NSTAR 2026

15th International Workshop on the Physics of Excited Nucleons

GPD and TDA Measurements from Hard Exclusive Meson Electroproduction with CLAS at JLab

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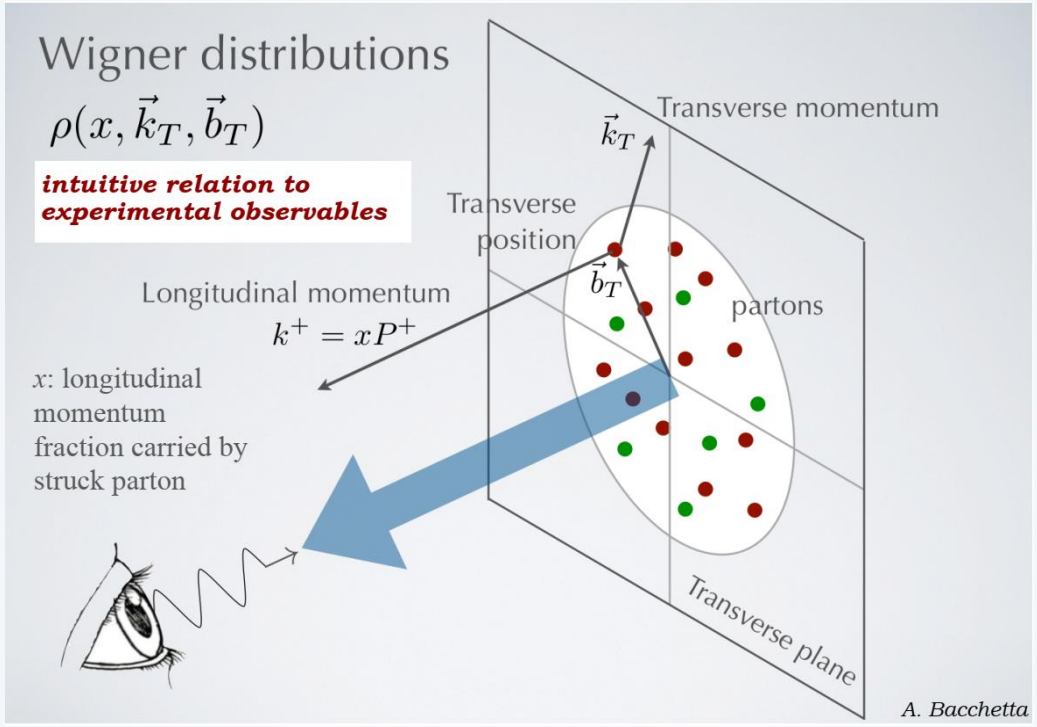
Seville · 7–11 September 2026

One object, two branches: TMDs and GPDs



X. Ji, PRL 91, 062001 (2003); A. V. Belitsky, X. Ji, F. Yuan, PRD 69, 074014 (2004)

Correlates x with transverse position b_t and transverse momentum k_T.

The most complete picture — but not directly measurable.

Integrate over b_T → TMDs: correlate transverse and longitudinal momentum. From SIDIS.

Integrate over k_T → GPDs: correlate transverse position with longitudinal momentum. From exclusive reactions.

This talk follows the GPD branch.

Four chiral-even, four chiral-odd

N/q	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

Rows: nucleon polarization. Columns: quark polarization.

Eight GPDs at leading twist

Chiral-even GPDs $H \quad E \quad \widetilde{H} \quad \widetilde{E}$

Chiral-odd GPDs $H_T \quad E_T \quad \widetilde{H}_T \quad \widetilde{E}_T$

Forward limits

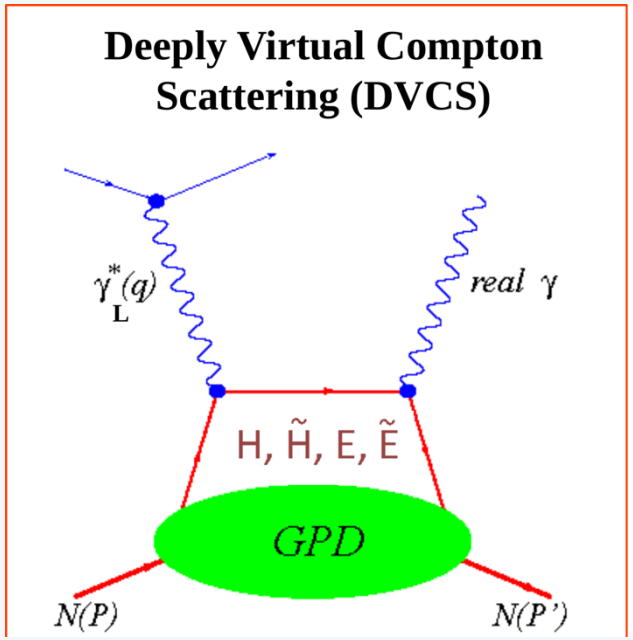
$$H \to q(x) \qquad \widetilde{H} \to \Delta q(x) \qquad H_T \to \delta q(x)$$

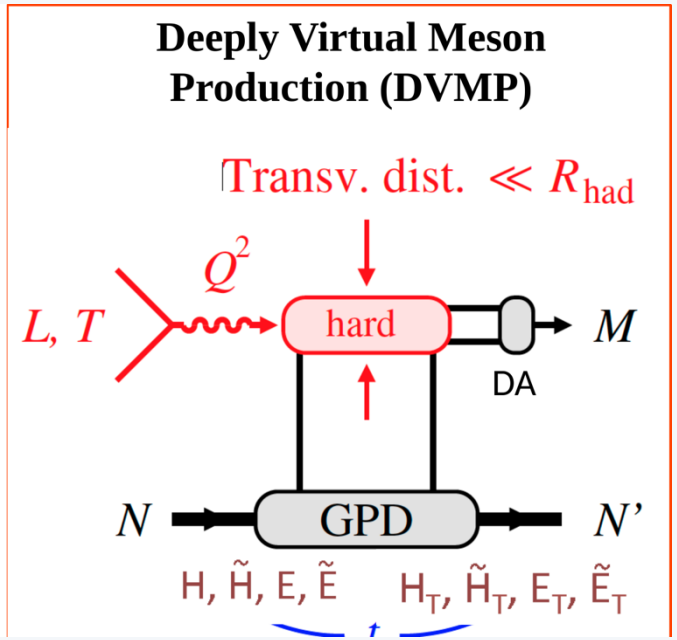
$$\bar{E}_T = 2\widetilde{H}_T + E_T \;\to\; \kappa_T$$

transverse anomalous magnetic moment

Ji's sum rule $$J^q = \frac{1}{2}\int dx\, x\,[\,H^q + E^q\,]$$

How to study GPDs: hard exclusive reactions





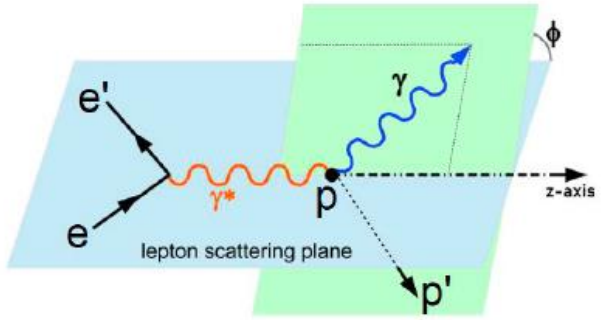
DVCS — gives the four chiral-even GPDs. The cleanest way to access GPDs: a real photon, no distribution amplitude.

