Mechanical properties of the nucleon with the CLAS12

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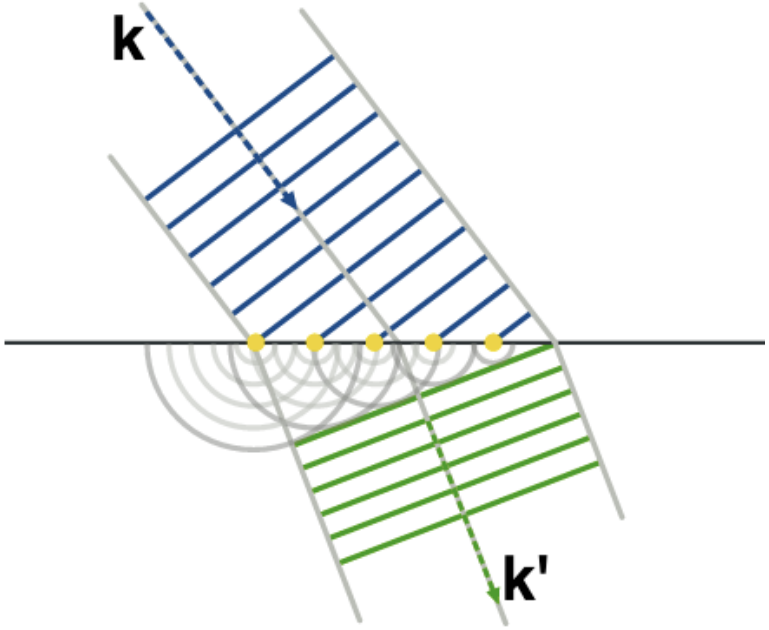
Diffraction and Imaging

Huygens-Kirchhoff-Fresnel principle

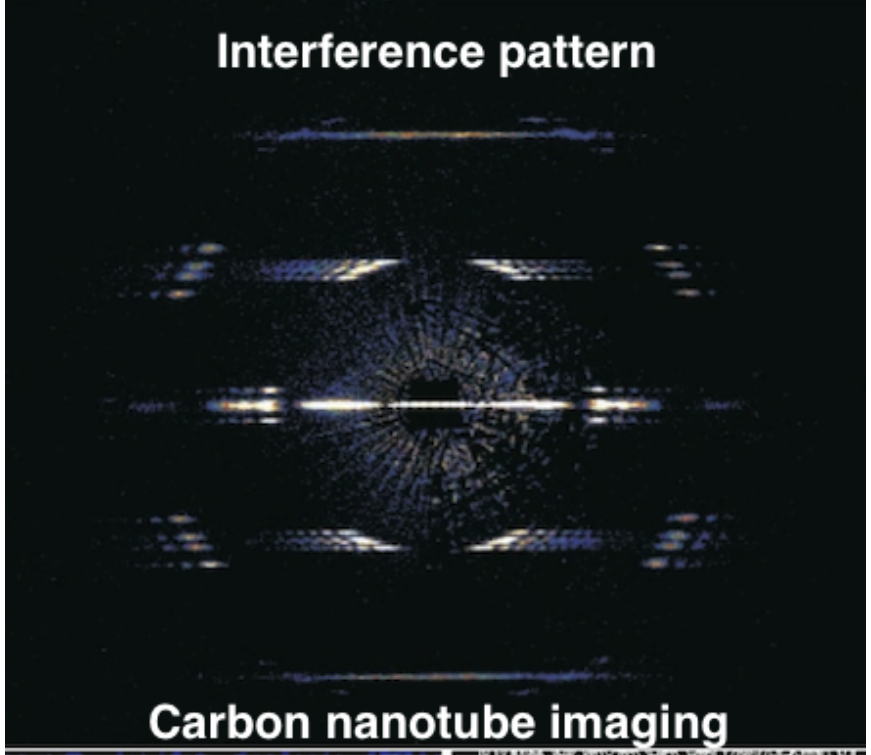


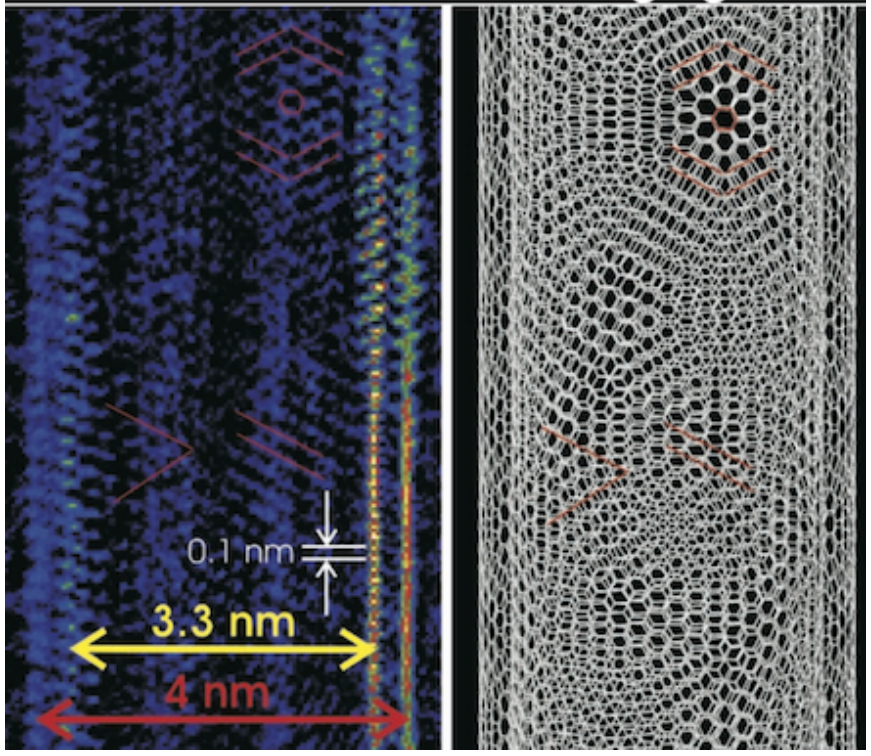
$\vec{q} = \vec{k} - \vec{k'}$

The interference pattern is given by the superposition of spherical wavelets

$$f(\Omega_{\vec{q}}) = \int \frac{\mathrm{d}^3\vec{r}}{(2\pi)^3} F(\vec{r}) \mathrm{e}^{i\vec{q}\cdot\vec{r}}$$

