New deeply γ and π^0 electroproduction results from Hall A at JLab

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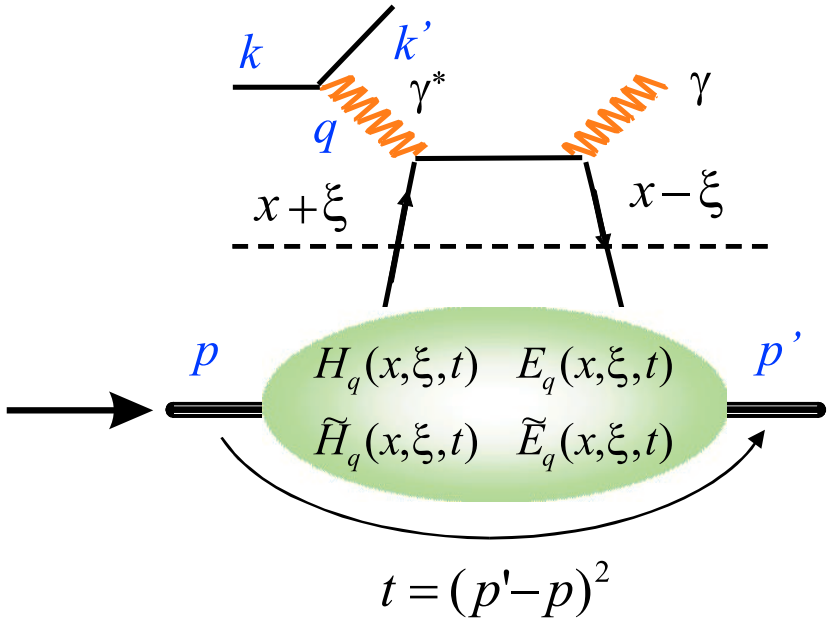
Nucleon and Resonance Structure with Hard Exclusive Processes
May 29–31, 2017

Outline

1. Very brief experimental introduction to DVCS
2. Recent DVCS results from Hall A at JLab
   - DVCS: beam energy dependence of the cross section (arxiv:1703.09442)
   - π^O: off the neutron $\rightarrow$ flavor separation (arXiv:1702.00835)
3. Outlook
   - Jefferson Lab at 12 GeV: Hall A $\rightarrow$ C programs

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



Handbag diagram

High Q^2
Perturbative QCD

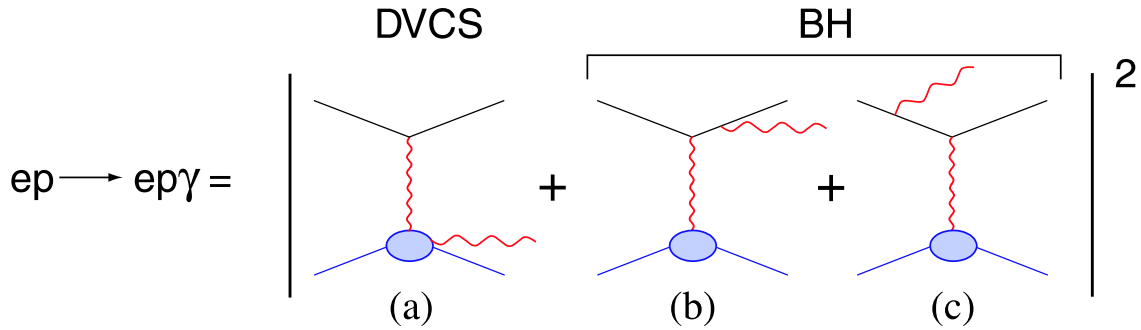
Non-perturbative
GPDs

Bjorken limit:

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

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

DVCS experimentally: interference with Bethe-Heitler



At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = 2\,\Im m\left(T^{BH}\cdot T^{DVCS}\right)$$

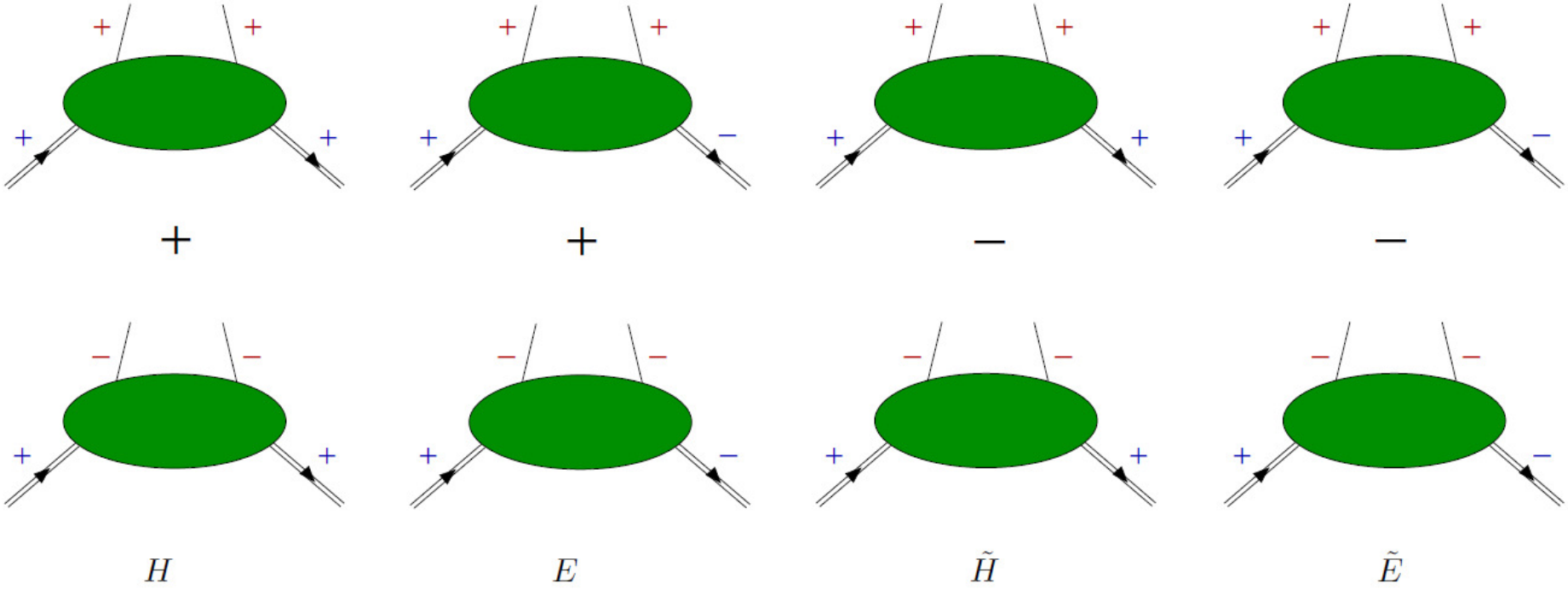
$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + 2\,\Re e\left(T^{BH}\cdot T^{DVCS}\right) + |DVCS|^2$$

