

New results on hard exclusive processes from Jefferson Lab

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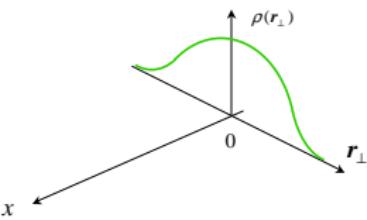
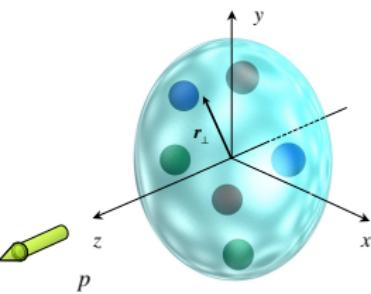
Light Cone, Mumbai
Sep 18–22, 2017

Outline

- ➊ Brief experimental introduction to DVCS
- ➋ Recent DVCS results from Hall A at JLab
 - DVCS: beam energy dependence of the cross section
(arxiv:1703.09442)
 - π^0 : off the neutron → flavor separation
(arXiv:1702.00835, PRL 118 (2017))
- ➌ Outlook
 - Jefferson Lab at 12 GeV: Hall A → C programs

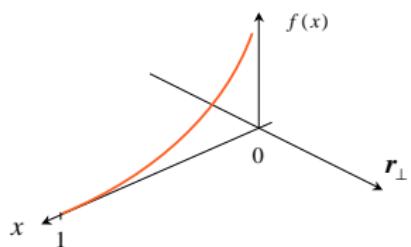
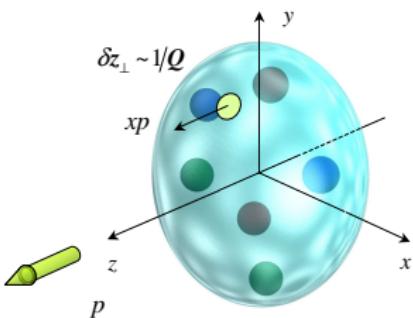
Studying nucleon structure experimentally

Elastic scattering



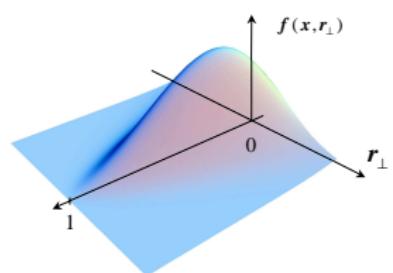
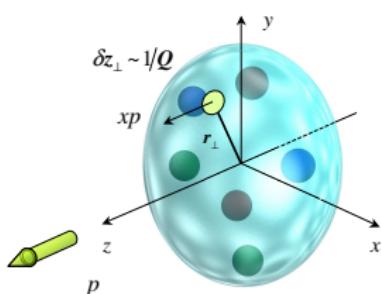
Form factors

Deep inelastic scattering



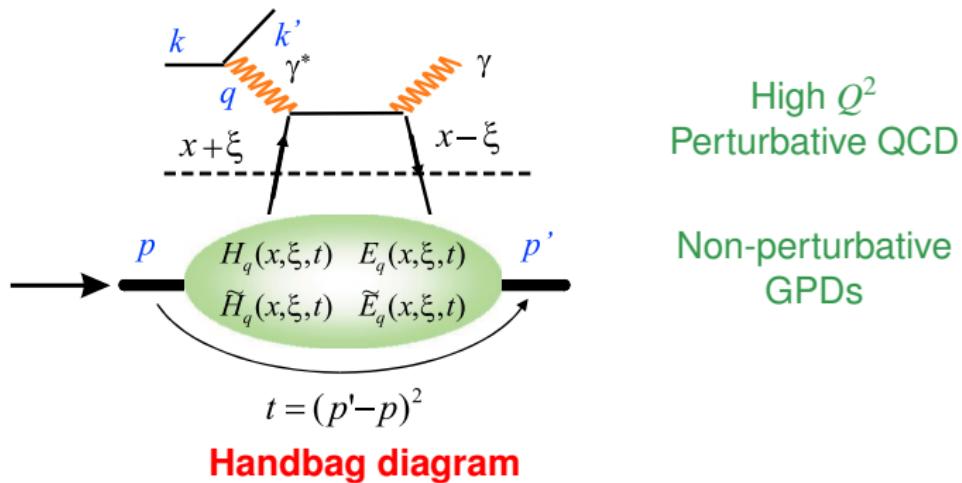
Parton distributions

Hard exclusive processes



Generalized Parton Distributions (GPDs)

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

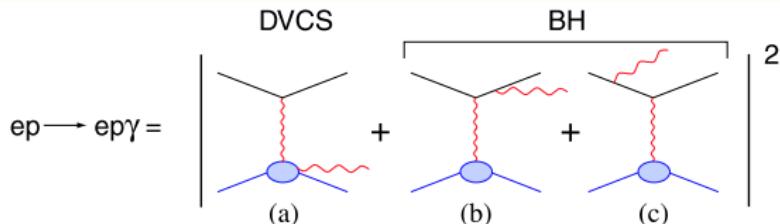


Bjorken limit:

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

- GPDs accessible through DVCS *only* at $Q^2 \rightarrow \infty$
 - Actual value of Q^2 *must* be tested and established **by experiment**

DVCS experimentally: interference with Bethe-Heitler



At leading twist:

$$d^5 \vec{\sigma} - d^5 \overset{\leftarrow}{\sigma} = 2 \Im m (T^{BH} \cdot T^{DVCS})$$

