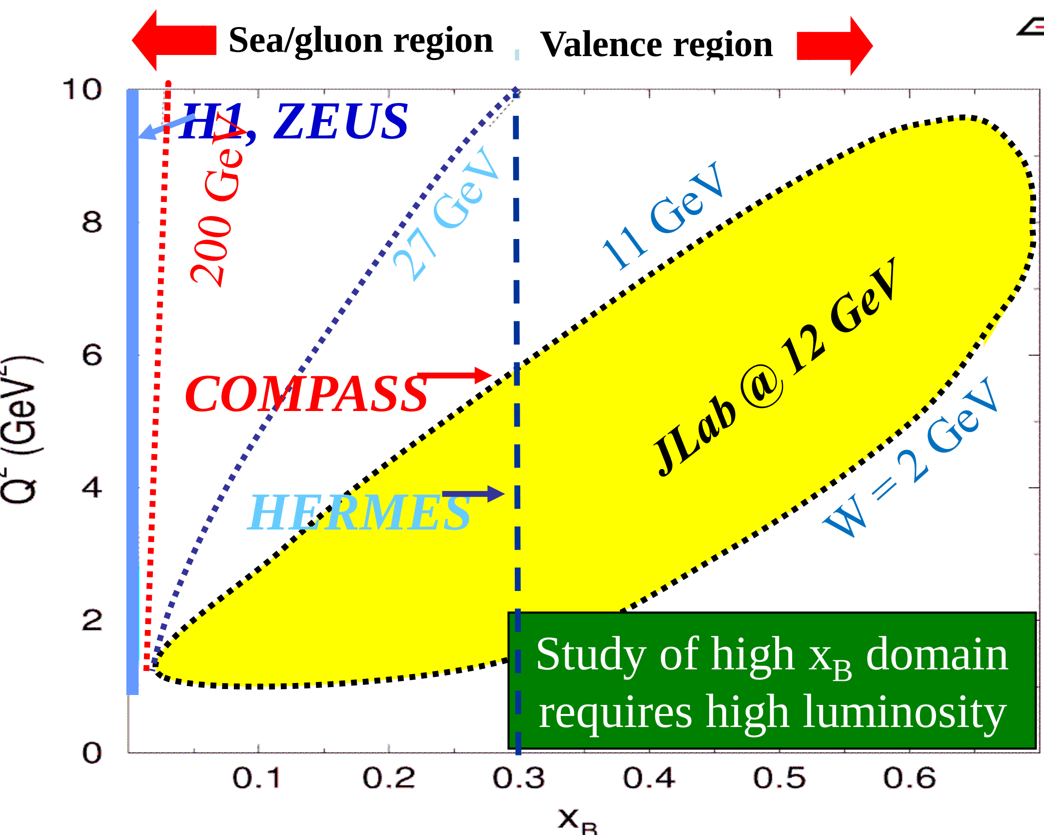
E= 2.2, 4.4, 6.6, 8.8, 11 GeV
for the Halls A, B, C

Beam polarization > 80%

Upgrade completed in 2014



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



GPDs experiments at 11 GeV have been approved for the **halls A, B, and C**

Complementary programs:

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

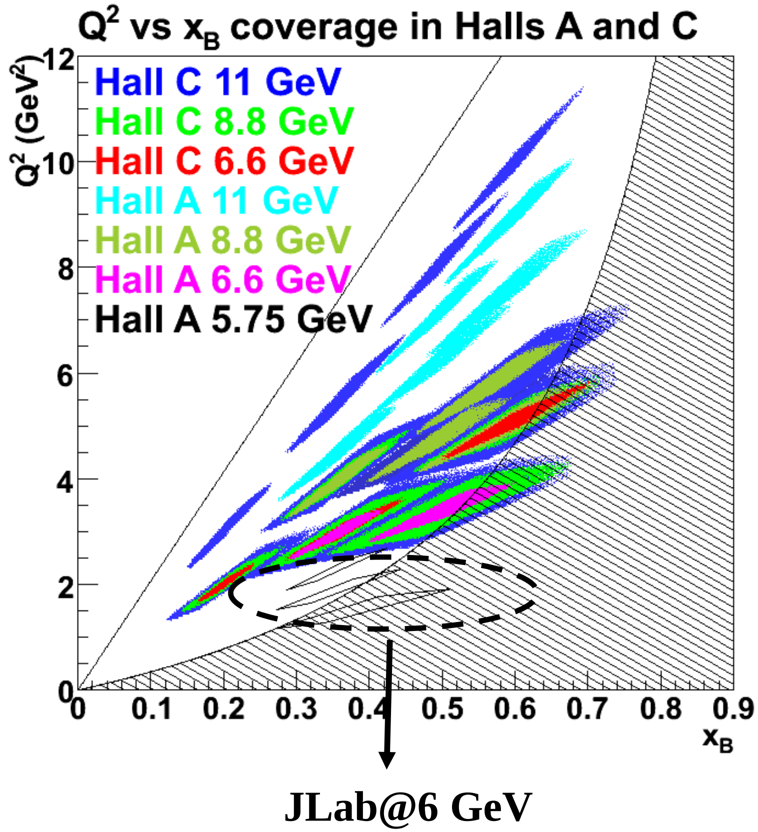
pDVCS at 11 GeV in the Halls A and C

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

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 dσ at fixed x_B
- Increased kinematical coverage

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



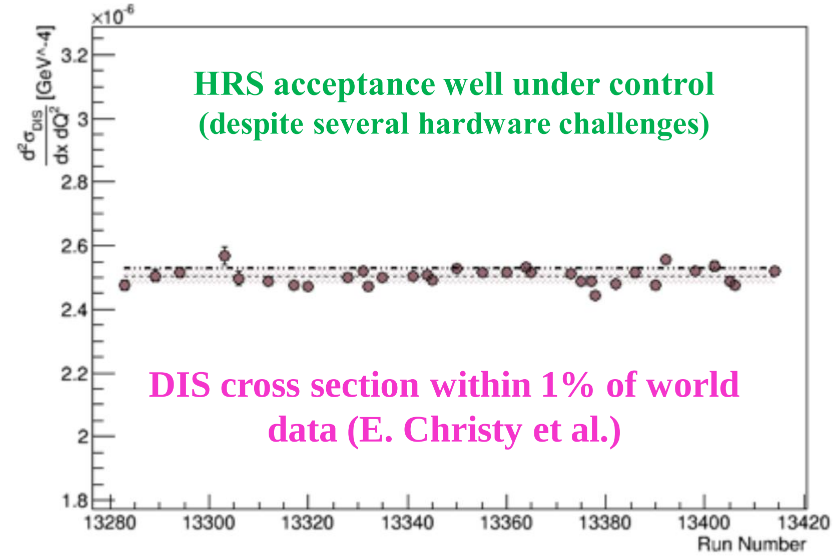
Hall C:
- Energy separation of the DVCS cross section
- Higher Q^2: measurement of higher twist contributions
- Low-x_B extension (thanks to sweeping magnet)

