Exclusive neutral pion electroproduction measurement at Jefferson Lab Hall A experiment E12-06-114

HADRON 2021
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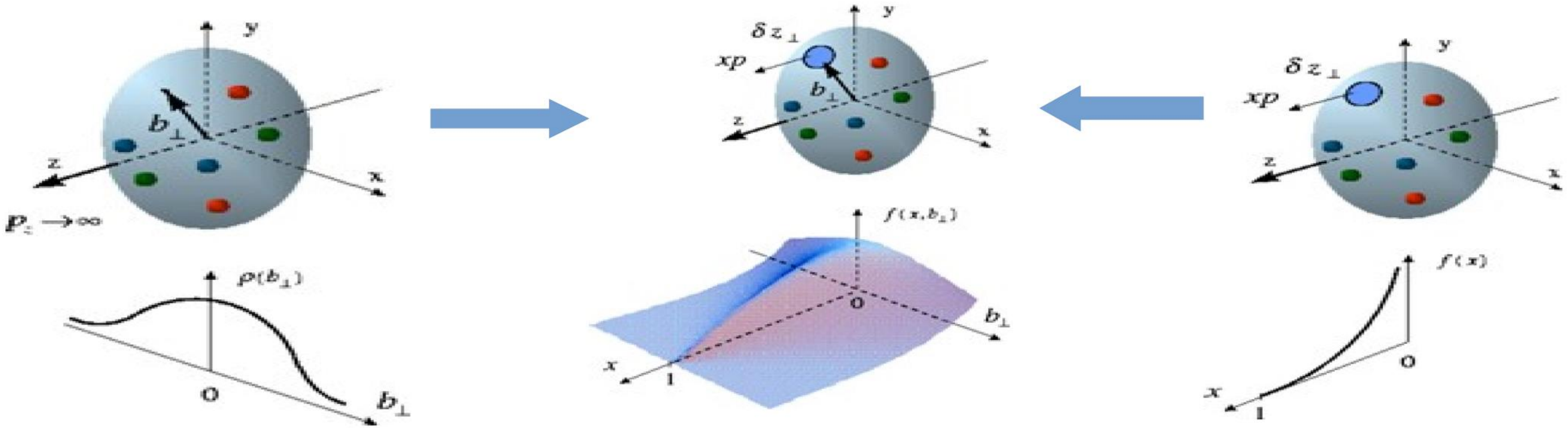
Po-Ju Lin
IJCLab – Orsay & CEA, Université Paris-Saclay
on behalf of the JLab Hall A DVCS collaboration

Picture of Nucleon



- **F**orm **F**actors **(FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution

- **G**eneralized **P**arton **D**istributions **(GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution

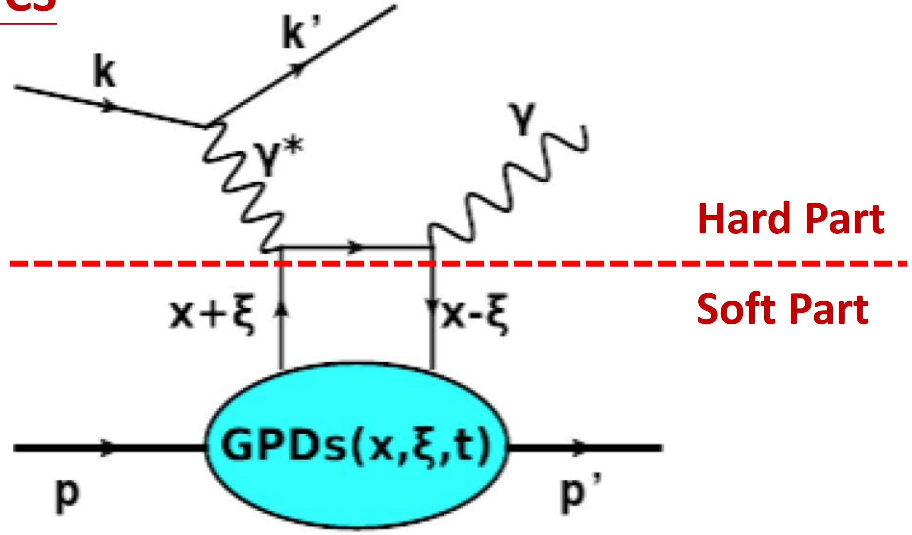
- **P**arton **D**istribution **F**unctions **(PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

GPDs

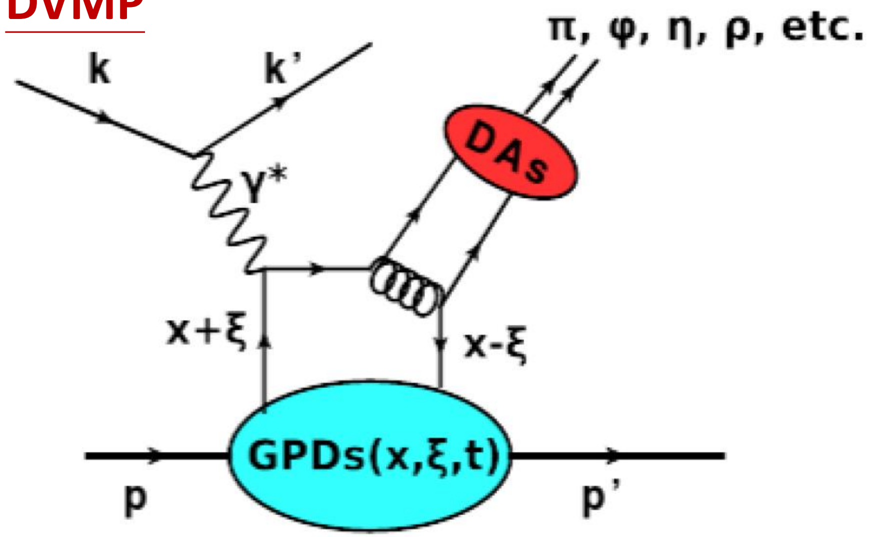
- **Correlates the transverse position to the longitudinal momentum of the partons and thus provides a 3-D information of the nucleon.**
- **Accessible through exclusive processes.**

Deep Exclusive Processes

DVCS



DVMP



- The GPDs depend on the variables:

  x: average longitudinal momentum frac.

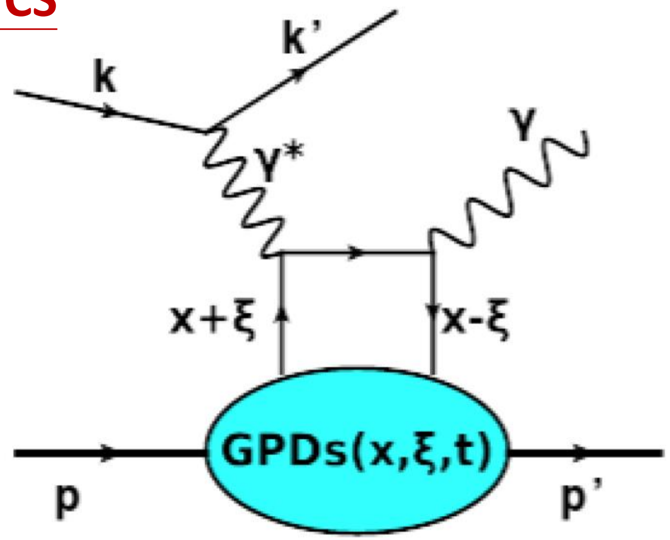
  ξ: longitudinal momentum diff. $\approx x_B/(2-x_B)$