Fourier imaging

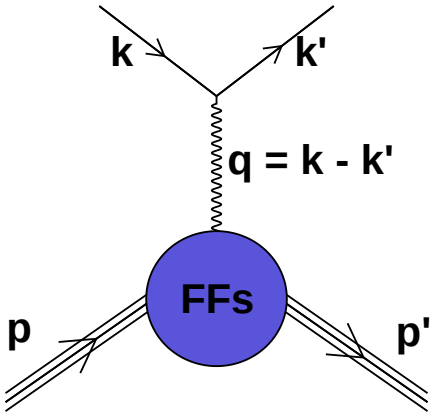




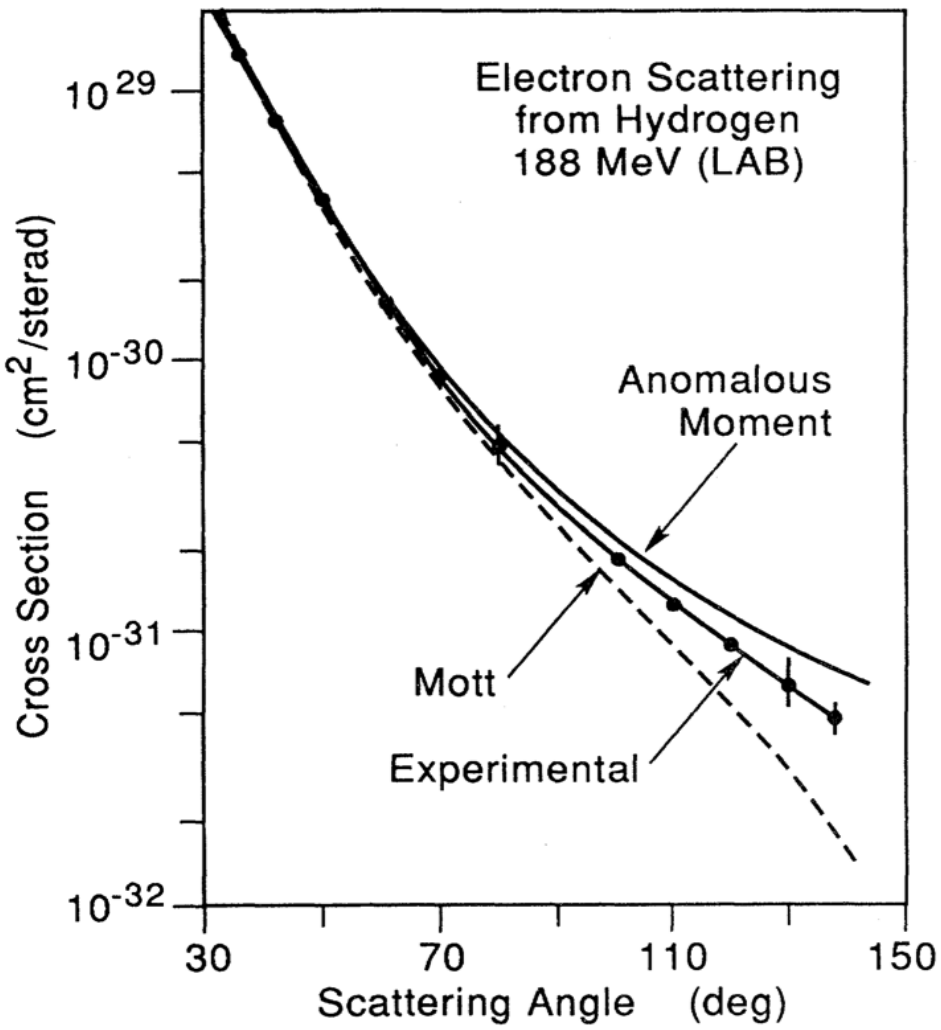
Elastic scattering

Form Factors

Probing deeper using virtual photons



$$
\begin{aligned}
J^{\mu}_{\mathrm{EM}} &= F_1\gamma^{\mu} + \frac{\kappa}{2M}F_2 i\sigma^{\mu\nu}q_{\nu} \\
\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} &= \frac{\sigma_{\mathrm{Mott}}}{\epsilon(1+\tau)}\left[\tau G_{\mathrm{M}}^2 + \epsilon G_{\mathrm{E}}^2\right] \\
\tau &= \frac{Q^2}{4M^2} \\
Q^2 &= -\left(k-k'\right)^2 = -m^2_{\gamma^*} \\
\frac{1}{\epsilon} &= 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2} \\
G_{\mathrm{E}} &= F_1 - \tau F_2 \\
G_{\mathrm{M}} &= F_1 + F_2
\end{aligned}
$$



Hofstadter Nobel prize 1961

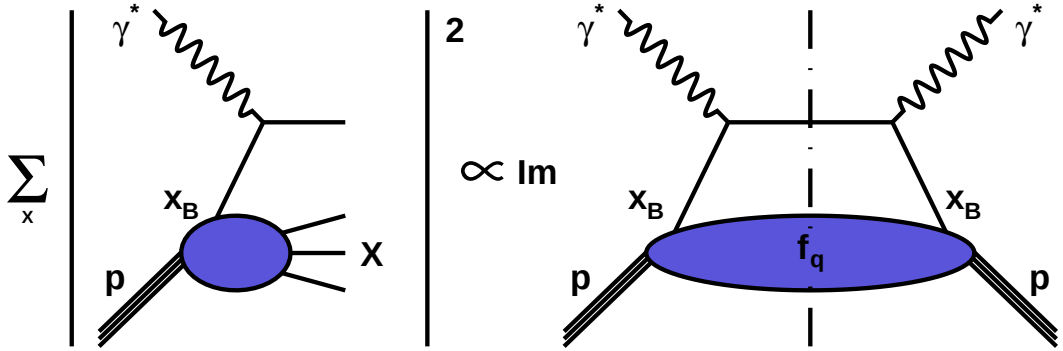
"The best fit in this figure indicates an rms radius close to $0.74 \pm 0.24 \times 10^{-13}$ cm."

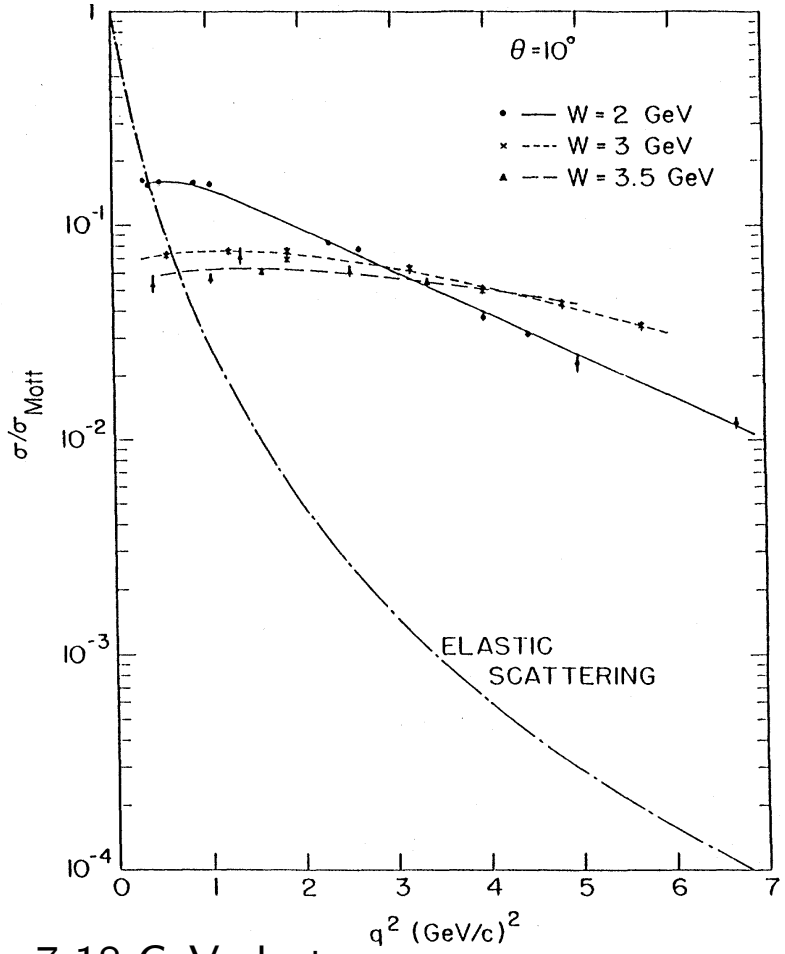
Imaging in transverse impact parameter space

Deeply Inelastic Scattering

Parton Distributions

Optical theorem





The total cross section is given by
the imaginary part of the forward amplitude

$$\nu = E_{\gamma^*} \quad , \quad x_B = \frac{Q^2}{2M\nu}$$

$\sigma_{\text{DIS}}(x_B, \cancel{Q^2}) \rightarrow$ scaling, point-like constituents

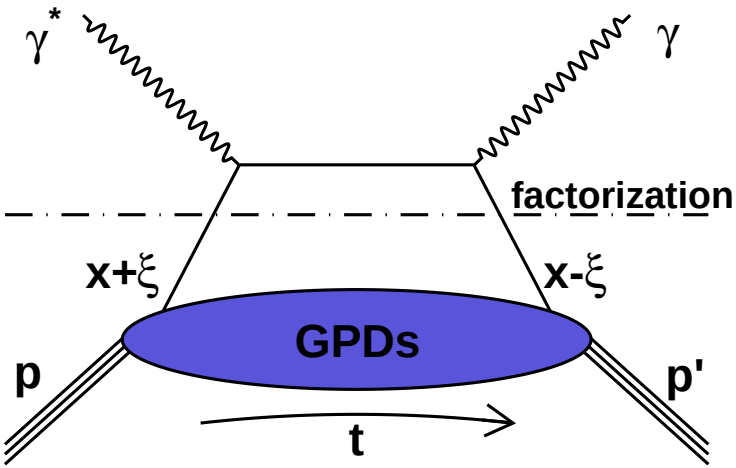
Discovery of quarks, SLAC-MIT group, 7-18 GeV electron
Friedman, Kendall, Taylor, Nobel prize 1990

