Coherent Nuclear DVCS on ^{3}He

Jackson Pybus, Xuan Li

29 June 2026

Los Alamos NATIONAL LABORATORY

Three-dimensional Hadron Imaging

Exclusive processes at large mass scale Q^2 involve transferring momentum to the hadron by removing a quark (or gluon) and reinserting it at a different momentum

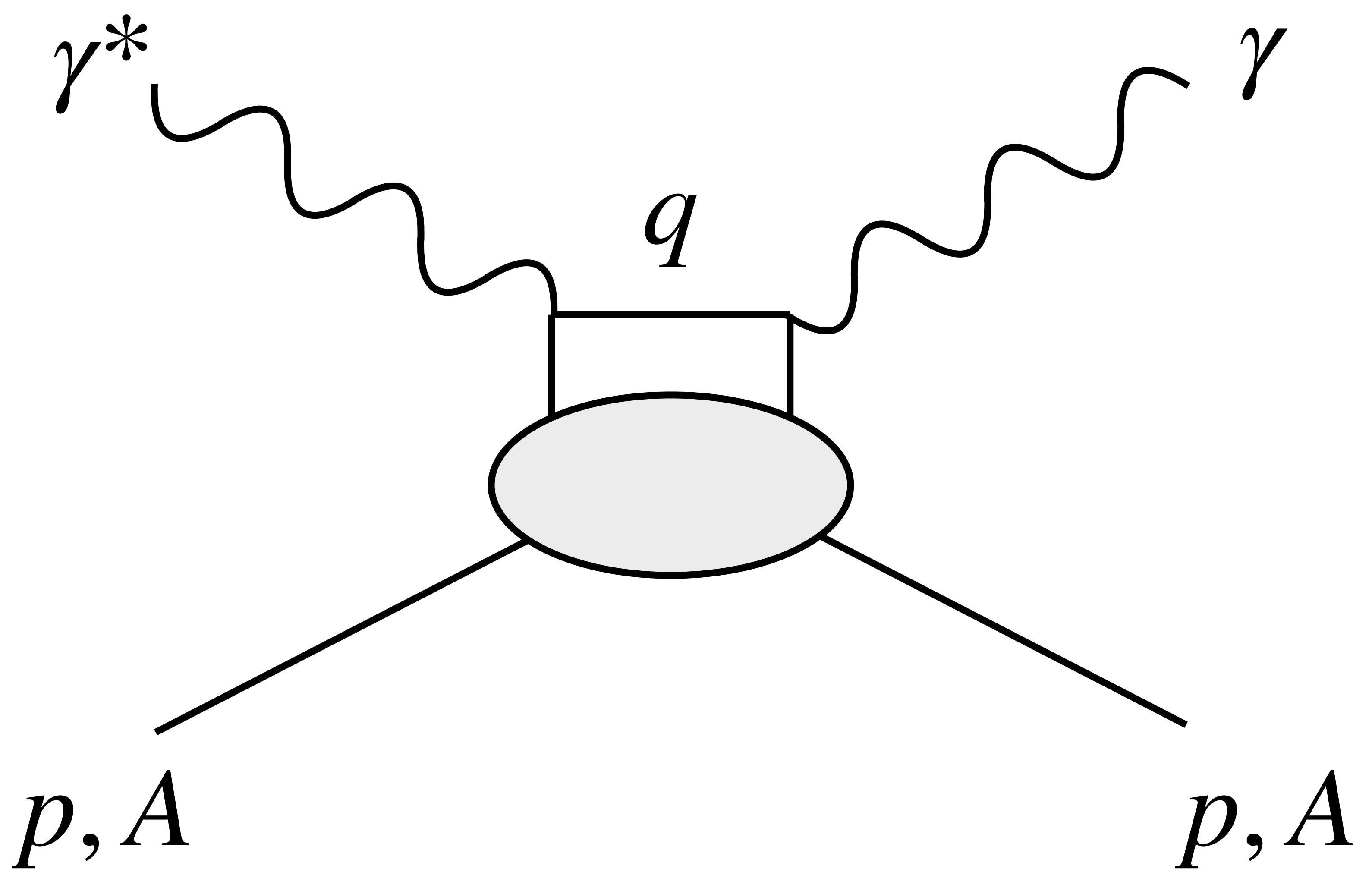
The amplitude for this process is characterized by **Generalized Parton Distributions** (GPDs), depending on

- Parton momentum-fraction x
- Longitudinal momentum-transfer ξ
- Squared total momentum-transfer t

Momentum-transfer is conjugate to spatial distribution of partons within the target

Deeply-Virtual Compton Scattering uses high-virtuality initial photon and real final-photon to access **Compton Form Factors**, which convolve GPDs with internal parton propagators

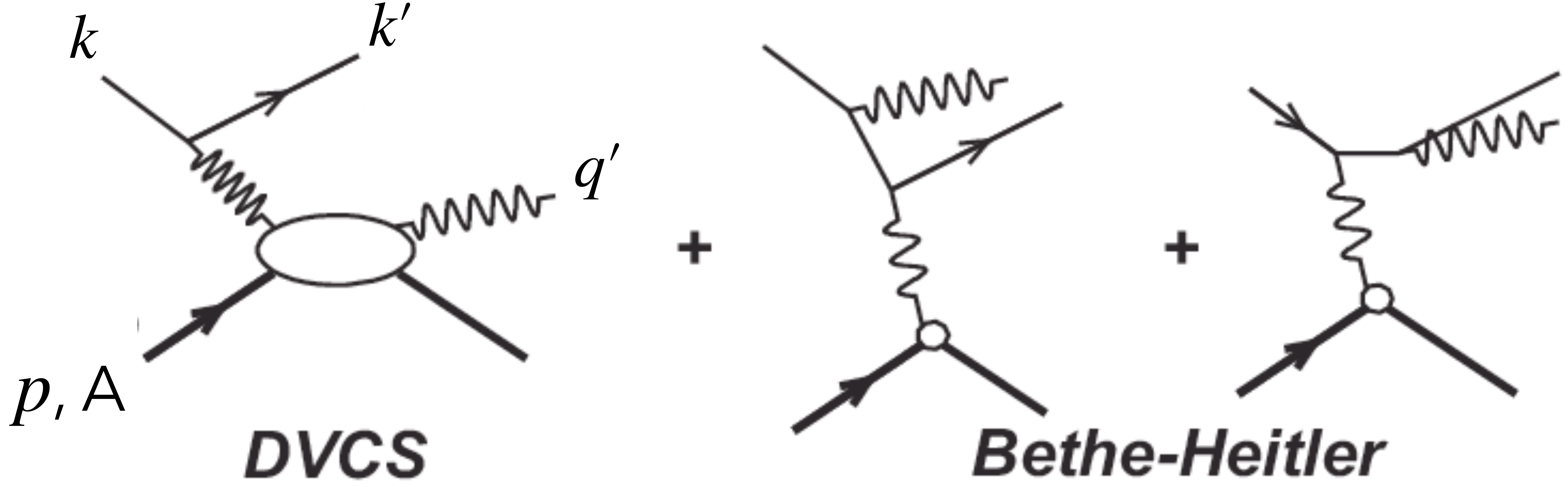
We extend this to spin-1/2 nucleus ^{3}He – how well does the behavior of quarks in the nucleus follow $2p + 1n$?



