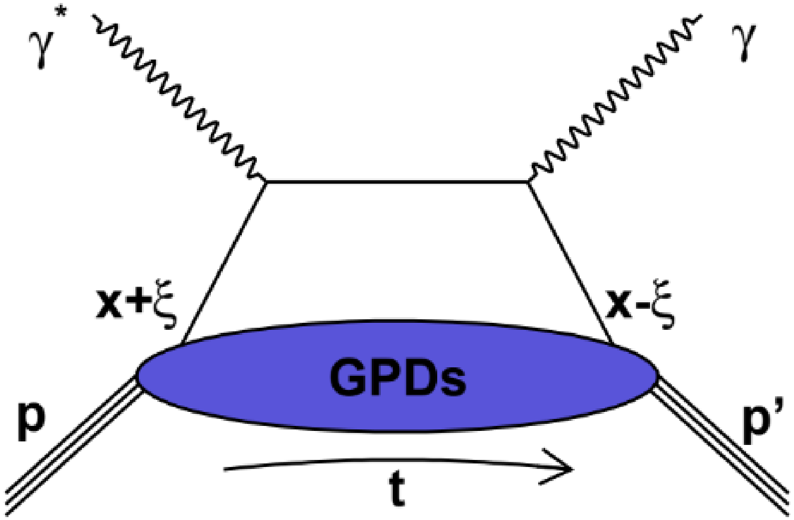
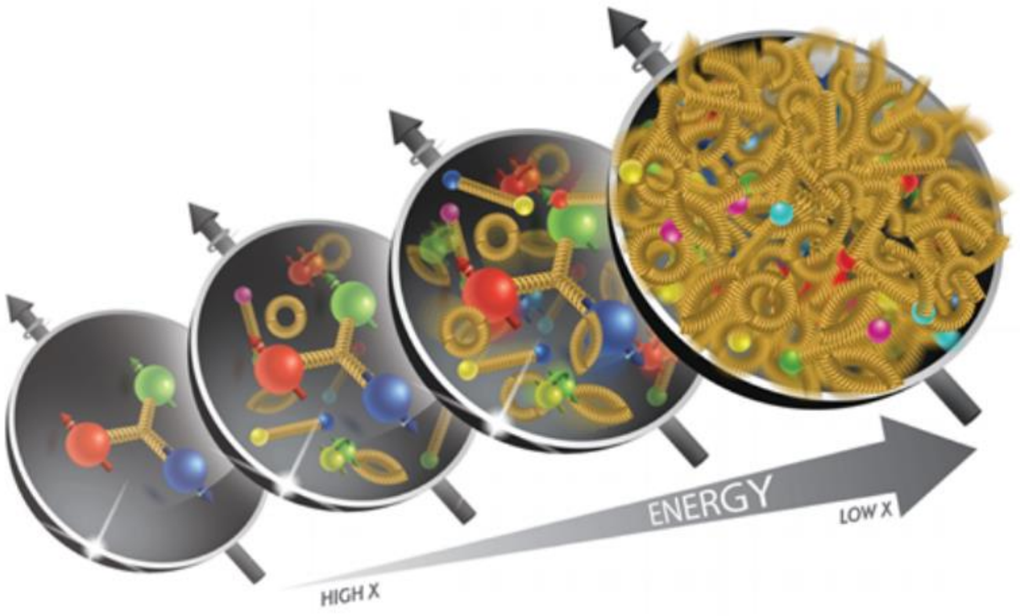
Deeply Virtual Compton Scattering and Spatial Imaging





Lecture 3

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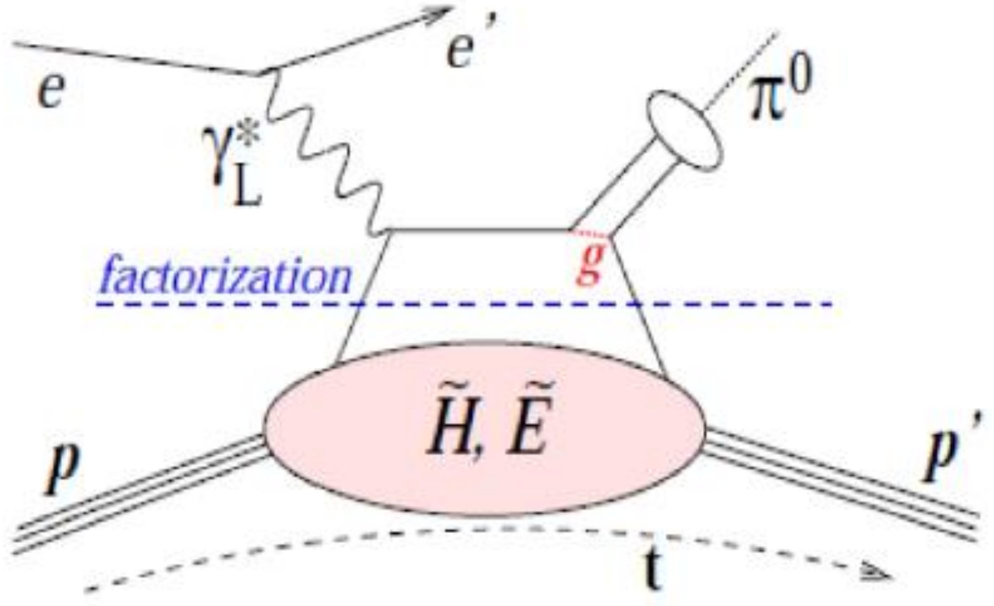
Outline

- Lecture 1: Introduction
  - Elastic scattering, form factors (FFs)
  - Deep Inelastic scattering, parton distribution functions (PDFs)
  - Exclusive reactions, Generalized Parton Distributions (GPDs)
- Lecture 2: Deeply Virtual Compton Scattering
  - Experimental results on proton targets
  - Flavor separation using quasi-free neutrons
- Lecture 3: Deeply Virtual Meson Production & GPD models
  - Rosenbluth separation
  - Access to transversity GPDs
  - GPD models and parametrizations
- Lecture 4: GPDs at JLab12 and beyond
  - Review of GPD programs in other facilities worldwide
  - Future experiments at JLab at 12 GeV
- Lecture 5: Electron-Ion Collider
  - Imaging gluons inside the nucleon
  - The EIC project

Deeply Virtual Meson Production



Different quark weights: flavor separation of GDPs

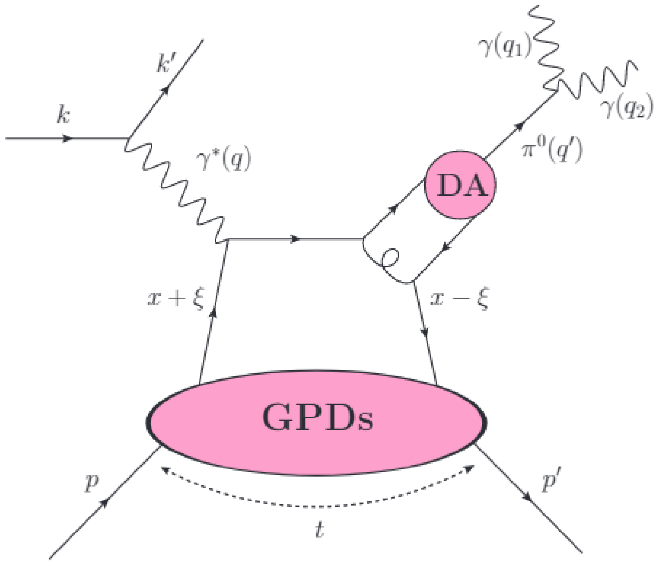
$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\{|u\bar{u}\rangle - |d\bar{d}\rangle\} \qquad \widetilde{H}_{\pi^0} = \frac{1}{\sqrt{2}}\left\{\frac{2}{3}\widetilde{H}^u + \frac{1}{3}\widetilde{H}^d\right\}$$

$$|p\rangle = |uud\rangle \qquad H_{DVCS} = \frac{4}{9}H^u + \frac{1}{9}H^d$$

Deeply Virtual Meson Production: high Q^2 limit

$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6}$$

$$\sigma_T \propto \frac{1}{Q^8}$$



Invariants

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

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

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

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

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

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

$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z}\right] \int_{-1}^{1} dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \times \left\{\Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0}\right\}$$