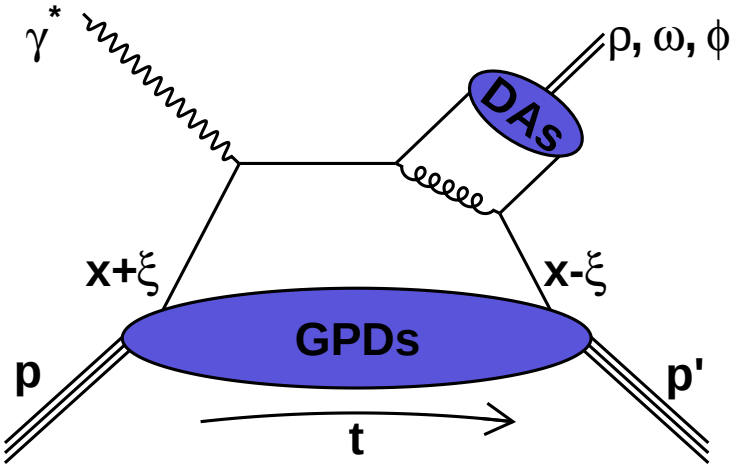
$$\lim_{Q^2 \to \infty} \sigma_{\text{DIS}}(x_B) = \int_{x_B}^{1} \frac{d\xi}{\xi} \sum_a f_a(\xi, \mu) \hat{\sigma}^a \left(\frac{x_B}{\xi}, \frac{Q}{\mu} \right)$$

1-D distribution in longitudinal momentum space

Deep Exclusive Scattering

Generalized Parton Distributions





$$\gamma^* p \to \gamma p', \; \gamma^* p \to \begin{cases} \rho p' \\ \omega p' \\ \phi p' \end{cases}$$

Bjorken regime :
$Q^2 \to \infty$, x_B fixed

t fixed $\ll Q^2$, $\xi \to \frac{x_B}{2-x_B}$

$$\frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \langle p' | \bar{\psi}_q(0) \gamma^+ (1+\gamma^5) \psi(y) | p \rangle$$

$$= \bar{N}(p') \left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t) i\sigma^{+\nu} \frac{\Delta_\nu}{2M} \right.$$

$$\left. + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5 \frac{\Delta^+}{2M} \right] N(p)$$

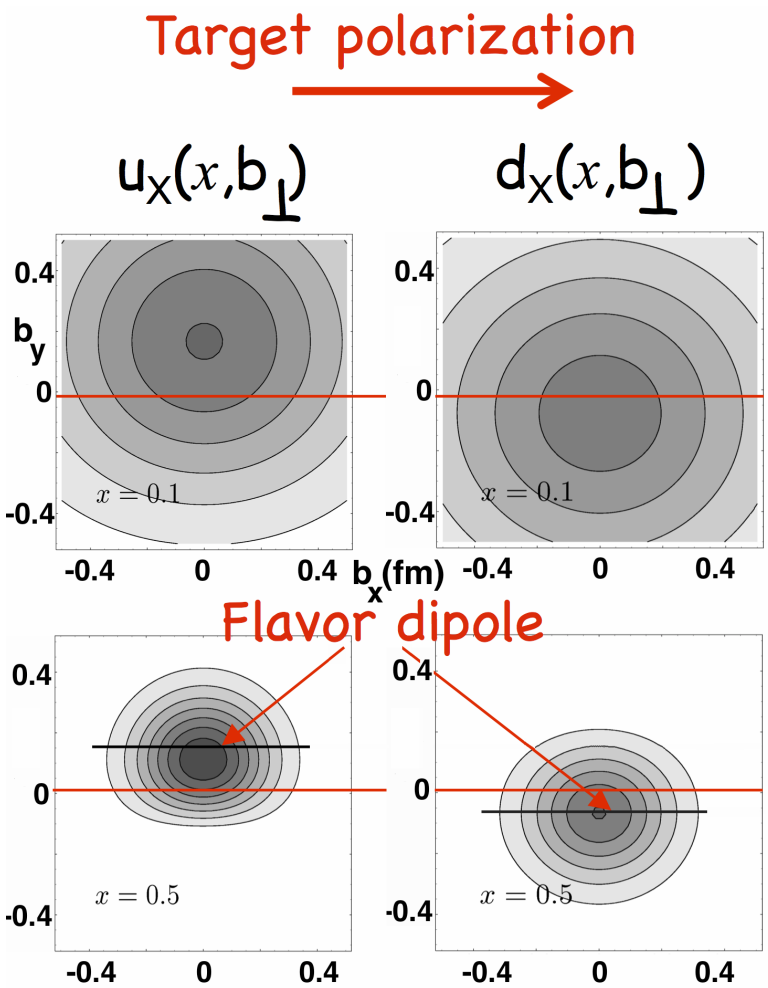
spin	N no flip	N flip
q no flip	H	E
q flip	$\tilde{H}$	$\tilde{E}$

3-D Imaging conjointly in transverse impact parameter and longitudinal momentum

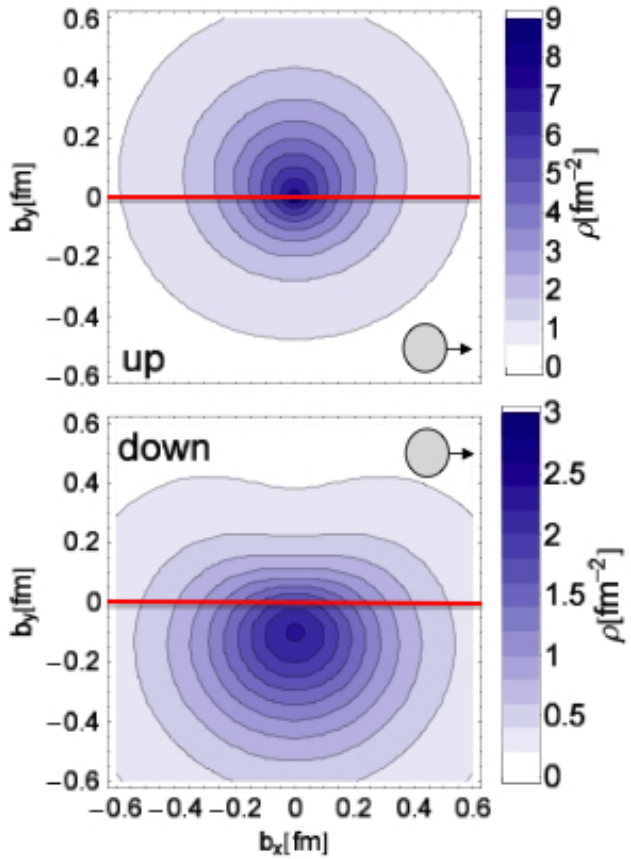
GPDs and Transverse Imaging

(x_B, t) **correlations**

$$q_X(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} \left[H(x,0,t) - \frac{E(x,0,t)}{2M} \frac{\partial}{\partial b_y} \right] e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp}$$



Lattice calculation



GPDs and Energy Momentum Tensor

(x, ξ) correlations

Form Factors accessed *via* second x-moments :

$$\langle p'|\hat{T}^q_{\mu\nu}|p\rangle = \bar{N}(p')\left[\; M_2^q(t)\,\frac{P_\mu P_\nu}{M} + J^q(t)\,\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\;\right]N(p)$$

Angular momentum distribution

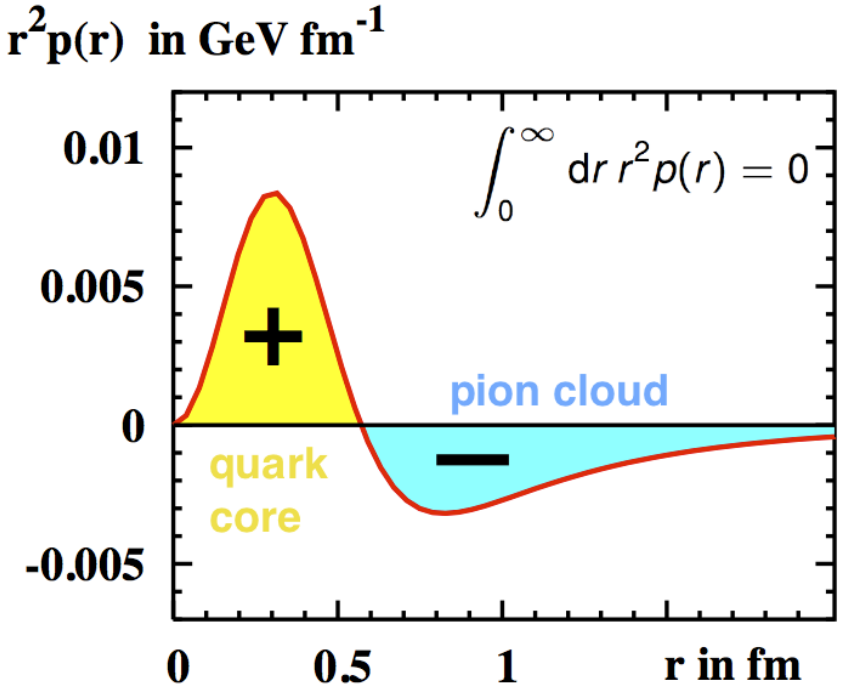
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Mass and force/pressure distributions

$$M_2^q(t) + \frac{4}{5}d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x H^q(x,\xi,t)$$

