

**E12-06-114:**

**Deeply Virtual Scattering &  
Exclusive  $\pi^0$  Electroproduction**

Carlos Muñoz Camacho,  
IJCLab-Orsay, CNRS/IN2P3 (France)

(for the Hall A DVCS Collaboration)

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# History

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- Experiment proposed in 2006 (PAC30): approved with A rating
- PAC38 (2011) allocated its full beam time request: 100 days
- In 2014, PAC41 rated the experiment as 'High Impact'
- Experiment was scheduled as the 1<sup>st</sup> 12 GeV experiment in Fall 2014
- Experiment stayed in the floor until Fall 2016 (3 years; 5 run periods) and collected half of its data (50 out of 100 PAC days)
  - Spring'14 + Fall'14 + Spring'15 : 6 days of data (but 879 shifts taken over 139 days)
  - Spring'16 + Fall'16: 44 days of data
- Remaining 50 days went into jeopardy in 2019. Remaining time was approved by PAC47 to run with NPS in Hall C (beamtime reduced to 35 days)

# Outline

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- Physics motivation & goals of the experiment

- Recent results:

- Exclusive  $\pi^0$  electroproduction cross sections

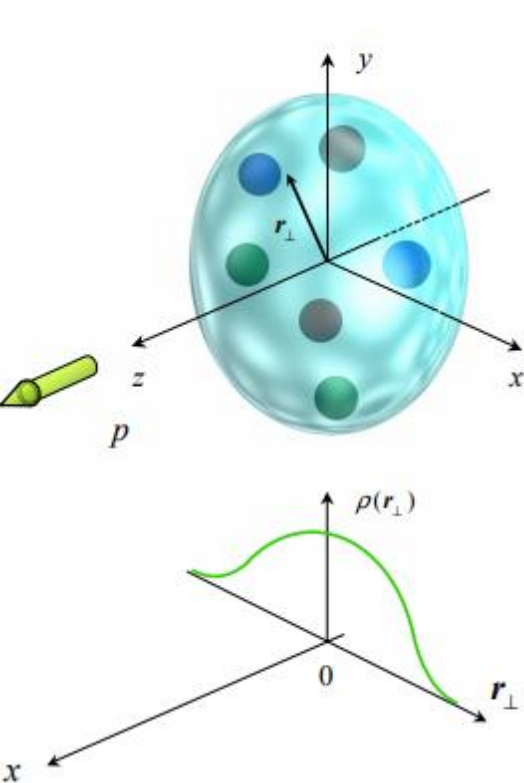
- ([Phys. Rev. Lett. 127 \(2021\) 15, 152301](#))

- Deeply Virtual Compton Scattering cross sections

- (arXiv [2201.03714](#) , submitted for publication in Dec'21)

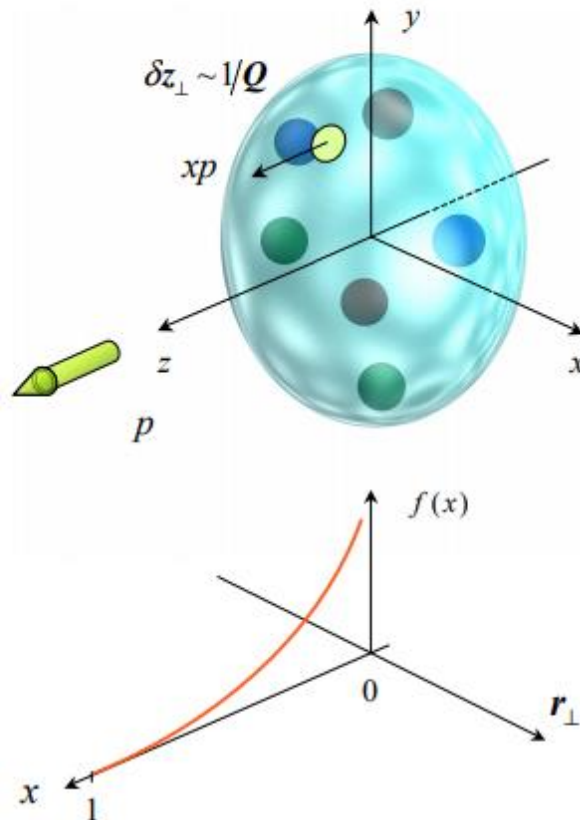
# Studying the structure of the nucleon experimentally