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

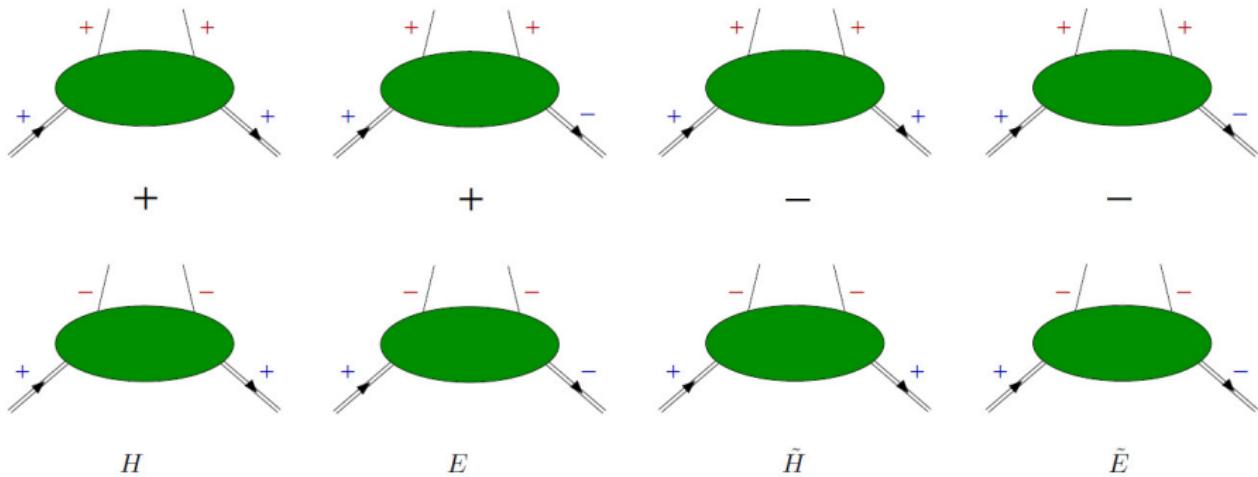
$$\begin{aligned} T^{DVCS} &= \int_{-1}^{+1} dx \frac{\mathbf{H}(x, \xi, t)}{x - \xi + i\epsilon} + \dots = \\ &\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{\mathbf{H}(x, \xi, t)}{x - \xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi \mathbf{H}(x = \xi, \xi, t)}_{\text{Access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

Access in helicity-independent cross section

Access in helicity-dependent cross-section

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

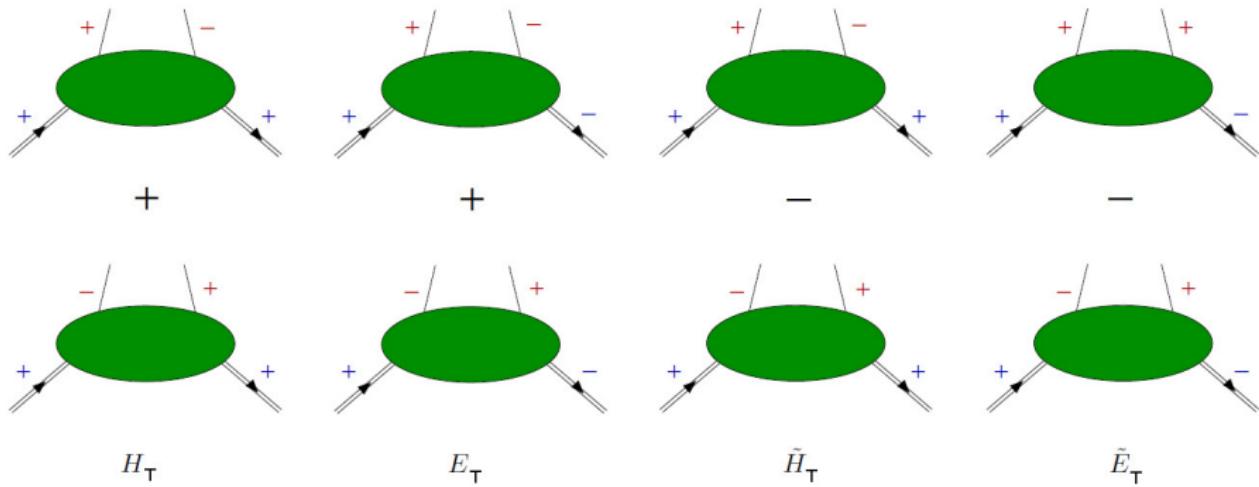


4 chiral-even GPDs: conserve the helicity of the quark

Access through DVCS (and DVMP)

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

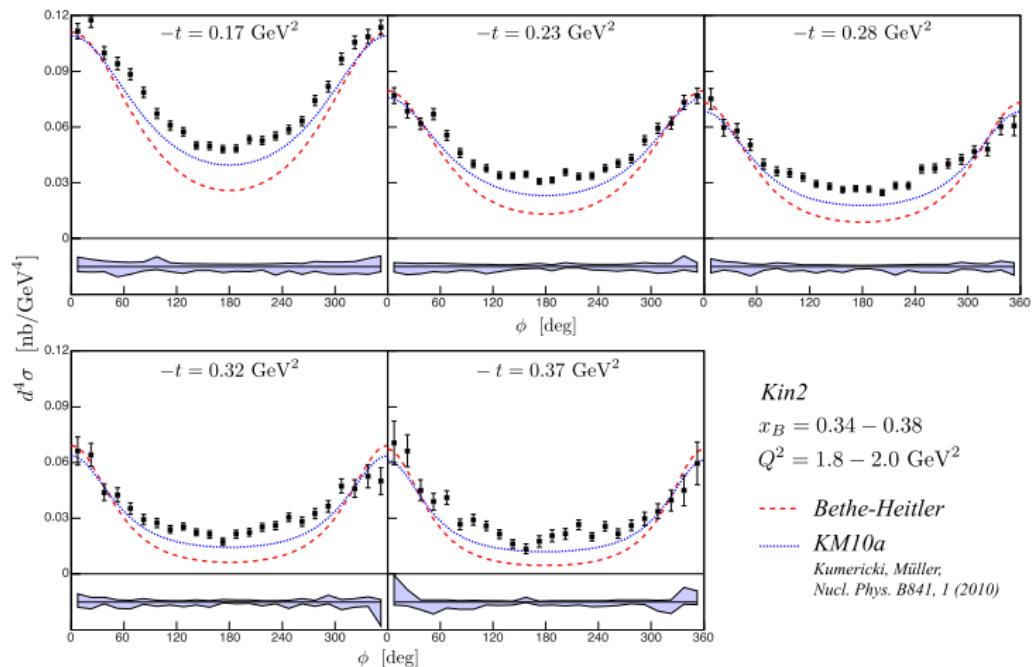


4 chiral-odd GPDs: flip helicity of the quark
“transversity GPDs”

Experimental access more complicated (π^0 electroproduction?)

