# Nucleon-structure studies with exclusive reactions: perspectives for upgrades at JLab


CEBAF Large Acceptance Spectrometer

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J-Future, Messina (Italy), 28/3/2022

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# Outline

**Nucleon structure studies with exclusive reactions: GPDs**

**GPDs & experiments: where do we stand**

**What’s missing from the GPD picture**

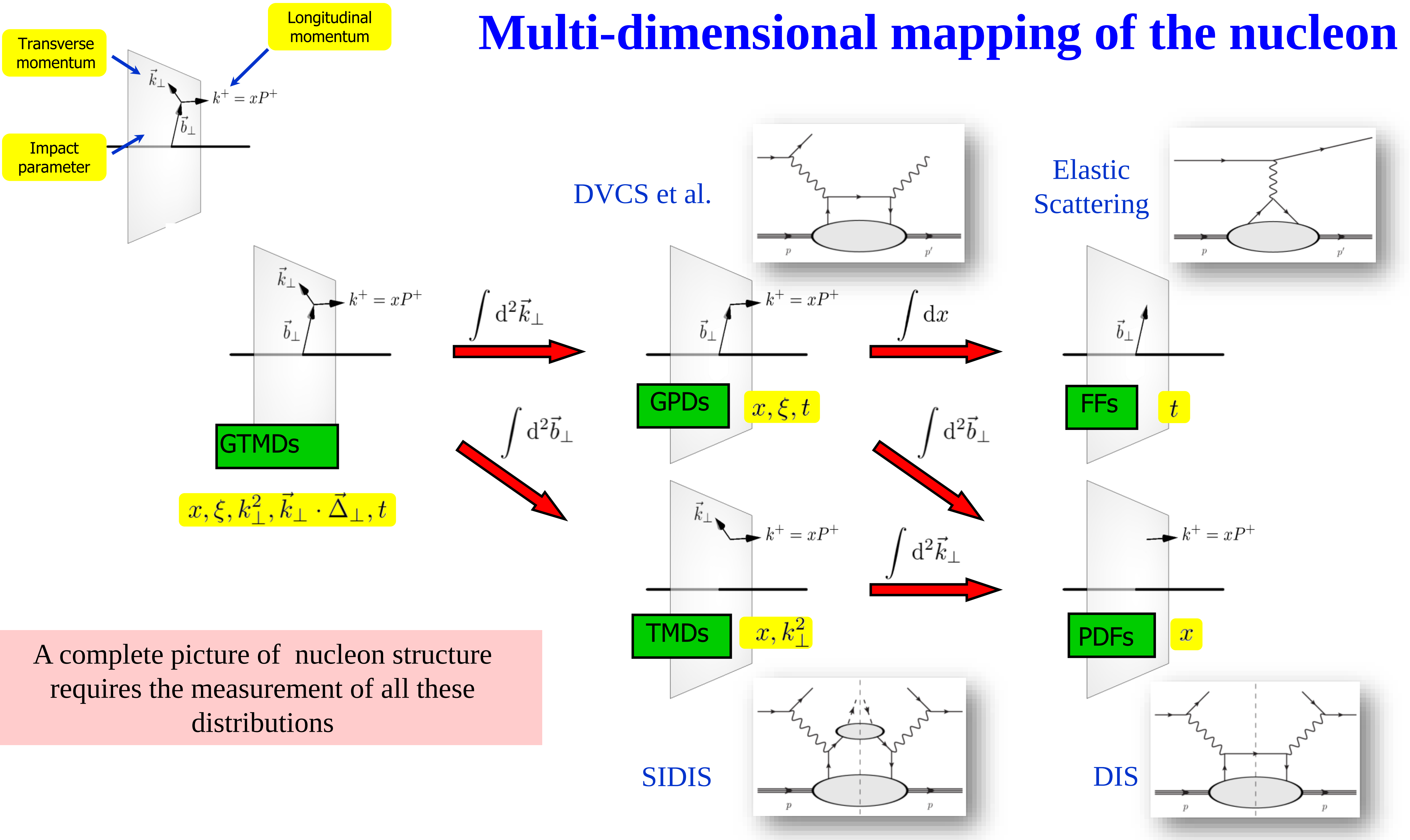
**Plans for DVCS with polarized positrons beam**

**Plans for DDVCS with high-lumi μCLAS12**

**Perspectives for DVCS@CLAS22**

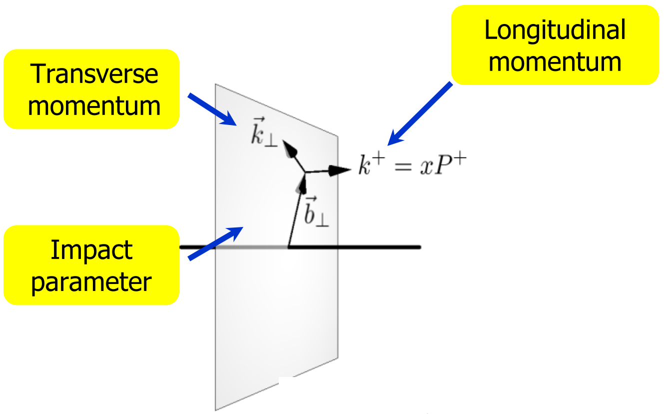
**Conclusions: what should we point on to be « competitive » to the EIC**

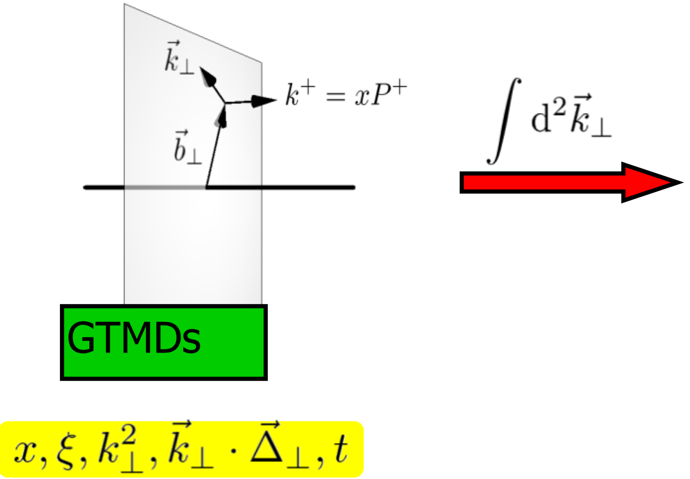
# Multi-dimensional mapping of the nucleon



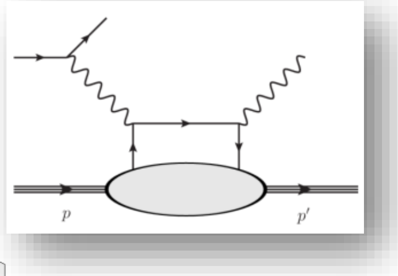

A complete picture of nucleon structure requires the measurement of all these distributions

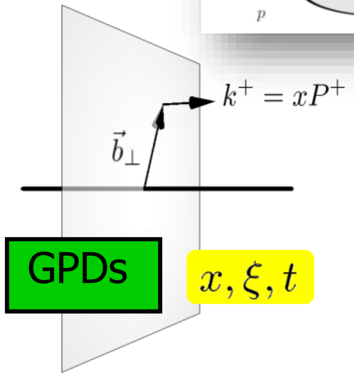
# Multi-dimensional mapping of the nucleon




DVCS et al.




**Nucleon tomography**

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

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

**Generalized Parton Distributions**:

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

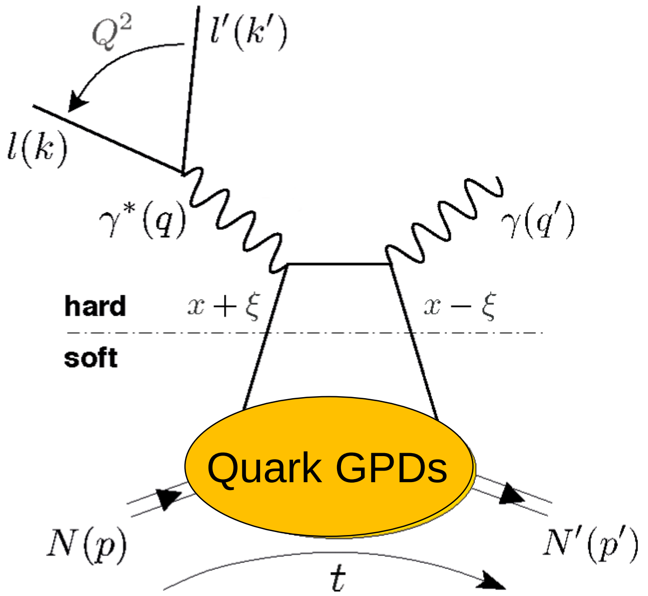
✓ linked to **FFs** and **PDFs**

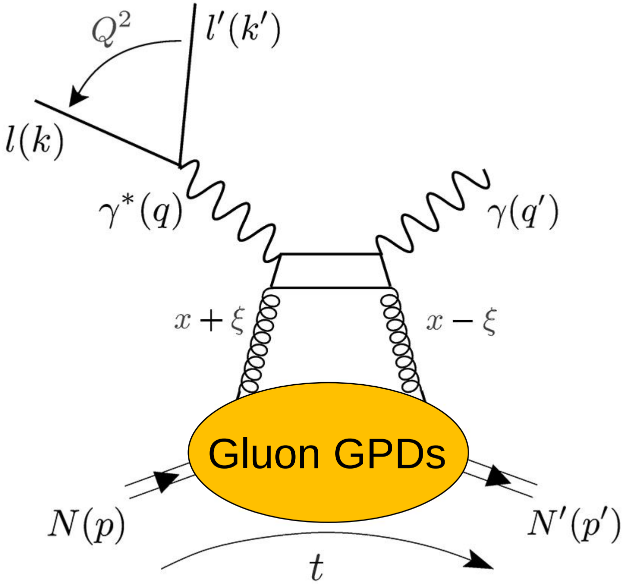
✓**Accessible in exclusive reactions**

**Quark angular momentum (Ji's sum rule)**

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

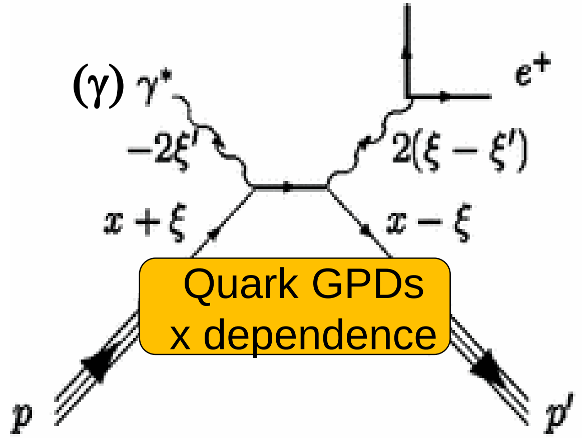
# Exclusive reactions giving access to GPDs