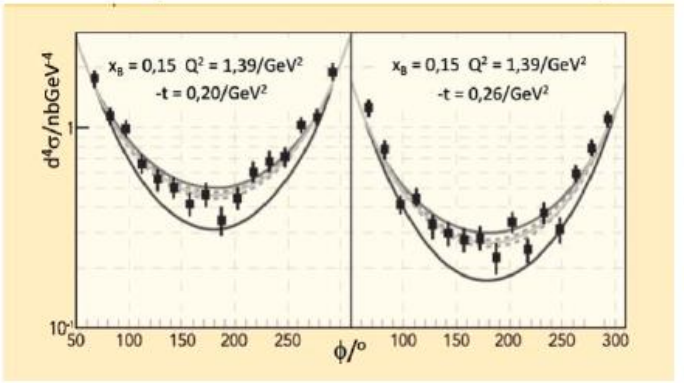
DVMP — gives all eight, including the four chiral-odd. The price: the meson distribution amplitude, and weaker factorization for transverse amplitudes.

Observables of the DVCS process

How can we measure the CFFs in the DVCS process?

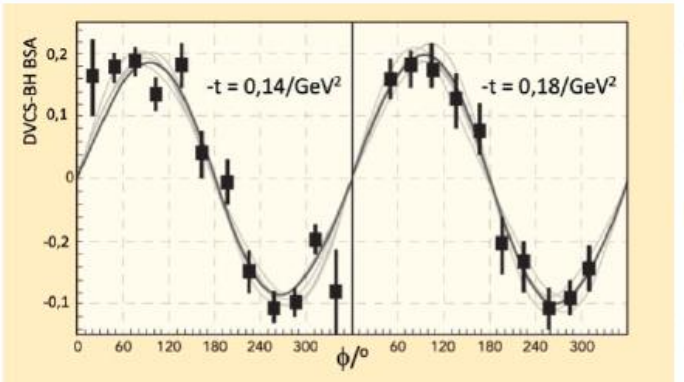
1. Cross-section $\sigma^{ep\gamma}(x,Q^2,t,\phi) \propto \boxed{Re\{\mathcal{H}\}}$





2. Beam-Spin Asymmetry

$$BSA(x,Q^2,t,\phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \boxed{Im\{\mathcal{H}\}} \sin\phi$$



V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

Flavour and spin sensitivity beyond DVCS

	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

Two capabilities meson production adds

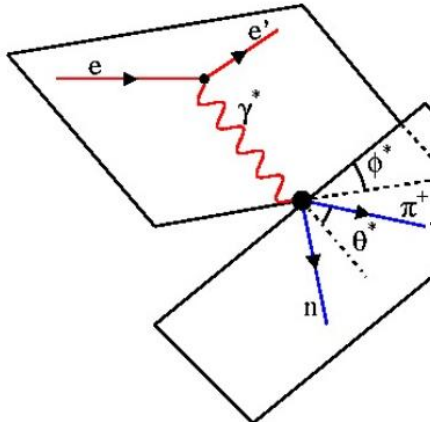
Flavour filtering. Different mesons weight different quark flavours.

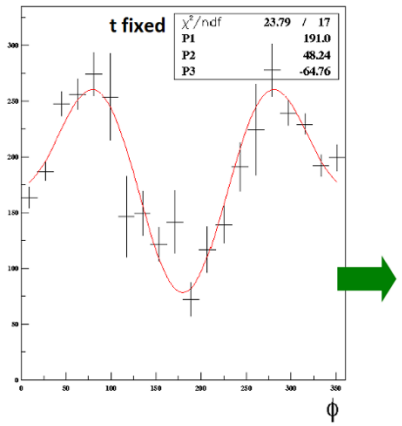
Spin selectivity. Transverse amplitudes reach the chiral-odd GPDs.

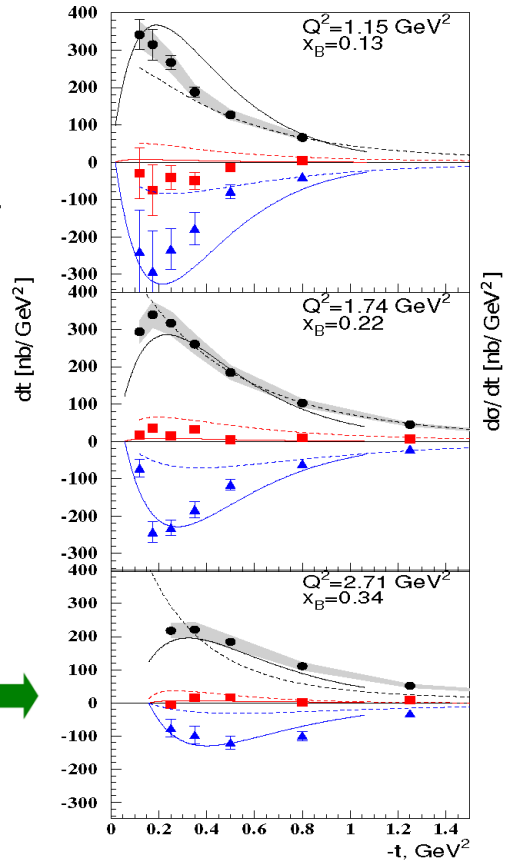
ϕ meson provides an access to the gluon GPDs.

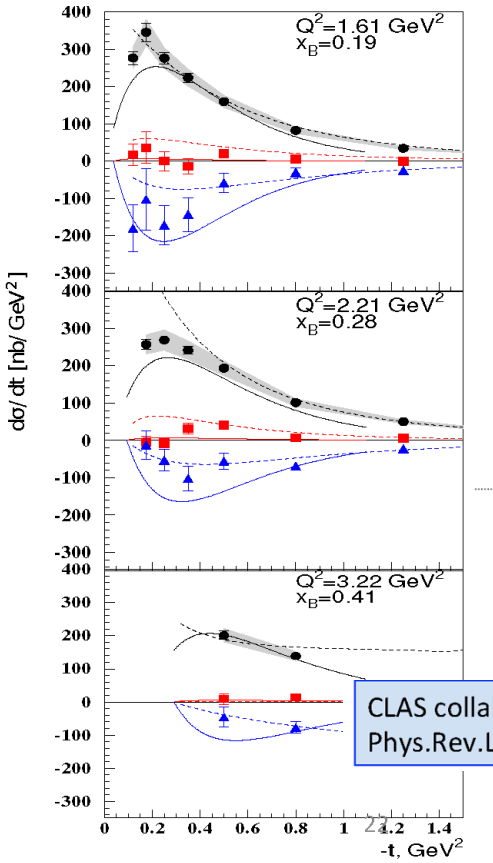
DVMP ($\pi 0$) Differential Cross Section

$$2\pi \frac{d^2\sigma}{dtd\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$









