Forward detection requirements at the EIC
- flavor, neutron structure, light and heavy ions

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Outline

- Detection requirements
- Brief overview of key processes
- Overview of detection implementation(s)

Forward detection – questions

- Which processes drive the requirements for acceptance and resolution?
  - What physics would we lose with only a partial capability?
- How do we build a forward spectrometer to meet these requirements?
  - Can the capabilities be shared between two IRs?

Forward detection – processes and requirements

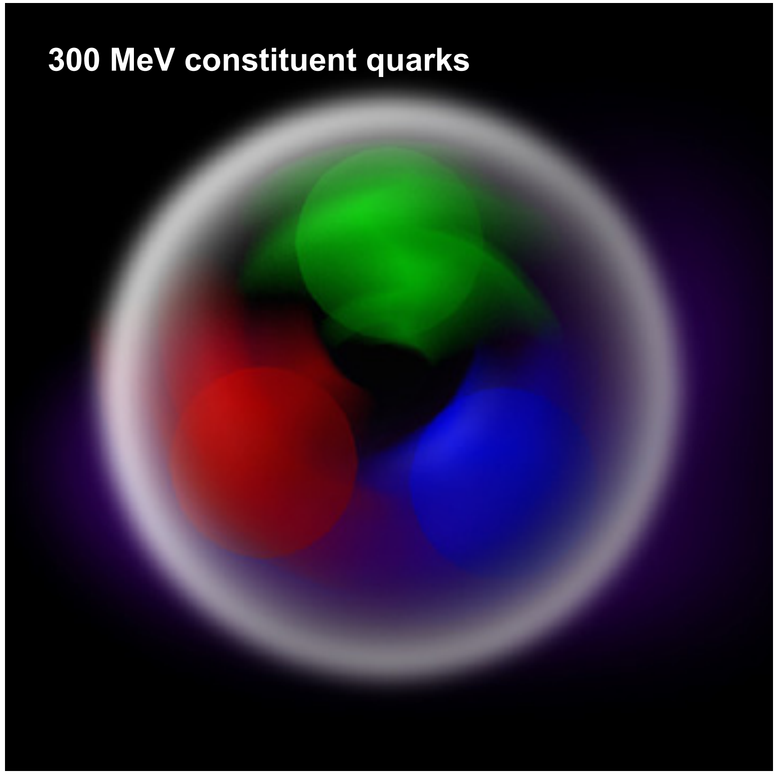
- Which processes drive the near-beam (small p_T) acceptance?
  - Coherent diffraction on light nuclei (detecting recoiling ion for clean signal)
  - DIS and (in)coherent diffraction on medium- and heavy nuclei (detecting residual nucleus)