	Helicity-Conserving	**Helicity-Flip**
Unpolarized	$\mathscr{H}$	$\mathscr{E}$
Polarized	$\tilde{\mathscr{H}}$	$\tilde{\mathscr{E}}$

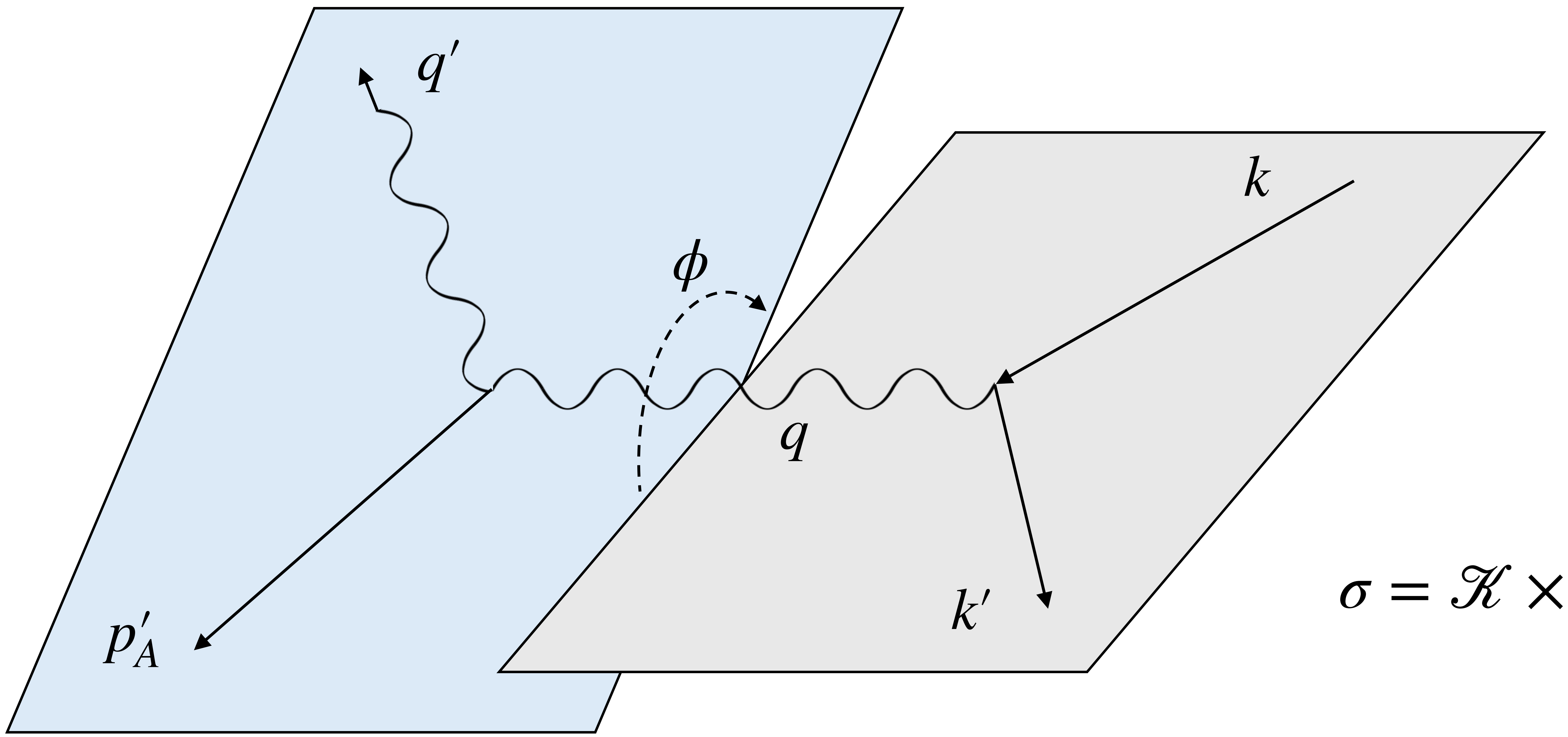
Spin-1/2 target has ***4*** *GPDs and CFFs, each complex*

DVCS and QED Bethe-Heitler process interfere in measured $eA \to e'A\gamma$ events



$$|\mathcal{M}|^2 = |\mathcal{M}_{BH}|^2 + |\mathcal{M}_{DVCS}|^2 + \mathcal{I}$$

Angular modulations are sensitive to interference terms — access to different GPDs



$$\sigma = \mathscr{K} \times \left(c_0 + \sum_n \left(c_n \cos n\phi + s_n \sin n\phi \right) \right)$$

Different harmonic terms for **BH**, **DVCS**, and **interference**

Single beam-spin asymmetries isolate interference terms

Electron beam

Proton/ion beam

Electron-spin asymmetry $A_{LU} \sim \text{Im}\mathscr{H}(\xi, t)$

Ion-spin asymmetry $A_{UL} \sim \text{Im}\tilde{\mathscr{H}}(\xi, t)$

$$A = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \sim \sin\phi$$

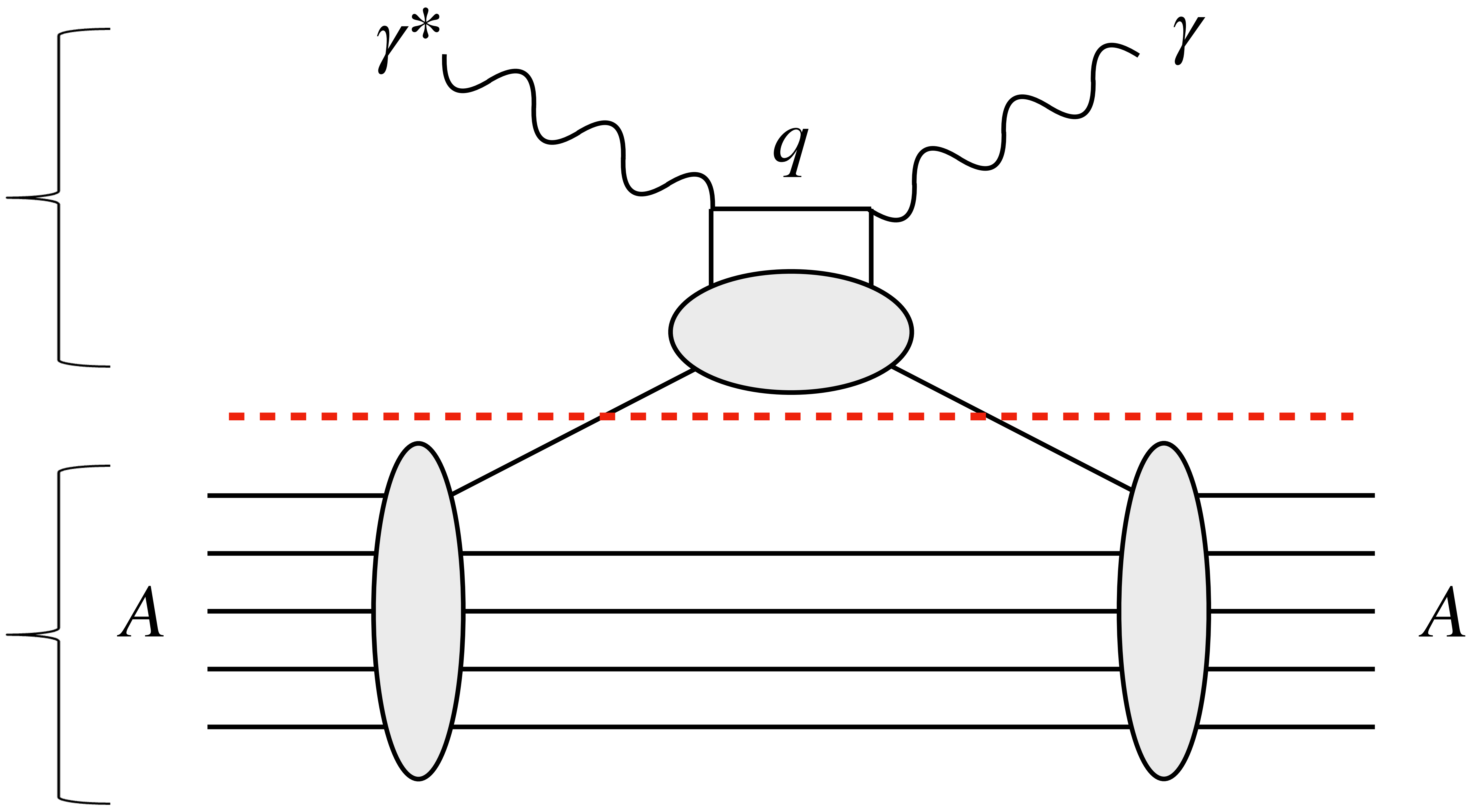
Only considering longitudinal single-spin asymmetries right now, but others exist:

