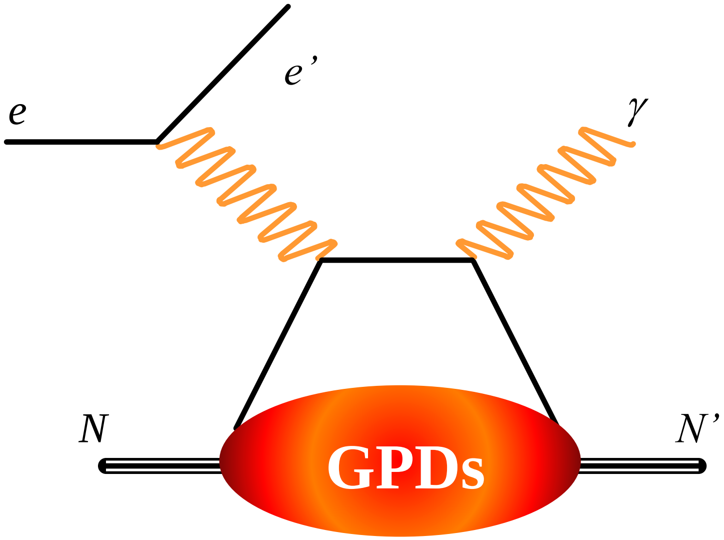
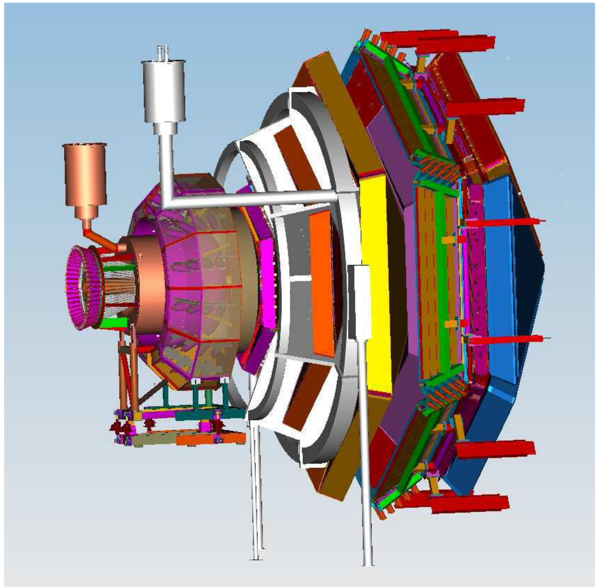
DVCS and DVMP: results from CLAS and the experimental program of CLAS12



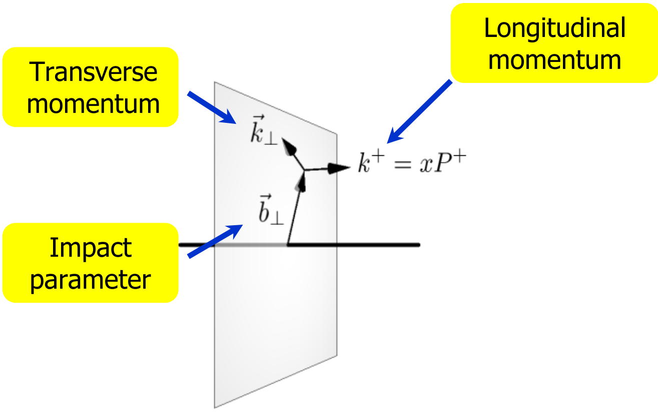


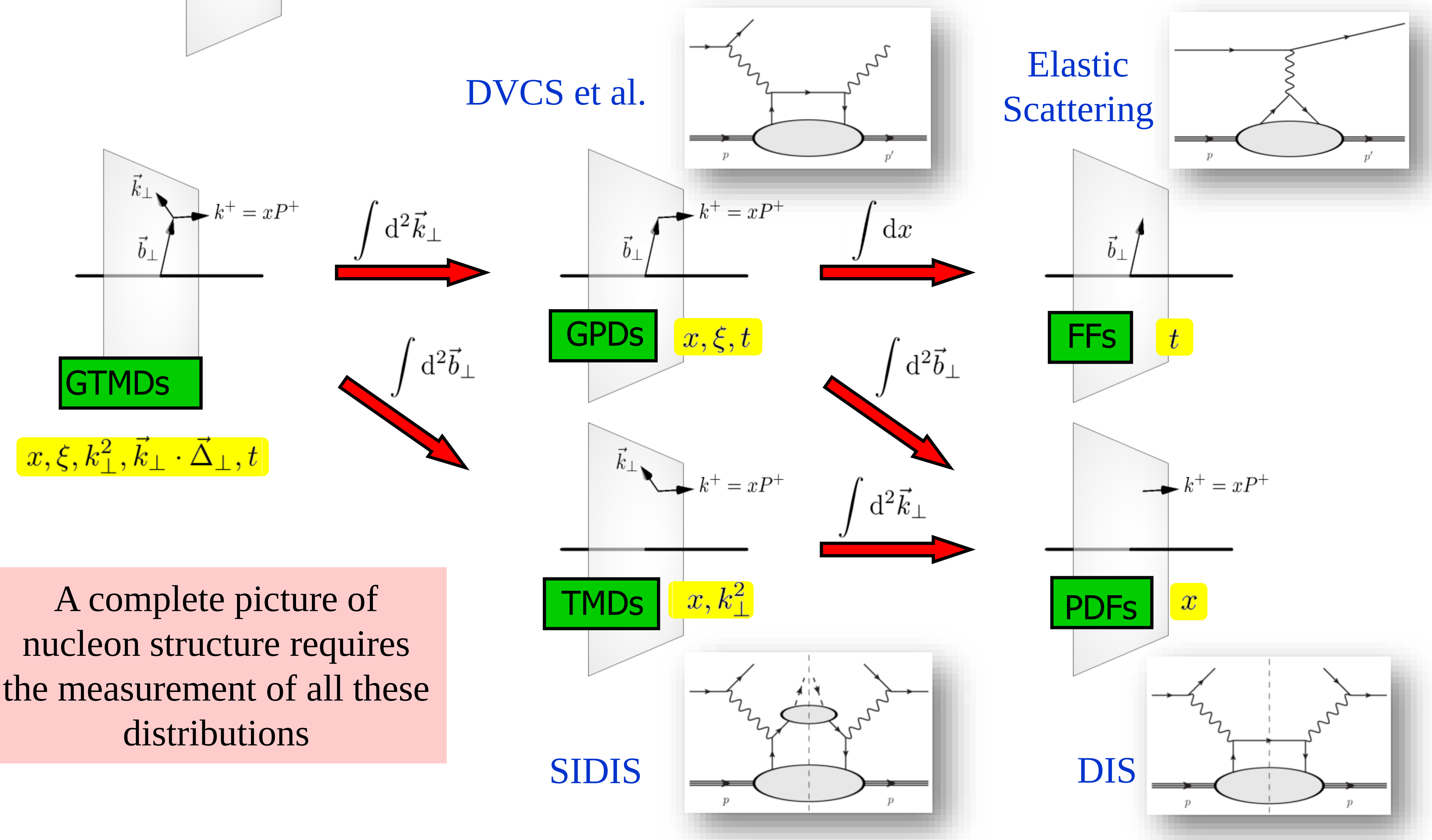
- Accessing GPDs via DVCS and DVMP
- Recent results from Jefferson Lab
- What we have learned
- The JLab 12 GeV upgrade
- Upcoming CLAS12 experiments

Silvia Niccolai, IPN Orsay
& CLAS Collaboration

INT-17 -3
29/8/2017, Seattle, WA (USA)

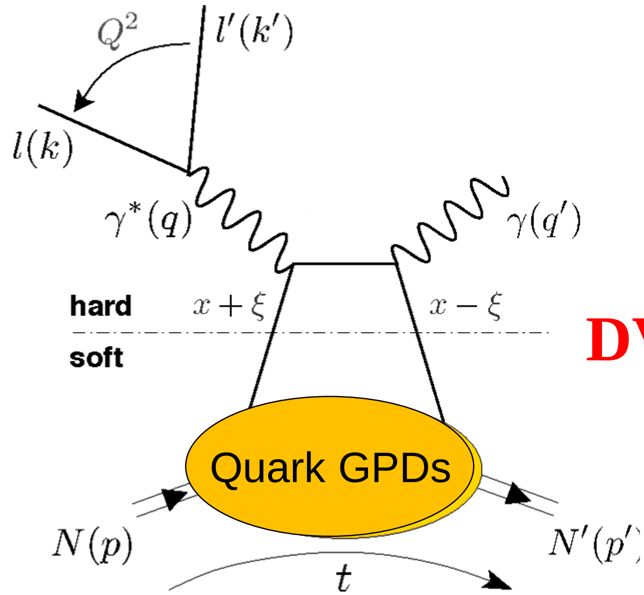
Multi-dimensional **mapping of the nucleon**

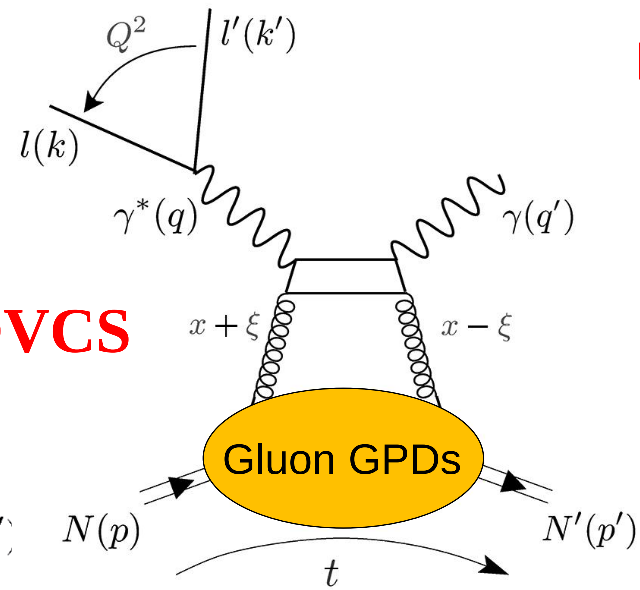




A complete picture of nucleon structure requires the measurement of all these distributions

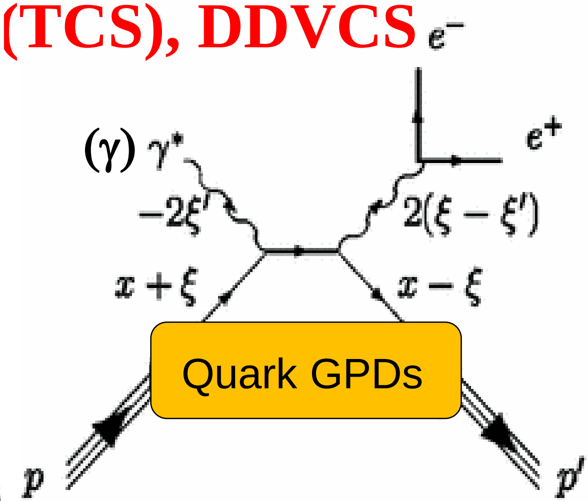
Exclusive reactions giving access to GPDs



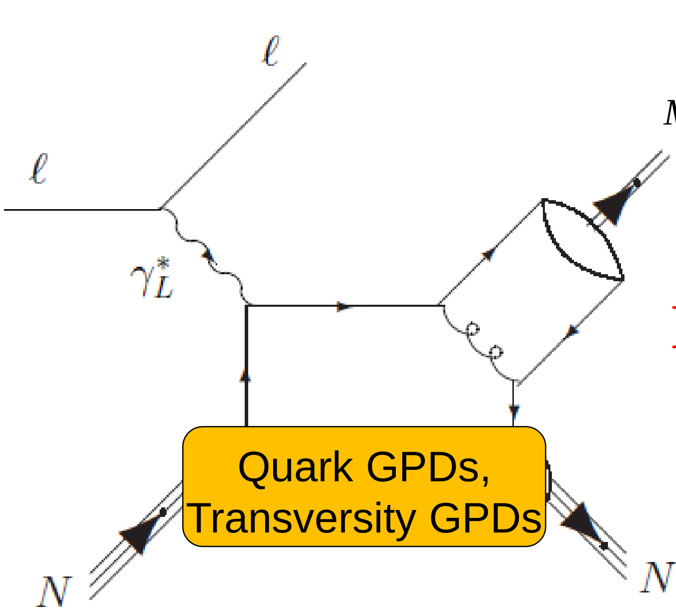


DVCS

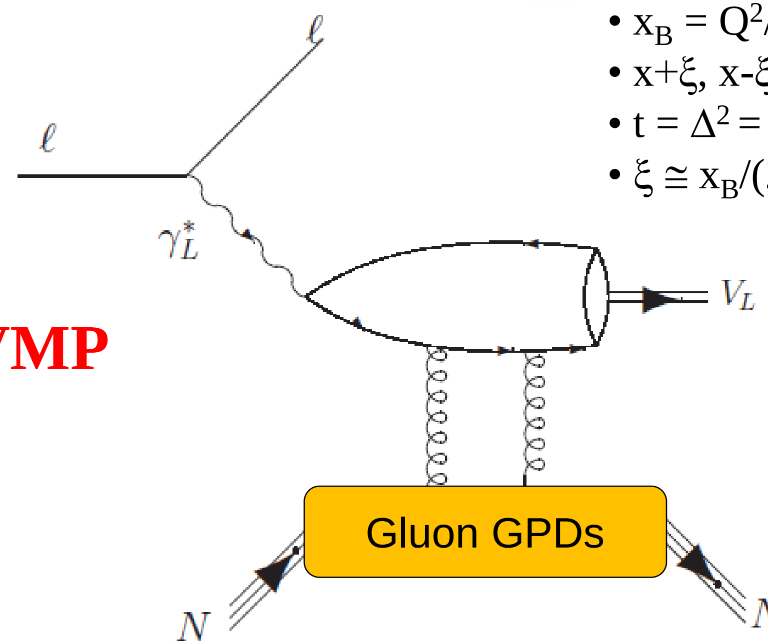
(TCS), DDVCS



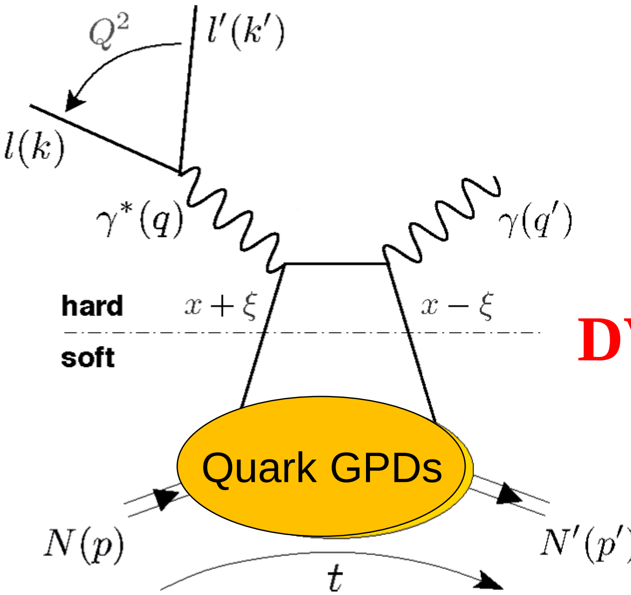
- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$



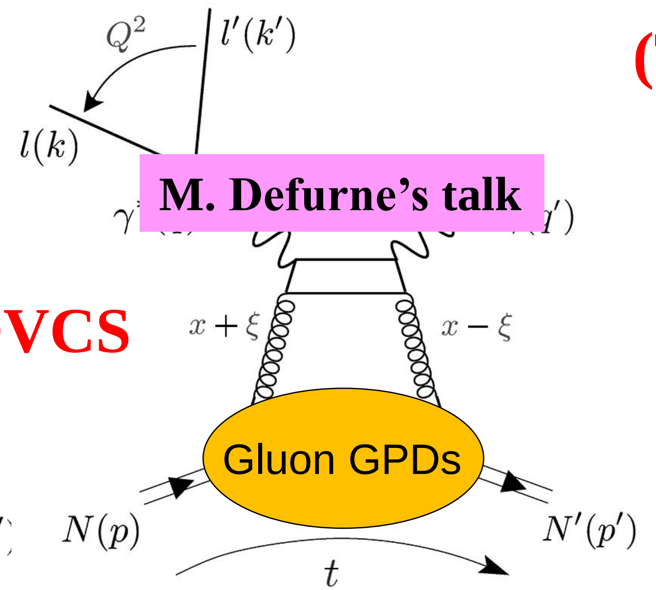
DVMP



Exclusive reactions giving access to GPDs

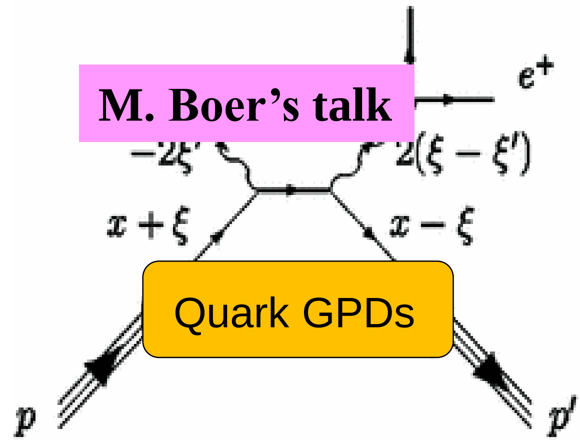


DVCS



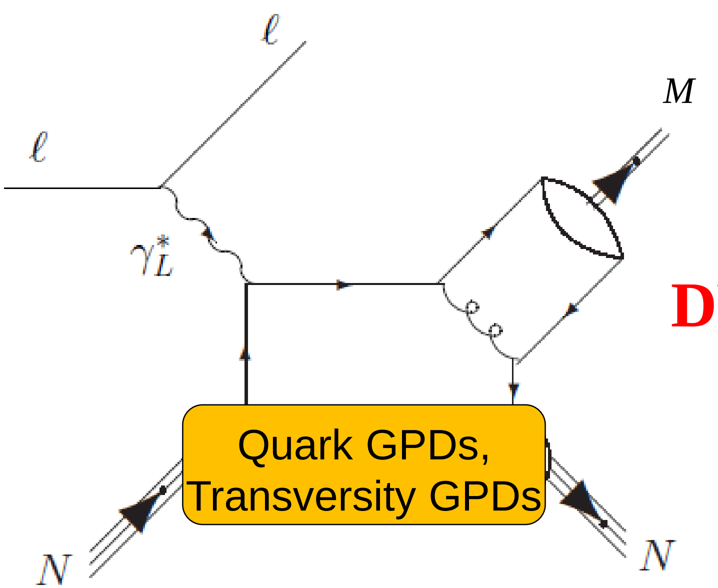
M. Defurne's talk

(TCS), DDVCS

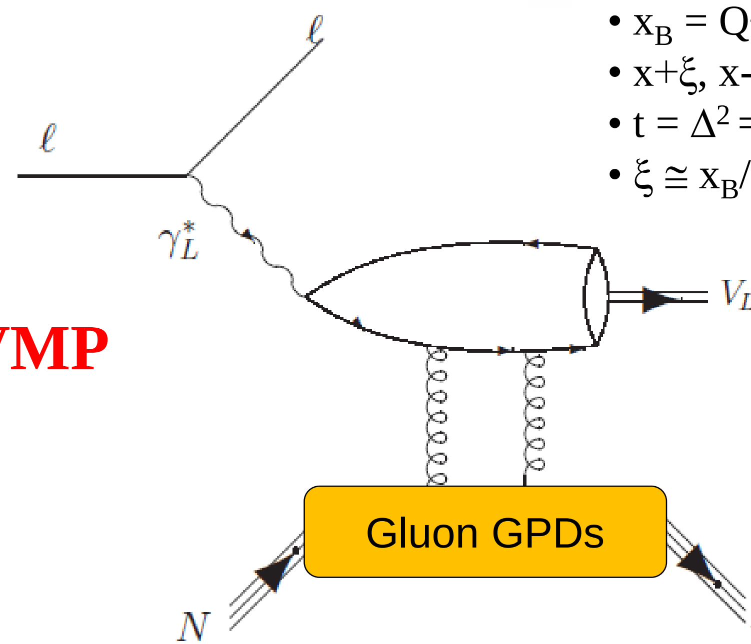


M. Boer's talk

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



DVMP



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**

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

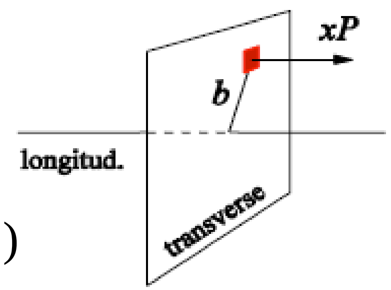
Forward limit: **PDFs**
(not for E, Ẽ)

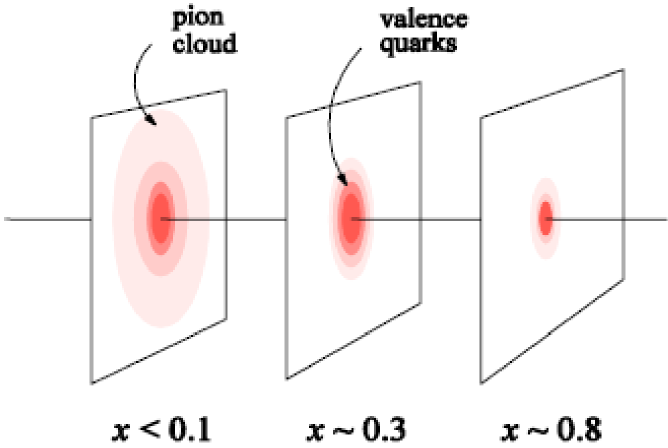
Nucleon tomography

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

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

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

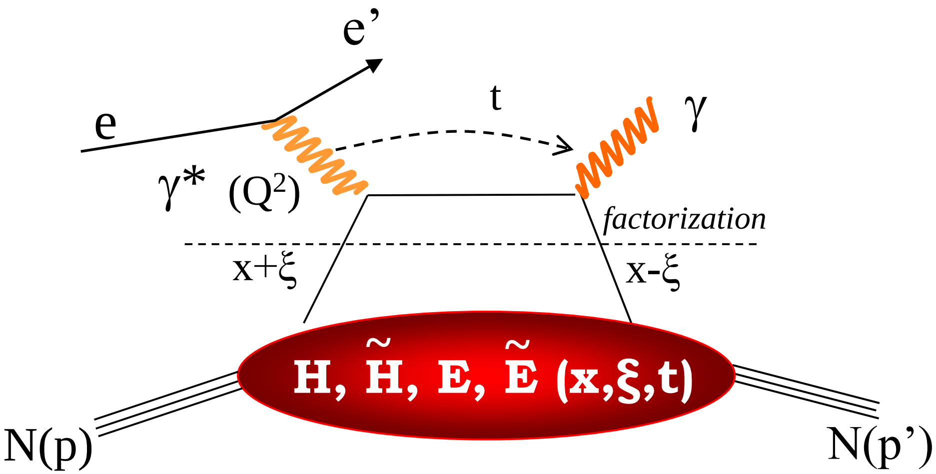
J

Intrinsic spin of the quarks ΔΣ ≈ 25%

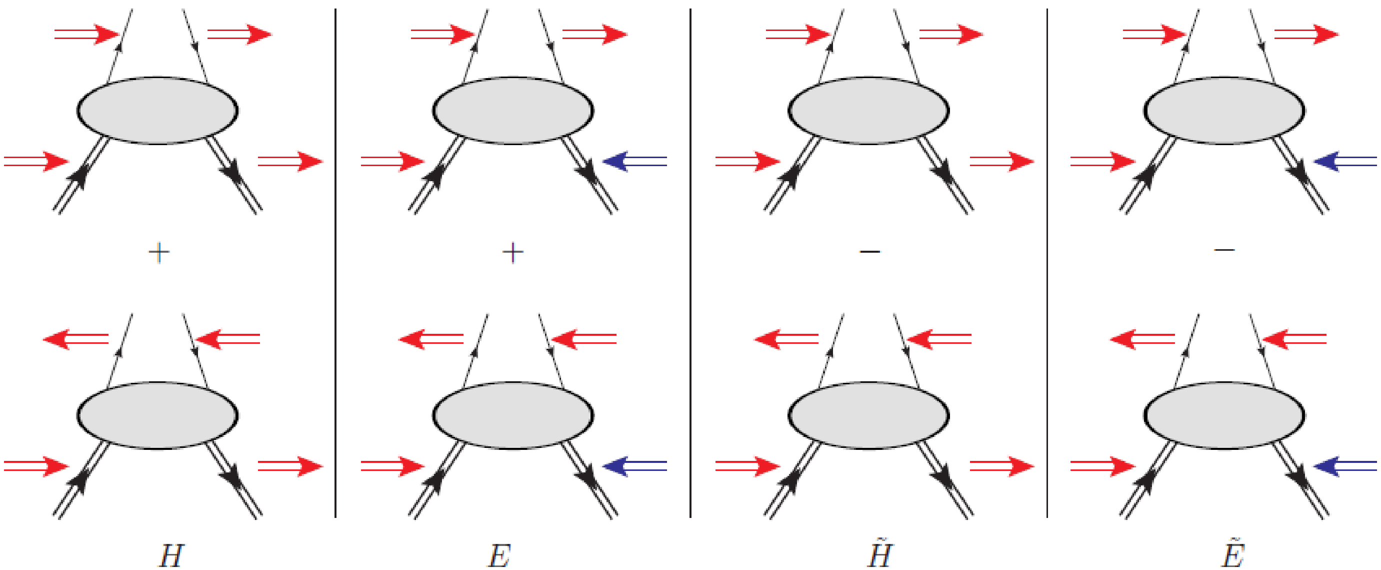
Intrinsic spin on the gluons ΔG ≈ 0 (??)