Deeply Virtual Meson Production: high Q^2 limit

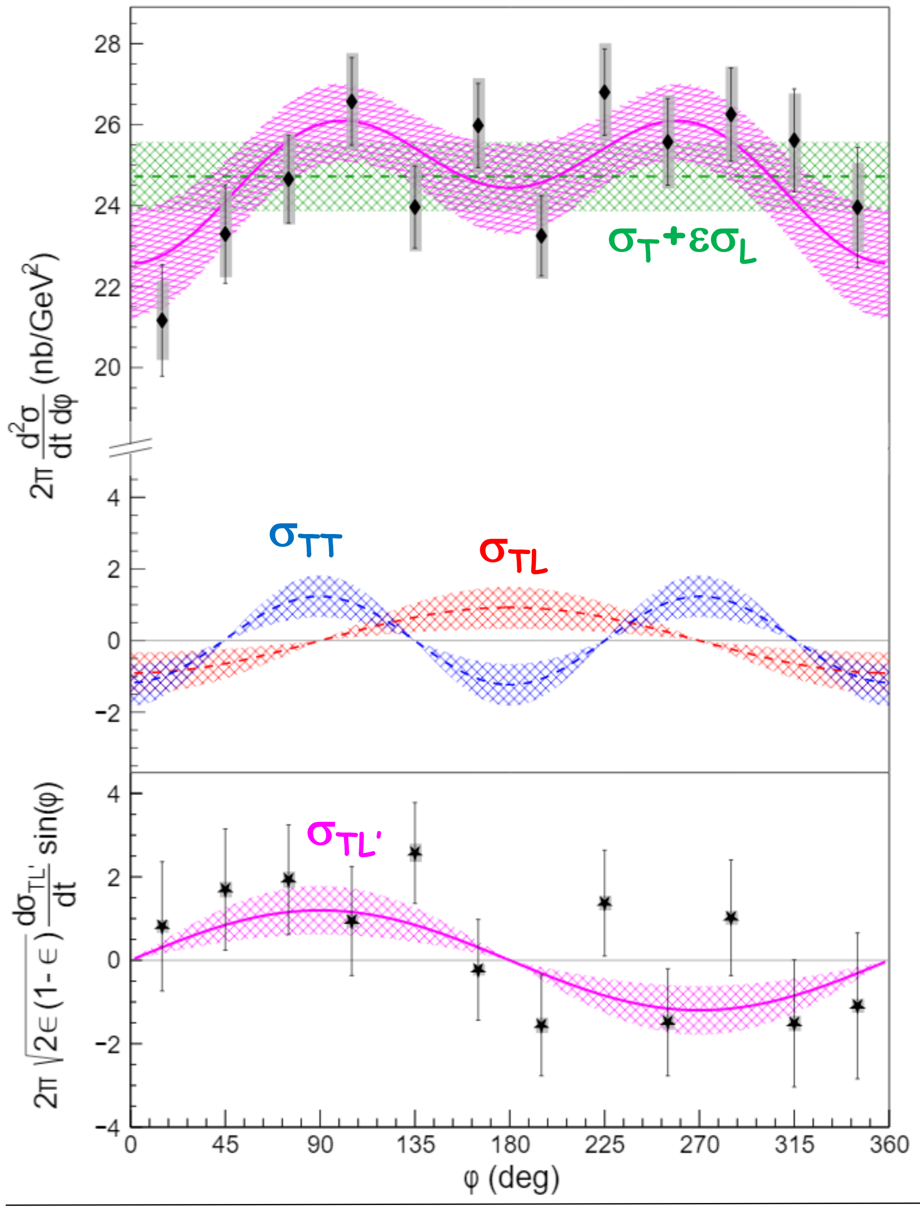
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\frac{d^2\,\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E) \times$$

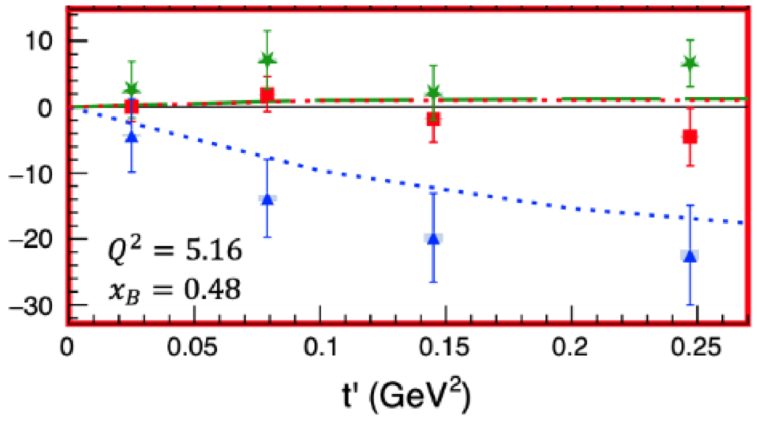
$$\left[\frac{d\sigma_{\mathrm{T}}}{dt} + \epsilon\frac{d\sigma_{\mathrm{L}}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{\mathrm{TL}}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{\mathrm{TT}}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{\mathrm{TL'}}}{dt}\sin(\phi)\right]$$

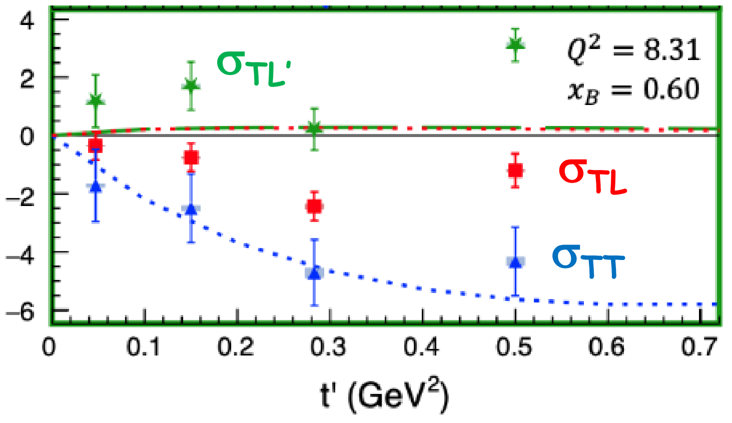
Beam helicity

Depends on beam energy

Azimuthal dependence



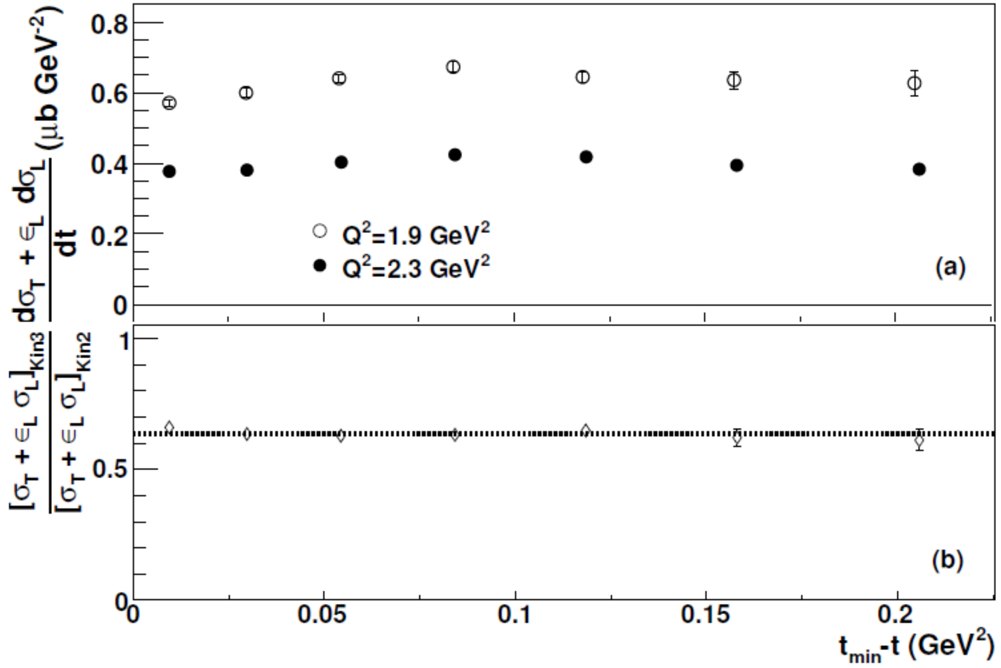


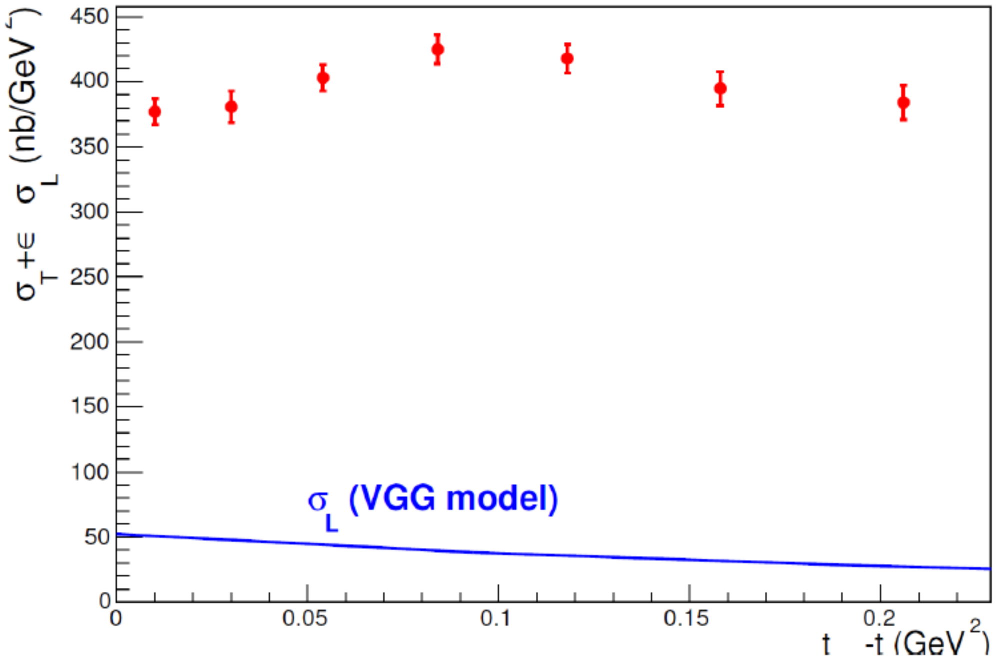


- $\sigma_{TT} \gg \sigma_{TL}, \sigma_{TL'}$
- Indication of significant transverse component

ArXiv: 2011.11125

Exclusive π^0 cross section: GPD prediction





- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$
  (similar to $\sigma_T(ep \to ep\pi^+)$ measured in Hall C)
- GPDs predict $\sigma_L \sim Q^{-6}$
- σ_T likely to dominate at these Q^2,
  but L/T separation necessary ($\to$ new experiment. . .)

