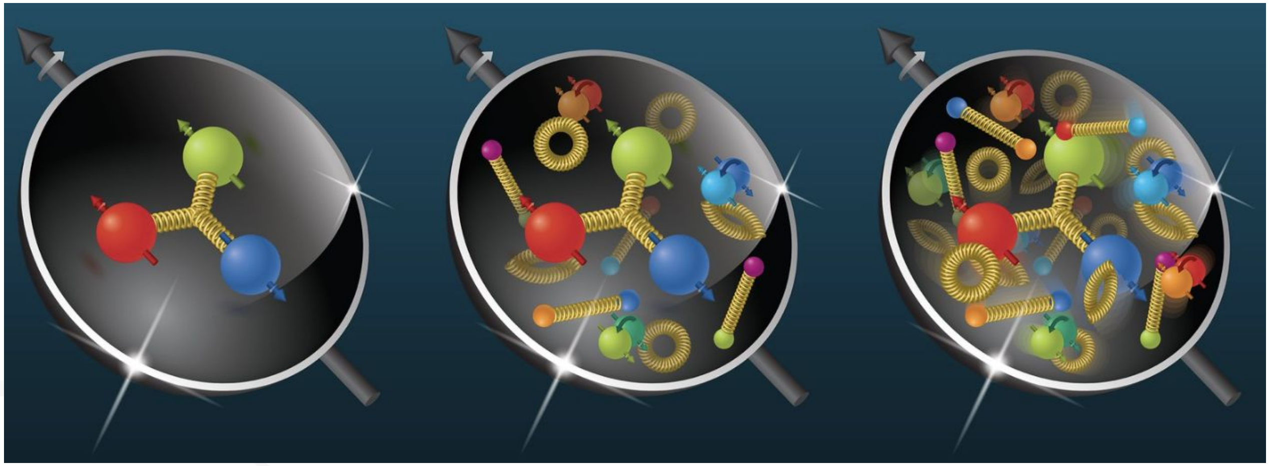
Deeply Virtual Exclusive Processes



Towards improved hadron femtography with hard exclusive reactions, edition IV, Jefferson Lab, 2025

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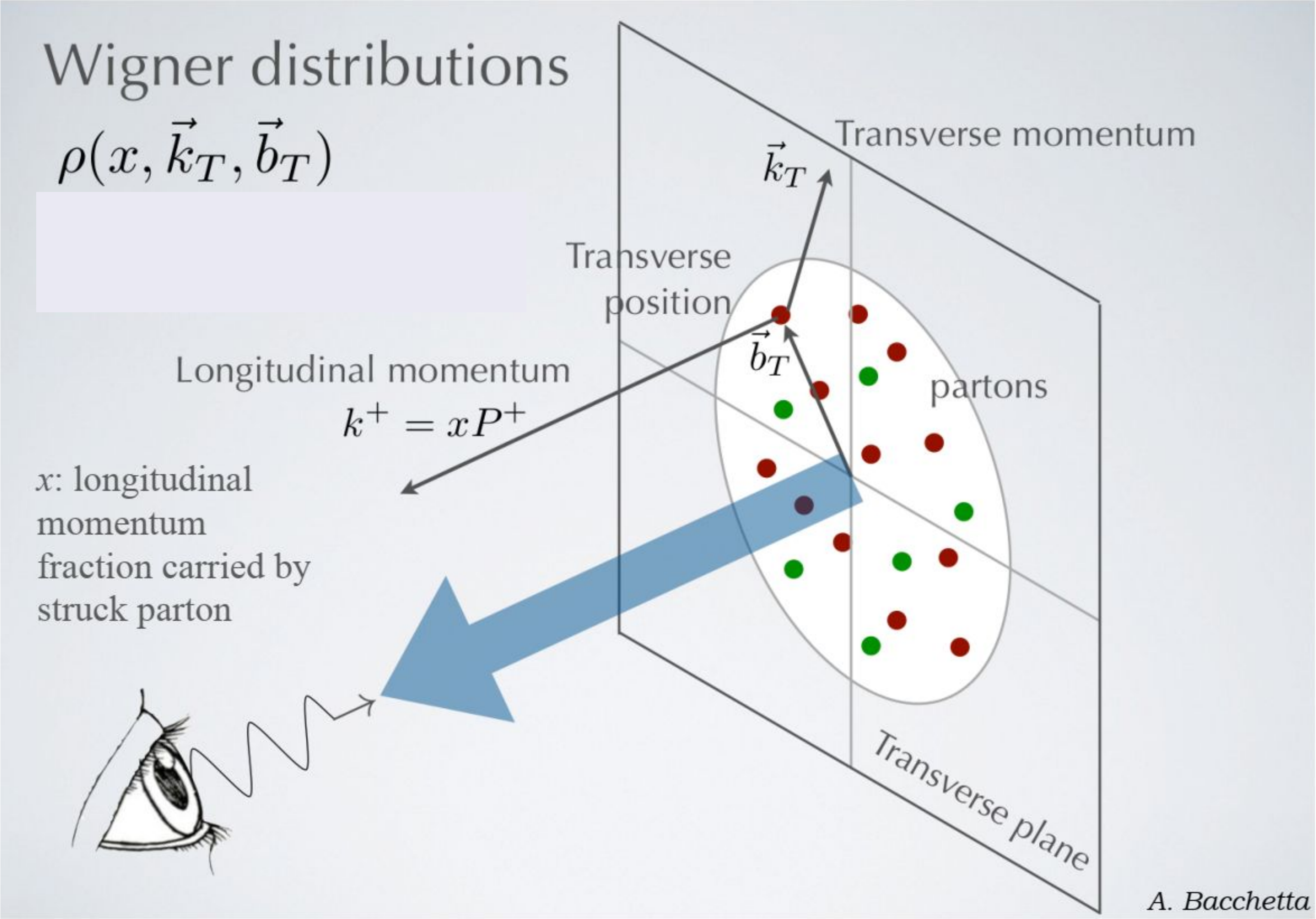
July 29, 2025

3-Dimensional Imaging of Quarks and Gluons



Generalized Parton Distributions (GPDs)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

S. Liuti et al., Phys. Rev. D 84, 034007 (2011) (GGL)

P. Kroll et al., Eur. Phys. J. A 47, 112 (2011) (GK)

Integrate over transverse ***momentum*** space

Generalized Parton Distributions (GPD)

3-D nucleon images in the transverse coordinate and longitudinal momentum space

quark pol.

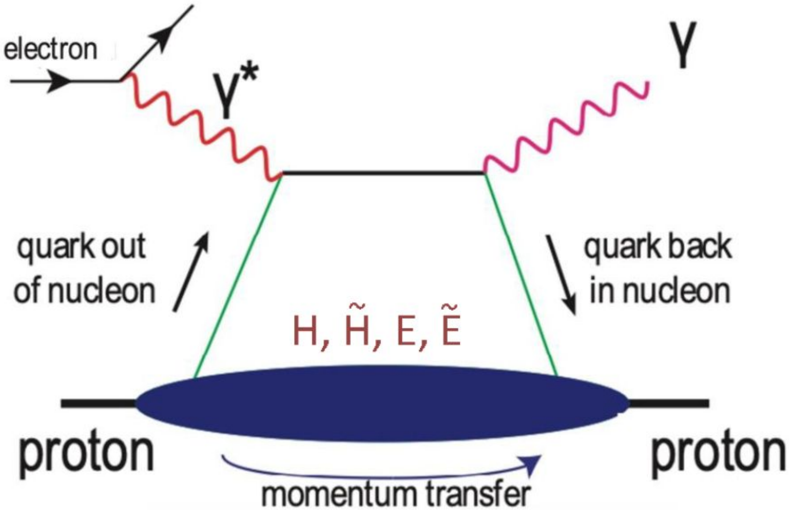
nucleon pol.

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

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

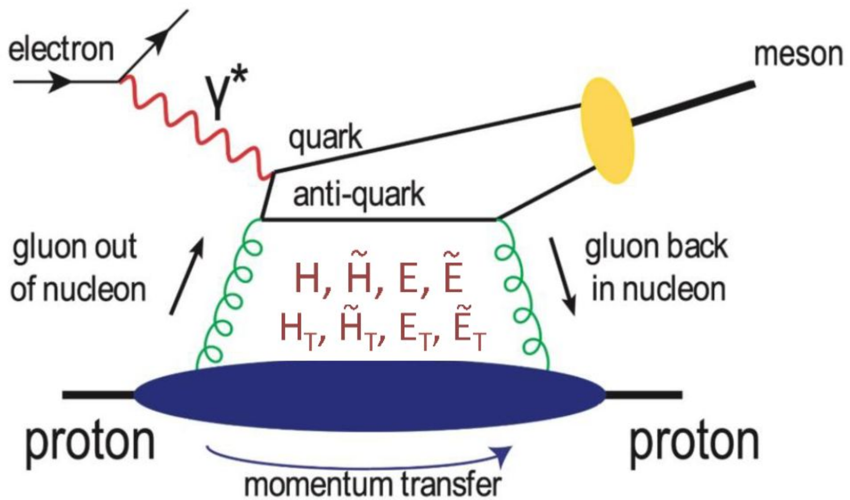
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



Deeply Virtual Compton scattering:
real photon is produced

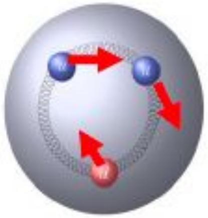
Deeply Virtual Meson Production (DVMP)



Deeply Virtual Meson production:
quark-antiquark bound state is produced

➔ Access to Generalized Parton Distributions (GPDs)

Physics Content of GPDs: From GPDs and CFFs to the D-term



- GPDs can not be directly measured with the DVCS and DVMP processes

DVCS Process: Observables are the Compton-FFs (CFF)

→ Complex integrals over the *x*-dependence of the GPDs

$$\underbrace{\mathrm{Re}\mathcal{H}(\xi,t)}_{\textbf{CFF}} + i\,\underbrace{\mathrm{Im}\mathcal{H}(\xi,t)}_{\textbf{CFF}} = \sum_q e_q^2 \int \mathrm{d}x \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] \underbrace{H^q(x,\xi,t)}_{\textbf{GPD}}$$

GPD, Compton-FFs and the pressure within the nucleon:

- GPDs provide indirect access to mechanical properties of the nucleon ➔ gravitational form factors

