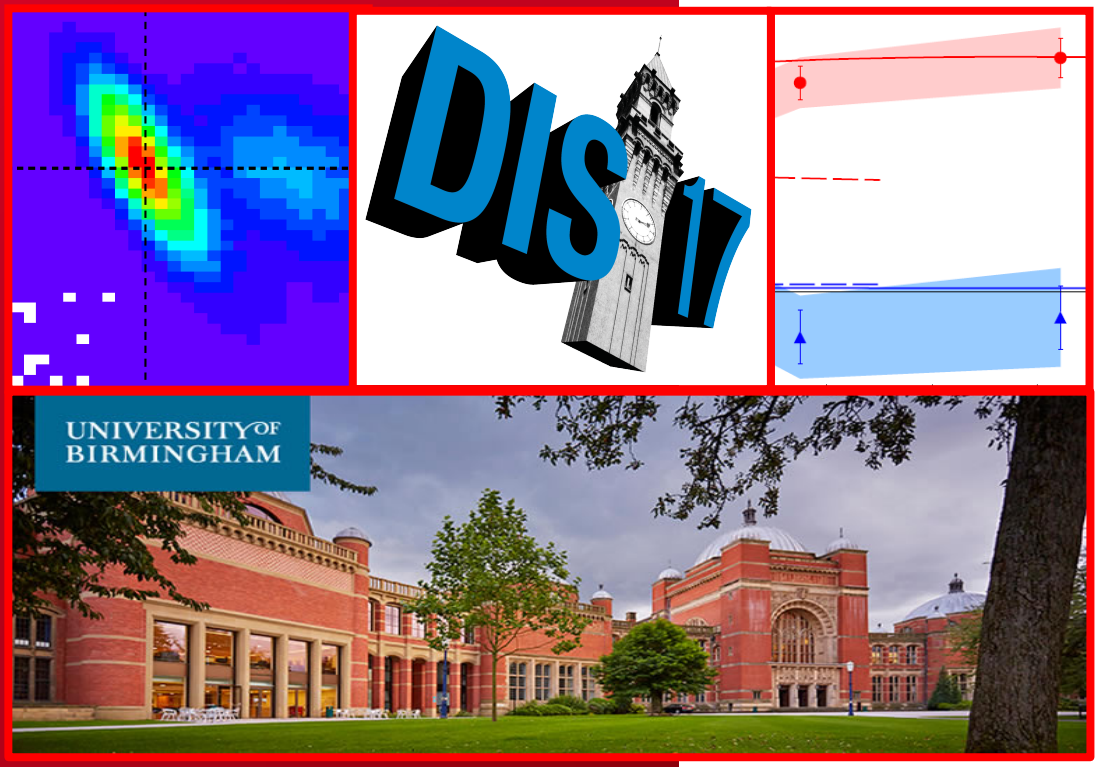
Separated π^0 electroproduction cross sections off the nucleon at Jefferson Lab Hall A

F. Sabatié – CEA Saclay

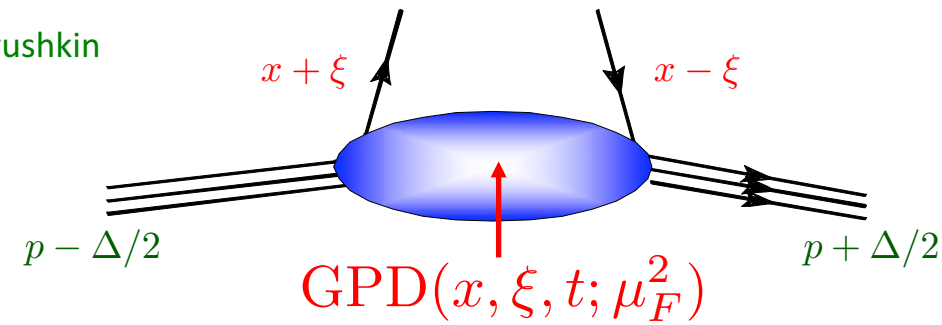
DE LA RECHERCHE À L'INDUSTRIE



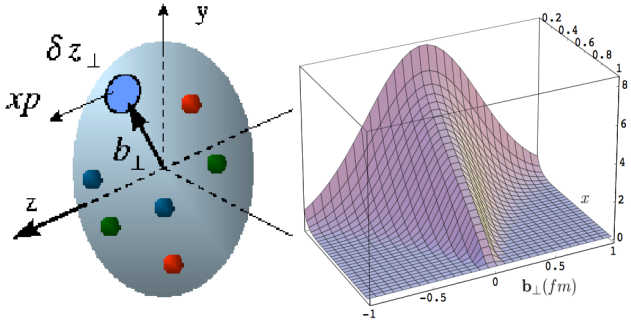
- Introduction
- Generalized Parton Distributions
- $ep \to ep(\gamma/\pi^0)$ to access GPDs
- π^0 analysis & proton results
  PRL 117, 262001 (2016)
- π^0 electroproduction off the **neutron** (first time ever !)
  arXiv:1702.00835
- Summary & Conclusion

Generalized Parton Distributions

Müller
Ji, Radyushkin



$(x+\xi)$ and $(x-\xi)$: longitudinal momentum fractions of quarks



Impact parameter space Interpretation
Burkardt, Diehl, …

The structure of the nucleon can be described at leading-twist by

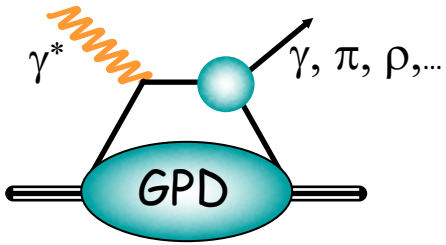
4 chiral-even **Generalized Parton Distributions** :

$$H, \widetilde{H}, E, \widetilde{E}(x,\xi,t;\mu_F^2)$$

4 chiral-odd $H_T, \widetilde{H}_T, E_T, \widetilde{E}_T(x,\xi,t;\mu_F^2)$

> They enter the $\gamma^* p \to (\gamma \text{ or } M)\ p$ amplitude

as convolution integrals : no direct access



Deep Exclusive Processes
Parton distributions in both coordinate and momentum space