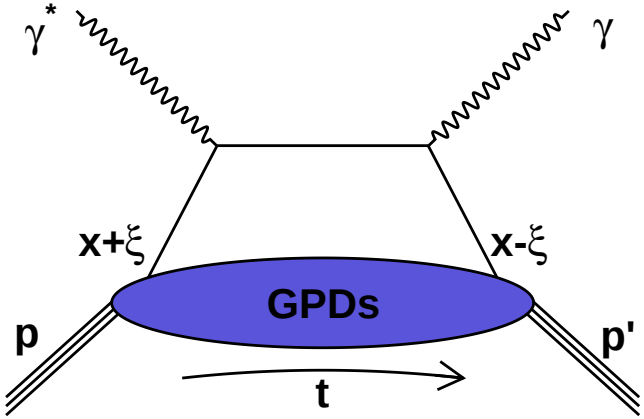
$$d_1(t) = 15M\int \mathrm{d}^3\vec{r}\,\frac{j_0(r\sqrt{-t})}{2t}\,p(r)$$

Distribution of pressure

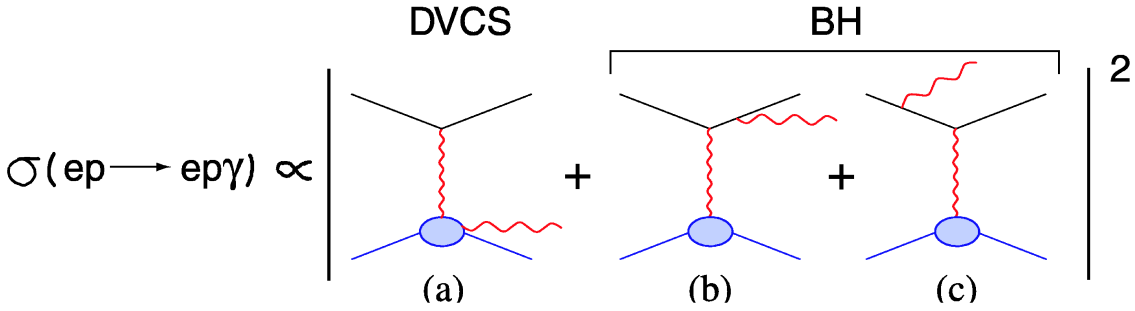


Deeply Virtual Compton Scattering

The cleanest GPD probe at low and medium energies

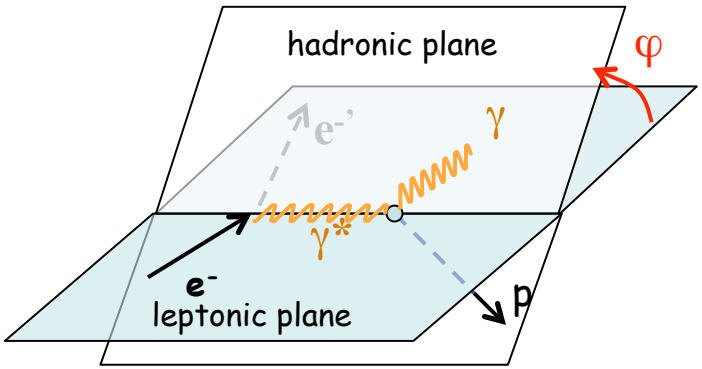


$$ep \to ep\gamma$$



Diehl, Gousset, Pire, Ralston (1997)

Belitsky, Müller, Kirchner (2002, 2010)



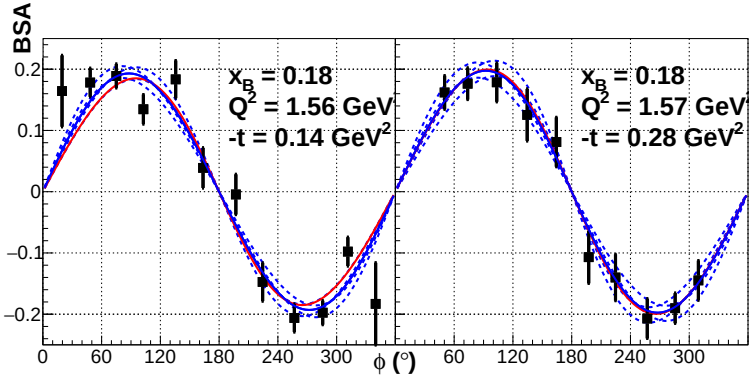
$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{1 + \beta\cos\phi}$$

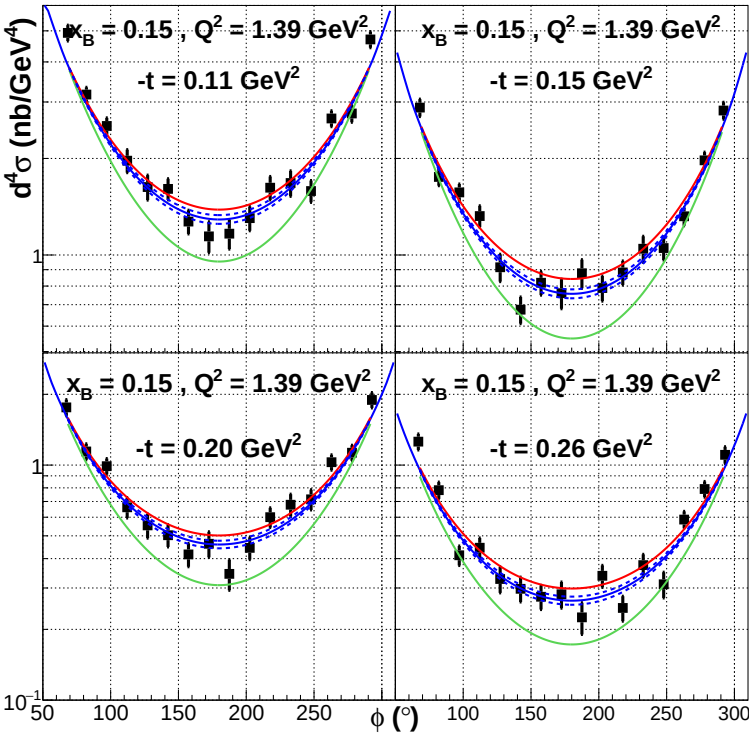
$$\alpha \propto \mathcal{I}\mathrm{m}\left(F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

$$\mathcal{H}(\xi,t) = i\pi H(\xi,\xi,t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x\, \frac{H(x,\xi,t)}{x-\xi}$$

$$A_{UL} \propto \mathcal{I}\mathrm{m}\left(F_1\tilde{\mathcal{H}} + \xi G_M\mathcal{H} + G_M\frac{\xi}{1+\xi}\mathcal{E} + \cdots\right)\sin\phi$$

Global Fits to extract the D-term





Beam Spin Asymmetries

$$\mathrm{Im}\mathcal{H}(\xi,t) = \frac{r}{1+x}\left(\frac{2\xi}{1+\xi}\right)^{-\alpha(t)}\left(\frac{1-\xi}{1+\xi}\right)^{b}\left(\frac{1-\xi}{1+\xi}\,\frac{t}{M^2}\right)^{-1}$$