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

X. D. Ji, PR**D 55**, 7114-7125 (1997)
M. Polyakov, PL**B 555**, 57-62 (2016)

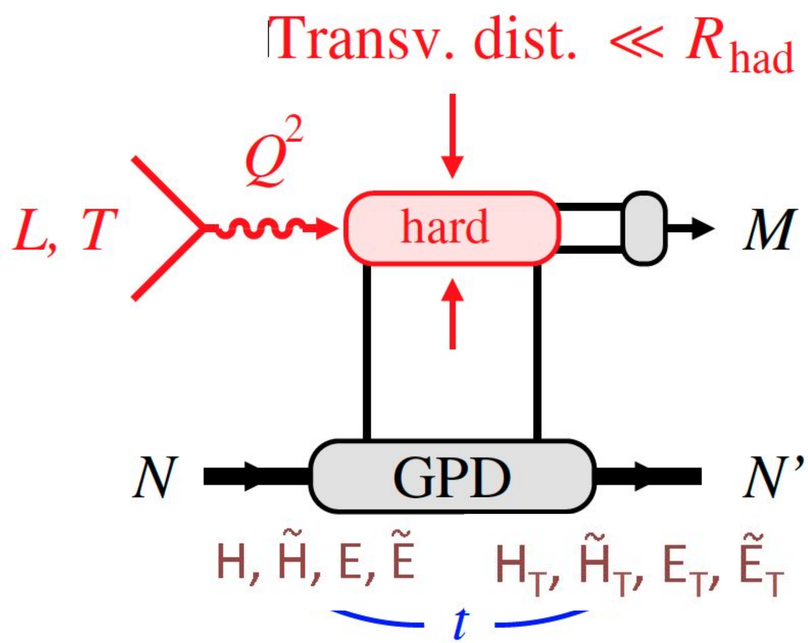
- Real- and imaginary part of the Compton-FF $\mathcal{H}$ follow the dispersion relation:

$$\boxed{\mathrm{Re}\mathcal{H}(\xi,t)} \propto \boxed{D(t)} + \frac{2}{\pi}\mathcal{P}\int \mathrm{d}x \frac{x\,\boxed{\mathrm{Im}\mathcal{H}(x,t)}}{\xi^2 - x^2}$$

M. Diehl, D. Y. Ivanov, Eur. Phys. J. C 2007, 52, 919

Deeply Virtual Meson Production in the GPD regime

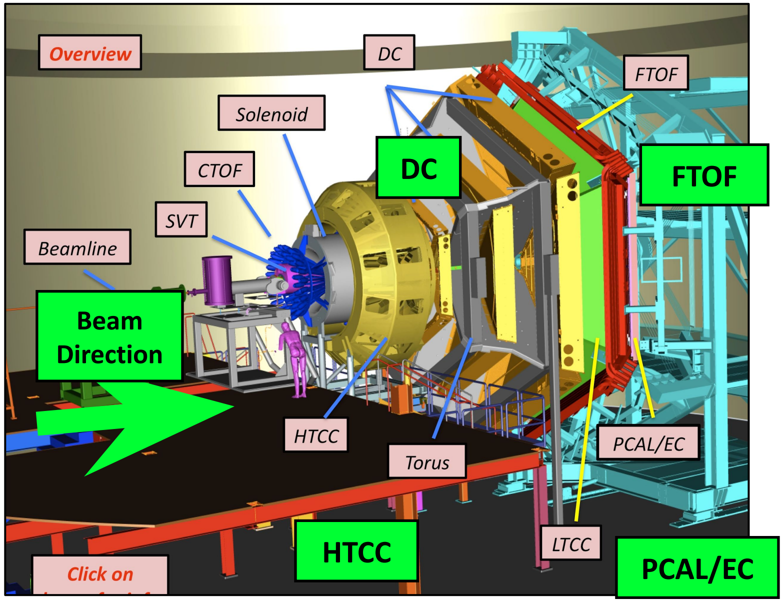
	Meson	Flavor
$\bar{\mathcal{H}}_T, \bar{\mathcal{E}}_T$ $\tilde{\mathcal{H}}, \tilde{\mathcal{E}}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

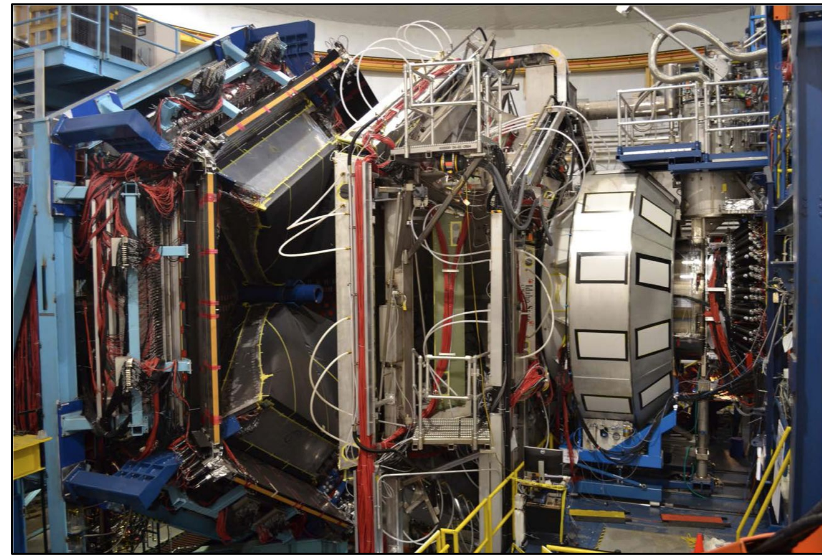


- DVMP enables Flavour decomposition of GPDs.
- The small-size regime: the production of $q\bar{q}$ pair with sizes << hadronic size dominates.
  - ❖ QCD factorization and GPD extraction assume that this regime is attained.

CEBAF Large Acceptance Spectrometer (CLAS12) in Hall B

https://www.jlab.org/Hall-B/clas12-web/

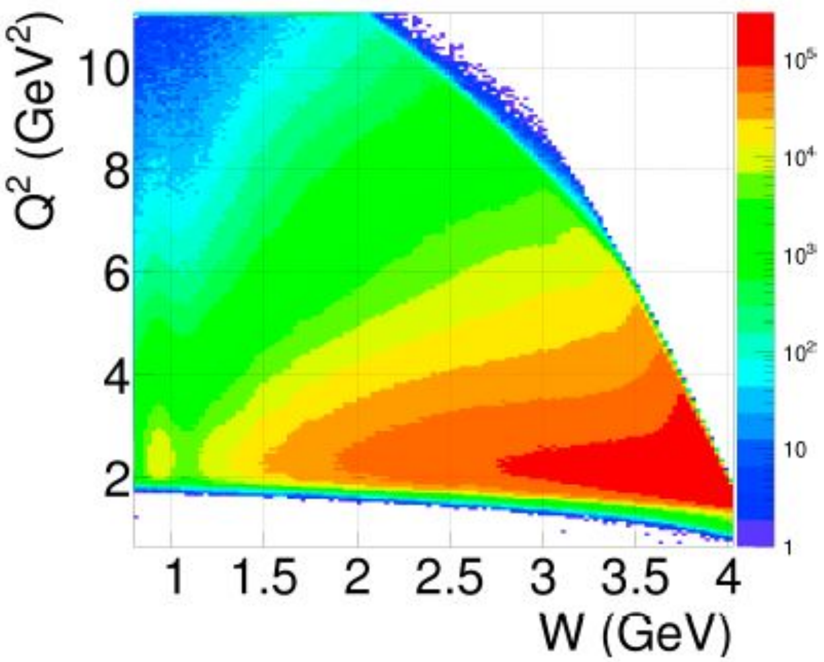


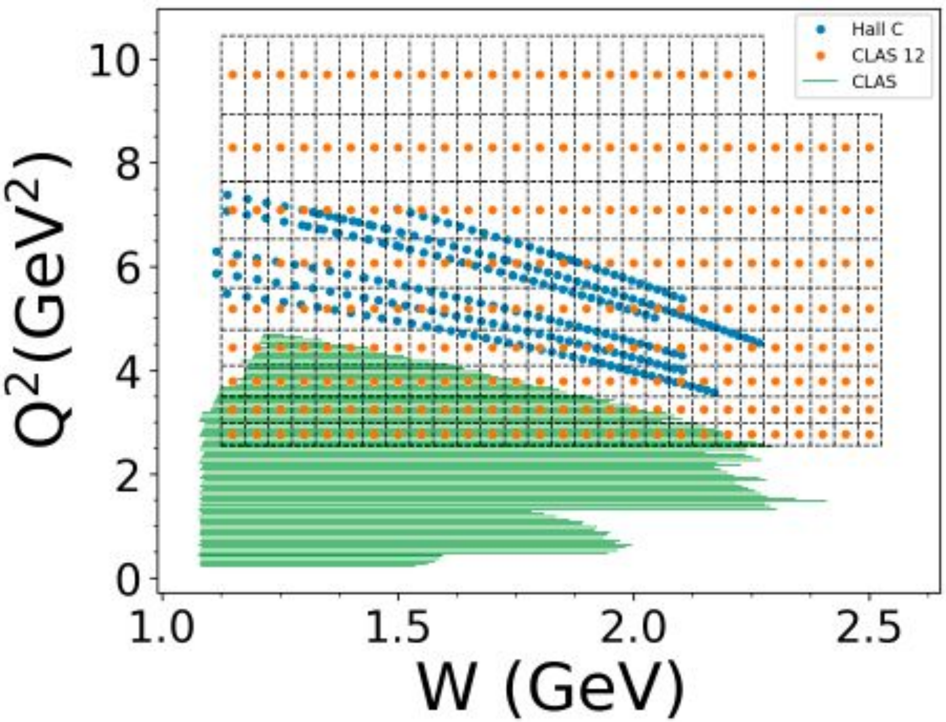


V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- CLAS12: 10^{35} $cm^{-2}sec^{-1}$ luminosity, nearly 4π acceptance, $0.05\ GeV^2 < Q^2 < 10.0\ GeV^2$ coverage over photon virtuality.
- Began data taking in Spring 2018 – many “run periods” now available
- Data from Fall 2018 - 10.6 GeV electron beam, longitudinally polarized beam, liquid H_2 target.