> Forward limit $(t=\xi=0)$ of H and $\widetilde{H}$: PDFs

> First moment in x : Form Factors

> Second moment of $(H+E)$ when $t \to 0$: total angular momentum

Definition of Chiral-Odd or helicity-flip GPDs

Belitsky and Mueller'00, Diehl'01

- Quark helicity flip GPDs

$$\frac{1}{2}\int \frac{d\lambda}{2\pi} e^{ixP^+\lambda} \langle N(p')|\bar{\Psi}(-\lambda n/2) i\sigma^{+i} \Psi(\lambda n/2)|N(p)\rangle$$
$$= \frac{1}{2P^+}\bar{U}(p')\left[H_T^q i\sigma^{+i} + \tilde{H}_T^q \frac{P^+\Delta^i - \Delta^+ P^i}{m^2}\right.$$
$$\left. + E_T^q \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde{E}_T^q \frac{\gamma^+ P^i - P^+\gamma^i}{m}\right] U(p),$$

- Gluon helicity flip GPDs

$$\frac{1}{P^+}\int \frac{d\lambda}{2\pi} e^{ixP^+\lambda} \langle p'|\mathbb{S} G^{+i}(-\lambda n/2) G^{j+}(\lambda n/2)|p\rangle$$
$$= \mathbb{S}\,\frac{1}{2P^+}\frac{P^+\Delta^j - \Delta^+ P^j}{2mP^+}\bar{U}(p')\left[H_T^g i\sigma^{+i} + \tilde{H}_T^g \frac{P^+\Delta^i - \Delta^+ P^i}{m^2}\right.$$
$$\left. + E_T^g \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde{E}_T^g \frac{\gamma^+ P^i - P^+\gamma^i}{m}\right] U(p),$$

Accessing Generalized Parton Distributions

Deeply Virtual Compton Scattering

- Theory is under control : up to α_S^2 , twist-3, target mass corrections, etc.

Müller et al,
Braun et al, ...

- Sensitive to the quark combination : $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s$

- At Jefferson Lab energies, *mostly* sensitive to valence quarks

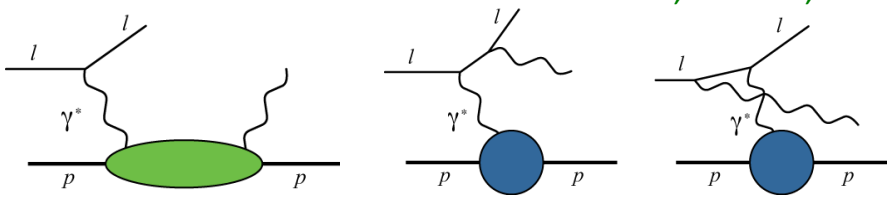
Moutarde, Pire,
F S , Wagner, ...

- Actually sensitive to *gluon* GPDs at NLO or beyond (even at somewhat large x)

- At LO, direct access the GPDs on the line $x = \xi$ through Beam Spin Asymmetries

sensitive to the interference with known Bethe-Heitler process

Diehl, Gousset,
Pire, Ralston, ...

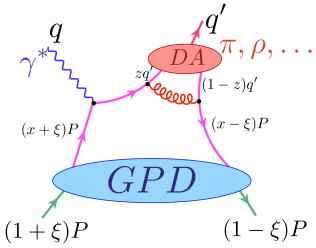


Hard Meson Electroproduction

- Many channels available for flavor separation (ρ^0, ρ^+, π^0, π^+, φ, ...)

- J/Ψ and ϕ access gluon GPDs. Surprises with the π^0 (later in this talk)

- Theory less under control : convolution with (unknown) meson WF,



potentially slow scaling, large power and NLO corrections

Hard π^0 electroproduction: a puzzle

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

$$\Gamma_{\gamma^*}(Q^2, x_B, E_e) = \frac{\alpha}{8\pi}\frac{Q^2}{M^2E_e^2}\frac{1-x_B}{x_B^3}\frac{1}{1-\epsilon}$$

$$\epsilon = \frac{1 - y - \frac{Q^2}{4E_e^2}}{1 - y + \frac{y^2}{2} + \frac{Q^2}{4E_e^2}}$$

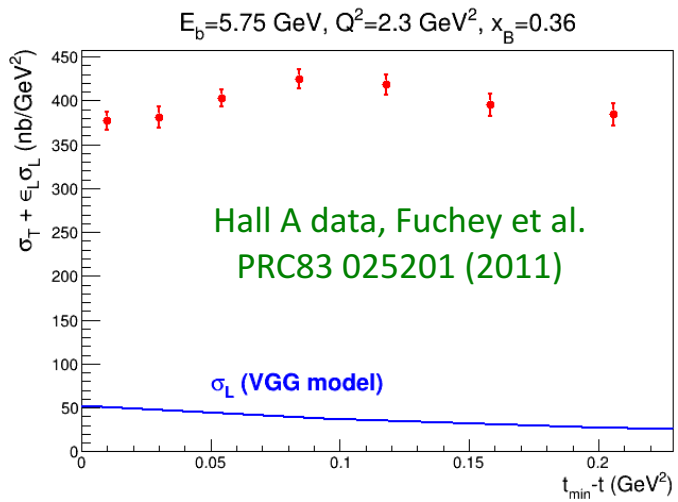
Factorization proven for L cross section only. $\frac{d\sigma_L}{dt}$ is mostly sensitive to $\widetilde{H}$:

$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^6}\left[(1-\xi^2)\left|\left\langle\widetilde{H}\right\rangle\right|^2 + ...\right]$$

However, exciting results in the last few years

- Hall A and CLAS π^0 un-separated cross section data overshoot chiral-even GPD models by a factor ~10 (Figure: Hall A data, similar findings from CLAS)

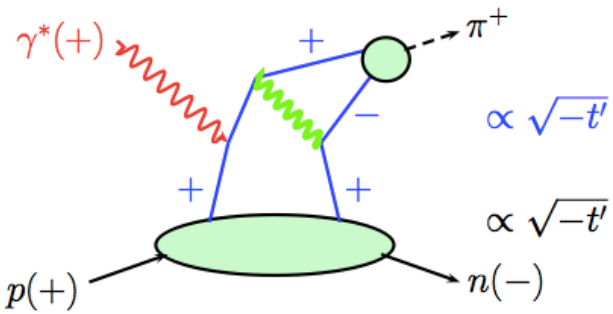
- Q^2 dependence is too large for γ_L-π transition and actually compatible with a γ_T-π transition (Hall A)



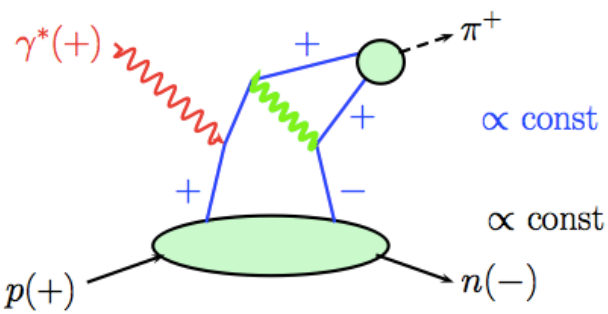
Hard π^0 electroproduction: higher-twist trick?