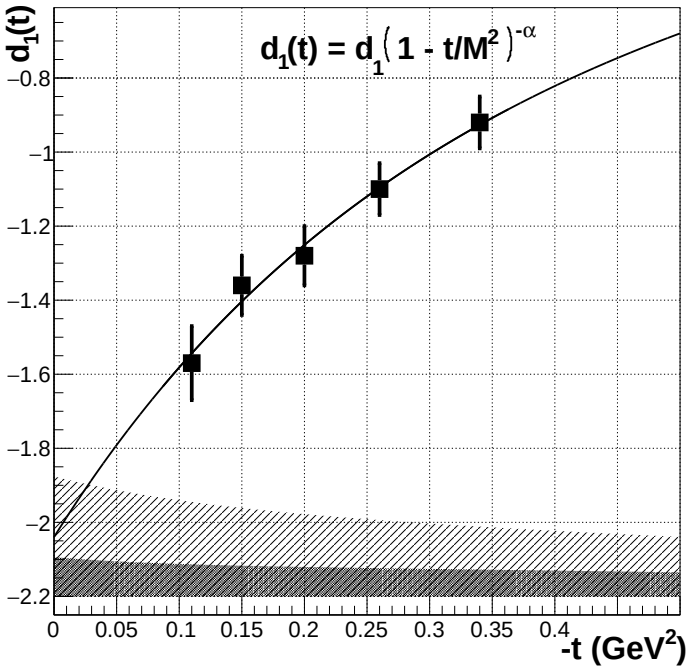
Unpolarized cross-sections
Use dispersion relation:

$$\mathrm{Re}\mathcal{H}(\xi,t) = D + \mathcal{P}\int \mathrm{d}x\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right)\mathrm{Im}\mathcal{H}(\xi,t)$$

pure Bethe-Heitler
local fit + uncertainty range
resulting global fit

D-term Extraction

$$D^q(\tfrac{x}{\xi}, t) = \left(1 - \tfrac{x^2}{\xi^2}\right)\left[d_1^q(t) C_1^{3/2}(\tfrac{x}{\xi}) + d_3^q(t) C_3^{3/2}(\tfrac{x}{\xi}) + \cdots\right]$$



t-dependence of the D-term :

Dipole gives singular pressure at $r = 0$

Quadrupole implied by counting rules?

Exponential?

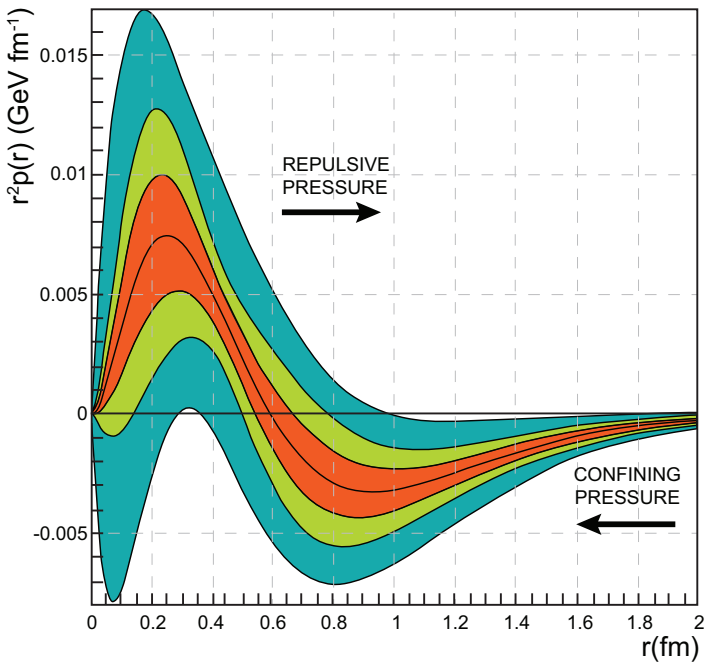
...

$d_1(0) < 0$ dynamical stability of bound state

$d_1(0) = -2.04 \pm 0.14 \pm 0.33$

First Measurement of new fundamental quantity

Proton Pressure distribution results



The pressure at the core of the proton is $\sim 10^{35}$ Pa
About 10 times the pressure at the core of a neutron star

Positive pressure in the core (repulsive force)
Negative pressure at the periphery: pion cloud
Pressure node around $r \approx 0.6$ fm

Stability condition : $\int_0^\infty dt\, r^2 p(r) = 0$

Rooted into Chiral Symmetry Breaking

World data fit

CLAS 6 GeV data

Projected CLAS12 data E12-16-010B

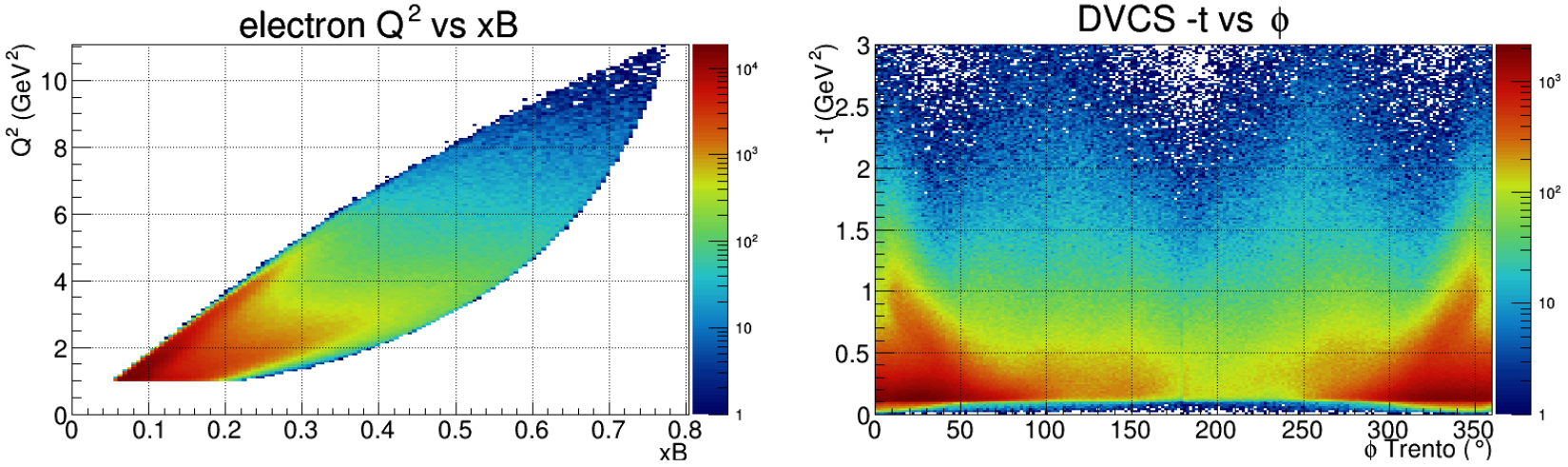
V. Burkert, L. Elouadrhiri, F.X. G., Nature **557** (2018) 396

CLAS12 Deep Exclusive Scattering Program

Preliminary Results at DNP2020

Kubarovsky	3D Nucleon Structure and Deeply Virtual Meson Production	DQ 00005
Diehl	N→N* transition GPD measurements with CLAS12 at JLab	FQ 00002
Clary	Exclusive ϕ Meson Electroproduction with CLAS12	FQ 00007
Lee	DVCS Cross Section Measurements with CLAS12	RL 00002
Elouadrhiri	First Determination of the Shear Forces Inside the Proton	RL 00006
Price	Measuring DVCS on the Neutron with CLAS12 at JLab	SL 00001
Tan	DVCS at Multi-Energy Polarized Electron Beam with CLAS12	SL 00003
Christiaens	DVCS on Proton with CLAS12	SL 00004
Johnston	DVπ^0 Production Cross Section at CLAS12	SL 00006
Kim	DVπ^0 Production with CLAS12 at Jefferson Lab	SL 00008