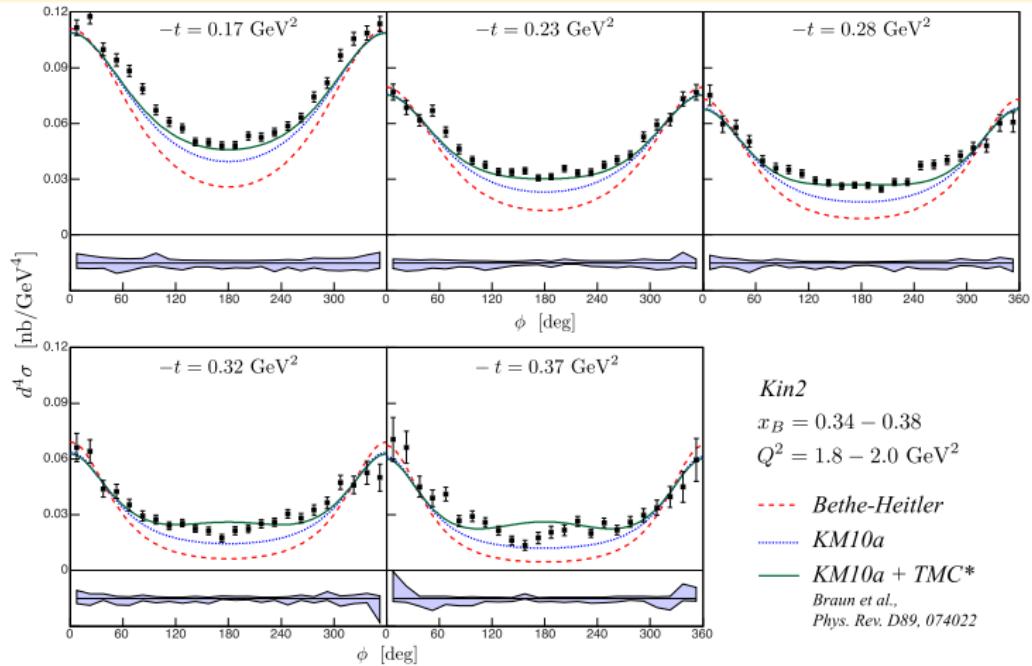
Ahmad, Goldstein, Liuti (2009)
 Goloskokov, Kroll (2011)

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)

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:
 - 1 Belitsky et al. (“BKM”, 2002–2010): light-cone axis in plane (q, P)
 - 2 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 $Q^2 = 2 \text{ GeV}^2$, $x_B = 0.36$, $t = -0.24 \text{ GeV}^2$)

Rosenbluth-like separation of the DVCS cross section

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

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

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

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

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

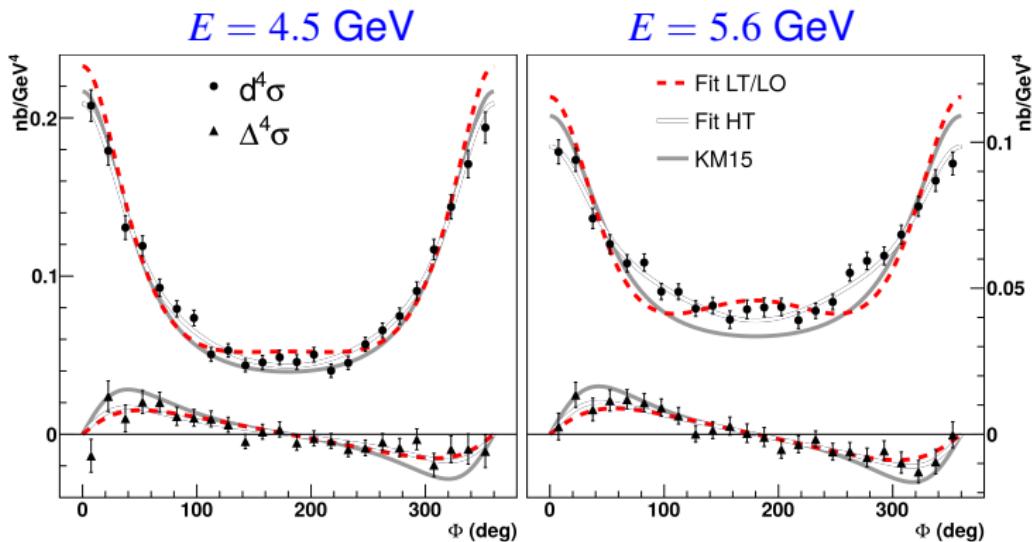
φ -dependence provides 5 independent observables:

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

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.

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}_{++} , $\widetilde{\mathbb{E}}_{++}$

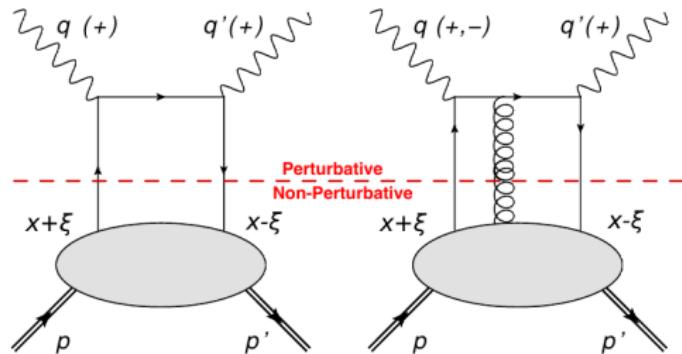
Beyond Leading Order (LO) and Leading Twist (LT)

Two fit-scenarios:

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

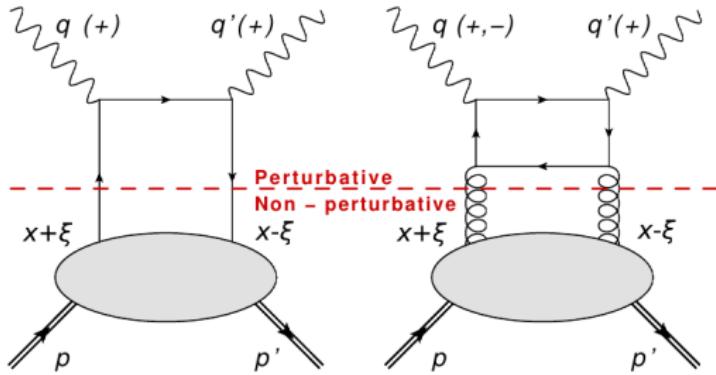
LO/LT + HT

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



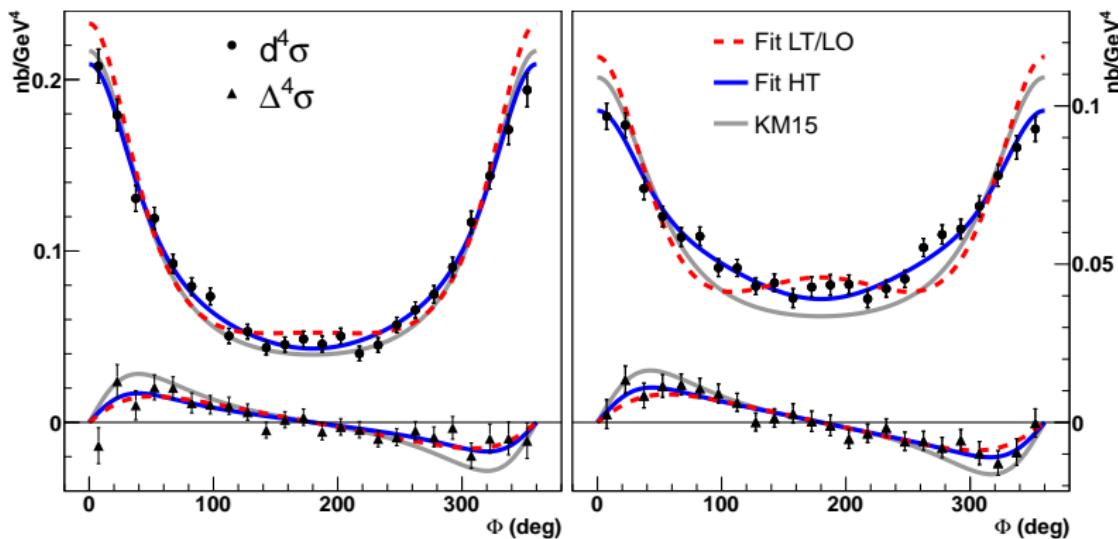
LO/LT + NLO

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



E07-007: DVCS beam-energy dependence

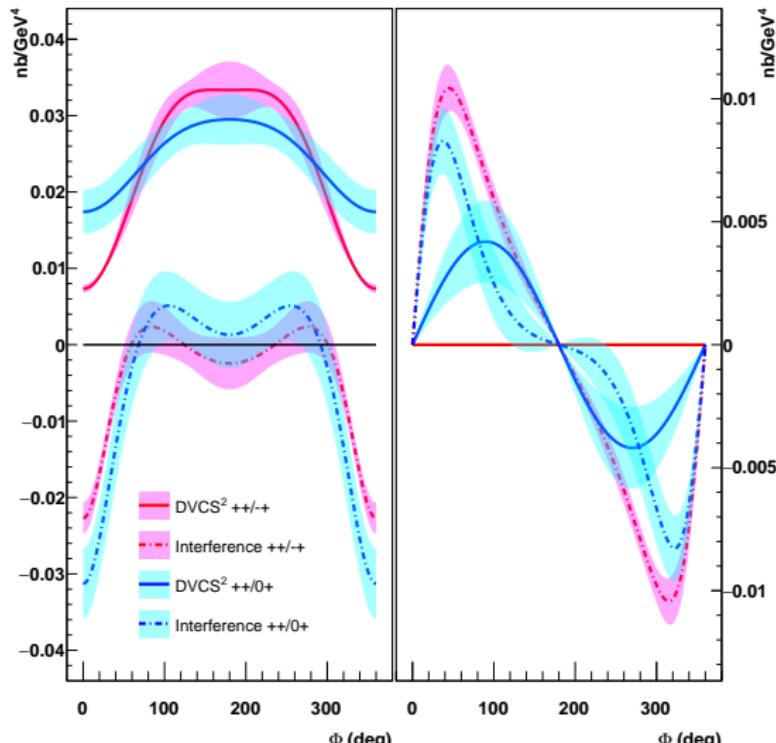
- Cross section measured at 2 beam energies and constant Q^2 , x_B , t



- 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

DVCS² and \mathcal{I} (DVCS·BH) separation

DVCS² and \mathcal{I} (DVCS·BH) separated in NLO and higher-twist scenarios



- DVCS² & \mathcal{I} significantly different in each scenario
- Sizeable DVCS² contribution in the higher-twist scenario in the helicity-dependent cross section

arXiv:1703.09442

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

At leading twist:

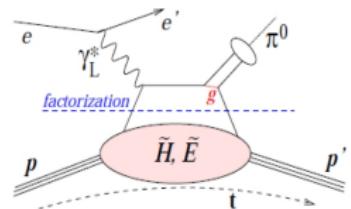
$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \quad \sigma_T \propto \frac{1}{Q^8}$$

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

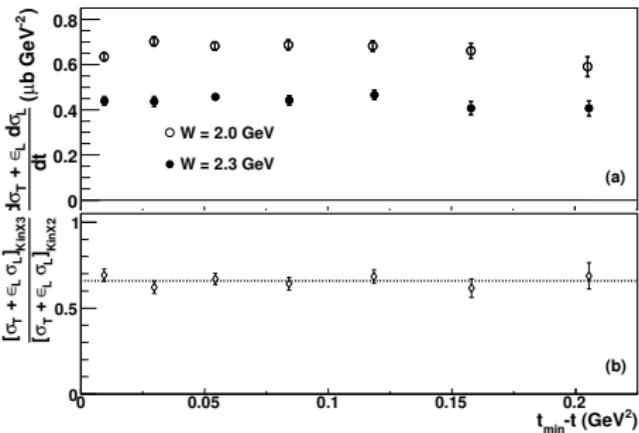
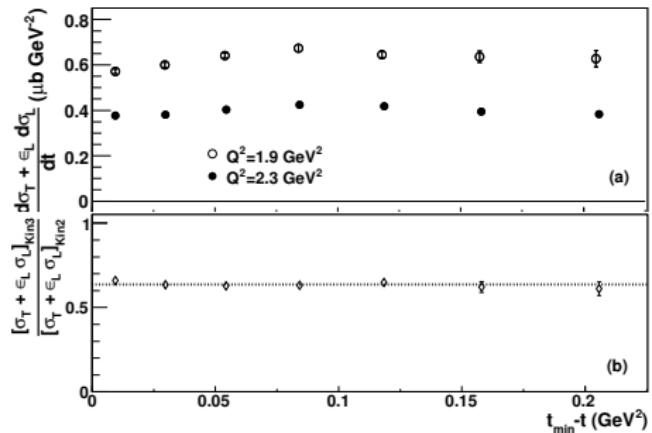
Different quark weights: flavor separation of GPDs

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

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



Exclusive π^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 $\sigma_L \sim Q^{-6}$
- σ_T likely to dominate at these Q^2 ,
but L/T separation necessary (\rightarrow new experiment...)

