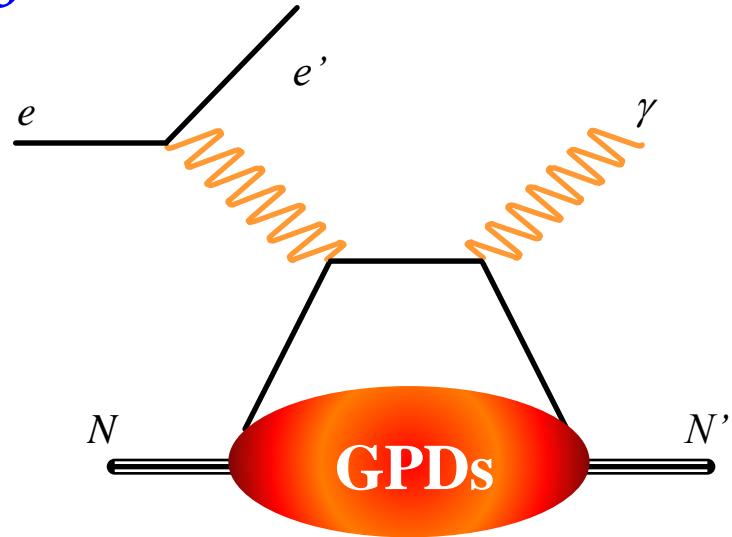


Nucleon structure studies at IN2P3

- Open questions in QCD
- Interest of GPDs for nucleon structure studies
- GPDs and Deeply Virtual Compton Scattering
 - Recent DVCS results from Jefferson Lab
 - The JLab 12 GeV GPD program
 - Plans for the EIC



Silvia Niccolai, IJCLab and CLAS Collaboration



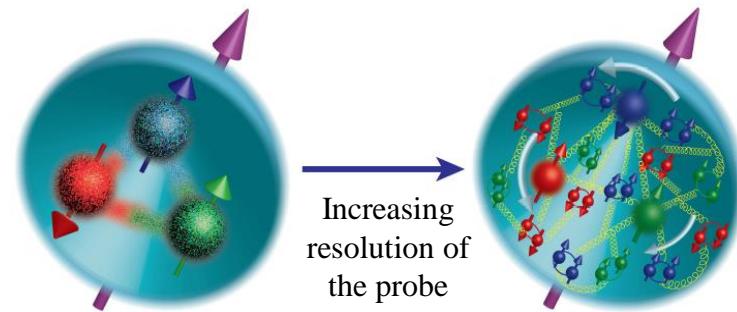
Exploring the partonic structure of the nucleon

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**.

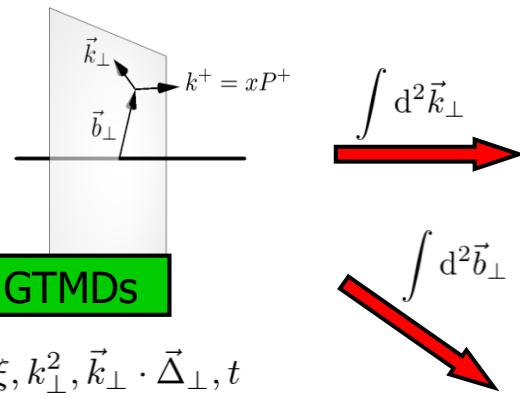
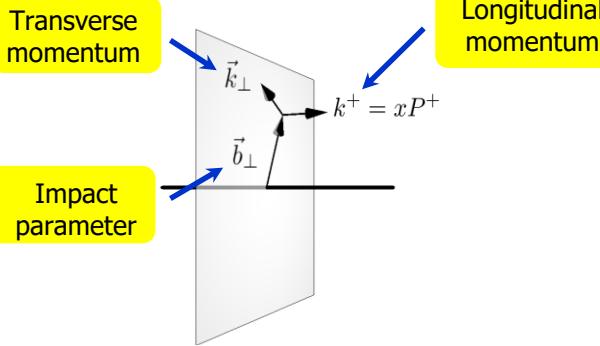


Increasing
resolution
of the probe

- 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?

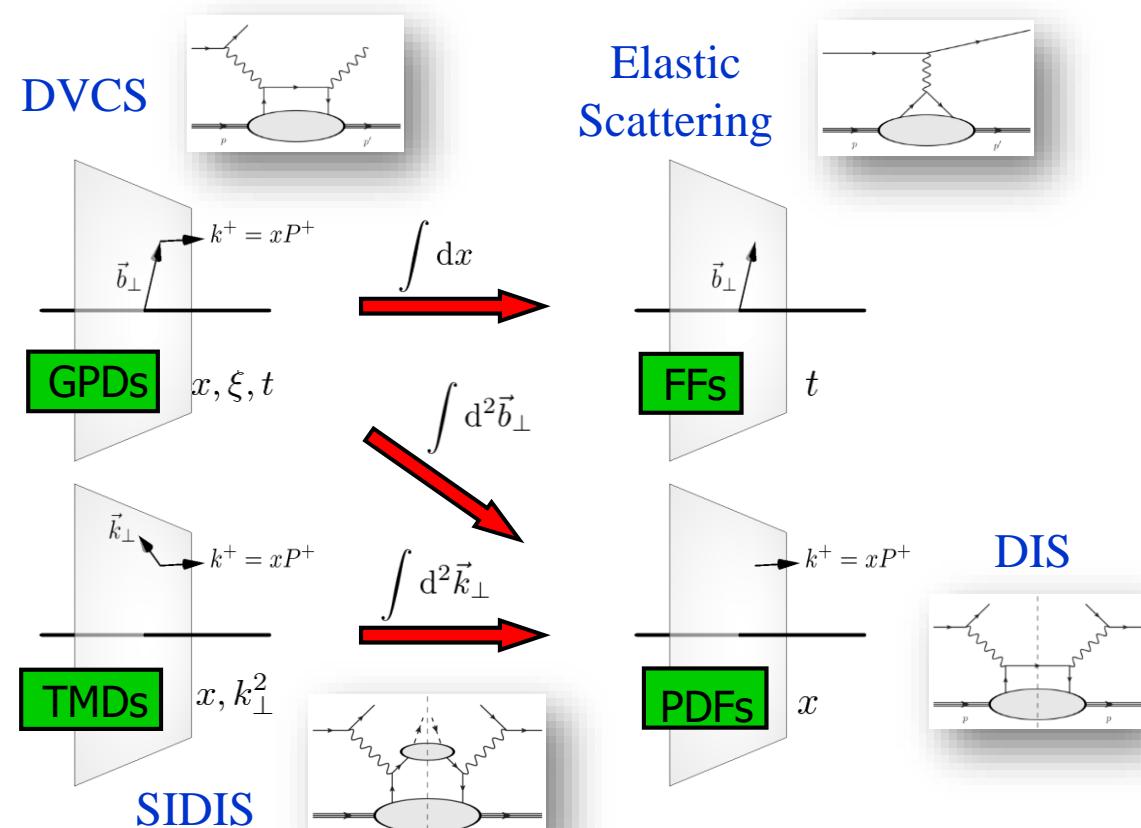
Understanding how the nucleon is built in terms of its underlying quark and gluon degrees of freedom is an important and challenging issue in hadron physics nowadays

Multi-dimensional mapping of the nucleon

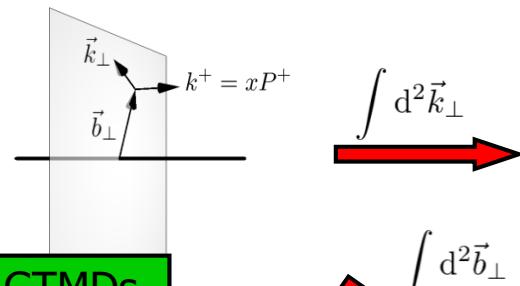
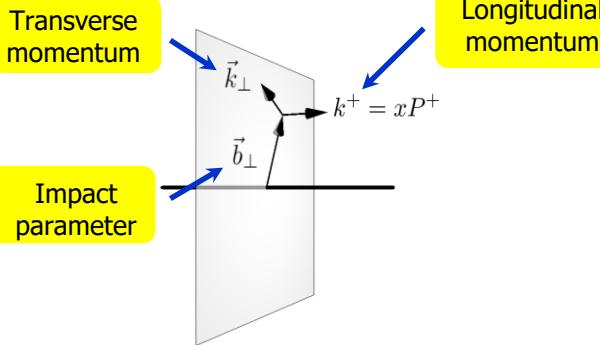


$$x, \xi, k_{\perp}^2, \vec{k}_{\perp} \cdot \vec{\Delta}_{\perp}, t$$

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

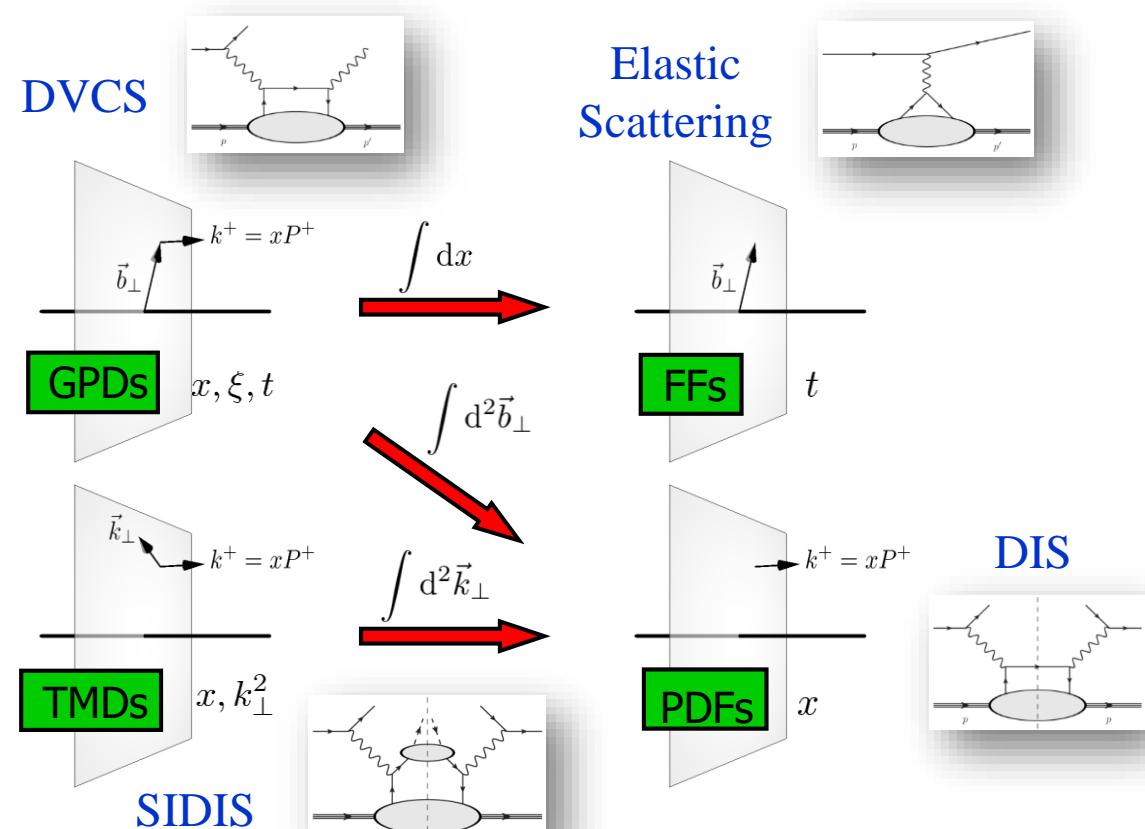


Multi-dimensional mapping of the nucleon

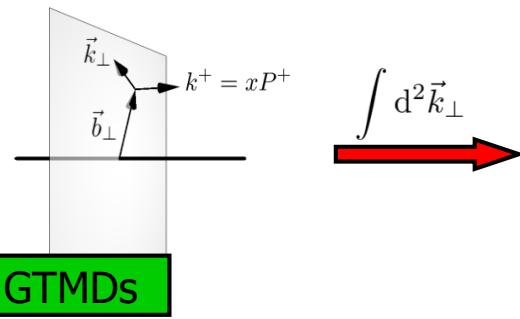
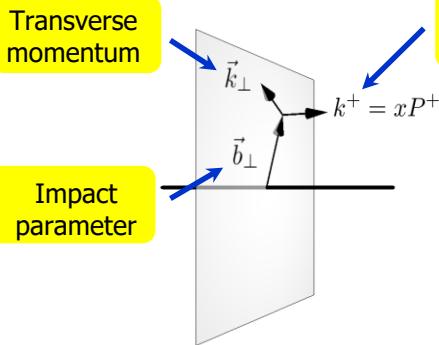


$$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$$

See next talk by A. Guskov for planned measurements of TMDs in hadron-hadron collisions with SPD@NICA



Multi-dimensional mapping of the nucleon

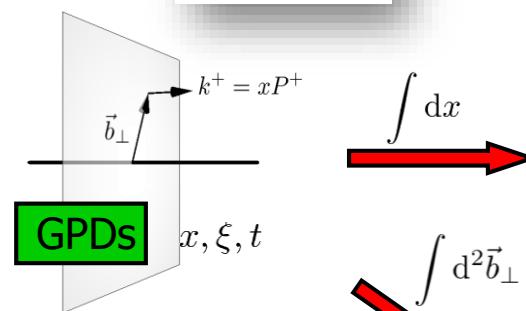
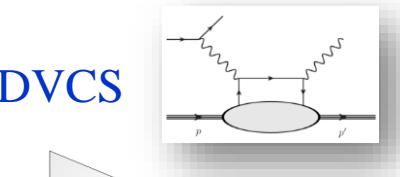


$$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$$

Generalized Parton Distributions:

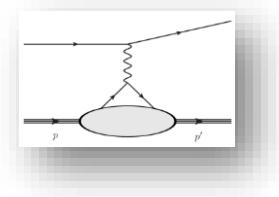
- ✓ fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space
 - ✓ linked to **FFs** and **PDFs**
- ✓ accessible in **hard exclusive** reactions (DVCS, meson production)

DVCS



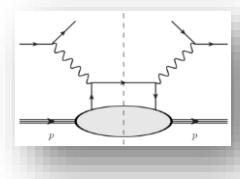
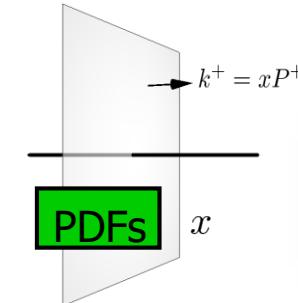
x, ξ, t