## Elastic scattering



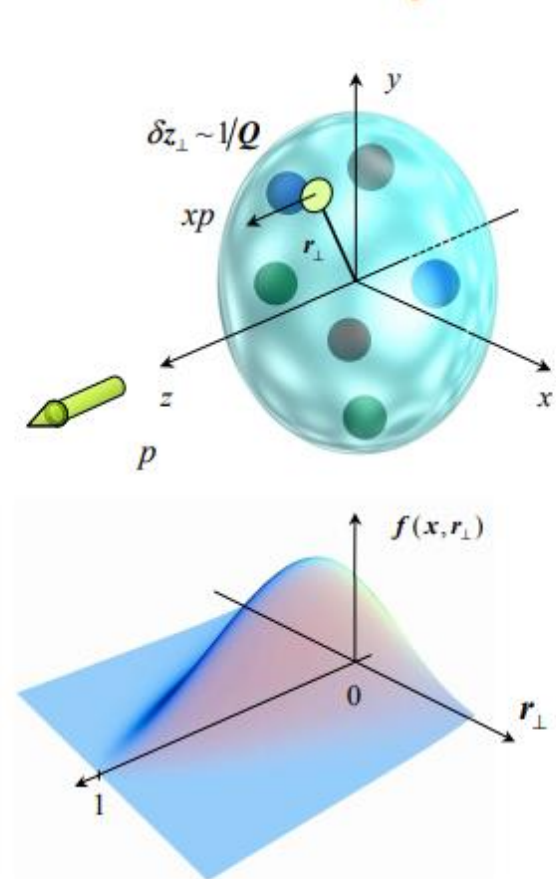
Form factors

## Deeply Inelastic Scattering



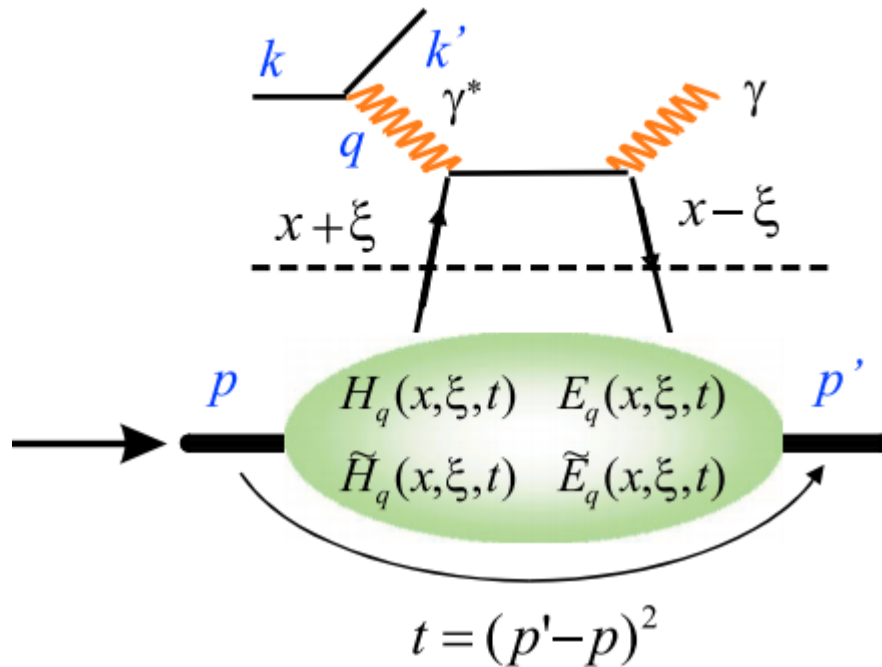
Parton distributions

## Hard exclusive processes



Generalized Parton Distributions (GPDs)

# Deeply Virtual Compton Scattering



## Handbag diagram

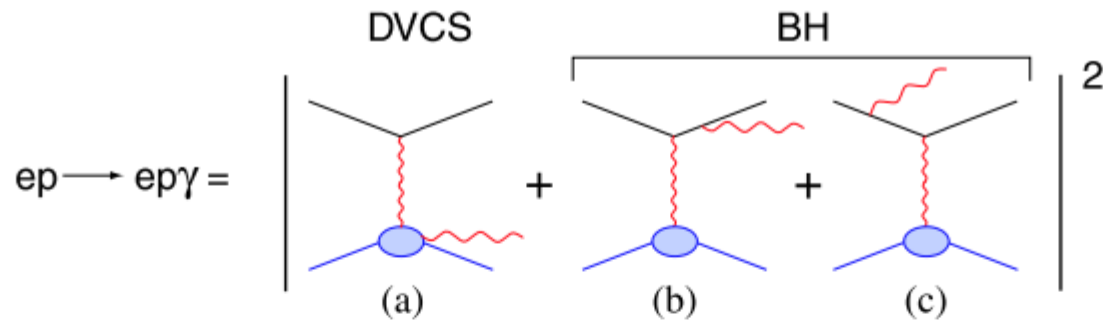
### Bjorken limit:

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

High  $Q^2$   
Perturbative QCD

## Non-perturbative GPDs

# DVCS experimentally: interference with Bethe-Heitler



At leading twist:

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

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

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

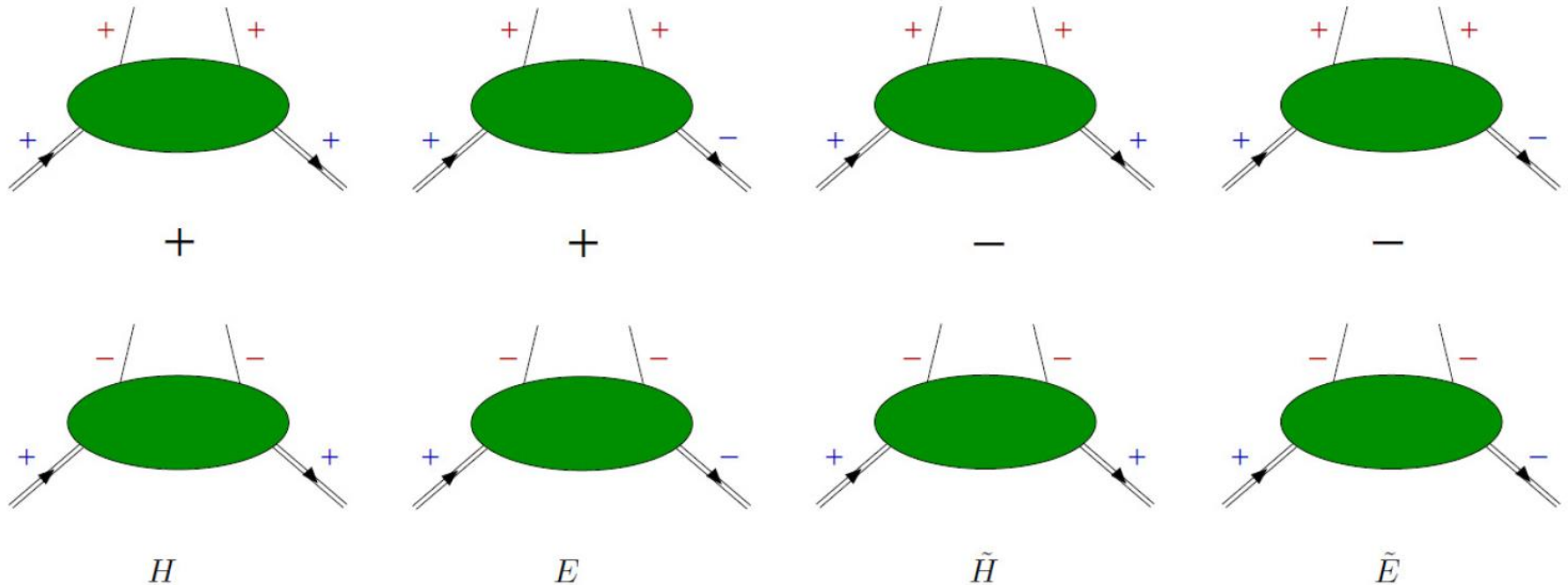
$$\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi H(x = \xi, \xi, t)}_{\text{Access in helicity-dependent cross-section}} + \dots$$