Fuchey et al. (2011)

Rosenbluth separation

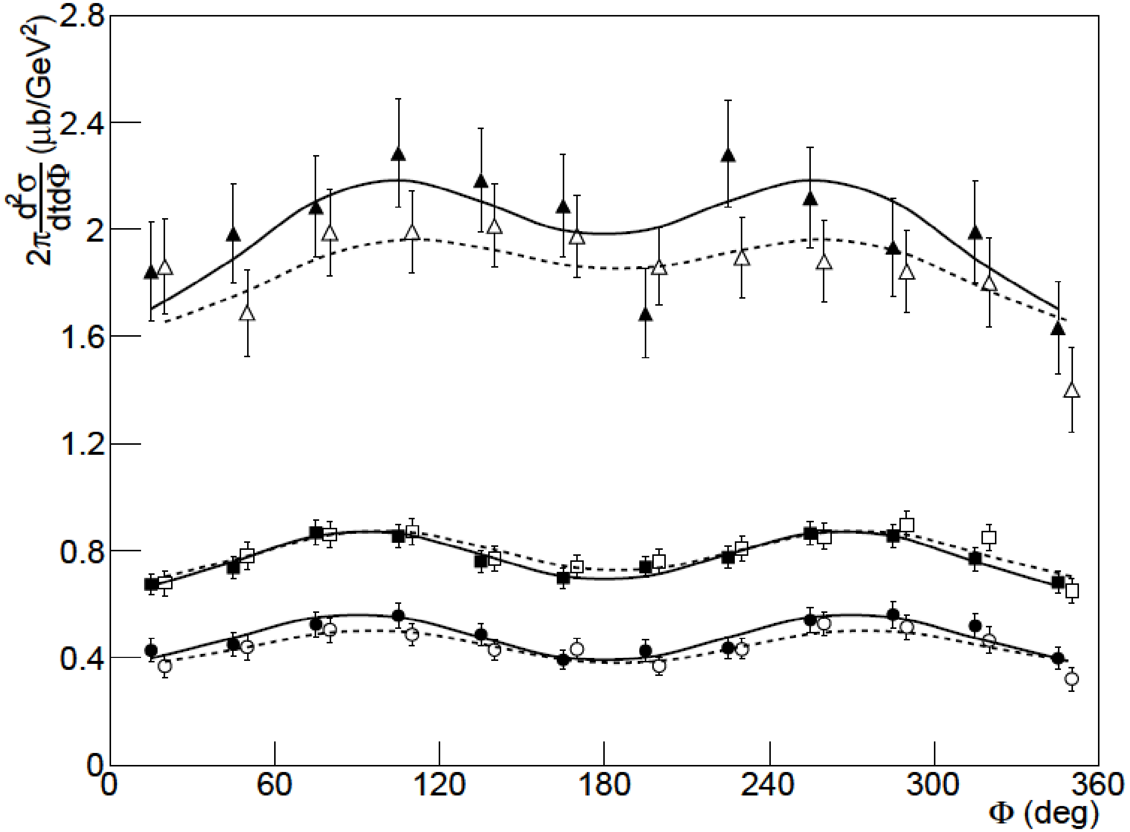
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)\right]$$

Depends on beam energy

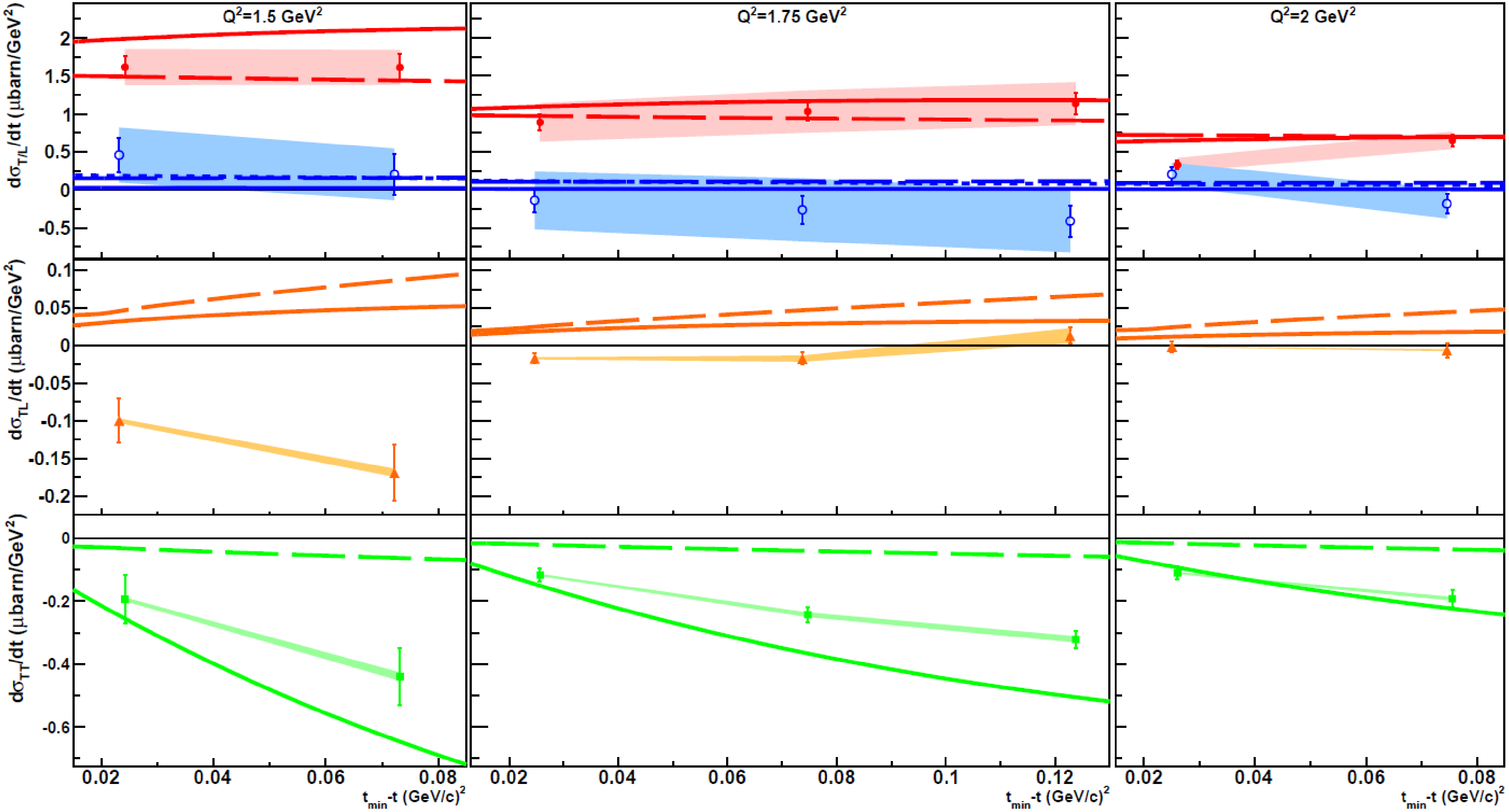
Kinematics

Setting	Q^2 (GeV^2)	x_B	E^{beam} (GeV)	ϵ
Kin1	1.50	0.36	3.355	0.52
			5.55	0.84
Kin2	1.75	0.36	4.455	0.65
			5.55	0.79
Kin3	2.00	0.36	4.455	0.53
			5.55	0.72

