Coherent DVCS from Polarized Nuclei at the EIC

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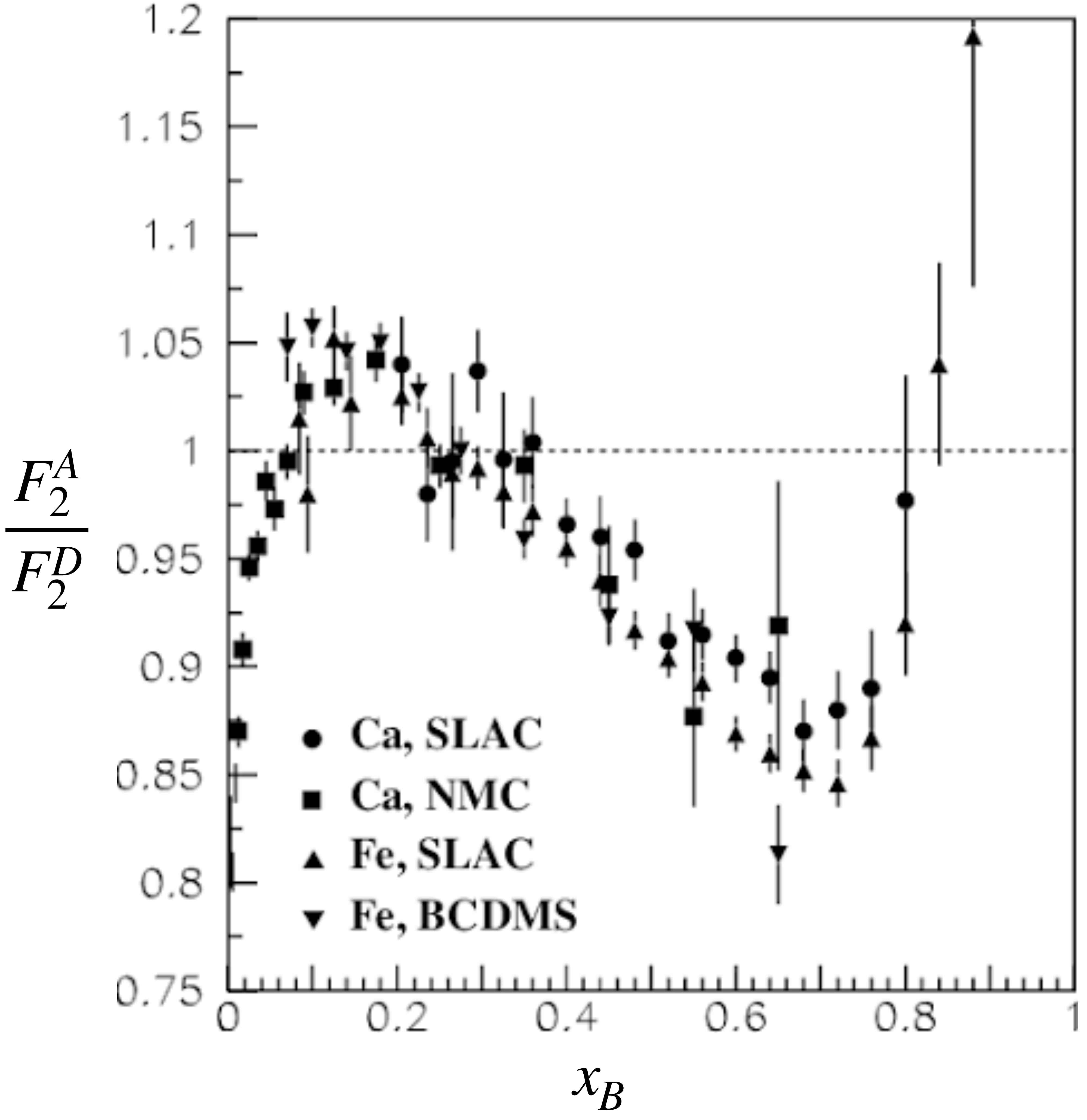
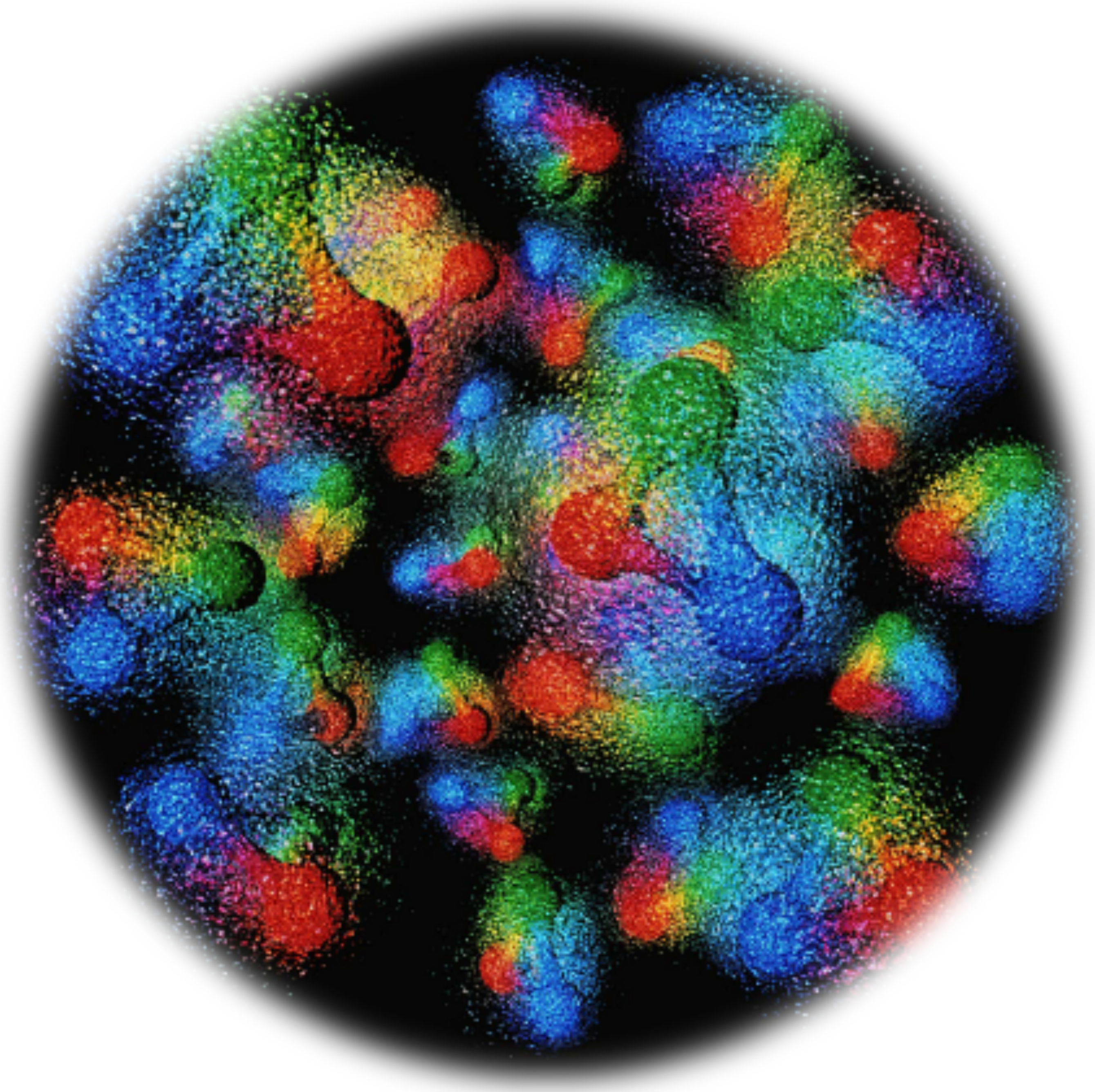
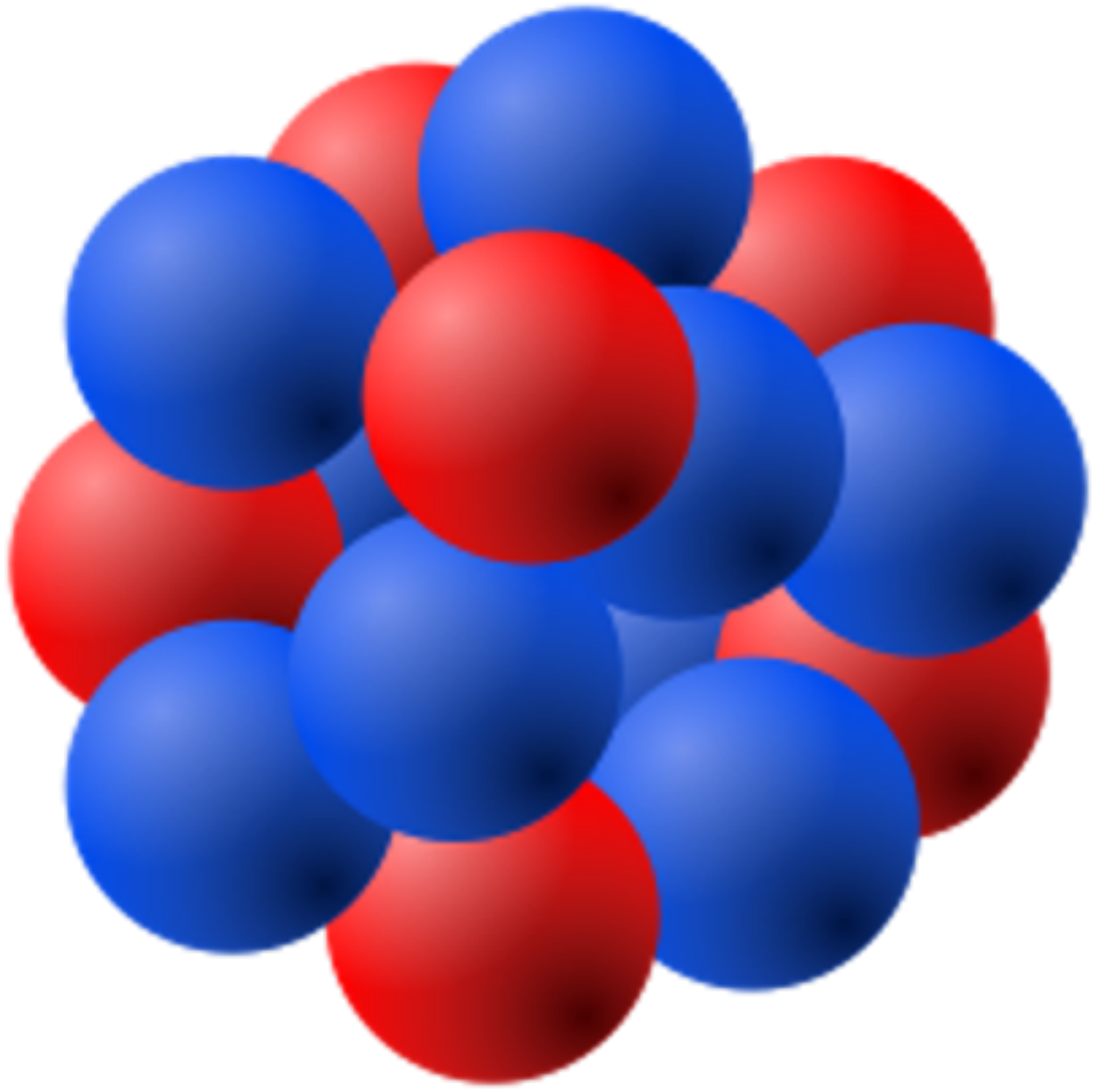
The nucleus is not simply a collection of nucleons!

- Bound nucleon ≠ Free nucleon
- Nuclear medium modifies partonic structure across all x_B, from EMC effect to shadowing
- Studies of this effect are largely limited to measurement of nPDFs via DIS, Drell-Yan, W/Z boson production
- **Understanding nuclear effects requires moving beyond 1-dimensional momentum distributions**



EIC will shine light on QCD in the nucleus





- How does the nuclear environment affect quarks and gluons?
- Are quarks and gluons in a nucleus confined?
- What is the role of saturation at high gluon densities?

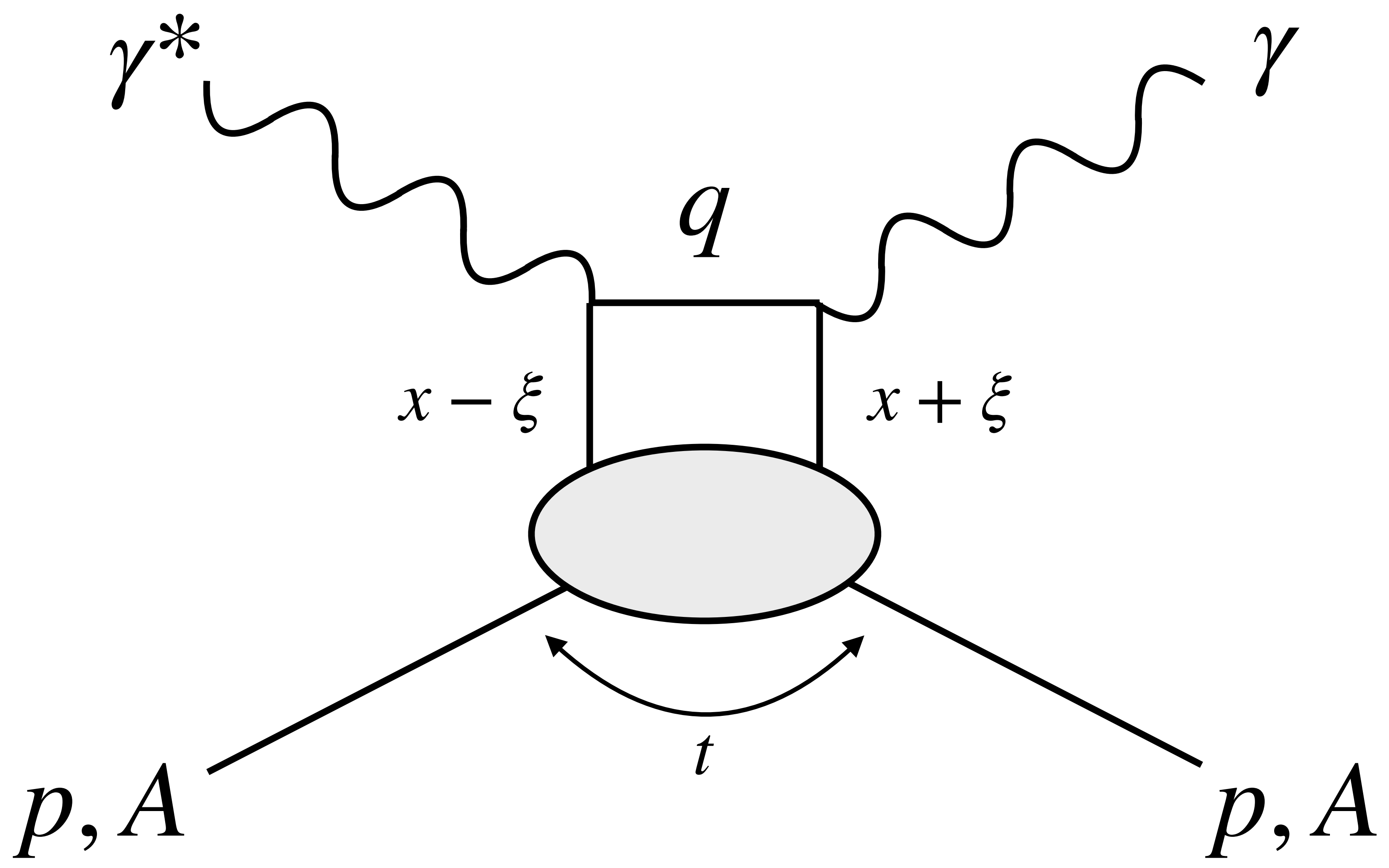
– EIC Whitepaper

Deeply-Virtual Compton Scattering

- **Deeply-Virtual Compton Scattering** from the nucleus probes 3-dimensional partonic structure
- Generalized Parton Distributions accessed via complex **Compton Form Factors**, which depend on **Generalized Parton Distributions:**

$$\mathcal{H} = \int_{-1}^{1} dx\ H(x, \xi, t)\ \left(\frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon} \right)$$

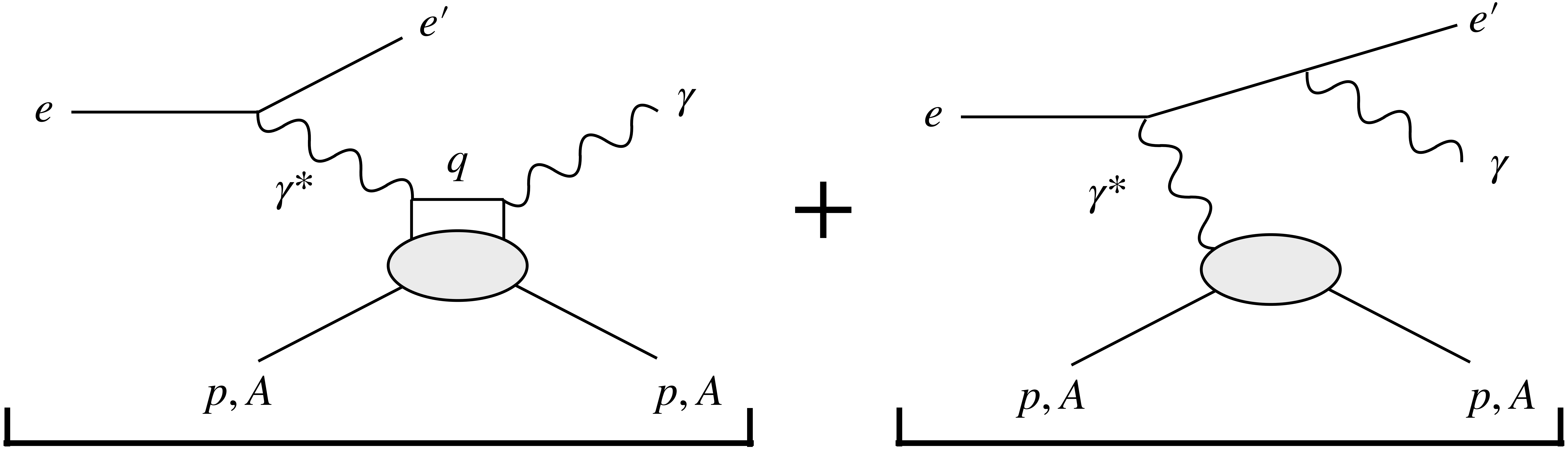
- GPDs depend on:
  - Parton momentum-fraction x
  - Longitudinal momentum-transfer ξ
  - Squared total momentum-transfer t



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

*Spin-1/2 target has **4** GPDs and CFFs; Spin-0 has only $\mathcal{H}$*

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

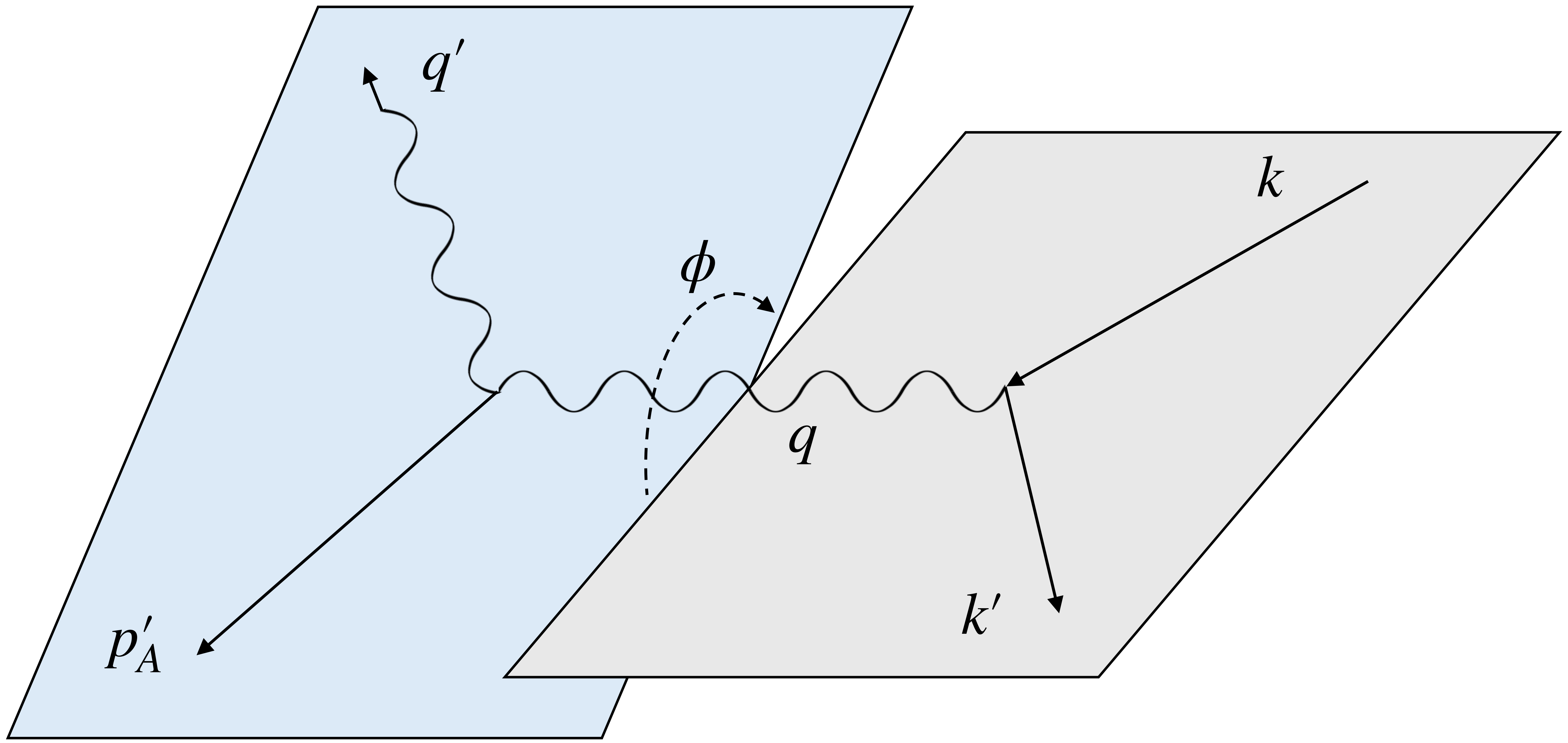


DVCS

Bethe-Heitler

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

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

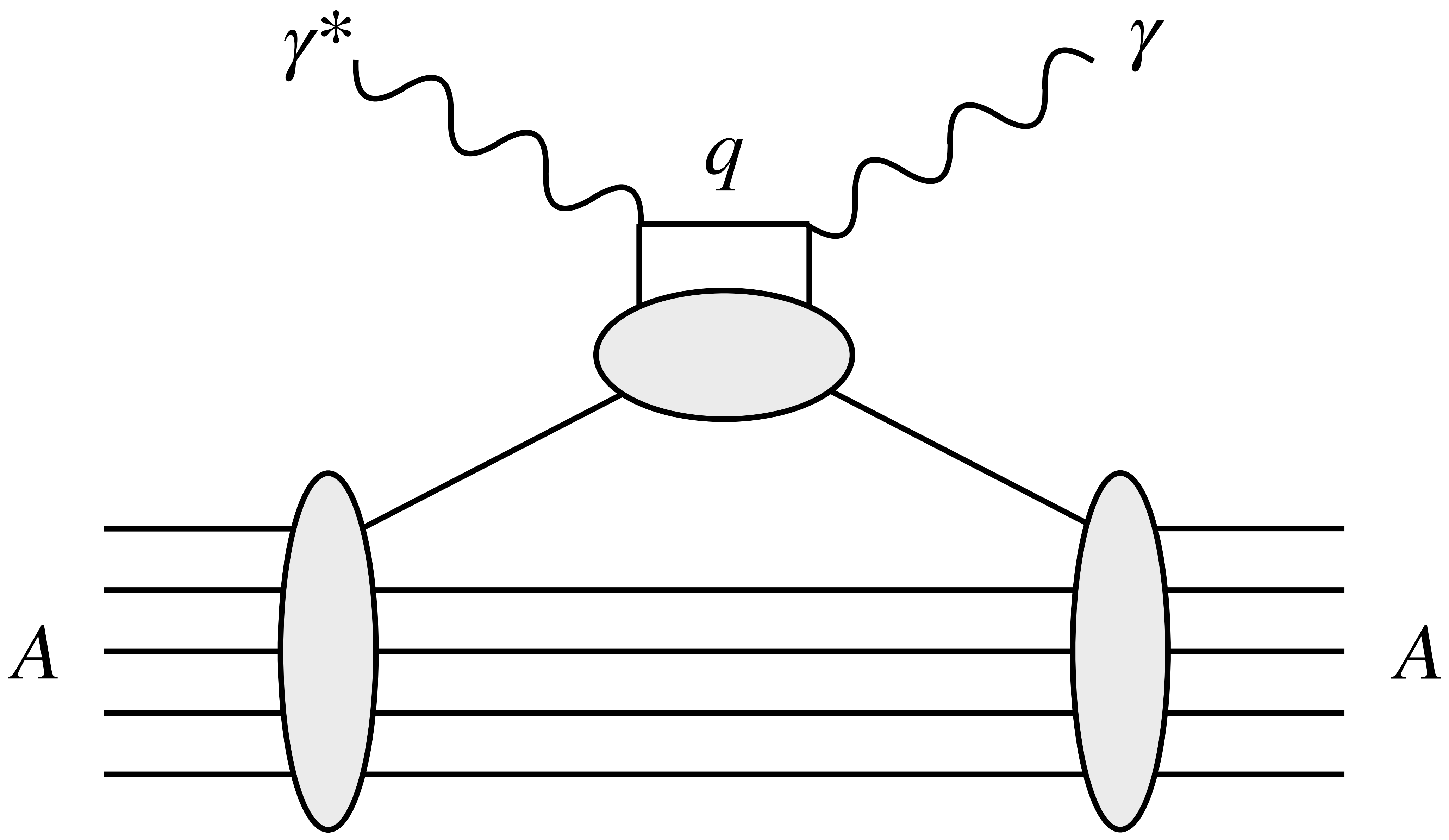


$$\sigma = \mathscr{K} \times \left(c_0 + \sum_n \left(c_n \cos n\phi + s_n \sin n\phi \right) \right)$$

