Opportunities for nuclear measurements with a 2nd EIC detector

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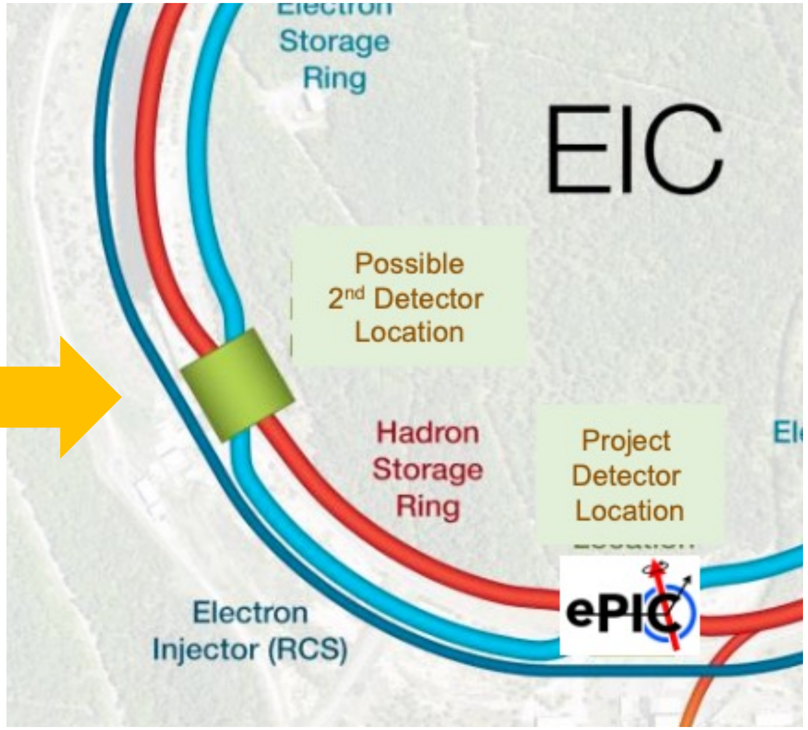
2[nd] Detector @ IP8



BNL-INT Joint Workshop: Bridging Theory and Experiment at the Electron-Ion Collider, INT, Seattle, June 2-6, 2025

Motivation for two detectors

JLAB-PHY-23-3761

Motivation for Two Detectors at a Particle Physics Collider

Paul D. Grannis* and Hugh E. Montgomery†

(Dated: March 27, 2023)

It is generally accepted that it is preferable to build two general purpose detectors at any given collider facility. We reinforce this point by discussing a number of aspects and particular instances in which this has been important. The examples are taken mainly, but not exclusively, from experience at the Tevatron collider.

arXiv: 2303.08228

Inspired by Mont's talk at the first EIC 2nd detector workshop in December 2022.

A second detector for the EIC

- Independent cross check of results and confirmation of discoveries
  - Crucial for the EIC which is a facility that is unique worldwide.
  - Requires a general-purpose collider detector supporting the full EIC science program.

- Additional physics opportunities – more details later in the talk

- Cost-effective
  - Adding a 2^{nd} detector is does not significantly increase operations costs of the facility
  - Construction is a one-time cost – limited impact on annual nuclear physics budgets

- Timeline - lessons from Fermilab
  - The D0 detector came 7 years after CDF, but both made comparable contributions to the science program.
  - A 2^{nd} EIC detector would come online when the machine operates nominal parameters (after early running)
  - A slightly longer timeline may allow users who currently have other commitments to get involved with the EIC

- Adding a second detector will benefit ePIC
  - Users who are interested in a 2^{nd} detector may join the EIC early
  - This happened with spectroscopy in CLAS before GlueX was built

EIC UG 2nd detector working group

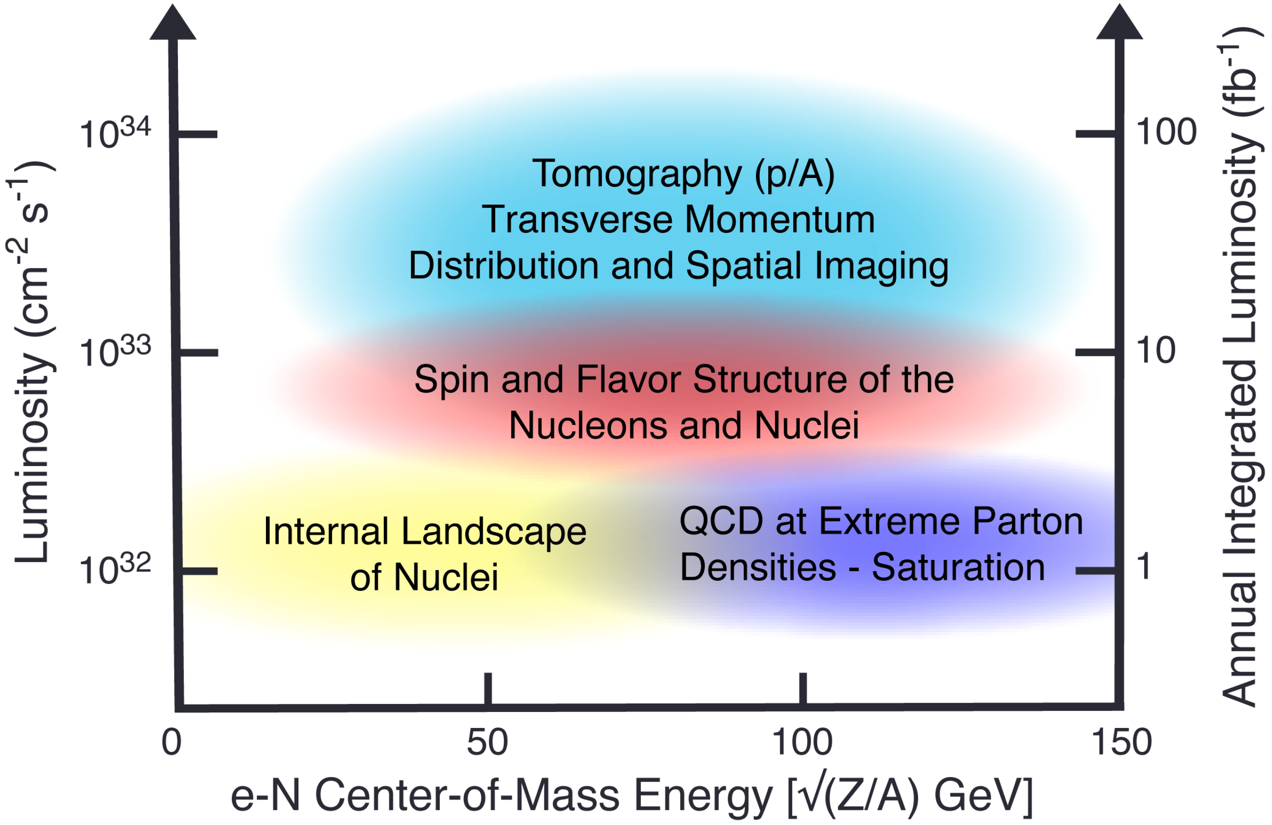
- Established in 2022 following DPAP and the establishment of the ePIC collaboration

- After a break last fall, monthly public meetings will resume later this summer
  - If you have something you would like to show or discuss, please contact the conveners below

- An important charge is to prepare for a 2nd detector white paper – theory input will be essential

- Current conveners
  - Anselm Vossen (Duke U) anselm.vossen at duke.edu
  - Björn Schenke (BNL) bschenke at bnl.gov
  - Charles Hyde (ODU) chyde at odu.edu
  - Charlotte van Hulse (U of Alcalà) charlotte.barbara.van.hulse at cern.ch (also EIC UG steering committee)
  - Pawel Nadel-Turonski (U of SC) turonski at sc.edu
  - Simonetta Liuti (UVA) sl4y at virginia.edu
  - Vasiliy Morozov (ORNL) morozovvs at ornl.gov
  - Wenliang “Bill” Li (MS State U) wenliang.li at msstate.edu