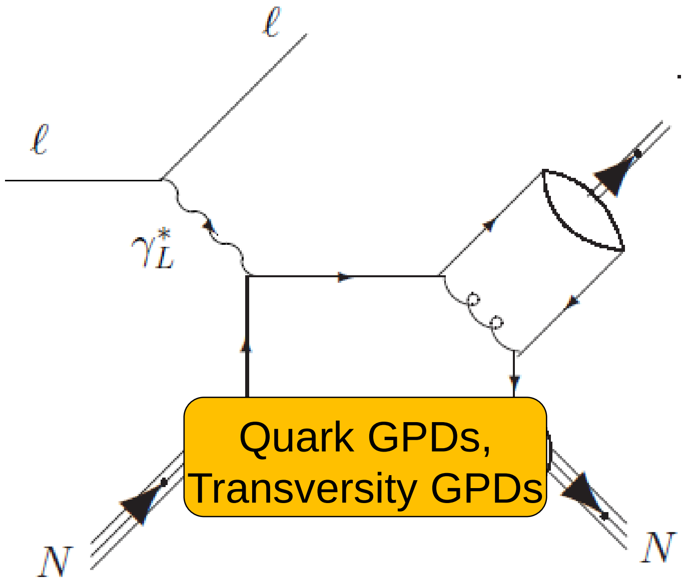



**DVCS**

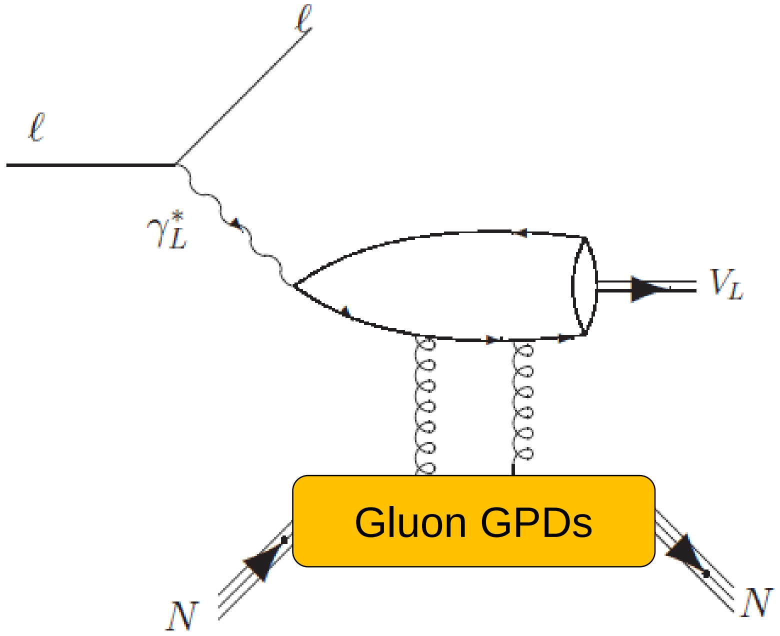
**(TCS), DDVCS**



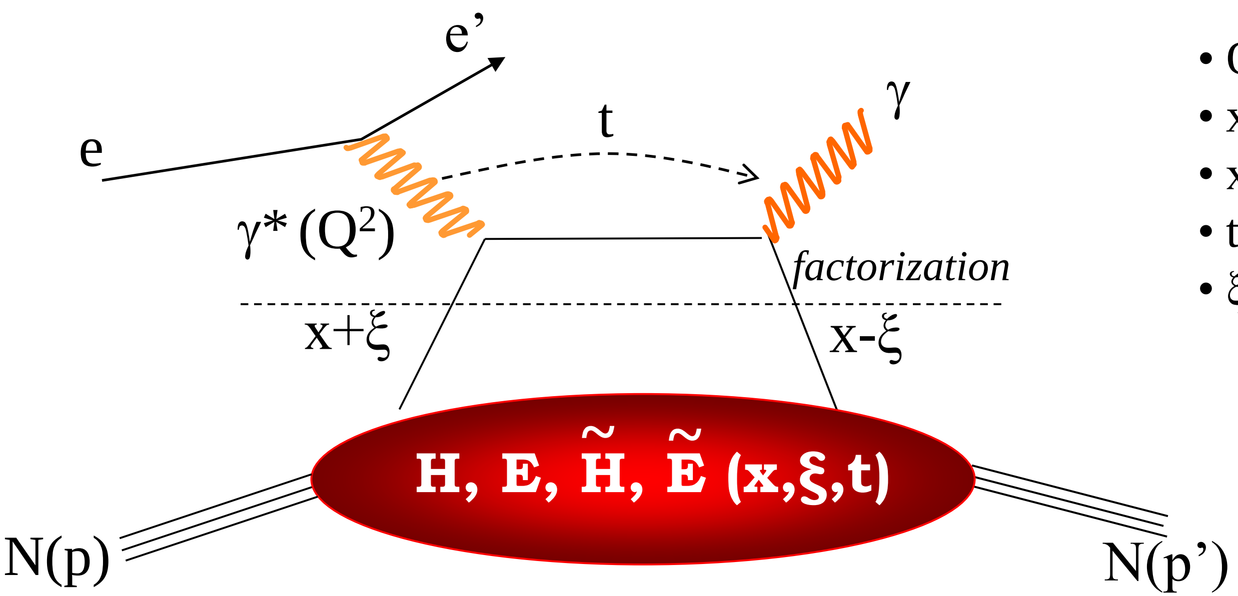




**DVMP**

$M$



# Deeply Virtual Compton Scattering and GPDs




- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

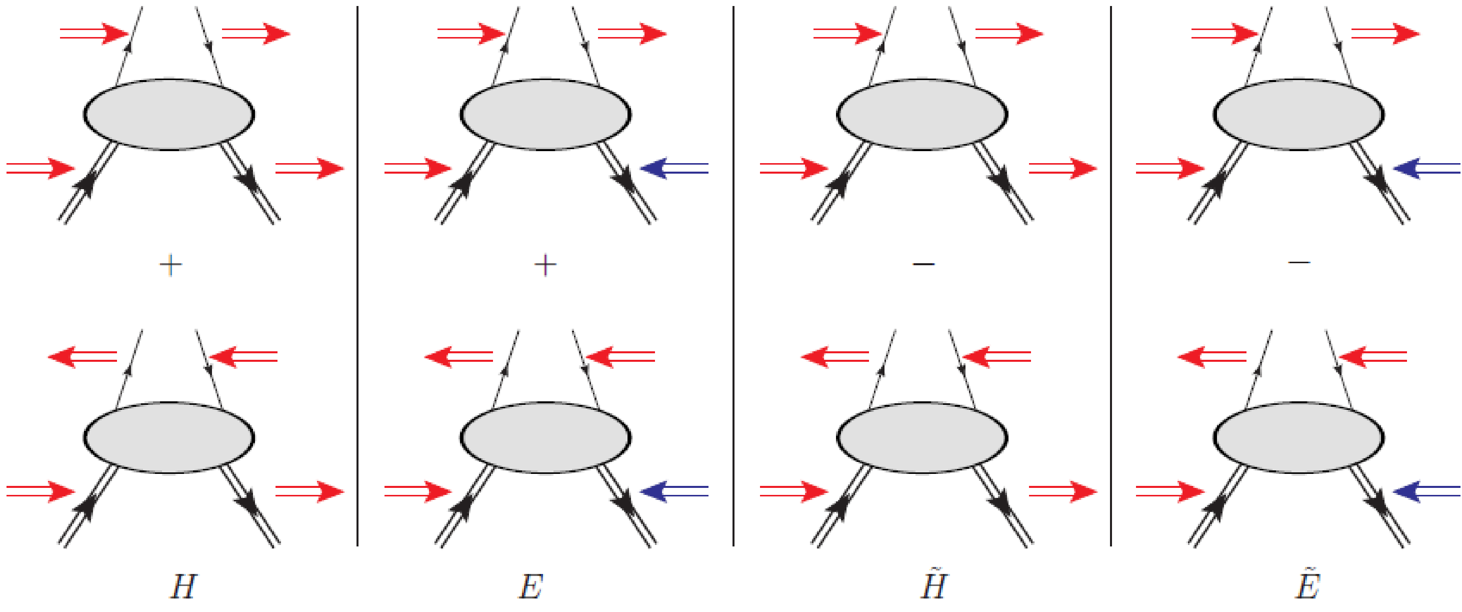
**« Handbag »** factorization, valid in the **Bjorken regime** (**high $Q^2$** and **$\nu$,** fixed $x_B$)**, $t \ll Q^2$**

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

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

**conserve nucleon spin**

**flip nucleon spin**



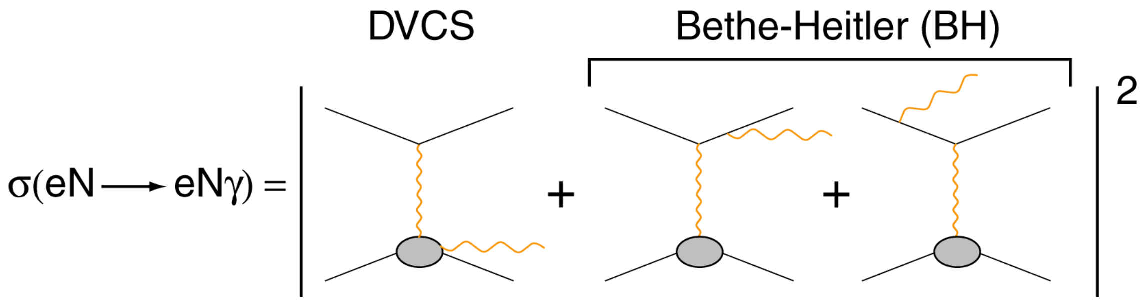

**Vector** **Tensor** **Axial-vector** **Ps.scalar**

# Accessing GPDs through DVCS

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

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

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




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

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

Proton Neutron

Polarized beam, unpolarized target:

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

Unpolarized beam, longitudinal target:

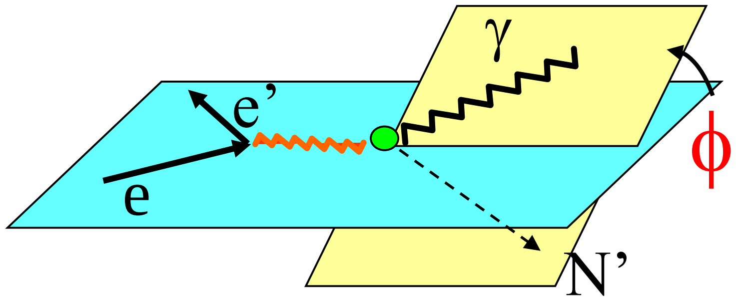
$\Delta\sigma_{UL} \sim \sin\phi Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⟹ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

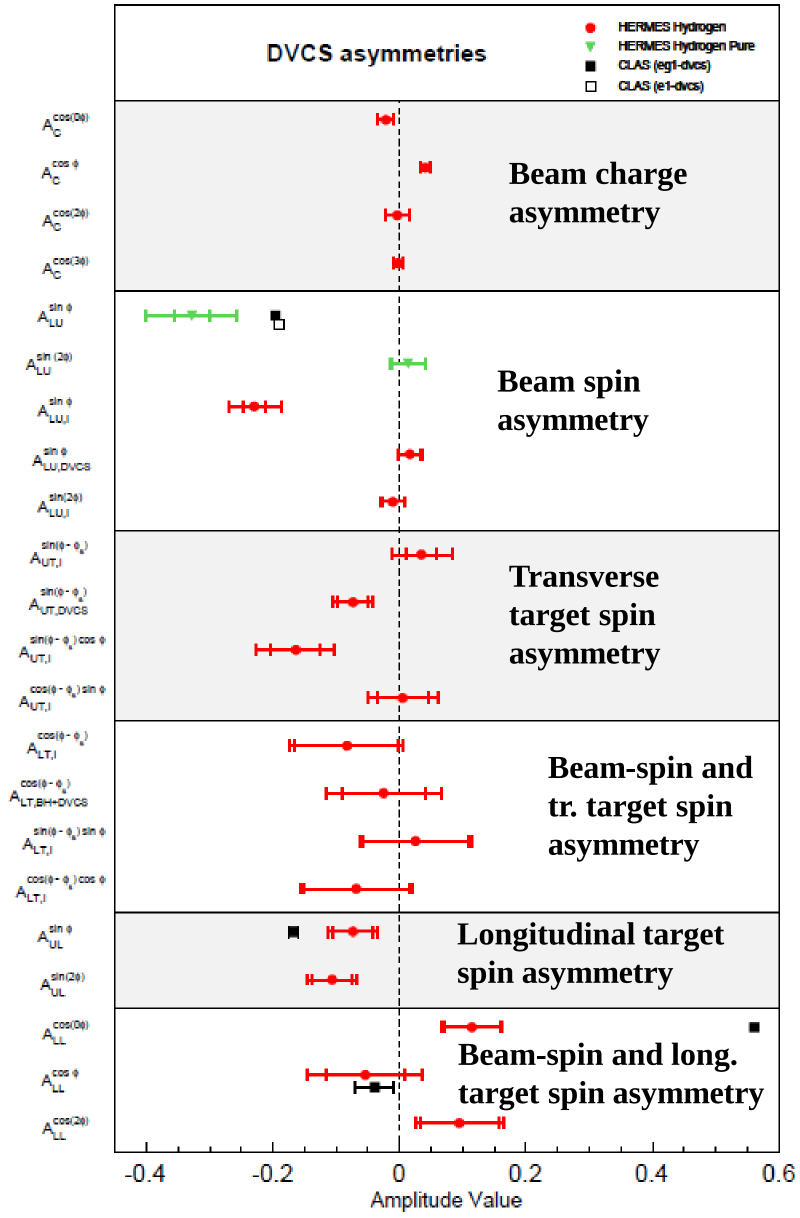
$\Delta\sigma_{LL} \sim (A + B\cos\phi) Re\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\}$ ⟹ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

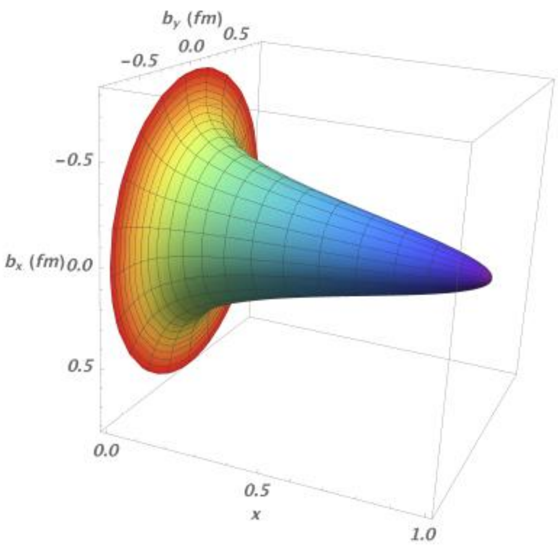
Unpolarized beam, transverse target:

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



# Measured p-DVCS observables and constraints on GPDs

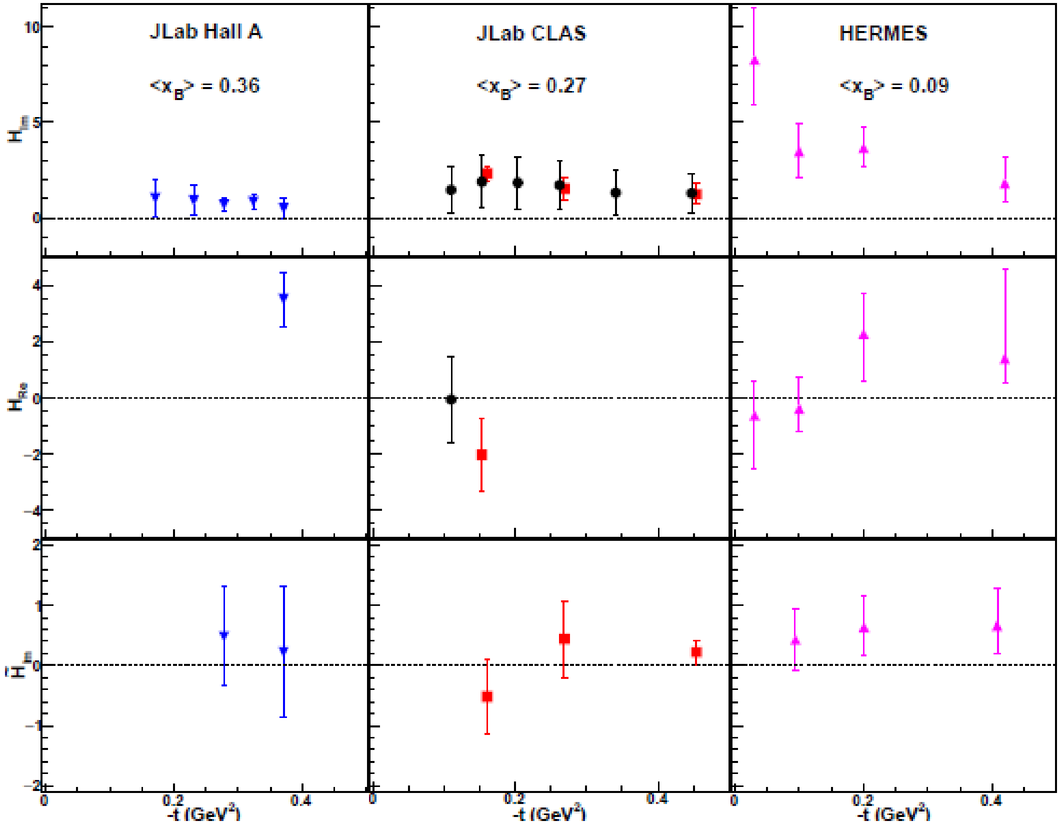



**Proton tomography**

obtained from local fits to HERMES, CLAS, and Hall-A data (Im$\mathcal{H}$ + model dependent assumptions for x dependence)

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




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

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

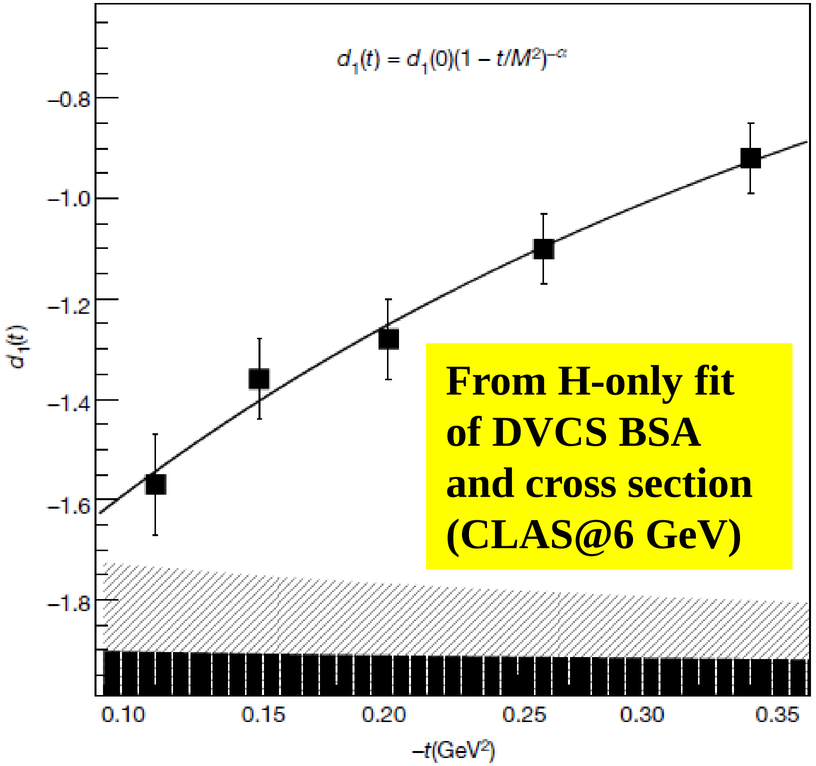
Second Mellin moment of H in x: **Gravitational form factor** → shear forces and pressure

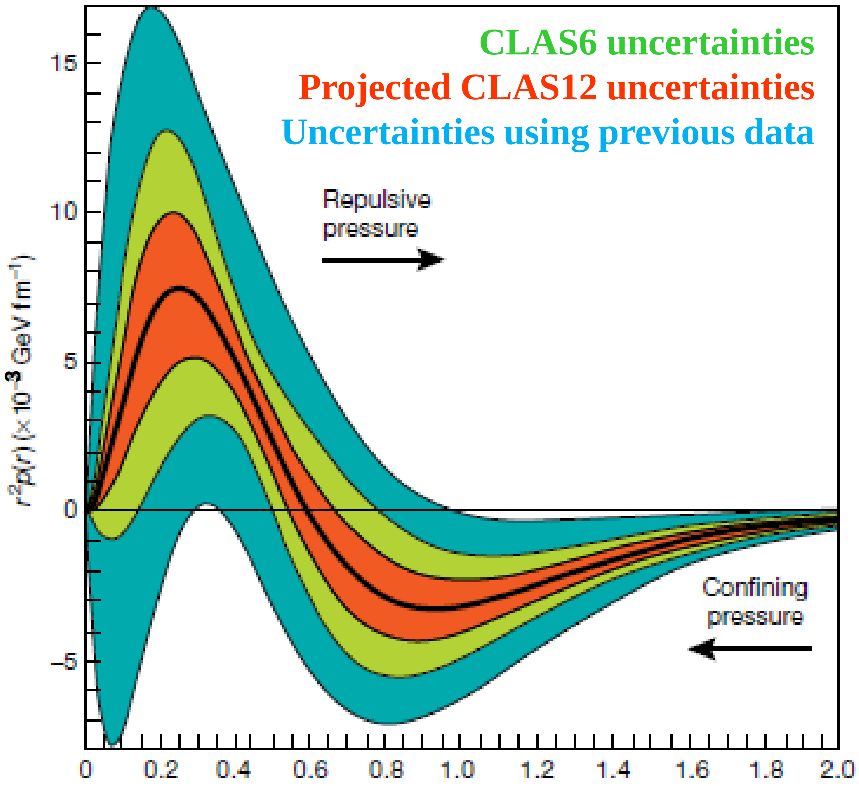
$$\mathrm{Re}\mathcal{H}(\xi,t) + i\mathrm{Im}\mathcal{H}(\xi,t) = \int_{-1}^{1}\mathrm{d}x\left(\frac{1}{\xi-x-i\epsilon} - \frac{1}{\xi+x-i\epsilon}\right)H(x,\xi,t) \quad (1)$$