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

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

Leading twist GPDs

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

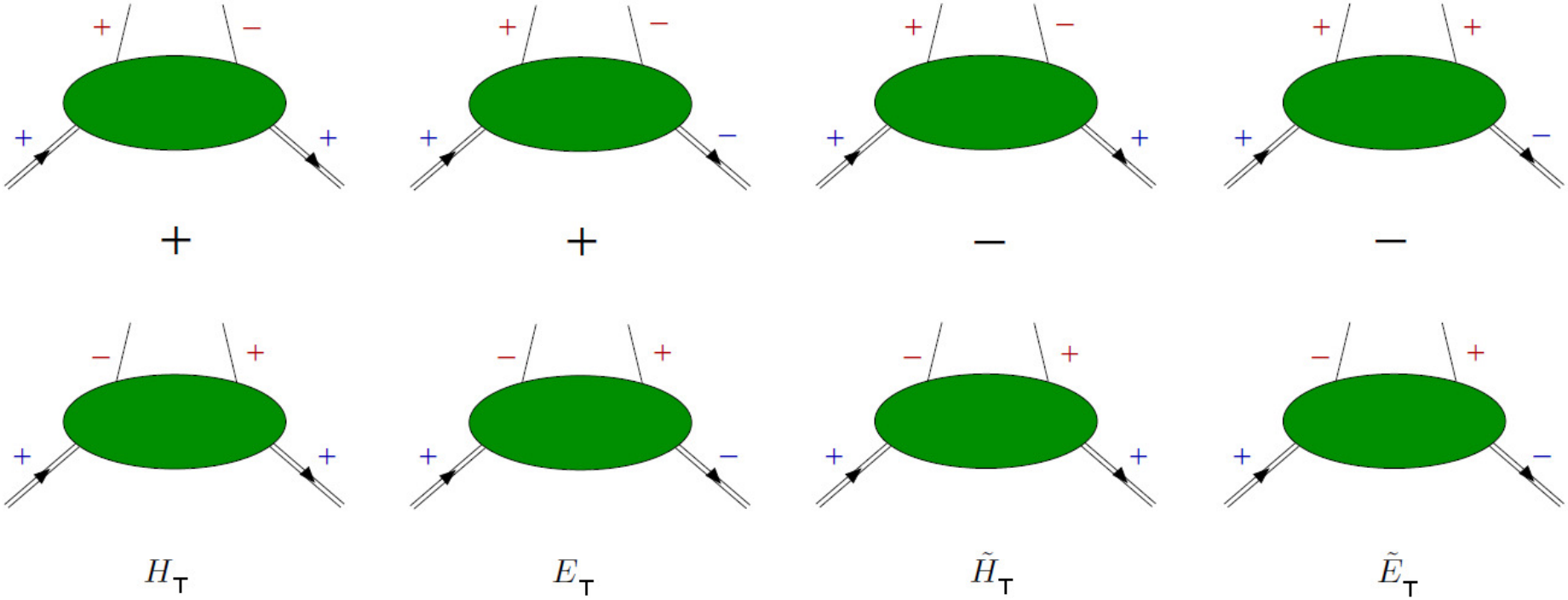


4 chiral-even GPDs: conserve the helicity of the quark

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

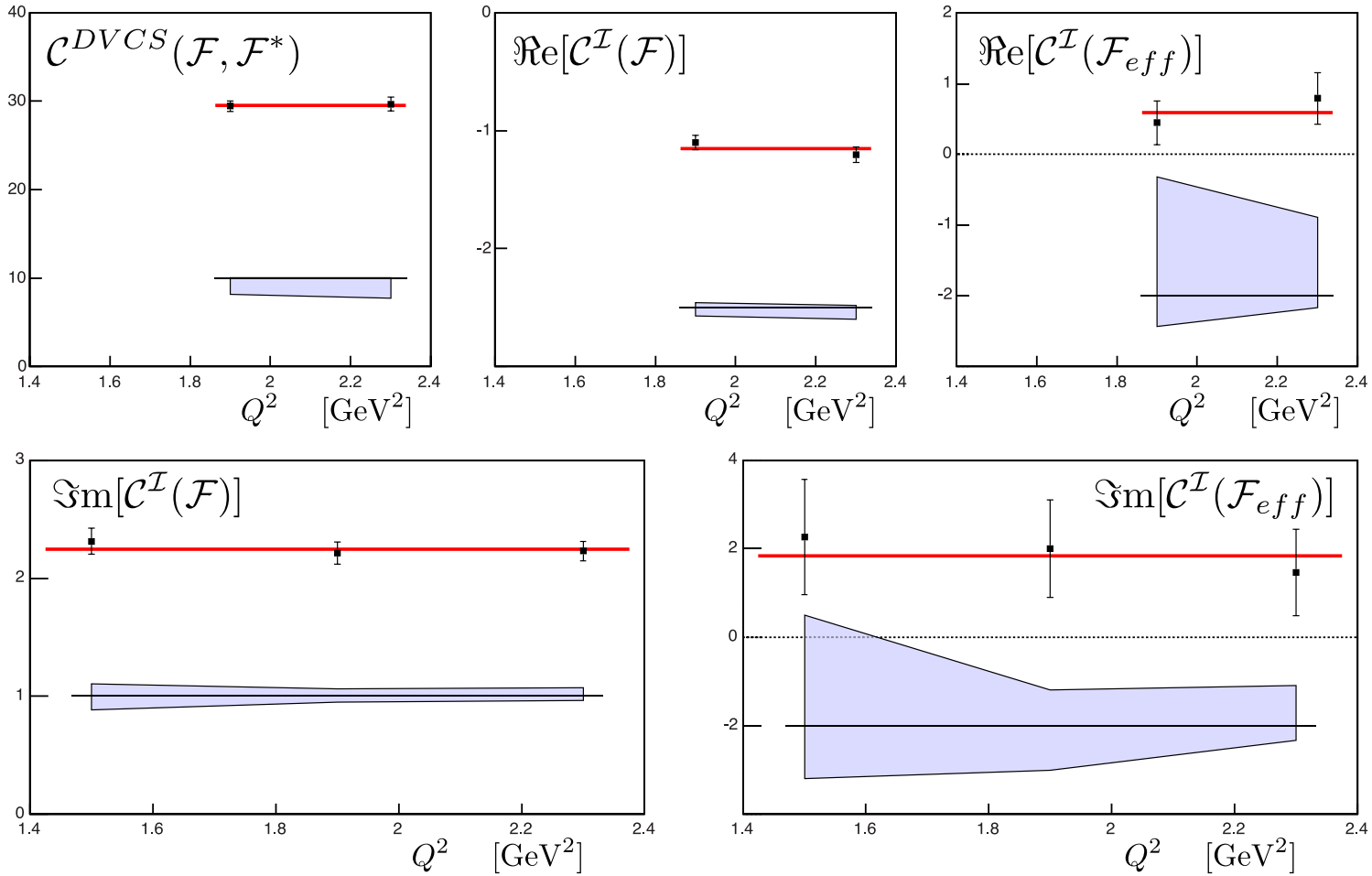
"transversity GPDs"

Experimental access more complicated (π^0 electroproduction?)

Ahmad, Goldstein, Liuti (2009)

Goloskokov, Kroll (2011)

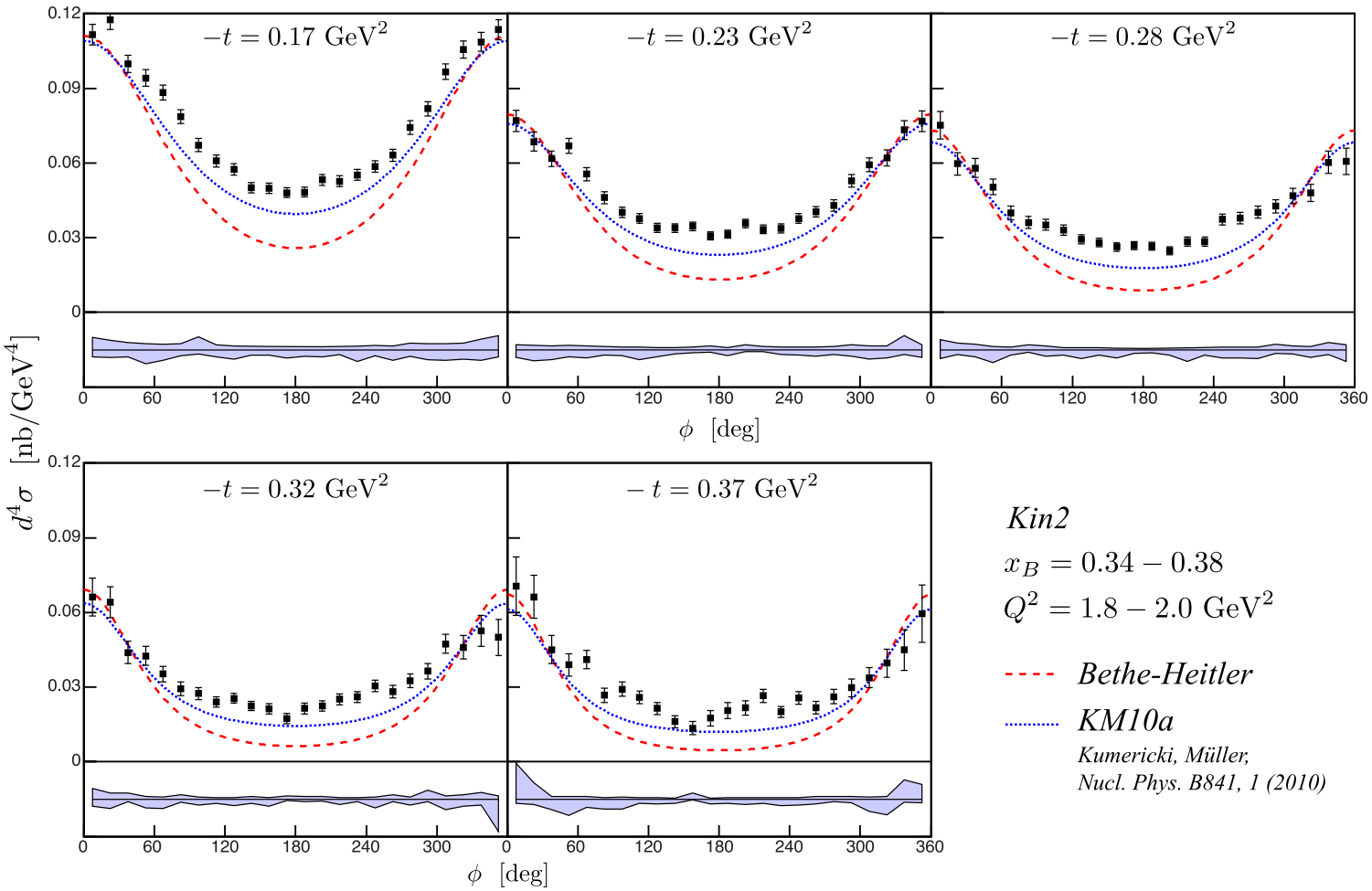
DVCS cross sections: Q^2–dependance



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

Phys. Rev. **C92** (2015) 055202

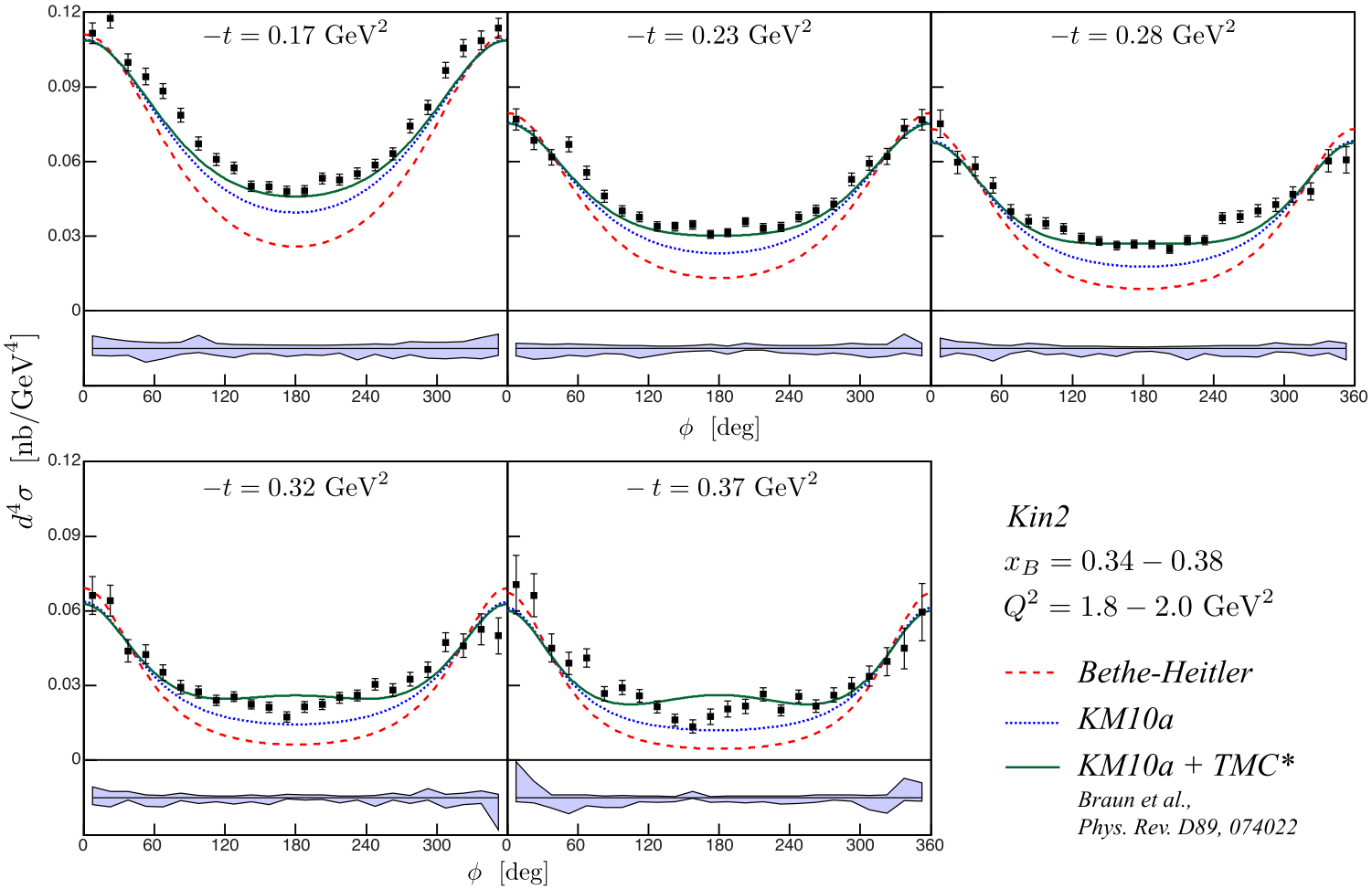
DVCS cross sections: higher twist corrections



- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries

  Kumericki and Mueller (2010)

DVCS cross sections: higher twist 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. ("BMK", 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 $\sim \mathcal{O}(M^2/Q^2)$, $\sim \mathcal{O}(t/Q^2)$

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

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

Rosenbluth-like separation of the DVCS cross section

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

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

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

BMK-2010 – at leading twist $\to$ 7 independent GPD terms:

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

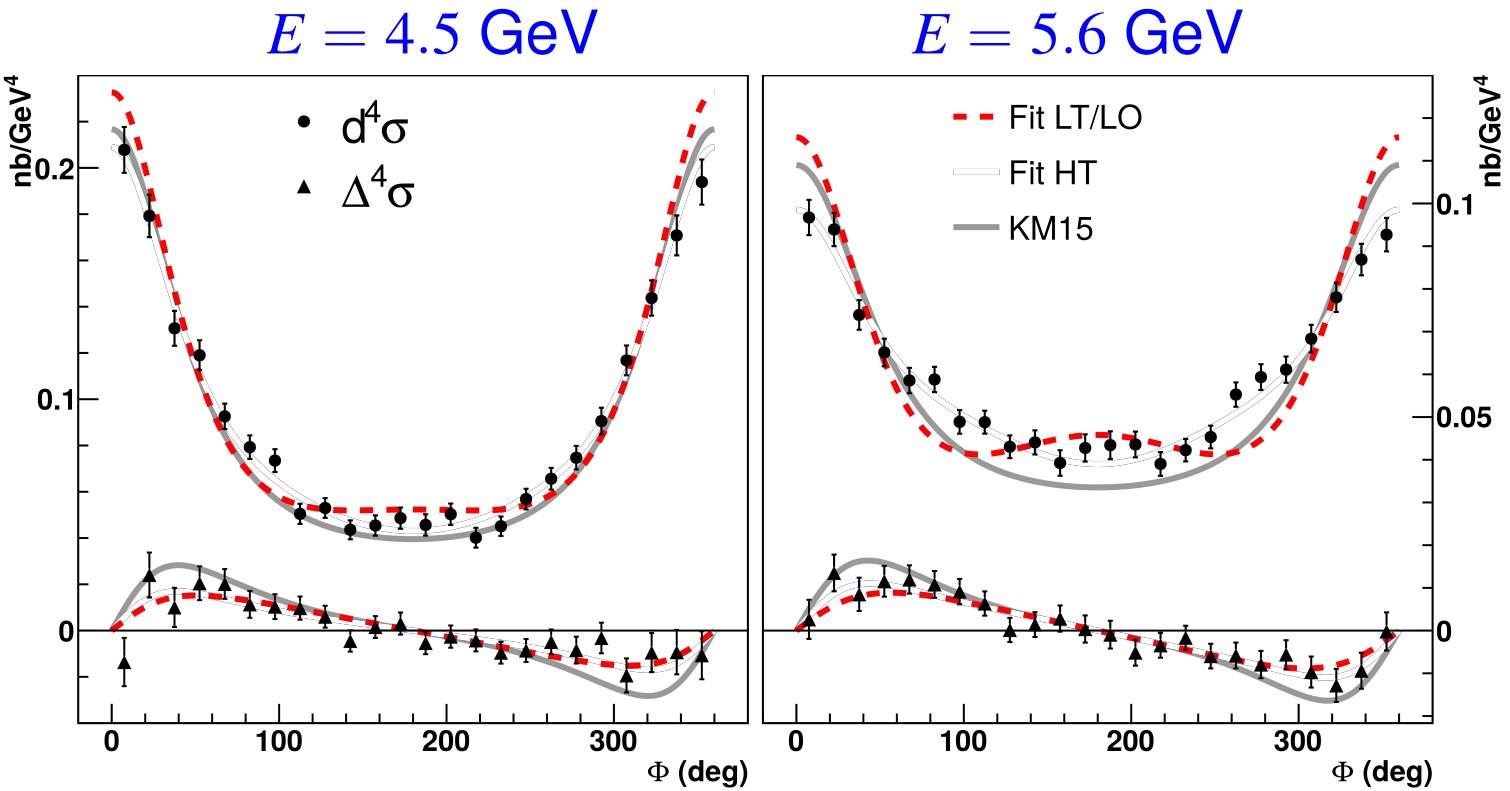
φ-dependence provides 5 independent observables:

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

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.*): $\mathbb{H}_{++}$, $\widetilde{\mathbb{H}}_{++}$, $\mathbb{E}_{++}$, $\widetilde{\mathbb{E}}_{++}$

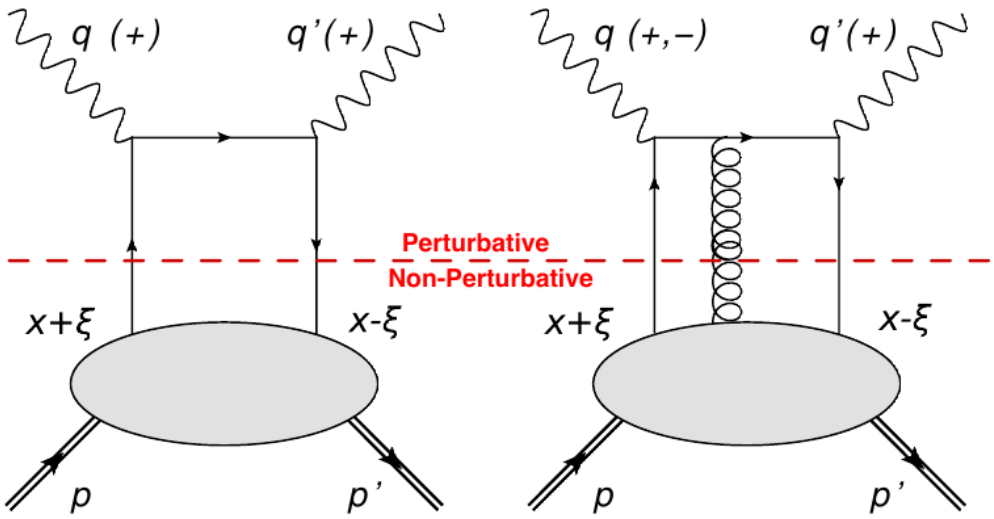
Beyond Leading Order (LO) and Leading Twist (LT)

Two fit-scenarios:

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

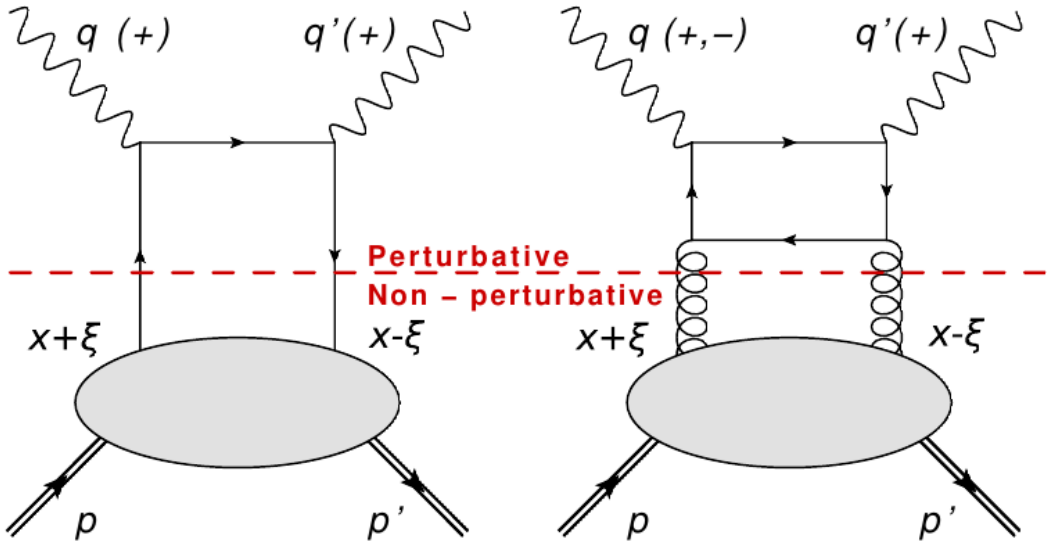
LO/LT + HT

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



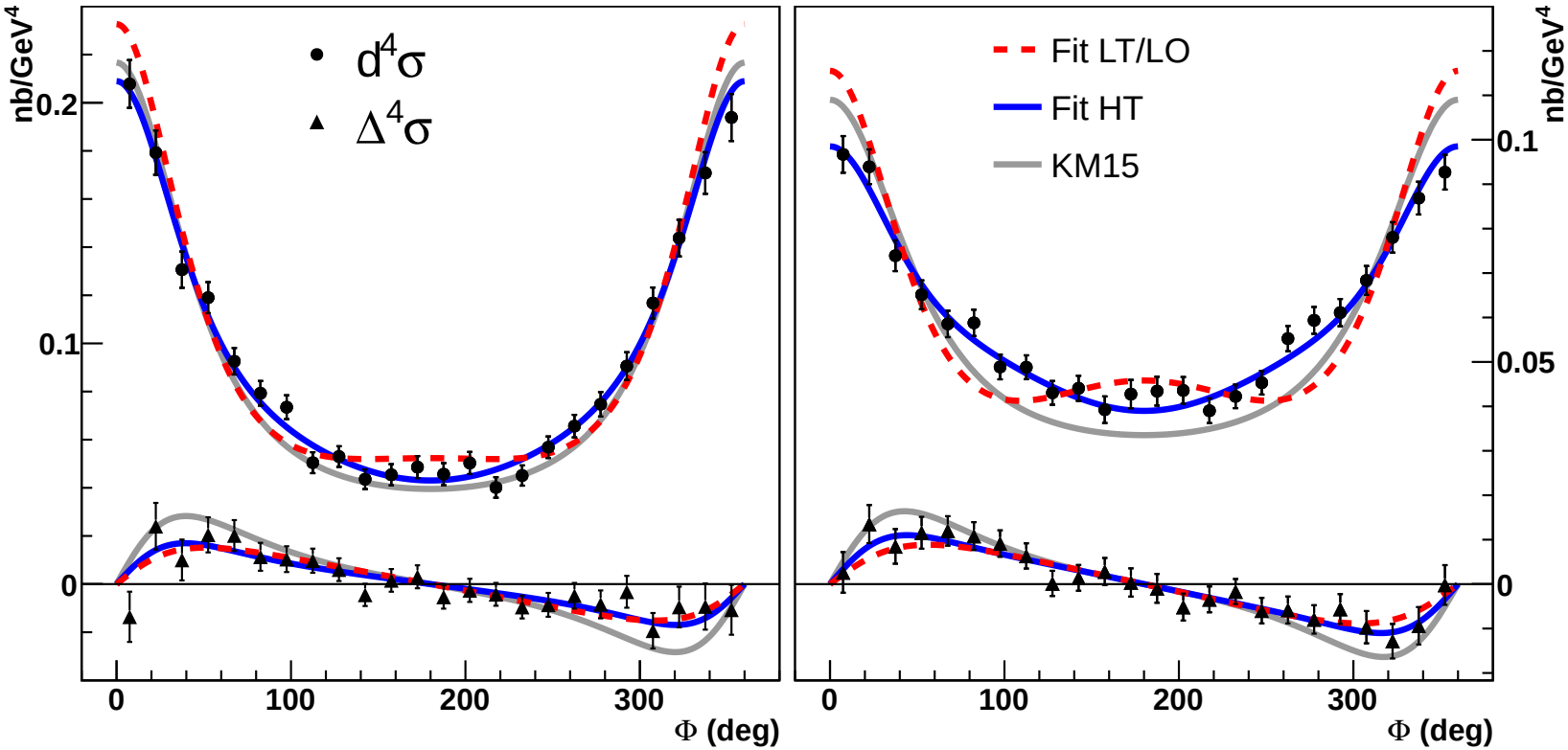
LO/LT + NLO

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



E07-007: DVCS beam-energy dependence

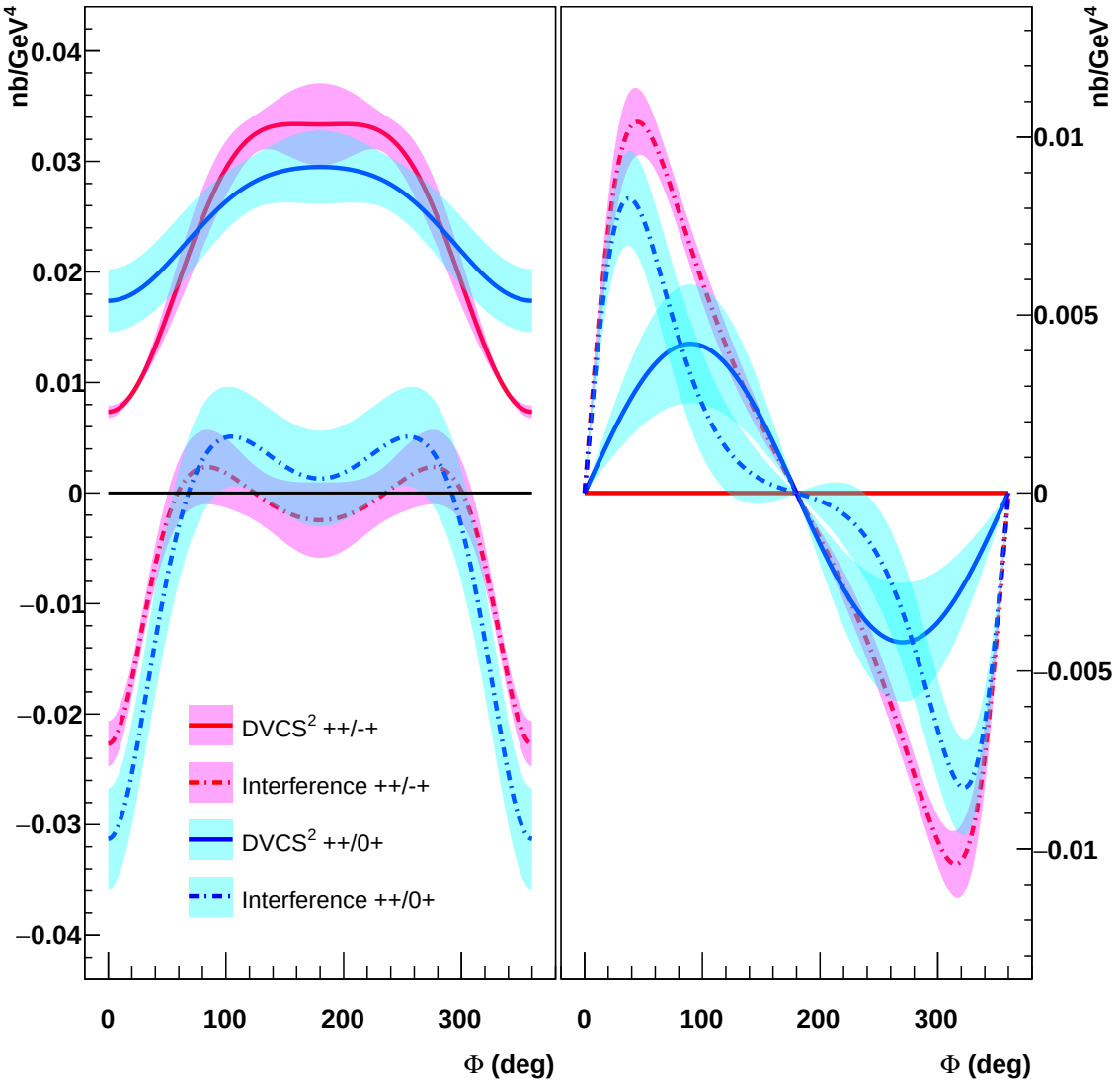
- Cross section measured at 2 beam energies and constant Q^2, x_B, t



- 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

$DVCS^2$ and $\mathcal{I}$(DVCS·BH) separation

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



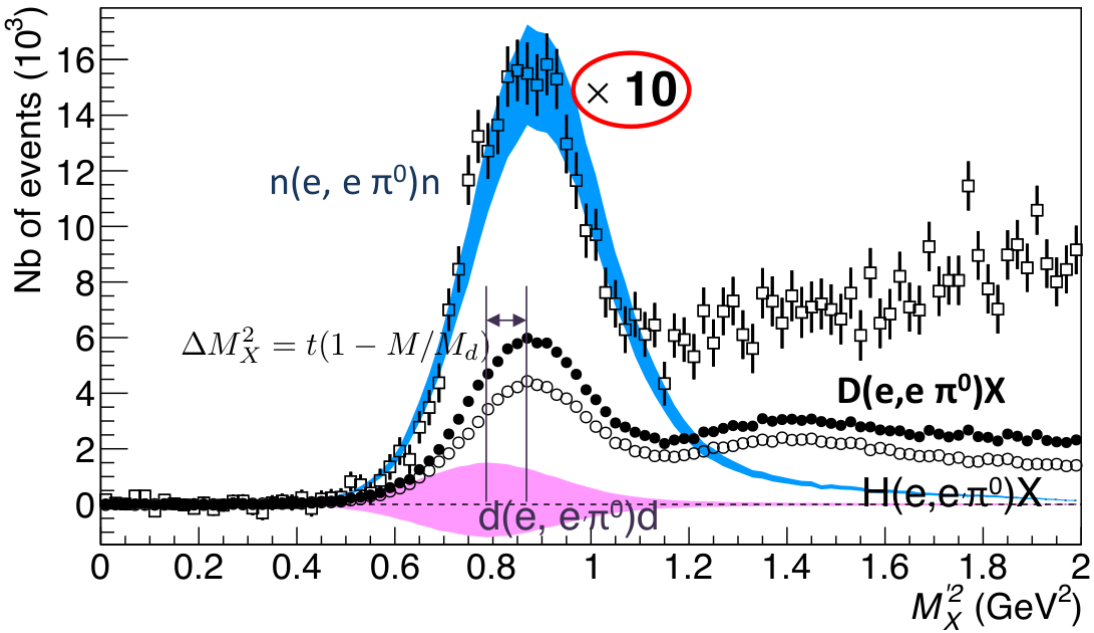
- $DVCS^2$ & $\mathcal{I}$ significantly different in each scenario
- Sizeable $DVCS^2$ contribution in the higher-twist scenario in the helicity-dependent cross section

arXiv:1703.09442

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

- LD_2 as a target
- Quasi-free p evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LH2/LD2 $\rightarrow$ minimize uncertainties

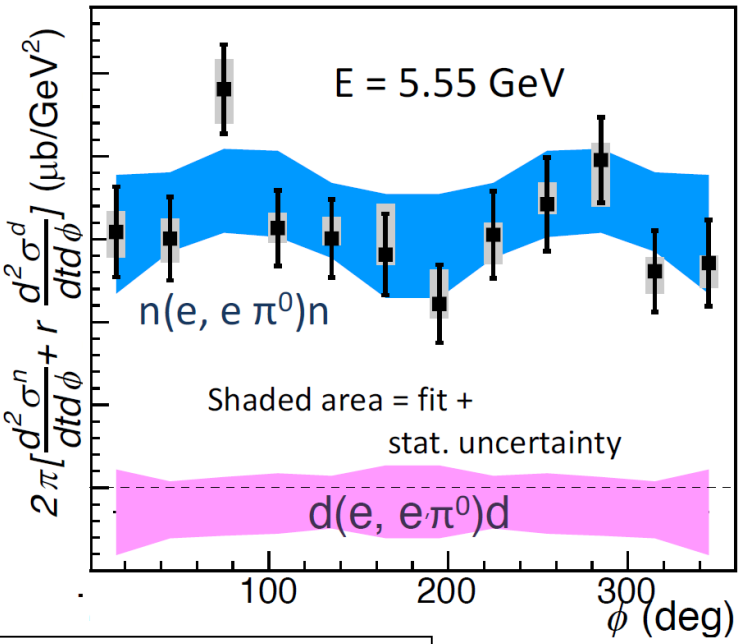
$$D(e,e\,\pi^0)X - p(e,e\,\pi^0)p = n(e,e\,\pi^0)n + d(e,e\,\pi^0)d$$