Orbital angular momentum of the quarks ΔL ?

Deeply Virtual Compton Scattering and quark GPDs



« **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)**

Accessing GPDs through DVCS

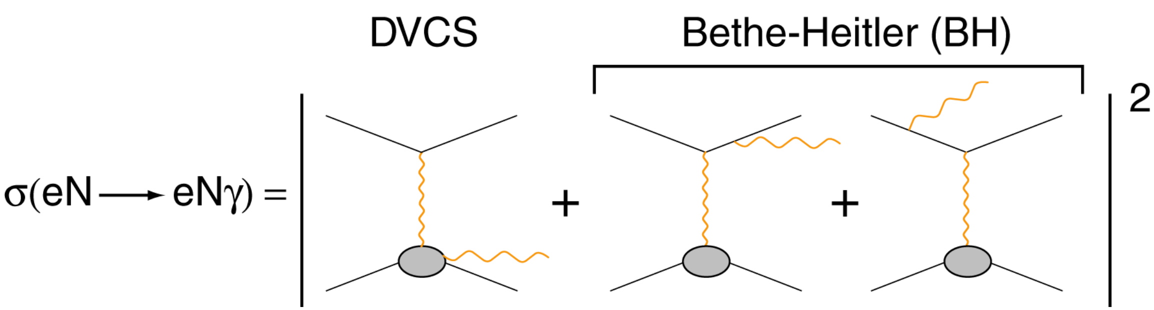
DVCS allows access to 4 complex GPDs-related quantities: **Compton Form Factors (ξ,t)**

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

Only ξ and t are accessible experimentally

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

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

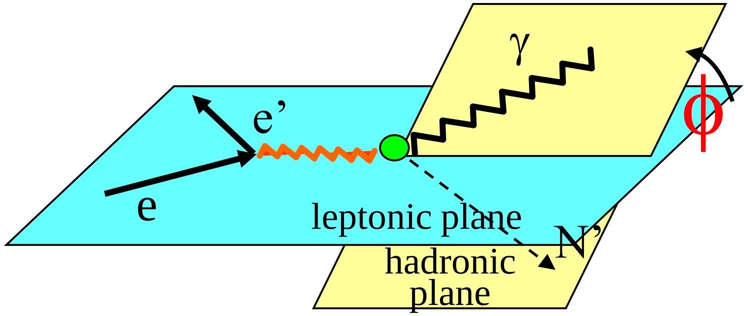


BH is calculable (electromagnetic FFs)

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

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

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



Sensitivity to CFFs of DVCS spin observables

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

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

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

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

Proton Neutron

Polarized beam, unpolarized target:

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

Unpolarized beam, longitudinal target:

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

Polarized beam, longitudinal target:

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

Unpolarized beam, transverse target:

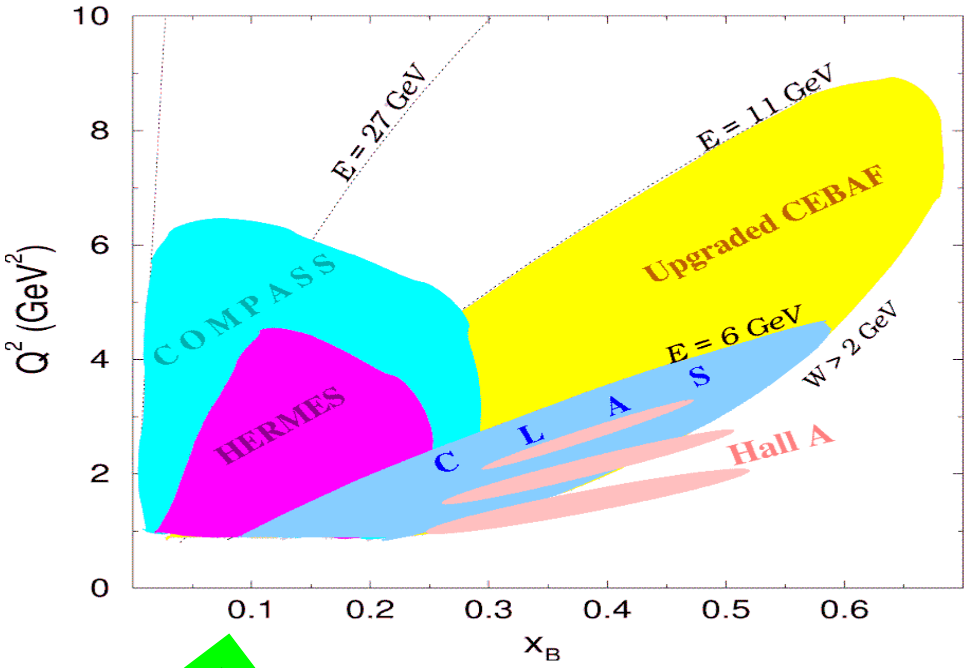
$\Delta\sigma_{UT} \sim \sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

DVCS experiments worldwide

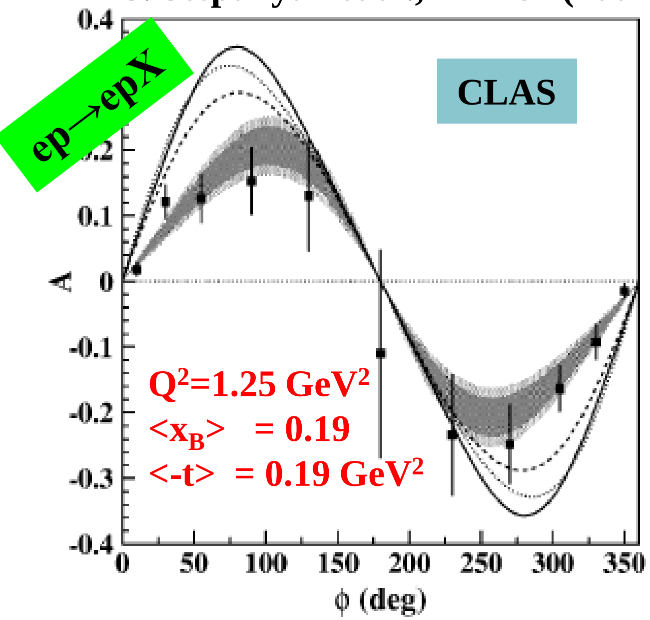
JLAB	
Hall A	*CLAS (Hall B)*
p,n-DVCS (Bpol.) CS	p-DVCS BSA,lTSA,DSA,CS

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

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



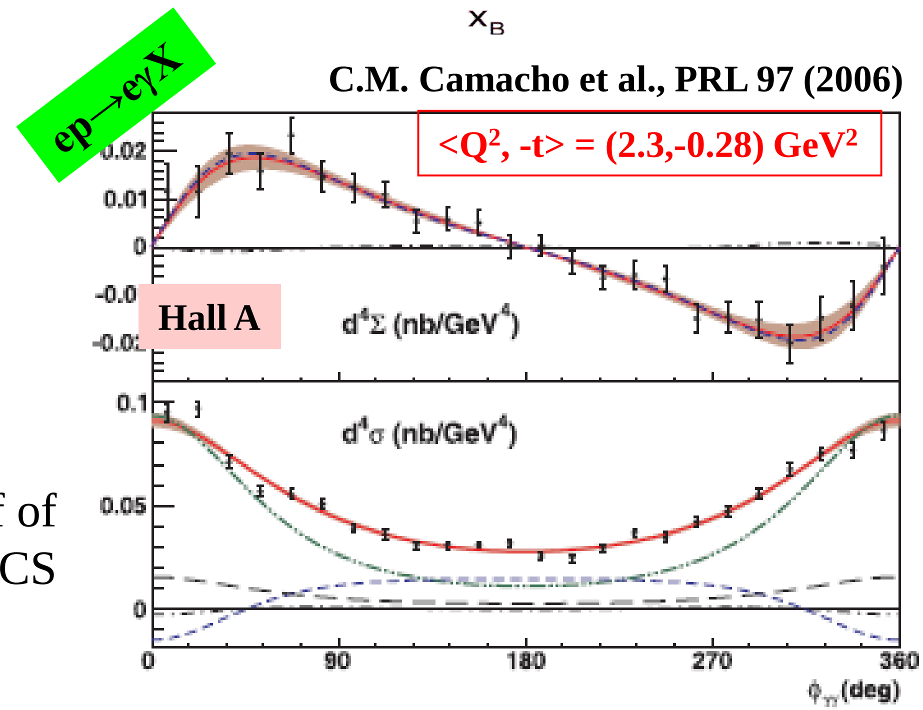
S. Stepanyan et al., PRL 87 (2001)



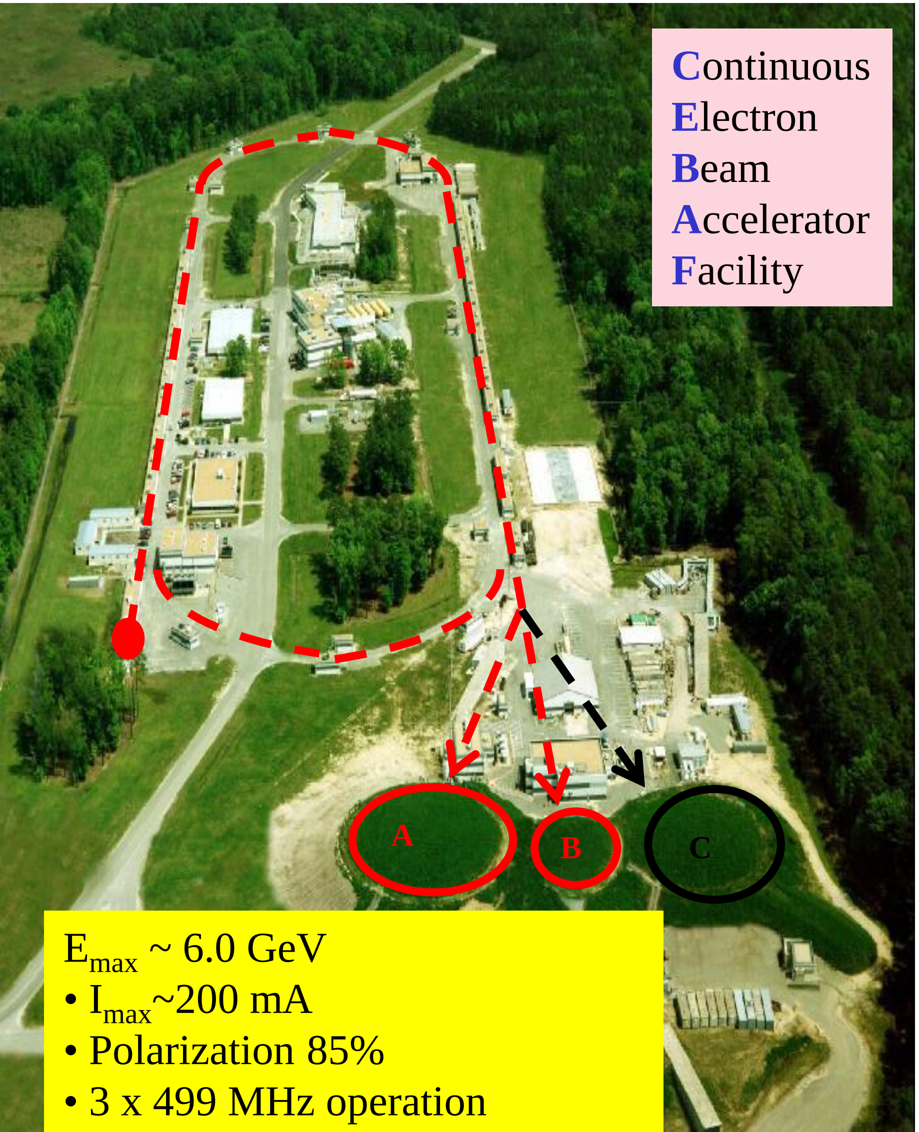
CLAS: first observation of DVCS-BH interference

Hall A: proof of scaling for DVCS

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



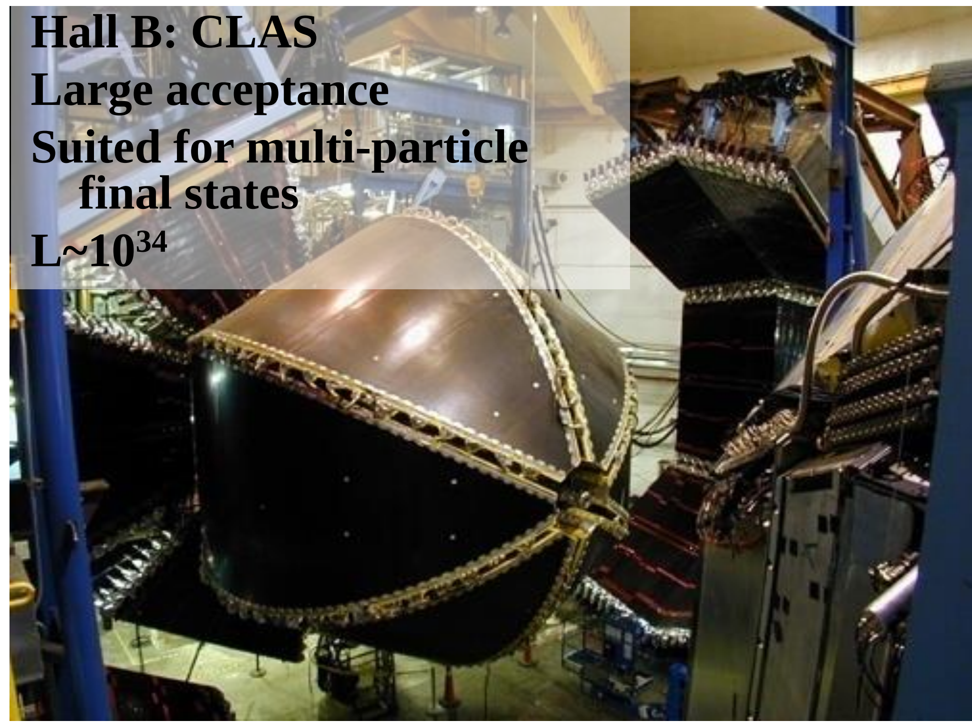
JLab@6 GeV



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

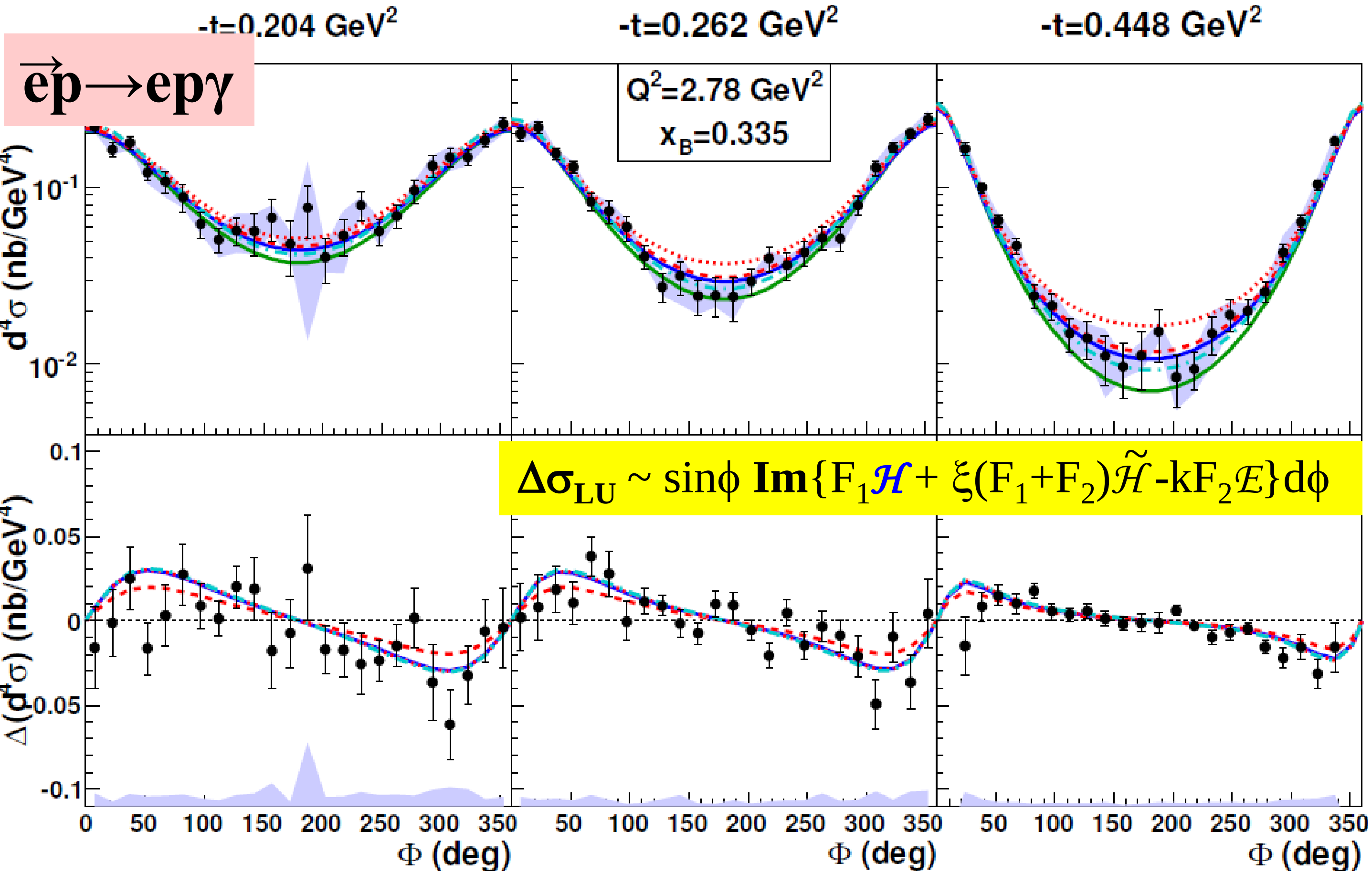
Hall A: 2 HRS
High resolution
High luminosity (L~10^{37})
Limited coverage



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

CLAS: unpolarized and beam-polarized cross sections

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



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

BH — VGG — KM10 ······ KM10a - - -

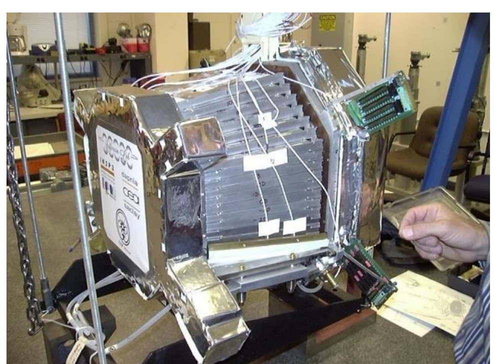
H.S. Jo et al., PRL 115, 212003 (2015)

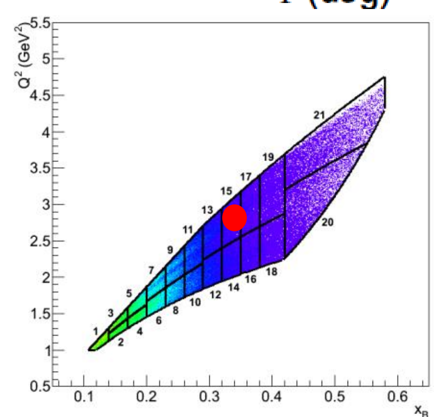
- **Largest kinematic ever covered**
- **Two observables extracted**