- $A_{LL} \rightarrow \text{Re}\tilde{\mathscr{H}}$
- $A_{UT} \rightarrow \text{Im}\mathscr{E}$
- $A_{LT} \rightarrow \text{Im}\tilde{\mathscr{E}}$

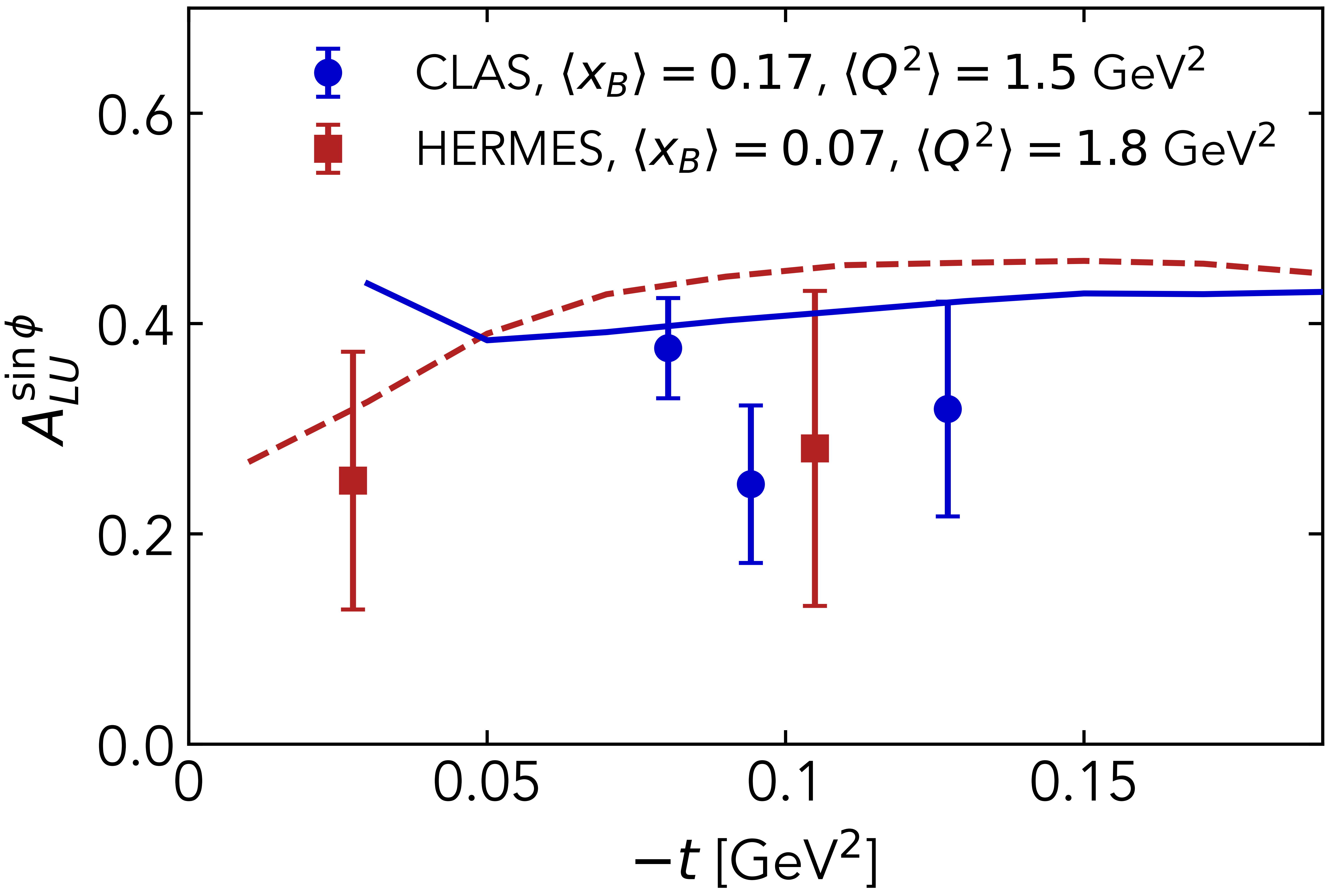
Nucleus can be modeled using a plane-wave-like factorized approach

High-energy dynamics:
Large Q^2, driven by nucleon Compton Form Factors

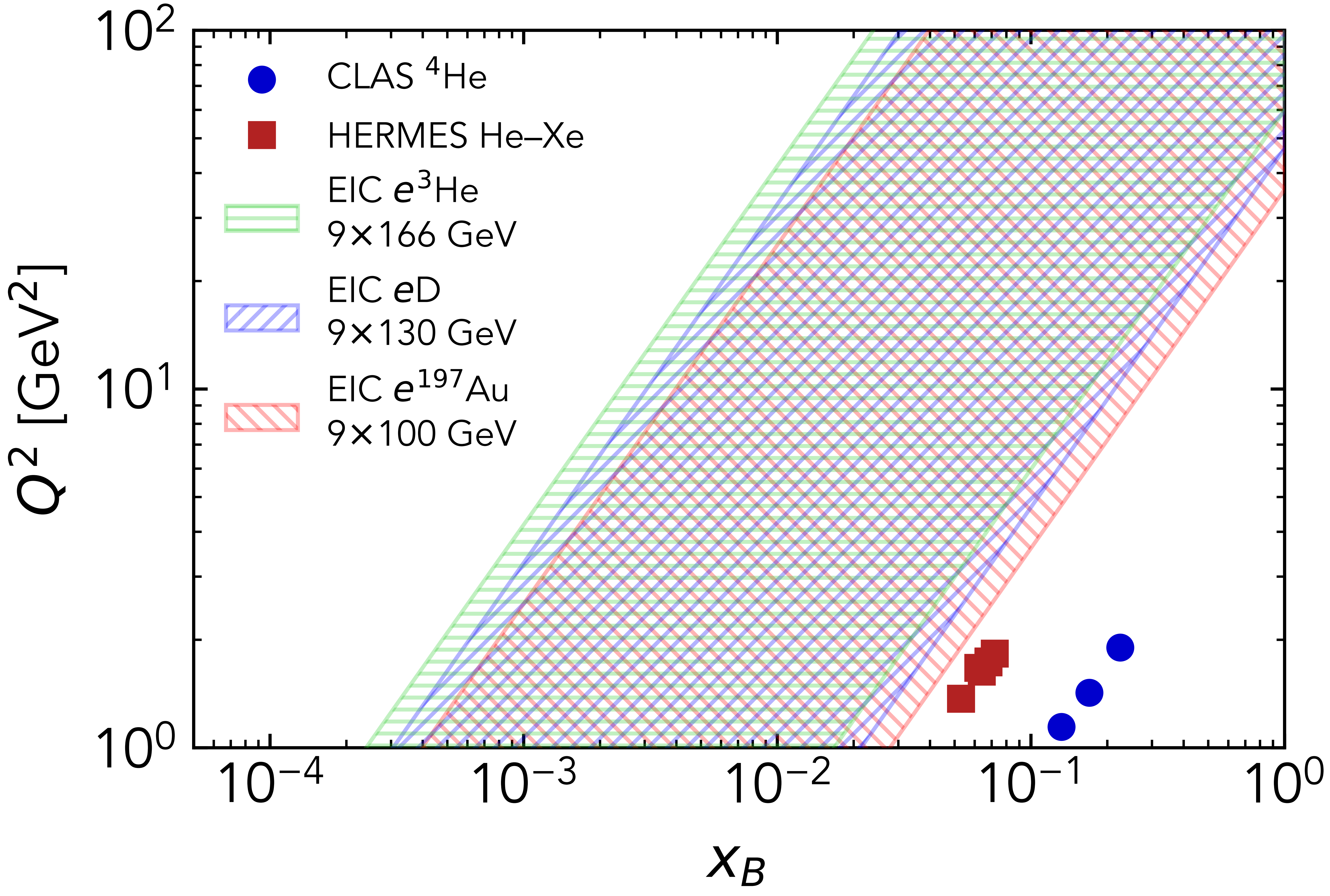
Low-energy dynamics:
Small $|t|$ and $|p_N|$, driven by nuclear off-diagonal spectral function