$t_{\text{min}} - t = 0.025\ \text{GeV}^2$

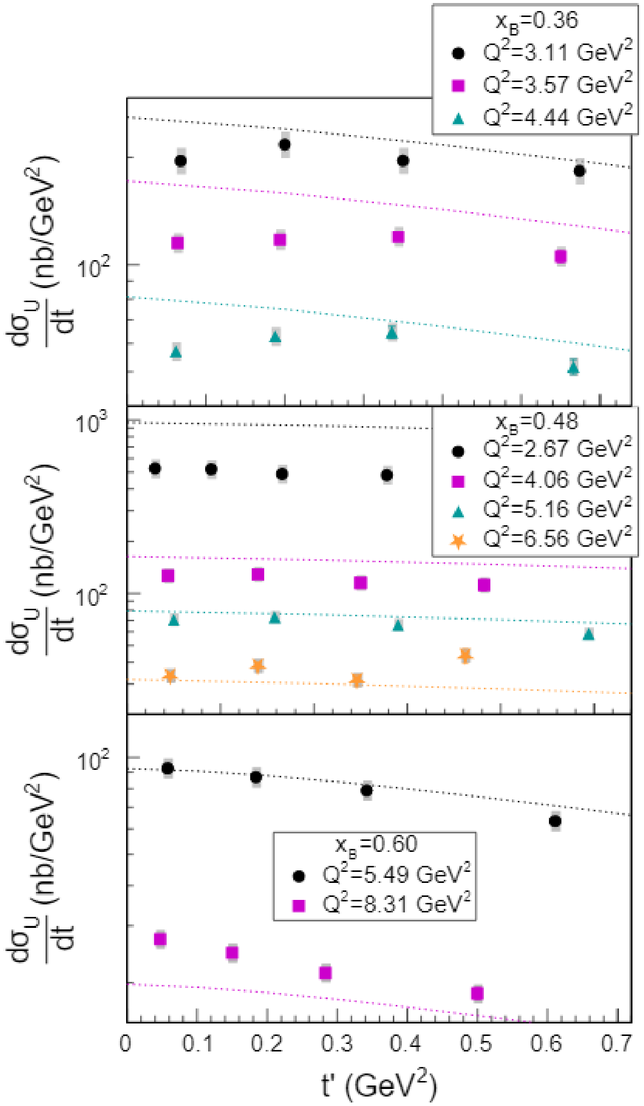


Rosenbluth separation



M. Defurne et al. (2016)

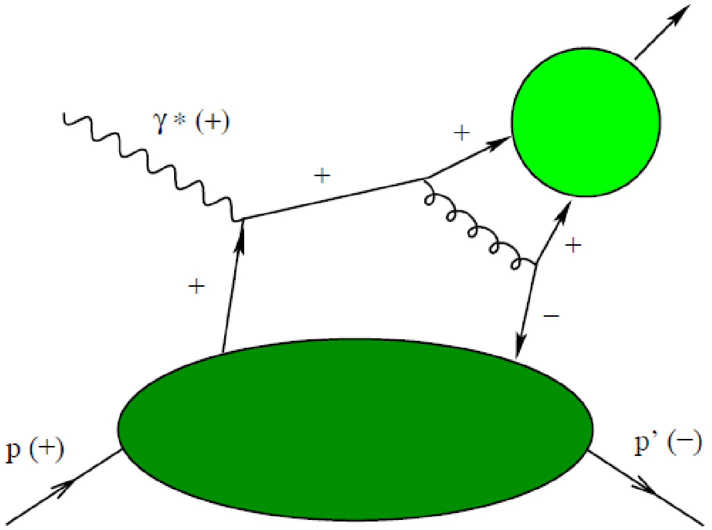
Modified factorization approach



ArXiv: 2011.11125

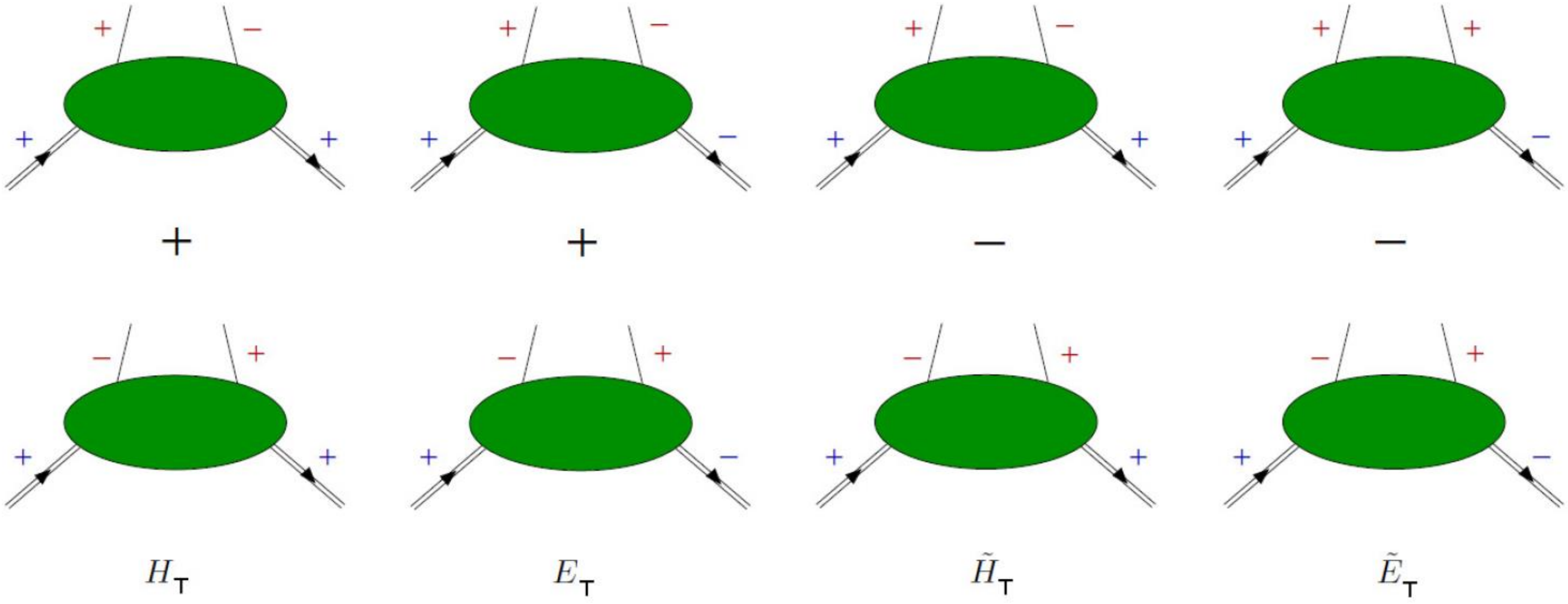
- Singularities with transverse photons regularized by transverse momenta kT of meson quarks/antiquarks

- Transverse amplitude: convolution of transversity GPDs of the nucleon with a higher twist pion wave function



Goloskokov and Kroll (2011)
https://arxiv.org/abs/1106.4897

Transversity GPDs



4 chiral-odd GPDs: flip helicity of the quark

"transversity GPDs"

GPDs from off-forward quark distributions

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,\gamma^+\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$= \frac{1}{2P^+}\bar u(p',\lambda')\left[H^q\,\gamma^+ + E^q\,\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}\right]u(p,\lambda),$$

Helicity conserving distributions

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,\gamma^+\gamma_5\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$= \frac{1}{2P^+}\bar u(p',\lambda')\left[\tilde H^q\,\gamma^+\gamma_5 + \tilde E^q\,\frac{\gamma_5\Delta^+}{2m}\right]u(p,\lambda),$$

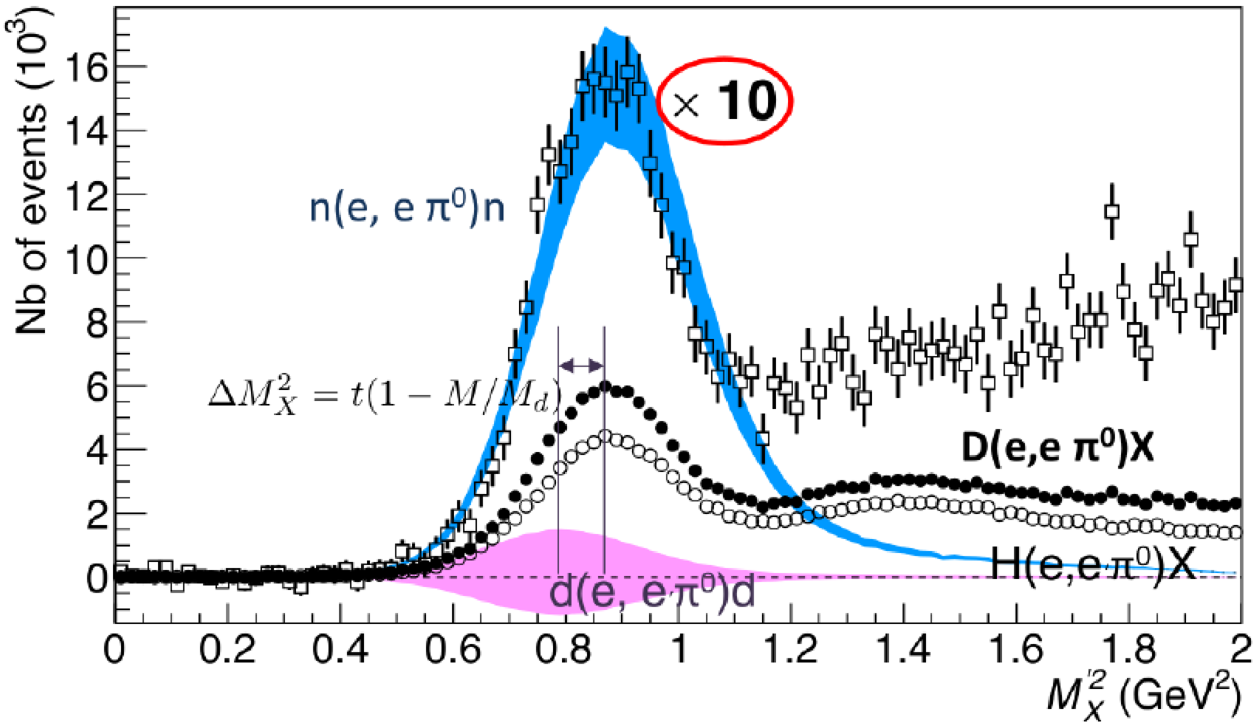
Quark-helicity flip

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p',\lambda'|\,\bar\psi(-\tfrac{1}{2}z)\,i\sigma^{+i}\,\psi(\tfrac{1}{2}z)\,|p,\lambda\rangle\Big|_{z^+=0,\,\mathbf{z}_T=0}$$
$$= \frac{1}{2P^+}\bar u(p',\lambda')\left[H_T^q\, i\sigma^{+i} + \tilde H_T^q\,\frac{P^+\Delta^i - \Delta^+P^i}{m^2} + E_T^q\,\frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde E_T^q\,\frac{\gamma^+P^i - P^+\gamma^i}{m}\right]u(p,\lambda)$$

See eg. Dielh (2001)
https://arxiv.org/pdf/hep-ph/0101335.pdf

π^0 electroproduction off the neutron

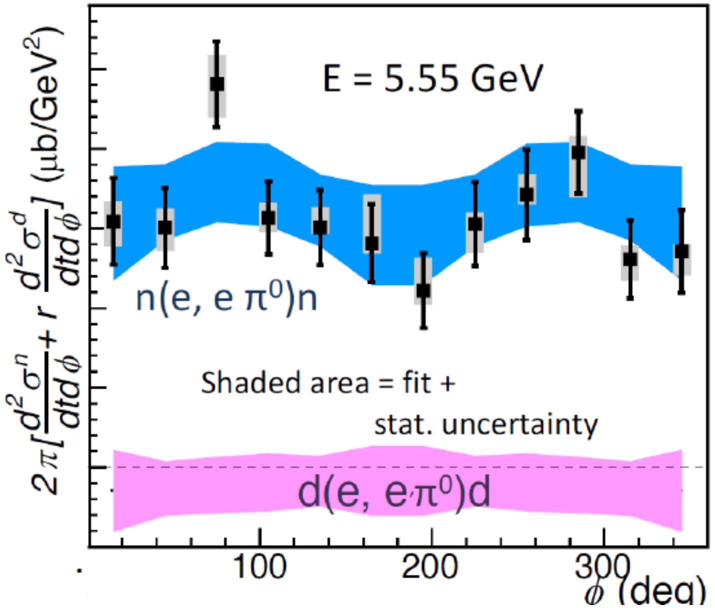
$$D(e, e\,\pi^0)X - p(e, e\,\pi^0)p = n(e, e\,\pi^0)n + d(e, e\,\pi^0)d$$