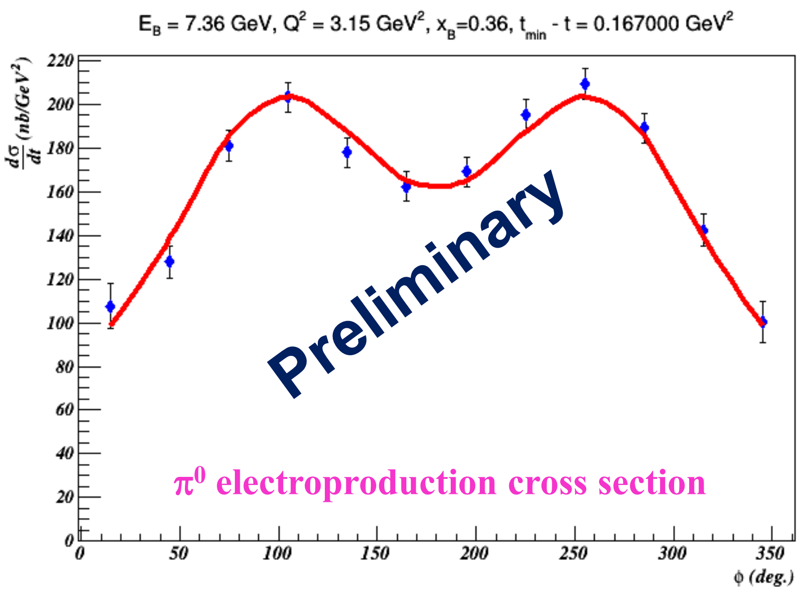
E12-06-114 DVCS/Hall A Experiment at 11 GeV

100 PAC days approved:

- **High impact experiment for nucleon 3D imaging program**
- High precision scaling tests of the DVCS cross section at constant x_B
- CEBAF12 will allow to explore for the first time the high x_B region

50% of the experiment completed in 2014-2016





Data under final stages of analysis
Publication drafts expected by the end of the year

Analysis path:

- **Jun'18:** Preliminary results on π^0 at x_B=0.36
- **Oct'18:** Preliminary results on DVCS
- **Nov'18:** Publication on π^0 electroproduction
- **Jan'19:** Short publication on DVCS
- **Jul'19:** Long archival paper (DVCS & pi0)

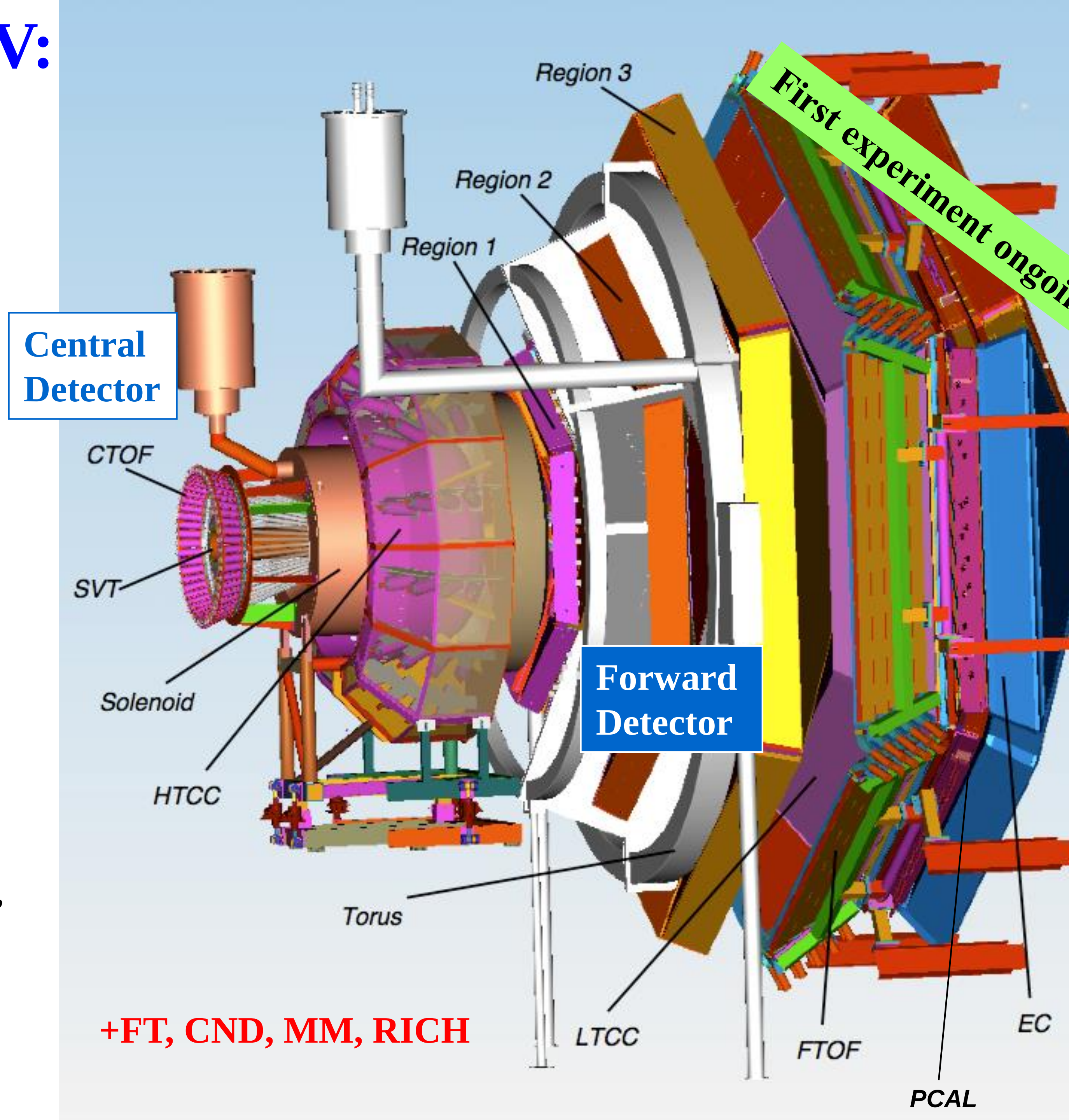
Hall B@12 GeV: CLAS12

Design luminosity
L ~ 10^{35} cm^{-2}s^{-1}

Acceptance for charged particles:
- **Central (CD), 40°<θ<135°**
- **Forward (FD), 5°<θ<40°**

