From nucleon to nuclear GPDs

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Outline

- Nuclear GPDs in coherent and incoherent reactions

- High-energy nuclear scattering

- Existing and future measurements

- Not covered in this talk: vector meson photo/electroproduction (EIC/UPC)
    - → Nuclear gluon GPDs
   - → Leading twist nuclear shadowing

    ↪ but see Spencer Klein's talk

    [Nuclear Shadowing one nucleon at a time; Rinaldi et al PRL '22]

Nuclear GPDs: Same…

$$\frac{1}{2} \int \frac{\mathrm{d}z^-}{2\pi} \, e^{ixP^+z^-} \langle p' | \bar{q}(-\tfrac{1}{2}z)\gamma^+ q(\tfrac{1}{2}z) | p \rangle \Big|_{z^+=0, \mathbf{z}=0}$$

- QCD operator, evolution, factorization etc.

- Non-perturbative objects that depend on x, ξ, t

- Forward limit: PDFs

- Polynomiality (covariance)

  Mellin moments $\rightarrow$ polynomials in ξ multiplied with generalized FF
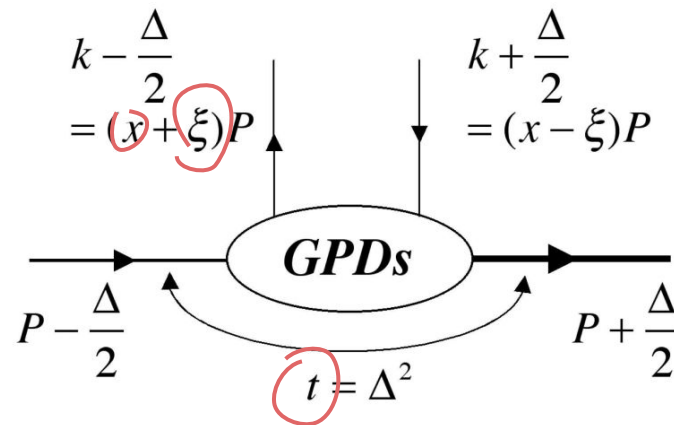
  $\hookrightarrow$ EM, gravitational $\rightarrow$ talk Lorcé

- Experimentally probed in hard exclusive reactions

Nuclear GPDs: … but different

Cern Courier

- **Many different nuclei**
  - → Spin / isospin
    - ↳ ^{4}He (0), ^{3}He/^{3}H (½), deuteron (1)
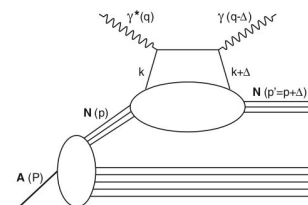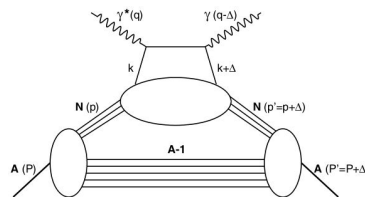 - → Binding, density, clustering
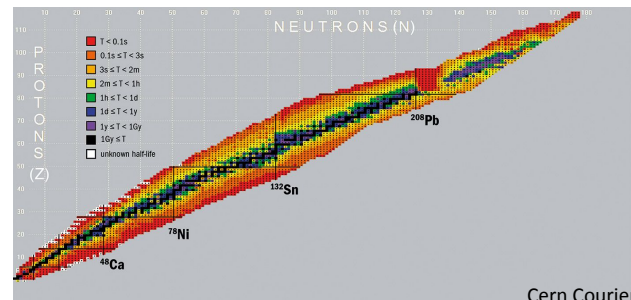
- **Natural description as a collection of protons and neutrons**
  - → GPDs: Nuclei as a bound system of quarks and gluons
    - ↳ influence of nuclear interactions
  - → Non-nucleonic components?
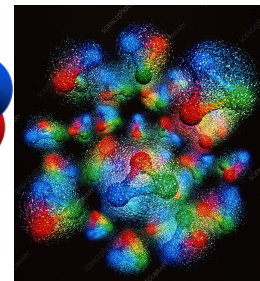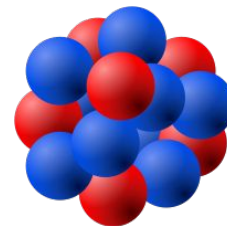
- **In the hard exclusive scattering**
  - → Nucleus can remain intact (**coherent**)
  - → Many different possibilities for breakup (**incoherent**)