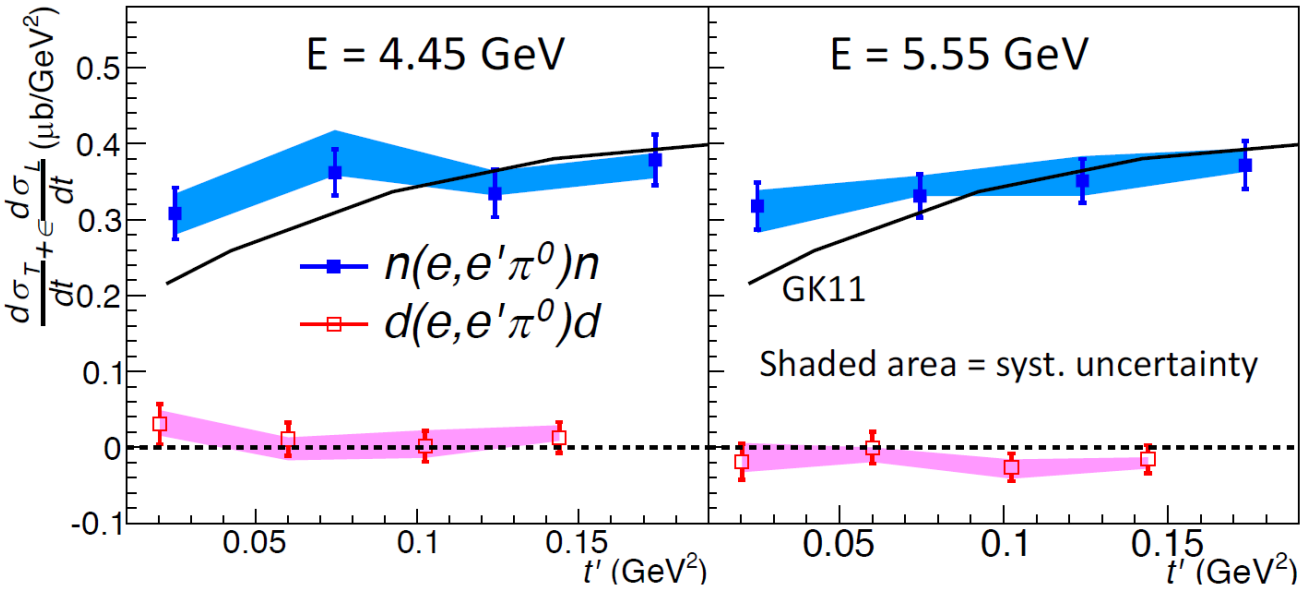


The average momentum transfer to the target is much larger than the np relative momentum, justifying this **impulse approximation**

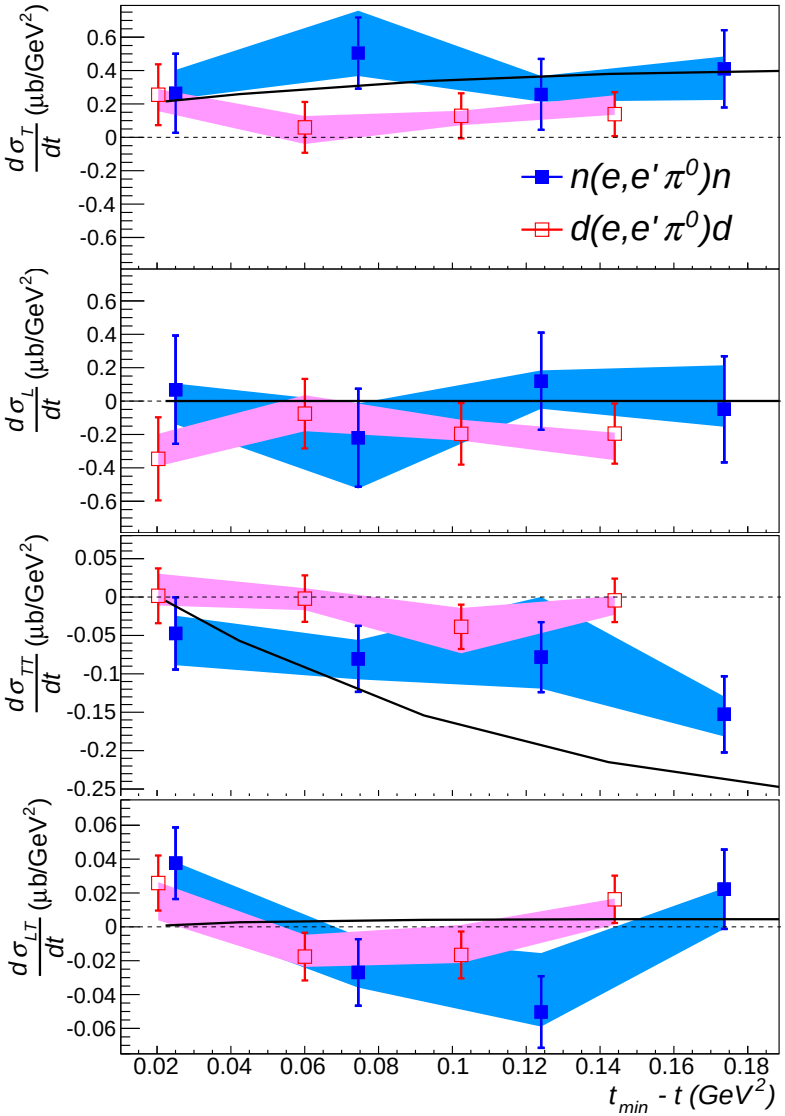
π^0 electroproduction cross section off the neutron

- Cross section off coherent d found negligeable within uncertainties
- Very low E_{beam} dependence of the n cross section $\rightarrow$ dominance of σ_T





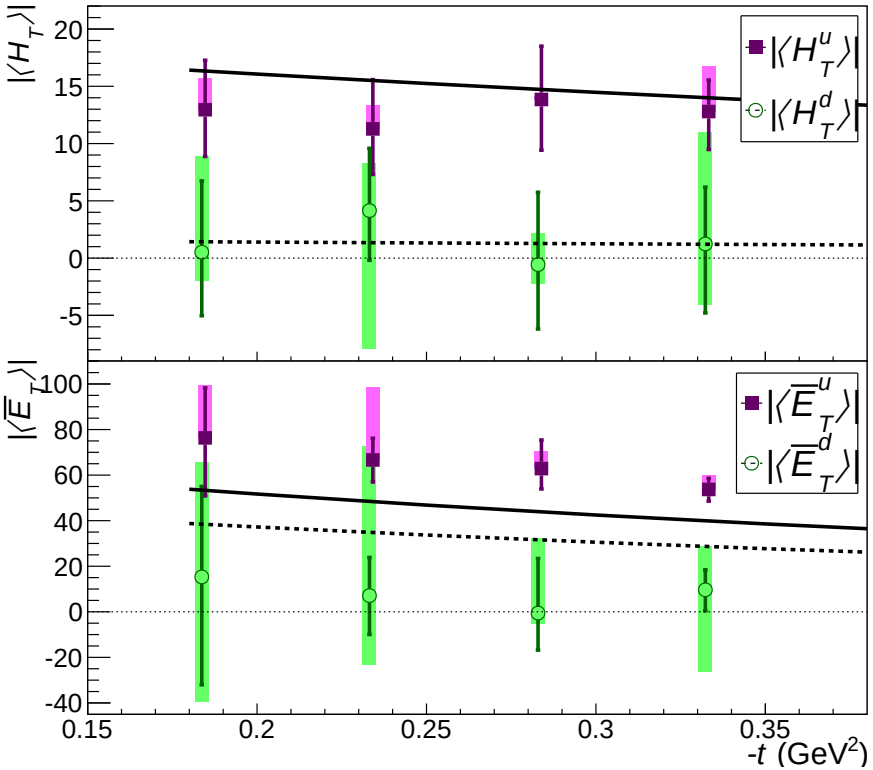
Separated π^0 cross section off the neutron



M. Mazouz et al, arXiv:1702.00835
Phys. Rev. Lett., in press

In the modified factorization approach (KG):