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

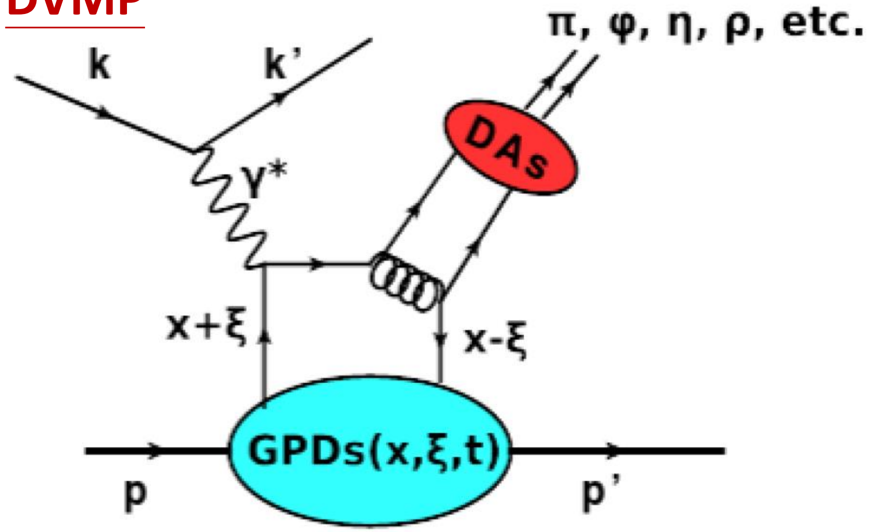
- Deeply Virtual Compton Scattering (DVCS) & Deeply Virtual Meson Production (DVMP)
  - Hard exclusive production of a single photon or meson
- In Bjorken limit (Q^2& $\nu \rightarrow \infty$) at fixed x_B
  - Hard Part: Calculable perturbatively
  - Soft Part: Nucleon structure parameterized by GPDs
- 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

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

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

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

- **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

Exclusive π^0 Production

$e\ p \rightarrow e\ \pi^0\ p$

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

ϵ: degree of longitudinal polarization

h: helicity of the initial lepton

- $\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$
- $\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$
- $\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$
- $\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$

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

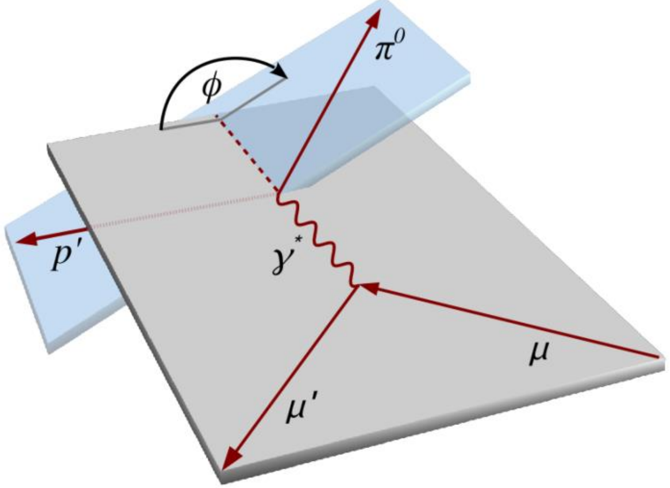


Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

S. V. Goloskokov and P. Kroll, Eur. Phys. J. A 47 (2011) 112

I. Bedlinskiy, et al. (CLAS Collaboration), Phys. Rev. C 90 (2014) 025205

Exclusive π^0 Production

$e\,p \rightarrow e\,\pi^0\,p$

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

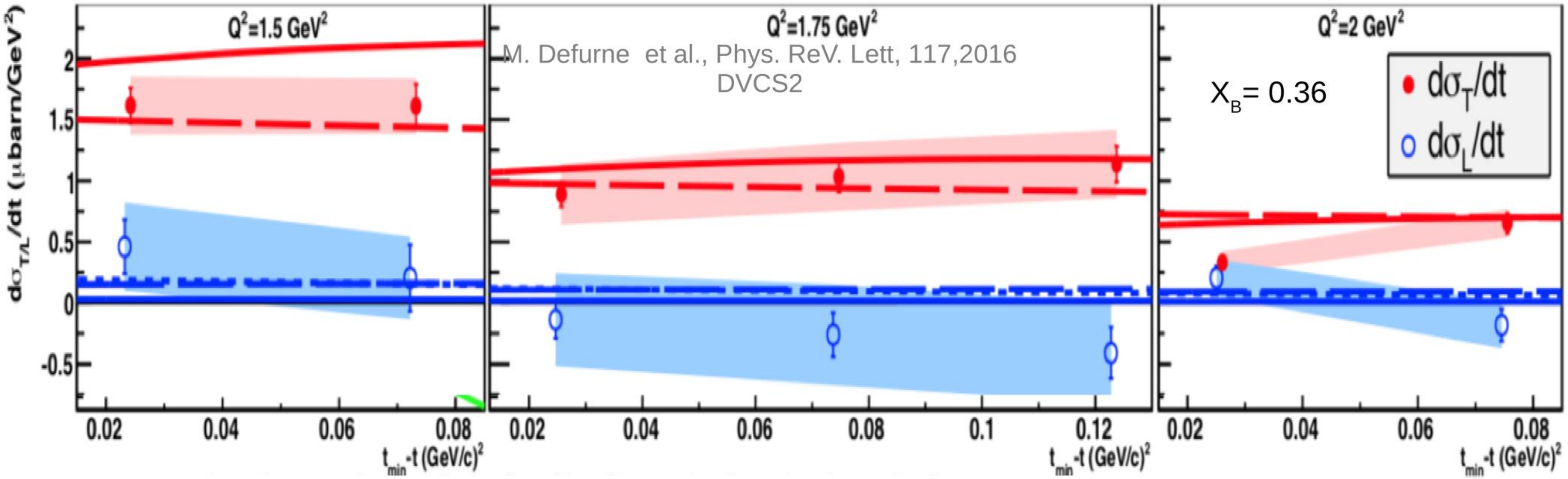
ϵ: degree of longitudinal polarization
h: helicity of the initial lepton

- 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 $\propto Q^{-8} \rightarrow \sigma_L$ dominance
- Previous experiments with limited reach in Q^2 show dominance of σ_T
- Modeling of $\sigma_T \rightarrow$ coupling between transversity GPDs and twist-3 pion amplitude