[Dupre, Scopetta EPJA '16]

High-energy nuclear scattering

- **Interplay of two scales**
  - → High-energy scattering
 - → Low-energy nuclear structure

- **Can be separated using** [Frankfurt Strikman 80s]
  - → Light-front quantization
  - → QCD factorization

- **Off-shell effects remain finite**

- **Nuclear input as light-front momentum distributions**
  spectral functions

  - → Still low-energy nuclear physics, just formulated differently
  - → Relativistic spin effects included

[WC, C. Weiss PRC '20]

$$\alpha_p = A \frac{p_p^+}{p_A^+}$$

High-energy nuclear scattering

[WC, B Pire '18]
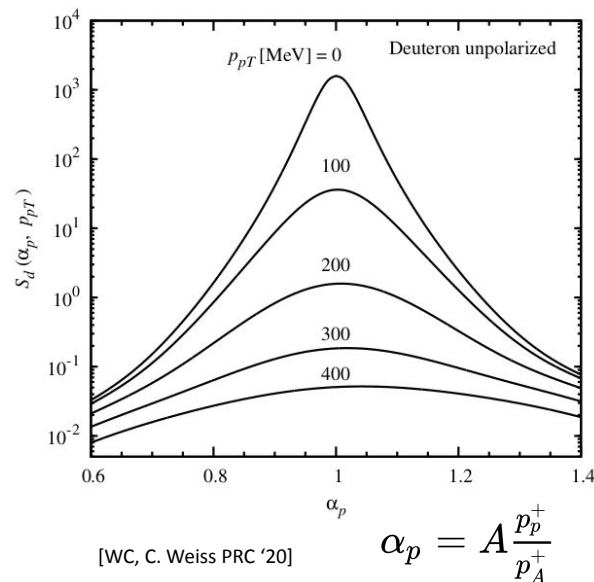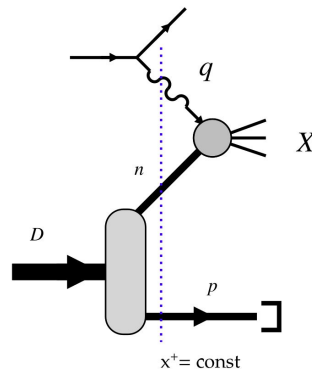
- Nuclear distributions as convolutions of
  - → (Off-)diagonal (light-front) **nuclear** densities / spectral functions
  - → **Nucleon** distributions / form factors

- Truncation in Fock space (A-nucleon component)
  - → Breaks covariance
  - → No nuclear GPD polynomiality for most existing model calculations
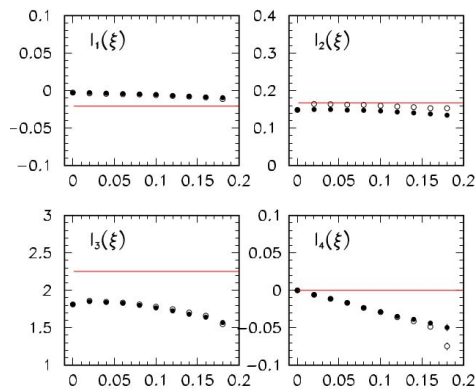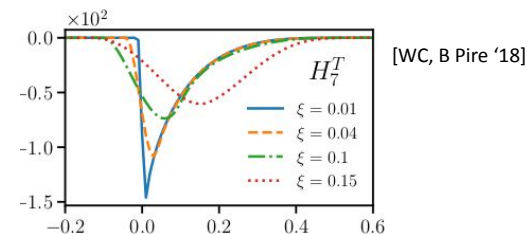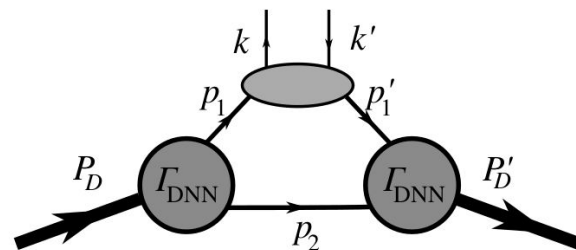
↪ however, see talk A. Freese on Wednesday

