Opportunities with a 2nd EIC detector

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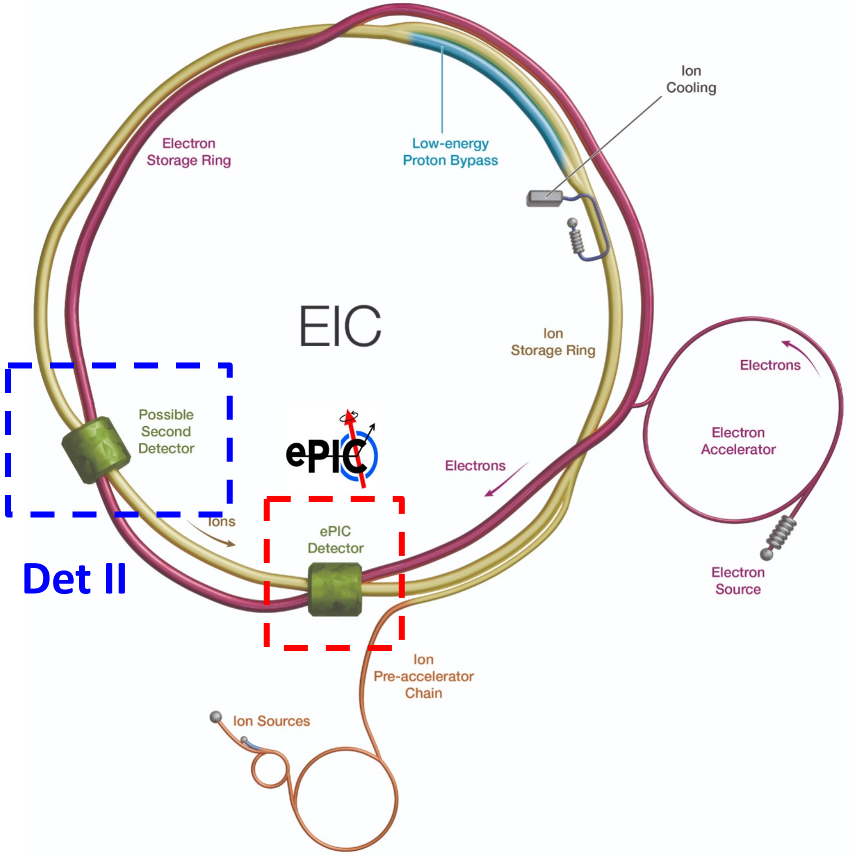
2^nd Detector @ IP8



New opportunities for beyond-the-Standard Model searches
at the EIC, CFNS, Stony Brook, July 21-24, 2025

Motivation for two detectors

JLAB-PHY-23-3761

Motivation for Two Detectors at a Particle Physics Collider

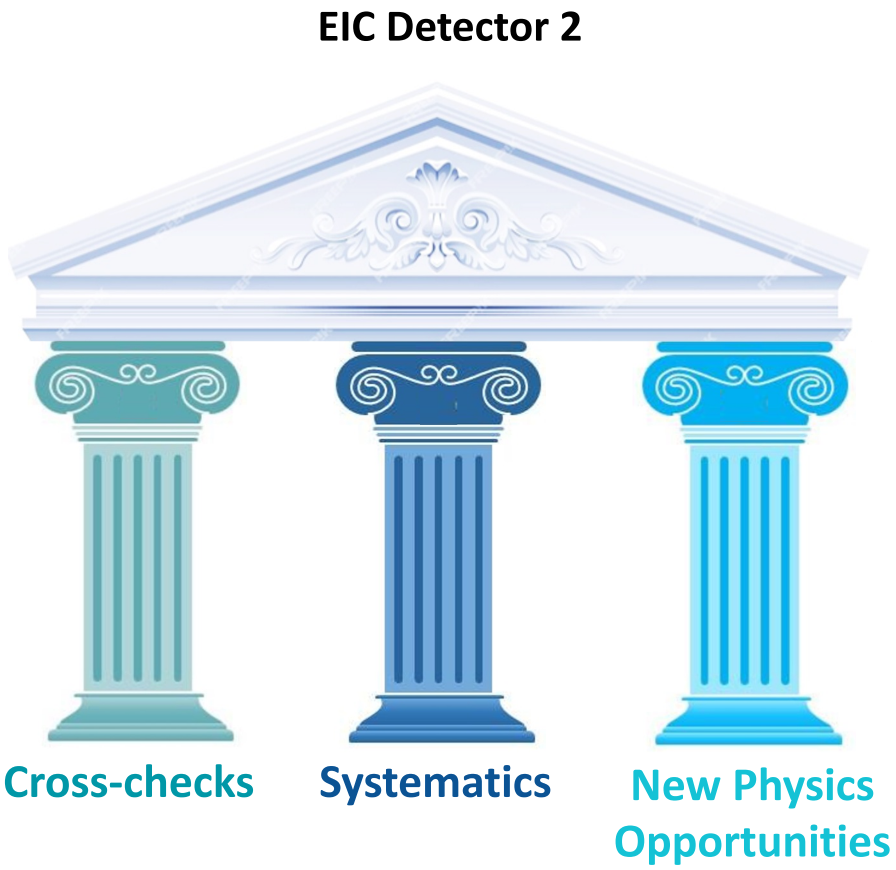
Paul D. Grannis* and Hugh E. Montgomery†
(Dated: March 27, 2023)

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 2^{nd} 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 unique facility
  - Requires a general-purpose collider detector supporting the full EIC science program.
- **Complementarity to ePIC**
  - Combining data from two general-purpose detectors can reduce the systematic uncertainties (*cf*. H1 and ZEUS)
- **New Physics Opportunities**
  - Capitalize on new design ideas and detector technologies

A second detector for the EIC – additional considerations

- Cost-effective
  - Adding a 2nd detector does not significantly increase operations costs of the EIC
  - 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 2nd 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 2nd detector may join the EIC early
  - This happened with spectroscopy in CLAS before GlueX was built

EIC UG 2nd detector working group

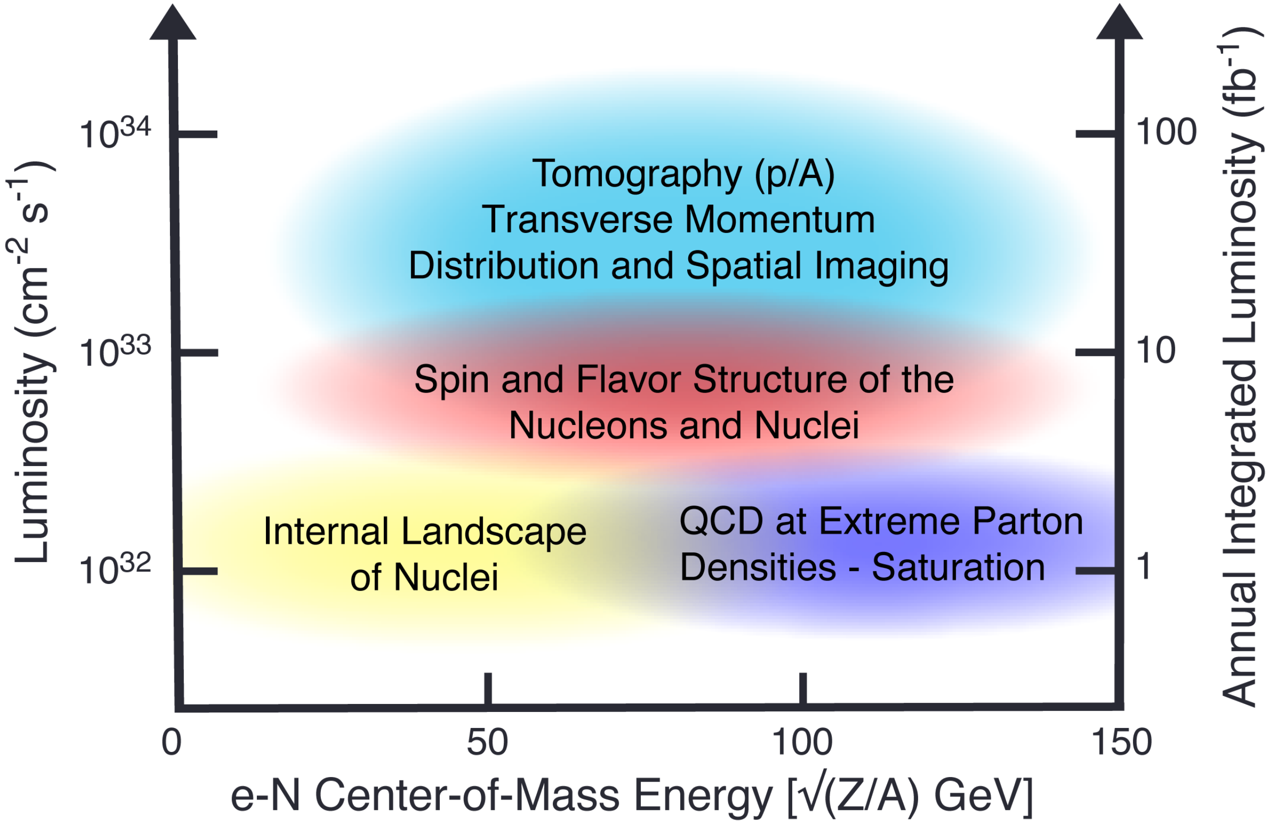
- Set up in 2022 following DPAP and the establishment of the ePIC collaboration

- Monthly meetings will resume in August
  - If you have ideas you would like to show or discuss, please contact the conveners below!