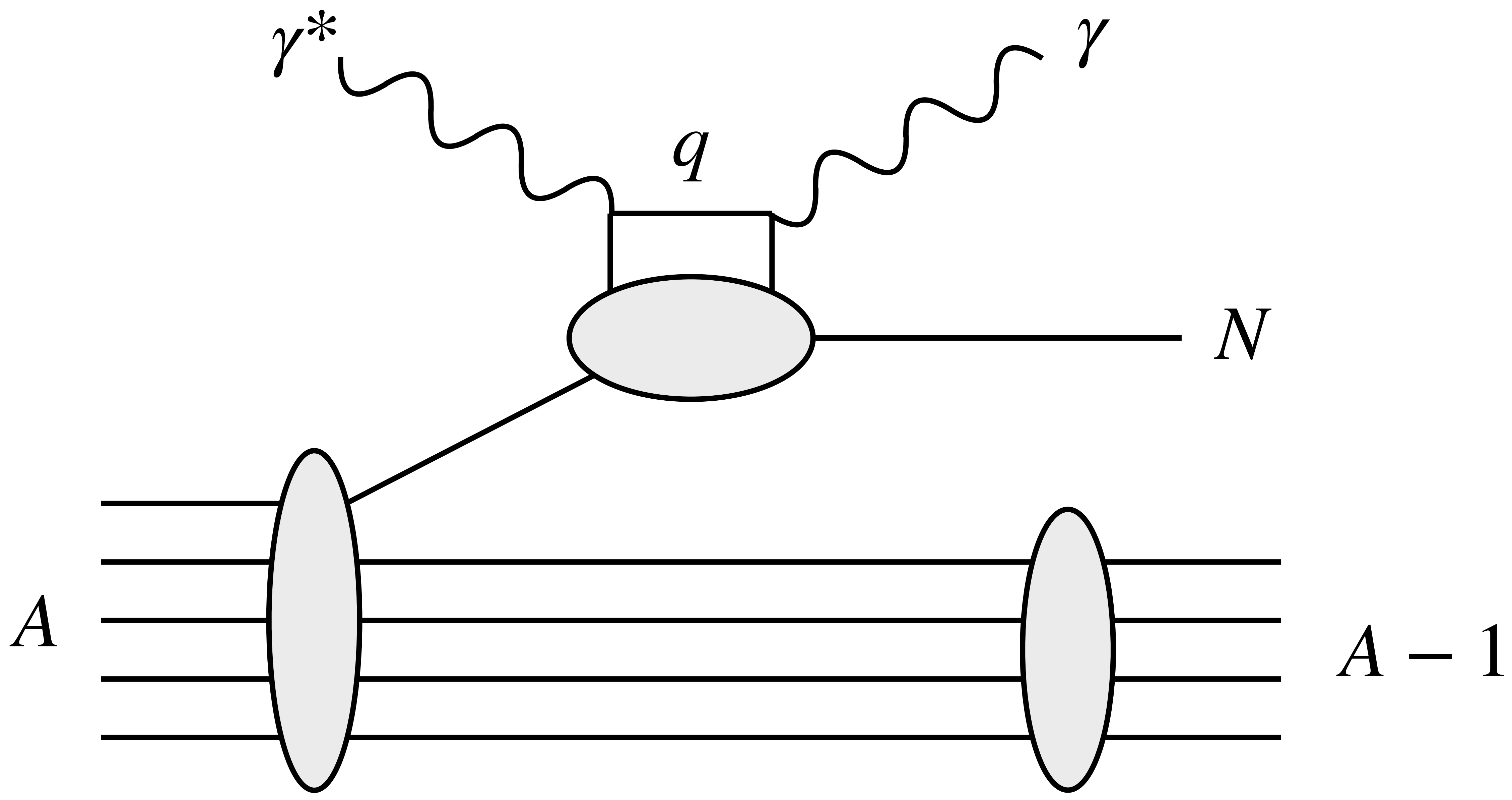
Different harmonic terms for **BH**, **DVCS**, and **interference**

Typically $|\mathscr{M}_{BH}|^2 \gg \mathscr{I} \gg |\mathscr{M}_{DVCS}|^2$; Most measurements exploit interference behavior for different spin states to extract CFF components

Coherent vs. Incoherent Nuclear DVCS



Coherent DVCS:
Probes nuclear structure and size



Incoherent DVCS:
Probes individual bound nucleons

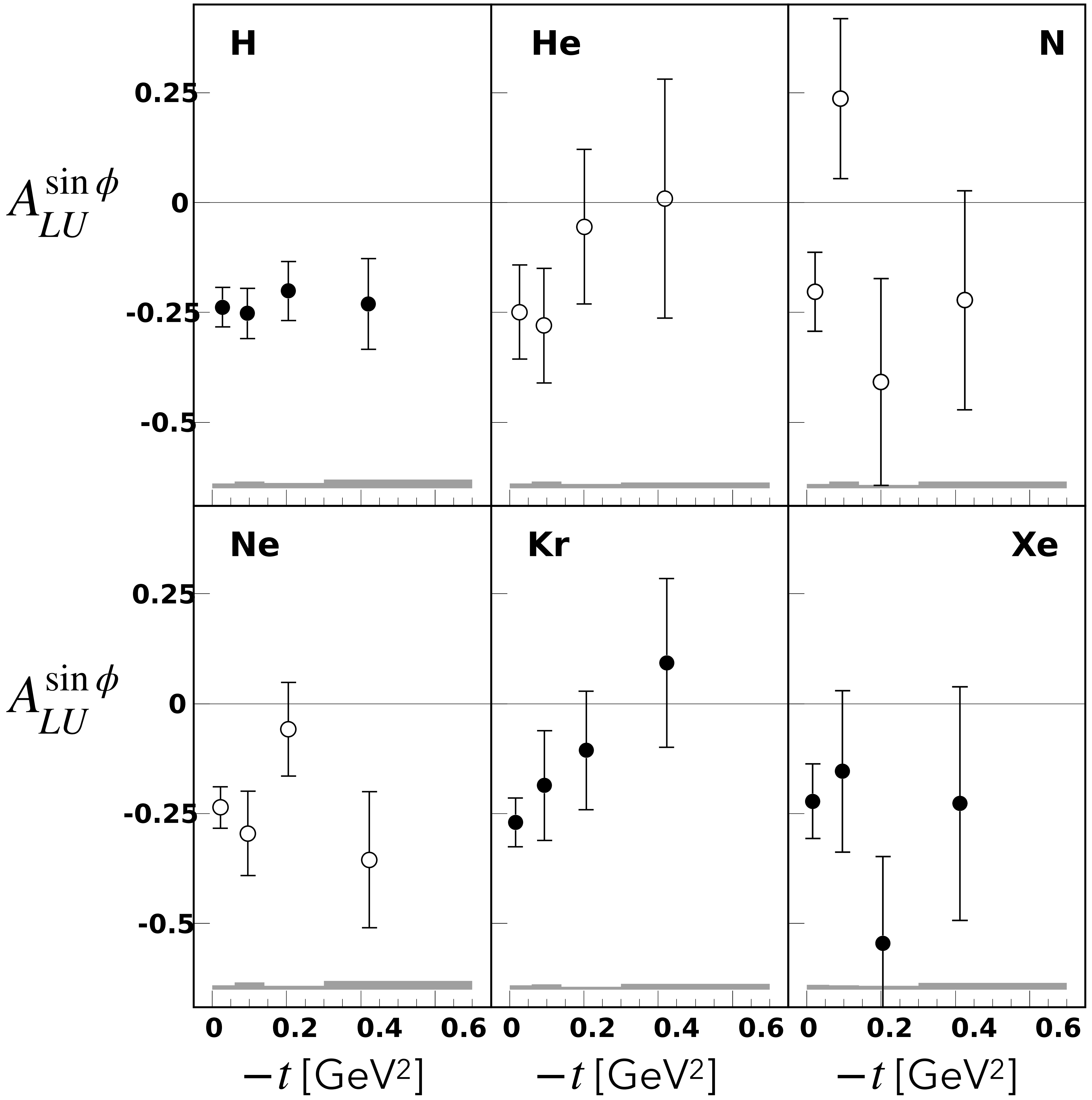
These processes must be distinguished — sensitive to different physics

HERMES: First measurement of nuclear DVCS

- Lepton (positron) beam-spin asymmetry A_{LU} projects out Im$\mathscr{H}$:

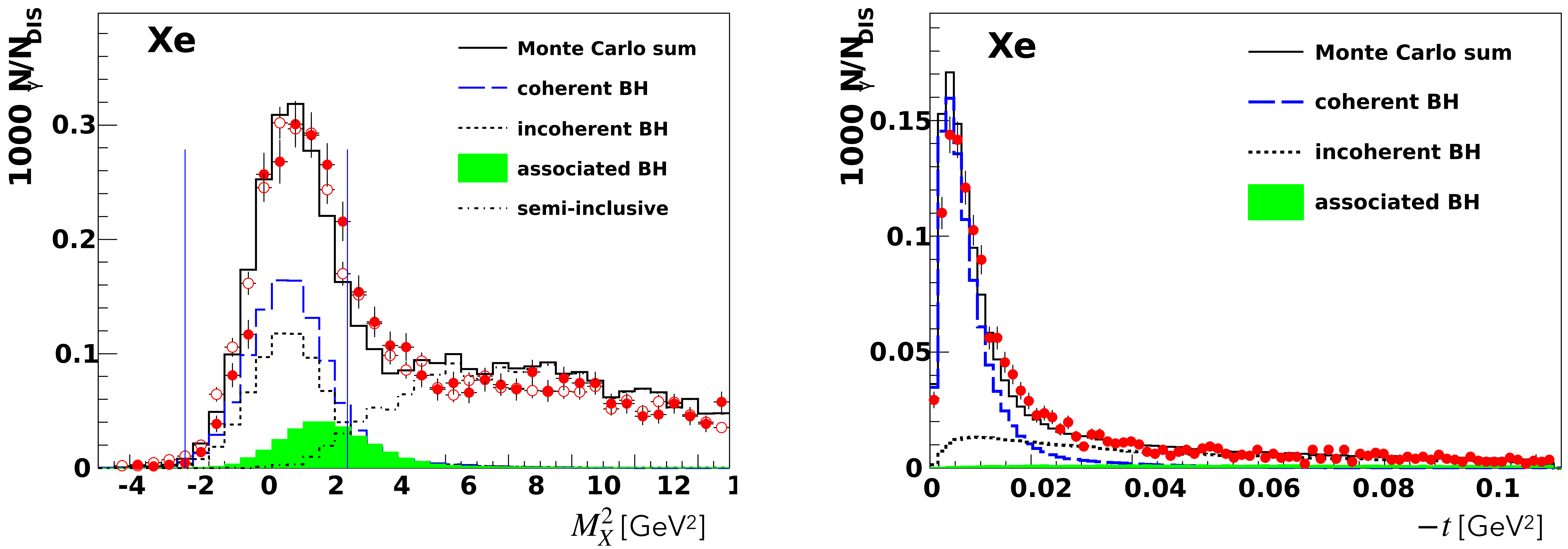
$$A_{LU}(\phi) = \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}} \propto \text{Im}\mathscr{H} \sin\phi + \cdots$$

- Fit $A_{LU}(\phi) \simeq A_{LU}^{\sin\phi} \sin\phi + A_{LU}^{\sin 2\phi} \sin 2\phi$
- HERMES measured nuclei from He to Xe; did not observe significant nuclear dependence



Airapetian et al. PRC (2010)

HERMES: First measurement of nuclear DVCS

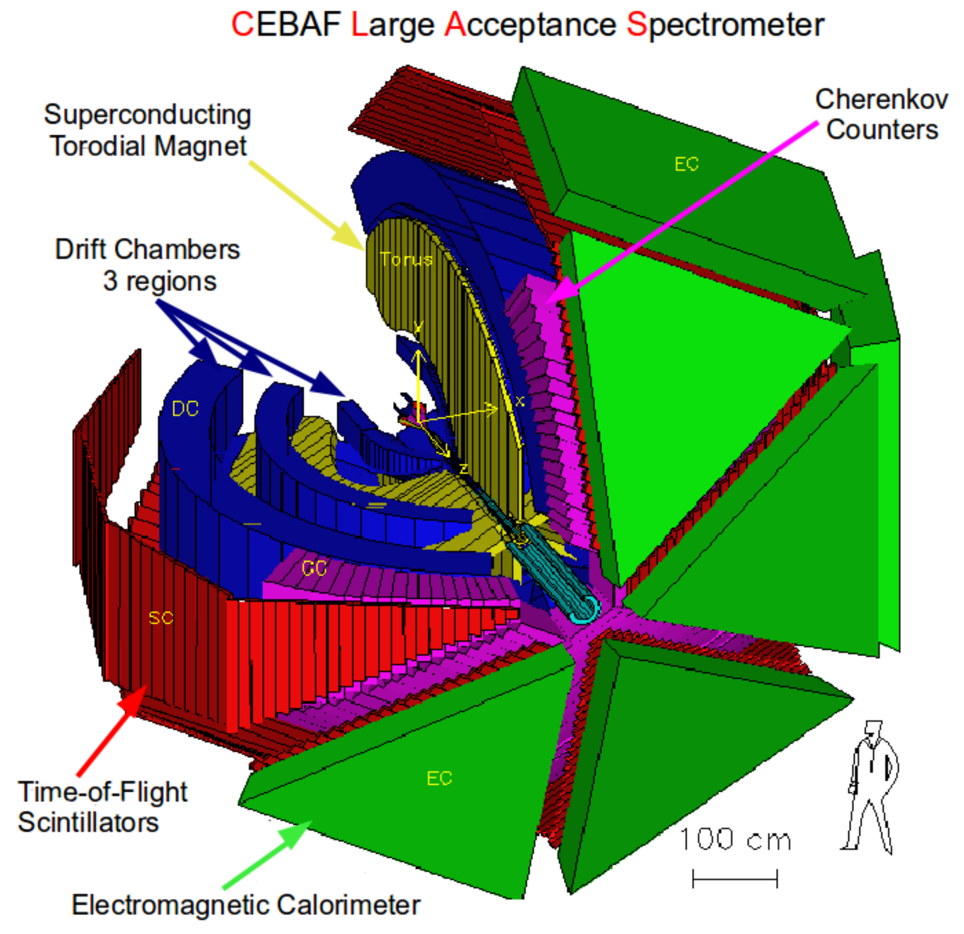


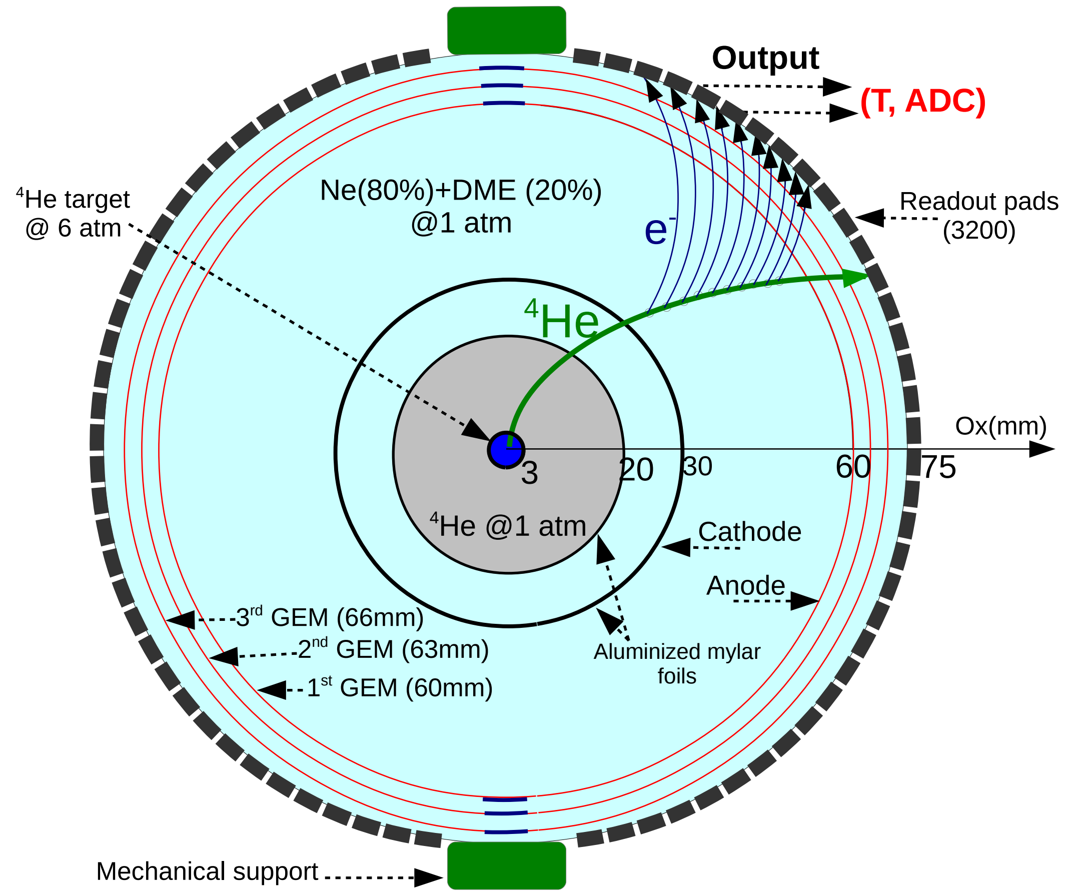
Lack of exclusive measurement → significant background from incoherent DVCS and other processes, especially at large $-t$

Airapetian et al. PRC (2010)

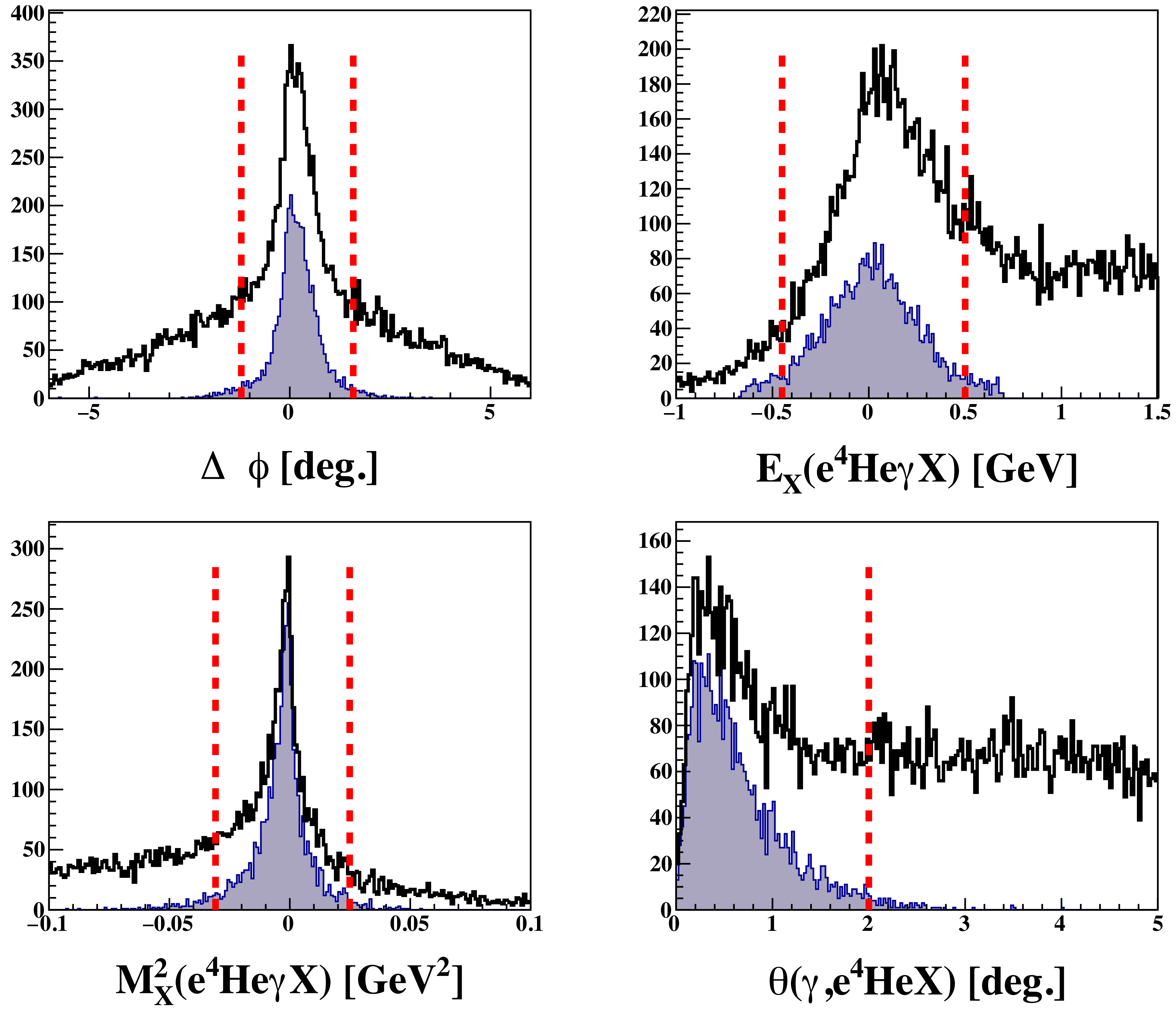
Exclusive nDVCS at CLAS

Dupré et al. NIMA (2018)



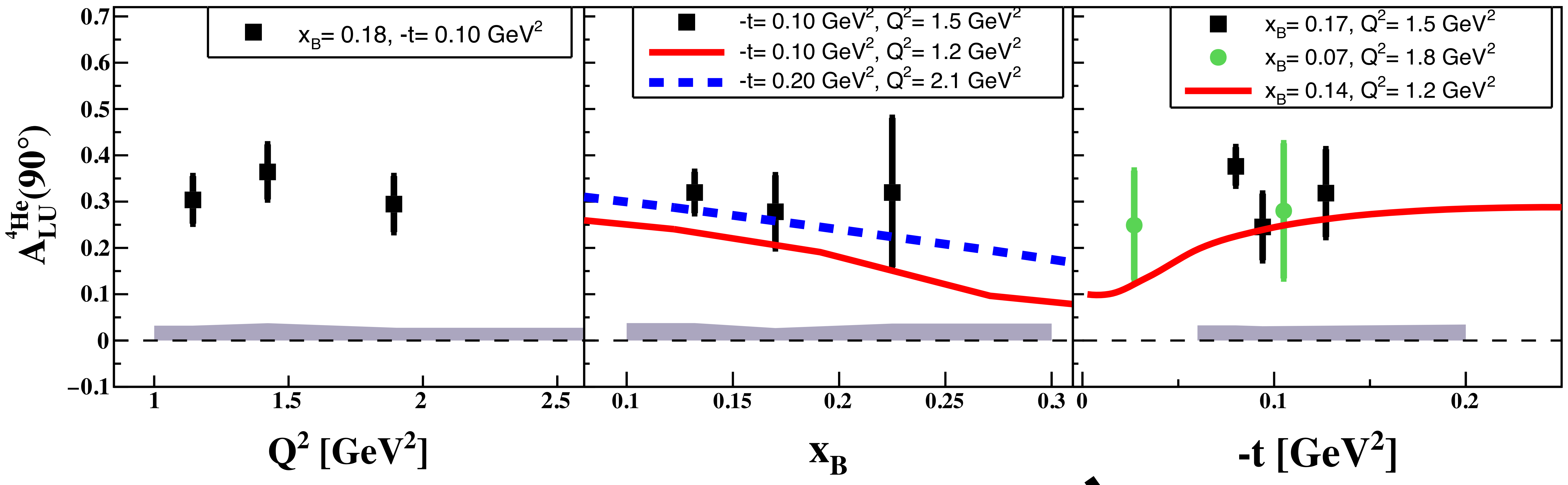


- CLAS RTPC detector used for low-energy recoil nuclear tagging
- Allowed full event exclusivity – coherent/incoherent separation