Latest GK : Kroll, Moutarde, Goloskokov, **F S**, EPJC73, 2278 (2013)
Chiral-odd GK: Goloskokov, Kroll, EPJA47, 112 (2011)

Explanation: chiral-odd GPD may contribute to transverse part

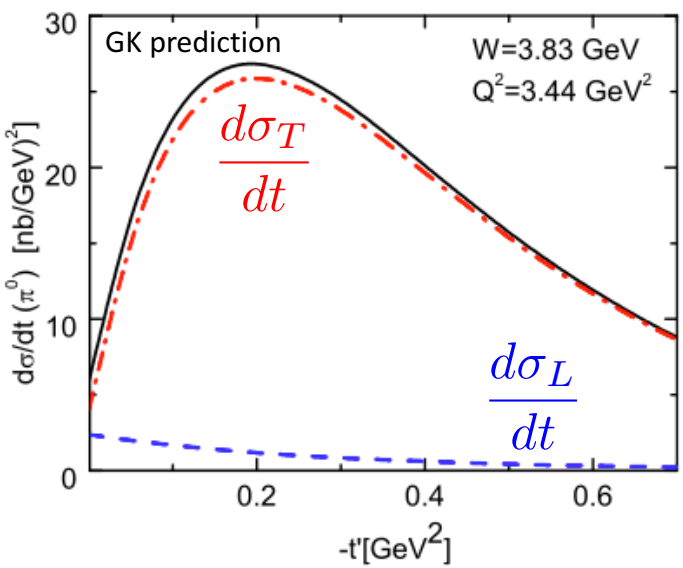


Full leading-twist diagram



This diagram requires a Twist-3 pion w.f.
Suppressed by μ_π/Q wrt leading twist, BUT

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \simeq 2.5 \text{ GeV}$$



In this approach :

$$\frac{d\sigma_T}{dt} \propto \frac{1}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - (t'/8m^2)\left|\langle \bar{E}_T\rangle\right|^2\right]$$

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

Low-*t'* behavior results from interplay between $H_T, \bar{E}_T$

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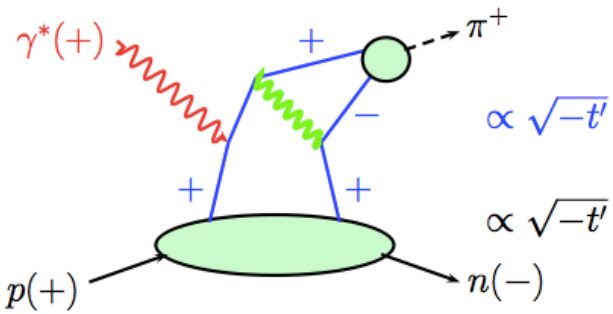
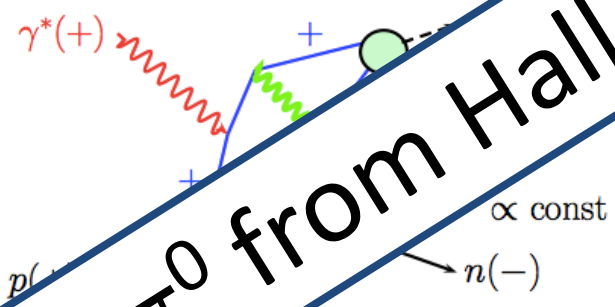
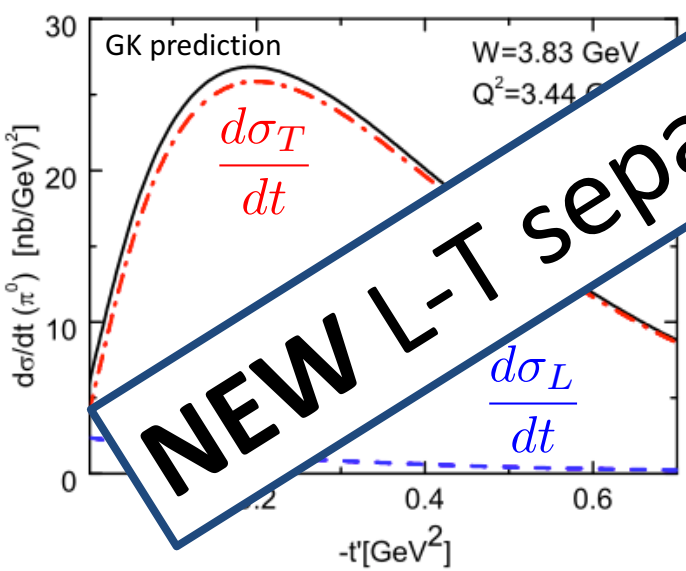


Full leading-twist diagram



equires a Twist-3 pion w.f.
by μ_π/Q wrt leading twist, BUT

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \simeq 2.5 \text{ GeV}$$



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Low-*t'* behavior results from interplay between $H_T, \bar{E}_T$