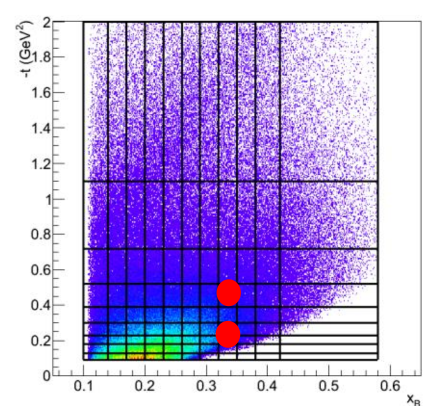
KM10 model fits Hall A 2006 data using « anomalous » $\tilde{H}$

- 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





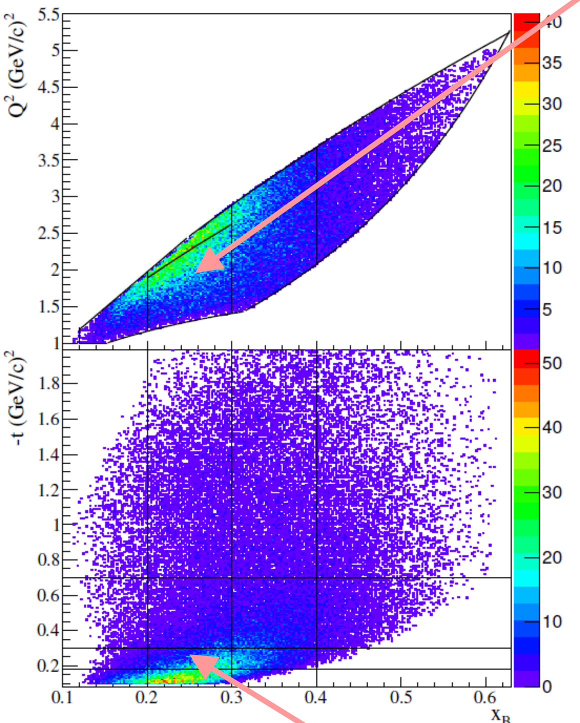


CLAS: DVCS on longitudinally polarized target

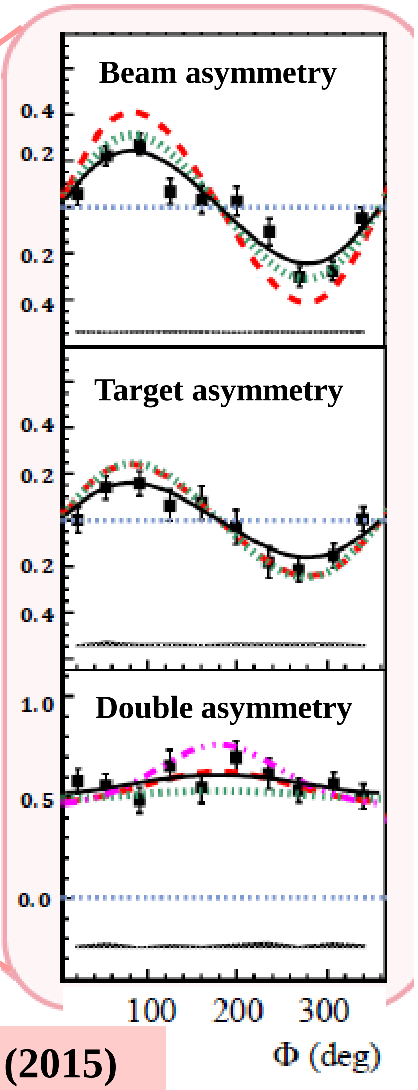
$\vec{e}\vec{p} \to ep\gamma$

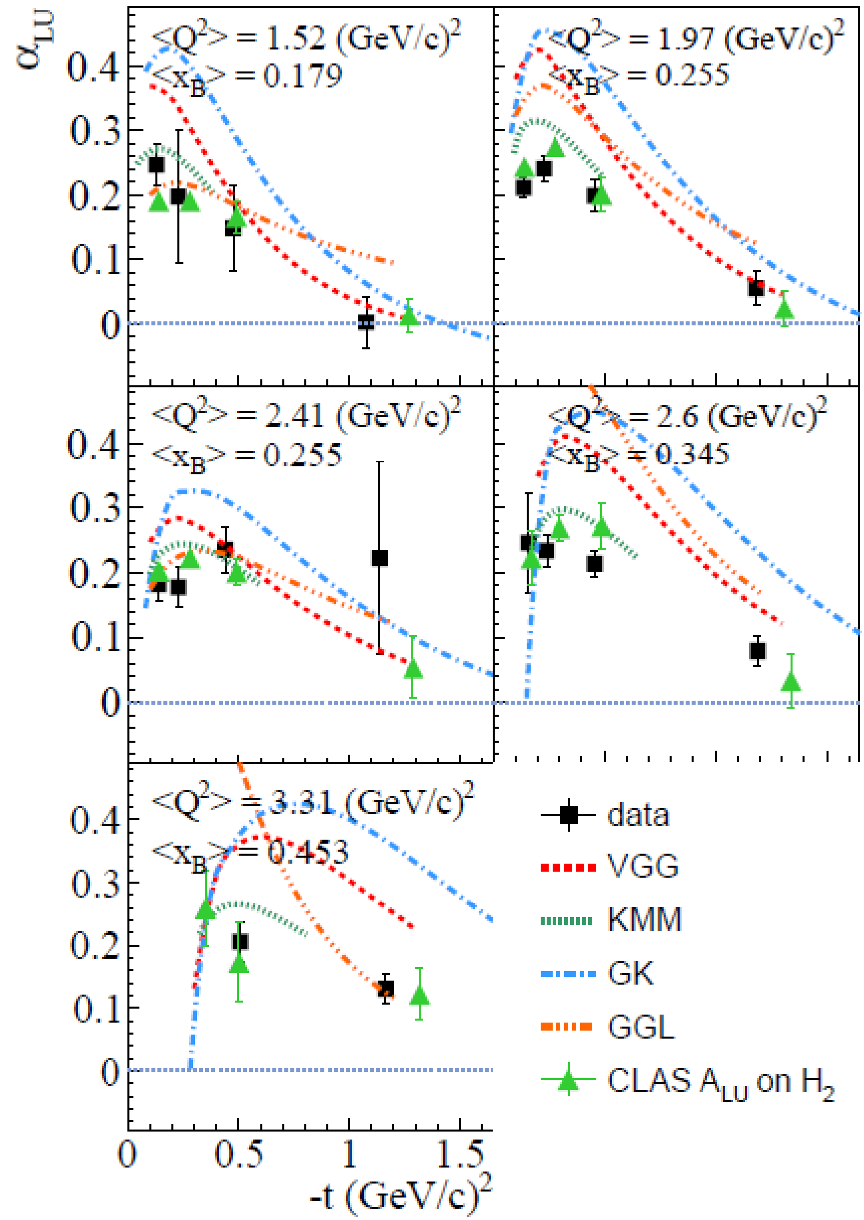
- Data taken in **2009, eg1-dvcs**
- Beam energy **~5.9 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**

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



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





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

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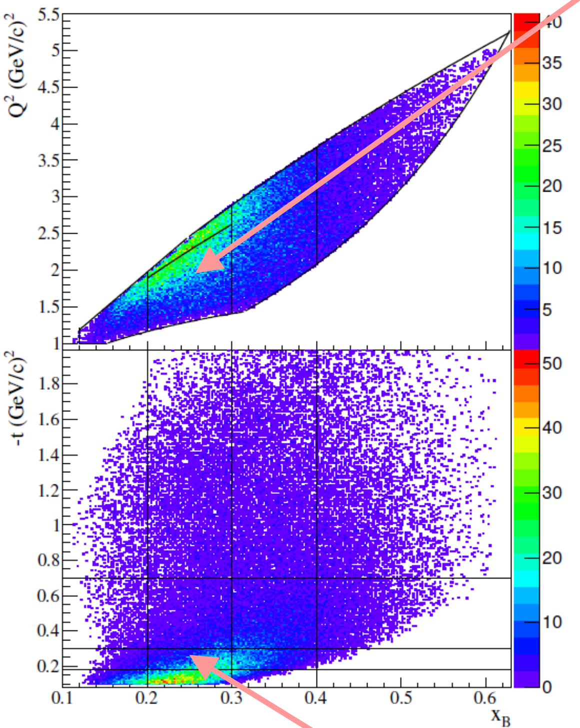
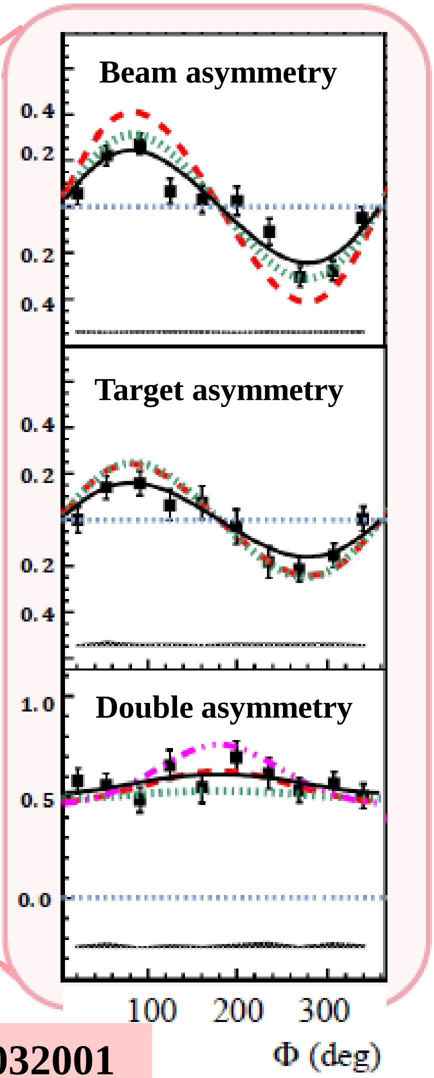
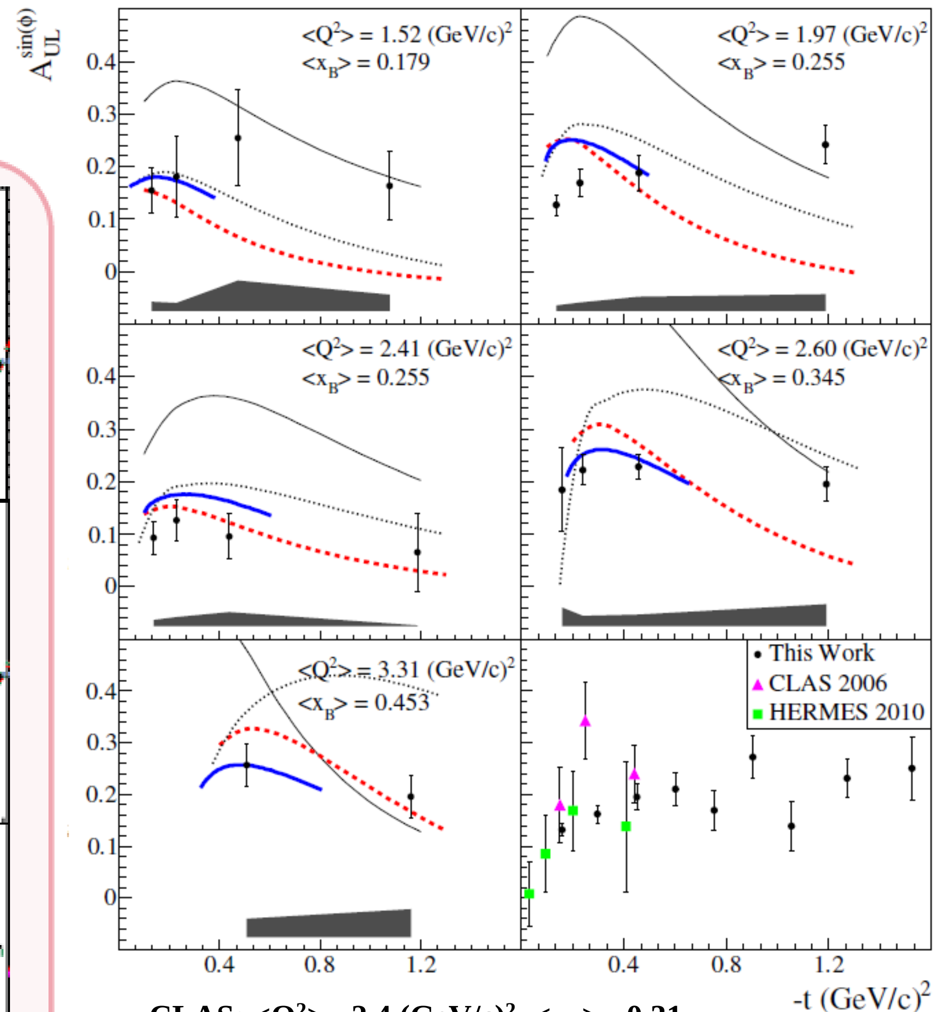
- **3 DVCS observables**

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

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

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

CLAS: DVCS on longitudinally polarized target

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

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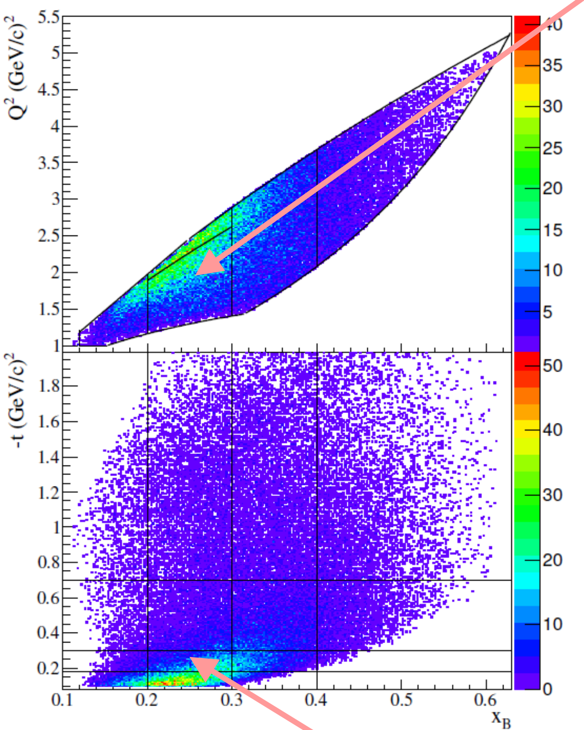
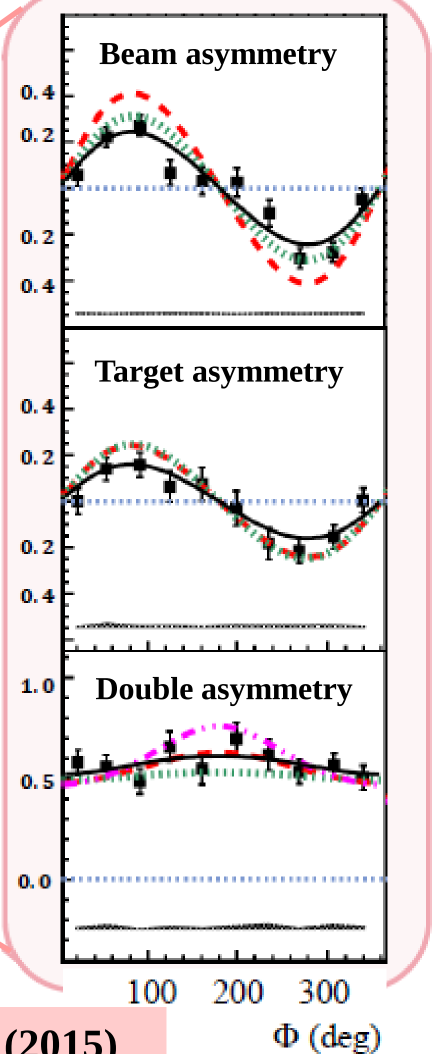
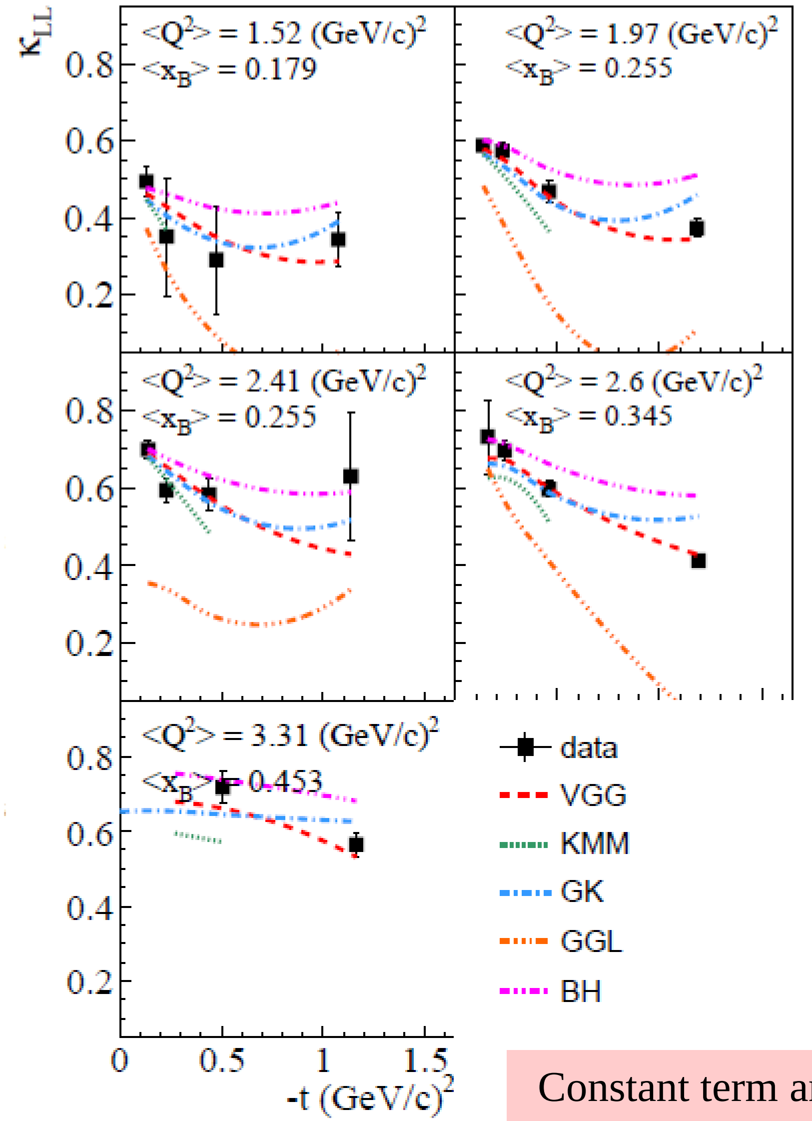
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**

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



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





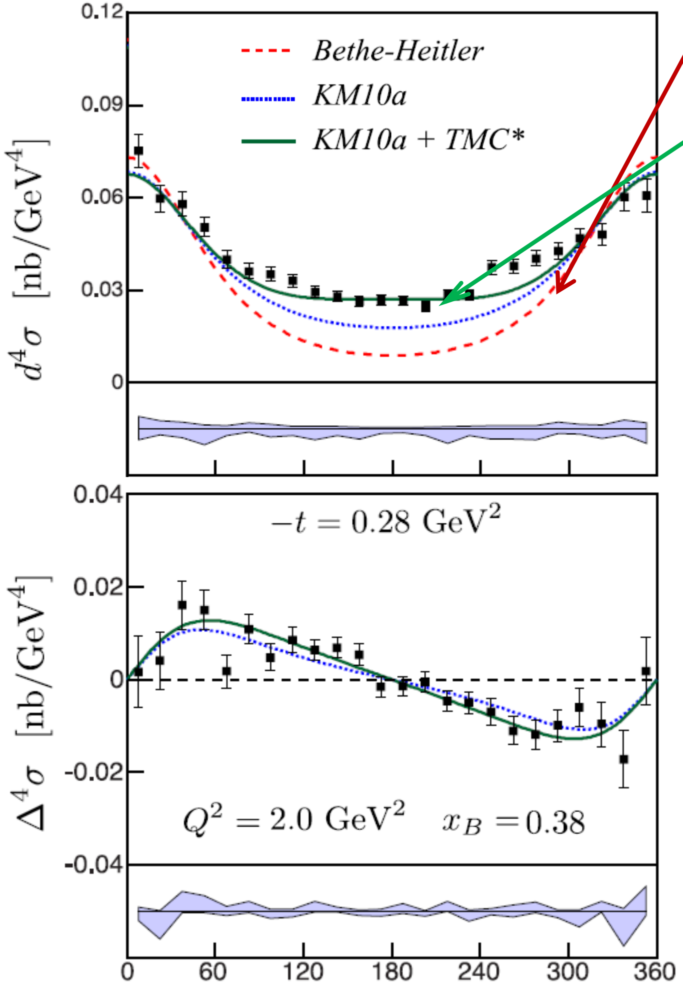
Constant term and cosϕ term are dominated by **BH**