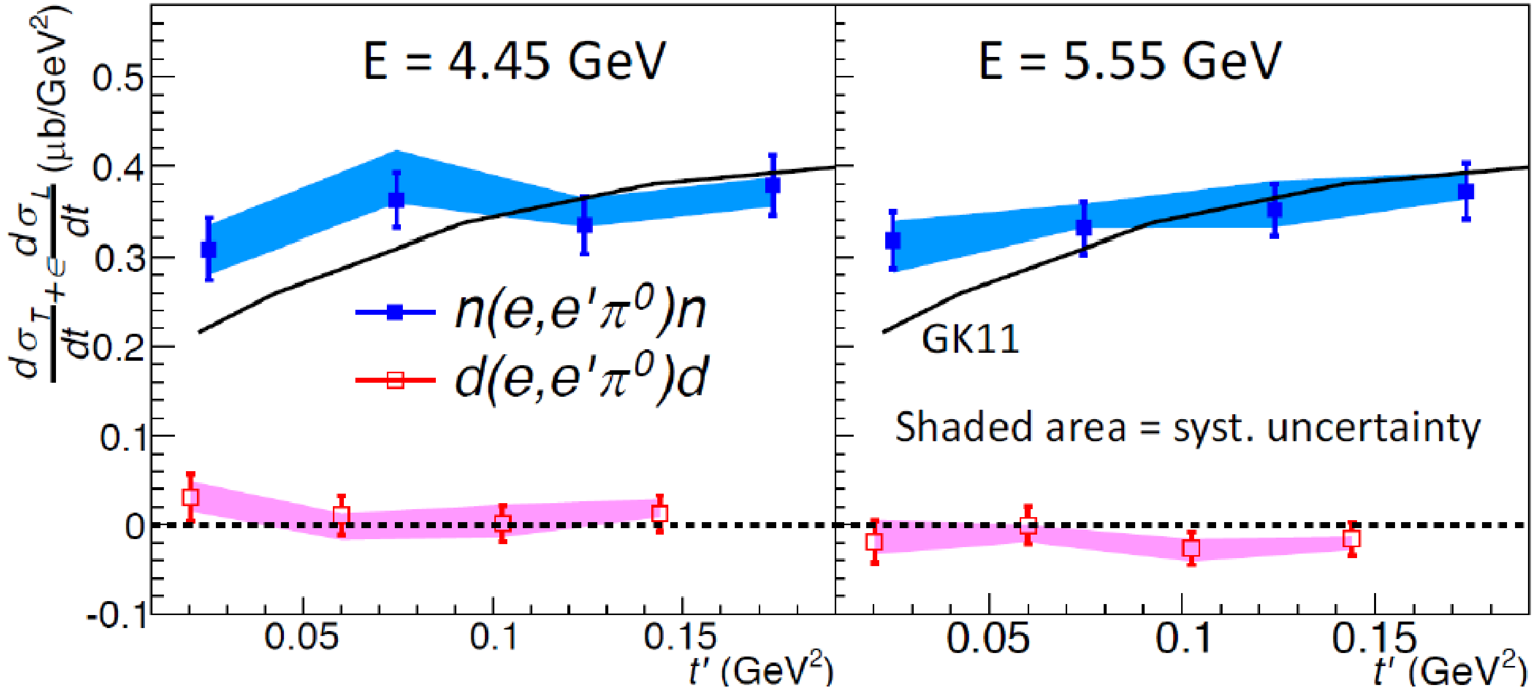


- LD2 as a target
- Quasi-free p events subtracted using normalized data with LH2 target

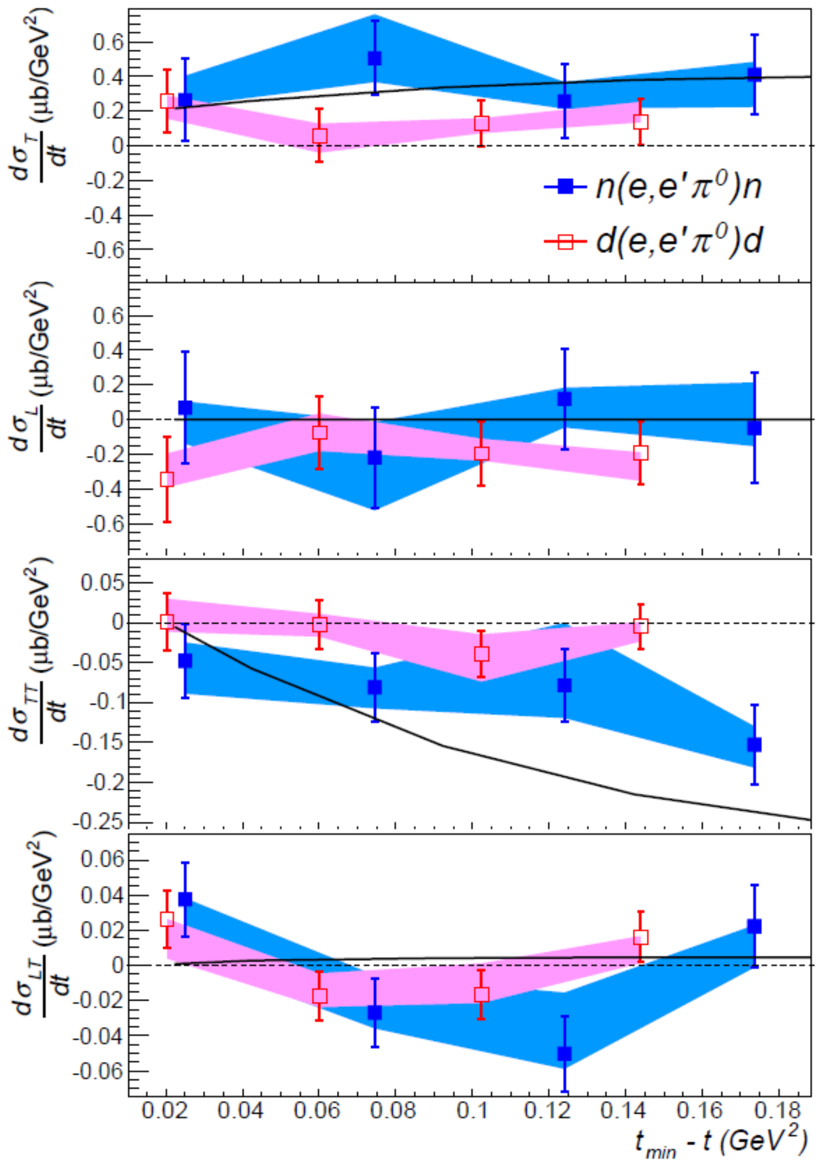
π^0 electroproduction off the neutron: cross section

- Cross section off coherent d found negligible within uncertainties
- Very low E_{beam} dependence of the n cross section → dominance of σ_T





π^0 electroproduction: L/T separation



- Dominated by the transverse cross section
- Relative large uncertainties due to the correlations between *d* and *n* cross sections
- Access to transversity GPDs in the modified factorization approach
- Flavor decomposition possible when combined with data off the proton

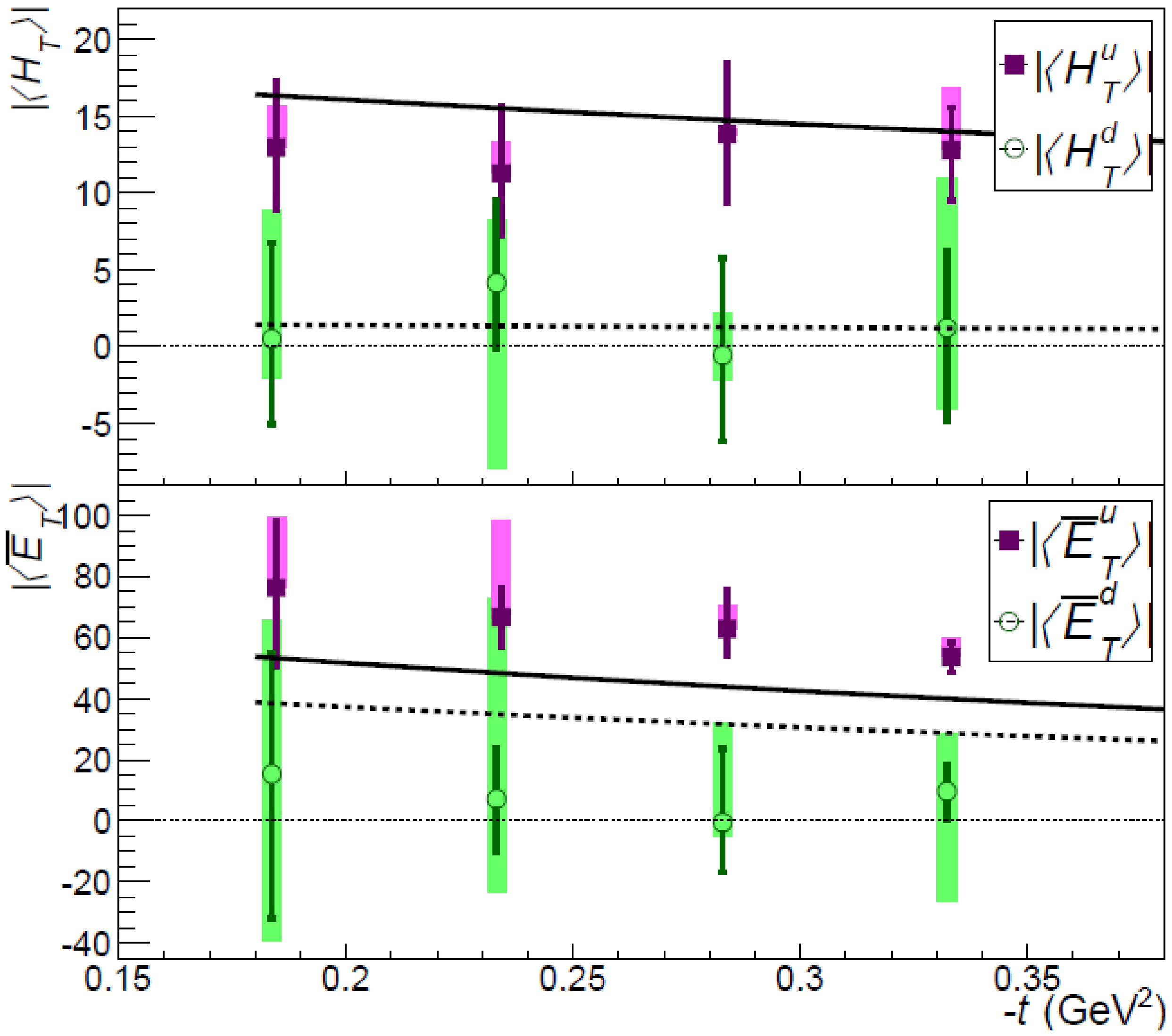
M. Mazouz et al. (2017)