CLAS in Hall B
E=6 GeV

- σ_0
- σ_{TT} → cos(2φ)
- σ_{LT} → cos(φ)

— GK

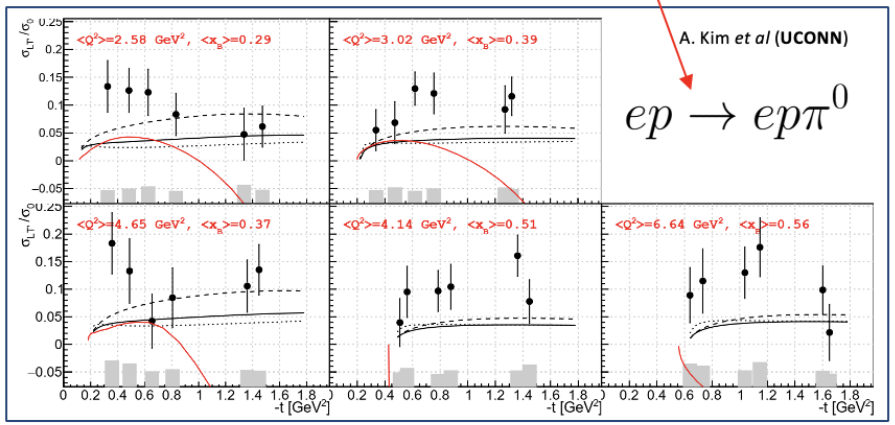
- - - GGL

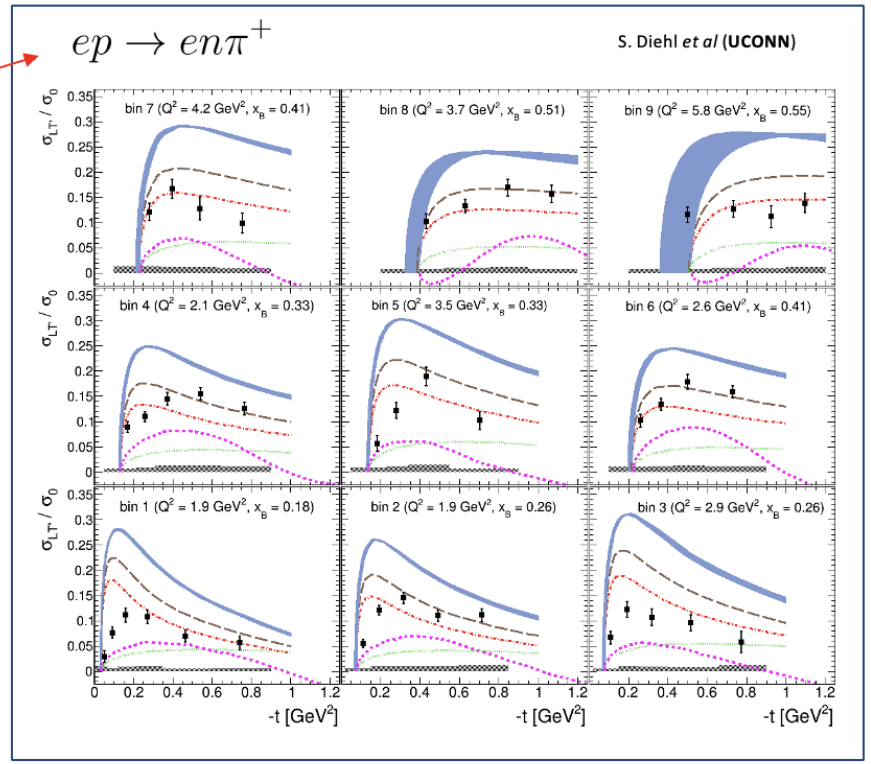
CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

The polarized structure-function ratio for π^0 and π^+

E=10.6 GeV

$$\sigma_{LT'} = \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\times \times \mathrm{Im}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle + \langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$





GK model

JML model

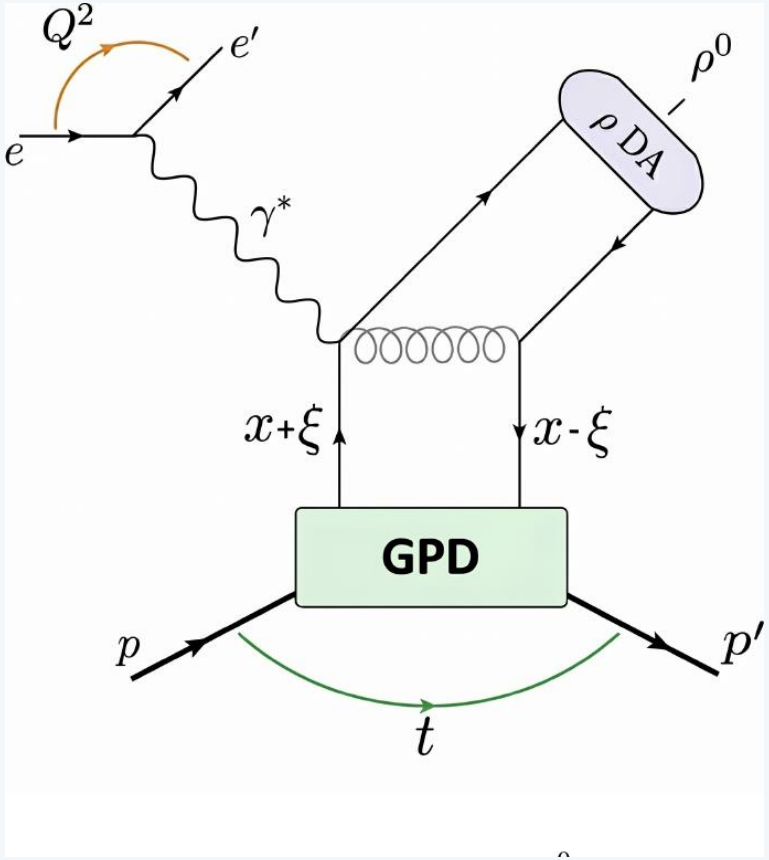
$\bar{E}_T$ is related to the proton's anomalous tensor magnetic moment.

H_T is related to the proton's tensor charge.

$$\kappa_T^u = \int dx \bar{E}_T^u(x,\xi,t=0) \quad \delta_T^u = \int dx H_T^u(x,\xi,t=0)$$

$$\kappa_T^d = \int dx \bar{E}_T^d(x,\xi,t=0) \quad \delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

A complementary probe of the chiral-odd GPDs



Hard subprocess × ρ^0 distribution amplitude × GPD-parametrized proton matrix element.