Elastic Scattering

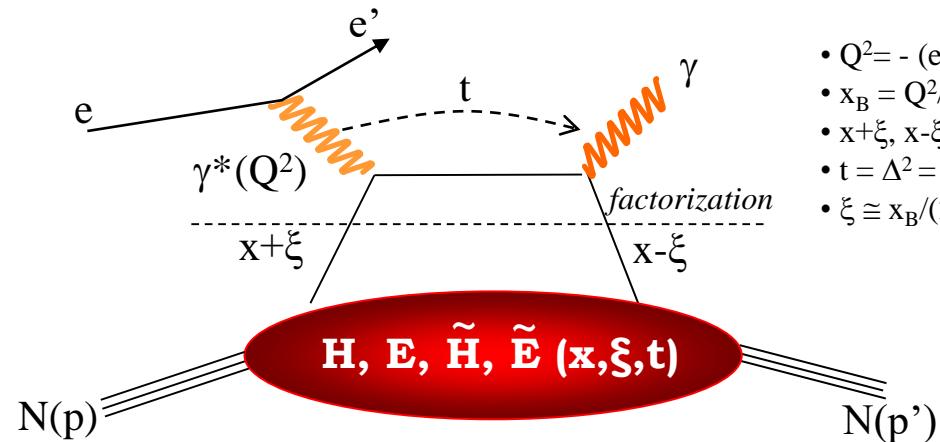


t

DIS



Deeply Virtual Compton Scattering and GPDs



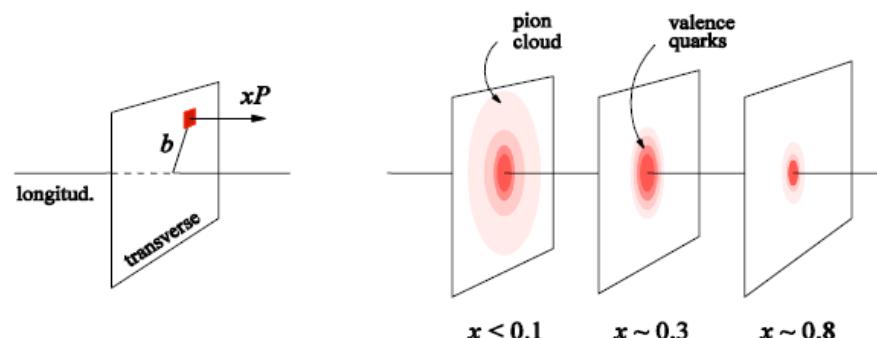
- $Q^2 = -(\mathbf{e} - \mathbf{e}')^2$
- $x_B = Q^2/2Mv$ $v = E_e - E_{e'}$
- $x+\xi, x-\xi$ long. mom. fractions
- $t = \Delta^2 = (\mathbf{p} - \mathbf{p}')^2$
- $\xi \equiv x_B/(2-x_B)$

At leading order QCD, twist 2, chiral-even (quark helicity is conserved), quark sector
→ 4 GPDs for each quark flavor
 Several polarization observables must be measured, different reactions and target types

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

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

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, Phys.Rev.Lett.78,610(1997)

Nucleon spin: $\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta L + \Delta G$

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

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

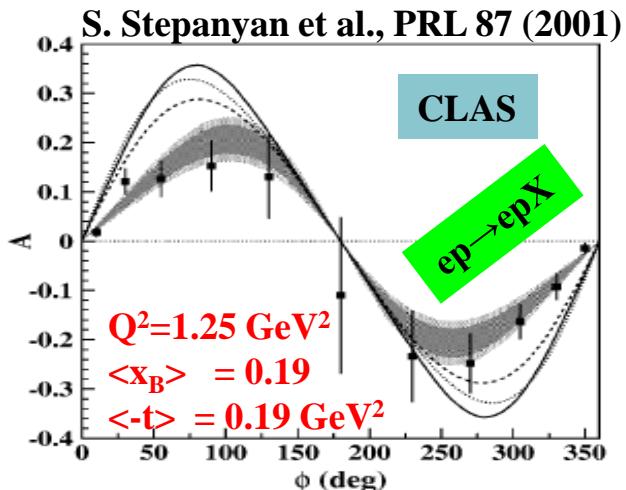
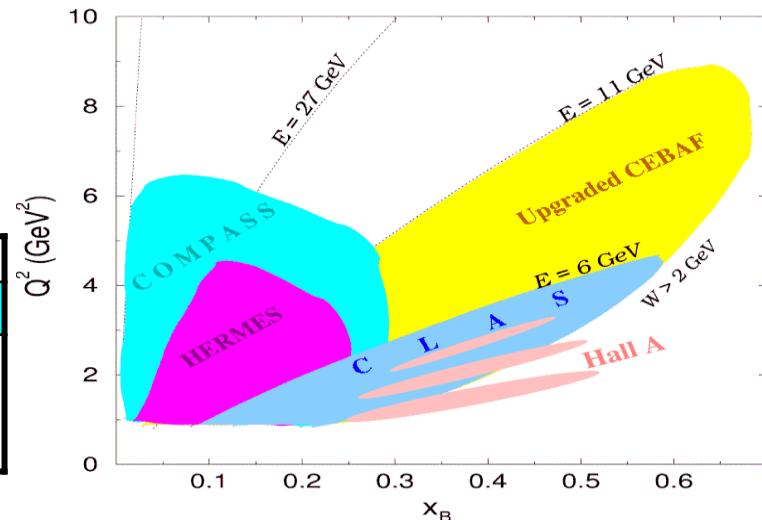
Orbital angular momentum of the quarks ΔL ?

DVCS experiments worldwide

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

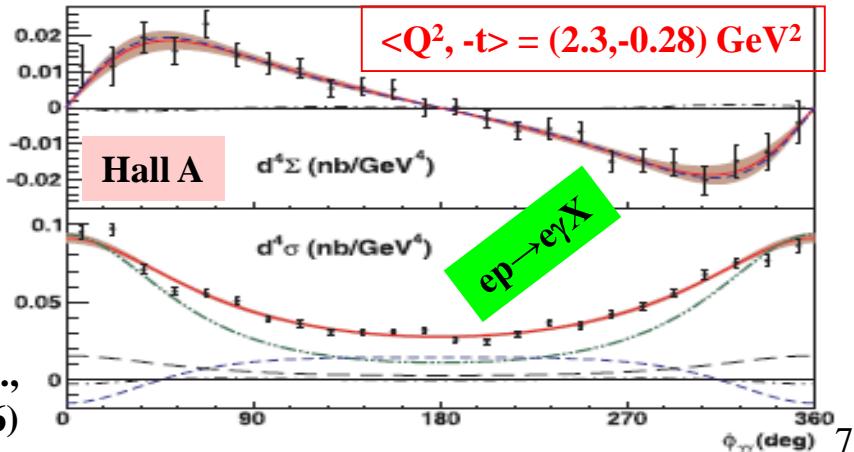
DESY	
HERMES	H1/ZEUS
p-DVCS,BSA,BCA, tTSA,ITSA,DSA	p-DVCS,CS,BCA

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



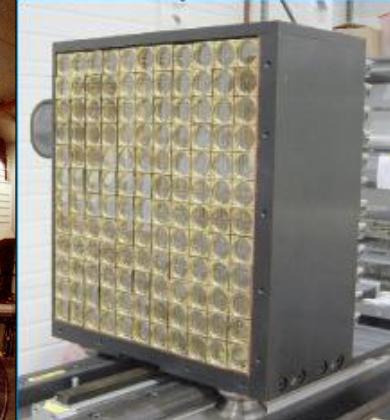
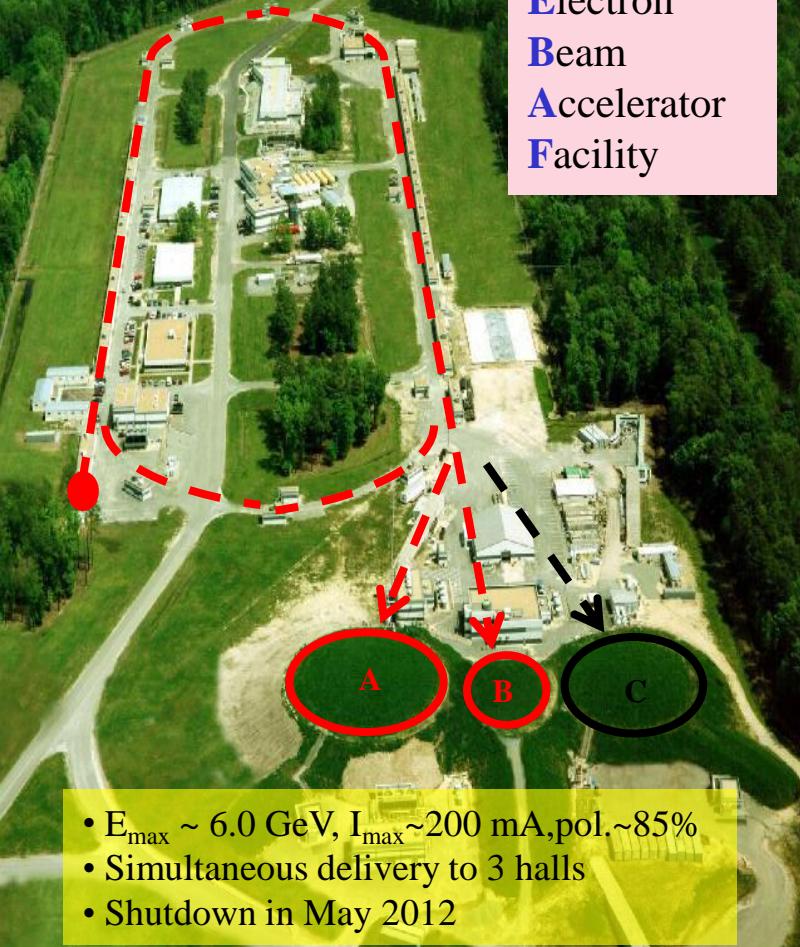
CLAS, HERMES:
 first observation of
 DVCS-BH
 interference

Hall A: proof of
 scaling for DVCS
 C.M. Camacho et al.,
 PRL 97 (2006)



JLab@6 GeV

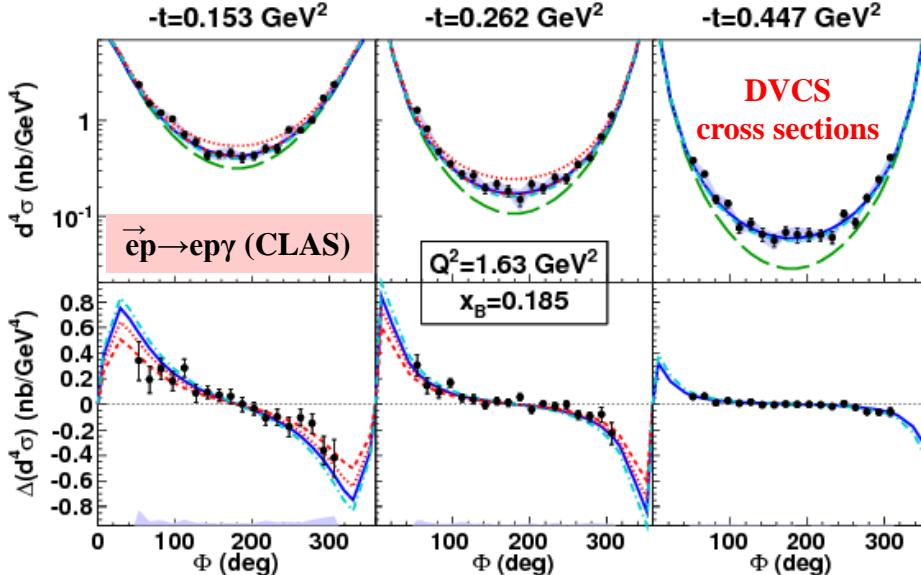
Continuous
Electron
Beam
Accelerator
Facility



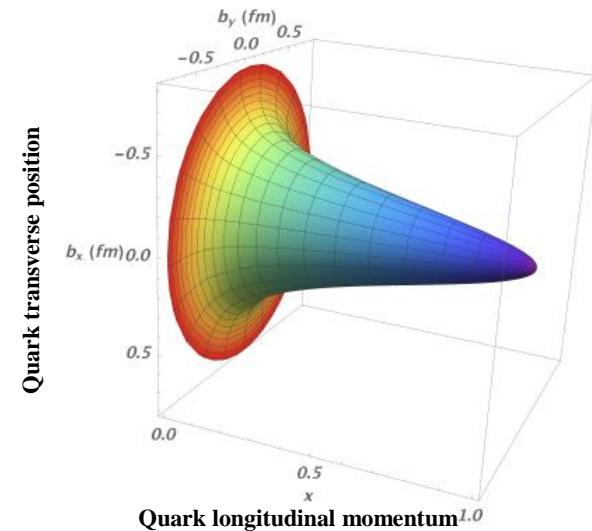
+ dedicated
calorimeters to
detect forward-
emitted DVCS-
BH photons



Results for DVCS with JLab@6 GeV (IN2P3)