π^0 electroproduction: L/T separation

In the modified factorization approach (KG):

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

$$\left| \langle H_T^{p,n} \rangle \right|^2 = \frac{1}{2} \left| \frac{2}{3} \left\langle H_T^{u,d} \right\rangle + \frac{1}{3} \left\langle H_T^{d,u} \right\rangle \right|^2$$



M. Mazouz et al. (2017)

Modeling GPDs

Reminder lecture 1: GPD properties

Forward limit:

$$\begin{aligned} H^f(x,0,0) &= q_f(x)\,, \\ \tilde{H}^f(x,0,0) &= \Delta q_f(x) \end{aligned}$$

Polynomiality:

$$\int_{-1}^{1} dx\, x^n\, H(x,\xi,t) = a_0 + a_2\xi^2 + a_4\xi^4 + \cdots + a_n\xi^n$$

1st moments:

$$\int_{-1}^{1} dx\, H^f(x,\xi,t) = F_1^f(t) \qquad \forall\xi$$

$$\int_{-1}^{1} dx\, E^f(x,\xi,t) = F_2^f(t) \qquad \forall\xi$$

$$\int_{-1}^{1} dx\, \tilde{H}^f(x,\xi,t) = G_A^f(t) \qquad \forall\xi$$

$$\int_{-1}^{1} dx\, \tilde{E}^f(x,\xi,t) = G_p^f(t) \qquad \forall\xi$$

Polynomiality: highly non-trivial property

x and ξ dependencies are interrelated:

$$\int_{-1}^{1} dx\, x^N H(x,\xi) = \xi^0 h_0^{(N)} + \xi^2 h_2^{(N)} + \ldots + \xi^{N+1} h_{N+1}^{(N)}$$

Radyushkin (1997): solution in terms of double distribution Ansatz

$$H_{DD}(x,\xi) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(x-\beta-\alpha\xi) f(\beta,\alpha)$$

Polyakov & Weiss (1999): D-term is needed to respect the polynomiality in the full form

$$H(x,\xi) = H_{DD}(x,\xi) + \theta(|x| \leq \xi) D\left(\frac{x}{\xi}\right)$$

Belitsky, Müller, Kirchner (2002): General solution

$$H(x,\xi) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(x-\beta-\alpha\xi)(f(\beta,\alpha) + \xi g(\beta,\alpha))$$

Usual choice in models using Double Distributions

$$f(\beta,\alpha) = h(\beta,\alpha)q(\beta)$$

Profile function | Parton distribution

$$\int_{-1+|\beta|}^{1-|\beta|} d\alpha h(\beta,\alpha) = 1 \quad \Rightarrow \quad h(\beta,\alpha) = C\frac{[(1-|\beta|)^2-\alpha^2]^b}{(1-|\beta|)^{2b+1}}$$

Normalization constant

Profile function only depends on **b**

- *Larger b imply softer ξ-dependence of the GPD*

t-dependence

Factorized dependence:

$$H^q_{DD}(x,\xi,t) = H^q_{DD}(x,\xi)F^q_1(t)$$

1st moments:

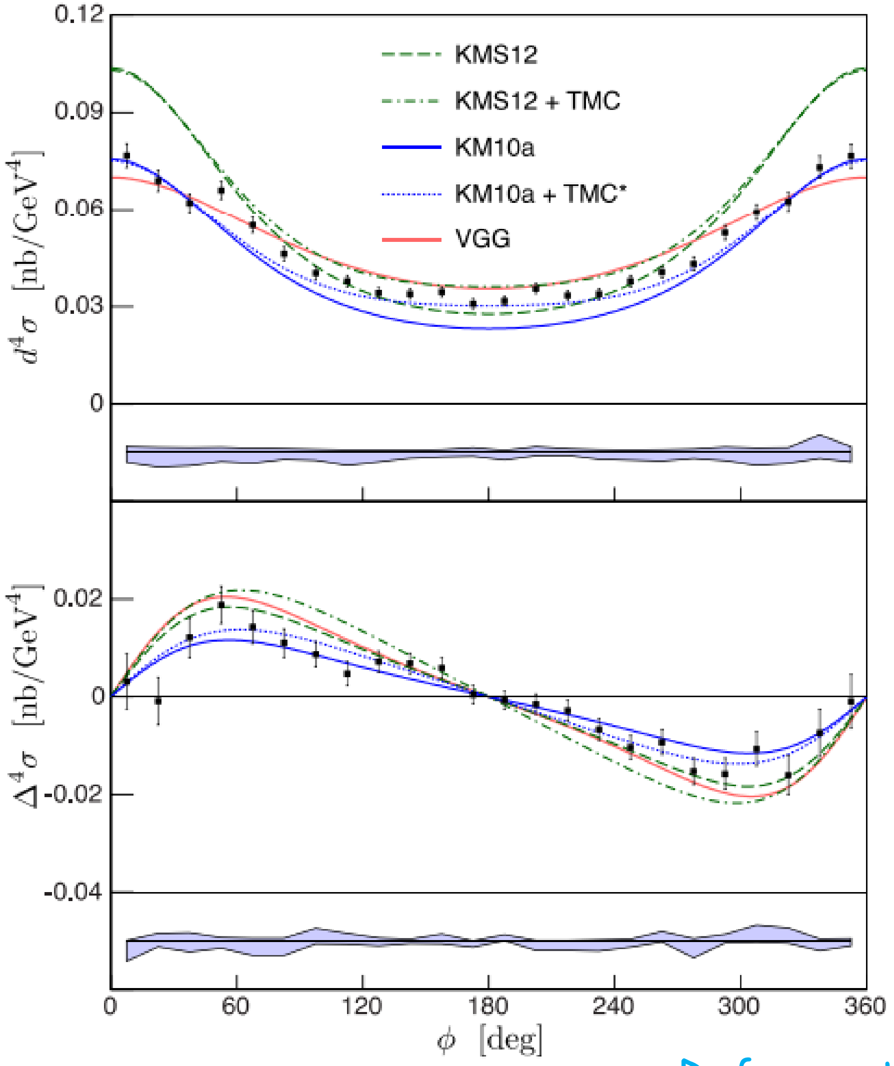
$$\int_{-1}^{1} dx\, H^f(x,\xi,t) = \quad F^f_1(t) \qquad \forall\xi$$

More sophisticated options, inspired in different physical models; eg:

$$H^q(x,\xi=0,t) = \frac{1}{x^{\alpha' t}} q(x)$$

α' : free parameter

GPD models: comparaison to data



Defurne et al (2015)

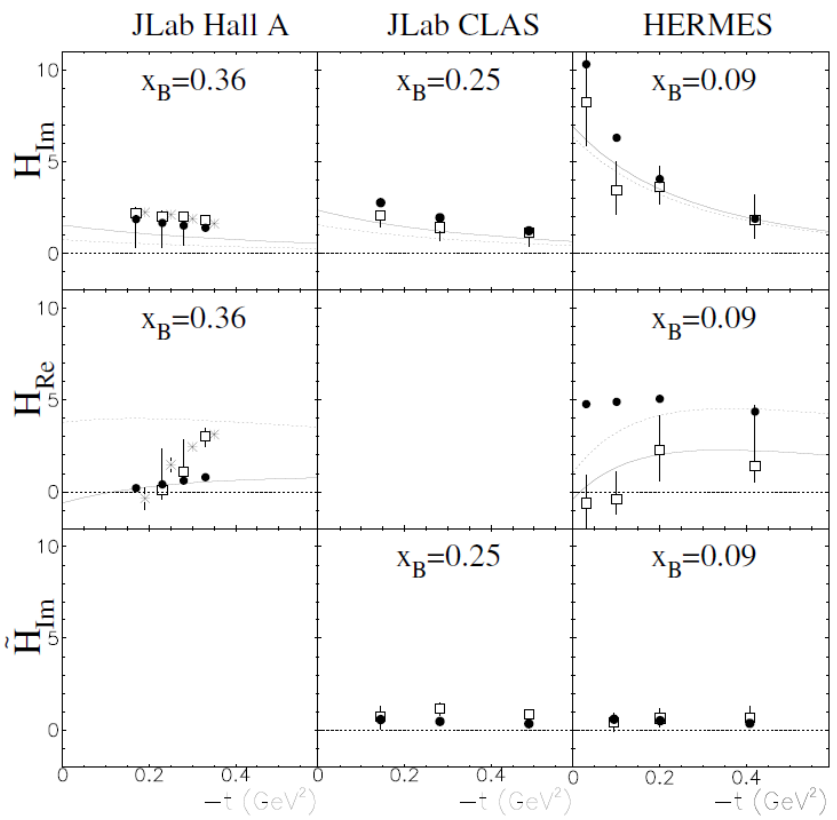
- Reasonable agreement with experiment
- Exact azimuthal dependence difficult to describe by current models

A complentary approach: fits (CFFs) to data

Several techniques:

- **Local fits:**
  Take each kinematic bin independently.
  Fit $\mathcal{R}e(\mathcal{H})$, $\mathcal{I}m(\mathcal{H})$, ... independently.
  M. Guidal
- **Global fits:**
  Take all kinematic bins at the same time.
  Use a parametrization of CFFs or GPDs.
  G. Goldstein et al., K. Kumericki and D. Müller...
- **Hybrid local/global fits:**
  Combine 2 previous methods to estimate systematic errors
  H. Moutarde
- **Neural netwoks:**
  Already used for PDFs fits. In progress for GPDs.
  K. Kumericki and D. Müller

