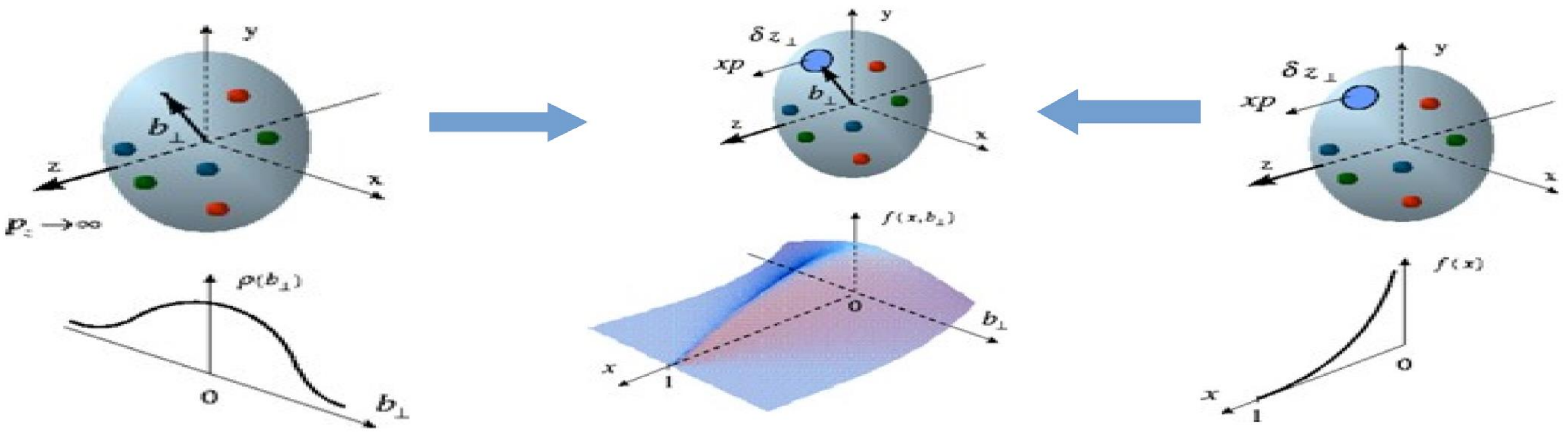
Measurement of the exclusive neutral pion electroproduction at Jefferson Lab Hall A experiment E12-06-114

TQCD Meeting

January 18, 2022

Po-Ju Lin

Picture of Nucleon



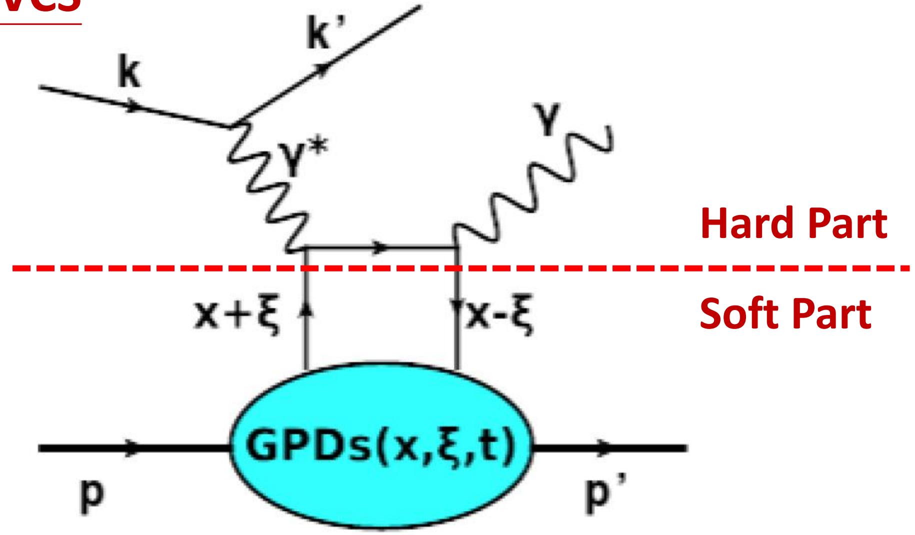
- **F**orm **F**actors **(FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution
- **G**eneralized **P**arton **D**istributions **(GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution
- **P**arton **D**istribution **F**unctions **(PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

GPDs

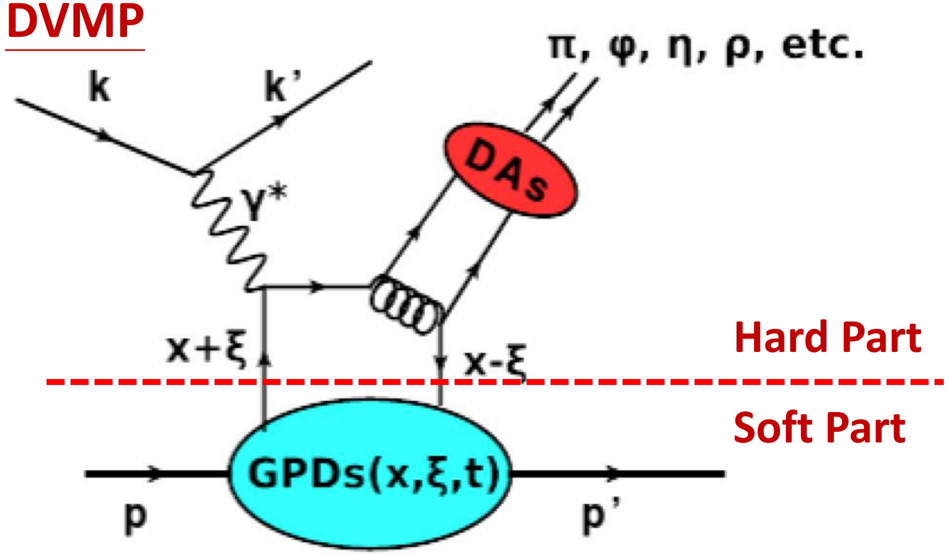
- **Correlate the transverse position to the longitudinal momentum of the partons and thus provides a 3-D information of the nucleon.**
- **Accessible through exclusive processes.**

Deep Exclusive Processes

DVCS



DVMP



- The GPDs depend on the variables at fixed Q^2:

  x: average longitudinal momentum frac.

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

  t: four momentum transfer

➢ Deeply Virtual Compton Scattering (DVCS) & Deeply Virtual Meson Production (DVMP)

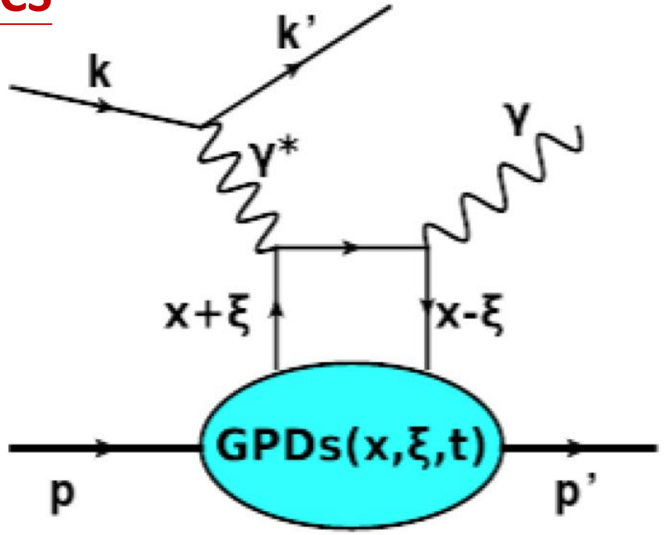
- Hard exclusive production of a single photon or meson

➢ In Bjorken limit (Q^2& $\nu \rightarrow \infty$ at fixed x_B)

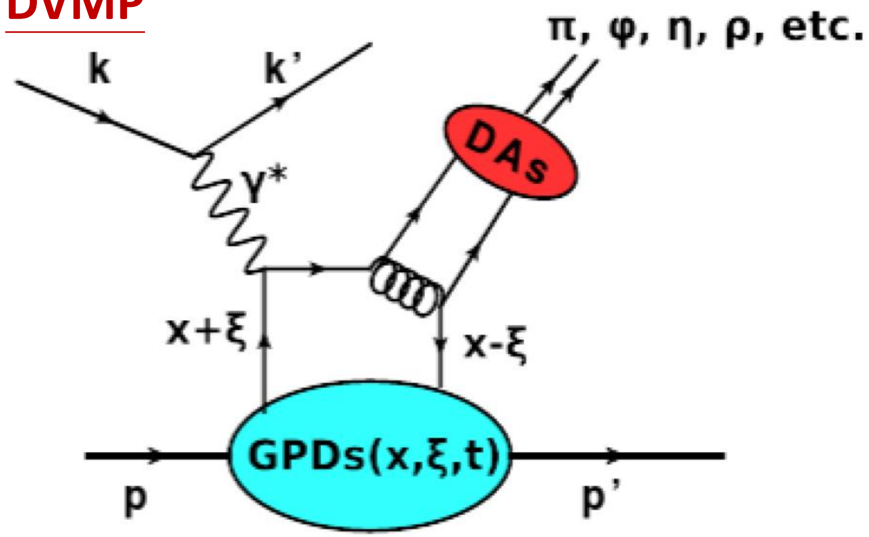
- Hard Part: Calculable perturbatively
- Soft Part: Nucleon structure described by GPDs

Deep Exclusive Processes

DVCS



DVMP



4 chiral-even GPDs: helicity of parton unchanged

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

via **DVCS** **DVMP**

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

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

via **DVMP**

- **DVCS**
  - Golden channel, simple and clean final state
- **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

- 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 suggest the dominance of σ_T

Exclusive π^0 Production

e p → e π^0 p

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

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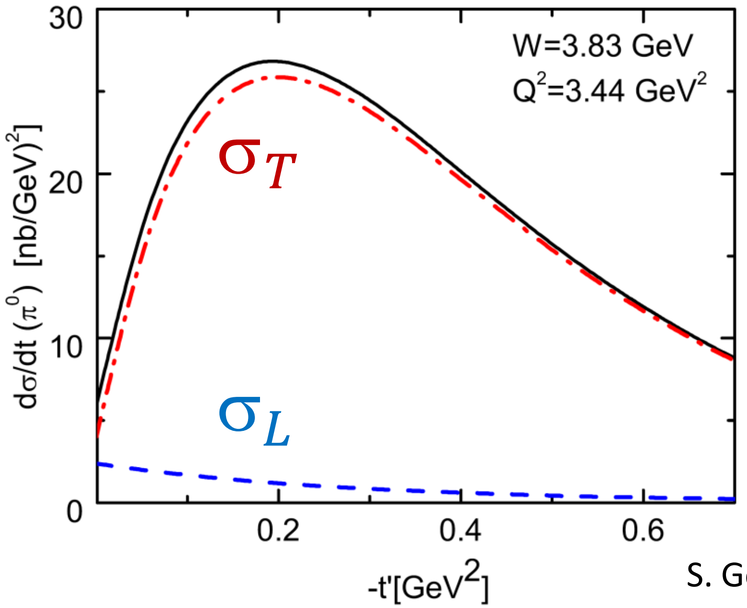


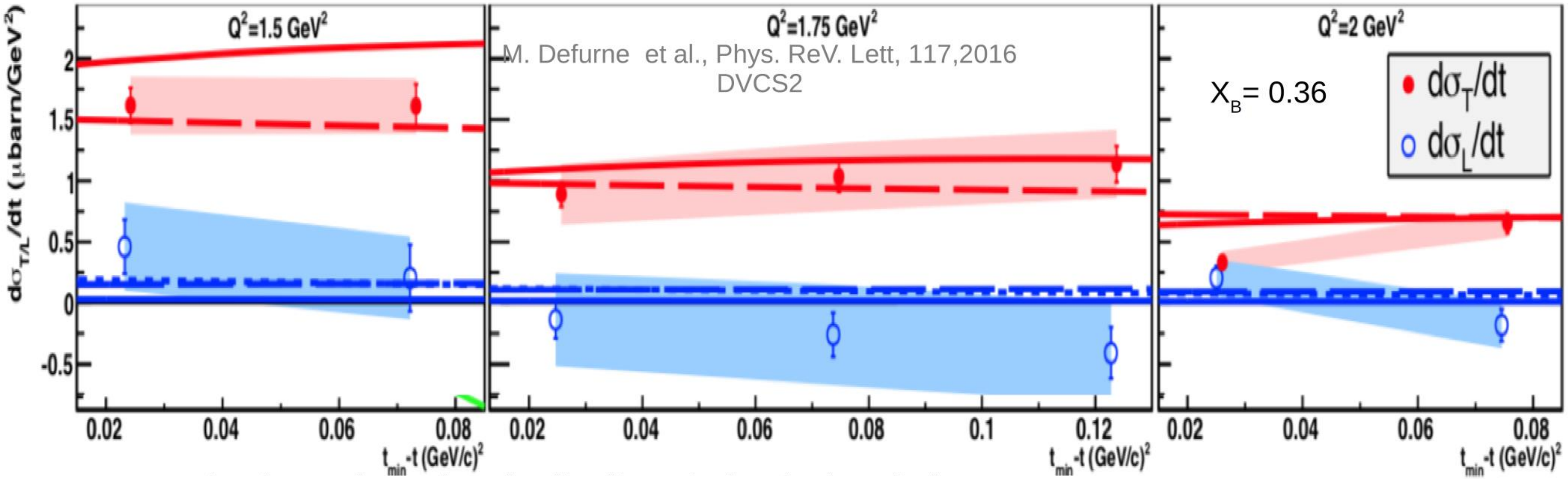
- Modeling of σ_T → coupling between transversity GPDs and twist-3 pion amplitude