Compare model to spin-0 ^{4}He asymmetry data



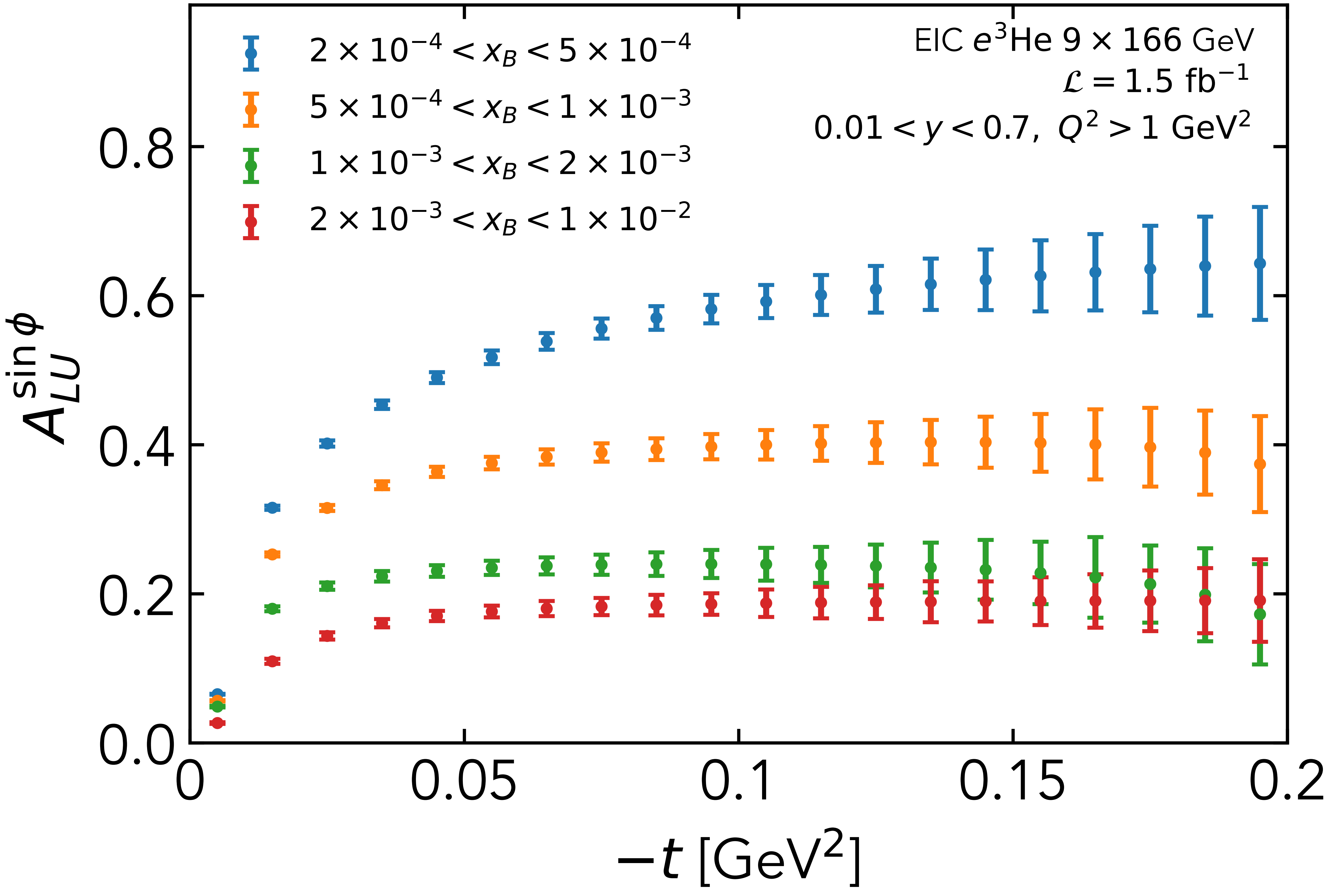
EIC energy and acceptance – much larger coverage than current nuclear data!



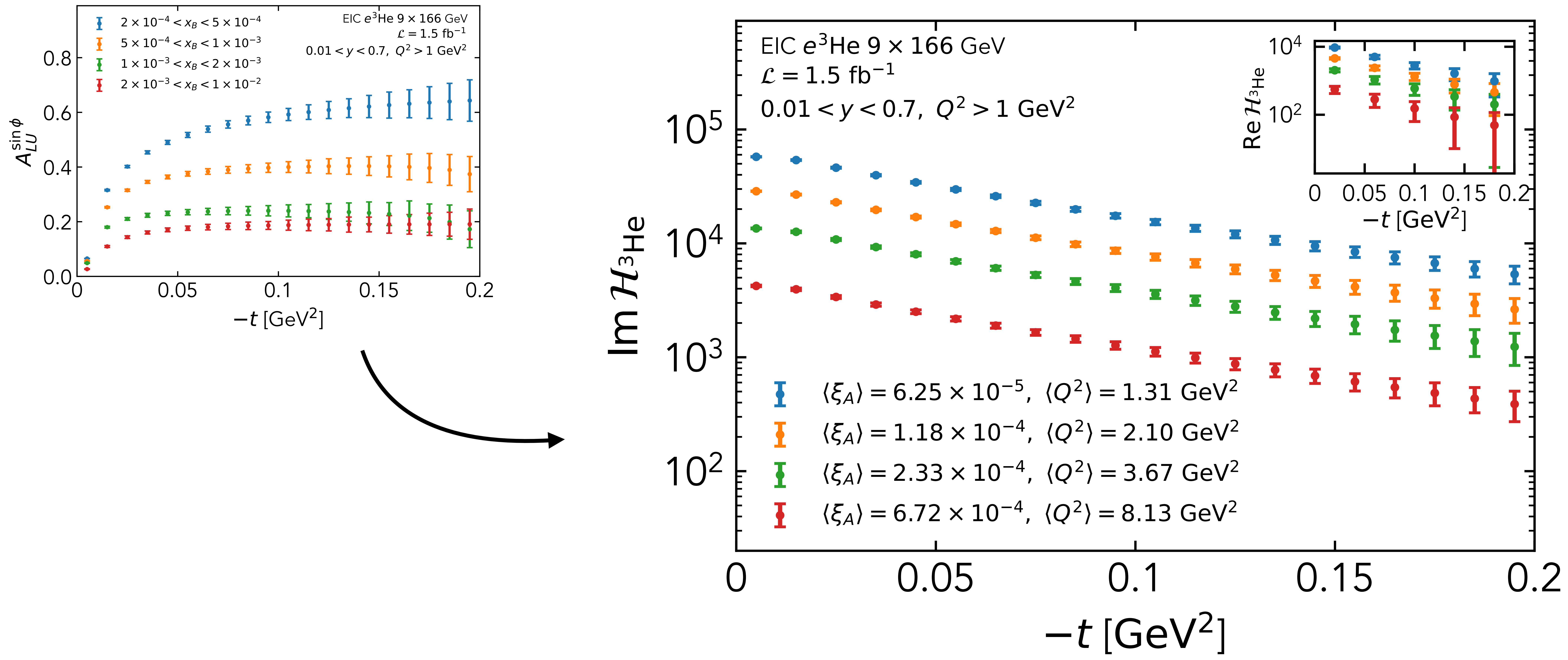
Projected lepton-spin asymmetry for EIC early-science measurement of ^{3}He