- A new charge is to prepare for a 2nd detector white paper – your 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

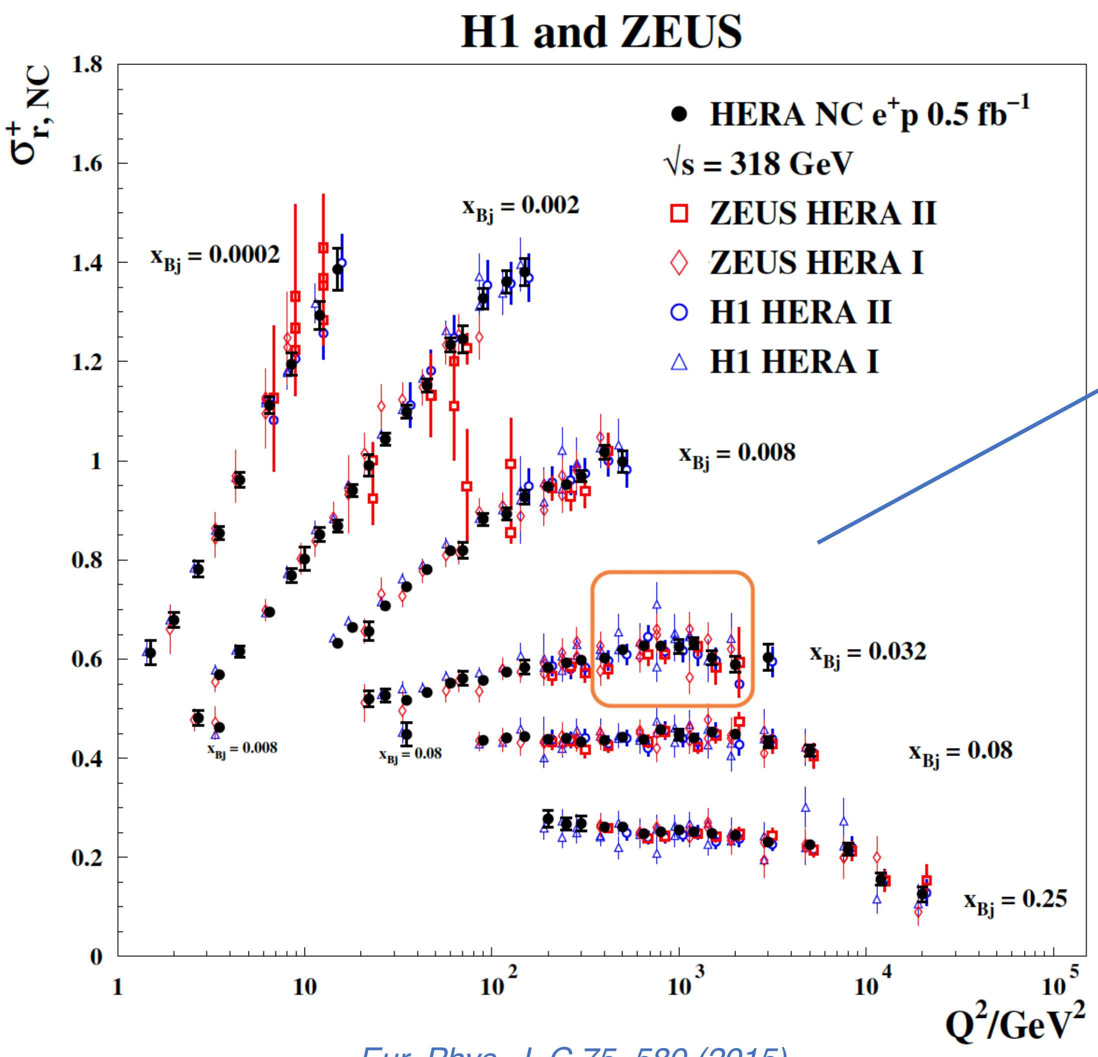
Luminosity, acceptance, and systematics



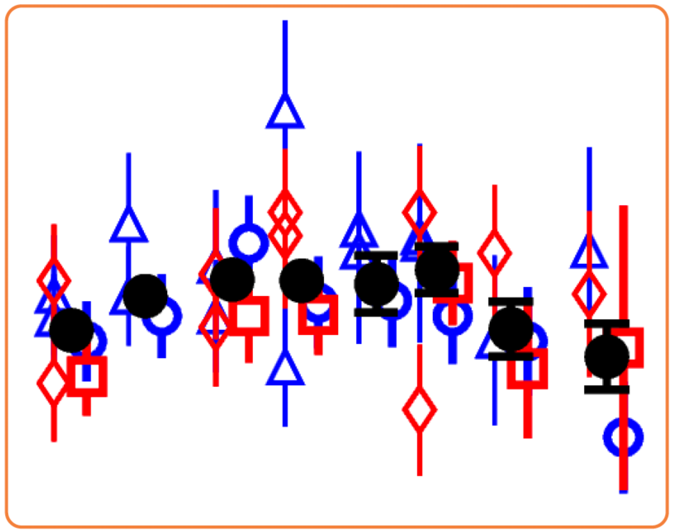
A 2nd detector with improved far-forward acceptance will have a large impact on all aspects of the EIC science program.

- 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

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 near-beam hadron detection in an IR with a second focus
  - 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
  - Efficiently vetoing breakup of heavier nuclei by detecting the produced fragments
  - Tagging a wide range of spectator nuclei – including A-1 and A-2 for reactions on a bound nucleon
  - Properties of the nuclear final state – hypernuclei, rare isotopes, etc, (including gamma spectroscopy)

- Complementarity with ePIC and synergies with the forward detection, which could include
  - 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**, **PVDIS**)
  - Improved hadron PID in the barrel from continued DIRC R&D – (SIDIS, jets, **hadron spectroscopy**)

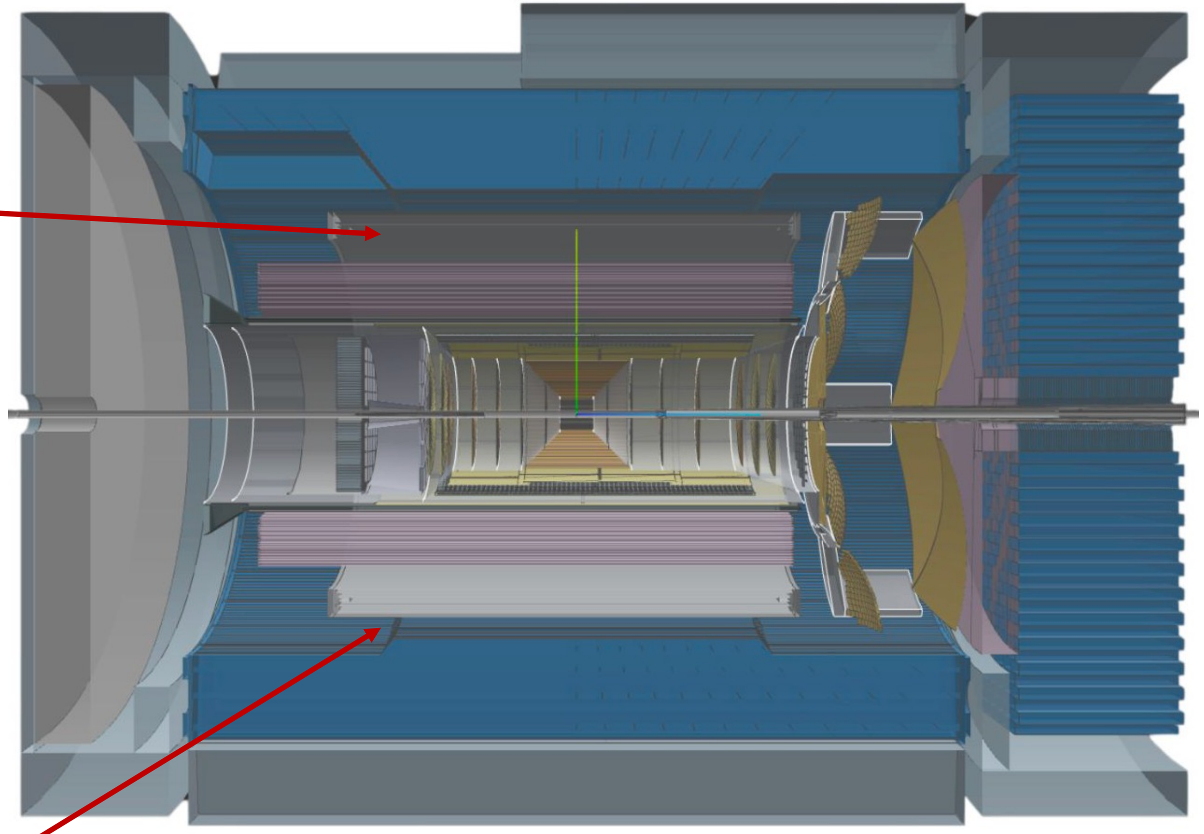
What else would we want for BSM searches?

A starting point for the 2nd detector

- How long should the solenoid be?
  - In ePIC the solenoid is significantly longer than the tracker with a lot of extra coil on the e-side
  - A shorter coil and more symmetric tracker could create more interior space
  - Complementarity with ePIC - simplified interior?
    - Example: AC-LGAD TOF replacing the pfRICH, which is most important for 18 GeV electrons
  - A shorter, symmetric detector would make accelerator integration easier (including B0)

- How wide should the solenoid be?
  - The bore should roughly match the radius of the ePIC *inner* detector
  - This can be achieved while reducing the empty space in-between the EMcal and the solenoid cryostat by 20 cm

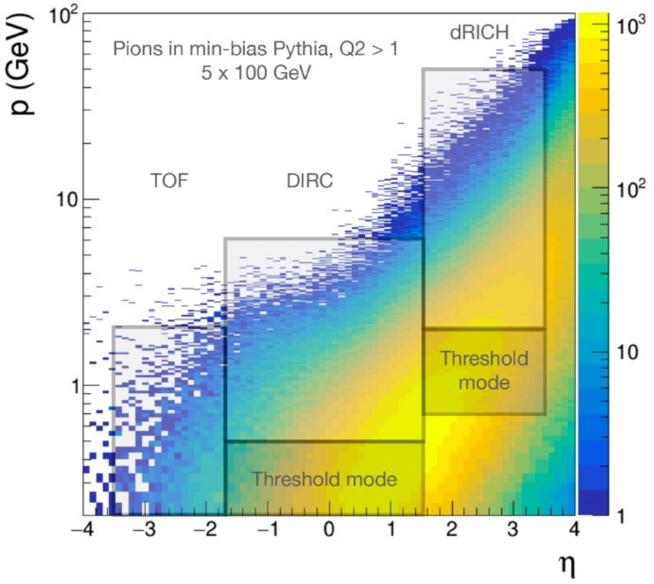
ePIC

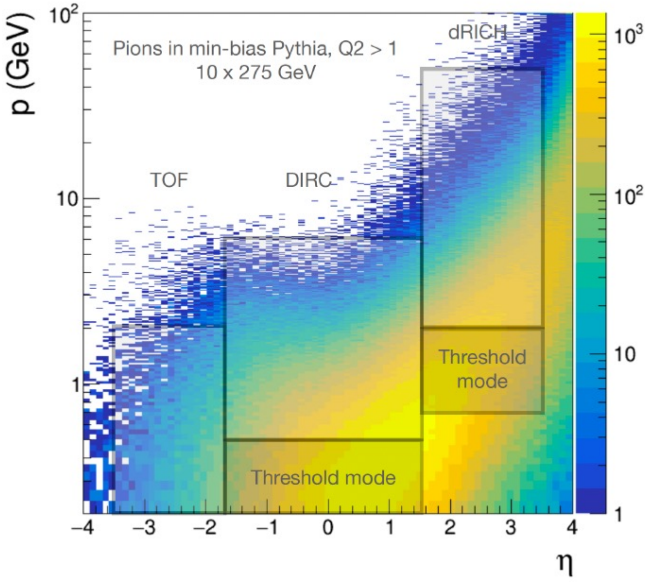


- 142 cm inner (bore) radius of the SC solenoid (similar to BaBar)
- 116 cm outer radius of the barrel EM calorimeter (from J. Lajoie)
- **ePIC would fit into a bore with a ~120 cm radius**