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

Exclusive π^0 Production

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

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



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

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

Exclusive π^0 Production

e p → e π^0 p

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

ϵ: degree of longitudinal polarization

h: helicity of the initial lepton

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

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

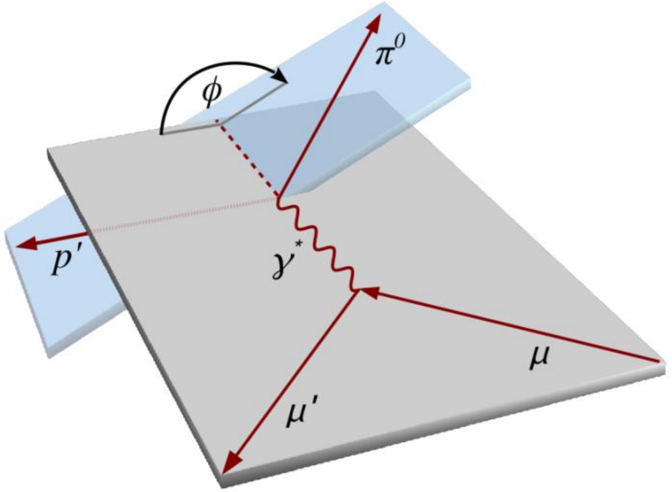


Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

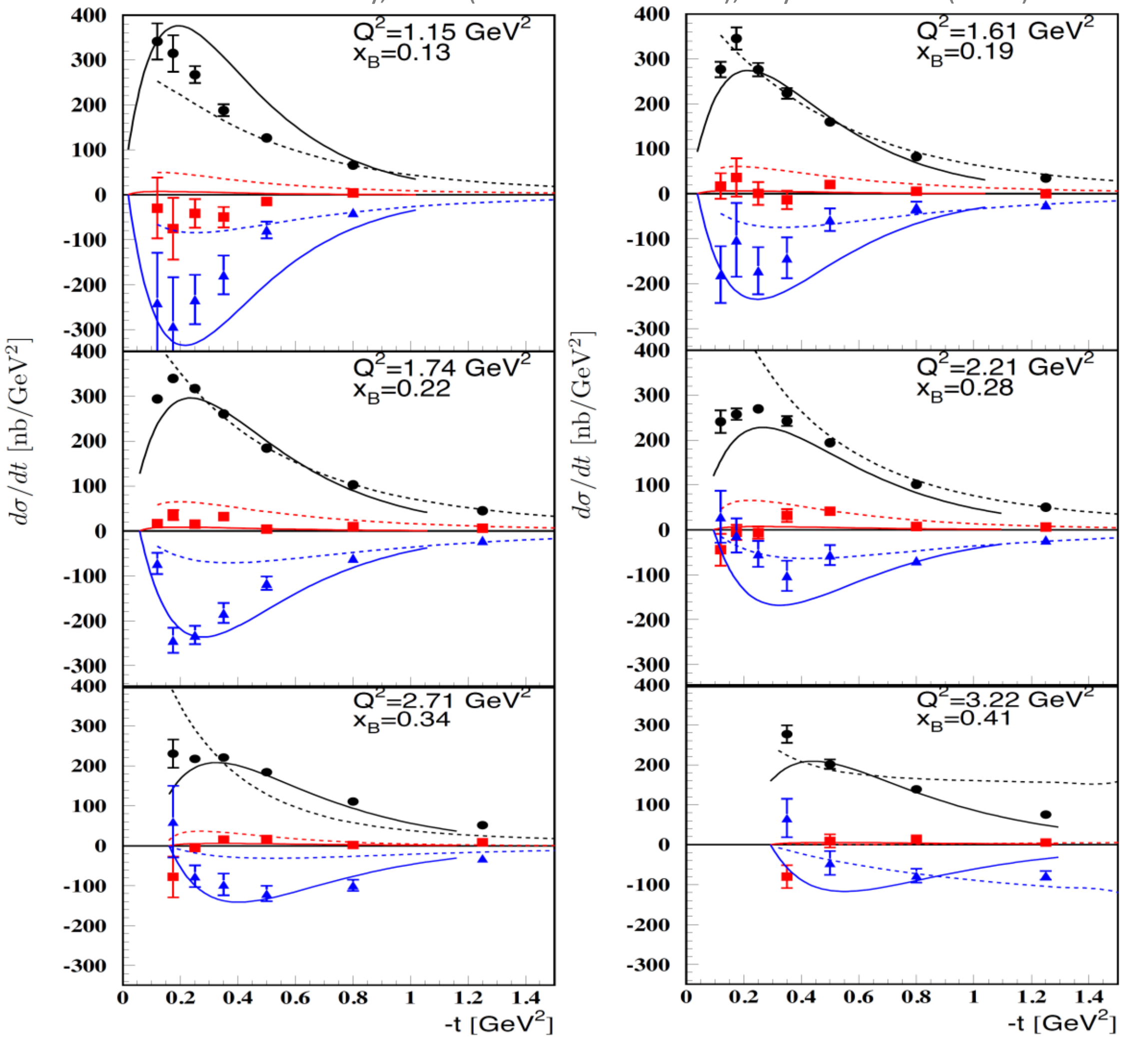
S. V. Goloskokov and P. Kroll, Eur. Phys. J. A 47 (2011) 112

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

Other Exclusive π^0 Measurements

CLAS

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

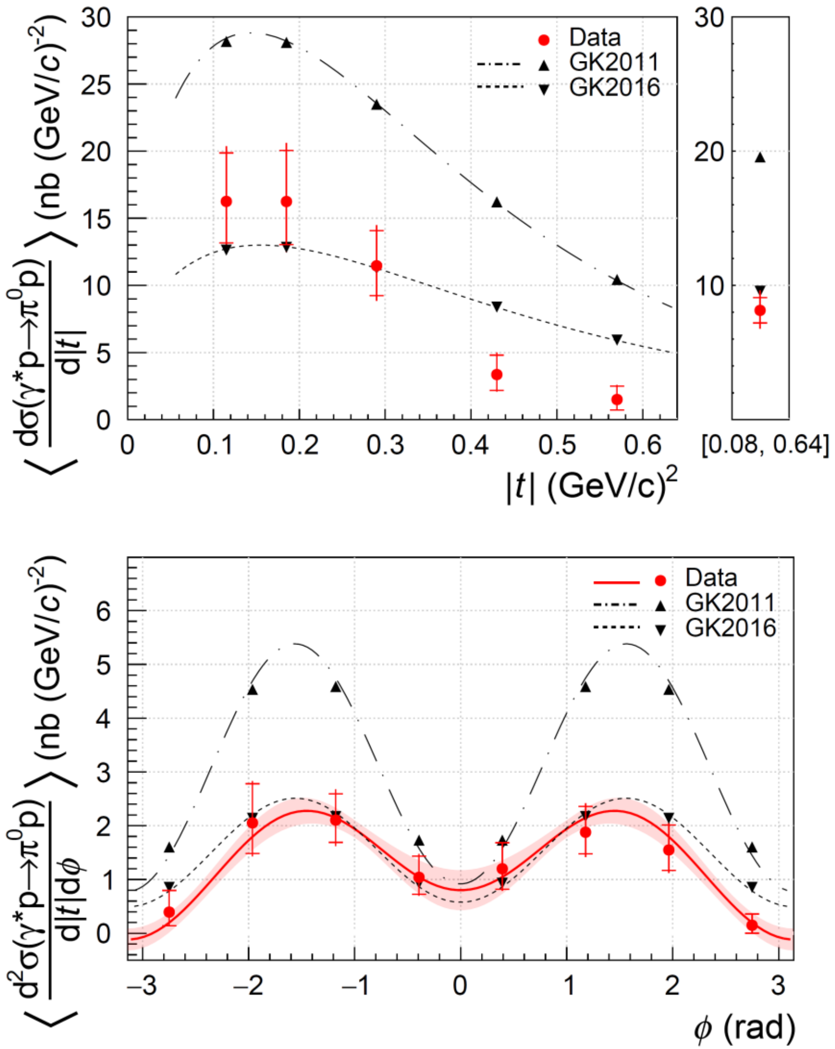


GK Model
GHL Model

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

COMPASS -

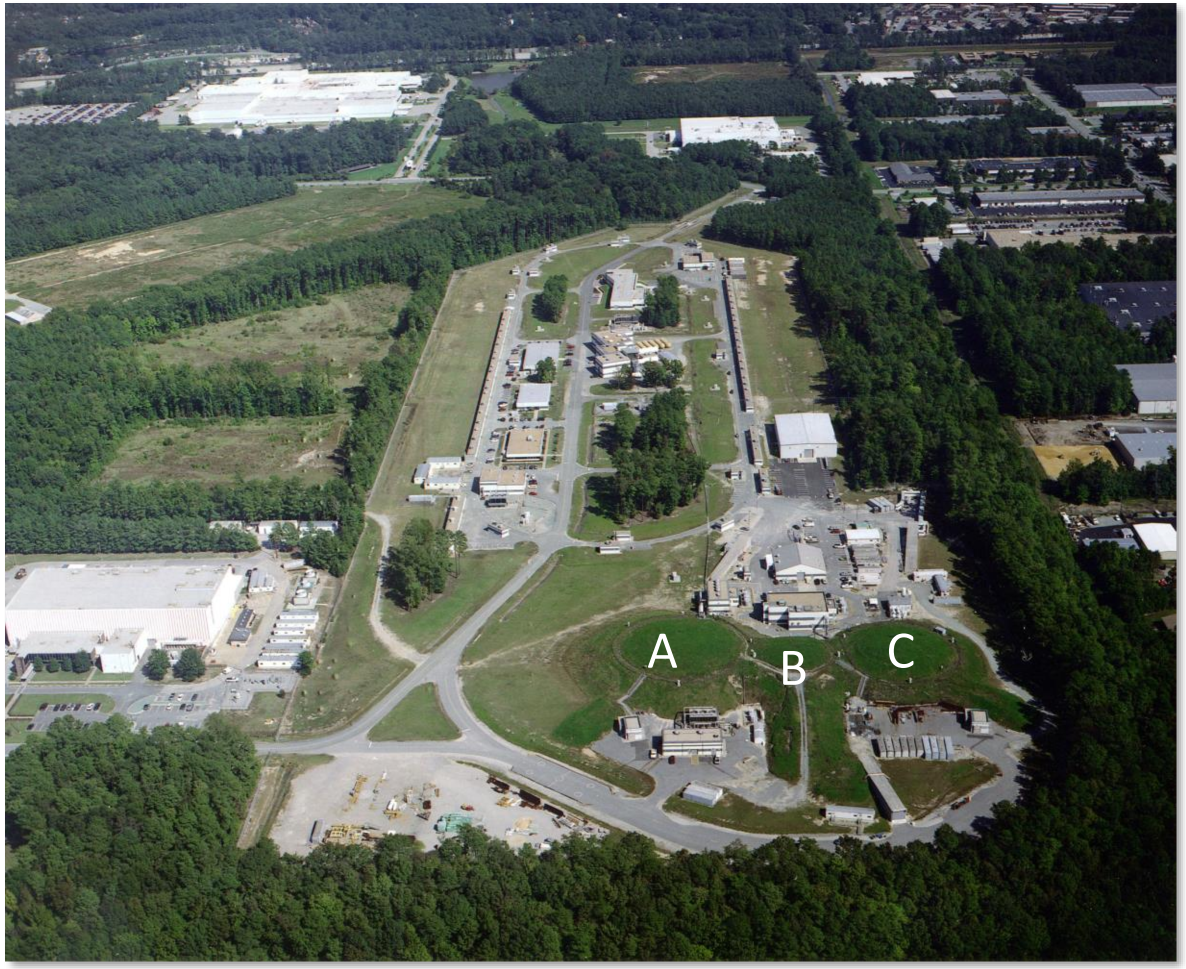
$\langle Q^2 \rangle = 2.0\ (\mathrm{GeV}/c)^2$
$\langle x_{Bj} \rangle = 0.093$



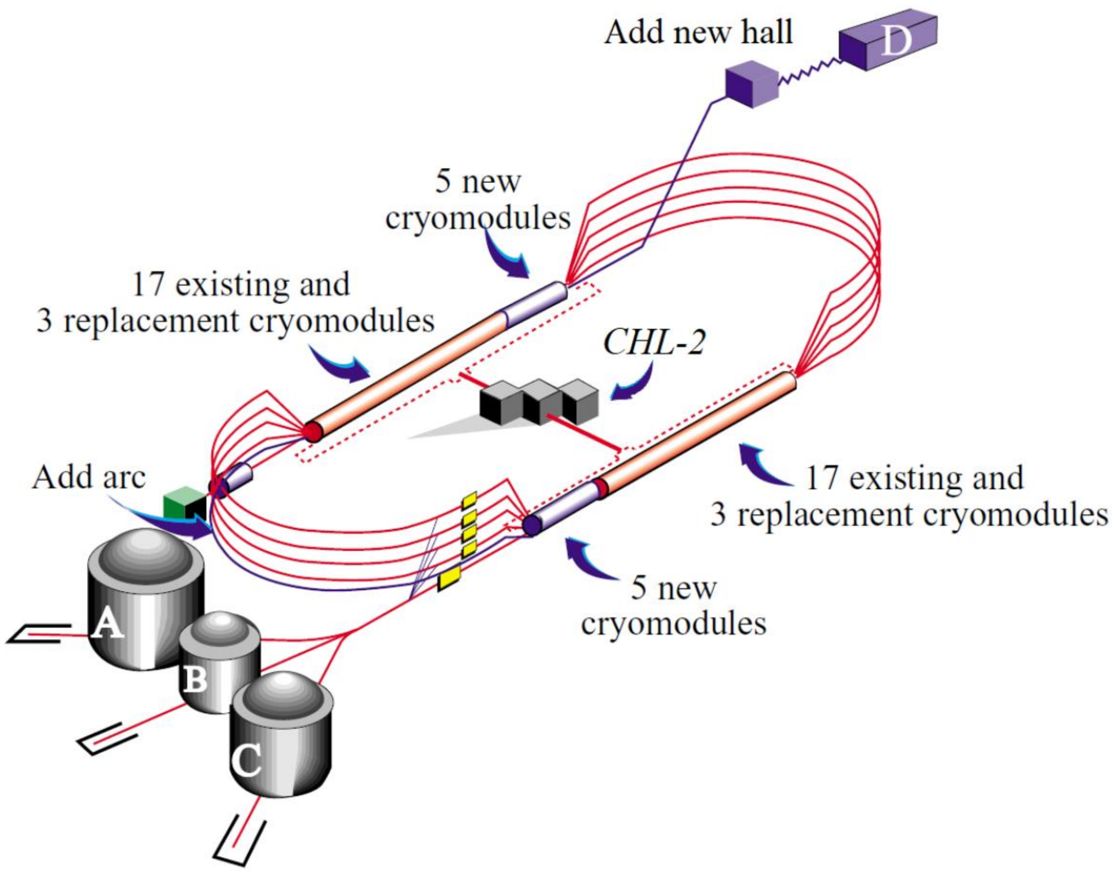
M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