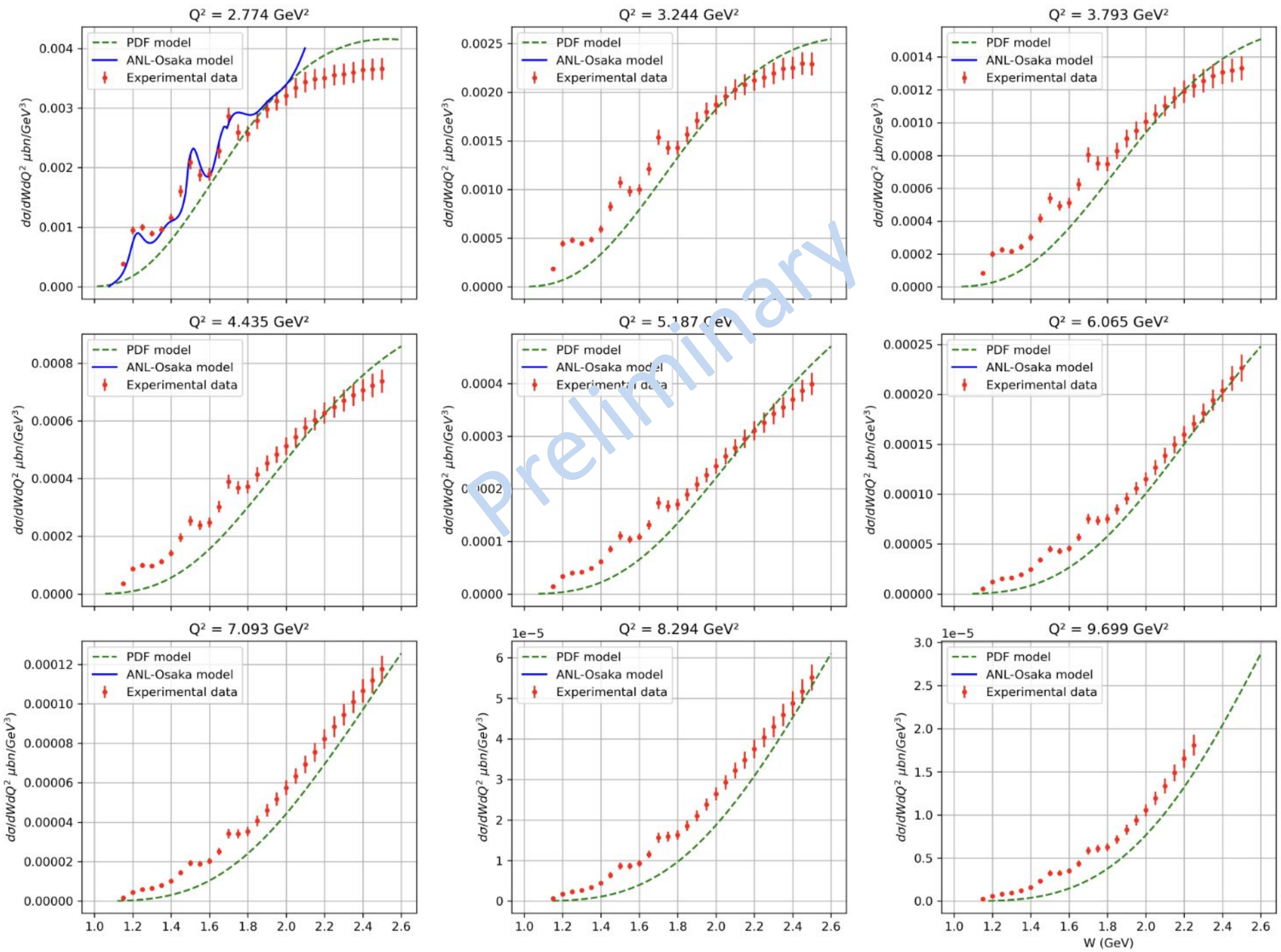
Inclusive Electron Scattering Kinematic Coverage with CLAS12





Orange: CLAS12
Green: CLAS6
Blue: Hall C

Preliminary Cross Sections vs. W (GeV)



W (GeV)

Red: CLAS12

Blue: ANL-Osaka Model

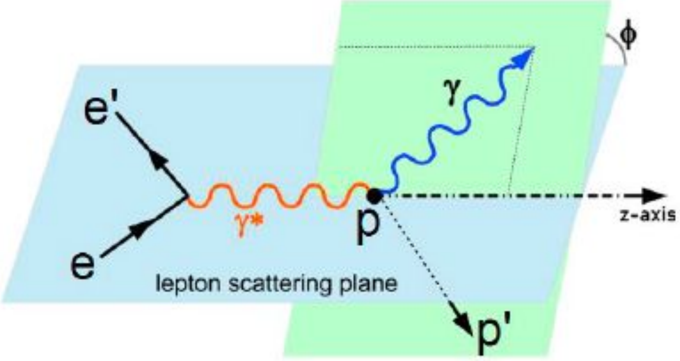
Green: CTEQ-6 PDFs

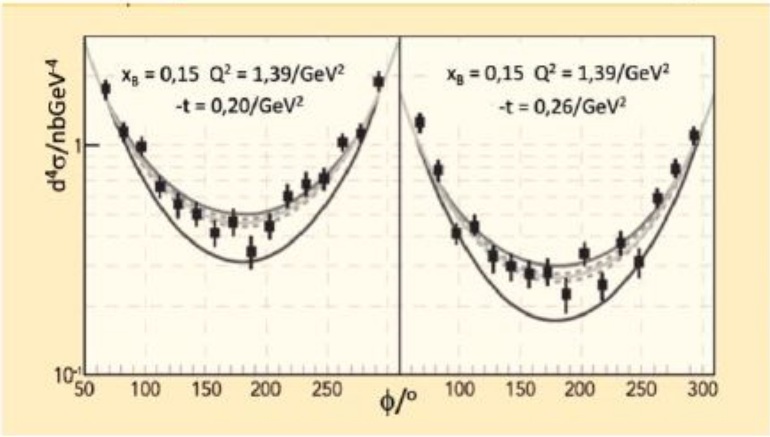
Accepted to PRC

Observables of the DVCS process

How can we measure the CFFs in the DVCS process?

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

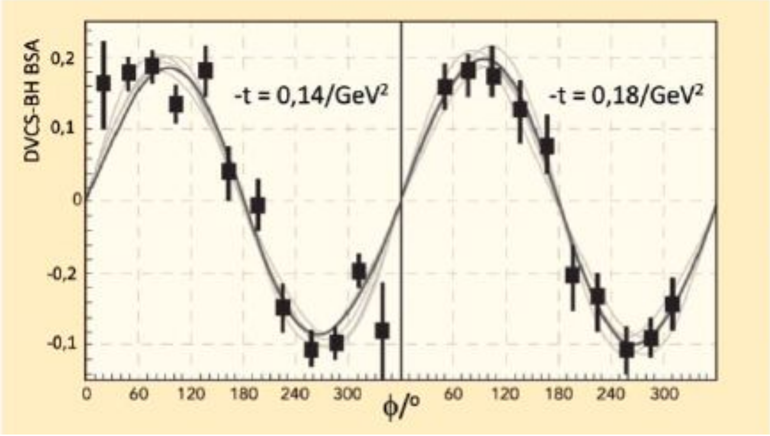




2. Beam-Spin Asymmetry

$$\mathrm{BSA}(x, Q^2, t, \phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

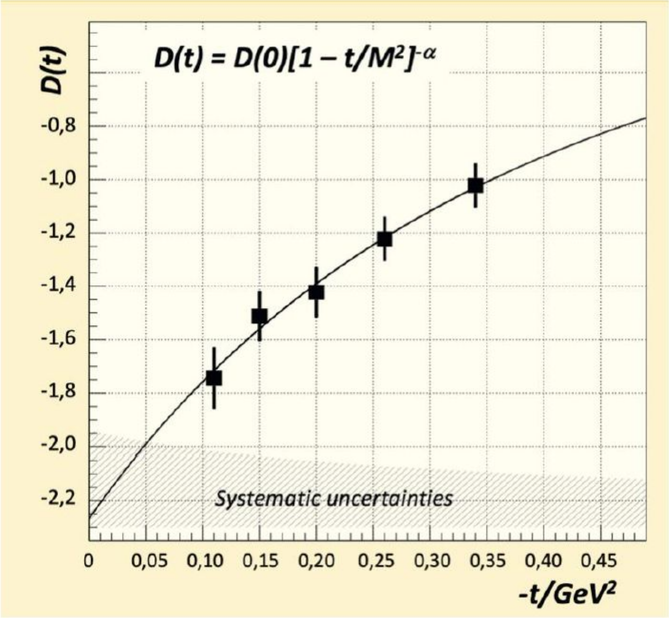
$$\propto \boxed{Im\left\{\mathcal{H}\right\}} \sin\phi$$



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

From the D-term to the pressure distribution

$$\boxed{\mathrm{Re}\mathcal{H}(\xi,t)} \propto \boxed{D(t)} + \frac{2}{\pi}\mathcal{P}\int \mathrm{d}x \frac{x\,\boxed{\mathrm{Im}\mathcal{H}(x,t)}}{\xi^2 - x^2}$$



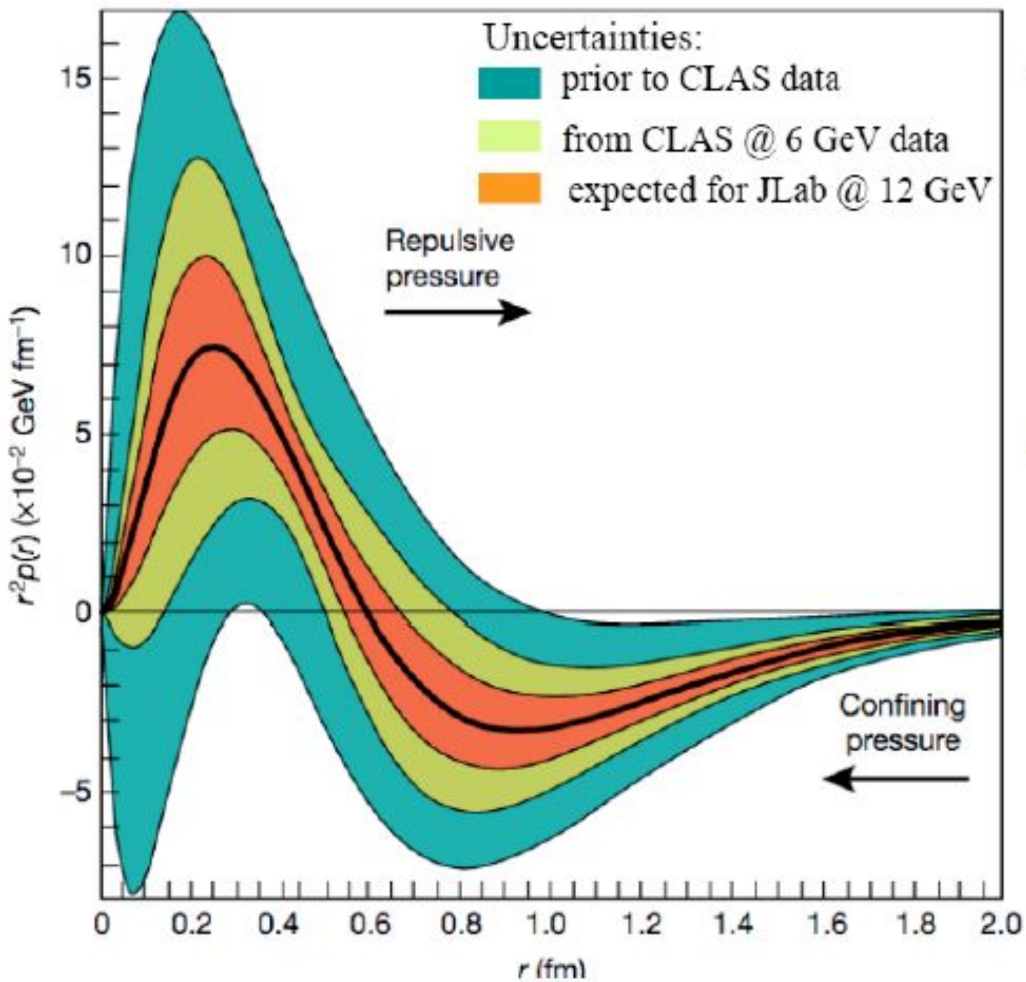
V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396 (2018)