[Cano, Pire '04]

Coherent scattering

- Probe of **nuclear** GPDs

- Tomography of bound nuclear states
  in quark/gluon degrees of freedom

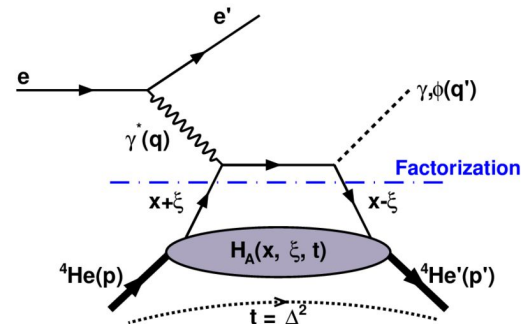- Gravitational form factors of nuclei (mass/spin/mechanical properties)
  ↪ talk Hatta on Tue

- Non-nucleonic degrees of freedom
  At ξ > width LF mom. distribution
  [Berger et al. PRL 04]

- Off-forward EMC effect [Guzey, Strikman '03;
  Guzey, Siddkov '06]
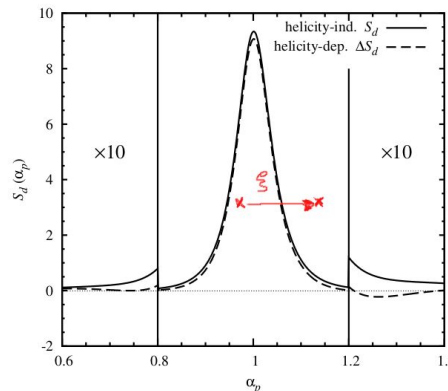
  Shadowing at low *x* [Goeke, Guzey, Siddikov '09]

[ALERT proposal]

We find $\beta \approx 1.7$

to be compared with $\beta = \dfrac{7}{3}$ $\beta \approx 1$ $\beta \approx 2.26$

Polyakov   Liuti, Taneja   Guzey, Siddikov

First, we see that the d-constant is negative. The effect of the finite width of the nuclear "skin" also has a negative sign. The corresponding formula can be easily derived:

$$d(0) = -\frac{4\pi}{3} m_A \gamma R^4 \left(1 + \frac{5\pi^2}{3}\frac{a^2}{R^2}\right), \qquad (16)$$

[Polyakov PLB '03]

Spin-1 GPDs / Gravitational FFs

[Berger, Cano, Diehl, Pire '01]
[WC, Pire '19]
[Holstein '06]
[Abidin, Carlson '08]
[Taneja, Kathuria, Liuti, Goldstein '12]
[Cotogno, WC, Freese, Lorcé '19]