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

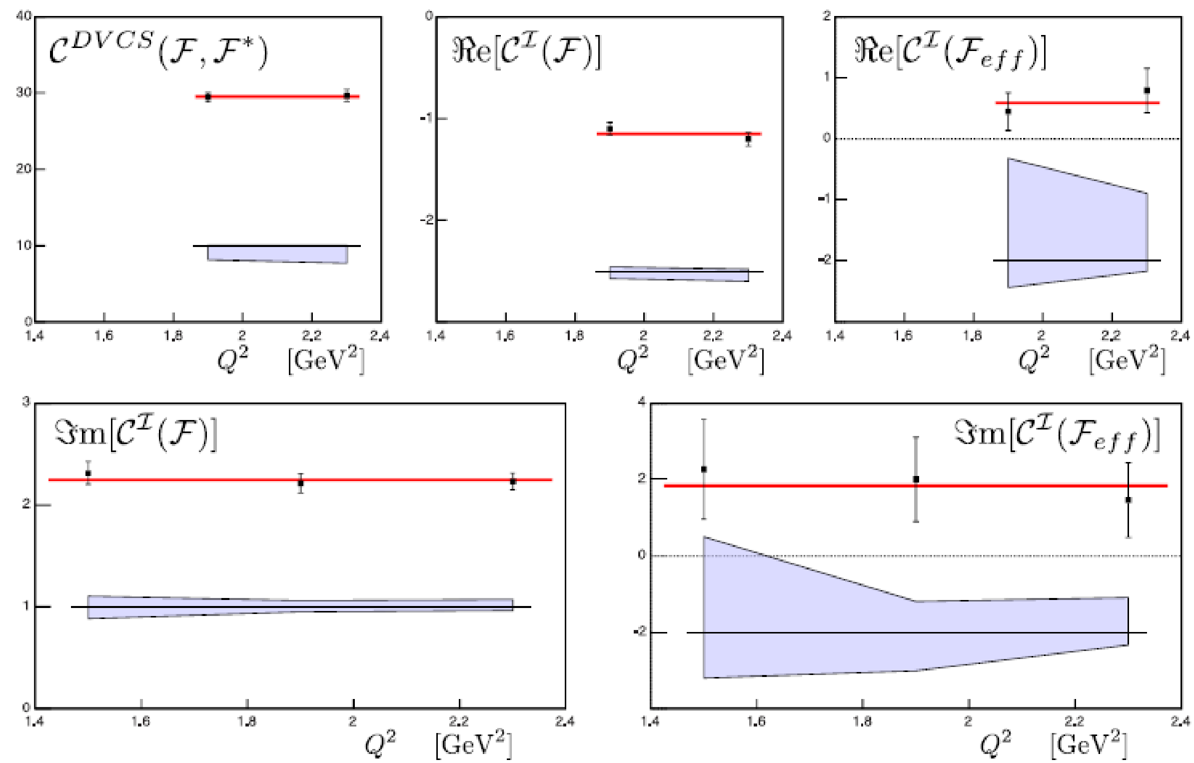
DVCS on the proton in Hall A

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

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



New results from 2009 data: see M. Defurne's talk

Extraction of Compton Form Factors from DVCS observables

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

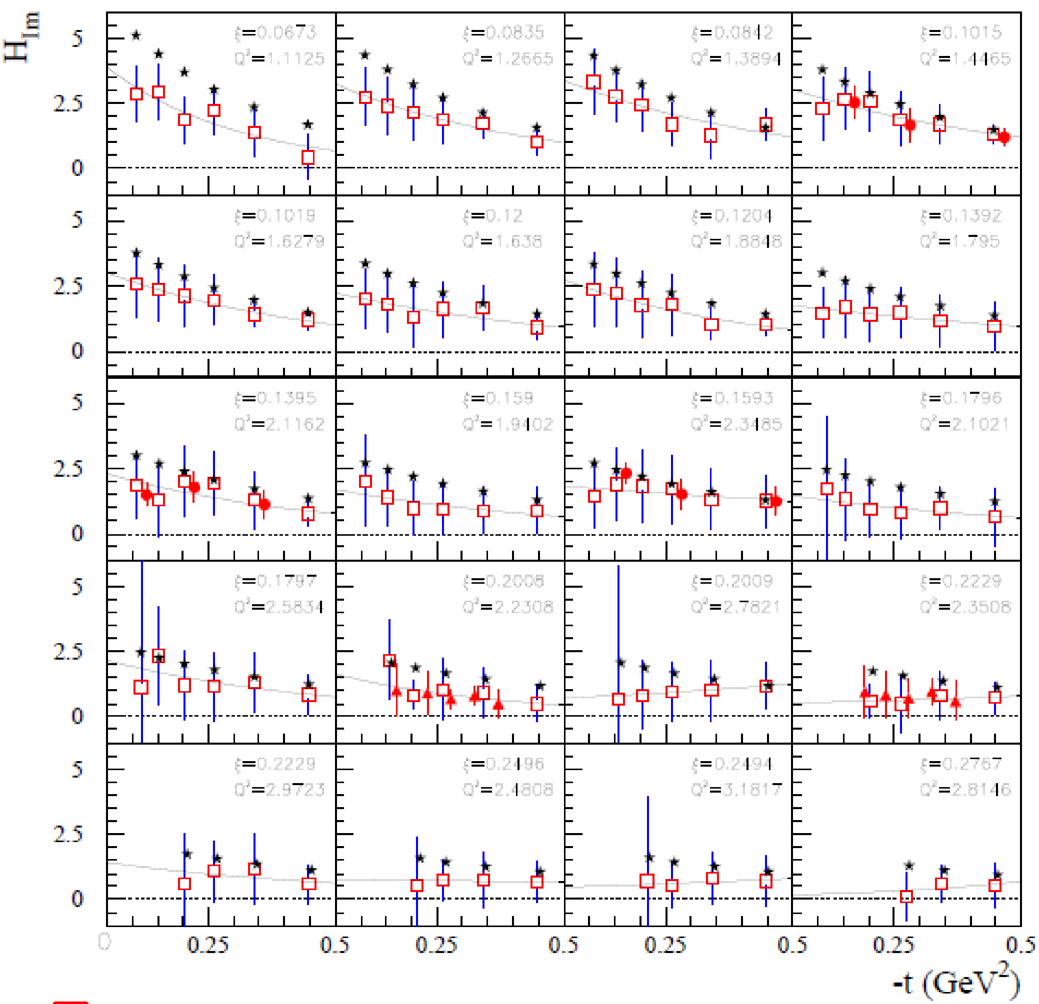
8 CFF

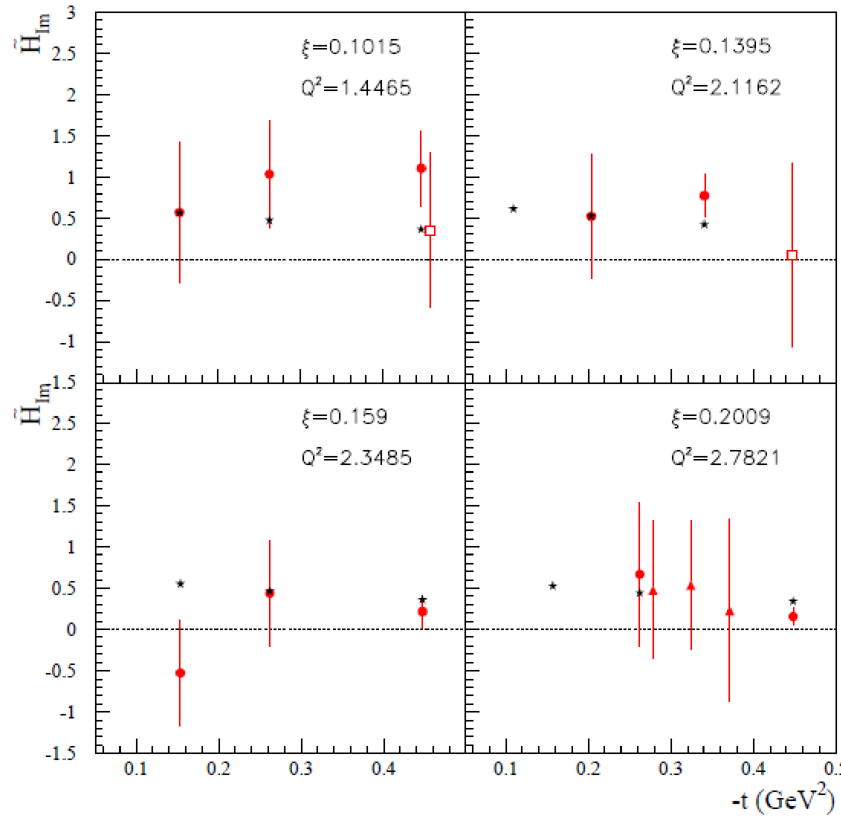
$$\left\{\begin{aligned}
\mathrm{Re}(\mathcal{H}) &= P\int_0^1 dx\left[H(x,\xi,t) - H(-x,\xi,t)\right]C^+(x,\xi)\\
\mathrm{Re}(\mathcal{E}) &= P\int_0^1 dx\left[E(x,\xi,t) - E(-x,\xi,t)\right]C^+(x,\xi)\\
\mathrm{Re}(\tilde{\mathcal{H}}) &= P\int_0^1 dx\left[\tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)\right]C^-(x,\xi)\\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

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

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

Results for H_{Im} and $\tilde{H}_{Im}$ from the fits of JLab 2015 data



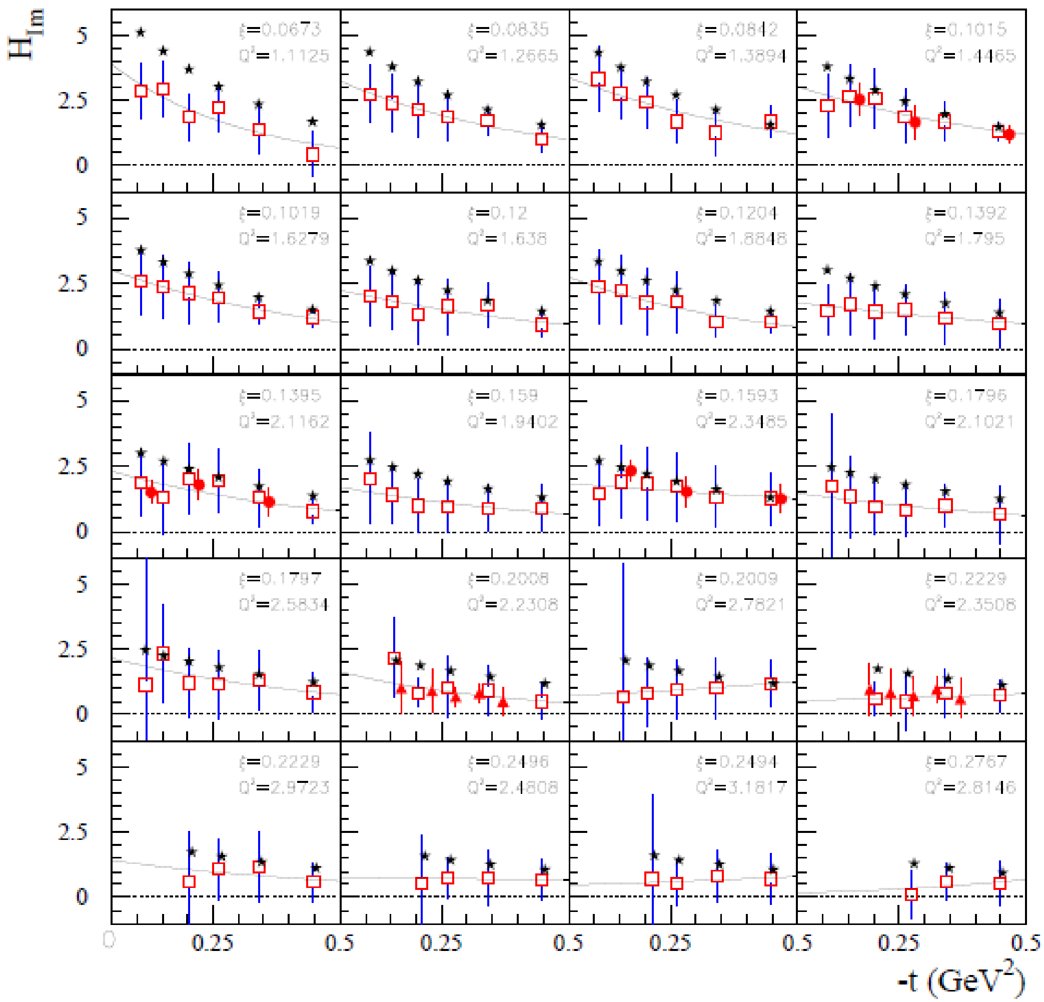


- □ Fit to CLAS c.s. and beam pol. c.s.
- ● Fit to CLAS c.s., beam pol. c.s., lTSA, DSA
- ▲ Fit to Hall A c.s. and beam pol. c.s.
- ★ VGG model

H_{Im} has steeper t-slope than $\tilde{H}_{Im}$: the axial charge (~Δu-Δd) is more "concentrated" than the electric charge

R. Dupré, M. Guidal, S.Niccolai, M. Vanderhaegen, arXiv: 1704.07330

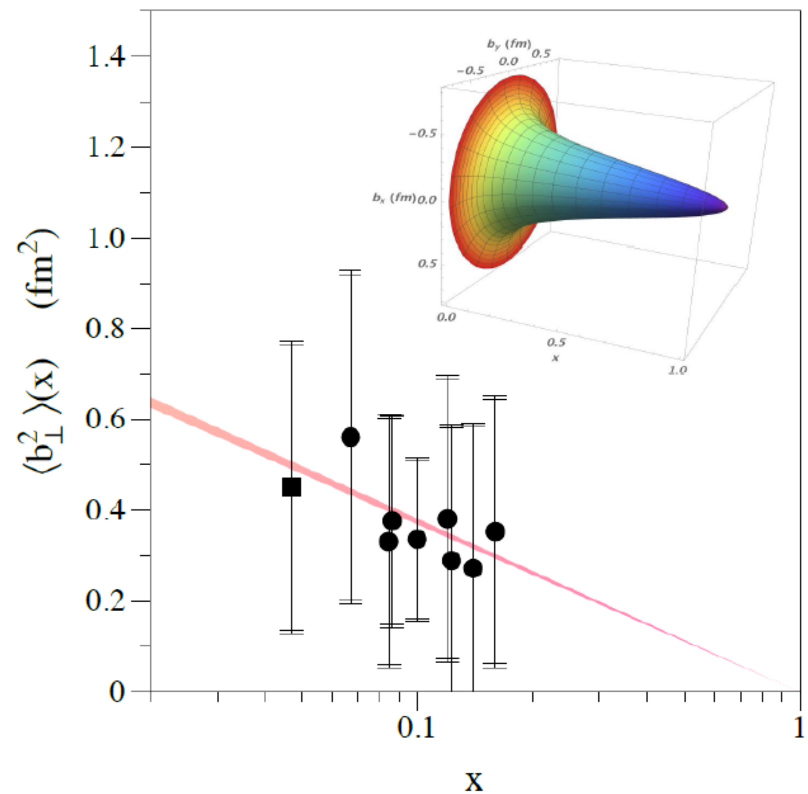
From CFFs to proton tomography



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

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

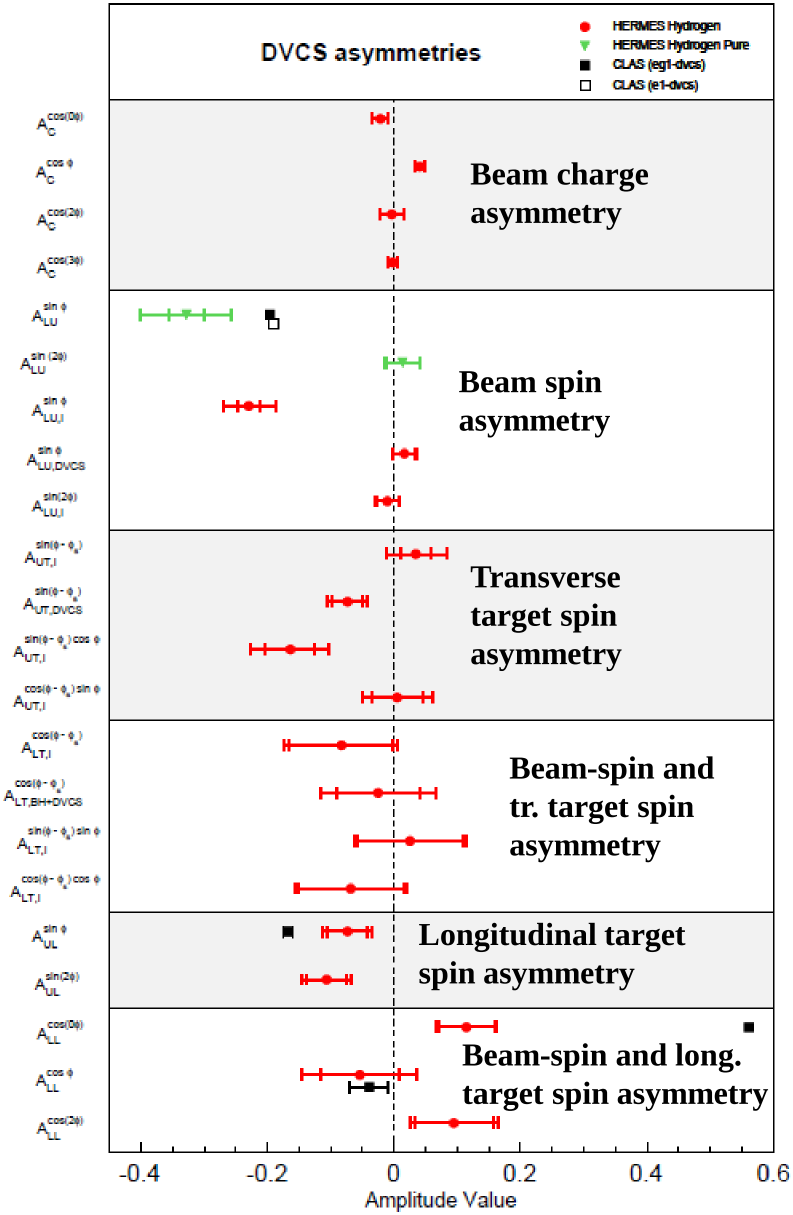
$$B(\xi) = a_B \ln(1/\xi) \qquad a_B \;=\; 1.07 \pm 0.26\ \mathrm{GeV}^{-2}$$

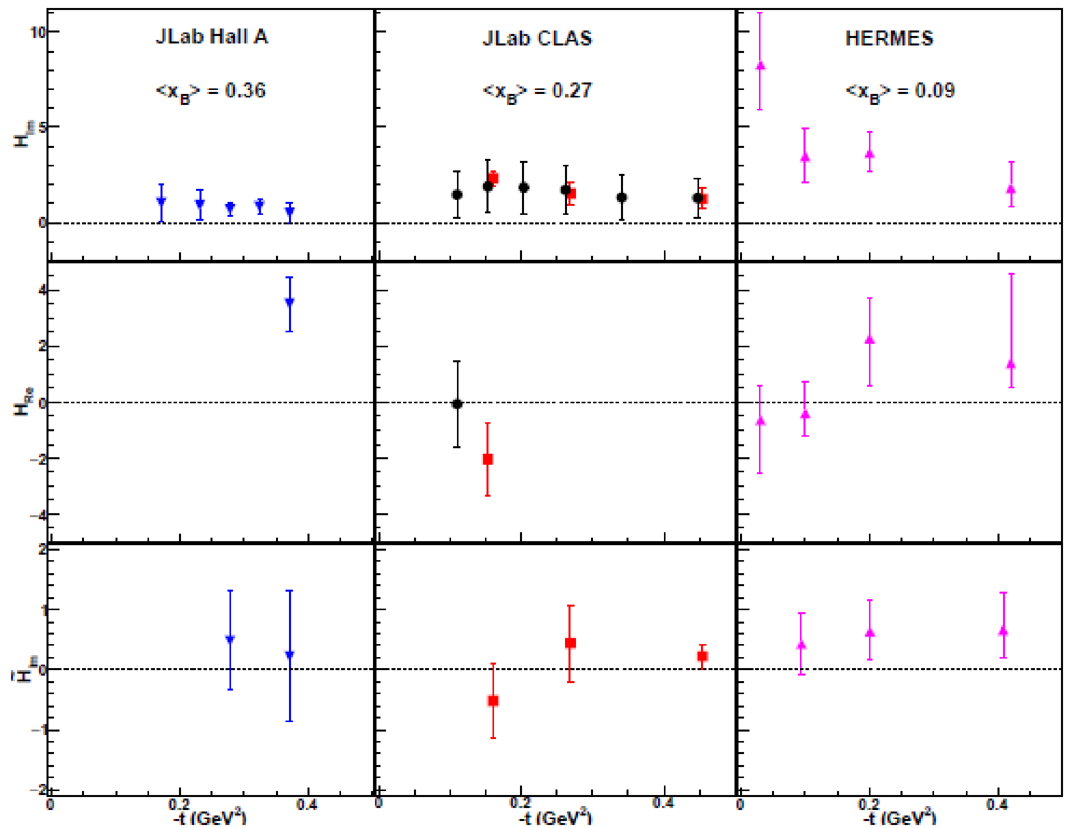


« Integrated » radius from elastic form factor F_1:

$$\langle b_\perp^2 \rangle = 0.43 \pm 0.01\ \mathrm{fm}^2$$

Summary of proton-DVCS spin observables and GPDs extraction





Hall A (2015)

CLAS C.S.