Acceptance for photons:
- **Forward tagger T 2°<θ<5°**
- **EC, 5°<θ<40°**

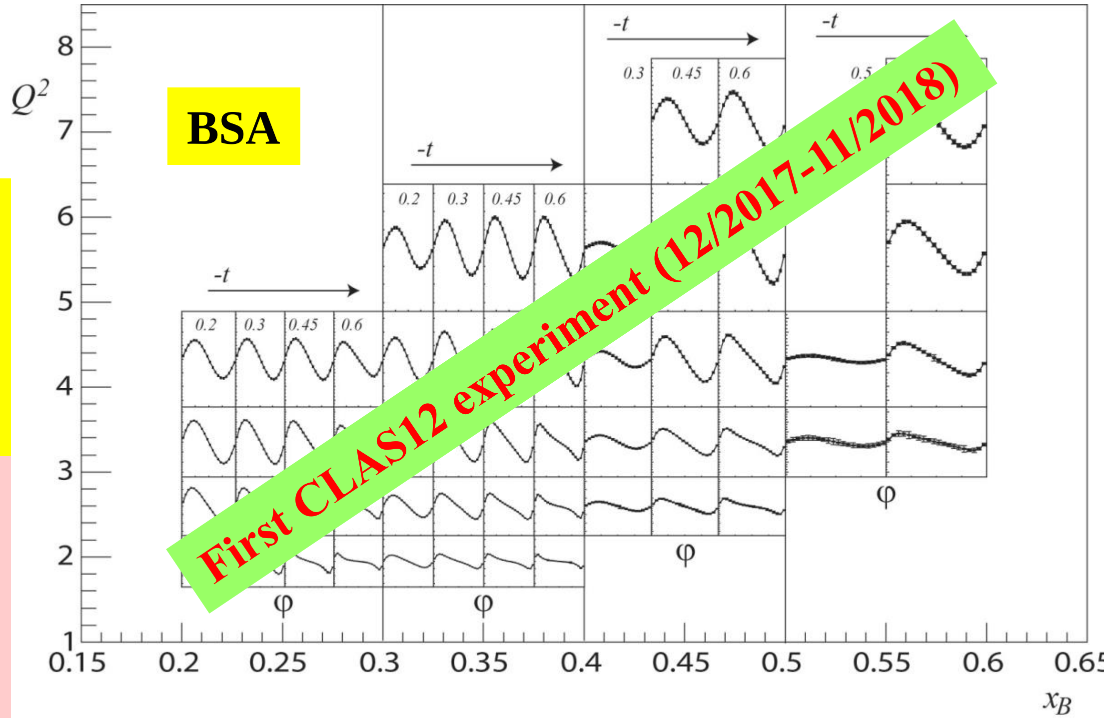
High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes

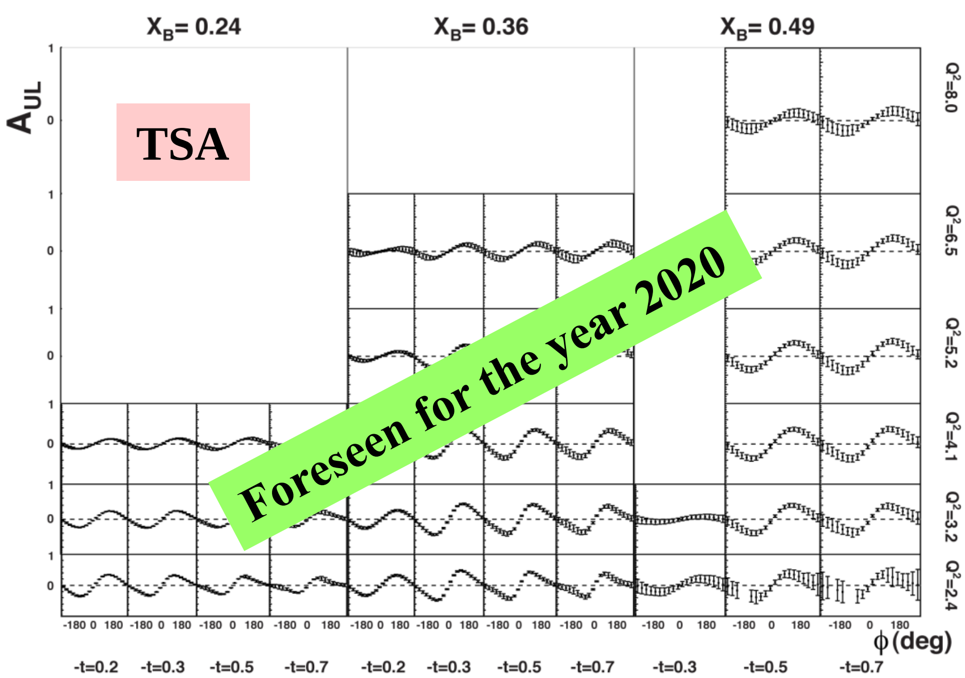


DVCS BSA and TSA with CLAS12 & 11 GeV beam

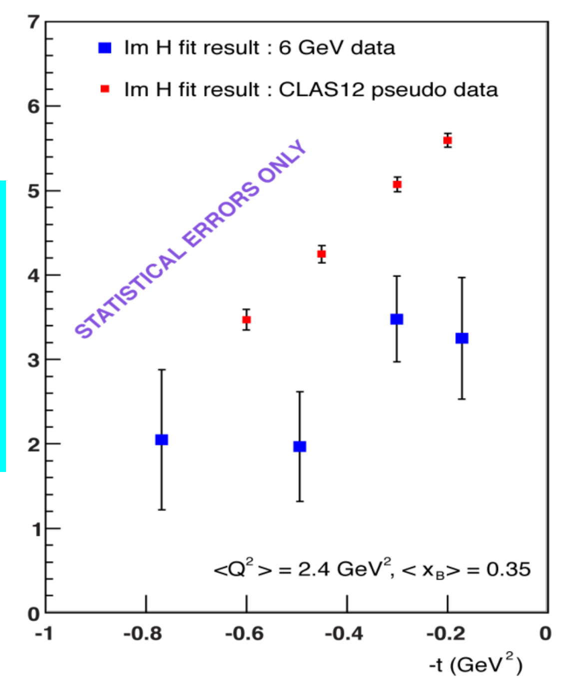
85 days of beam time
P_{beam} = 85%
L = 10^{35} $cm^{-2}s^{-1}$
Statistical error: 1% to 10% on sinϕ moments
Systematic uncertainties: ~6-8%

120 days of beam time
P_{beam} = 85%, P_{target} = 80%
L = 2.10^{35} $cm^{-2}s^{-1}$
Statistical error: 2% to 15% on sinϕ moments
Systematic uncertainties: ~6-8%