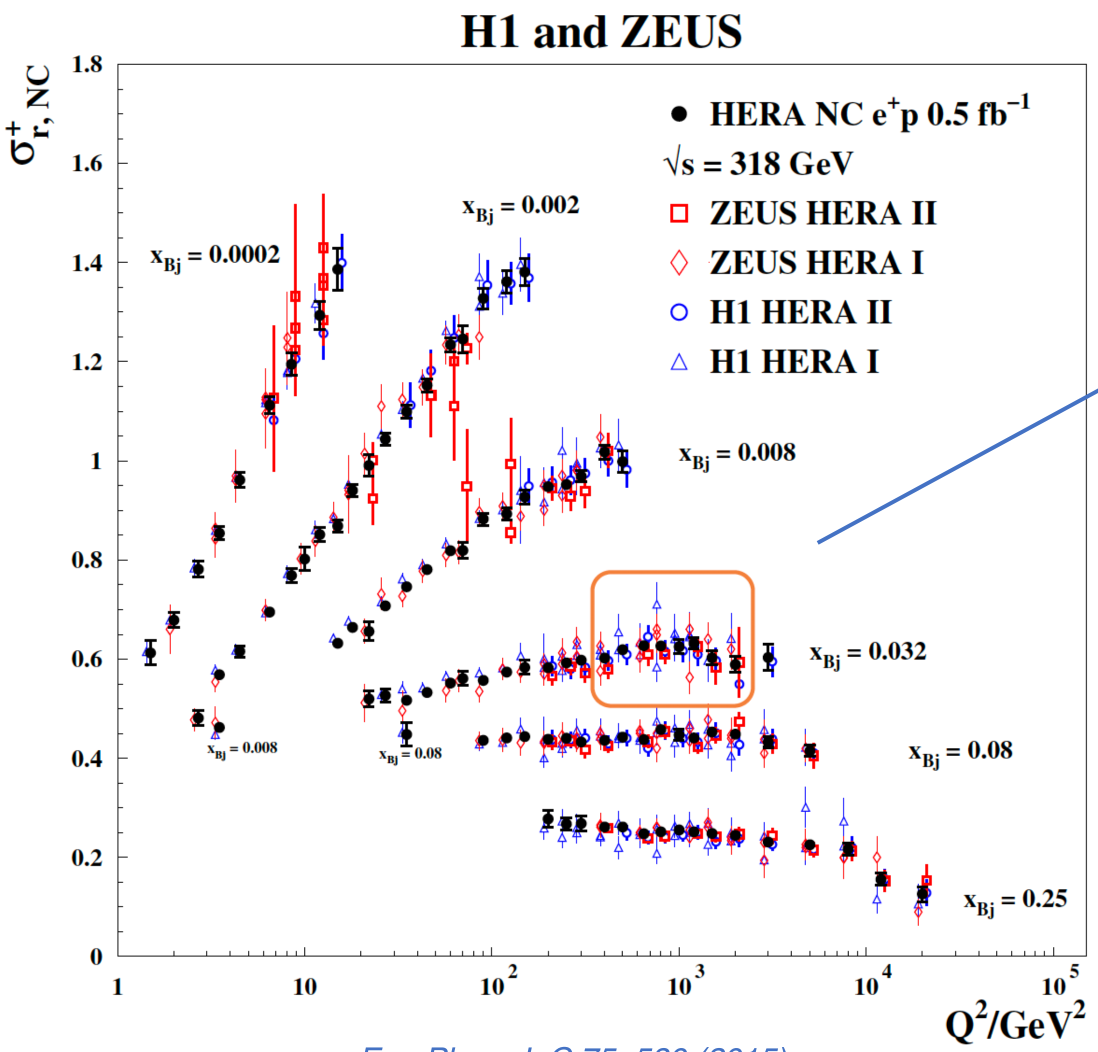
Luminosity, acceptance, and systematics



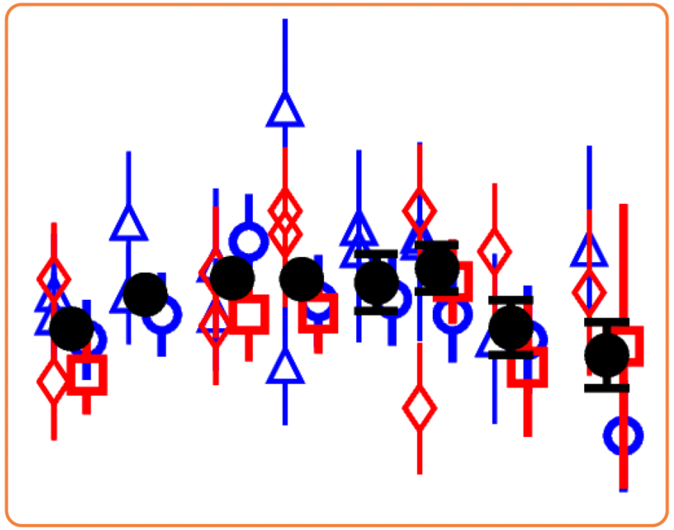
- Tomography / imaging require high luminosity – but also benefit most from better far-forward **acceptance**
- After reaching design luminosity, many EIC measurements will become **systematics** limited.
- While It is natural to focus on early running, one should not forget what will be the EIC legacy

A 2nd detector with improved far-forward acceptance will have a large impact on all aspects of the EIC science program.

Reduction of systematics at HERA



Eur. Phys. J. C 75, 580 (2015)



- If two complementary detector are not *too* different (as at JLab), and use similar binning, it is possible to combine data.
- In some kinematics the combined data have dramatically reduced systematic uncertainties.
- The EIC luminosity will be 100 times higher.

A second detector for the EIC – new opportunities

The details the 2nd detector are not yet defined.
Users will have a significant impact on design and construction.
Still, there are some natural ways for a second detector to expand the capabilities of the EIC.

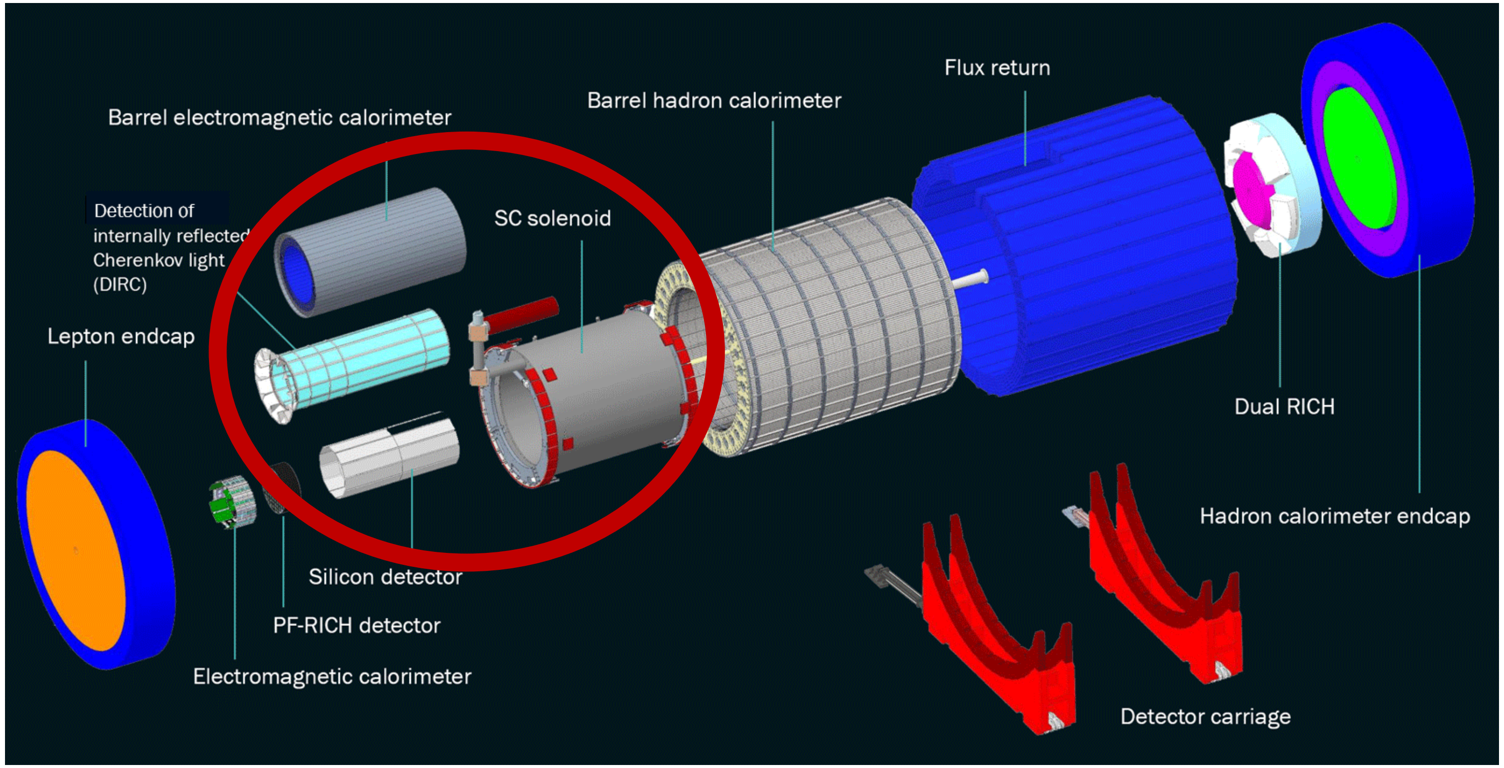
- Taking advantage of much-improved near-beam hadron detection enabled by a second focus in IR8
  - Low-x / low-p_T proton acceptance – (exclusive / diffractive reactions)
  - Detection of light nuclei from coherent processes – (down to p_T = 0 at mid-to-high x)
  - Tagging a wide range of spectator nuclei, including A-1 for reactions on a bound nucleon
  - Vetoing breakup of heavier nuclei by being able to detect the produced fragments
  - Properties of the nuclear final state – (hypernuclei, rare isotopes, etc, including gamma spectroscopy)

- Pursue complementarity with ePIC and synergies with the forward detection, which could include
  - Much-improved muon identification – (quarkonia, TCS/DDVCS, jets, BSM, …)
  - Higher magnetic field for better tracking resolution – (diffraction on heavy nuclei, hadron spectroscopy)
  - High-resolution barrel EMcal – (DVCS on nuclei, hadron spectroscopy)
  - Improved hadron PID in the barrel from continued DIRC R&D – (SIDIS, jets, hadron spectroscopy)

A starting point for the 2nd detector

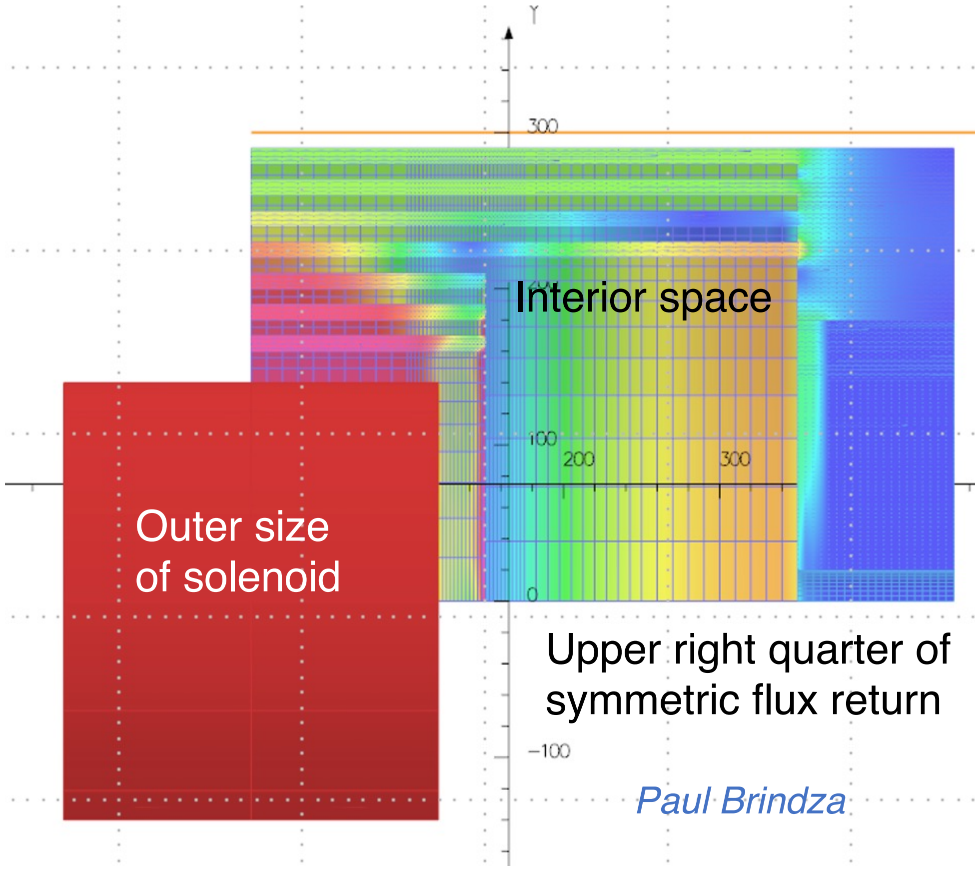
- How wide should it be?
  - The solenoid should roughly match the size of the ePIC inner detector (not solenoid or Hcal)
  - This can be done while increasing the field from 2 T to 3 T by reducing the empty space in-between the EMcal and the solenoid cryostat by 20 cm
- How long should it be?
  - A slightly shorter solenoid would create more interior space making it possible to revert to the original DPAP specification of +/- 4.5 m
  - A shorter, symmetric detector makes accelerator integration easier
- Not the only possibility, but a reasonable starting point.