The pressure distribution: $$p(r) = \frac{1}{6m_\mathrm{p}}\int \frac{\mathrm{d}^3\Delta}{(2\pi)^3}\, t\,\boxed{D(t)}\, e^{-i\Delta r}$$

with $t = -\Delta^2$

K. Goeke et al., Phys. Rev. D 75, 094021 (2007)

Pressure inside the proton



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

- Positive maximal pressure of 10^{35} Pa in the center at r = 0 fm

  ➔ Highest known pressure in the universe

  ➔ Resulting forces away from the center avoid a collaps of the quark matter

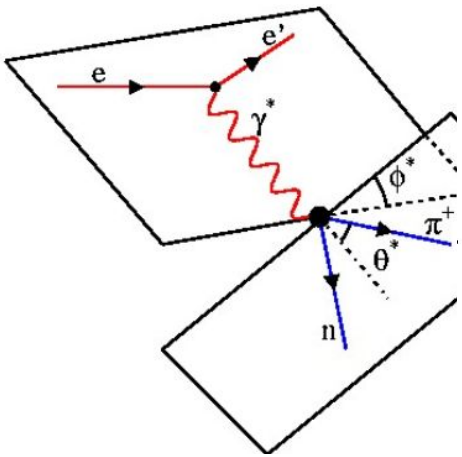
- Negative pressure in the outer areas of the proton, for r > 0,6 fm

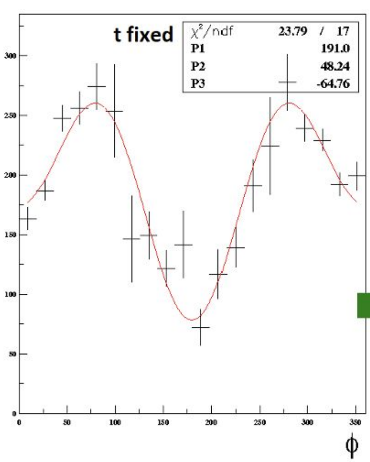
  ➔ Forces towards the center stabilize the proton

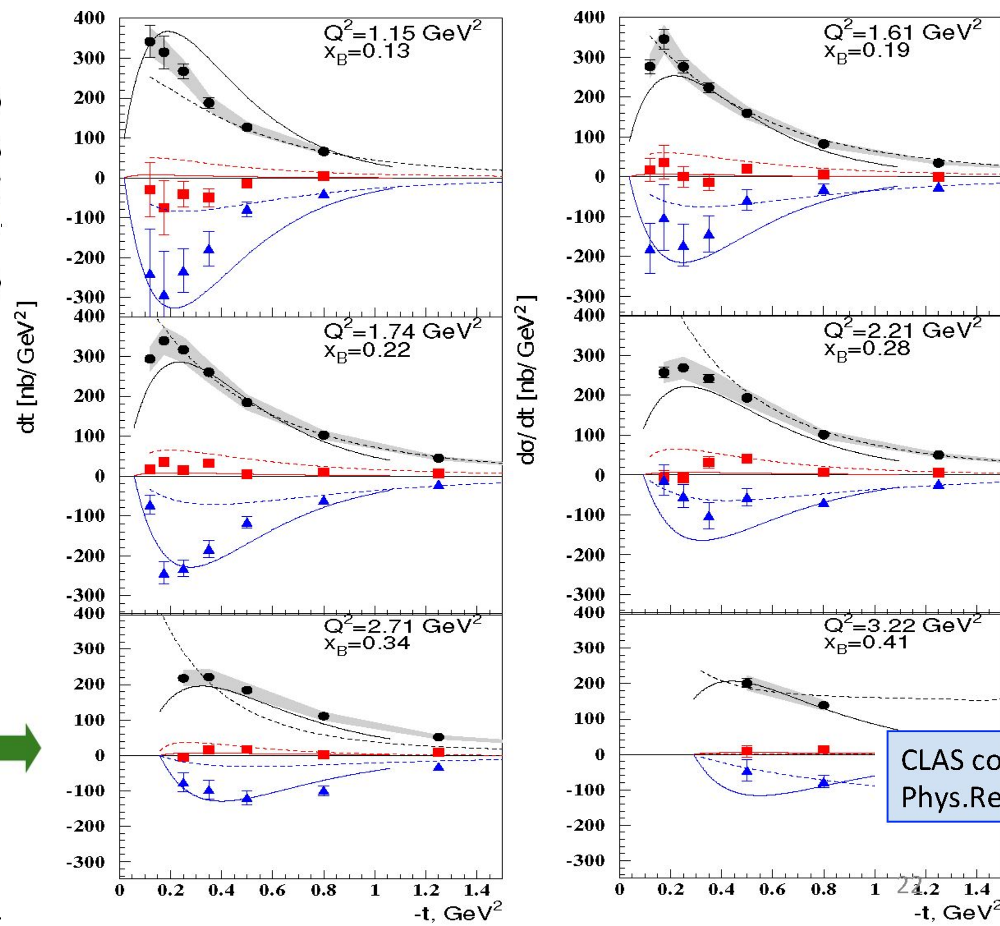
➡ **Interplay of the two regions leads to the stability of the proton**

DVMP (π^0) Differential Cross Section

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







CLAS in Hall B
E=6 GeV

- σ_0
- $\sigma_{TT} \rightarrow \cos(2\varphi)$
- $\sigma_{LT} \rightarrow \cos(\varphi)$

— GK

- - GGL

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

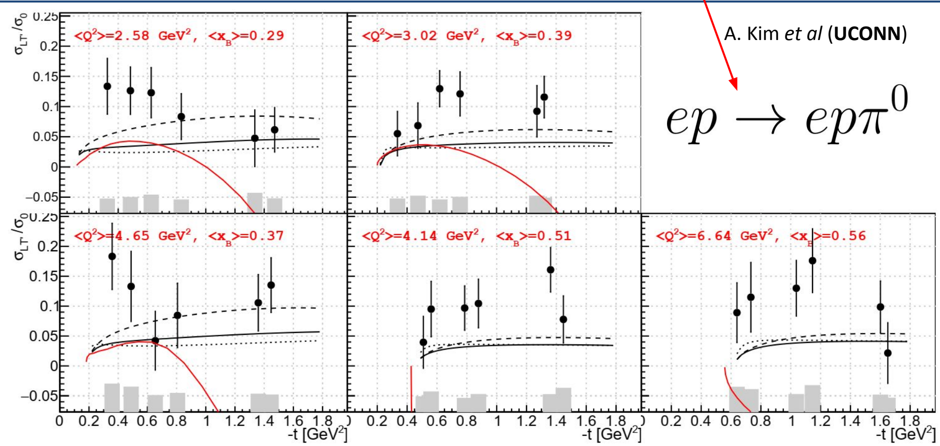
Pseudoscalar meson electroproduction with CLAS12

E=10.6 GeV

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

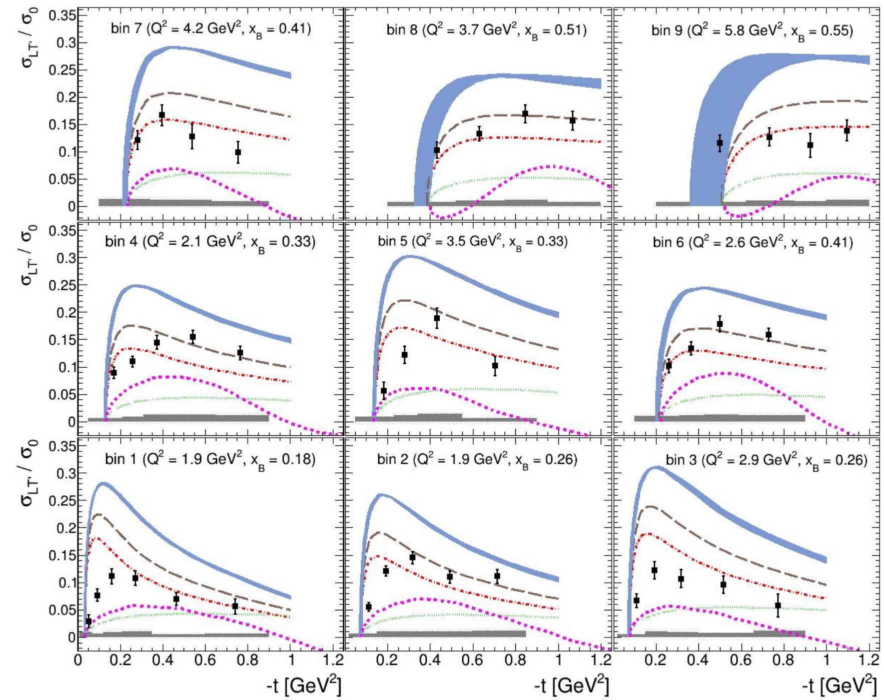
A. Kim *et al* (**UCONN**)