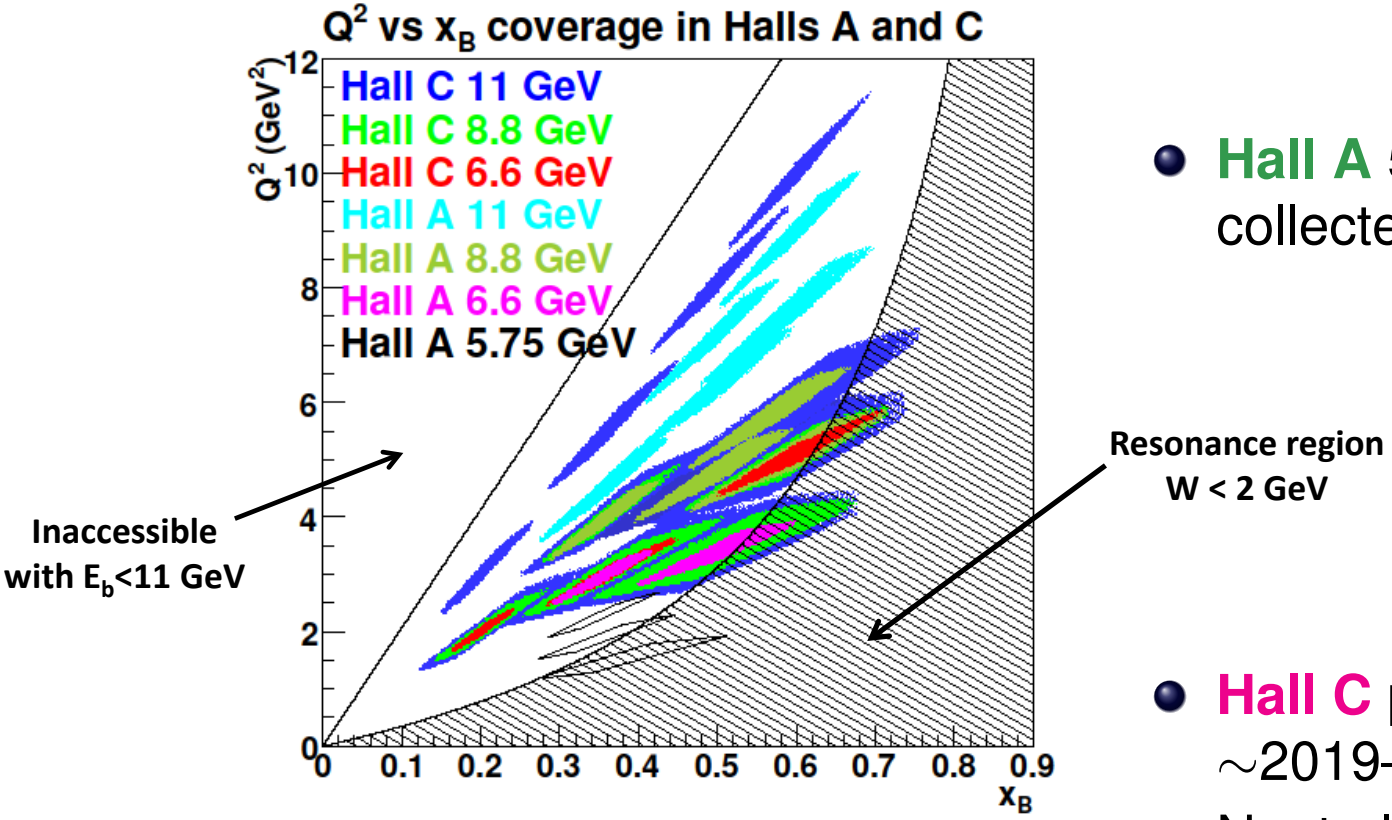
- $d\sigma_T \propto \left[\left(1-\xi^2\right) \left|\langle H_T \rangle\right|^2 - \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2 \right]$
- $d\sigma_{TT} \propto \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2$



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

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

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



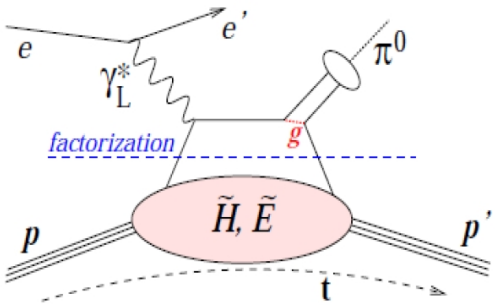
- **Hall A** 50% of data already collected (2014–2016):
  analysis underway. . .
- **Hall C** program could start ∼2019–2020:
  Neutral Particle Spectrometer (NPS) under construction

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^2 and BH-DVCS interference in the $ep \to e\gamma p$ 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

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



At leading twist:

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

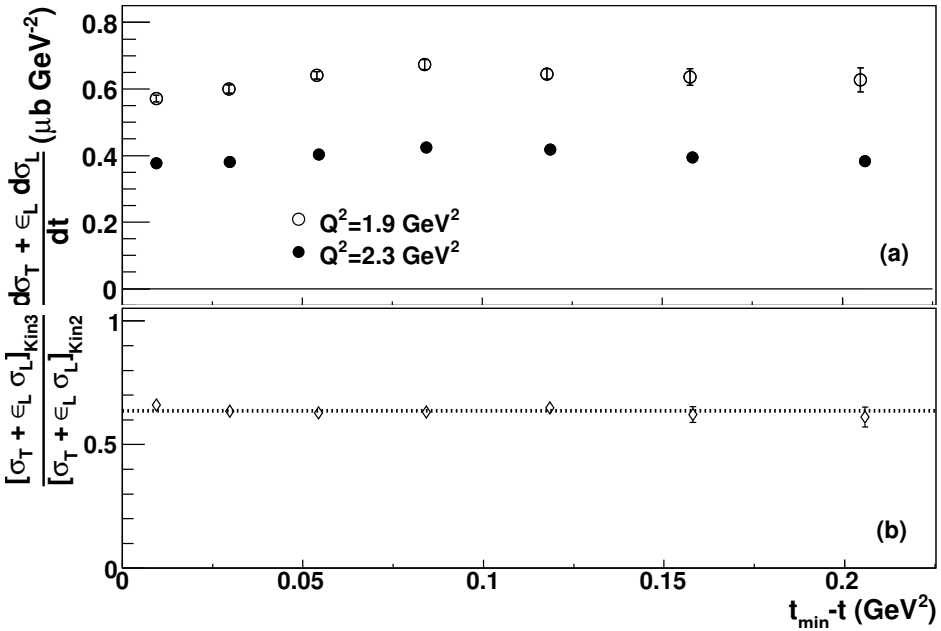
$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z}\right] \int_{-1}^1 dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \times \left\{\Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0}\right\}$$

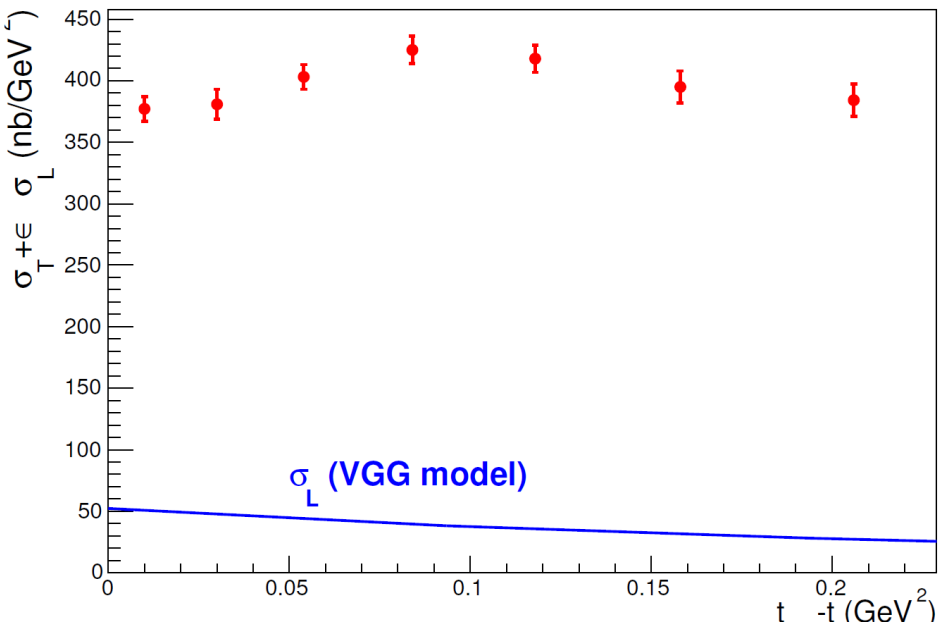
Different quark weights: flavor separation of GPDs

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

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

Exclusive π^0 electroproduction cross-sections – Hall A

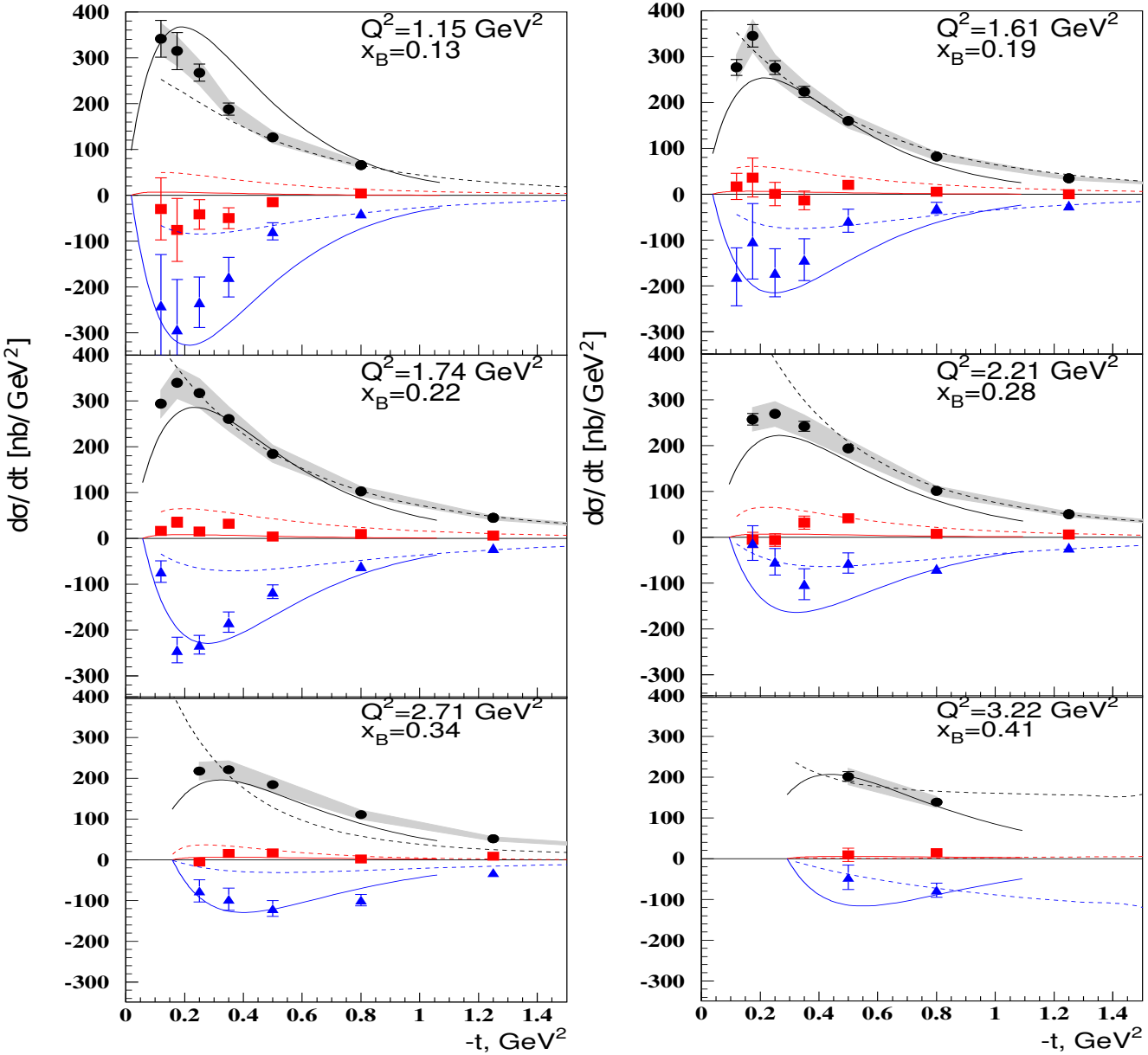




- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$
  (similar to $\sigma_T(ep \to ep\pi^+)$ measured in Hall C)
- GPDs predict $\sigma_L \sim Q^{-6}$
- σ_T likely to dominate at these Q^2,
  but L/T separation necessary ($\to$ new experiment...)