CLAS12 10.6 GeV DVCS Coverage

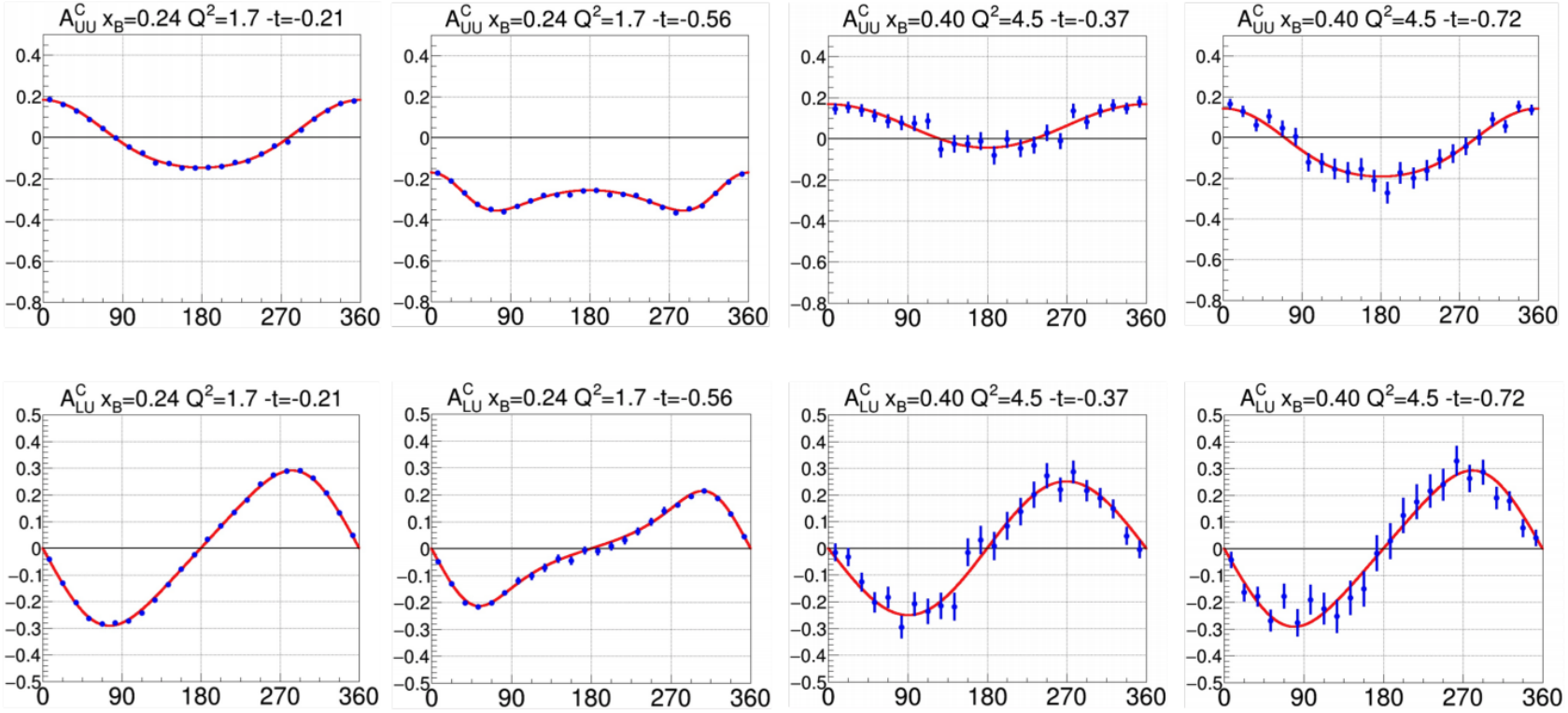


DVCS with a Polarized Positron beam

PEPPo production injecting 60 MeV **100 nA positron polarized at 60%**

(PEPPo Collaboration) D. Abbott *et al.* , **PRL**116 (2016) 214801 ; L. Cardman *et al.* AIP CP 1970 (2018) 050001

Proposal 100 days (80+20) at $\mathcal{L} = 0.6 \times 10^{35}$ cm^{-2}s^{-1}

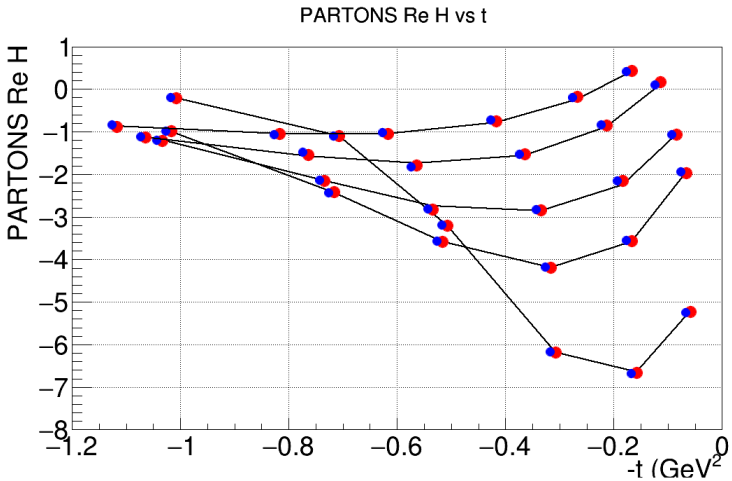


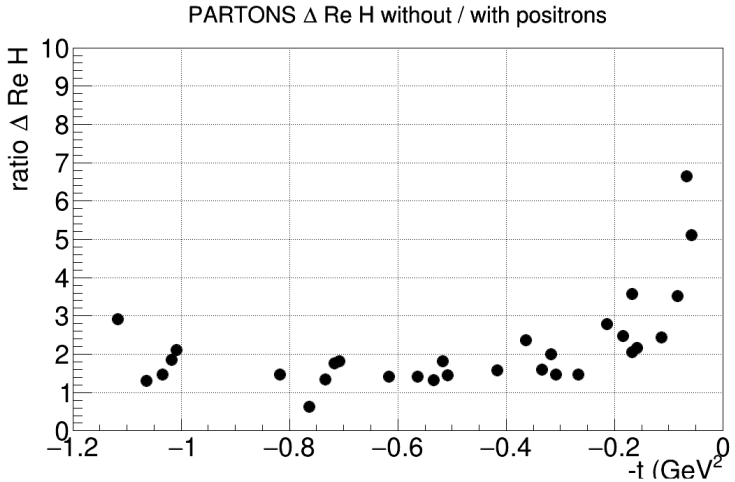
Impact of the CLAS12 Positron data

Global analysis of CLAS12 program observables $\{\sigma_{UU}, A_{LU}, A_{UL}, A_{LL}, A^C_{UU}, A^C_{LU}\}$

unpolarized beam charge asymmetry $\mathbf{A^C_{UU}}$ sensitive to the amplitude **real part**
polarized beam charge asymmetry $\mathbf{A^C_{UU}}$ sensitive to the amplitude **imaginary part**

Fitting $\{\mathcal{H}, \tilde{\mathcal{H}}\}$ assuming model values for $\{\mathcal{E}, \tilde{\mathcal{E}}\}$





Improvement of the **statistical** and **systematical** uncertainties

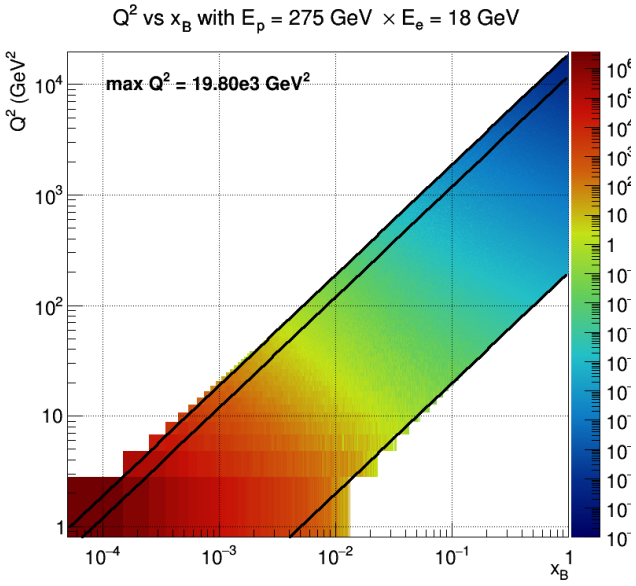
Model independent separation of the Interference with BH and DVCS^2

Outlook: EIC proton DVCS Observables

	$\int \mathcal{L}$	Observables	$A_{e,p}$		
unpolarized	200 fb^{-1}	σ	A_{LU}		
L polarized	100 fb^{-1}	A_{UL}	A_{LL}		
T polarized	100 fb^{-1}	A_{UTx}	A_{UTy}	A_{LTx}	A_{LTy}
e^+	100 fb^{-1}	A^C	A^C_{LU}		

$$N_{events} = \int \mathcal{L} \times \sigma \times KPS$$
$$KPS = \Delta x_B \Delta Q^2 \Delta t \Delta \phi$$

$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\sqrt{N_{events}}} \oplus 5\%$$



$$\Delta A_{LU} = \frac{1}{P_e}\sqrt{\frac{1-P_e^2 A_{LU}^2}{N}} \oplus 3\%_{relative} \qquad P_e = 70\%$$