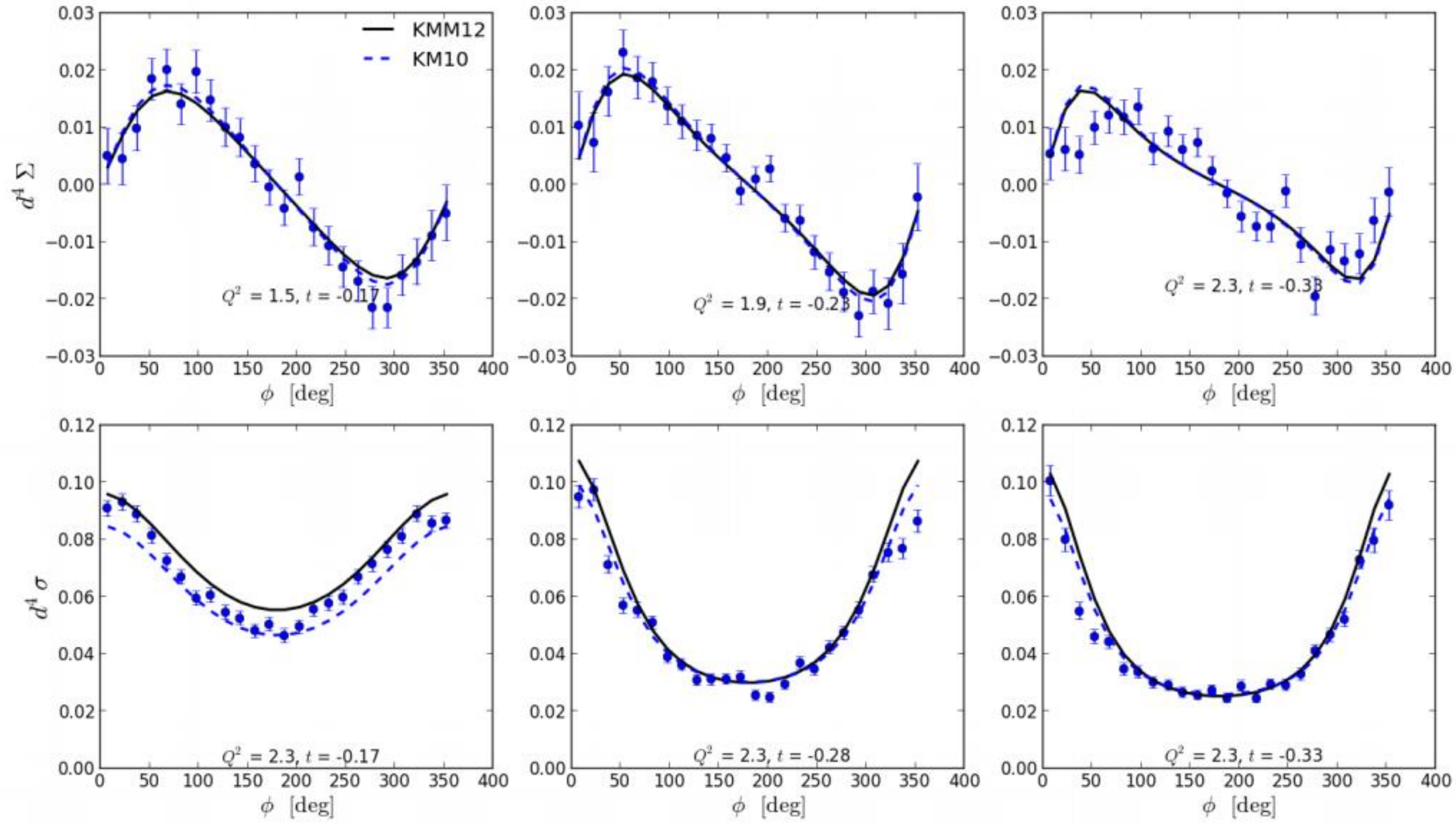
Local fits



- t–slope related to the size of the object (Fourier transform)
- Valence (large x) quarks are more concentrated than the sea (low x)
- Axial charge (H) more concentrated than electromagnetic charge ($\tilde{H}$)

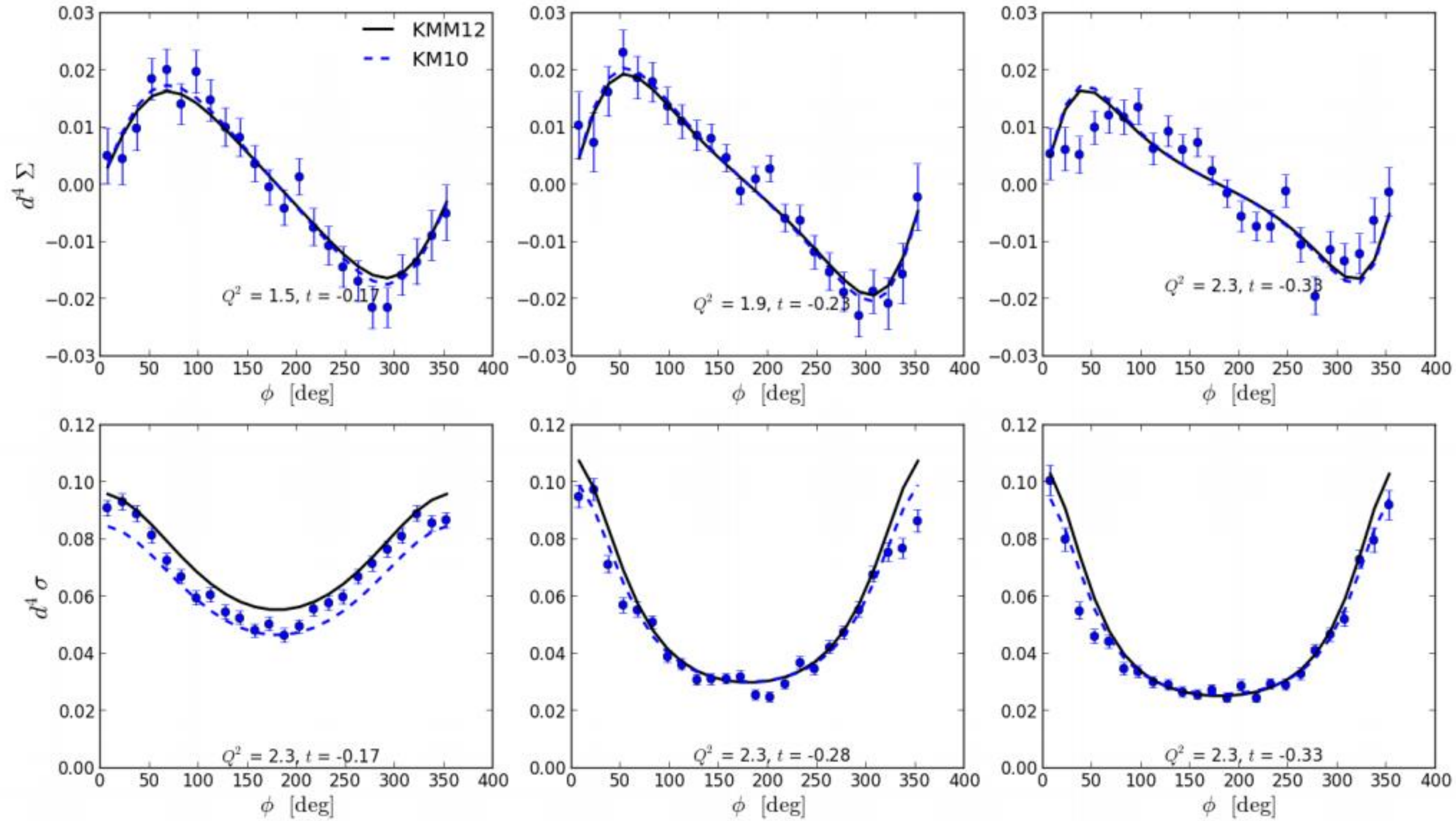
Guidal (2008)

Global fits



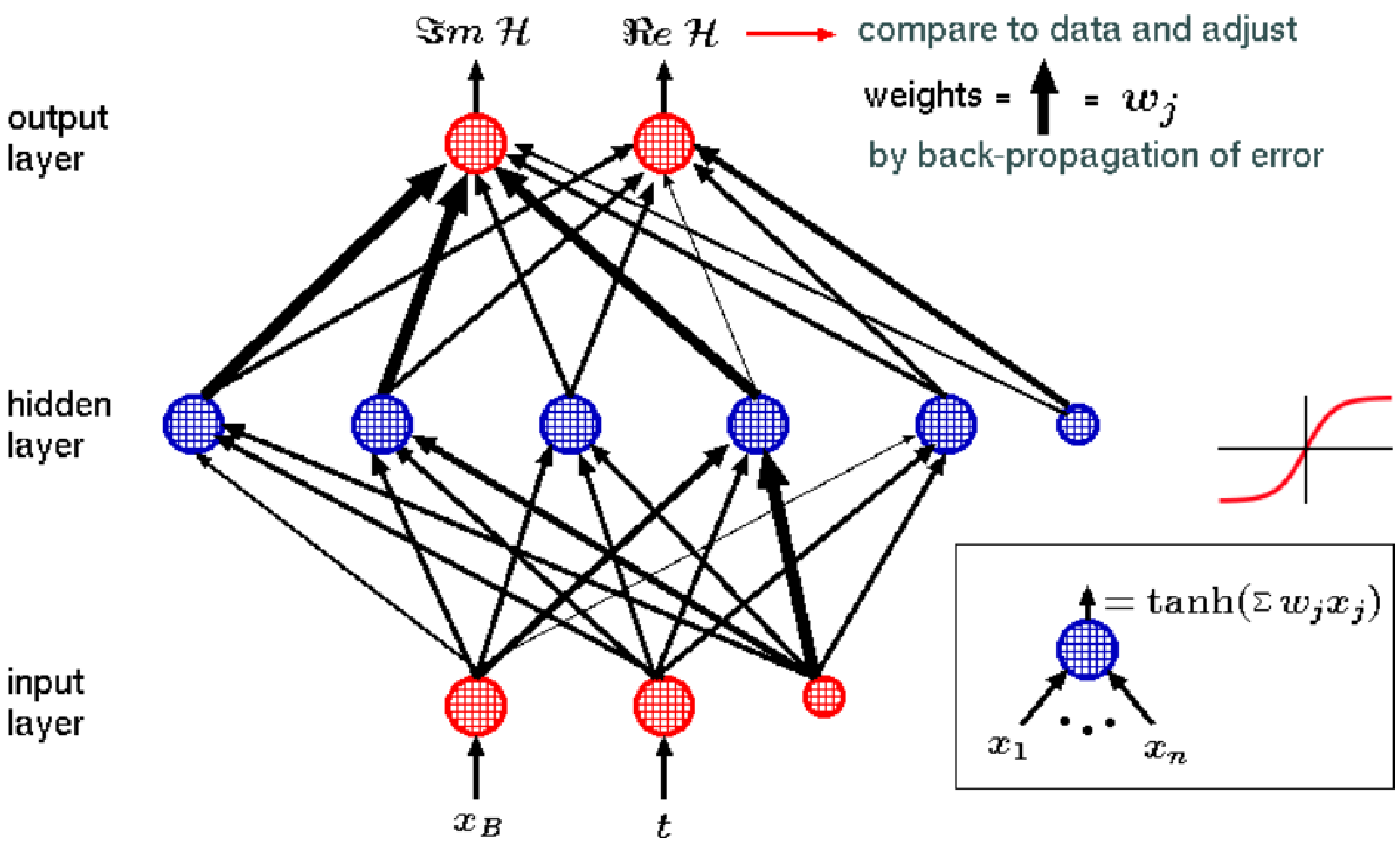
Kumericki (2014)