$ep \to ep\pi^0$



$ep \to en\pi^+$

S. Diehl *et al* (**UCONN**)



GK model

JML model

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

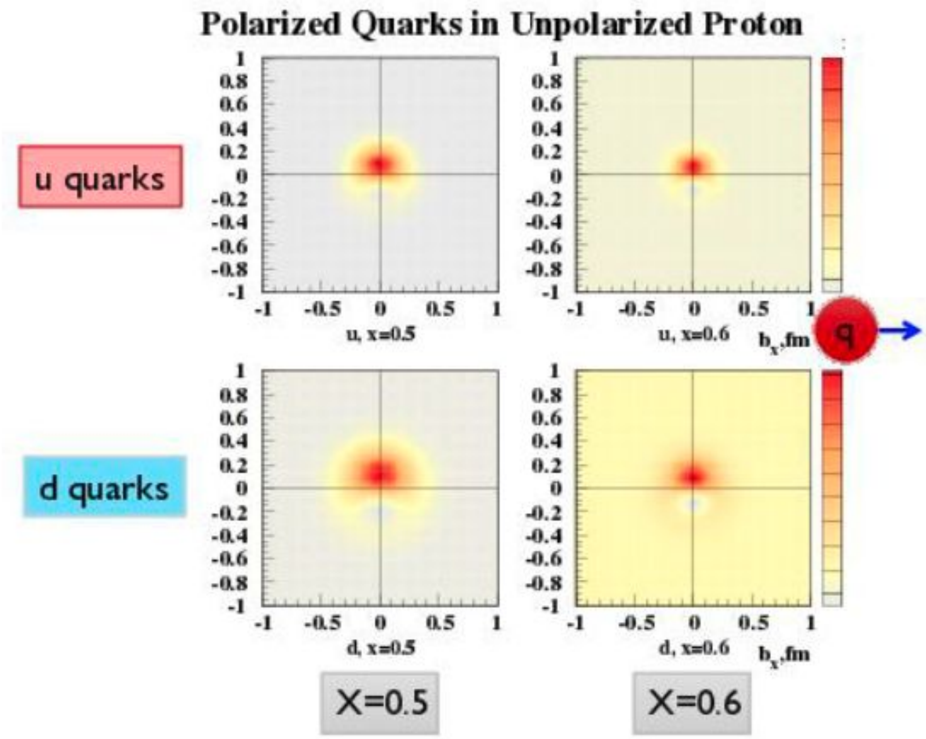
H_T is related to the proton's tensor charge.

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

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

Transverse densities for u and d quarks in the proton (after global fit)

- $\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon



V. Kubarovsky et al.

$\bar{E}_T$ is similar to Boer Mulders TMD function in SIDIS.

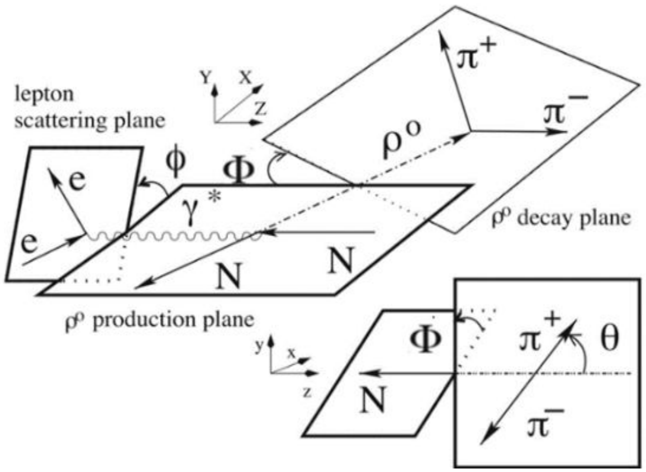
The fit results agree with the large-N_c limit analysis by P. Schweitzer and C. Weiss *Phys.Rev.C* 94 (2016) 4, 045202

GPD parameterization used in GK model can be improved through global fits using existing Hall A and Hall B data

Exclusive vector meson ρ^0 production with CLAS12

Exclusive vector meson ρ^0 production is sensitive to

$$\mathcal{H}, \mathcal{E}$$



$$\frac{d^4\sigma}{dQ^2\ dx_B\ dt\ d\Phi} = \Gamma(Q^2, x_B, E)$$

$$\frac{1}{2\pi}\left\{\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right.$$

$$+ \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\Phi) + \sqrt{2(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos(\Phi)$$

$$\left. + \lambda\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin(\Phi)\right\}$$

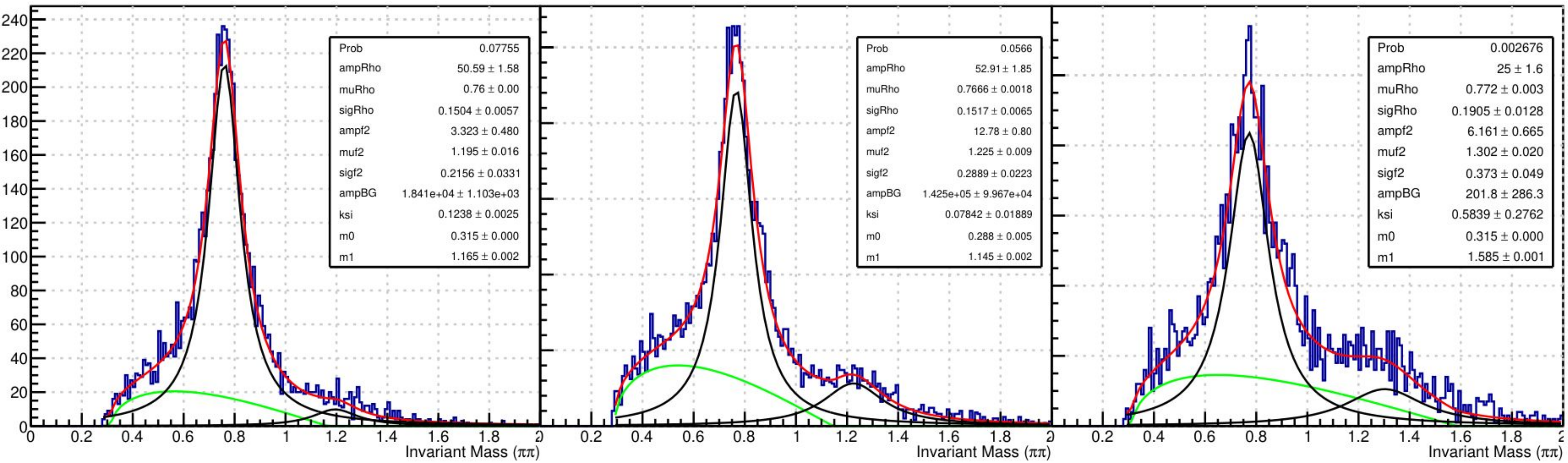
where λ is the helicity state of the incident electron beam

$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim \sigma_{LT'} \sim r^8_{00} \sim \ \mathrm{Im}\left[\langle H_T\rangle^*\langle E\rangle + \langle \bar{E}_T\rangle^*\langle H\rangle\right]$$

Exclusive ρ^0 production with CLAS12: fitting

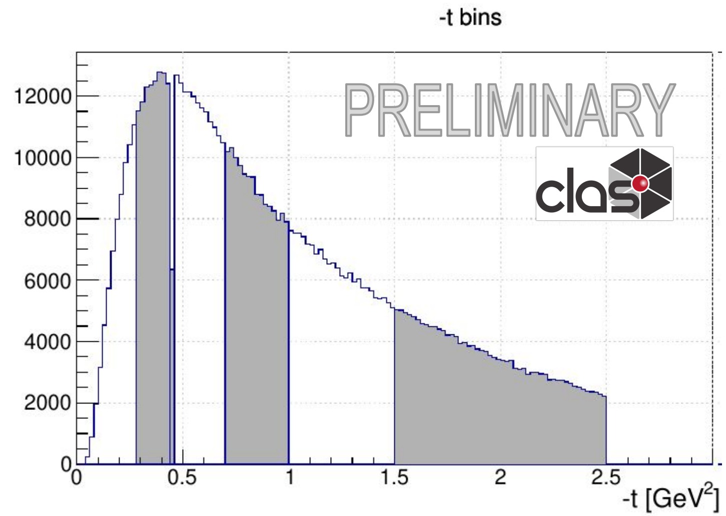
- simultaneous fit of both helicities

$$\frac{dN}{dM_{\pi\pi}} = BW_{\rho^0}(M_{\pi\pi}) + BW_{f_2}(M_{\pi\pi}) + BG$$



examples of the invariant mass fits

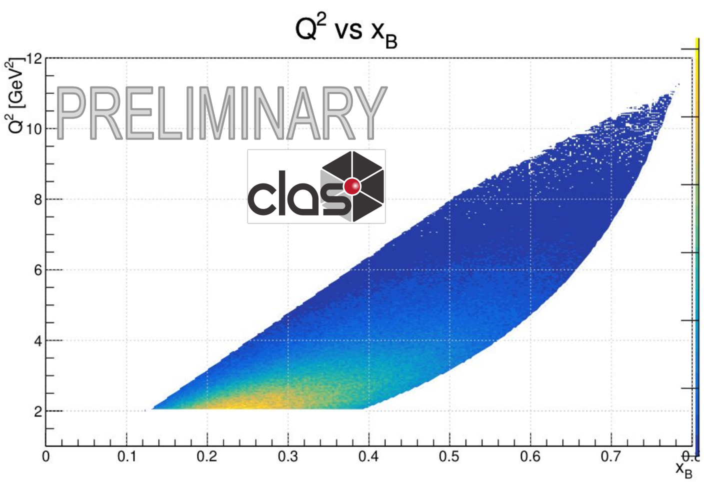
Exclusive ρ^0 production with CLAS12: 1-D binning

