

# 3D images of the nucleon

Carlos Muñoz Camacho

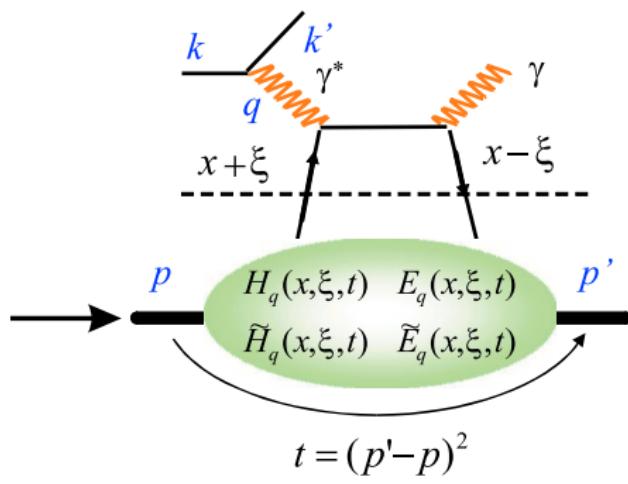
Laboratoire Irène Joliot-Curie, CNRS/IN2P3 (France)

Teleworkshop on Strong QCD from Hadron Structure Experiments

# Outline

- ① Introduction
- ② Deeply Virtual Compton Scattering (DVCS):  $ep \rightarrow ep\gamma$ 
  - Results on both **proton** and **neutron**
- ③ Exclusive  $\pi^0$  electroproduction (DVMP):  $eN \rightarrow eN\pi^0$ 
  - Also: **proton** + **neutron**  $\Rightarrow$  *flavor separation*
- ④ Summary

# Deeply Virtual Compton Scattering (DVCS): $\gamma^* p \rightarrow \gamma p$



**Handbag diagram**

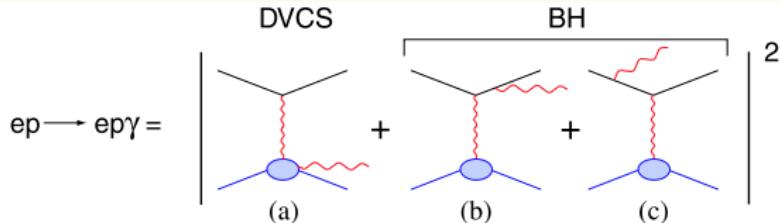
**Bjorken limit :**

$$Q^2 = \left. \begin{array}{l} -q^2 \\ \nu \end{array} \right\} \rightarrow \infty \quad \left. \begin{array}{l} \infty \\ \infty \end{array} \right\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

High  $Q^2$   
Perturbative QCD

Non-perturbative  
GPDs

# DVCS experimentally: interference with Bethe-Heitler



At leading order in  $1/Q$  (leading twist) :

$$d^5 \vec{\sigma} - d^5 \overleftarrow{\sigma} = \Im m (T^{BH} \cdot T^{DVCS})$$

$$d^5 \vec{\sigma} + d^5 \overleftarrow{\sigma} = |BH|^2 + \Re e (T^{BH} \cdot T^{DVCS}) + |DVCS|^2$$

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} + \dots =$$

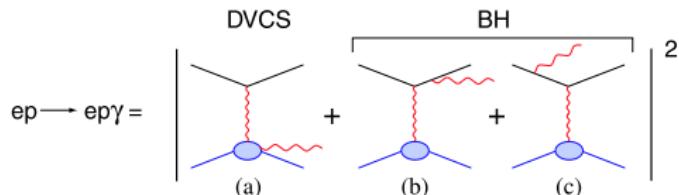
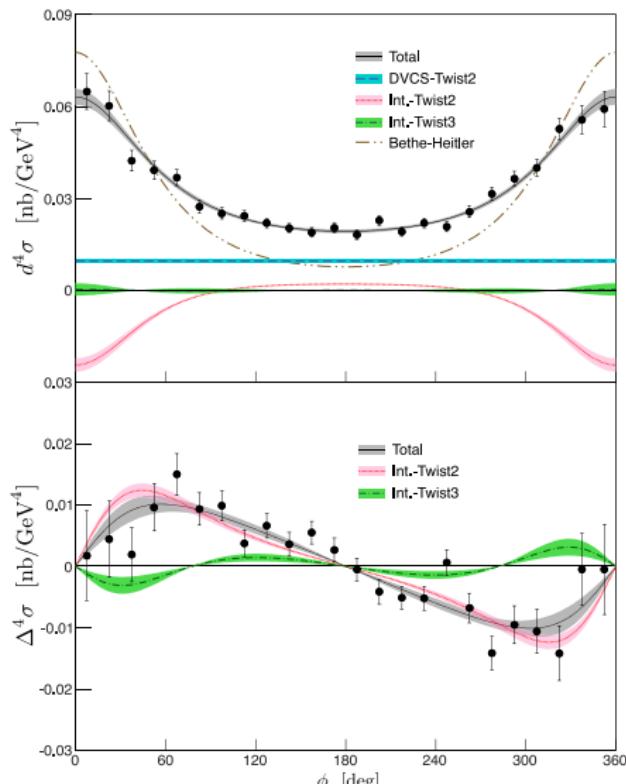
$$\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi H(x = \xi, \xi, t)}_{\text{Access in helicity-dependent cross-section}} + \dots$$

Access in helicity-independent cross section

Access in helicity-dependent cross-section

# DVCS cross sections: azimuthal analysis

$$Q^2 = 2.36 \text{ GeV}^2, x_B = 0.37, -t = 0.32 \text{ GeV}^2$$



$$d^4\sigma = \mathcal{T}_{\text{BH}}^2 + \mathcal{T}_{\text{BH}} \mathcal{R}\text{e}(\mathcal{T}_{\text{DVCS}}) + \mathcal{T}_{\text{DVCS}}^2$$

$$\mathcal{R}\text{e}(\mathcal{T}_{\text{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}} \cos \phi + c_2^{\mathcal{I}} \cos 2\phi$$