From DVCS observables to GPDs
to proton imagining

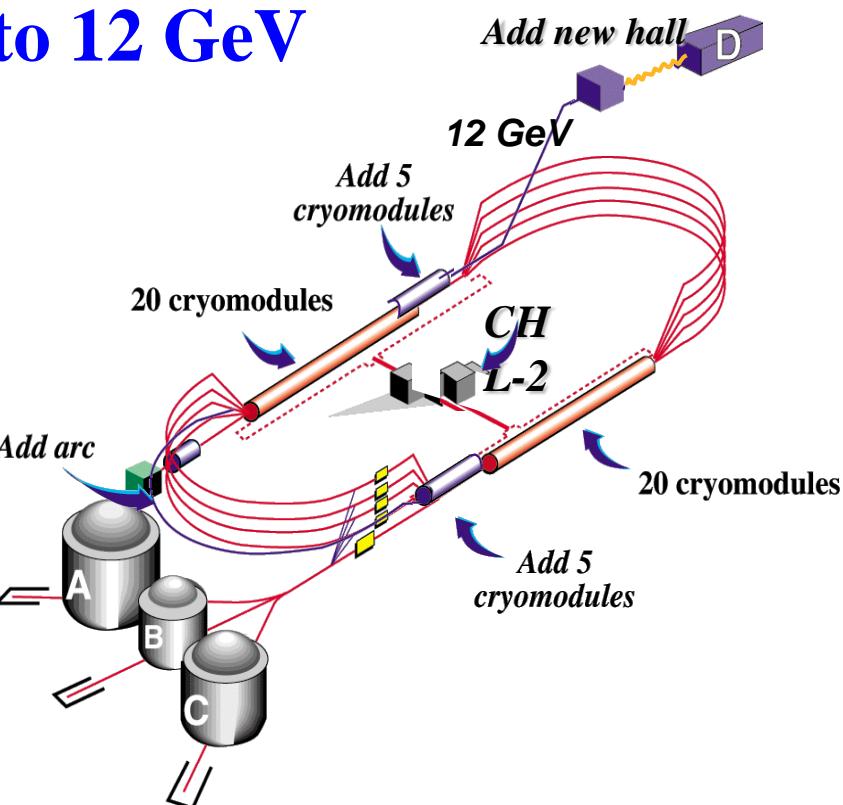
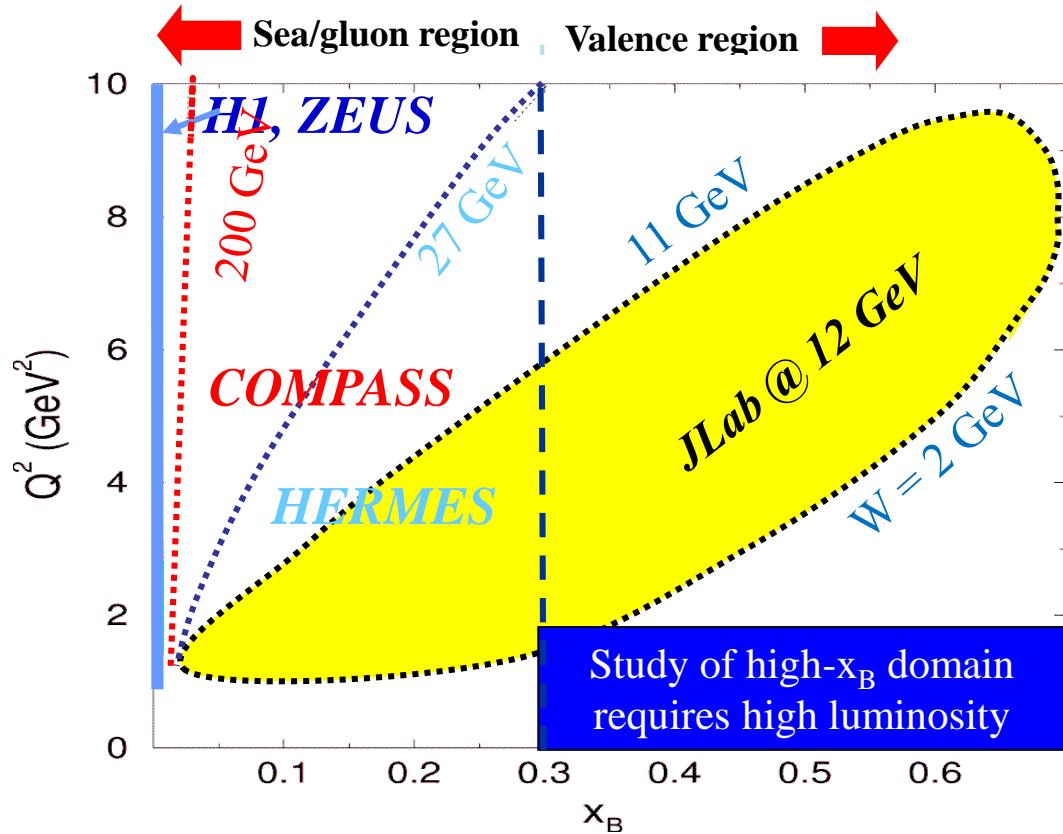


Proton tomography:
➤ Valence quarks are at the core of the proton,
sea quarks are at its periphery

PRD95, 011501 (2017); EPJA 53, 171 (2017)

JLab upgrade to 12 GeV

Upgrade of CEBAF completed in 2015



IN2P3 physicists are spokespersons in all the GPD experiments planned for the 12-GeV program of JLab (Halls A, B, C)

DVCS on the neutron with CLAS12 - JLab@12 GeV

Central Neutron Detector



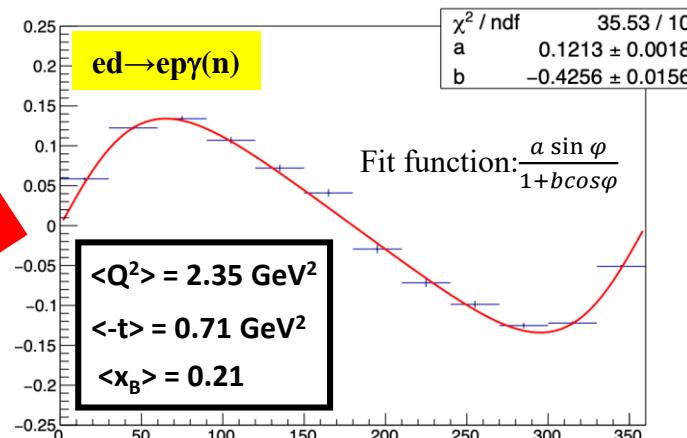
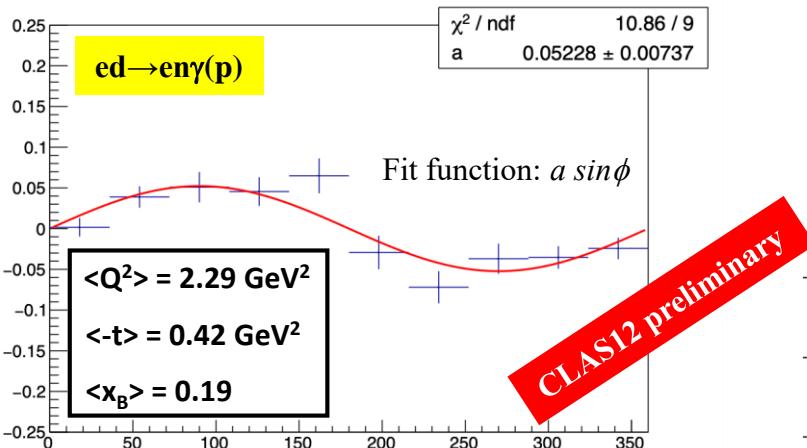
Goals: extract the E GPD (\rightarrow quarks' angular orbital momentum),
flavor separation of GPDs

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

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

Data taking in 2019-early 2020 \rightarrow ~1/2 half of the approved beam time
Obtained PAC approval for 2nd half

Ongoing analyses at IJCLab:
Beam-spin asymmetries for nDVCS and pDVCS
PRL foreseen for summer 2021



nDVCS
experiment on
longitudinally
polarized target
will run in 2022

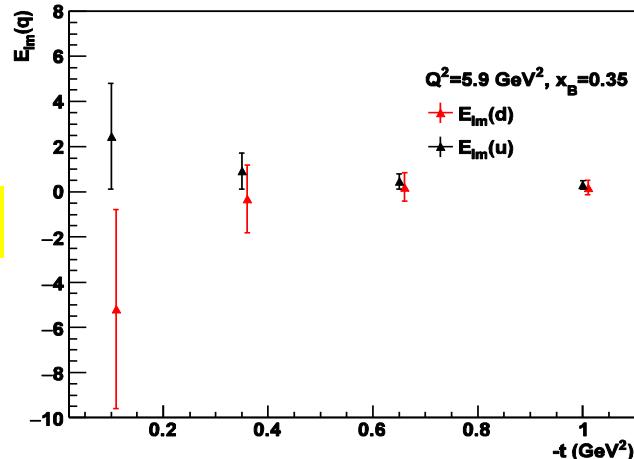
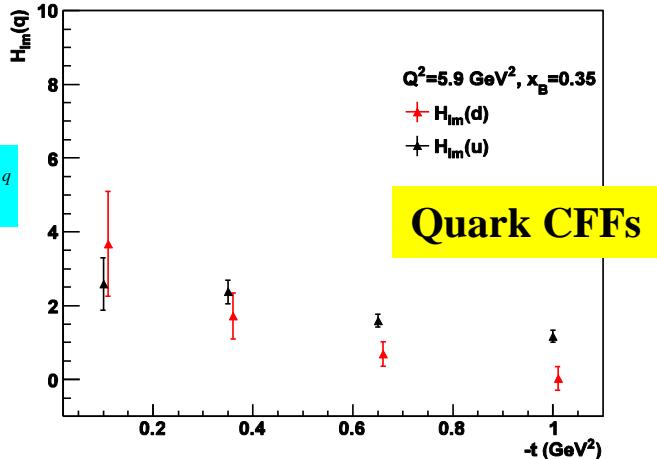
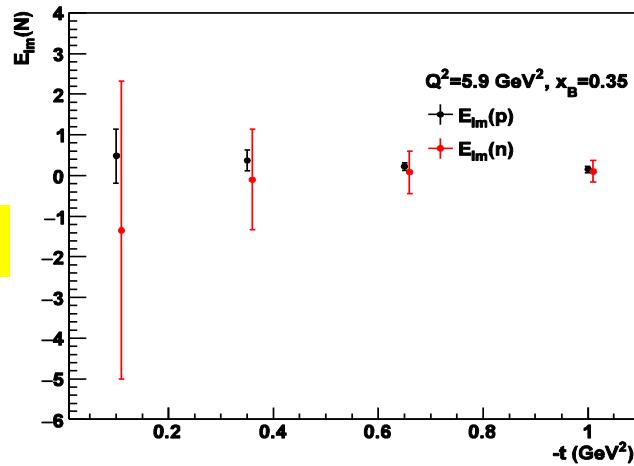
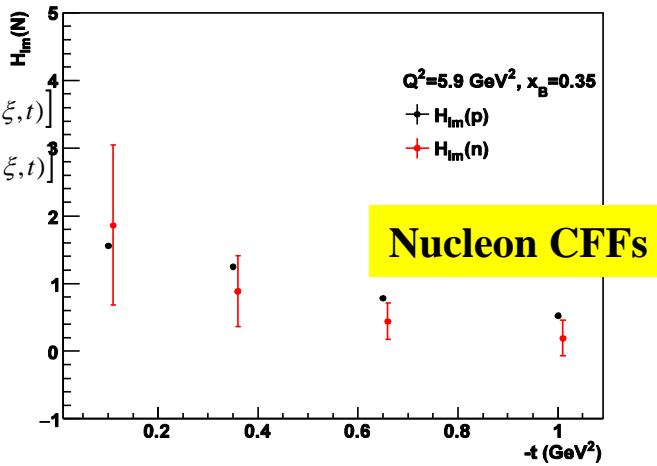
CLAS12: projections for flavor separation ($\text{Im}\mathcal{H}$, $\text{Im}\mathcal{E}$)

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

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

Fits done to all the projected observables for pDVCS (BSA, ITSA, IDSA, tTSA, CS, Δ CS) and nDVCS (BSA, ITSA, IDSA) of the CLAS12 program

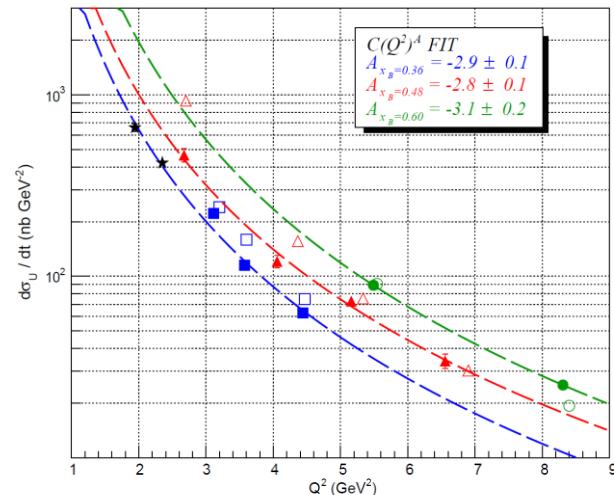
$$\frac{1}{2} \int_{-1}^1 x dx (H^q(x, \xi, t=0) + E^q(x, \xi, t=0)) = J^q$$



GPDs at JLab@12 GeV: beyond DVCS

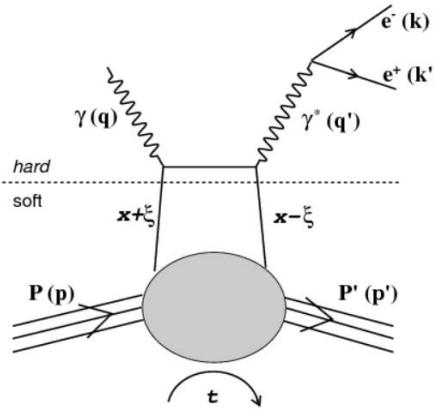
Hall A 11 GeV DVCS experiment:
results submitted to Phys. Rev. Lett.