- **More independent structures than for the nucleon**
  - → 9 (5/4) chiral even / 9 chiral odd GPDs at leading twist
  - → More challenging to disentangle in measurements
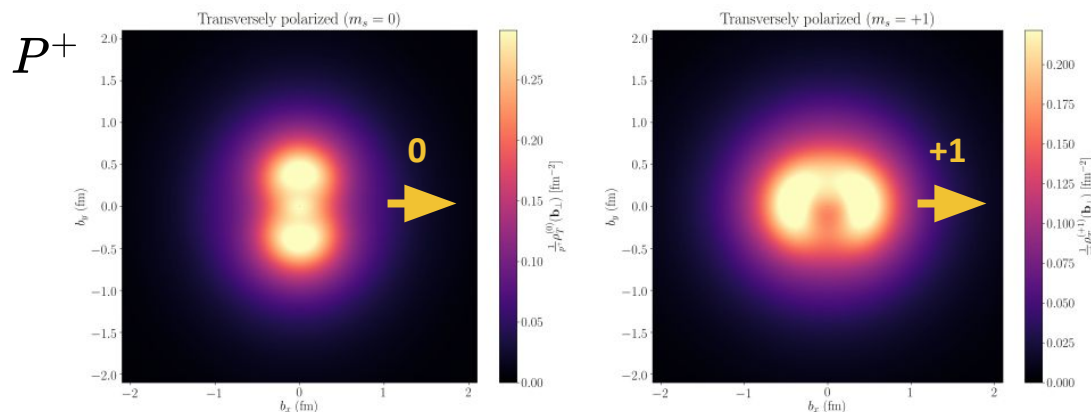
- **Spin-1 spin sum rule**

$$J_a^z = \int_{-1}^{1} dx \frac{x}{2} \left[H_2^a(x,0,0) + H_5^a(x,0,0) \right],$$

$$J^z = \sum_{a=q,g} \int_{-1}^{1} dx \frac{x}{2} H_2^a(x,0,0) = 1.$$

$$L_q^z = \int_{-1}^{1} dx\, x \left[\frac{1}{2} H_5^q(x,0,0) - G_6^q(x,0,0) \right].$$

$$f_{1LL}^a(x) = H_5^a(x,0,0)$$

↪ enters in tensor polarized b_1 structure function

- **Spatial densities**

P^+

Transversely polarized ($m_s = 0$)

0

Transversely polarized ($m_s = +1$)

+1

[A Freese, WC '22]

Incoherent scattering / tagging

- Probes **nucleon** GPDS

- Neutron GPDs
  - → Flavor separation

- Medium modifications of nucleon GPDs

- Tagging: measurement of breakup (A-1, multinucleon final states, …)
  - → Momenta of tagged particles **control initial nuclear configuration**
  - → Needs accounting for **final state interactions** (slow moving nucleons!)
  - → On-shell extrapolation for **free neutron** structure
  - → Higher spectator momenta: which nuclear configurations cause medium modifications
  - → Well developed phenomenology for (deuteron) DIS, can be adapted to exclusive channels
    - ↪ Also see talk Nguyen on Tue for ^{3}He w tagging

[Sargsian, Strikman '03]
[Kaptari, Ciofi et al. '04+]
[WC, C. Weiss 19+]
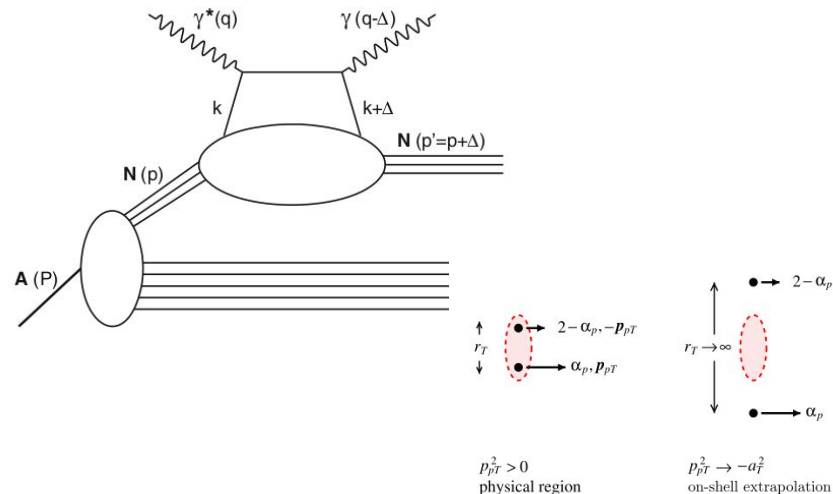
Measurements