ePIC



- 142 cm inner (bore) radius of the SC solenoid (similar to BaBar)
- 116 cm outer radius of the barrel EM calorimeter (from J. Lajoie)
- **ePIC would fit into a bore with a 120 cm radius**

First study of a detector 2 solenoid

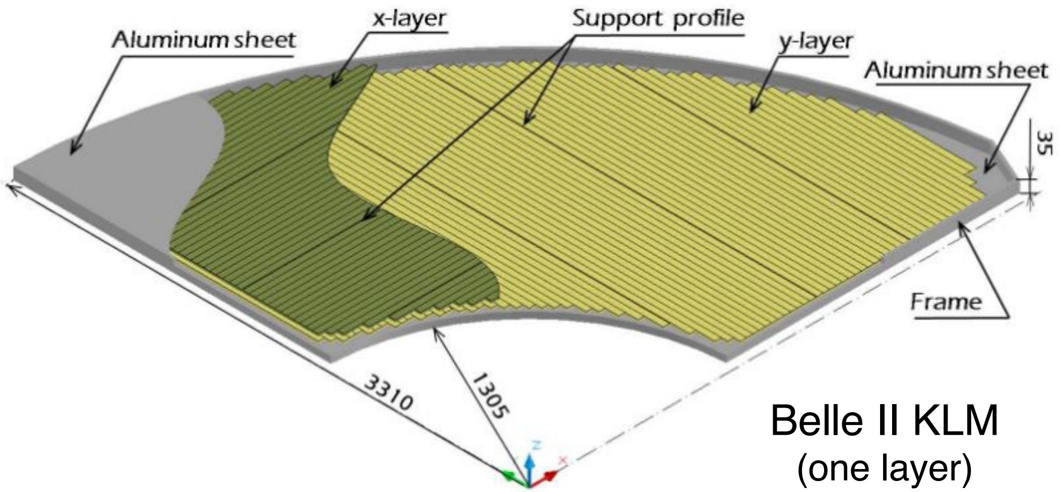


- Comparison with ePIC (MARCO) solenoid
  - 30% (1 m) shorter coil
  - 15% smaller inner (bore) radius
  - 3 T achievable within a 3 m outer radius
  - More interior space available closer to the endcaps where many services will be routed.
- Symmetric flux return
  - Reduced coil forces → thinner cryostat
  - +/- 4.5 m overall detector length (original DPAP spec)
    - same solenoid-to-endcap desistance on hadron side, and more space on the electron side than in ePIC
  - Integrated with KLM-like Hcal in the barrel

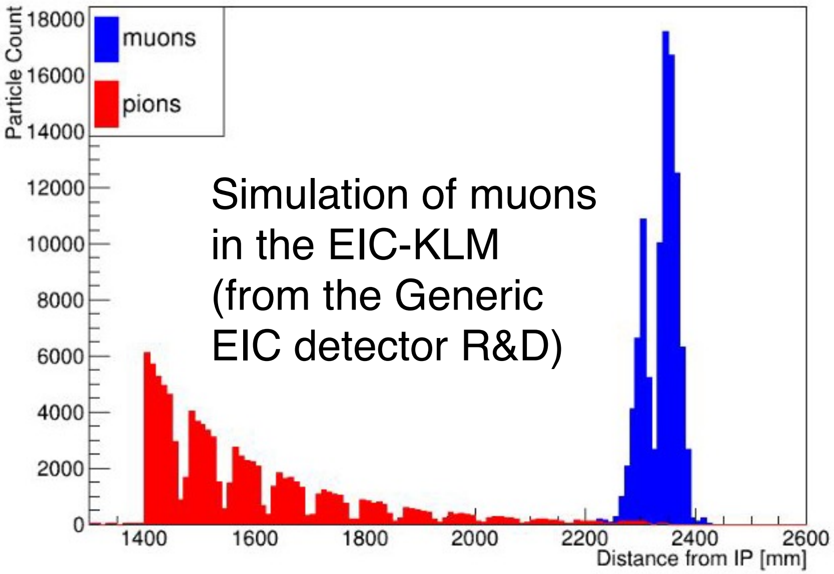
Note: the tracking resolution depends on the B-field and the tracker radius – not the solenoid radius

Muon identification for a 2nd EIC detector

- Most Hcals can provide some level of muon ID, but an optimized system would improve both the efficiency and purity.
  - A high level of segmentation along the muon path is more advantageous than typical Hcal “towers”
- Ongoing R&D uses the Belle II KLM as a starting point, but adds precision timing and energy measurements in each layer.
  - In combination with AI methods for reconstruction, simulations suggest that the EIC-KLM seems to be a surprisingly good Hcal.
- Since the Hcal is part of the solenoid flux return, they should be designed and optimized together.

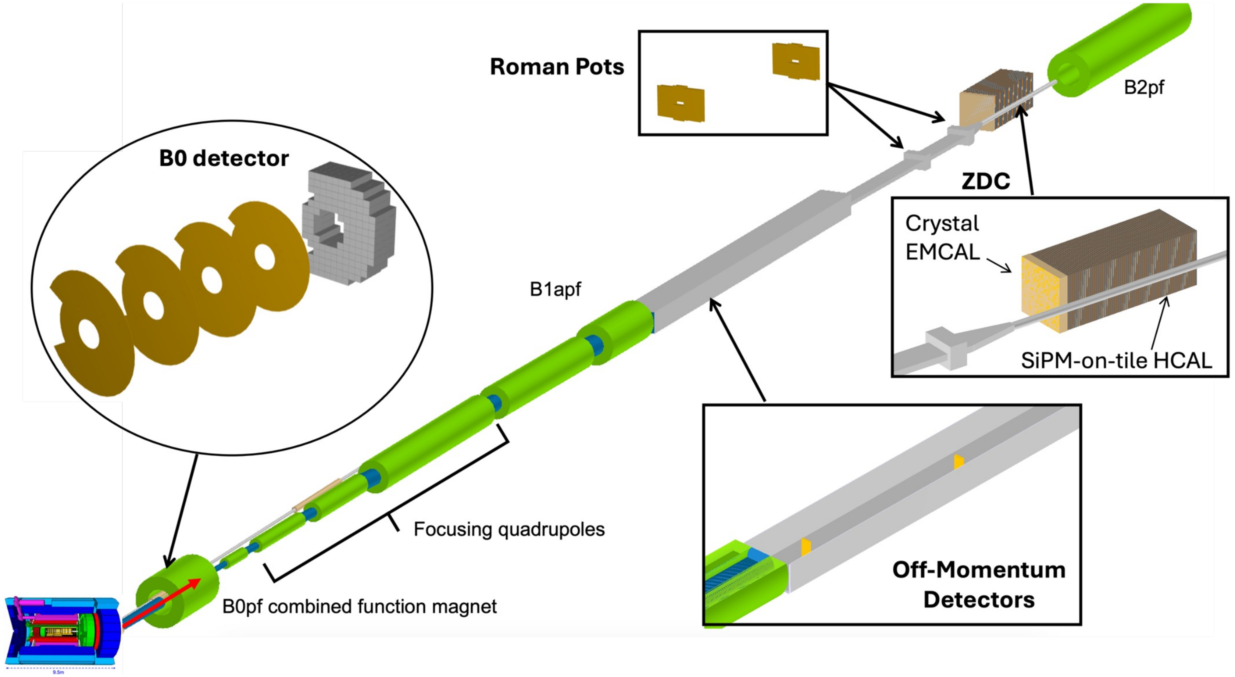


Belle II KLM
(one layer)



Simulation of muons in the EIC-KLM (from the Generic EIC detector R&D)