Access in helicity-independent cross section

Access in helicity-dependent cross-section

# Leading twist GPDs

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

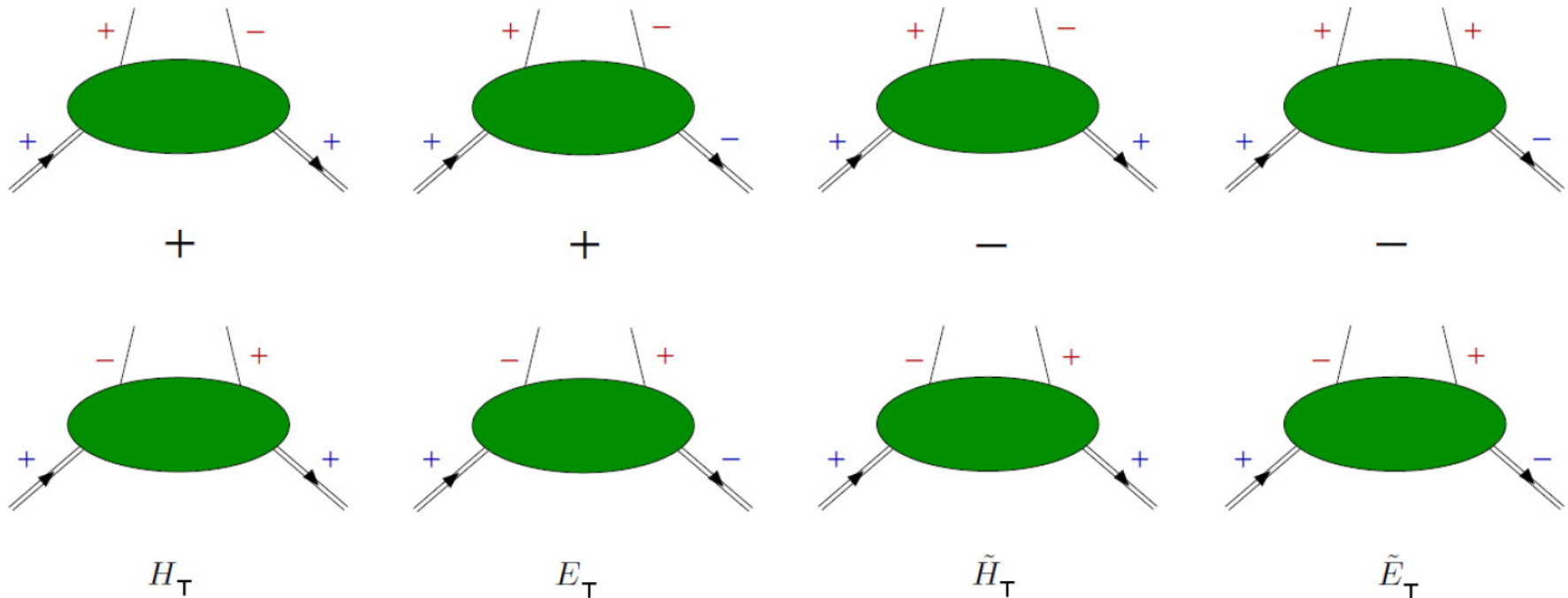


4 chiral-even GPDs: conserve the helicity of the quark

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”

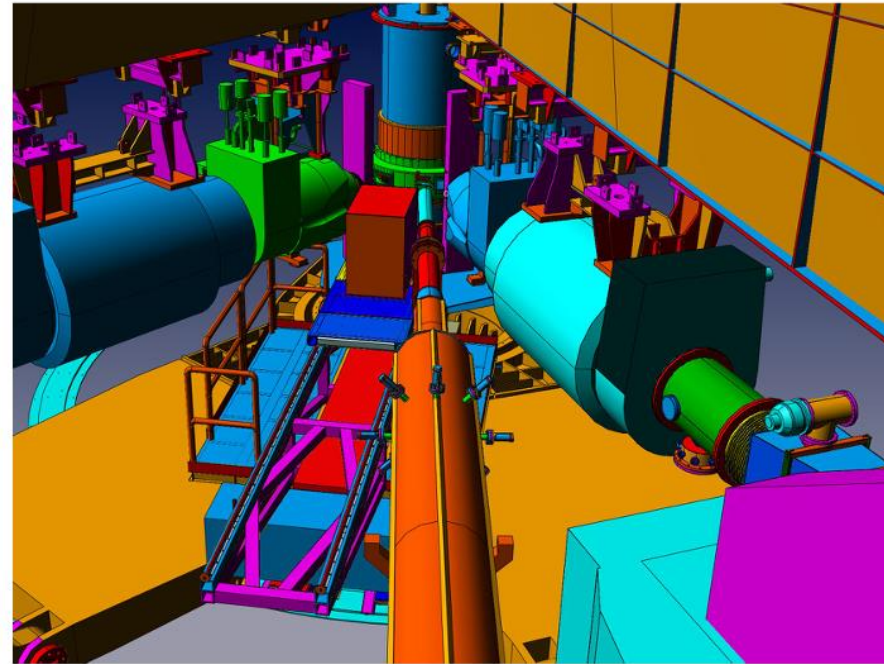
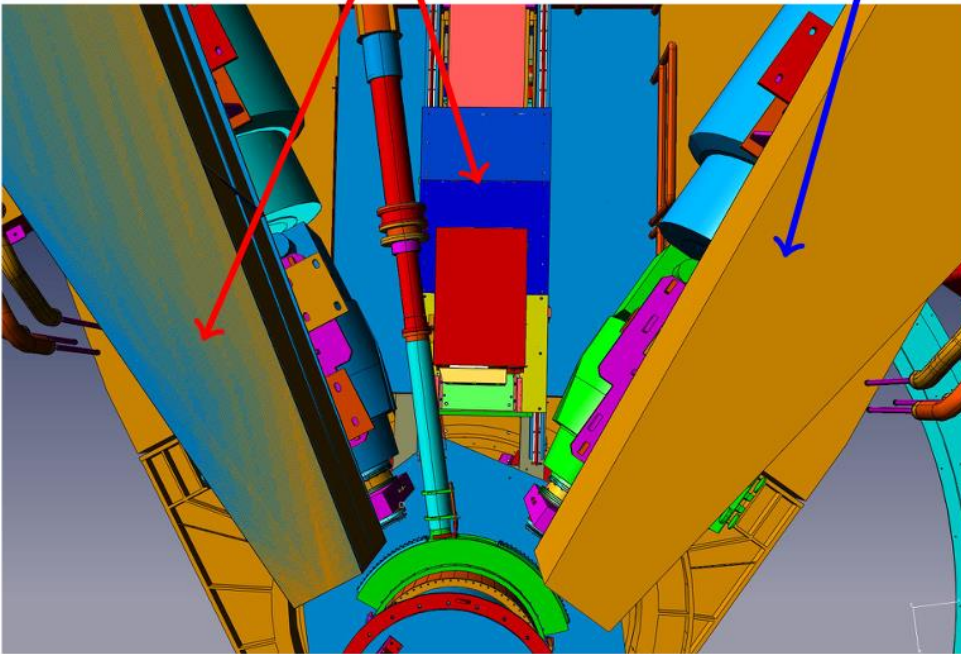
Experimental access more complicated ( $\pi^0$  electroproduction?)