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

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

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t}p(r)\mathrm{d}^3r$$




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

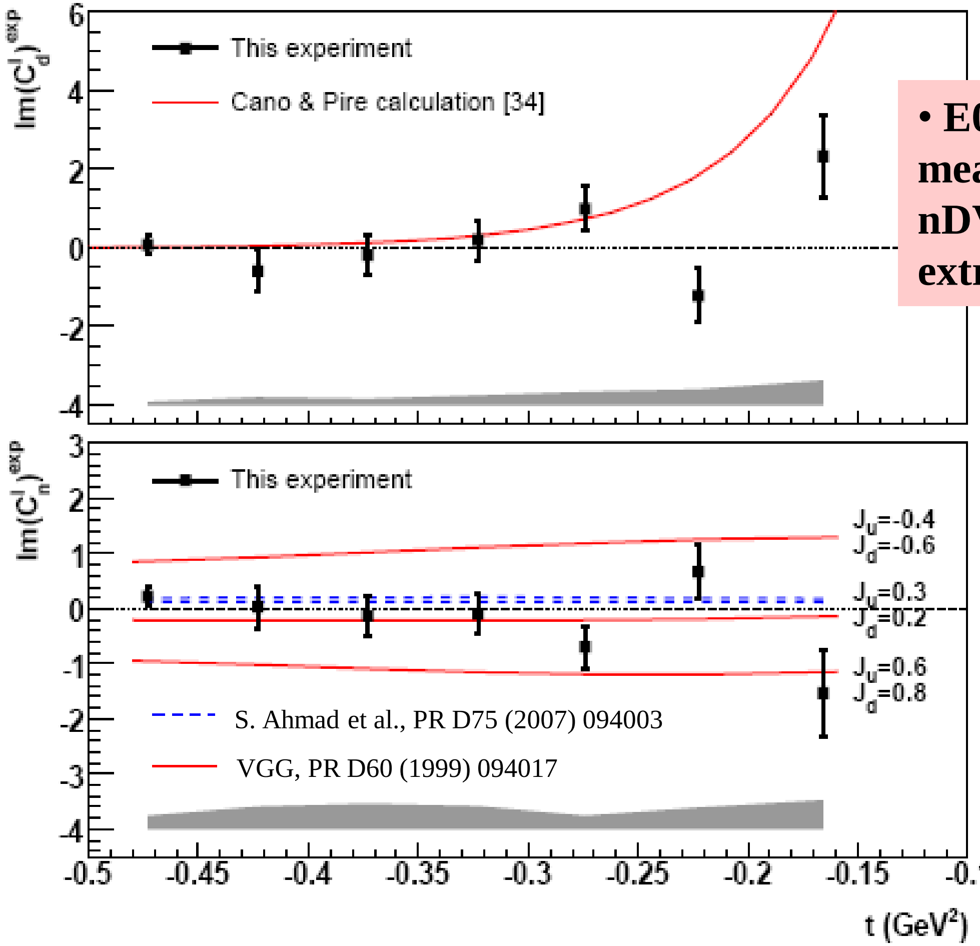
$\vec{e}d \to e\gamma(np)$

# DVCS on the neutron in Hall A at 6 GeV

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

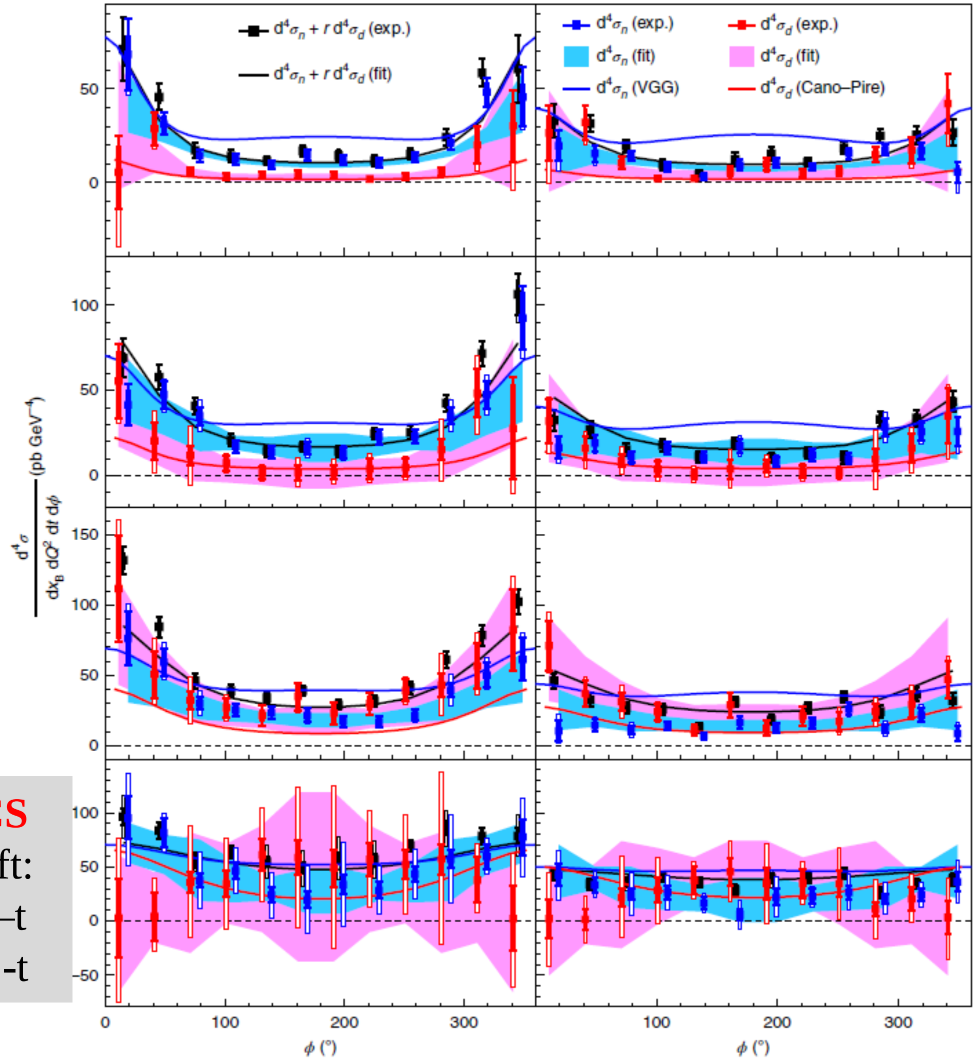
$Q^2$=1.9 $GeV^2$ $x_B$=0.36

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




- **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




nDVCS and coherent dDVCS separated through $MM^2_X$ shift:

- large correlations at low –t
- good separation at larger -t

**Hall-A experiment E08-025 (2010)**

- Beam-energy « Rosenbluth » separation of nDVCS CS (two beam energies)
- First observation of non-zero nDVCS CS
- **M. Benali et al., Nature 16 (2020)**

# JLab@12 GeV DVCS program

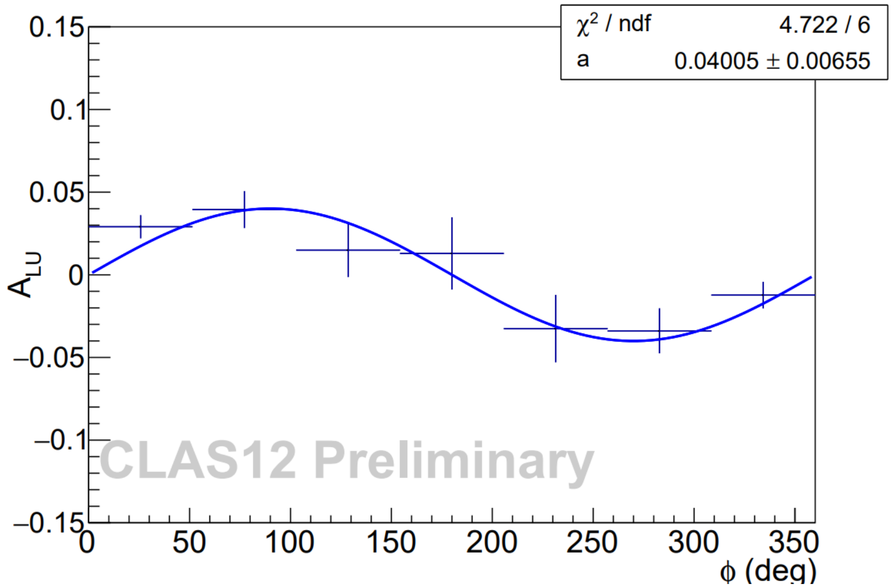
| Observable (target) | 12-GeV experiments | CFF sensitivity | Status |
| --- | --- | --- | --- |
| $\sigma$, $\Delta\sigma_{beam}(p)$ | Hall A<br>CLAS12<br>Hall C | Re$\mathcal{H}$(p), Im$\mathcal{H}$(p) | Hall A: data taken in 2016;<br>e-Print: 2201.03714 [hep-ph]<br>CLAS12: data taken in 2018-2019:<br>CS analysis in progress<br>Hall C: experiment planned for 2023 |
| BSA(p) | CLAS12 | Im$\mathcal{H}$(p) | BSA publication at Ad Hoc review stage |
| lTSA(p), lDSA(p) | CLAS12 | Im$\tilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p), Re$\tilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p) | Experiment will run in summer 2022 |
| tTSA(p) | CLAS12 | Im$\mathcal{H}$(p), Im$\mathcal{E}$(p) | Experiment foreseen for ~2025 |
| BSA(n) | CLAS12 | Im$\mathcal{E}$(n) | Data taken in 2019-2020, BSA analysis being finalized |
| lTSA(n), lDSA(n) | CLAS12 | Im$\mathcal{H}$(n), Re$\mathcal{H}$(n) | Experiment will run in summer 2022 |

**Hall A/C: high luminosity → precision, small kinematic coverage, eγ topology**
**CLAS12: lower luminosity, large kinematic coverage, fully exclusive final state**

# Preliminary CLAS12 results: BSA for nDVCS

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

**First-time measurement of nDVCS with detection of the active neutron**




$\langle Q^2 \rangle = 2.27\ GeV^2$

$\langle -t \rangle = 0.44\ GeV^2$

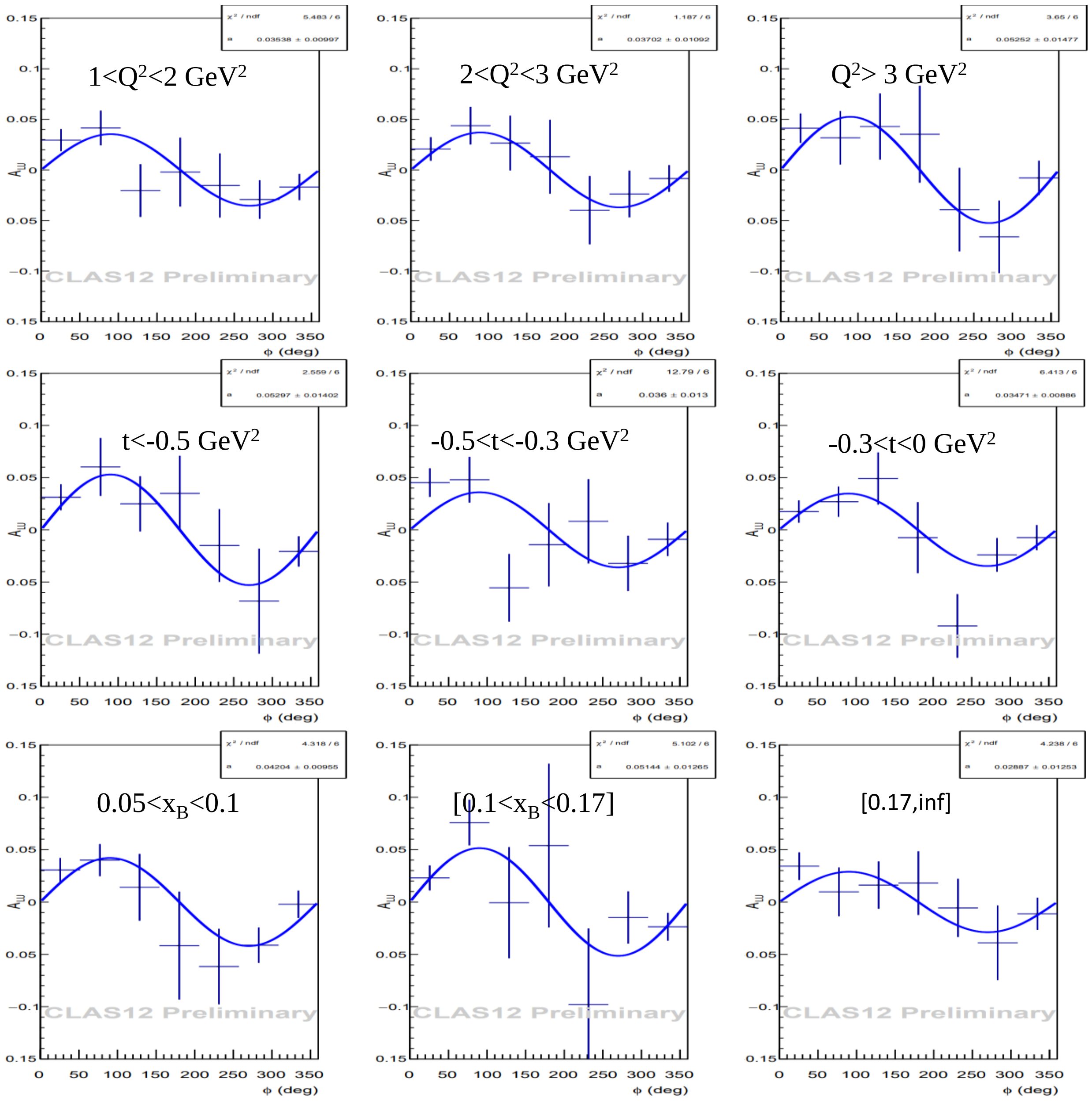
$\langle x_B \rangle = 0.19$

**Analysis by H. Hobart**

**$Q^2$ bins**

**t bins**

**$x_B$ bins**




The BSA for nDVCS is very small (2%-6%)

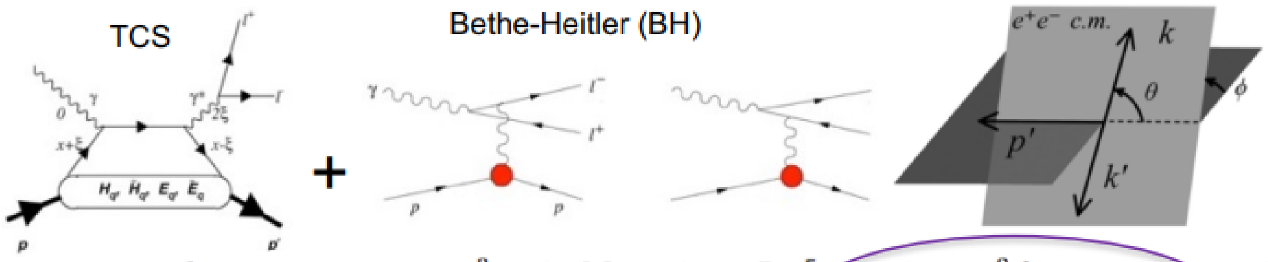
Limited statistical precision

**→ increased luminosity could be very beneficial**

# First-ever measurement of Timelike Compton Scattering (CLAS12)

- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and probes the universality of GPDs
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $D_q(t)$ (linked to the D-term) that relates to the mechanical properties of the nucleon (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.
- Limits: very small cross section → high luminosity is necessary for a precise measurement