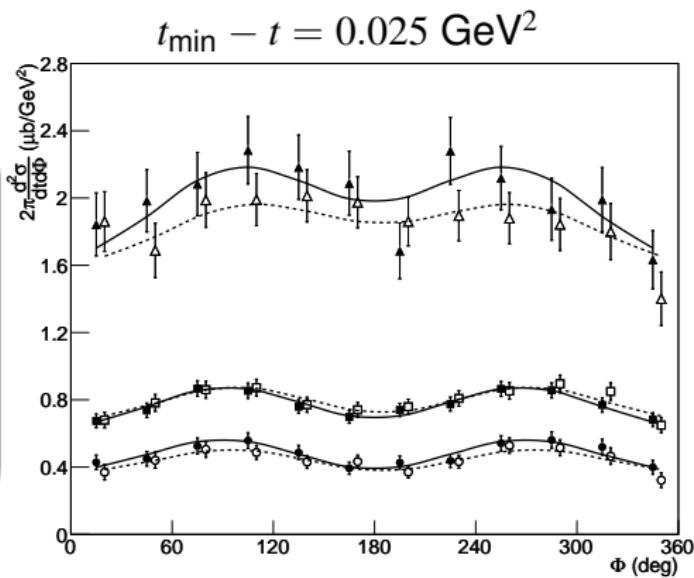
E. Fuchey et al., Phys. Rev. C83 (2011), 025125

Rosenbluth separation

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

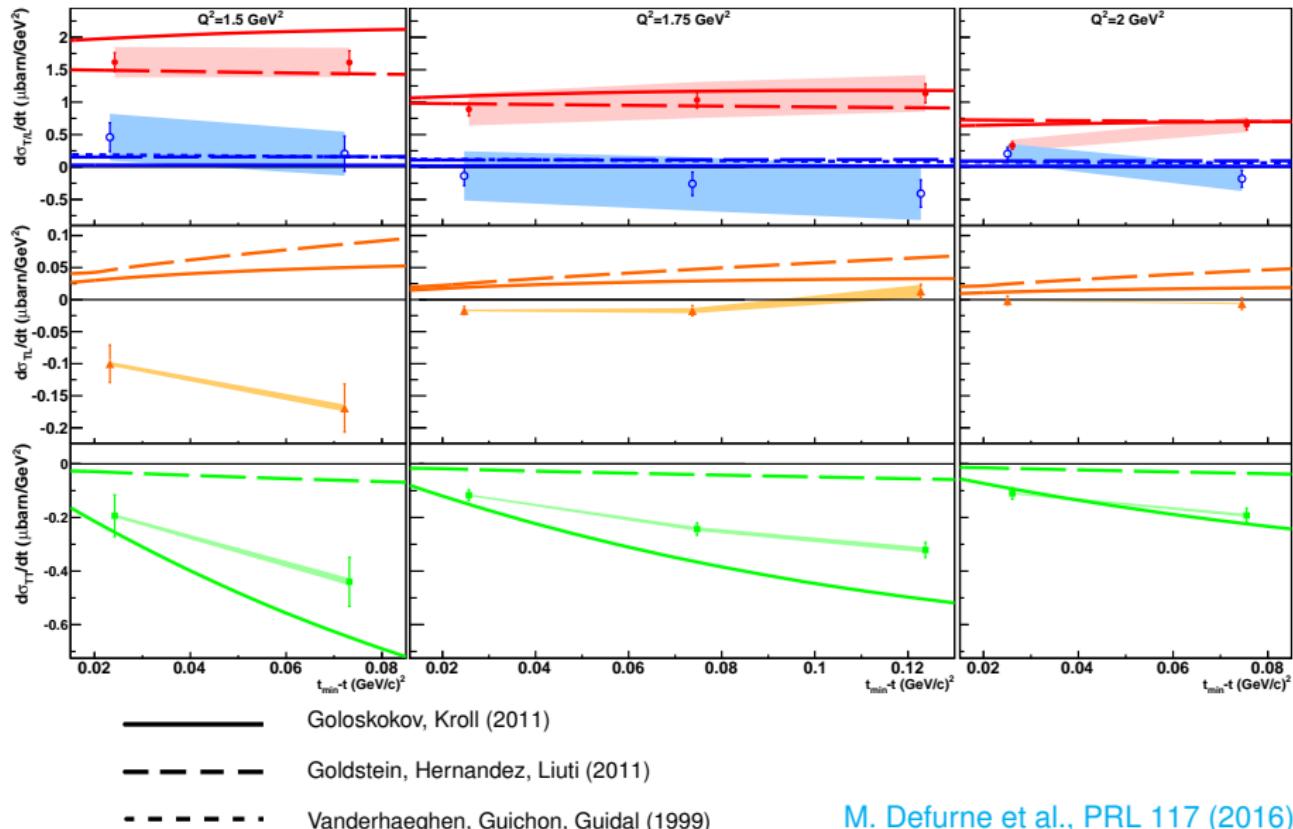
Kinematics

Setting	Q^2 (GeV ²)	x_B	E^{beam} (GeV)	ϵ
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