PID: pions and kaons plotted separately for 5x100 and 10x275

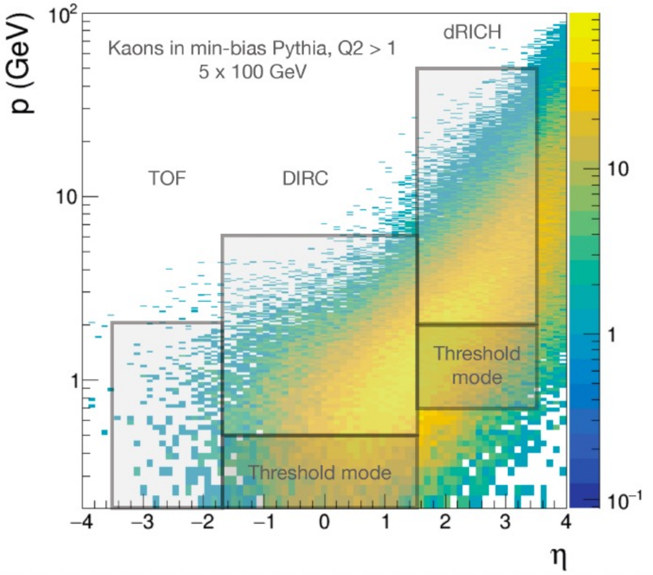
Pions 5x100

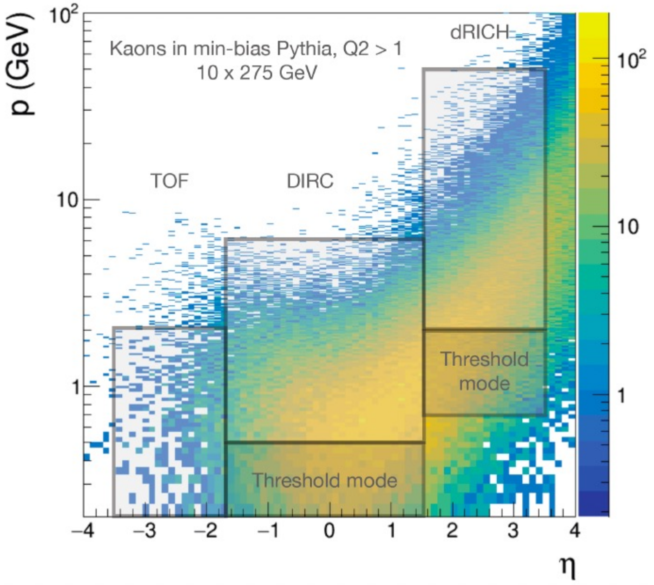




Pions 10x275

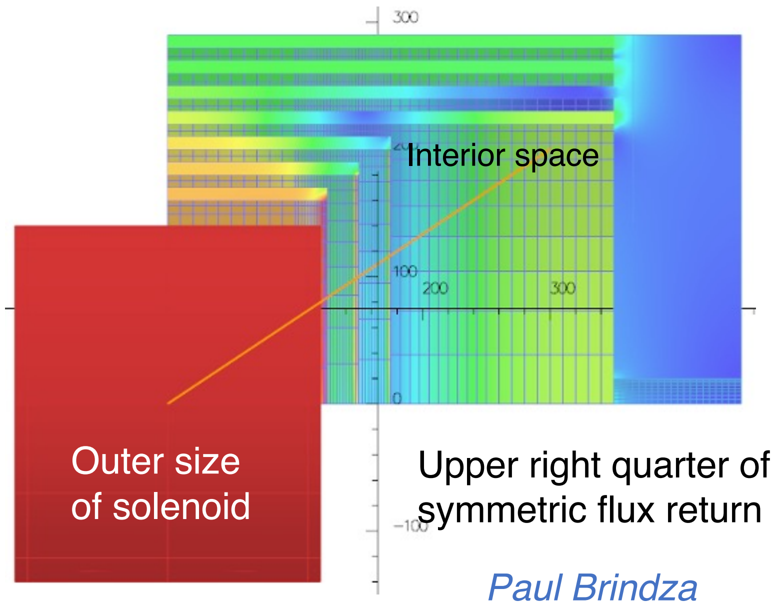
Kaons 5x100





Kaons 10x275

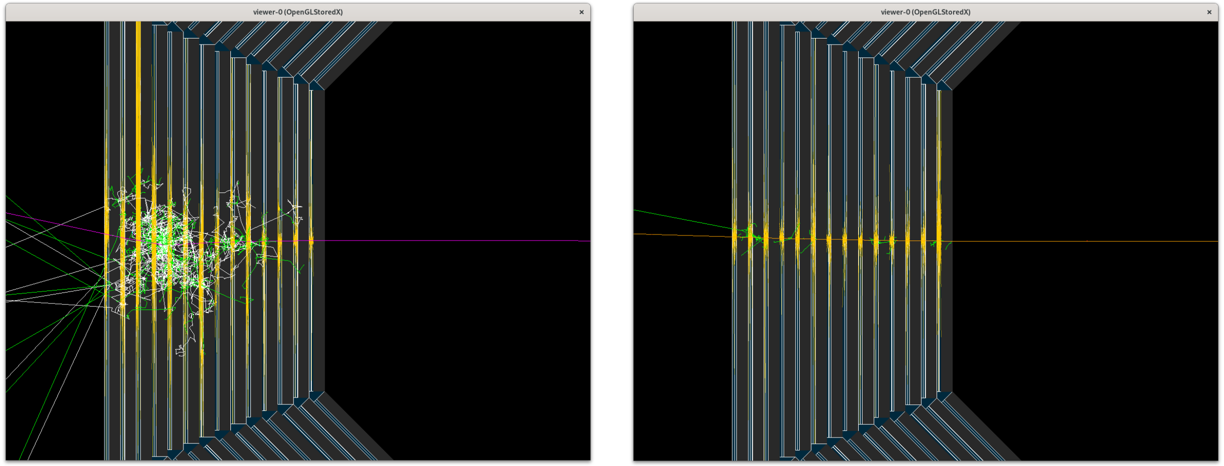
Initial study of a 3T Detector-2 solenoid



- Comparison with ePIC (MARCO) solenoid
  - 30% (1 m) shorter → more internal space
  - 15% smaller inner (bore) radius
    - tracking resolution depends on the *tracker* radius
- 3 T field on axis at IP
  - Achievable within a 3 m flux return outer radius
  - High-field region is matched to the length of tracker
  - Rapid transition to "projective" field in the dRICH gas
- Moderate risk
  - Currents and stored energy comparable to ePIC
  - Symmetric design eliminates longitudinal coil forces
  - Field specs less stringent than for CLAS12 5 T solenoid
- Symmetric flux return
  - +/- 4.5 m overall detector length (original DPAP spec)
  - Reduced coil forces → thinner cryostat
  - Integrated with KLM-like Hcal in the barrel

Muon identification for a 2nd EIC detector

- **Muon ID:** most Hcals 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"
- **Hcal**: ongoing R&D uses the Belle II KLM as a starting point, but adds precision timing and energy measurements in each layer.
  - With AI methods for reconstruction, the EIC-KLM seems to be a surprisingly good Hcal.

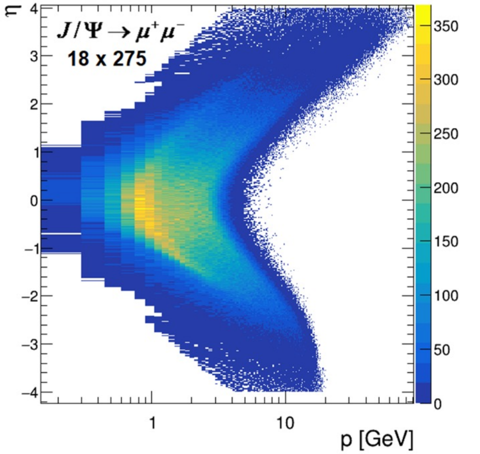


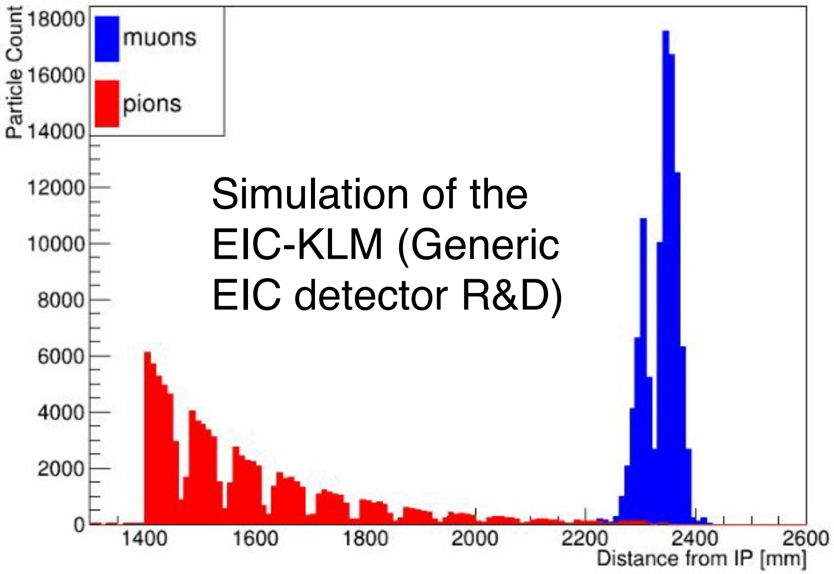
Simon Schneider, Rowan Kelleher, Nilanga Wikaramachchi