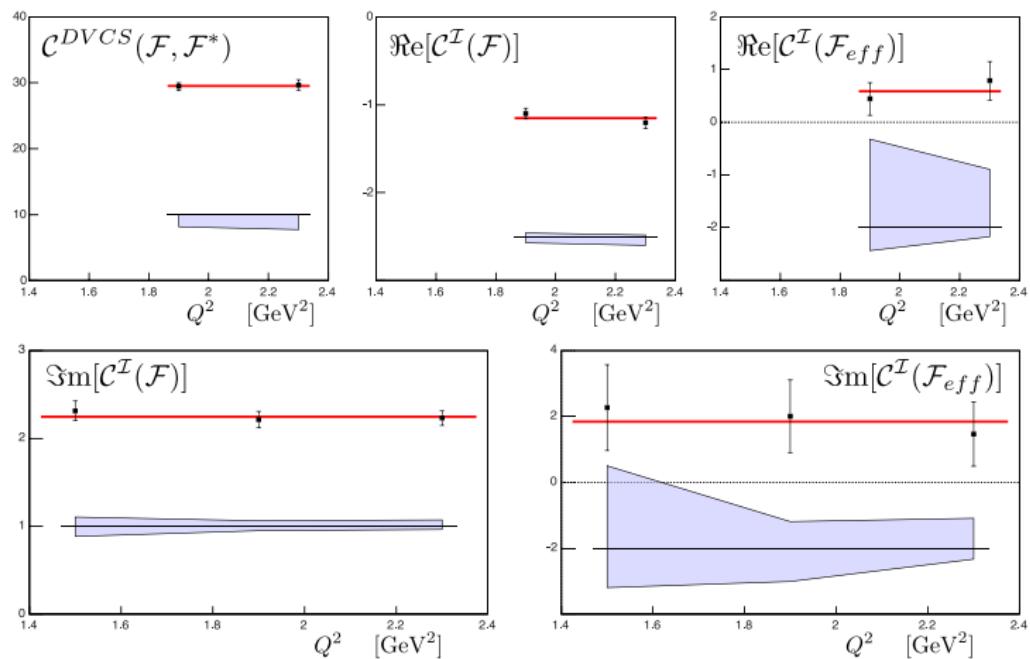
$$\mathcal{T}_{\text{DVCS}}^2 \sim c_0^{\text{DVCS}} + c_1^{\text{DVCS}} \cos \phi$$

$$\Delta^4\sigma = \frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}\text{m}(\mathcal{T}_{\text{DVCS}})$$

$$\mathcal{I}\text{m}(\mathcal{T}_{\text{DVCS}}) \sim s_1^{\mathcal{I}} \sin \phi + s_2^{\mathcal{I}} \sin 2\phi$$

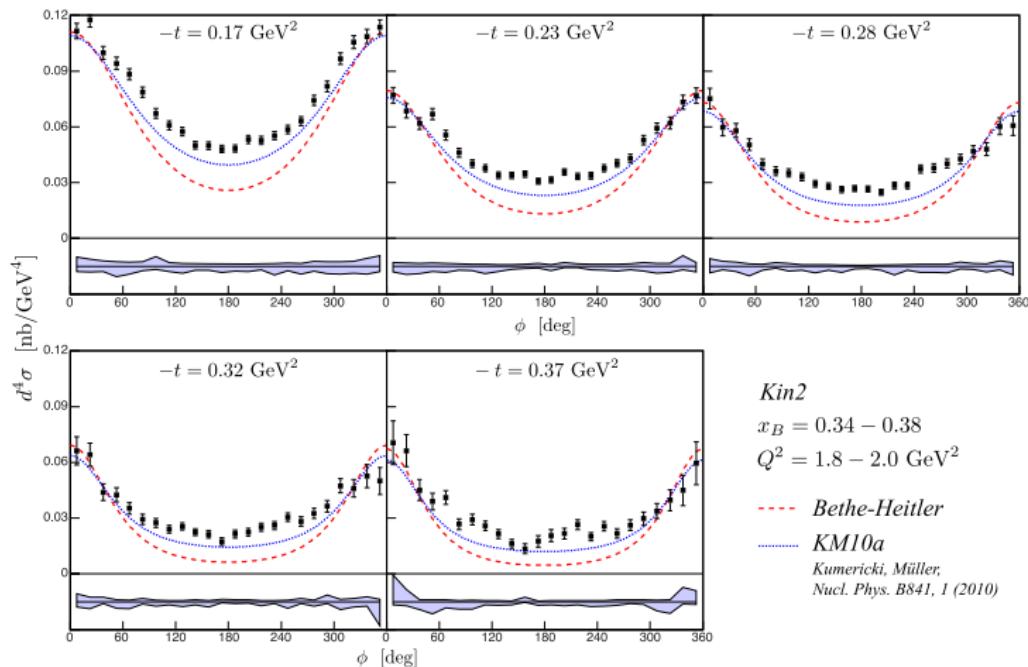
M. Defurne et al. Phys. Rev. C 92, 055202

# DVCS cross sections: $Q^2$ -dependance



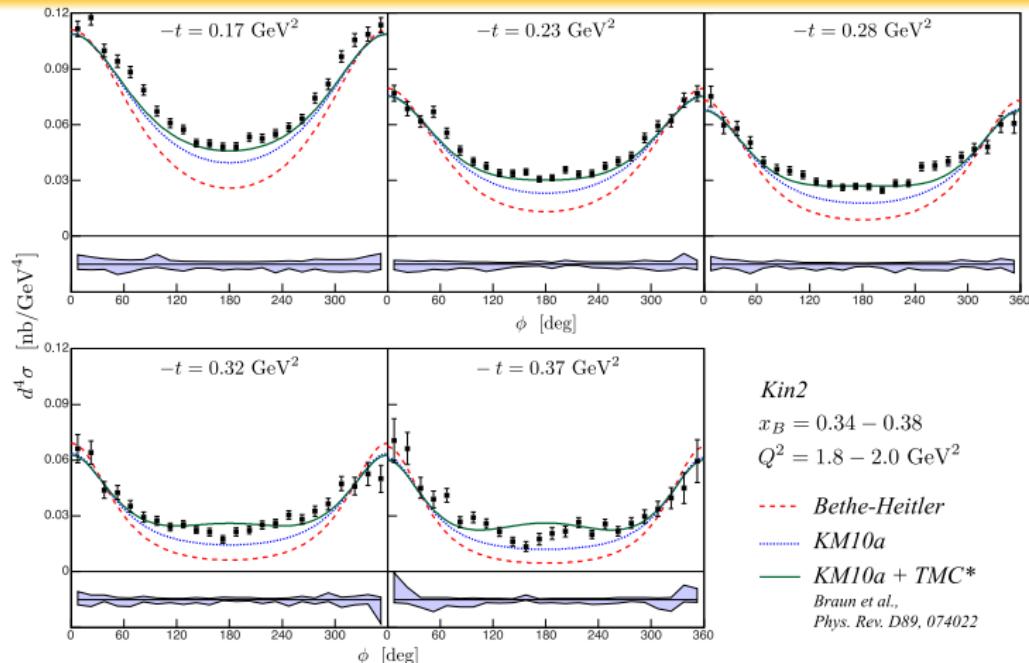
No  $Q^2$ -dependance within limited range  $\Rightarrow$  leading twist dominance

# DVCS cross sections: kinematical power corrections



- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries  
Kumericki and Mueller (2010)

# DVCS cross sections: kinematical power corrections



- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries  
Kumericki and Mueller (2010)
- Target-mass corrections (TMC):  $\sim \mathcal{O}(M^2/Q^2)$  and  $\sim \mathcal{O}(t/Q^2)$   
Braun, Manashov, Mueller and Pirnay (2014)

# Rosenbluth-like separation of the DVCS cross section

$$\sigma(ep \rightarrow ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$

$$|T^{DVCS}|^2 \propto 1/y^2 = (k/\nu)^2$$

BKM-2010 – at leading twist  $\rightarrow$  7 independent GPD terms:

$$\{\Re e, \Im m [\mathcal{C}^{\mathcal{I}}, \mathcal{C}^{\mathcal{I},V}, \mathcal{C}^{\mathcal{I},A}] (\mathcal{F})\}, \quad \text{and} \quad \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}^*).$$

$\varphi$ -dependence provides 5 independent observables:

$$\sim 1, \sim \cos \varphi, \sim \sin \varphi, \sim \cos(2\varphi), \sim \sin(2\varphi)$$

The measurement of the cross section at **two or more beam energies** for exactly the **same  $Q^2$ ,  $x_B$ ,  $t$  kinematics**, provides the additional information in order to extract all leading twist observables independently.