- To access these nuclear GPD we need data (or lattice simulations)

- Compared to the proton….relatively little data
  - → Beam spin/charge asymmetry in DVCS (linear in Compton FF)
  - → Lots of uncharted territory

- HERMES: No observation of any nuclear dependence
  - → No direct detection of nuclear remnant system
  - → Kinematical separation of coherent/incoherent

[Hermes PRC '10]
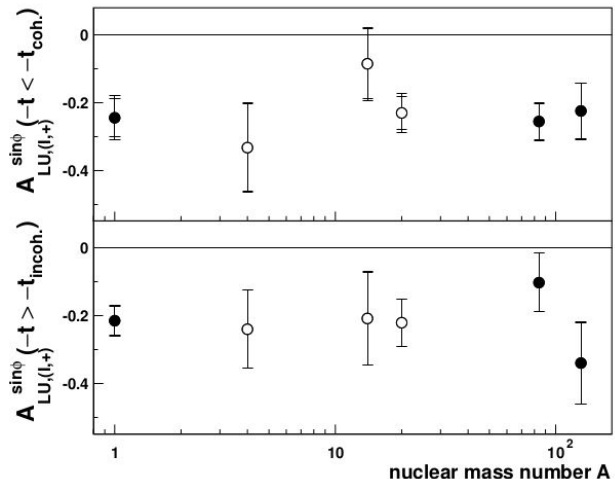
JLab Hall A deuteron DVCS

- Binning in missing mass to separate coherent/incoherent

- Proton DVCS subtracted

- Simultaneous fit for Compton FF

- Model based extraction of quark AM constraint $J_u + J_d/5 = 0.18 \pm 0.14$
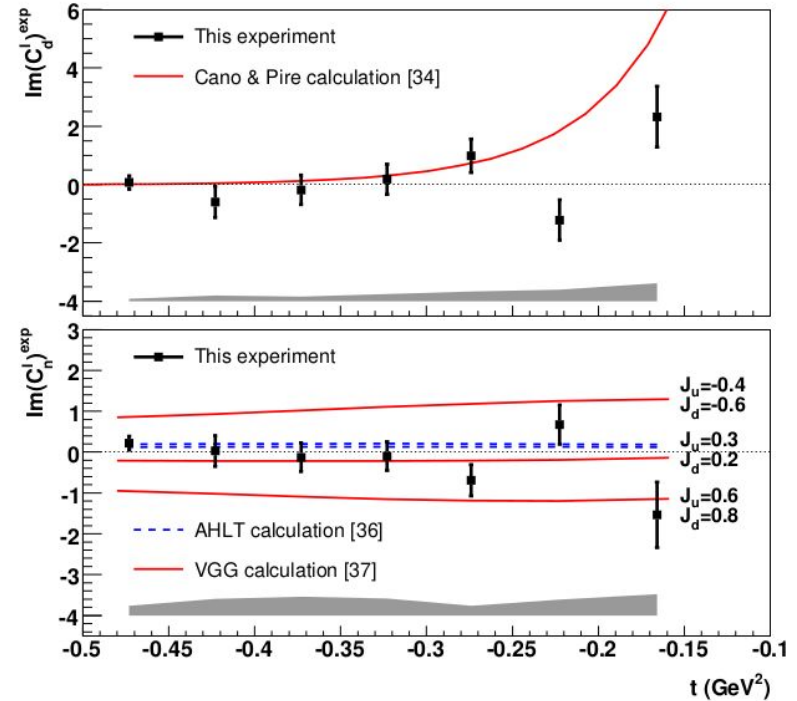
[Mazouz et al. (CLAS) PRL '07]