Physics examples

- Timelike Compton scattering, Double DVCS
- Charmonium production
- BSM

arXiv:2209.00496



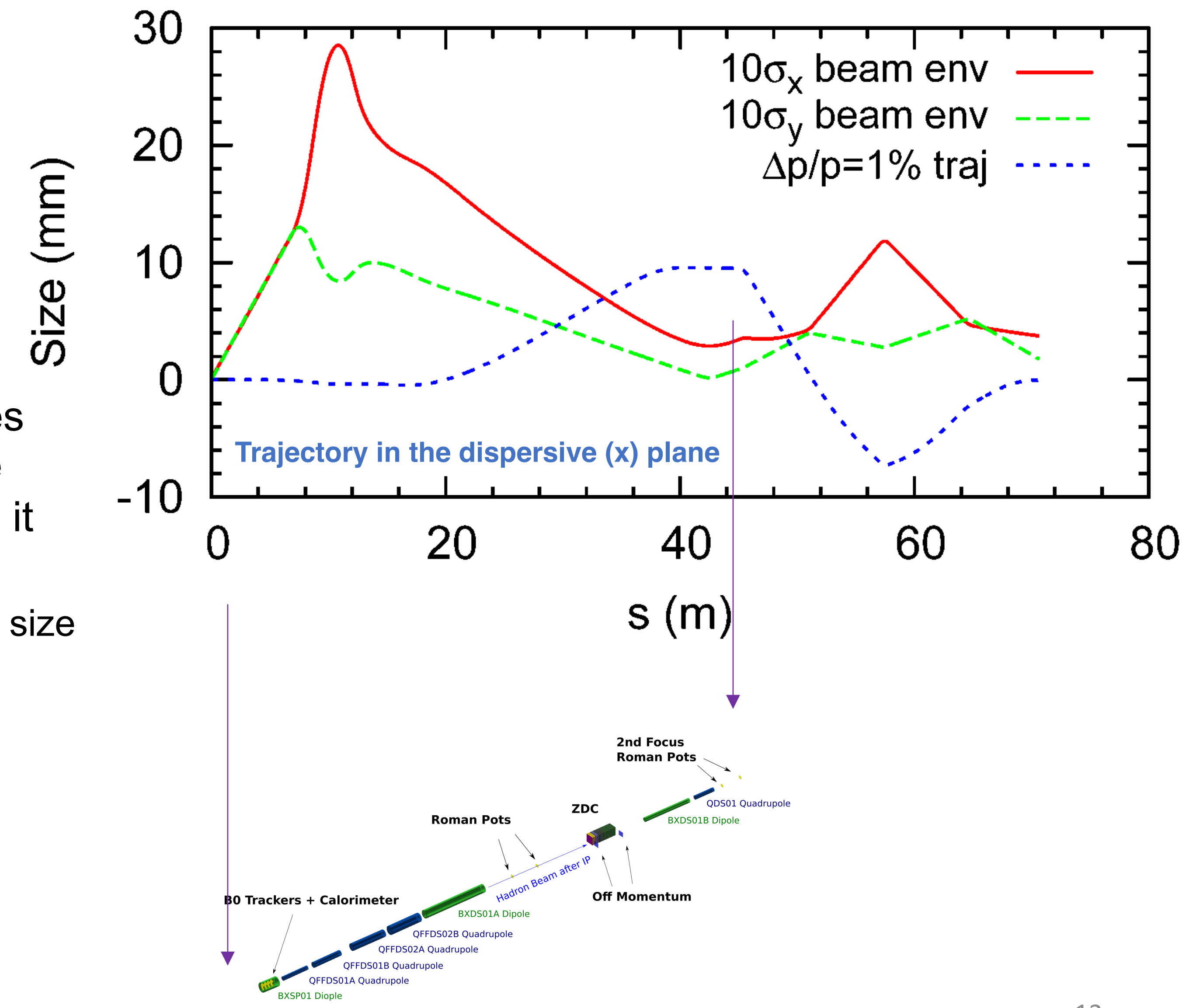


How the second focus works

- 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

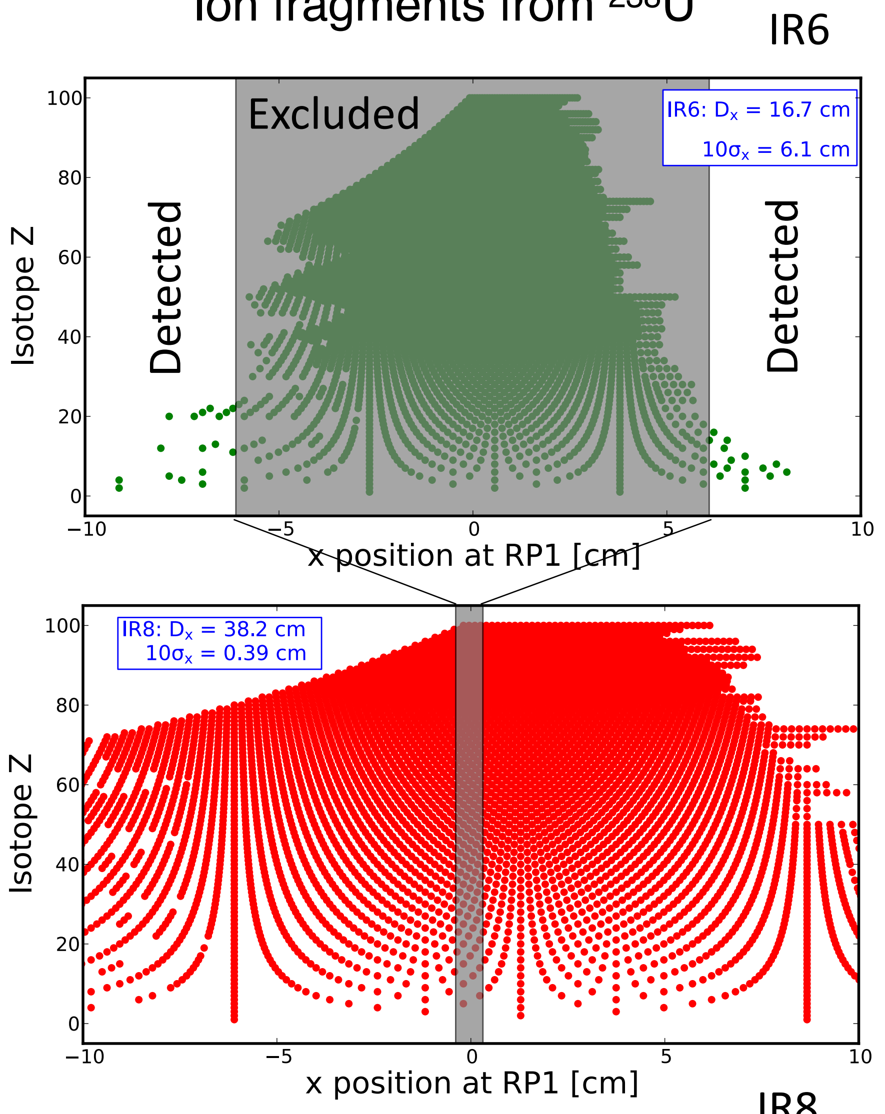
- A particle (blue) initially scattered at 0 degrees ($p_T = 0$) briefly emerges from the beam at the second focus about 40 m downstream where it can be detected
  - Compare trajectory with horizontal (red) beam size
  - Particles with $p_T > 0$ emerge earlier

- 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

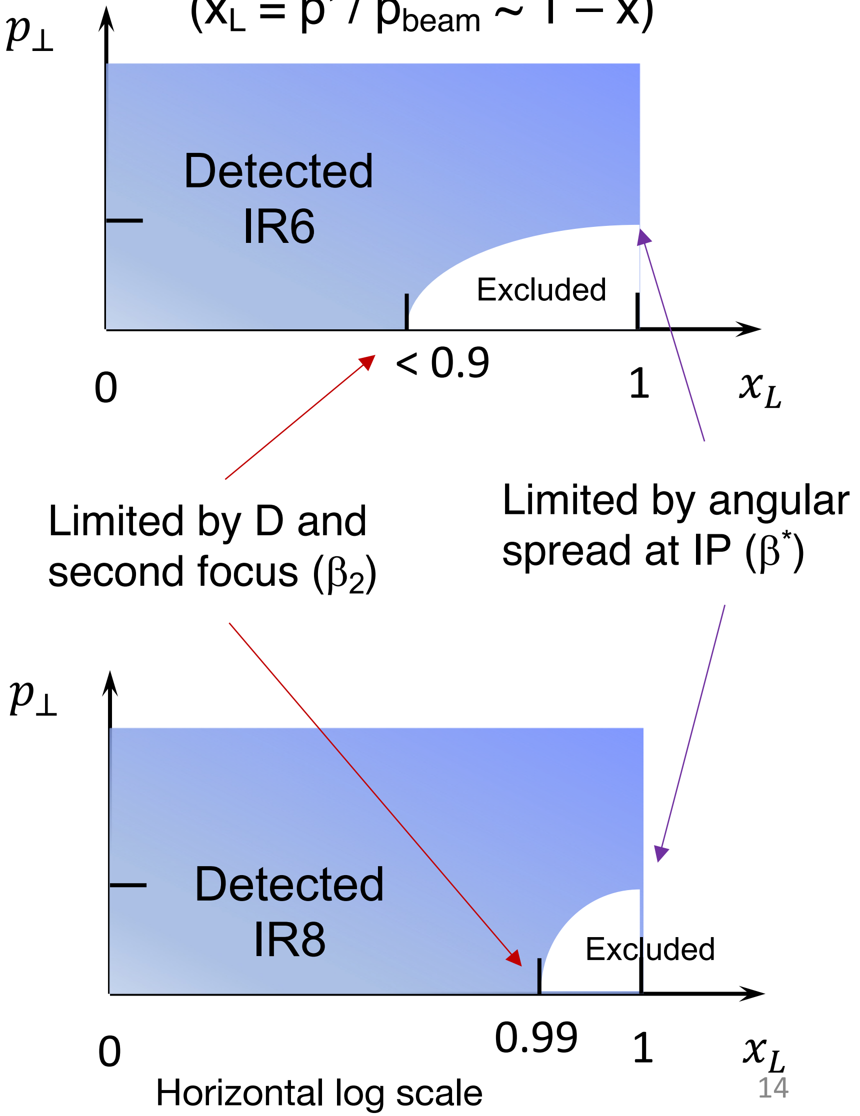
Without 2nd focus:
(ePIC @IR6)

With 2nd focus:
(Detector 2 @ IR8)