# DVCS process: leading twist ambiguity

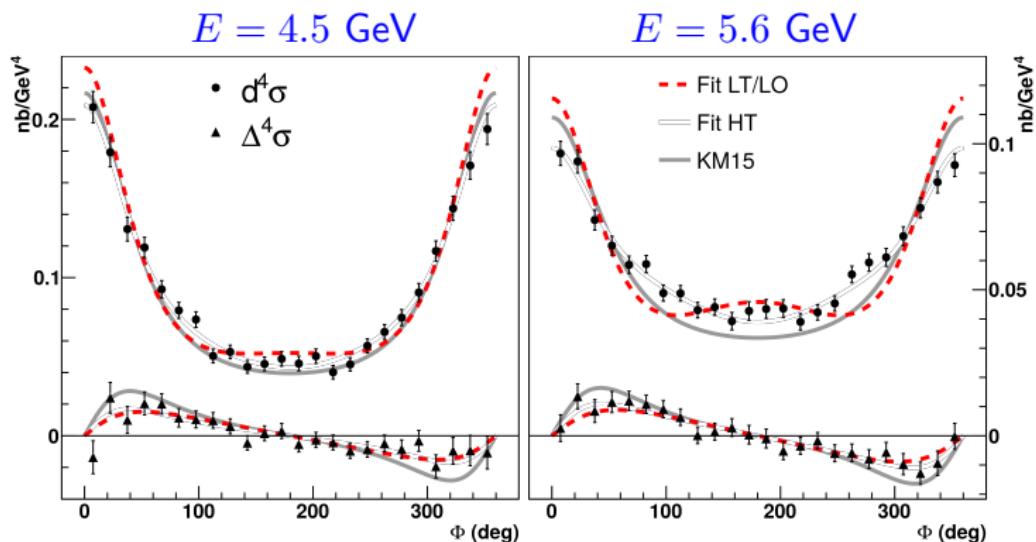
- DVCS defines a preferred axis: light-cone axis
- At finite  $Q^2$  and non-zero  $t$ , there is an ambiguity:
  - ➊ Belitsky et al. ("BKM", 2002–2010): light-cone axis in plane  $(q, P)$
  - ➋ Braun et al. ("BMP", 2014): light-cone axis in plane  $(q, q')$   
easier to account for kin. corrections  $\sim \mathcal{O}(M^2/Q^2)$ ,  $\sim \mathcal{O}(t/Q^2)$

$$\left. \begin{array}{l} \mathcal{F}_{++} = \mathbb{F}_{++} + \frac{\chi}{2} [\mathbb{F}_{++} + \mathbb{F}_{-+}] - \chi_0 \mathbb{F}_{0+} \\ \mathcal{F}_{-+} = \mathbb{F}_{-+} + \frac{\chi}{2} [\mathbb{F}_{++} + \mathbb{F}_{-+}] - \chi_0 \mathbb{F}_{0+} \\ \mathcal{F}_{0+} = -(1 + \chi) \mathbb{F}_{0+} + \chi_0 [\mathbb{F}_{++} + \mathbb{F}_{-+}] \end{array} \right\} \xrightarrow{\begin{array}{l} \mathbb{F}_{-+} = 0 \\ \mathbb{F}_{0+} = 0 \end{array}} \left\{ \begin{array}{l} \mathcal{F}_{++} = (1 + \frac{\chi}{2}) \mathbb{F}_{++} \\ \mathcal{F}_{-+} = \frac{\chi}{2} \mathbb{F}_{++} \\ \mathcal{F}_{0+} = \chi_0 \mathbb{F}_{++} \end{array} \right.$$

(eg.  $\chi_0 = 0.25$ ,  $\chi = 0.06$  for  $Q^2 = 2$  GeV $^2$ ,  $x_B = 0.36$ ,  $t = -0.24$  GeV $^2$ )

# E07-007: DVCS beam-energy dependence

- Cross section measured at 2 beam energies and constant  $Q^2$ ,  $x_B$ ,  $t$



- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

**Light-cone axis in the  $(q, q')$  plane (Braun et al.):**  $\mathbb{H}_{++}$ ,  $\widetilde{\mathbb{H}}_{++}$ ,  $\mathbb{E}_{++}$ ,  $\widetilde{\mathbb{E}}_{++}$

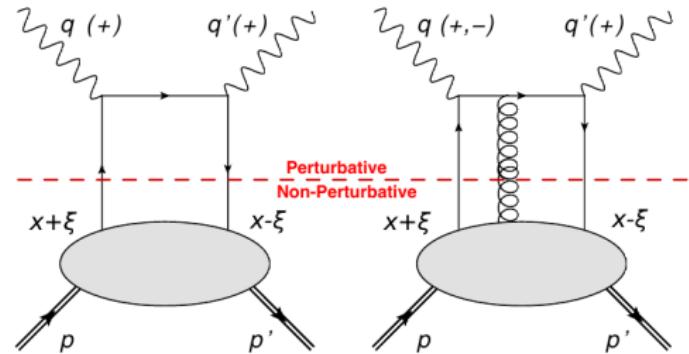
# Beyond Leading Order (LO) and Leading Twist (LT)

**Two fit-scenarios:**

**Light-cone axis in  
the  $(q,q')$  plane (Braun et al.)**

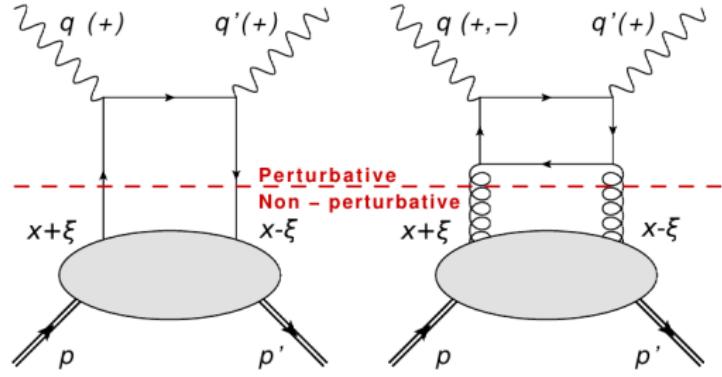
**LO/LT + HT**

$\mathbb{H}_{++}, \tilde{\mathbb{H}}_{++}, \mathbb{H}_{0+}, \tilde{\mathbb{H}}_{0+}$