# Experimental configuration

DVCS:  $ep \rightarrow e'\gamma p$

$G_M^p$ :  $ep \rightarrow e'p$

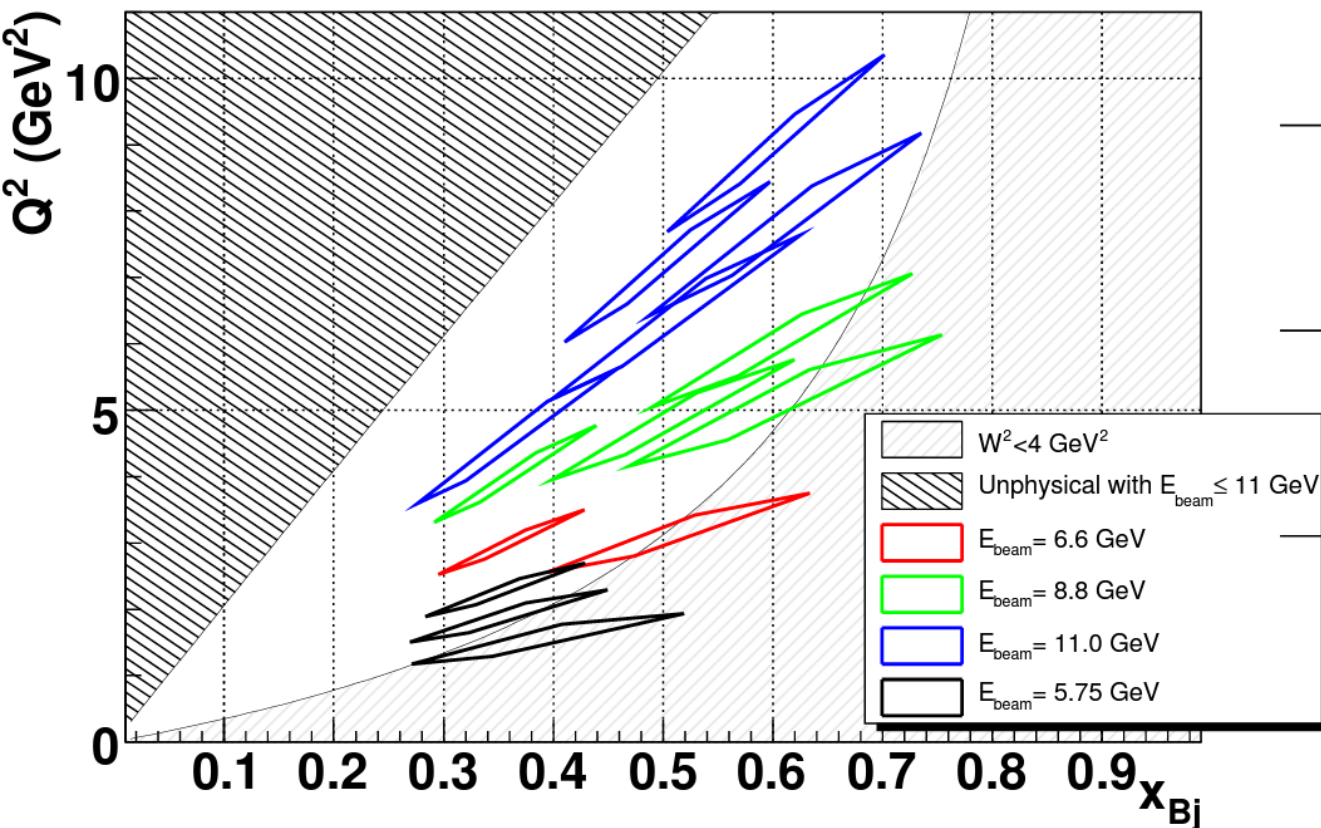


# Kinematics and beamtime

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)