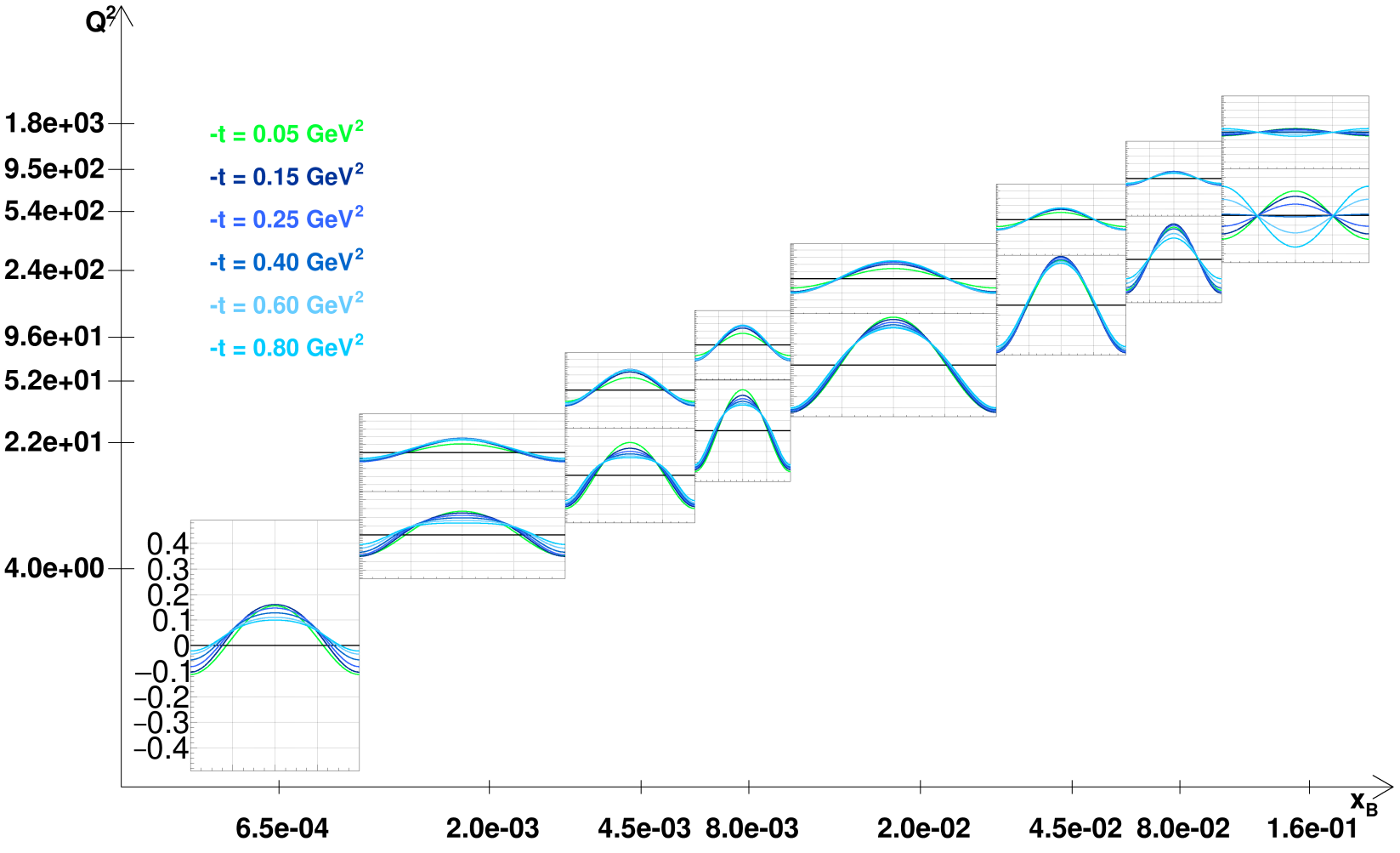
$$\Delta A_{UL} = \frac{1}{P_p}\sqrt{\frac{1-P_p^2 A_{UL}^2}{N}} \oplus 3\%_{relative} \qquad P_p = 70\%$$

$$\Delta A_{LL} = \frac{1}{P_e P_p}\sqrt{\frac{1-P_e^2 P_p^2 A_{LL}^2}{N}} \oplus 3\%_{relative} \oplus 3\%_{relative}$$

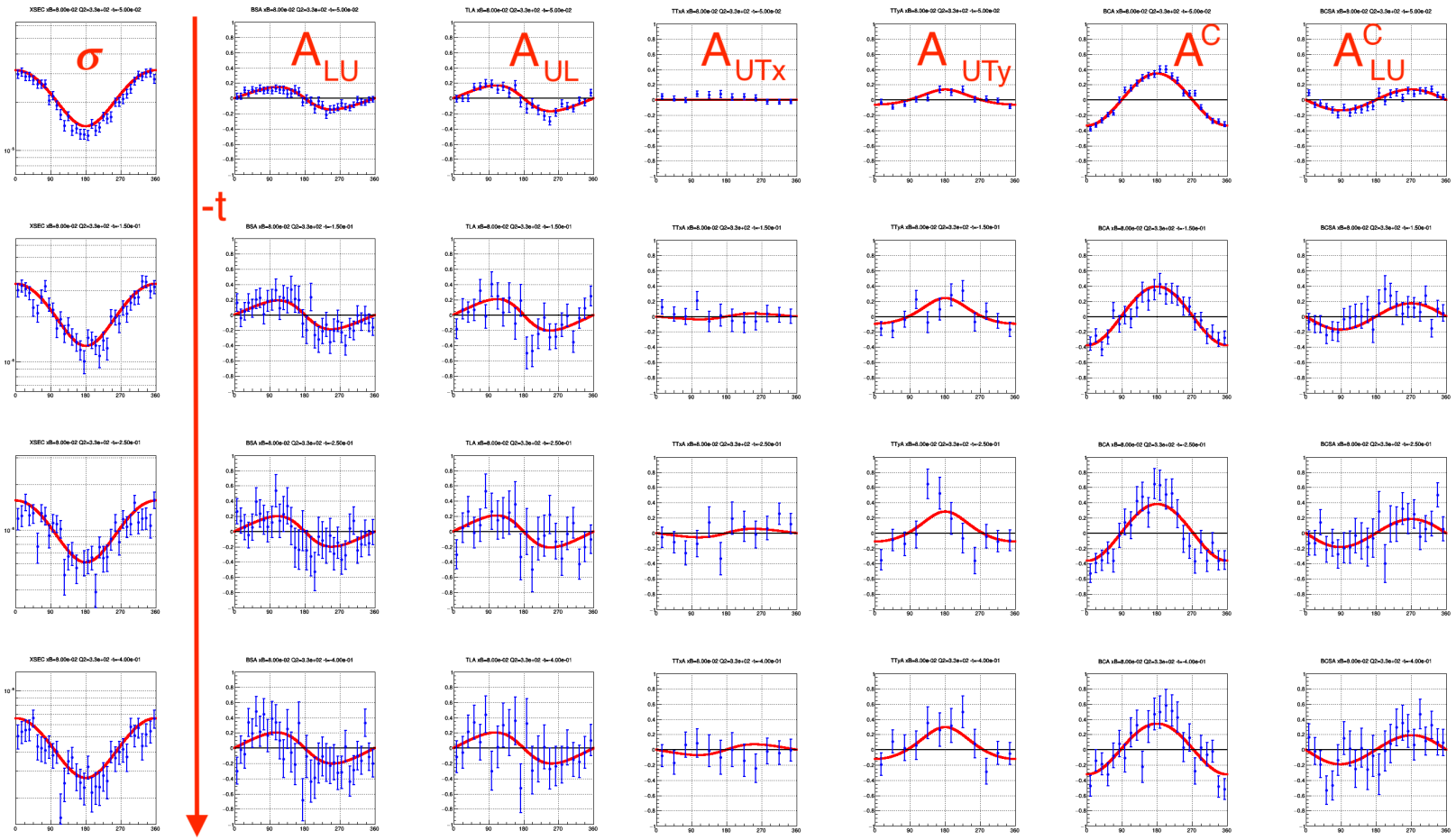
$$\Delta A_C = \sqrt{\frac{1-A_C^2}{N}} \oplus 3\%_{relative}$$

$$\Delta A_{LC} = \frac{1}{P_{e^+}}\sqrt{\frac{1-P_{e^+}^2 A_{LC}^2}{N}} \oplus 3\%_{relative} \qquad P_{e^+} = 70\%$$