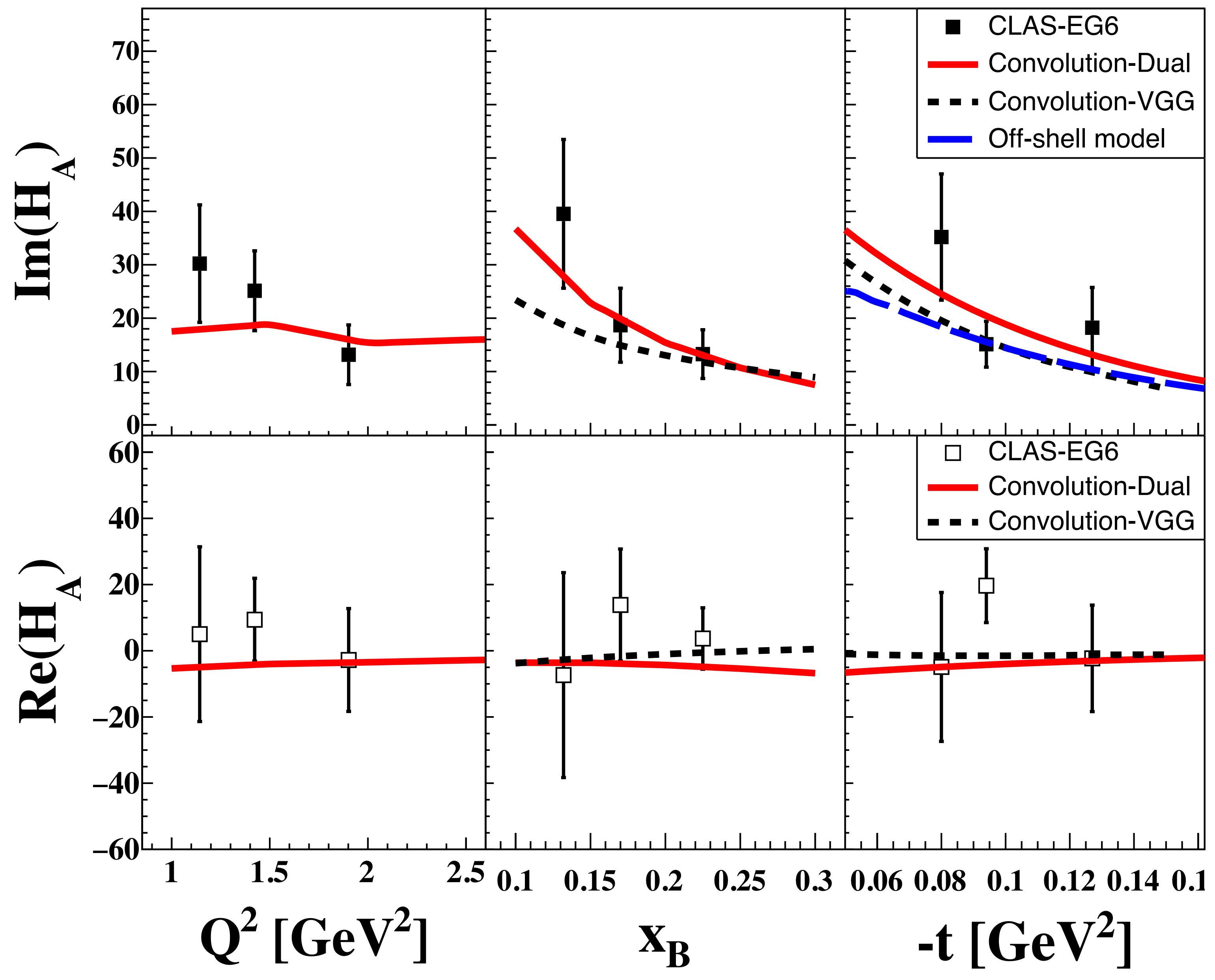
Hattawy et al. PRL (2017)

Exclusive nDVCS at CLAS



Full ϕ-dependence sensitive to both components of $\mathscr{H}$ →

First extraction of nuclear CFF

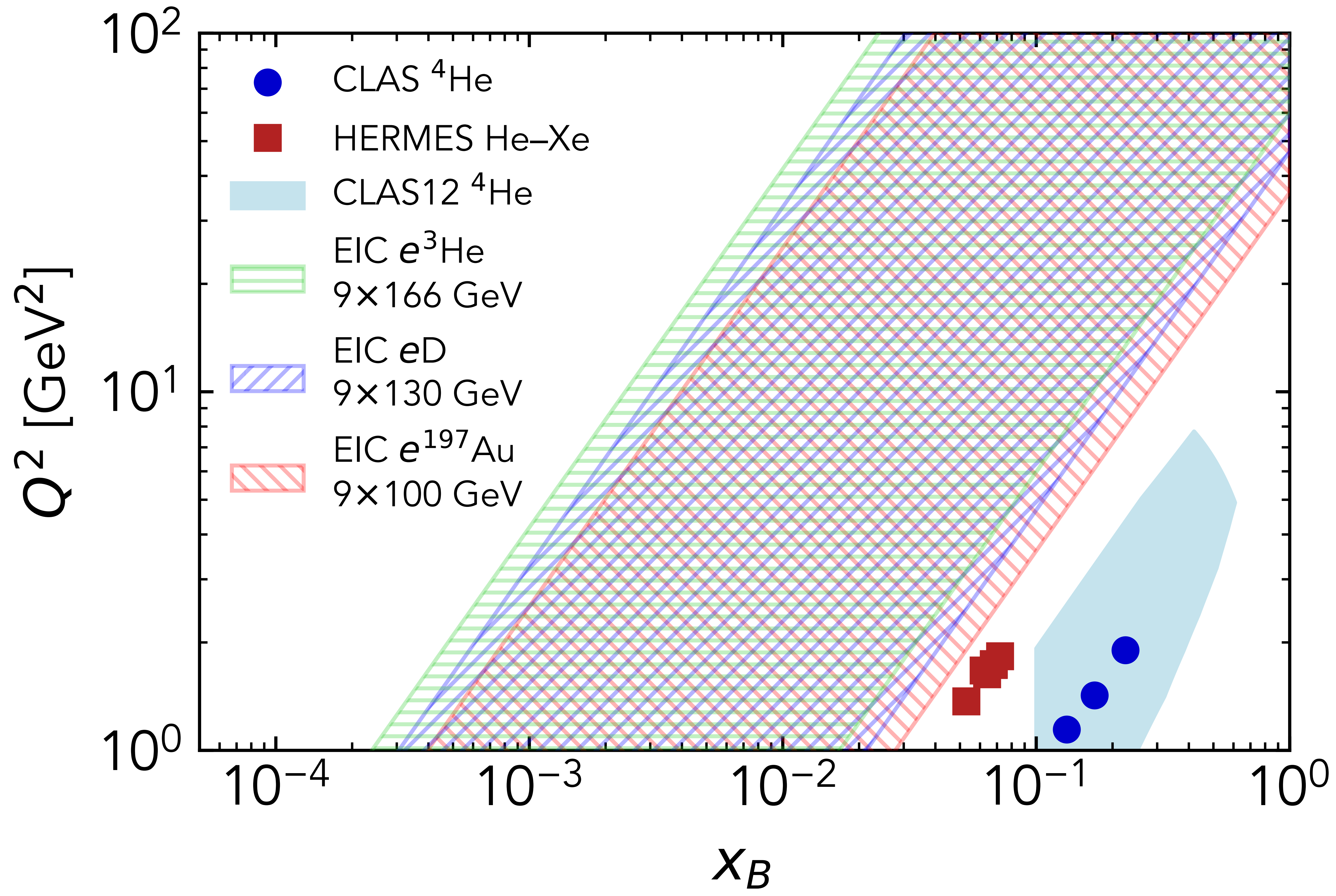


$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\mathrm{Im}\mathscr{H}}{\alpha_1(\phi) + \alpha_2(\phi)\mathrm{Re}\mathscr{H} + \alpha_3(\phi)\left(\left(\mathrm{Re}\mathscr{H}\right)^2 + \left(\mathrm{Im}\mathscr{H}\right)^2\right)}$$

Hattawy et al. PRL (2017)

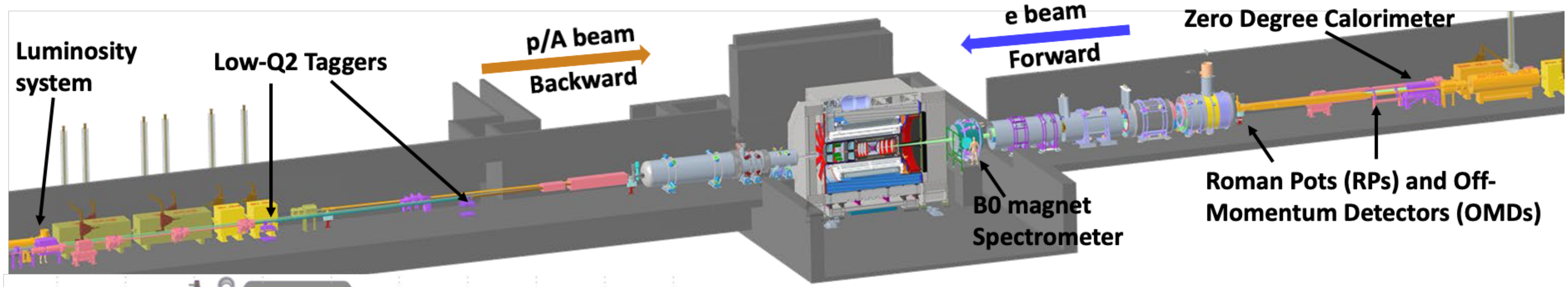
EIC will expand study of nuclei to low-x_B region

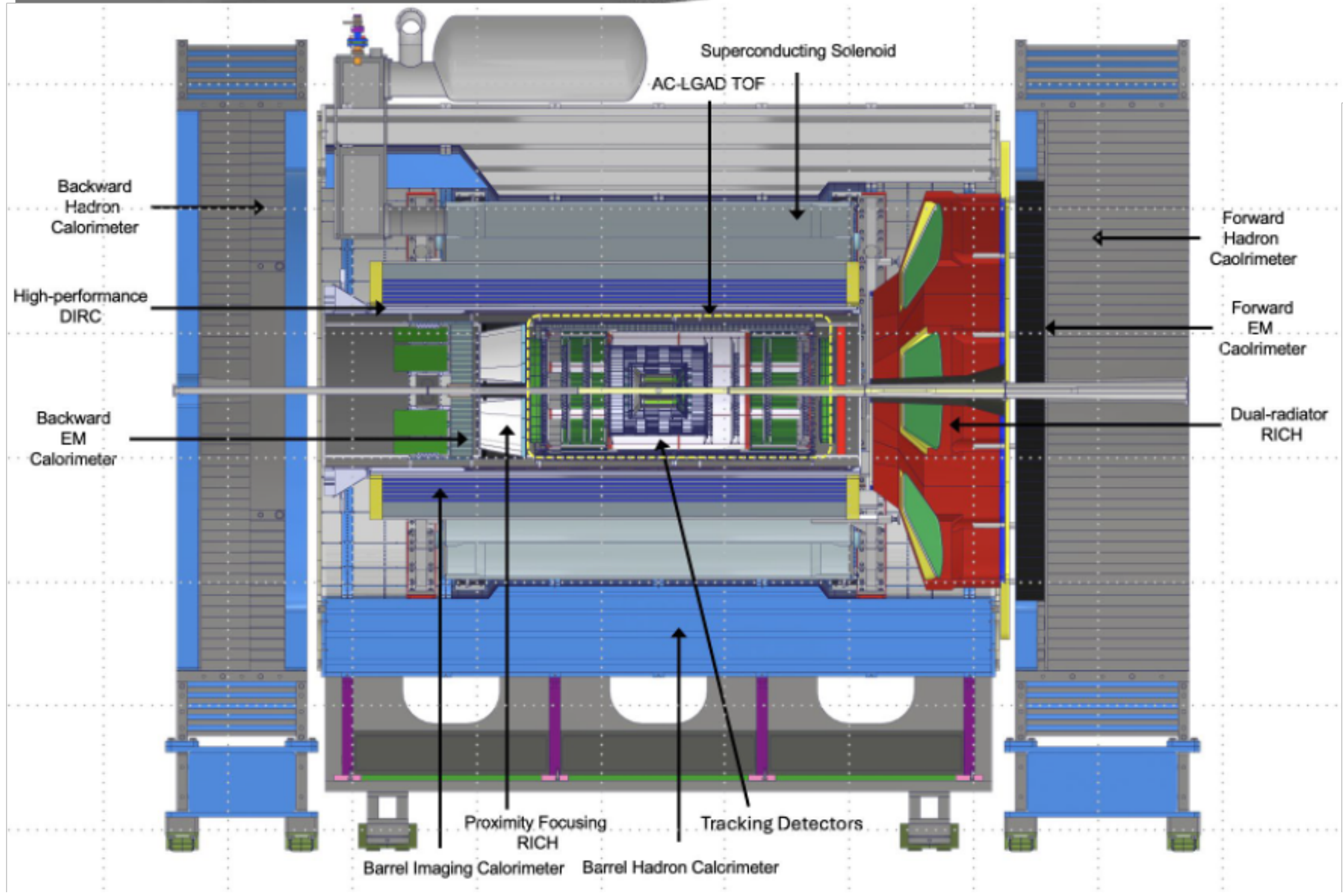
- EIC will access nuclear structure down to $x_B < 10^{-3}$
- Many ion species planned for running
- **Key EIC feature – ion beam polarization**
  - Allows for measurement of proton and ion spin structure



Pybus et al. arXiv:2606.11491

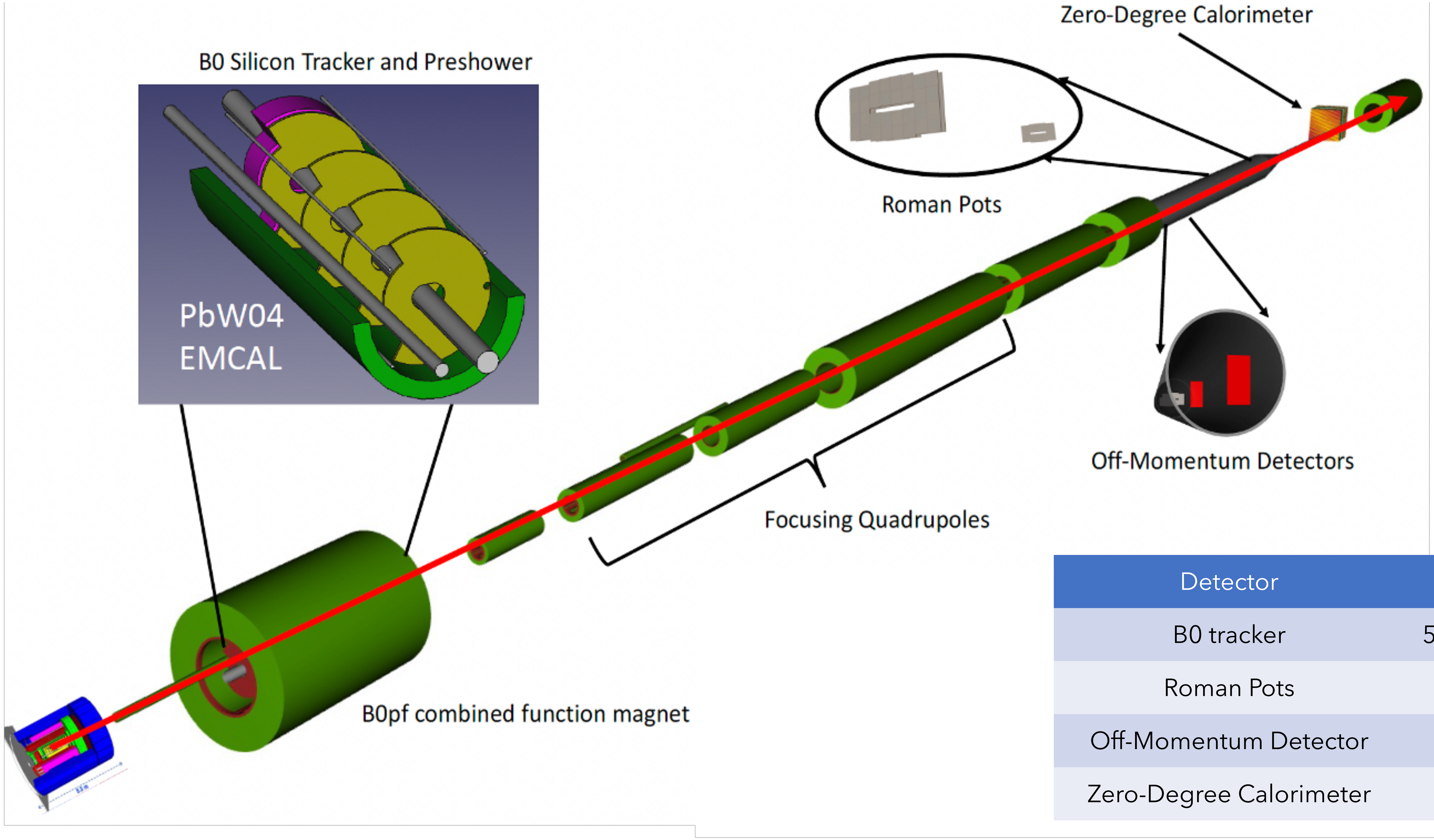
The ePIC Detector





- 26 subsystems over ±40m along the beamline.
- Central detector (9.5m X 6.7m) includes vertexing, tracking, PID, EMCal and HCAL subsystems around a 1.7 T magnet → high precision hadron and jet measurements within $-3.5 < \eta < 3.5$.
- Far-forward subsystem for nuclear breakup and exclusive processes
- Far-backward subsystem for luminosity and low-Q^2

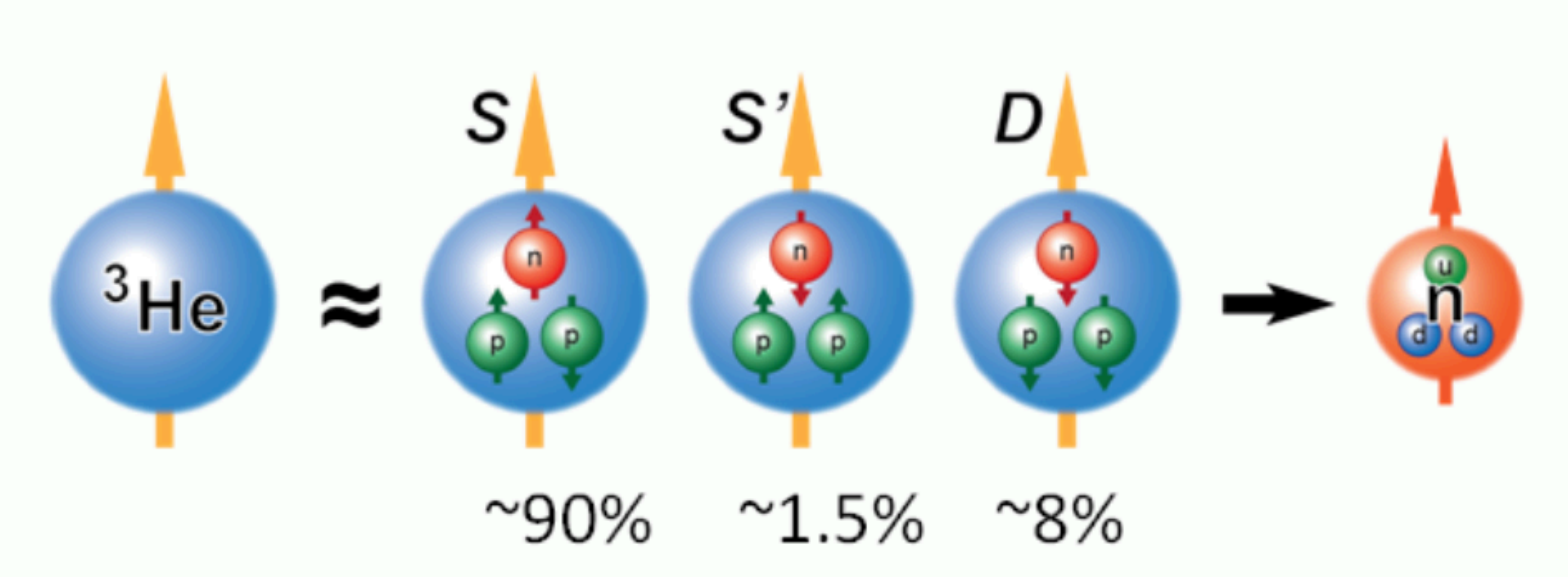
The ePIC Far-Forward Detectors



Detector	Coverage
B0 tracker	5.5<θ<20 mrad (4.6<η<5.9)
Roman Pots	0<θ<5 mrad (η>6)
Off-Momentum Detector	0<θ<5 mrad (η>6)
Zero-Degree Calorimeter	θ<5.5 mrad (η>6)

Helium-3: Key polarized ion at the EIC

- Helium-3 is arguably the simplest polarized nucleus
- Neutron carries ~87% of nuclear spin – highly sensitive to neutron spin structure
- Ion polarization gives access to other nuclear CFFs:
  - $A_{UL} \rightarrow \mathrm{Im}\tilde{\mathcal{H}}$
  - $A_{LL} \rightarrow \mathrm{Re}\tilde{\mathcal{H}}$
  - $A_{UT} \rightarrow \mathrm{Im}\mathcal{E}$
  - $A_{LT} \rightarrow \mathrm{Im}\tilde{\mathcal{E}}$



Focus on lepton and ion single-spin asymmetries as benchmarks

DVCS constrains proton/ion spin structure via GPDs:

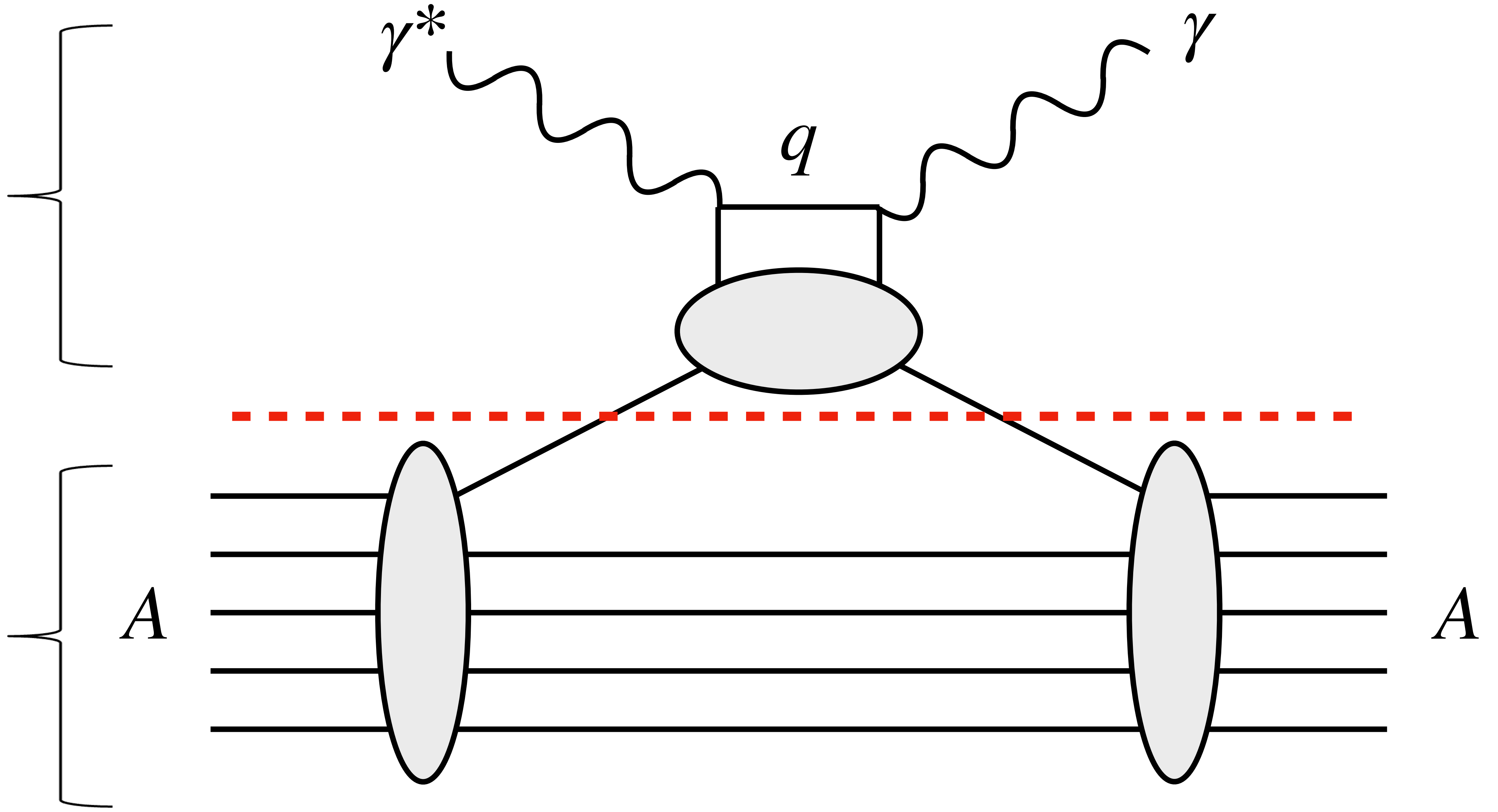
$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right]$$

$$\Delta\Sigma_q = \int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t=0)$$

