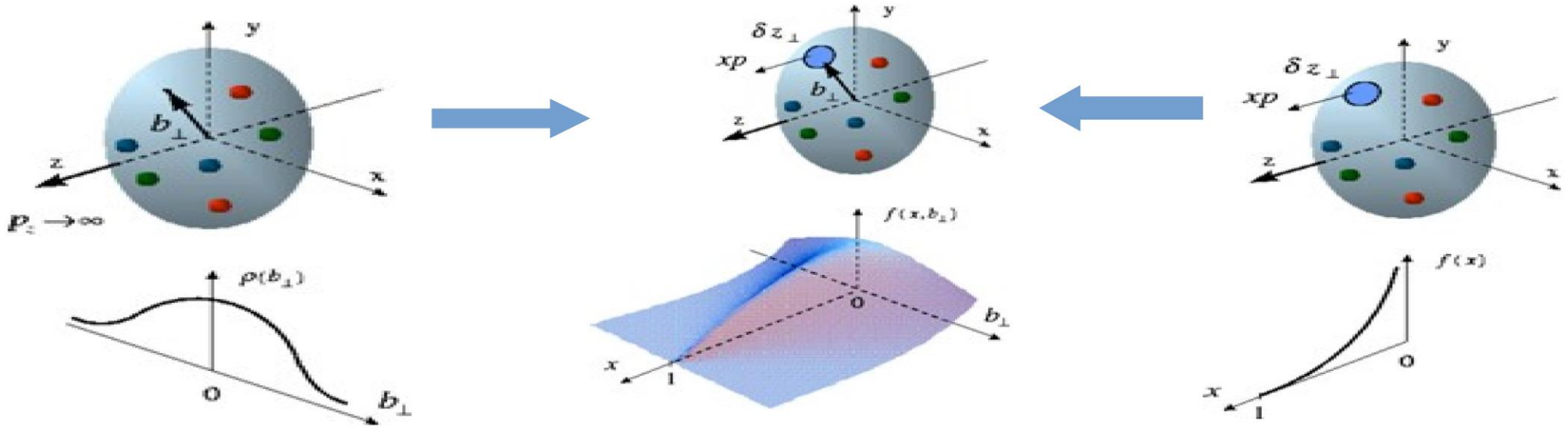
E12-06-114: DVCS/π^0 Results

Hall-A Winter Collaboration Meeting
January 21, 2021

Po-Ju Lin
CEA, Université Paris-Saclay & IJCLab – Orsay
on behalf of the DVCS collaboration

Picture of Nucleon



- **Form Factors (FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution

- **Generalized Parton Distributions (GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution

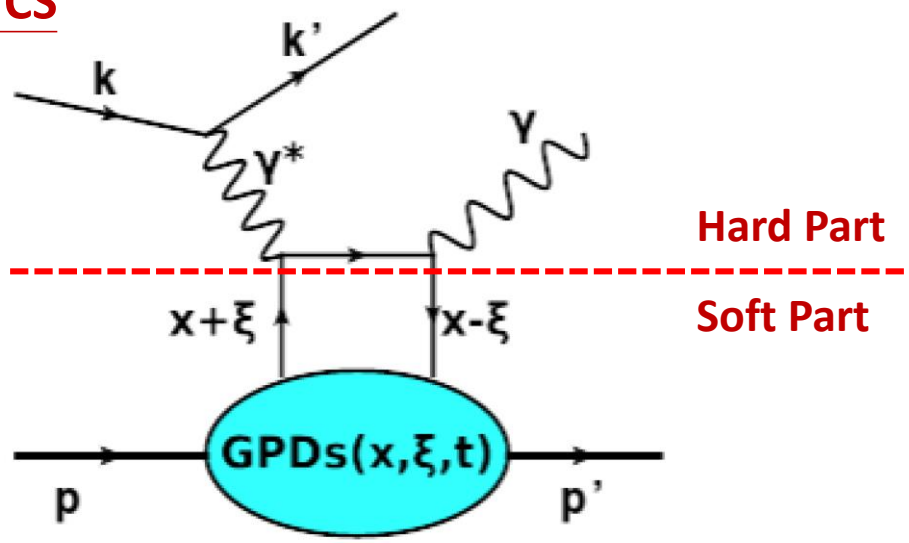
- **Parton Distribution Functions (PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

GPDs

- **Correlates the transverse position to the longitudinal momentum of the partons and thus provides a 3-D information of the nucleon.**
- **Accessible through exclusive processes.**

Factorization

DVCS



- The GPDs depend on the variables:

  x: average longitudinal momentum frac.

  ξ: longitudinal momentum diff. $\approx x_B/(2-x_B)$

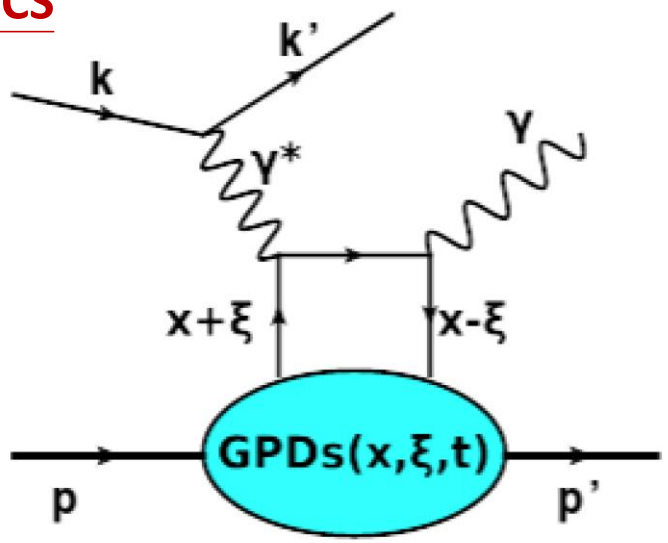
  t: four momentum transfer
  (correlated to $b_\perp$ via Fourier transform)

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

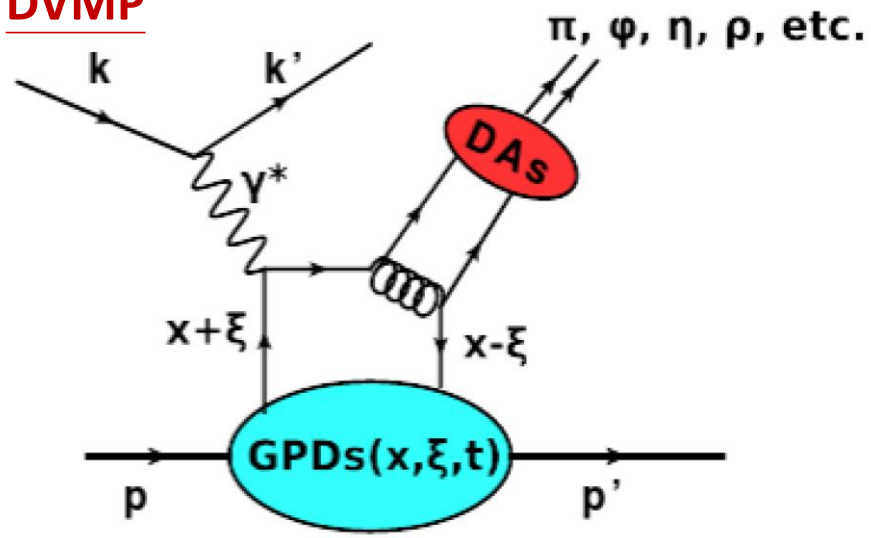
- Deeply Virtual Compton Scattering (DVCS)
  - Hard exclusive production of a single photon
- In Bjorken limit ($Q^2 \& \nu \to \infty$) at fixed x_B
  - Hard Part: Calculable perturbatively
  - Soft Part: Nucleon structure parameterized by GPDs
- The minimum Q^2 at which factorization holds shall be tested through experiments