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

Exclusive π^0 electroproduction cross-sections – Hall B



- $\sigma_T + \epsilon\sigma_L$
- σ_{TL}
- σ_{TT}

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

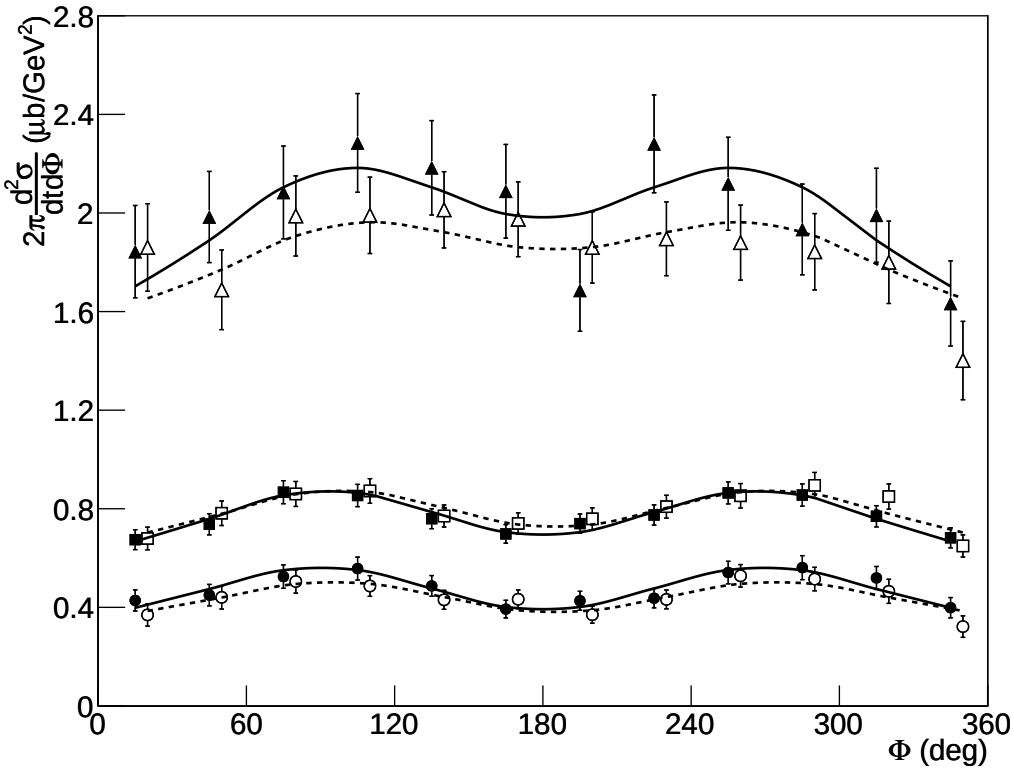
Rosenbluth separation

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

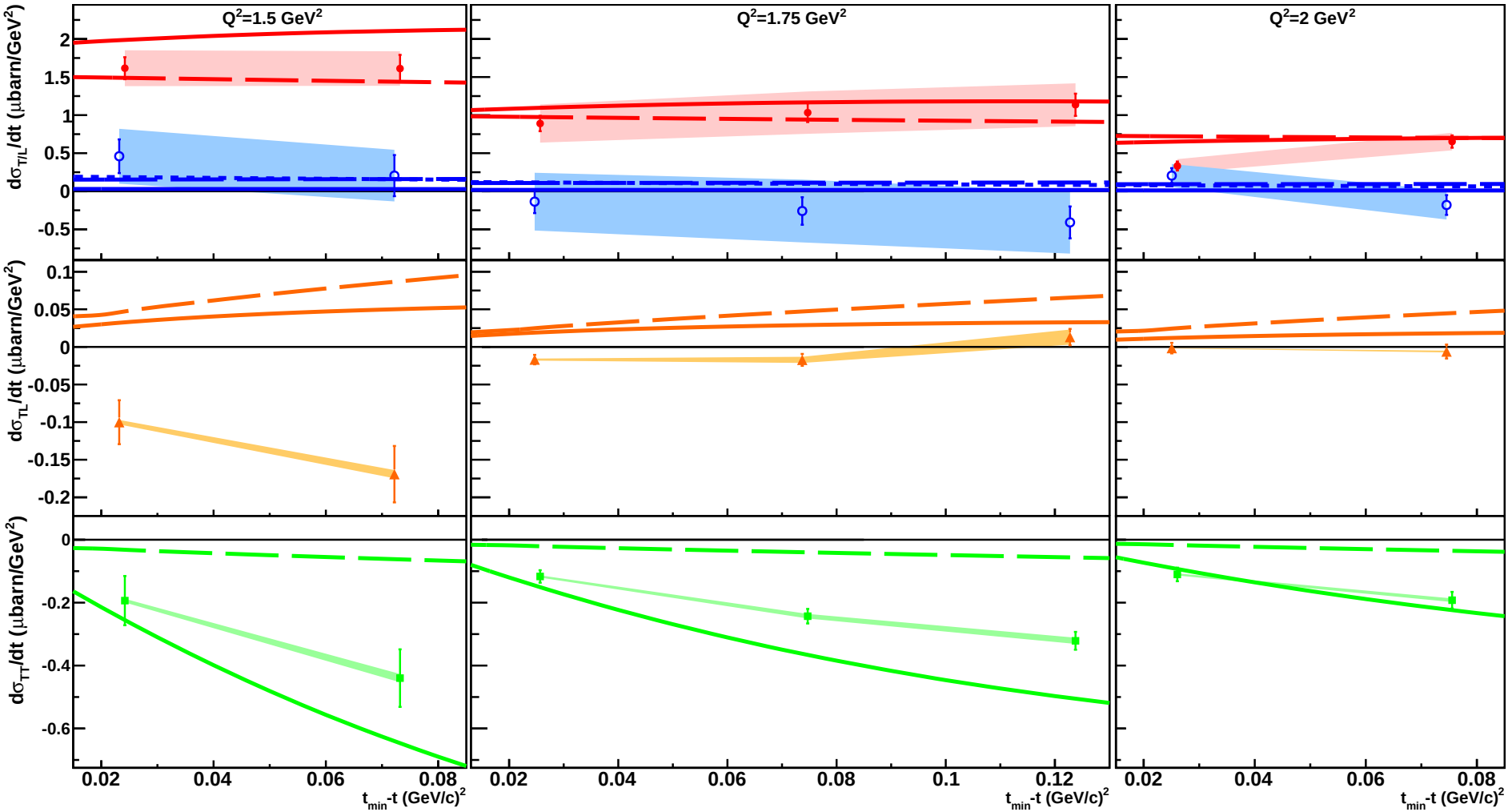
Kinematics

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

$t_{\text{min}} - t = 0.025$ GeV^2



π^0 separated response functions



Goloskokov, Kroll (2011)

Goldstein, Hernandez, Liuti (2011)

Vanderhaeghen, Guichon, Guidal (1999)

arXiv:1608.01003

π^0 L/T separated cross section

- Cross section largely dominated by transverse component

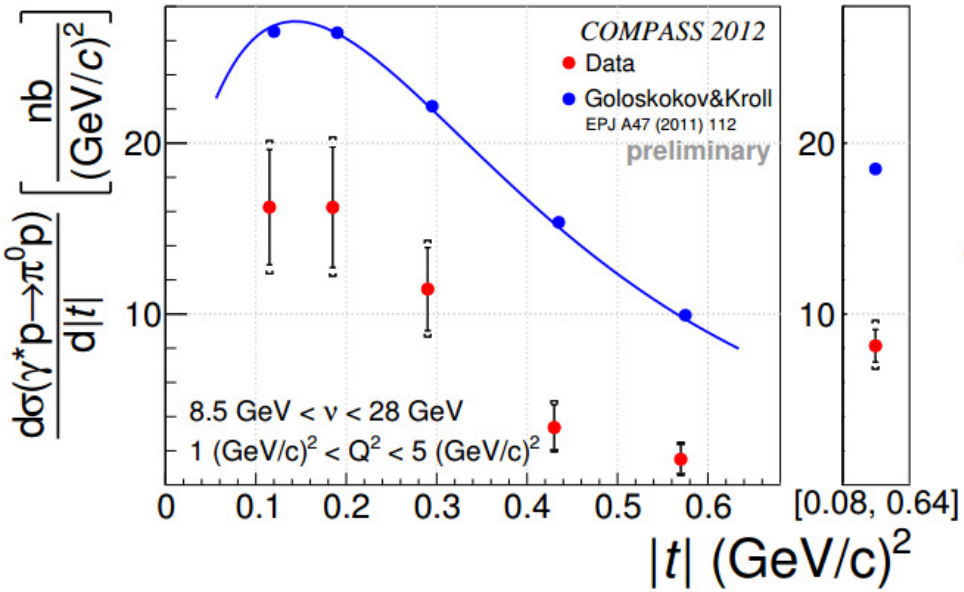
  $\rightarrow$ far from asymptotic prediction of QCD