Exclusive π^0 Production

e p → e π^0 p

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



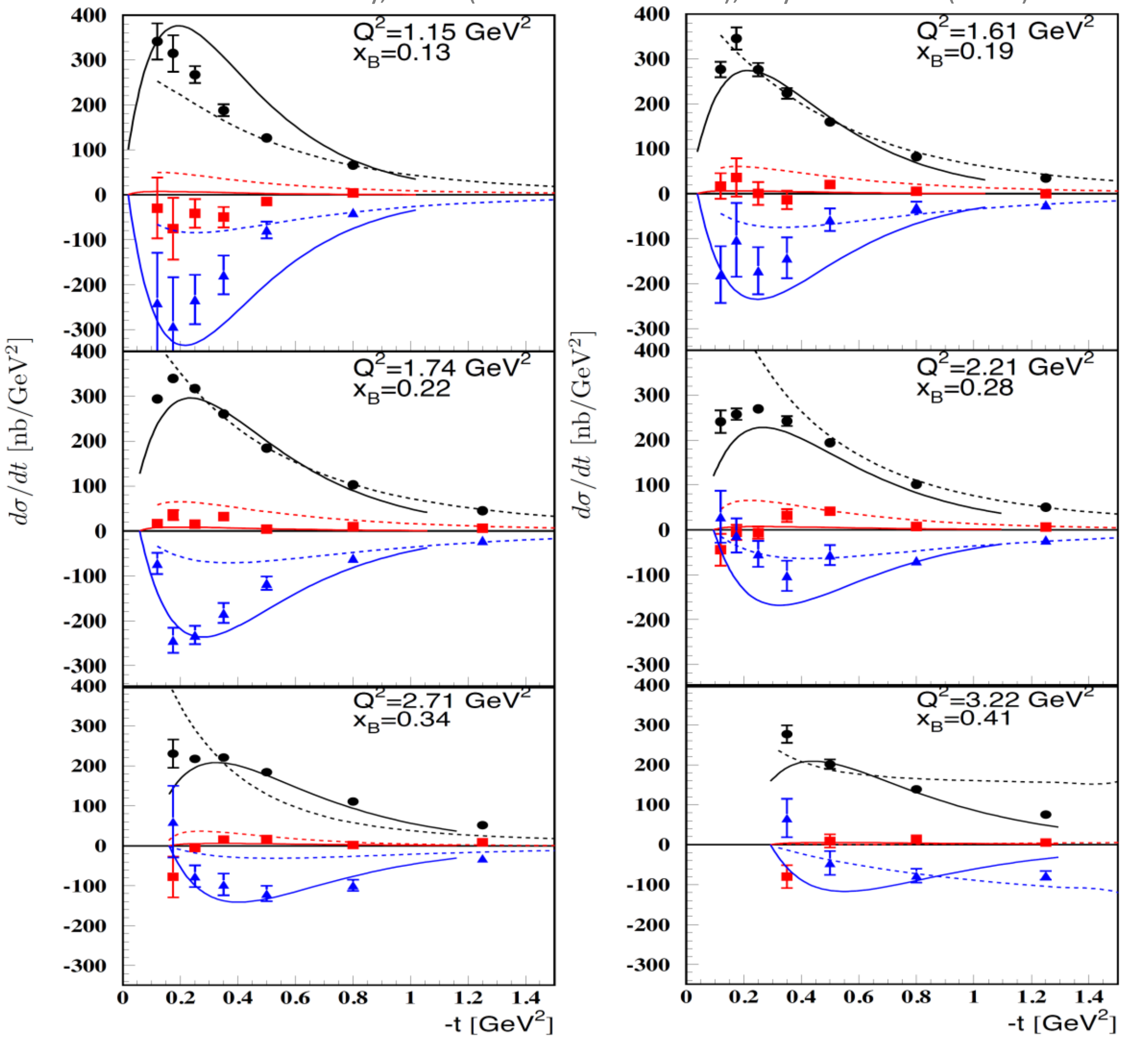
— S. V. Goloskokov and P. Kroll, Eur. Phys. J. C65:137 (2010)

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

Other Exclusive π^0 Measurements

CLAS

I. Bedlinskiy, et al. (CLAS Collaboration), Phys. Rev. C 90 (2014) 025205



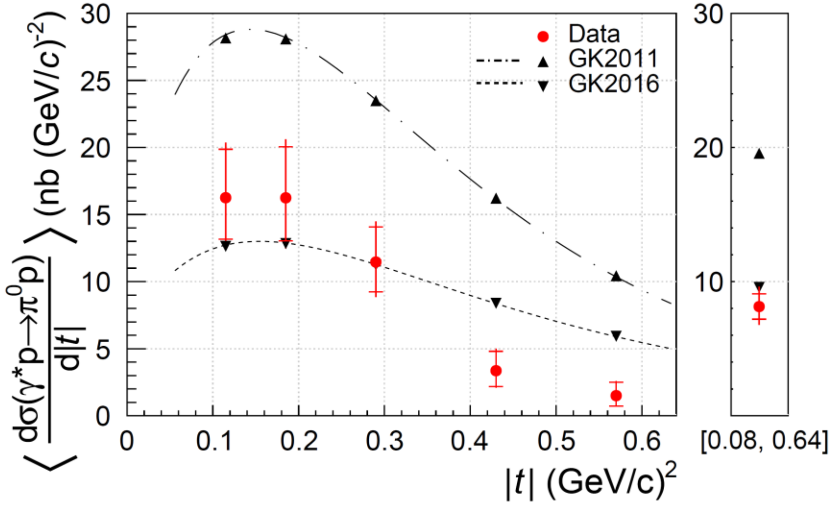
GK Model
GL Model

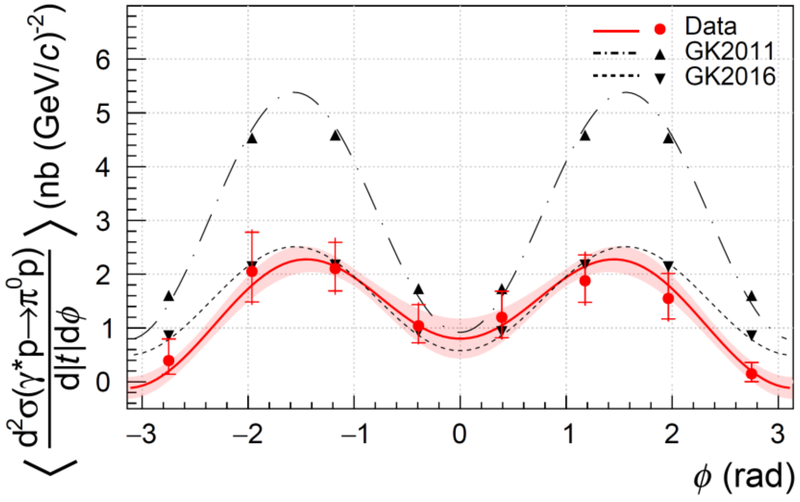
● $d\sigma_T + \varepsilon d\sigma_L$ ■ σ_{TL} ▲ σ_{TT}

