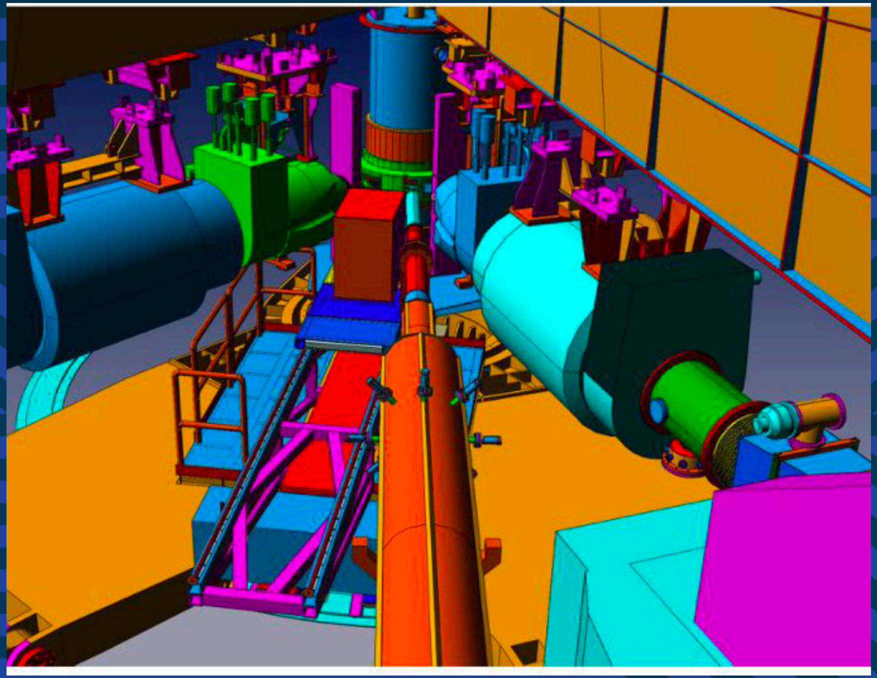

Deeply Virtual Compton and π^0 Electroproduction

Charles Hyde

For the E12-06-114, Collaboration

F. Georges *et al., Phys.Rev.Lett.* **128** (2022) #25, 252002

M. Dlamini *et al., Phys.Rev.Lett.* **127** (2021) #15, 152301

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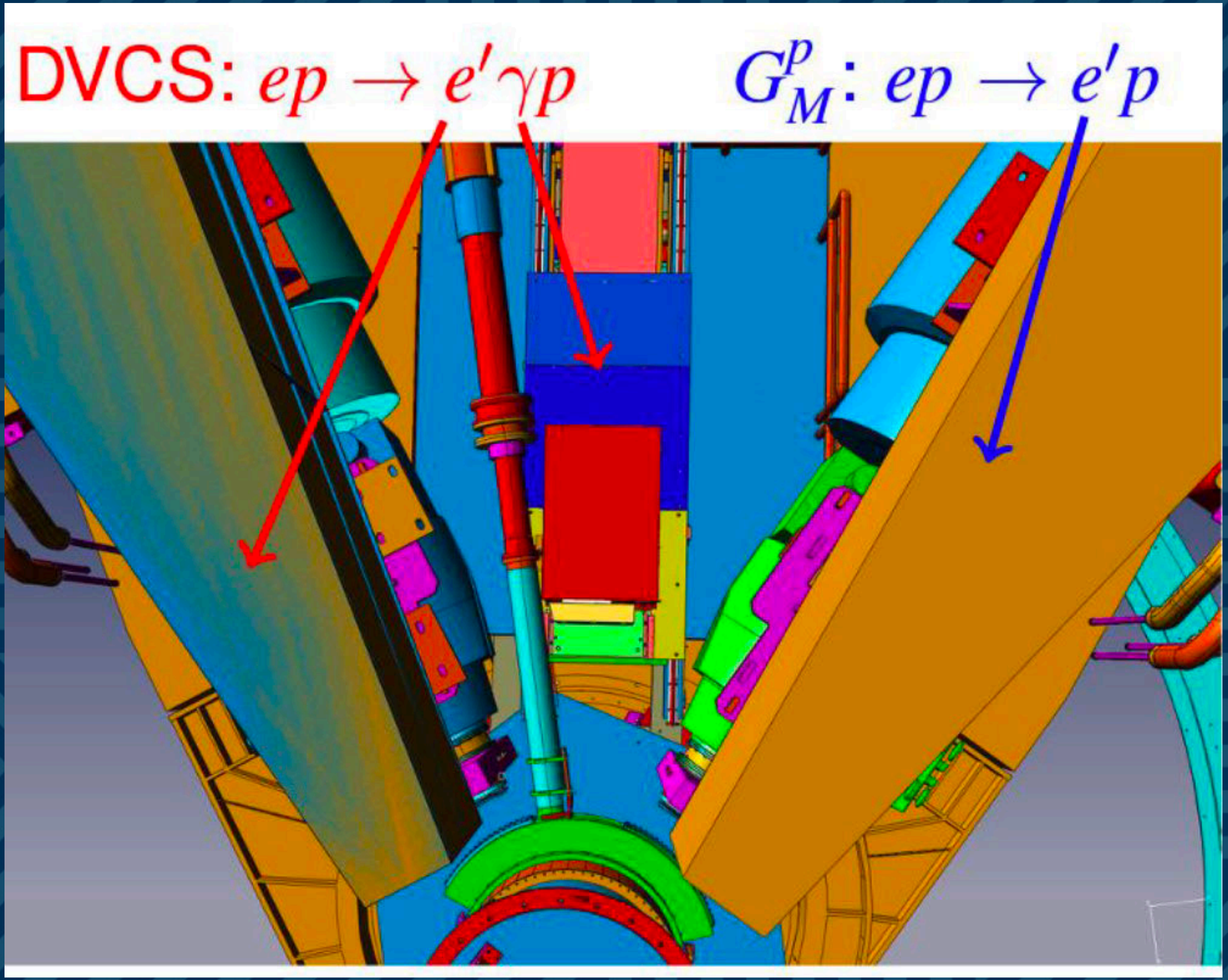
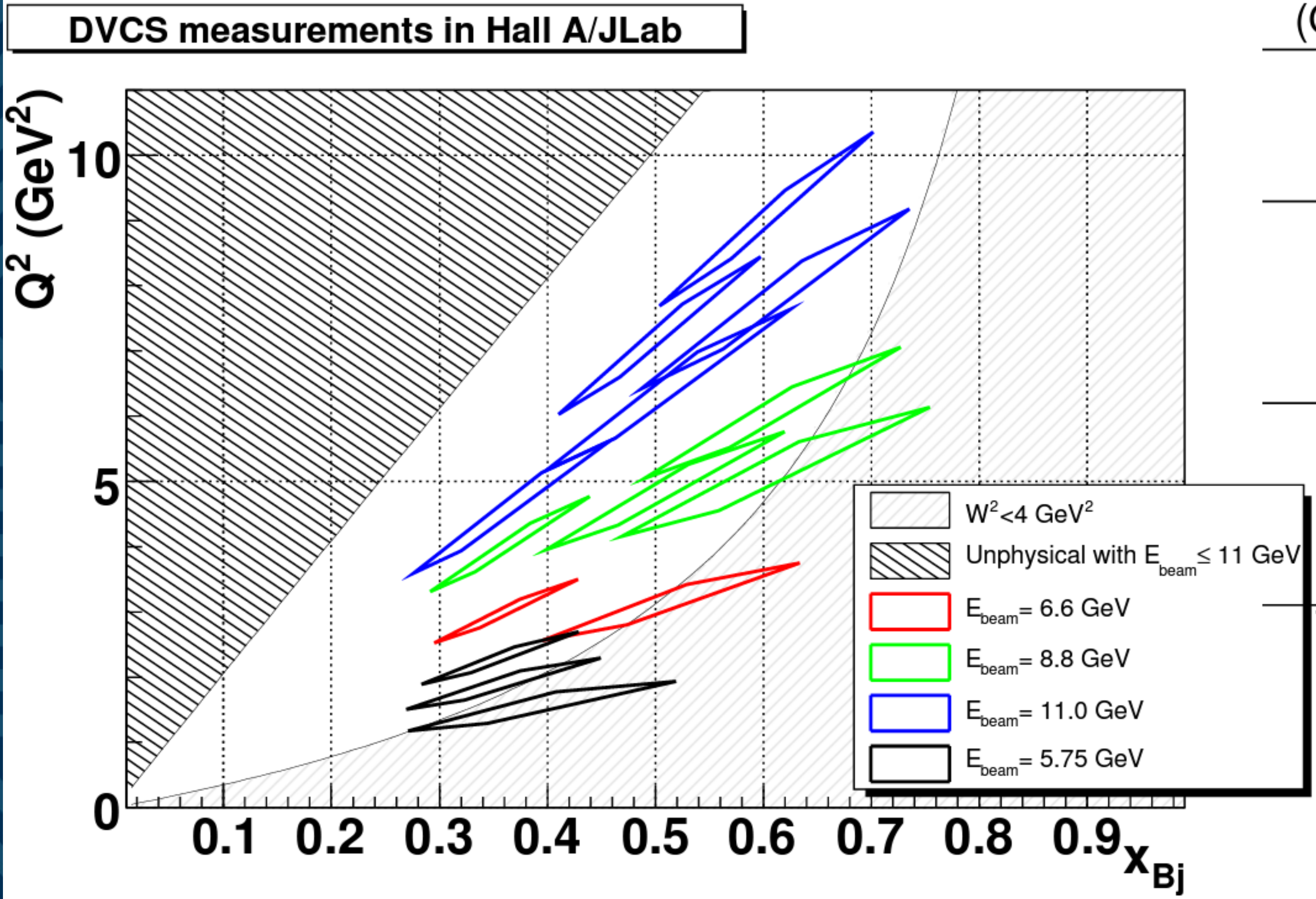
Hall A DVCS Experiment at 11 GeV: 2014-2016

- H(e,e’γ)p & H(e,e’π^0)p
- Cryogenic H_2 target
- Electron in HRS-L Spectrometer
  - Replace Q1 in middle of experiment
- PbF_2 calorimeter for gamma-rays
  - Cherenkov only, fast signals for pileup rejection.
  - 1 GHz Digitizer
- Exclusivity by missing mass
  - H(e,e’γ)X
  - H(e,e’$\gamma\gamma$)X



Kinematics and Beamtime (proposed)

JLab12 with 3, 4, 5 pass beam
(6.6, 8.8, 11.0 GeV beam energy)



Beam time (days)