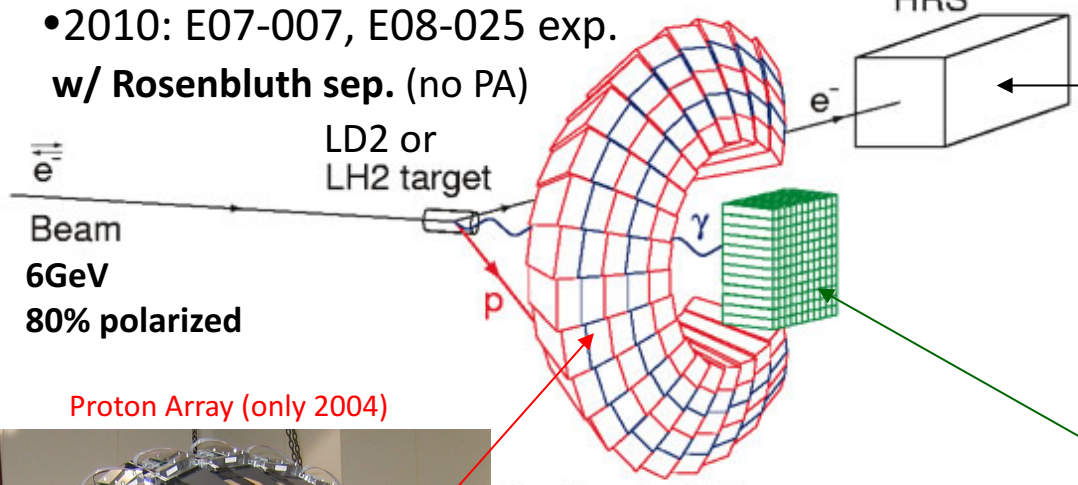
NEW L-T separation of π^0 from Hall A !

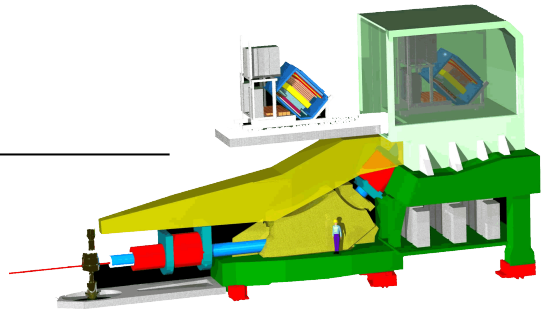
Jefferson Lab Hall A DVCS/π^0 experiment

Two run periods:

- 2004: E00-110, E03-106 exp. (pioneering)
- 2010: E07-007, E08-025 exp.

w/ Rosenbluth sep. (no PA)





HRS spectrometer in Hall A

Proton Array (only 2004)

100 scintillator blocks

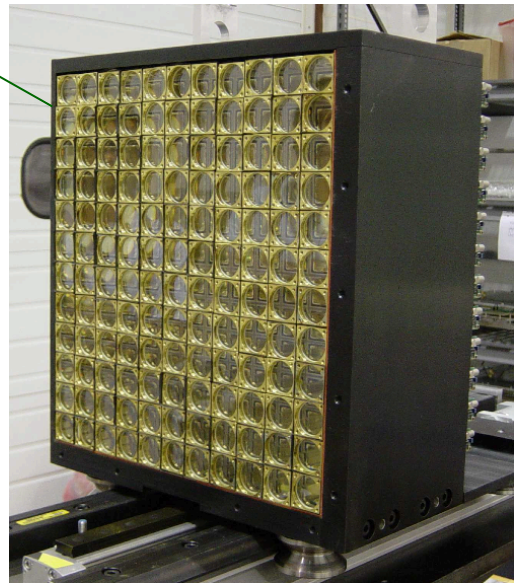
E_e=5.75 GeV

2004	0.36	1.5
	0.36	1.9
	0.36	2.3

E_e=3.45, 4.55, 5.55 GeV

2010	0.36	1.5	0.52 , 0.84
	0.36	1.75	0.65 , 0.79
	0.36	2	0.53 , 0.72

Electromagnetic Calorimeter

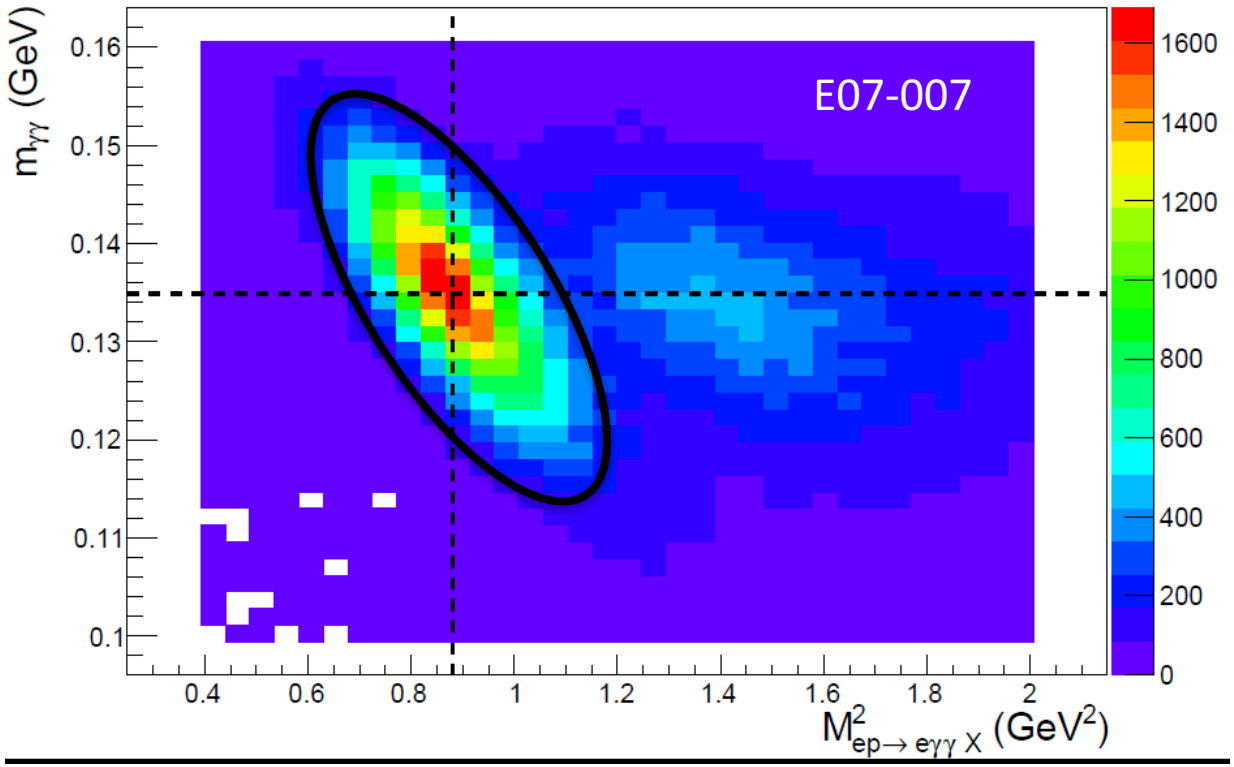


132 PbF_2 blocks
(208 in 2010)

π^0 analysis principle, proton target

Inclusive electron trigger (99% pure) using Hall A Left HRS
Require **two clusters in the calorimeter**