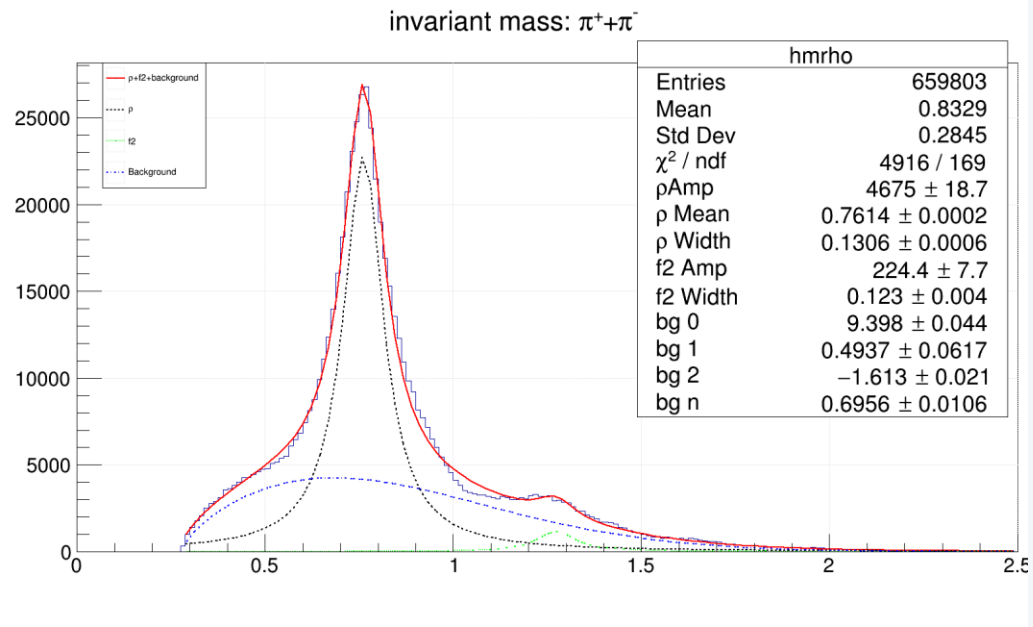
$\sigma_{LT'}$ for ρ^0 probes the interference of the chiral-even H with the chiral-odd H_T and $\bar{E}_T$, the latter entering through the twist-3 component of the longitudinal ρ^0.

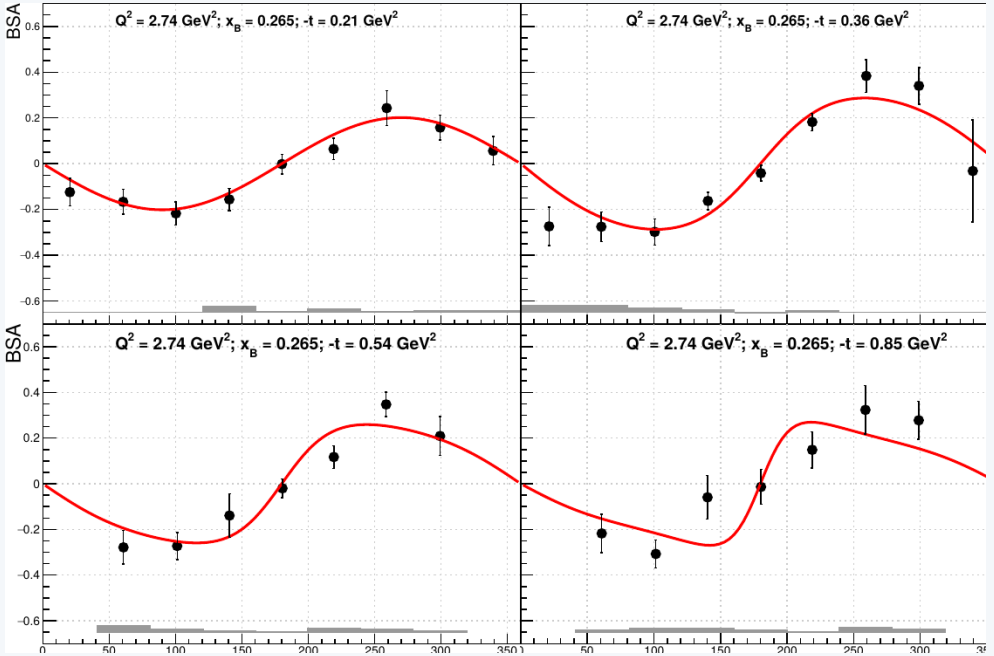
Complementary combinations of chiral-even and chiral-odd GPDs.

An independent test of the transversity description built on pseudoscalars.

S. V. Goloskokov, P. Kroll, EPJ C 74, 2725 (2014)

$\rho^0 \to \pi^+\pi^-$ with CLAS12 Run Group A





ep → e′pρ⁰ at 10.6 GeV; ≈ 1.5 M events.

$\pi^+\pi^-$ mass fit → ρ^0 yields → $A_{LU}(\phi)$ → $\sigma_{LT'}/\sigma_0$. Systematics 0.017–0.020.

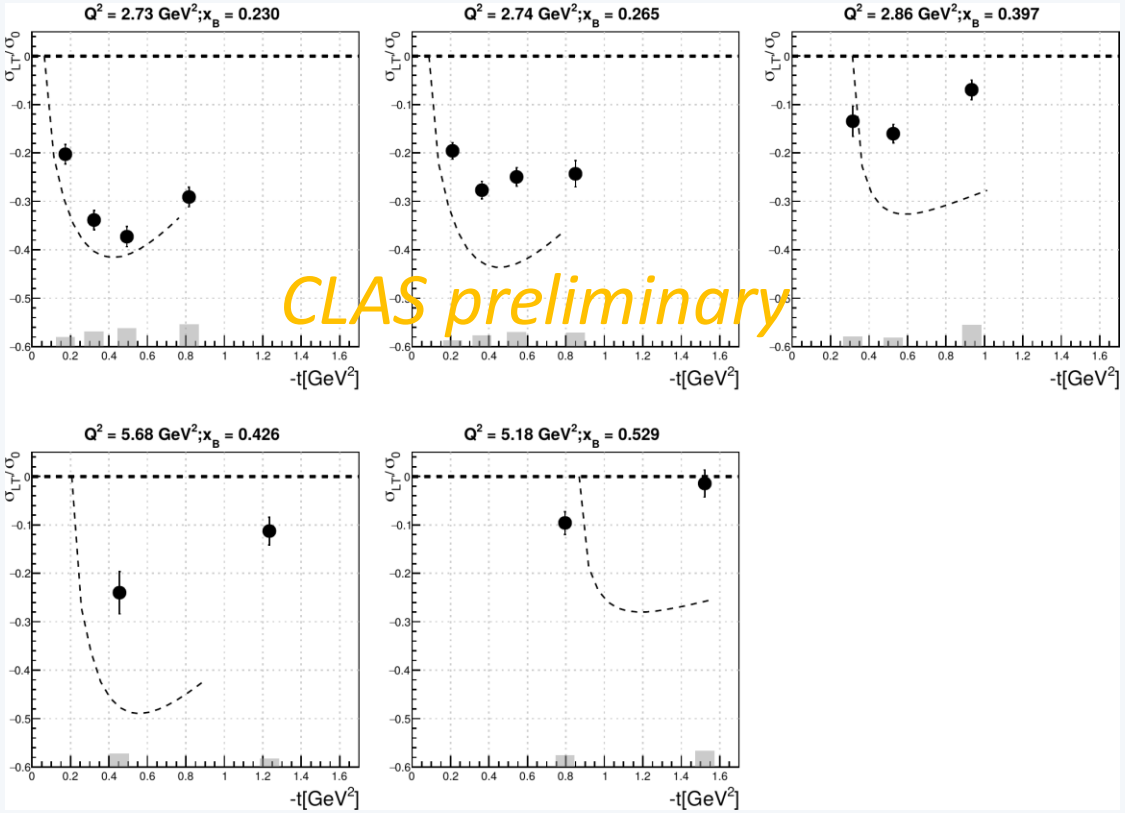
The ratio versus −t in five kinematic bins

First multidimensional $\sigma_{LT'}/\sigma_0$ for exclusive ρ^0.