COMPASS -

$\langle Q^2 \rangle = 2.0\ (\mathrm{GeV}/c)^2$

$\langle x_{Bj} \rangle = 0.093$

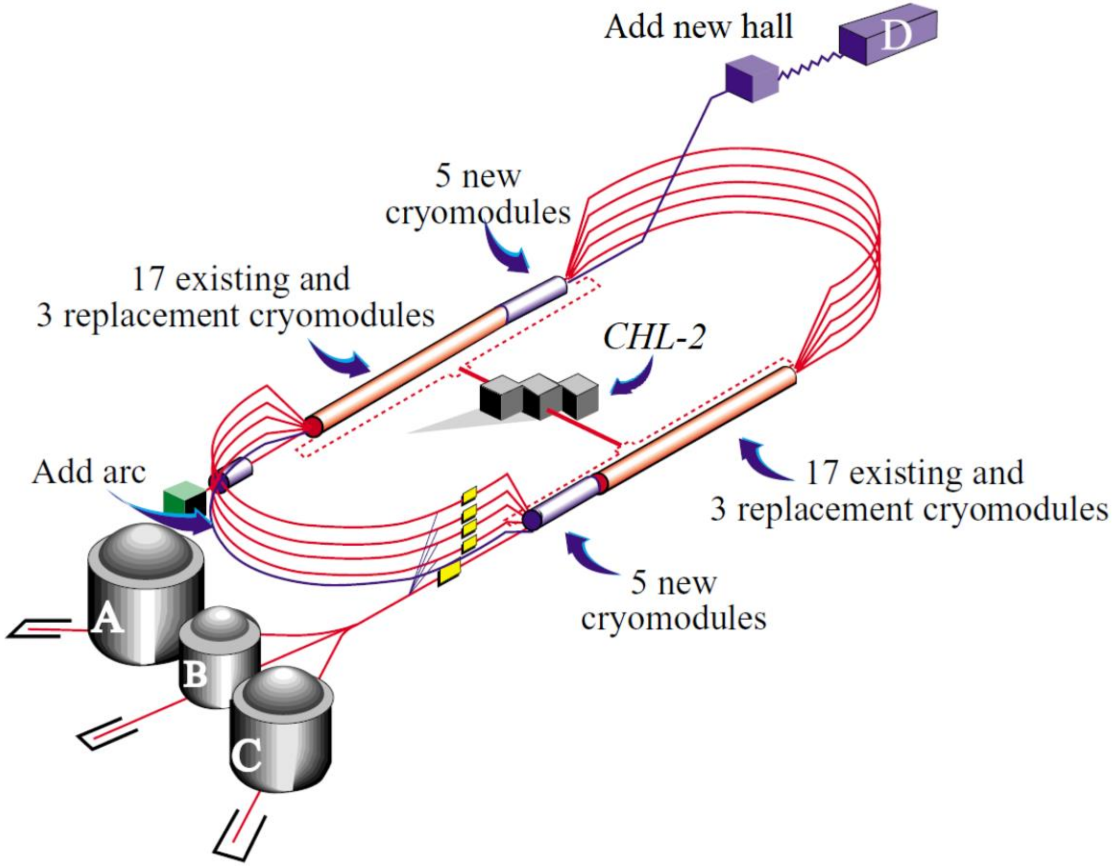


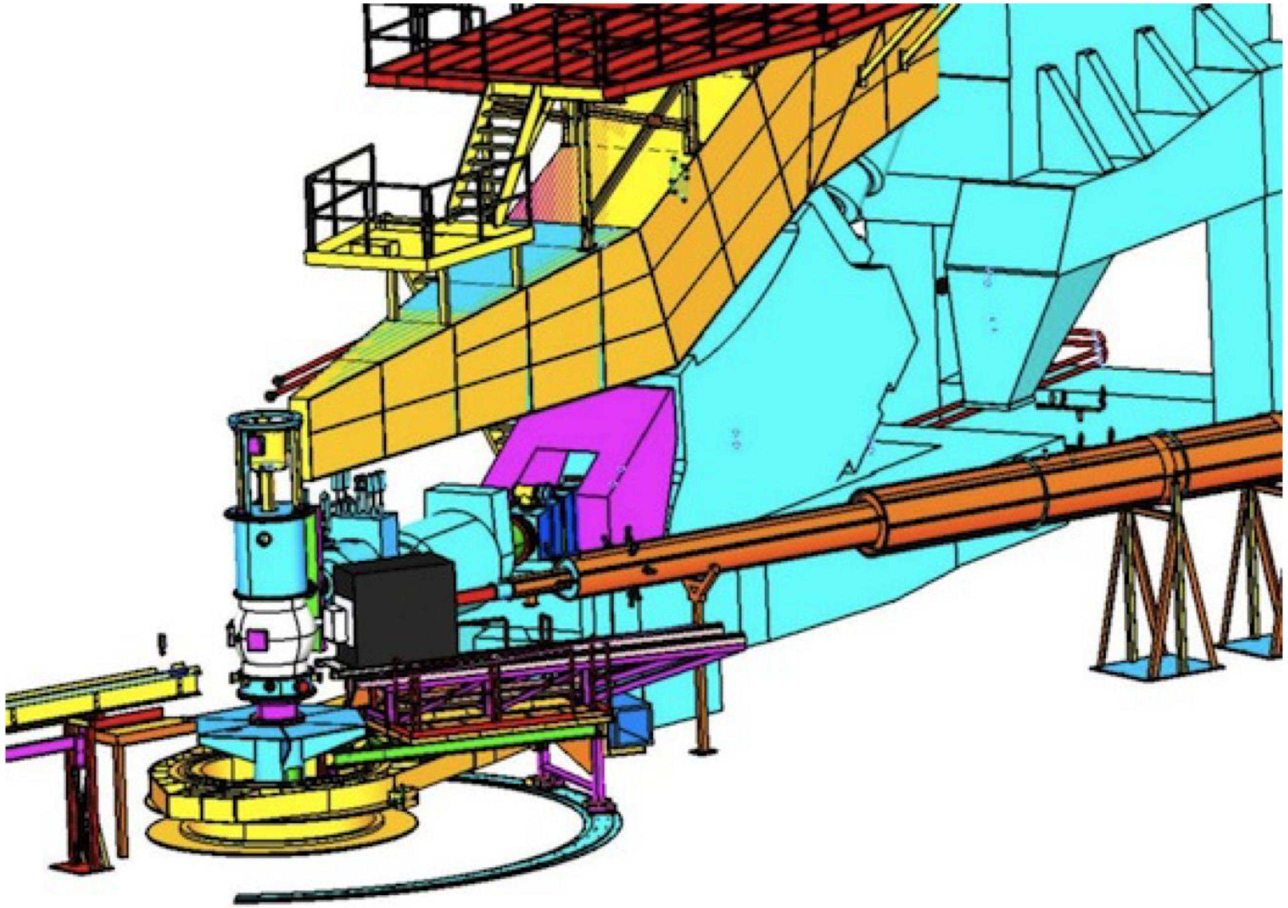


M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

Jefferson Lab Hall A experiment E12-06-114

https://www.jlab.org/div_dept/physics_division/GeV/whitepaperv11/index.html





- ➢ High beam polarization → 85%
- ➢ High luminosity → 10^{37} Hz/cm^2
- ➢ High energy → Hall A, B and C max. 11 GeV, Hall D 12 GeV

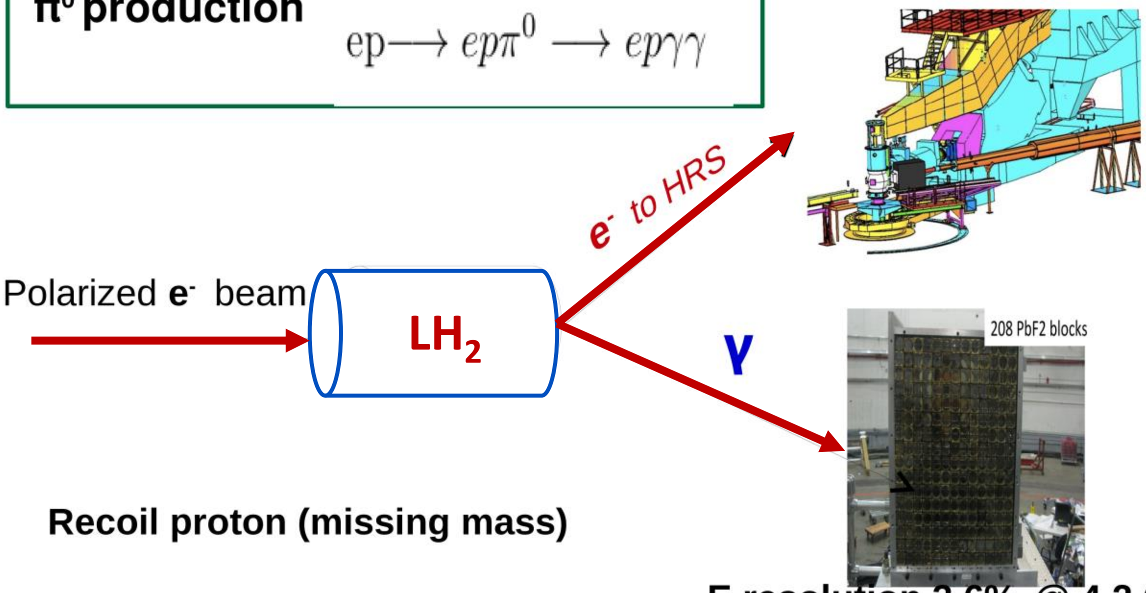
- ➢ 3rd Generation DVCS project → CEBAF12 grants ability to explore high x_B with extended Q^2.