$e p \rightarrow e p \pi^0$ cross section
for $x_B = 0.36, 0.48, 0.60$

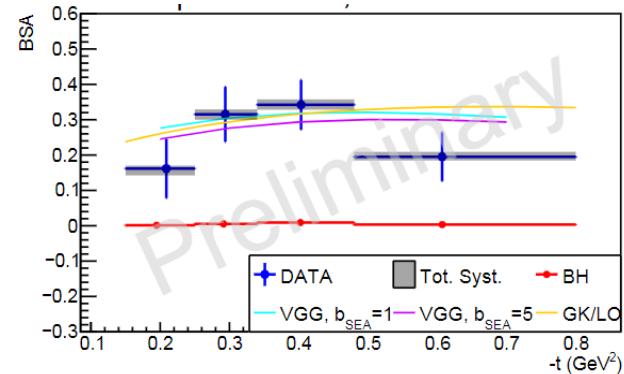


Dominance of the transverse amplitude: access to transversity GPDs of the nucleon

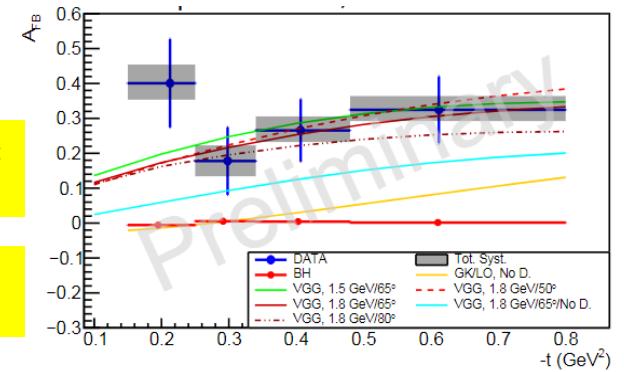
CLAS12@11 GeV: First-time observation of Timelike Compton Scattering - PRL in preparation



Beam-spin asymmetry for TCS (BSA):
Test of universality of GPDs



Forward-backward asymmetry (A_{FB}):
Access to mechanical properties of the proton



Plan for JLab@12 GeV...and beyond

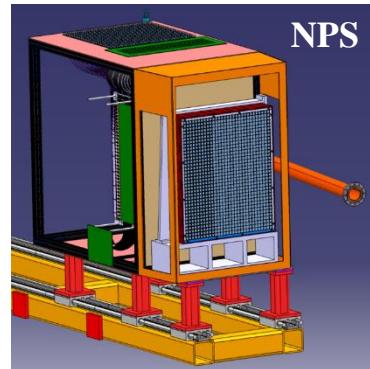
All these experiments have **IJCLab spokespersons** and a **technical contribution** of IN2P3

pDVCS and nDVCS à CLAS12 + CND with longitudinally
(2022) and transversely (~2025) polarized target

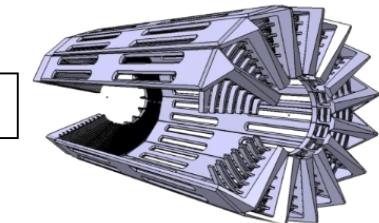


NPS

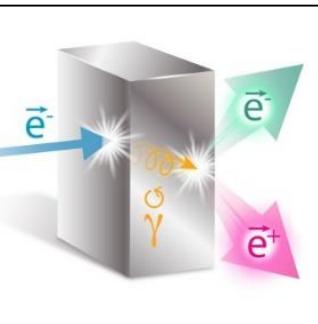
pDVCS and π^0 @ Hall C + NPS (2022-2023)



DVCS on nuclei – ALERT @ CLAS12 (2023)



GPDs with polarized positrons beam (> 2025)



Long term: Electron-Ion Collider (EIC) (>2028)

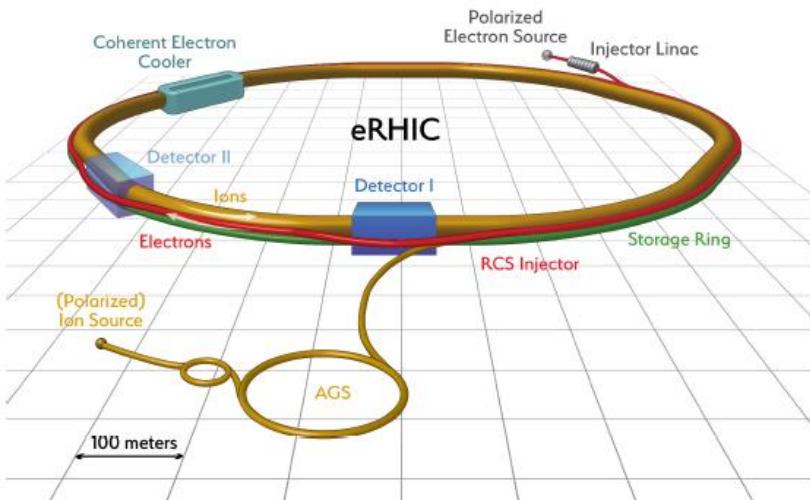
Electron-Ion Collider (EIC)

Open questions in QCD, in the gluons sector:

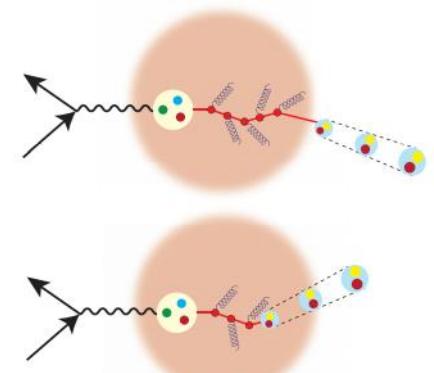
- Saturation: QCD in the non-linear regime
- Distributions of position, momentum, angular momentum...
- Role of gluons in the nuclear medium

EIC: the ideal laboratory to study QCD at high E /small x

EIC will be at Brookhaven National Lab



Start of operation: 2030



➤ Collisions e-p/A at EIC:

- ✓ Polarized beams : e, p, d/ 3 He
- ✓ Electron beam : 3-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$ (100-1000 x HERA)
- ✓ $E_{cdm} = 20-100$ (140) GeV
- ✓ Wide choice of ions

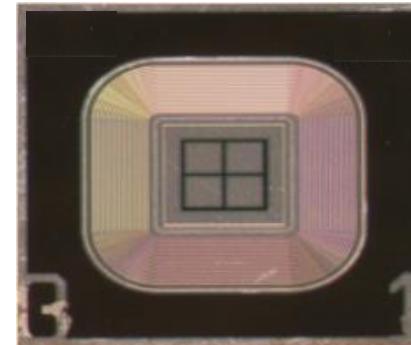
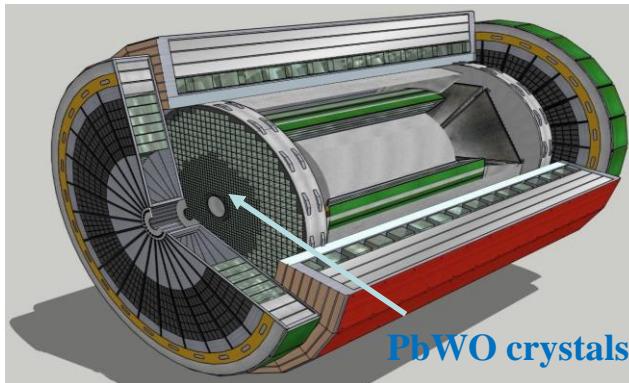
**EIC Users group: 1174 physicists (+ students & engineers),
33 countries, 240 institutions (>30% europeans)**

EIC was presented at the Scientific Council of IJCLab (11/2020)

EIC activities at IN2P3 (IJCLab)

- After CD-0, the EIC project started with an **intense program of activities**:
 - The **EIC Yellow Report**: participation of IJCLab as conveners of the physics group and sub-group devoted to exclusive processes.
 - **Expression of Interest (EoI)** for the construction of detectors (11/2020)
 - **Projects at IJCLab:**
 - Calorimetry: conception, mechanics (R&D activity started in 2015 with BNL funds)
 - Roman pots: micro-electronics R&D, development and test of an ASIC prototype coupled to an LGAD-AC new generation sensor (collaboration IJCLab, IJCLab/PHE/ATLAS-HGTD, OMEGA, BNL)

EIC detector concept



Proposed detector technology for the Roman Pots:
AC-coupled Low Gain Avalanche Diodes (LGADs)

Summary

- ✓ The study of the how **nucleon properties** arise from the **dynamics of its constituents** is one of the central issues in nuclear/hadron physics
- ✓ GPDs are a unique tool to explore the **internal dynamics of the nucleon – complementary to TMDs**:
 - **3D quark/gluon imaging** of the nucleon
 - **orbital angular momentum** carried by quarks
- ✓ Many **results** on various DVCS observables from JLab (**CLAS** and **Hall-A**) experiments at 6 GeV
 - First **tomographic interpretations** of the quarks in the **proton**:
 - ✓ **valence quarks** are concentrated in its **center**, **sea quarks** at its **perifery**
- ✓ The 12-GeV-upgraded JLab is **the only facility** to perform DVCS experiments **in the valence region**, for Q^2 up to 11 GeV
- ✓ Long term: **EIC** to study the impact of **gluons** in nucleon structure – **complementary to SPD@NICA**

Back-up slides

BSA for DVCS on the *neutron* with CLAS12

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

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

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

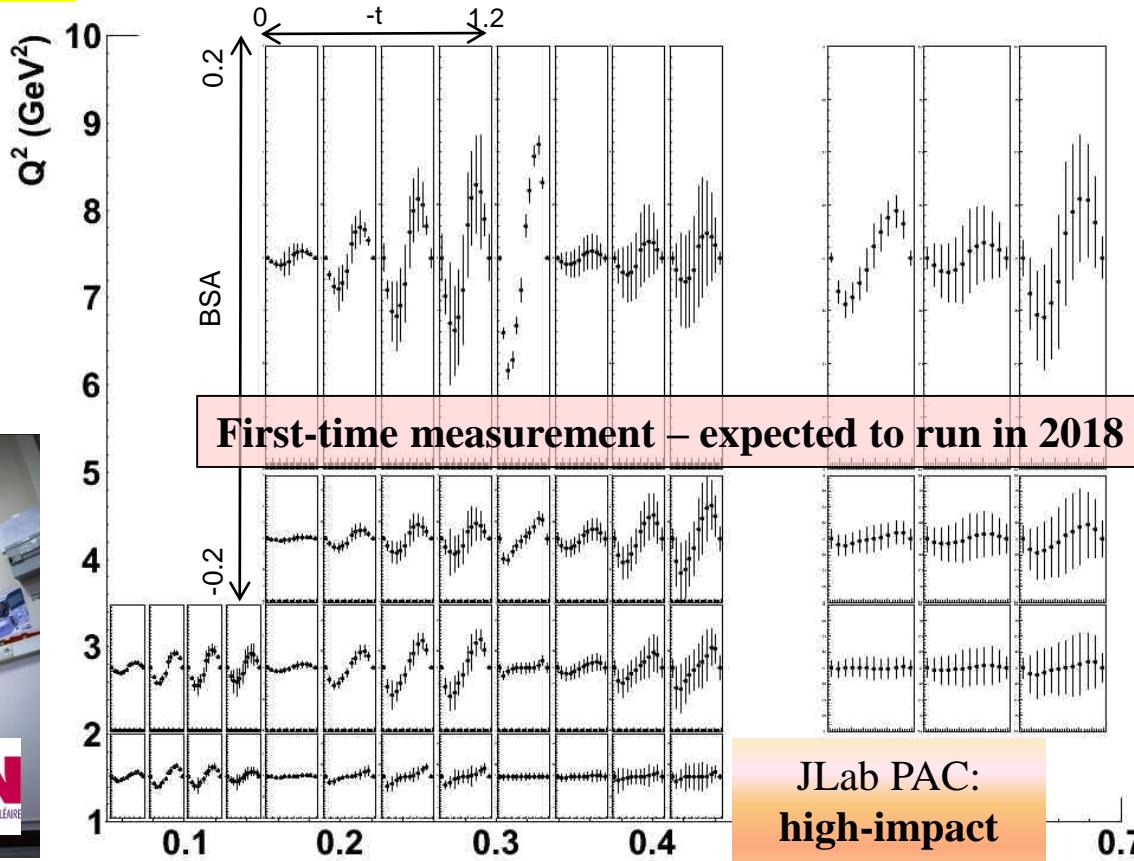
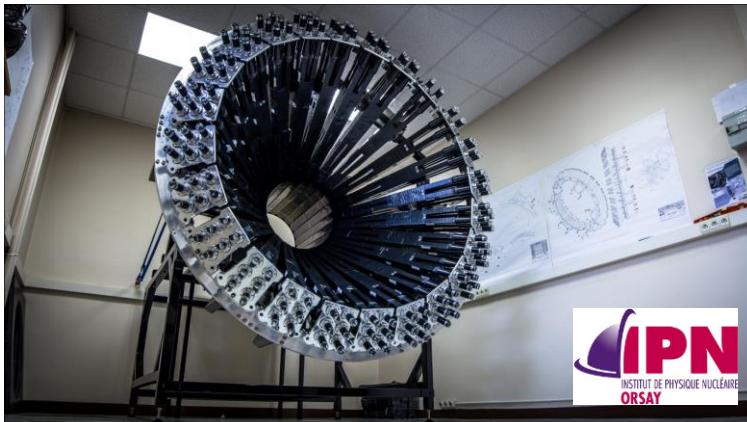
- The most sensitive observable to E

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

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

- Flavor separation of CFFs

Central Neutron Detector



BSA for DVCS on the *neutron* with CLAS12

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

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

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

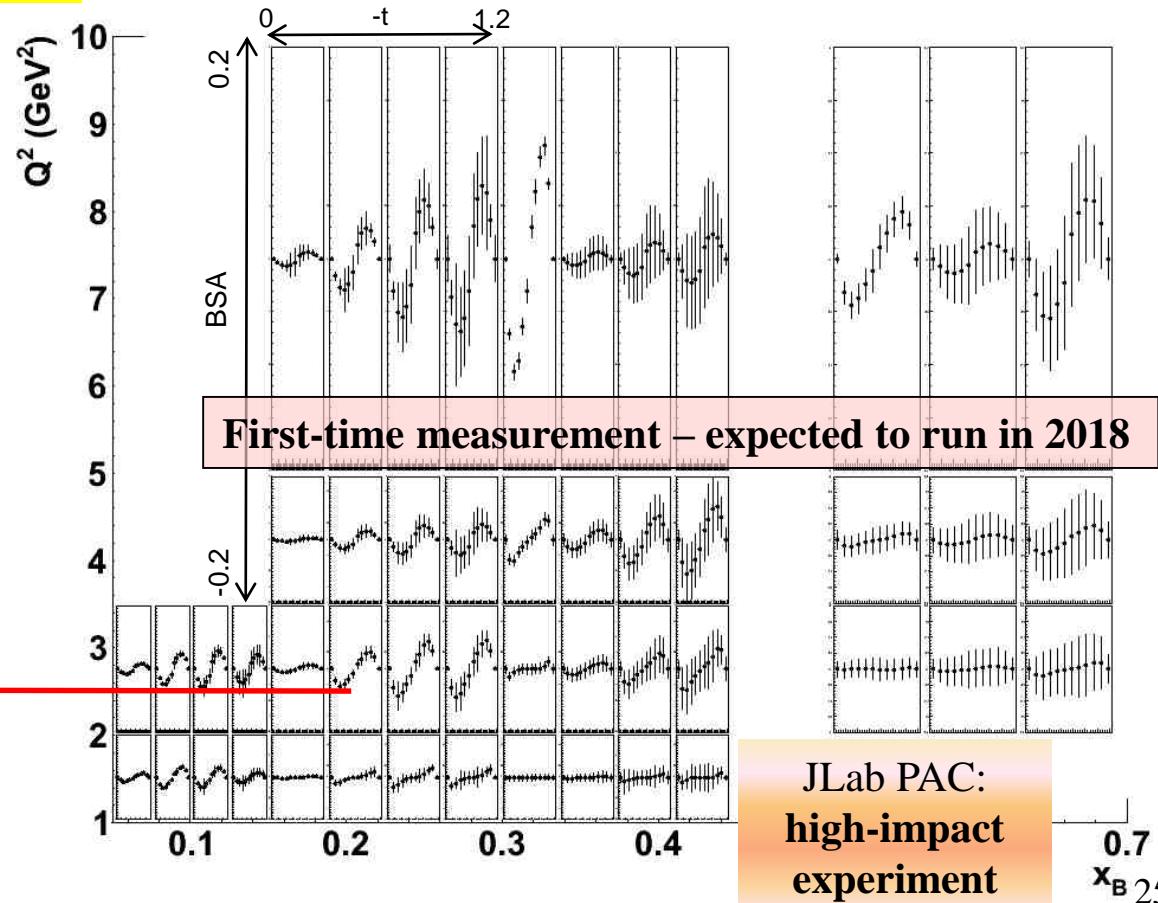
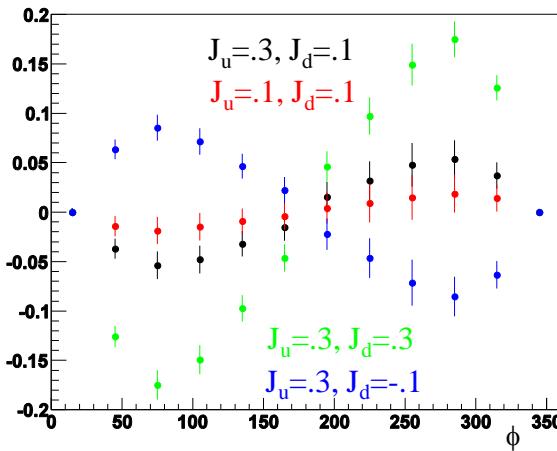
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$$(H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]$$