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



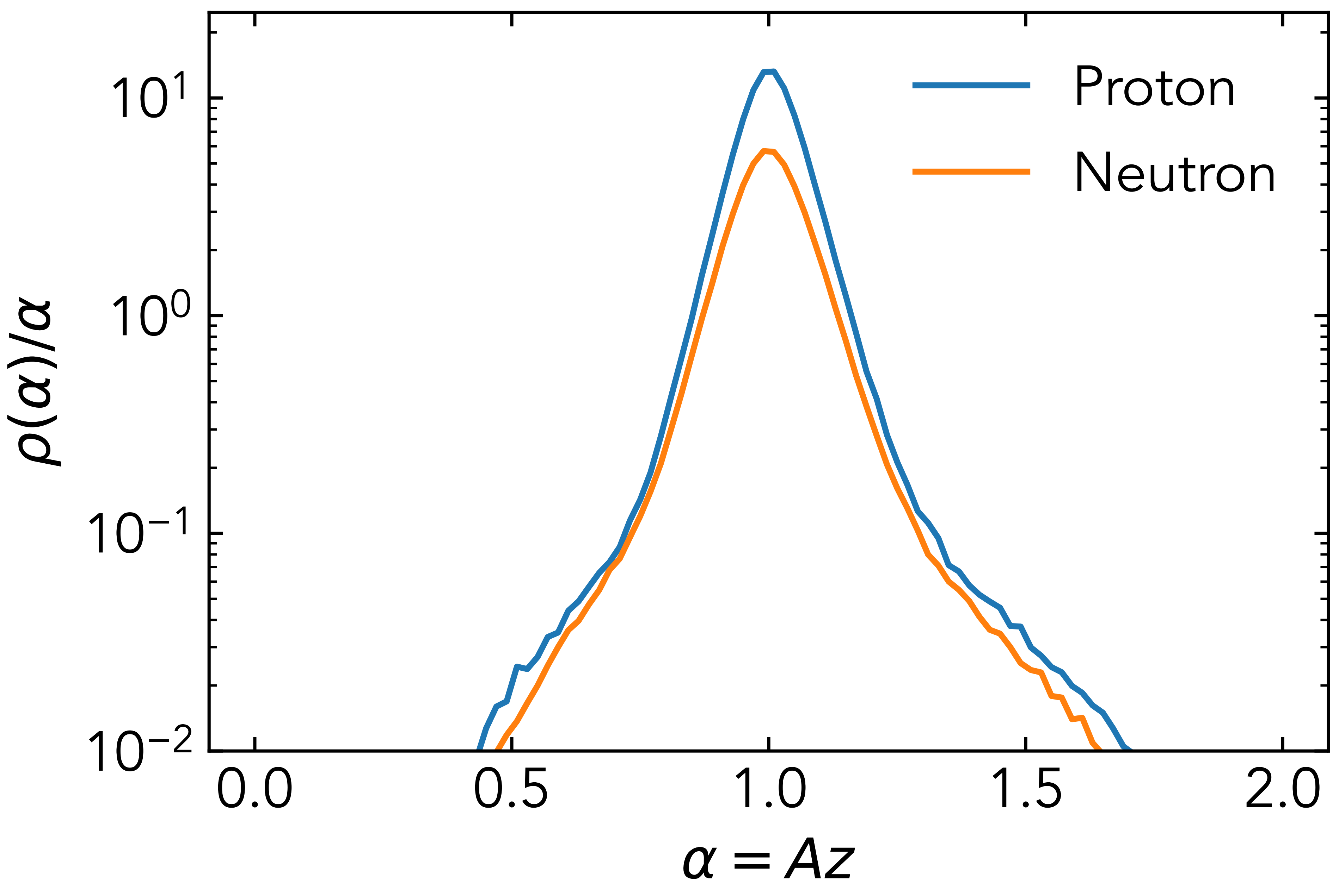
$$\mathcal{H}^A(\xi_A, t) \approx \sum_{N=p,n} \int_{\xi_A}^{1} \frac{dz}{z} h_N^A(z, \xi_A, t) \mathcal{H}^N\left(\frac{\xi_A}{z}, t\right)$$

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

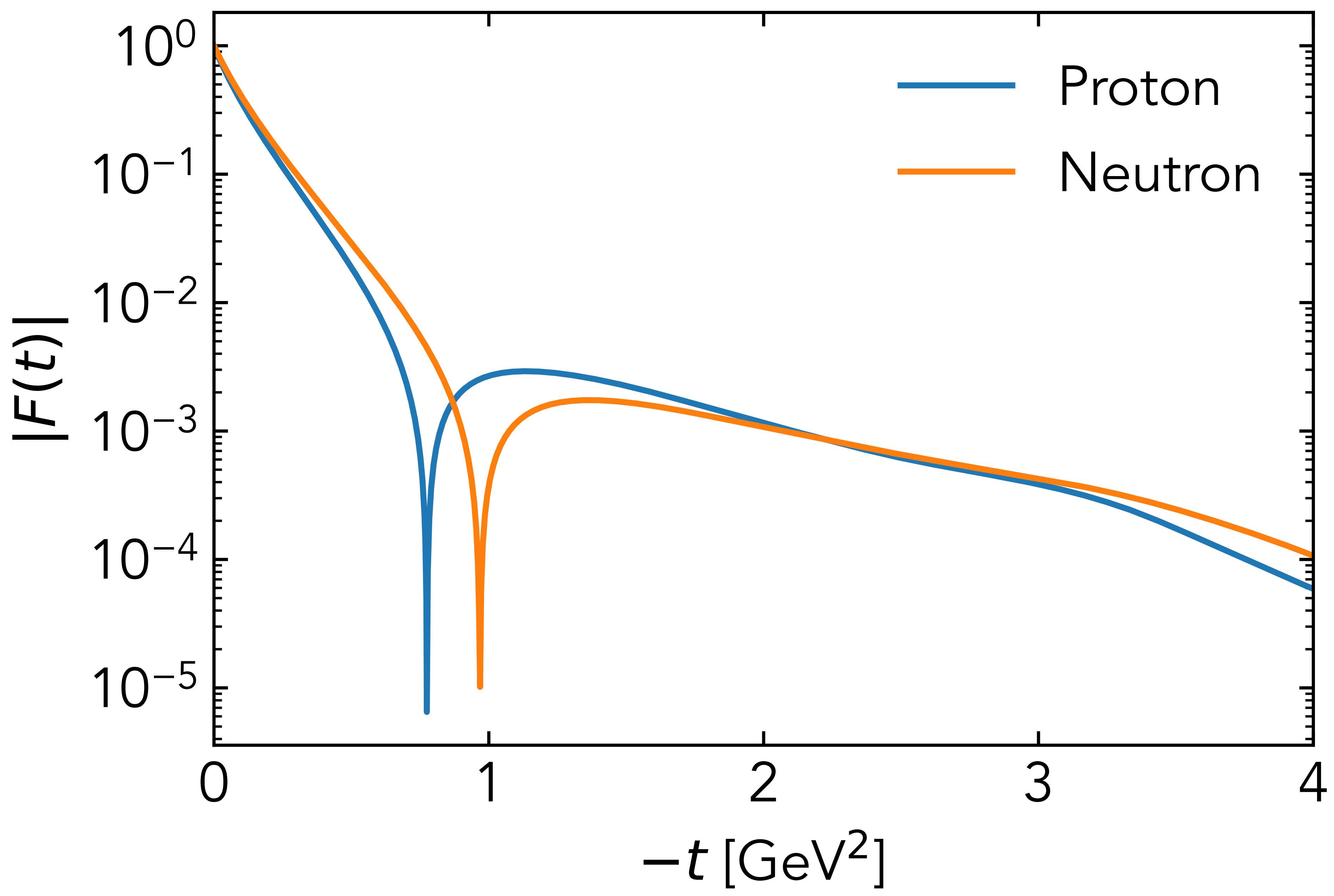
Scopetta et al PRC (2004), PRC (2009);
Guzey et al. PRC (2003), PRC (2008);
Liuti et al. PRC (2005);
Fucini et al. PRC (2018), FBS (2021)…

For small ξ, we factorize nuclear structure into longitudinal momentum and transverse position:

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



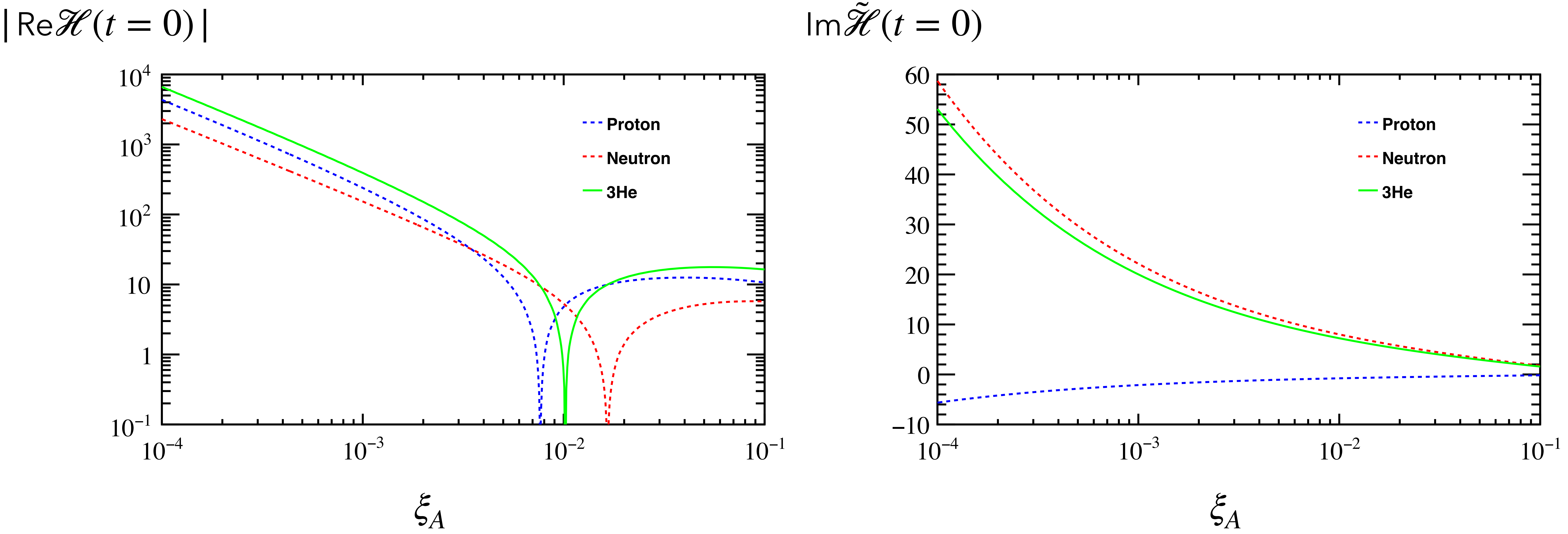
VMC spectral function from Ciofi et al. PRL (2005)



VMC position distribution from Wiringa et al. PRC (2014)

Pybus et al. arXiv:2606.11491

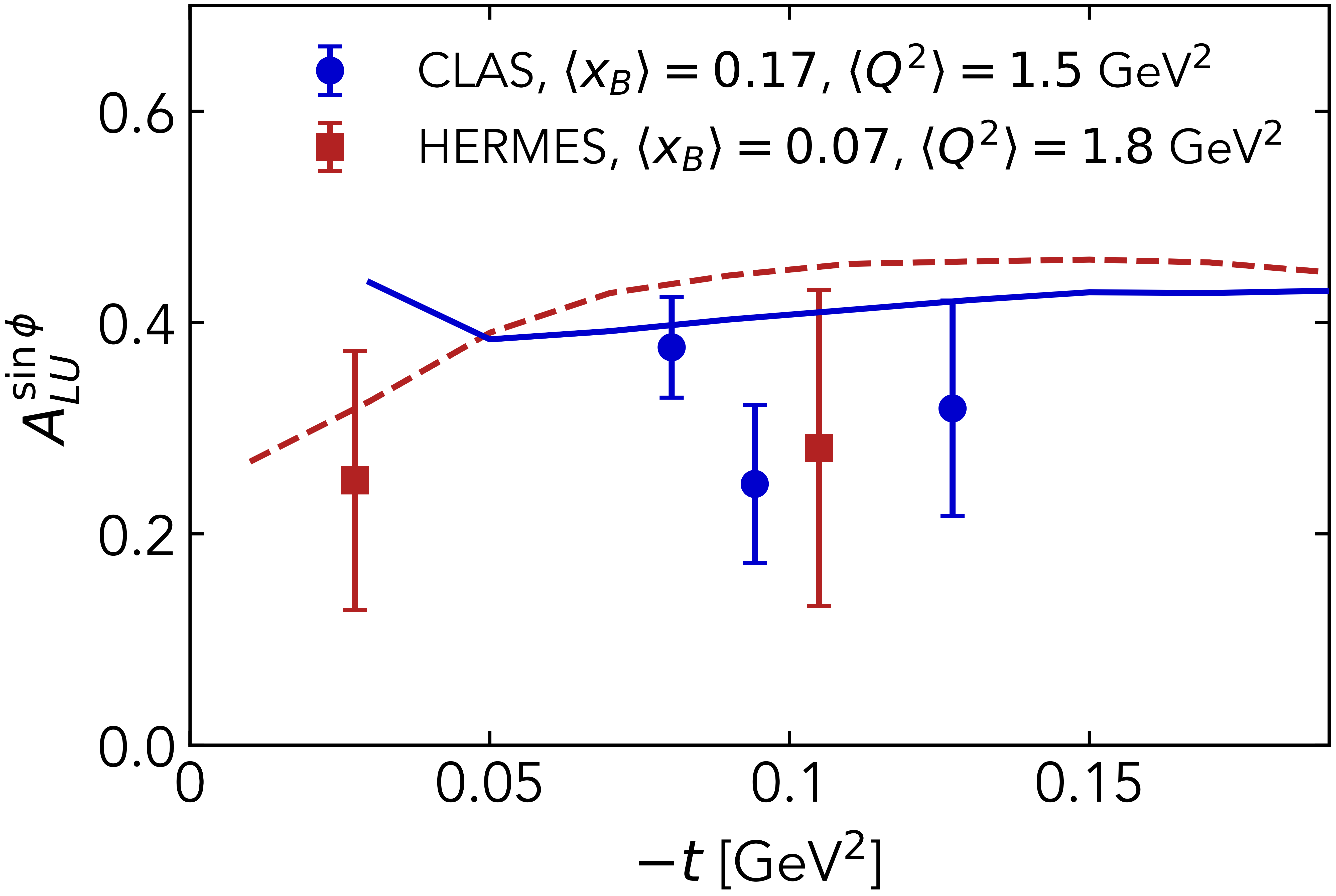
Nuclear Compton Form Factors



- Proton GPDs taken from Kumerički-Müller interpretation of JLab + HERA results, NPB (2010)
- Unpolarized CFF $\mathcal{H}$ has significant contributions from both nucleons
- Polarized CFF $\tilde{\mathcal{H}}$ dominated by neutron contribution – also grows much more slowly with decreasing ξ

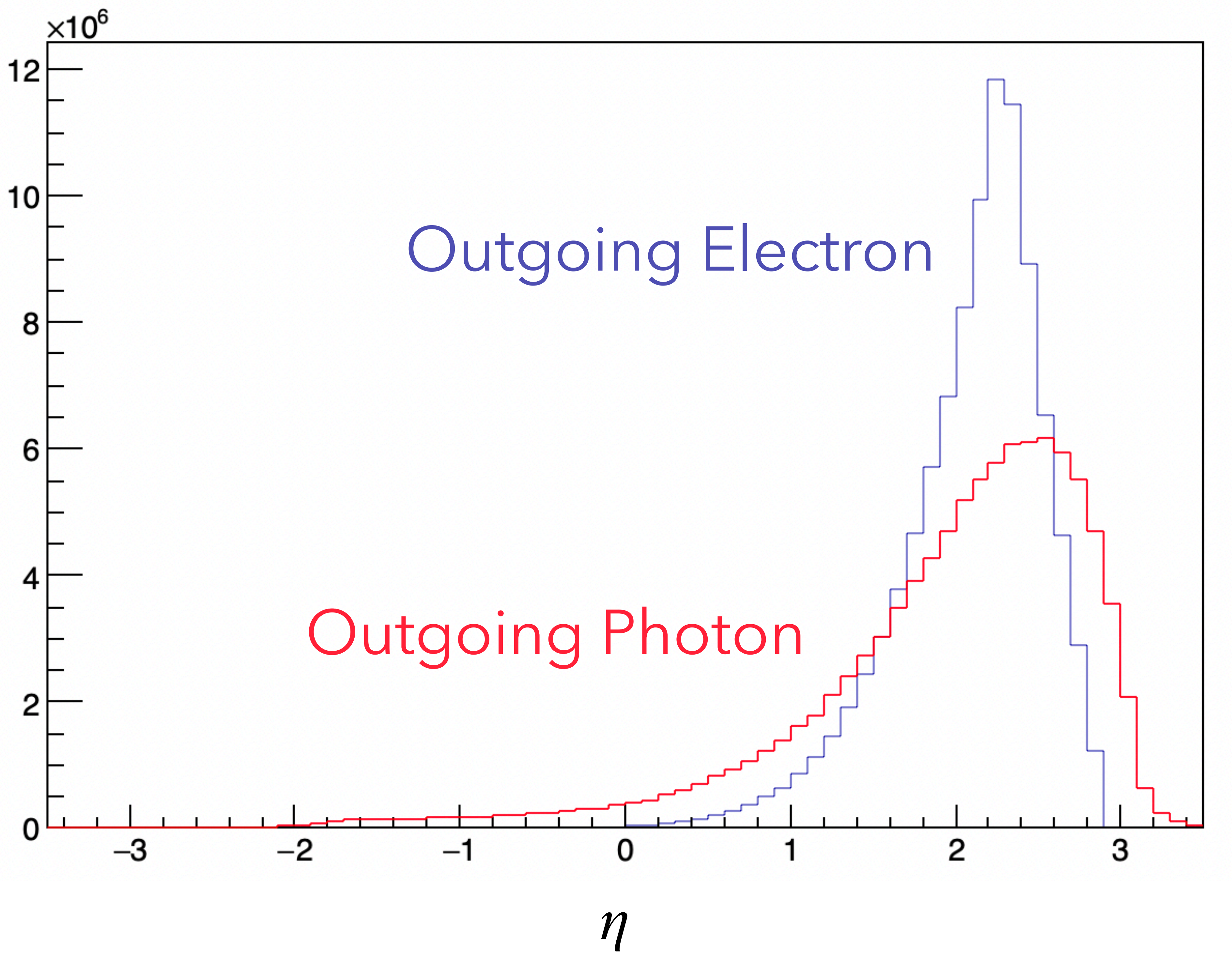
Pybus et al. arXiv:2606.11491

PWIA model describes fixed-target data; Move next to estimating EIC event rates

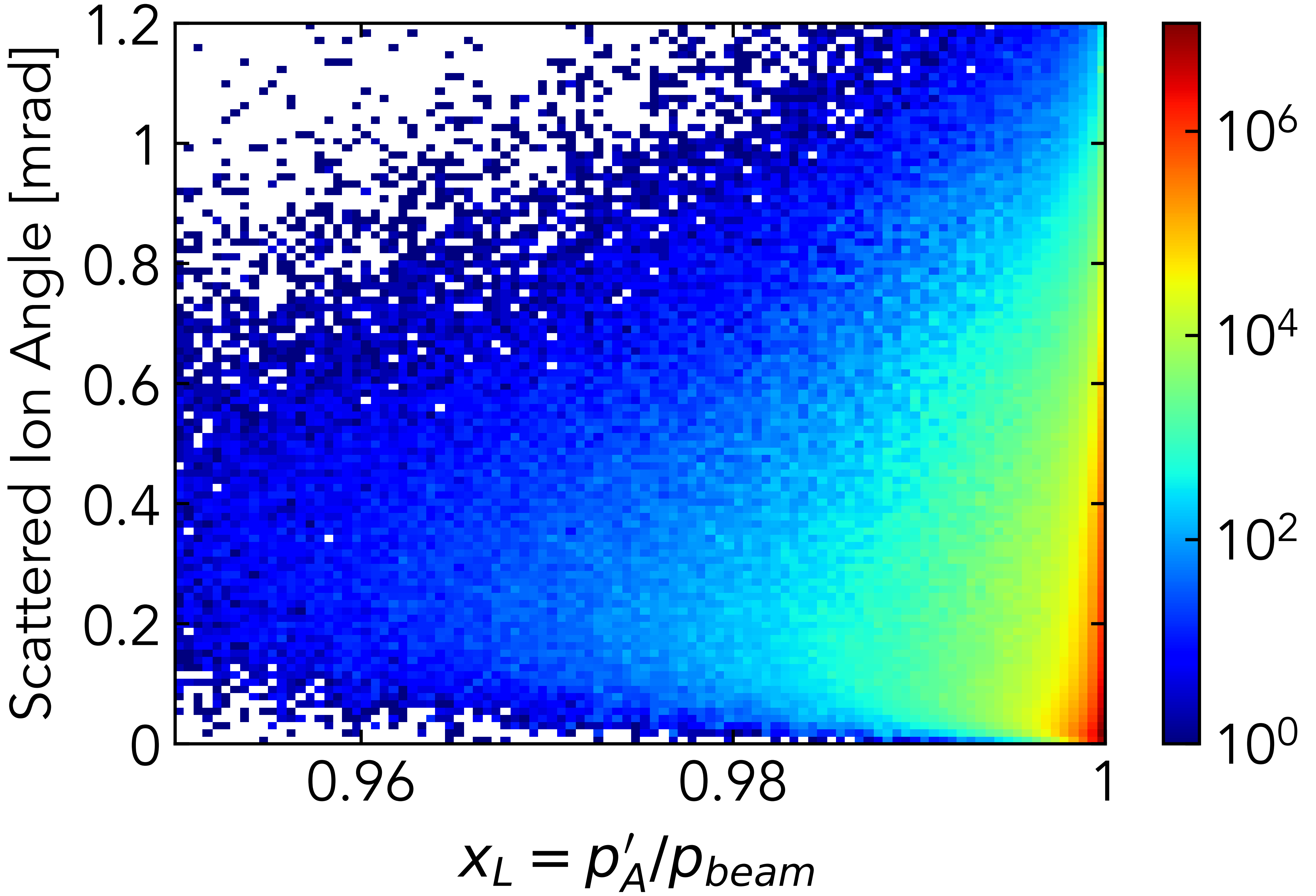


Pybus et al. arXiv:2606.11491

Coherent DVCS Kinematics at the EIC



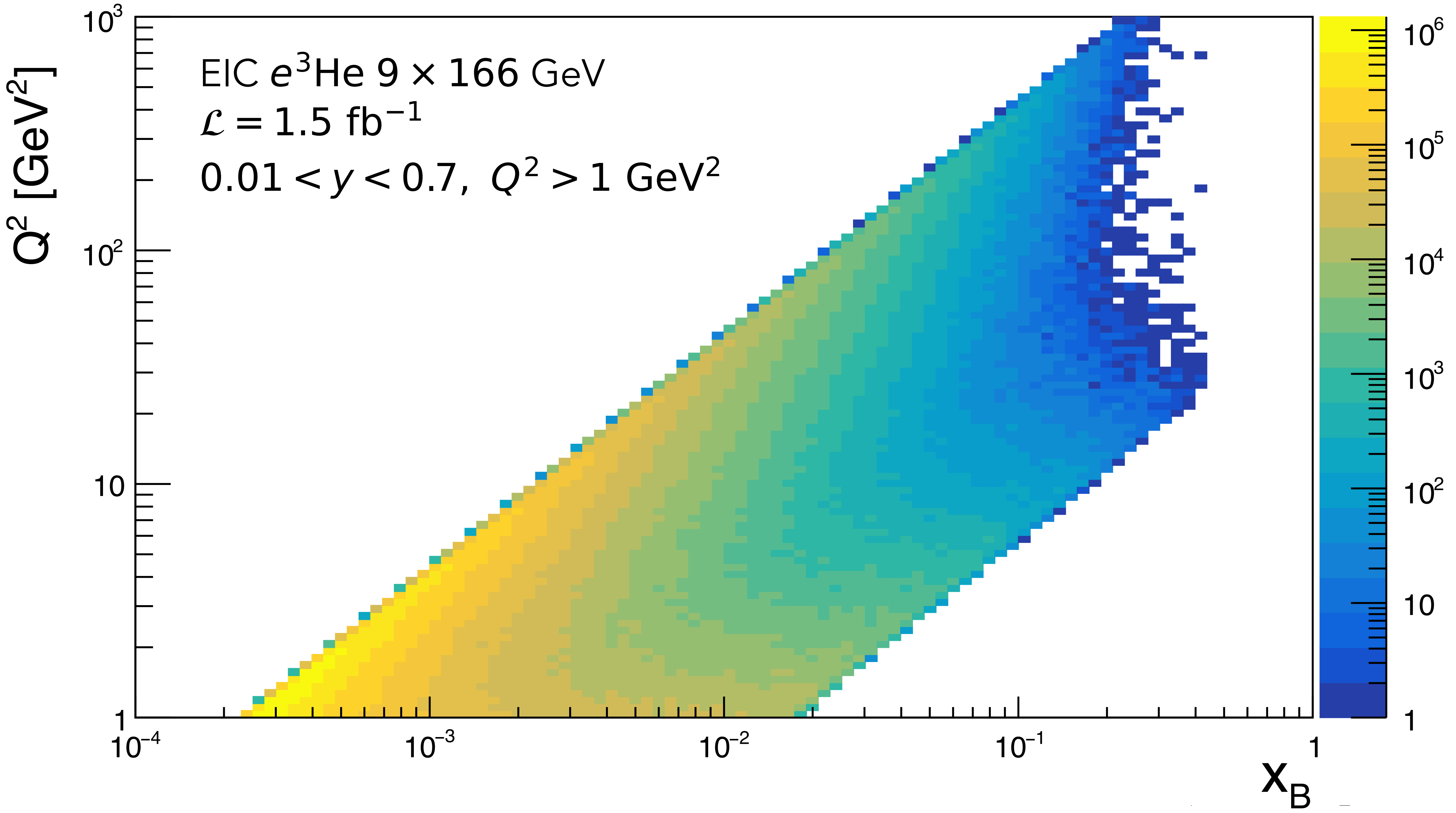
Scattered electron and leptoproduced photon fall within central detector kinematics