Setup and Data Taken

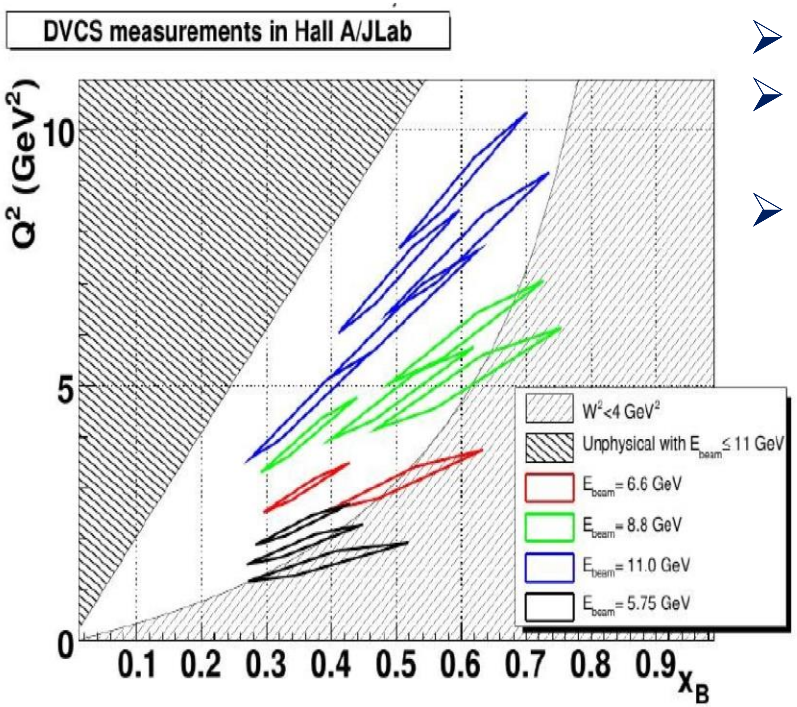
DVCS $ep \to ep\gamma$

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

δP/P Resolution 10^{-4} @ 4.3 GeV

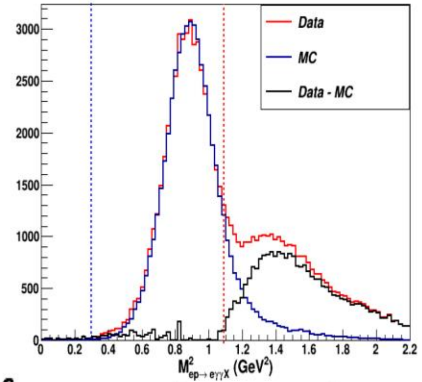


E resolution 3.6% @ 4.2 GeV

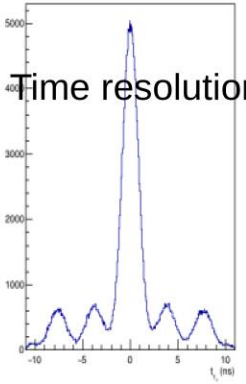


- Ran in 2014 & 2016
- ~50% of allocated 100 PAC days
- Missing PAC days reallocated in Hall C

Recoil proton (missing mass)



$$M^2_{ep\to e'\gamma\gamma X} = (e + p - e' - \gamma_1 - \gamma_2)^2$$

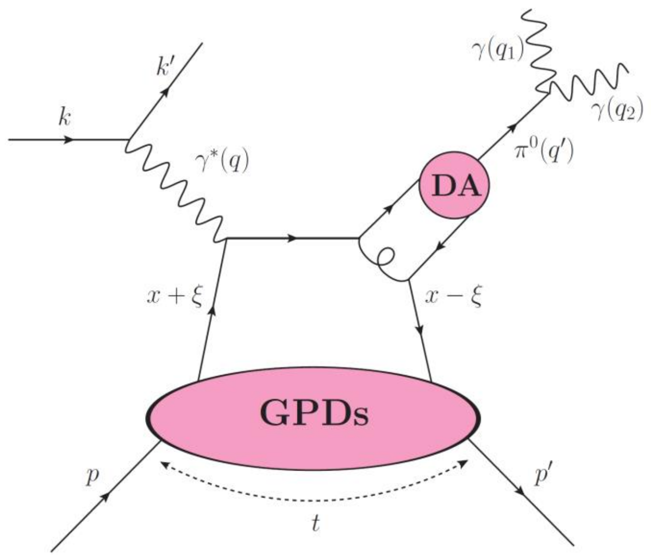


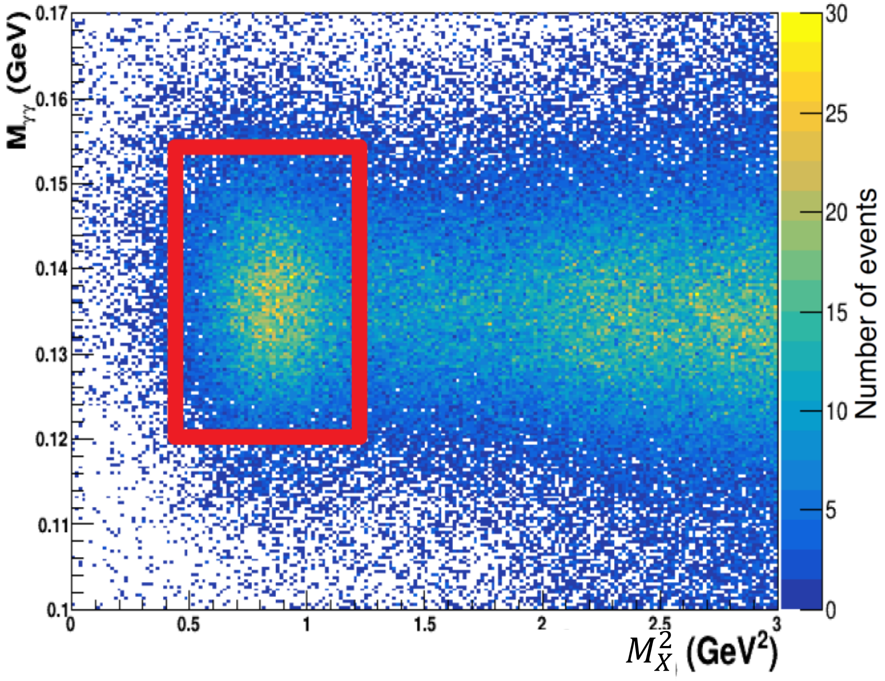
Time resolution ~1ns

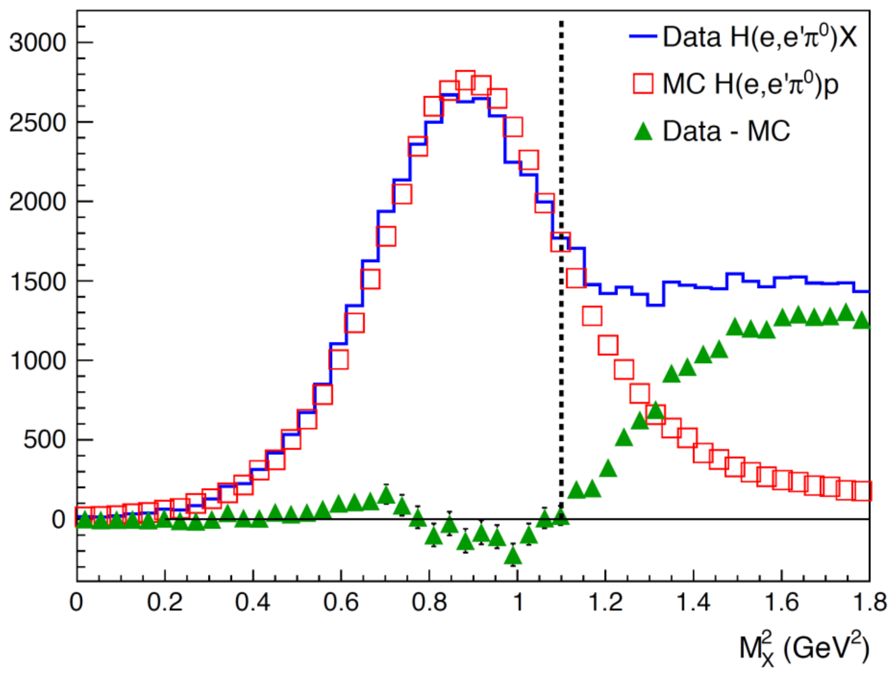
- Average values of kinematic variables of the 9 settings of this work