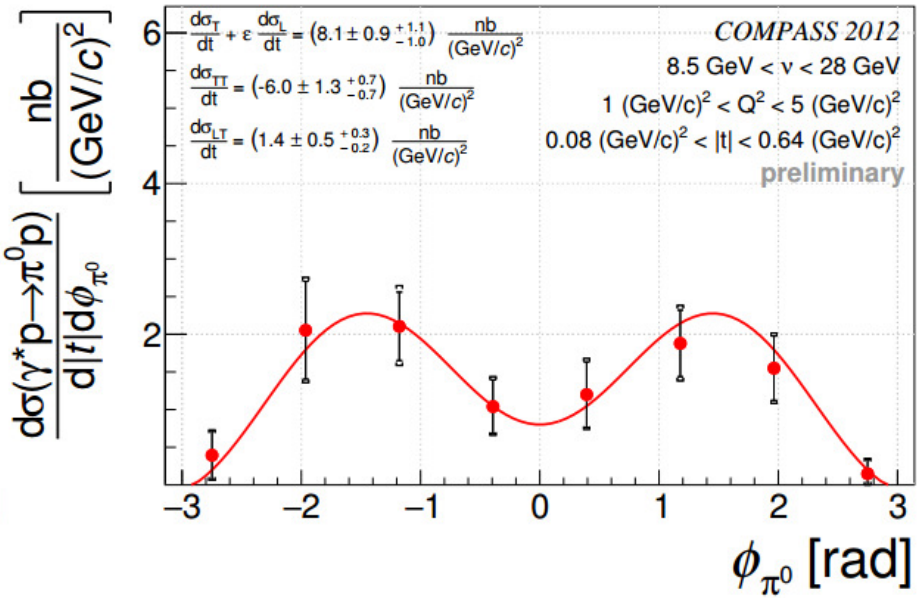
- Fair agreement with models using modified factorization approach

  $\rightarrow$ potential access to transversity GPDs

- Indications of small longitudinal response through non-zero σ_{LT}

Exclusive π^0 cross section from COMPASS 2012 run

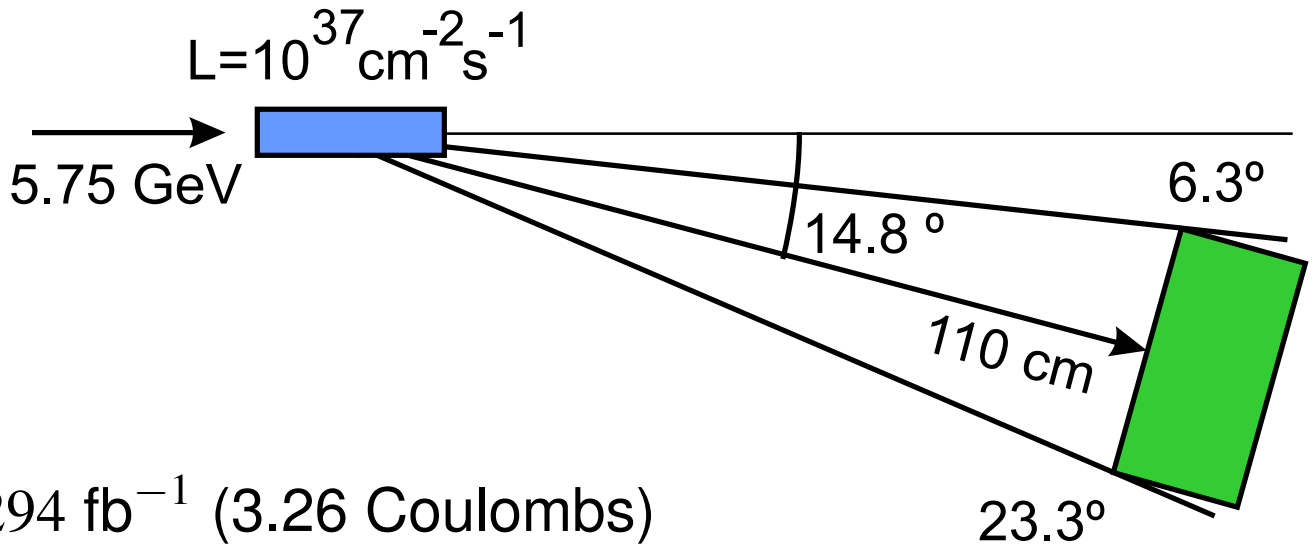




Results also in fair agreement with transversity GPD models

Kinematic settings: testing Q^2–dependance

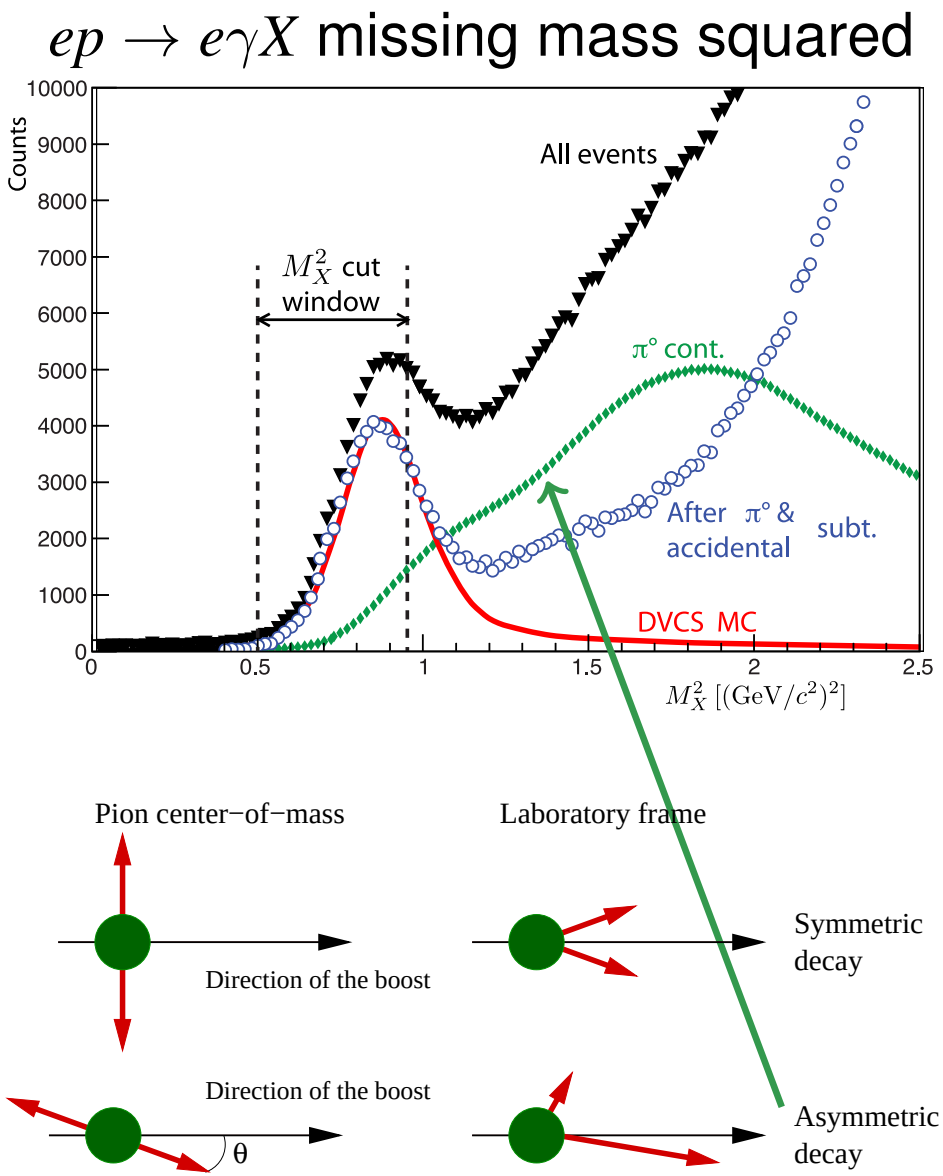
Kin	Q^2 (GeV^2)	x_B	θ_e (deg.)	θ_{γ^*} (deg.)	P_e (GeV)
1	**1.5**	0.36	15.6	**22.3**	3.6
2	**1.9**	0.36	19.3	**18.3**	2.9
3	**2.3**	0.36	23.9	**14.8**	2.3

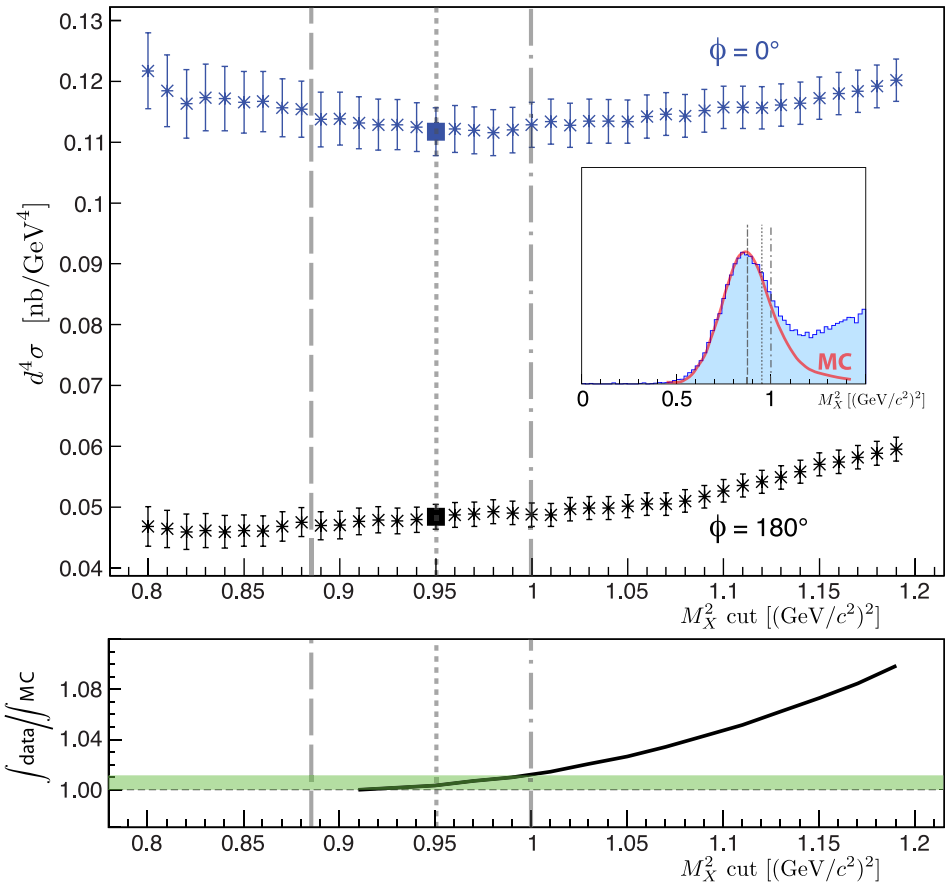


$\mathcal{P} = 75.3\%$

$\int \mathcal{L}\, dt = 13294$ fb^{-1} (3.26 Coulombs)

Data analysis: exclusivity and background subtraction





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