Order-of-magnitude improvement in forward acceptance

Exclusive protons

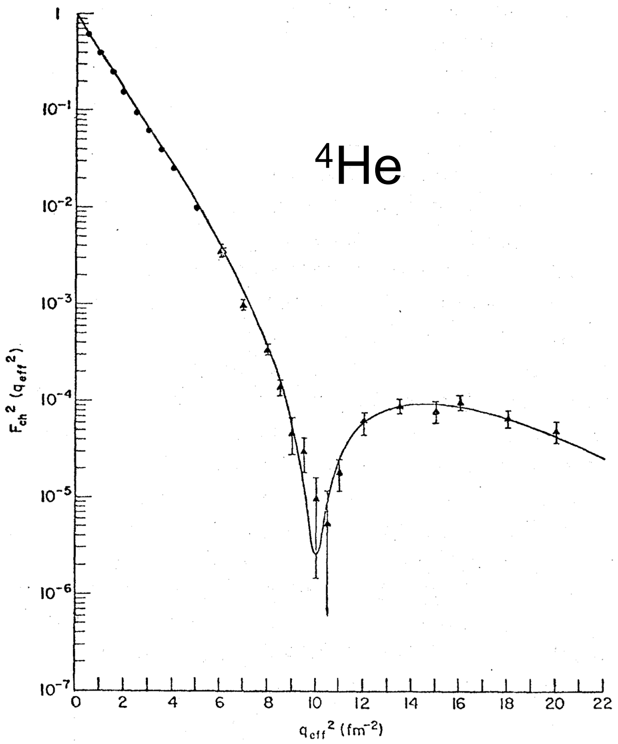
($x_L = p' / p_{beam} \sim 1 - x$)



Coherent scattering on nuclei

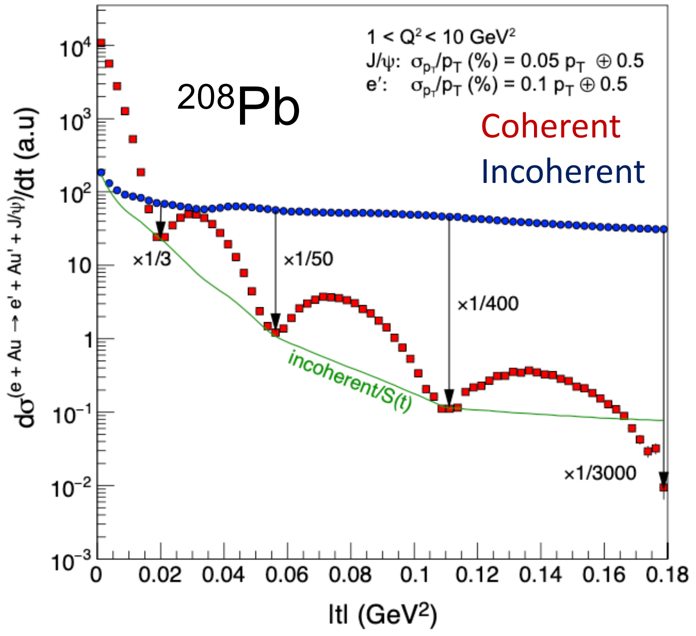
Light ions

- Reoiling light ion detected
- 2nd focus provides acceptance over the full t-range for He and Li



Medium- and heavy ions

- Efficient vetoing of break up due to fragment detection at the 2nd focus
- DVCS, DVMP on O, Ca, *etc*
- Coherent diffraction: J/ψ, φ on ^{90}Zr, ^{120}Sn, ^{208}Pb



The bound nucleon

A-1 processes

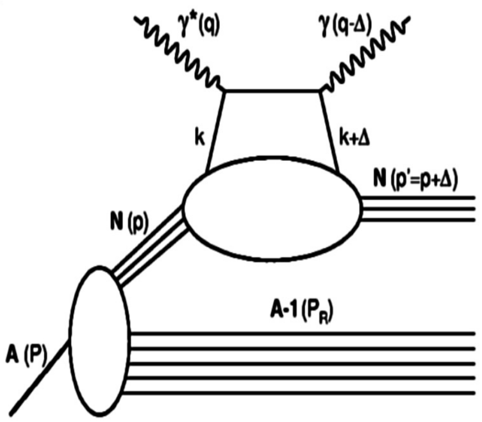
- A second focus enables measuring a bound proton in any nucleus while tagging the spectator A-1 system
- Comparison with free protons and A-dependence of medium modifications

A-2 processes

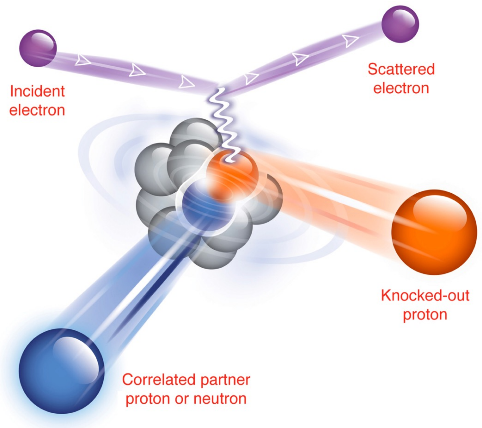
- Striking a nucleon in a short-range correlation (SRC) leads to the ejection of both nucleons
- A 2nd focus allows tagging the A-2 system for any type of SRCs: (A-2)nn, (A-2)pp, (A-2)np
  - Medium A for the most challenging np SRCs

Any primary process can be studied:

Exclusive, semi-inclusive, inclusive



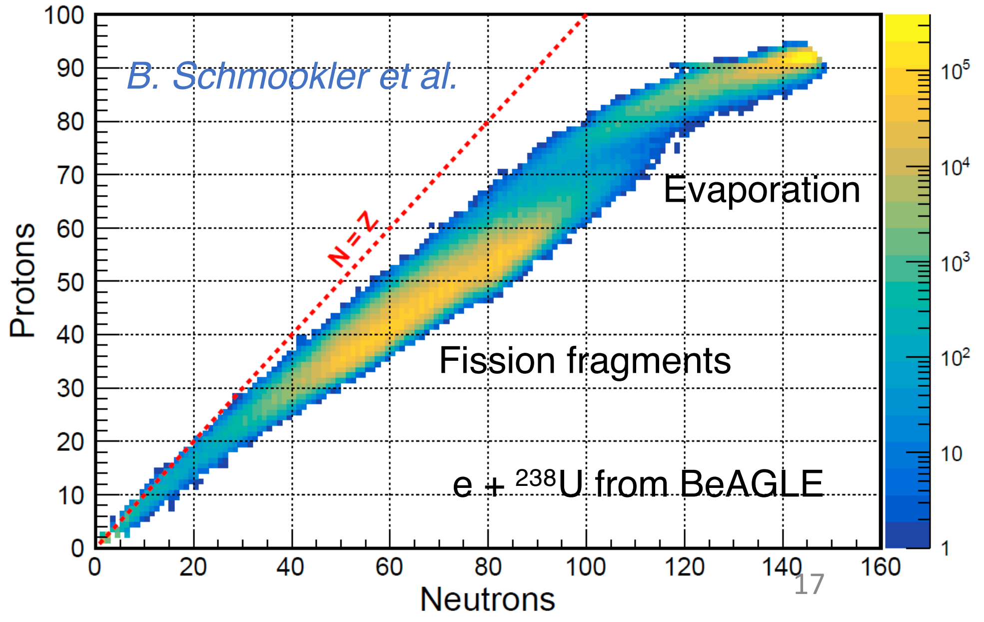
Eur. Phys. J., A52(6):159, 2016



Fragmenting nuclei

Rare isotopes

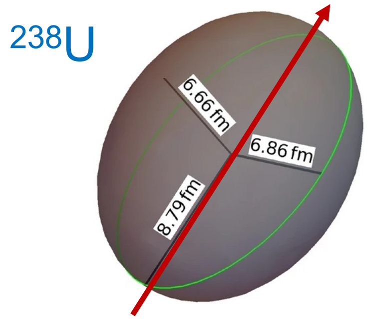
- In eA, all kinds of isotopes are produced through evaporation and fission.
- With a 2nd focus these can be detected and identified - and the gamma photons from their de-excitation can reveal their internal structure



Increasing the nuclear thickness?

- Nuclear targets make it possible to map out the onset of gluon saturation at the EIC.
- However, if one could select a subset of events where a deformed nucleus (e.g., 238U) was preferentially struck along the long axis, this would correspond to nuclear thickness of a A ~ 500 nucleus.
- With a 2nd focus, we can use the complete final state to select a subset of events where the average thickness is significantly larger.