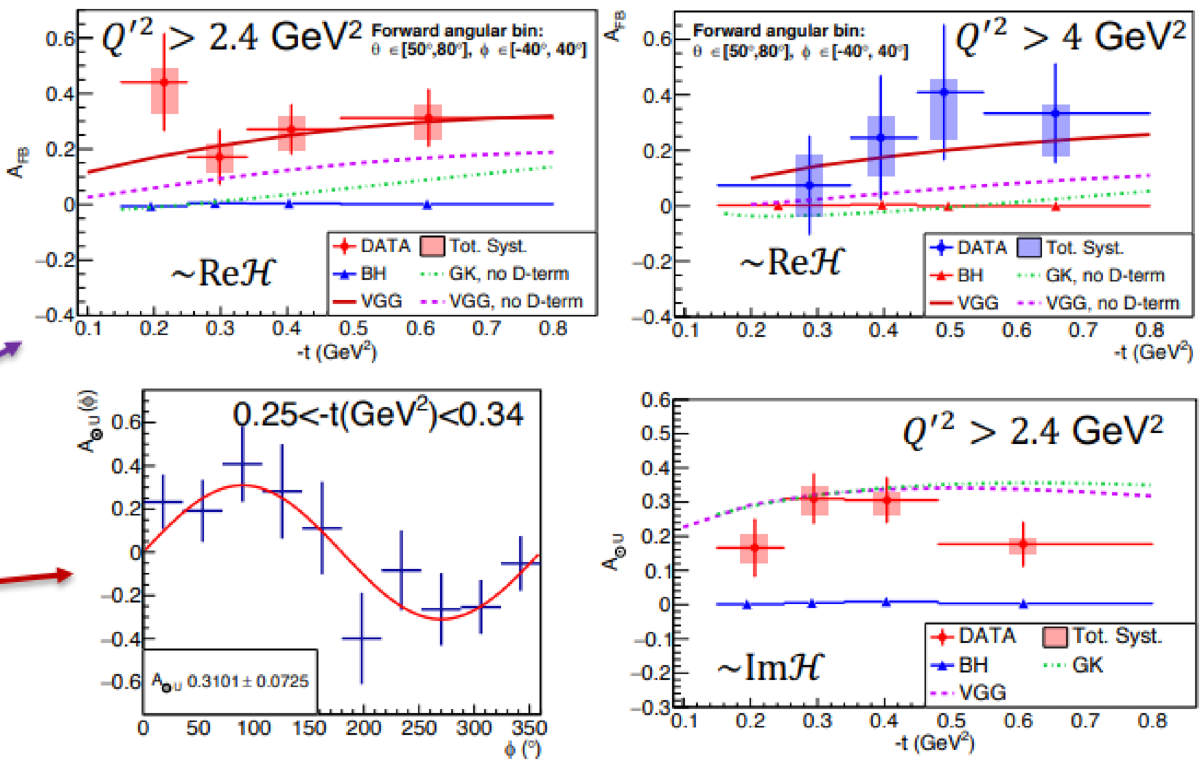
*TCS – time-reversal symmetric process to DVCS:*
incoming photon is real, and the outgoing photon has large time-like virtuality.




$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\tilde{M}^{+-} + O\!\left(\frac{1}{Q'}\right)\right]$$

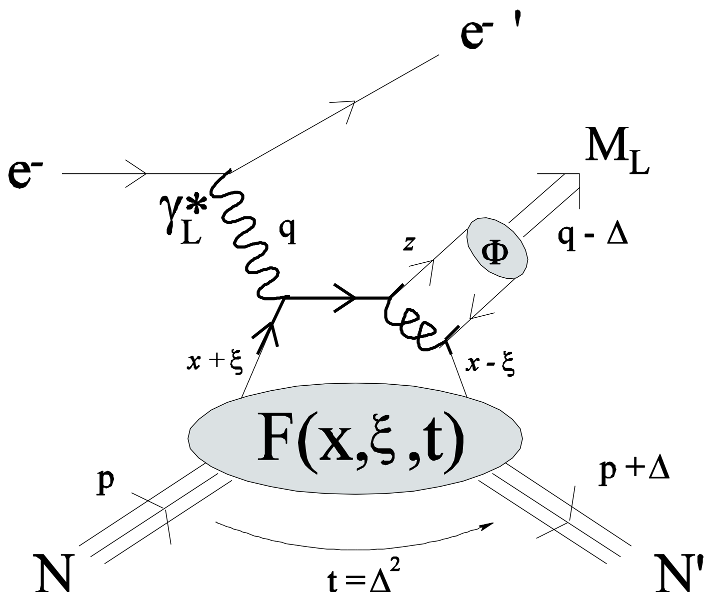
$$-\lambda\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\tilde{M}^{+-} + O\!\left(\frac{1}{Q'}\right)\right].$$

Incoming photon polarization




P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127, 262501 (2021)

# Deeply virtual meson production and GPDs




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

Different mesons → different sensitivity to GPDs

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

| | |
|---|---|
| $\pi^0$ | 2Δu+Δd |
| η | 2Δu-Δd |

| | |
|---|---|
| $\rho^0$ | 2u+d |
| ω | 2u-d |
| $\rho^+$ | u-d |

**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 $\rho^0$, $\omega$, $\phi$ and $\rho^+$ electroproduction on the proton with CLAS

K. Lukashin *et al.*, Phys. Rev. C 63, 065205, 2001 **($\phi$@4.2 GeV)**

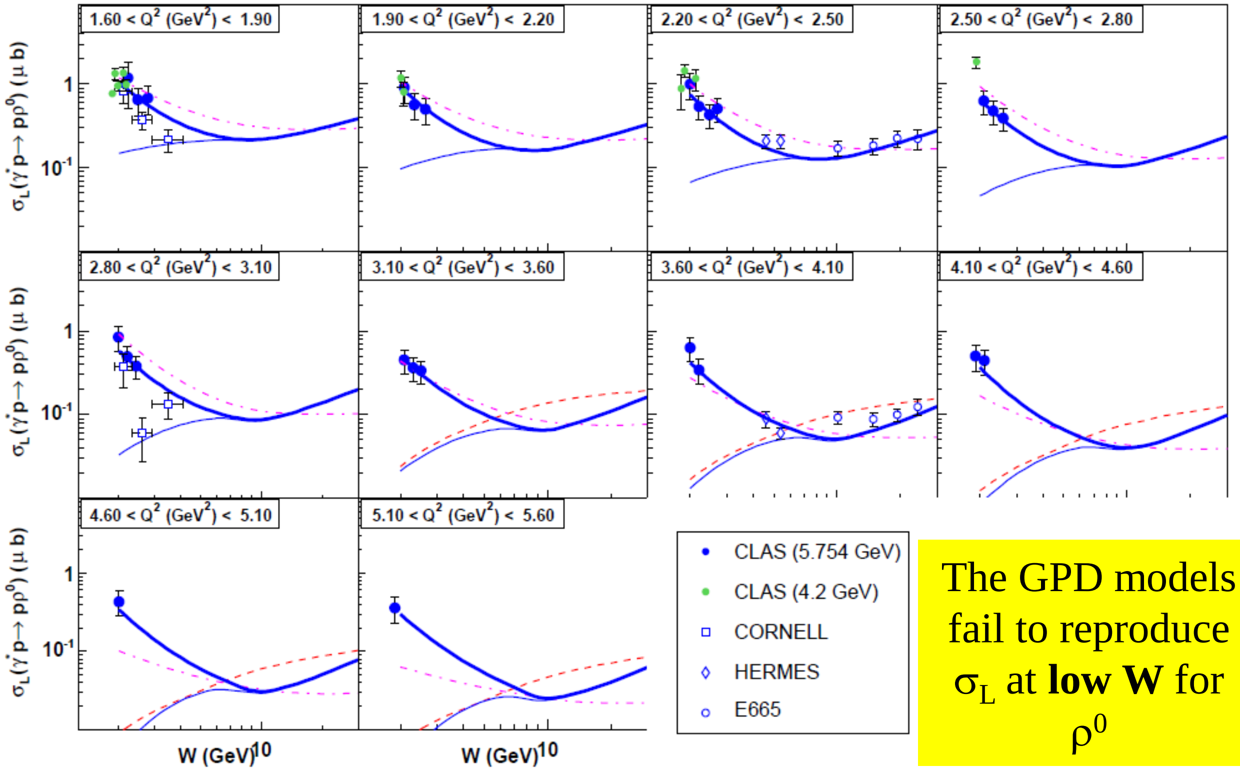
C. Hadjidakis *et al.*, Phys. Lett. B 605, 256-264, 2005 **($\rho^0$@4.2 GeV)**

L. Morand *et al.*, Eur. Phys. J. A 24, 445-458, 2005 **($\omega$@5.75GeV)**

J. Santoro *et al.*, Phys. Rev. C 78, 025210, 2008 **($\phi$@5.75 GeV)**

S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009 **($\rho^0$@5.75GeV)**

A. Fradi, Orsay Univ. PhD thesis **($\rho^+$@5.75 GeV) Not published**




The GPD models fail to reproduce $\sigma_L$ at **low W** for $\rho^0$

**Pseudoscalar mesons:** exclusive $\pi^0$ and $\eta$ electroproduction on the proton with CLAS

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

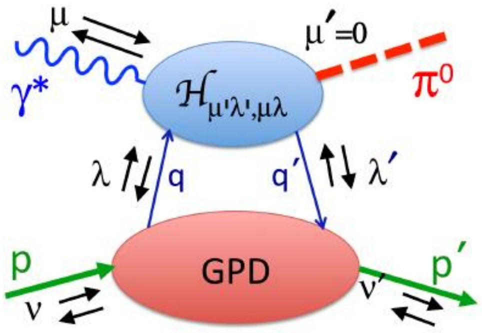
K. Park *et al.*, Phys. Rev. C 77, 015208, 2008 **($\pi^+$@5.75 GeV)**

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

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

The measured pseudo-scalar cross sections show a **strong transverse contribution** and are well described by transversity GPD models:

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



# Recap: what have we learned so far

- ImH well constrained, in CLAS (and soon CLAS12) kinematics
- ReH constrained mainly by Hall A measurements in selected kinematics; important for D-term and distribution of forces
- Initial constraints on $\tilde{\mathcal{H}}$ from longitudinally polarized target experiments, more data coming soon
- Potential of TCS for Re$\mathcal{H}$, D-term, universality of GPDs
- Importance of nDVCS for $E_n$ sensitivity and flavor separation, but low statistics
- pDVCS on transverse target is vital to constrain $E_p$
- Still no information on x dependence of GPDs
- DVMP: only pseudo-scalars had until now a « succesful » GPD interpretation (transversity) → higher $Q^2$ may be necessary

# Perspectives for upgrades at JLab

**Polarized positrons beam: talk by J. Grames Wed 17:15**

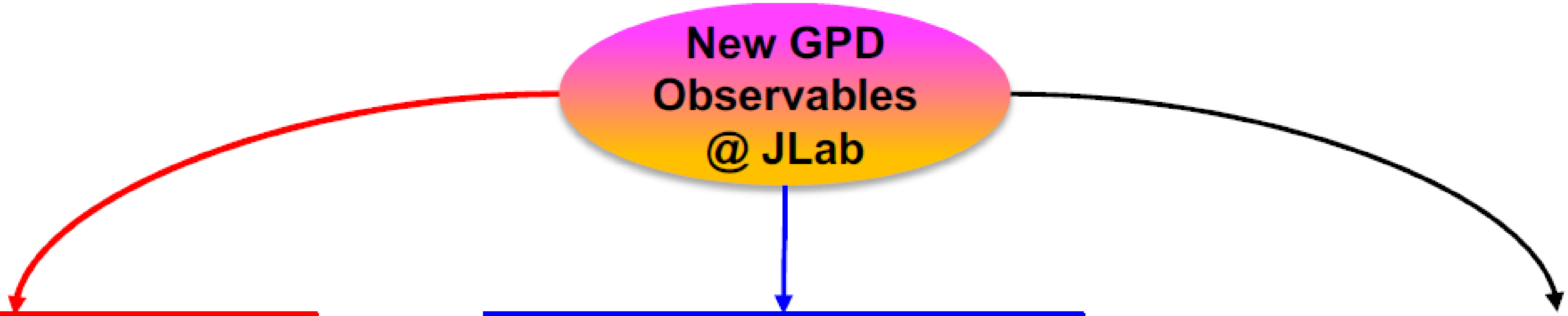
**High luminosity: talks by A. D'Angelo Tue 17:00 (detector), J. Benesch Wed 17:45 (beam)**

**Double beam energy: talk by V. Burkert Tue 17:30 (detector), A Bogacz Wed 16:45 (beam)**

# DVCS with polarized positrons beam at JLab

The important of beam-charge asymmetry for DVCS was highlighted by the pioneering HERMES experiment
Disposing of a polarized positron/electron beams at JLab → new observables = different sensitivities to GPDs
Beam Charge Asymmetries proposed to be measured at CLAS12:

- The unpolarized beam charge asymmetry $\mathbf{A_C^{UU}}$, which is sensitive to the real part of the CFF → D-term, forces in the proton
- The polarized beam charge asymmetry $\mathbf{A_C^{LU}}$, which is sensitive to the imaginary part of the CFF
- The neutral beam spin asymmetry $A_0^{LU}$, which is sensitive to higher twist effects




$$A^C_{UU} = \frac{(Y_+^+ + Y_-^+) - (Y_+^- + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

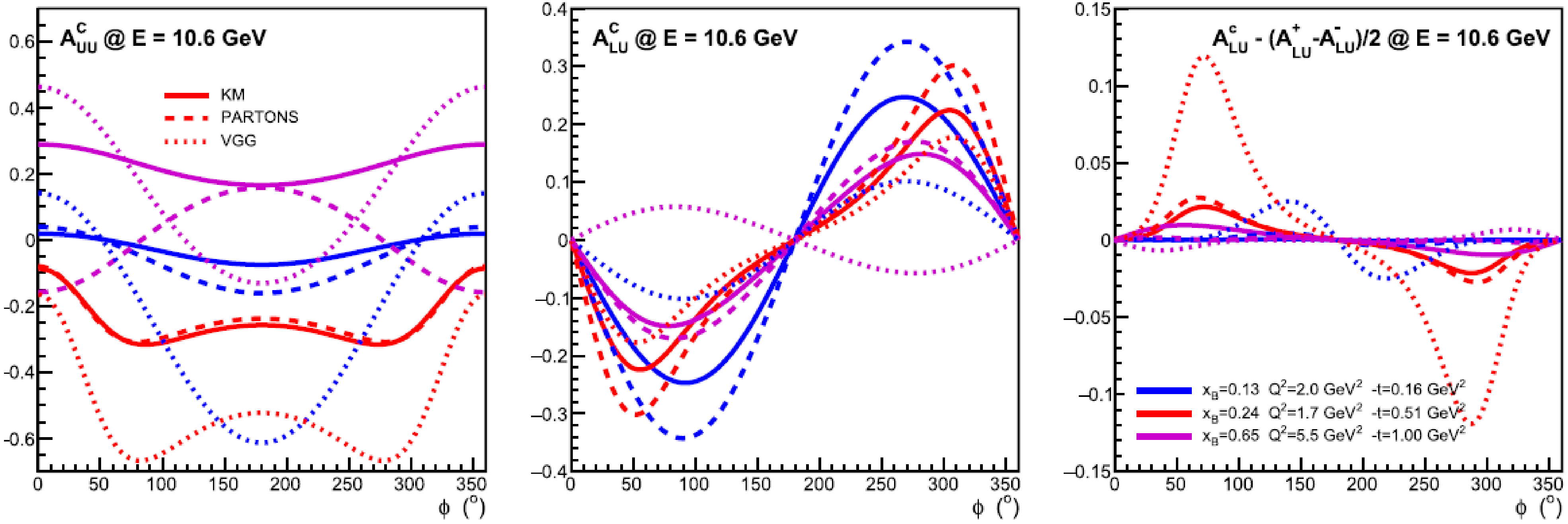
$$A^C_{LU} = \frac{(Y_+^+ - Y_-^+) - (Y_+^- - Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^0_{LU} = \frac{(Y_+^+ + Y_+^-) - (Y_-^+ + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\tilde{\sigma}_{DVCS}}{\sigma_{BH} + \sigma_{DVCS}}$$