DVCS measurements in Hall A/JLab



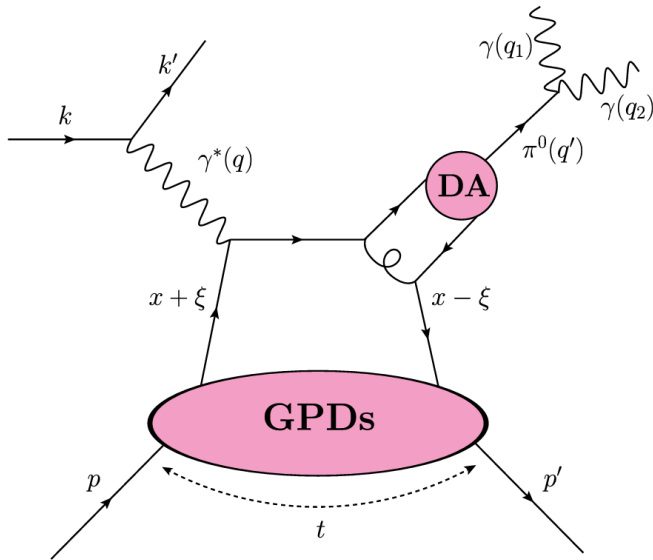
$Q^2$ ( $\text{GeV}^2$ )	Beam time (days)		
	$x_{\text{Bj}}$ 0.36	0.50	0.60
3.0	3		
4.0	2		
4.55	1		
3.1		5	
4.8		4	
6.3		4	
7.2		7	
5.1			13
6.0			16
7.7			13
9.0			20
Total	6	20	62

88 days

250k events/setting

Total = 100 PAC days approved (88+12 days of calibration),

# Exclusive $\pi^0$ electroproduction



## Invariants

$$Q^2 = -(k - k')^2$$

$$x_B = \frac{Q^2}{2q \cdot p}$$

$$W^2 = (q + p)^2$$

$$y = \frac{q \cdot p}{k \cdot p}$$

$$t = (q - q')^2$$

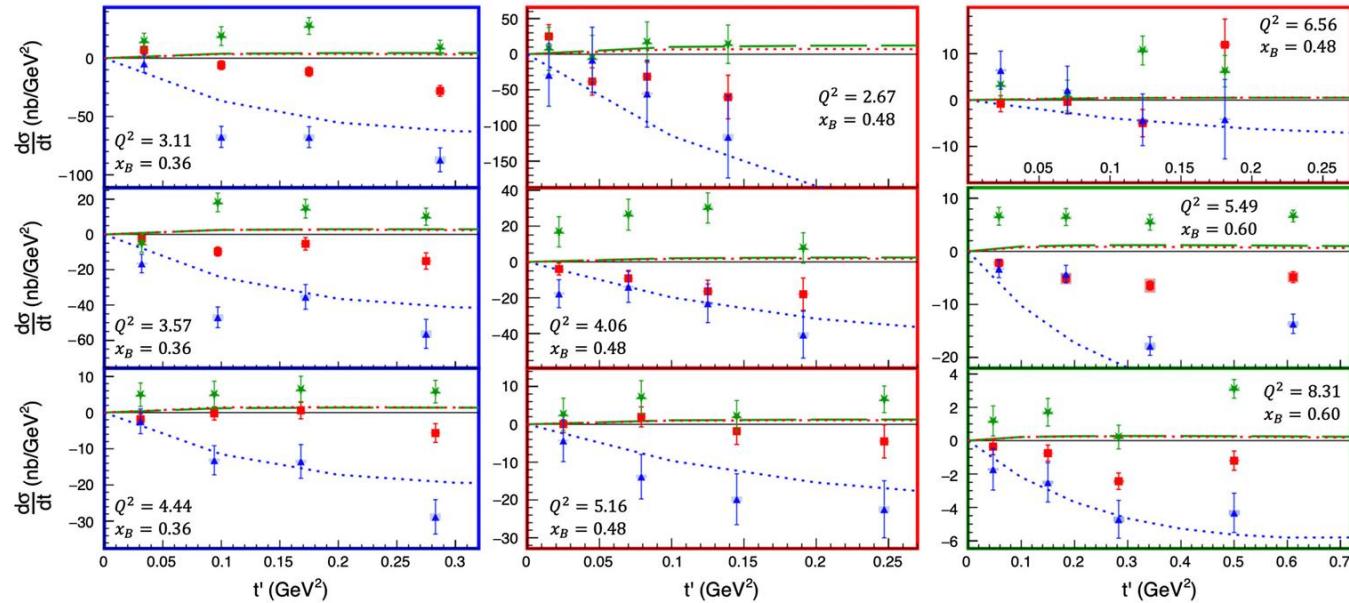
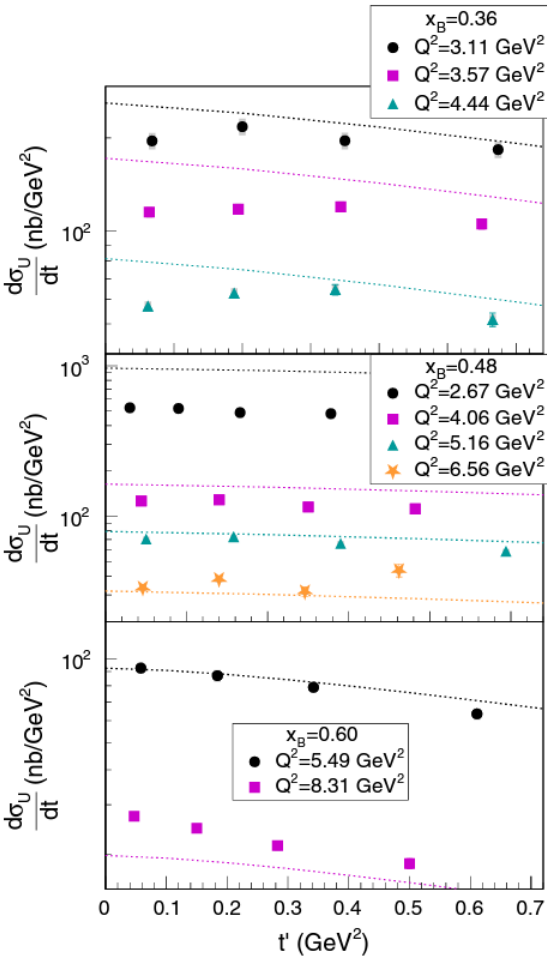
$$t' = t_{\min} - t$$

- Collinear factorization proven for  $\sigma_L$  (chiral-even GPDs)
- Modified factorization approach (model-dependent) for  $\sigma_T$  (chiral-odd/transversity GPDs)