EIC 275 GeV × 18 GeV A^C

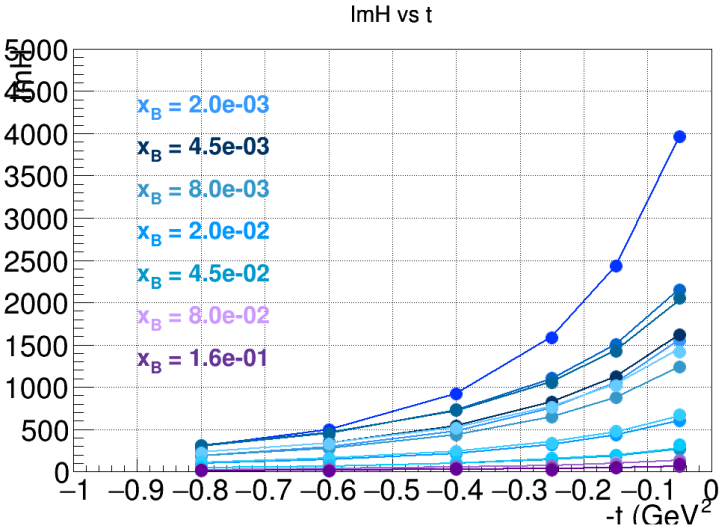


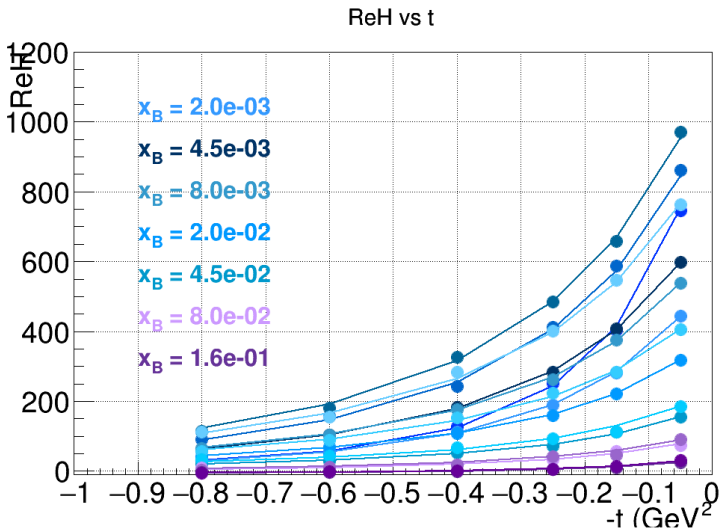
EIC 275 **GeV** $\times$ 18 **GeV** $\quad x_B = 0.08 \pm 0.02 \qquad Q^2 = 329 \pm 175$ **GeV**^{2}

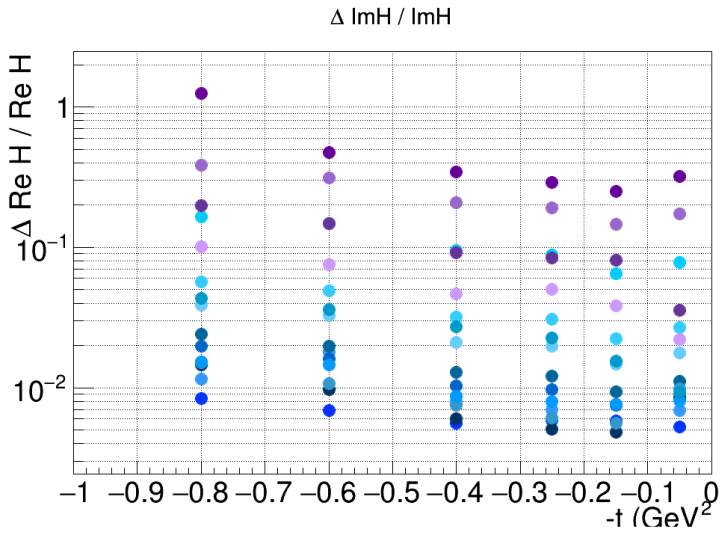


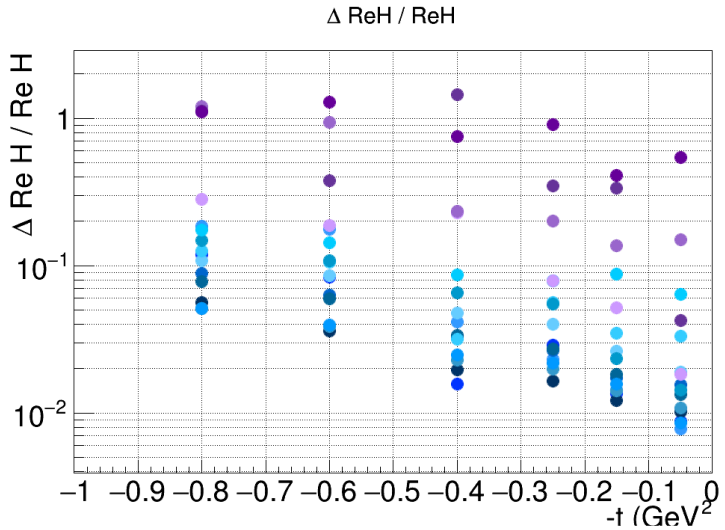
Not shown here: A_{LL} A_{LTx} A_{LTy} are small
Smearing both statistics and systematics

Locally extracted H CFF at EIC



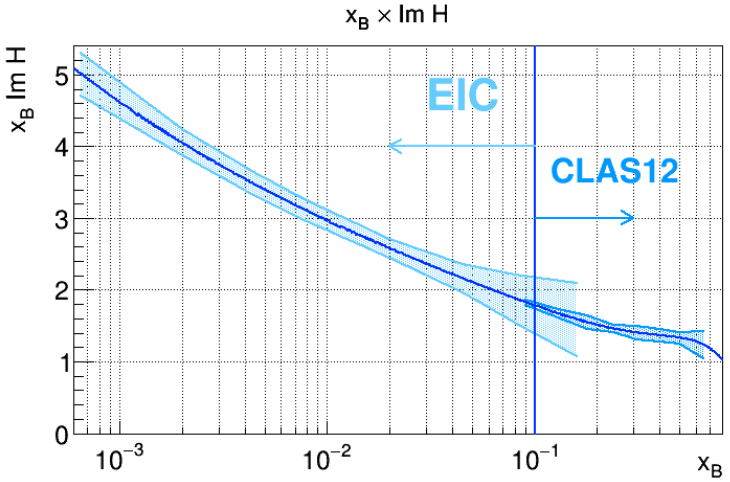


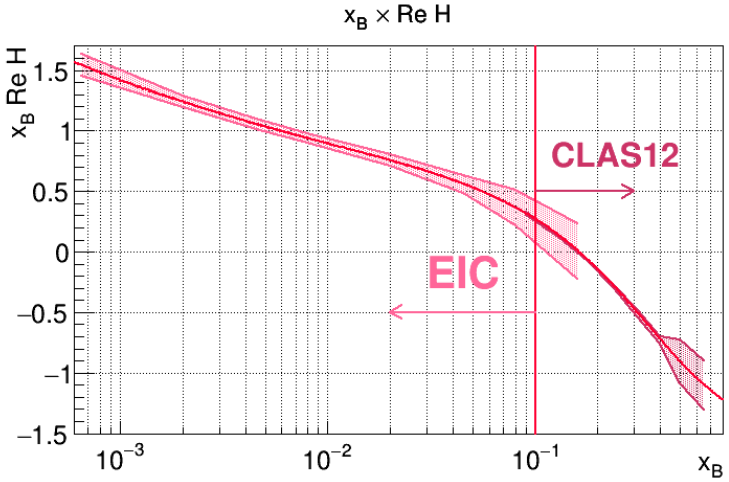




Nucleon Mechanical Structure from JLab to EIC

Exciting times: **Golden Age of Hadronic Physics**





- **CLAS12** Entering the precision era in the valence region
- Many **preliminary results** presented at this meeting
- **Positron beam** crucial for model independent extraction
- Natural extension of the program at **EIC** to map out the sea and gluons
- Mechanical structure: new insights into **confinement dynamics**