Impact of CLAS12 DVCS-BSA data on CFF fit

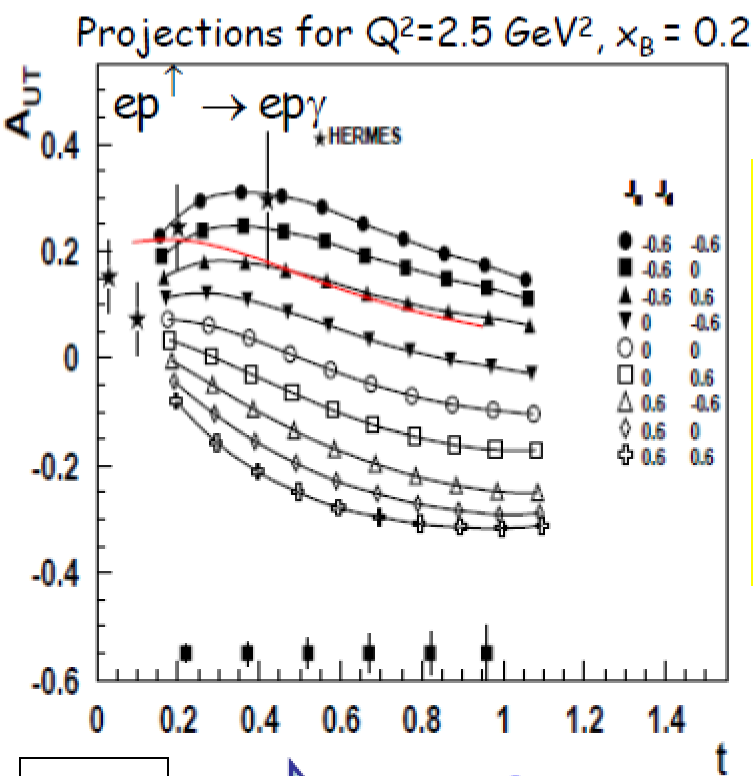


CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time

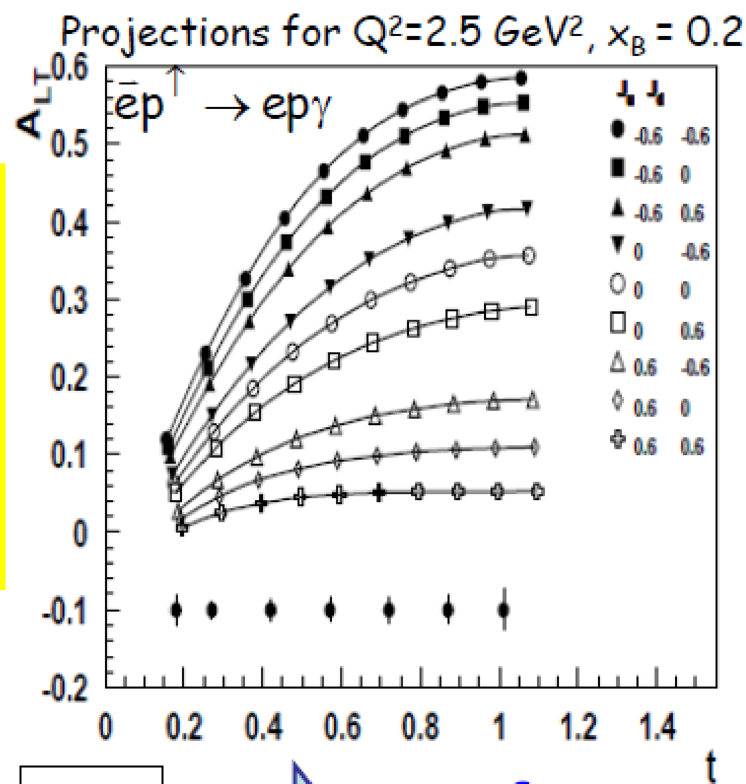
Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = 5×10^{33} $cm^{-2}s^{-1}$

$1 < Q^2 < 10$ 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
Tests on HDIce target are ongoing

DVCS *on the neutron* with CLAS12

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

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

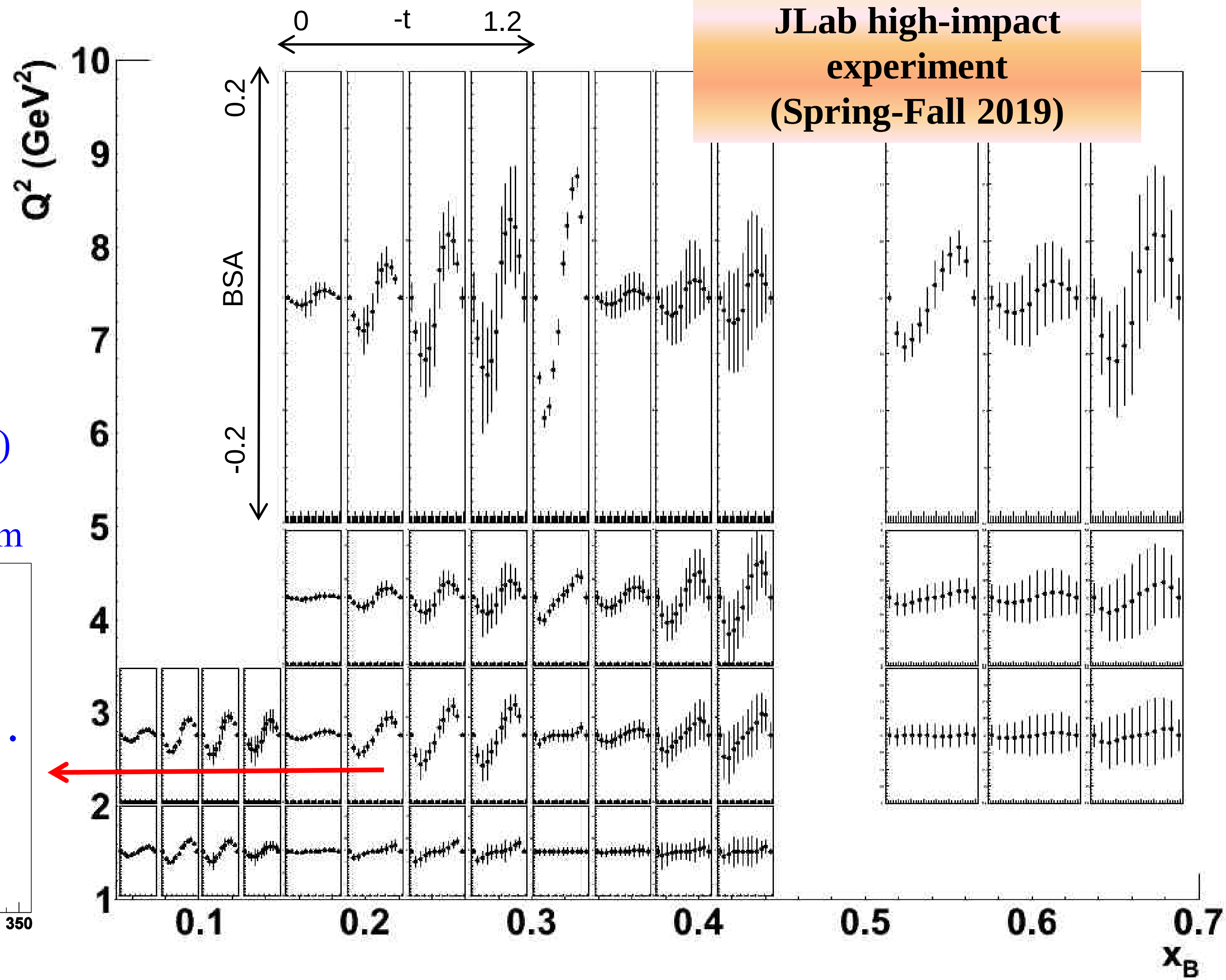
$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$