Q^2 (GeV^2)	x_{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	26

88 days
250k events/setting

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

JLab Hall A DVCS, Actual Physics Run: 2014-2016

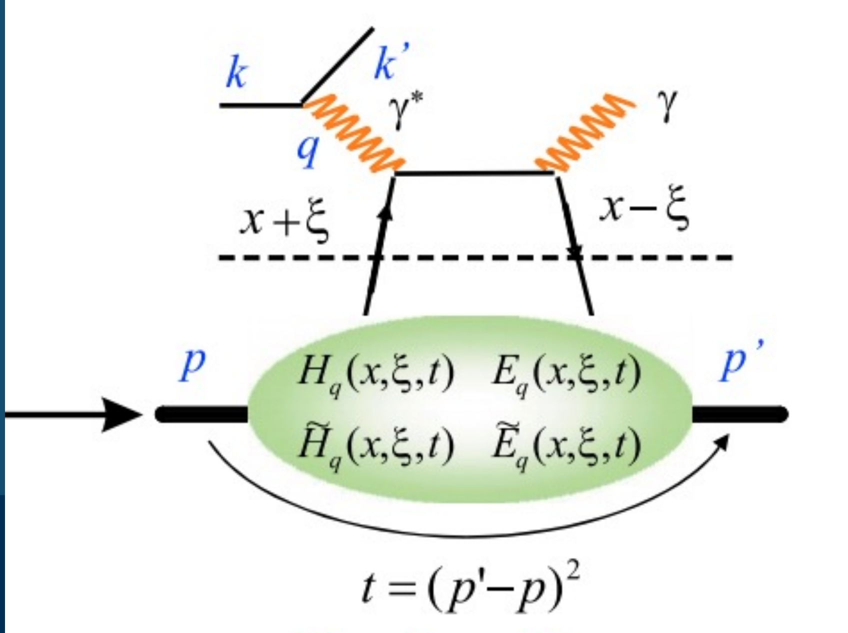
Setting	Kin-36-1	Kin-36-2	Kin-36-3	Kin-48-1	Kin-48-2	Kin-48-3	Kin-48-4	Kin-60-1	Kin-60-3
x_B	0.36			0.48				0.60	
E_b (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV^2)	3.20	3.60	4.47	2.70	4.37	5.33	6.90	5.54	8.40
E_γ (GeV)	4.7	5.2	6.5	2.8	4.7	5.7	7.5	4.6	7.1
$-t_{min}$ (GeV^2)	0.16	0.17	0.17	0.32	0.34	0.35	0.36	0.66	0.70
$\int Q\,dt$ (C)	1.2	1.7	1.3	2.2	2.2	3.7	5.7	6.4	18.5
# data bins	672			912				480	

E12-06-114, 50 “PAC days”

“Scaling” Predictions of Deep Virtual Exclusive Scattering

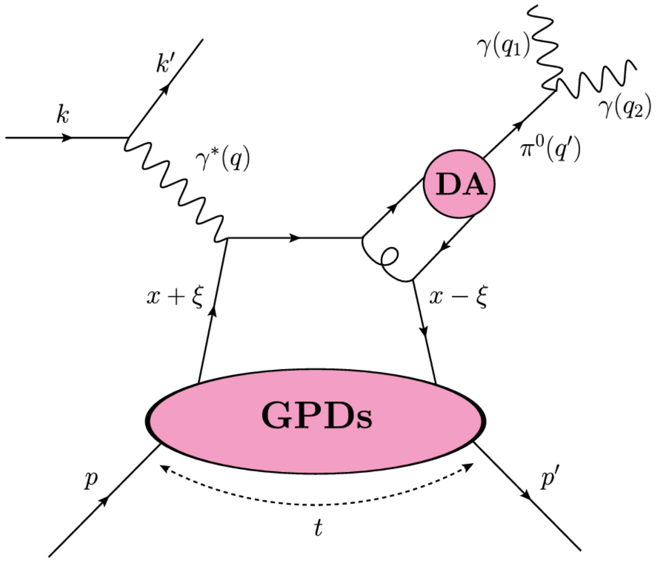
- The general $\gamma^*p \rightarrow \gamma p$ amplitude has 12 complex helicity amplitudes
  - At leading-twist there are just to just 4 complex helicity conserving amplitudes
  - QCD factorization implies Q^2-dependence follows combination of DGLAP & ERBL evolution in $\ln(Q^2)$
- DVCS should be dominated by “$d\sigma_T$”
- Deep π^0 should be dominated by “$d\sigma_L$”

Longitudinal & Transverse Momentum Coordinates



- DIS defines a unique light-cone direction from q^μ & P^μ
- DVCS coordinate system is ambiguous up to order t/Q^2
- Light-cone from
  - q^μ & P^μ DIS
  - $(q+q')^\mu$ & $(P+P')^\mu$ Symmetrized
  - q^μ & q'^μ V. Braun *et al.*

Deep Exclusive π^0 Production



Invariants

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

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

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

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

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

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

- Co-linear factorization proven for σ_L (chiral-even GPDs)
- Modified factorization approach (model-dependent) for σ_T (chiral-odd/transversity GPDs)