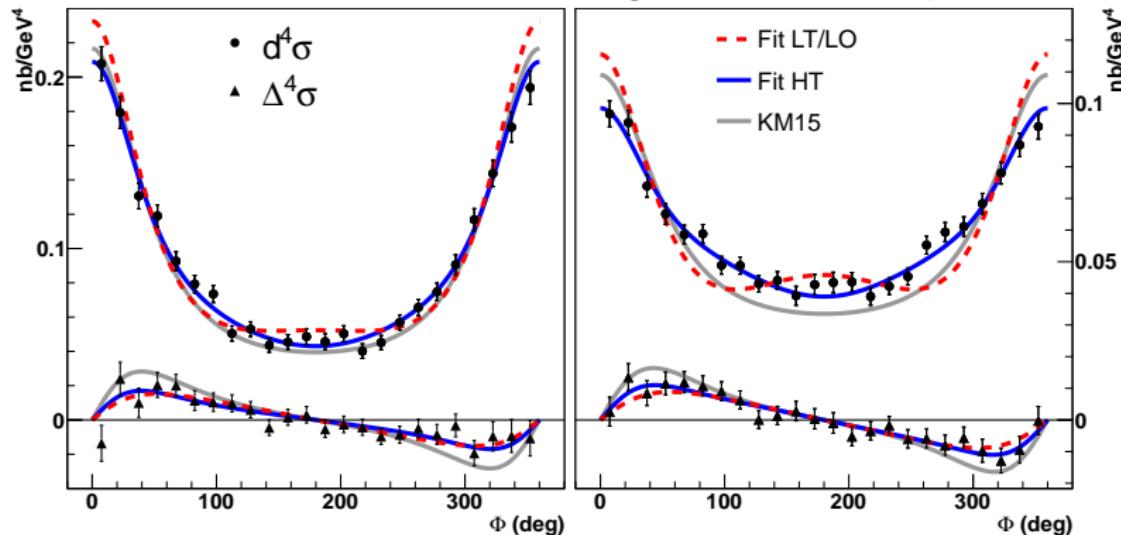
**LO/LT + NLO**

$\mathbb{H}_{++}, \tilde{\mathbb{H}}_{++}, \mathbb{H}_{-+}, \tilde{\mathbb{H}}_{-+}$



# E07-007: DVCS beam-energy dependence

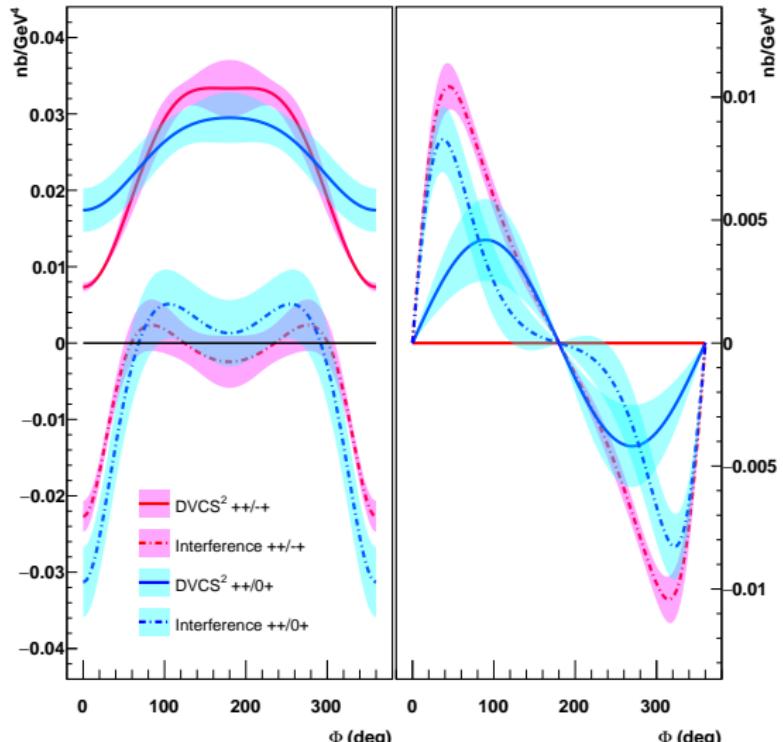
- Cross section measured at 2 beam energies and constant  $Q^2$ ,  $x_B$ ,  $t$



- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data
- Including either NLO or higher-twist effects (dark solid line) satisfactorily reproduce the angular dependence

# DVCS<sup>2</sup> and $\mathcal{I}$ (DVCS·BH) separation

DVCS<sup>2</sup> and  $\mathcal{I}$ (DVCS·BH) separated in NLO and higher-twist scenarios



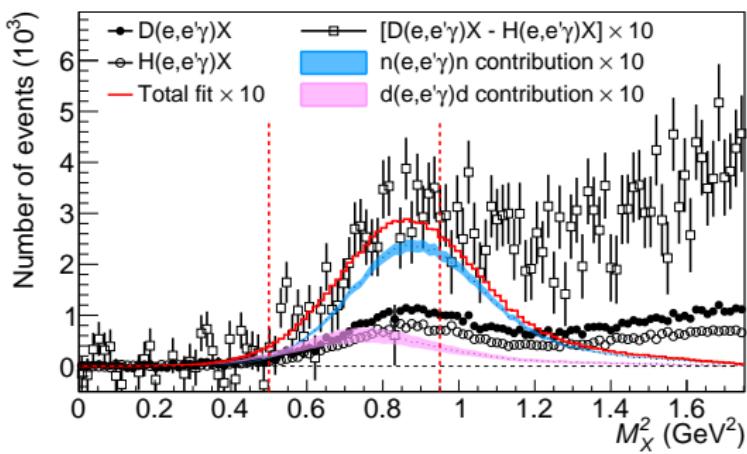
- DVCS<sup>2</sup> &  $\mathcal{I}$  significantly different in each scenario
- Sizeable DVCS<sup>2</sup> contribution in the higher-twist scenario in the helicity-dependent cross section

Nature Commun. 8, 1408 (2017)

# E08-025: DVCS off the neutron at different beam energies

- LD<sub>2</sub> as a target  $(Q^2 = 1.75 \text{ GeV}^2, x_B = 0.36)$
- Quasi-free  $p$  evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 → minimize uncertainties