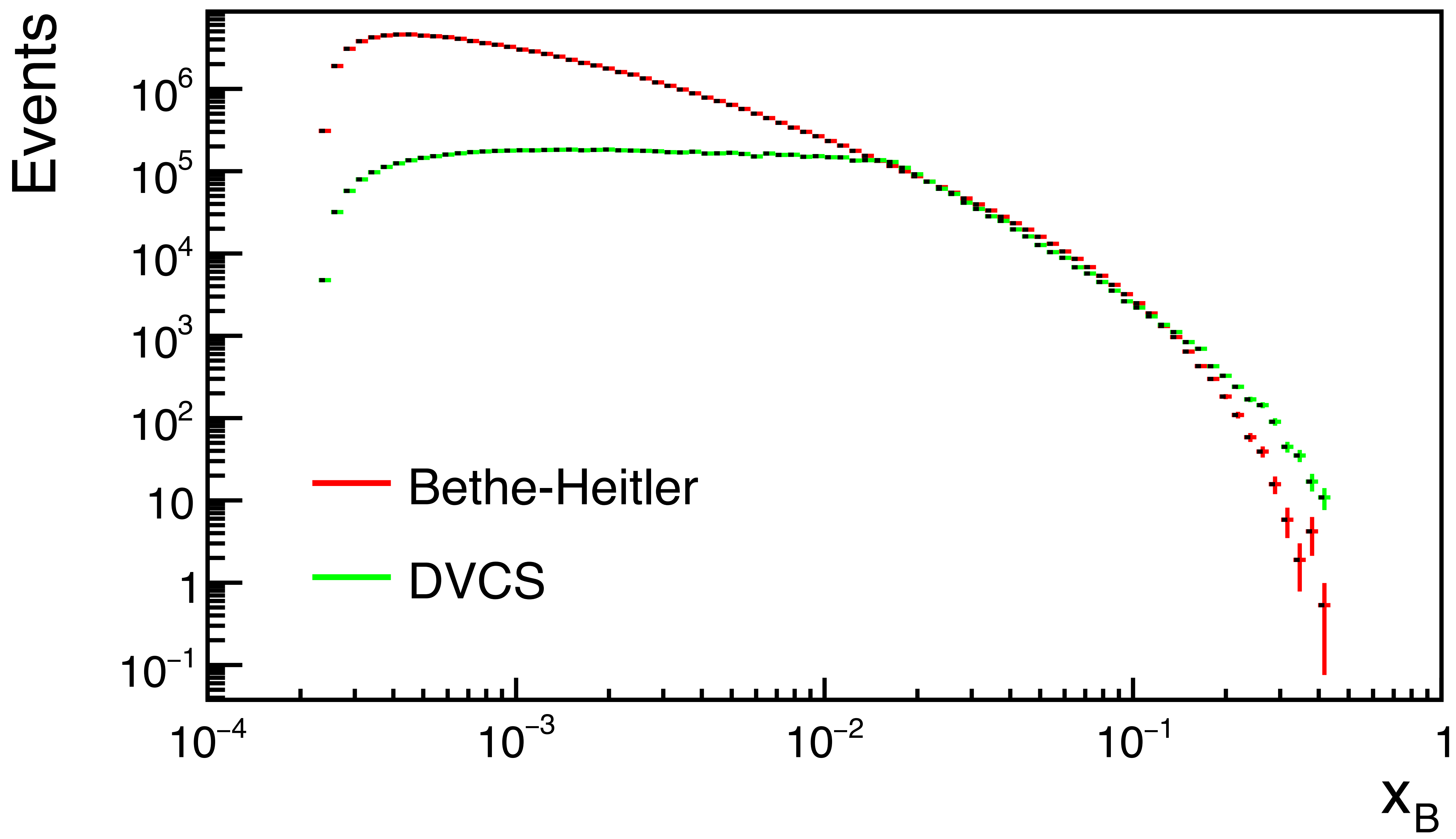


Scattered ion is largely unperturbed; provides detection challenges

Pybus et al. arXiv:2606.11491

Coherent DVCS Kinematics at the EIC





- As in fixed-target kinematics, Bethe-Heitler dominates event rate, except at large x_B and small y
- For 9×166 GeV/nucleon, coherent DVCS is dominated by small x_B and moderate Q^2

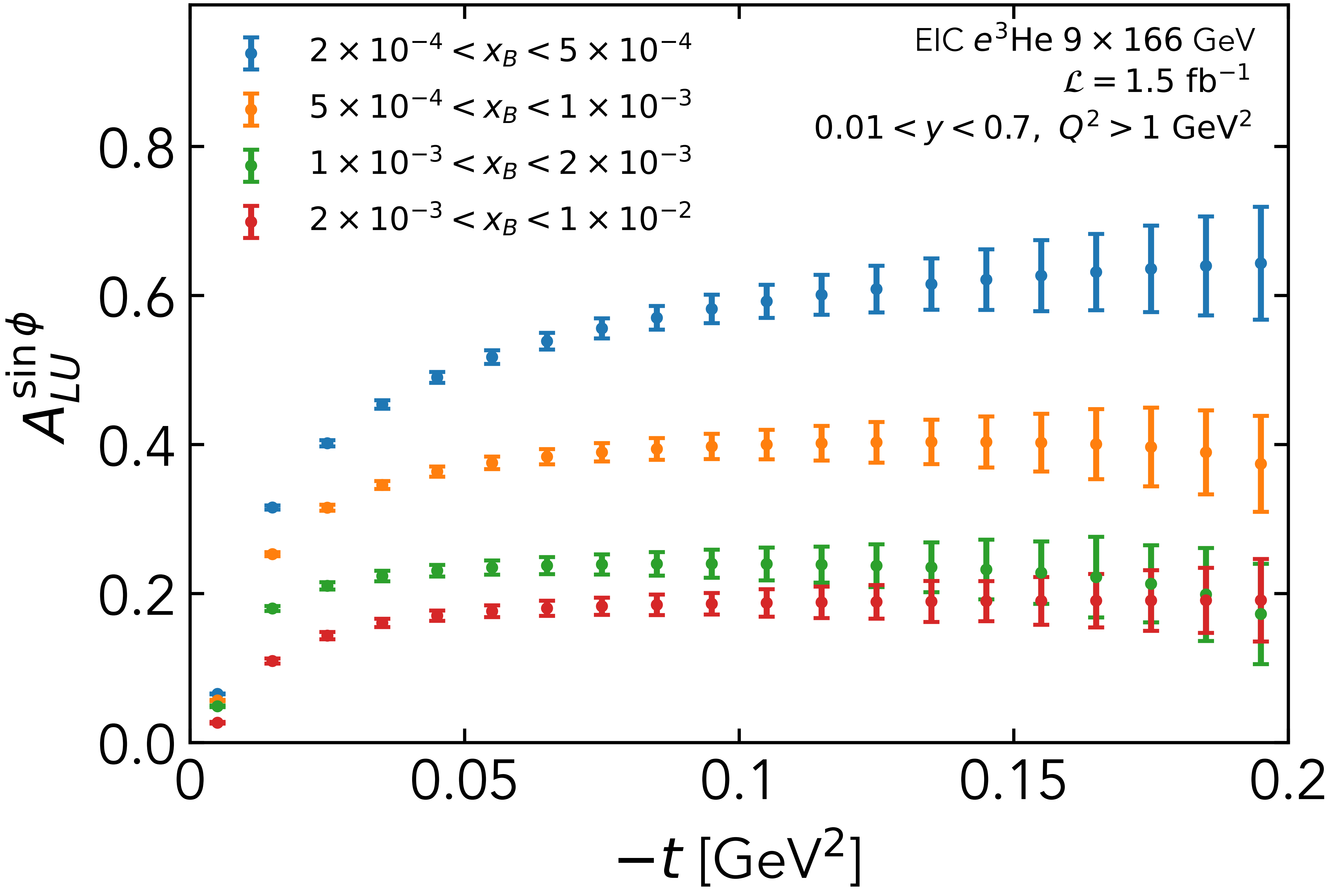
Pybus et al. arXiv:2606.11491

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

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

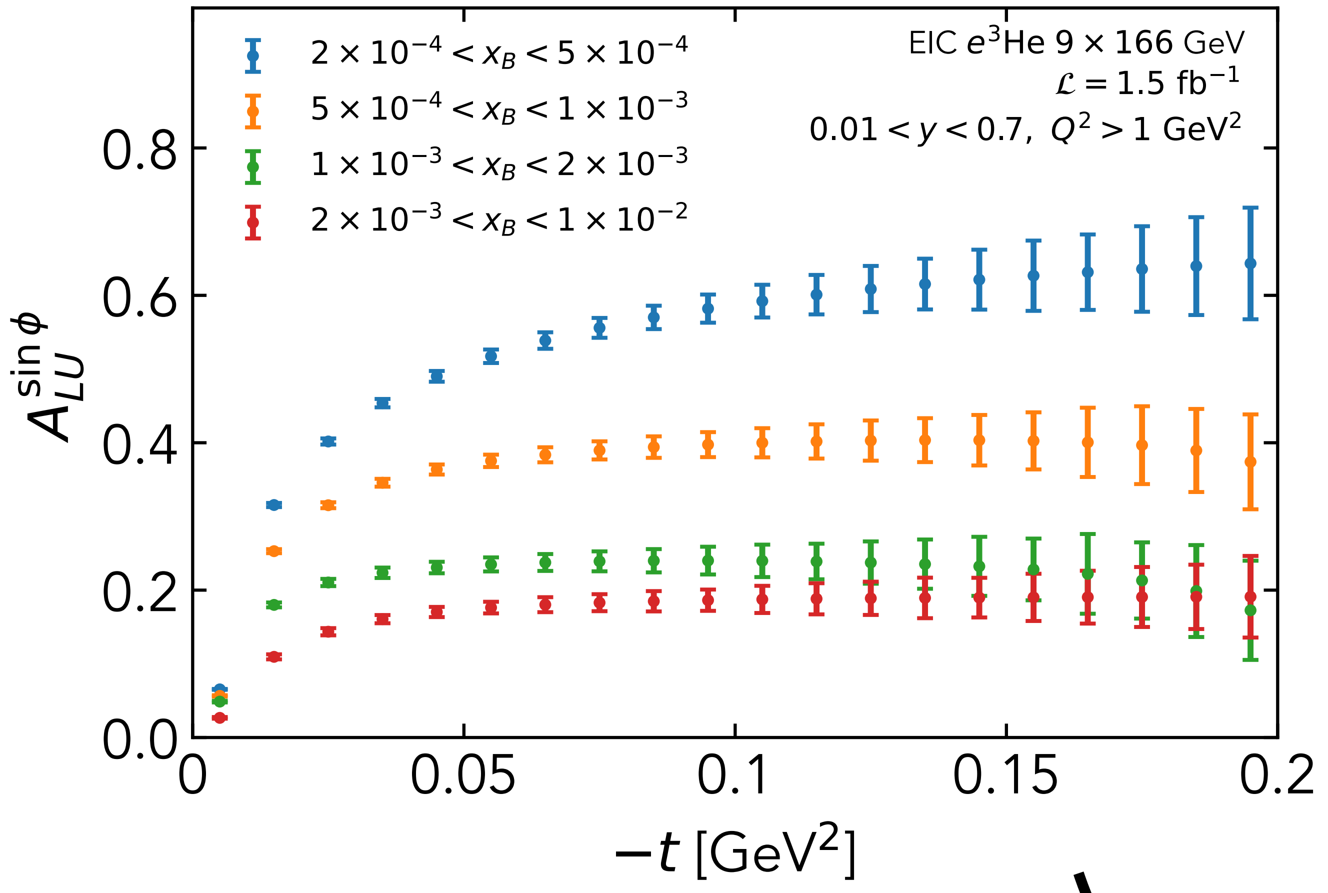
Projected event yields (binned by x_B, t, and ϕ) give statistical uncertainties for propagation into fit parameters using Fisher information:

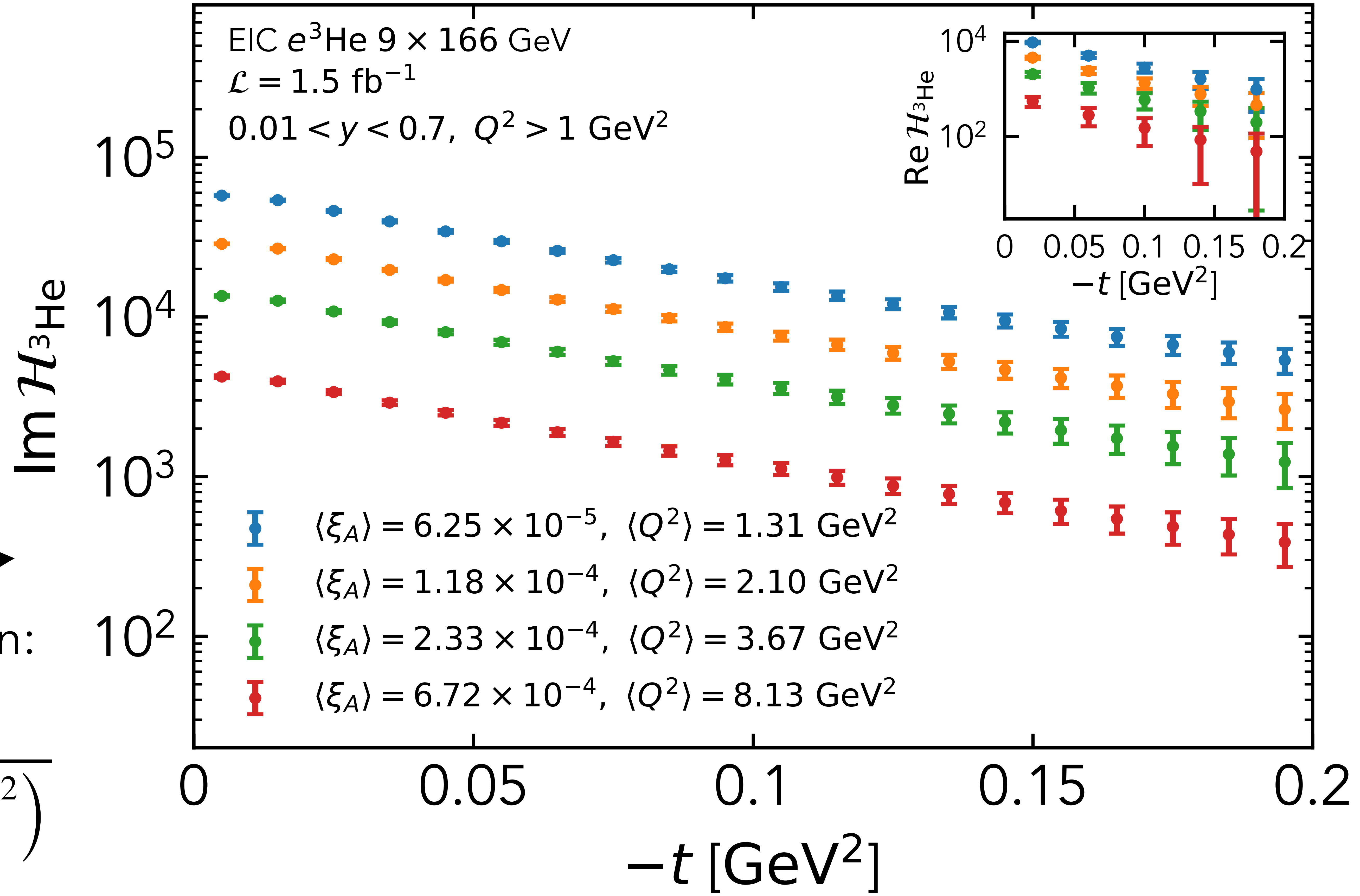
$$\delta N(x_B, t, \phi) \rightarrow \delta A_{LU}(x_B, t)$$



Pybus et al. arXiv:2606.11491

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





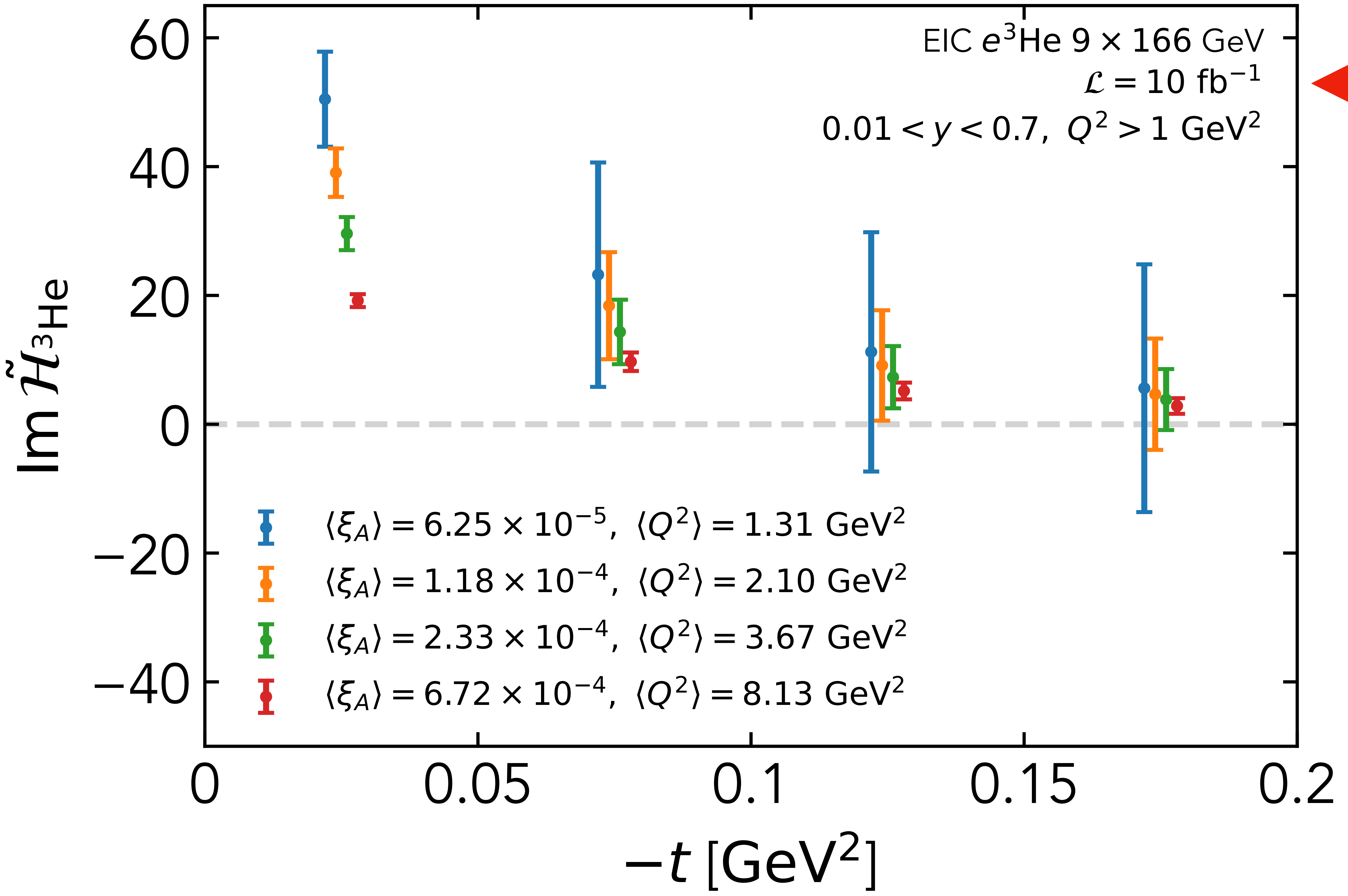
Following the approach of CLAS ^{4}He CFF extraction:

$$A_{LU}(\phi) \approx \frac{\alpha_0(\phi)\mathrm{Im}\mathscr{H}}{\alpha_1(\phi)+\alpha_2(\phi)\mathrm{Re}\mathscr{H}+\alpha_3(\phi)\left(\left(\mathrm{Re}\mathscr{H}\right)^2+\left(\mathrm{Im}\mathscr{H}\right)^2\right)}$$

Pybus et al. arXiv:2606.11491

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

$$A_{UL}(\phi) \approx \frac{\tilde{\alpha}_0(\phi)\mathrm{Im}\tilde{\mathscr{H}}}{\alpha_1(\phi) + \alpha_2(\phi)\mathrm{Re}\mathscr{H} + \alpha_3(\phi)\left(\left(\mathrm{Re}\mathscr{H}\right)^2 + \left(\mathrm{Im}\mathscr{H}\right)^2\right)}$$

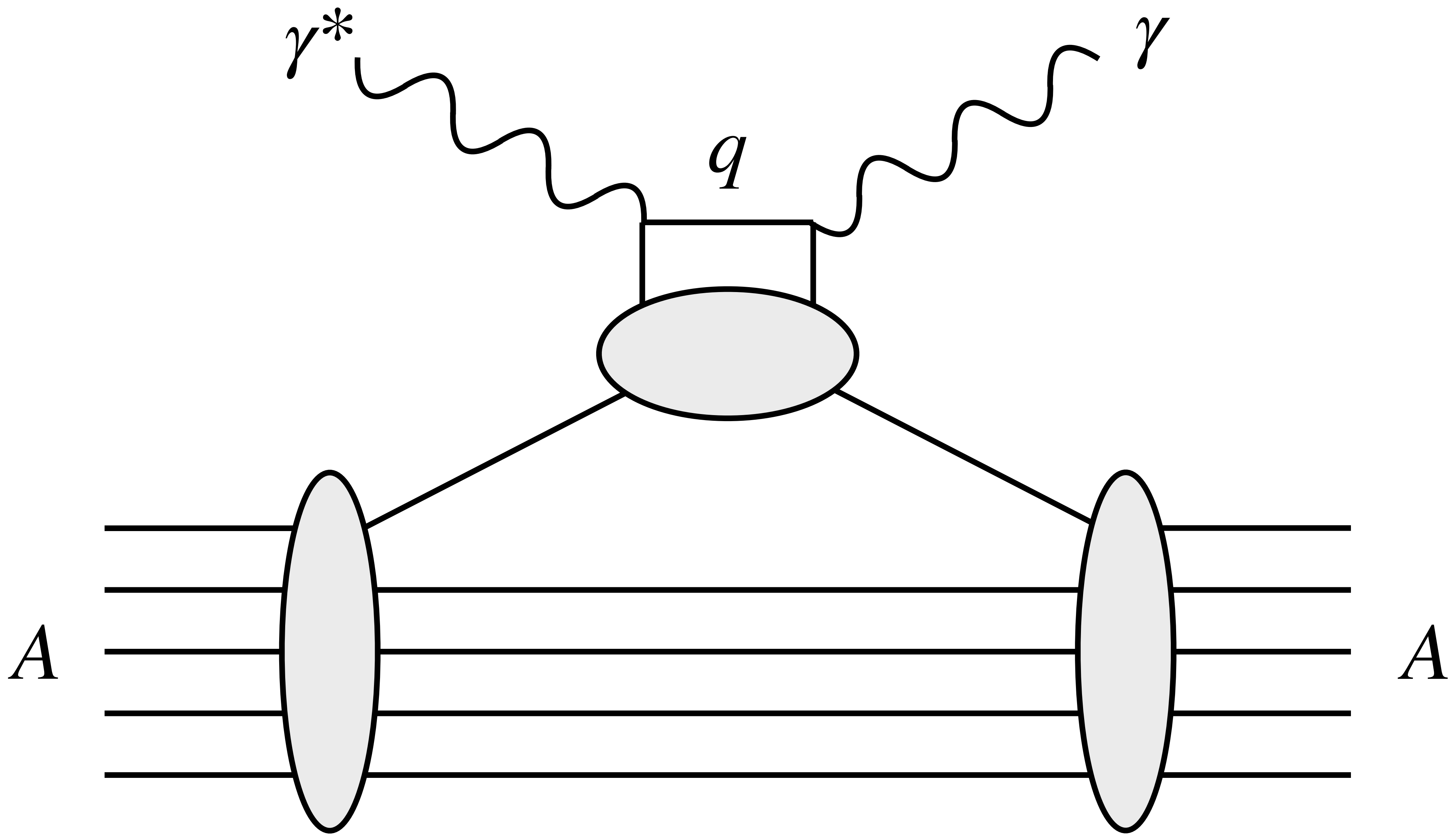


Long-term measurement

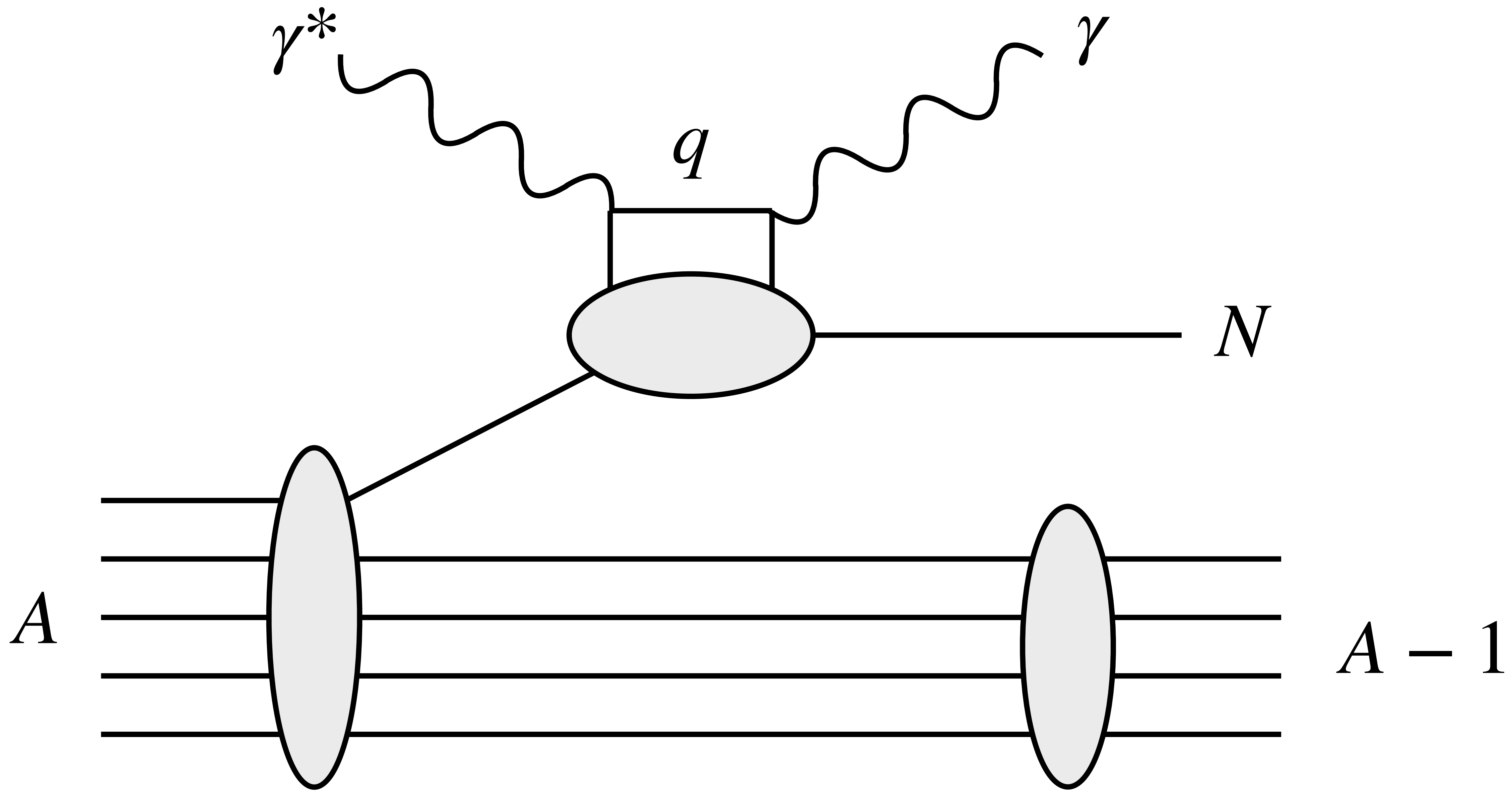
- Measurement precision on $\mathrm{Im}\tilde{\mathscr{H}}$ is good, but polarized CFF is much smaller
- Constraints on nonzero $\mathrm{Im}\tilde{\mathscr{H}}$ will require extended ^{3}He measurement