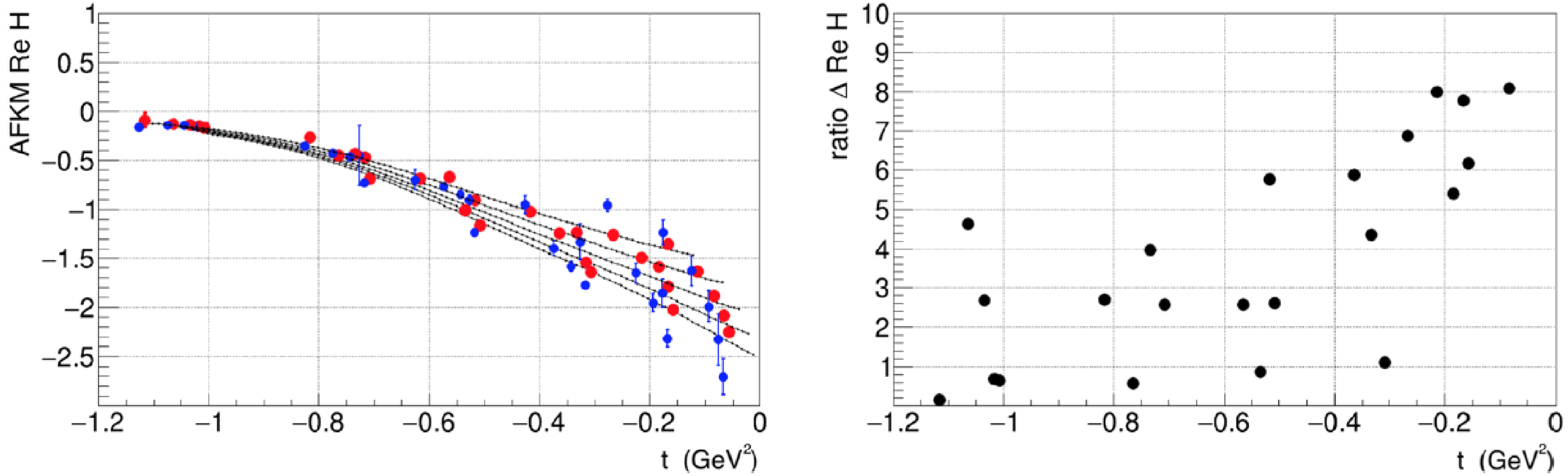
☛ $$A^C_{LU} \neq A^{\pm}_{LU} = \frac{\pm(\tilde{\sigma}_{INT} \pm \tilde{\sigma}_{DVCS})}{\sigma_{BH} + \sigma_{DVCS} \pm \sigma_{INT}}$$

# pDVCS with polarized positrons beam at CLAS

Model predictions for the three observables

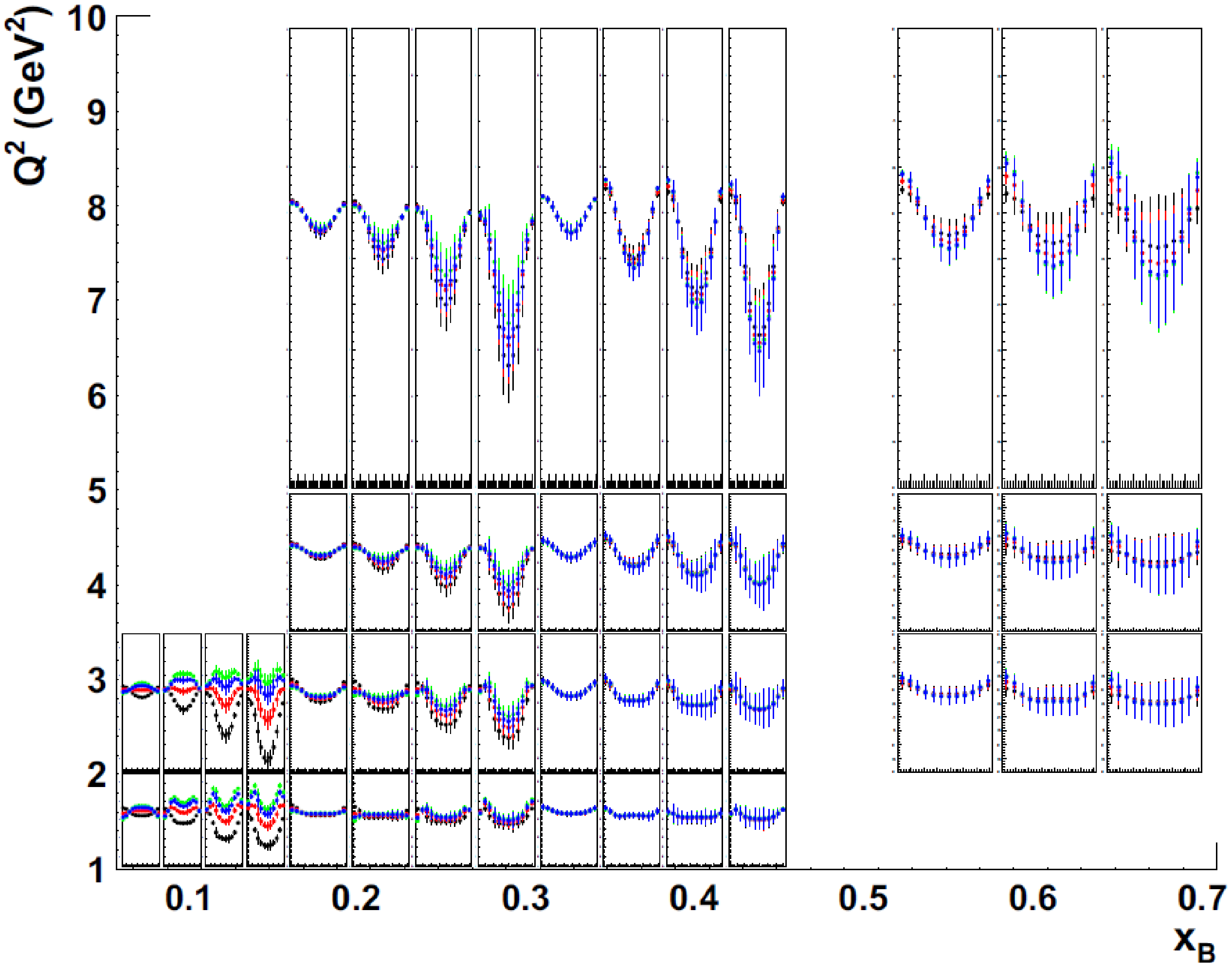



Impact of positron projected data on the extraction of ReH via global fits: major reduction of relative uncertainties, especially at low -t



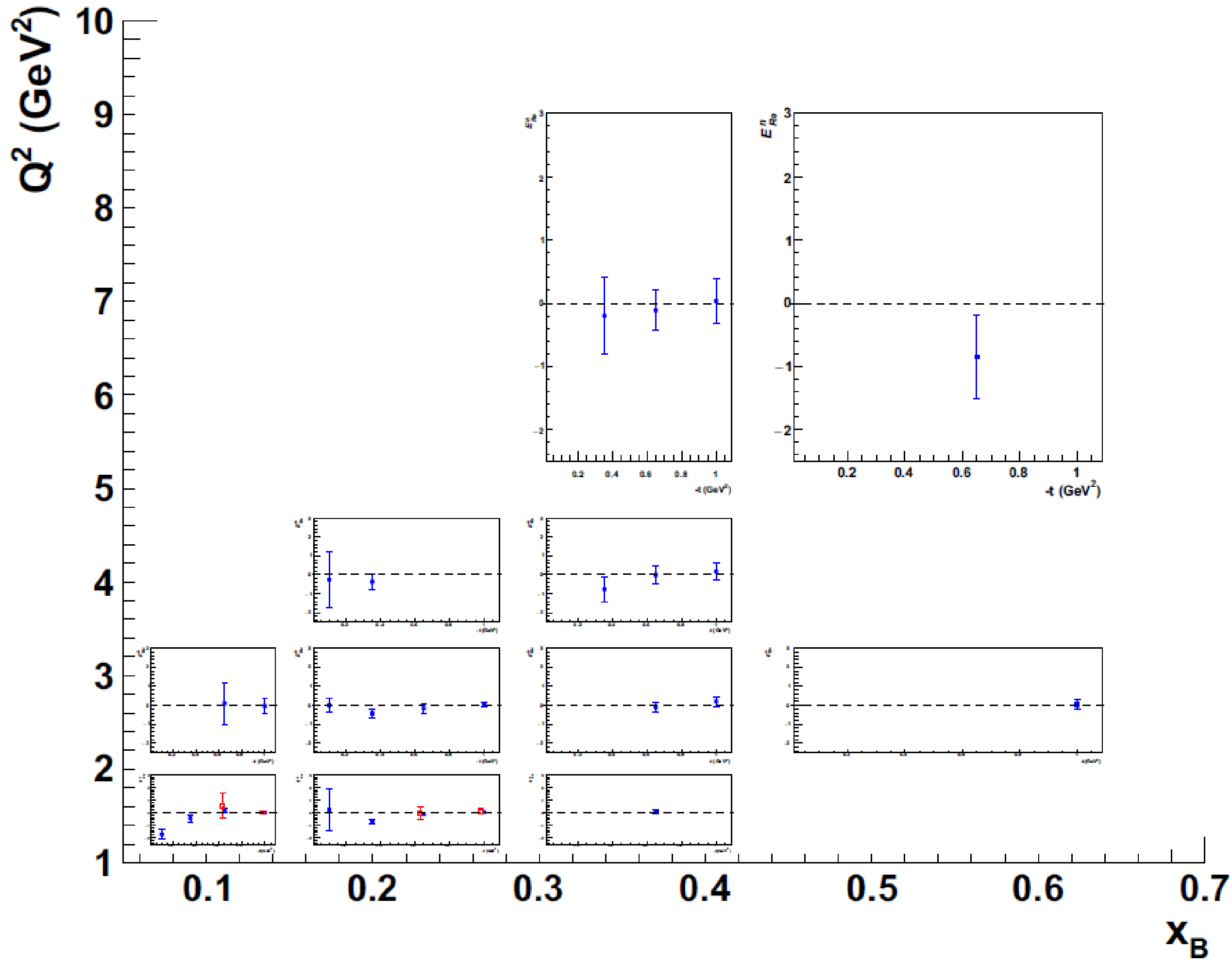

**V. Burkert et al., Eur. Phys. J. A (2021) 57:186**

# nDVCS with polarized positrons beam at CLAS12



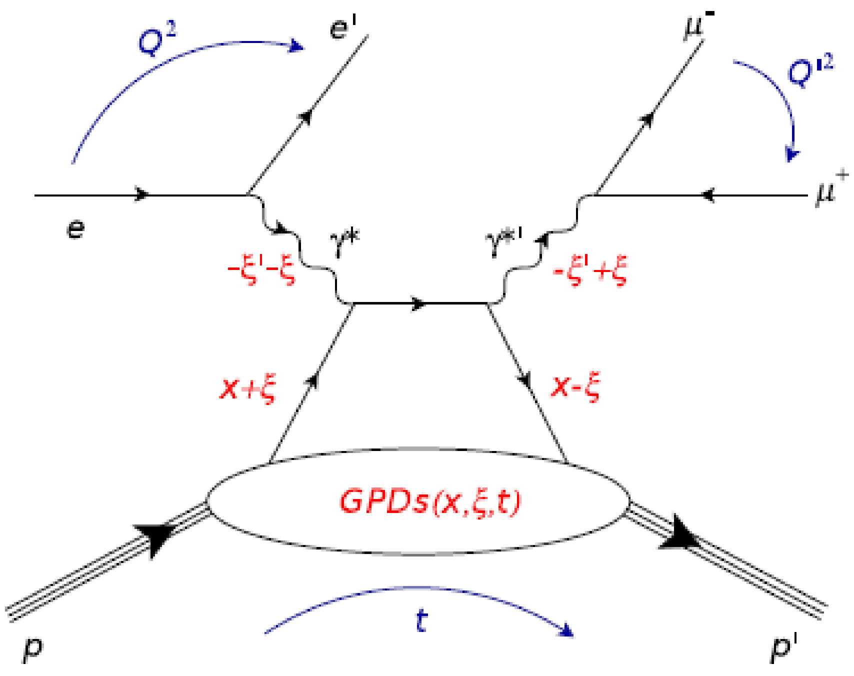

**Projections (VGG) for the BCA, for various values of $J_u$, $J_d$**
**0.3, 0.1; 0.2/0.0; 0.1/−0.1; 0.3/−0.1**

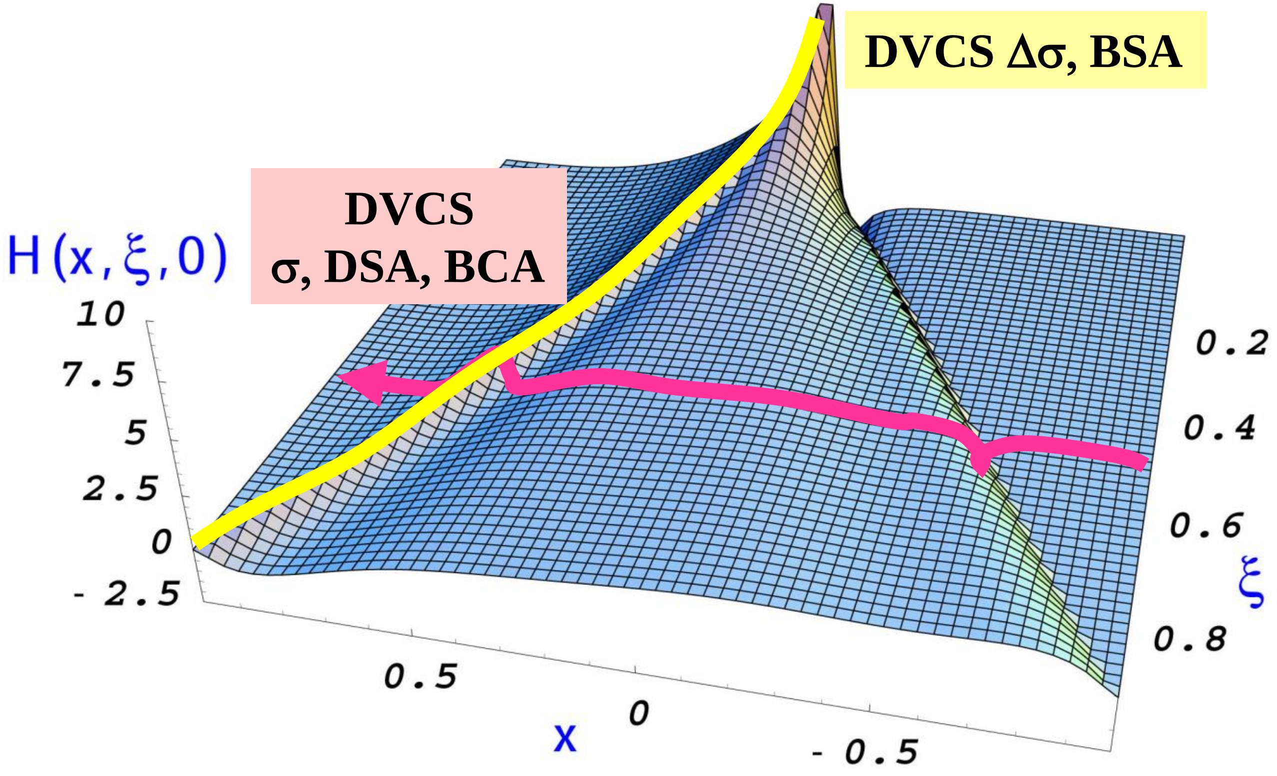
**S.N. et al, Eur. Phys. J. A (2021) 57:226**