The most sensitive observable to the GPD E

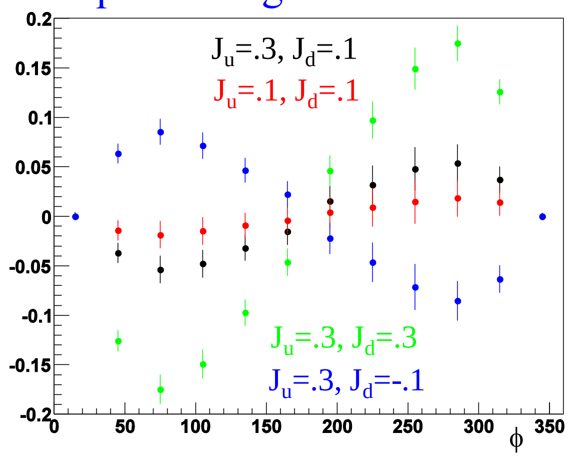
ed→ e(p)nγ

Experiments also planned with longitudinally polarized ND_3 target (2020)

JLab high-impact experiment (Spring-Fall 2019)



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



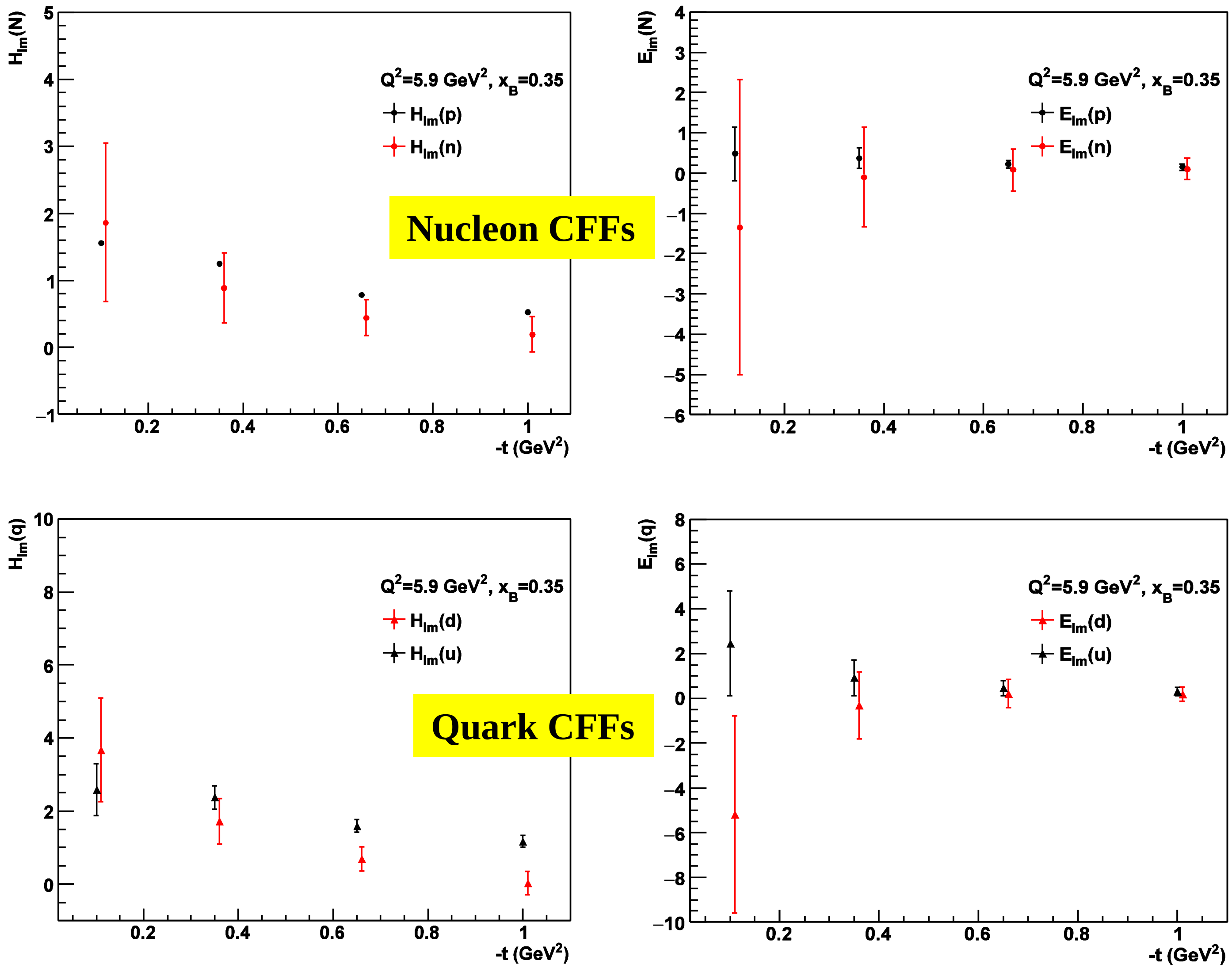
CLAS12: projections for flavor separation ($Im\mathcal{H}$, $Im\mathcal{E}$)

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

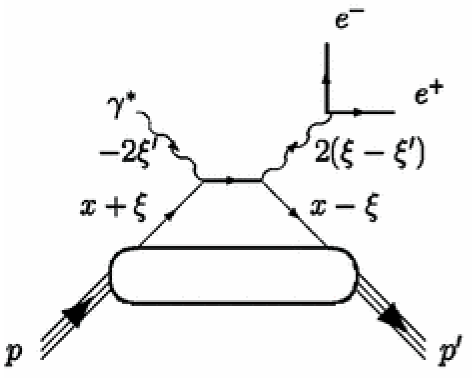
$$(H,E)_d(\xi,\xi,t) = \frac{9}{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

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

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

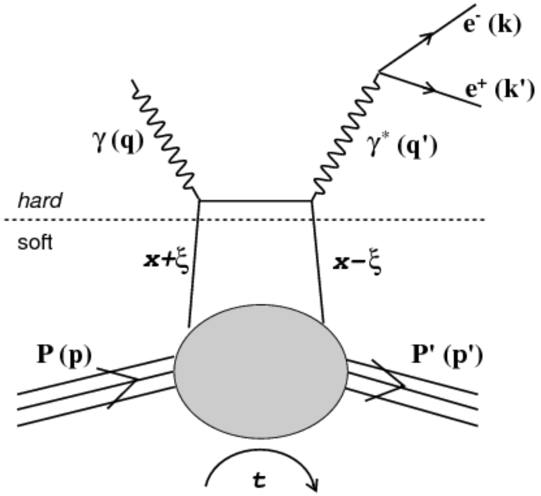


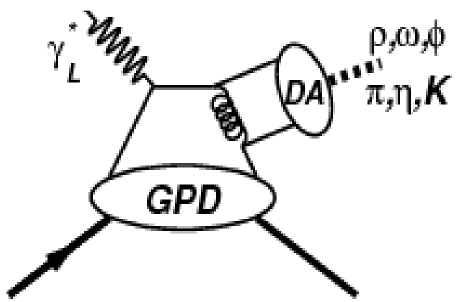
GPDs: beyond DVCS



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

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





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

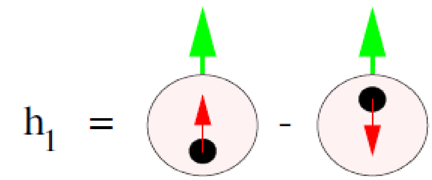
Chiral-odd GPDs

- 4 chiral-odd GPDs (parton helicity flip)
- Difficult to access (helicity flip processes are **suppressed**)
- Chiral-odd GPDs are very **little constrained**
- Anomalous tensor magnetic moment:

$$\kappa_T = \int_{-1}^{+1} \mathrm{d}x\, \bar{E}_T(x, \xi, t=0) \qquad \bar{E}_T = 2\widetilde{H}_T + E_T$$