Far-forward near-beam detection at the EIC

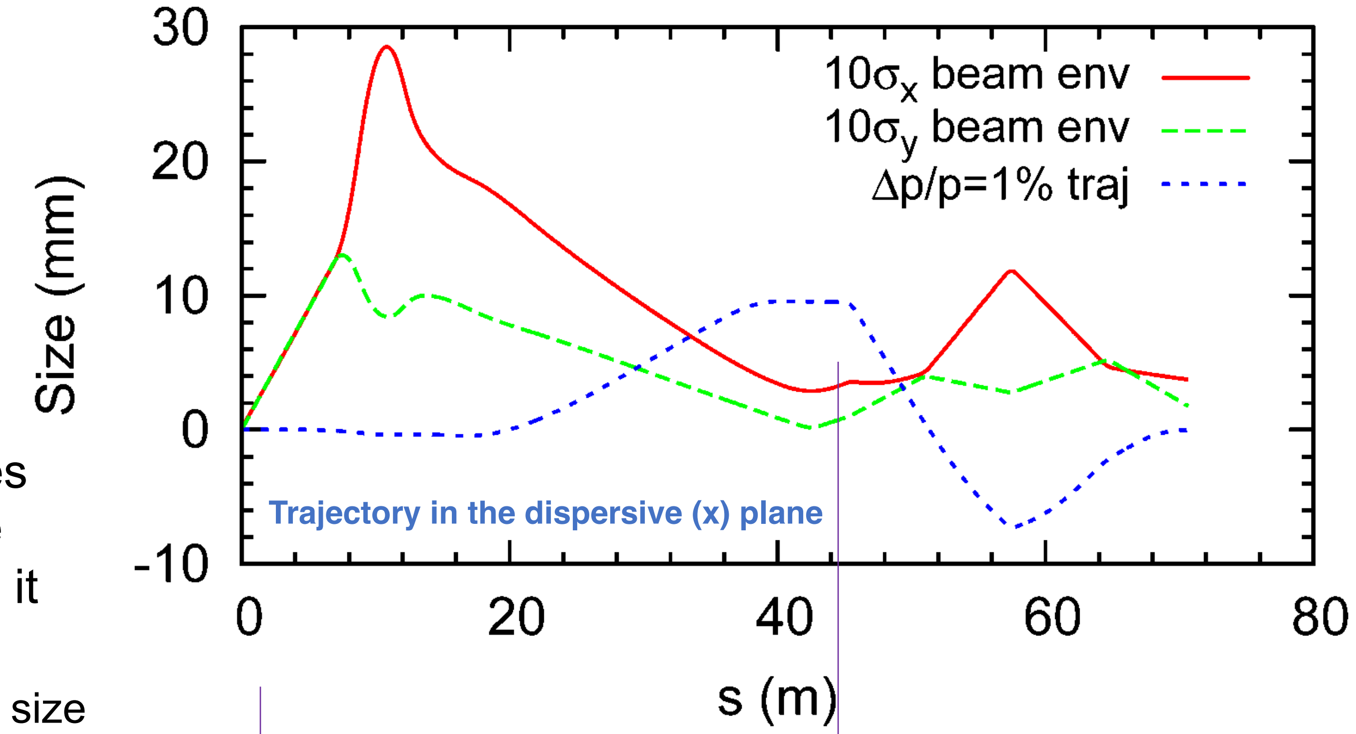


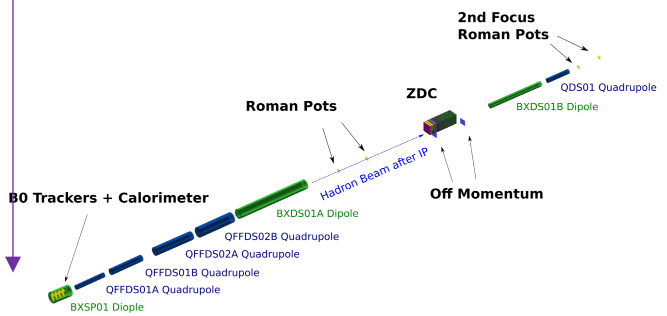
- The ePIC IR (IR6) provides a comprehensive set of forward detectors at several locations.
  - Inside B0 dipole, off-momentum detectors, ZDC, Roman Pots
  - Fully integrated with the accelerator
  - A great jump in capability compared with HERA

- However, an optics with a second focus at the Roman pots would offer further improvement.

How the second focus works

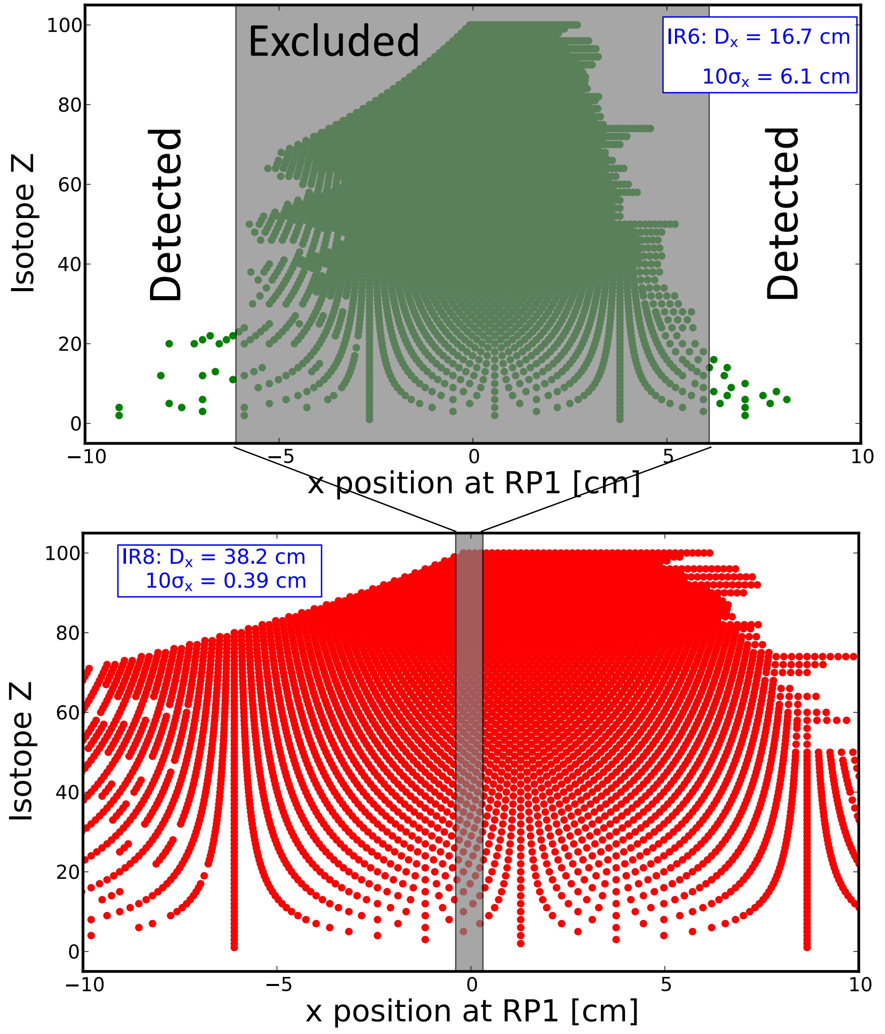
- Idea: make the beam small at the location where the transverse displacement of scattered particles is the greatest
  - Displacement: dr = dispersion * dp/p
  - In DIS, dp/p ~ x
- A particle (blue) initially scattered at 0 degrees ($p_T = 0$) briefly emerges from the beam at the second focus about 40 m downstream where it can be detected
  - Compare trajectory with horizontal (red) beam size
  - Particles with $p_T > 0$ emerge earlier
- With a second focus one is not as limited by the angular spread of the beam at the IP
  - Makes it possible to combine high luminosity and good forward acceptance.





EIC far-forward acceptance with and without a 2nd focus

Ion fragments from ^{238}U



x position ~ A/Z

Without 2nd focus:
(EPIC @IR6)

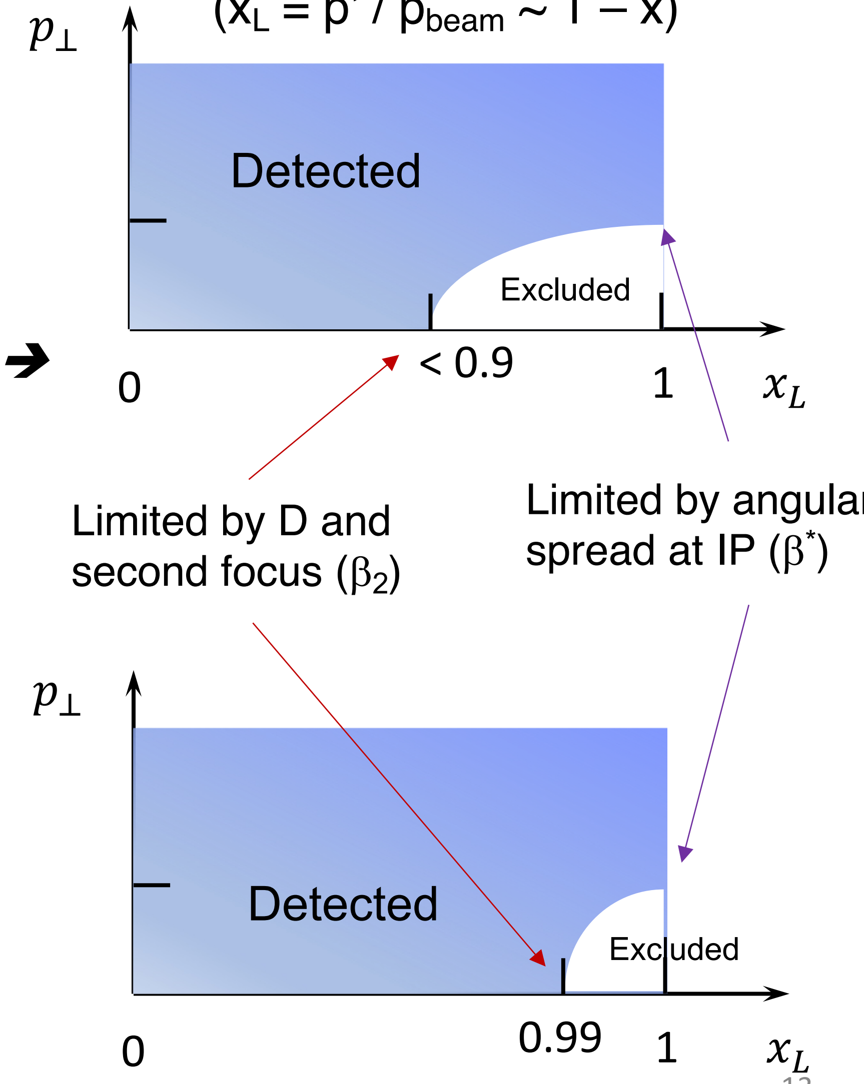
← Z' vs x_{RP} $p_\perp$ vs x_L →

With 2nd focus:
(Detector 2 @ IR8)

Order-of-magnitude improvement in forward acceptance

Exclusive protons

($x_L = p' / p_{beam} \sim 1 - x$)



^{238}U – using deformed nuclei to increase the effective nuclear thickness

- At the EIC, nuclei will be used to probe gluon saturation

$$Q_s^2 \sim A^{1/3}/x^{0.3}$$

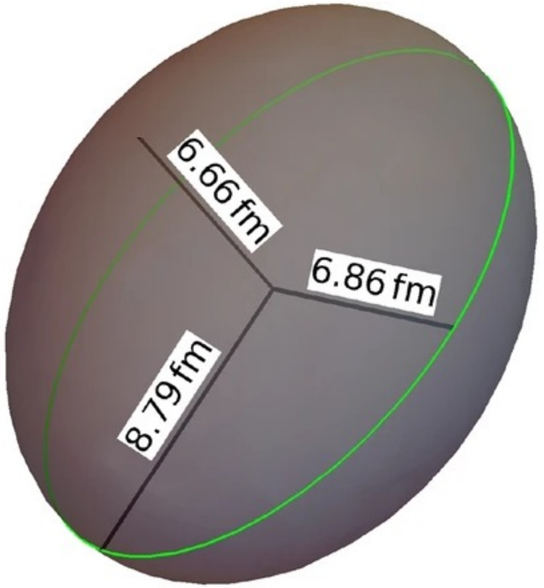
- However, not all nuclei are spherical.
  - In ^{238}U the long axis is 1.3 times longer than the short ones.
  - If we could isolate events with hits along the long axis, it would correspond to doubling the actual mass (**A ~ 500**).