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

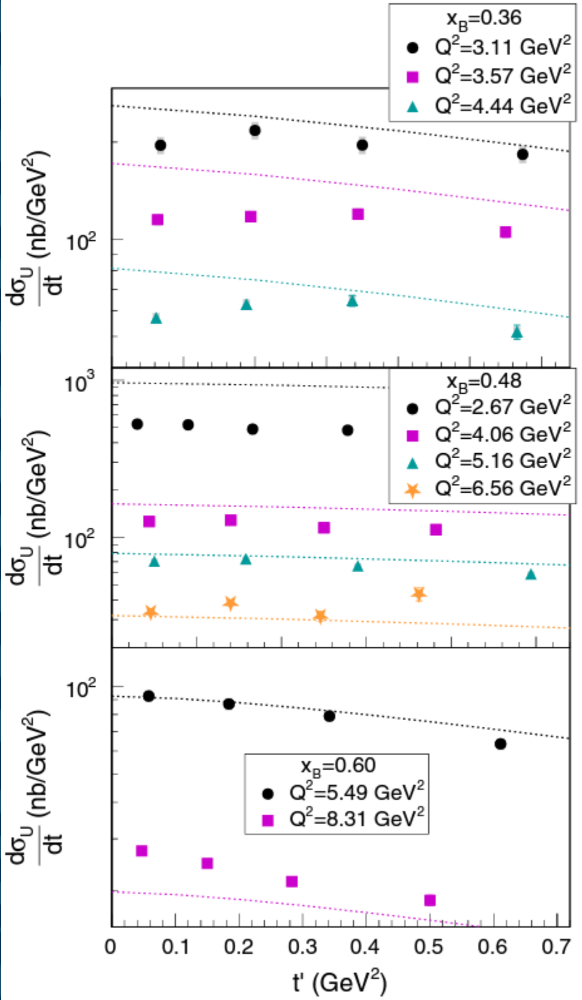
ϵ: degree of longitudinal polarization
h: helicity of the initial lepton

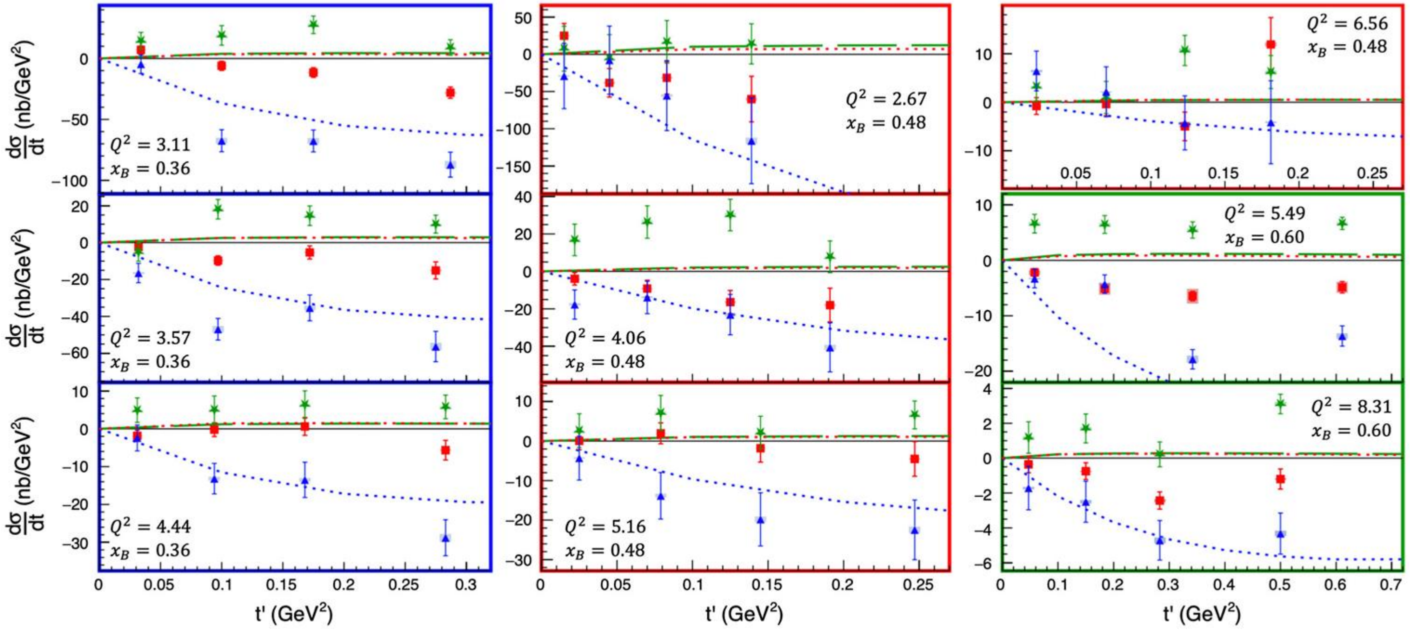
Deep Virtual π^0 Results

- Previous 6 GeV data
  - Hall A Rosenbluth-separation clearly identified $d\sigma_T >> d\sigma_L$
    - D(e,e'π^0)np: Mazouz et al *Phys.Rev.Lett.* 118 (2017) 22, 222002
    - H(e,e'π^0)p: Defurne et al., *Phys.Rev.Lett.* 117 (2016) 26, 262001
  - Similar conclusions from CLAS data, including both π^0, η (but without Rosenbluth separations)
- Dominance of Transversity GPDs$\otimes$[Twist-3 pion DA]
  - Amplitude induced by strong Chiral Symmetry Breaking
  - *Ahmad, Goldstein, Liuti, Phys.Rev.D* 79 (2009) 054014
  - *Goloskokov, Kroll, Eur.Phys.J.A* 47 (2011)

12 GeV Hall A H(e,e'π^0)p: cross sections

- M. Dlamini et al., PRL **127** (2021) 152301
- Evidence for σ_T dominance ➔ Transversity GPDs