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

$\epsilon$ : degree of longitudinal polarization  
 $h$ : helicity of the initial lepton

# Exclusive $\pi^0$ electroproduction: cross sections



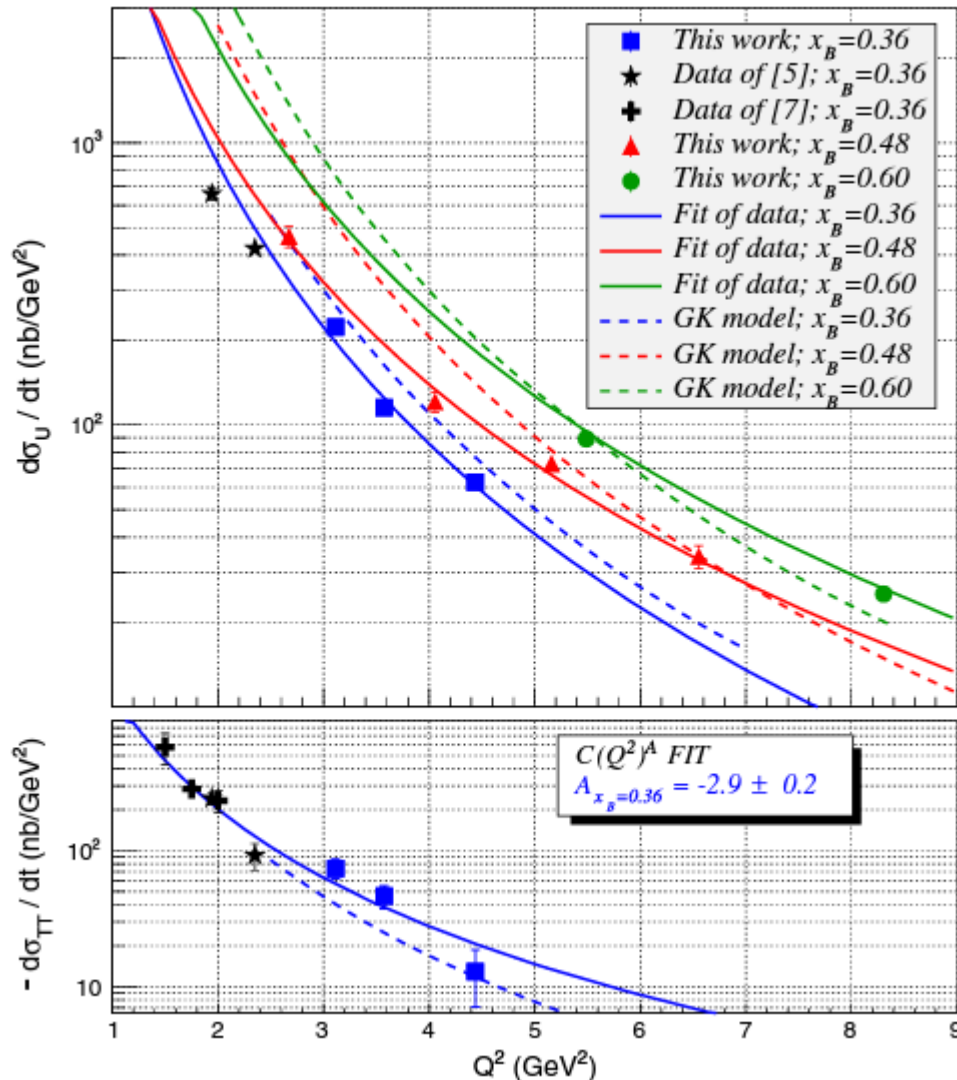
▲  $\sigma_{TT}$     ■  $\sigma_{TL}$     ★  $\sigma_{TL'}$

- $\sigma_{TT}$  larger than  $\sigma_{TL}$  and  $\sigma_{TL'}$ : indication of strong T component
- The modified factorization approach of the GK model (dotted lines) reproduce fairly well  $\sigma_{TT}$ .
- GK model underestimate  $\sigma_{TL}$  and  $\sigma_{TL'}$
- Reasonable agreement in  $\sigma_U = \sigma_T + \epsilon \sigma_L$

Strong evidence of  $\sigma_T$  dominance → access to transversity GPDs



# Exclusive $\pi^0$ electroproduction: $Q^2$ -dependence



QCD asymptotic limit:

- $\sigma_L \sim Q^{-6}$
- $\sigma_T \sim Q^{-8}$

Data shows (approx.):

- $\sigma_U = \sigma_T + \epsilon \sigma_L \sim Q^{-6}$

Model predicts (approx.):

- $\sigma_U = \sigma_T + \epsilon \sigma_L \sim Q^{-7}$

Model predicts a steeper  $Q^2$ -dependence than observed in the data

(additional hint of non-negligible  $\sigma_L$  component)