$ep \rightarrow ep\pi^0$ process cleanly selected by dual cut on $\gamma\gamma$ invariant mass and *p* missing mass



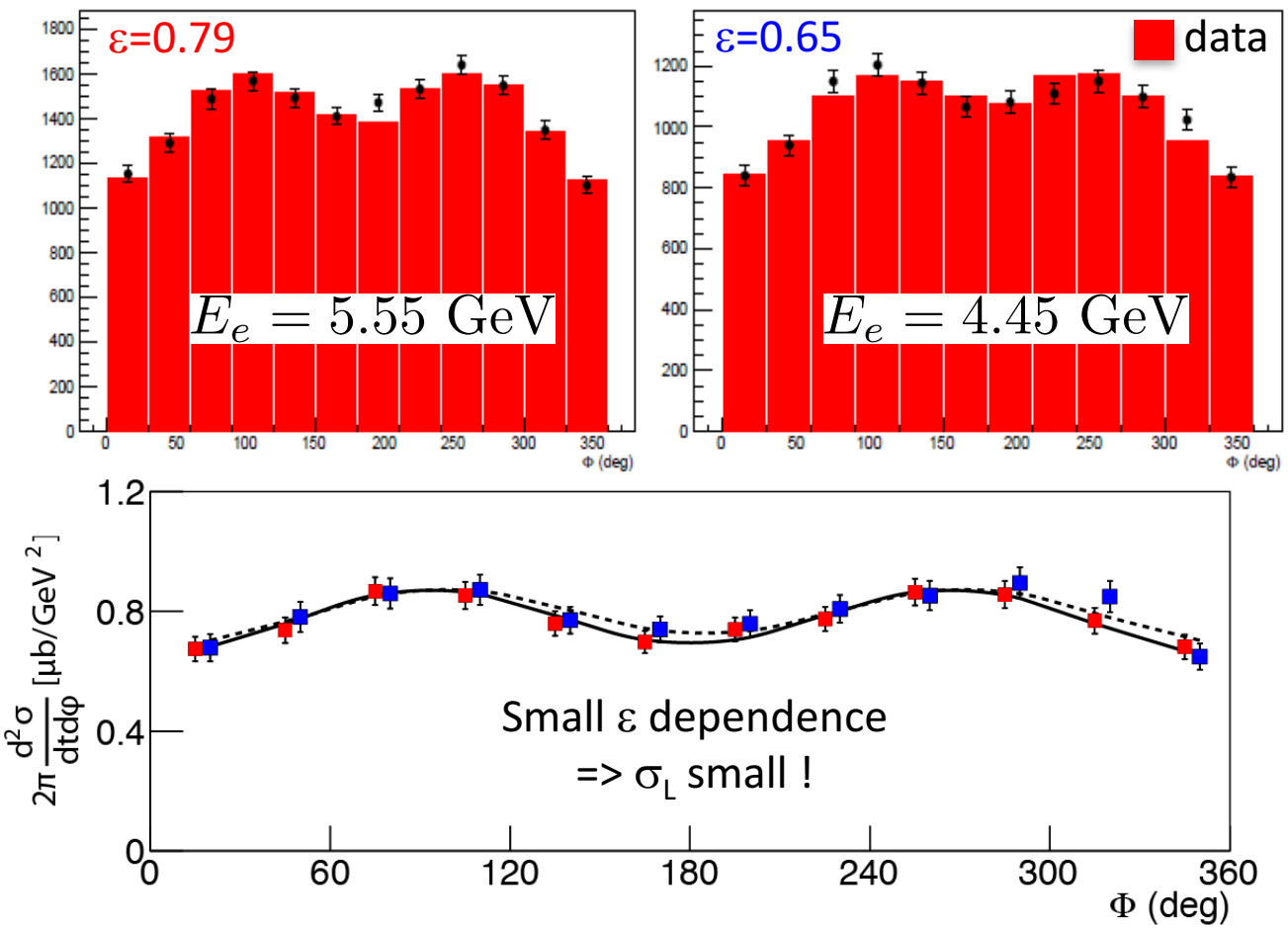
Matching of Monte-Carlo and data resolutions of utmost importance to reduce systematic uncertainties from the cuts

π^0 electroproduction cross section extraction (proton)