Pybus et al. arXiv:2606.11491

Coherent DVCS must be separated from major backgrounds



Coherent DVCS:
Probes nuclear structure and size

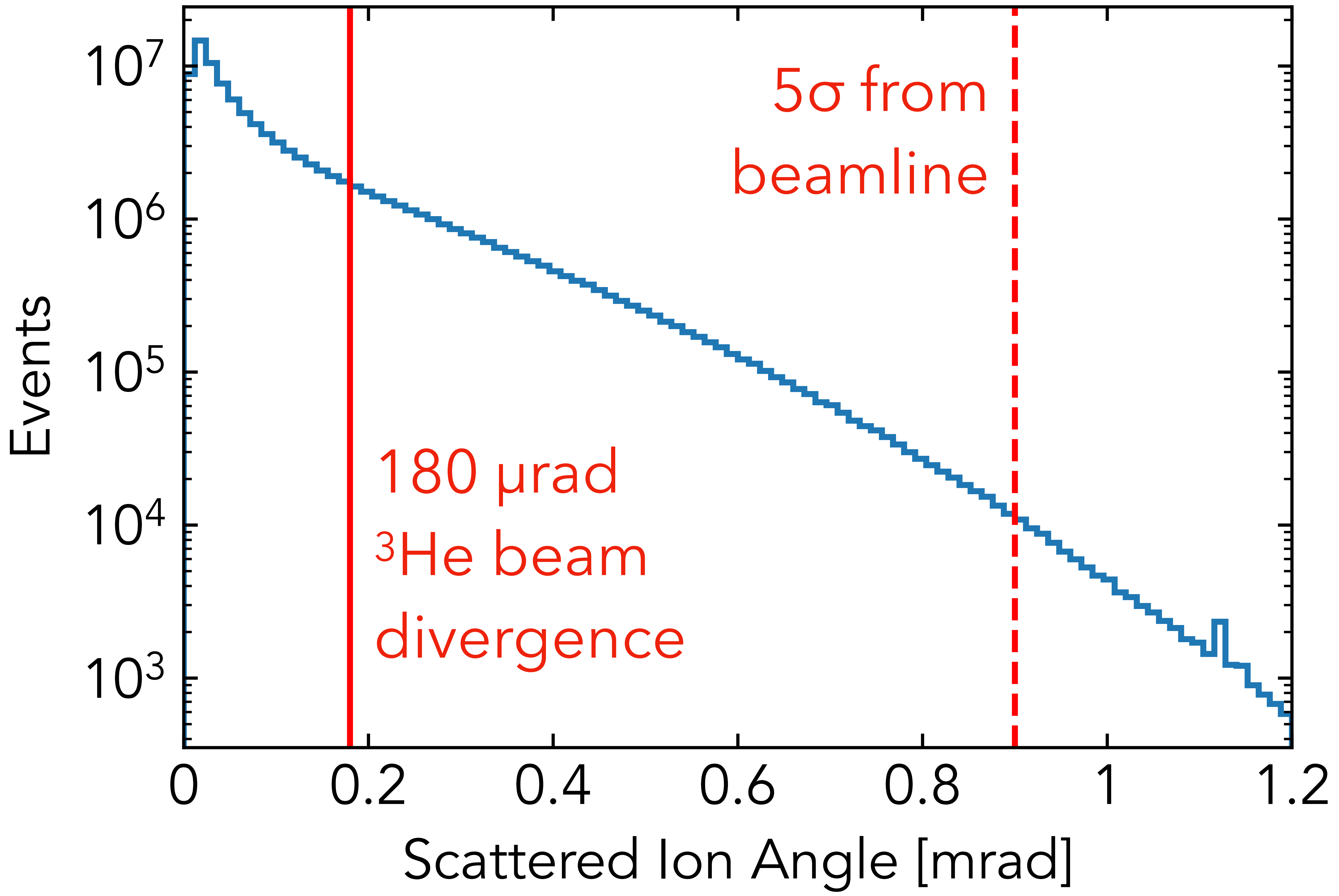


Incoherent DVCS:
Probes individual bound nucleons

Pybus et al. arXiv:2606.11491

How well can we count on coherent exclusivity for small-A?

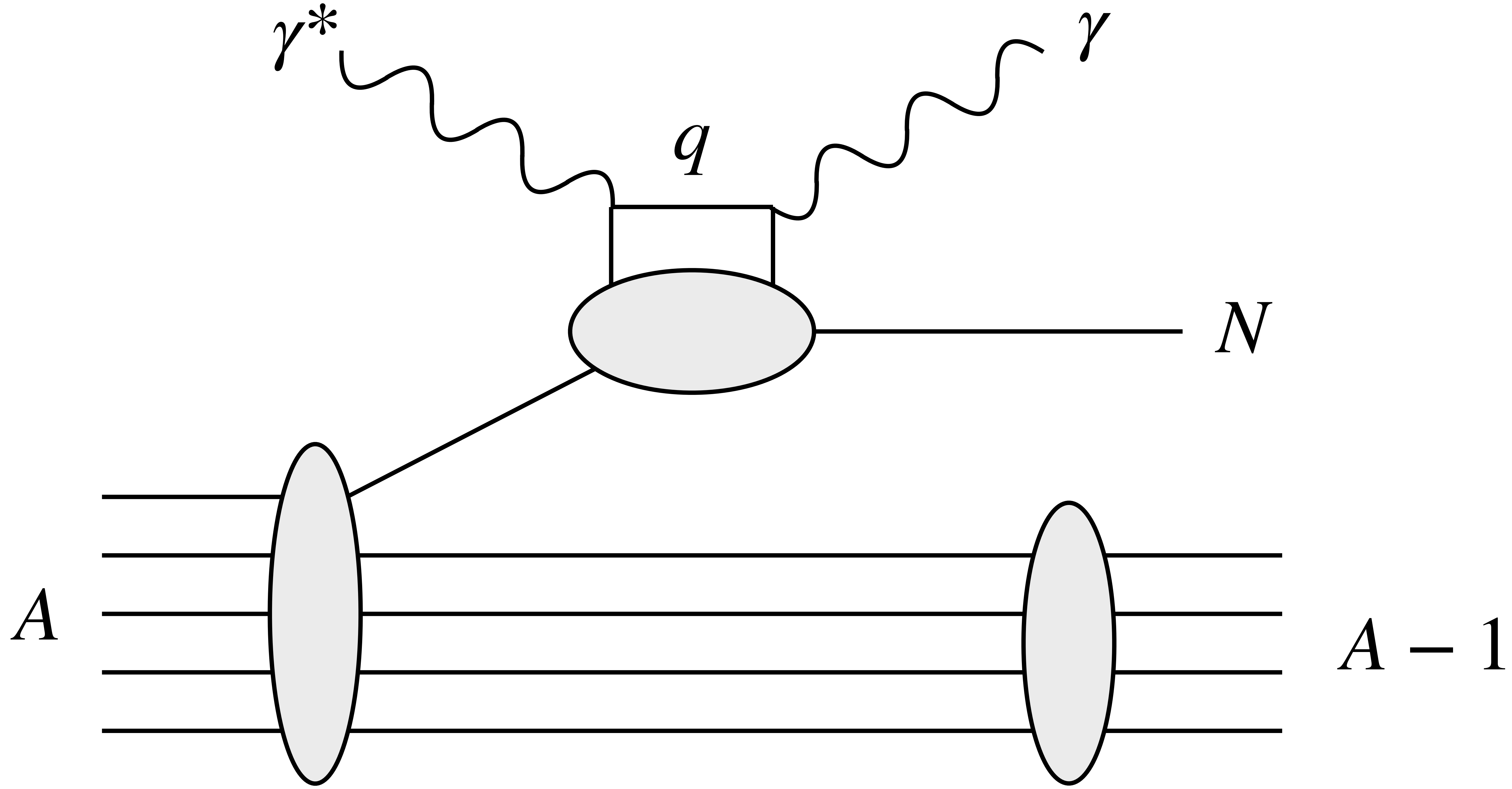
- Small $|t|$ of coherent DVCS does not divert scattered nucleus from ion beamline!
- Measurement is likely not exclusive
- Need to know how well we can veto on background channels to isolate coherent events



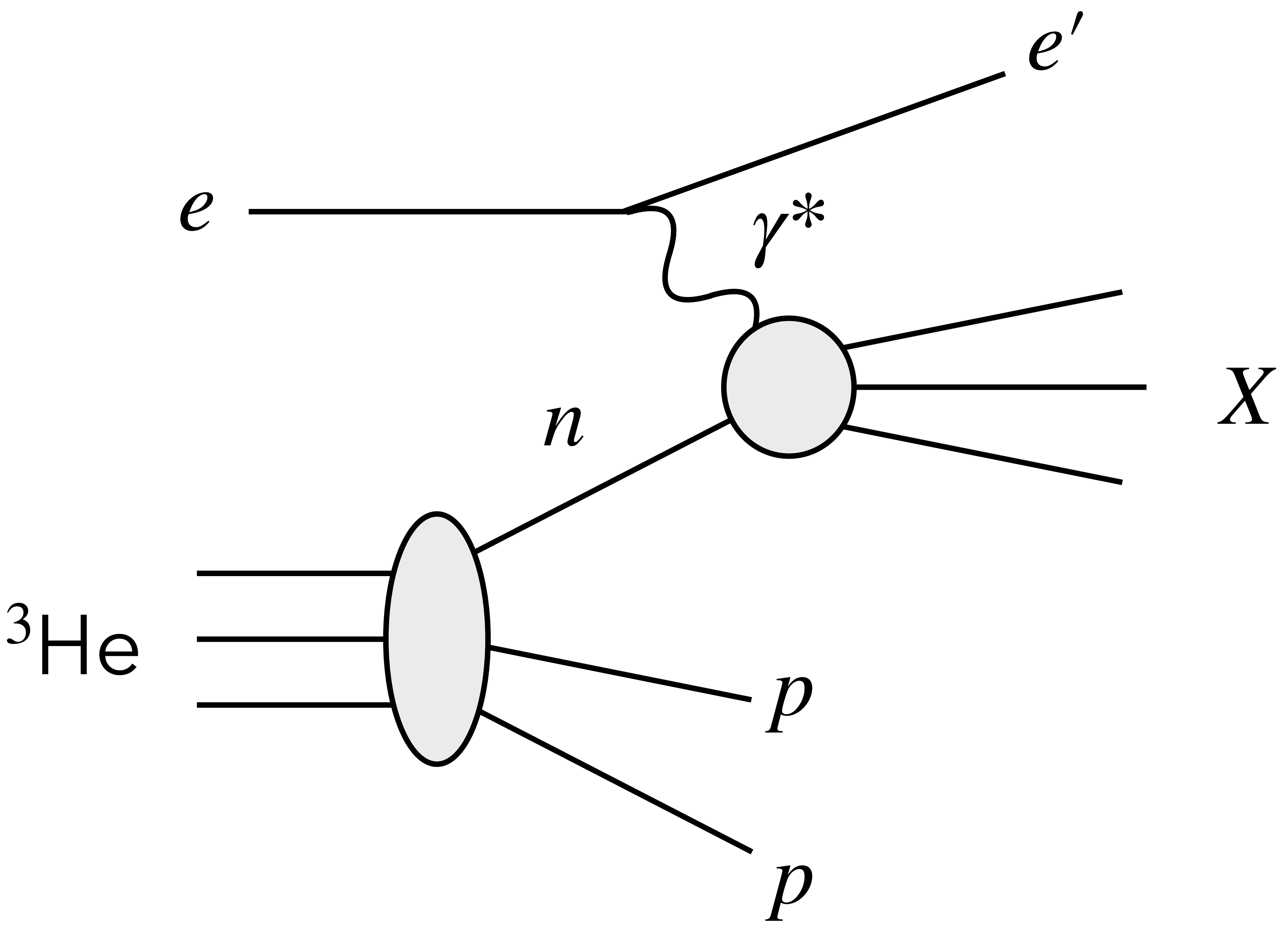
Pybus et al. arXiv:2606.11491

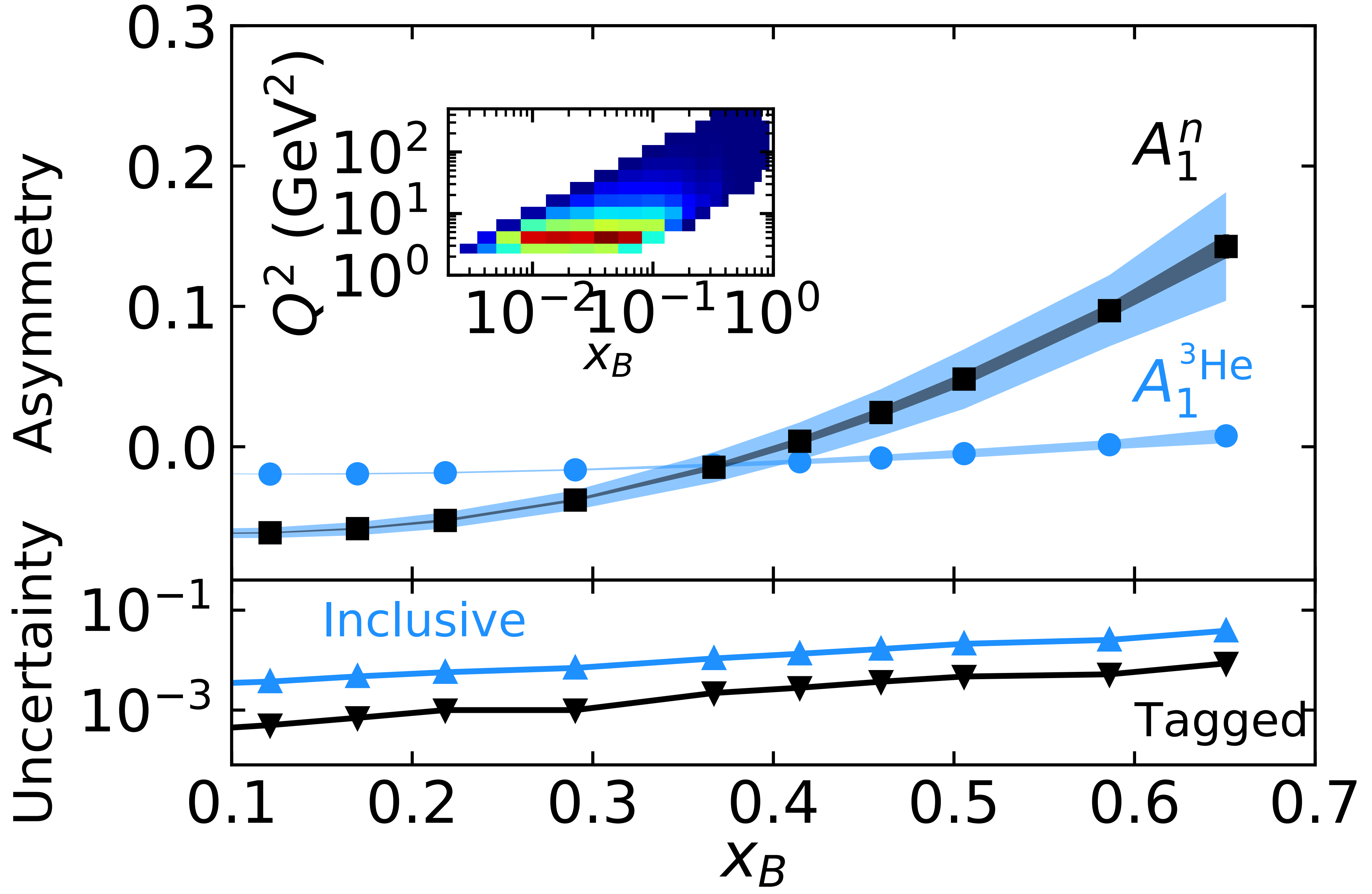
Incoherent Nuclear DVCS

- Next priority is modeling <u>incoherent</u> nuclear DVCS
- Incoherent will dominate at larger $|t|$, limited imaging potential unless controlled
- **Incoherent DVCS also has strong potential to study bound nucleon 3D structure**



^{3}He Spectator Tagging at the EIC



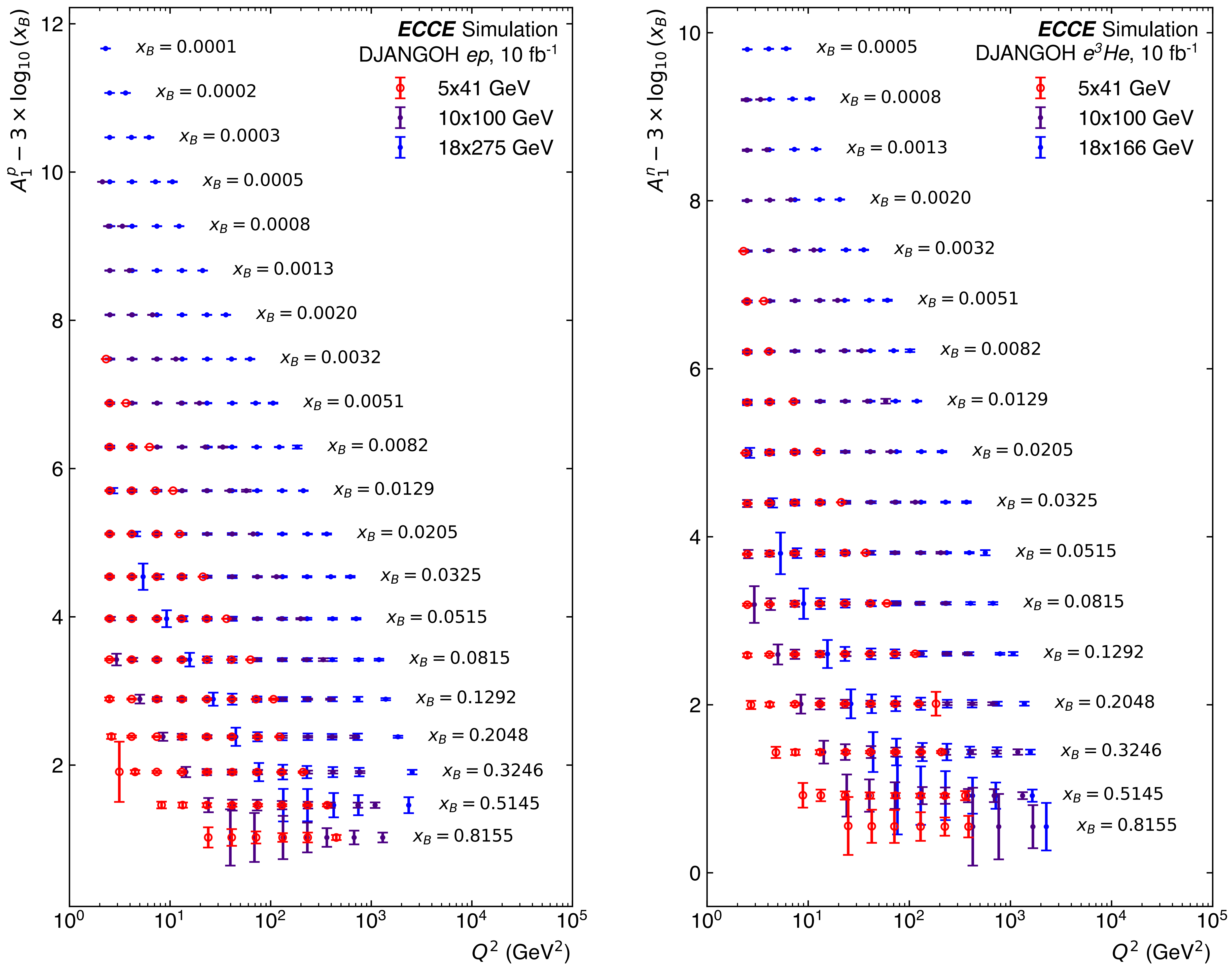


- DIS from ^{3}He has been studied as probe of neutron structure function $g_1^n(x_B, Q^2)$
- Spectator proton tagging isolates neutron contribution to asymmetry
  - Up to $10\times$ improvement on inclusive extraction of A_1^n

Friscic et al. PLB (2021)

^{3}He Spectator Tagging at the EIC

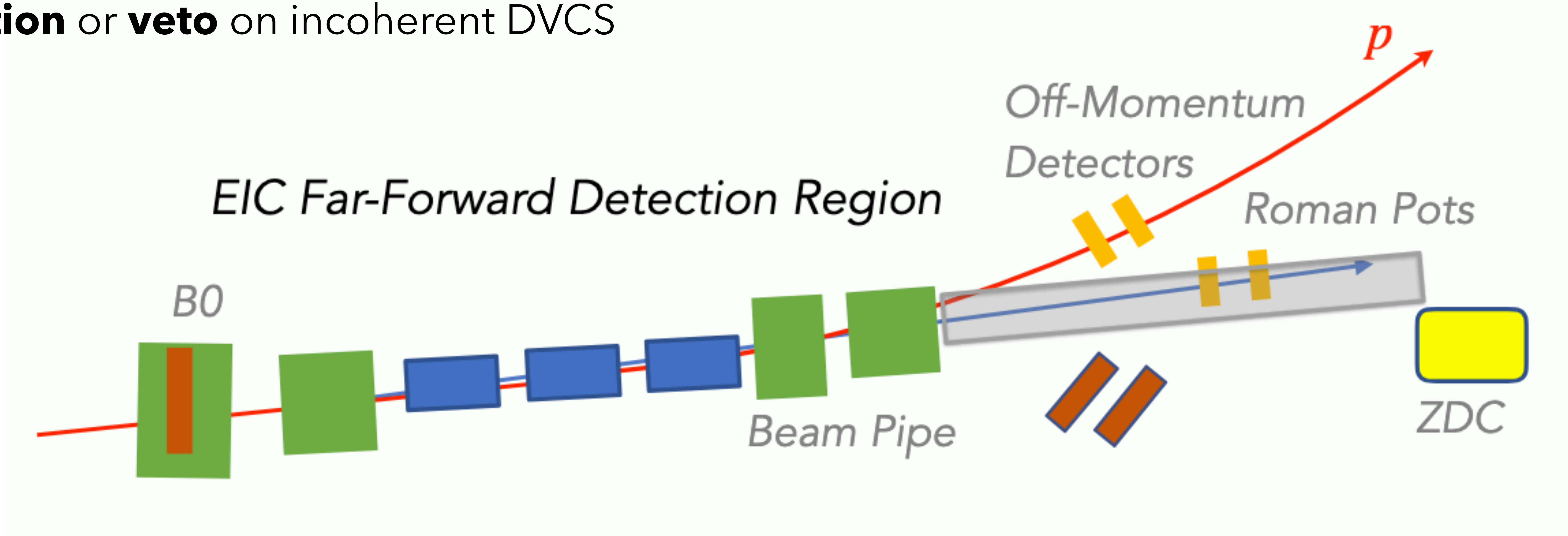
- Study of ^{3}He spectator tagging began for EIC Yellow Report
- ECCE studies examined proton and neutron spin asymmetries → flavor decomposition of nucleon sea quark spin
- Ongoing studies extend to ePIC detector with more detailed study of systematics



Abdul Khalek et al. NPA (2022); Friscic et al. PLB (2021); Bylinkin et al. NIMA (2023); Kutz et al. PRD (2024); Adkins et al. NIMA (2025)