Jefferson Lab

https://en.wikipedia.org/wiki/Thomas_Jefferson_National_Accelerator_Facility



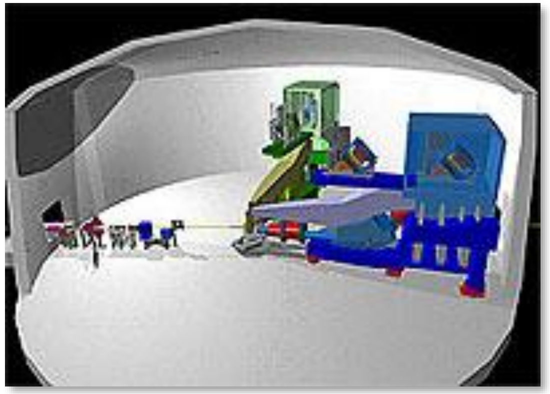
https://www.jlab.org/div_dept/physics_division/GeV/whitepaperv11/index.html



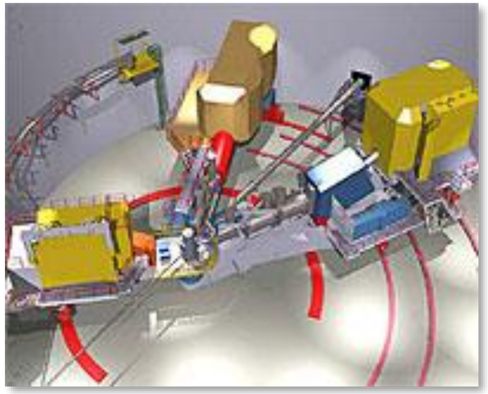
Jefferson Lab: US national laboratory located in Newport News, Virginia
→Continuous Electron Beam Accelerator Facility (CEBAF) + exp. Halls.

Jefferson Lab Experimental Halls

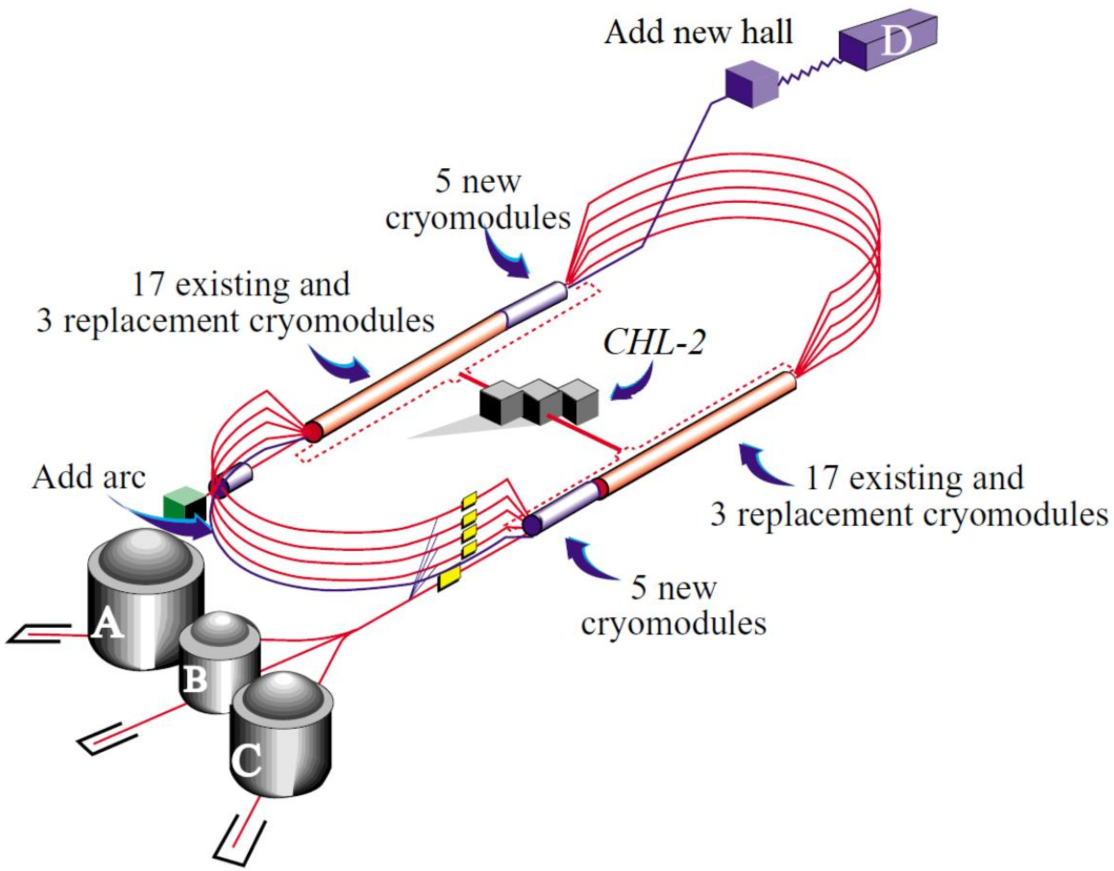
Hall A



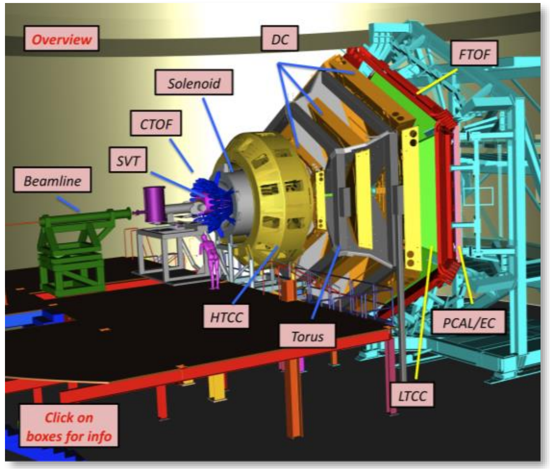
Hall C



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



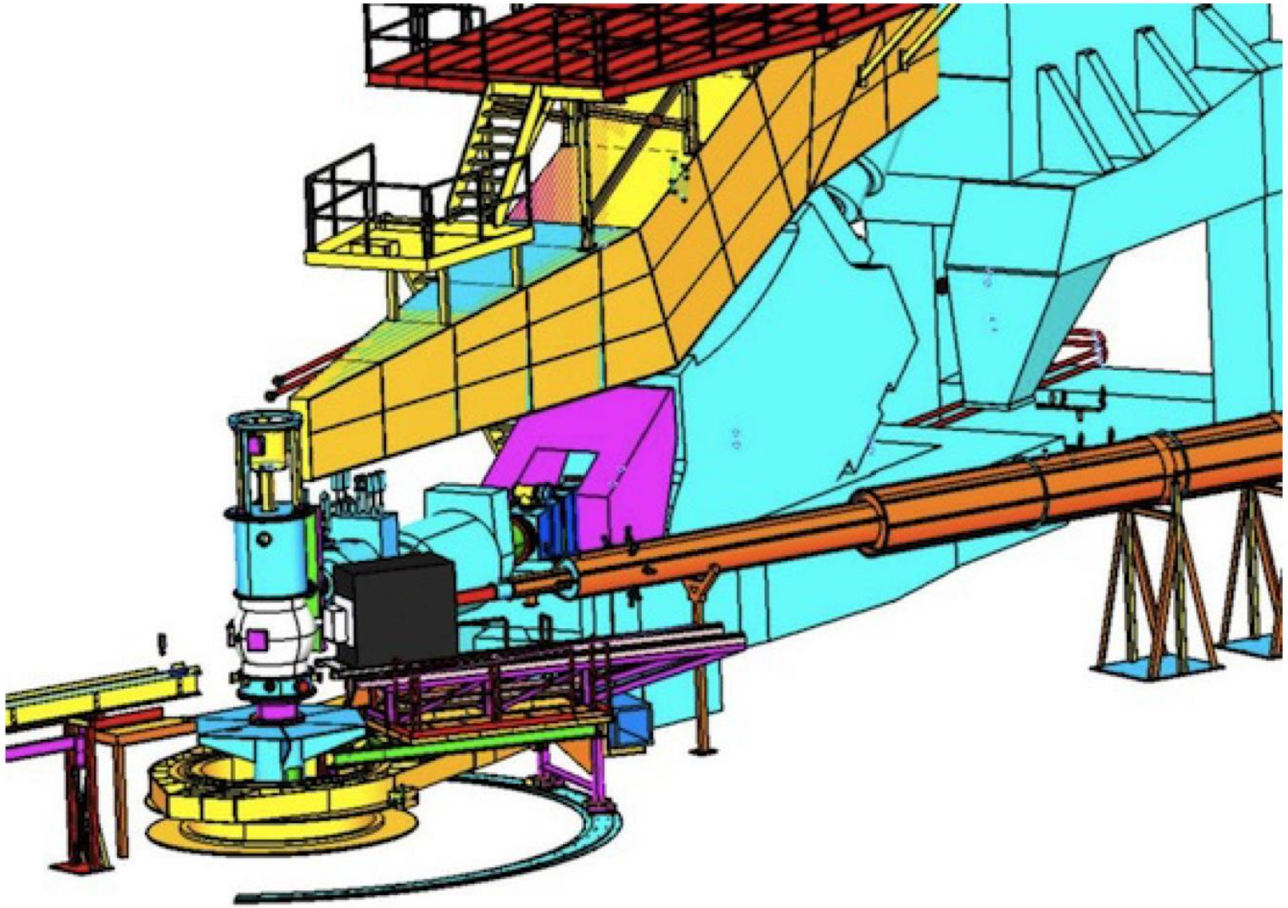
- High luminosity, limited kinematic coverage
  → Test the validity of theoretical formalism