CLAS C.S. +TSA+DSA

HERMES

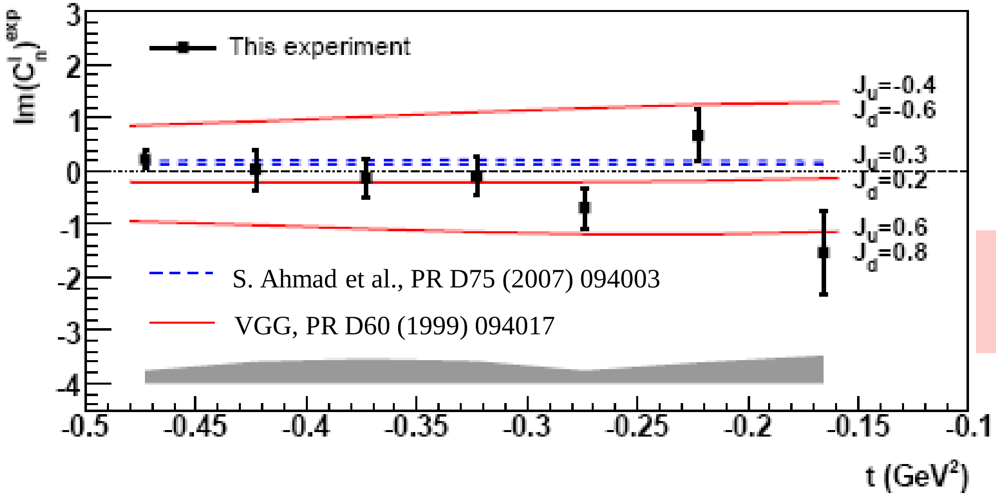
Beam Charge Asymmetry: strong constraint for H_{Re}

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

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

DVCS on the neutron in Hall A

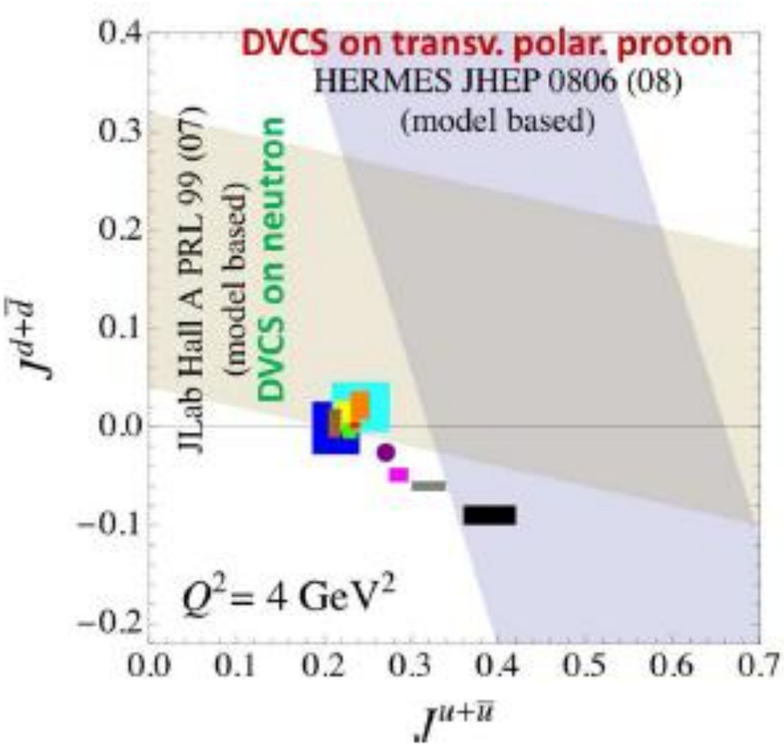
M. Mazouz et al., PRL 99 (2007) 242501



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

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

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



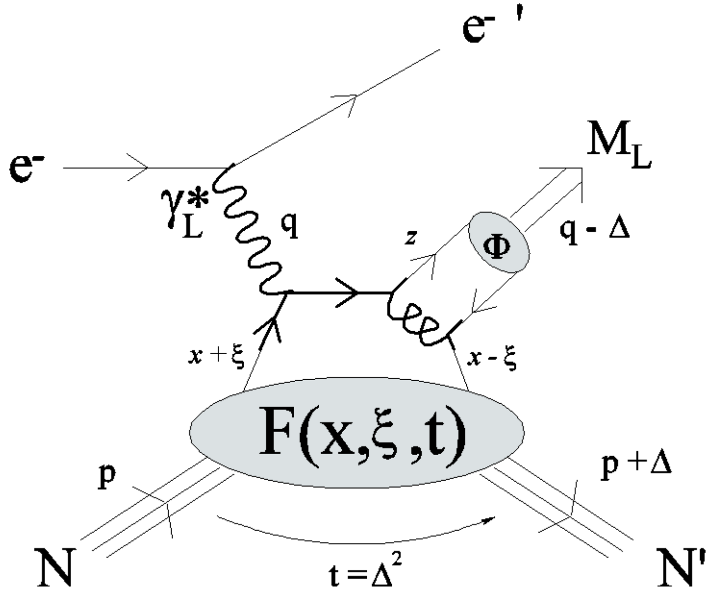
• **E08-025**: Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target

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

Deeply virtual meson production and GPDs



Different mesons → different sensitivity to GPDs

H	**$\tilde{H}$**
E	**$\tilde{E}$**
↓	↓
Vector mesons (ρ, ω, φ)	**Pseudoscalar** mesons (π, η)

π^0	2Δu+Δd
η	2Δu-Δd

ρ^0	2u+d
ω	2u-d
ρ^+	u-d

Factorization proven only for **longitudinally polarized** virtual photons

quark flavor decomposition accessible via meson production

$$\mathcal{A}_L = -\frac{2ie}{9}\left(\int_0^1 dz \frac{\Phi(z)}{z}\right)\frac{4\pi\alpha_S(Q^2)}{Q}\int_{-1}^{+1} dx \left\{\left[\frac{1}{x-\xi+i\epsilon}+\frac{1}{x+\xi-i\epsilon}\right]F(x,\xi,t)\right\}$$

Complications: effective scale in the hard scattering process, meson distribution amplitude

Deeply virtual meson production at CLAS

Vector mesons: exclusive ρ^0, ω, ϕ and ρ^+ electroproduction on the proton with CLAS

K. Lukashin *et al.*, Phys. Rev. C 63, 065205, 2001 **(ϕ@4.2 GeV)** C. Hadjidakis *et al.*, Phys. Lett. B 605, 256-264, 2005 **(ρ^0@4.2 GeV)**	e1-b (1999)
L. Morand *et al.*, Eur. Phys. J. A 24, 445-458, 2005 **(ω@5.75GeV)** J. Santoro *et al.*, Phys. Rev. C 78, 025210, 2008 **(ϕ@5.75 GeV)** S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009 **(ρ^0@5.75GeV)**	e1-6 (2001-2002)
A. Fradi, Orsay Univ. PhD thesis **(ρ^+@5.75 GeV)**	e1-DVCS (2005)

Pseudoscalar mesons: exclusive π^0 and η electroproduction on the proton with CLAS

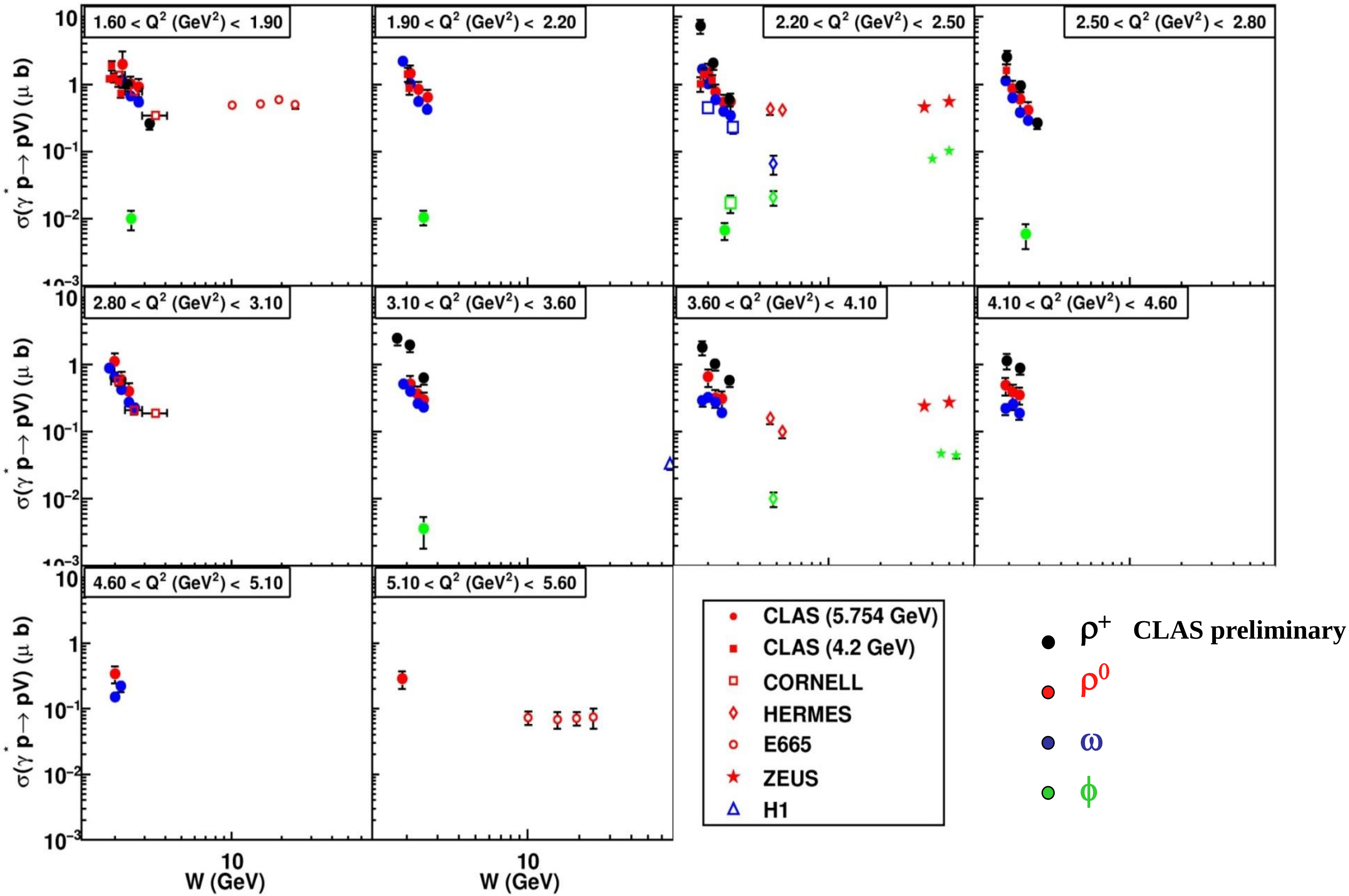
R. De Masi *et al.*, Phys. Rev. C 77, 042201(R), 2008 **(π^0@5.75GeV)**

K. Park *et al.*, Phys. Rev. C 77, 015208, 2008 **(π^+@5.75 GeV)**

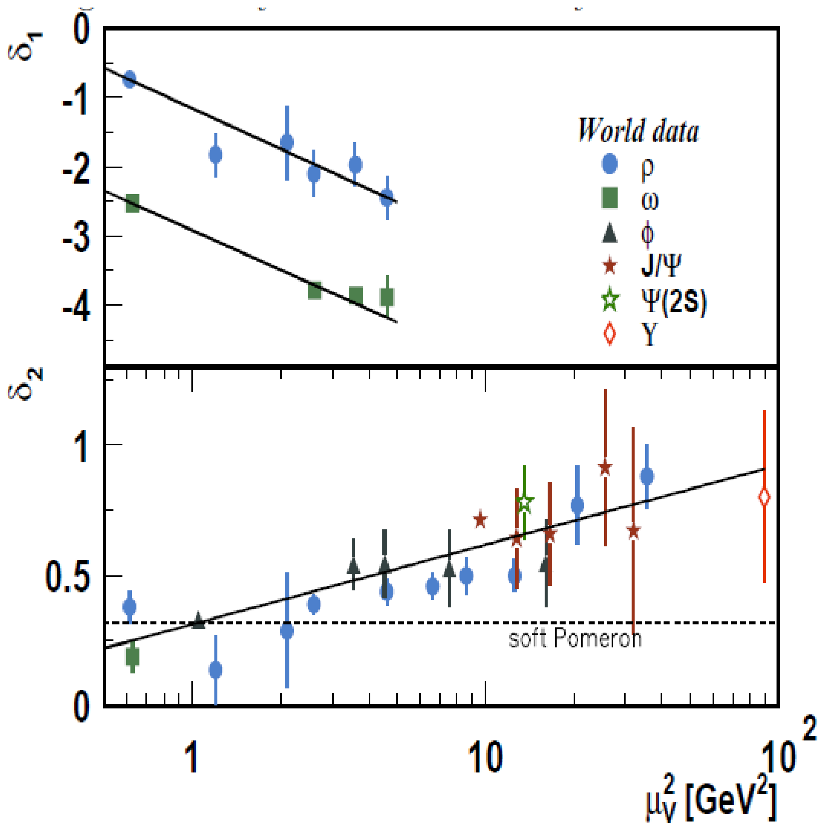
I. Bedlinskiy *et al.*, Phys. Rev. Lett. 109 (2012) 112001; Phys. Rev. C 90, 039901 (2014) **(π^0@5.75GeV)**

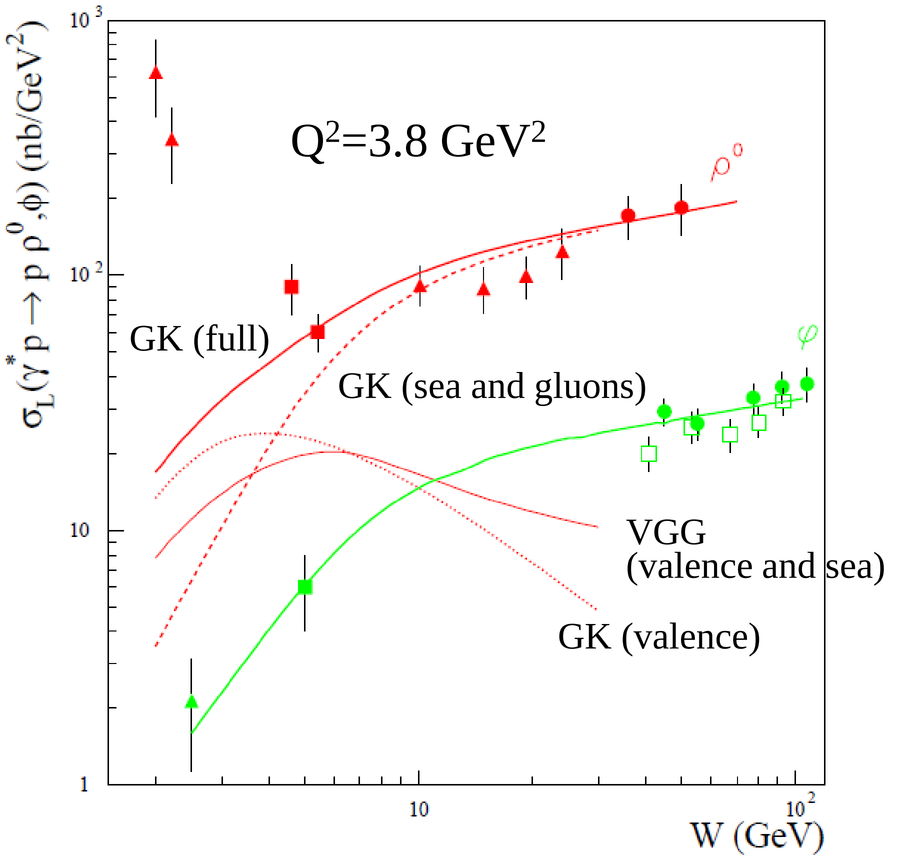
I. Bedlinskiy *et al.*, Phys. Rev. C 95, 035202 (2017) **(η@5.75GeV)**

Comparison between vector mesons (σ)



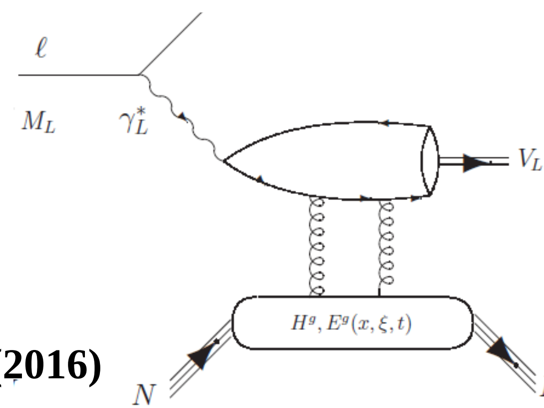
Comparison between vector mesons (σ, σ_L)





$$\sigma_V(W, \mu_V^2) = a_1 W^{\delta_1(\mu_V^2)} + a_2 W^{\delta_2(\mu_V^2)}$$

$$\mu_V^2 = Q^2 + M_V^2$$



The GPD models fail to reproduce σ_L at **low W** for ρ^0

L. Favart, M. Guidal, T. Horn, P. Kroll, EPJA 52, 158 (2016)

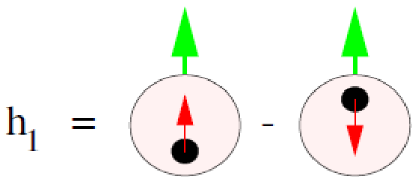
Chiral-odd GPDs

- 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:

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

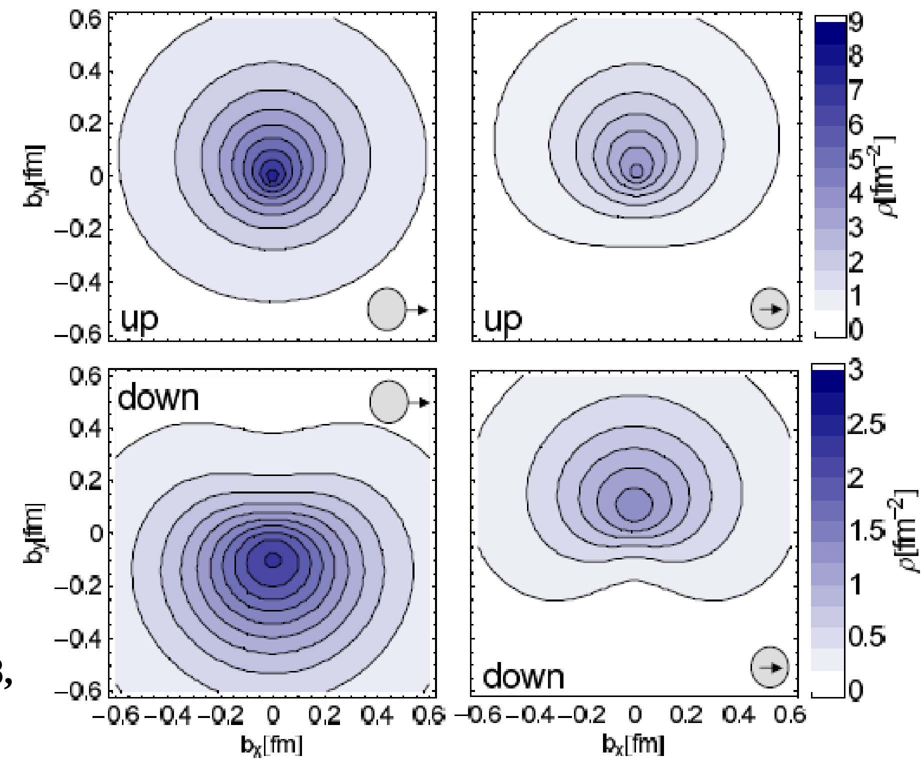
- Link to the **transversity** distribution: $H_T^q(x,0,0) = h_1^q(x)$

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



Transverse Densities for u and d quarks in the nucleon

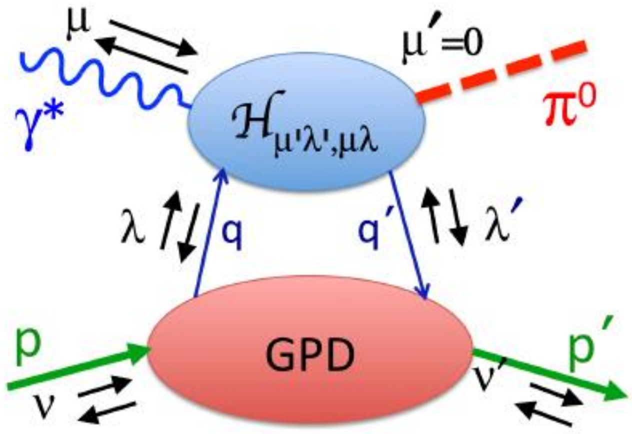
Distributions of unpolarized quarks in a transversely polarized nucleon, **linked to *E***

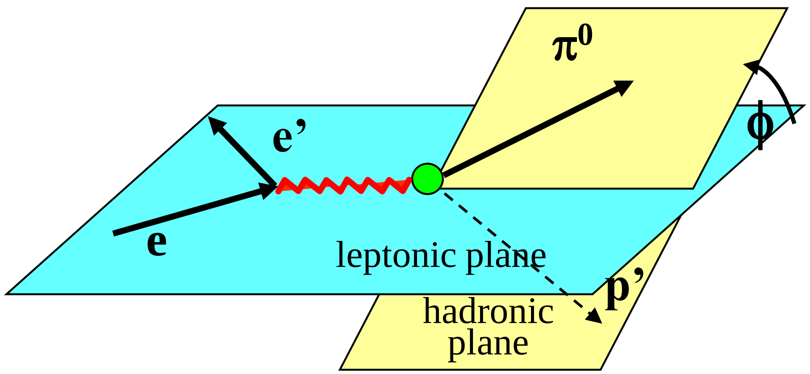


Distribution of transversely polarized quarks in an unpolarized nucleon, **linked to $\bar{E}_T$**

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

Exclusive π^0 electroproduction





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

Leading twist: $\sigma_L = \frac{4\pi\alpha_e}{k'Q^6}\left[(1-\xi^2)|<\tilde{H}>|^2 - 2\xi^2\,\mathrm{Re}(<\tilde{H}>^* <\tilde{E}>) - \frac{t'}{4m^2}\xi^2|<\tilde{E}>|^2\right]$

σ_L is suppressed: $\tilde{H}^\pi = \frac{1}{3\sqrt{2}}\left[2\tilde{H}^u + \tilde{H}^d\right]$

Generalized Compton Form Factors

$$<\tilde{H}> = \sum_\lambda \int_{-1}^{1} \mathrm{d}x\, M(x,\xi,Q^2,\lambda)\tilde{H}(x,\xi,\mathrm{t})$$

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

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

Transversity GPD models:

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

CLAS results

I. Bedlinskiy et al., Phys. Rev. Lett. 109 (2012) 112001; Phys. Rev. C 90, 039901 (2014)

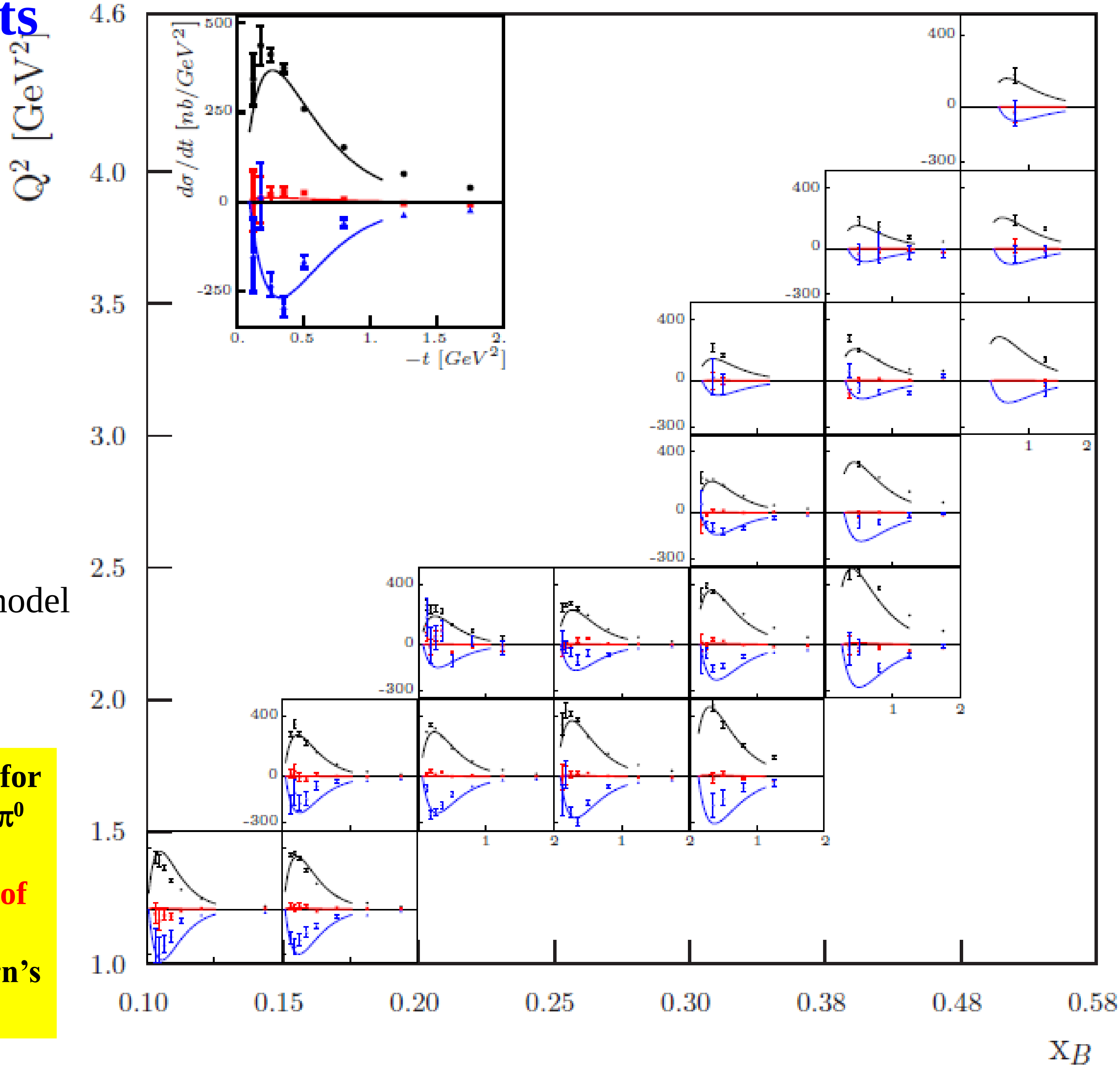
$\sigma_T+\varepsilon\sigma_L$

σ_{LT}

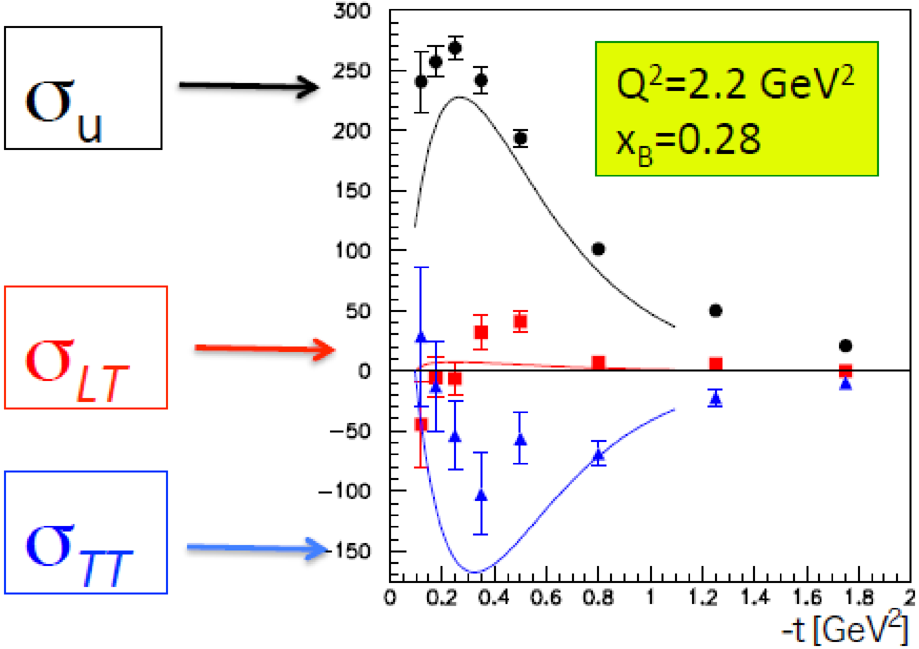
σ_{TT}

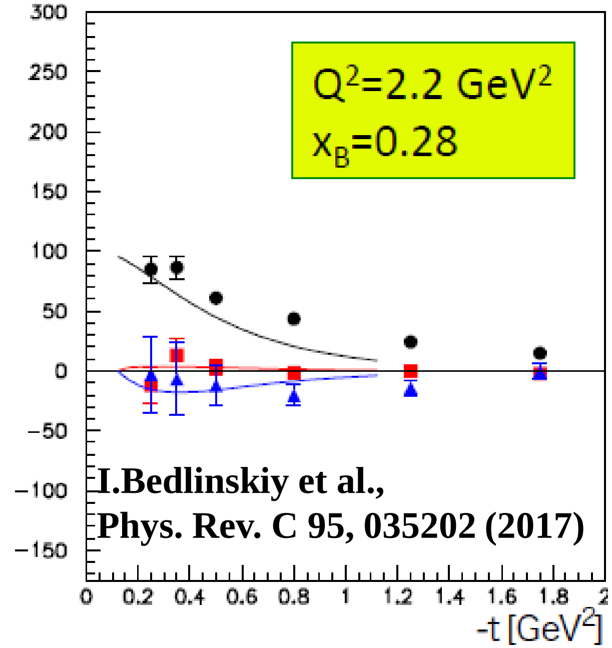
Goloskokov-Kroll model
Transversity GPDs

Recent Hall A results for proton and neutron π^0 electroproduction
→ flavor separation of transversity GPDs
(M. Defurne's, T. Horn's talks)

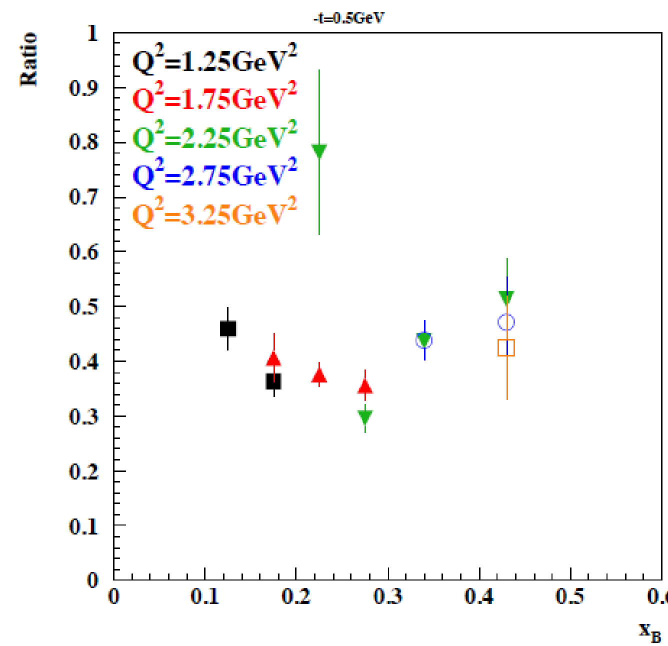


Comparison π^0/η





- Very little dependence on x_B and Q^2
- Chiral-odd GPD models predict this ratio to be **~1/3** at CLAS kinematics
- Chiral-even GPD models predict this ratio to be around 1 (at low –t)



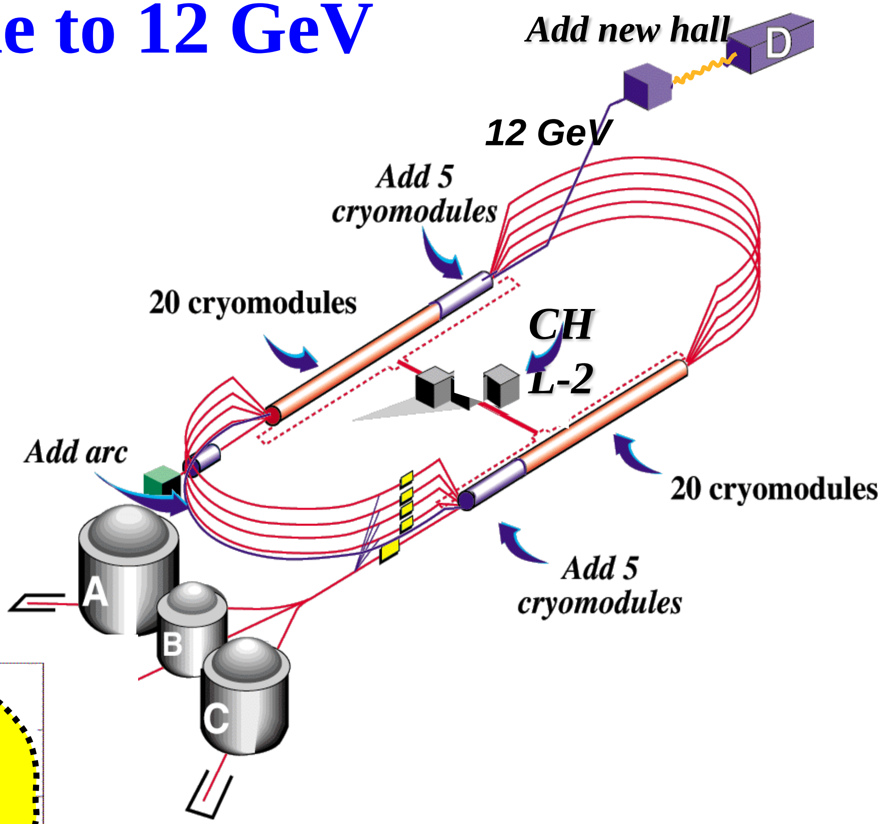
Potentially one can perform **flavor separation of transversity GPDs** combining π^0 and η

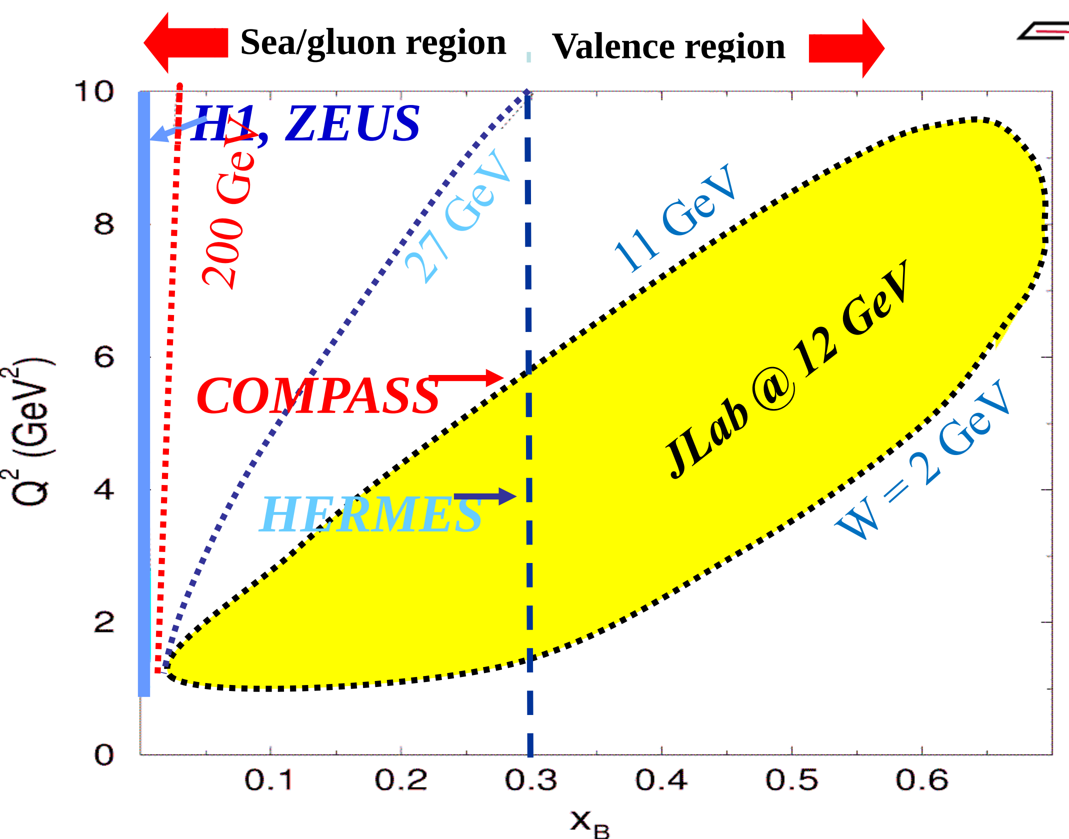
JLab upgrade to 12 GeV

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

Beam polarization > 80%

Upgrade completed in 2014

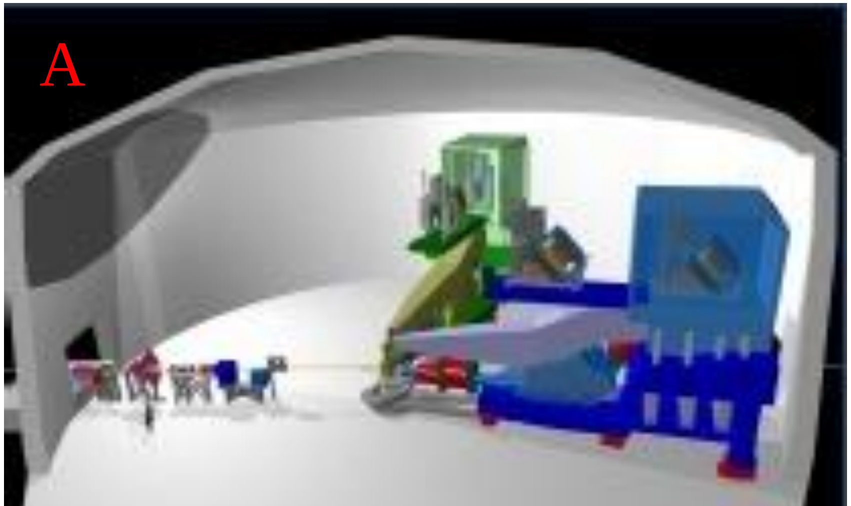




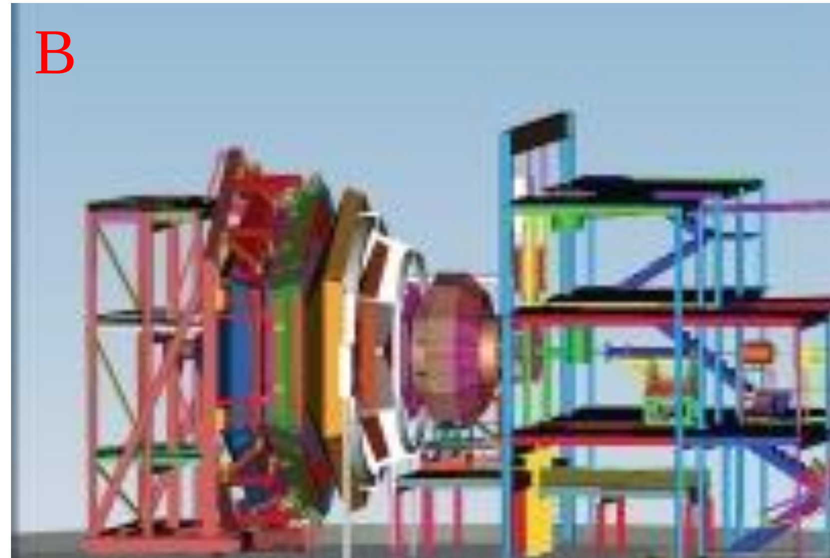
Study of high x_B domain requires high luminosity

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

GPDs 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

M. Defurne and T. Horn will present Halls A and C

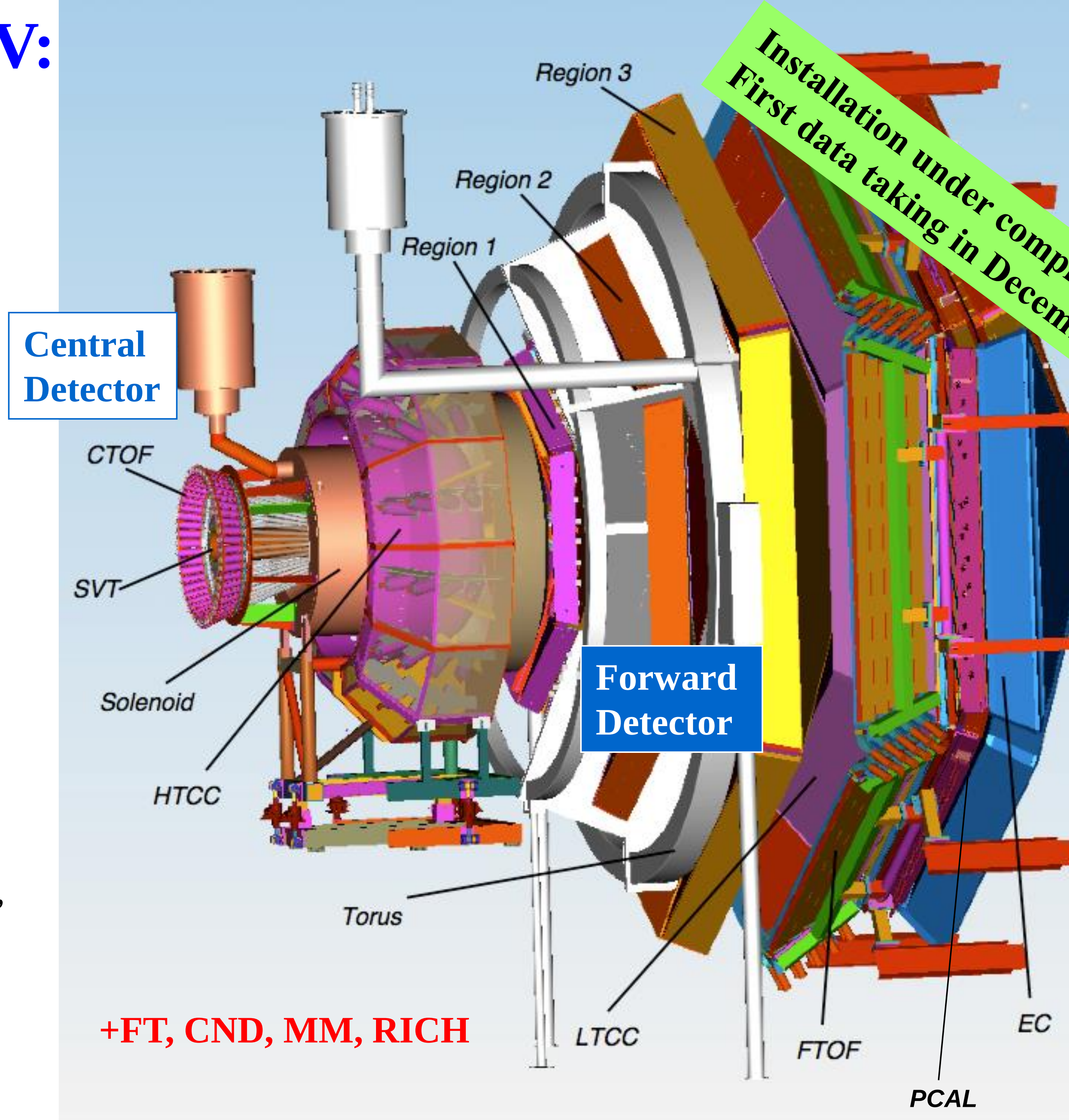
Hall B@12 GeV: CLAS12

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

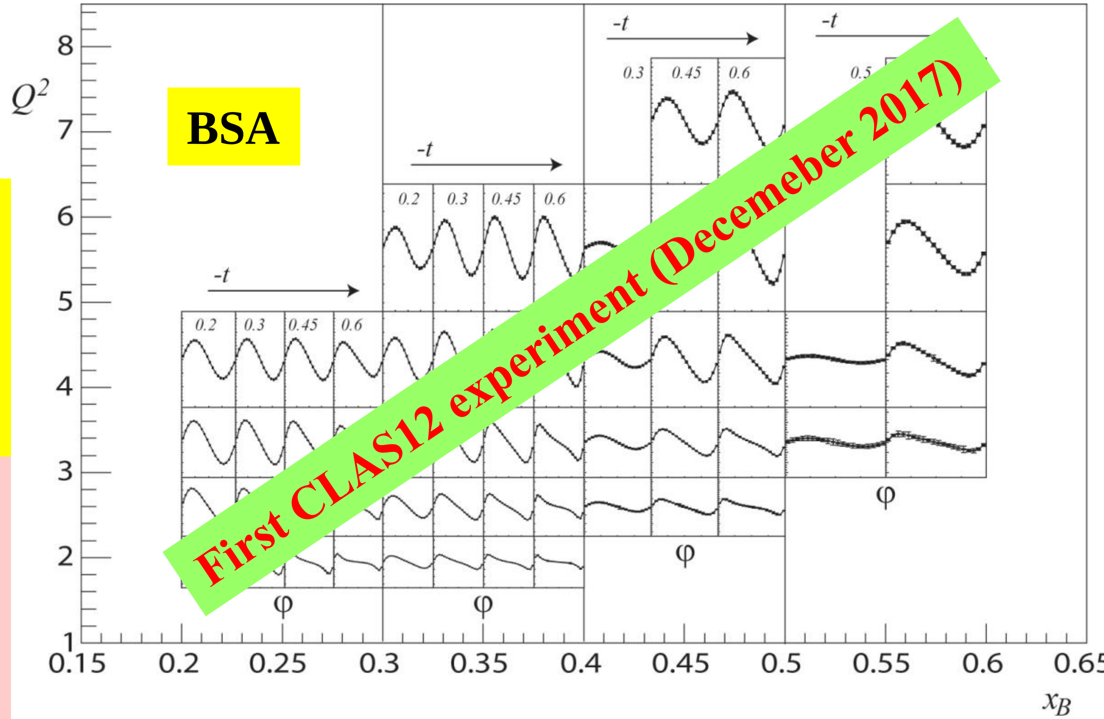


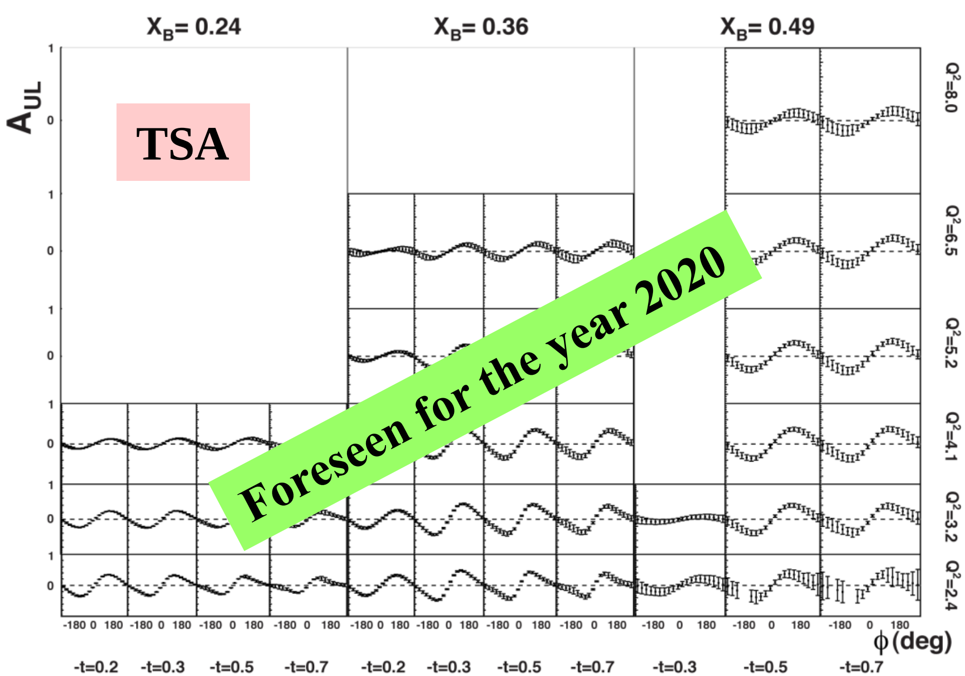
+FT, CND, MM, RICH

DVCS BSA and TSA with CLAS12 & 11 GeV beam

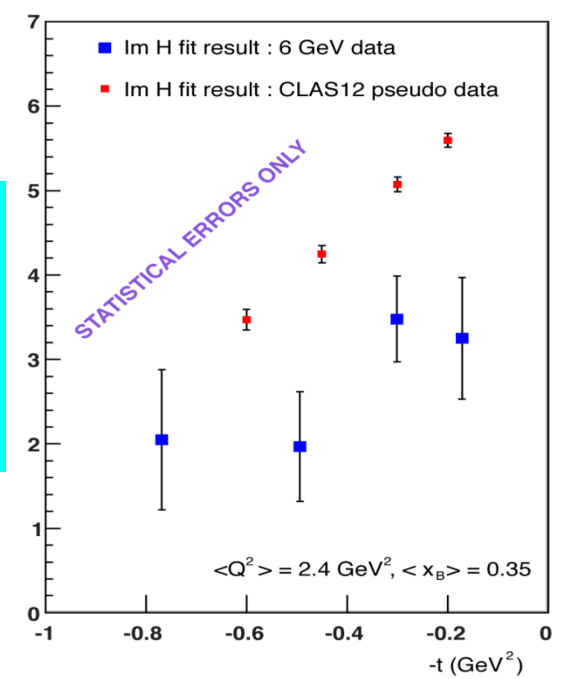
85 days of beam time
P_{beam} = 85%
L = 10^{35} $cm^{-2}s^{-1}$
Statistical error: 1% to 10% on sinϕ moments
Systematic uncertainties: ~6-8%