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



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

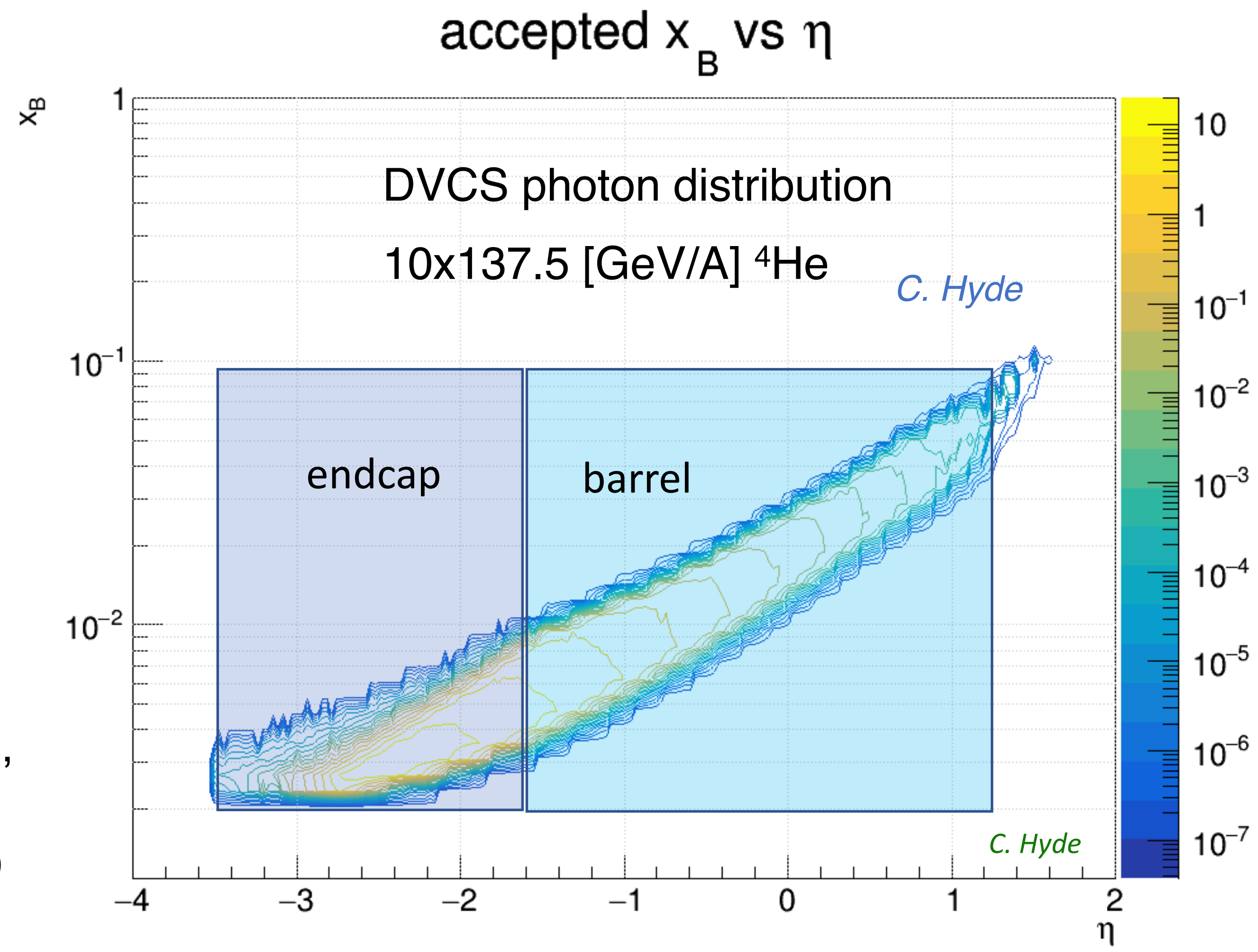
Example of synergies: DVCS on nuclei

- DVCS on the *proton*: *t* can be determined from the **proton**
  - the photon is detected for exclusivity

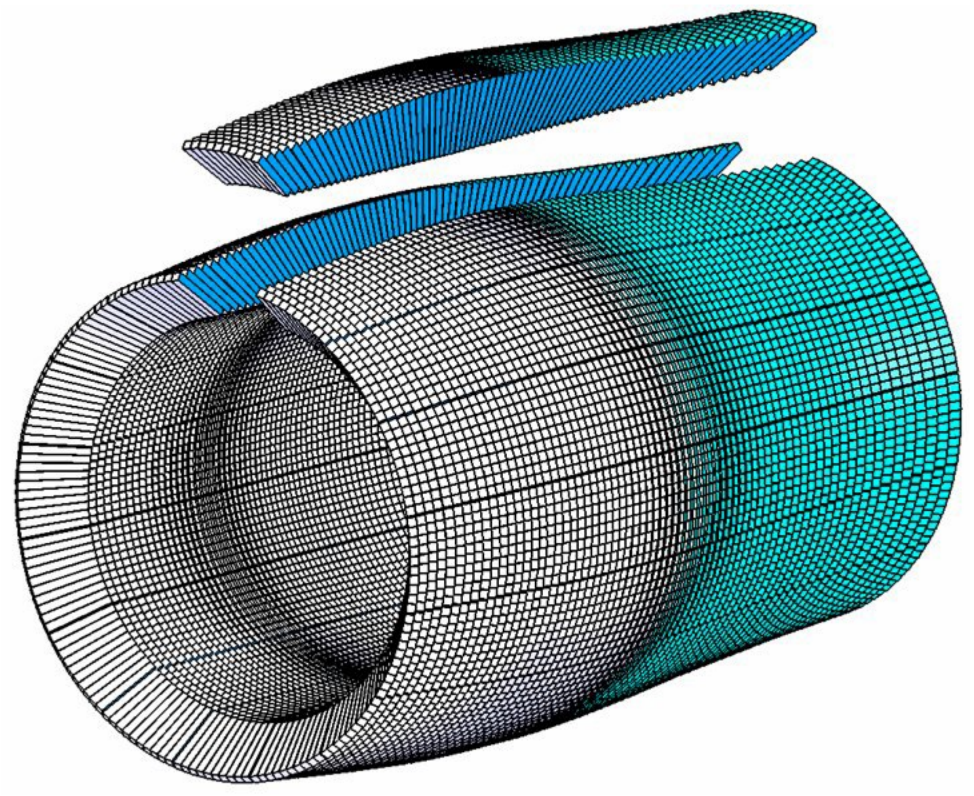
- DVCS on *nuclei*: t is best determined from the **photon**
  - The nucleus has to be detected or breakup vetoed for coherence and exclusivity.

    (*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



Possible synergies with PVDIS – photon and electron detection



PANDA $PbWO_4$ EM calorimeter

- A key method for electron identification is E/p
- High-resolution EM calorimetry (E) and tracking (p) improve efficiency and purity

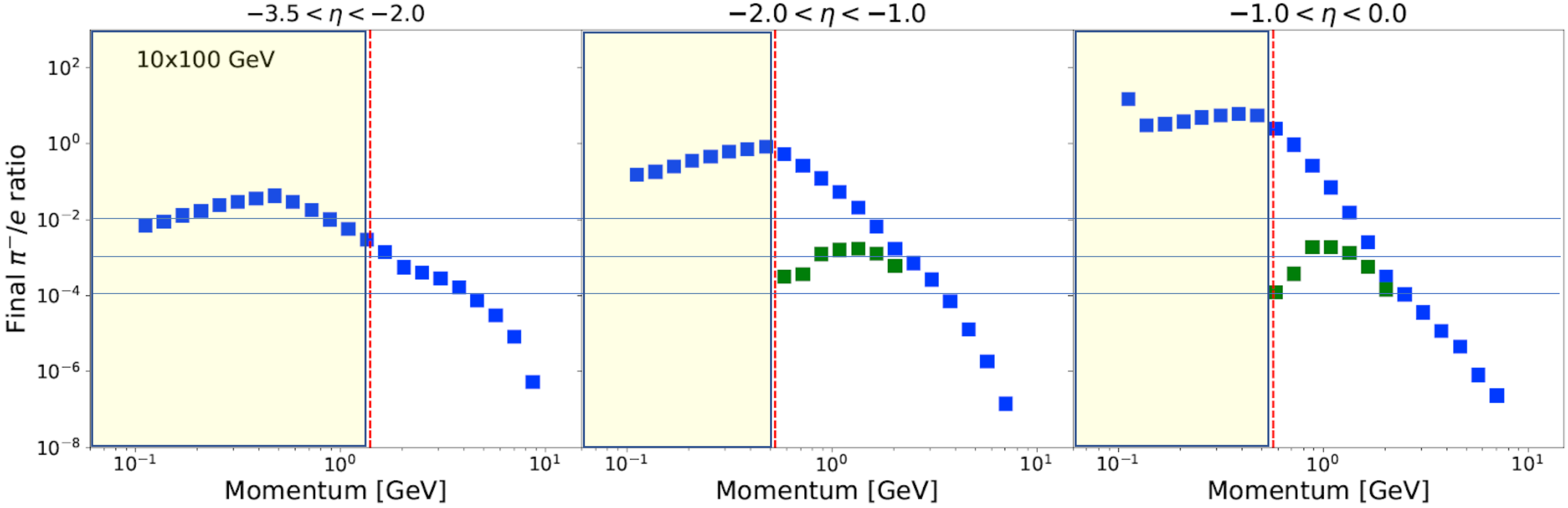
- ePIC uses the GlueX EMcal with a multi-layer silicon-based (AstroPix) “imaging” pre-shower
- The pre-shower is good for γ/π^0 separation and helps with e/π, but does not affect the resolution

- A $PbWO_4$ barrel calorimeter like in PANDA would improve EMcal resolution by a factor 3
  - also reduced constant term

Other technologies for improving EMcal resolution can also be considered if of interest for BSM studies

DPAP example:

CORE G-2: pi- vs. e- rejection (combined plot for all sources)



Study by B. Schmookler for ATHENA and CORE (GlueX and $PbWO_4$ barrel EMcals, respectively)

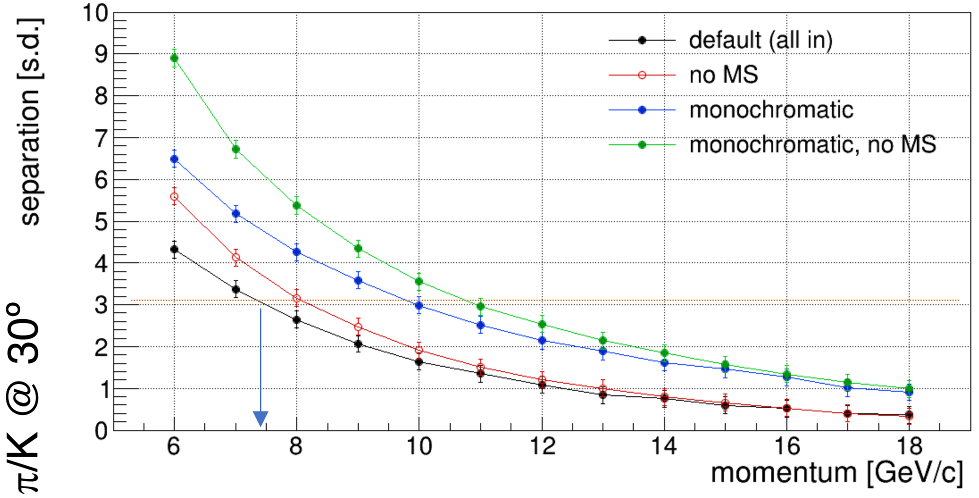
The plot shows the remaining pi contamination for the combined effects of all sources of discrimination.

The blue points show the effect of the $PbWO_4$ EMcal and kinematic constraints. The green points show the total effect of also including the DIRC (in the momentum range where it is applicable).