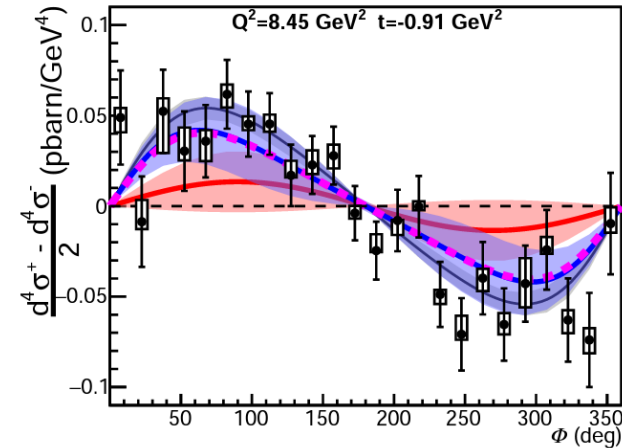
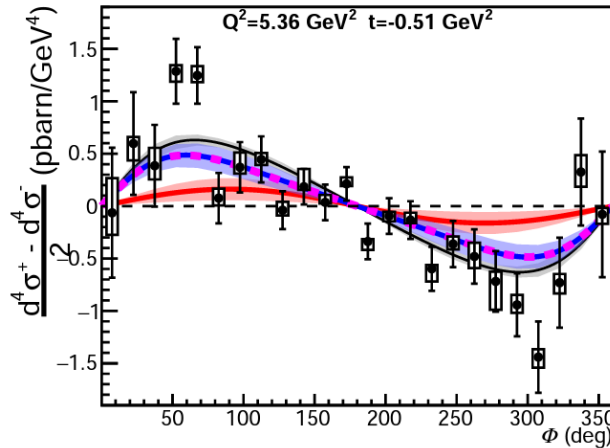
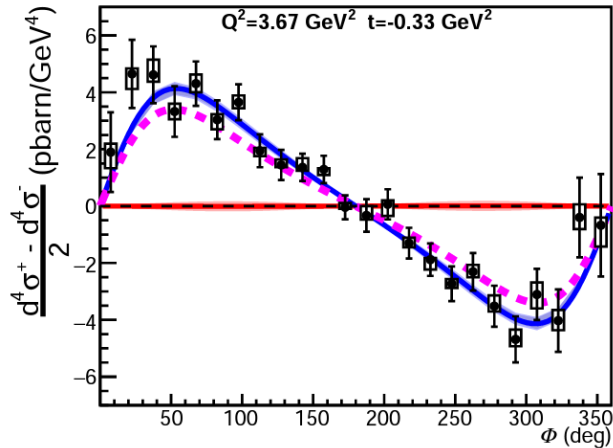
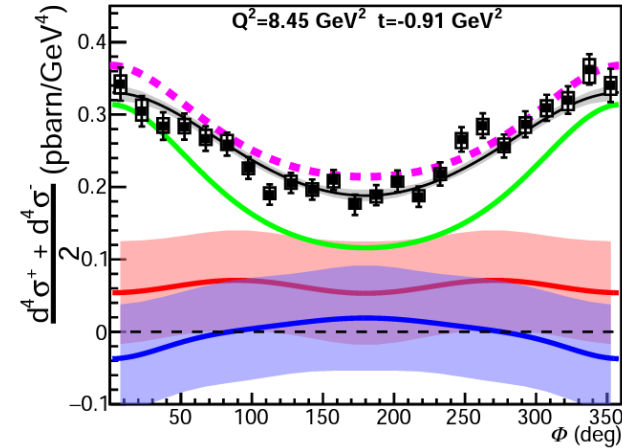
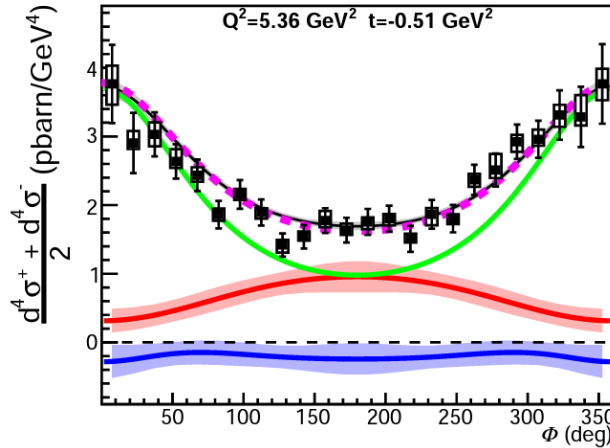
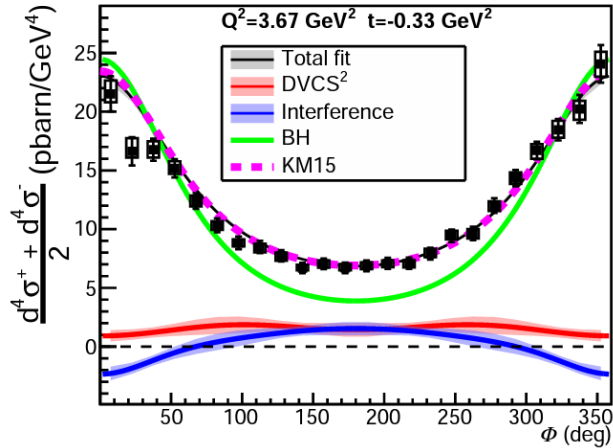
Need of an L/T separation (planned in Hall C with NPS)