- We cannot polarize heavy nuclei
  - ^{238}U in particular has a 0^+ ground state.

- But can we use the final state to select events with a favorable orientation of the long axis (*i.e.*, maximize the thickness)?

- Could be applied to any process that breaks up the nucleus.

^{238}U

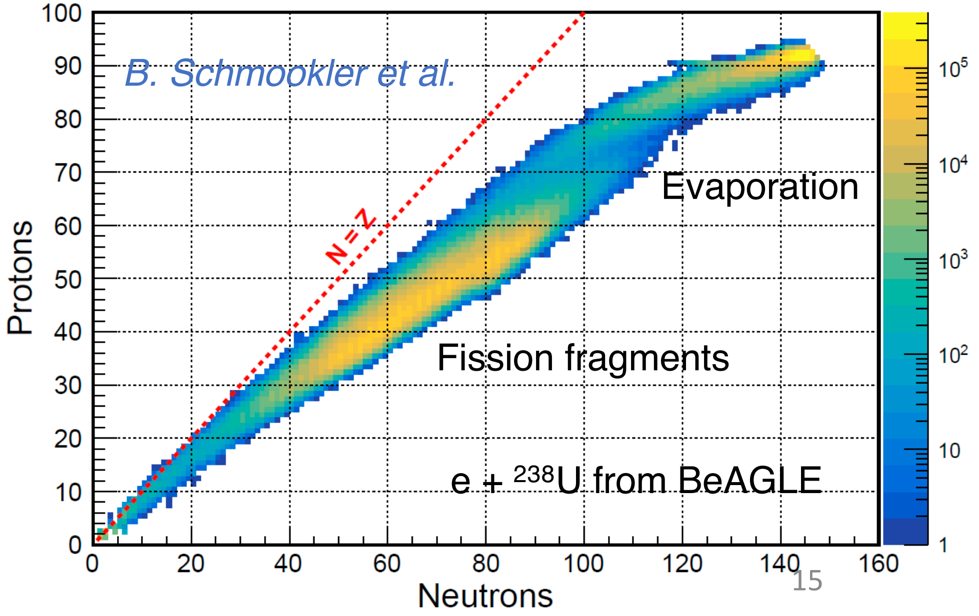


Nucl. Sci. Tech. 35, 218 (2024)

Correlating nuclear thickness with forward activity

- In high-energy eA scattering most nuclei can fission, but ^{238}U fissions most of the time.

- An event with a large thickness is likely to produce more breakup, but the forward activity is more than ”evaporation” neutrons.
  - Fission fragment produce neutrons
  - Protons and light ions are also emitted (high excitation)

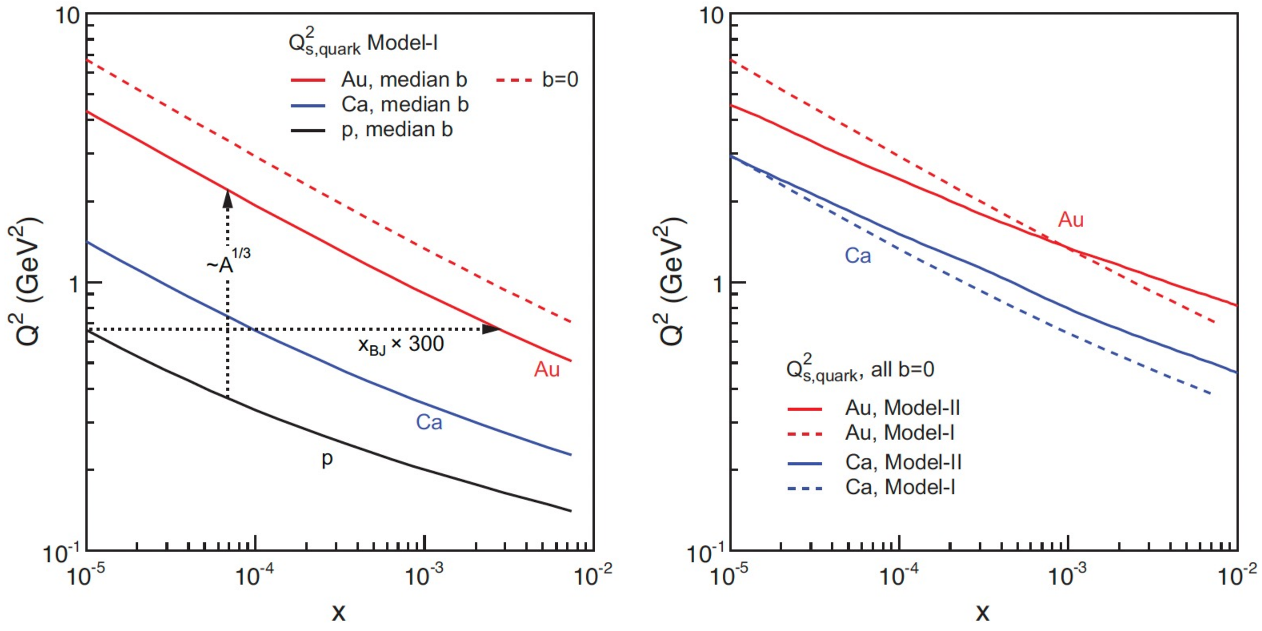


- With a second focus we can detect the complete final state including the fission fragments.

- Initial studies in 2017 (M. Baker) showed a distinct “tail” of events corresponding to large thicknesses. Recently, B. Schmookler has started a study using current versions of the BeAGLE generator and EIC parameters. Stay tuned for results!

Impact parameter contribution mentioned in the EIC white paper

EIC WP arXiv:1212.1701

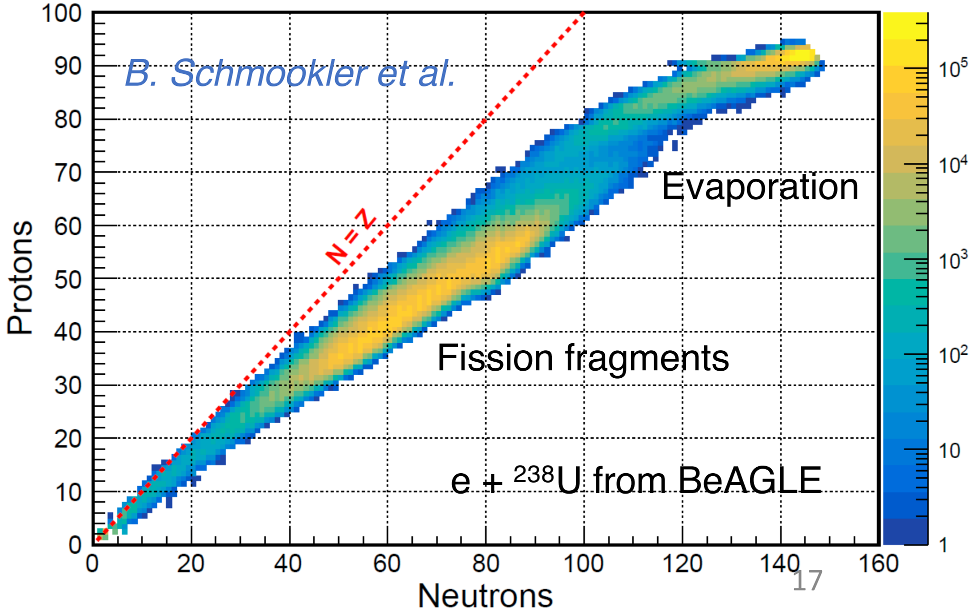


- The EIC WP showed the standard $A^{1/3}$ enhancement compared with b = 0.
- However, BeAGLE studies suggest that average and max thickness (b = 0) are not as easily distinguishable as a hit along the long axis in a deformed nucleus.
- The impact parameter and orientation add.

Using final-state information to select a subsample with a larger nuclear thickness could complicate the theoretical interpretation, but also create new opportunities.

Fragment detection – exotic nuclei and rare isotopes

- Nuclear fragments produced in eA scattering are interesting in their own right.
- The EIC will continuously produce exotic nuclei that could be detected using a second focus.
  - Associated γ photons (boosted to a higher energy) can be detected in the ZDC and possibly B0.



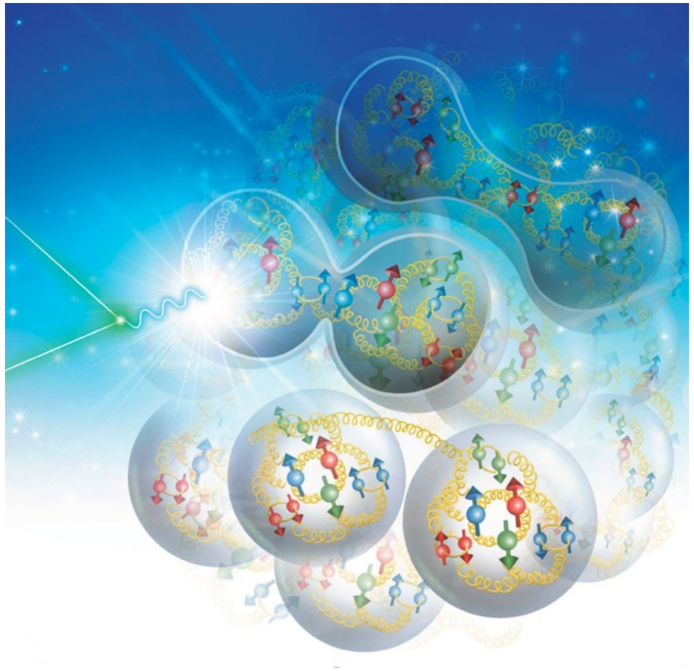
- The EIC will not reach the rare isotope production rates of specific runs at FRIB, but can be comparable in certain regions
- The very different reaction mechanism and ability to create unusual states before the start of de-excitation though pion production makes has created an interest in the FRIB community.
  - Even a moderate involvement by the low-energy NP community could be important for a 2nd detector.