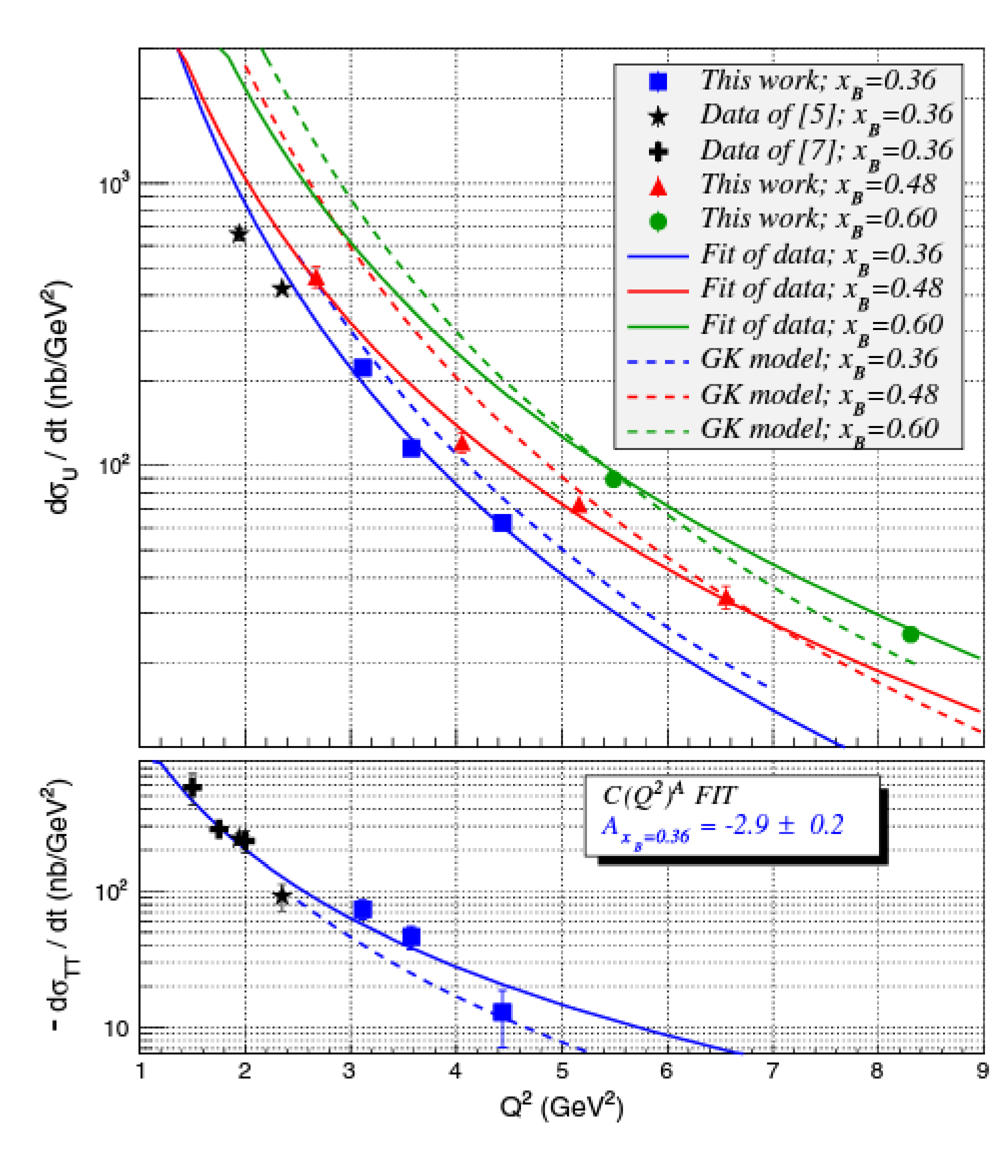




▲ σ_{TT} ■ σ_{TL} ★ $\sigma_{TL'}$

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

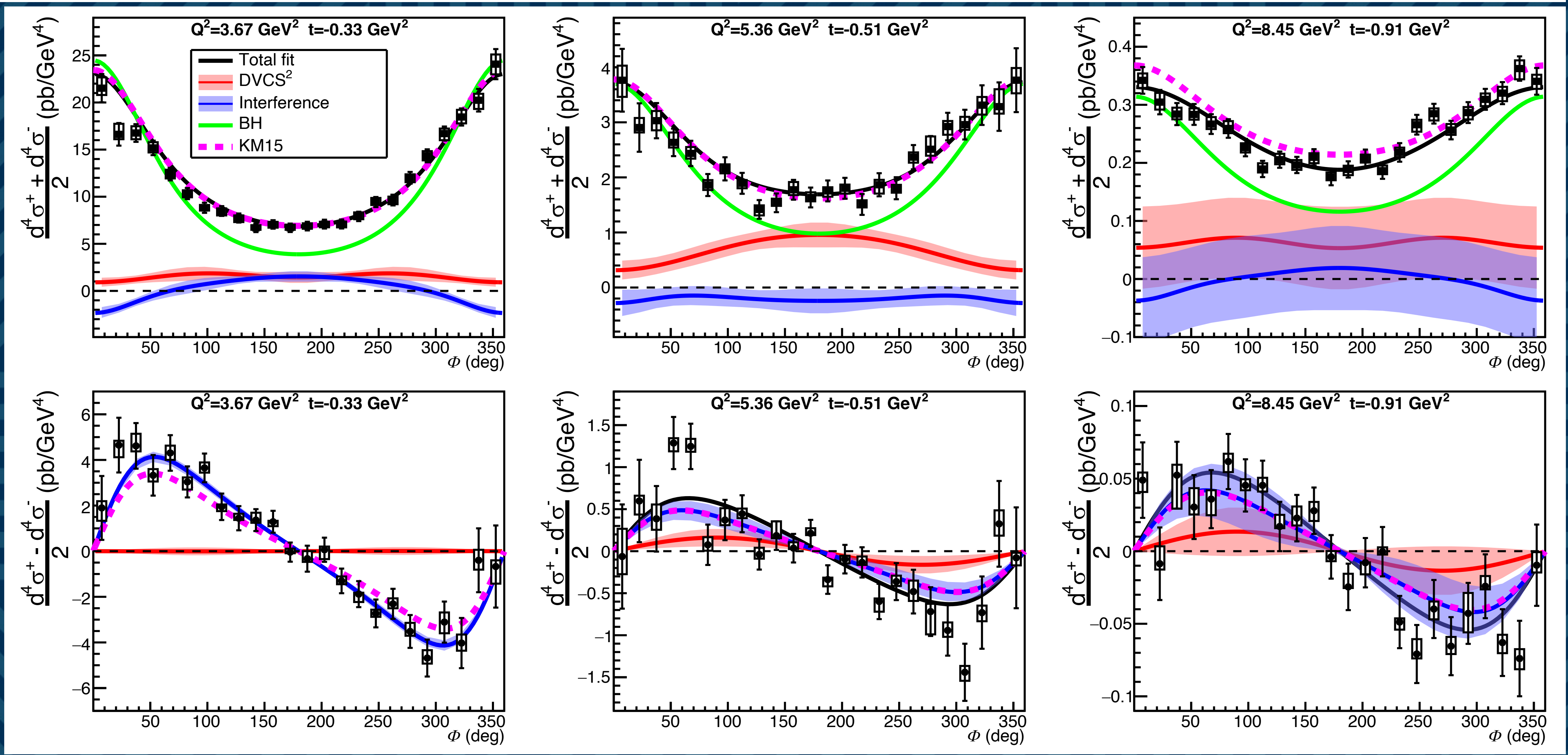
Exclusive π^0 Electroproduction: Q^2-Dependence