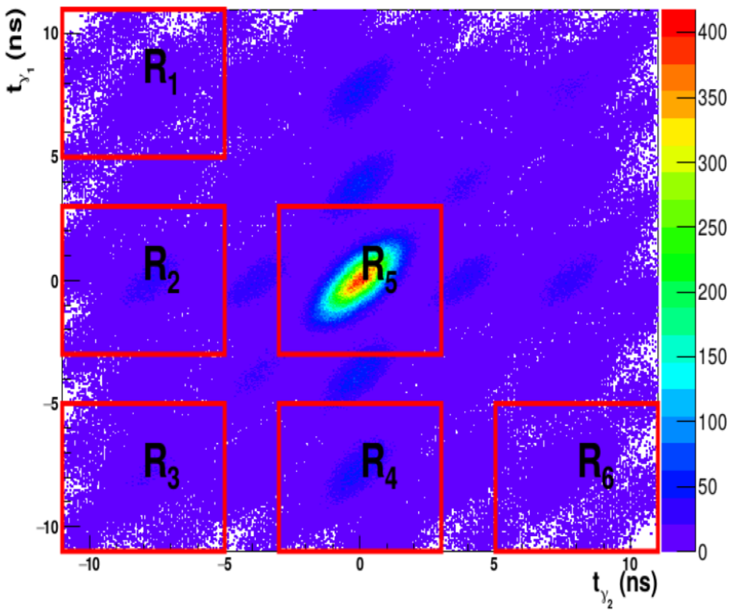
x_B-label	0.36			0.48				0.60	
$\langle x_B\rangle$	0.36	0.36	0.36	0.48	0.45	0.46	0.46	0.59	0.60
E (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV^2)	3.11	3.57	4.44	2.67	4.06	5.16	6.56	5.49	8.31

Exclusive π^0 Event Selection



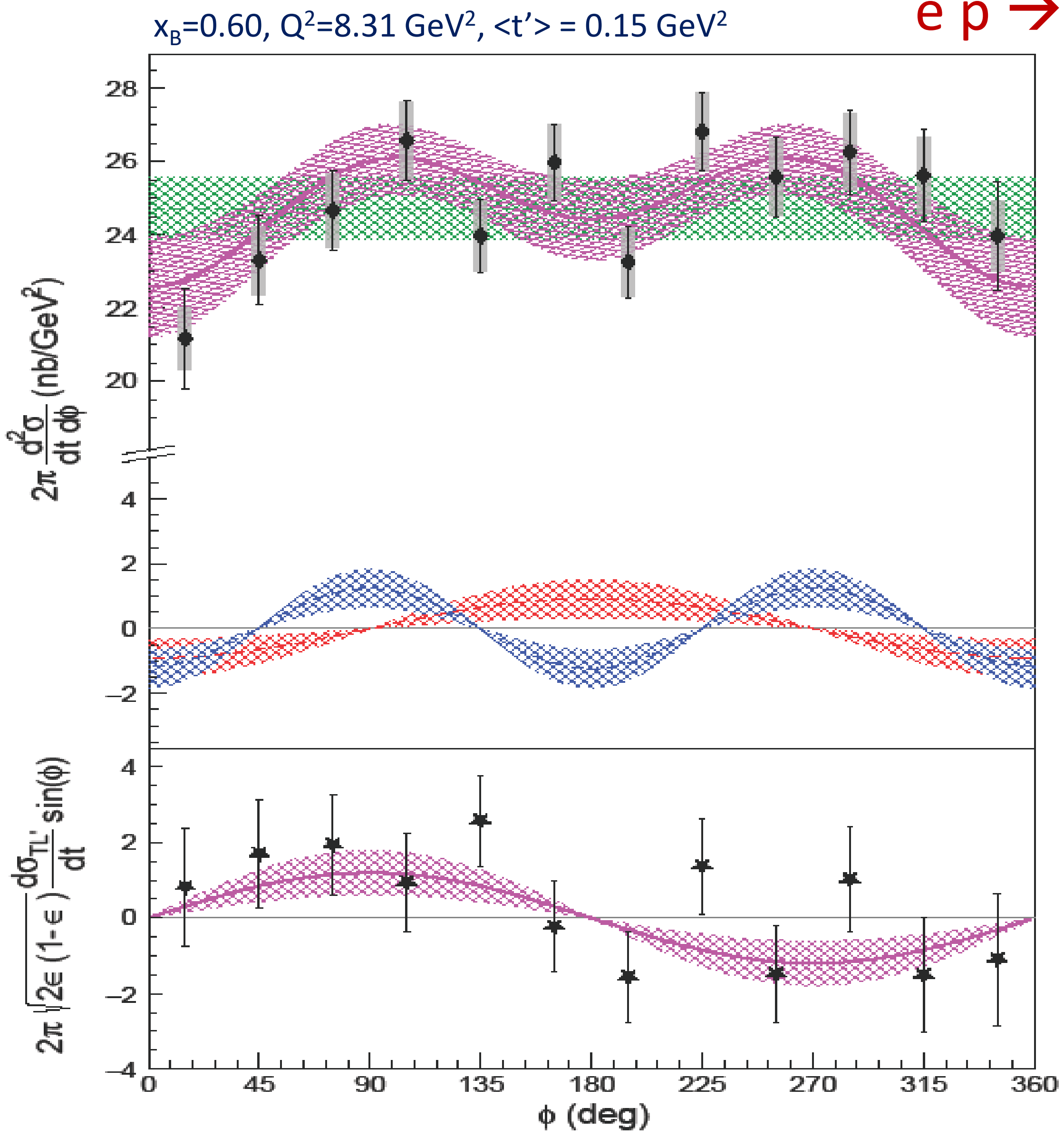






- π^0 events → select events with invariant mass $M_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$ around the π^0 mass
- Exclusivity → remove the M_X^2 contribution from inclusive channels, threshold ≈ 1.15 GeV^2
- Main background: accidentals. The backgound in the signal coincidence window, [-3,3] ns, is estimated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