Fit $A_{LU}(\phi)$ to $\dfrac{A \sin\phi}{1 + B\cos\phi}$ functional form

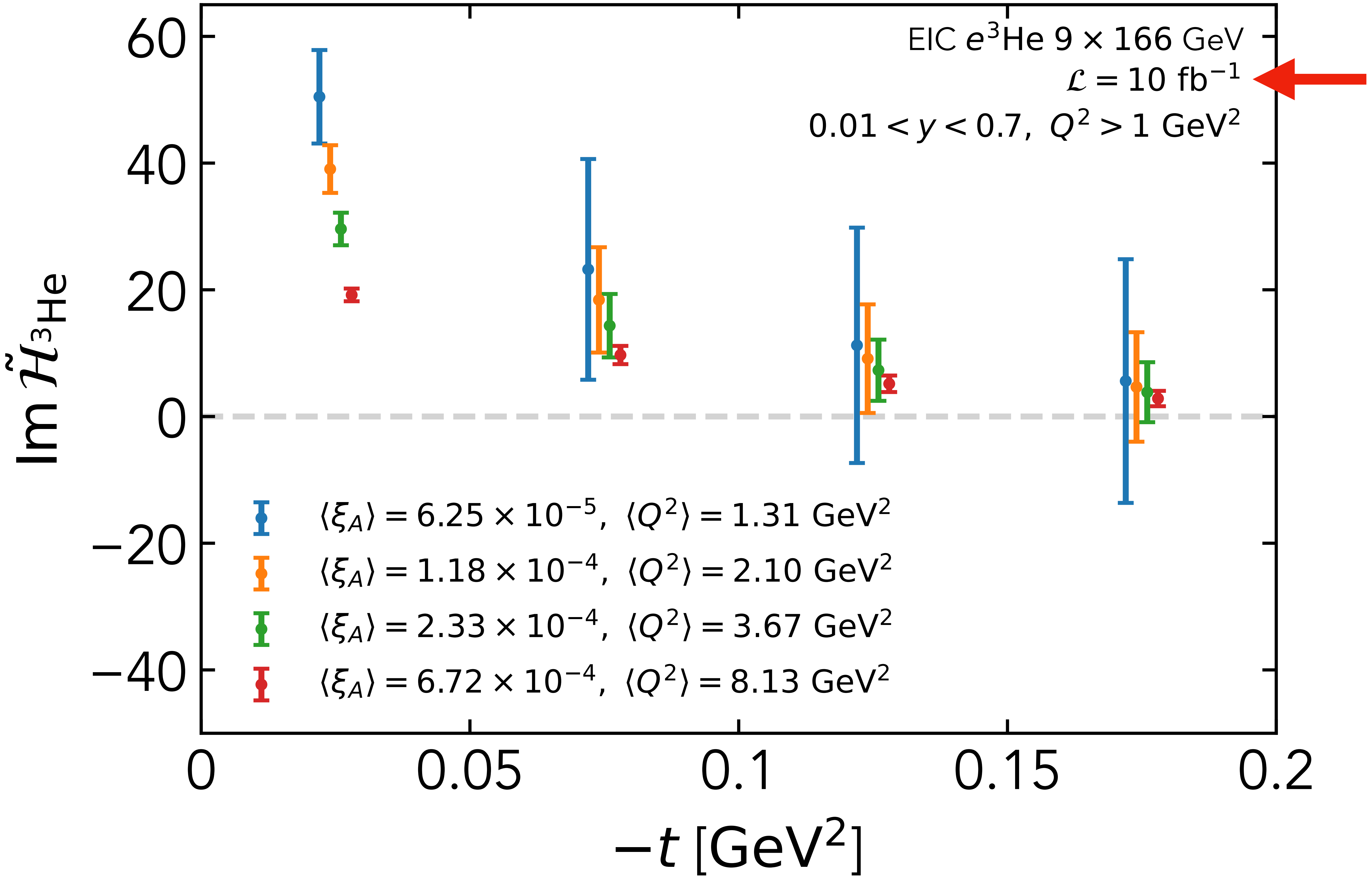
Projected event yields (thrown-only) give statistical uncertainties for propagation into fit parameters using Fisher information matrix



Fourier decomposition of A_{LU} gives access to complex $\mathscr{H}$ CFF for ^{3}He

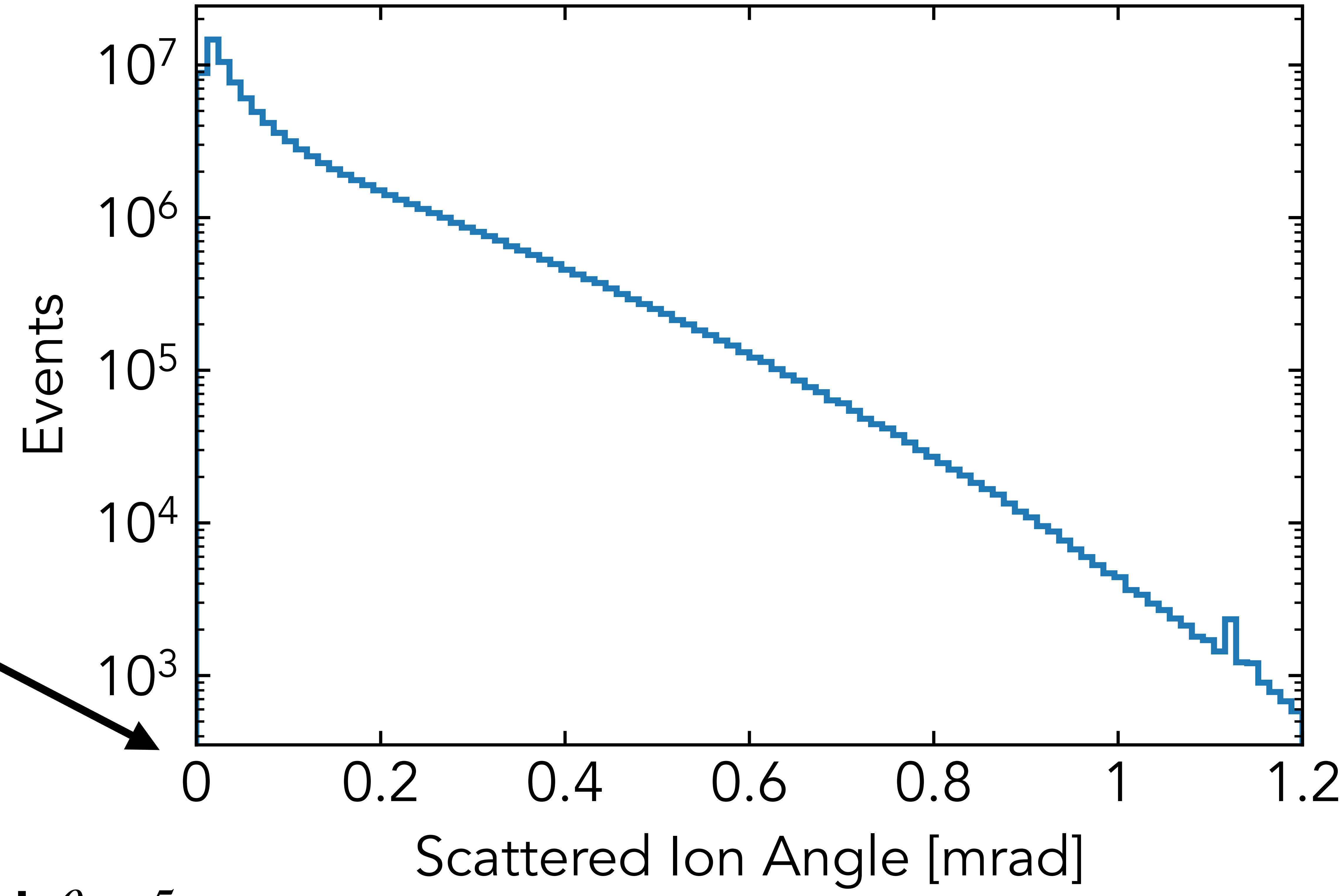


Ion-spin asymmetry accesses polarized CFF $\tilde{\mathscr{H}}$; much smaller asymmetry!