- Flavor separation of CFFs

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

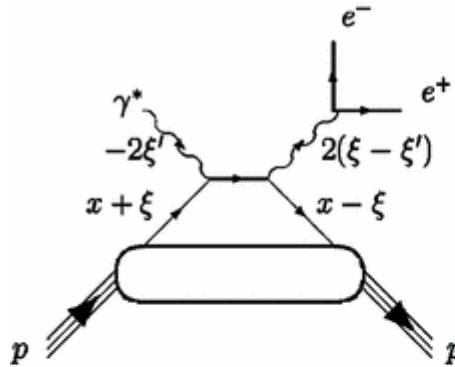


First-time measurement – expected to run in 2018

JLab PAC:
high-impact
experiment

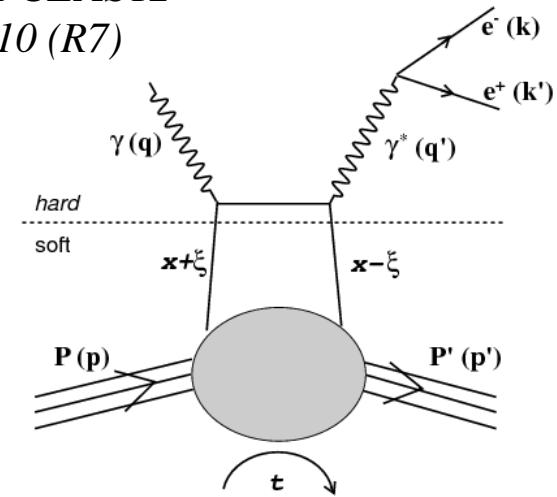
0.7
 x_B 25

GPDs: beyond DVCS



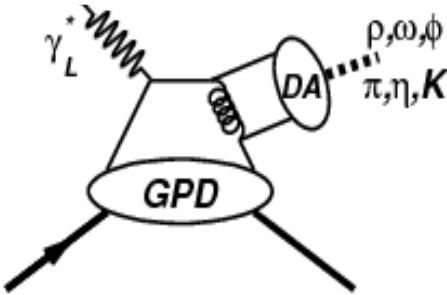
Double DVCS: $\gamma^* p \rightarrow p \gamma^* \rightarrow p l^+ l^-$

- Access to **x dependence** of GPDs, decorrelated from ξ
- LOI for SOLID (Hall A), and plans for CLAS12
- See talk by A. Camsonne, today at 14:10 (R7)*



Time-like Compton Scattering: $\gamma p \rightarrow p \gamma^* \rightarrow p l^+ l^-$

- Sensitive to **real part** of CFFs, test of **universality** of GPDs
- CLAS12 experiment running in 2017, with pDVCS



Deeply virtual meson production: $\gamma^* p \rightarrow p M$

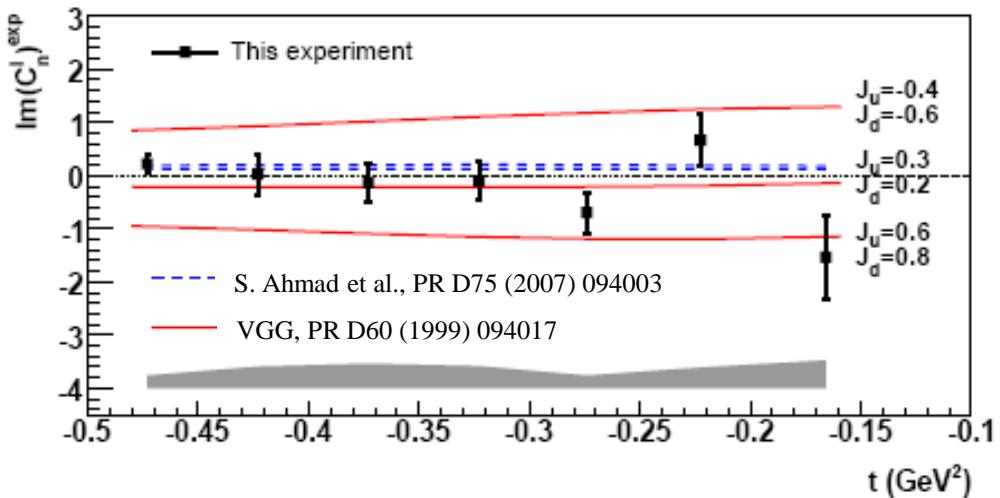
- Flavor separation** of GPDs, **universality**
- Transversity GPDs** (pseudoscalars mesons)
- Experiments in Hall A, CLAS12

DVCS on the *neutron* in Hall A

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

$\vec{e}\bar{d} \rightarrow e\gamma(np)$

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

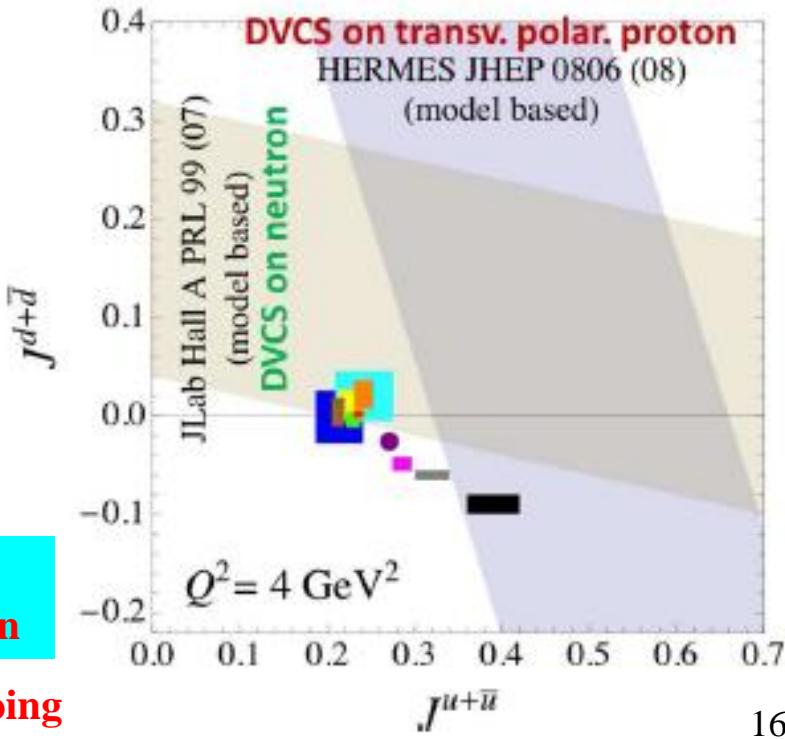


$$\mathcal{H}_p(\xi, t) = \frac{4}{9}\mathcal{H}_u(\xi, t) + \frac{1}{9}\mathcal{H}_d(\xi, t); \quad \mathcal{H}_n(\xi, t) = \frac{1}{9}\mathcal{H}_u(\xi, t) + \frac{4}{9}\mathcal{H}_d(\xi, t)$$

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

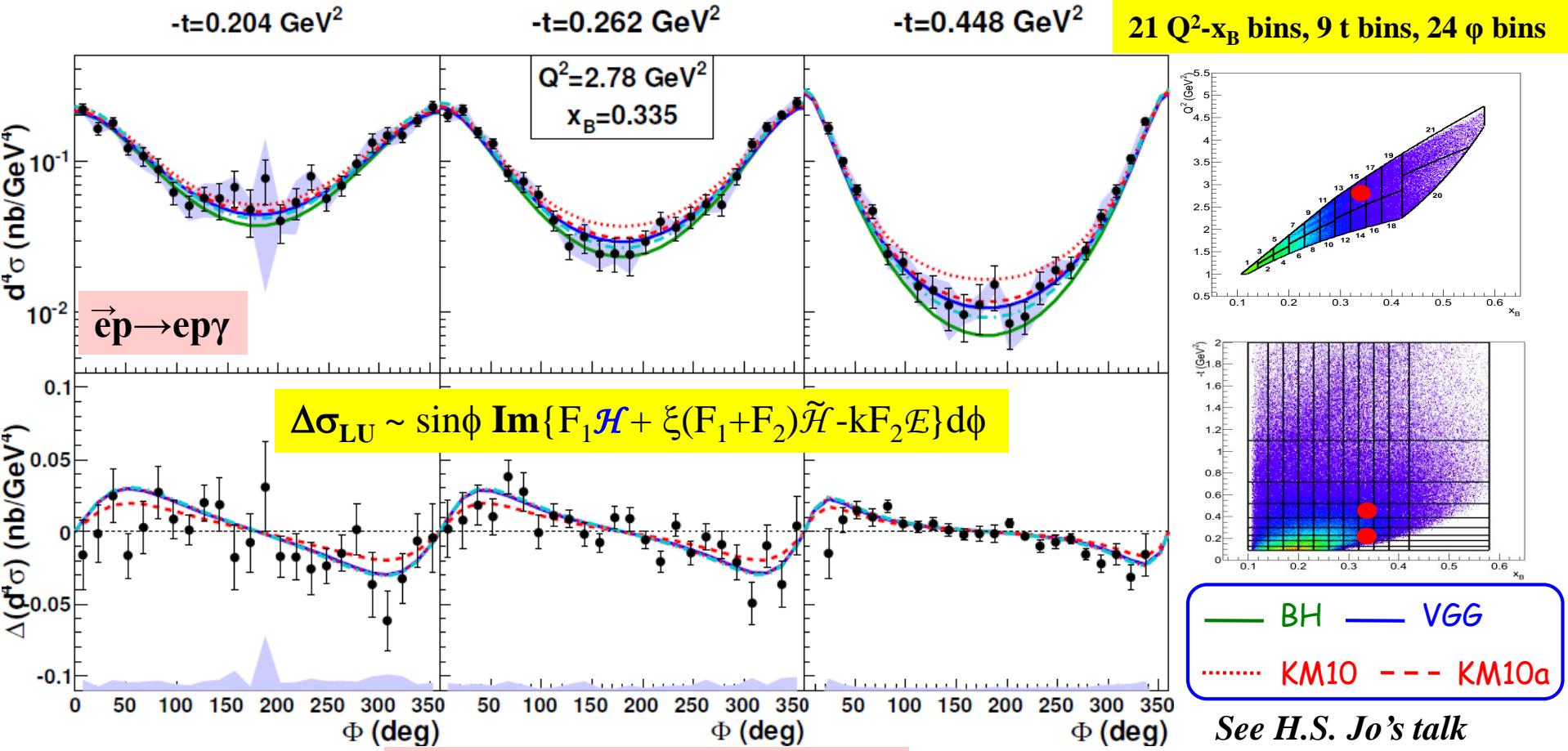
$$\frac{1}{2} \int_{-1}^1 x dx (H^q(x, \xi, t=0) + E^q(x, \xi, t=0)) = J^q$$

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



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

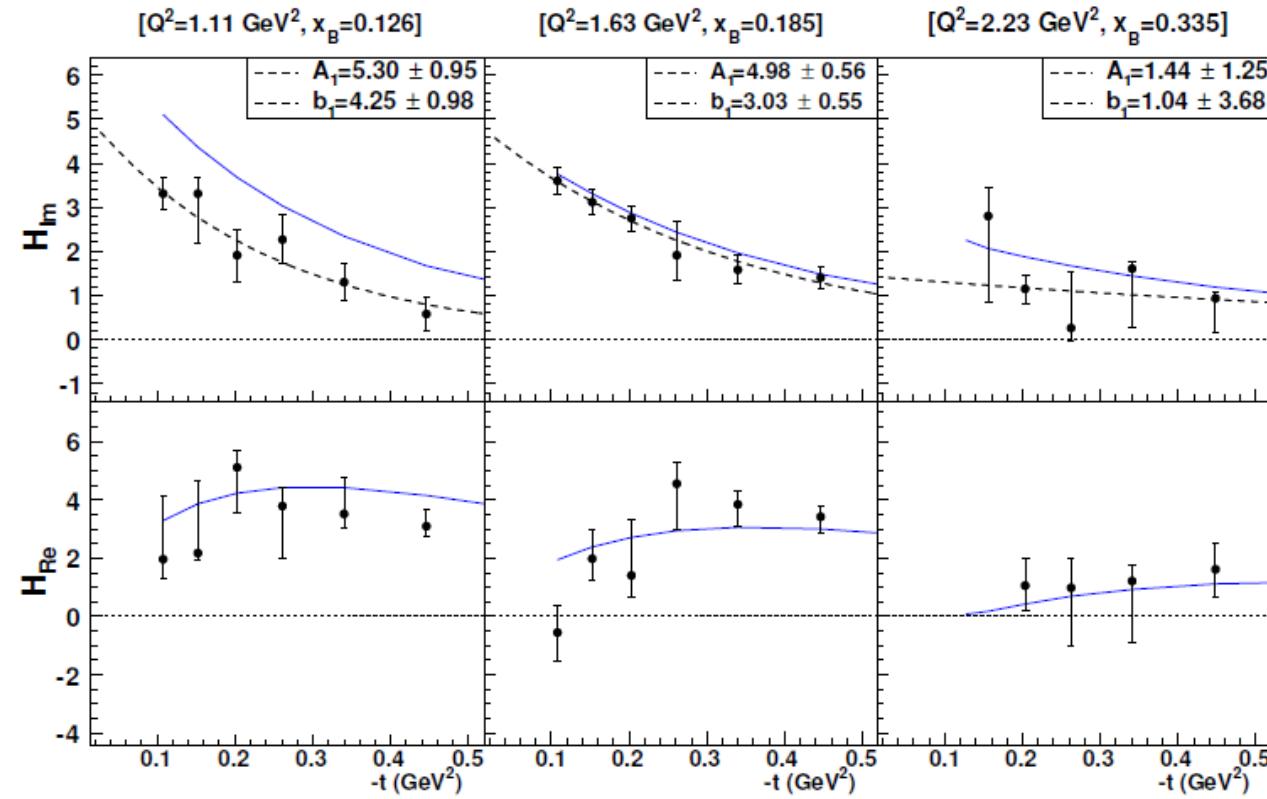
CLAS: unpolarized and beam-polarized cross sections