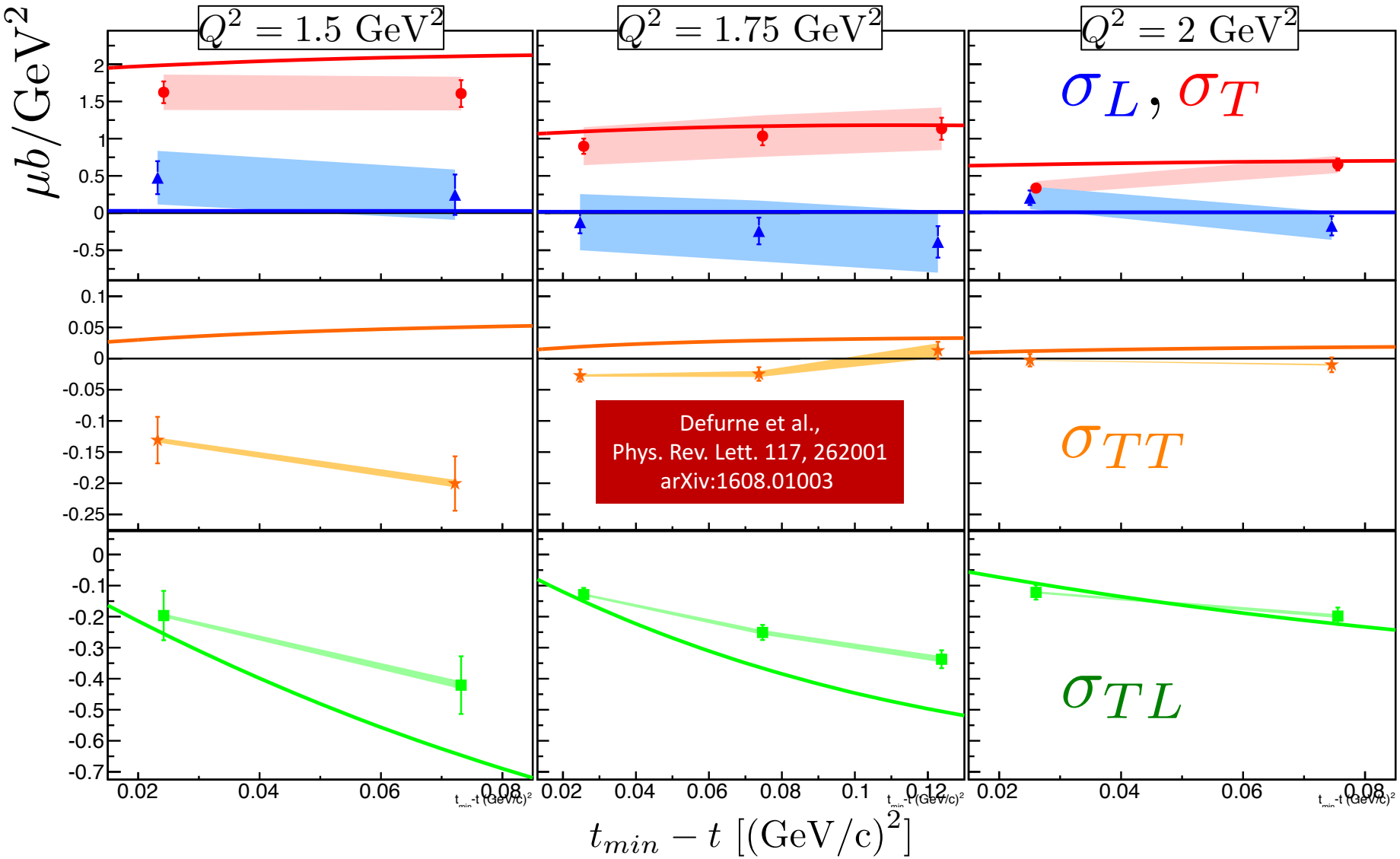
Extraction of all the (unpolarized) responses by a simultaneous fit to the 2 beam energies