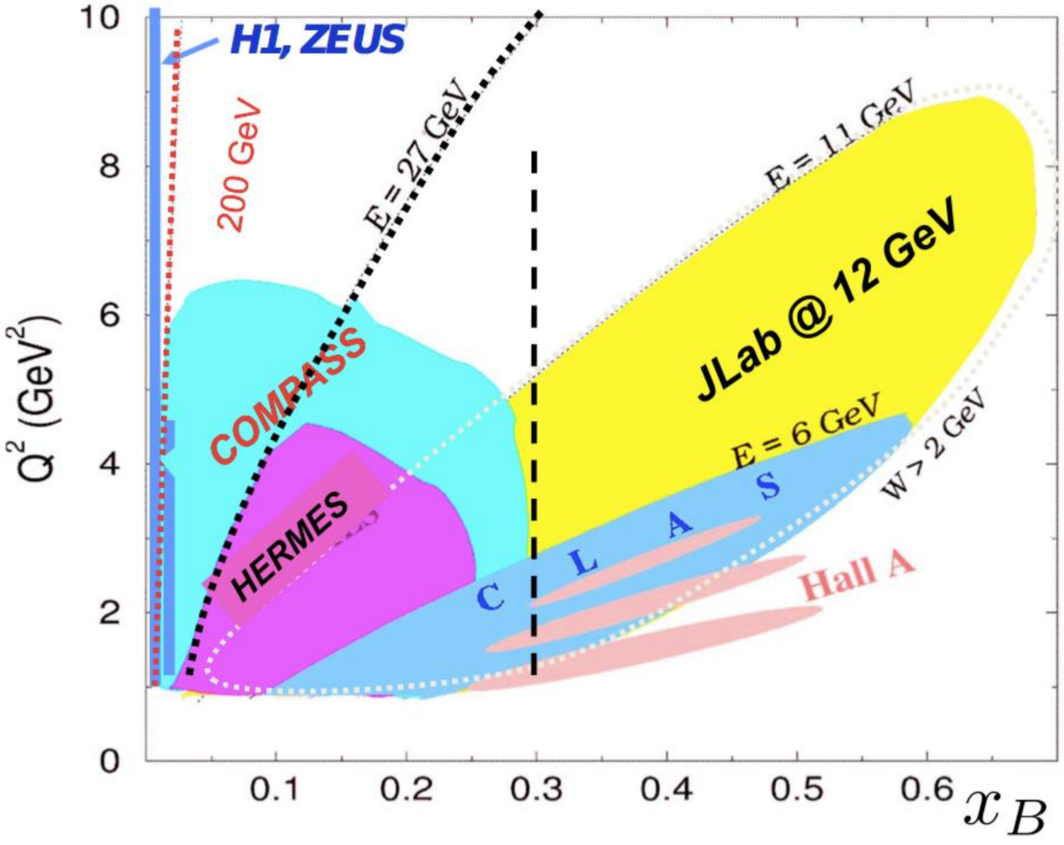


Hall B – CLAS 12

- Lower luminosity, wide kinematic coverage → Map the GPDs

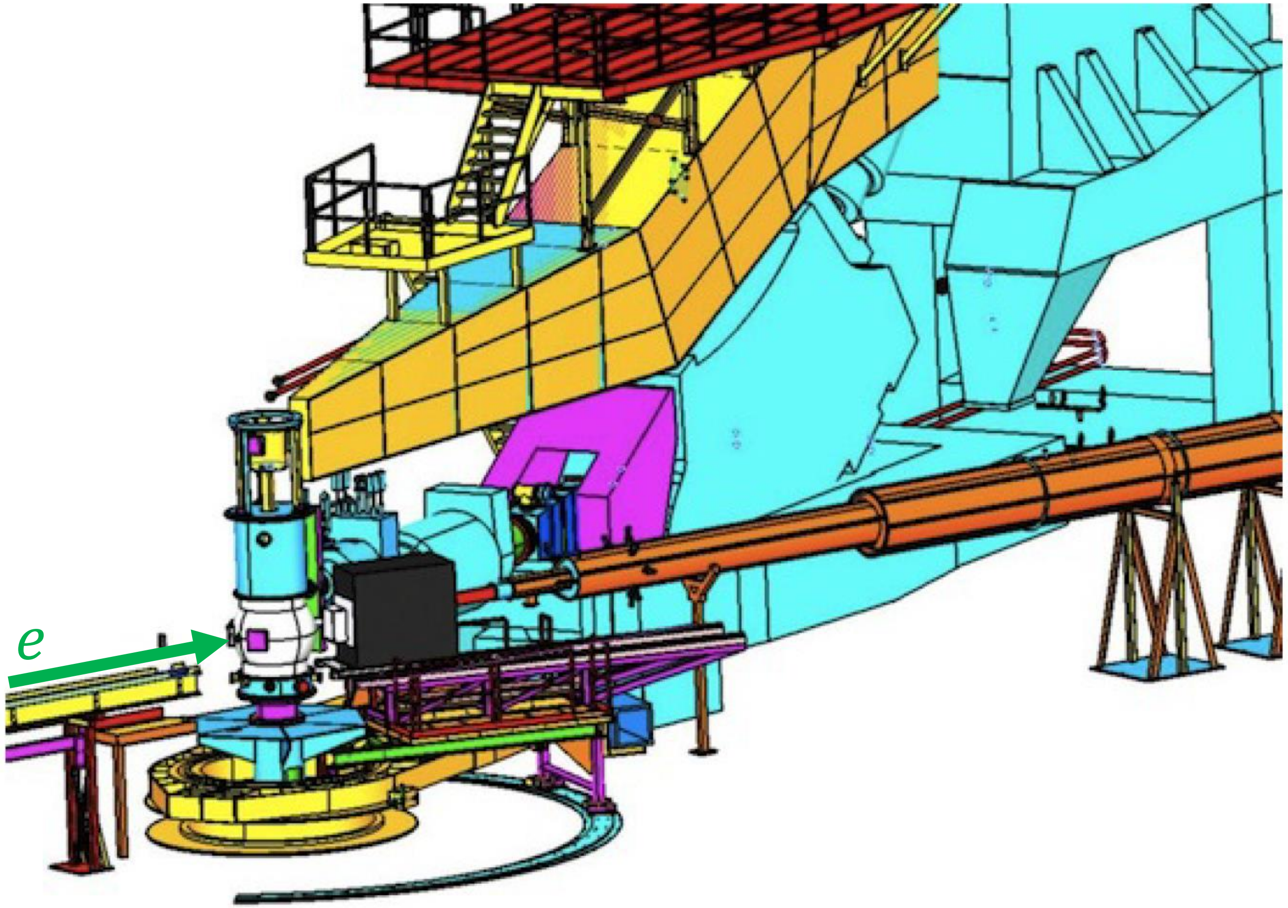
Jefferson Lab Hall A experiment E12-06-114



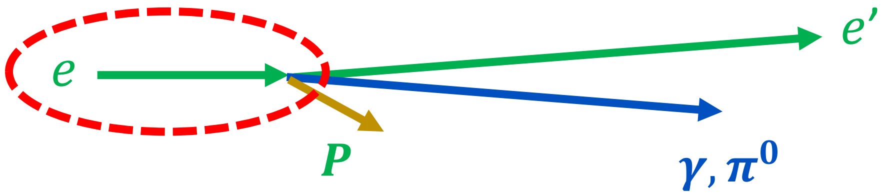


➢ 3rd Generation DVCS project @ Hall A→ CEBAF12 grants the ability to explore high x_B with extended Q^2.

E12-06-114 Experimental Setup

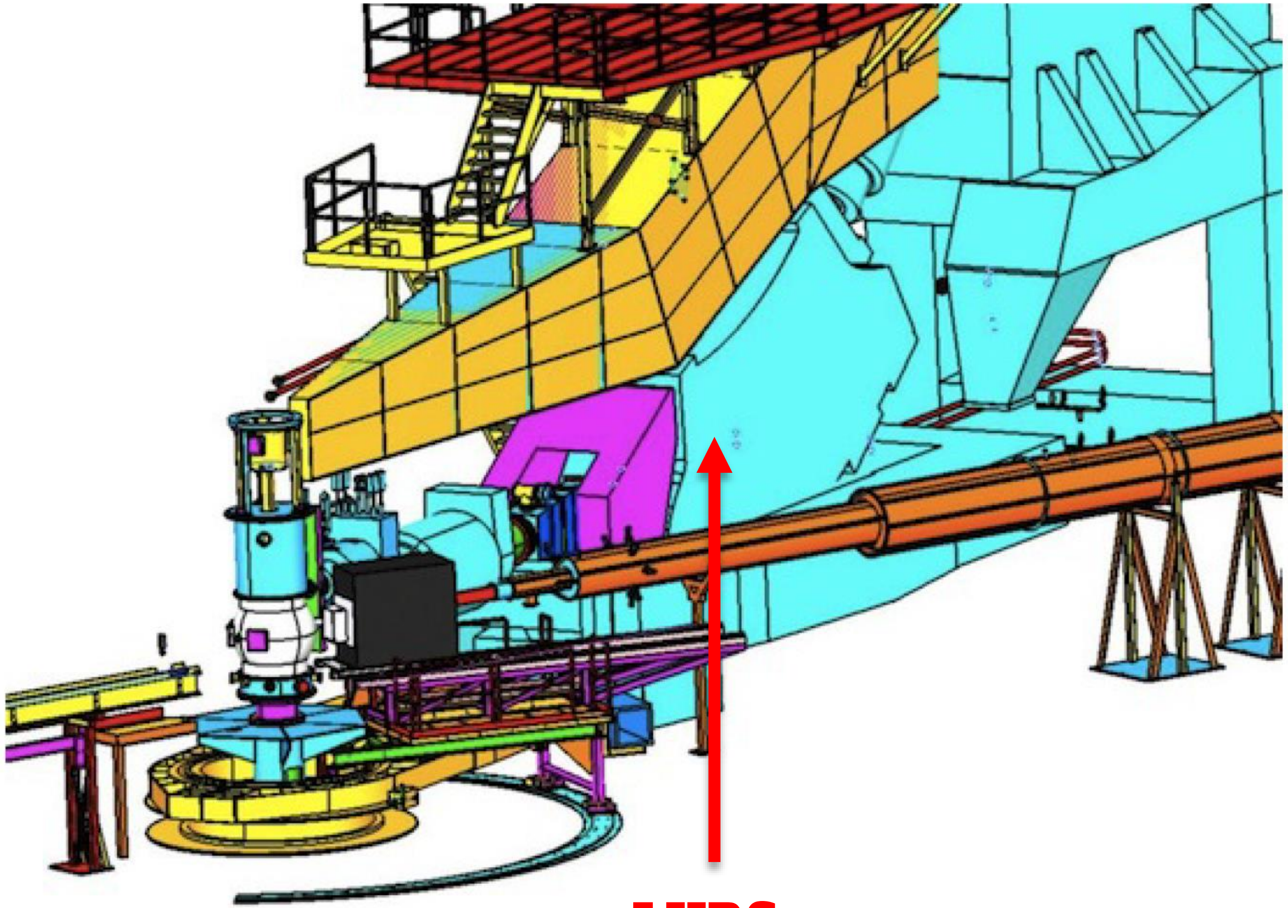


DVCS & Exclusive π^0 Production

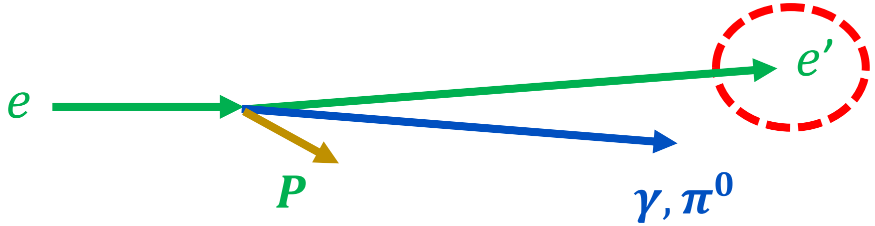


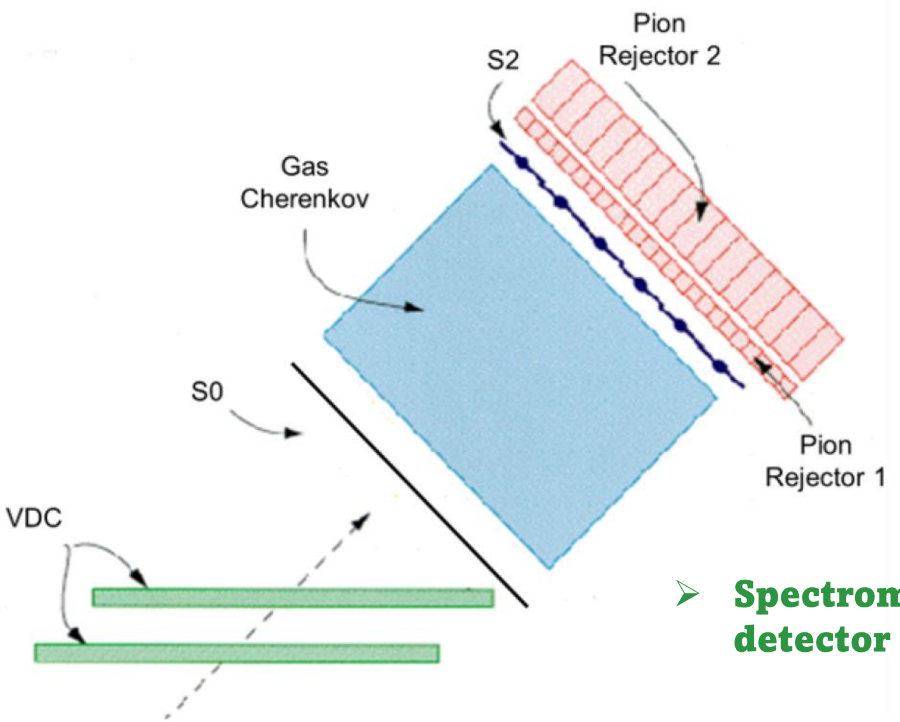
- **Electron beam**
  - **- polarisation ~ 85%**
  - **- helicity flipped at 30 Hz**
  - **- luminosity: ~ 10^{38} Hz/cm^2**
- **LH_2 target**
  - **- 6.35 cm diameter, 15 cm long**