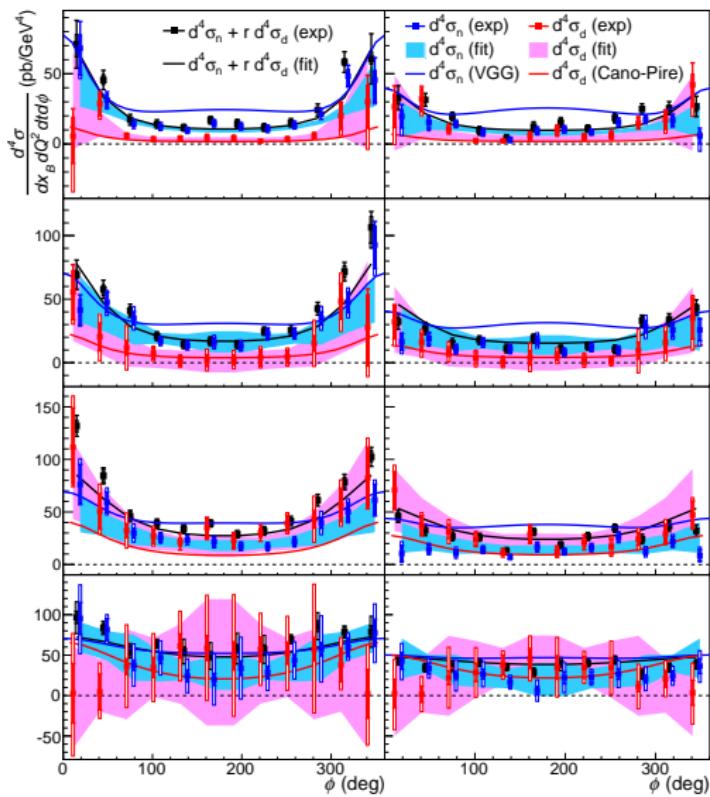
$$D(e, e'\gamma)X - p(e, e'\gamma)p = n(e, e'\gamma)n + d(e, e'\gamma)d$$



$n$ DVCS &  $d$ DVCS  
shifted by  $t/2$  in  $M_X^2$

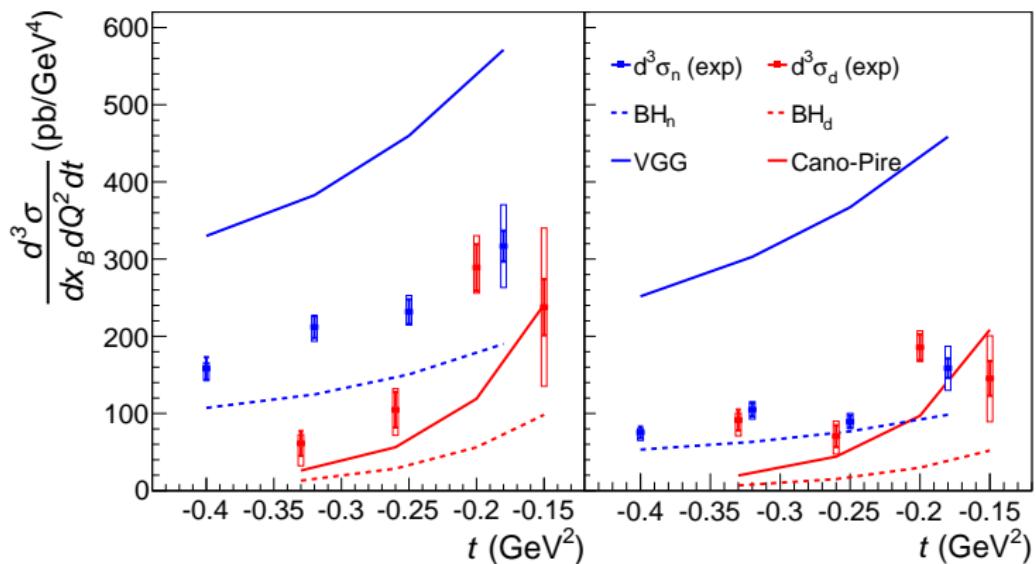
# DVCS cross sections off the $n$ & $d$

- Large correlations at low  $-t$
- Good separation at larger  $-t$
- dDVCS very small  
(compatible with theory)
- nDVCS: significant signal  
**(first observation of DVCS off the nucleon)**



M. Benali et al., Nature Physics 16, 191 (2020)

# DVCS off the neutron: $t$ -dependence



- First experimental determination of the unpolarized  $en \rightarrow e\gamma n$  cross section
- $\sigma(en \rightarrow e\gamma n) > \sigma(BH_n)$ : **Sizeable DVCS off the neutron**

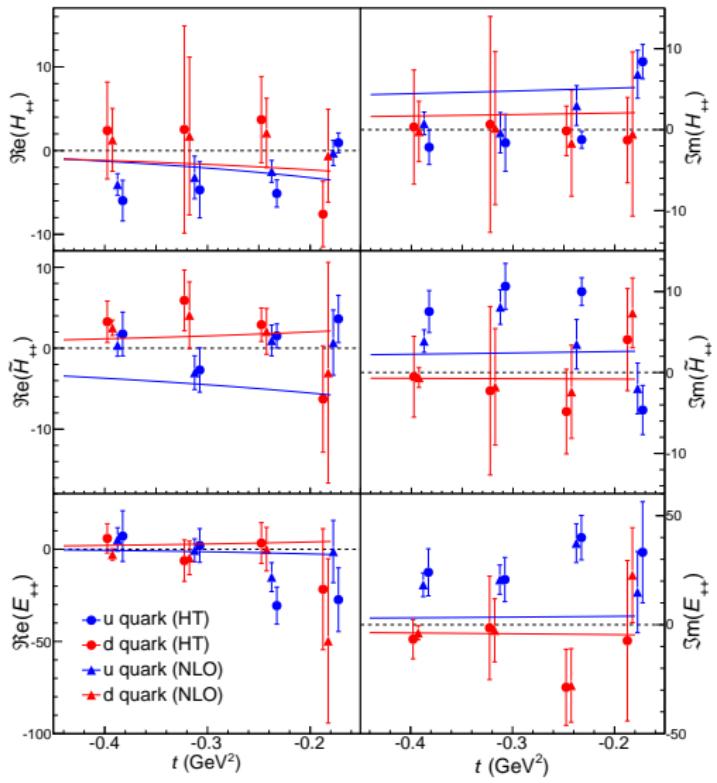
M. Benali et al., Nature Physics 16, 191 (2020)

# DVCS off the neutron: flavor-separated CFFs

Global fit of all Hall A DVCS data off proton & neutron, with CFFs of up and down quarks as free parameters

- $H^u$  and  $H^d$ : same sign (as forward & large  $N_c$  limits, models...)
- $\tilde{H}^u$  and  $\tilde{H}^d$ : opposite sign (as forward & large  $N_c$  limit, models...)
- Data suggest same sign for  $\text{Re}(E^u)$  and  $\text{Re}(E^d)$  (against predictions from the large  $N_c$  limit)

M. Benali et al., Nature Physics 16, 191(2020)



# E12-06-114: DVCS at 12 GeV

# E12-06-114: CFFs extraction

- Extraction of all CFFs  
 $(++, 0+, -+)$  as a function of  $x_B$
- GPD  $H$  well constraint
- Sensitivity to  $E$  and  $\tilde{E}$

# $\pi^0$ electroproduction ( $ep \rightarrow ep\pi^0$ )

At leading twist:

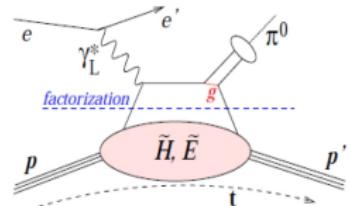
$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \quad \sigma_T \propto \frac{1}{Q^8}$$