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

$$t = -0.02\ \mathrm{GeV}^2, Q^2 = 1.75\ \mathrm{GeV}^2$$



Large dominance of transverse cross section



Shaded area: 2% normalization uncertainty

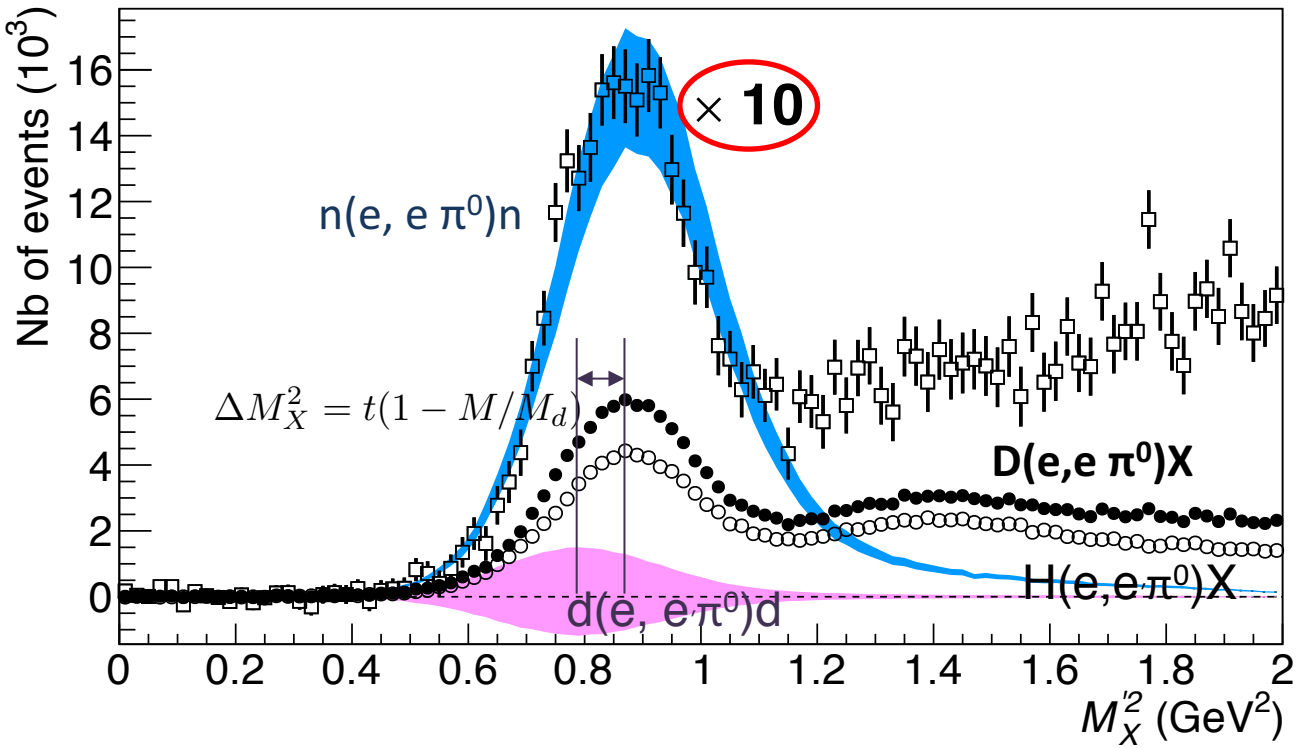
Solid line: GK model

Reasonable agreement with GK model as described before

π^0 electroproduction off the neutron

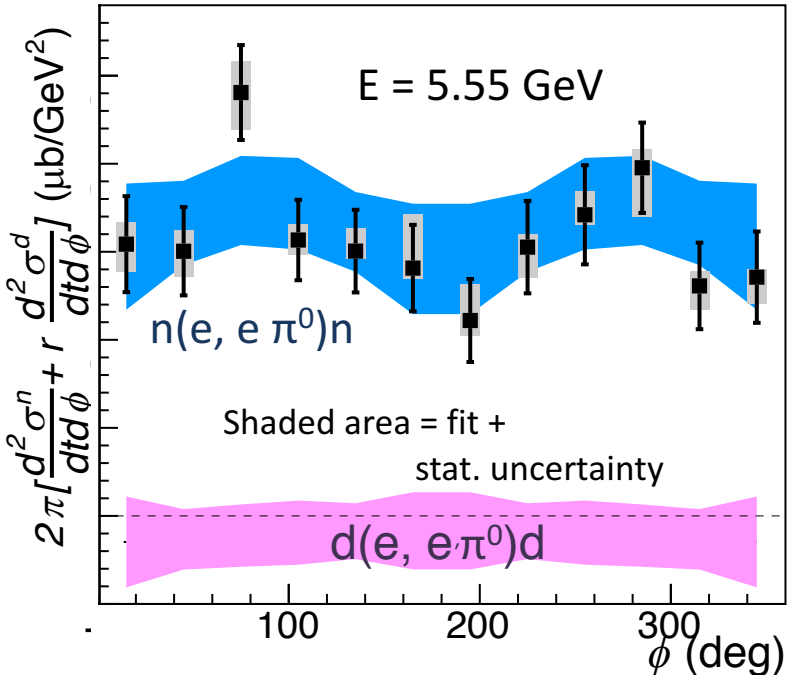
The quasi-free π^0 electroproduction events off the proton are **subtracted using the (normalized) data from E07-007** (concurrent data taking, just switching the LH2 target with the LD2 target)

D(e,e π^0)X - p(e,e π^0)p = n(e,e π^0)n + d(e,e π^0)d

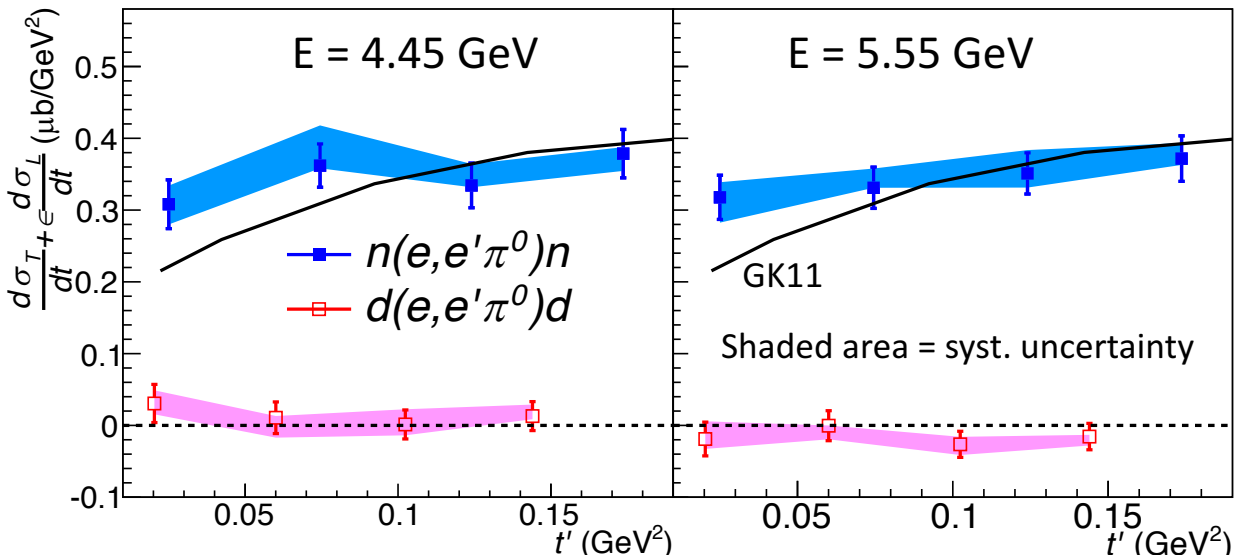


The average momentum transfer to the target is much larger than the np relative momentum, justifying this impulse approximation

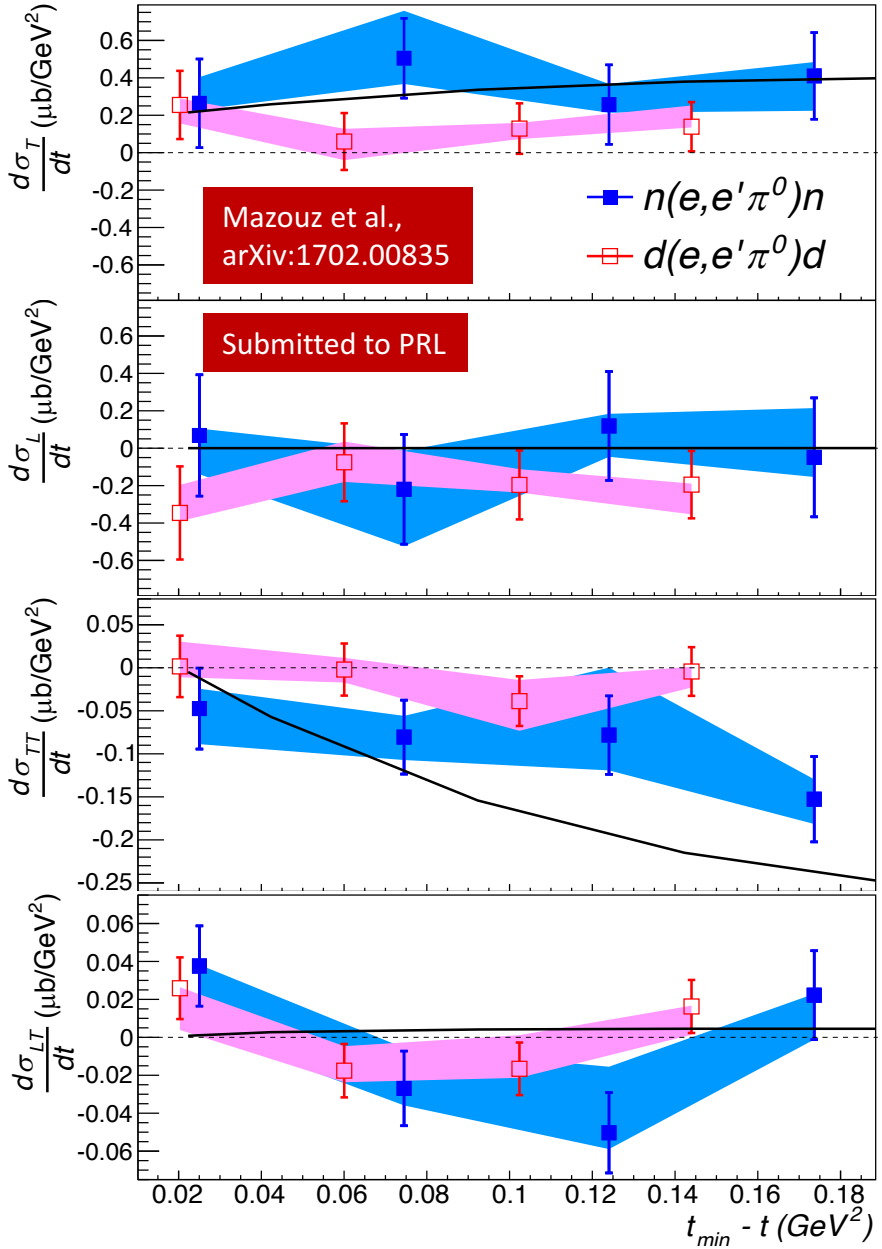
π^0 electroproduction cross sections off the neutron