Deep Exclusive Processes

DVCS



DVMP



4 chiral-even GPDs: helicity of parton unchanged

$H^q(x, \xi, t)$	$E^q(x, \xi, t)$
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$

via **DVCS** **DVMP**

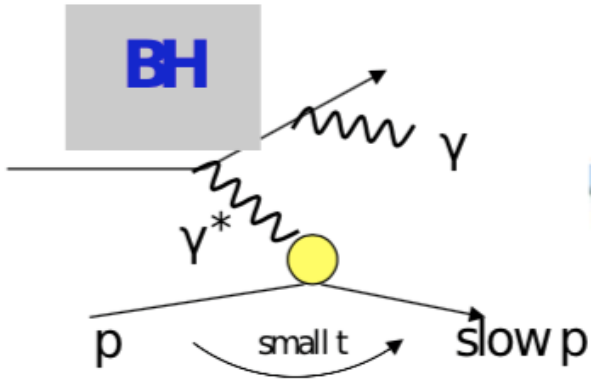
+ 4 chiral-odd (transversity) GPDs: helicity of parton changed

$H_T^q(x, \xi, t)$	$E_T^q(x, \xi, t)$
$\tilde{H}_T^q(x, \xi, t)$	$\tilde{E}_T^q(x, \xi, t)$

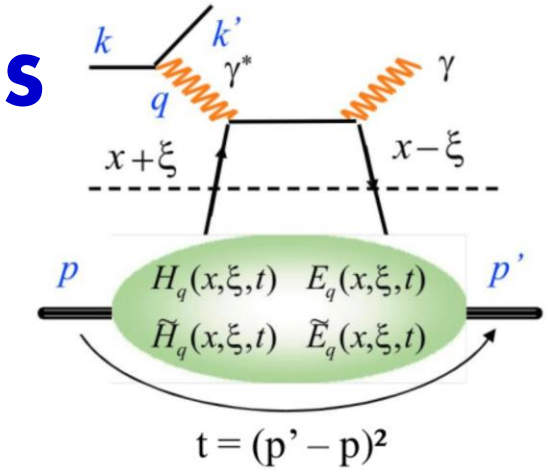
via **DVMP**

- **DVCS**
  - Golden channel, simple and clean final state
- **Deeply Virtual Meson Production (DVMP)**
  - Ability to probe the chiral-odd GPDs
  - Additional non-perturbative term from meson distribution amplitude

DVCS



DVCS



$$\frac{d^4\sigma(\ell p \to \ell p\gamma)}{dx_B dQ^2 d|t| d\phi} = \underbrace{d\sigma^{BH}}_{\text{Well known}} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell\, \mathrm{Im}\, I\right)$$