Negative over the whole range: $1 < Q^2 < 11$ GeV², and x_B from 0.1 to 0.8.

Reaches −0.3 to −0.45; trends toward zero at larger −t. No sign change.

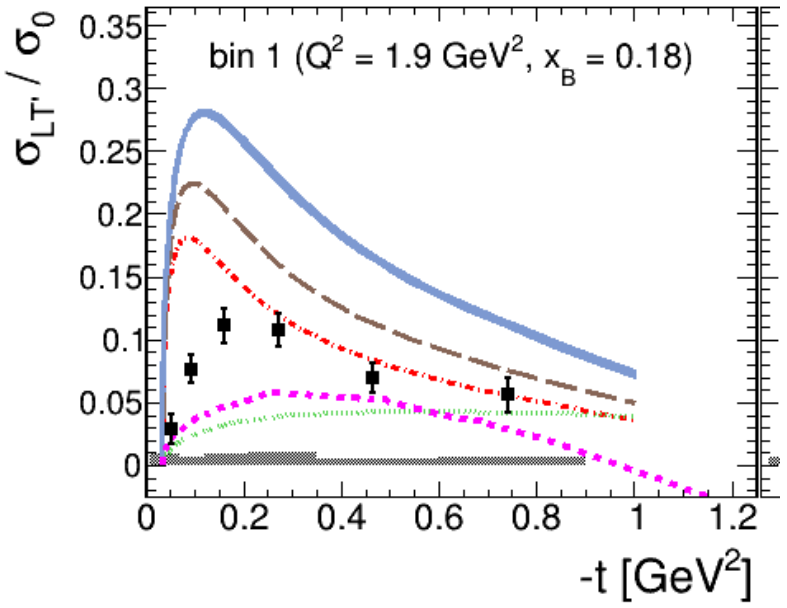
Q^2 and x_B are correlated — no independent Q^2 evolution. Dashed: Goloskokov–Kroll.



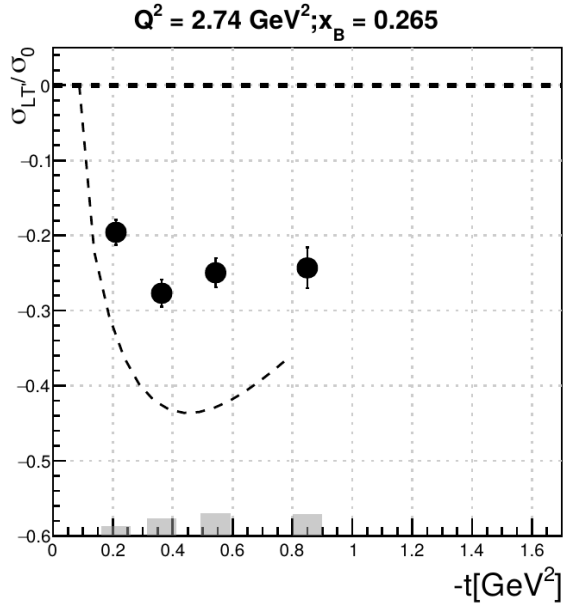
N. Trotta, A. Kim, S. Diehl, K. Joo (CLAS Collaboration)
CLAS preliminary, manuscript in preparation

A sign reversal, and what produces it

π^0 positive



ρ^0 negative



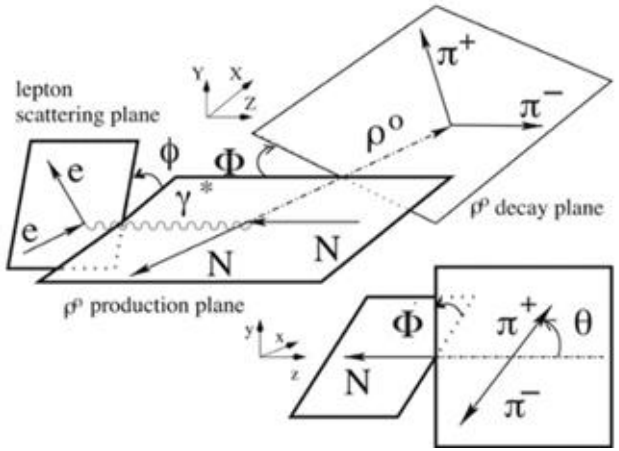
π^0 is sensitive to $\bar{E}_T$; ρ^0 measures H interfering with H_T and $\bar{E}_T$ — opposite in sign.

One GK framework predicts both signs — the sign is the robust feature.

SDMEs from Exclusive ρ production with CLAS12

- 23 SDME elements are extract using the MLM:

$$-\ln L(\mathcal{R}) = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}^{U+L}(\mathcal{R}; \Phi_i, \phi_i, \cos\Theta_i)}{\widetilde{\mathcal{N}}(\mathcal{R})}$$