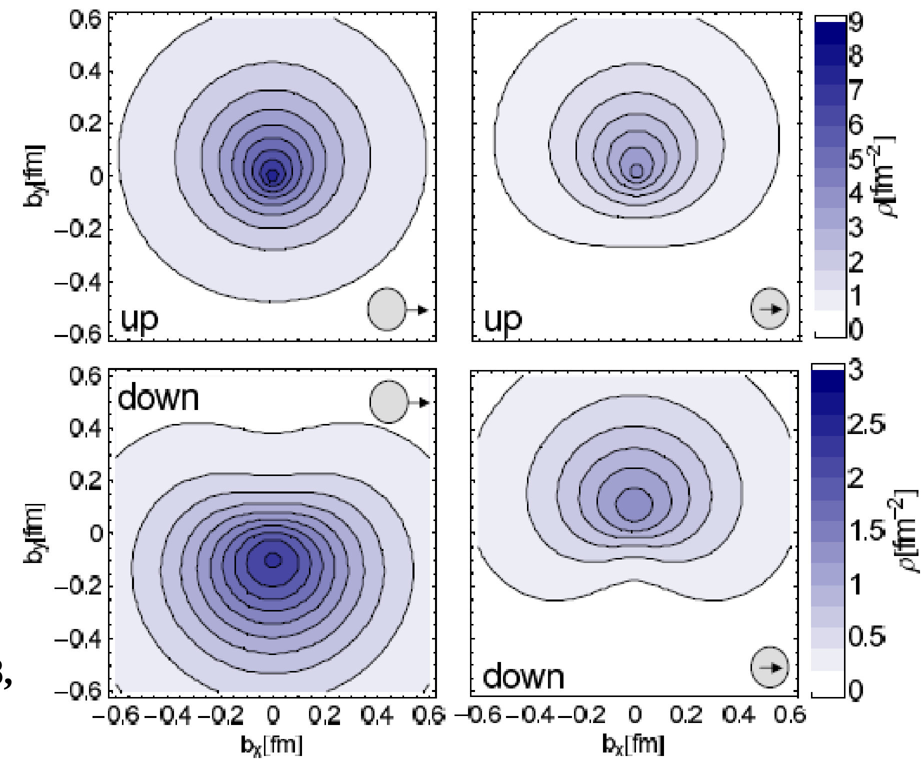
- Link to the **transversity** distribution: $H_T^q(x,0,0) = h_1^q(x)$

$\boldsymbol{H_T, \widetilde{H}_T, E_T, \widetilde{E}_T}$



Transverse Densities for u and d quarks in the nucleon

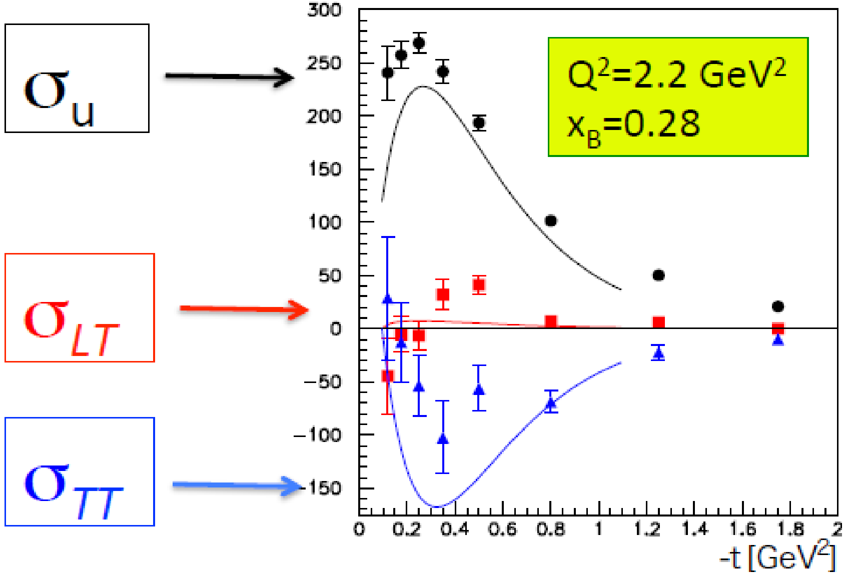
Distributions of unpolarized quarks in a transversely polarized nucleon, **linked to *E***

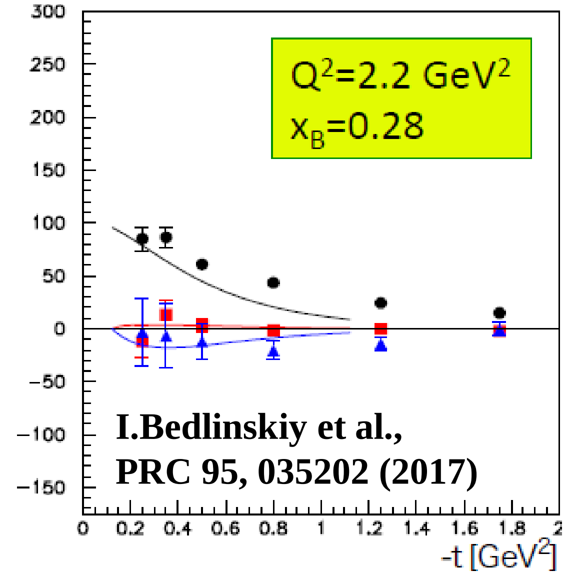


Distribution of transversely polarized quarks in an unpolarized nucleon, **linked to $\bar{E}_T$**

Gockeler et al, Phys. Rev. Lett. 98, 222001 (2007), lattice calculation

Ratio π^0/η (CLAS@6 GeV)





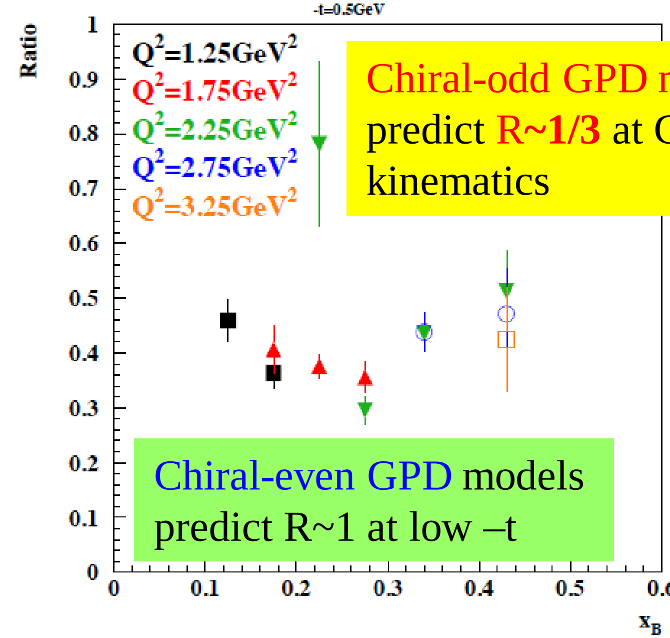
$$\frac{d\sigma}{dQ^2 dx_B\, d\phi dt} = \Gamma(Q^2, x_B)\,\frac{1}{2\pi}\left(\sigma_T + \varepsilon\sigma_L + \varepsilon cos2\phi\sigma_{TT} + \sqrt{2\varepsilon(1+\varepsilon)}cos\phi\sigma_{LT}\right)$$