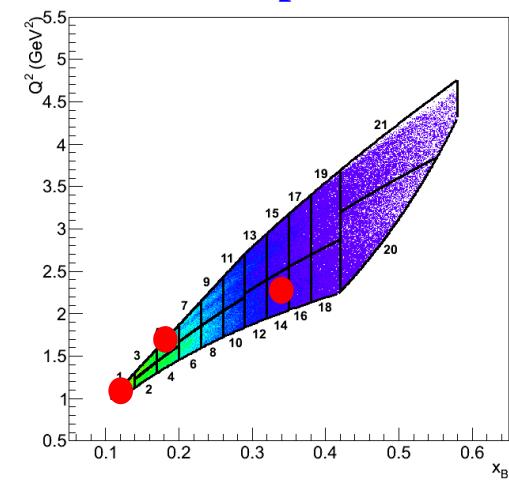
H.S. Jo et al., PRL 115, 212003 (2015)

See H.S. Jo's talk
today at 16:10 (R7)

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



*CFF fits by M. Guidal
(H and H only)
Ae^{-bt} fit
VGG predictions*



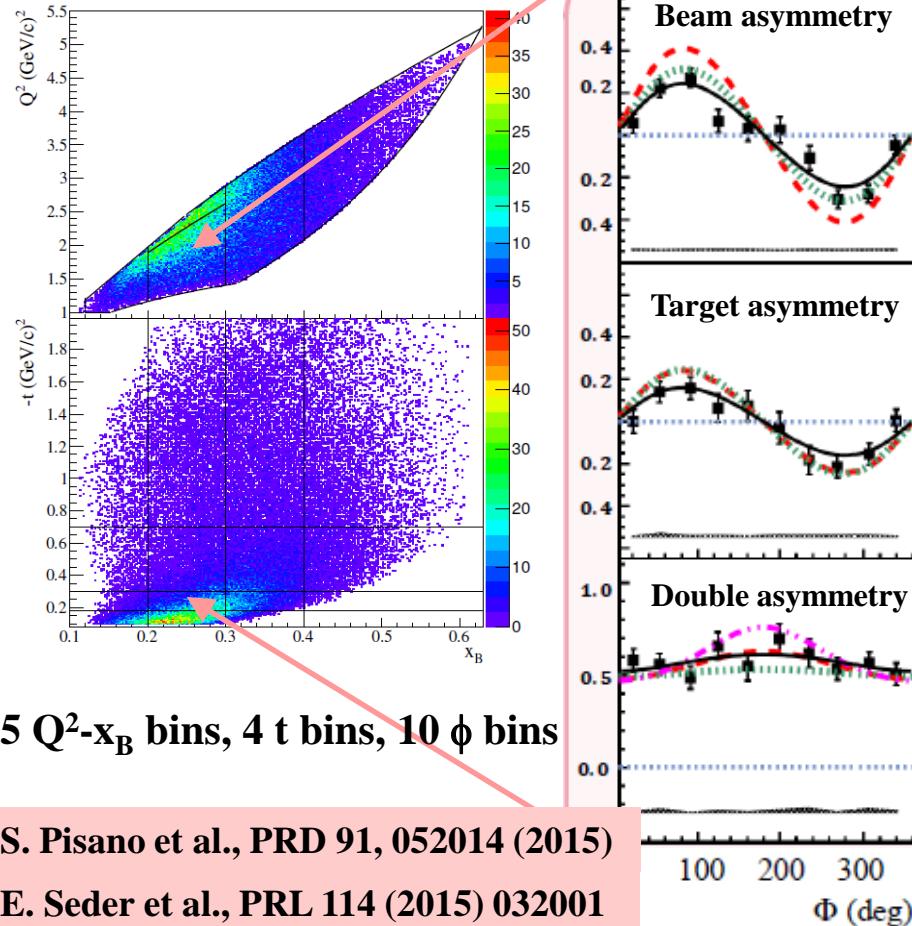
$$q(x, b_\perp) = \int_0^\infty \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i \Delta_\perp b_\perp} H(x, 0, -\Delta_\perp^2)$$

$\text{Im}(\mathcal{H}_p)$, 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

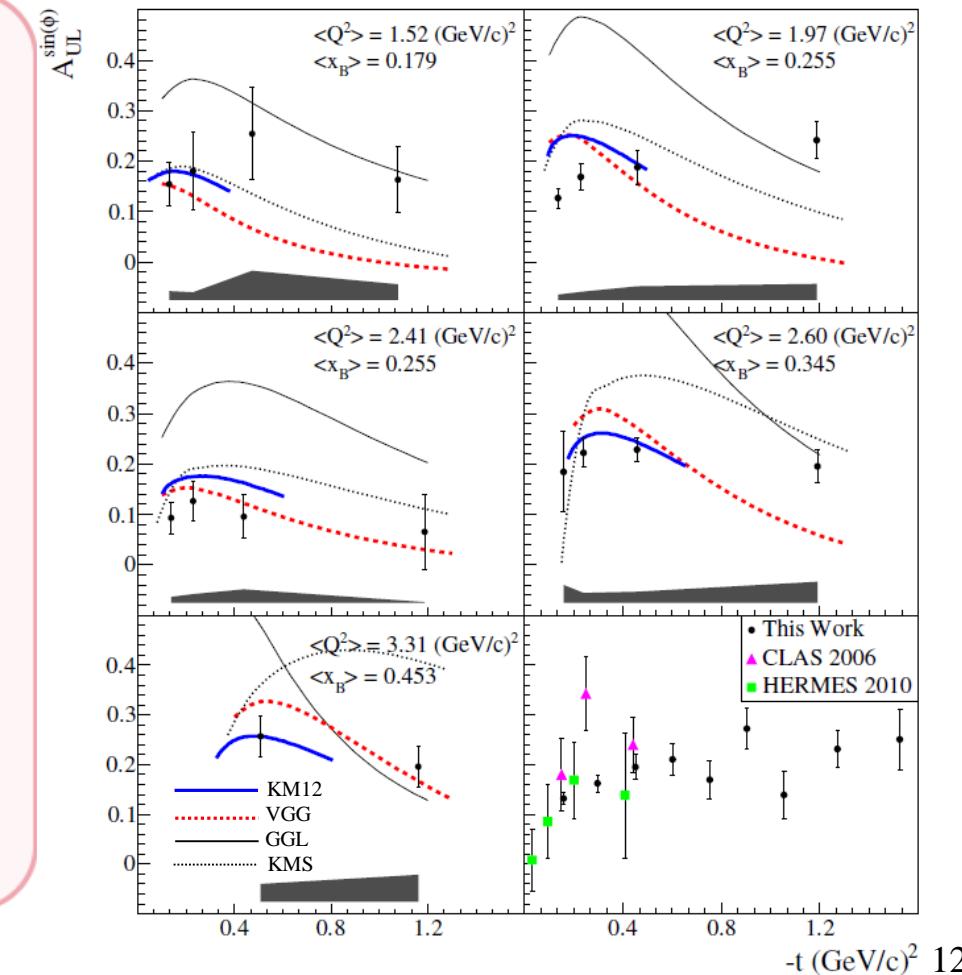
$\vec{ep} \rightarrow e\gamma$

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



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

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



Extraction of CFFs from CLAS TSA, BSA, DSA

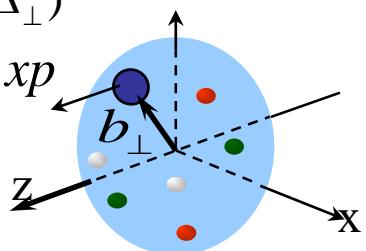
CFFs fitting code by M. Guidal (7 CFFs)

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

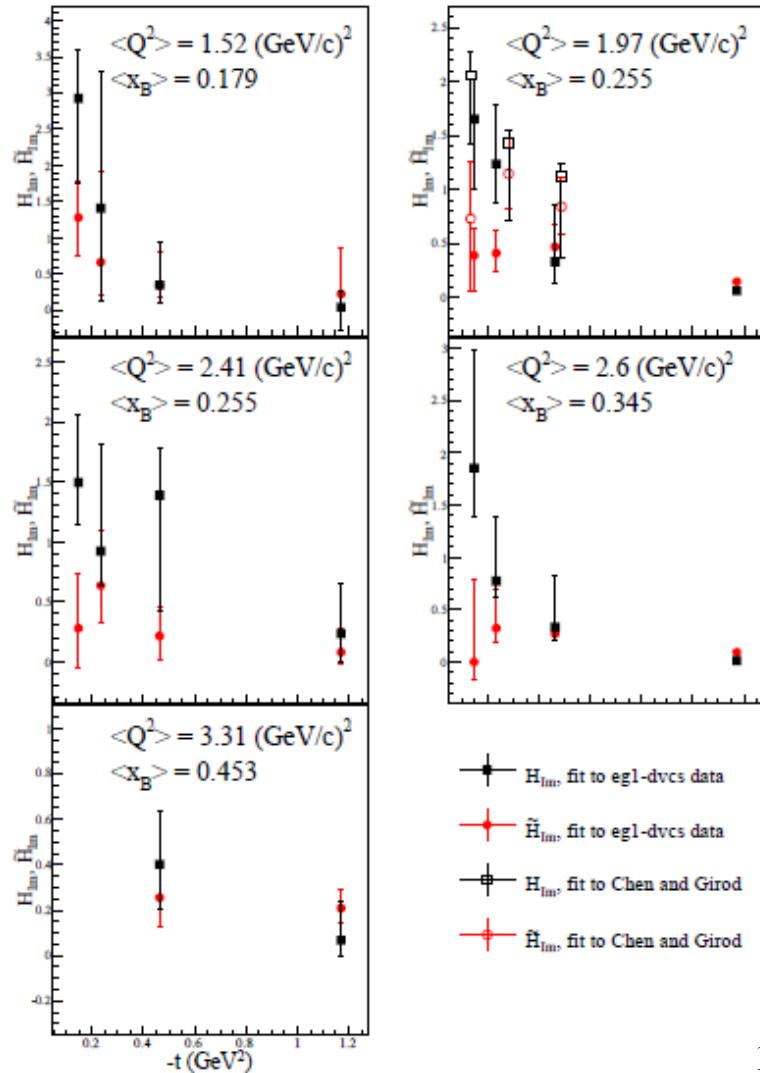
$$\Delta q(x, b_\perp) = \int_0^\infty \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i \Delta_\perp b_\perp} \tilde{H}(x, 0, -\Delta_\perp^2)$$

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

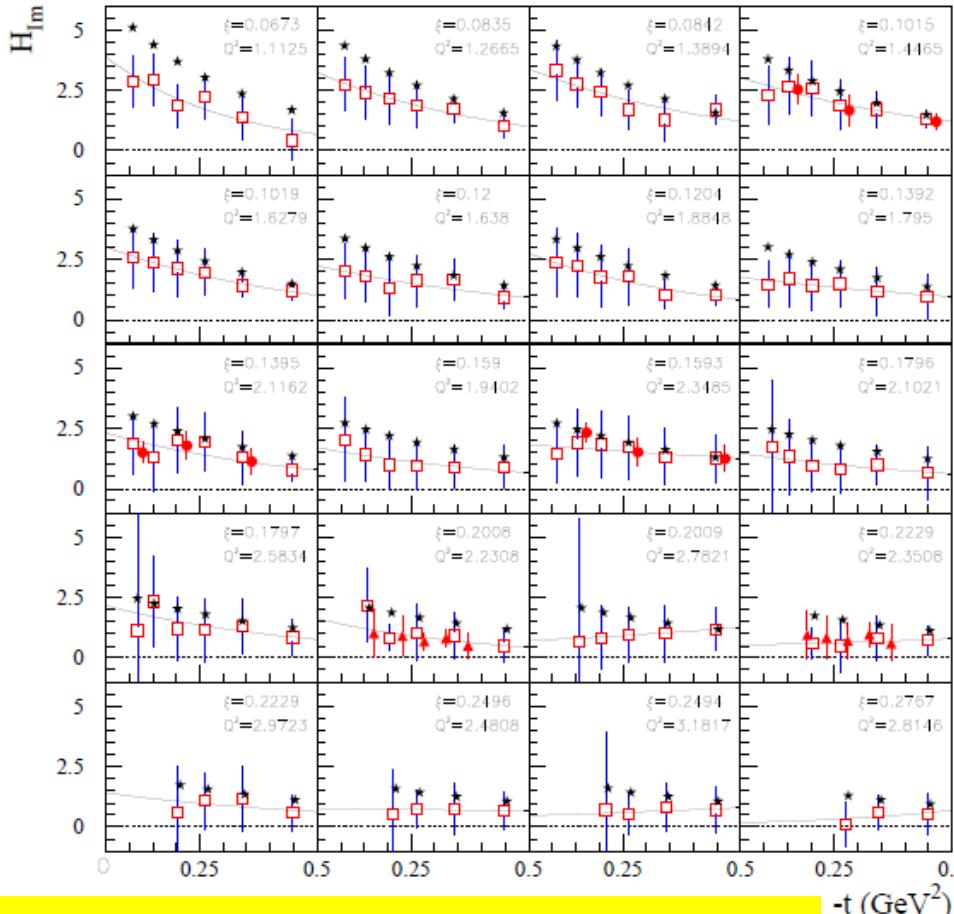
$$\int \tilde{H}(x, \xi, t) dx = G_A(t)$$