M. Defurne et al., PRL 117 (2016)

π^0 separated response functions



M. Defurne et al., PRL 117 (2016)

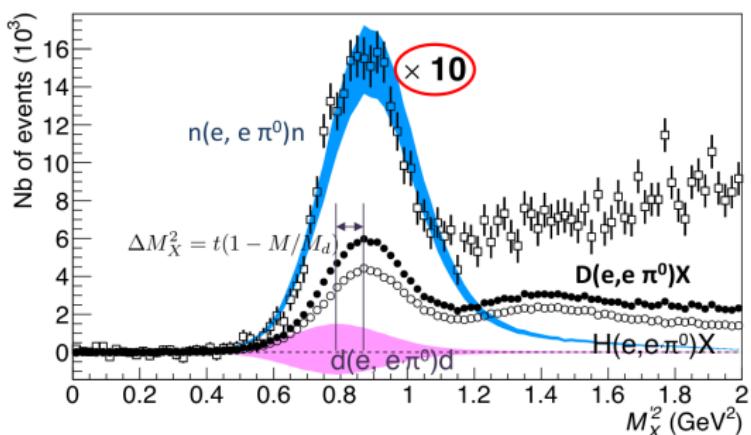
π^0 L/T separated cross section

- Cross section largely dominated by transverse component
 - far from asymptotic prediction of QCD
- Fair agreement with models using modified factorization approach
 - potential access to transversity GPDs
- Indications of small longitudinal response through non-zero σ_{LT}

E08-025: DVCS and π^0 off quasi-free neutrons

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

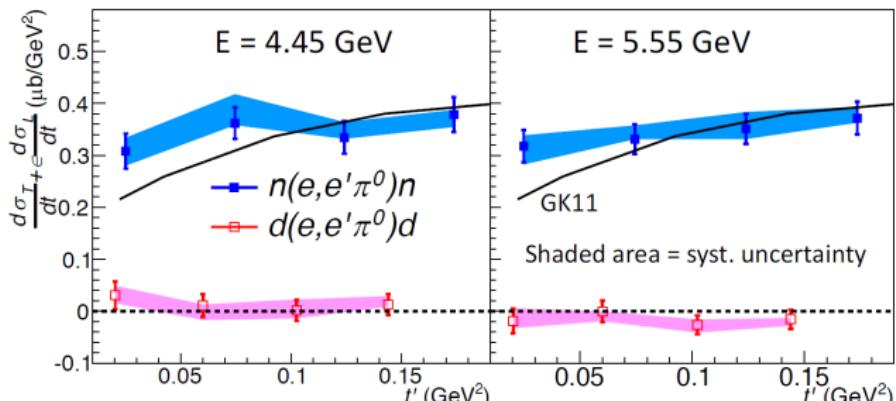
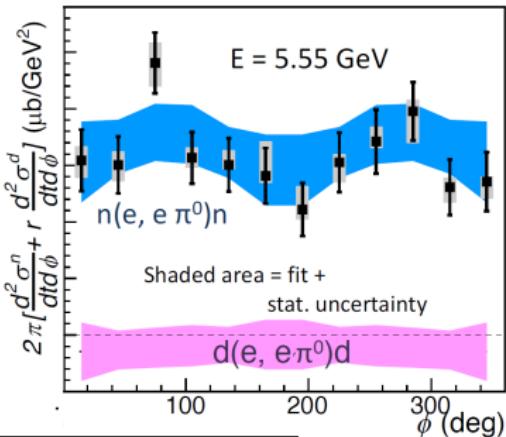
$$D(e, e \pi^0)X - p(e, e \pi^0)p = n(e, e \pi^0)n + d(e, e \pi^0)d$$



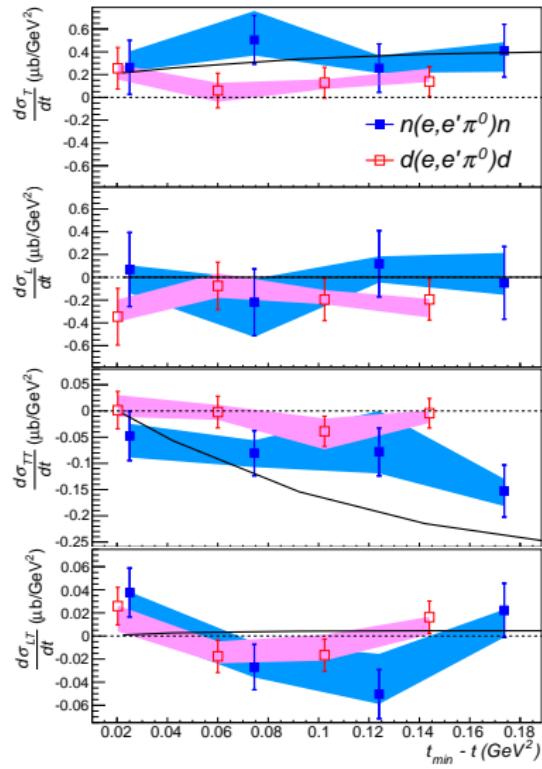
The average momentum transfer to the target is much larger than the np relative momentum, justifying this **impulse approximation**

π^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 σ_T

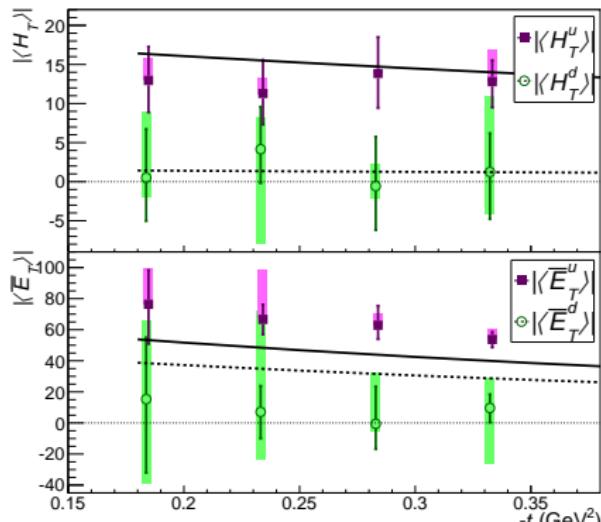


Separated π^0 cross section off the neutron



In the modified factorization approach (KG):