- QCD asymptotic limits
  - $d\sigma_L/dt \propto Q^{-6}$
    $d\sigma_T/dt \propto Q^{-8}$
- Data: $d\sigma_U = d\sigma_T + \varepsilon d\sigma_L \approx (Q^2)^{-3}$
- Goloskokov Kroll model
  - $d\sigma_U = d\sigma_T + \varepsilon d\sigma_L \approx Q^{-7}$
  - GK underestimating Long. Amplitude?
- NPS experiment coming this summer to Hall C
  - First 12 GeV π^0 Rosenbluth separations!

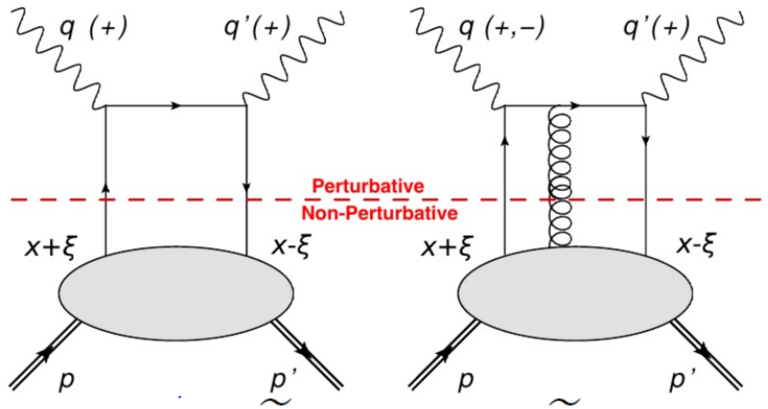
Example E12-06-114 DVCS Cross Sections

x_B=0.36, Q^2=3.7GeV^2, t=–0.33GeV^2; x_B=0.48, Q^2=5.4 GeV^2, t=–0.33 GeV^2; x_B=0.6, Q^2=8.4 GeV^2, t=–0.91 GeV^2



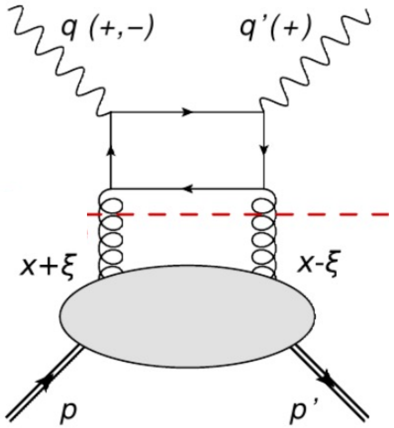
Braun, et al formalism

- Includes kinematic higher twist
- 12 complex CFFs
- $\mathbf{H}_{\lambda,\lambda'}$, $\widetilde{H}_{\lambda,\lambda'}$, $\mathbf{E}_{\lambda,\lambda'}$, $\tilde{\mathbf{E}}_{\lambda,\lambda'}$
  - **(λ,λ') = (+,+), (0,+), (–,+)**
- Each kinematic coefficient has different E_e, Q^2, x_B, t -dependence
- Our analysis:
  - At fixed (x_B,t) global fit to all 12 CFFs (neglecting QCD evolution)