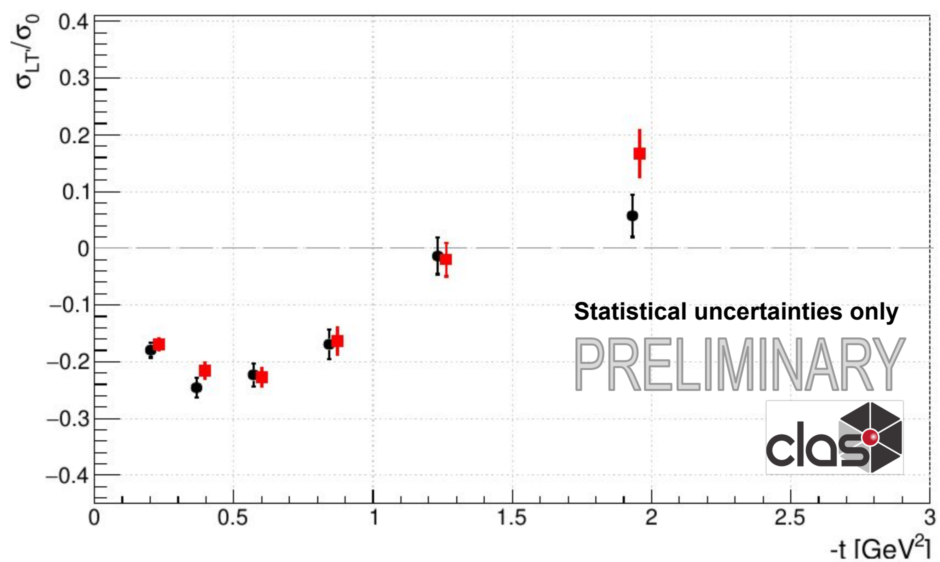


DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

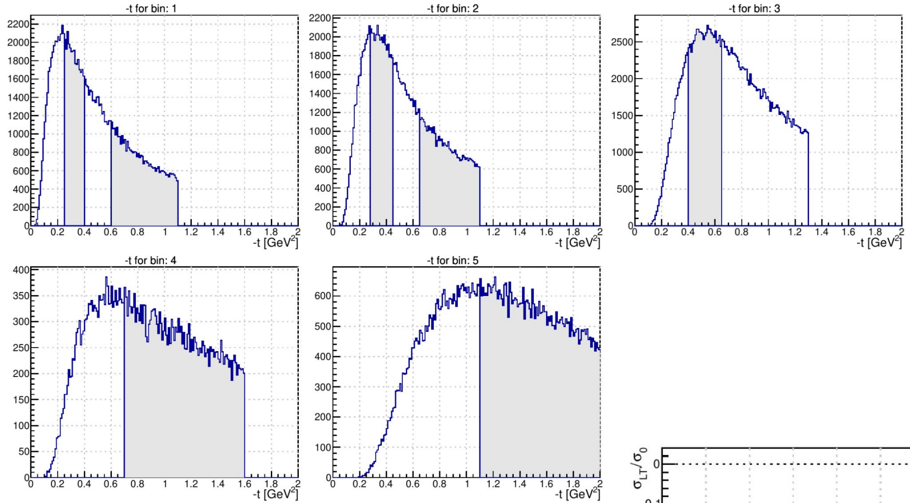
- 5 $\{-t\}$ bins
- 9 equidistant $\{\phi\}$ bins in each $\{-t\}$ bin

In total: 45 $\{-t, \phi\}$ bins





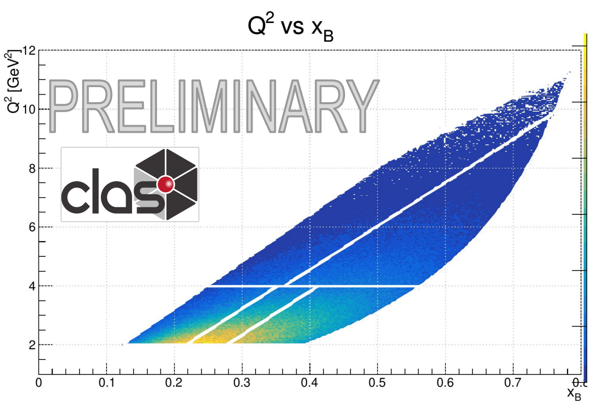
Exclusive ρ^0 production with CLAS12: 3-D binning

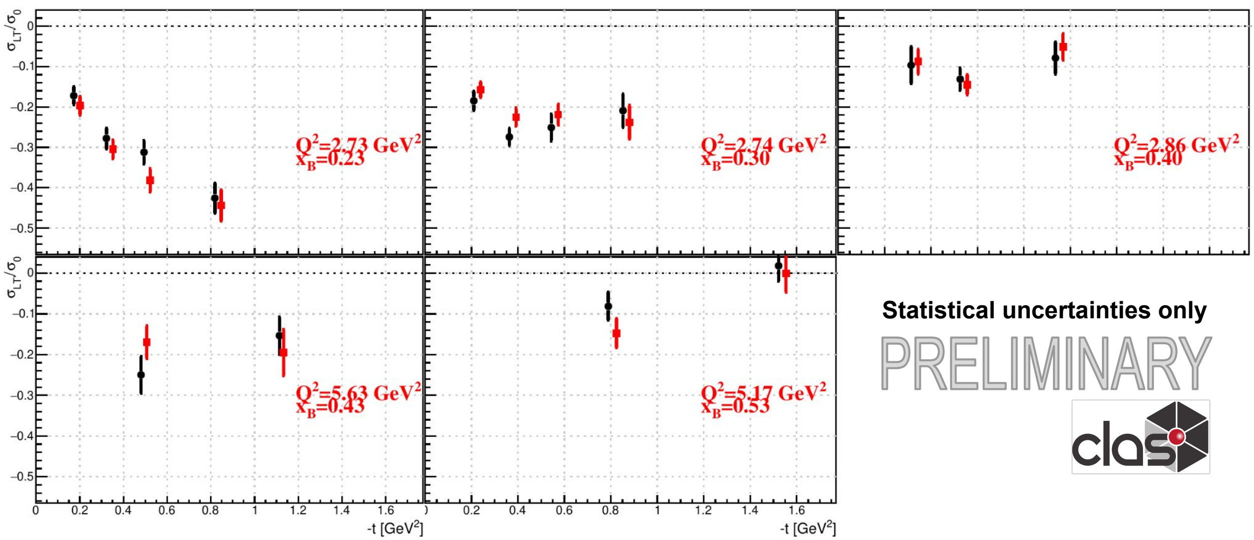


DIS cuts: $Q^2 > 2$ GeV^2 and $W > 2$ GeV

- 2-4 $\{-t\}$ bins for each of 5 $\{Q^2, x_B\}$ bin
- 9 $\{\phi\}$ bins for each $\{Q^2, x_B, -t\}$ bin

In total: 135 $\{Q^2, x_B, -t, \phi\}$ bins





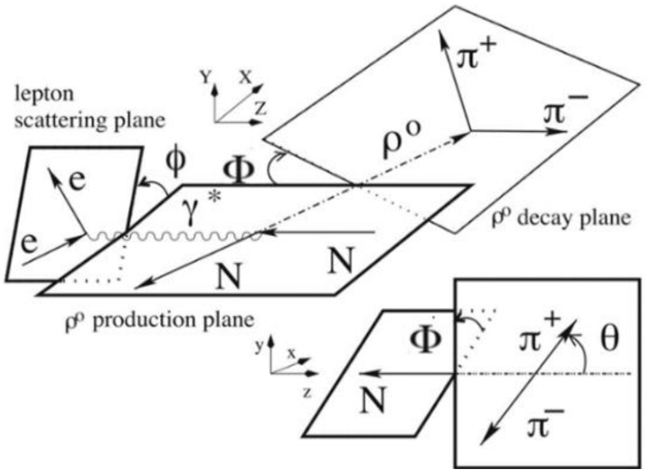
Statistical uncertainties only

PRELIMINARY

SDMEs from Exclusive ρ production with CLAS12

- 23 SDME elements are extract using the MLM:

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



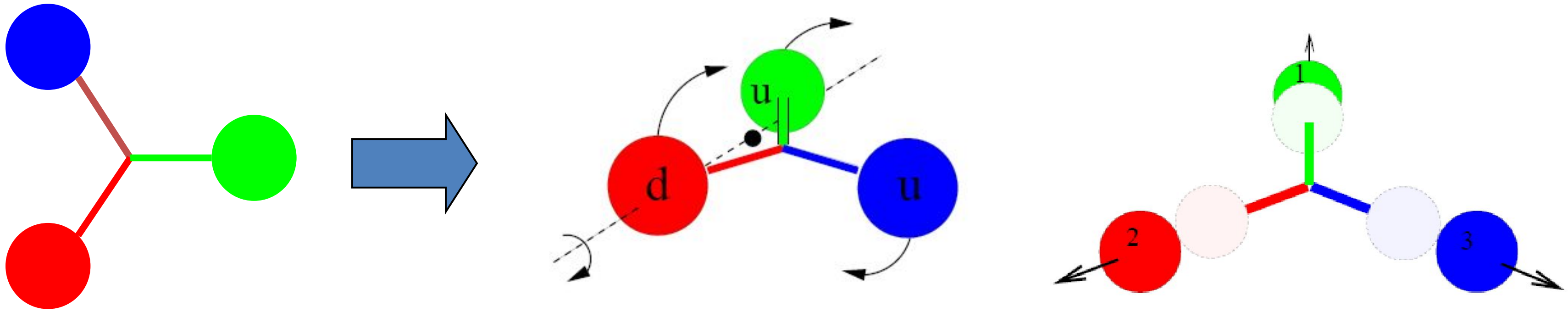
15 unpolarized SDMEs

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

8 polarized SDMEs

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

From the ground state nucleon to resonances



How does the excitation 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**

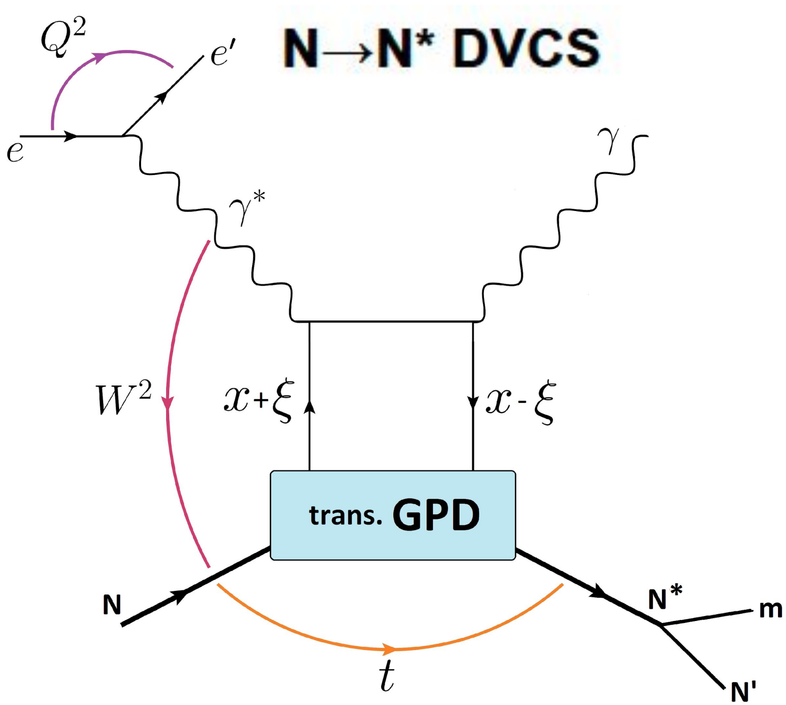
<u>Simplest case</u><u>: N→Δ transition</u> ➔ **16 transition GPDs**

- **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).