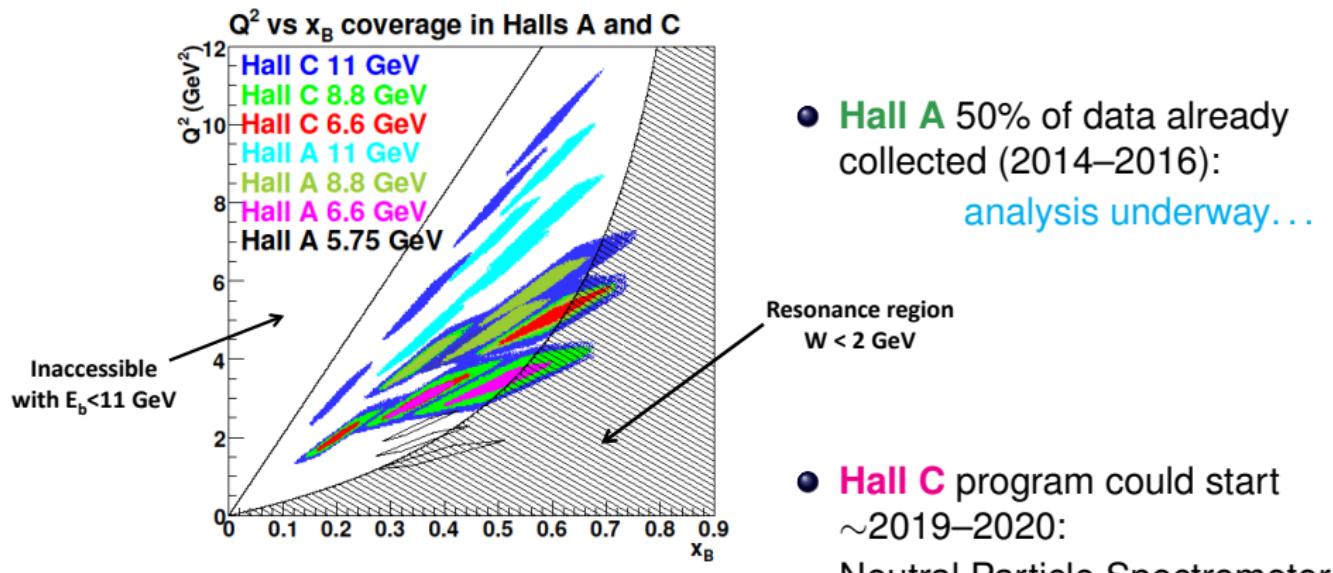
- $d\sigma_T \propto \left[(1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2 \right]$
- $d\sigma_{TT} \propto \frac{t'}{8M^2} |\langle \bar{E}_T \rangle|^2$



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

11 (and 8.8 and 6.6) GeV program in Halls A & C

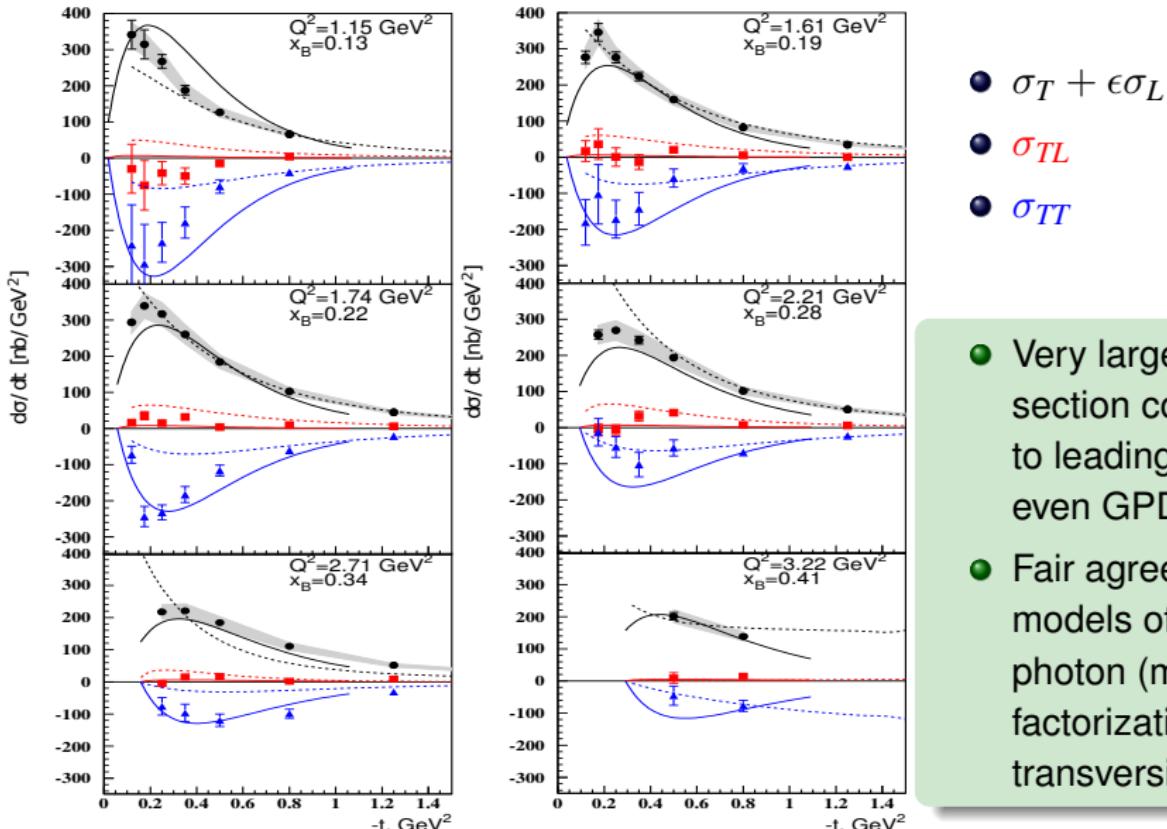
- Approved high precision DVCS & π^0 programs in Halls A & C