**Impact on the extraction of Re$\mathcal{E}$ using local fits, using the projections of approved CLAS12 nDVCS measurements with and without BCA**

# DDVCS: the gateway to the full kinematic mapping of GPDs




Thanks to the virtuality of the final photon, $Q'^2$, **DDVCS** allows a unique direct access to GPDs at **$x \neq \pm\xi$** (within $0 < 2\xi' - \xi < \xi$), which is fundamental for their modeling

Experimental challenges:

- Small cross section (300 times less than DVCS)
- Need to detect muons

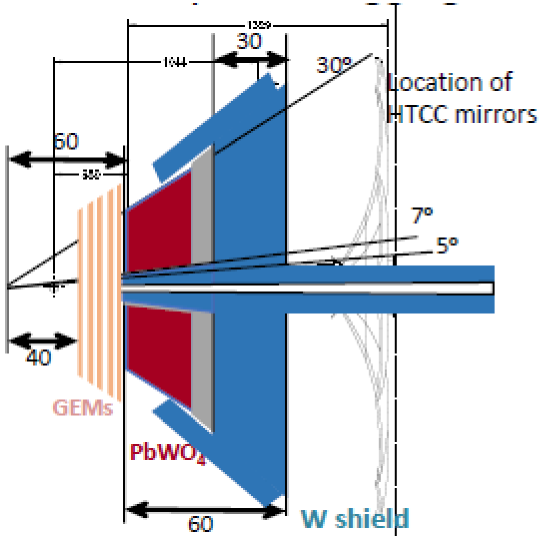
# μCLAS12 for DDVCS and J/psi (LOI12-16-004)

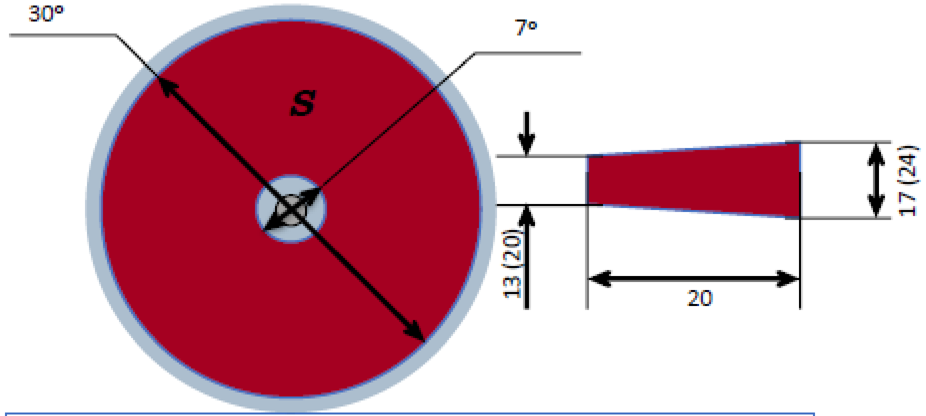
## $ep \rightarrow e'p'\mu^+\mu^-$ at $L \sim 10^{37}\ cm^{-2}s^{-1}$

• Remove HTCC and install in the region of active volume of HTCC
- a new Moller cone that extends up to 7°
- a new PbWO4 calorimeter that covers 7° to 30° polar angular range with 2π azimuthal coverage.

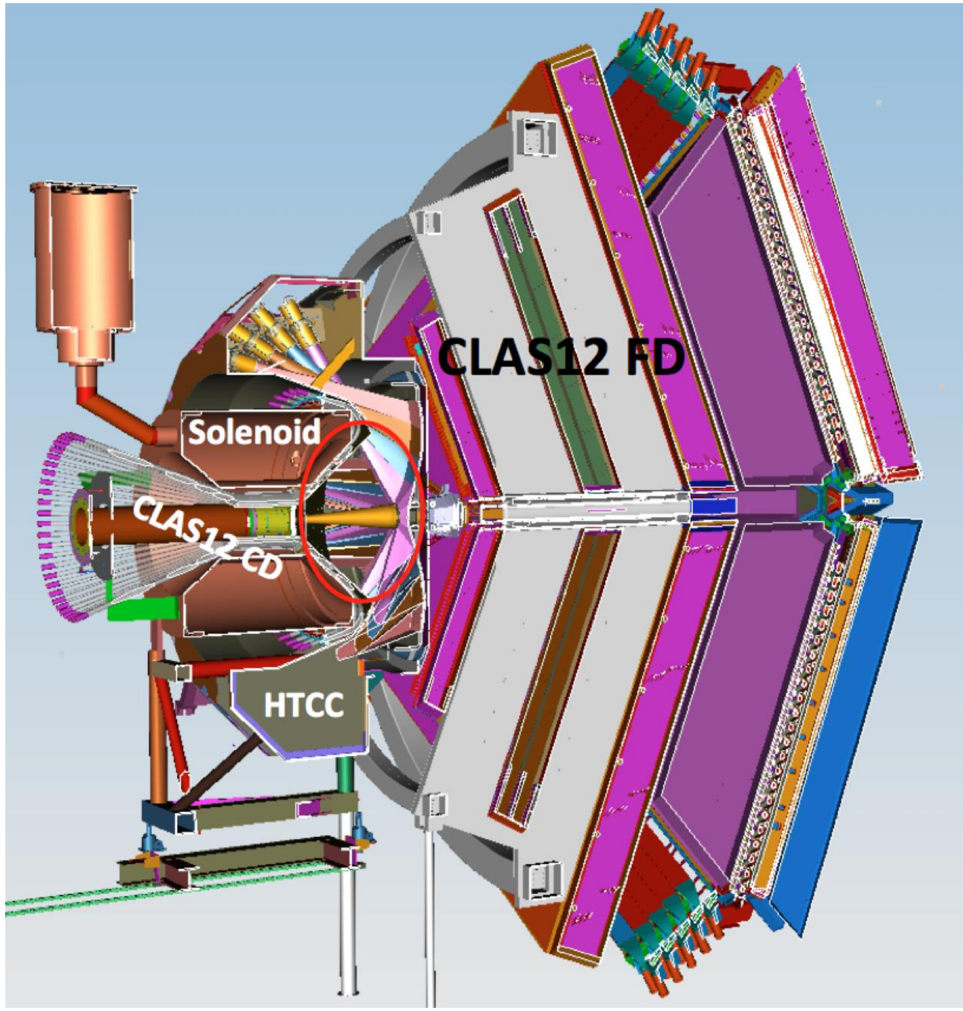
• Behind the calorimeter, a 30-cm-thick tungsten shield covers the whole acceptance of the CLAS12 FD

• MPGD tracker in front of the calorimeter for vertexing and inside the solenoid for recoil proton tagging



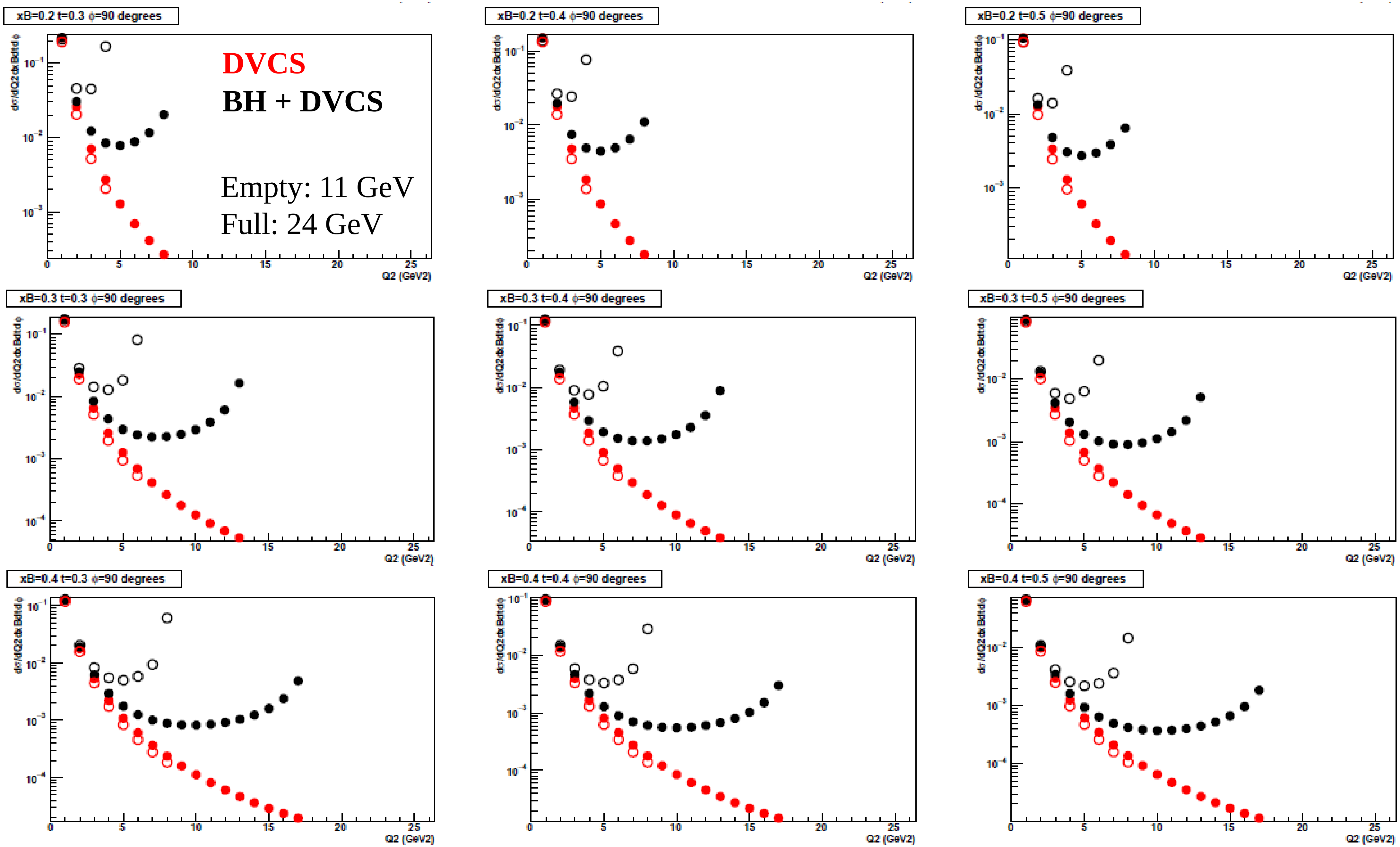




PbWO4 modules with APD readout - ~ 1200 modules



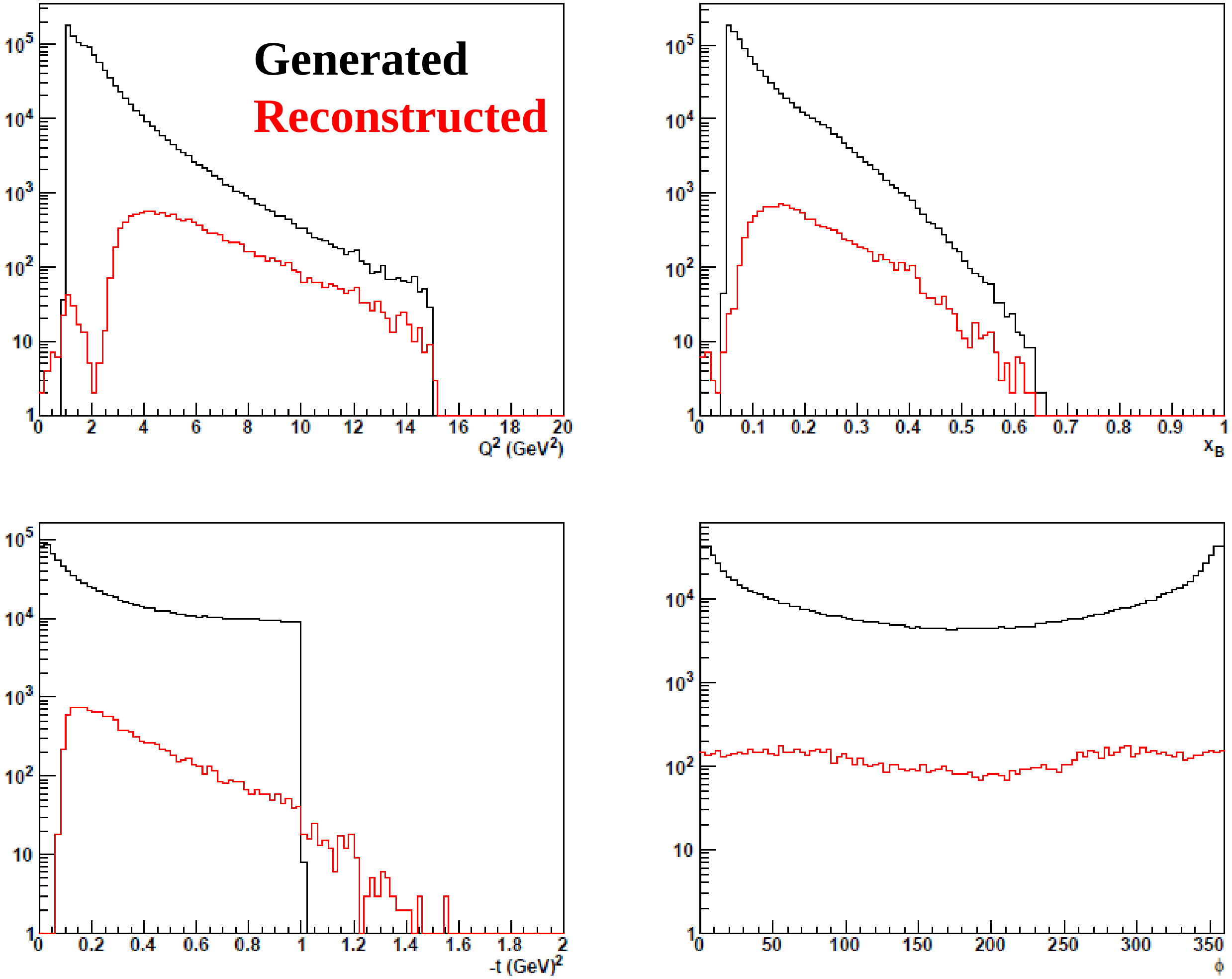

S. Stepanyan, CLAS collaboration meeting

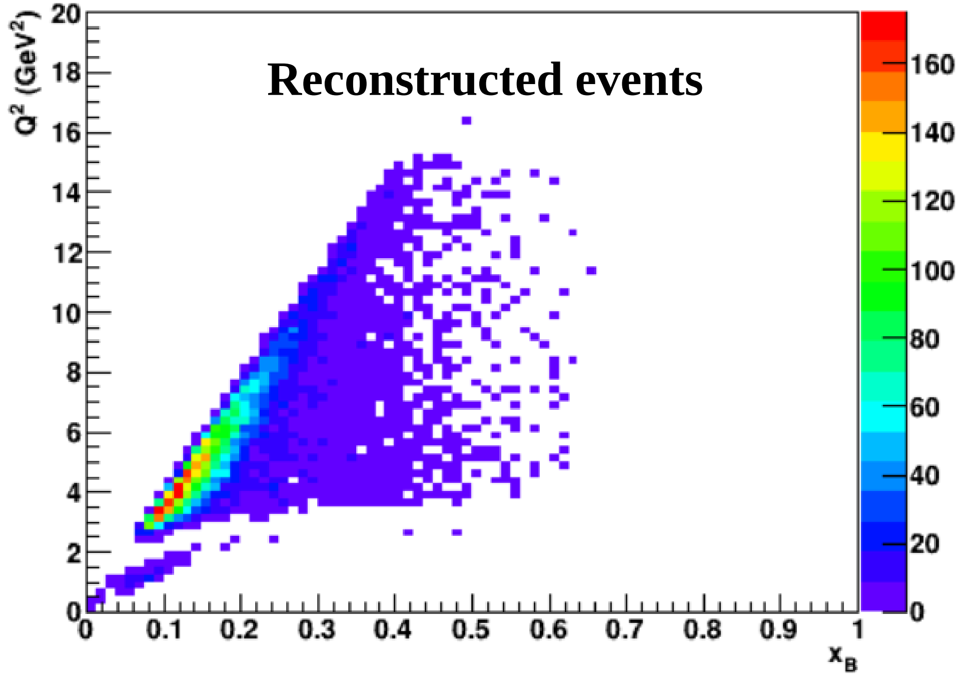
# Cross section DVCS @ 24 GeV, VGG predictions