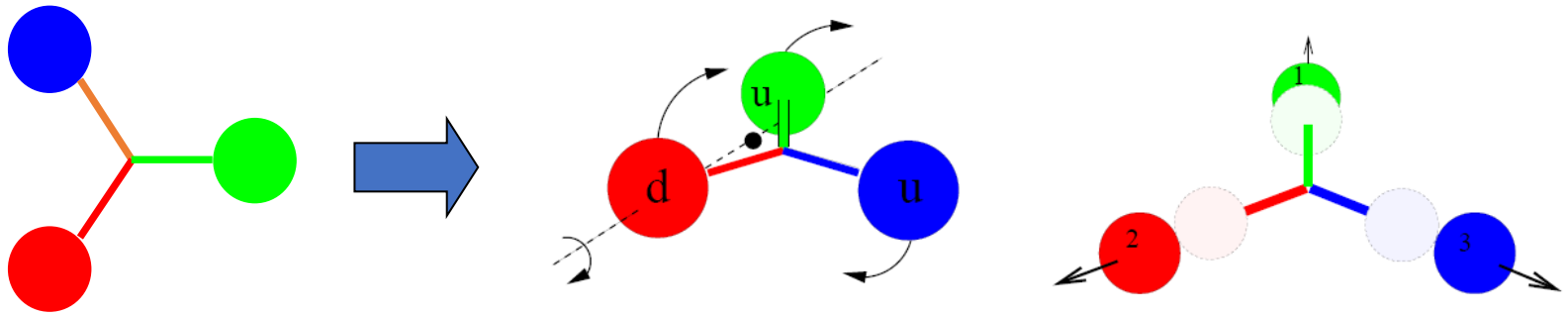
15 unpolarized SDMEs

$$W^{U}(\Phi,\phi,cos(\Theta)) = \frac{3}{8\pi^2}\left(\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2(\Theta)\right.$$
$$-\sqrt{2}Re r^{04}_{10}\sin(2\Theta)\cos(\phi) - r^{04}_{1-1}\sin^2(\Theta)\cos(2\phi)$$
$$-\epsilon\cos(2\Phi)[r^{1}_{11}\sin^2(\Theta) + r^{1}_{00}\cos^2(\Theta)$$
$$-2Re\{r^{1}_{10}\}\sin(2\Theta)\cos(\phi) - r^{1}_{1-1}\sin^2(\Theta)\cos(2\phi)]$$
$$-\epsilon sin(2\Phi)[\sqrt{2}Im\{r^{2}_{10}\}sin(2\Theta)sin(\phi)$$
$$+Im\{r^{2}_{1-1}\}\sin^2(\Theta)\sin(2\phi)]$$
$$\sqrt{2\epsilon(1+\epsilon)}\cos(\Phi)[r^{5}_{11}\sin^2(\Theta) + r^{5}_{00}\cos^2(\Theta)$$
$$-\sqrt{2}Re\{r^{5}_{10}\}\sin(2\Theta)\cos(\phi) - r^{5}_{1-1}\sin^2(\Theta)\cos(2\phi)]$$
$$+\sqrt{2\epsilon(1+\epsilon)}\sin(\Phi)[\sqrt{2}Im\{r^{6}_{10}\}\sin(2\Theta)\sin(\phi)$$
$$\left.+Im\{r^{6}_{1-1}\}\sin^2(\Theta)\sin(2\phi)]\right)$$

8 polarized SDMEs

$$W^{L}(\Phi,\phi,cos(\Theta)) = \frac{3}{8\pi^2}(\sqrt{1-\epsilon^2}[\sqrt{2}Im\{r^{3}_{10}\}\sin(2\Theta)\sin(\phi)$$
$$+Im\{r^{3}_{1-1}\}\sin^2(\Theta)\sin(2\phi)]$$
$$+\sqrt{2\epsilon(1+\epsilon)}\cos(\Phi)[\sqrt{2}Im\{r^{7}_{10}\sin(2\Theta)\sin(\phi)$$
$$+Im\{r^{7}_{1-1}\}\sin^2(\Theta)\sin(2\phi)]$$
$$+\sqrt{2\epsilon(1+\epsilon)}\sin(\Phi)[r^{8}_{11}\sin^2(\Theta) + r^{8}_{00}\cos^2(\Theta)$$
$$-\sqrt{2}Re\{r^{8}_{10}\}\sin(2\Theta)\cos(\phi) + r^{8}_{1-1}\sin^2(\Theta)\cos(2\phi)])$$

From the ground state nucleon to resonances



How does the exitation affect the 3D structure of the Nucleon?

 Pressure distributions, tensor charge, … of resonances?

Traditional way: Study of transition form factors (**2D picture** of transv. position)

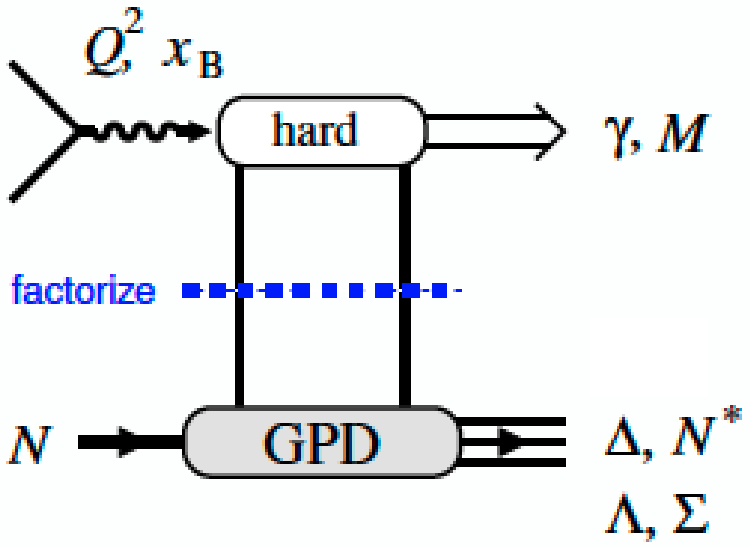
3D picture of the exitation process: Encoded in **transition GPDs**

Simplest case: N→Δ transition ➔ **16 transition GPDs**

- **8 helicity non-flip transition GPDs (twist 2)**
  - Related to the Jones-Scardon and Adler EM FF for the N → Δ transition
- **8 helicity flip transition GPDs (transversity)**

P. Kroll and K. Passek-Kumericki, Phys. Rev. D 107, 054009 (2023).
K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023).