JLab CLAS ^{4}He DVCS Beam-spin asymmetry

- Spin zero: **1** chiral even GPD at leading twist → easier extraction
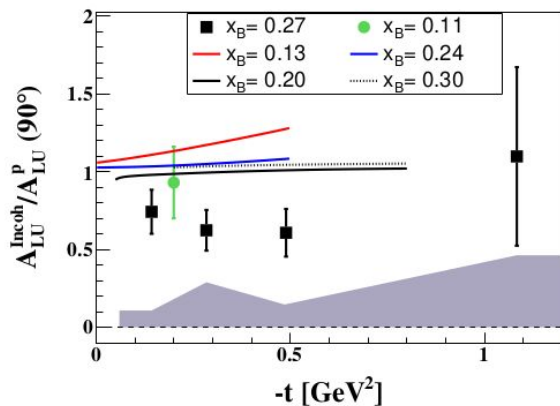
- Coherent → direct detection of scattered 4He
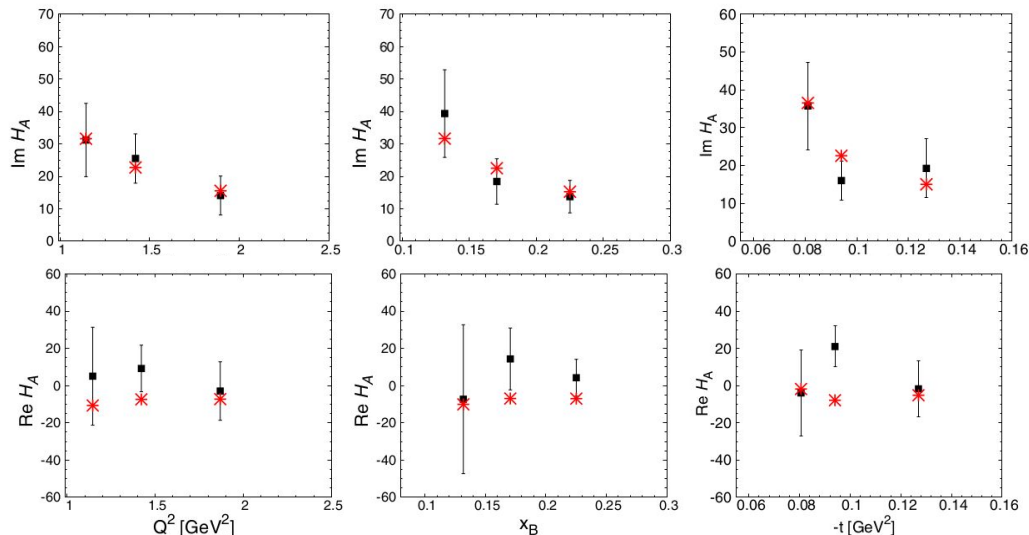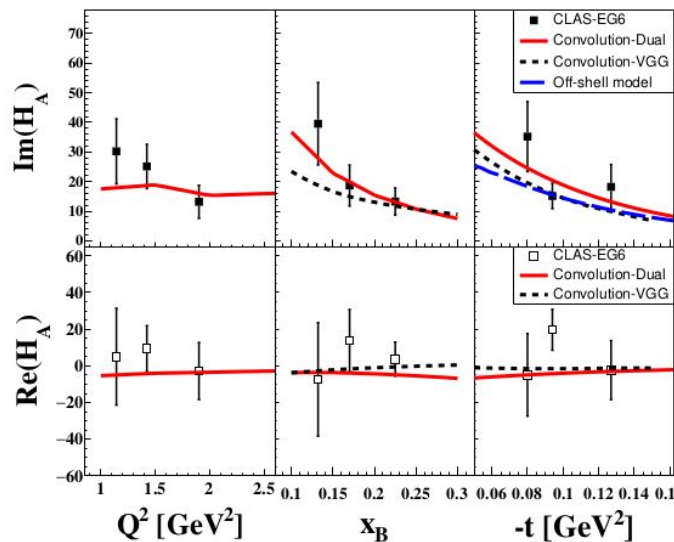
[Fucini, Scopetta, Viviani PRC '18]
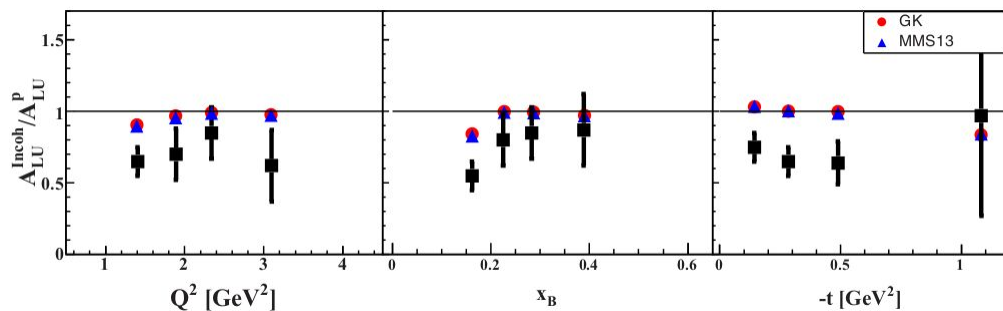
[Hattawy et al. (CLAS) PRL '17]
Curves [Liuti, Taneja '05; Guzey '08; Gonzalez-Hernandez et al. '13]