Bethe-Heitler

DVCS

Bilinear combination of GPDs

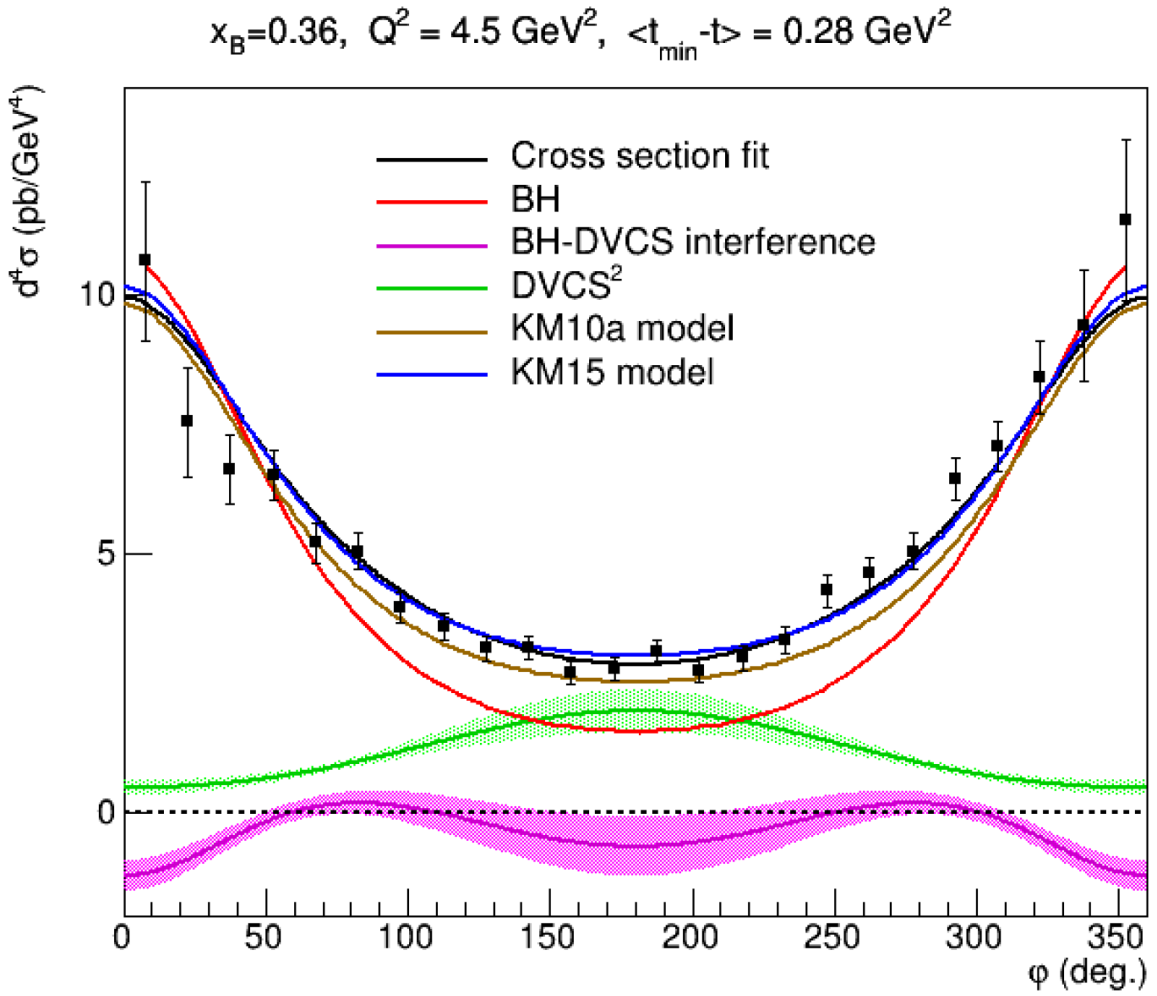
Interference

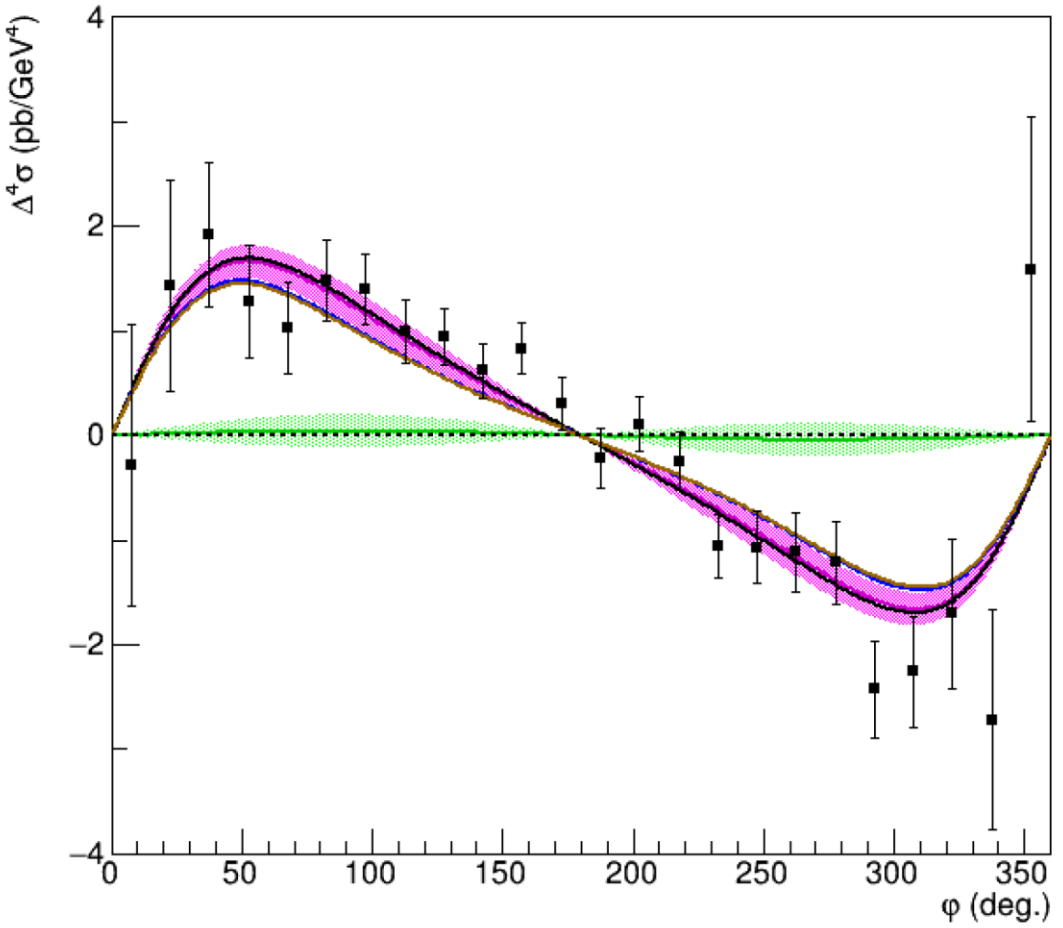
Linear combination of GPDs with FFs

- P_l : Beam or target polarization
- e_l : Lepton beam charge

DVCS – Results of the JLab 12 Experiment to Be Published

K. Kumericki and D. Muller EPJ Web of conference 112, 2015
K. Kumericki, S. Liuti, and H. Moutarde Eur. Phys. J. A. 52, 2016





➢ Results ready, paper drafting will be finalized soon.

Exclusive π^0 Production

e p → e π^0 p

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

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

- Factorization proven only for σ_L, which depends on chiral-even GPDs only
- At sufficiently high Q^2, expect $\sigma_L \propto Q^{-6}$ while σ_T asymptotically suppressed and $\propto Q^{-8}$ → σ_L dominance
- Previous experiments with limited reach in Q^2 show dominance of σ_T
- Modeling of σ_T → coupling between transversity GPDs and twist-3 pion amplitude

Exclusive π^0 Production

e p → e π^0 p

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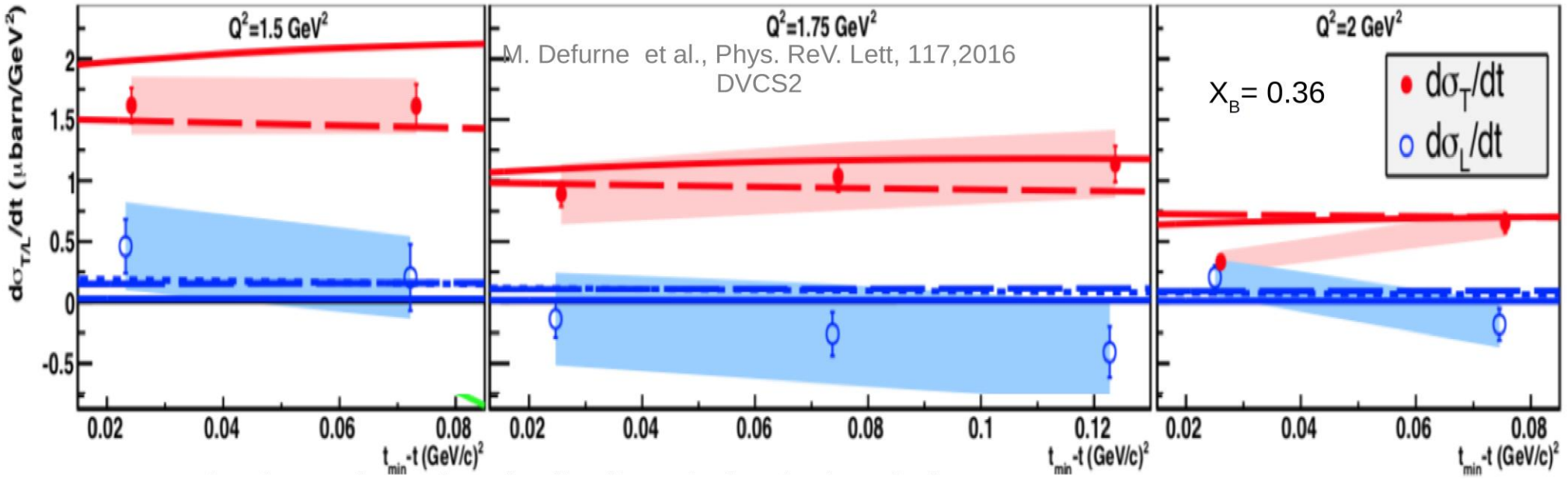


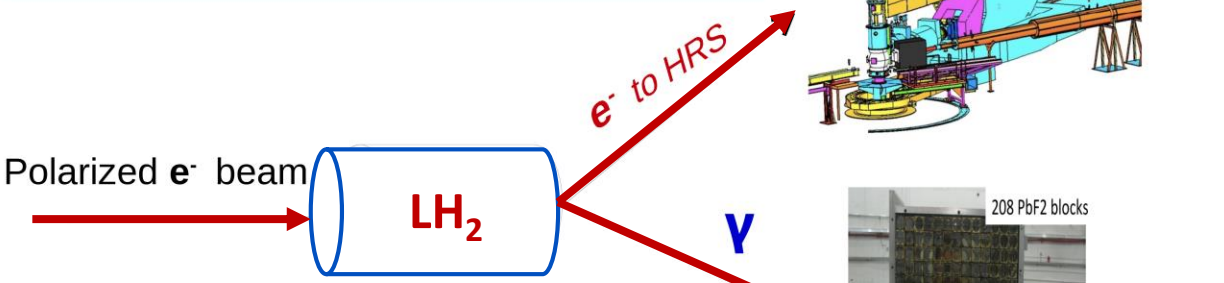
S. V. Goloskokov and P. Kroll, Eur. Phys. J. C65:137 (2010)