E12-06-114 Experimental Setup



DVCS & Exclusive π^0 Production

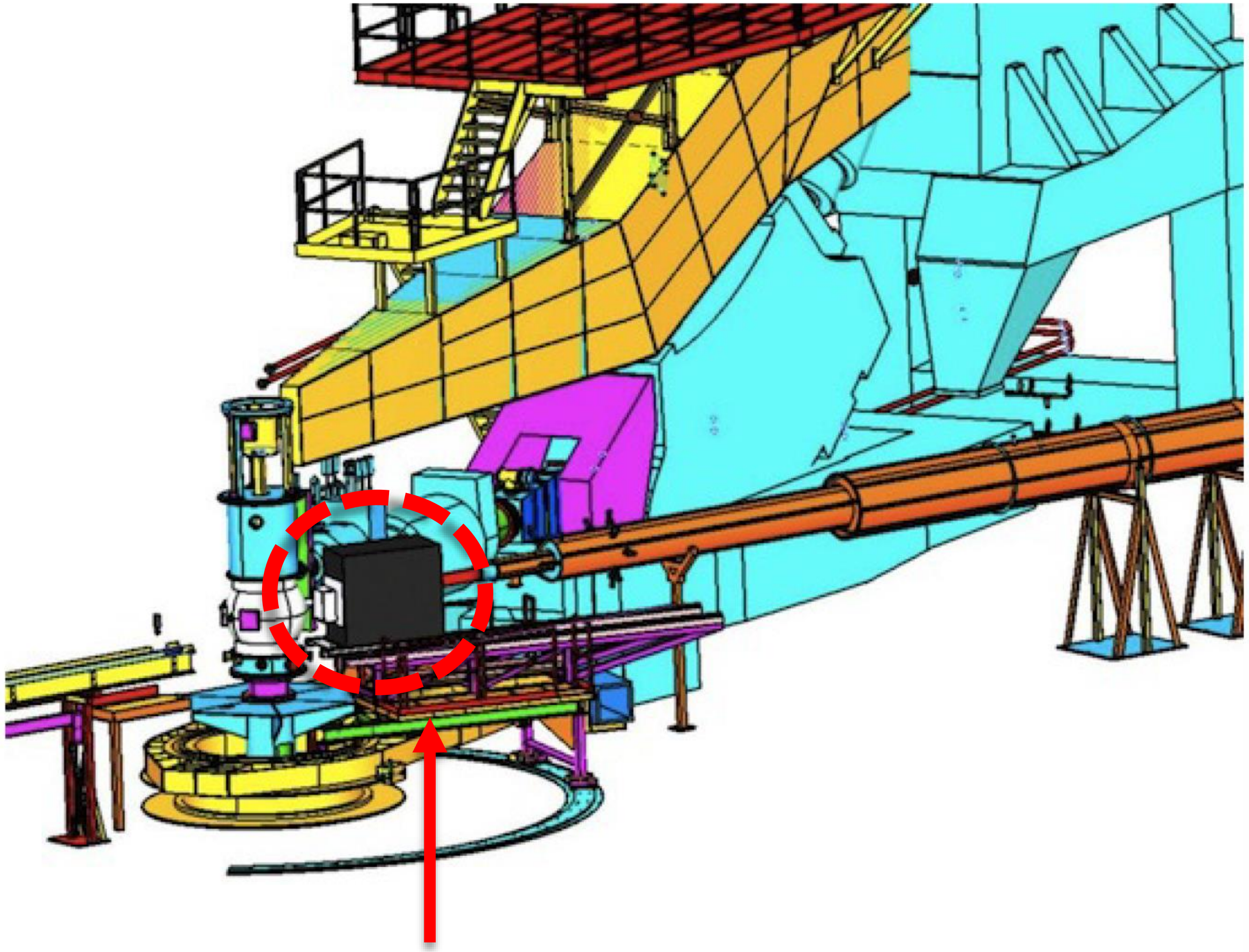




- **Spectrometer detector package**

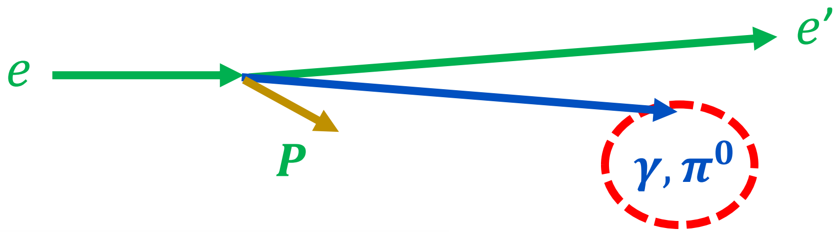
- **$\delta P/P$ resolution ~ 10^{-4} @ 4.3 GeV**

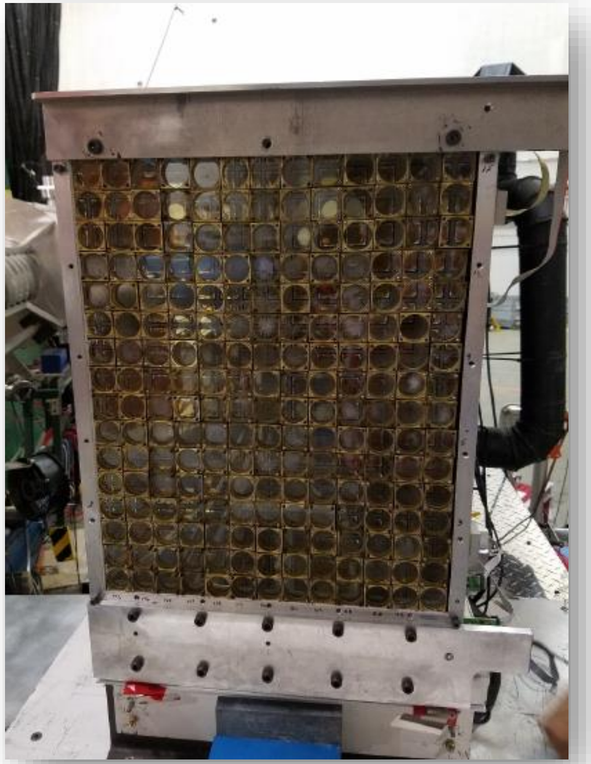
E12-06-114 Experimental Setup



ECAL

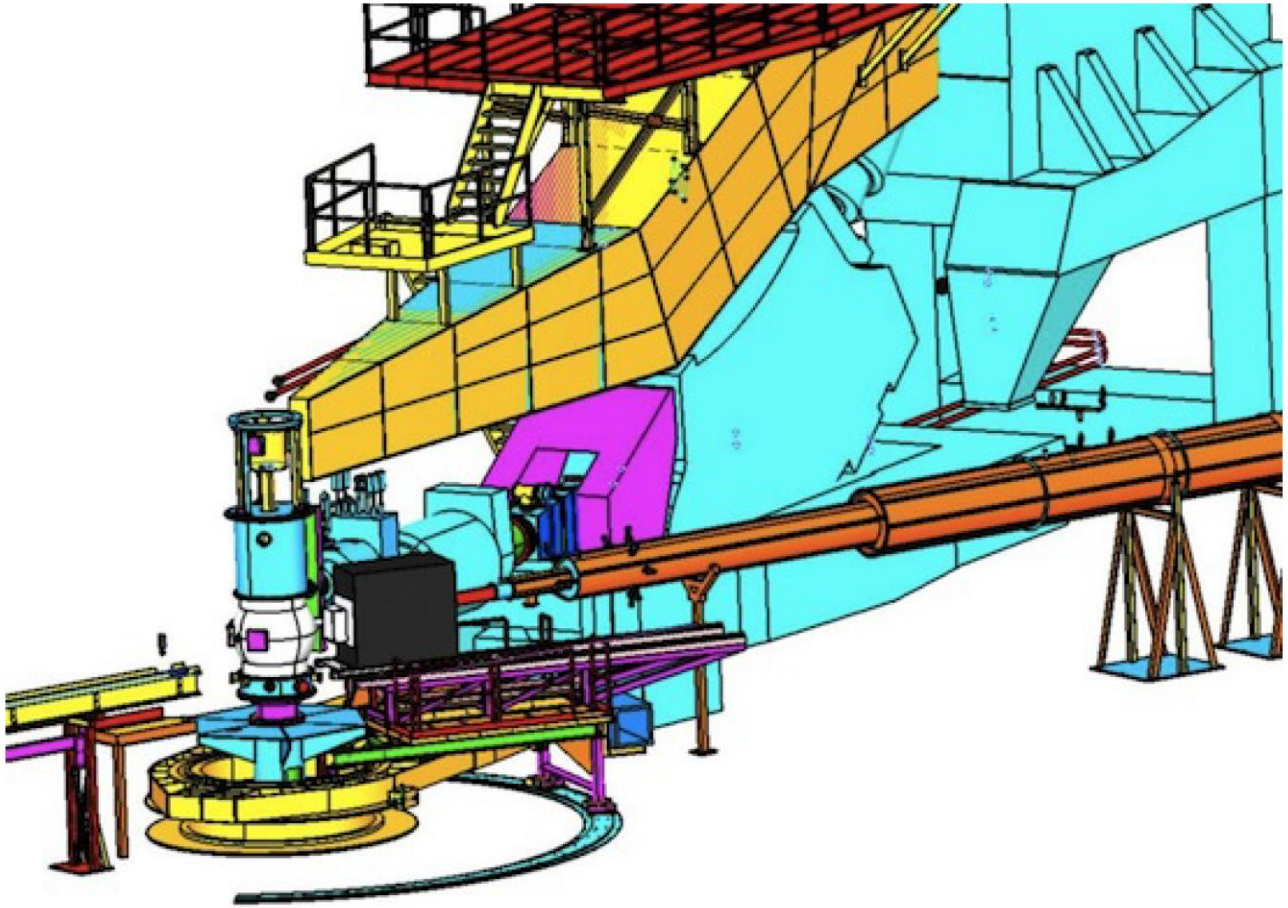
DVCS & Exclusive π^0 Production



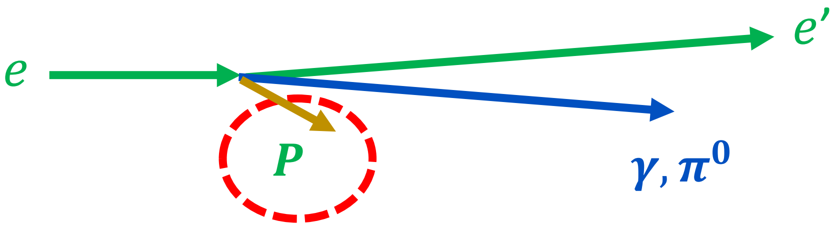


- **ECAL**
  - **208 blocks of PF_2**
  - **$3 \times 3 \times 18.6$ cm^3 each**
  - **~ 20 radiation lengths**
  - **Moliere radius 2.2cm**
  - **E resolution ~ 3% @ 4.2 GeV**

E12-06-114 Experimental Setup



DVCS & Exclusive π^0 Production

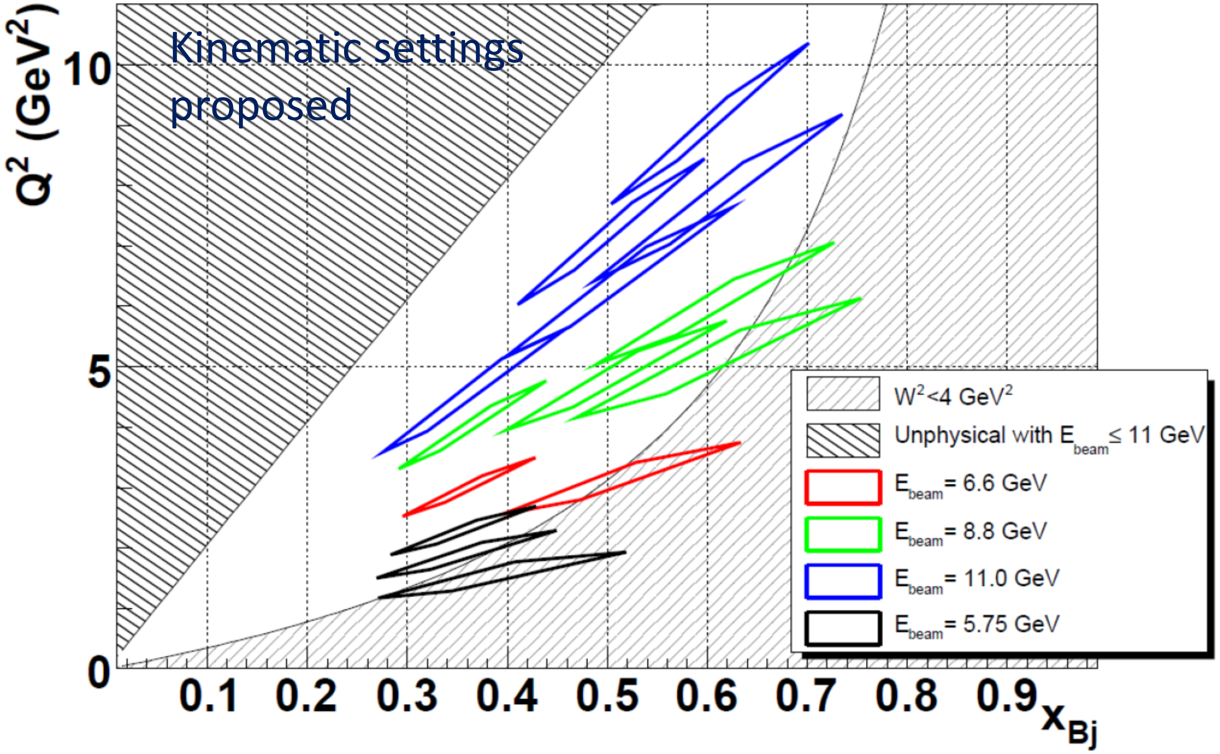


Recoil Proton

- **Not detected**
- **Exclusivity of events ensured using missing mass, M_X^2**

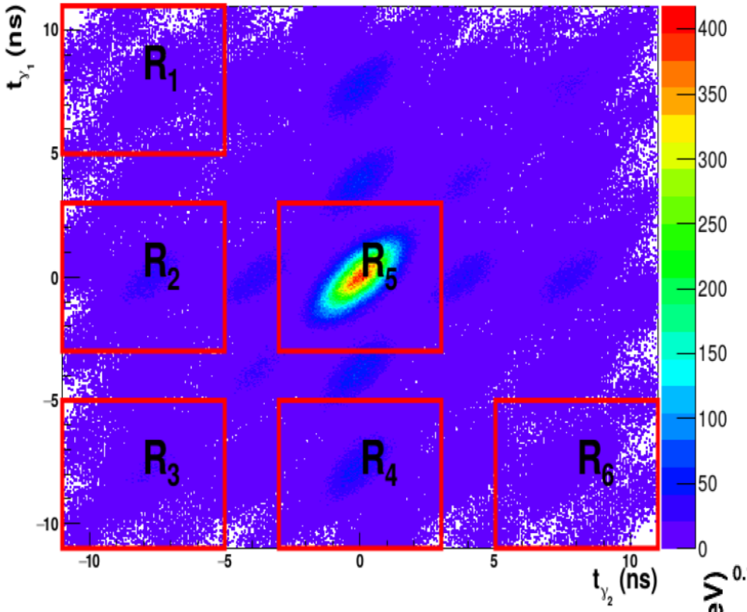
E12-06-114 Kinematic Settings

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
W^2 (GeV^2)	6.51	7.29	8.79	3.81	5.62	6.67	8.32	4.58	6.46
$-t_{\min}$ (GeV^2)	0.16	0.17	0.17	0.33	0.35	0.35	0.36	0.67	0.71
ϵ	0.61	0.62	0.63	0.51	0.71	0.55	0.52	0.66	0.50