JLab CLAS ^{4}He DVCS Beam-spin asymmetry

- Spin zero: **1** chiral even GPD at leading twist → easier extraction

- Incoherent → direct detection of scattered proton
  - → breakup not detected

[Hattawy et al. (CLAS) PRL '19]
Curves [Liuti, Taneja '05]

[Fucini, Scopetta, Viviani PRC '20]

- Calculations do not include final-state interactions

- Sizeable nuclear effects in numerator/denominator
  Almost cancels in ratio

Near future JLab measurements

- Bonus12 data (DVCS / meson production)
  ↪ deuteron: incoherent w tagged proton

- Other CLAS12 data → S. Niccolai's talk
  ↪ (in)coherent deuteron

- Approved neutron DVCS Hall C exp.
  ↪ (in)coherent deuteron

- ALERT: Summer '24
  ↪ 4He/deuteron coherent, incoherent **with tagging!** (3H, p)
  ↪ can handle higher lumi, differentiate various light nuclei
  Off-forward EMC effect
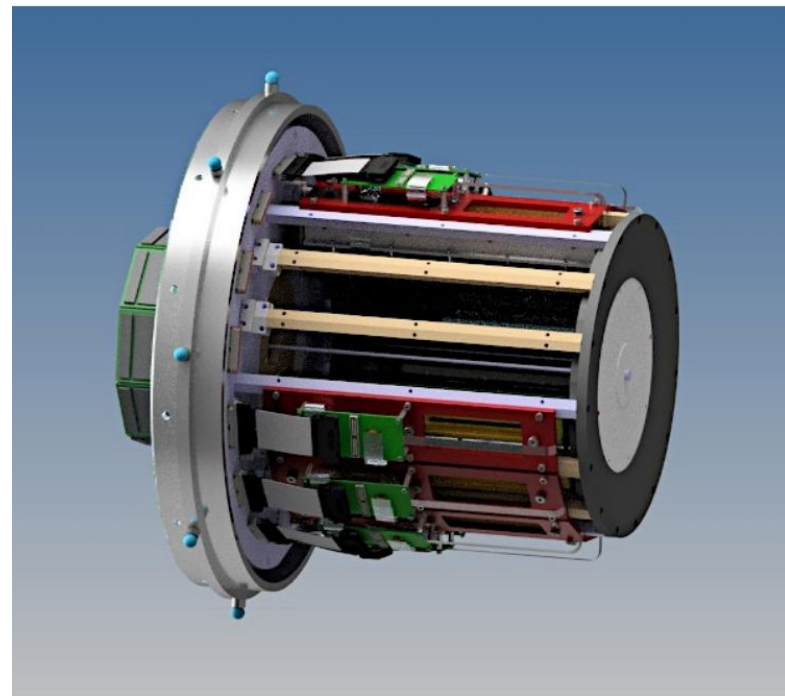
[ANL, IJCLab, JLab, NMSU, Miss.SU, ODU and Temple]