G. R. Goldstein, J. O. Hernandez, S. Liuti, Phys. Rev. D84 (2011)

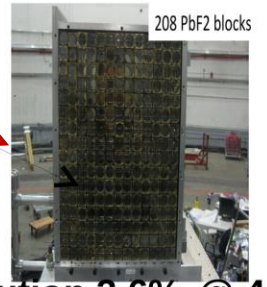
Setup and Data Taken

DVCS $ep \rightarrow ep\gamma$

π^0 production $ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$

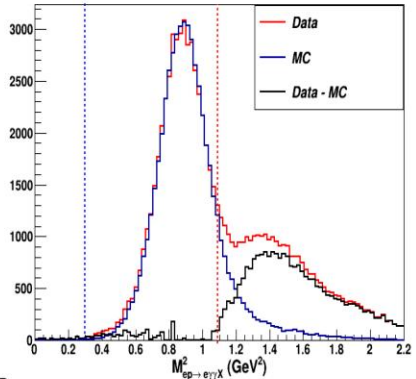


δP/P Resolution 10^{-4} @ 4.3 GeV

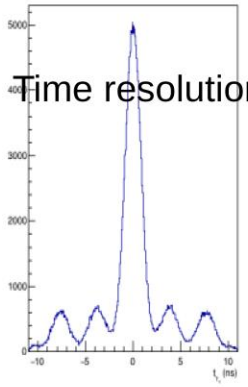


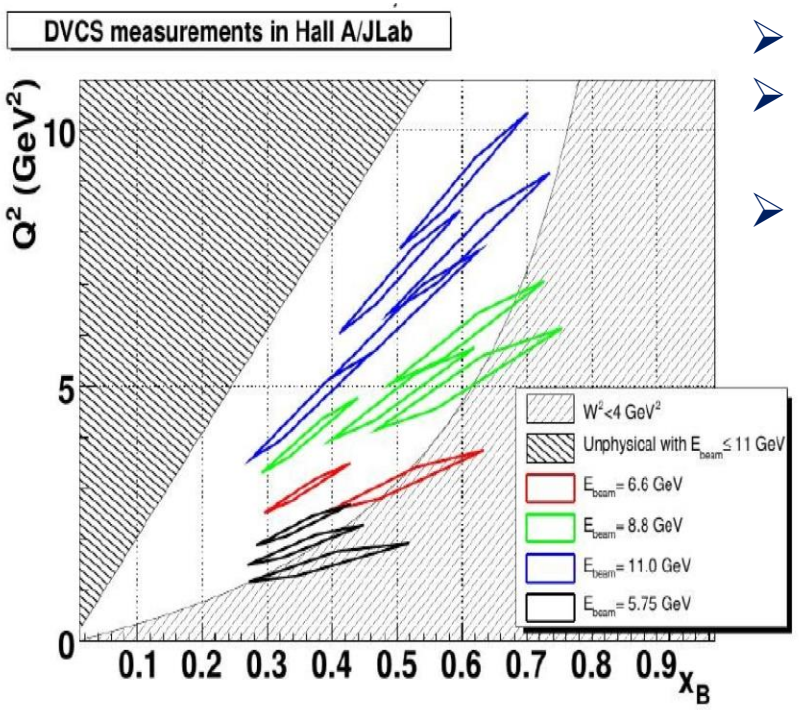
E resolution 3.6% @ 4.2 GeV

Recoil proton (missing mass)



$$M^2_{ep\to e'\gamma\gamma X} = (e + p - e' - \gamma_1 - \gamma)^2_2$$



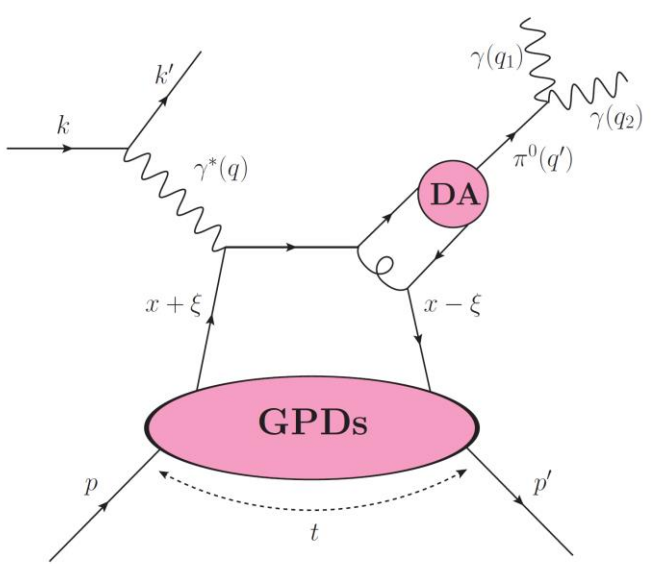


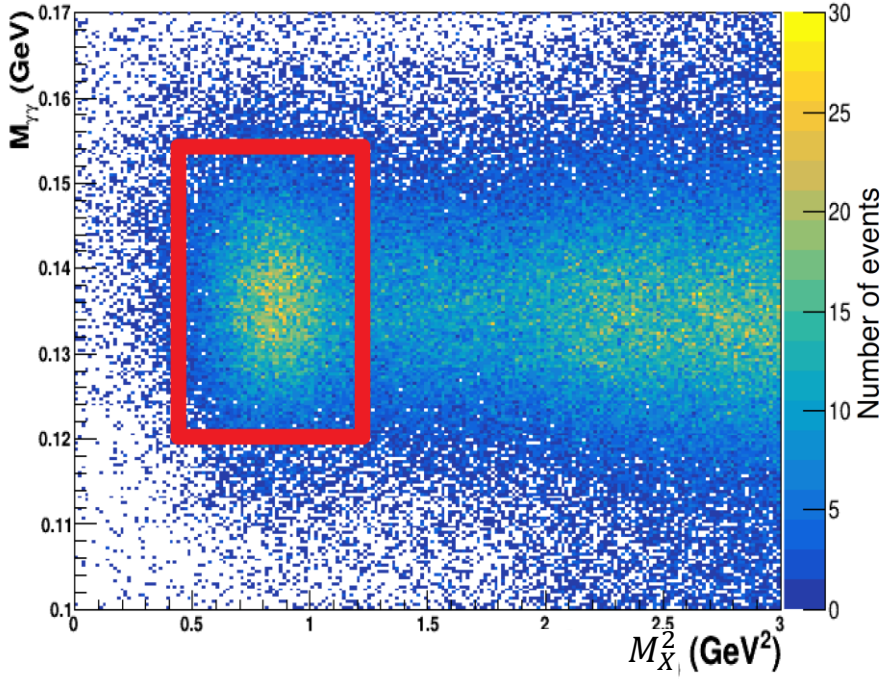
- Ran in 2014 & 2016
- ~50% of allocated 100 PAC days
- Missing PAC days reallocated in Hall C

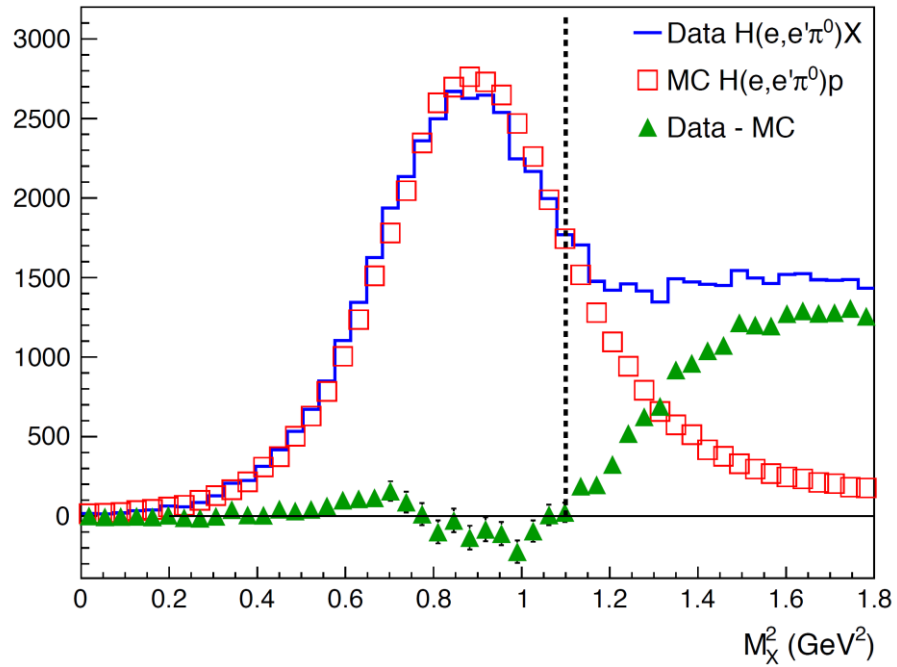
- Average values of kinematic variables of the 9 settings of this work

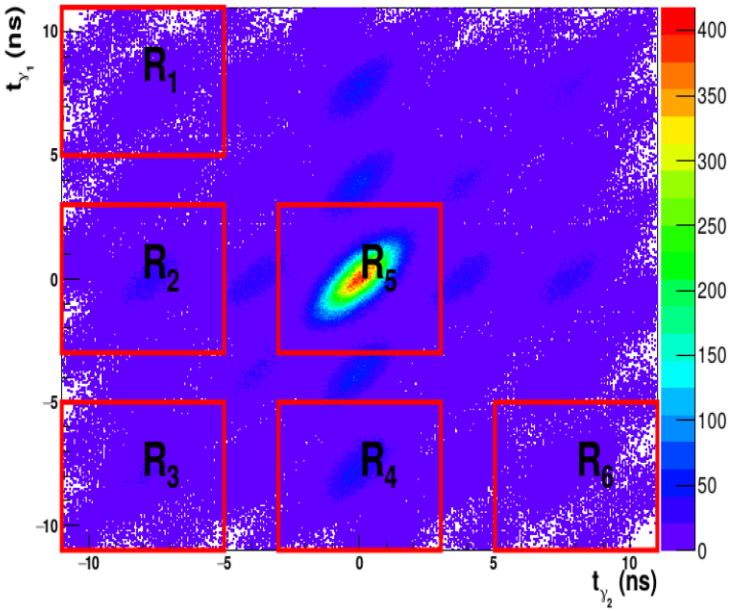
x_B-label	0.36			0.48				0.60	
$\langle x_B \rangle$	0.36	0.36	0.36	0.48	0.45	0.46	0.46	0.59	0.60
E (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV^2)	3.11	3.57	4.44	2.67	4.06	5.16	6.56	5.49	8.31