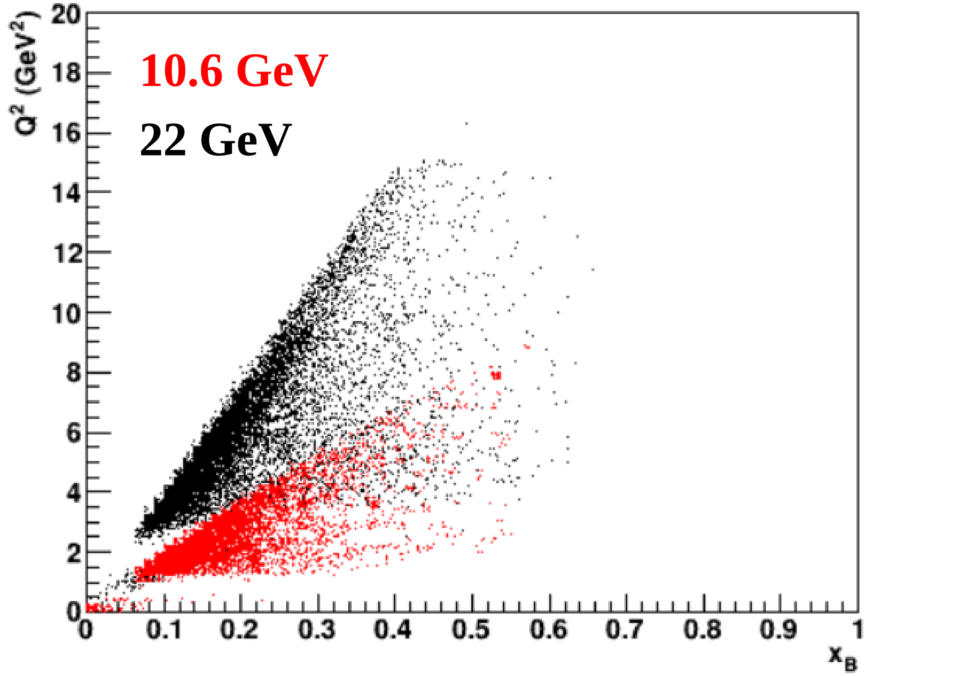


# pDVCS with 22-GeV beam (current CLAS12)

Simulated pDVCS events at 22 GeV (H. Avakian), passed through GEMC (current CLAS12) and standard CLAS12 reconstruction (R. De Vita)




With the current CLAS12 acceptance ~1%, mainly all new kinematics

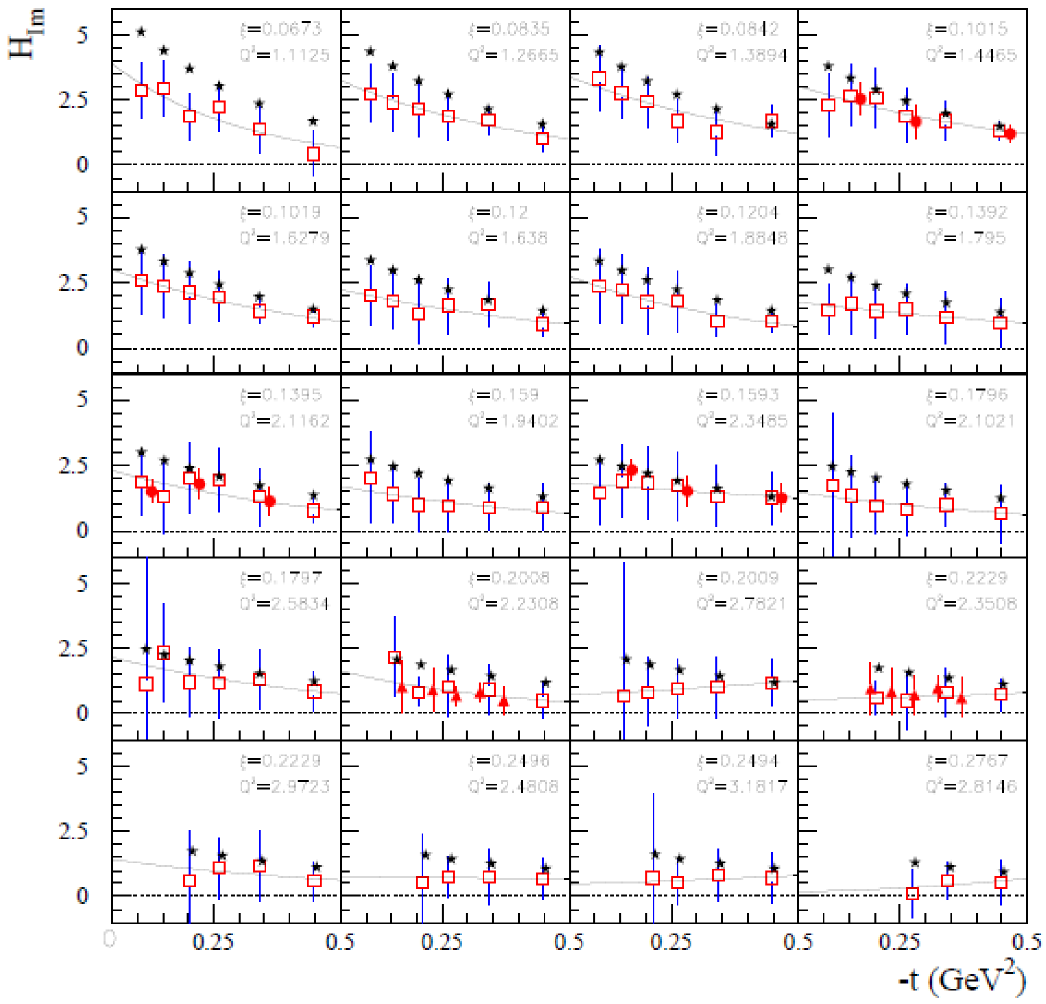
PID? Backgrounds? Further studies are needed

# Conclusions and outlook

- Exclusive reaction can provide a **wealth of information on nucleon structure**, via the measurement of **GPDs**: nucleon tomography, quark angular momentum, distribution of forces in the nucleon
- **pDVCS** has been and is being **extensively measured**, aside from **beam-charge and transverse-target observables**
- **nDVCS** measurements are ongoing, **cross sections and asymmetries are very small** → **higher luminosity** would be welcome, as well as measurements of **BCA**
- **TCS & <u>DDVCS</u>** are the **golden channels** that should be explored in the future to go beyond DVCS: universality of GPDs, real part of CFFs, x dependence of GPDs
- **Higher beam energy** will increase the **phase space for DVCS**, but also **lower cross sections** (strong BH dominance?); PID and backgrounds need to be studied; likely beneficial for **DVMP** measurements, but **let's have a look first at 11-GeV data**
- To have an **upgraded JLab** (CLAS12) **coexisting and competing with the EIC**, we should prove that it allows **UNIQUE physics**, not only **complementary kinematics**: pointing towards the measurements of **small-cross-section and unmeasured reactions/observables requiring high luminosity and/or polarized positrons beam can be a good strategy**; higher energy alone (without positrons and/or DDVCS) doesn't seem to me to lead to a strong enough physics case, at least in the GPDs field
- **Ideally, we should aim for high-lumi, energy, and positrons** ☺
- The CLAS Collaboration held sessions dedicated to the upgrades in the last 3 meetings; open discussion at the last meeting showed **strong interest in the community**; support from JLab management for Users' initiatives towards upgrades
- Next steps? Involving theorists for predictions; realistic simulations; LOIs & PAC proposals? R&D for detector developments?

# Back-up slides

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

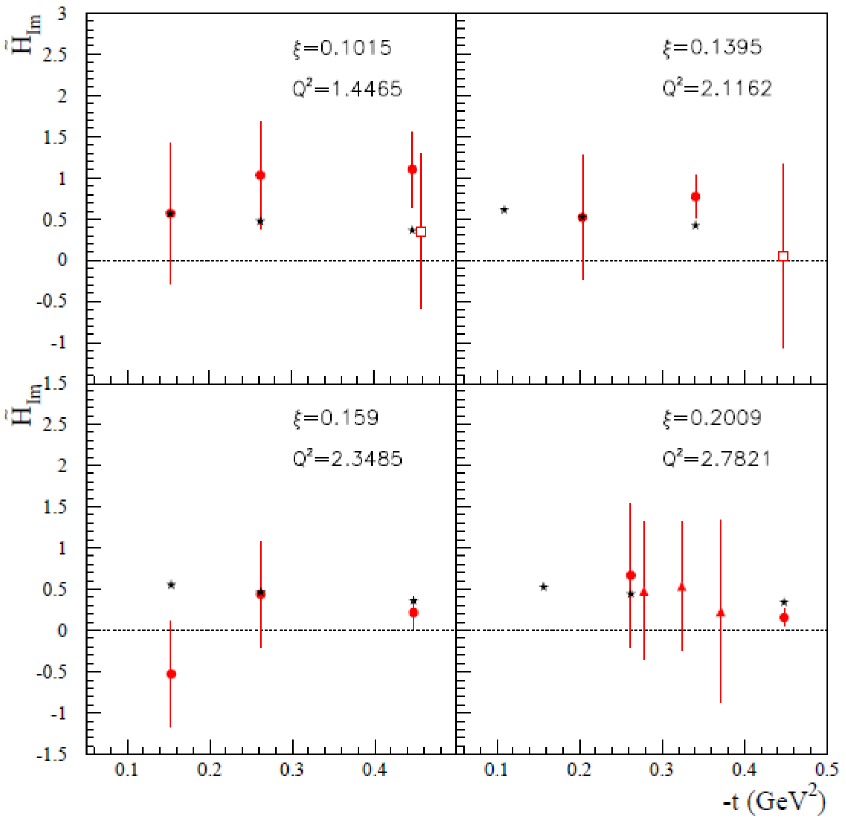



□ Fit to CLAS c.s. and beam pol. c.s.

● Fit to CLAS c.s., beam pol. c.s., lTSA, DSA

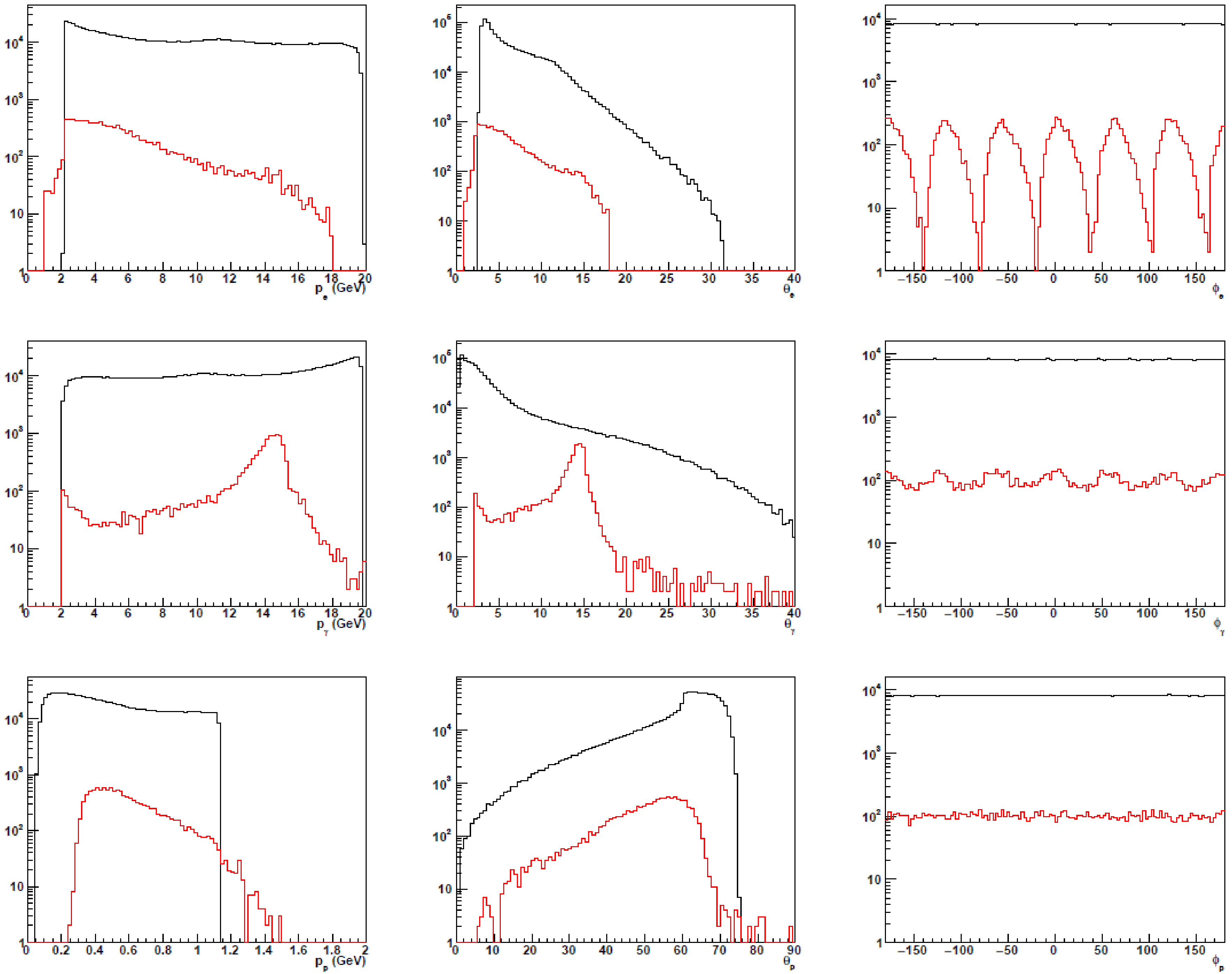
▲ Fit to Hall A c.s. and beam pol. c.s.