Key experimental constraint is measurement of the scattered intact ion

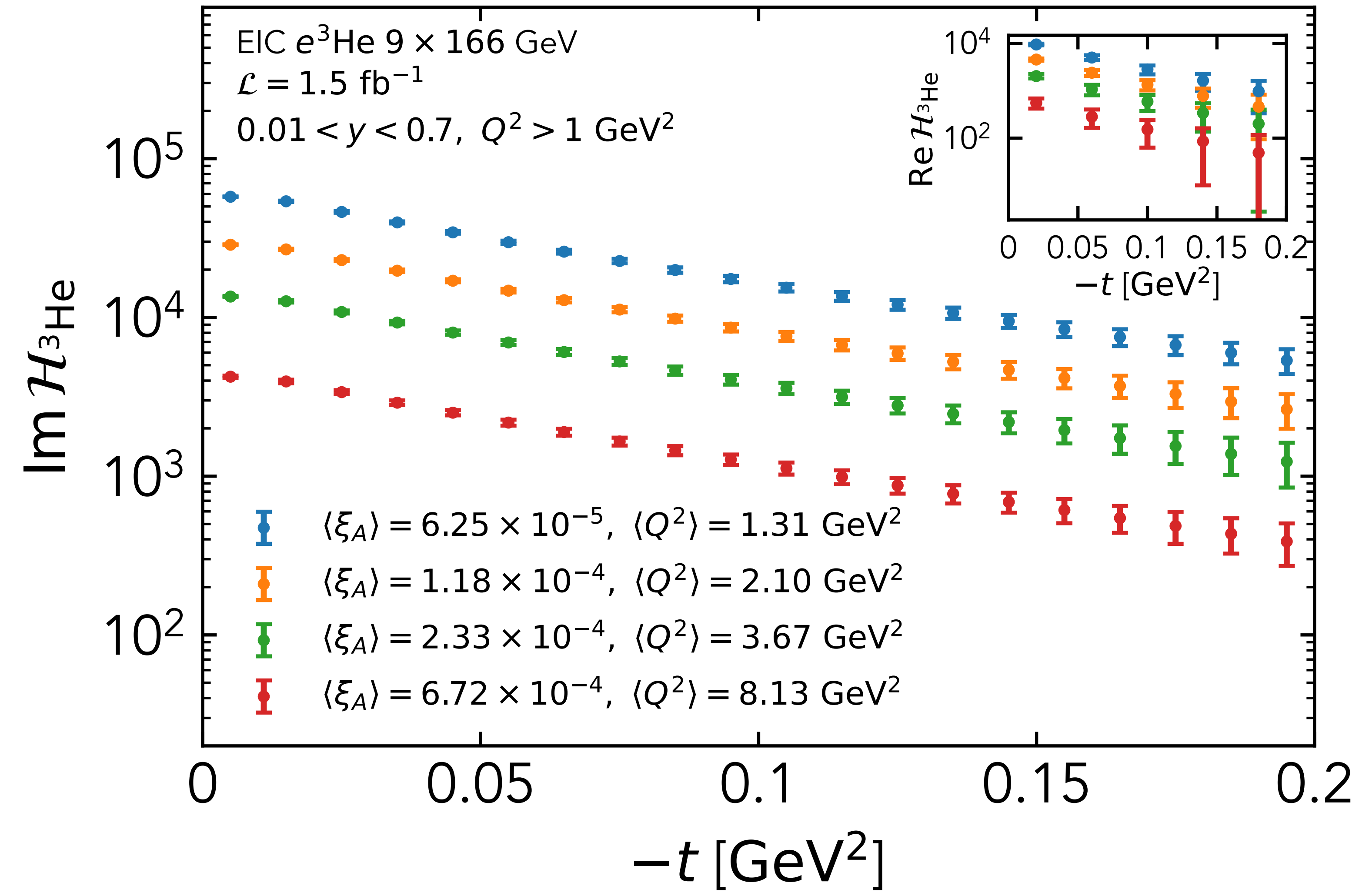
Most scattered ions continue almost unperturbed – go right along the beam line

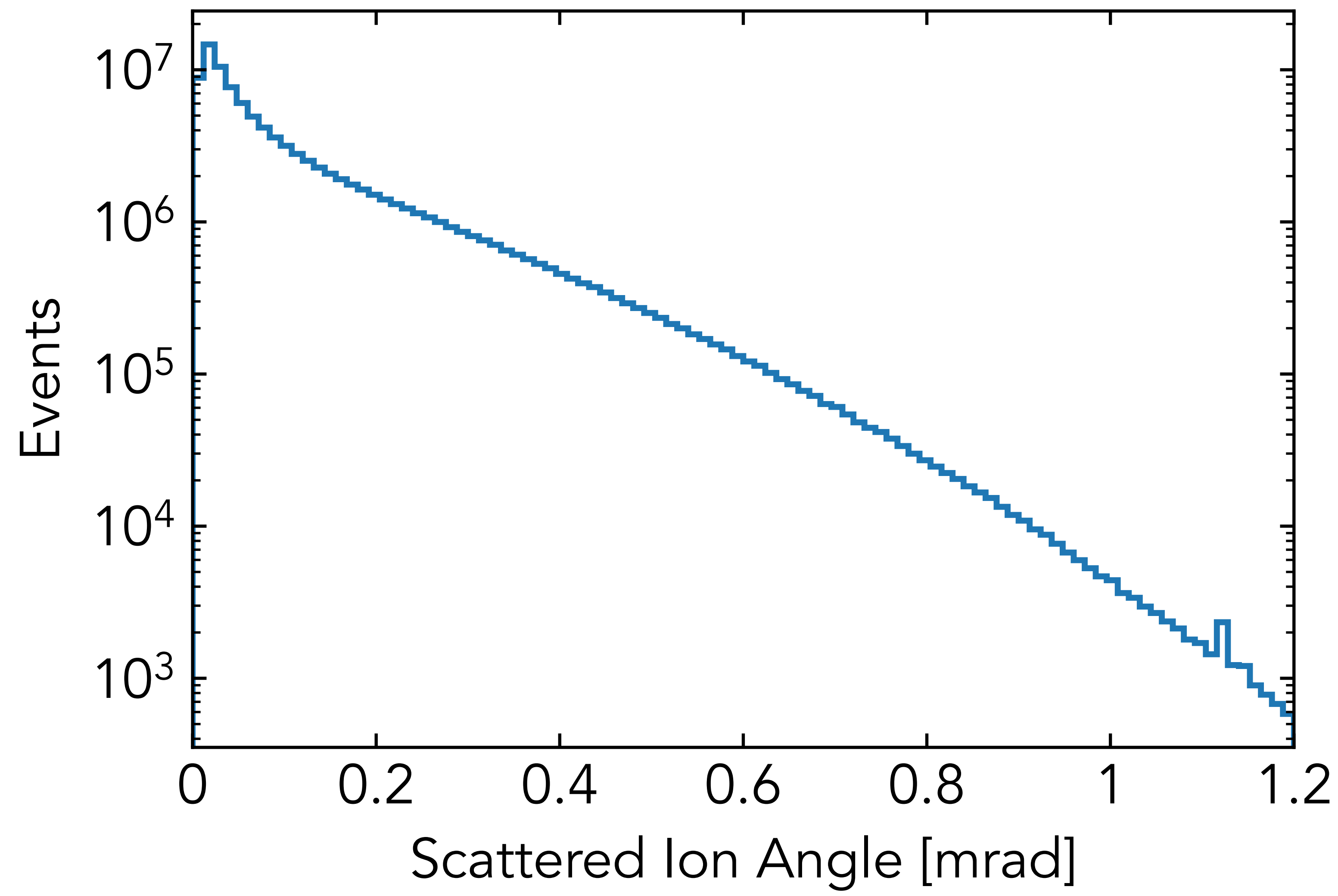


Roman pots cover small-angle tracks with $\theta < 5$ mrad, but how small in θ when M/Z is unchanged?