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

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

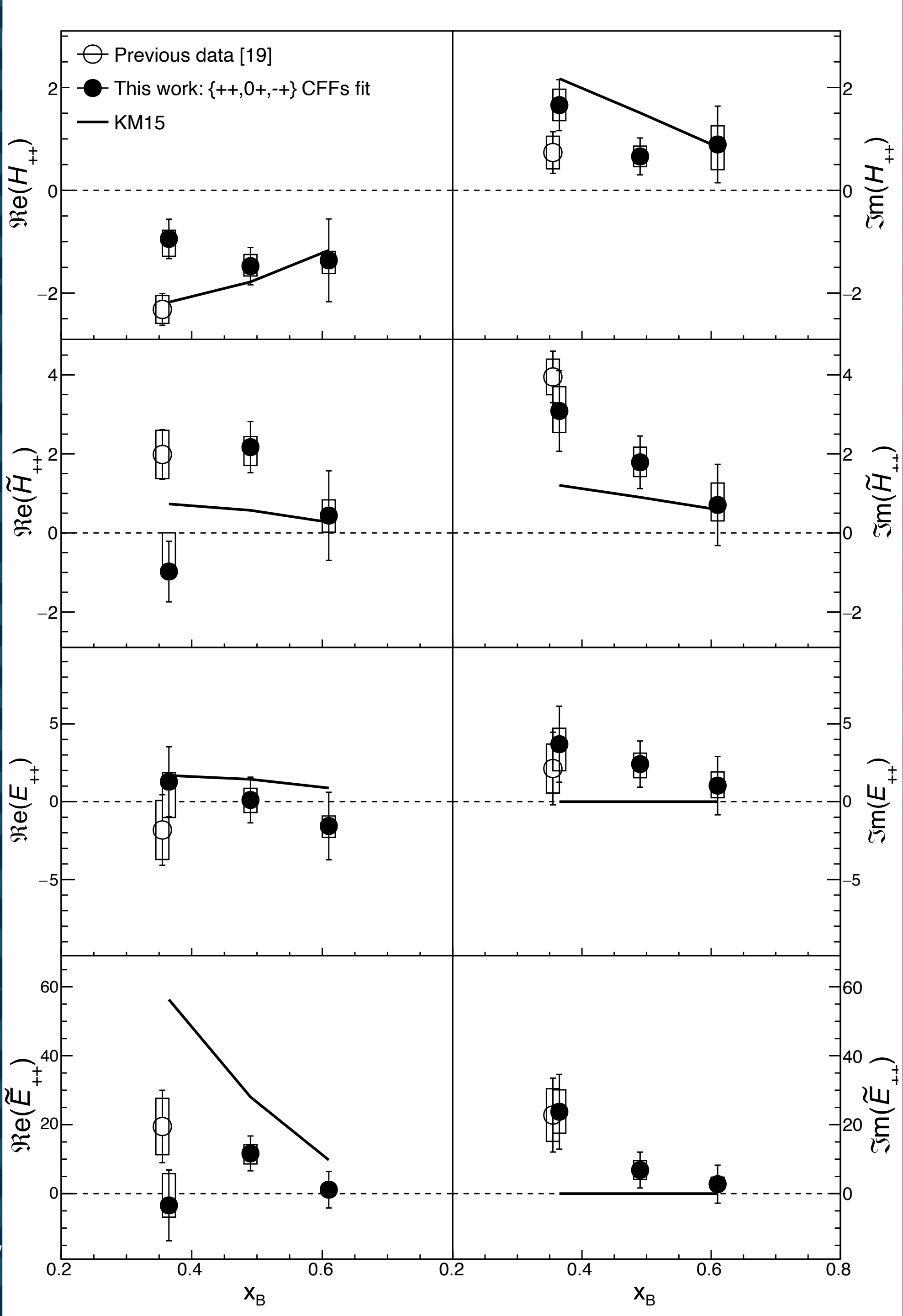


$\mathbb{H}_{-+}, \widetilde{\mathbb{H}}_{-+}$

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

CFF Extraction

- x_B-dependence of t-averaged results for Re & Im parts of all four helicity-conserving Compton Form Factors
- Helicity flip amplitudes included in fit, statistically consistent with zero, but necessary for realistic uncertainties.
- Im[**E**$_{++}$] and Im[**Ẽ**$_{++}$] arbitrarily 0 in Kumericki Mueller KM15 model



Conclusion and Outlook

- Realistic DVCS formalism essential for precision extraction of CFFs.
- 2023: Neutral Particle Spectrometer (NPS) DVCS run New $PbWO_4$ calorimeter: improved $M_X{}^2$ resolution
  - Sweep magnet to maintain low background in calorimeter
  - Higher momentum range of Hall C HMS and smaller angles for $PbWO_4$ allows access to full range of 12 GeV kinematics
- Multiple (2 or 3) incident beam energies at fixed (Q^2, x_B): E12-13-010
  - L/T separation of Deep Neutral Pion Production
  - Improved precision on extraction of Re/Im parts of CFF.
- Neutron DVCS/π^0 E12-22-006, approved by PAC-50, included in 2023-2024 run !
  - u/d-flavor separations