★ VGG model



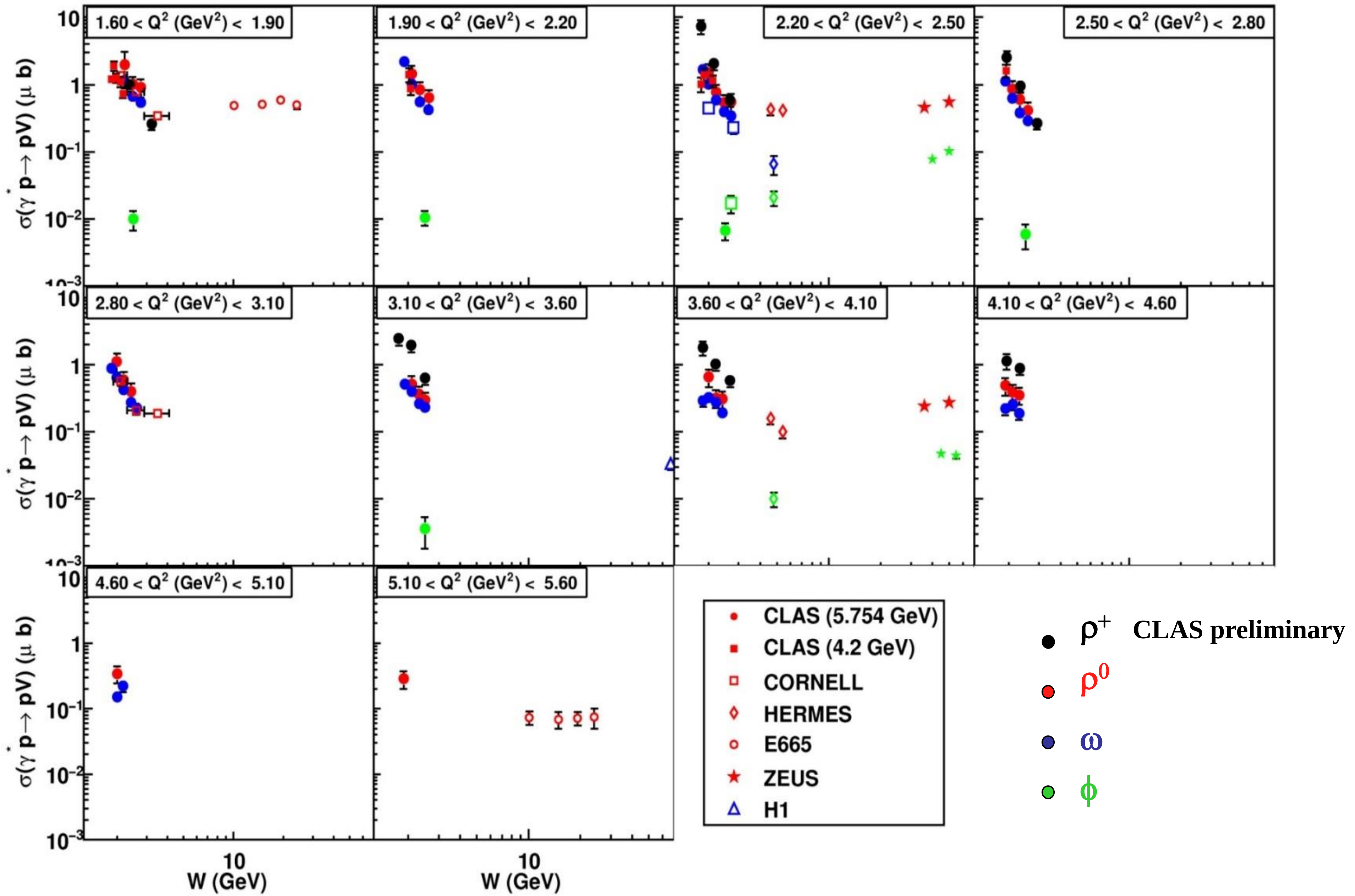

**$H_{Im}$ has steeper t-slope than $\tilde{H}_{Im}$: the axial charge (~Δu-Δd) is more “concentrated” than the electric charge**

**R. Dupré, M. Guidal, S.N. , M. Vanderhaegen, EPJA 53, 171 (2017)**



p_e (GeV)
θ_e
φ_e
p_γ (GeV)
θ_γ
φ_γ
p_p (GeV)
θ_p
φ_p

# Comparison between vector mesons (σ)



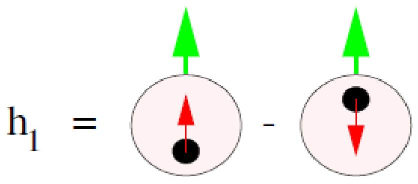
# Chiral-odd GPDs

- 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:

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

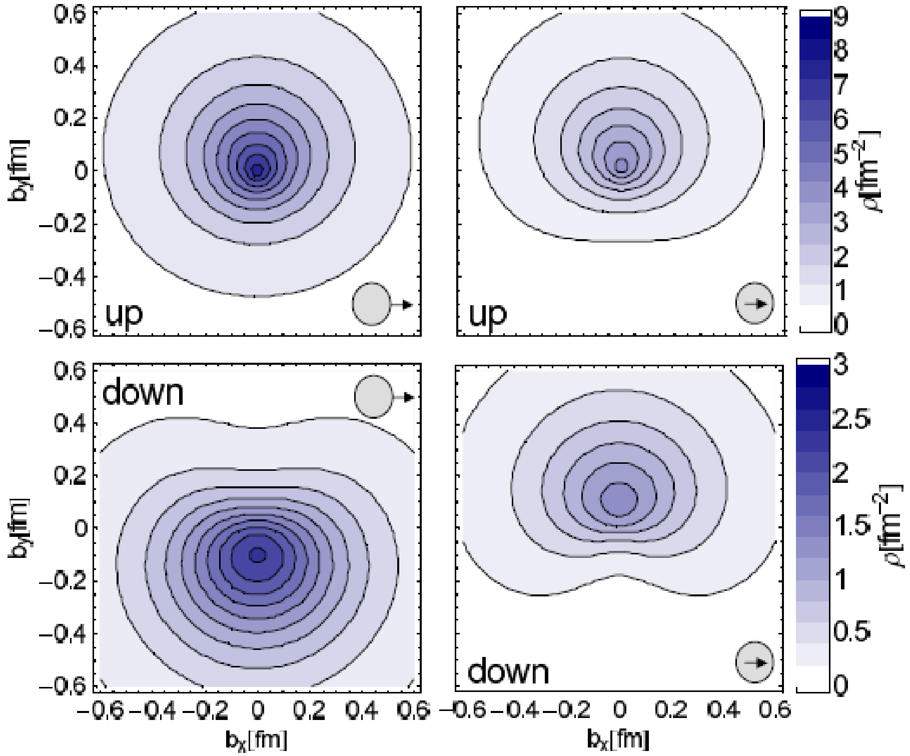
- Link to the **transversity** distribution: $H_T^q(x,0,0) = h_1^q(x)$

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




## Transverse Densities for u and d quarks in the nucleon

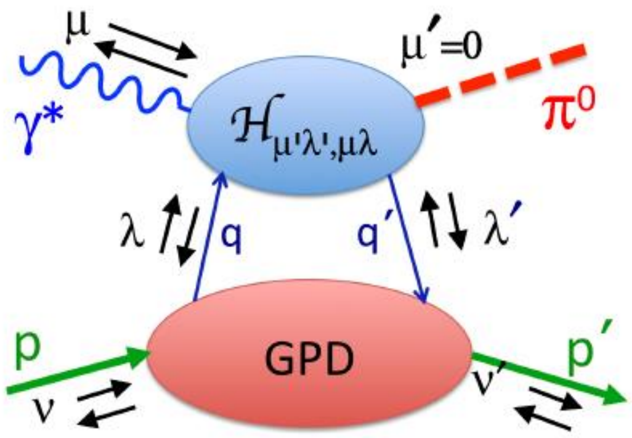
Distributions of unpolarized quarks in a transversely polarized nucleon, **linked to *E***

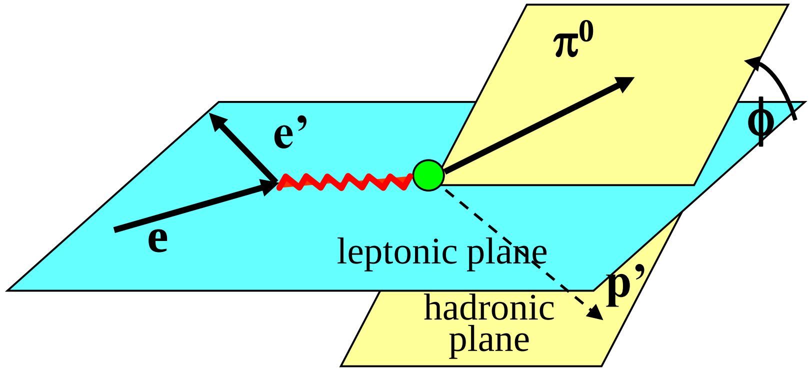



Distribution of transversely polarized quarks in an unpolarized nucleon, **linked to $\bar{E}_T$**

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

# Exclusive $\pi^0$ 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:** $\sigma_L = \frac{4\pi\alpha_e}{k'Q^6}\left[(1-\xi^2)|<\tilde{H}>|^2 - 2\xi^2\,\mathrm{Re}(<\tilde{H}>^*<\tilde{E}>) - \frac{t'}{4m^2}\xi^2|<\tilde{E}>|^2\right]$

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

Generalized Compton Form Factors

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

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

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

**Transversity GPD models:**

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

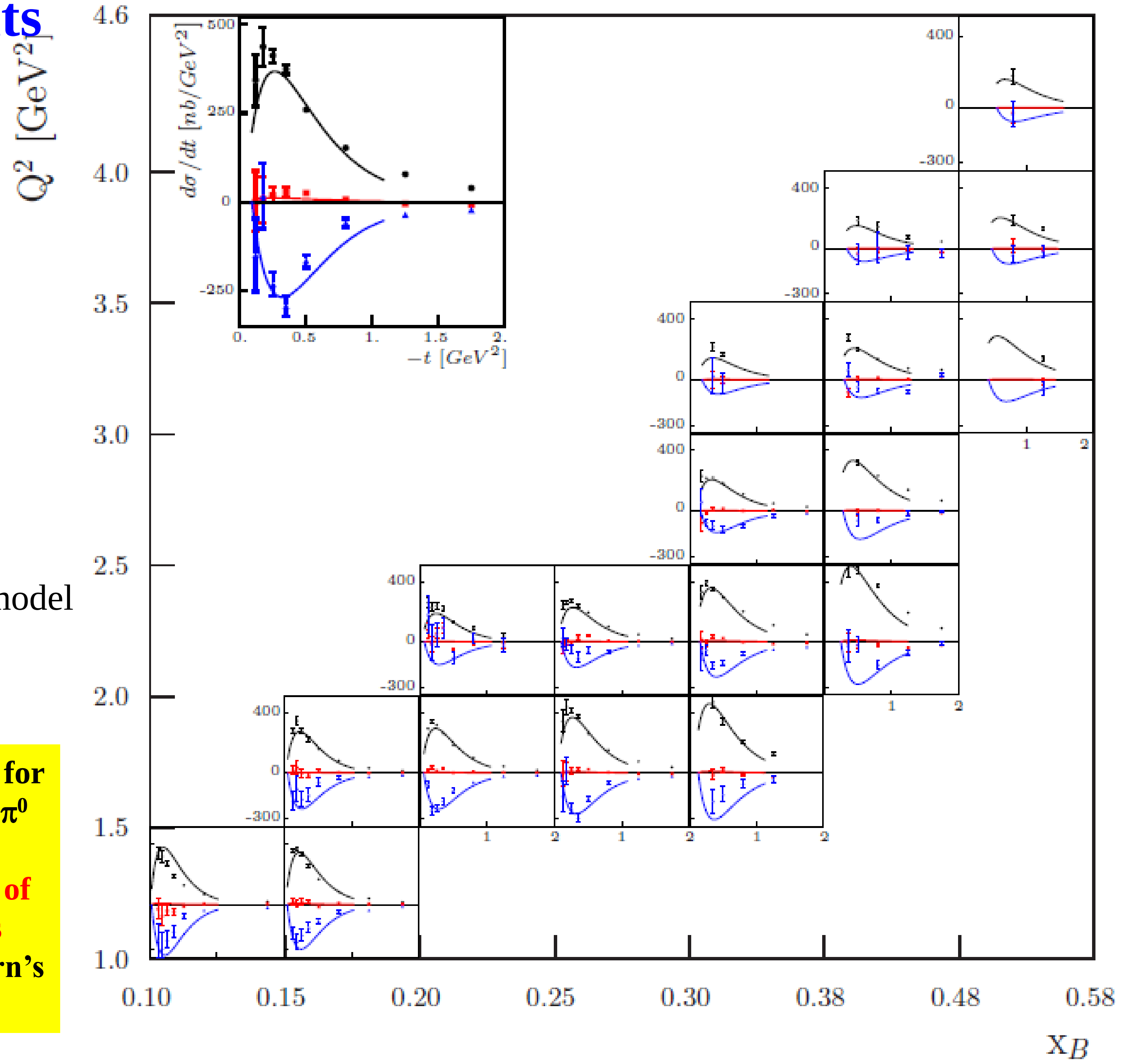
# CLAS results

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

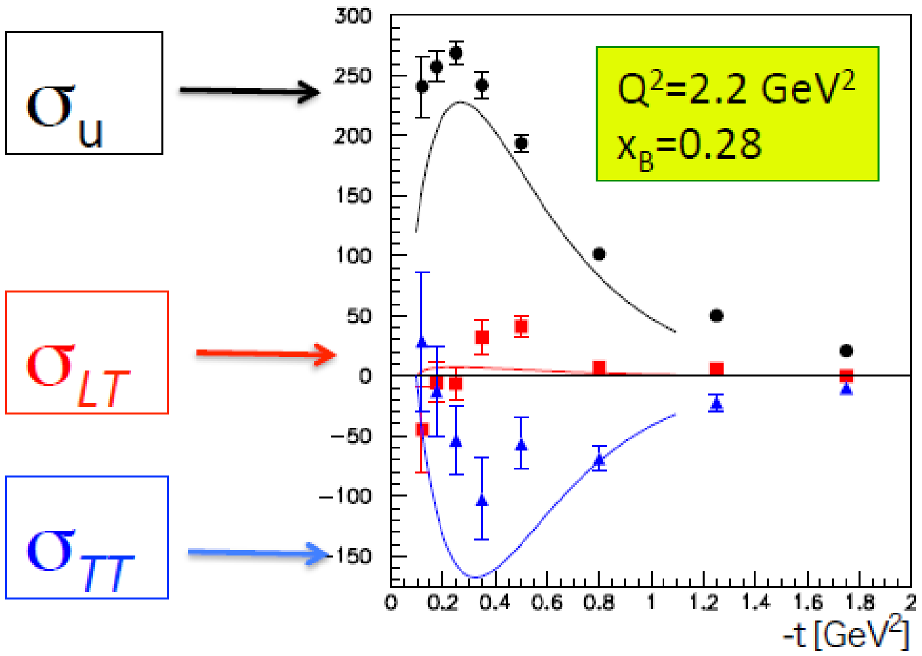
$\sigma_T + \varepsilon\sigma_L$
$\sigma_{LT}$
$\sigma_{TT}$

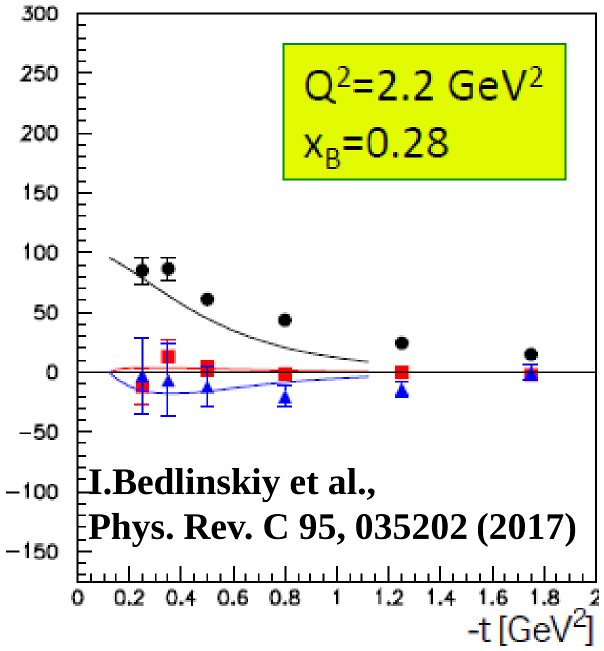
Goloskokov-Kroll model
Transversity GPDs

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

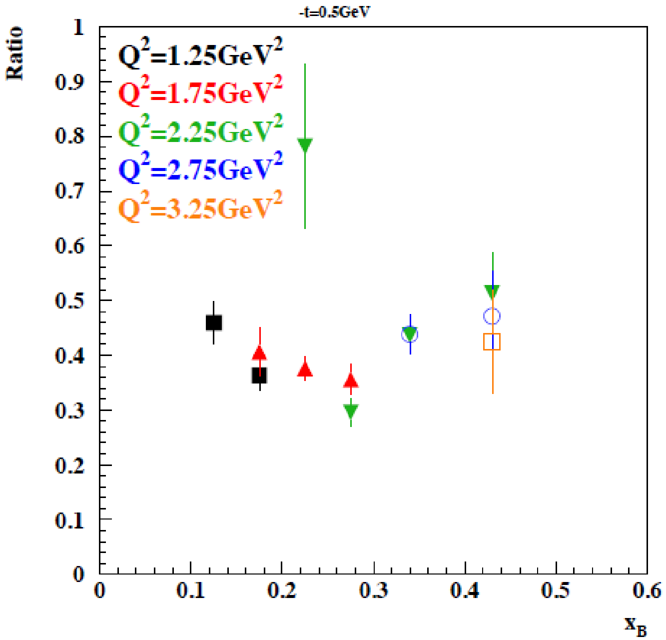


# Comparison $\pi^0/\eta$




- 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 $\pi^0$ and $\eta$