Cross-section Extraction



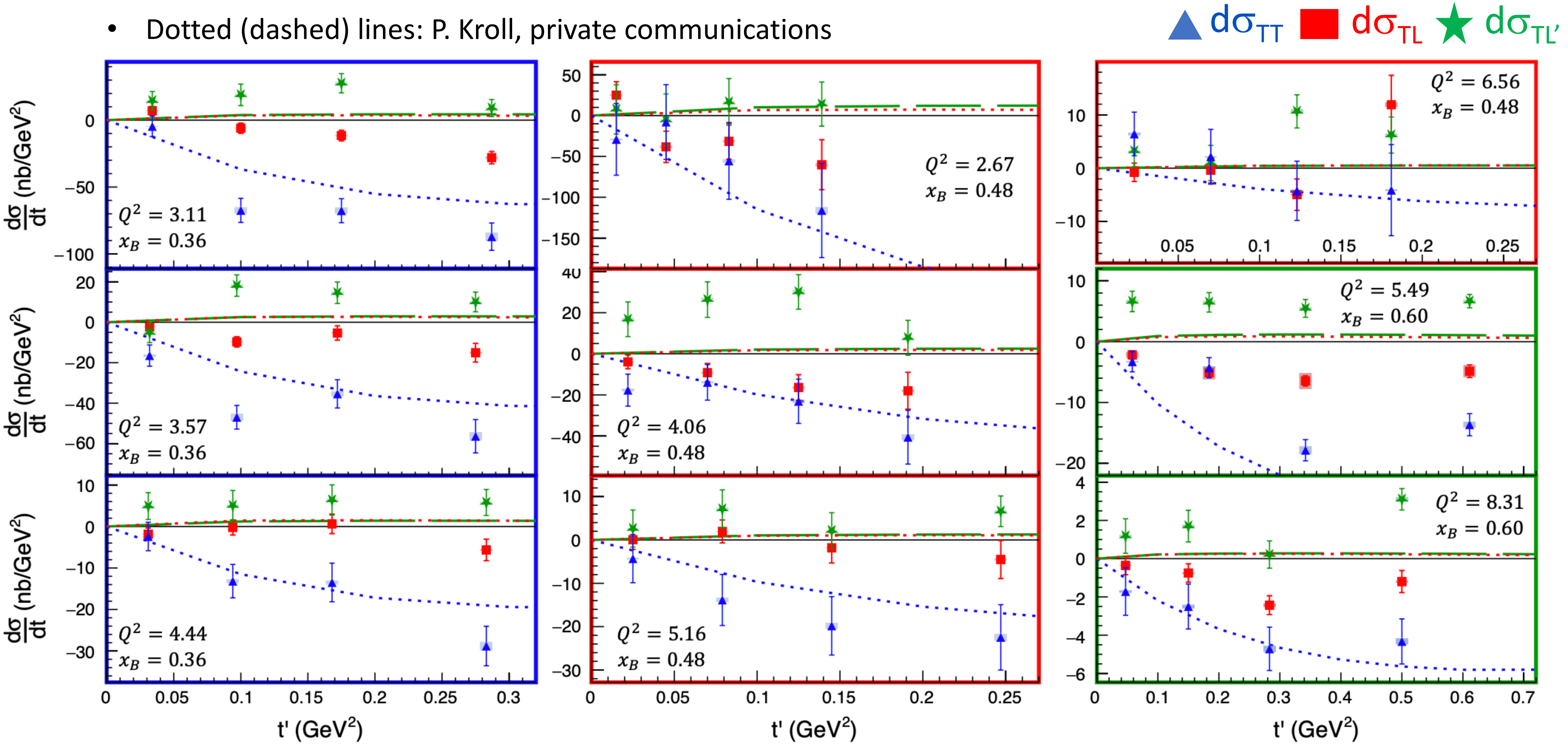
e p → e π^0 p

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

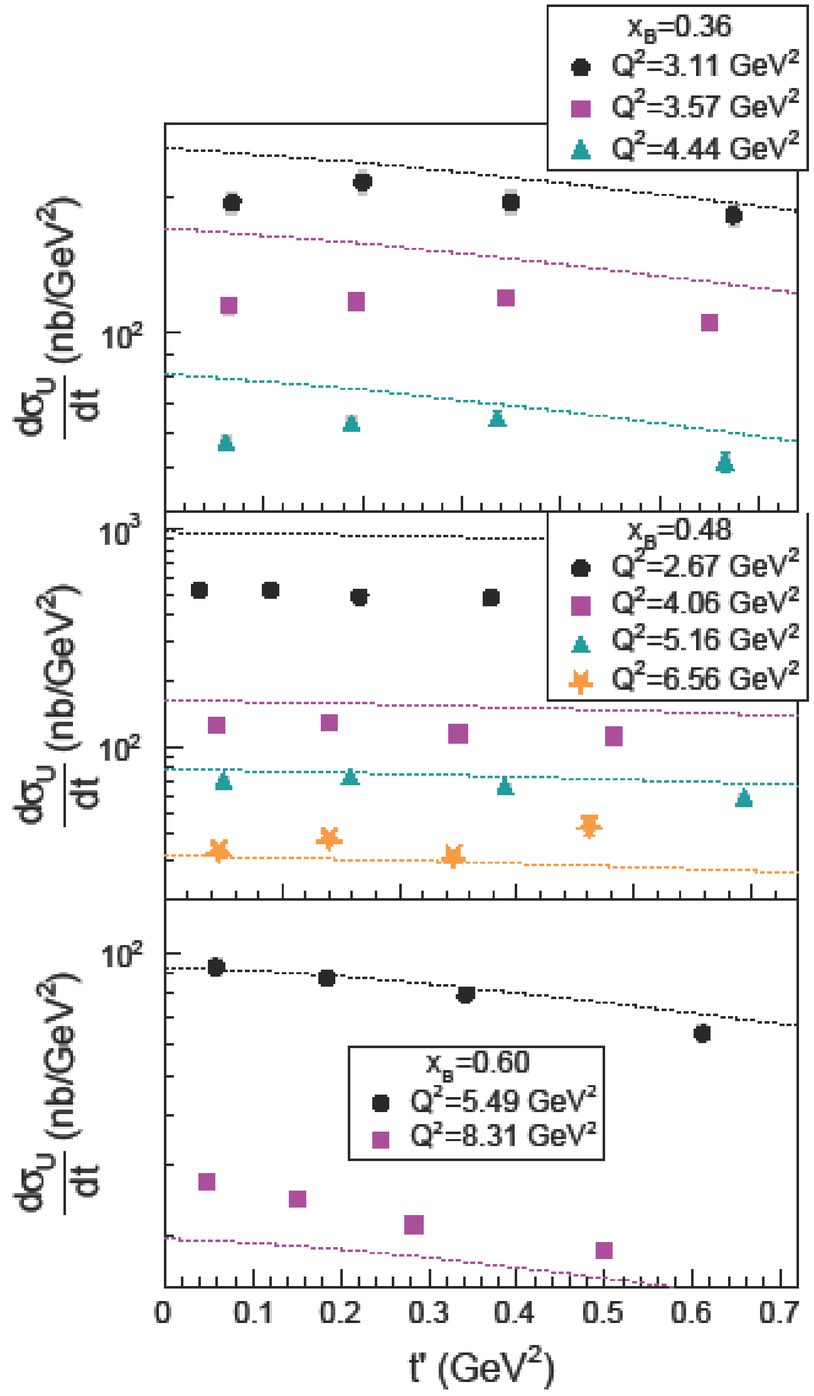
- Cross-sections extracted for all 9 kinematic settings
- Extract different terms via their corresponding ϕ dependence
- $d\sigma_T$ and $d\sigma_L$ can't be seperated, extracted as $d\sigma_U = d\sigma_T + \epsilon d\sigma_L$
- Main systematic errors come from deviation observed in DIS events and the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

Cross-sections

- Dotted (dashed) lines: P. Kroll, private communications



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



Cross-sections

- Solid Markers: Measured $d\sigma_U = d\sigma_T + \varepsilon d\sigma_L$
- Dotted lines: P. Kroll, private communications

➢ Reasonable agreement $d\sigma_U$ and $d\sigma_{TT}$

➢ $d\sigma_{TT}$ larger than $d\sigma_{TL}$ & $d\sigma_{TL'}$ in general

- Hint the dominance of σ_T → as suggested by the GK model

➢ GK underestimates bth σ_{TL} & $\sigma_{TL'}$

- Suggest a larger contribution of the logitudinal amplitude than the one expected by GK.