Exclusive π^0 Event Selection





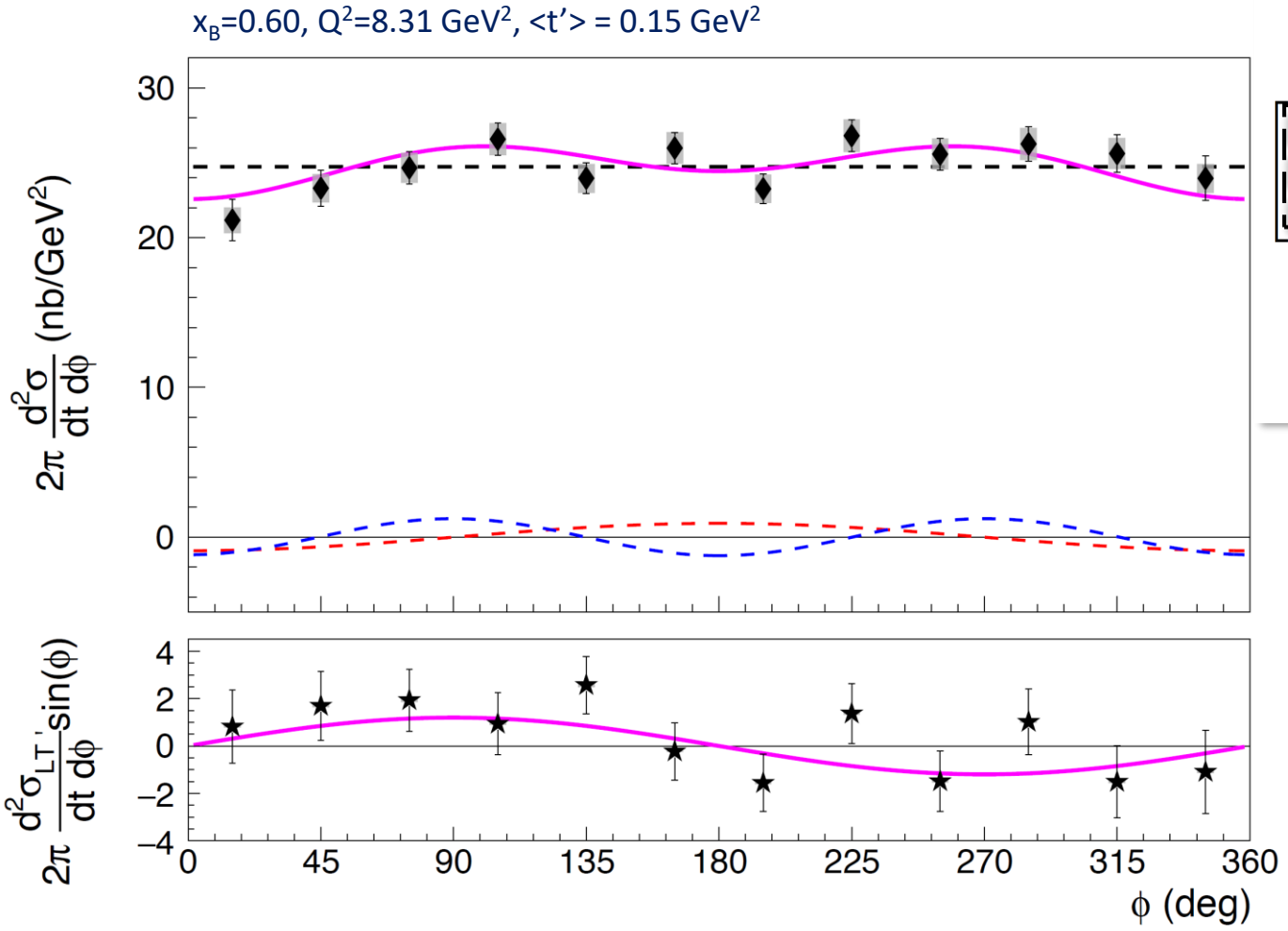




- π^0 events → select events with invariant mass $m_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$ around the π^0 mass
- Exclusivity → remove the M_X^2 contribution from inclusive channels, threshold ≈ 1.15 GeV^2
- Main background: accidentals. The backgound in the signal coincidence window, [-3,3] ns, is estimated via other time windows.

Cross-section Extraction

e p → e π^0 p

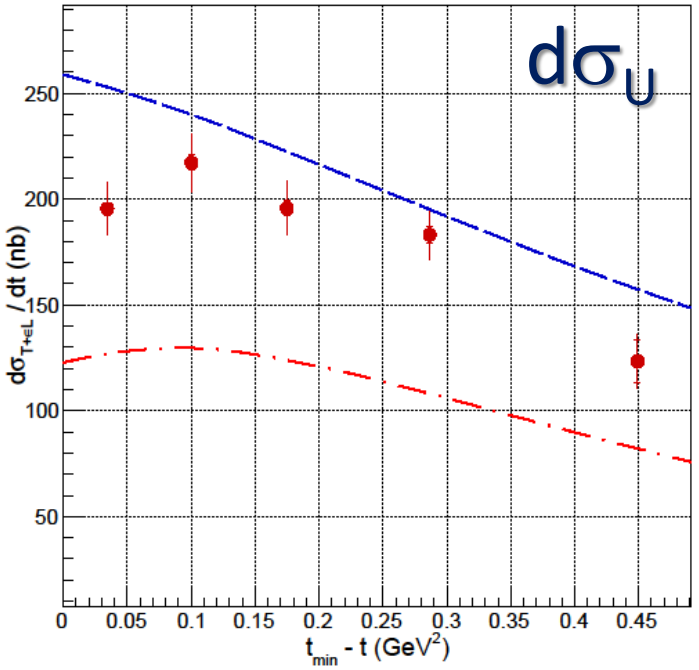


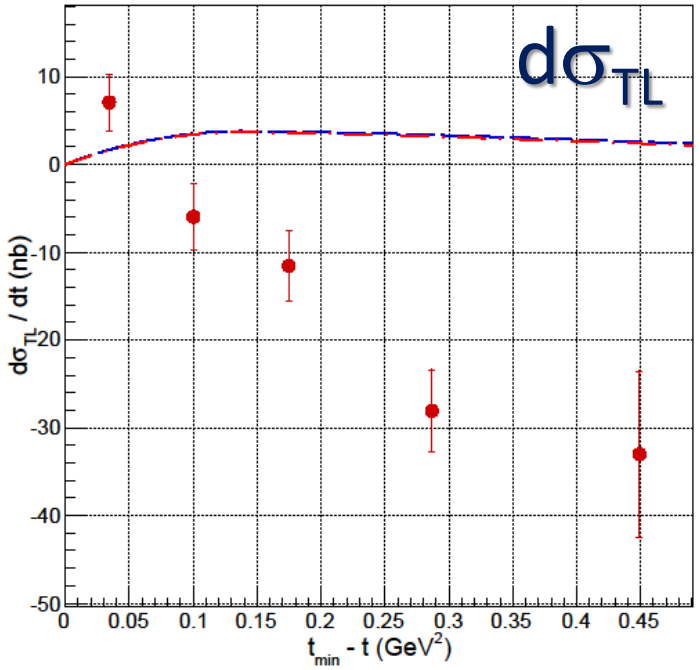
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\frac{d^2\,\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E)$$
$$\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)\right.$$
$$\left. + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin(\phi)\righ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