A-1 spectator tagging: the nucleon in a nuclear medium

- Neutron structure can be accessed by tagging the protons in deuterium or ^{3}He.

- However, A-1 spectator tagging becomes progressively more difficult the heavier the spectator nucleus is since its rigidity will differ little from the beam.

- A second focus enables tagging of most spectator nuclei, enabling comparisons of reactions on free and bound protons.
  - Nuclear theory input would be needed for the interpretation.



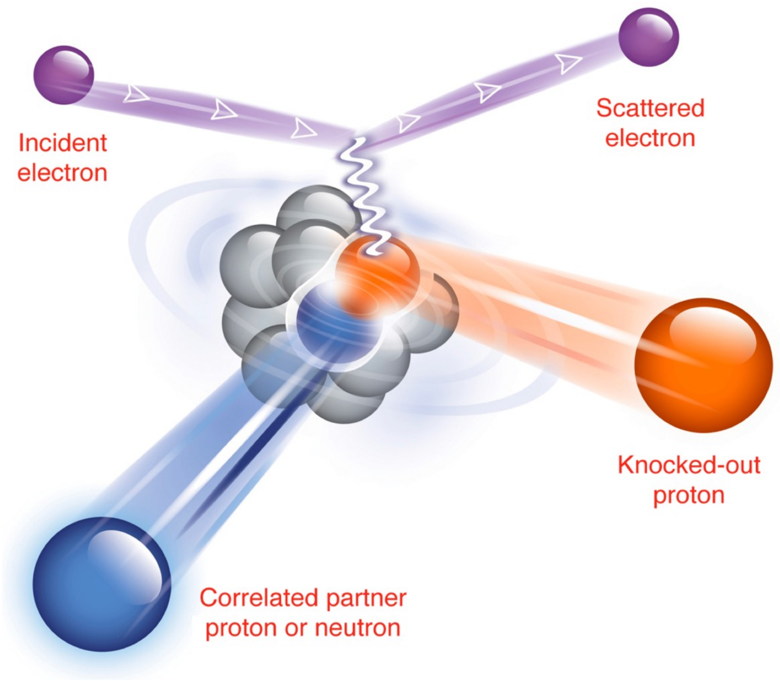
- Question: (how) do the spatial distributions of quarks (DVCS) and gluons (charmonium) in protons and neutrons change when they combines with other nucleons to form nuclei?
  - A high-res. EMcal for nuclear DVCS and muon ID for charmonium are synergetic capabilities

A-2 spectator tagging: short-range correlations

- Knockout of a nucleon in a short-range correlation (SRC) with another nucleon leads to the ejection of both.

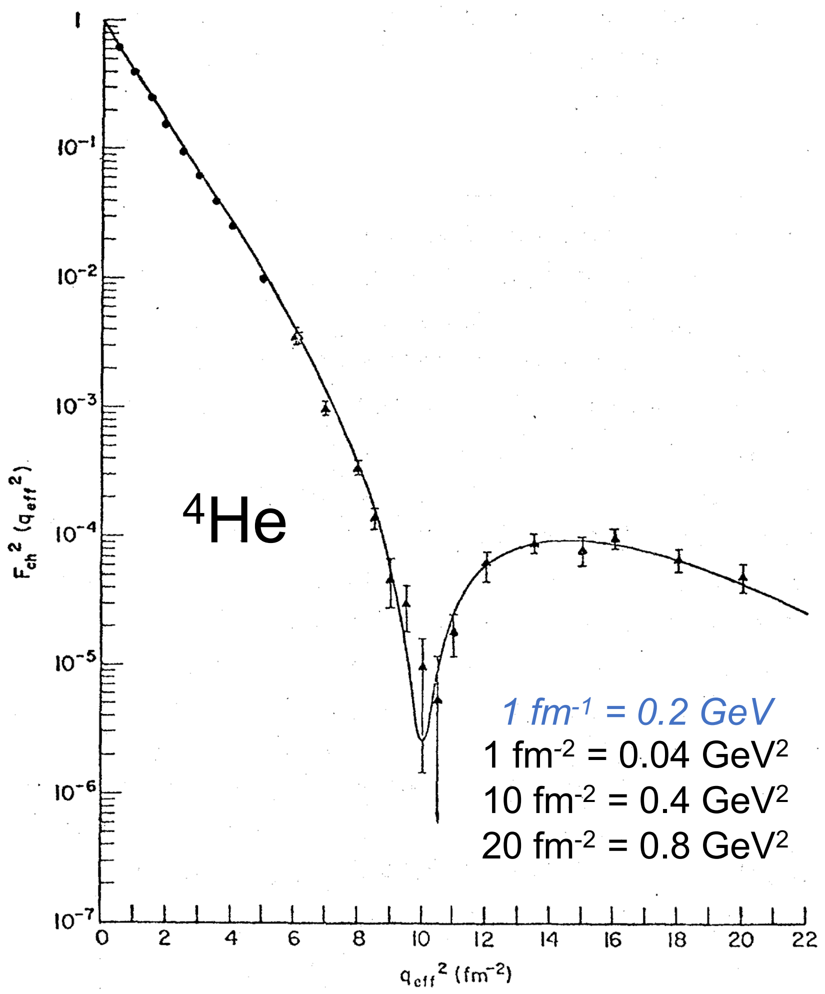
- Due to the large relative momentum, one of the two nucleons often ends up outside of the acceptance.

- If we would want to measure the structure of a nucleon in an SRC, it is often advantageous to detect one of the nucleons and the A-2 spectator nucleus.



- With a second focus we could detect the A-2 nucleus from both p-p and p-n SRCs.
  - Emission of both a proton and neutron only changes the magnetic rigidity by a small amount
  - For p-n, consider for instance ^{36}S to ^{34}P or ^{32}S to ^{30}P.

Coherent scattering on light nuclei



- Detection of the recoiling nucleus unambiguously separates coherent and incoherent scattering.

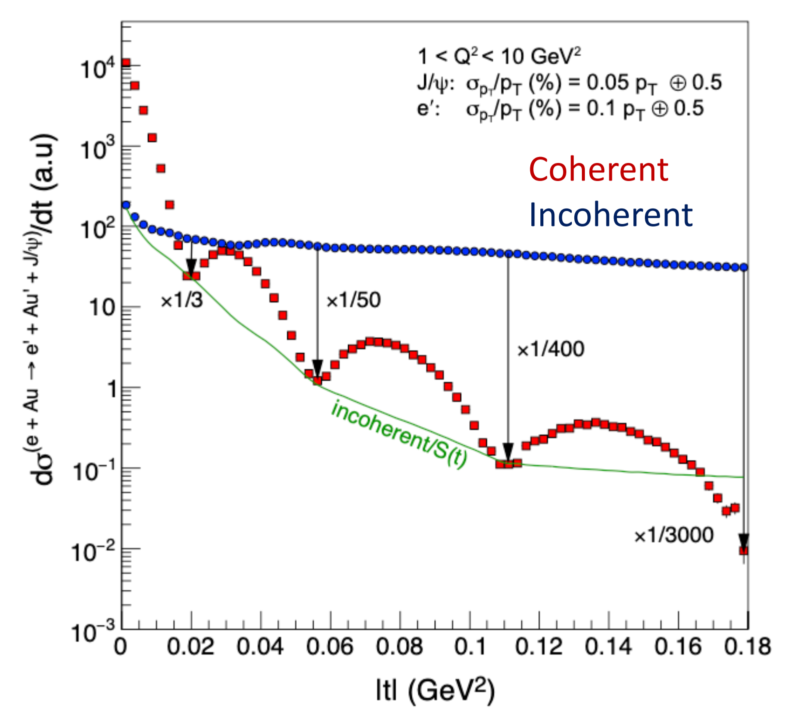
- For a given momentum transfer the response of the nucleus scales unfavorably with A.
  - Without a second focus one can only catch the high-t tail.

- A second focus makes it possible to detect events down to $p_T = 0$ for $x \gtrsim 0.01A$, and catch most of the distribution at lower x.
  - Essential for measurements on light ions like He and Li

- ^{7}Li is of particular interest since it may be polarized.
  - Ion source seems relatively straightforward to develop
  - The t-acceptance for ^{7}Li with a second focus would be better than for He without one.