Transversity GPD models:

- Goloskokov-Kroll
- Liuti-Goldstein
- $\sigma_L \ll \sigma_T$

$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|<\overline{E_T}>|^2$$

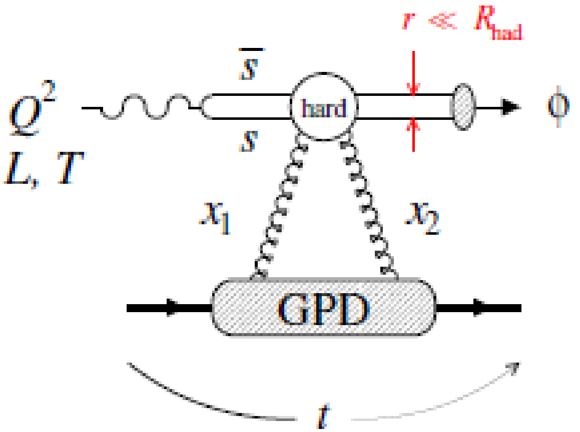
$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|<H_T>|^2 - \frac{t'}{8m^2}|<\overline{E_T}>|^2\right]$$



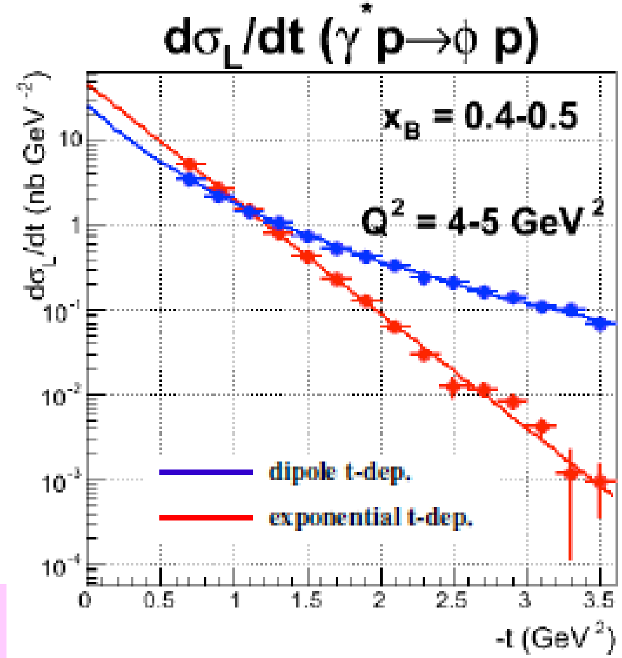
Chiral-odd GPD models predict **R~1/3** at CLAS kinematics

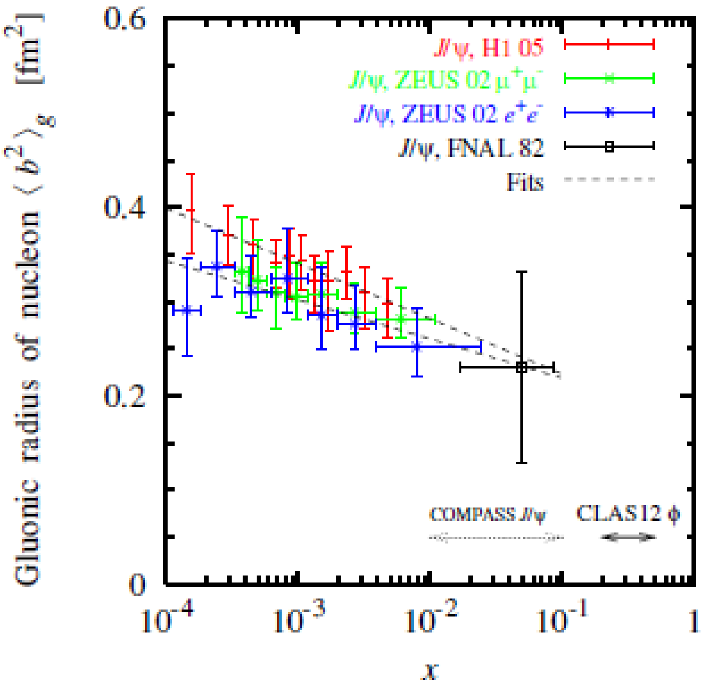
Chiral-even GPD models predict R~1 at low –t

DVMP @ CLAS12: exclusive ϕ electroproduction

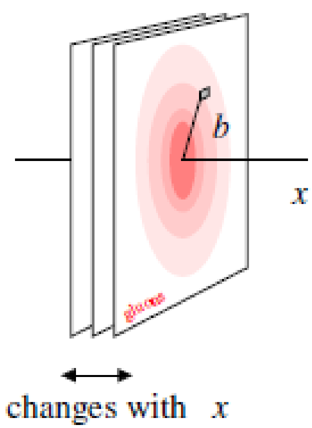


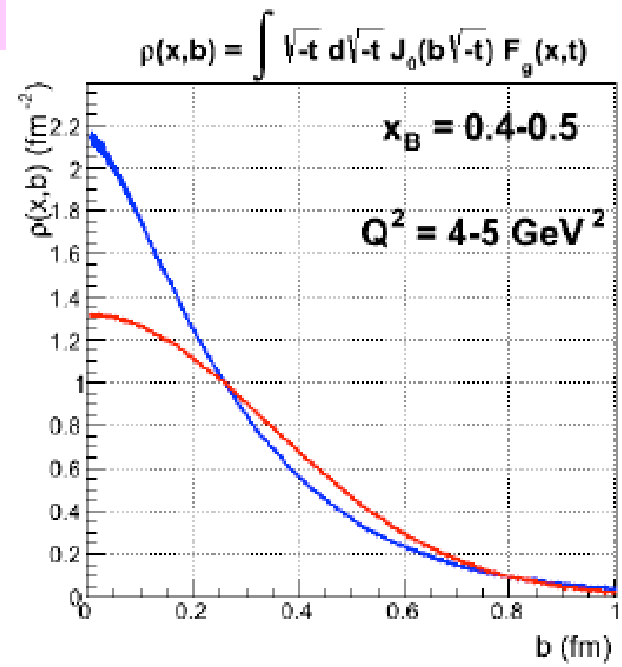
- Differential c.s. → extraction of **structure functions**
- **L-T separation** from **ϕ→KK** decay distributions
- t dependence of **$d\sigma_L/dt$**