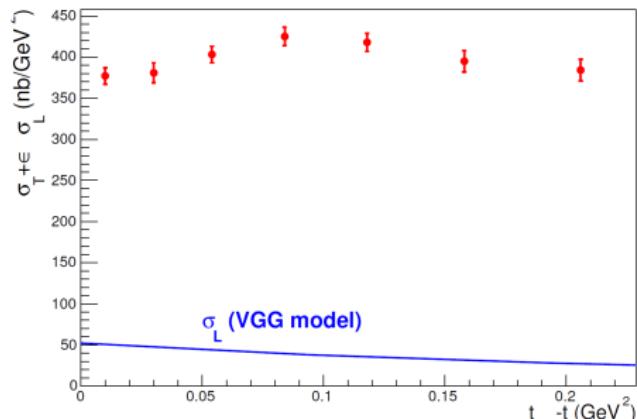
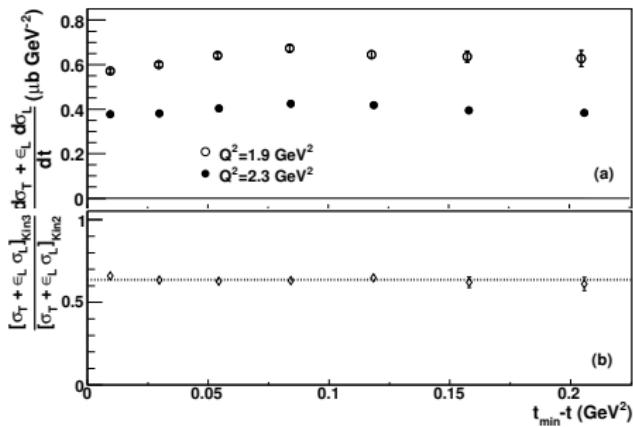
$$\mathcal{M}^L \propto \left[ \int_0^1 dz \frac{\phi_\pi(z)}{z} \right] \int_{-1}^1 dx \left[ \frac{1}{x - \xi} + \frac{1}{x + \xi} \right] \times \left\{ \Gamma_1 \tilde{H}_{\pi^0} + \Gamma_2 \tilde{E}_{\pi^0} \right\}$$

Different quark weights: flavor separation of GPDs

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\{|u\bar{u}\rangle - |d\bar{d}\rangle\} \quad \tilde{H}_{\pi^0} = \frac{1}{\sqrt{2}} \left\{ \frac{2}{3}\tilde{H}^u + \frac{1}{3}\tilde{H}^d \right\}$$

$$|p\rangle = |uud\rangle \quad H_{DVCS} = \frac{4}{9}H^u + \frac{1}{9}H^d$$



Exclusive  $\pi^0$  electroproduction cross-sections

- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$   
 (similar to  $\sigma_T(ep \rightarrow ep\pi^+)$  measured in Hall C)
- GPDs predict  $\sigma_L \sim Q^{-6}$
- $\sigma_T$  likely to dominate at these  $Q^2$ ,  
 but L/T separation necessary ( $\rightarrow$  new experiment...)

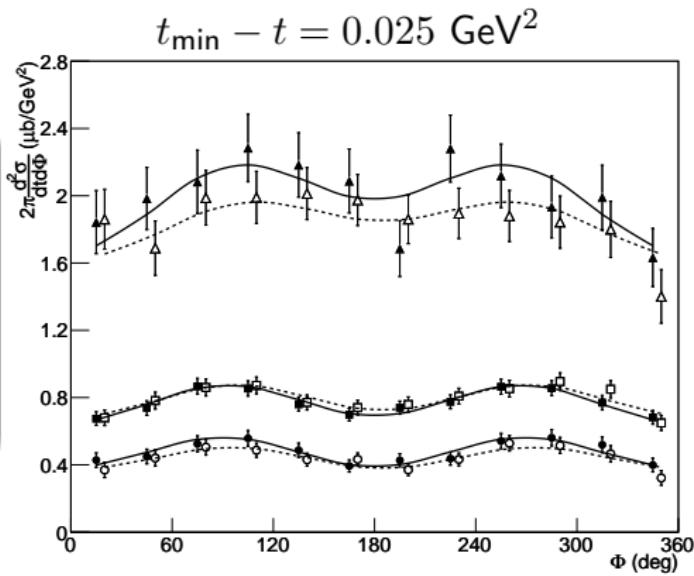
E. Fuchey et al., Phys. Rev. C83 (2011), 025125

# Rosenbluth separation

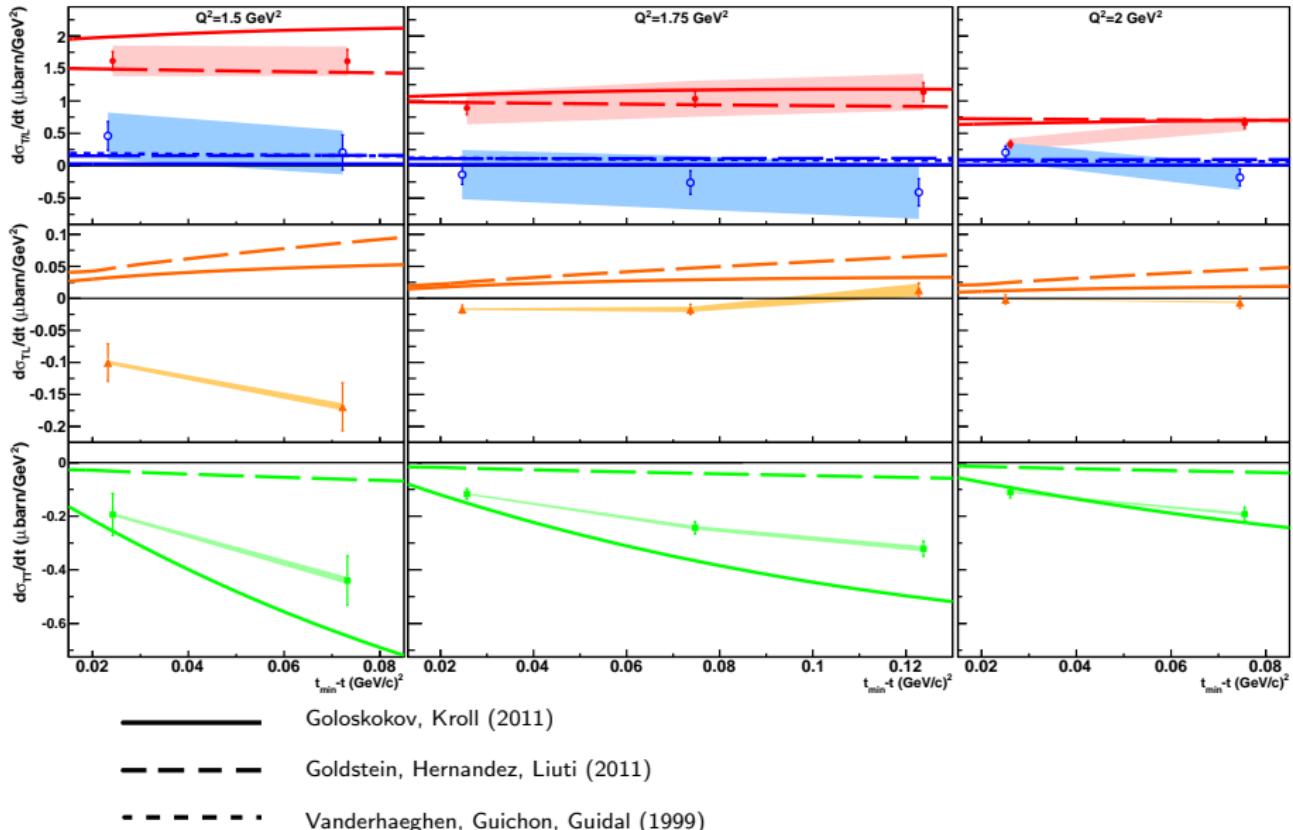
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi} \Gamma(Q^2, x_B, E) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos^2\phi \right]$$