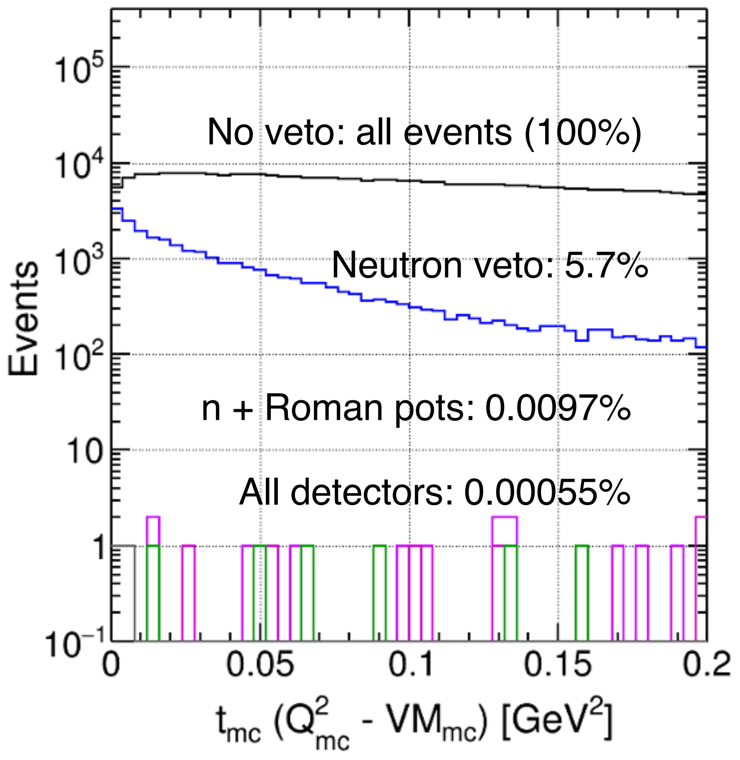
Coherent diffraction on heavy nuclei vetoing breakup with a second focus

Reference from EIC YR p.352



At the third diffractive minimum, a rejection factor for incoherent event better than 400:1 (0.0025% inefficiency) must be achieved

Veto inefficiency for incoherent events

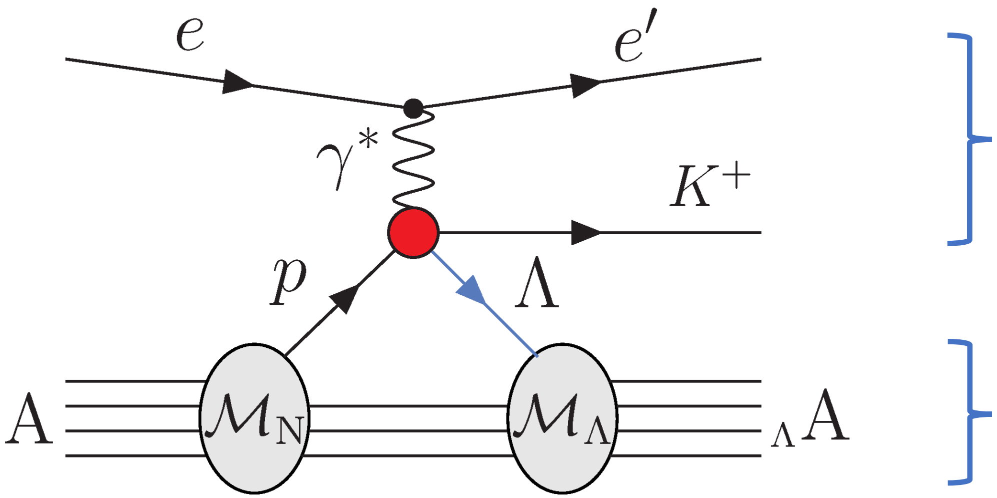


J. Kim

Fragment detection in Roman pots at the second focus suppresses incoherent backgrounds even at large *t*.

Also applicable to, *e.g.*, DVCS on medium nuclei

Production and detection of hypernuclei



Detected in the central detector

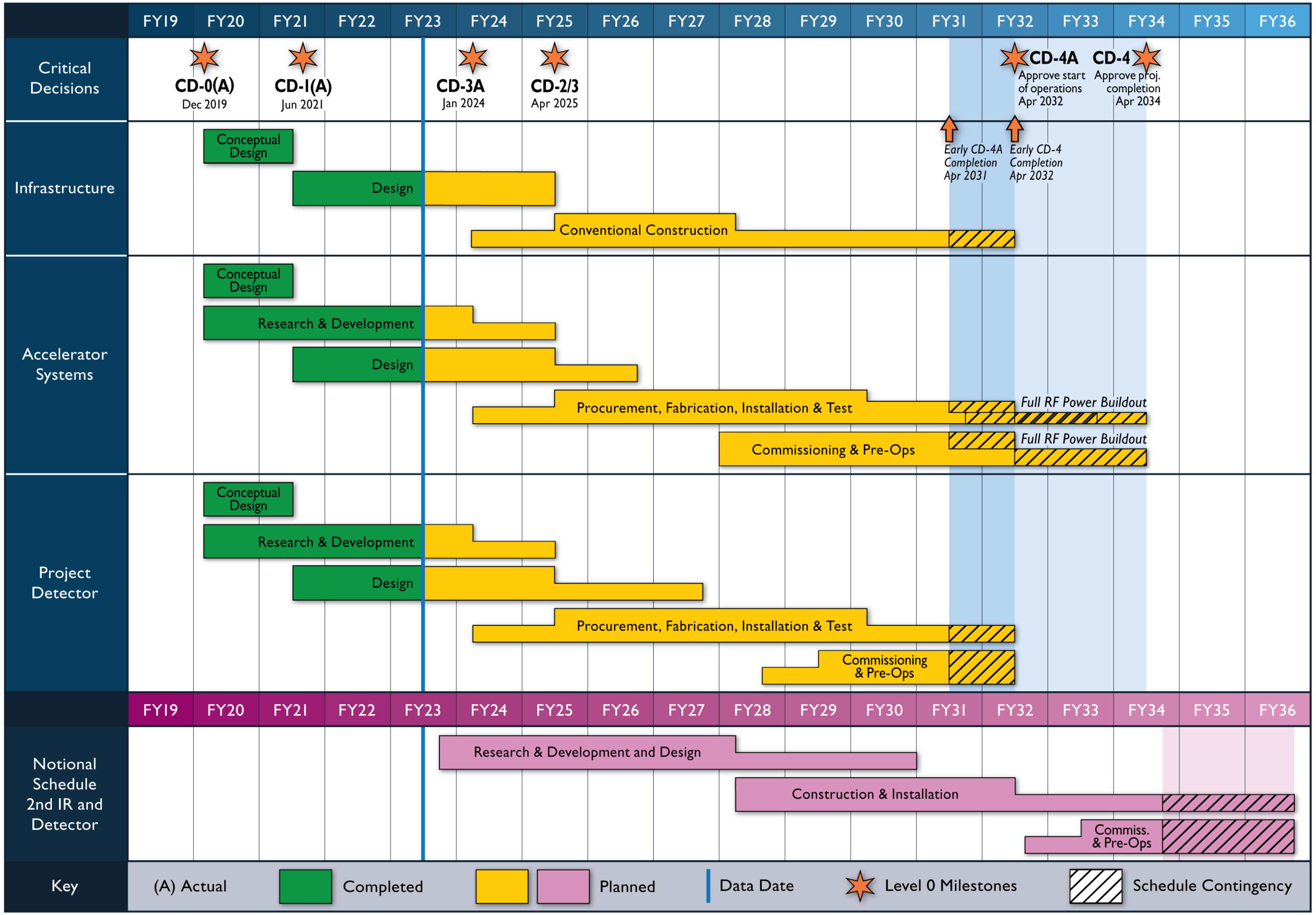
Detected in the far-forward detectors

- Coherent exclusive K^+ production creates a hypernucleus differing by one unit of charge.
  - Sufficient for any hypernucleus to be detected by the 2^{nd} detector using the second focus of IR8
    - Many will decay in flight, but there is a long straight between the magnets and detection point
  - Coincidence with K^+ will provide a clean signature

- Hypernuclei can be discovered and characterized
  - Boosted gamma photons can be detected at the ZDC and B0
  - Synergistic with studies of rare isotopes

Tentative schedule including a 2nd detector

Jim Yeck, EIC 2nd detector workshop, May 2023



A little out of date but nevertheless illustrative

2nd detector

Summary and outlook

- Having two detectors at the EIC will provide the necessary cross checks of discoveries and reduce systematic uncertainties (*cf.* H1 and ZEUS)

- A 2nd detector will also introduce new and opportunities beyond the Yellow Report

- Expanded eA capabilities form a natural path for a 2nd detector and could form an important part of its program

- A white paper for a 2nd EIC detector is on the horizon. Your participation is essential to make it a success!

Thank you!

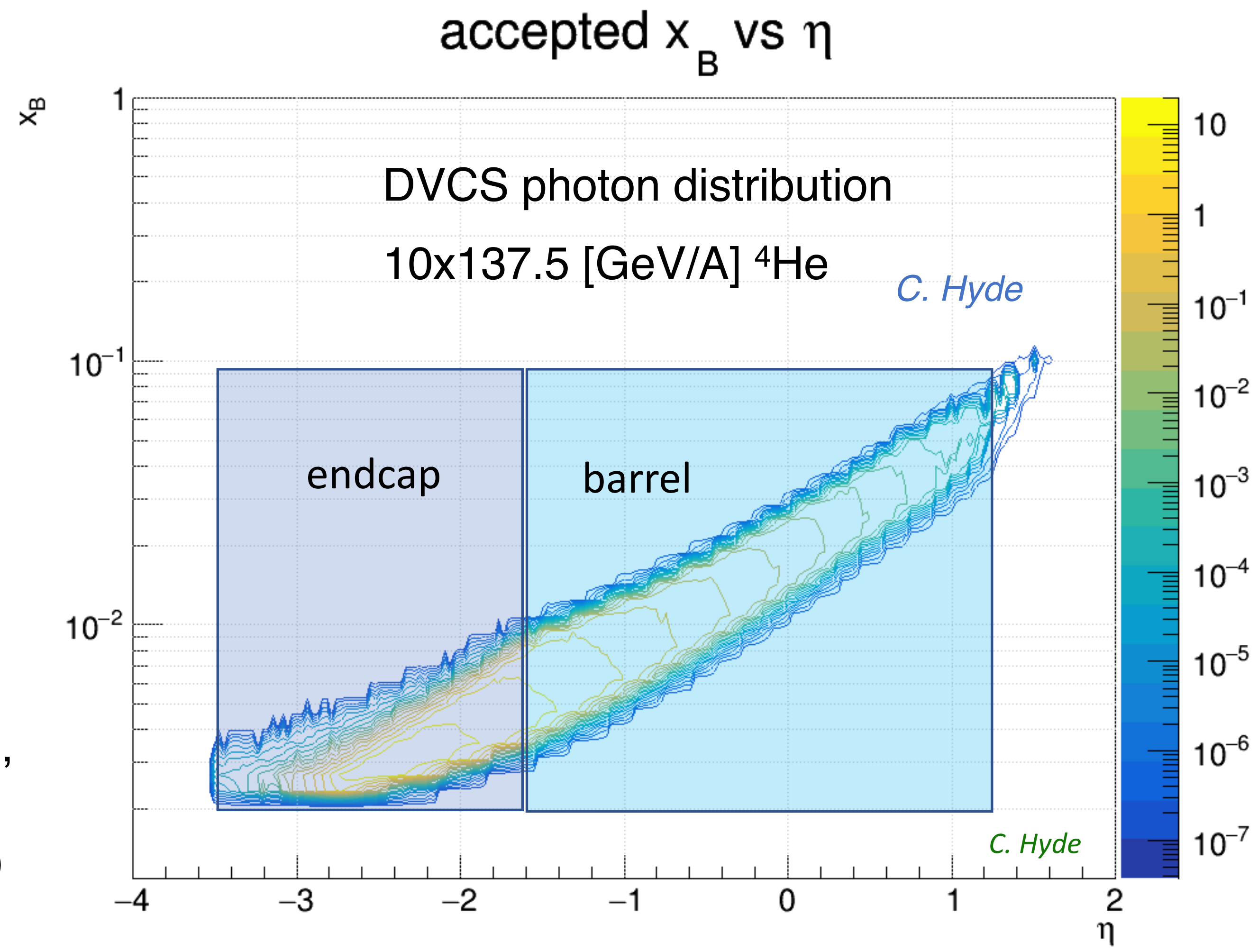
DVCS on nuclei

- In DVCS on the *proton*, both the photon and proton are detected for exclusivity
  - t can be determined from the ***proton***