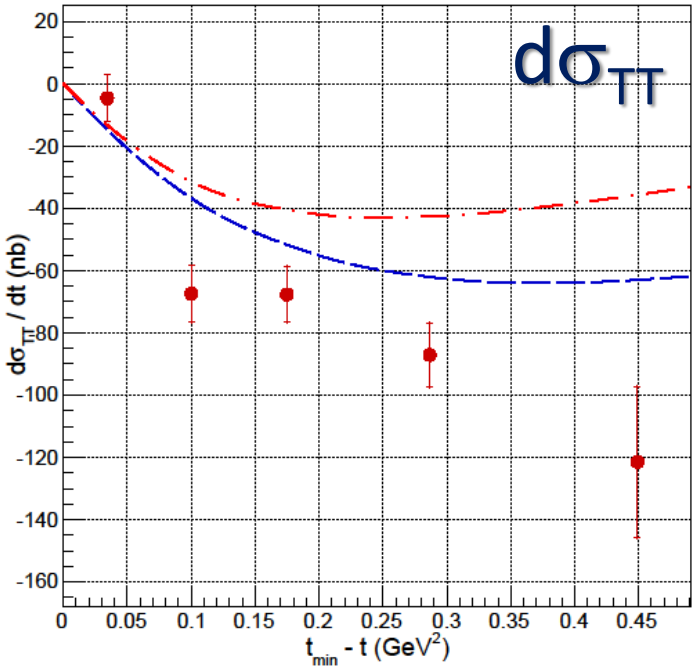
- Cross-sections extracted for all 9 kinematic settings
- Extract different terms via their corresponding ϕ dependence
- $d\sigma_T$ and $d\sigma_L$ can't be seperated, extracted as $d\sigma_U = d\sigma_T + \varepsilon d\sigma_L$
- Main systematic errors come from deviation observed in DIS events and the exclusivity cuts

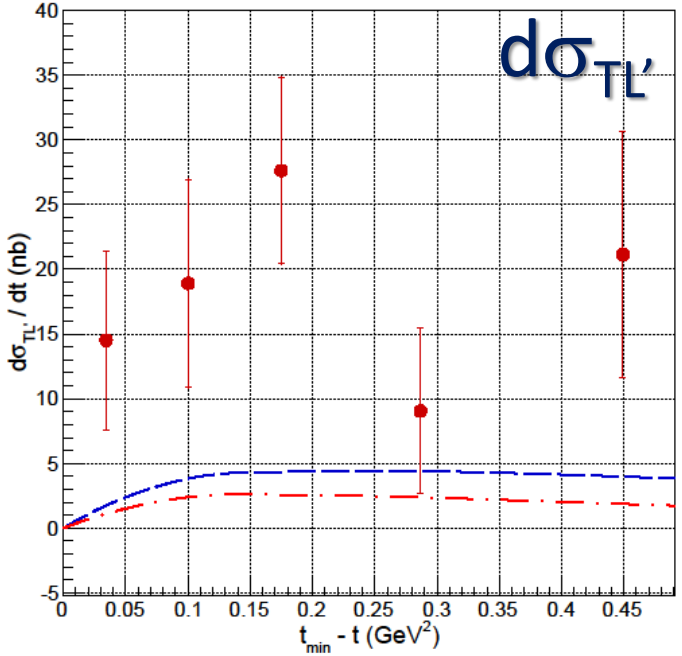
Cross-sections

- x_B=0.36, Q^2=3.11 GeV^2









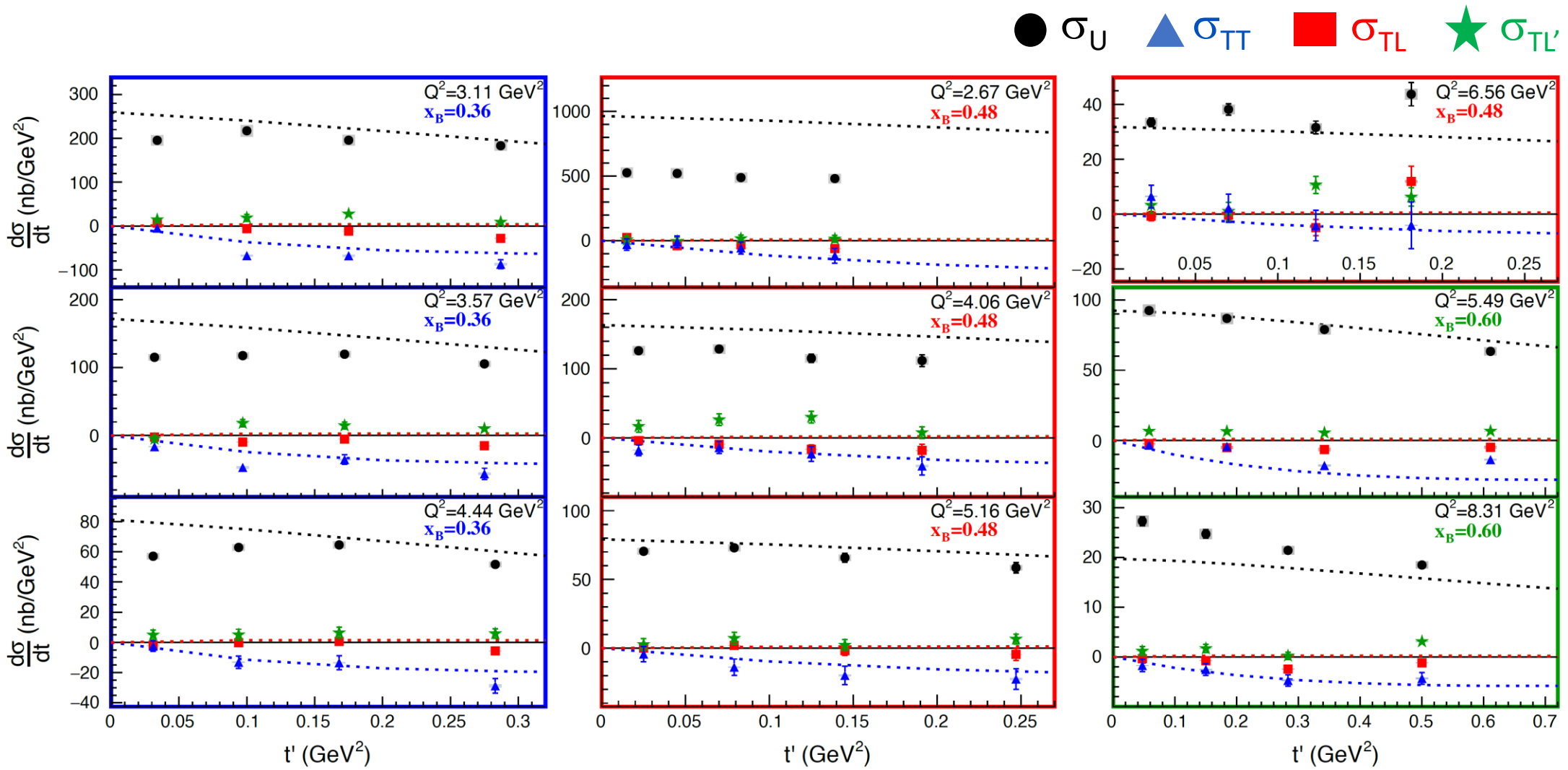
● Cross section extracted at x_B = 0.36, Q^2 = 3.11