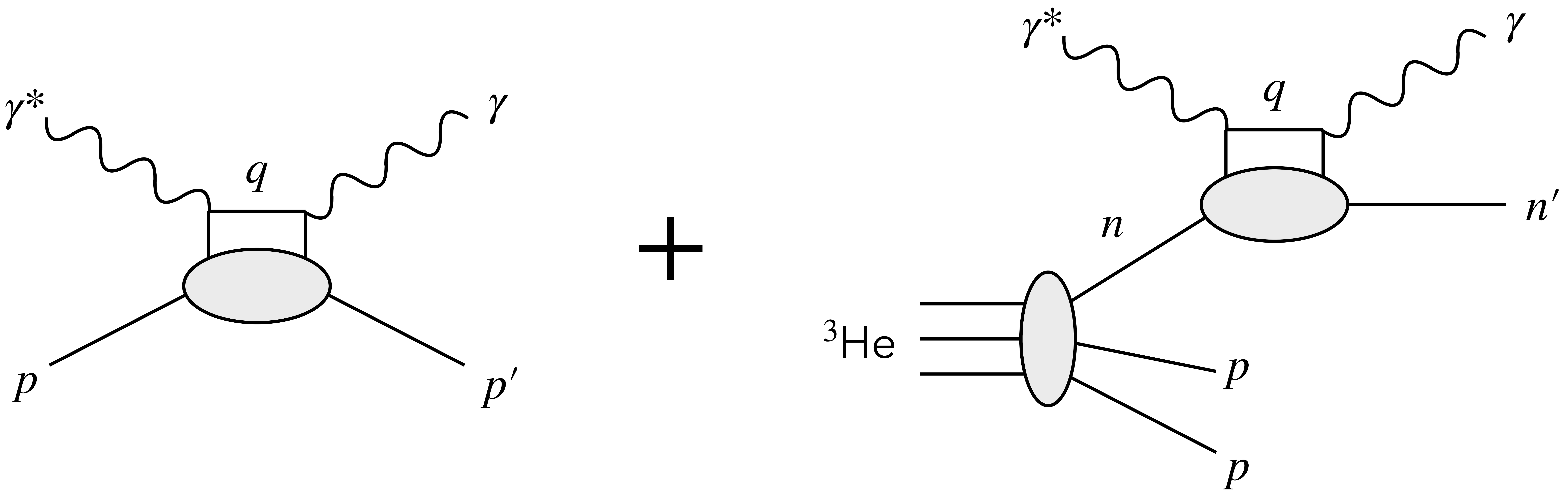
^{3}He Spectator Tagging at the EIC

- Difference in rigidity between beam and nuclear fragment allows efficient spectator detection
- Same technique can be applied to DVCS, allowing **selection** or **veto** on incoherent DVCS



Friscic et al. PLB (2021)

Polarized Neutron Tomography



- Spectator-tagged incoherent DVCS from ^{3}He gives access to 3D structure and CFFs of polarized neutron at low x_B
- Combining with proton DVCS measurements at EIC, gives flavor-dependent tomography of nucleon sea

The “EIC Polarized IOn Source” (EPIOS) Consortium

- Effort to centralize polarized ion physics efforts for the EIC
- Work includes improving ion source polarization, beam intensity, polarimetry precision, and physics motivation and formalisms
- CFNS kick-off workshop March 19-12, 2026, with whitepaper in PRC
- Planning for two-week INT workshop March 22 - April 2, 2027

PHYSICAL REVIEW C **113**, 060501 (2026)

Perspective

Realizing the scientific program with polarized ion beams at the future BNL Electron Ion Collider

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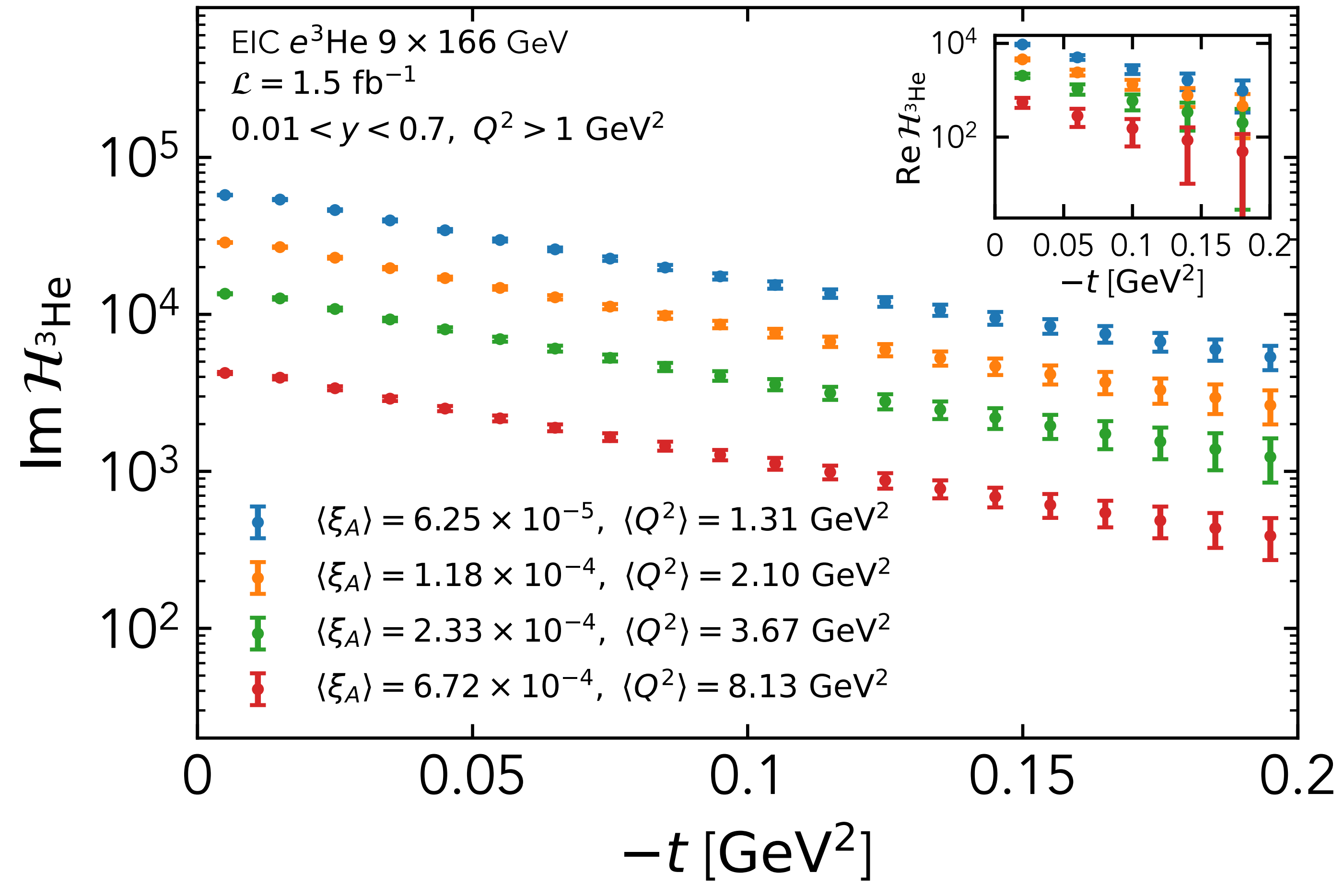
(EPIOS Scientific Consortium)

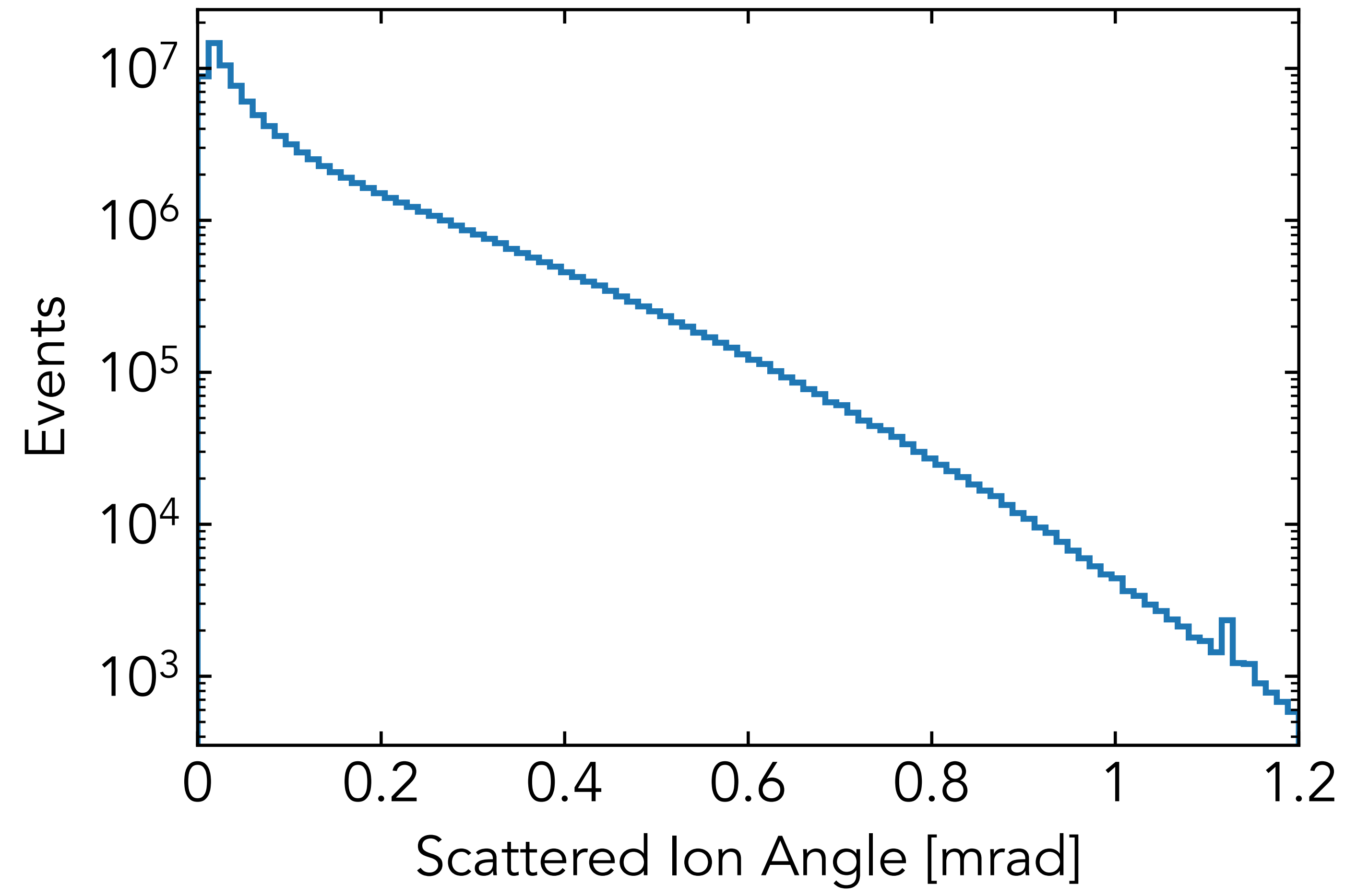
Atoian et al. PRC (2026)

Conclusions

Pybus et al. arXiv:2606.11491

- We have explored the process of 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 limits exclusivity
- Future work requires incoherent DVCS from ^{3}He, also giving access to neutron tomography
- Will also require full ePIC simulation to account for detector response and systematic effects





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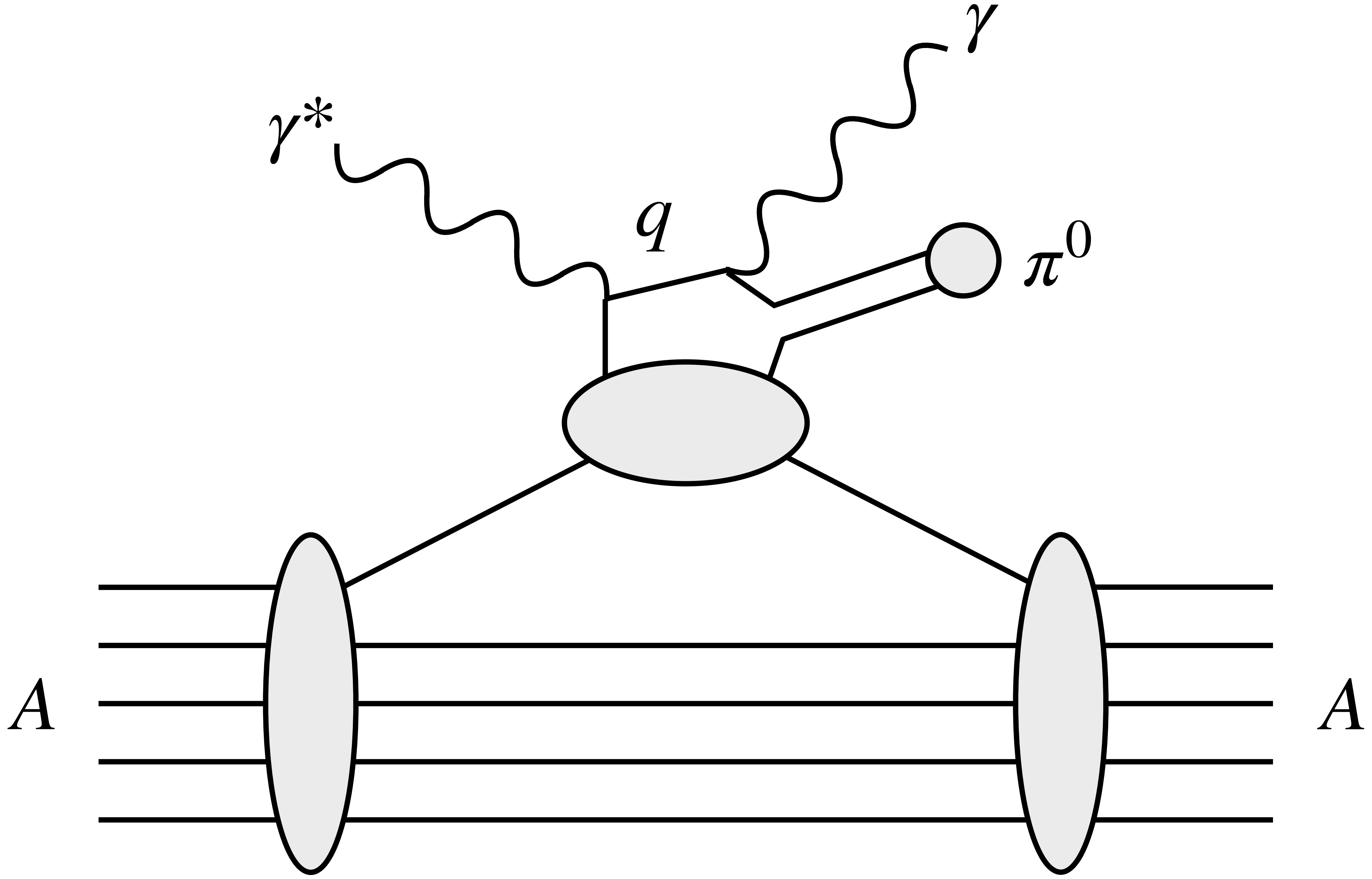
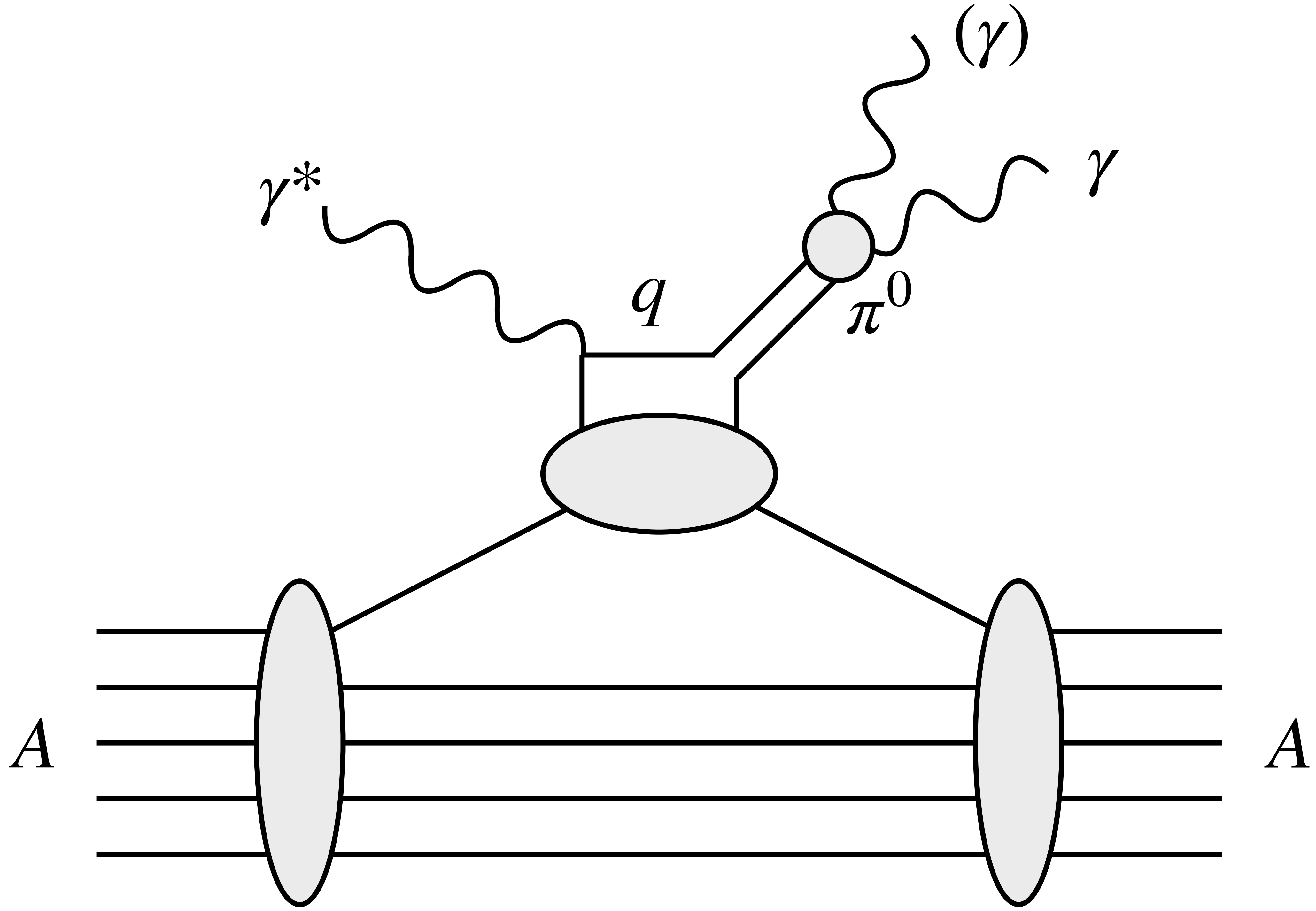
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Backup

Non-Exclusive Backgrounds



Associated DVCS:
Undetected pion produced along with a DVCS photon



Deeply-Virtual π^0 Production:
Pion decay photon mistaken for DVCS photon

Pybus et al. arXiv:2606.11491

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

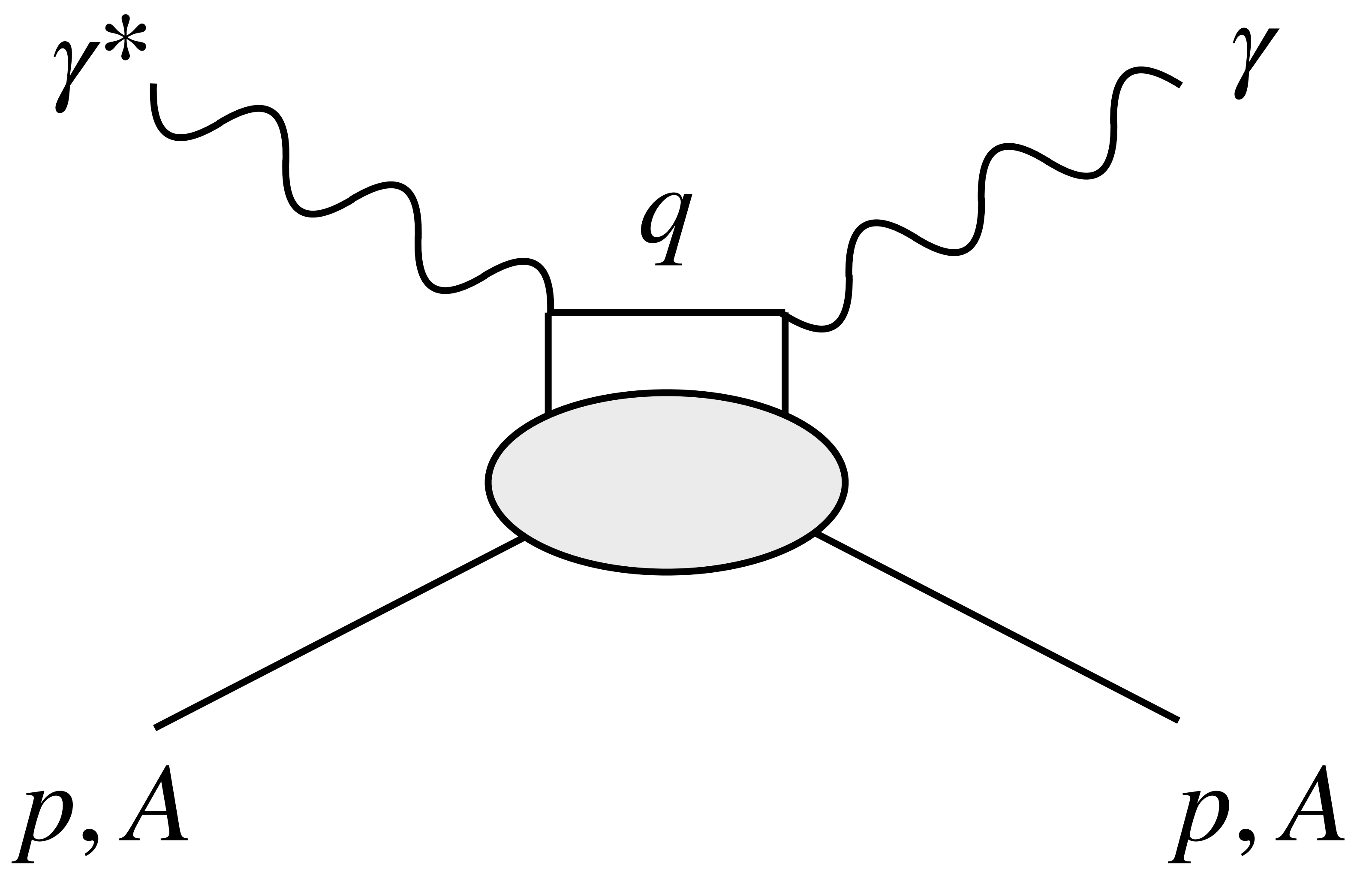
The amplitude for this process is characterized by **Generalized Parton Distributions** (GPDs), depending on

- 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*

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:

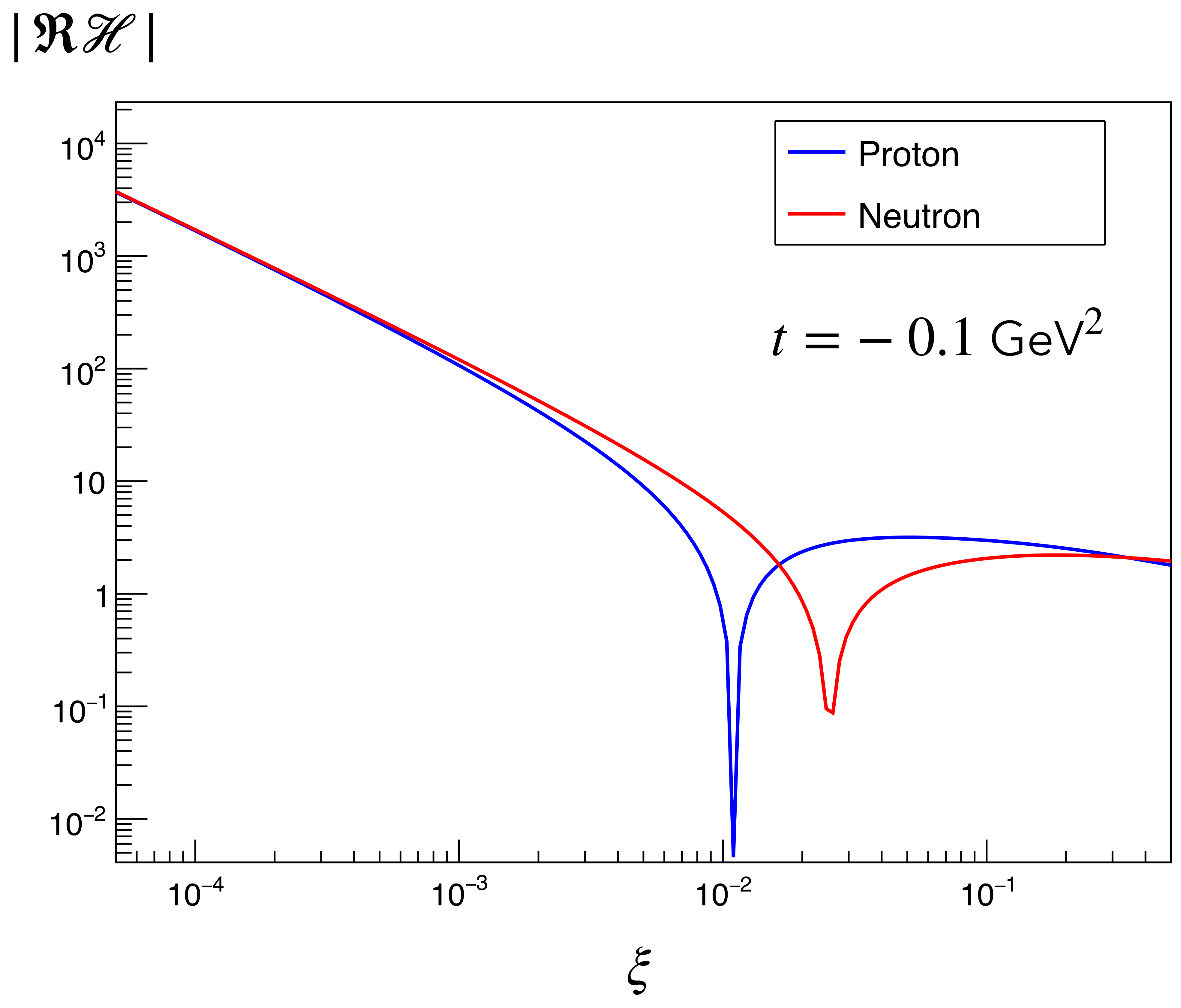
$$h_A^N(z, \xi_A, t) = \sum_{S, s_N} \int d^2\vec{p}_\perp dE_{A-1}$$
$$\langle P^+ + \xi, \overrightarrow{P}_\perp + \overrightarrow{\Delta}_\perp, S \,|\, zP^+ + \xi, \vec{p}_\perp + \overrightarrow{\Delta}_\perp, s_N; (1-z)P^+, \overrightarrow{P}_\perp - \vec{p}_\perp, E_{A-1} \rangle$$
$$\times \langle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