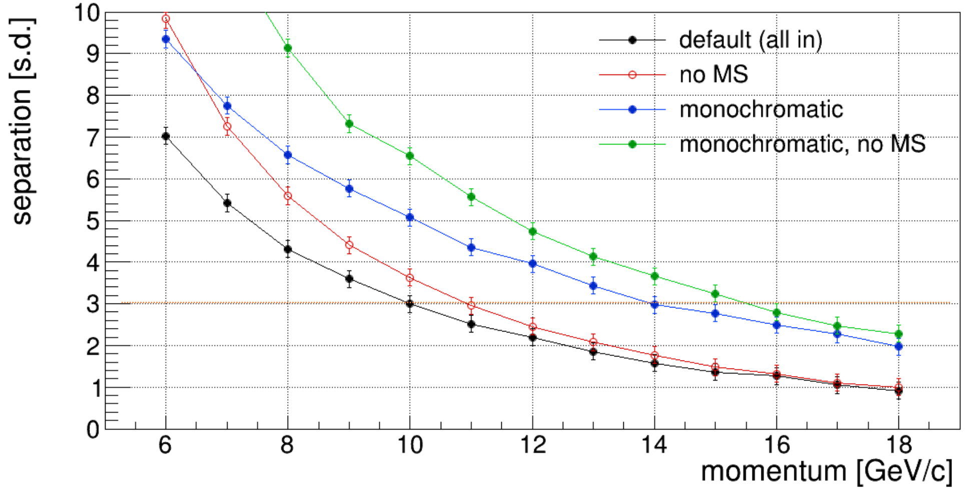
The remaining pion / electron ratio is at the level of 0.1% or better for all kinematics (above the yellow area which is excluded by standard event selection cuts).

Example: DIRC R&D – theoretical limits for PID in the barrel

1.7 mm pixels, 100 ps timing, **0.5 mrad tracking**



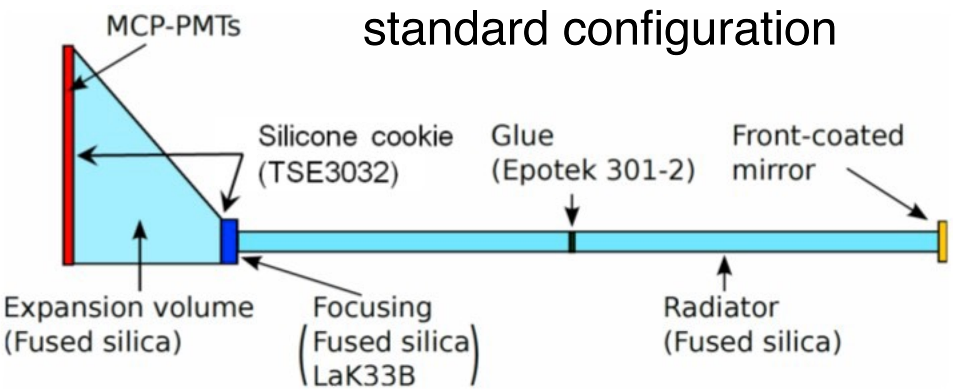
also ideal focusing

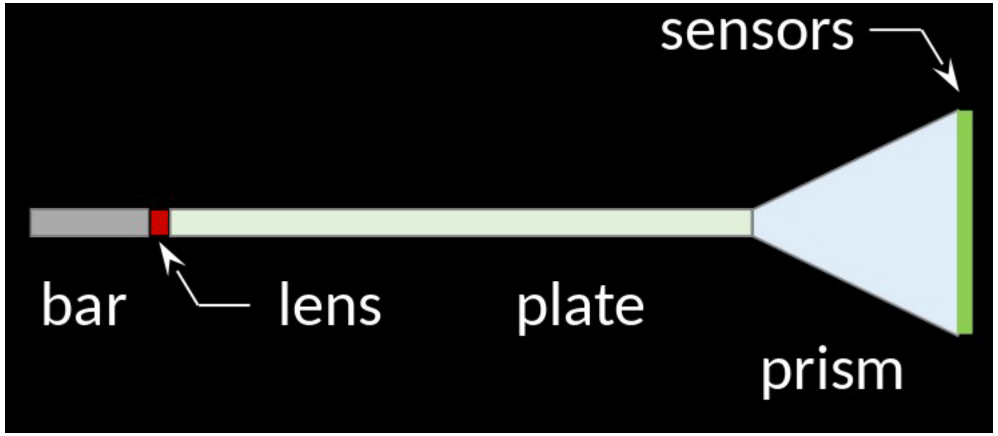


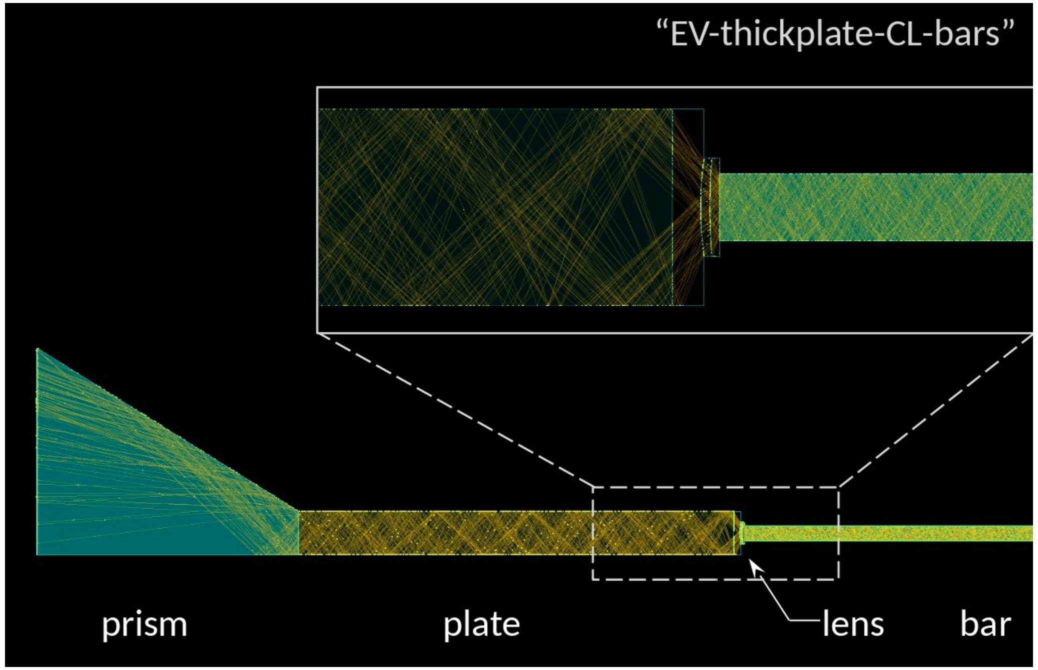
R. Dzhygadlo, EIC UG meeting, Warsaw, July 30, 2023

- Factors constraining performance
  - multiple scattering (MS) inside the bar (dominates at lower momentum)
  - chromatic dispersion of angle and time
  - aberrations of focusing system
  - timing precision
  - photo-sensor's pixel dimensions
  - angular resolution of tracker
- Possible improvements
  - 1.7 mm pixels are straightforward to implement
  - 100 ps is state-of-the-art
  - 0.5 mrad can be achieved without AC-LGAD TOF
  - Multiple scattering can be reduced, for instance by using thinner bars (**also improves e/π**)
  - Chromatic effects can be mitigated
- In a 2^{nd} detector it may be possible to increase the 3σ momentum reach **from 6 to 8-10 GeV/c** (|p| not p_T)

Example: DIRC R&D – alternative designs of the imaging system







- Above: a compact prism and photosensors with smaller pixels and total area
  - Could make it possible to use SiPMs (smaller area → less noise)
- Left: Inserting a plate in-between the focusing lens and expansion volume prism could improve performance and reduce cost
  - Plates are less expensive than bars

Summary and outlook

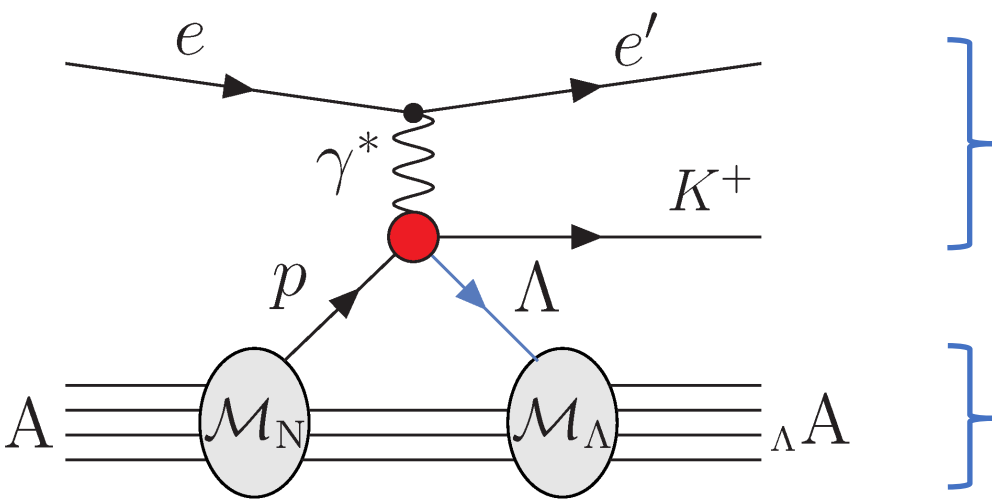
- Having two detectors at the EIC will provide the necessary cross checks of discoveries and reduce systematic uncertainties (*cf.* H1 and ZEUS)

- A 2nd detector will introduce new and opportunities beyond the Yellow Report
  - Expanded eA capabilities are a natural path for a 2nd detector
  - Can we also optimize it for BSM (PVDIS, rare decays, muons, etc)?

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

Thank you!