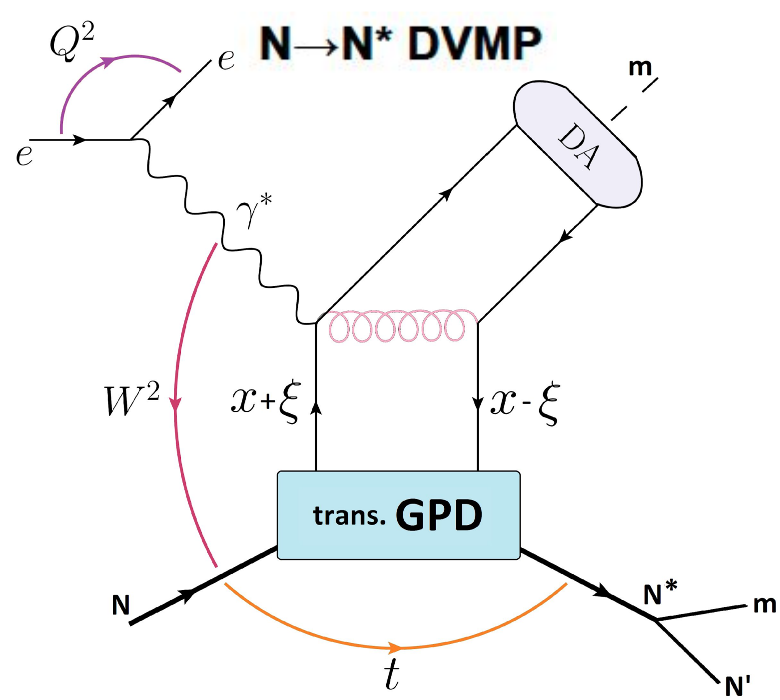
Non-diagonal DVCS / DVMP

non-diagonal DVCS



Access to the helicity non-flip transition GPDs

non-diagonal DVMP

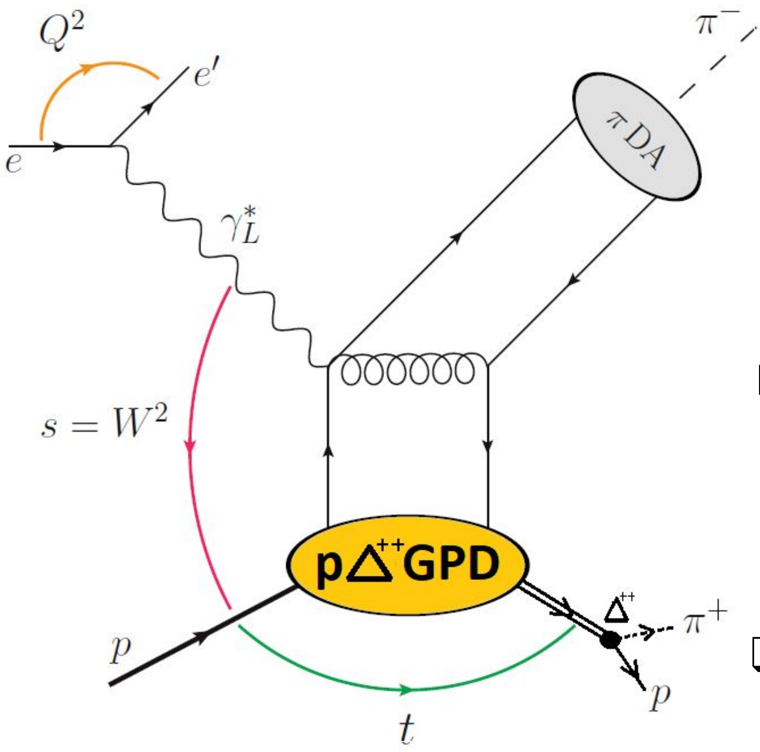


+ Access to the helicity flip transition GPDs

W > 2 GeV

Factorisation expected for: $-t / Q^2 << 1$, x_B fixed and $Q^2 > M^2_{N^*}$

$ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$



Factorization expected for:

-t / $Q^2 << 1$, x_B fixed, and $Q^2 > M_\Delta^2$

- Provides access to p-Δ transition GPDs

$$ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$$

$I_z = +3/2$

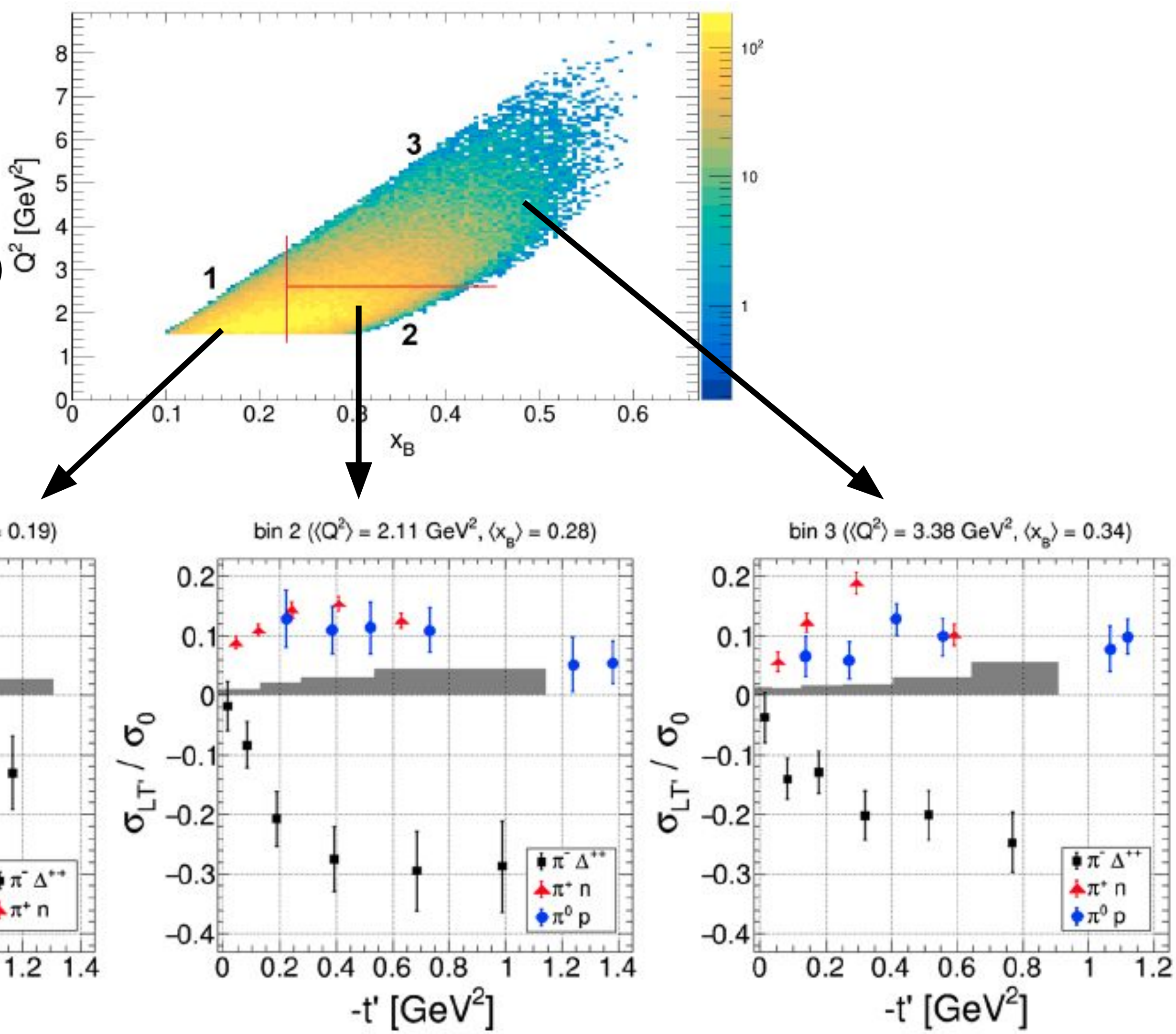
- The $p\pi^+$ final state can **only** be populated by **Δ-resonances ->** Large gap between Δ(1232) and higher resonances

Results

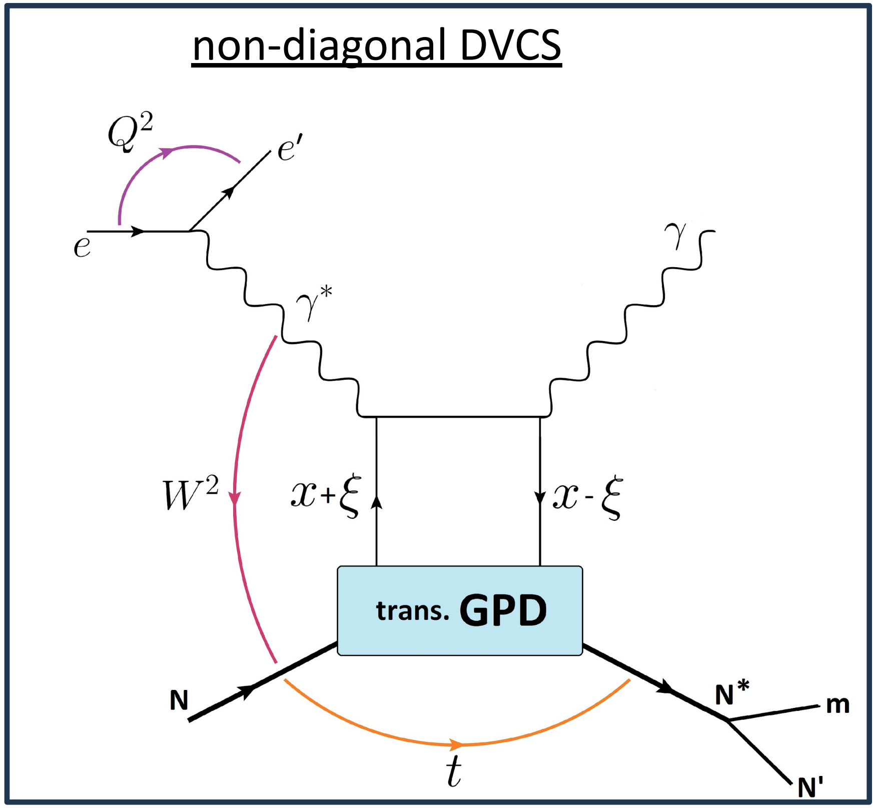
$$ep \to e\Delta^{++}\pi^{-}$$
$$\to ep\pi^{+}\pi^{-}$$