Summary

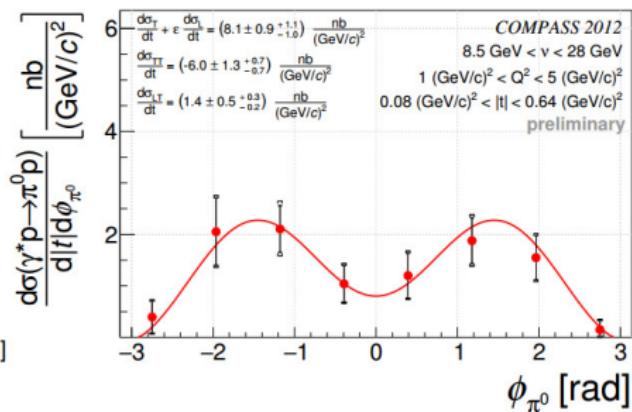
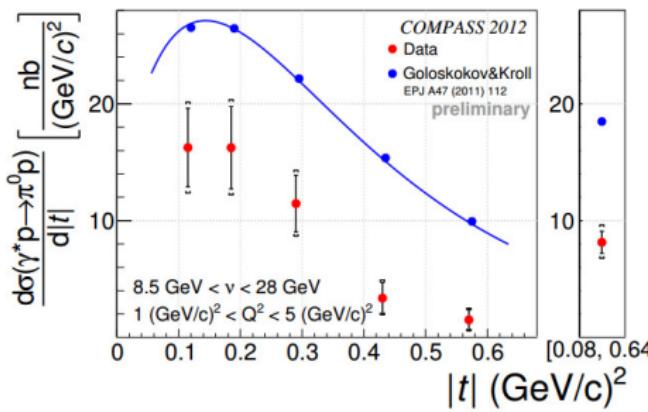
- Recent high precision DVCS cross sections from Hall A at JLab
- Need of higher twist and/or NLO contributions to fully describe the data (eg. in global GPD fits)
- First separation of DVCS² and BH-DVCS interference in the $ep \rightarrow e\gamma p$ cross section
- L/T separation of π^0 electroproduction cross section off neutron: dominance of σ_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

Exclusive π^0 electroproduction cross-sections – Hall B

- Very large cross section compared to leading chiral even GPD models
- Fair agreement w/ models of trans. photon (modified) factorization (& transversity GPDs)

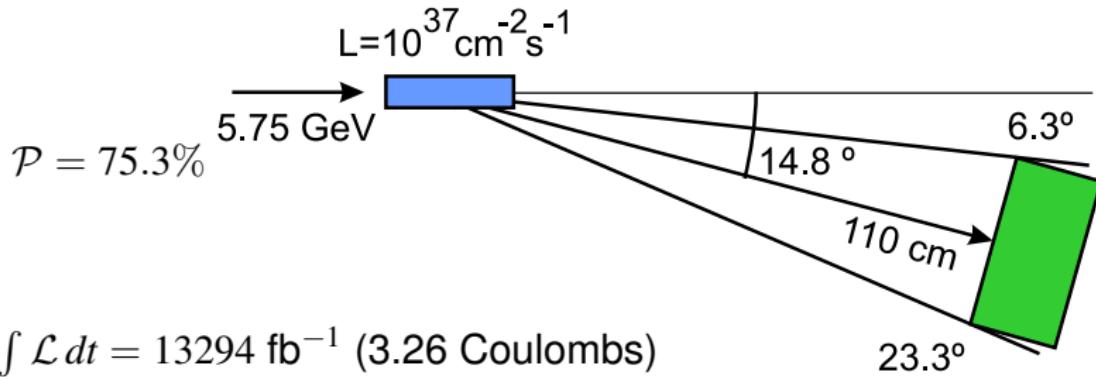
Exclusive π^0 cross section from COMPASS 2012 run



Results also in fair agreement with transversity GPD models

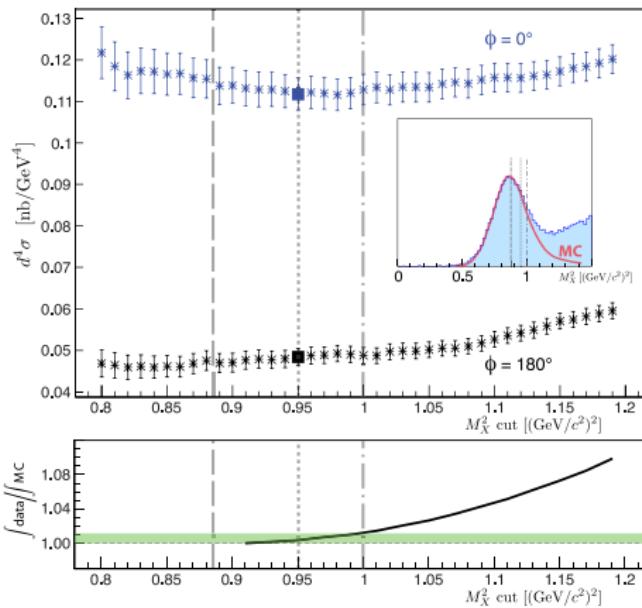
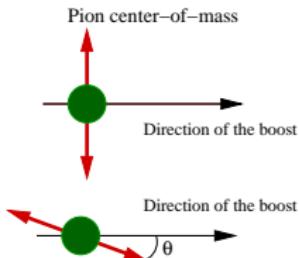
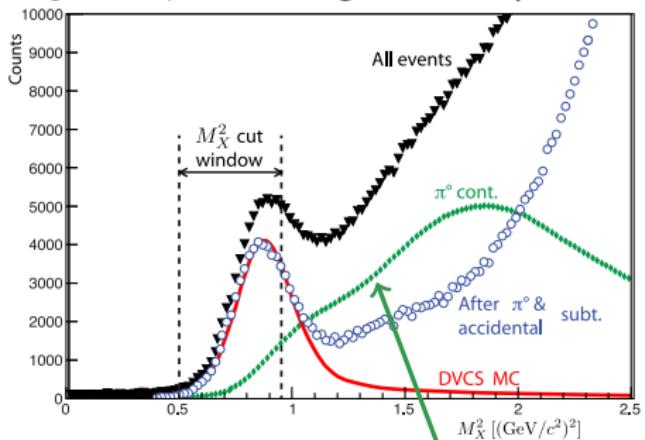
Kinematic settings: testing Q^2 -dependance

Kin	Q^2 (GeV 2)	x_B	θ_e (deg.)	θ_{γ^*} (deg.)	P_e (GeV)
1	1.5	0.36	15.6	22.3	3.6
2	1.9	0.36	19.3	18.3	2.9
3	2.3	0.36	23.9	14.8	2.3



Data analysis: exclusivity and background subtraction

$ep \rightarrow e\gamma X$ missing mass squared



- Only e' & γ detected + M_X^2 -cut
- 2-3% uncertainty on exclusivity