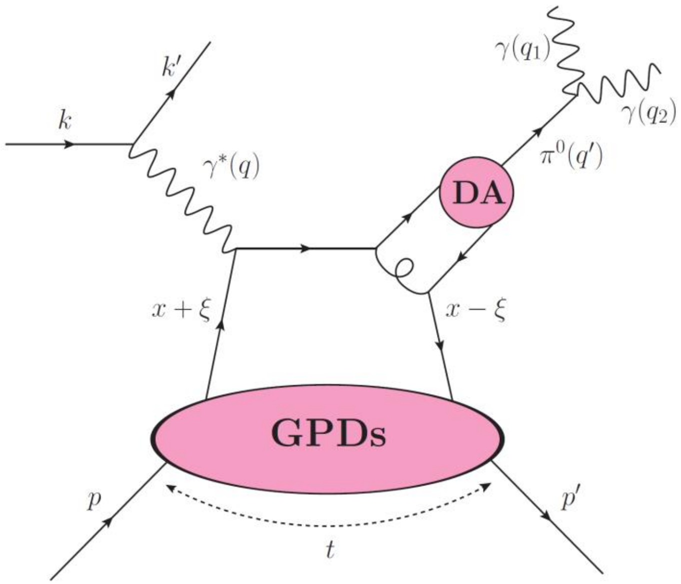


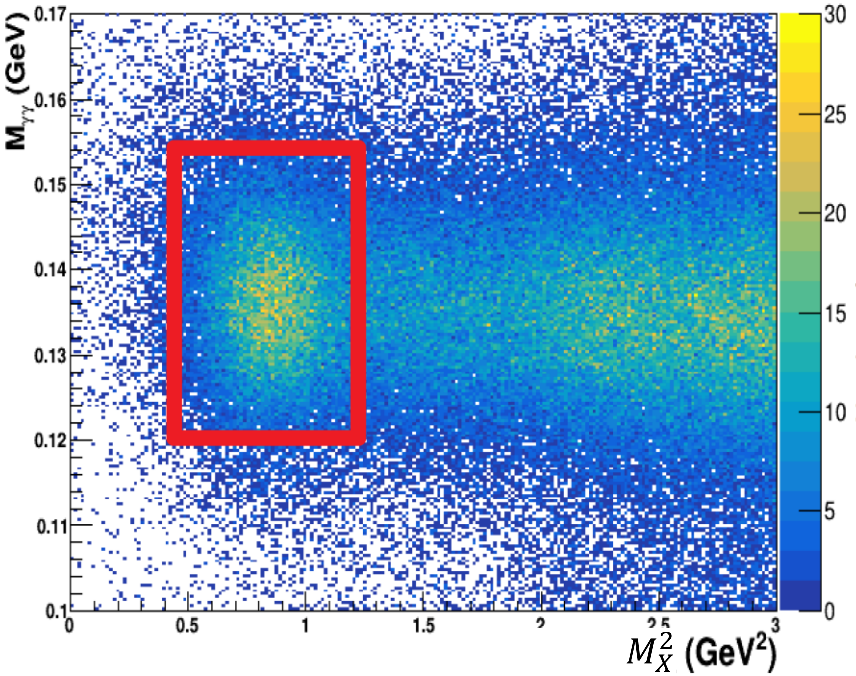
- Ran in 2014 & 2016
- 9 settings with x_B of 0.36, 0.48, and 0.6 and Q^2 ranging from about 3 to 8 GeV^2
- About 50% of allocated 100 PAC days
- Missing PAC days reallocated to the future experiment @ Hall C

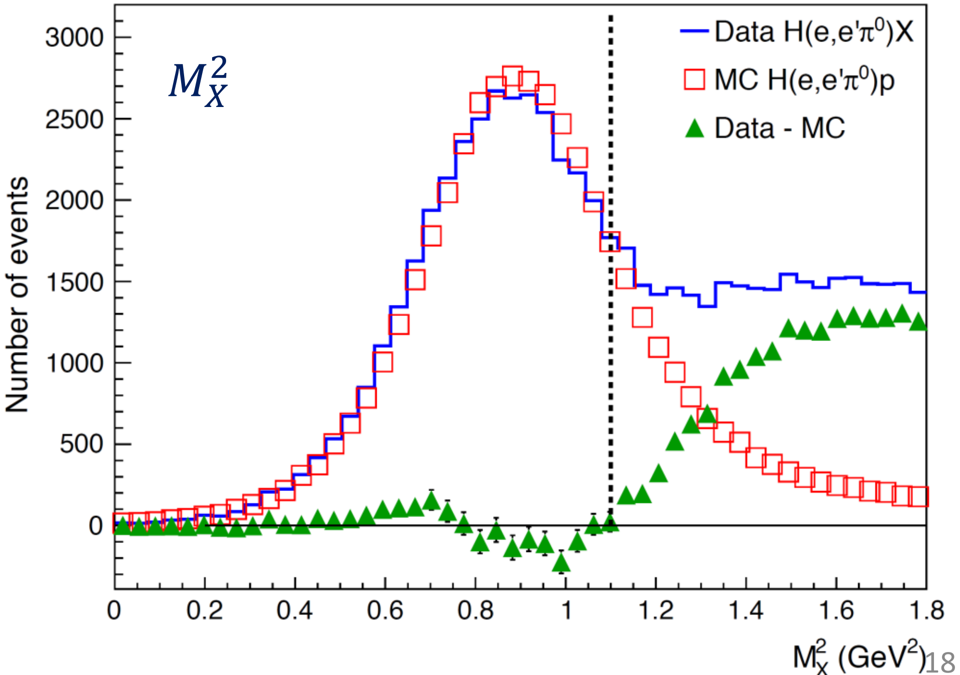
Exclusive π^0 Event Selection



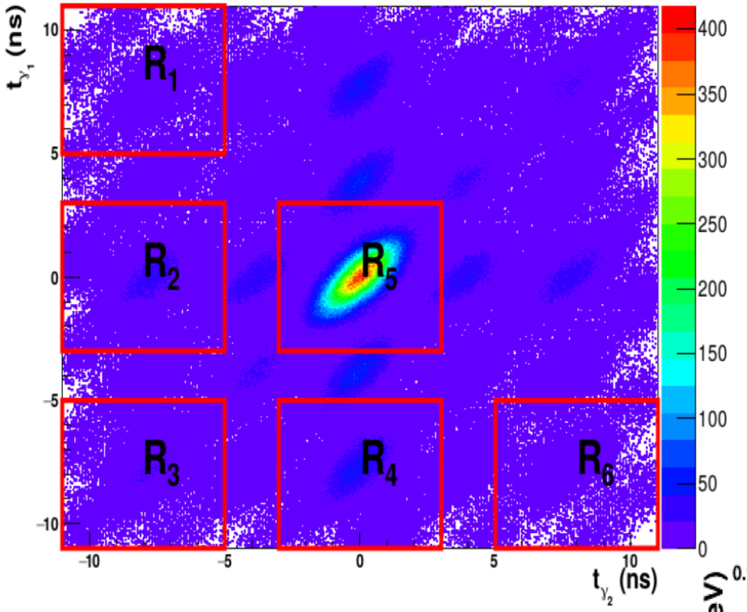
- Main background: accidentals. The backgound in the signal coincidence window, [-3,3] ns, is estimated via other time windows.
- Exclusivity → remove the $M_X^2 = (k + P - k' - q_1 - q_2)^2$ contribution from inclusive channels, threshold ≈ 1.15 GeV²
- π^0 events → select events with invariant mass $M_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$ around the π^0 mass







Exclusive π^0 Event Selection



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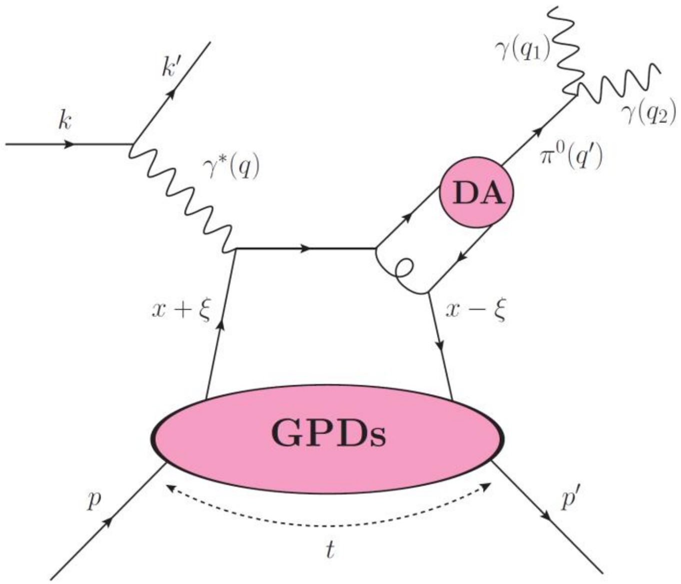
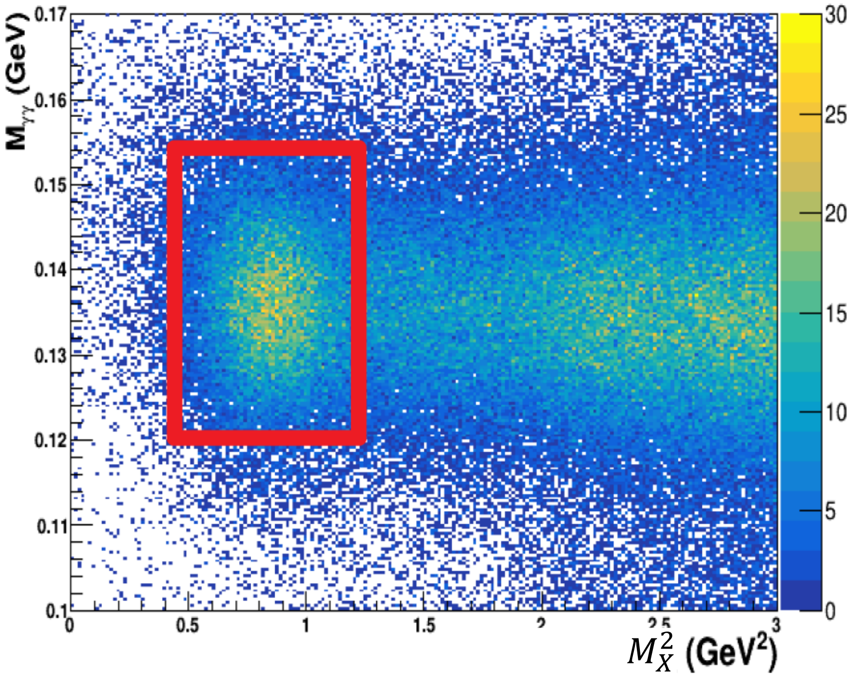
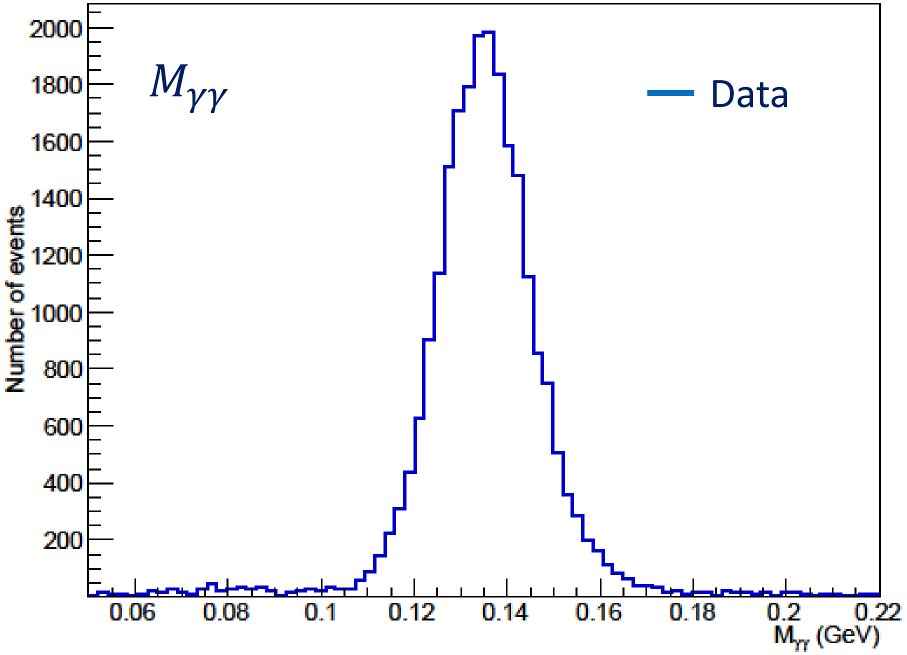
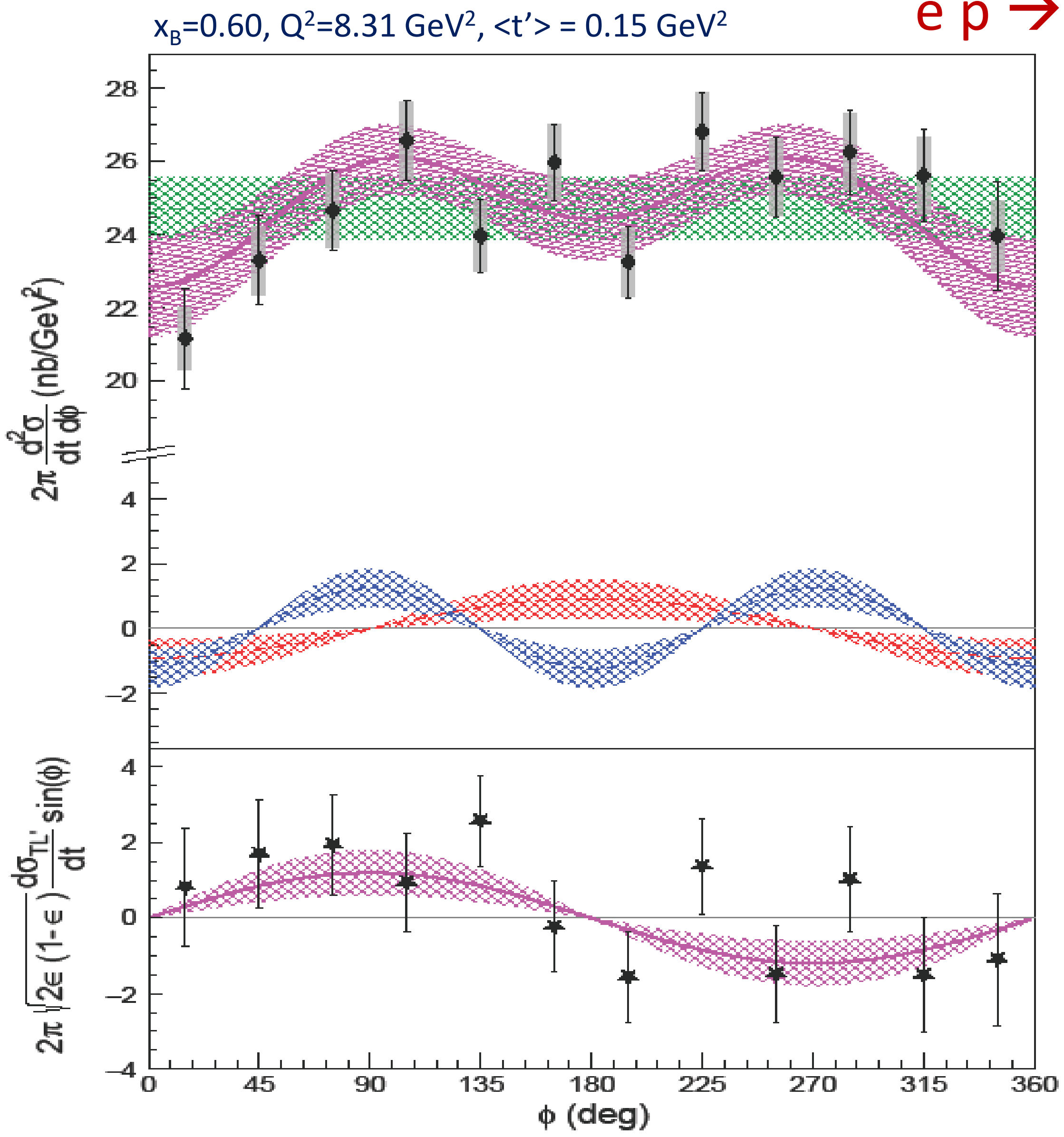