Future possibilities with EIC

- **Far-forward detectors (both IRs)**
  - → Nuclear fragments still have high momentum
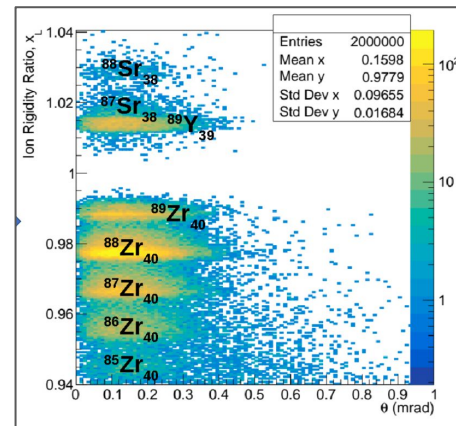 - → For breakup rigidity is different from the beam
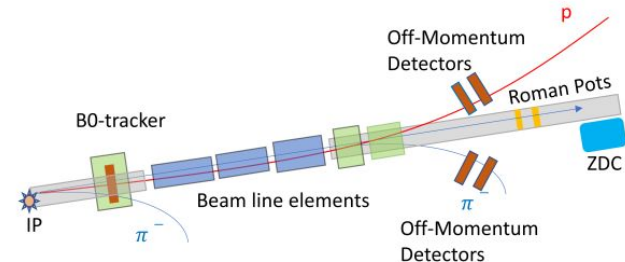
- **Possible addition of secondary focus**

For light nuclei, the 2nd focus enables *detection* with essentially 100% acceptance down to $p_T = 0$ (w.r.t the beam) for x > 0.01A.
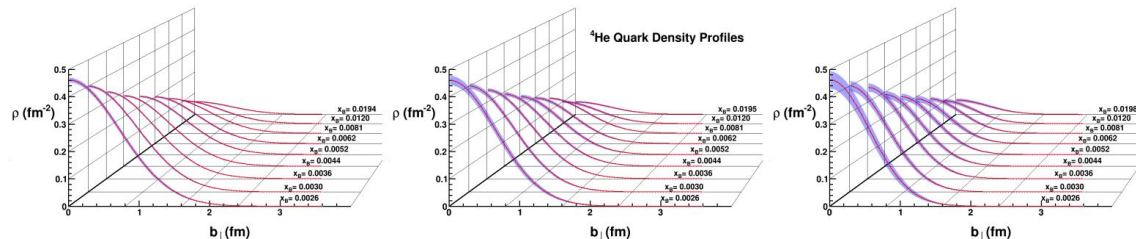
A 2nd focus will allow tagging of heavy spectators
- A-1 nuclei up to Zr-90
- A-2, *etc*, for almost any nucleus

[Nadel-Turonski @ EICUG Warsaw 23]

- **Kinematic coverage would enable nuclear tomography**

[EIC YR, TOPEG collaboration]

Conclusion

- Nuclear GPDs provide an avenue to a tomography of bound nuclear states

- Influence of nuclear interactions: bound nucleon tomography

- Tagged measurements will better constrain incoherent exclusive channels
  - → ALERT, EIC

- Many things left to explore/study
  - → Other channels (TCS, DVMP, etc.)
  - → Polarized light ions (tensor polarization)