Global fits



Kumericki (2014)

Neural networks

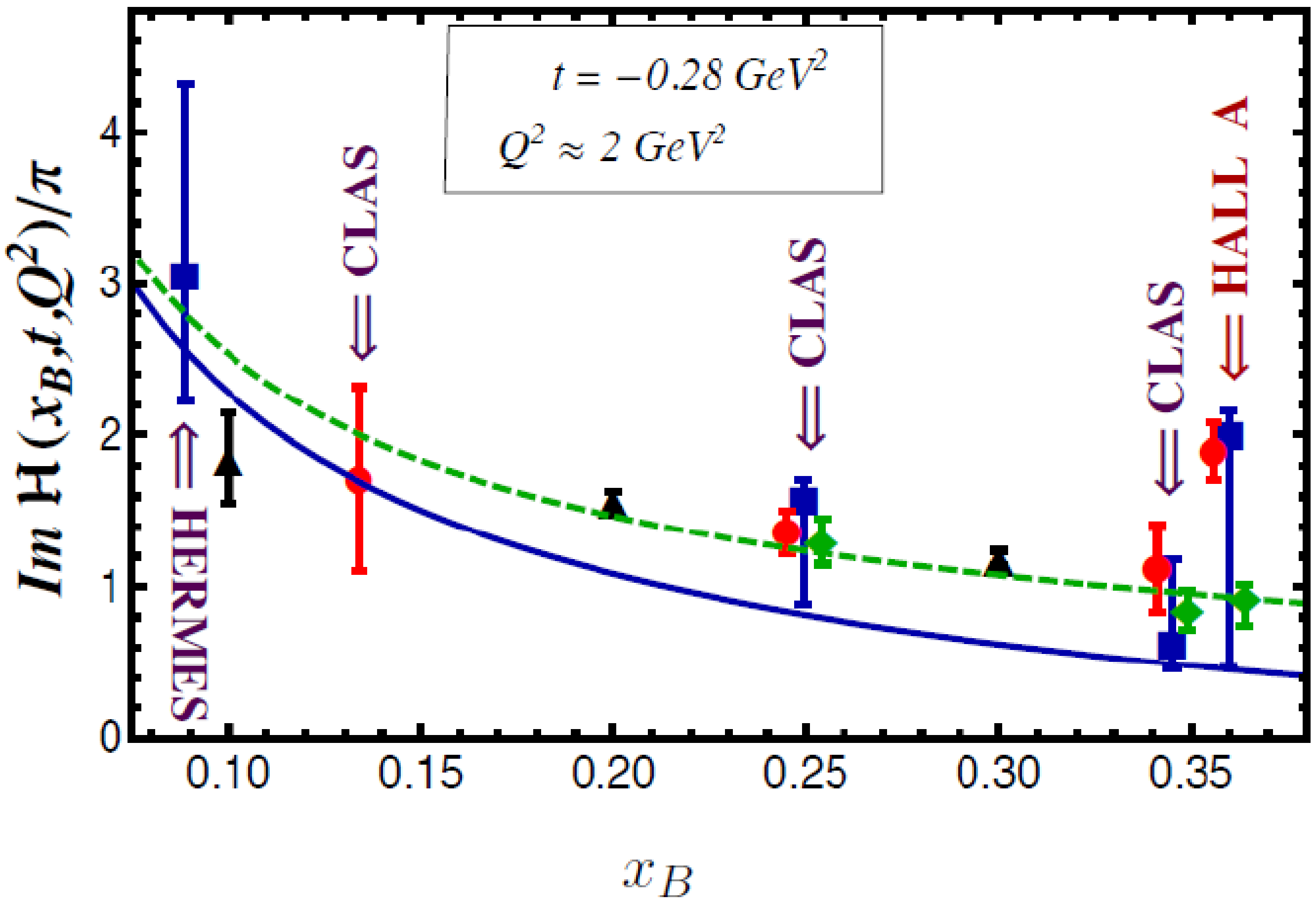


➢ Fit of a complicated many-parameter function

➢ No theoretical bias

Kumericki (2012)

Comparaison of different methods



[Guidal '08, Guidal and Moutarde '09], seven CFF fit (blue squares), [Guidal '10] $\mathcal{H}$, $\tilde{\mathcal{H}}$ CFF fit (green diamonds), [Moutarde '09] H GPD fit (red circles)

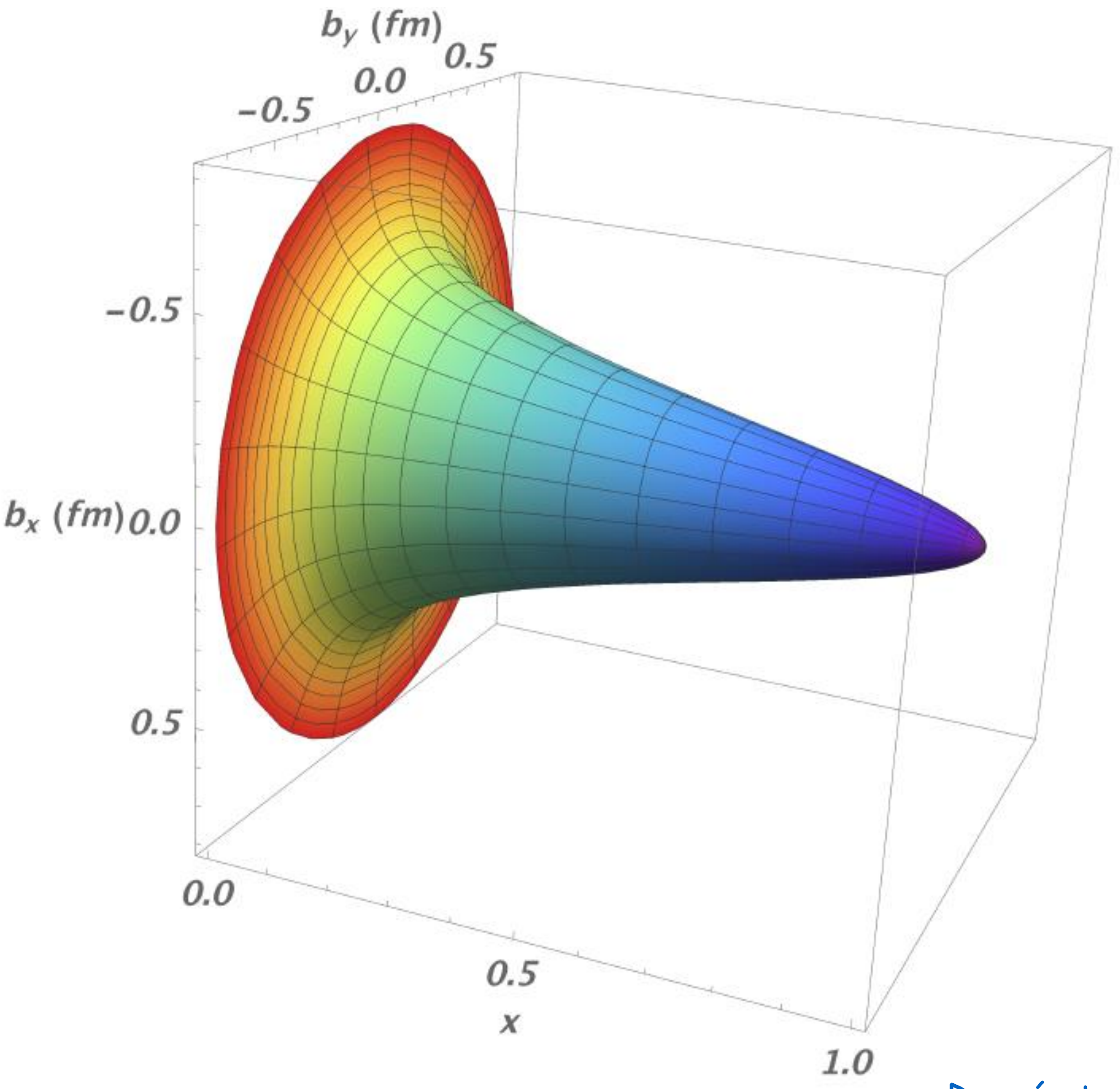
3D imaging from fits to DVCS data

From a simultaneous fit of JLab DVCS data:

- Fast-moving partons localized in the center of the proton
- Low energy and sea quarks mostly in the outer region

Much more to come with Jlab12 data:

neutron, polarized protons…



Dupré et al (2017)

Summary lecture 3

- Deeply Virtual Meson Production provides a complementary way to access GPDs of the nucleon

- At moderate values of Q^2 the DVMP cross section seems to be dominated by the transverse amplitude.

- π^0 electroproduction may allow to probe the transversity GPDs, which do not enter the handbag diagram of DVCS

- Modeling GPDs is challenging and great progress has been made recently within different approaches

- First 3D images of the internal structure of the nucleon start to come out based on experimental data