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

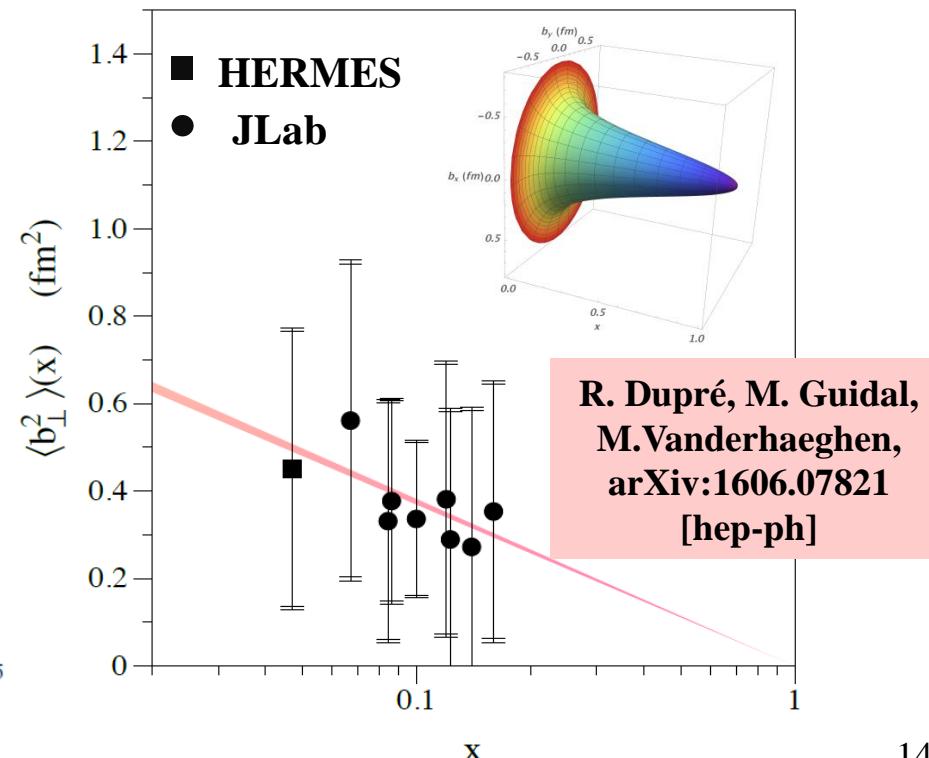


From CFFs to proton transverse size vs x

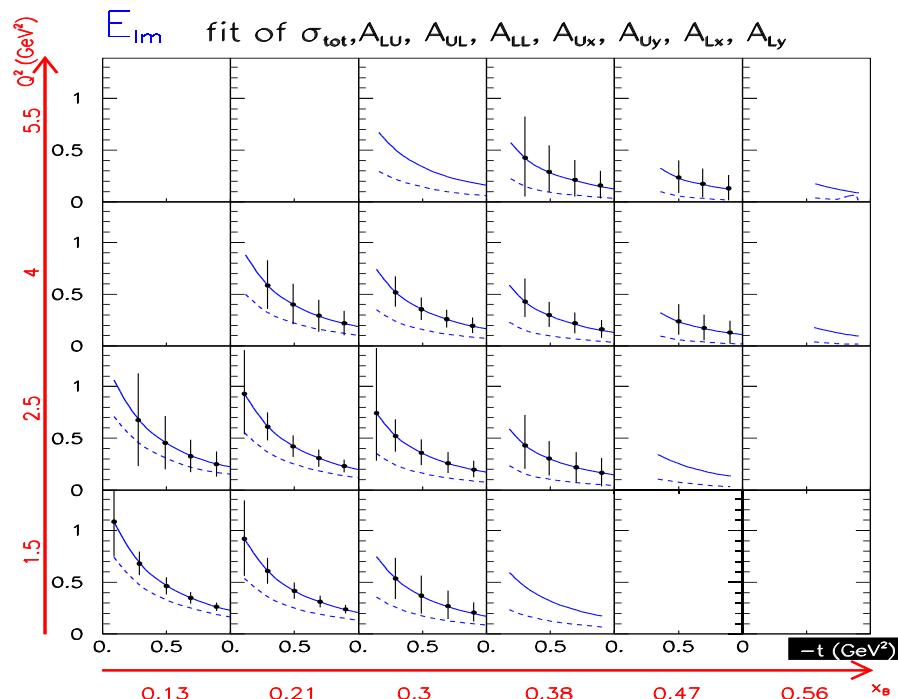
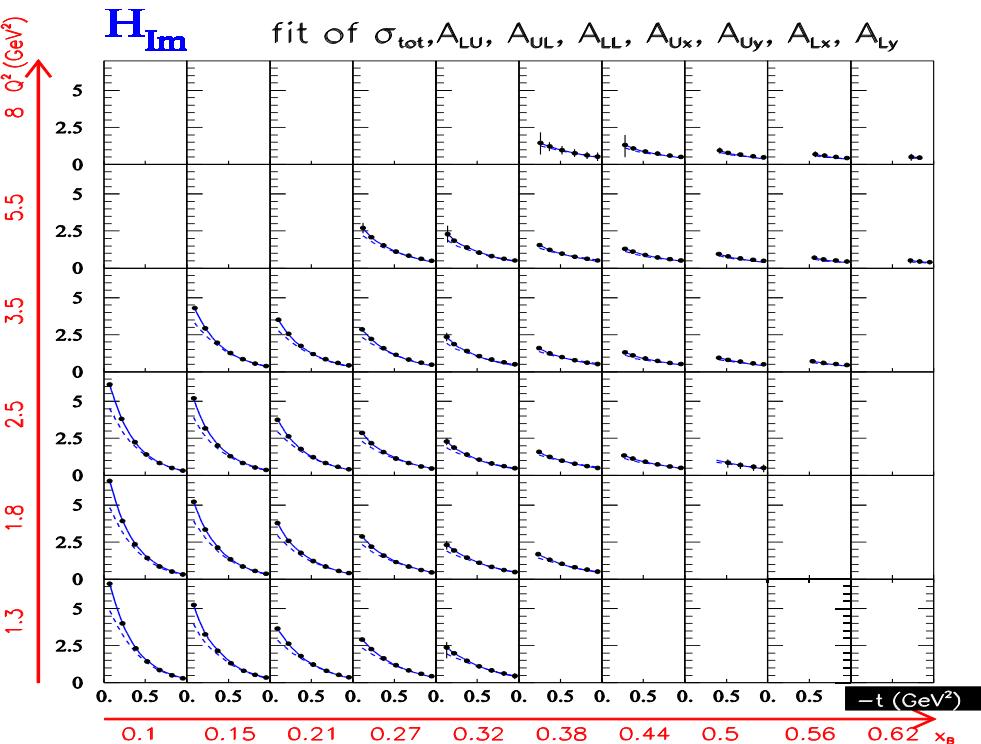


$$\langle b_\perp^2 \rangle^q(x) = -4 \frac{\partial}{\partial \Delta_\perp^2} \ln H_-^q(x, 0, -\Delta_\perp^2) \Big|_{\Delta_\perp=0}$$

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



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

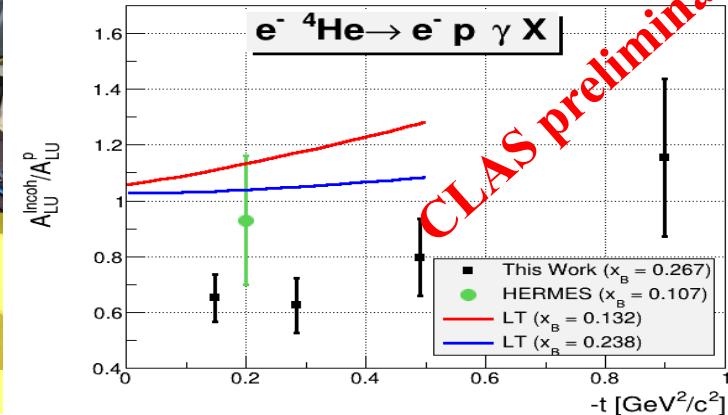
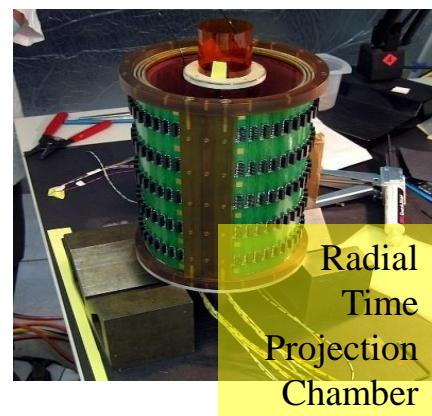
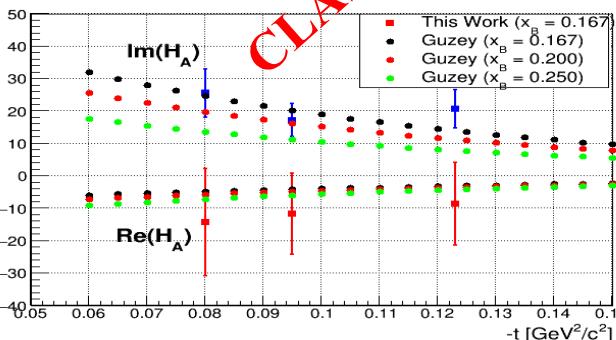
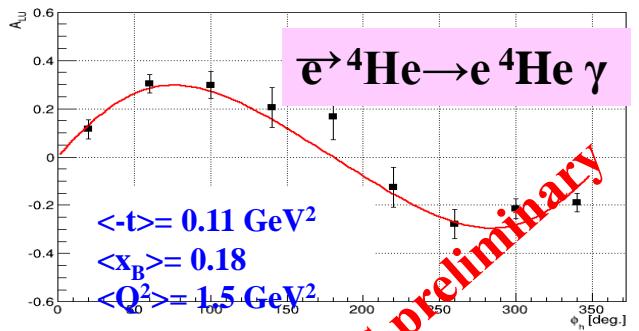
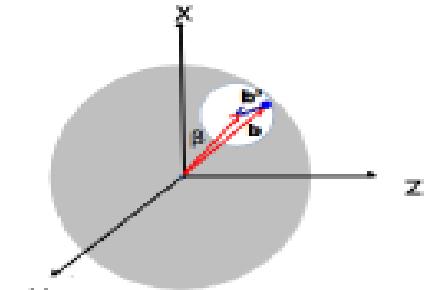


DVCS on nuclei: the CLAS eg6 experiment

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

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

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



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

Work by M. Hattawy, IPNO & ANL

Extraction of Compton Form Factors from DVCS observables

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

8 CFF

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

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)

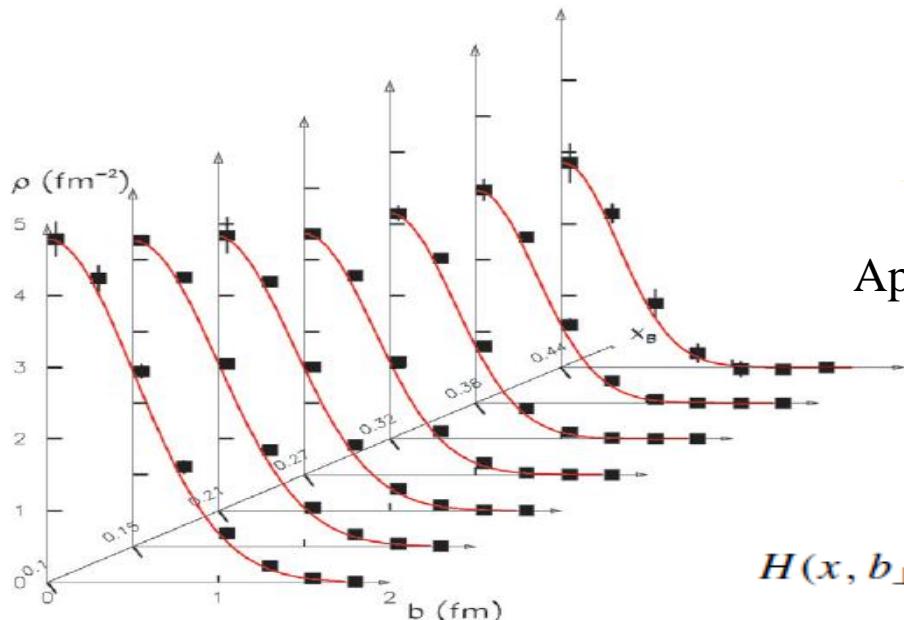
$$H_{\text{Im}}(\xi, t) \equiv H(\xi, \xi, t) - H(-\xi, \xi, t)$$

Applying a model-dependent “deskewing” factor:

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

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

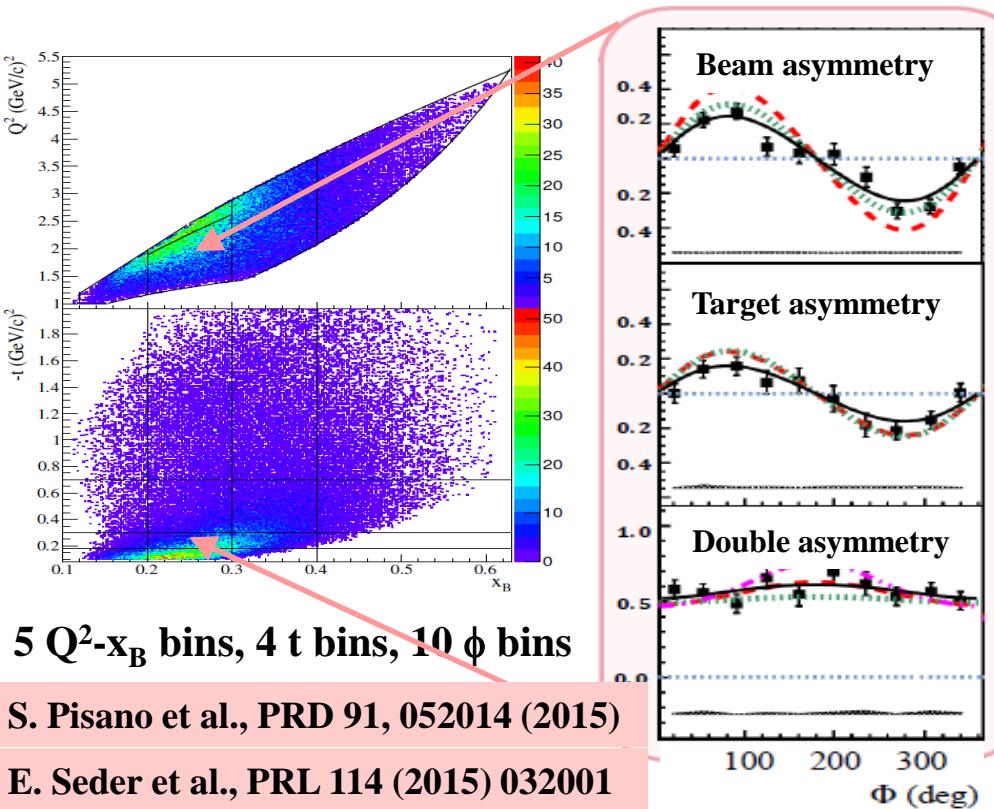
Burkardt (2000)



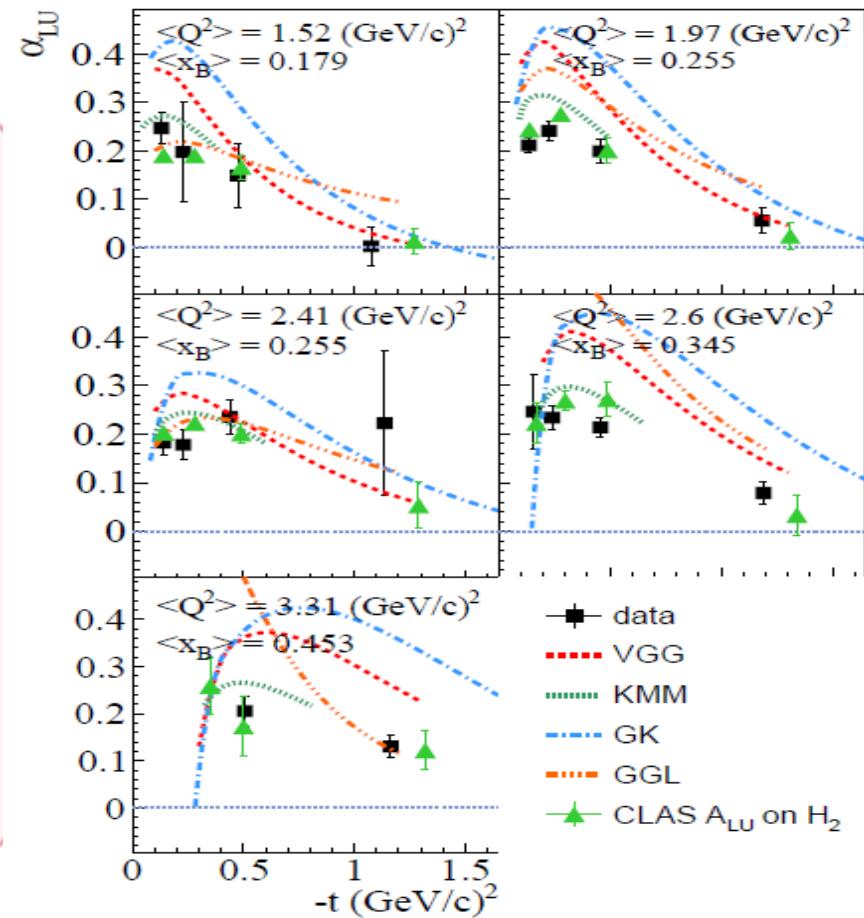
CLAS: DVCS on longitudinally polarized target

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

- Target: longitudinally polarized NH_3 ($P \sim 80\%$)
- **3 DVCS observables**



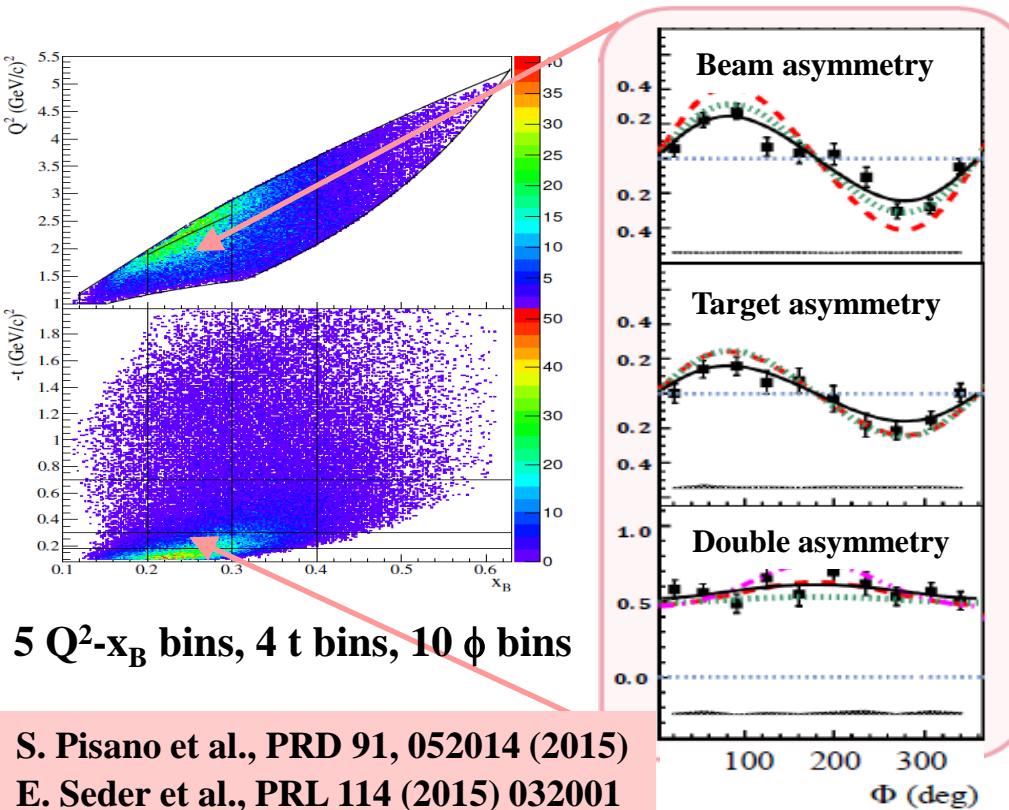
$$\text{BSA} \sim \text{Im}\{\mathcal{H}_p\}$$



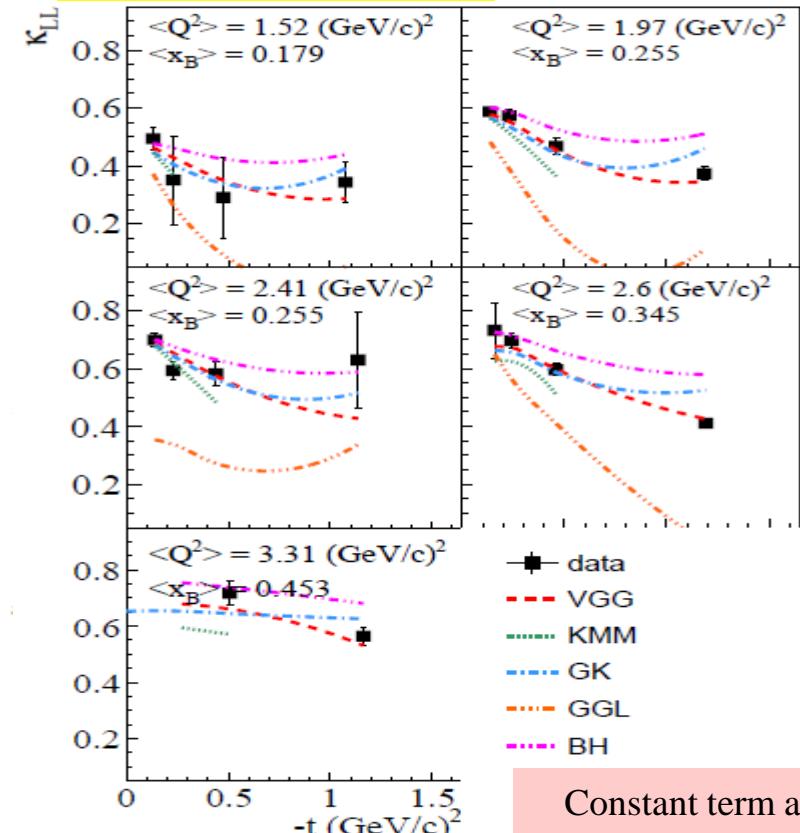
CLAS: DVCS on longitudinally polarized target

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

- Target: longitudinally polarized NH₃ (P~80%)
- **3 DVCS observables**

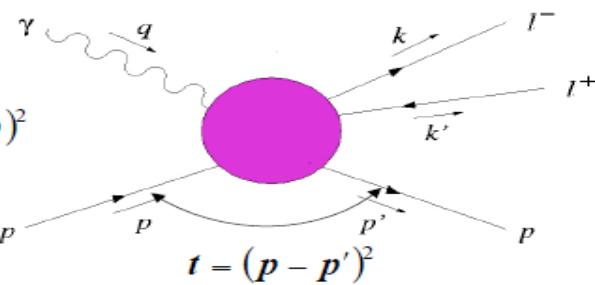


$$\text{DSA} \sim \text{Re}\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$$



Timelike Compton Scattering with CLAS12

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



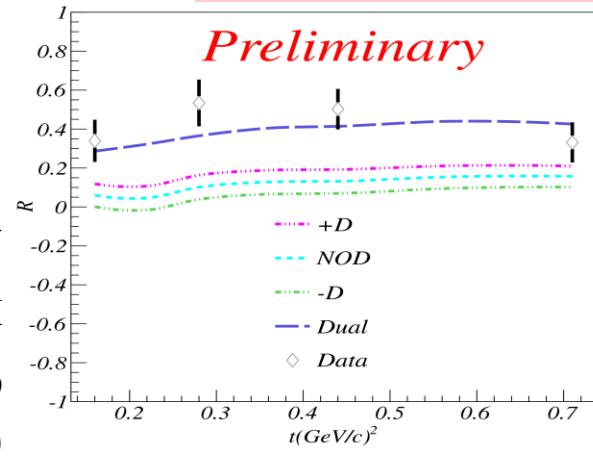
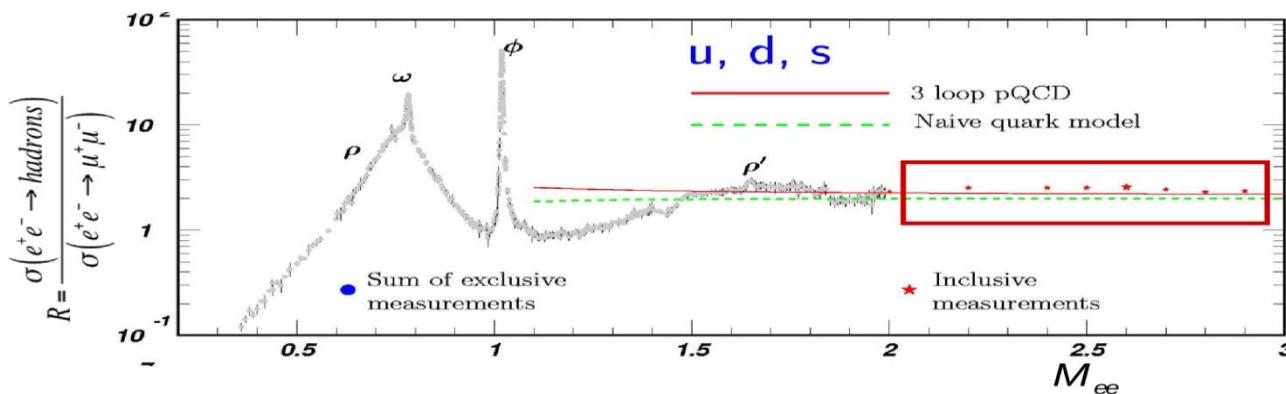
$$Q'^2 = M_{tr}^2 = (k + k')^2$$

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

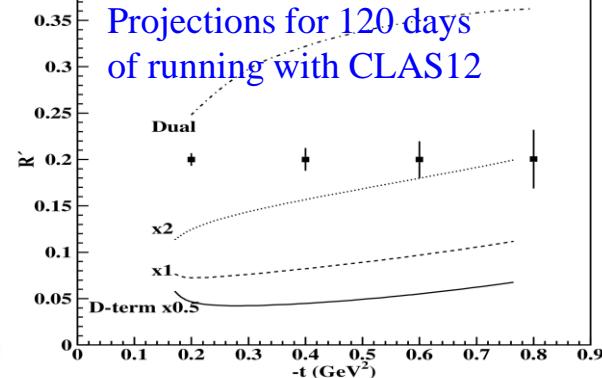
Exploratory
measurement with
CLAS@6 GeV
(R. Paremuzyan, IPNO
& Yerevan)

TCS: sensitivity to the real part of CFFs

$$R = \frac{\frac{2\pi}{0} d\phi \cos\phi \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \propto \tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{m} \frac{1 - \eta}{1 + \eta} \left[F_1 \mathcal{H} - \eta(F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4m^2} F_2 \mathcal{E} \right]$$



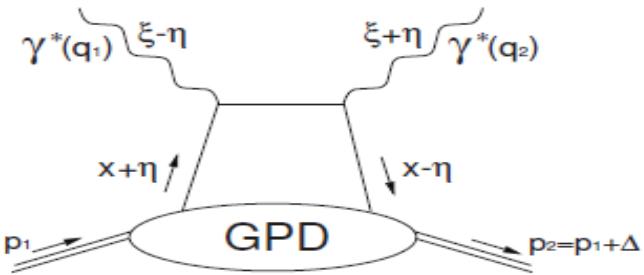
$\langle s \rangle = 15.5 \text{ GeV}^2, \langle Q'^2 \rangle = 5 \text{ GeV}^2$



Double DVCS at SoLID (Hall A)

$ep \rightarrow e\gamma^*(\rightarrow \mu^+\mu^-)$

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**