Production and detection of hypernuclei



Detected in the central detector

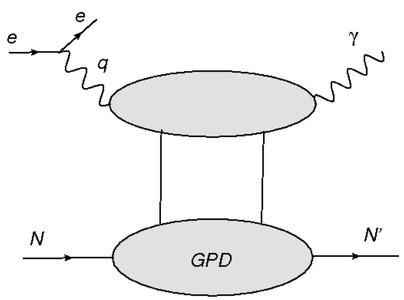
Detected in the far-forward detectors

- Coherent exclusive K^+ production creates a hypernucleus differing by one unit of charge.
  - Sufficient for any hypernucleus to be detected by the 2nd 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

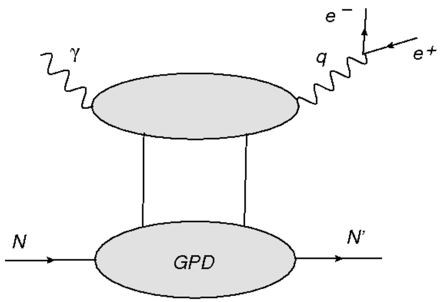
Timelike Compton Scattering (exclusive dilepton photoproduction)

(spacelike) DVCS



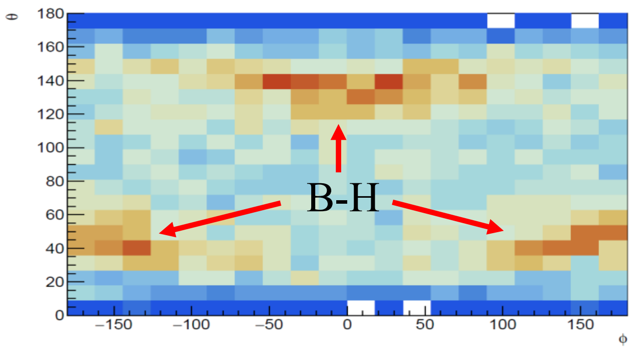
Initial photon spacelike, final photon real

timelike Compton scattering (TCS)

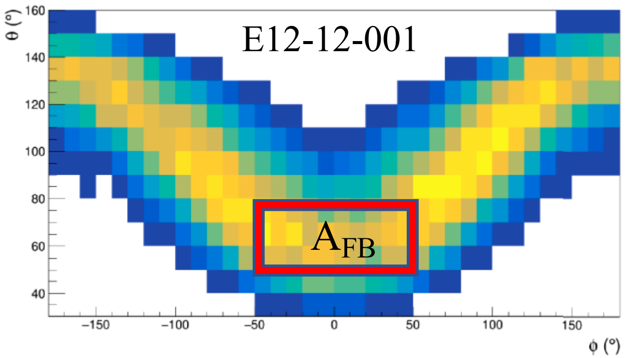


Initial photon real, final photon timelike → $l^+ l^-$

EIC detector



CLAS12



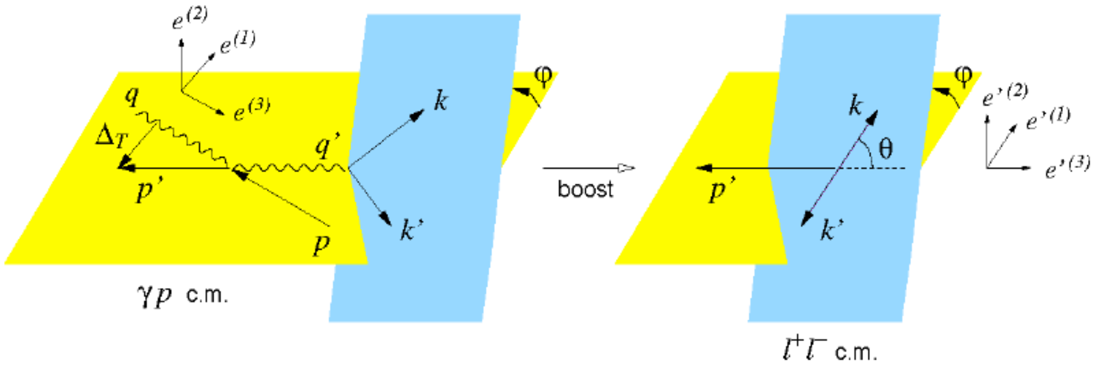
P. Chatagnon, EIC UG meeting, Warsaw, 2023

- 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)

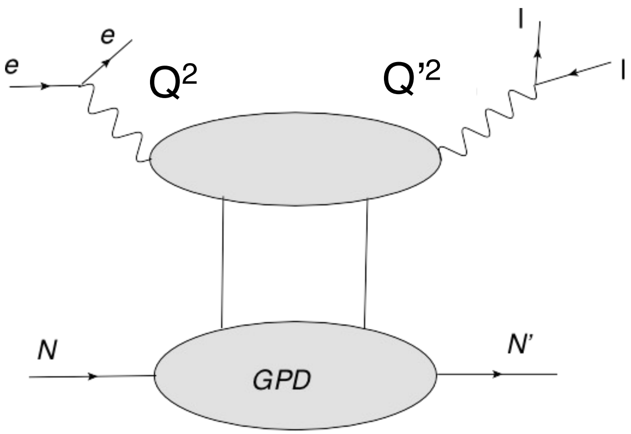
Challenging measurement Illustrative of many EIC / D2 features

events = luminosity x cross section x acceptance x time

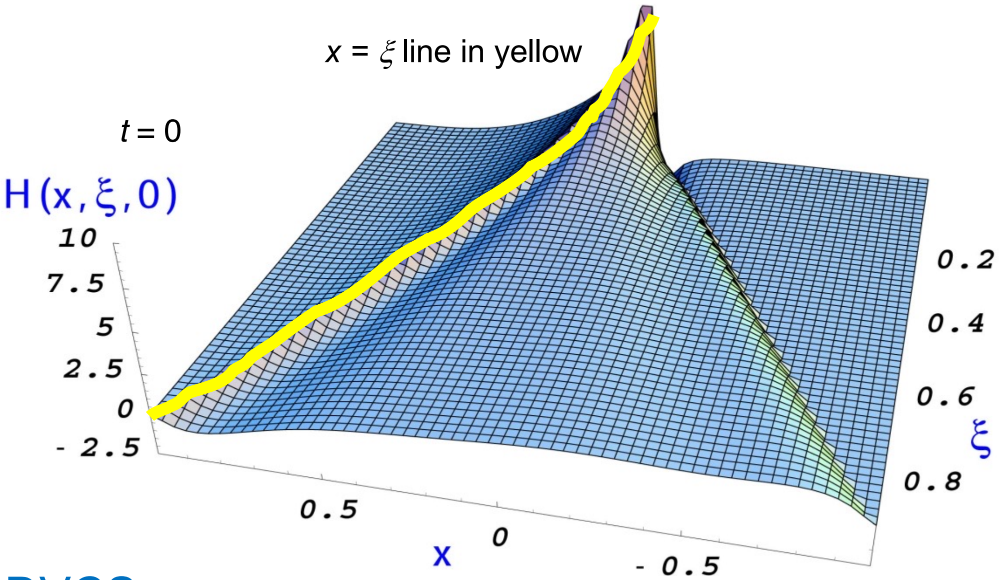
- Double DVCS can probe GPDs outside of the $x = \xi$ line.
  - Low rates challenging, but cross section increases at lower x
    - 0.14 pb - JLab @ 10.6 GeV
    - 4.7 pb - EIC @ 10 x 100 GeV

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)

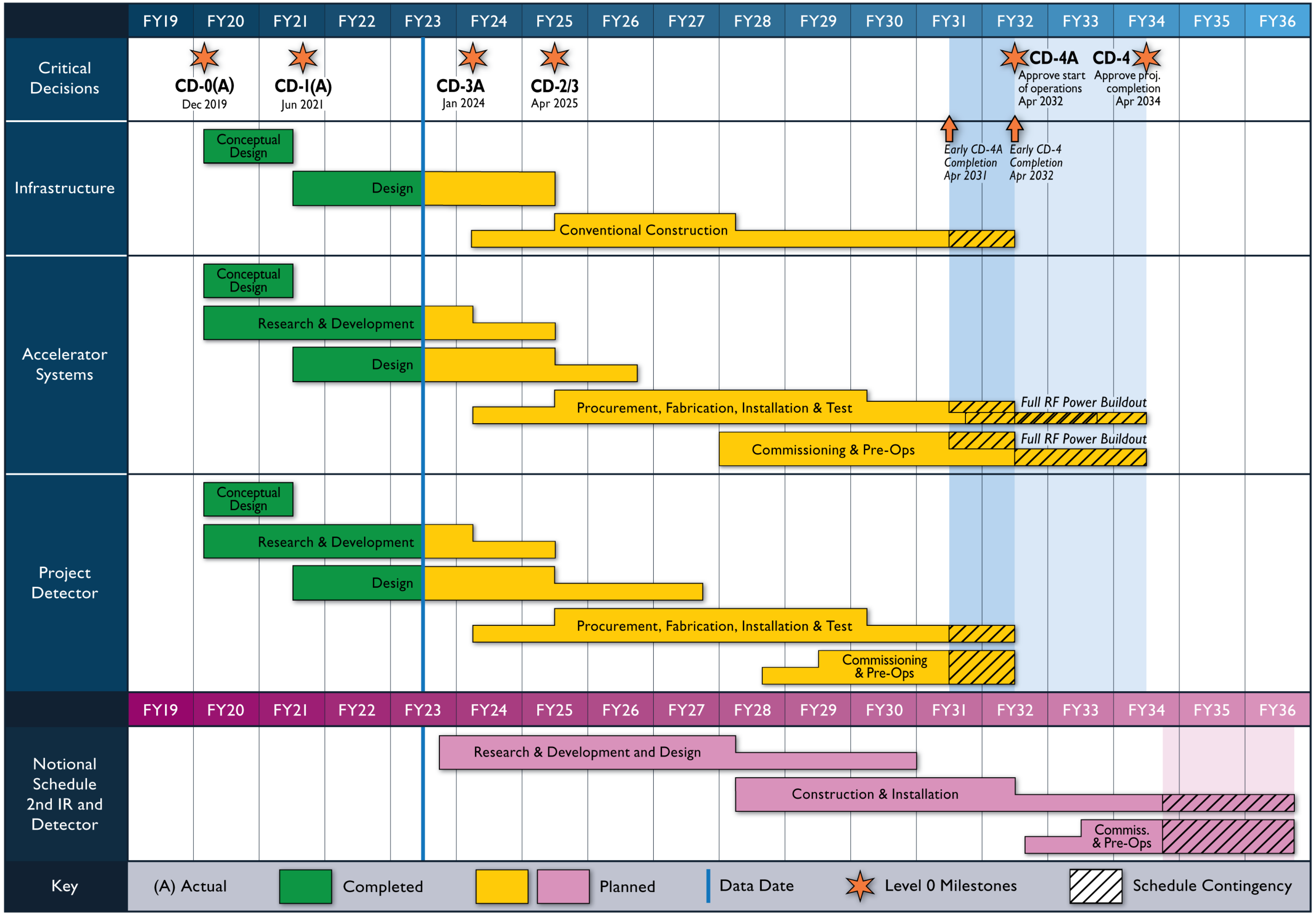


- Proton acceptance in an IR with a second focus
  - DDVCS measurements will focus on low t
  - 2nd focus gives a low-t proton acceptance close to 100%

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

Tentative schedule including a 2nd detector

Jim Yeck, EIC 2nd detector workshop, May 2023



A little out of date but nevertheless illustrative

2nd detector