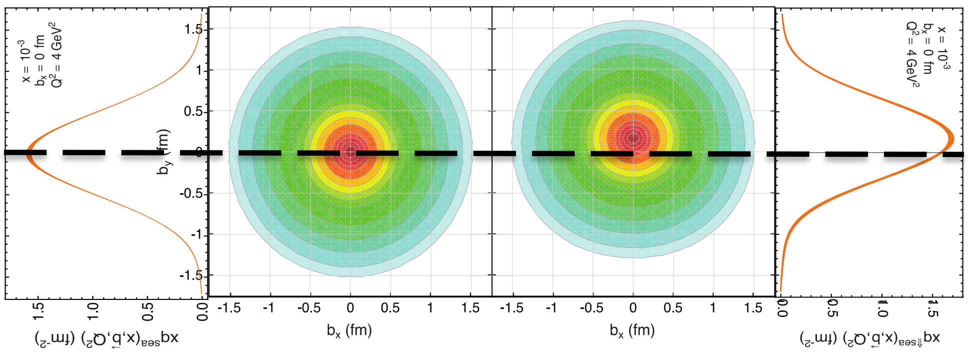
Transverse distribution of gluons in the proton



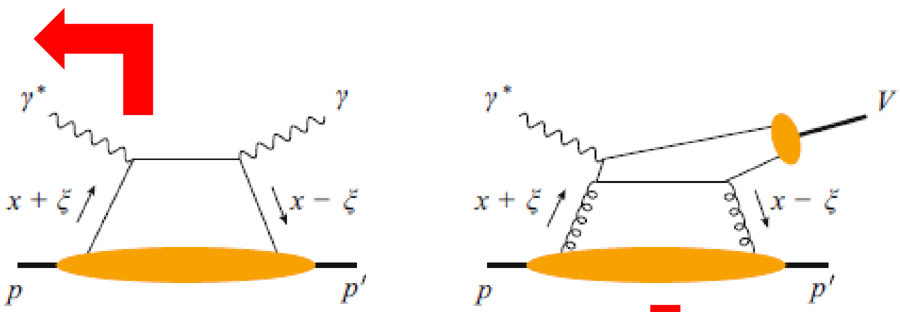


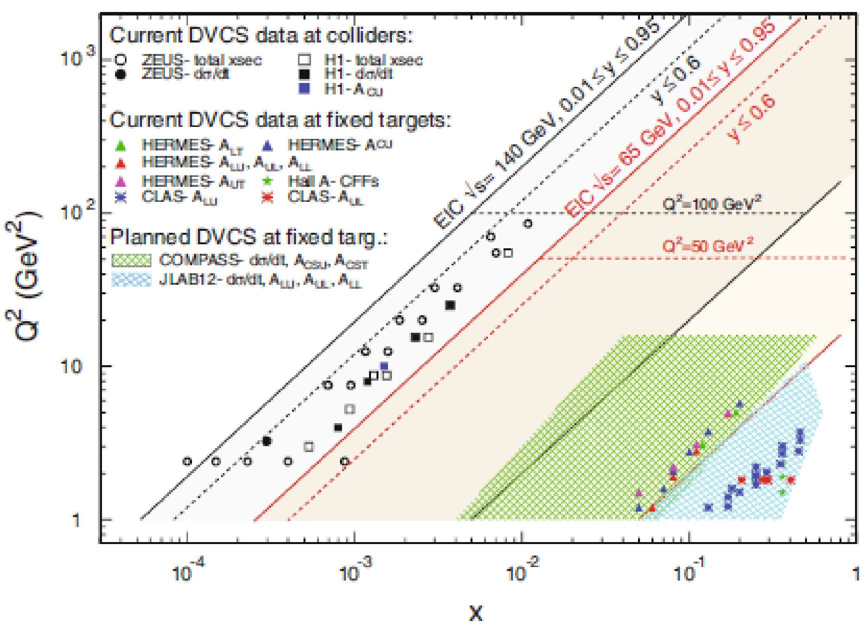
The future: Multi-D imaging of the nucleon with the Electron Ion Collider

Sea quarks
unpolarized polarized

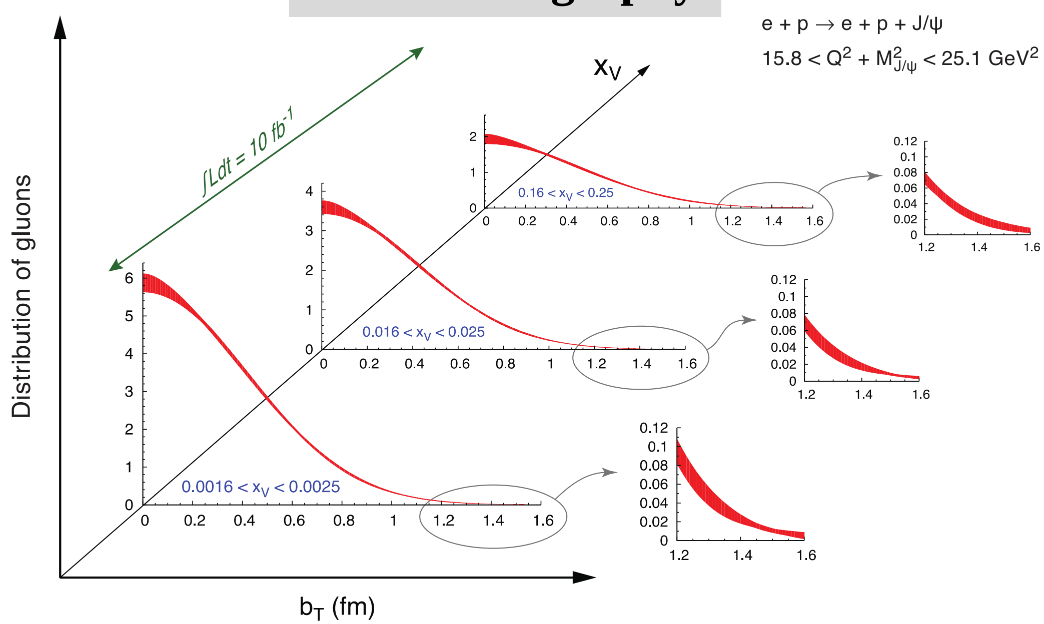


EIC (USA: BNL or JLab) ~ 2025





Gluon tomography



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 **difficult**:

- **4 GPDs for each quark flavor**
- they depend on **3 variables**, only two (ξ, t) experimentally accessible via DVCS

✓ Fitting methods allow to **extract CFFs from DVCS** observables → several **p-DVCS** and **n-DVCS observables** are needed, covering a **wide phase space**

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

✓ First **tomographic interpretations** of the quarks in the **proton** from DVCS:

✓ The 12-GeV-upgraded JLab is **the only facility** to perform GPD experiments **in the valence region**, for Q^2 up to 11 GeV

→ DVCS and DVMP experiments on both **proton** and **neutron** (pol. and unpol.) are planned for **3 of the 4 Halls at JLab@12 GeV: quarks' spatial densities, flavor separation, quarks' orbital angular momentum, gluon densities,…**

→ **Long-term future: EIC, for nucleon structure in terms of gluons…and beyond!**