Conclusions

- Constructed model and event generator for coherent DVCS from spin-1/2 Helium-3 nucleus
- Estimated ePIC statistical sensitivity to single-spin asymmetries and extracted $\mathscr{H}$ and $\tilde{\mathscr{H}}$ Compton Form Factors
- Strong constraints on nuclear CFFs, but low-angle ion tagging may be necessary for exclusivity
- Next will request simulation through full ePIC framework to account for detector response and systematic effects
- Also working on incoherent nuclear DVCS event generation – significant background to coherent DVCS, but provides access to polarized neutron tomography





Backup

Compton Form Factors

- Number of CFFs depends on spin of hadron
- At leading-twist:
  - Spin-0 (**^{4}He**, ^{12}C, ^{40}Ca, ^{96}Ru): only $\mathscr{H}$ = 1 CFF
  - Spin-½ (p, **^{3}He**): $\mathscr{H}, \mathscr{E}, \tilde{\mathscr{H}}, \tilde{\mathscr{E}}$ = 4 CFFs
  - Spin-1 (**^{2}H**): $\{\mathscr{H}_{1,2,3,4,5}\}, \{\tilde{\mathscr{H}}_{1,2,3,4}\}$ = 9 CFFs

- At low-x_B, low-t, "charge" CFF $\mathscr{H} = \mathscr{H}_1$ dominates DVCS

- Interference term (experimental signal) depends primarily on $F_1(t)\Re\left\{\mathscr{H}(\xi, t, Q^2)\right\}$ for **unpolarized** DVCS;

Polarization Observables in DVCS

Assuming a spin-½ nucleus, the interference term follows:

- **Total cross section:** $\sigma_{int}(\phi) \sim \cos\phi \; F_1 \; \Re\mathscr{H}$
- **Electron-spin asymmetry:** $A_{LU}(\phi) \sim \sin\phi \; F_1 \; \Im\mathscr{H}$
- **Nucleus-spin asymmetry:** $A_{UL}(\phi) \sim \sin\phi \; F_1 \; \Im\tilde{\mathscr{H}}$
- **Double longitudinal asymmetry:** $A_{LL} \sim \cos\phi \; F_1 \; \Re\tilde{\mathscr{H}}$
- **Transverse asymmetry:** $A_{UT}(\phi, \phi_S) \sim -\sin(\phi - \phi_S) \; F_1 \; \Im\mathscr{E}$
- **Longitudinal-transverse asymmetry:** $A_{LT}(\phi, \phi_S) \sim -\cos(\phi - \phi_S) \; F_1 \; \Im\tilde{\mathscr{E}}$

Asymmetries suppressed by $\sim \xi^3$, where $\xi \simeq \dfrac{x_B}{2 - x_B}$

Nuclear Convolution

- Nuclear Compton Form Factor approximated by integral over individual nucleons using "off-diagonal light-cone momentum distribution" $h_A^N(z, \xi_A, t)$:

$$\mathscr{H}^A(\xi_A, t) \approx \sum_{N=p,n} \int_{\xi_A}^1 \frac{dz}{z} h_N^A(z, \xi_A, t) \mathscr{H}^N\left(\frac{\xi_A}{z}, t\right)$$

- $h_A^N(z, \xi_A, t)$: probability of finding nucleon N in nucleus A with light-front momentum fraction $z \equiv p^+/\bar{P}_A^+$, giving it momentum transfer $\xi = \Delta^+$ and $t = \Delta^2$, and reinserting it into the nucleus:

$$h_A^N(z, \xi_A, t) = \sum_{S,s_N} \int d^2\vec{p}_\perp dE_{A-1}$$
$$\langle P^+ + \xi, \overrightarrow{P}_\perp + \overrightarrow{\Delta}_\perp, S | zP^+ + \xi, \vec{p}_\perp + \overrightarrow{\Delta}_\perp, s_N; (1-z)P^+, \overrightarrow{P}_\perp - \vec{p}_\perp, E_{A-1} \rangle$$
$$\times \langle zP^+, \vec{p}_\perp, s_N; (1-z)P^+, \overrightarrow{P}_\perp - \vec{p}_\perp, E_{A-1} | P^+, \overrightarrow{P}_\perp, S \rangle$$

- Also "spin-dependent off-diagonal light-cone momentum distribution"; approximate by factorizing into nucleon polarization and spin-independent ODLCMD:

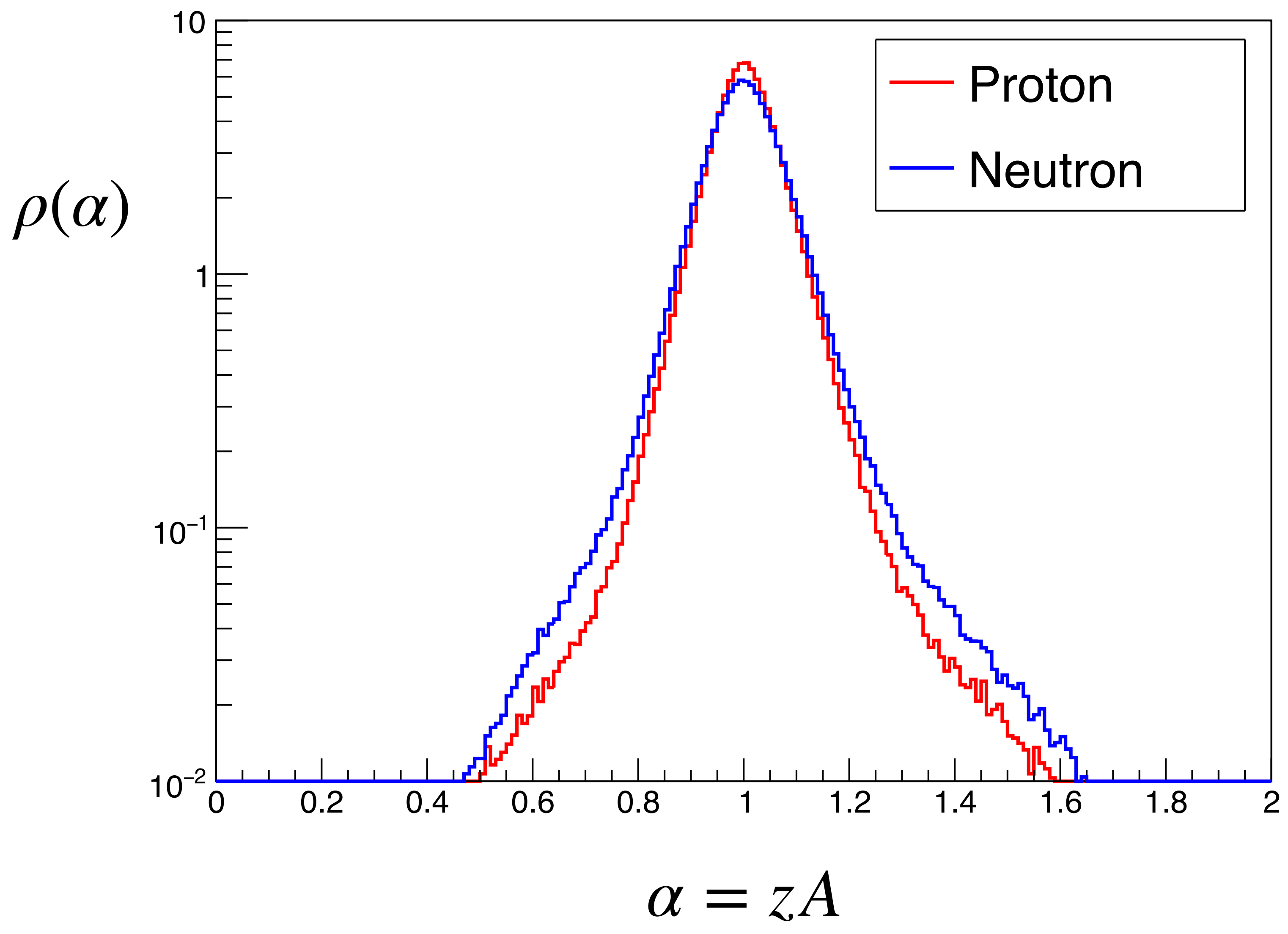
$$\tilde{h}_A^N(z, \xi_A, t) \approx P_N \times h_A^N(z, \xi_A, t)$$
$$\tilde{\mathscr{H}}^A(\xi_A, t) \approx \sum_{N=p,n} \int_{\xi_A}^1 \frac{dz}{z} \tilde{h}_N^A(z, \xi_A, t) \tilde{\mathscr{H}}^N\left(\frac{\xi_A}{z}, t\right)$$