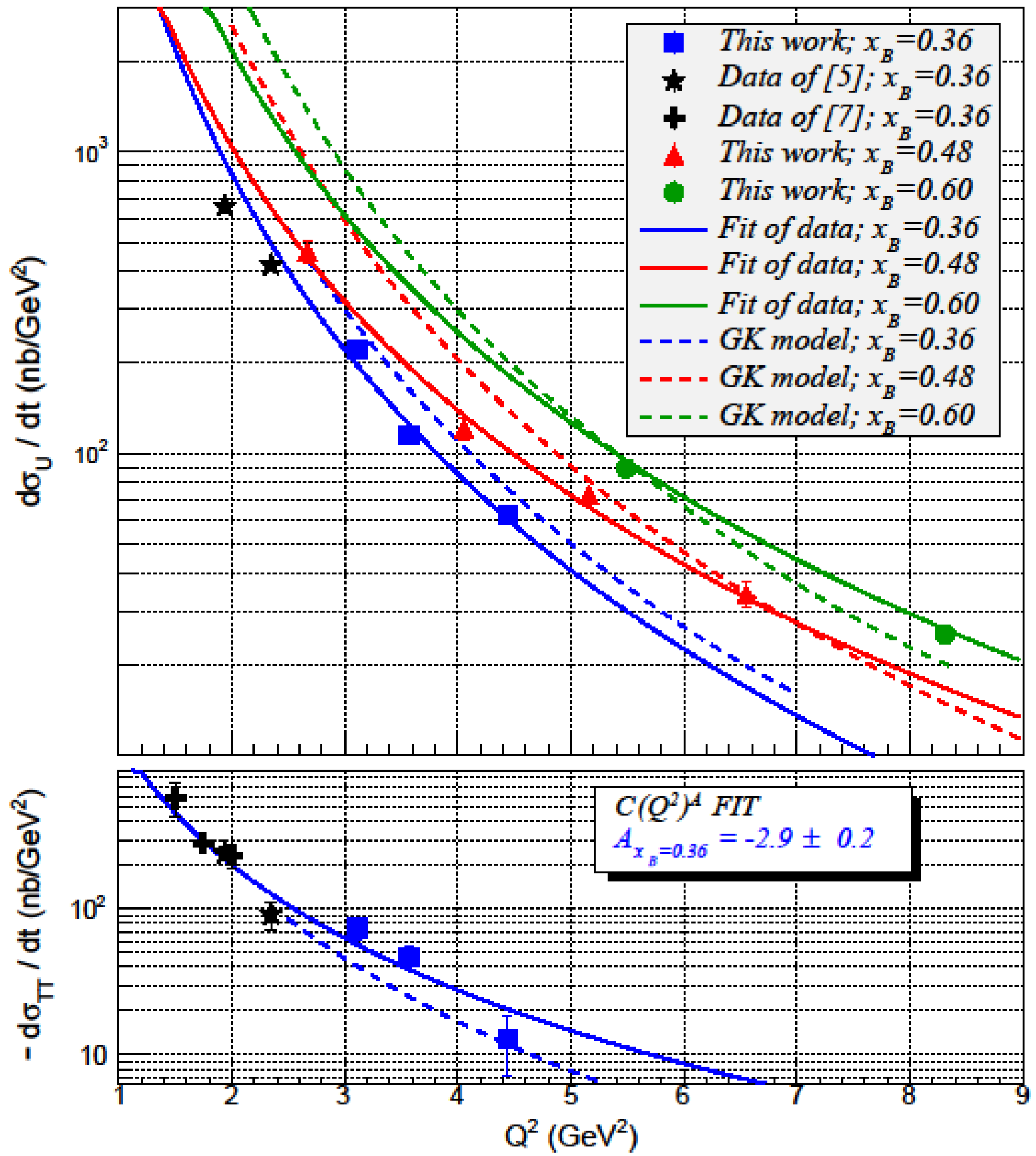
➢ Sign difference in σ_{TL}

- Involves real part of H_T & $\tilde{E}$, and $\bar{E}_T$ & $\tilde{H}$, which come in opposite sign

➢ Provide useful input for understanding the GPDs involved in the valence domain

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

Q^2 Dependence



- Dashed lines: 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)

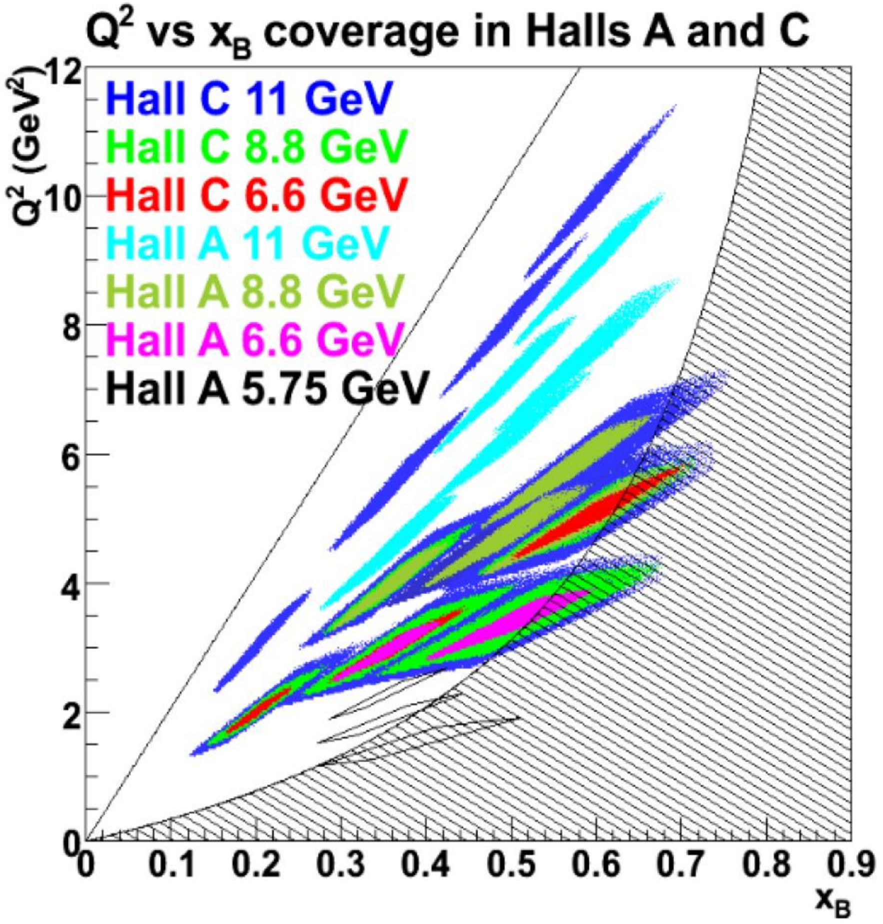
- ➢ $C(Q^2)^A \exp(-Bt')$ fit to experimental results in different x_B
- ➢ Q^2 dependence closer to Q^{-6}, rather than Q^{-8} as expected for σ_T at high Q^2
- ➢ At this Q^2 and x_B coverage, the asymptotic limit is not reached

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

Summary and Outlook

Exclusive π^0 Production

- Reasonable description of results by GK model
- Non-negligible contributions from longitudinal and transverse amplitudes are needed to describe the data
- Provide inputs for transversity GPD parameterization



Outlook

- Extension to higher Q^2 and lower x_B
- σ_T and σ_L separation of π^0 production at Hall C
- DVCS results will be released soon

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!