## Kinematics

Setting	$Q^2$ (GeV $^2$ )	$x_B$	$E^{beam}$ (GeV)	$\epsilon$
Kin1	1.50	0.36	3.355	0.52
			5.55	0.84
Kin2	1.75	0.36	4.455	0.65
			5.55	0.79
Kin3	2.00	0.36	4.455	0.53
			5.55	0.72



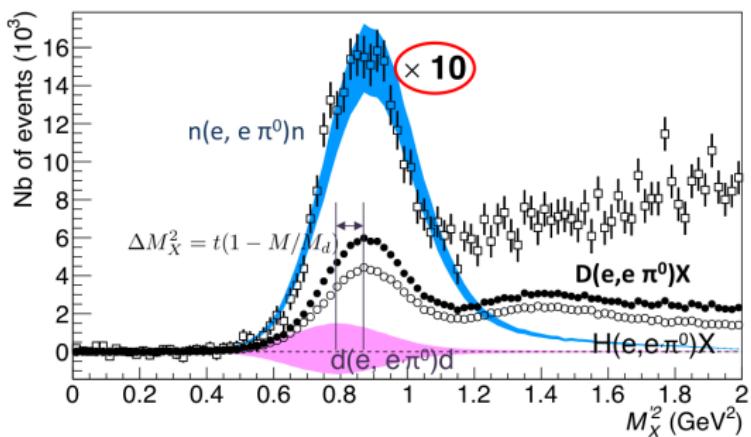
# $\pi^0$ separated response functions



E08-025: DVCS and  $\pi^0$  off quasi-free neutrons

- LD<sub>2</sub> as a target
- Quasi-free  $p$  evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 → minimize uncertainties

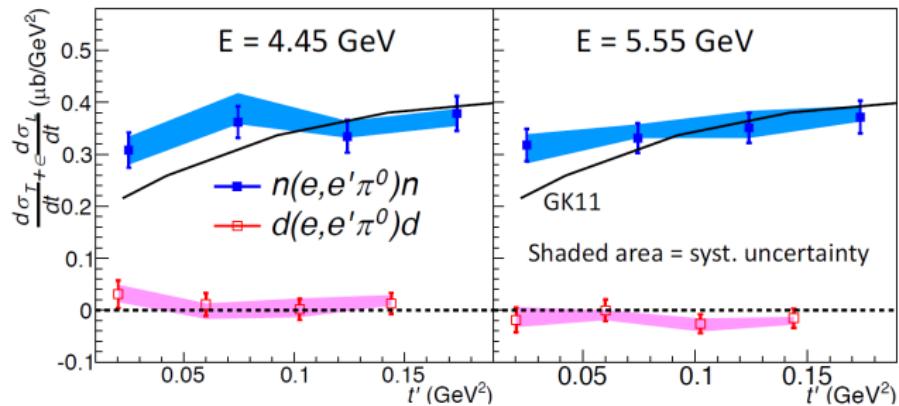
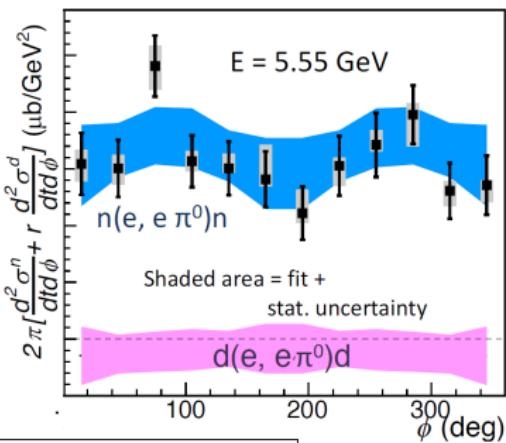
$$D(e, e \pi^0)X - p(e, e \pi^0)p = n(e, e \pi^0)n + d(e, e \pi^0)d$$

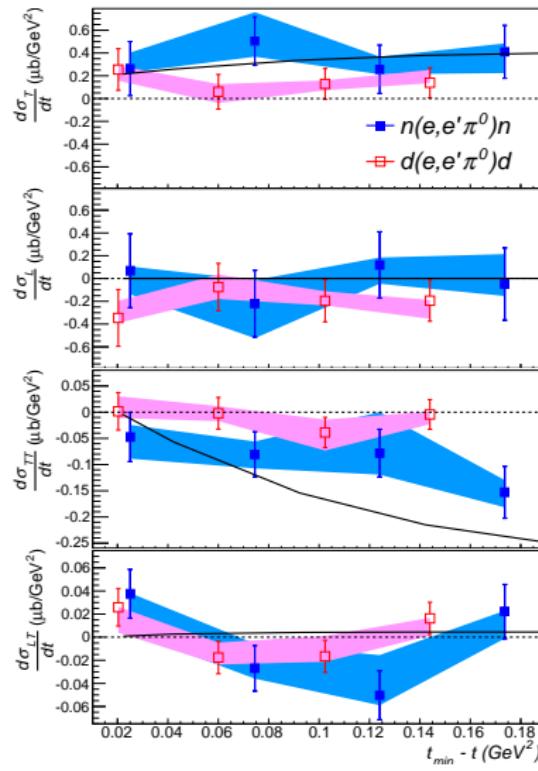


The average momentum transfer to the target is much larger than the  $np$  relative momentum, justifying this **impulse approximation**

# $\pi^0$ electroproduction cross section off the neutron

- Cross section off coherent  $d$  found negligible within uncertainties
- Very low  $E_{beam}$  dependence of the  $n$  cross section → dominance of  $\sigma_T$