S. V. Goloskokov and P. Kroll, Eur. Phys. J. A47, 112 (2011)

P. Kroll, private communications

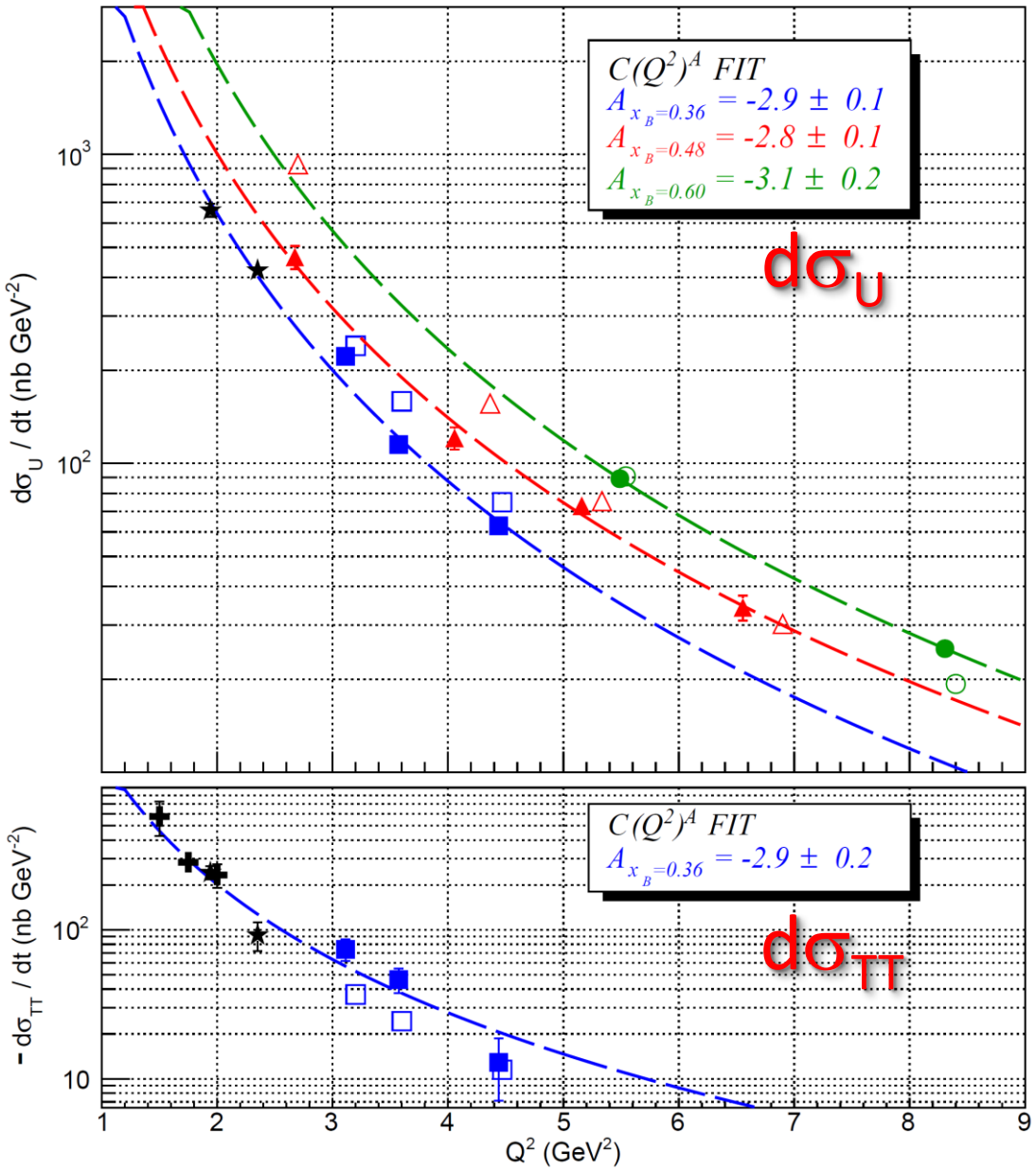
- Reasonable agreement σ_U and σ_{TT}
- Sign difference in σ_{TL}
- Small $\sigma_{TL'}$ with relatively large error
- Suggest a large σ_T in σ_U, and possibly a larger contribution of the logitudinal amplitude than the one expected by GK.
- Provide useful input for understanding the transversity GPDs in the valence domain

Cross-sections – Results of the JLab 12 Experiment submitted to PRL



M. Dlamini *et al*, arXiv:2011.11125 [hep-ex] 2020

Q^2 Dependence – Results of the JLab 12 Experiment submitted to PRL



- Open Markers: P. Kroll, private communications
- Solid Markers: Experimental measurements

<t'> = 0.1 GeV^2

- This work, x_B = 0.36
- This work, x_B = 0.48
- This work, x_B = 0.60
- E. Fuchey *et al*, Phys. Rev. C 83, 025201 (2011)
- M. Defurne *et al*, Phys. Rev. Lett. 117, 262001 (2016)

- $C(Q^2)^A$ fit to experimental results in different x_B
- Q^2 dependence closer to Q^{-6}, rather than Q^{-8} as expected for σ_T at high Q^2
- At this Q^2 and x_B coverage, the asymptotic limit is still far away

M. Dlamini *et al*, arXiv:2011.11125 [hep-ex] 2020

Summary and Outlook

DVCS

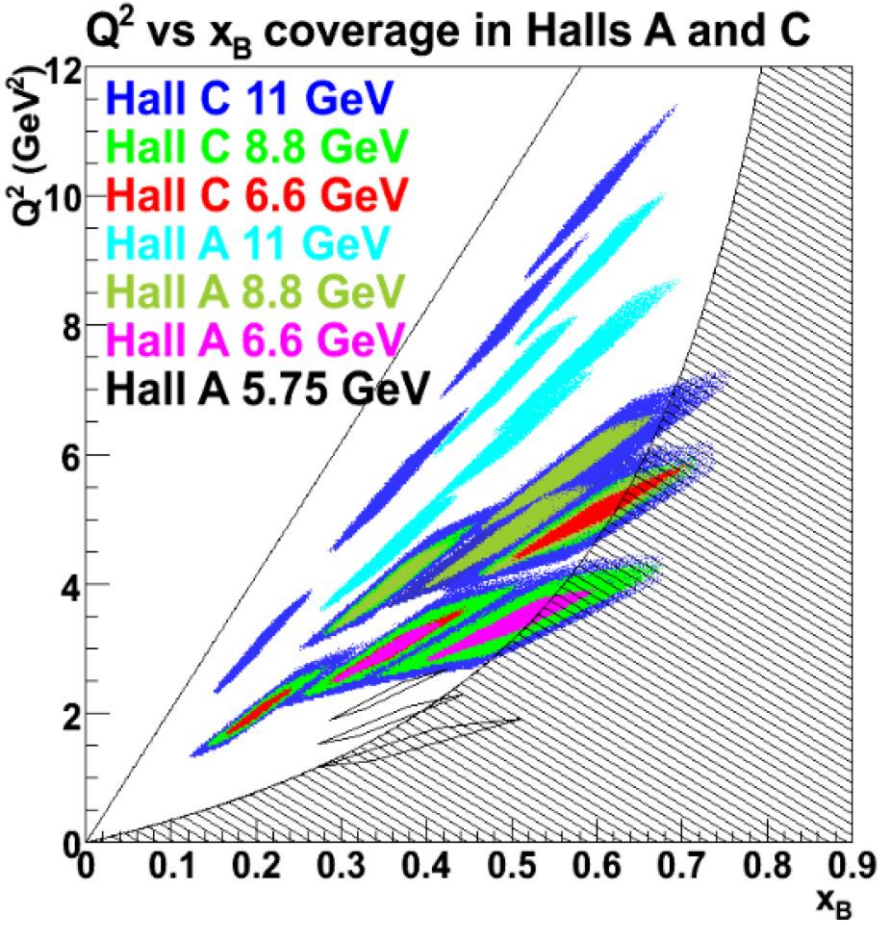
- Results ready. Paper drafting will be finalized soon

Exclusive π^0

- Reasonable description of results by GK model
- Non-neglibible contributions from longitudinal and transverse amplitudes are needed to describe the data
- Provide inputs for transversity GPD parameterization
- Paper submitted to PRL, being reviewed
  M. Dlamini *et al*, arXiv:2011.11125 [hep-ex] 2020

Outlook

- Extension to higher Q^2 and lower x_B
- Energy separation of DVCS cross section
- σ_T and σ_L separation of π^0 production