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

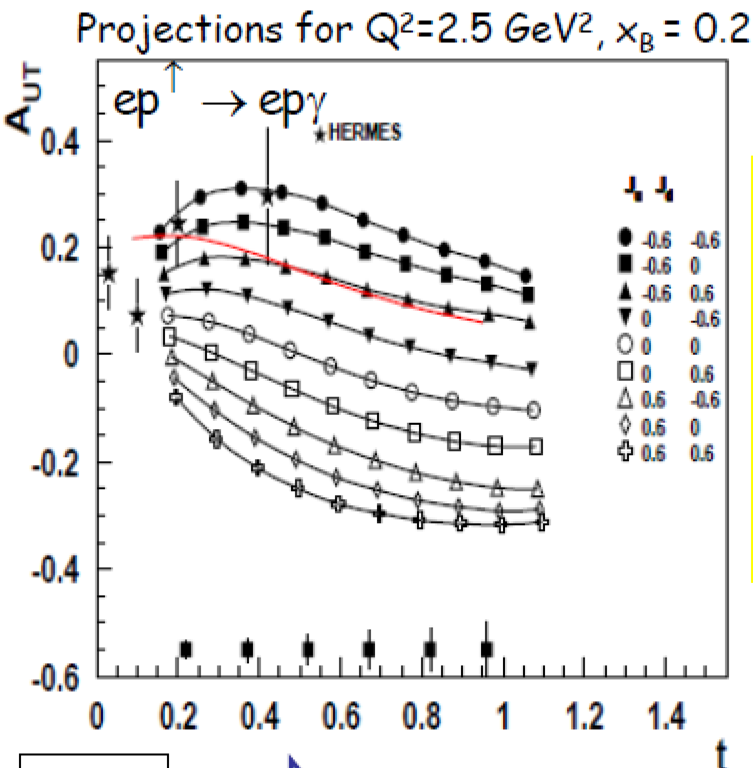


CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time

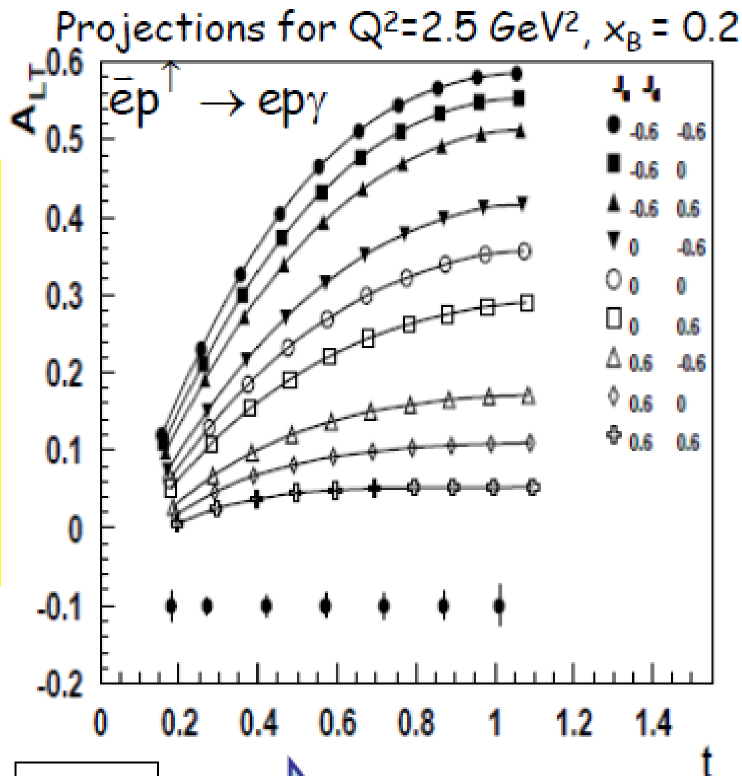
Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = 5×10^{33} $cm^{-2}s^{-1}$

$1 < Q^2 < 10$ 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.

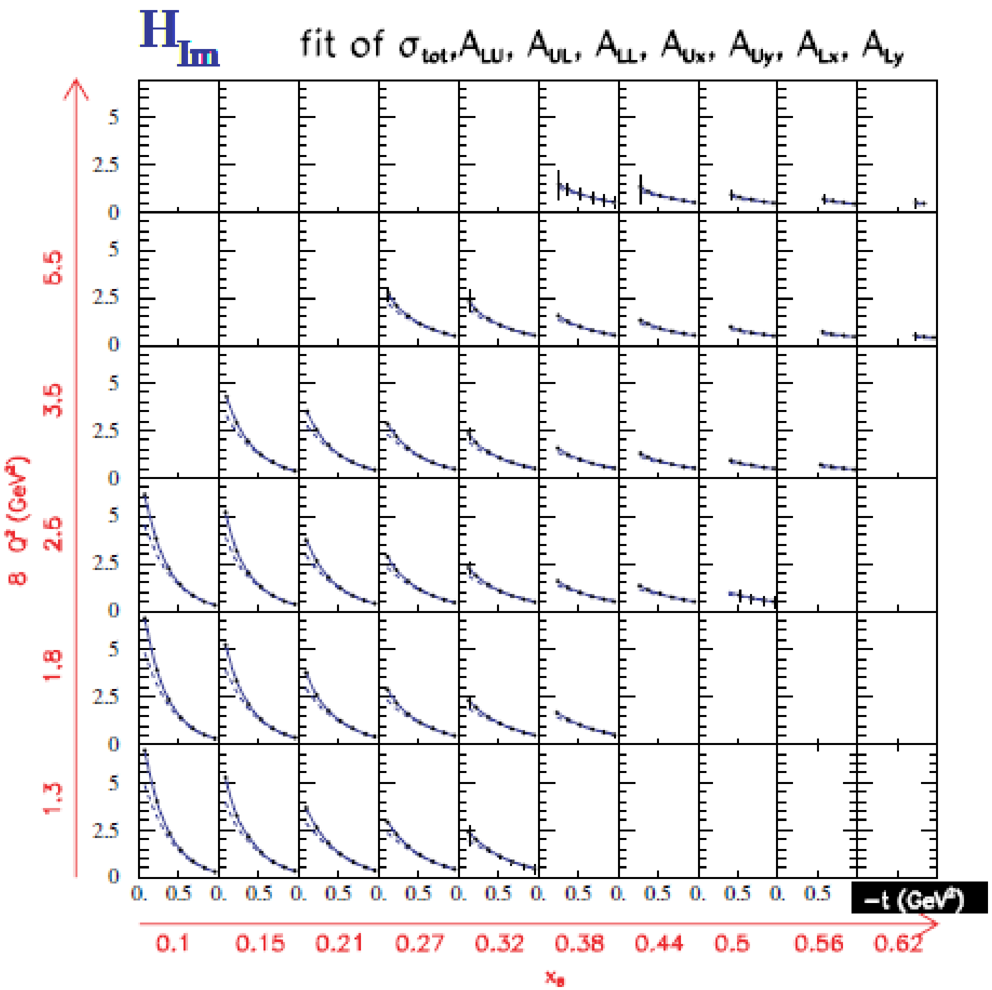


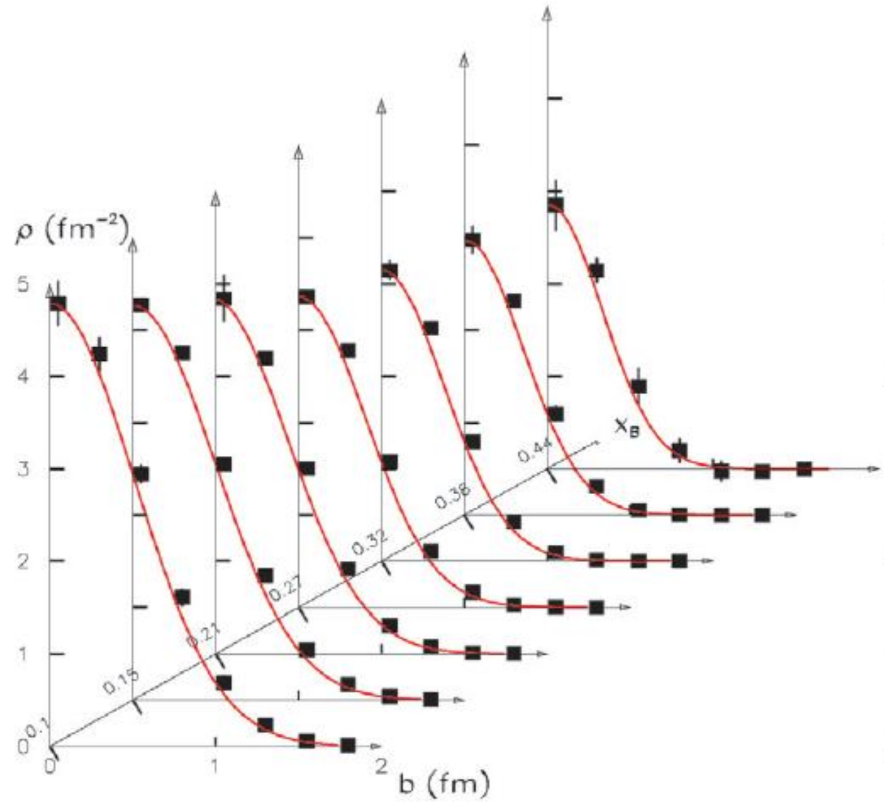
$\Delta\sigma_{LT}$ ⇒ $Re\{\mathcal{H}_p, \mathcal{E}_p\}$

JLab PAC:
high-impact experiment

Proposal conditionally approved by PAC39
Tests on HDIce target are ongoing

From CFFs to spatial densities





Projections for CLAS12

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

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

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

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

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

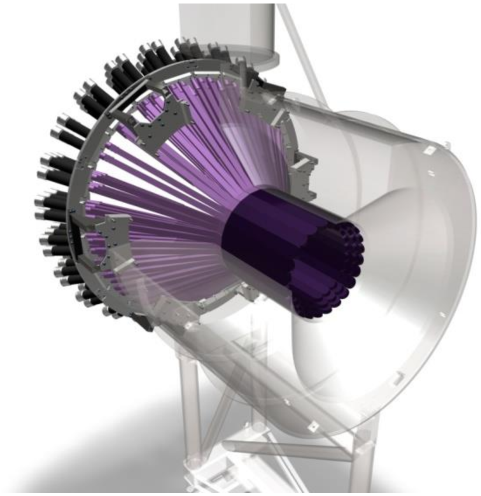
The most sensitive observable to the GPD E

First-time measurement

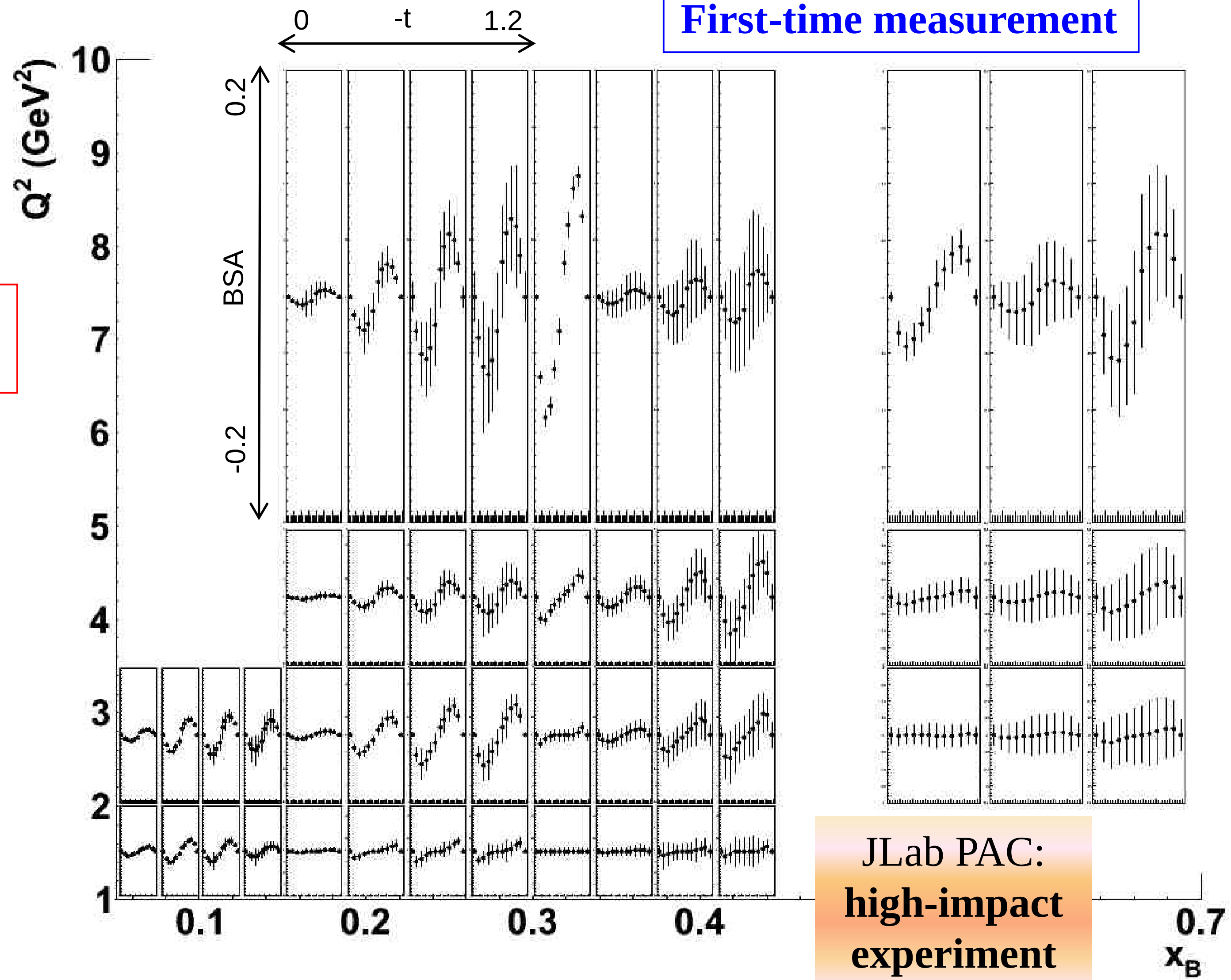
$ed \rightarrow e(p)n\gamma$

CLAS12 +
Forward Calorimeter +
Neutron Detector

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



Installation in 3 weeks (IPN Orsay)



JLab PAC:
high-impact experiment

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

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

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

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

The most sensitive observable to the GPD E

First-time measurement

ed→ e(p)nγ

CLAS12 +

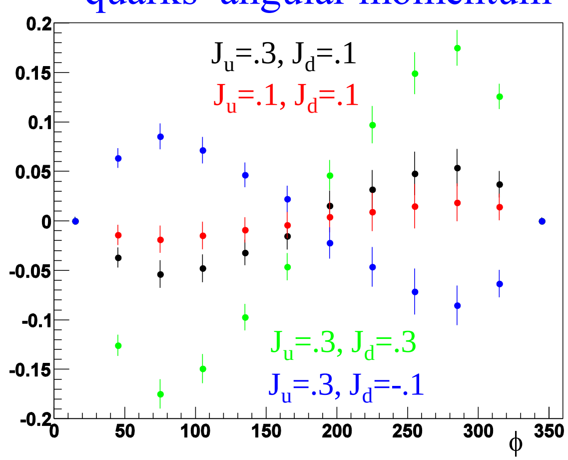
Forward Calorimeter +

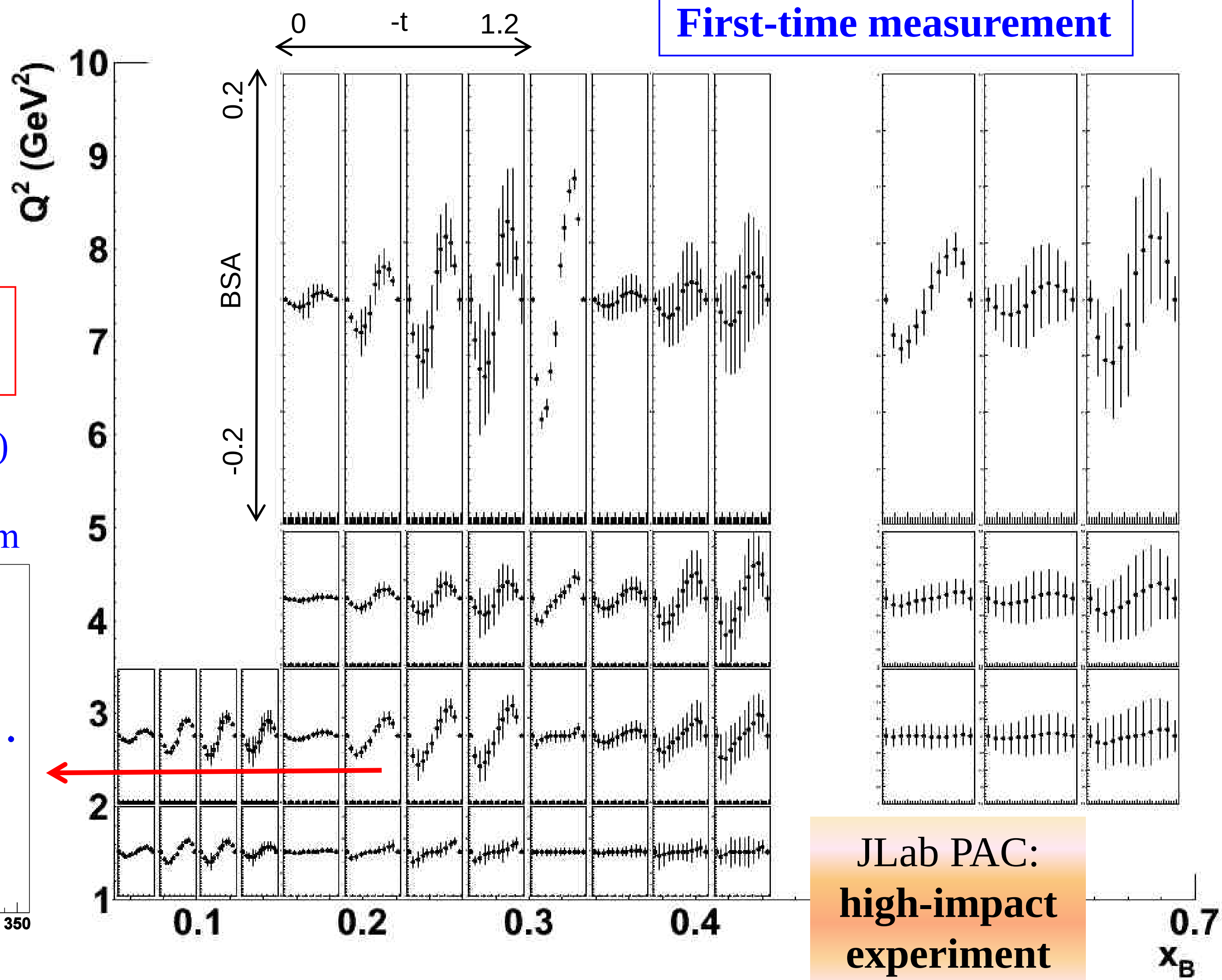
Neutron Detector

80 days of data taking

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

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





JLab PAC:

high-impact experiment

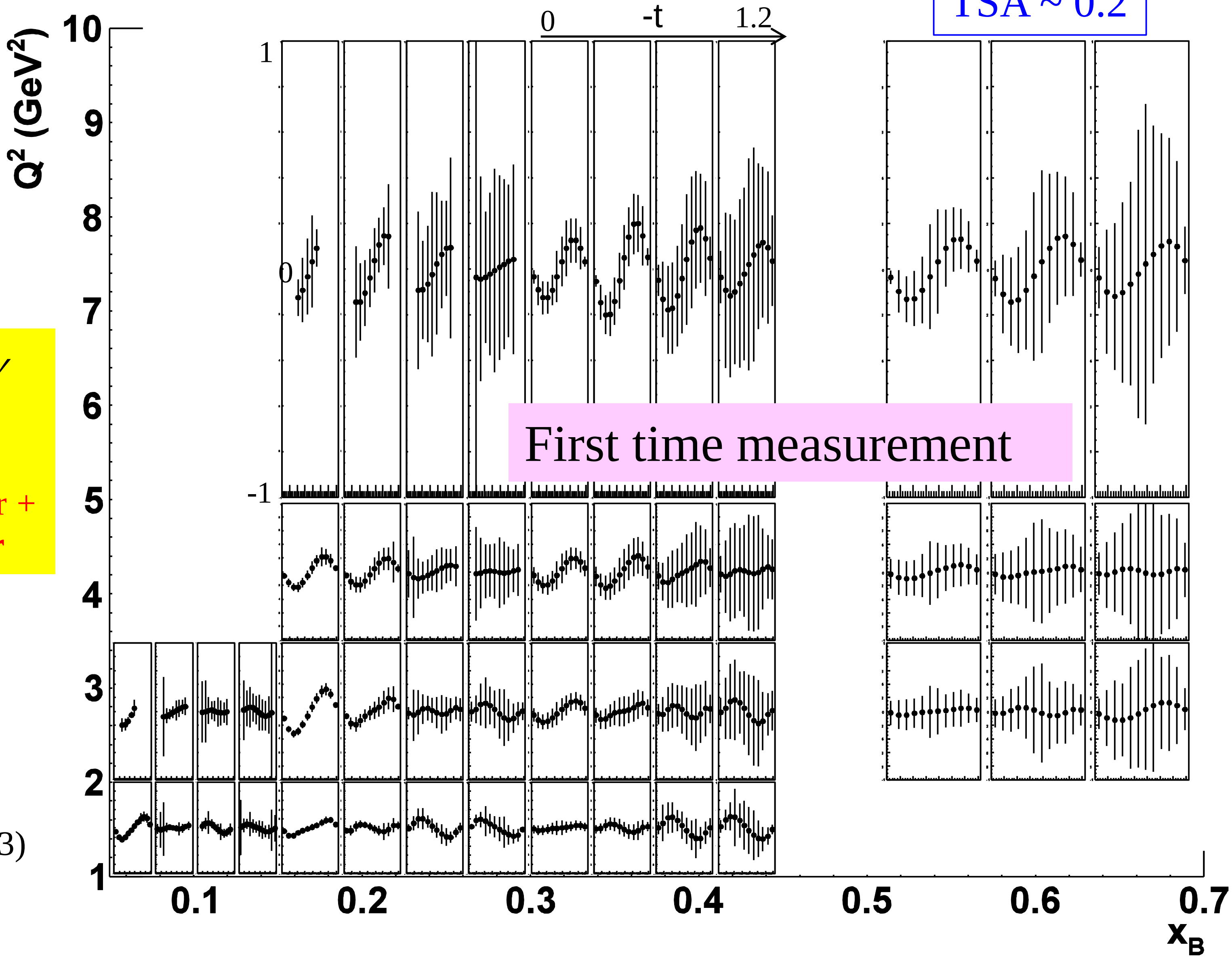
E12-06-109a: nDVCS, target-spin asymmetry

$$\sigma_A = \frac{1}{P_t} \cdot \frac{\sqrt{(1-P_t \cdot A)^2}}{\sqrt{N}}$$

$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \ldots\}$

TSA ~ 0.2

$L = 3/20 \cdot 10^{35} cm^{-2}s^{-1}$
Time = 50 days
$P_t = 0.4$



First time measurement

$eND_3 \rightarrow e(p)n\gamma$
CLAS12 +
Long. pol. target
Forward Calorimeter +
Neutron Detector