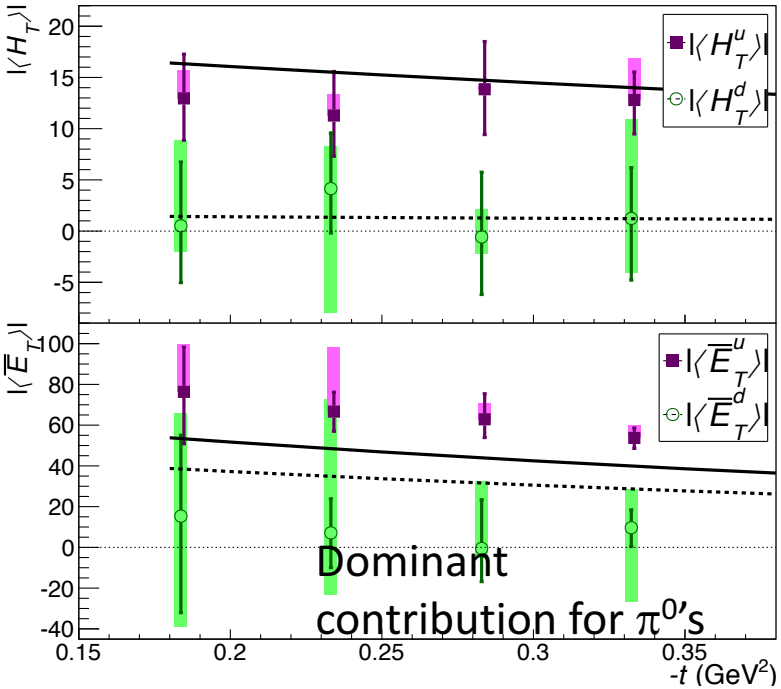
- The 4x2 separated cross sections for (n,d) are fit to the proton-subtracted deuterium data, for the two energy settings at once
- The unpolarized neutron cross section is found to have (again) a **very low dependence on the beam energy**, indicating a small L component
- Unpolarized cross sections are **compared to GK model, with reasonable agreement**



Separated π^0 electroproduction cross sections off the neutron

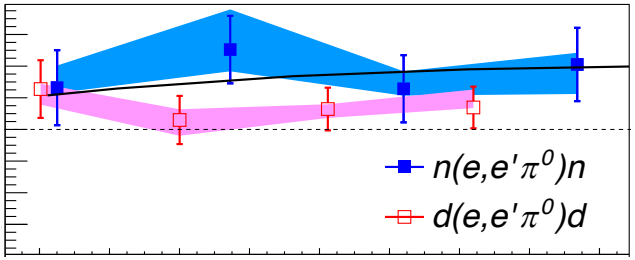


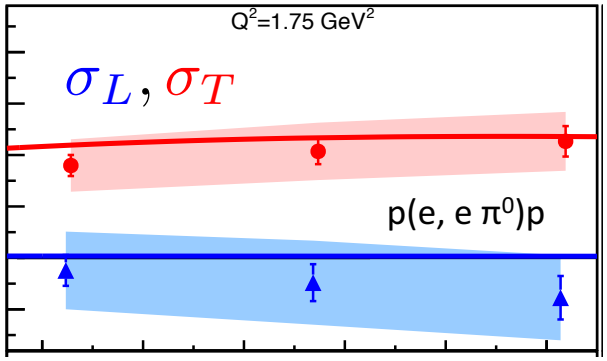
- Challenging measurement for the proton …**even more challenging for the neutron**
- However, **significant σ_T** and **σ_{TT}**
- And **σ_L still close to 0**, similarly to the proton
- Within GK framework, extraction of flavor dependence of $|\langle H_T \rangle|$, $|\langle \bar{E}_T \rangle|$ from neutron and proton data
- Data are compared to **GK model**, with **reasonable agreement**



Summary and Outlook

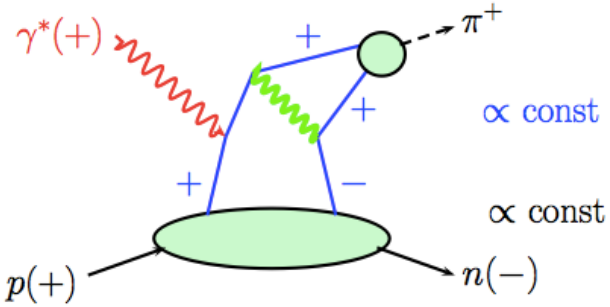
- Finally, **proof** that **transverse π^0 cross section is dominant, for both proton and neutron targets**





- Cross sections **are reasonably well described by the GK model** using transversity "helicity-flip" GPDs and a *Twist-3* pion wave function

  → **Access to the elusive chiral-odd GPDs**



- An **exciting future** ahead

  12 GeV experiments at JLab (Hall A already took some data)

  COMPASS data at lower x, and then an **exciting program at the EIC !**

JLab/EIC senior staff position at CEA-Saclay

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Experimental Hadron Physics

IRFU, SPhN, Saclay - Senior

Field of Interest: hep-ex, nucl-ex
Deadline: 2017-04-14
Region: Europe

Job description:
The CEA Paris-Saclay Nucleon Structure Laboratory (LSN) is opening a staff scientist position for an outstanding physicist in the field of experimental hadron physics, with a focus on both the development of the Electron-Ion Collider (EIC) project and the experiments using the recent 12GeV upgrade of the Jefferson Lab (US) electron accelerator.

DEADLINE : APRIL 14th