Cross-section Extraction



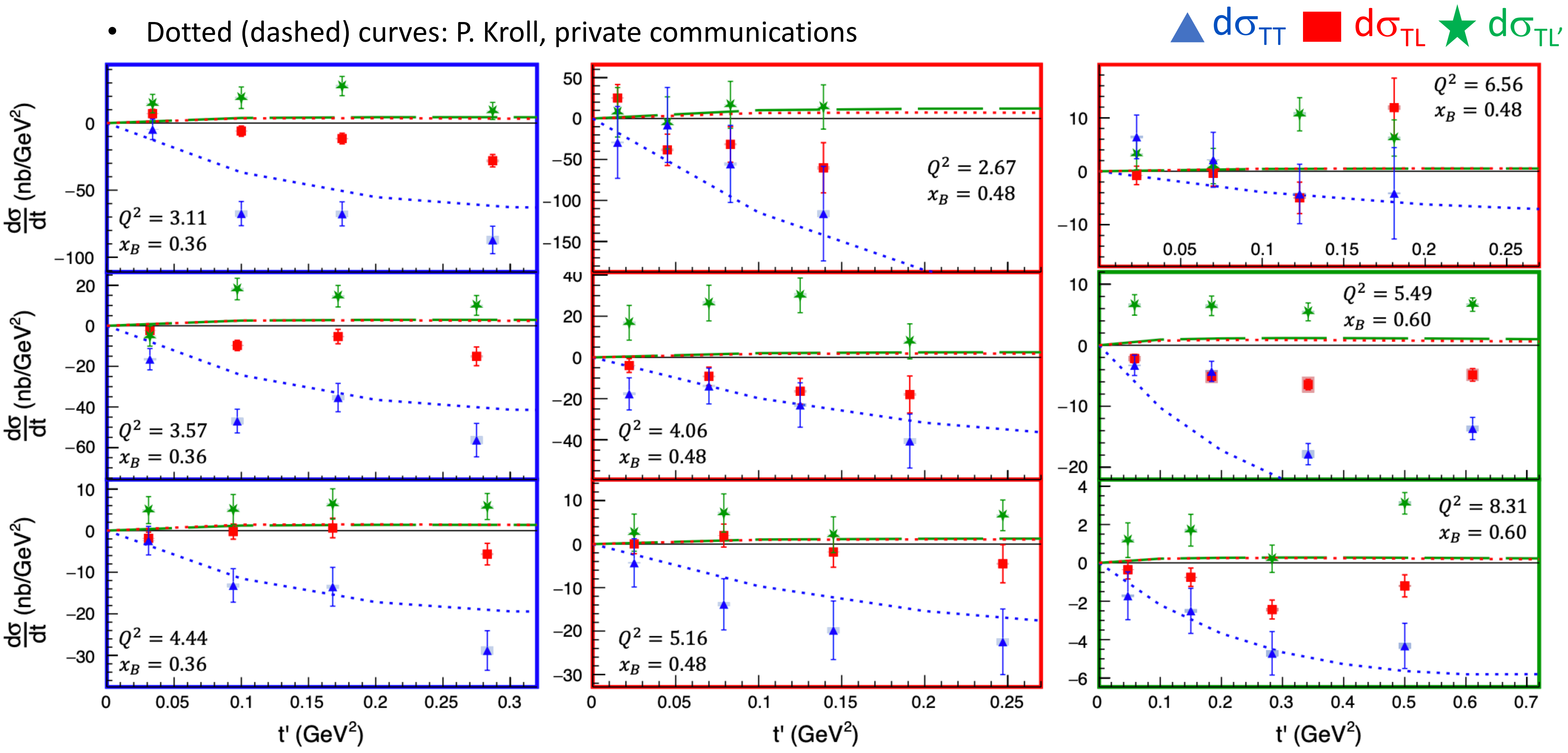
e p → e π^0 p

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

- 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

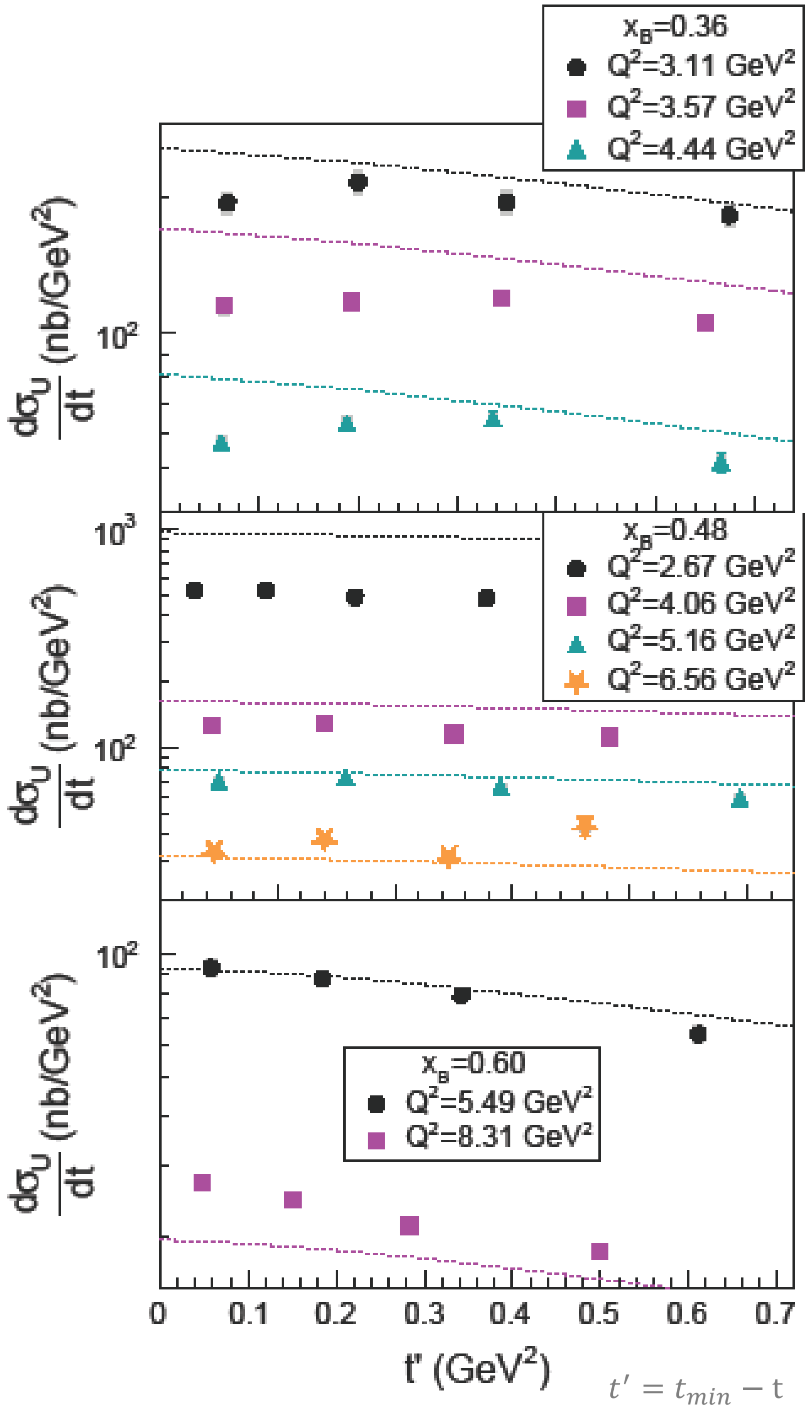
Cross-sections

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



$t' = t_{min} - t$

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301



$t' = t_{min} - t$

Cross-sections

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

➢ Reasonable agreement in $d\sigma_U$ 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 both σ_{TL} & $\sigma_{TL'}$

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

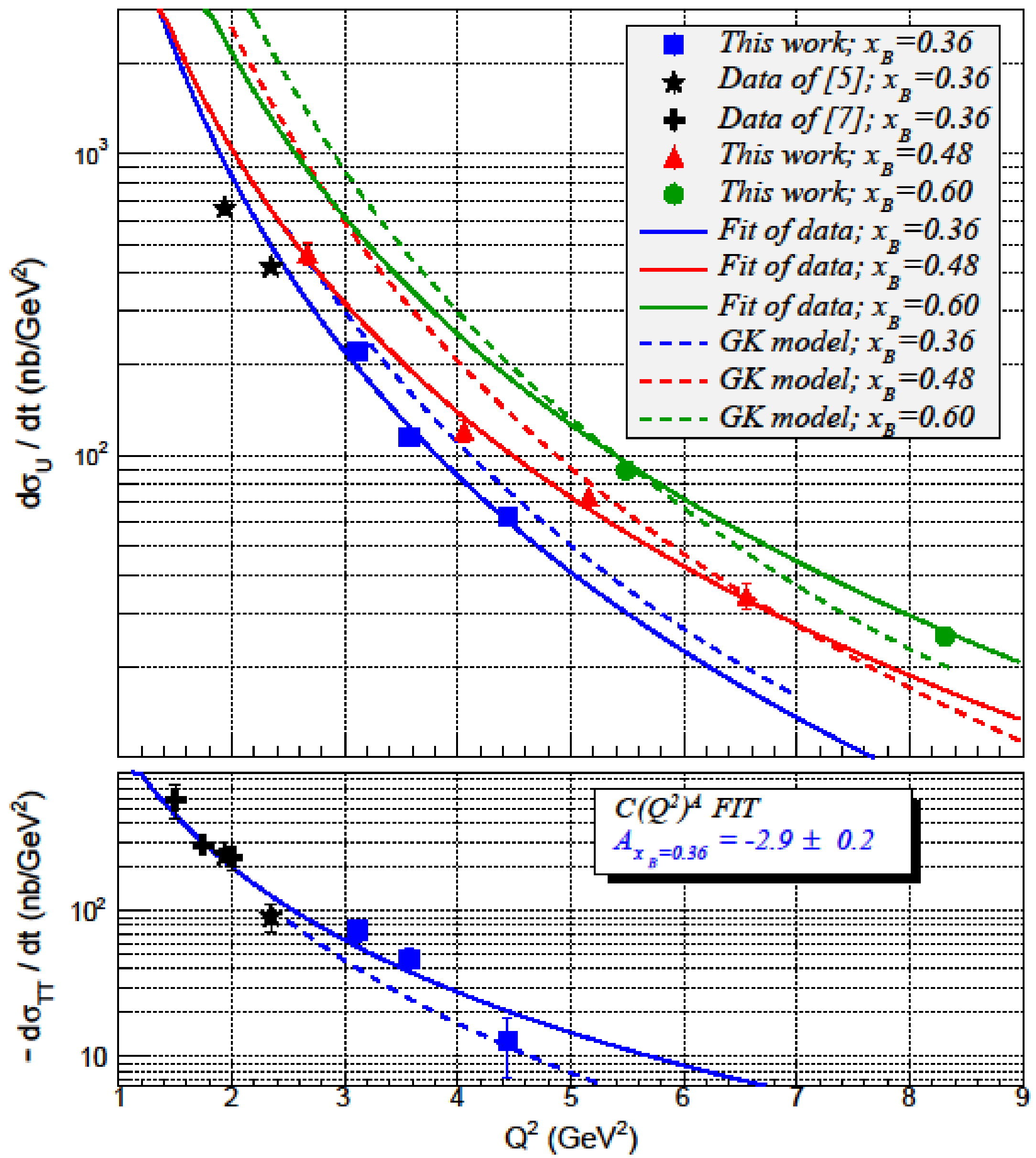
➢ Sign difference in σ_{TL}

- Different from Hall B or COMPASS results

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

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301

Q^2 Dependence



- Dashed curves: 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)