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

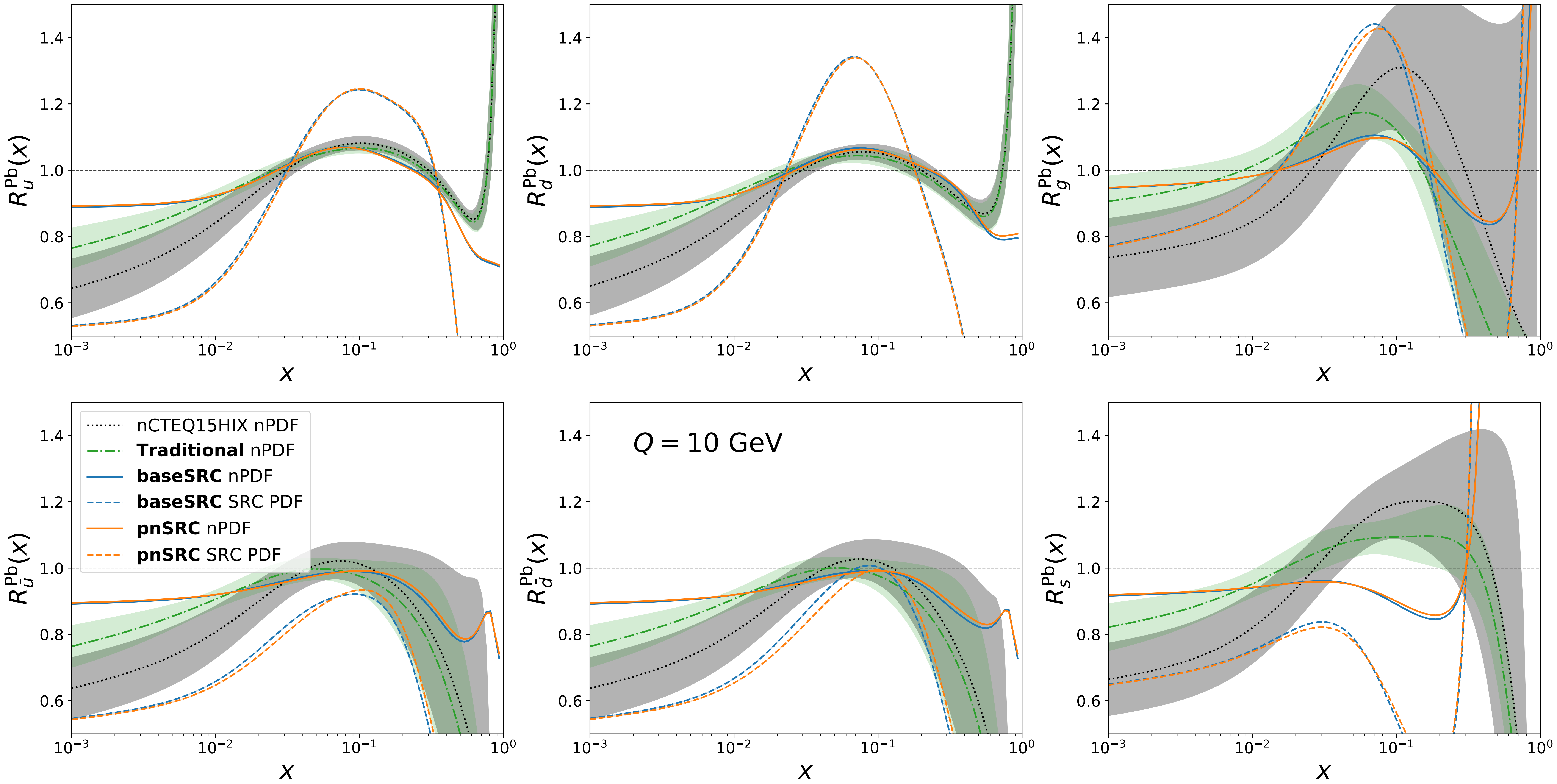
$$\tilde{h}_A^N(z, \xi_A, t) \approx P_N \times h_A^N(z, \xi_A, t)$$
$$\tilde{\mathscr{H}}^A(\xi_A, t) \approx \sum_{N=p,n} \int_{\xi_A}^1 \frac{dz}{z} \tilde{h}_N^A(z, \xi_A, t) \tilde{\mathscr{H}}^N \left(\frac{\xi_A}{z}, t \right)$$

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 CFFs at low ξ are $\mathscr{H}$ and $\tilde{\mathscr{E}}$



We want to understand the full partonic structure of nuclei



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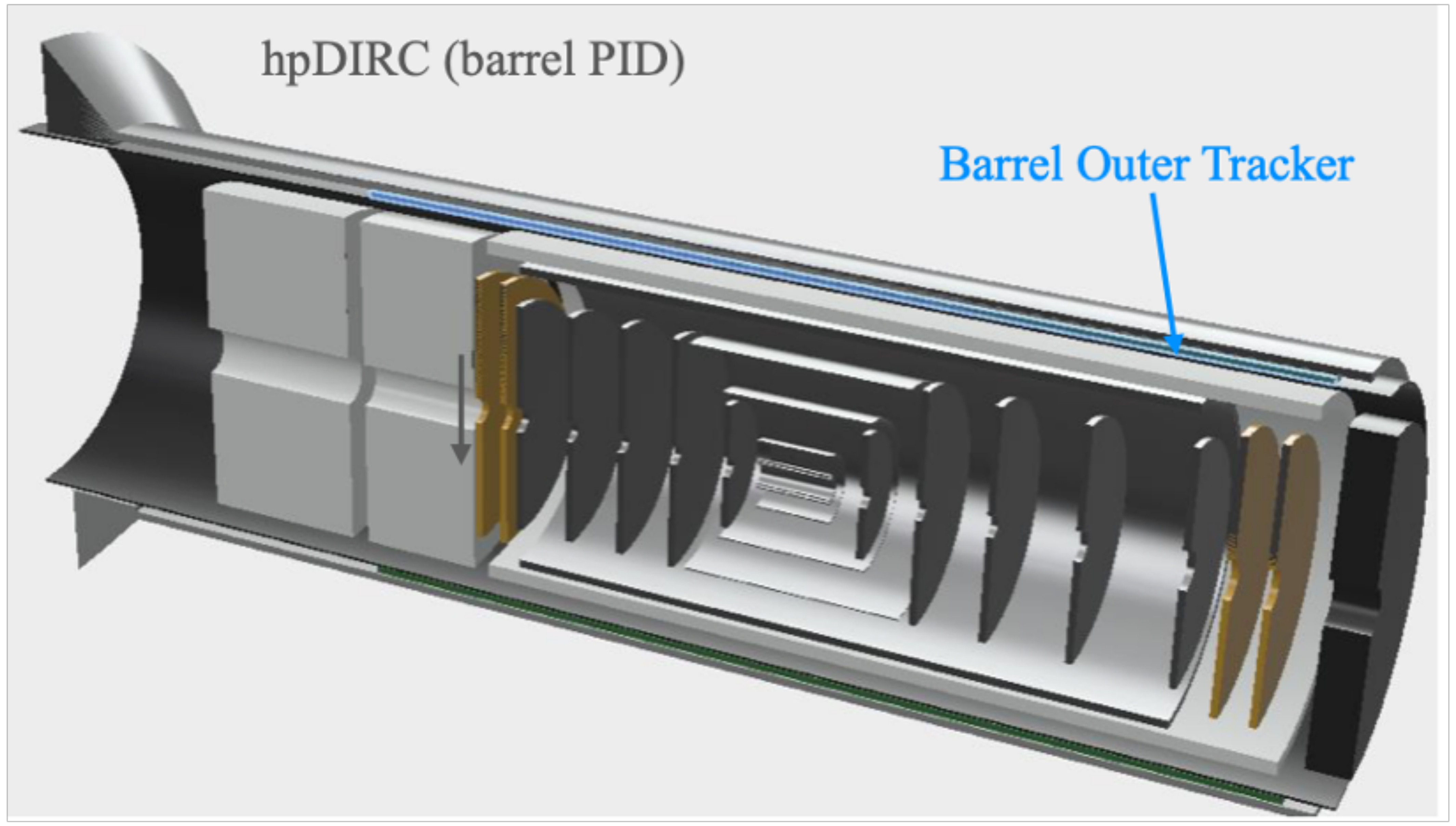
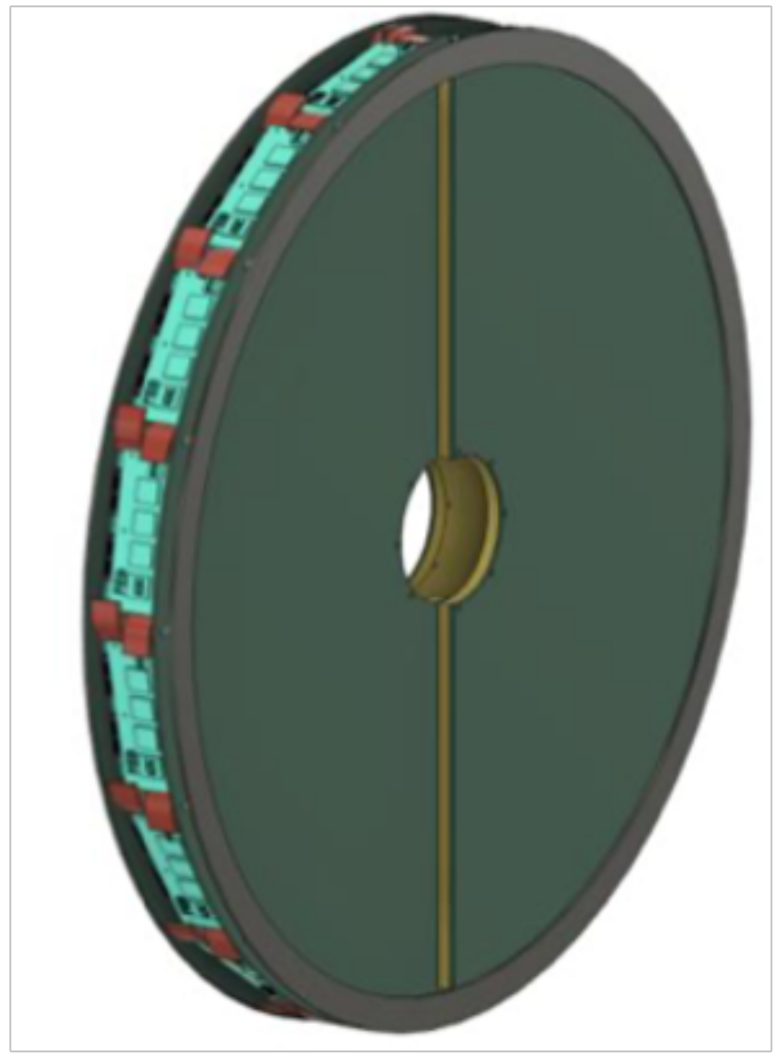
Denniston et al. PRL (2024)

ePIC MPGD detector



Outer Radius (cm)	Outer Active Reg. radius (cm)	Calculated Beam pipes radii (cm)	Offset (mm)	Inner Radius (cm)	Inner Active Reg. radius (cm)
50	45	5.58	22.5	9	10.5
50	45	5.31	19.9	9	10.5

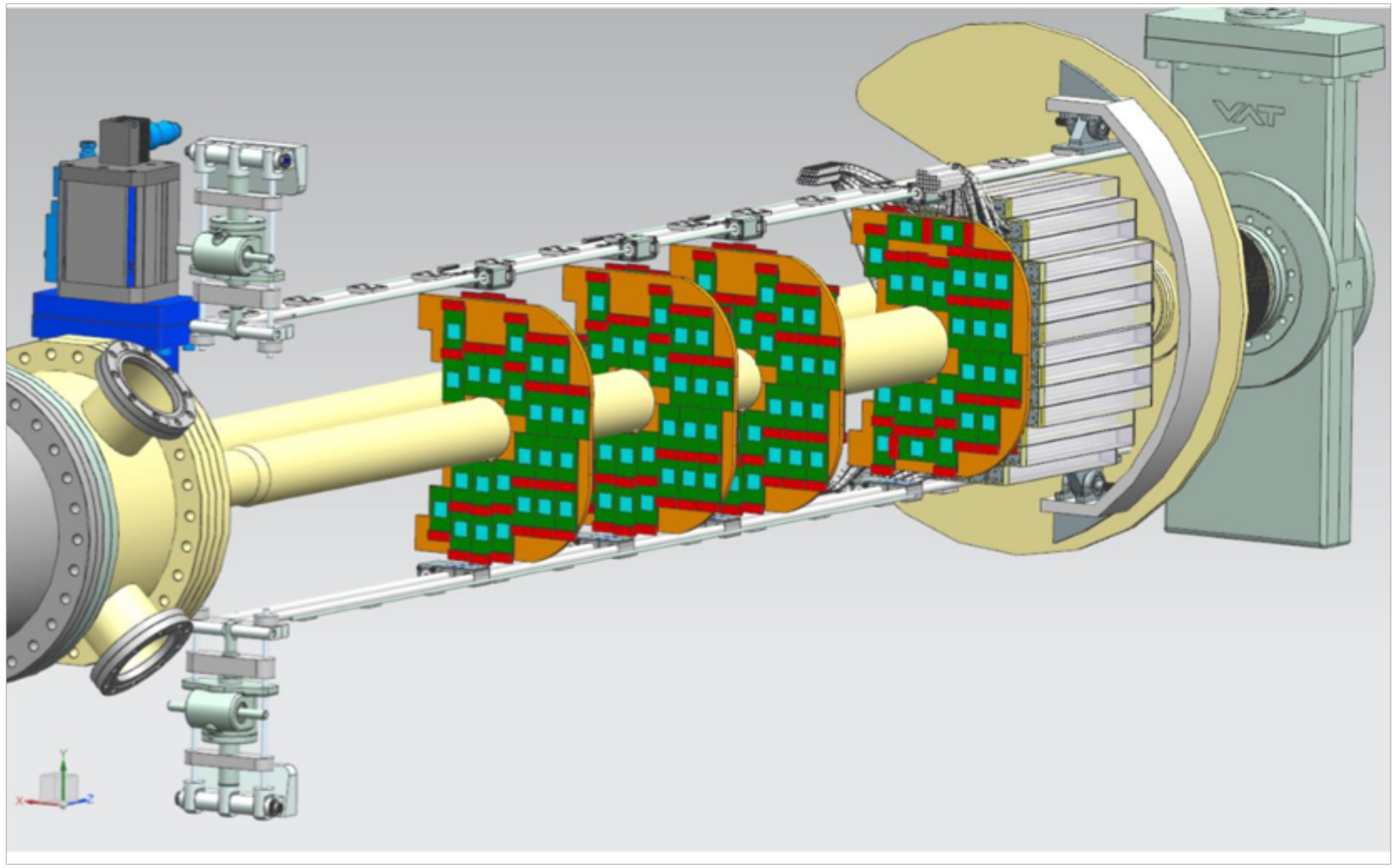


Individual MPGD disk

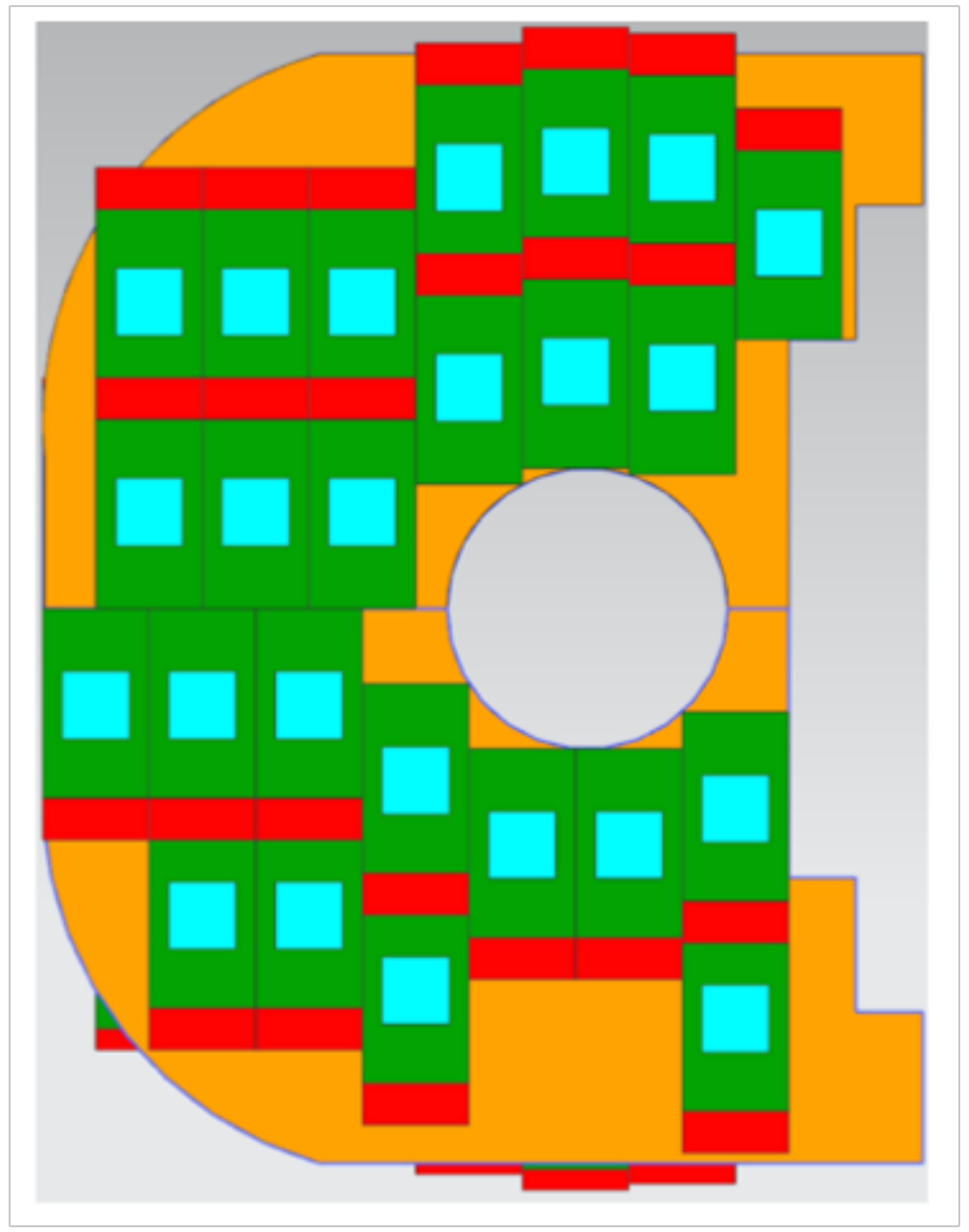
- See reference here (https://indico.phy.ornl.gov/event/510/contributions/2229/attachments/1719/3985/20241120_CPAD_Knoxville_ePIC_KG.pdf)

ePIC B0 Tracker

B0 tracker consists of 4 disks



Layout of individual B0 Tracker disk



- See reference here (https://indico.jlab.org/event/934/contributions/17281/attachments/13165/21204/FarForward_AC_LGAD_ePIC_Collab_Jentsch_7_15_2025.pdf)

The EPIOS Whitepaper

PHYSICAL REVIEW C **113**, 060501 (2026)

Perspective

Realizing the scientific program with polarized ion beams at the future BNL Electron Ion Collider

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The EPIOS Whitepaper

Polarized ion beams at the Electron Ion Collider (EIC) are essential to address some of the most important open questions at the twenty-first century frontiers of understanding of the fundamental structure of matter. **Here, we summarize the science case and identify polarized ^{2}H, ^{3}He, ^{6}Li, and ^{7}Li ion beams as critical technology that will enable experiments which address the most important science.** Furthermore, we discuss the required ion polarimetry and spin manipulation at the EIC. The current EIC accelerator design is presented. **We identify a significant research and development effort across national and international laboratories and universities that is required over about a decade to realize the polarized ion beams and estimate (based on previous experience) that it will require about 20 full-time equivalent (FTE) over 10 years (or a total of about 200 FTE-years) of personnel, including graduate students, postdoctoral researchers, technicians, and engineers.** Attracting, educating, and training a new generation of physicists in experimental spin techniques will be essential for the successful realization. Artificial intelligence and machine learning are seen as having significant potential for both acceleration of research and development and amplification of discovery in the optimal realization of this unique quantum technology on a cutting-edge collider. The research and development effort is synergistic with research in atomic physics and fusion energy science.

– EPIOS Whitepaper Abstract

Atoian et al. PRC (2026)

EIC Polarized DIS Data

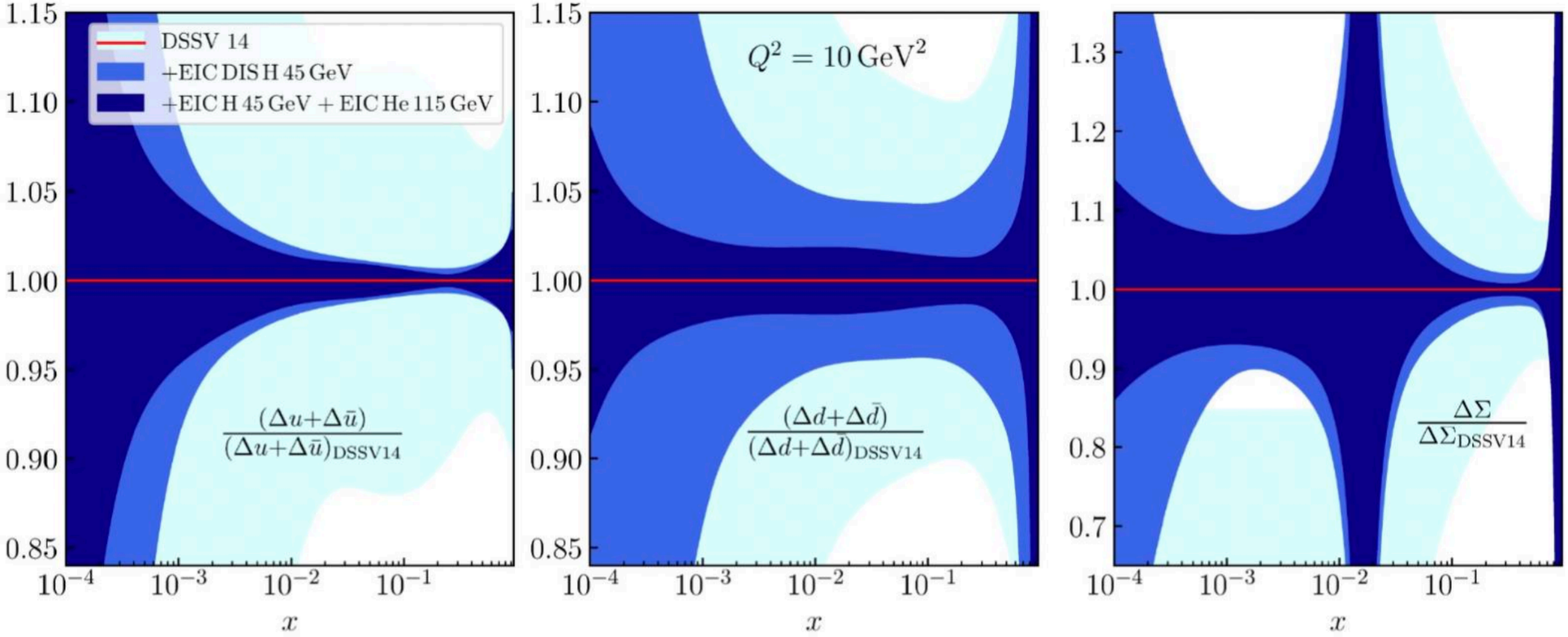

FIG. 2: The impact of projected inclusive scattering data off polarized proton and ^{3}He beams at the EIC on the relative uncertainties of the extracted up, down and quark singlet helicity distributions.

Atoian et al. PRC (2026)