Thank you, and more slides

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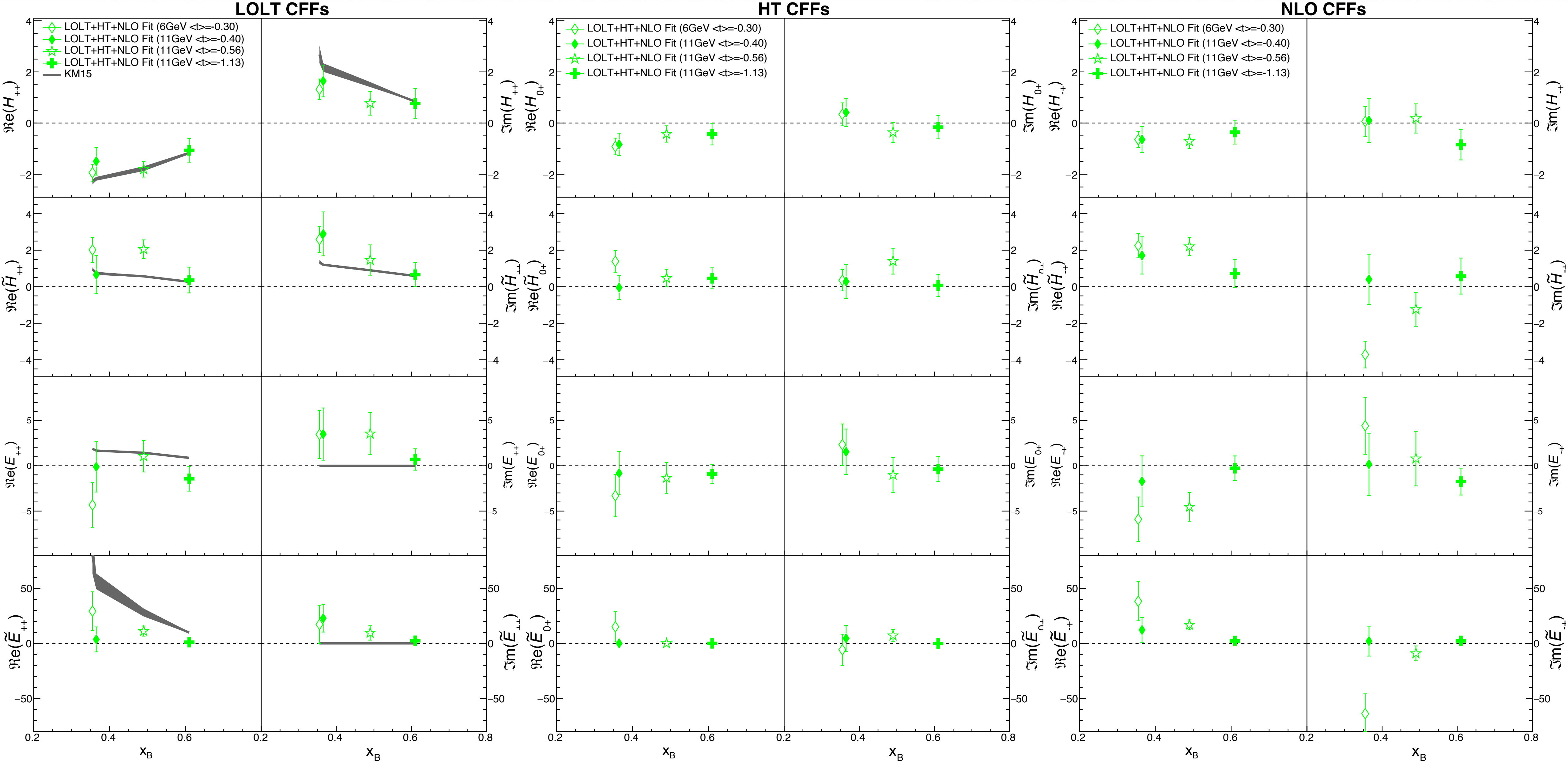
NPS DVCS $/\pi^0$

x_B	0.2				0.36						0.5			0.6			
Q^2 $(\text{GeV})^2$	2.0			3.0	3.0			4.0		5.5	3.4		4.8	5.1			6.0
E_b (GeV)	6.6	8.8	11		6.6	8.8	11	8.8	11		8.8	11		6.6	8.8	11	
k' (GeV)	1.3	3.5	5.7	3.0	2.2	4.4	6.6	2.9	5.1	2.9	5.2	7.4	5.9	2.1	4.3	6.5	5.7
θ_{Calo} (deg)	6.3	9.2	10.6	6.3	11.7	14.7	16.2	10.3	12.4	7.9	20.2	21.7	16.6	13.8	17.8	19.8	17.2
D_{Calo} (m)	6	4		6	3			4	3	4	3						
I_{beam} (μA)	11	5	50	11	28			50	28	50	28						
$\sigma_{M_X^2}$ (GeV^2)	0.17			0.22	0.13		0.12	0.15		0.19	0.09		0.11	0.09			
$-t_{min}$ (GeV^2)	0.04				0.16			0.17			0.37		0.39	0.65			0.67
$-t_{min}/(2\sigma_{M_X^2})$	0.1				0.6			0.55		0.4	2		1.7	3.6			3.7
LH_2 Days	1	1	1	1	1	2	1	1	3	5	3	2	5	5	1	5	10
LD_2 Days					1	2	1	1	3	5	3	2	5	5	1	5	10
					This Proposal: 44 days on LD_2												

TABLE I: Approved DVCS kinematics with NPS and an LH2 target (E12-13-010). The incident and scattered beam energies are k and k', respectively. The calorimeter is centered at the angle θ_{Calo}, which is set equal to the nominal virtual-photon direction. The front face of the calorimeter is at a distance D_{Calo} from the center of the target. The values of $-t_{min}/(2\sigma_{M_X^2})$ represent the minimal separation, in units of M_X^2 resolution, between the neutron and coherent deuteron DVCS signals in a M_X^2 spectrum. This value was about 0.4 in the previous E08-025 experiment.


LOLT CFFs
HT CFFs
NLO CFFs
LOLT+HT+NLO Fit (6GeV <t>=-0.30)
LOLT+HT+NLO Fit (11GeV <t>=-0.40)
LOLT+HT+NLO Fit (11GeV <t>=-0.56)
LOLT+HT+NLO Fit (11GeV <t>=-1.13)
KM15
x_B