- 4 bins in Q^2
- 4 bins in $-t$
- 4 bins in x_B
- 12 bins in φ

(Same as E12-11-003)

E12-06-109a: nDVCS, double spin asymmetry

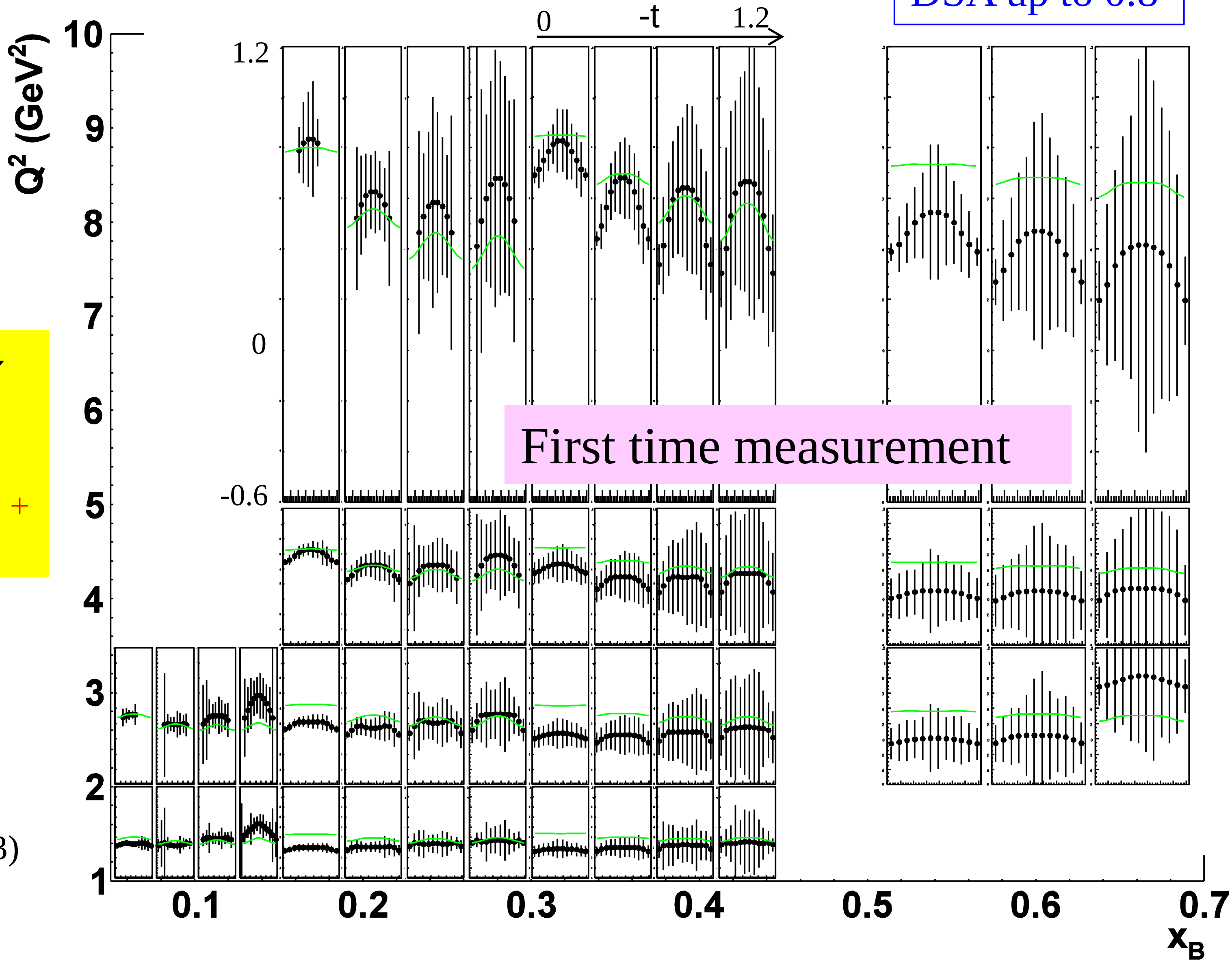
$\Delta\sigma_{LL} \sim (A+B\cos\phi)\ \mathrm{Re}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})-\xi k F_2\tilde{\mathcal{E}}+\ldots\}$

$$\sigma_A = \frac{1}{P_b P_t}\cdot\frac{\sqrt{(1-P_b P_t\cdot A)^2}}{\sqrt{N}}$$

DSA up to 0.8

L = $3/20\cdot10^{35}\,cm^{-2}s^{-1}$
Time = 50 days
P_t = 0.4; P_b = 0.85

$eND_3 \rightarrow e(p)n\gamma$
CLAS12 +
Long. pol. target
Forward Calorimeter +
Neutron Detector



First time measurement

- 4 bins in Q^2
- 4 bins in $-t$
- 4 bins in x_B
- 12 bins in φ

(Same as E12-11-003)

Green curves: Bethe-Heitler

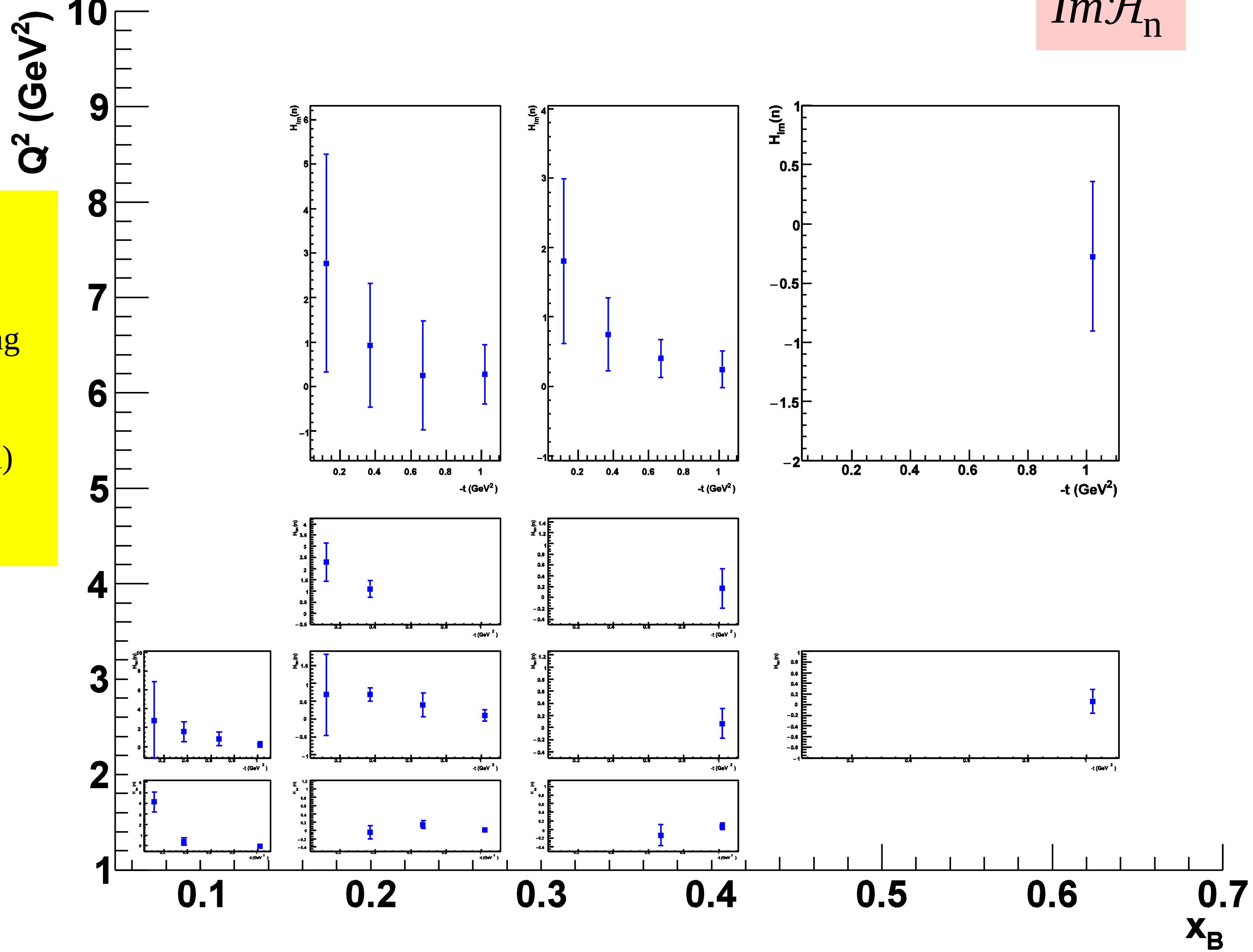
Combined analysis of all nDVCS CLAS12 projections

$Im\mathcal{H}_n$

Extraction of neutron CFFs using M. Guidal's fitting code. Fit of TSA, DSA (E12-06-109a) and BSA (E12-11-003)

7 CFFs as free fit parameters

$Im\tilde{\mathcal{E}} = 0$



DVCS on the nucleon: past, present, future

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**	$\Im m\mathcal{H}_n$		CLAS12
DSA(n)	**Long. pol. ND3**	$\Re e\mathcal{H}_n$		CLAS12

+ Timelike Compton Scattering @ CLAS12, DDVCS (SOLID? CLAS12?)…

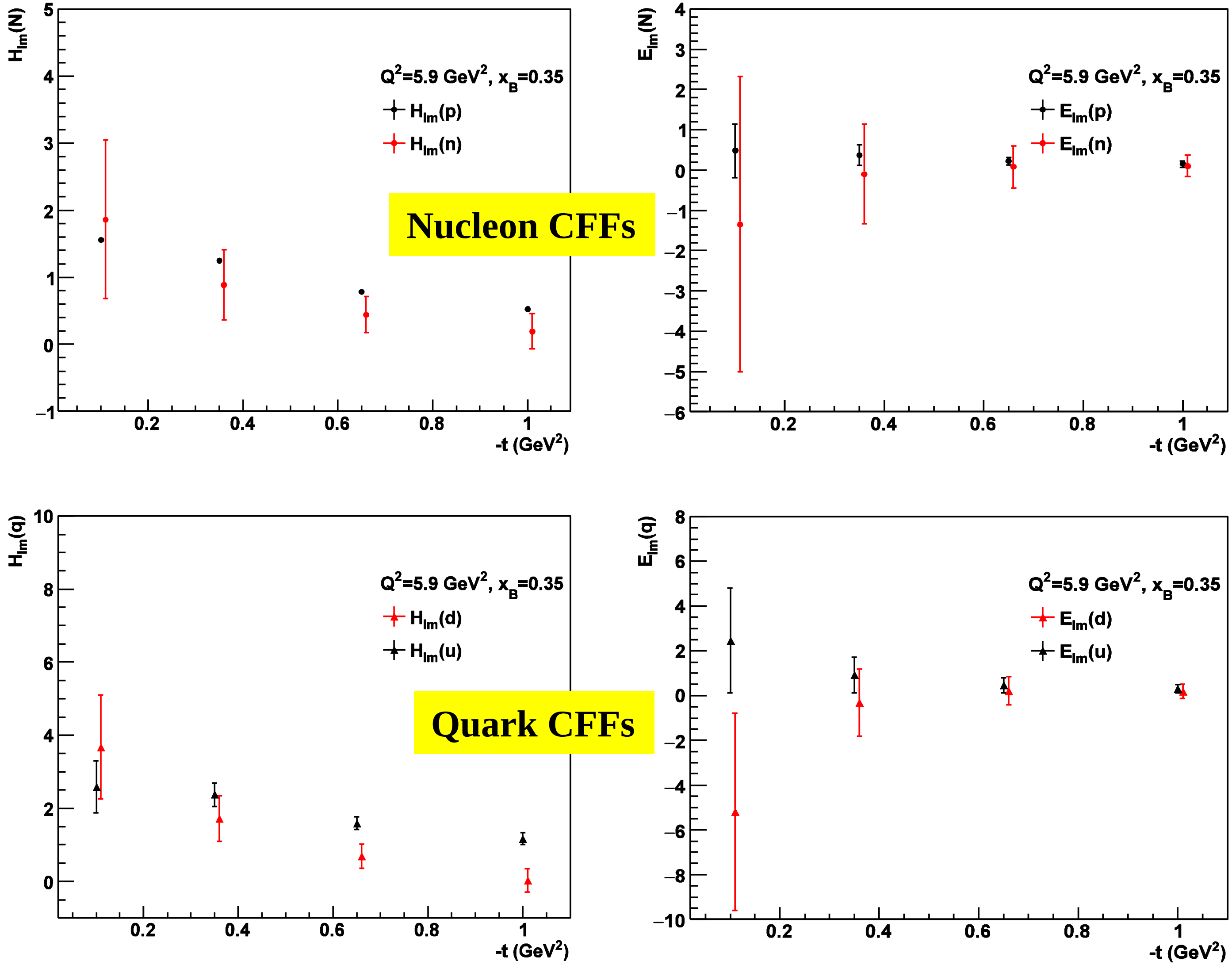
CLAS12: projections for flavor separation ($Im\mathcal{H}$, $Im\mathcal{E}$)

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

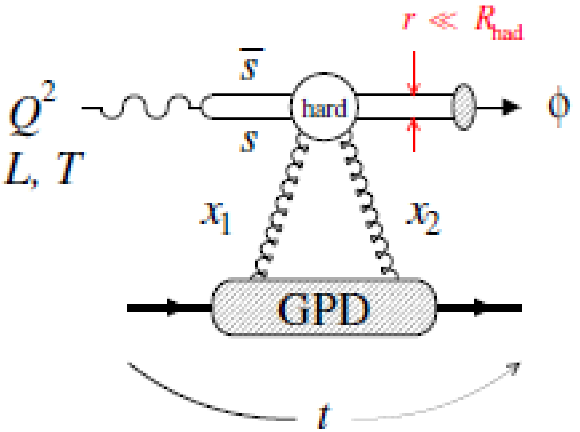
$$(H,E)_d(\xi,\xi,t) = \tfrac{9}{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

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

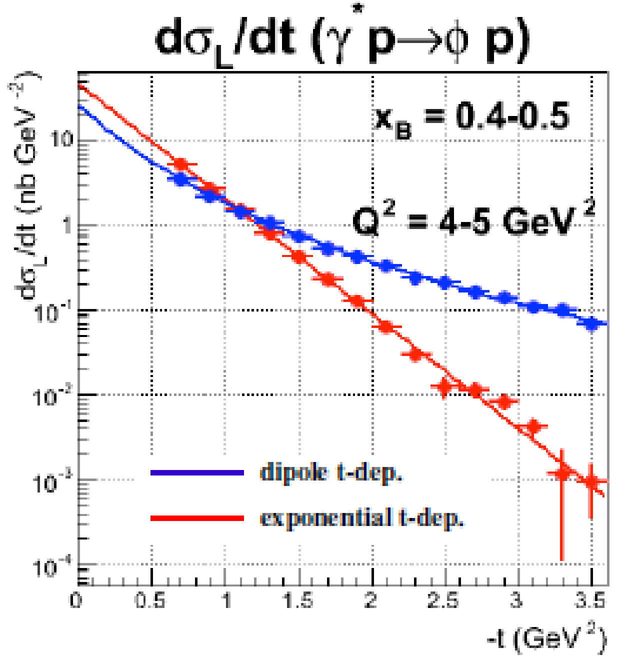
Fits done to all the projected observables for **pDVCS** (BSA, lTSA, lDSA, tTSA, CS, DCS) and **nDVCS** (BSA,lTSA, lDSA) of the CLAS12 program

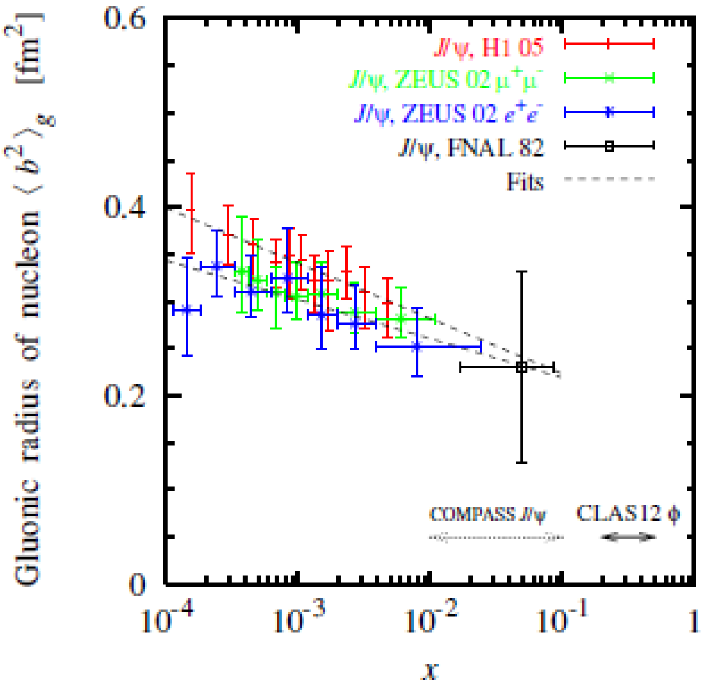


DVMP @ CLAS12: exclusive ϕ electroproduction

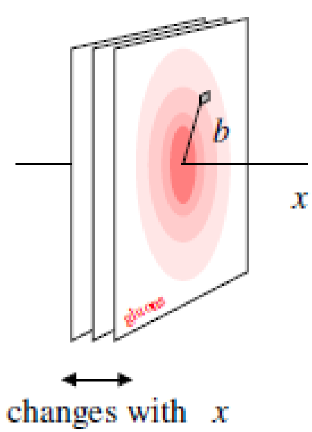


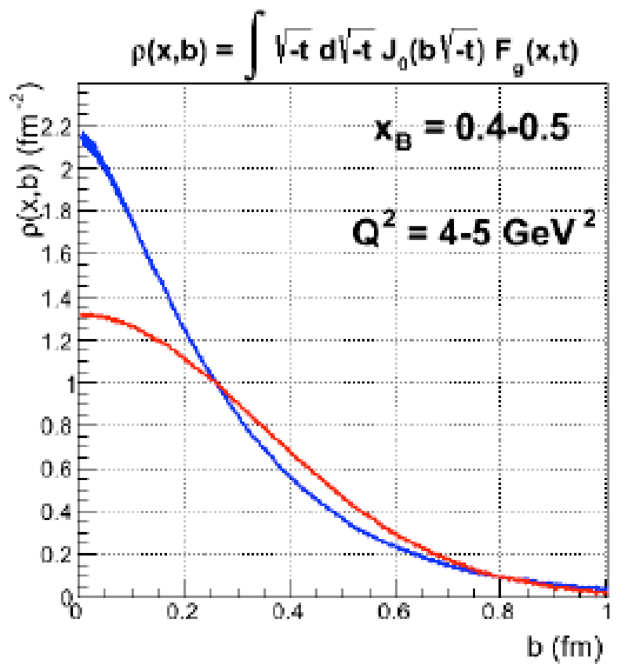
- Differential c.s. → extraction of **structure functions**
- **L-T separation** from **ϕ→KK** decay distributions
- t dependence of $\mathbf{d\sigma_L/dt}$





Transverse distribution of gluons in the proton





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** from DVCS:

- ✓ **valence quarks** are concentrated in its **center**, **sea quarks** at its **perifery**
- ✓ **axial charge** more concentrated than the **electric** one

✓ Things are more complicate for **DVMP**: unexplained low-W behavior for light vector mesons, **transversity GPDs** dominance for pseudo-scalars

→ 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,…**