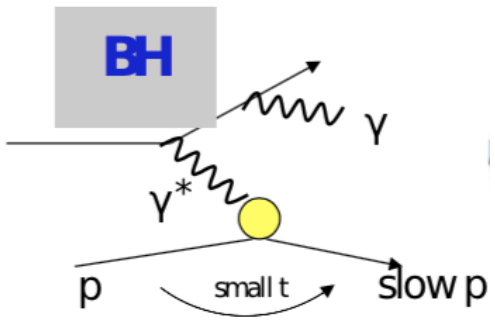
Acknowledgement

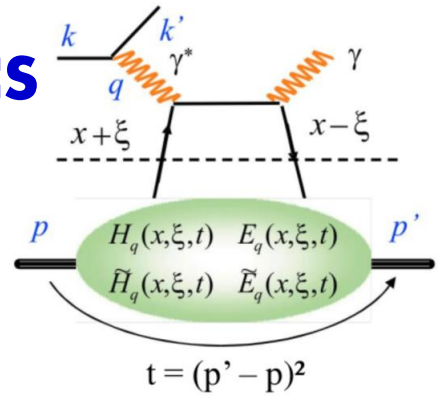
- Hall A Collaboration
- Hall A technical staff
- Accelerator staff
- K. Kumericki and D. Müller
- S. V. Goloskokov, P. Kroll, and S. Luiti

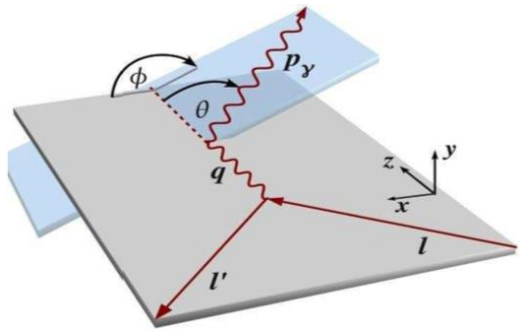
Thank you!

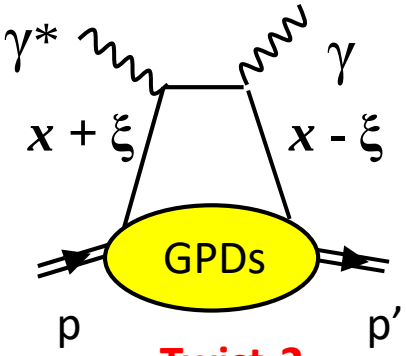
Backup Slides

DVCS









$$\frac{d^4\sigma(\ell p \to \ell p\gamma)}{dx_B dQ^2 d|t| d\phi} = \underbrace{d\sigma^{BH}}_{\text{Well known}} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell \,\mathrm{Im}\, I\right)$$

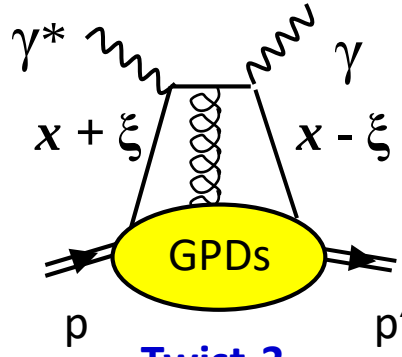
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

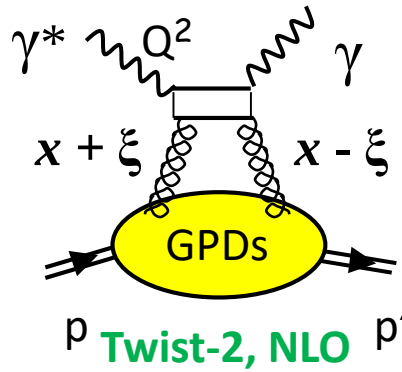
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

$$\mathrm{Re}\, I \propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi$$

$$\mathrm{Im}\, I \propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi$$

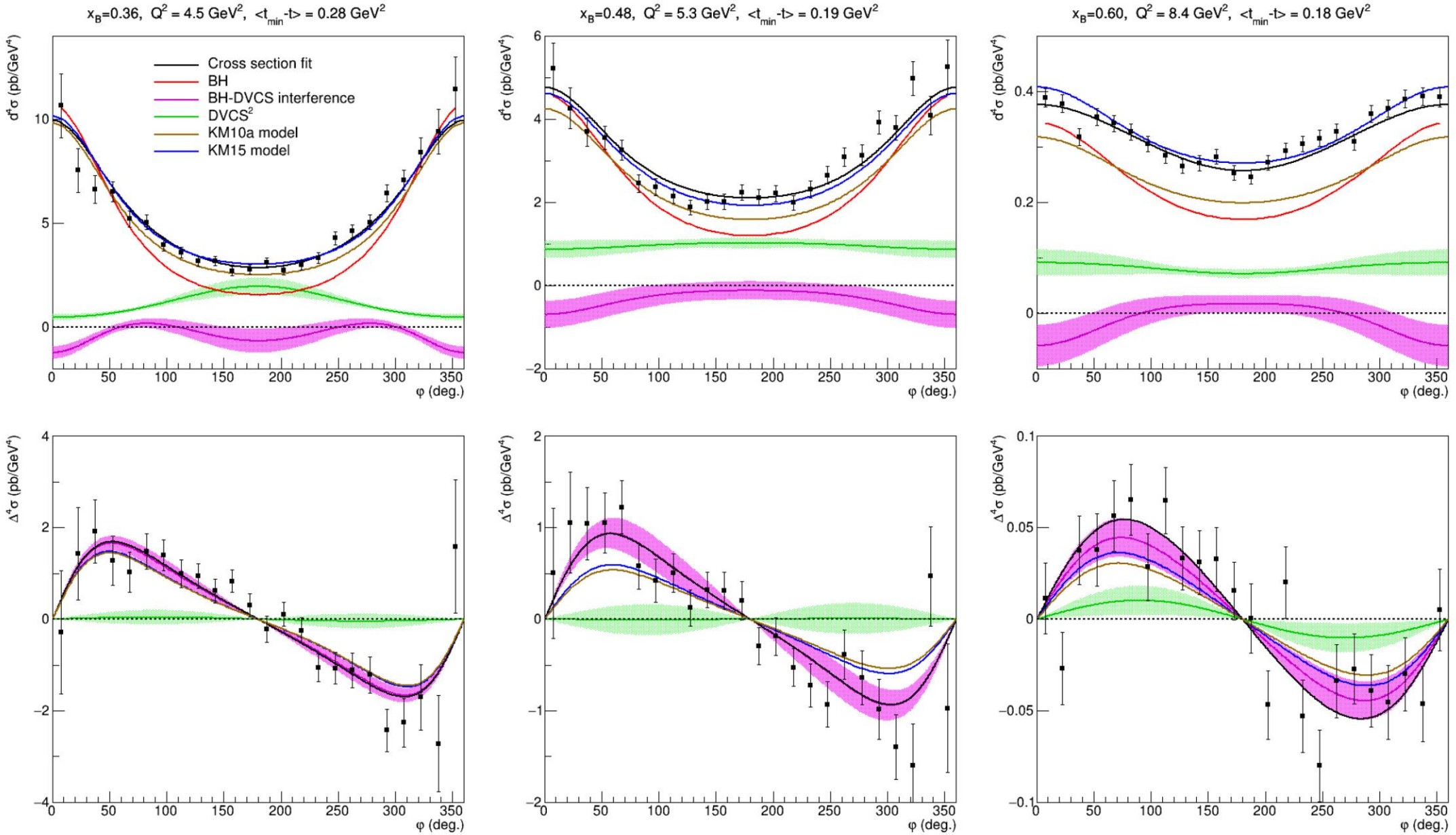




Twist-2 >> Twist-3, Twist-2 - double helicity flip for gluons (NLO)

A. V. Belitsky, D. Meller, A. Kirchner, Phys. Rev. D **82**

DVCS – Results of the JLab 12 Experiment to Be Published



Backup

e p → e π^0 p

$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

Leading twist expected be dominant

But measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\bar{E}_T^q = 2\tilde{H}_T^q + E_T^q$$