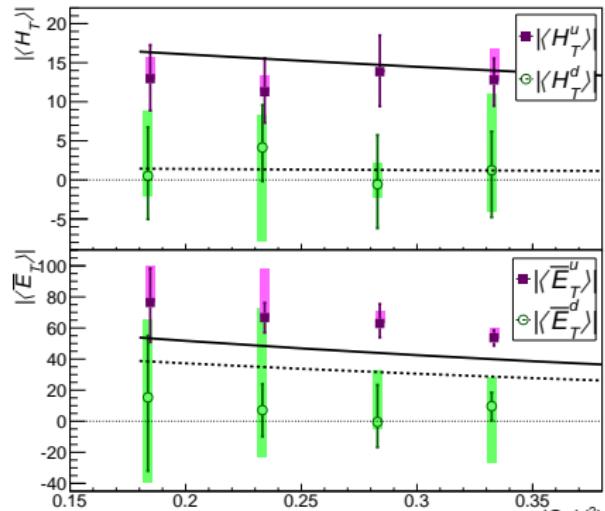


Separated  $\pi^0$  cross section off the neutron

M. Mazouz et al, Phys.Rev.Lett. 118 (2017)

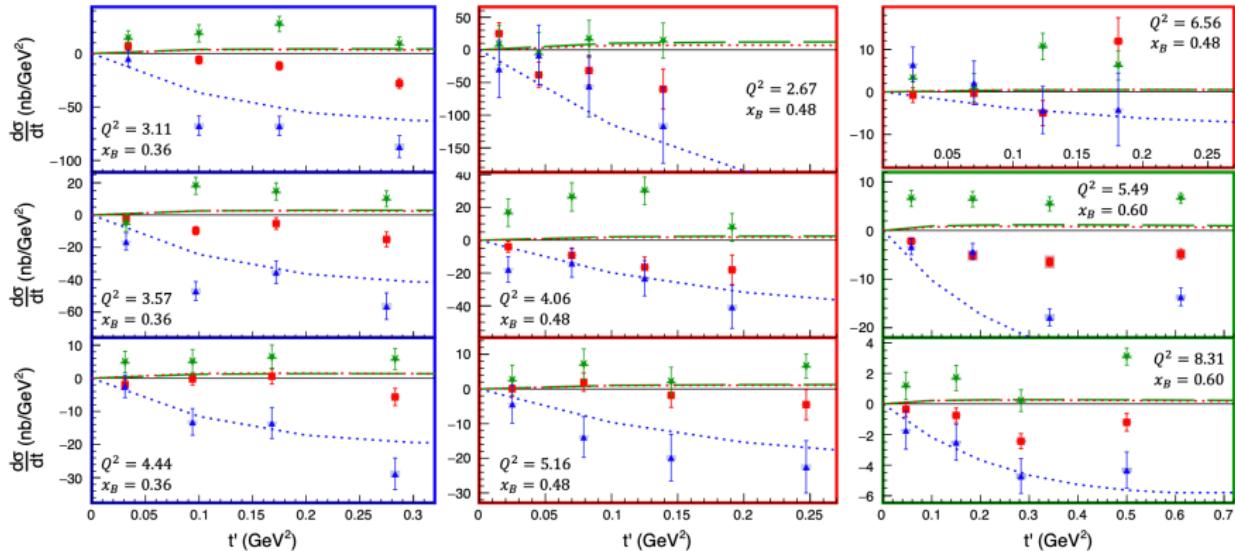
In the modified factorization approach (KG):

- $d\sigma_T \propto \left[ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2 \right]$
- $d\sigma_{TT} \propto \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2$



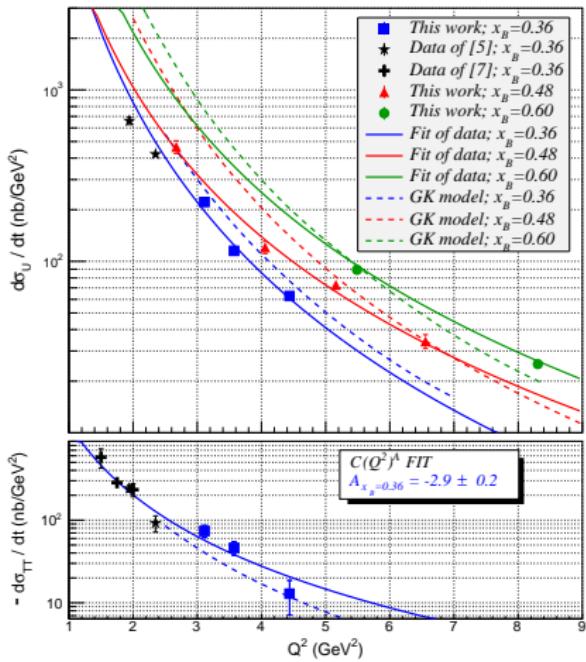
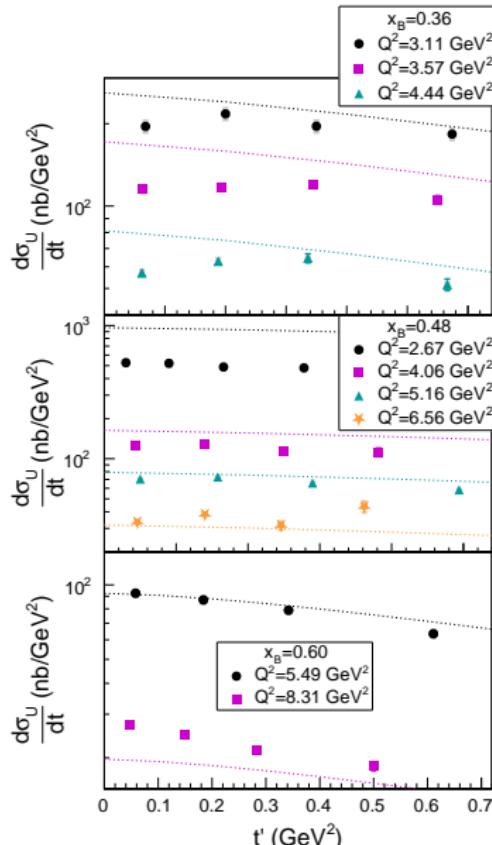
$$|\langle H_T^{p,n} \rangle|^2 = \frac{1}{2} \left| \frac{2}{3} \left\langle H_T^{u,d} \right\rangle + \frac{1}{3} \left\langle H_T^{d,u} \right\rangle \right|^2$$

# $\pi^0$ electroproduction at 12 GeV



- $\sigma_{TT} \gg \sigma_{TL,TL'}$
- Values well described by modified factorization approach

ArXiv:2011.11125

$\pi^0$  electroproduction at 12 GeV

ArXiv:2011.11125

# Summary

- Recent high precision DVCS cross sections from Hall A at JLab
- Need of higher twist and/or NLO contributions to fully describe the data (eg. in global GPD fits)
- First separation of DVCS<sup>2</sup> and BH-DVCS interference in the  $eN \rightarrow e\gamma N$  cross section, off the proton and neutron
- L/T separation of  $\pi^0$  electroproduction cross section off neutron: dominance of  $\sigma_T$  measured
- Flavor separation of transversity GPD convolutions within the modified factorization approach
- Approved program of experiments in Hall A and C to continue these high precision DVCS measurements at 12 GeV

# Back-up