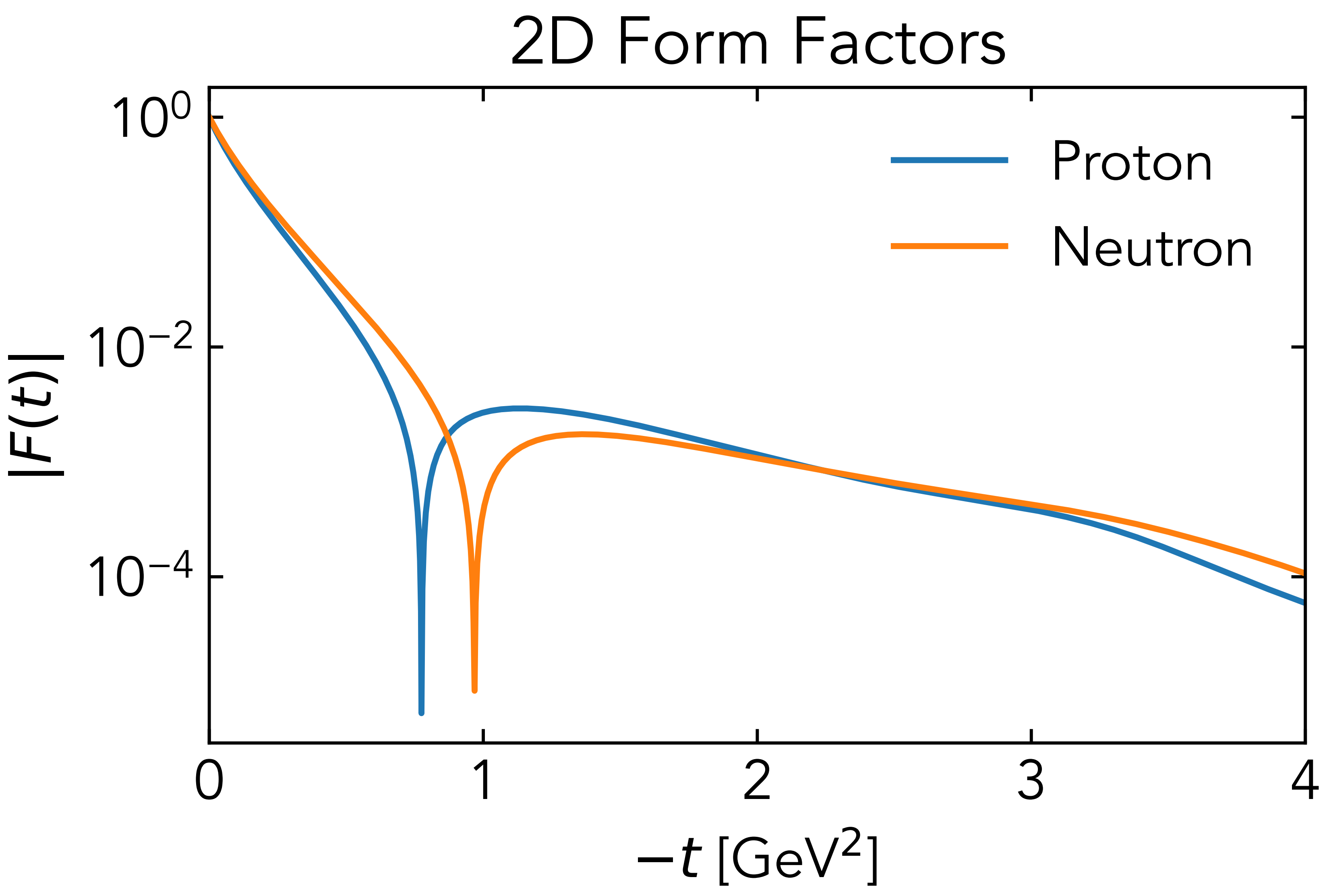
Nuclear Convolution

- At low-ξ, low-t, we assume the off-diagonal momentum density factorized into light cone momentum density and transverse nuclear form factor:

$$h_A^N(z, \xi_A, t) \approx \rho(z) \times F_A^N(t)$$

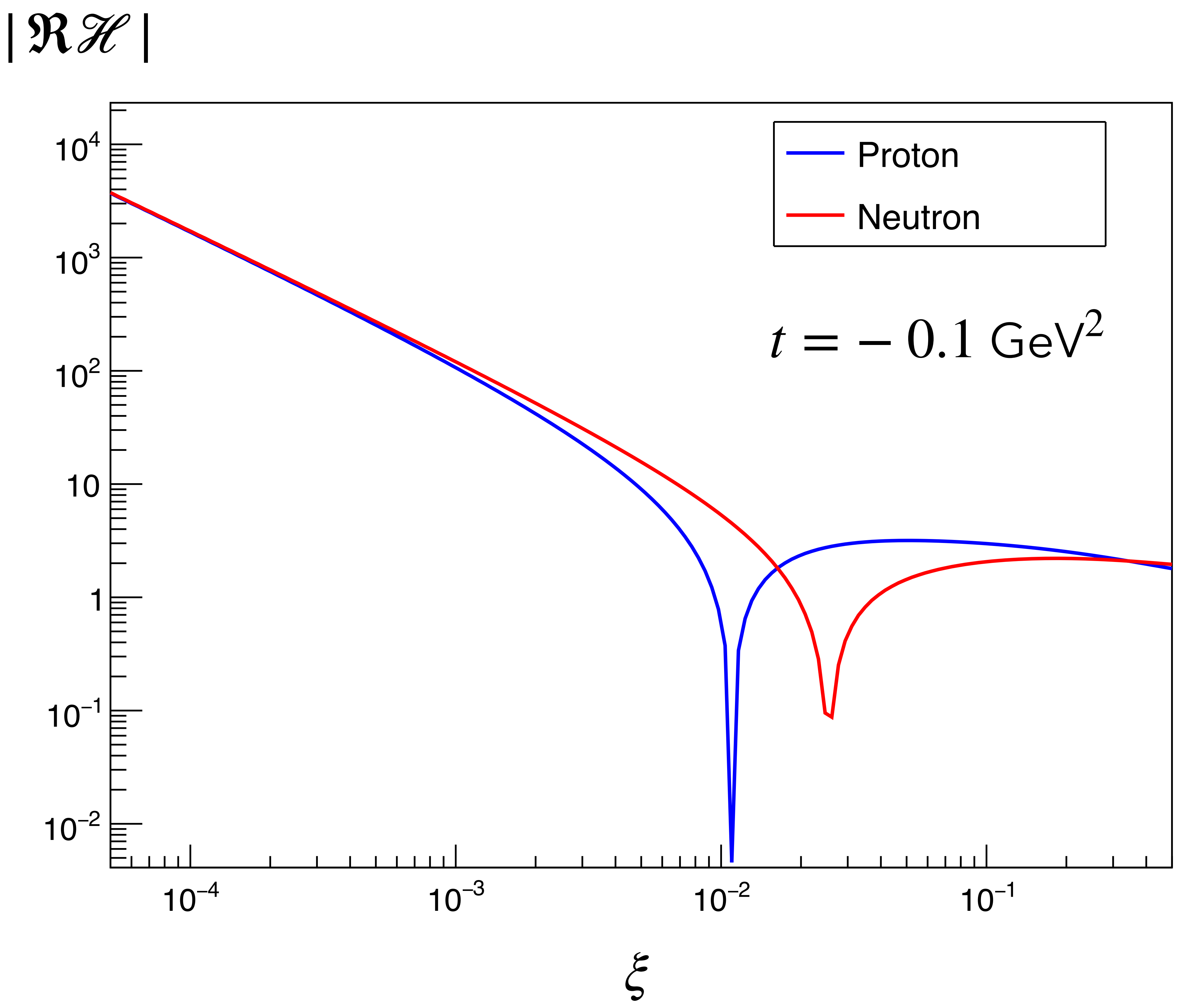
- Ab-initio nuclear calculations give both light cone momentum distributions and transverse position distributions:





Nucleon Compton Form Factors

- Proton GPDs taken from Kumerički-Müller interpretation of JLab + HERA results [Nuclear Physics B 841 (2010)]
- Valence weighting changed to convert to neutron form factor
- Dispersion relations connect real and imaginary CFFs
- Dominant CFF at low ξ is $\mathscr{H}$, followed by $\tilde{\mathscr{H}}$



Nuclear Compton Form Factors