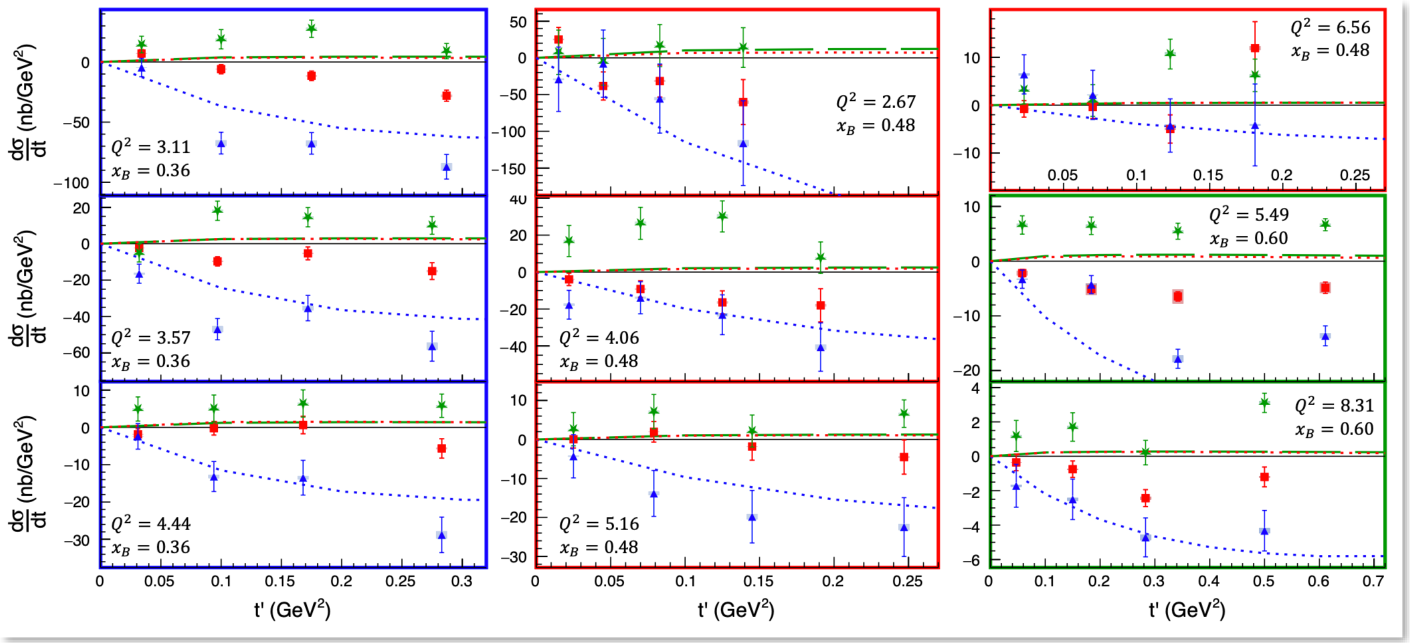
➢ $C(Q^2)^A \exp(-Bt')$ fit to experimental results of $d\sigma_U$ in different x_B → solid curves

$x_B = 0.36 \rightarrow A = -3.3 \pm 0.1$
$x_B = 0.48 \rightarrow A = -2.9 \pm 0.1$
$x_B = 0.60 \rightarrow A = -3.1 \pm 0.1$

➢ Q^2 dependence closer to Q^{-6}, rather than Q^{-8} as expected for σ_T at high Q^2

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301

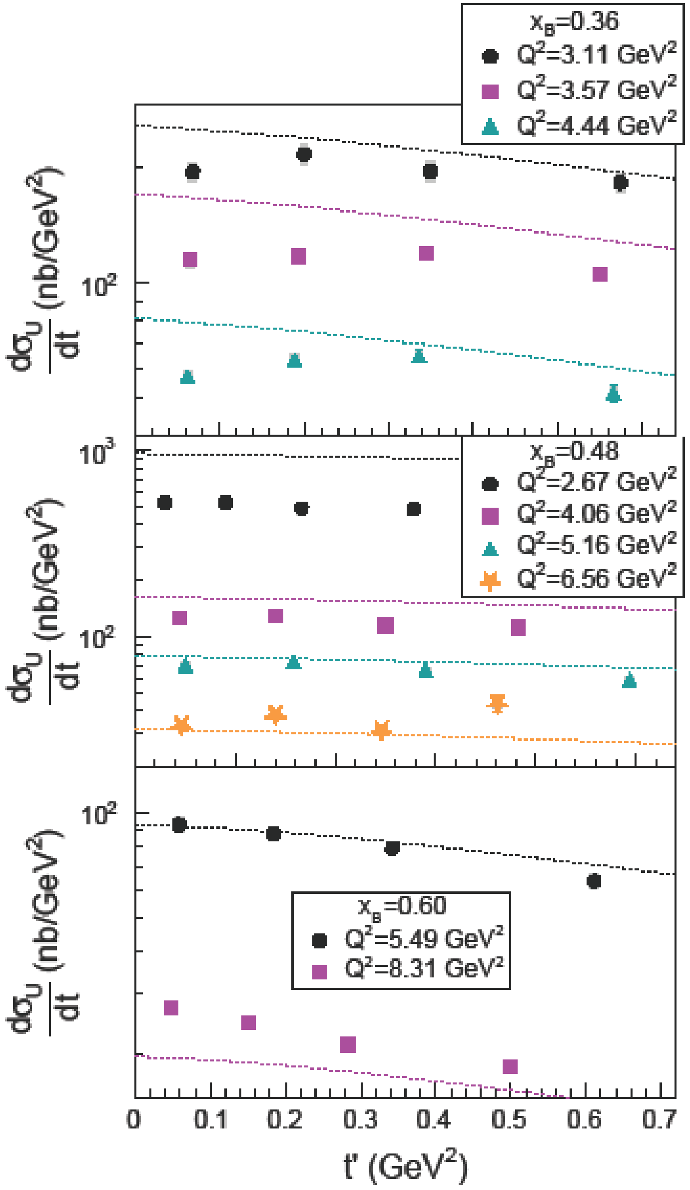
Summary



Exclusive π^0 Production

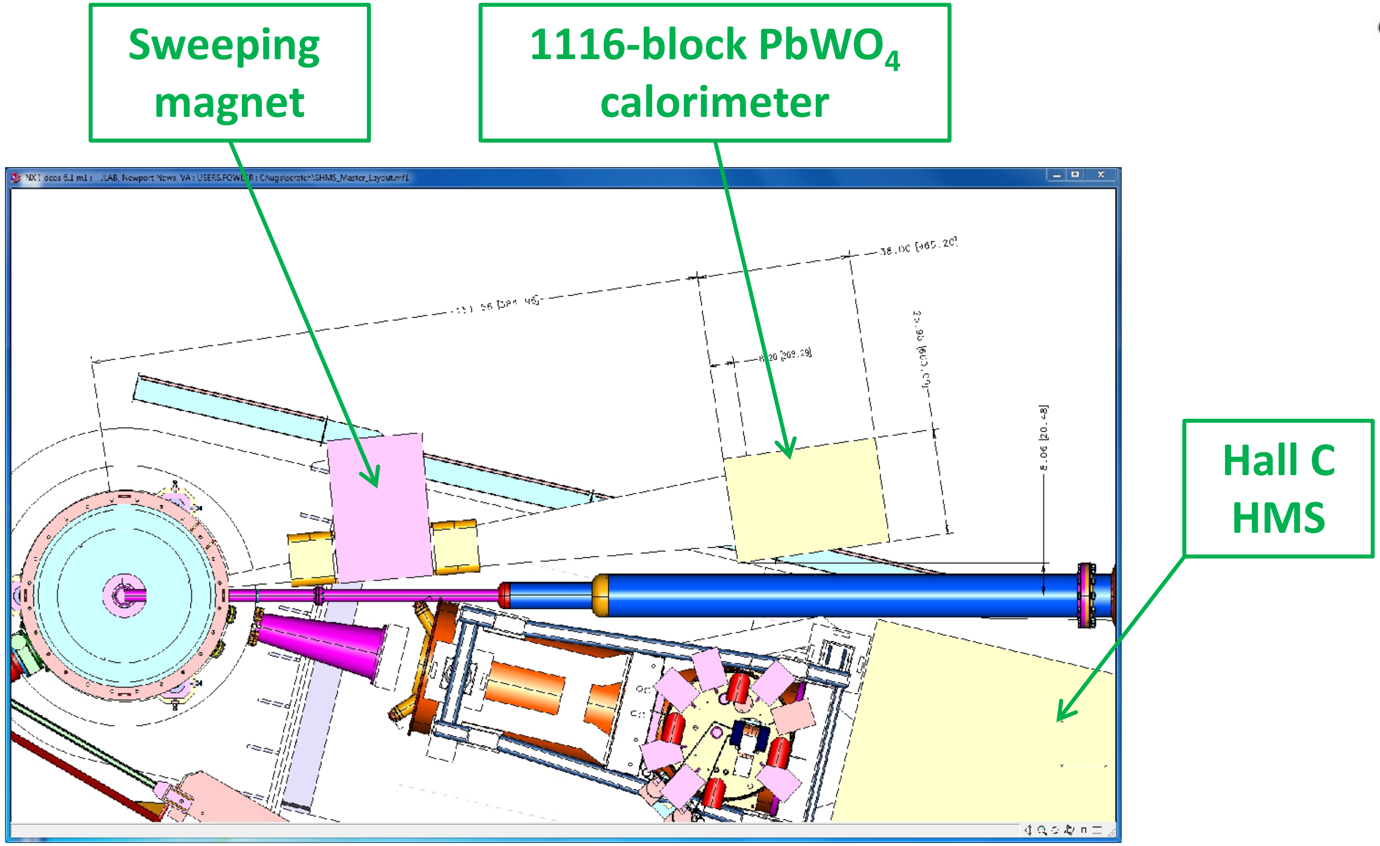
(M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301)

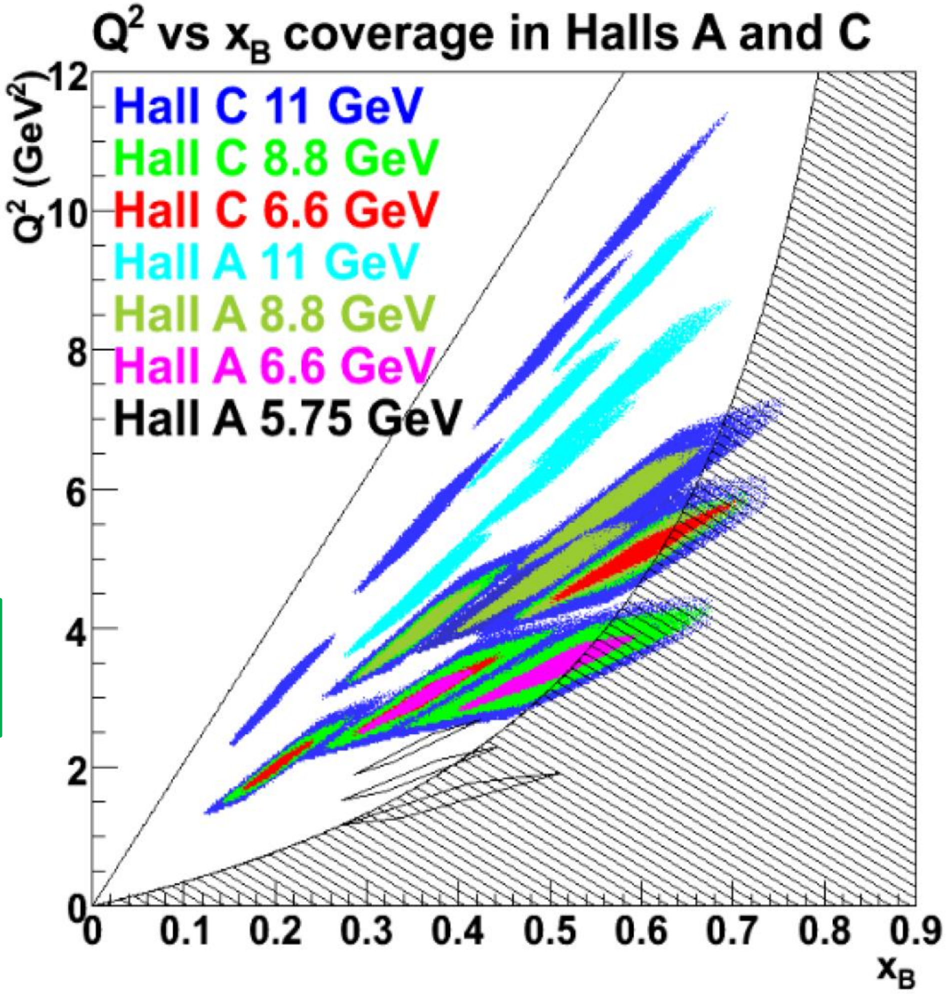
- ➢ Reasonable description of results by GK model
- ➢ Non-negligible contributions from longitudinal and transverse amplitudes are needed to better describe the data
- ➢ Provide inputs for transversity GPD parameterization



Outlook

- Extension to higher Q^2 and lower x_B
- σ_T and σ_L separation of π^0 production at Hall C





Thank you!