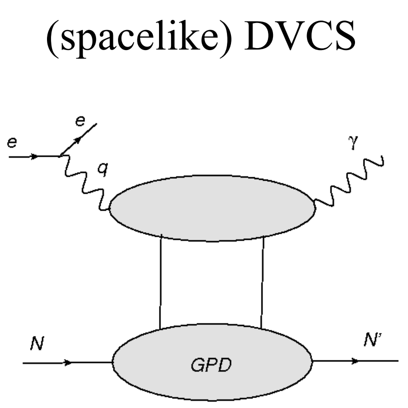
- In DVCS on the *nuclei*, the nucleus has to be detected or the breakup vetoed to ensured coherence and exclusivity.
  - t is determined from the ***photon***

  (*cf.* coherent VM production on nuclei)

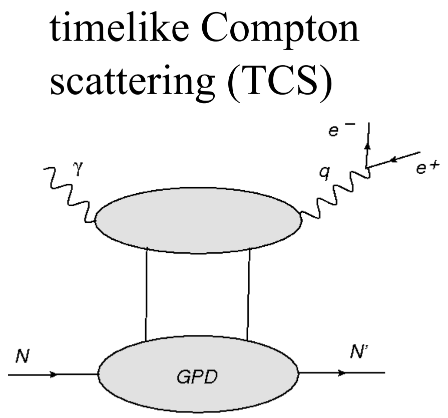
- For the best measurement of DVCS on nuclei, the 2nd EIC detector should have:
  - **low-t acceptance** (provided by the 2nd focus)
  - **high-resolution EMcal** coverage in the barrel



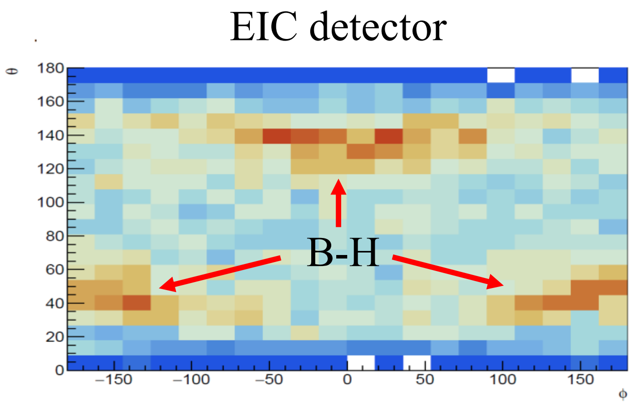
Timelike Compton Scattering (exclusive dilepton photoproduction)

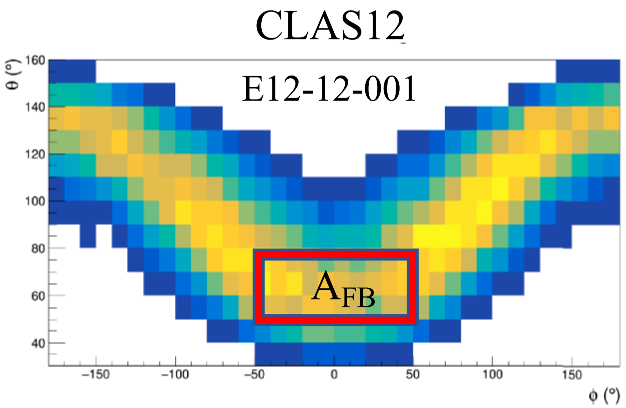


Initial photon spacelike, final photon real



Initial photon real, final photon timelike → $l^+ l^-$

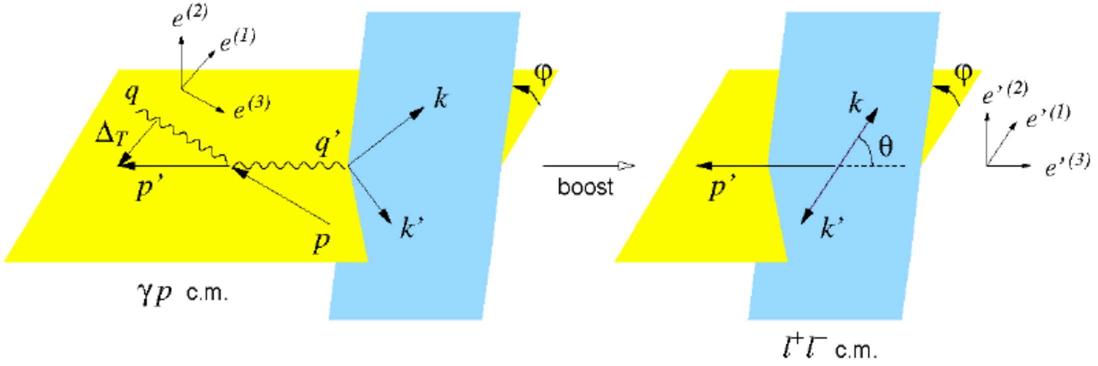




P. Chatagnon, EIC UG meeting, Warsaw, 2023

- TCS analysis uses the lepton c.m. angles θ and ϕ
  - Integration over the angles projects out amplitude (CFFs)

Eur. Phys. J. C 23, 675 (2002)



- Fixed-target experiments have limited forward acceptance
  - Loss of useful statistics and complicated systematics
- EIC benefits from excellent dilepton acceptance.

- k,k' = momentum of e^-, e^+ or μ^-, μ^+
- θ = angle between the scattered proton and the electron
- φ = angle between lepton scattering- and reaction planes

Double DVCS ($Q^2 < Q'^2$ => TCS-like)

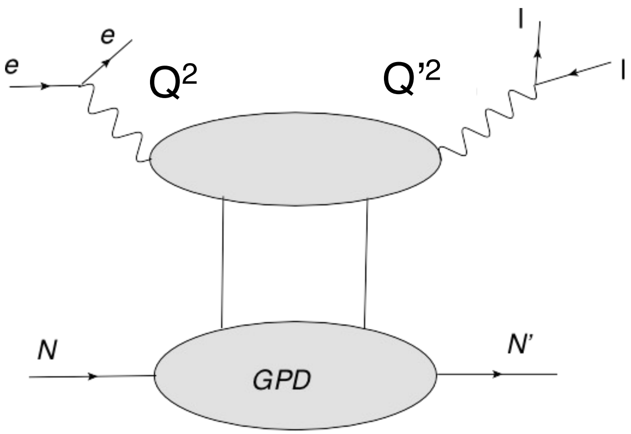
Challenging measurement Illustrative of many EIC / D2 features

events = luminosity x cross section x acceptance x time

- Double DVCS can probe GPDs outside of the $x = \xi$ line.
  - Low rates challenging, but cross section increases at lower x
    - 0.14 pb - JLab @ 10.6 GeV
    - 4.7 pb - EIC @ 10 x 100 GeV

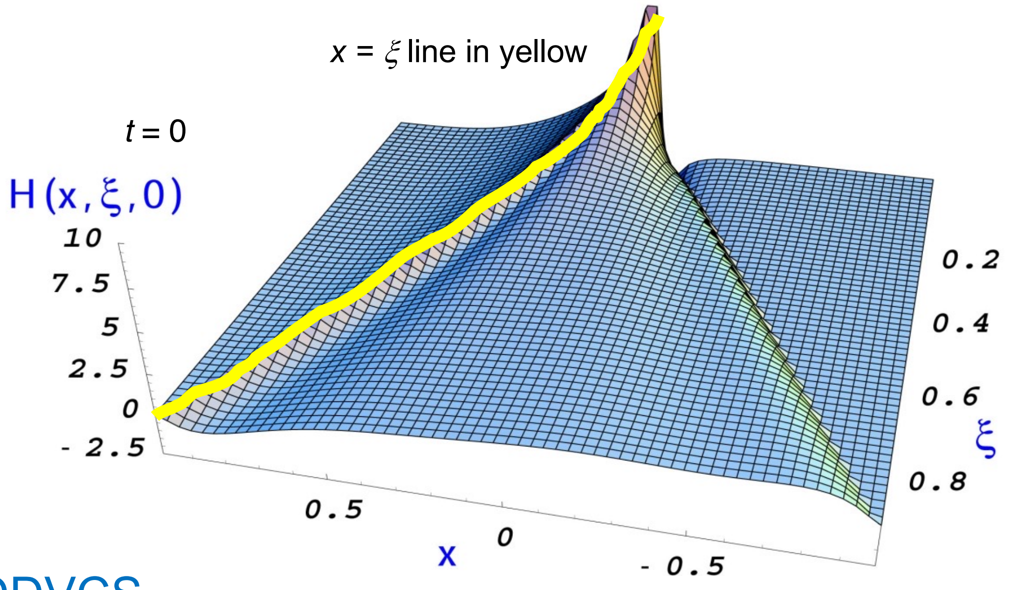
PRD 107, 094035 (2023)

DDVCS: initial *and* final photon virtual



- Lepton acceptance and identification
  - Muon ID is *necessary* in order to distinguish the scattered electron from the DDVCS decay leptons
  - EIC di-muon acceptance helpful (as in TCS)

- Proton acceptance in an IR with a second focus
  - DDVCS measurements will focus on low *t*
  - 2^{nd} focus gives a low-*t* proton acceptance close to 100%



A 2^{nd} EIC detector may give us the best chance for measuring DDVCS