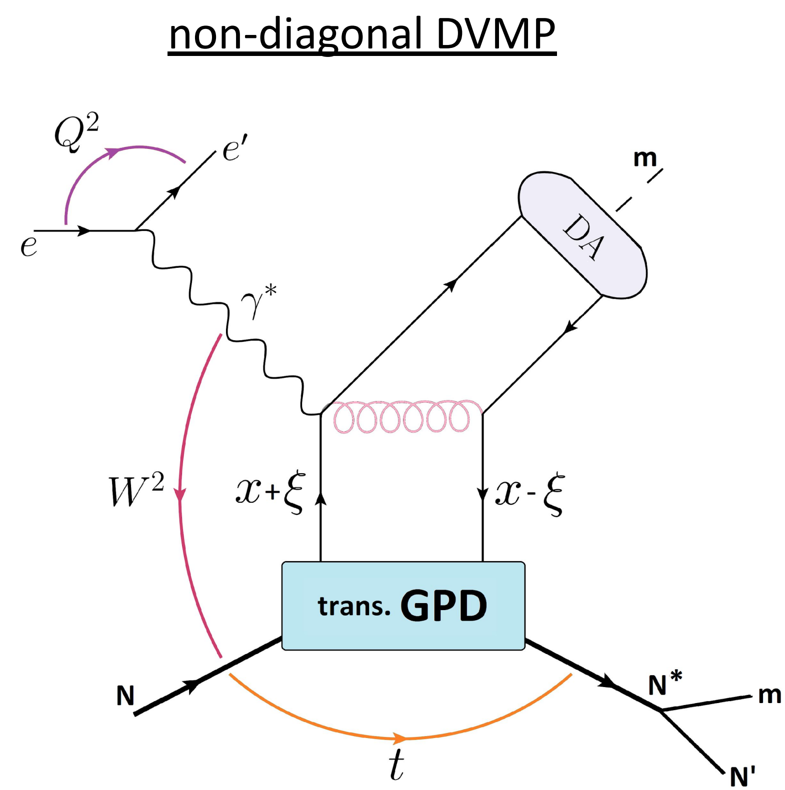
S. Diehl et al. (CLAS collab.),
Phys. Rev. Lett. 131, 021901 (2023)

S. Diehl et al. (CLAS collab.)
Phys. Lett. B 839, 137761 (2023)
A. Kim et al. (CLAS collab.)
Phys. Lett. B 849, 138459 (2024)



Non-diagonal DVCS / DVMP

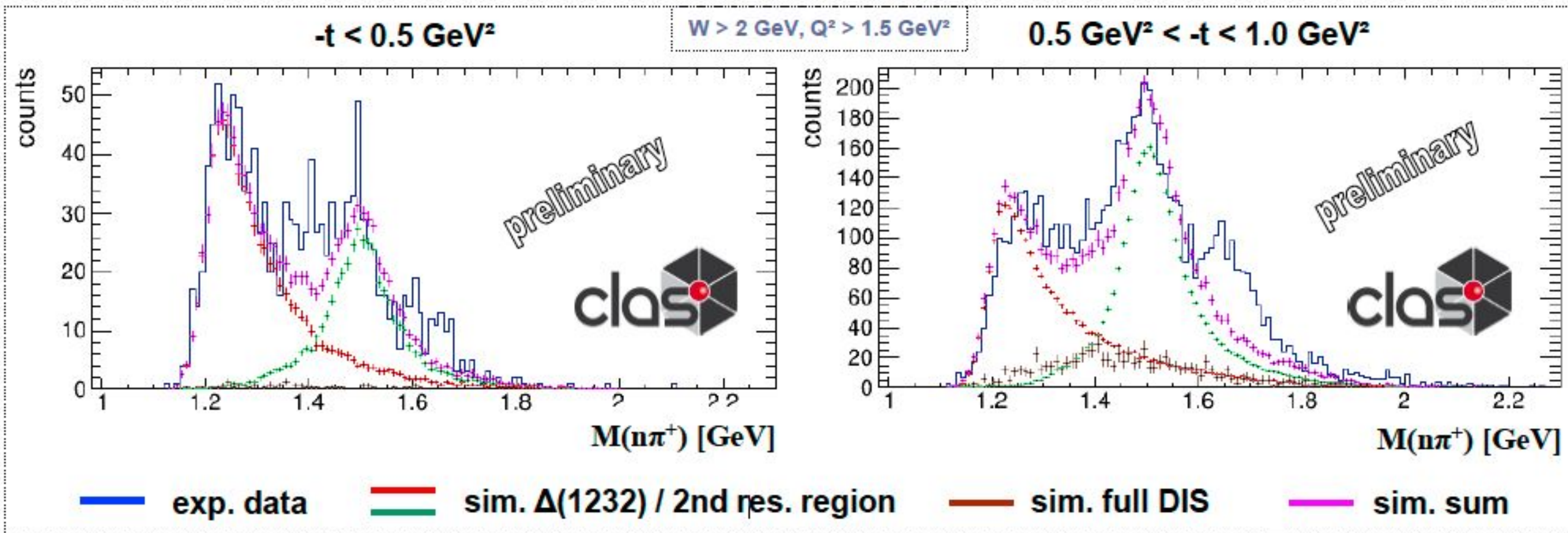




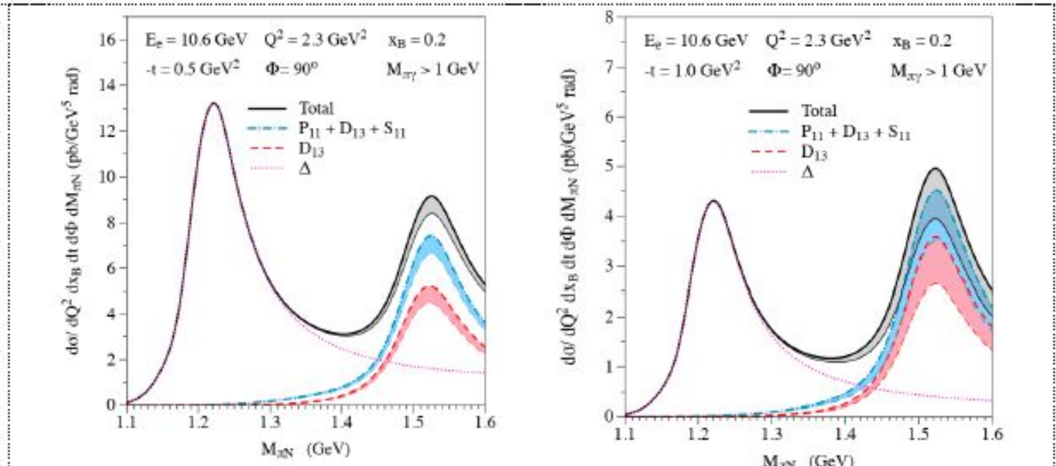
factorization expected for: $-t/Q^2$ small, $Q^2 > M^2_{N^*}$ x_B fixed

N->$\Delta(1232)$ transition GPDs: 8 twist-2 GPDs: 4 unpolarized, 4 polarized. K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023)

$N \rightarrow N^*$ DVCS Processes: $ep \rightarrow e'N^*\gamma \rightarrow e'n\pi^+\gamma$



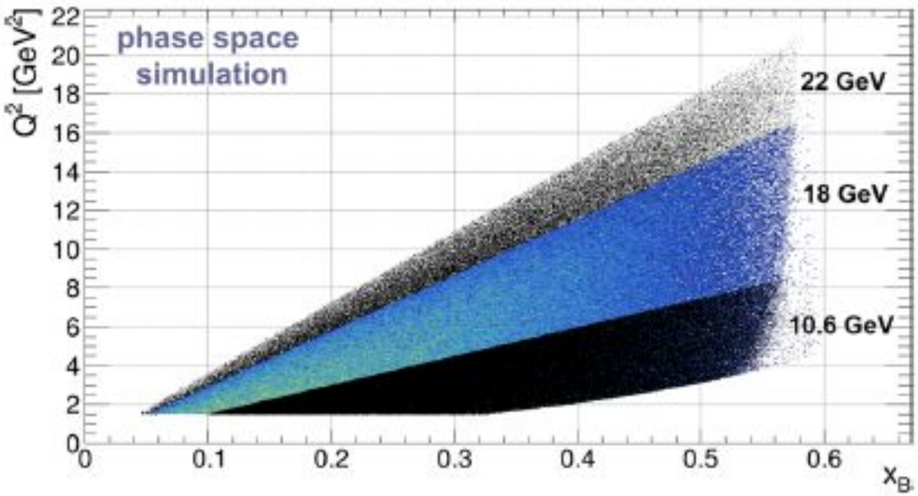
Experiment: S. Diehl (JLU Gießen + UConn)



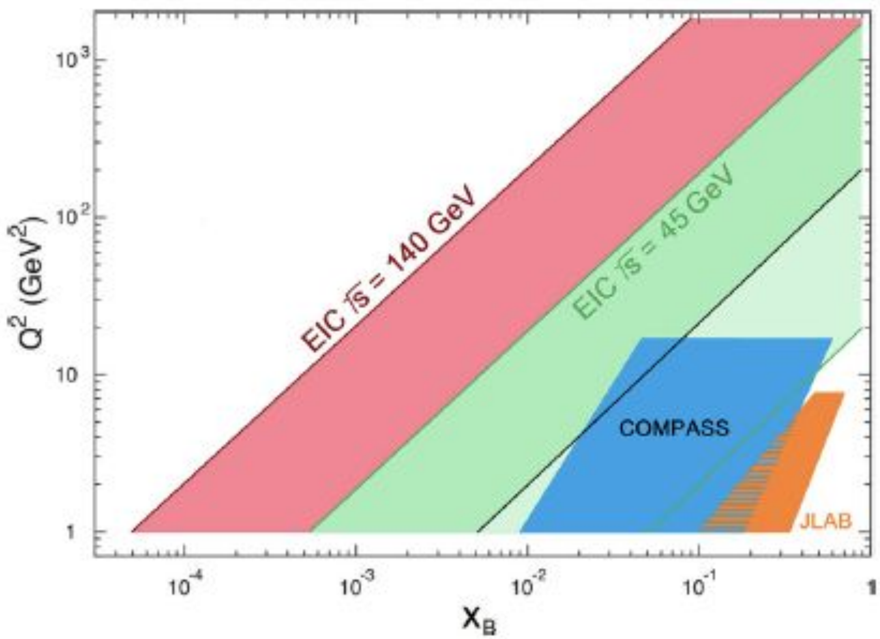
M($n\pi^+$) (GeV) M($n\pi^+$) (GeV)

Theroy: K. Semenov-Tian-Shansky, M. Vanderhaeghen, Phys. Rev. D 108, 034021 (2023)

From JLab 11 GeV to JLab 22 GeV to COMPASS to EIC



EIC: Extending the kinematic regime to the sea-quark and gluon sector.



Conclusion and Outlook

1. Deeply virtual exclusive processes (DVEP) will help us to map the spatial distributions of quarks and gluons in the nucleon and potentially also in baryon resonances.

2. JLab CLAS12 has a comprehensive program in deeply virtual exclusive processes.

3. One essential point concerns the approach to the small-size regime, where the production of $q\bar{q}$ pair with sizes << hadronic size dominates. QCD factorization and GPD extraction assume that this regime is attained (!).

4. At present 12 GeV kinematics, whether we attain this regime is under investigation.

5. EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all.

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