Exploring Transition GPDs with CLAS12



Transition GPDs

Factorization of hard exclusive processes

GPDs for resonance final states

Theoretical methods: Chiral dynamics, $1/N_c$ expansion of QCD

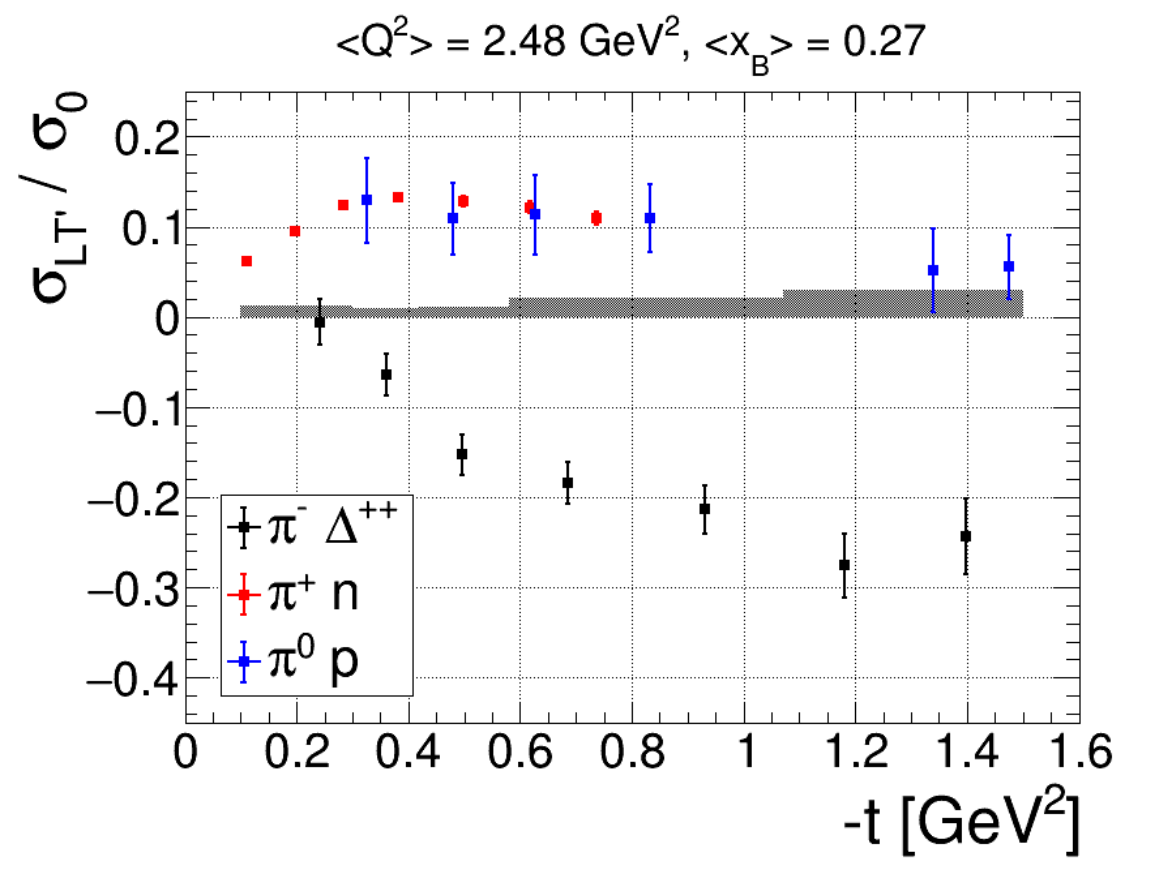
Processes

$N \to \Delta$ in DVCS

$N \to \Delta, N^*$ in π, η production

$N \to \Lambda, \Sigma$ in K, K^* production

The second picture: structure of Δ and N*



S. Diehl et al. (CLAS Collaboration) — preliminary, in preparation

N → Δ in DVCS and in π, η production; N → Λ, Σ in K and K*.

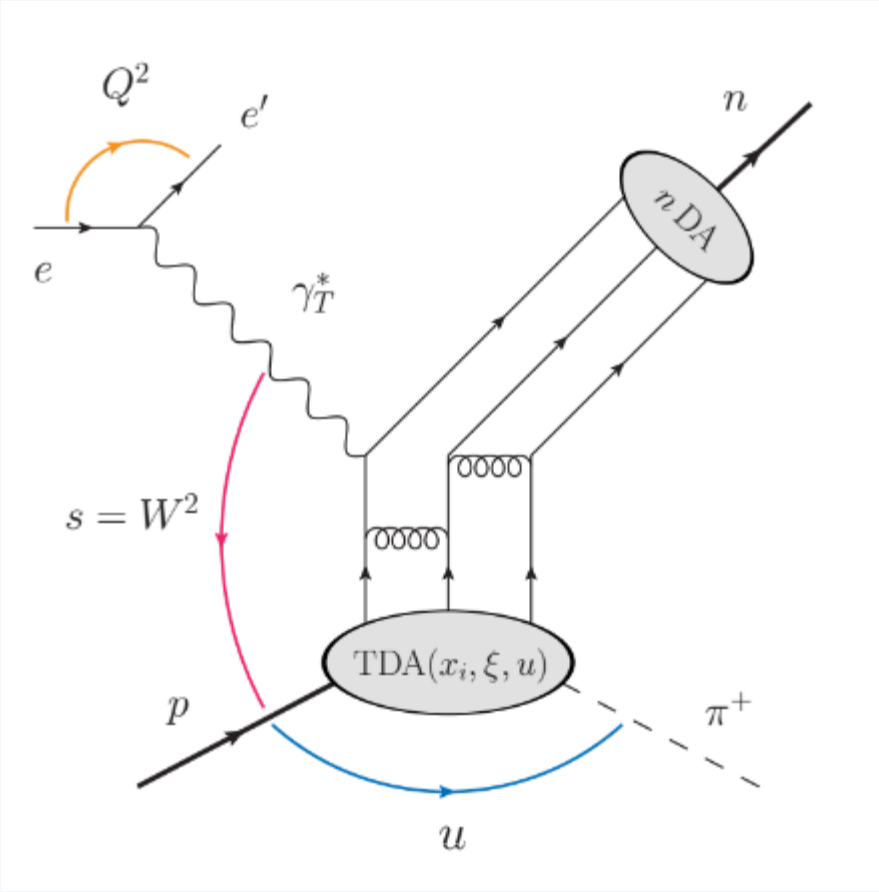
ep → e′π⁻Δ⁺⁺: negative $\sigma_{LT'}/\sigma_0$, while π⁺n and π⁰p are positive.

Gives the transverse structure of the excitation itself.

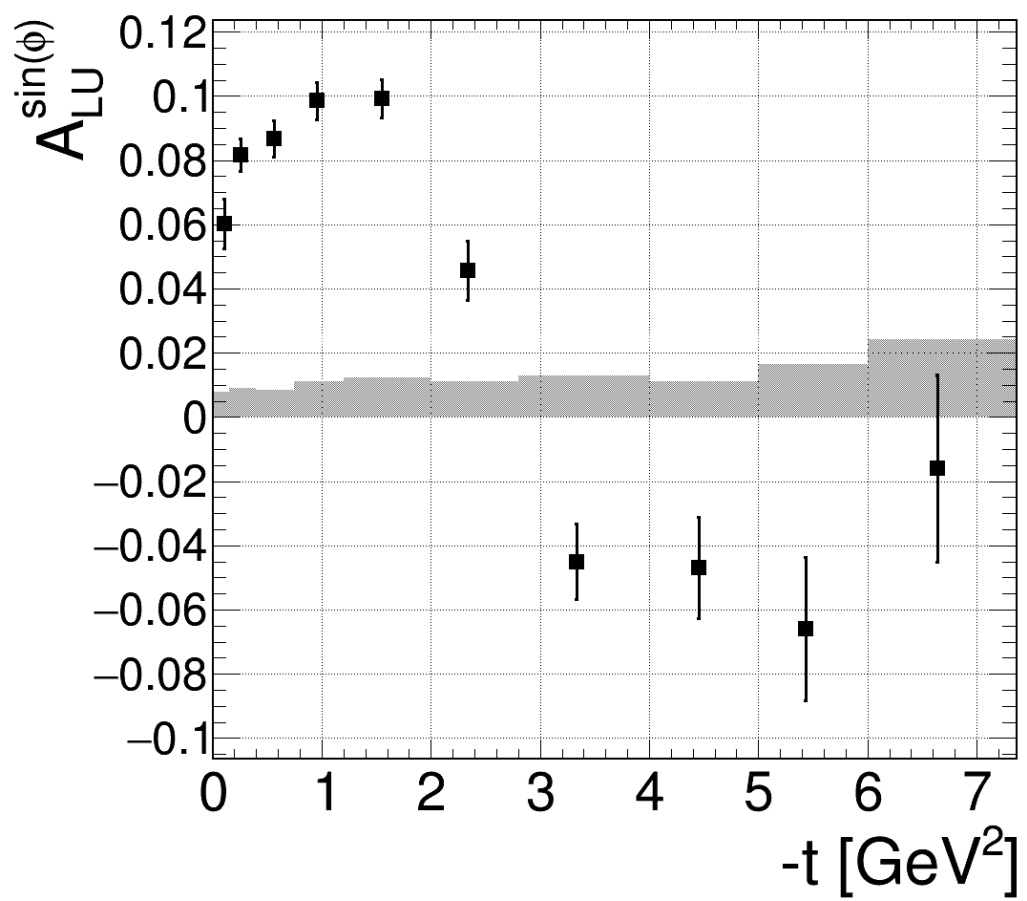
TDAs access the structure of the pion cloud

In backward pion production, the nonperturbative object is a nucleon-to-pion transition distribution amplitude.