# DVCS: cross sections

$x_B=0.36$

$x_B=0.48$

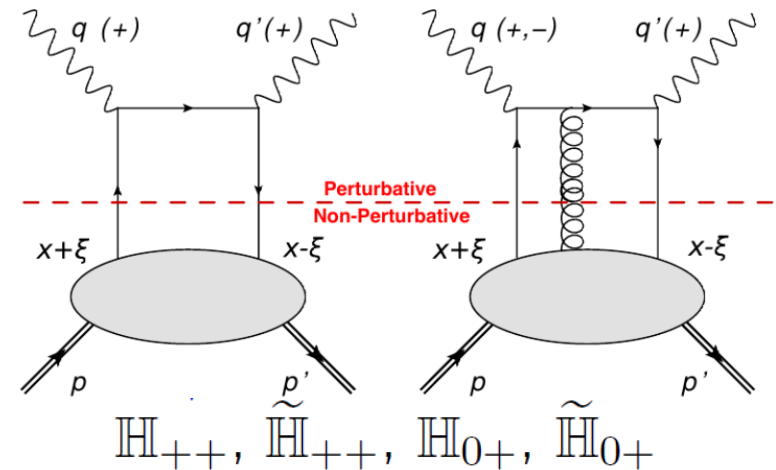
$x_B=0.60$



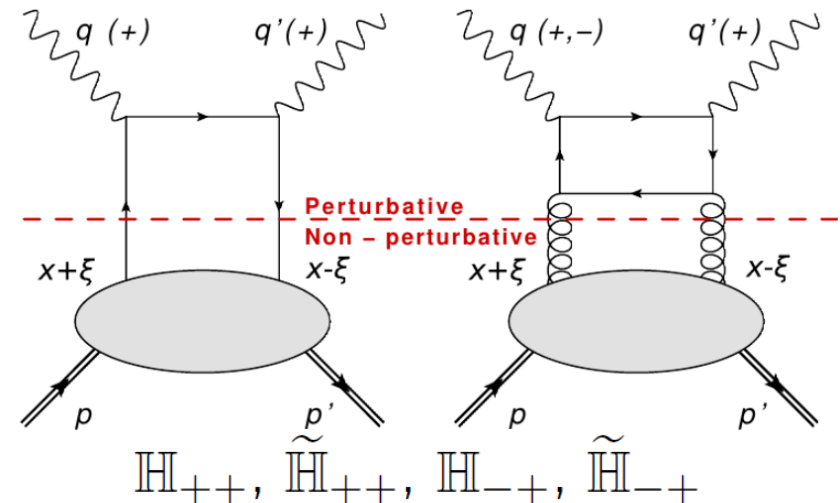
- Sample of dataset - multidimensional binning:  $3 x_B$  bins  $\times$  2-4  $Q^2$  bins  $\times$  3-5  $t$  bins  $\times$  24  $\phi$  bins
- More than 2000 data points in  $Q^2$ ,  $x_B$ ,  $t$  and  $\phi$

# DVCS cross sections: power corrections

- Braun et al. (2014) computed power corrections to DVCS  $\sim t/Q^2$  and  $\sim M^2/Q^2$
- These corrections proved to be necessary in JLab kinematics; see our previous results [Nat Commun 8, 1408 \(2017\)](#)
- These corrections require the introduction of helicity-flip (1 and 2 units) CFFs in addition to helicity-conserving CFFs

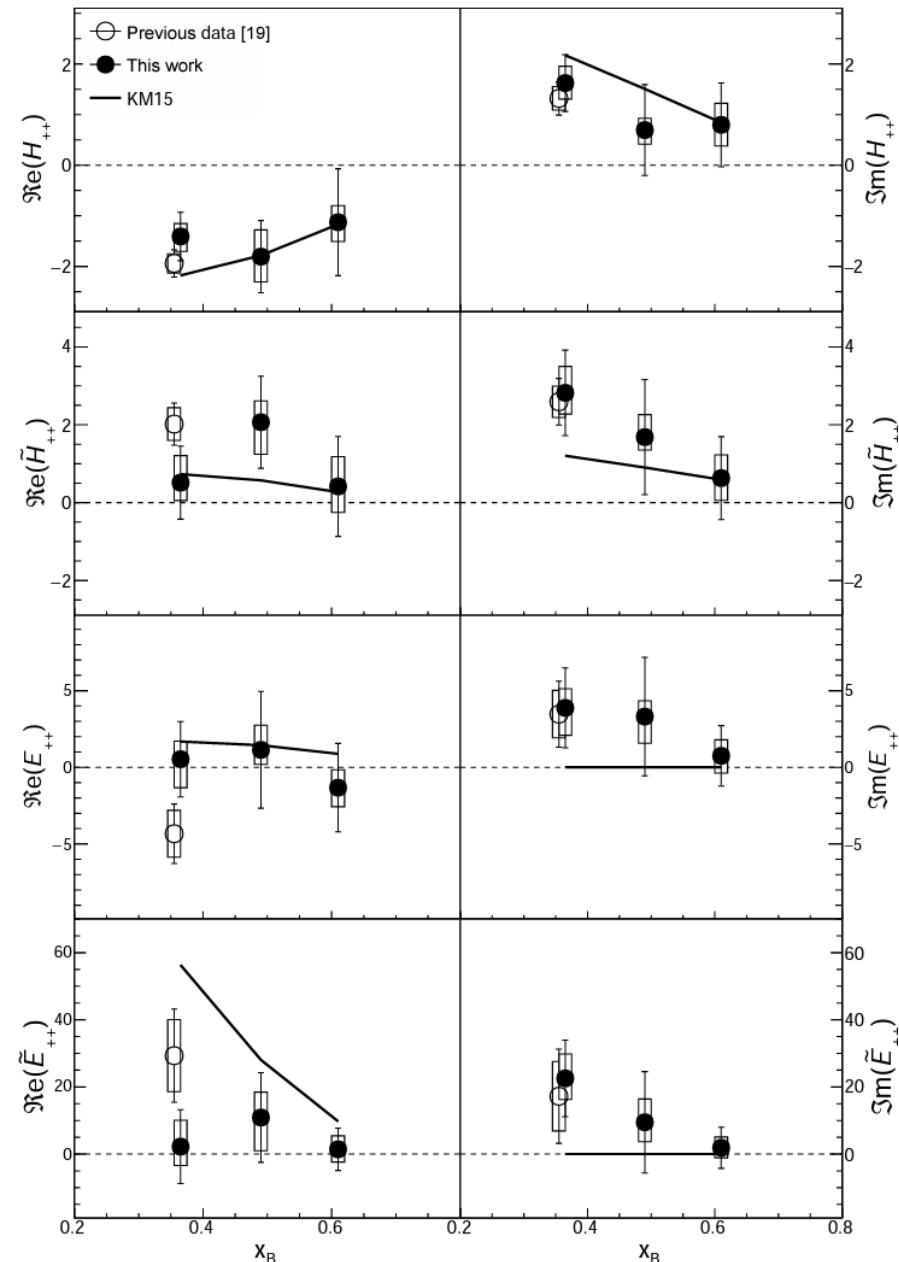


Helicity-flip (1 unit) CFFs  
Same  $Q^2$ -dependence as higher-twist



Helicity-flip (2 units) CFFs  
Same  $Q^2$ -dependence as NLO

# DVCS: Compton Form Factors



- Combined fit of all our data points
- All Compton Form Factors included (helicity-conserving and helicity-flip CFFs; a total of 24 parameters)
- First full extraction of Re and Im parts of  $H$ ,  $H$ -tilde,  $E$  &  $E$ -tilde CFF from data



# Summary and conclusion

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- E12-06-114 took half of its data in 2014-2016
- Two recent publications (1 PRL + 1 under review)
- Remaining beamtime will be collected in Hall C with NPS (>2023)

Thank you for your attention !