The πN TDA probes three-quark correlations connecting the nucleon and pion — providing access to the nucleon's pion-cloud component.



$ep \to en\pi^+$ in the backward regime



S. Diehl et al. (CLAS Collaboration), PRL 125, 182001 (2020)

The sinϕ asymmetry crosses zero and turns negative for $-t \gtrsim 3$ GeV².

First non-zero backward-angle beam-spin asymmetry.

Still needed: Q^2 scaling at fixed x_B, small-$|u|$ dependence, transverse dominance, and consistency across backward π, ω, ρ^o.

Accessibility is demonstrated; TDA factorization is not.

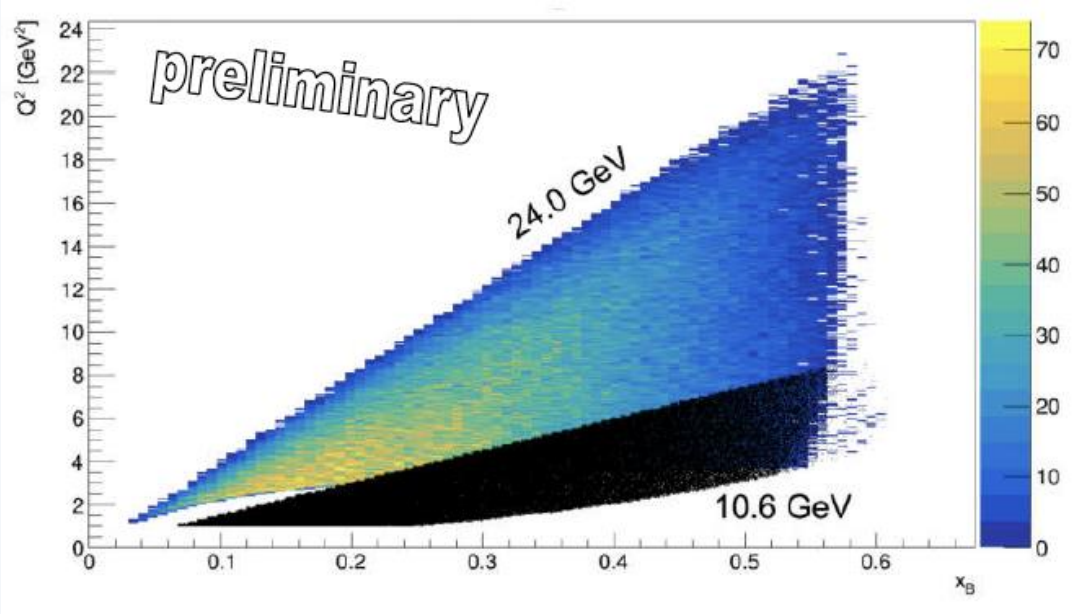
A broader exclusive-reaction program at 22 GeV

Extends DVCS, pseudoscalar- and vector-meson measurements to higher Q^2.

Broadens Q^2–x_B coverage for evolution studies and scaling tests.

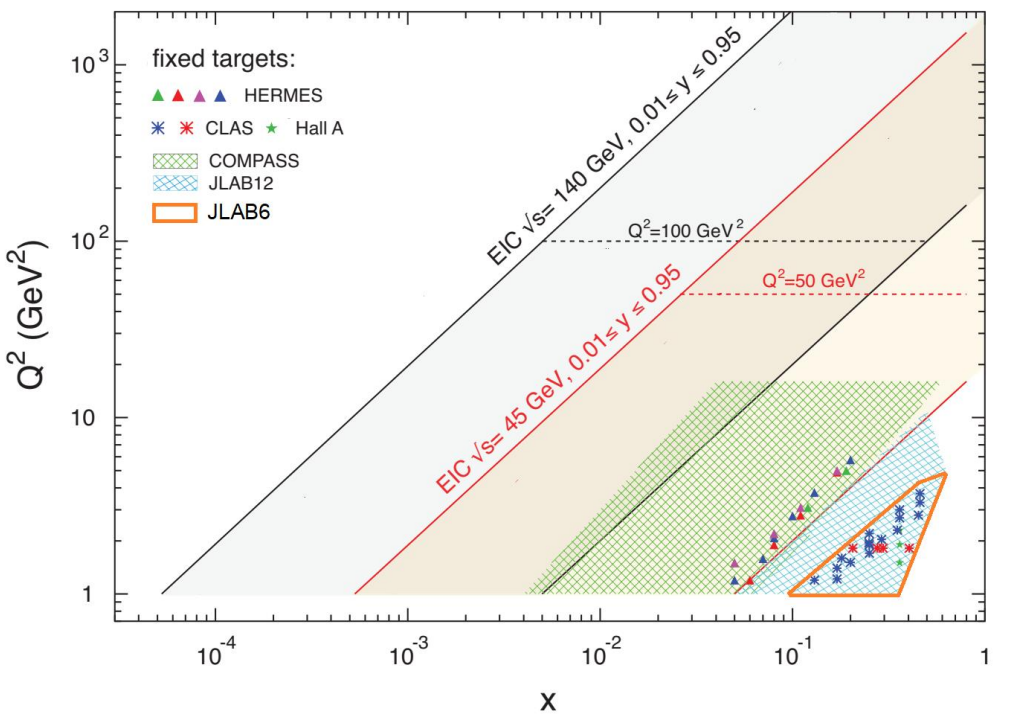
Strengthens L/T separations and tests of reaction mechanisms and factorization.

Opens new kinematics for transition-GPD and backward-angle TDA studies.



A 22 GeV upgrade adds the energy lever arm needed to turn CLAS12's multidimensional measurements into controlled QCD tests.

JLab, COMPASS and the EIC



Facility	Primary strength for exclusive mesons
JLab 12 GeV	High luminosity, detailed valence-region measurements
JLab 22 GeV	Extended Q^2 at moderate-to-large xB; scaling and factorization tests
COMPASS	Bridge between the valence and lower-x regimes
EIC	Sea-quark and gluon GPDs, especially through vector mesons

Together they give the x_B, Q^2 and t/u coverage needed to distinguish reaction mechanisms.

A complementary program for hadron tomography

DVCS constrains chiral-even GPDs; meson channels add flavor and helicity filters, including chiral-odd amplitudes.

Cross sections, BSAs and SDMEs probe different interference terms; GPD extraction requires a global amplitude analysis.

Transition GPDs map N→N*/Δ structure; backward pion production probes πN TDAs and the pion-cloud component.

L/T separation and broad Q^2, Bjorken-x and t/u coverage at CLAS12, COMPASS, 22 GeV JLab and the EIC will test factorization.