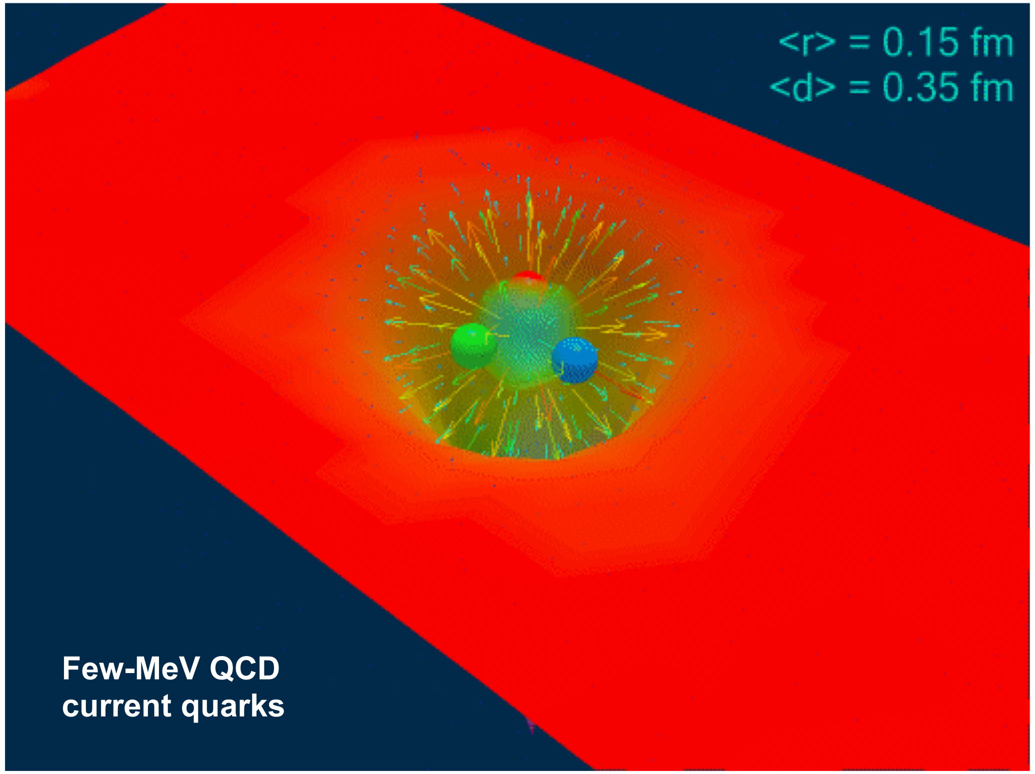
- Which processes drive the “large” angle (p_T) acceptance?
  - Tagging of spectator protons from nuclei (heavy ions and deuterium are most challenging)
  - Exclusive production of photons (DVCS) and mesons (DVMP) on the proton at large t at lower energies
  - Detection of photons and neutrons from nuclei (cone with line-of-sight)

- Which processes drive the resolution?
  - Magnetic: tagging of protons from nuclei (spectators have p ~ Fermi momentum)
  - Hcal (ZDC): tagging of neutrons from exclusive charged meson production on the proton and spectator neutron tagging (*e.g.*, for reactions on the proton in deuterium)
  - EMcal: Photons from nuclear de-excitations (coherent diffraction and rare isotopes)

Other processes are also important but do not push the requirements

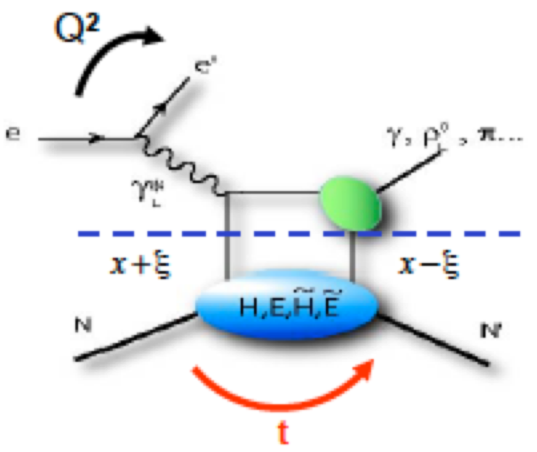
Spatial structure of nucleons (and nuclei)

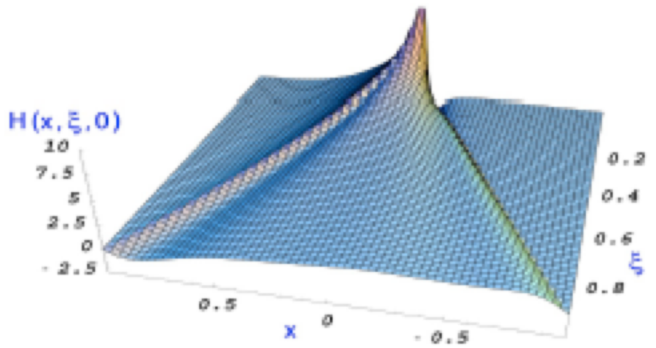


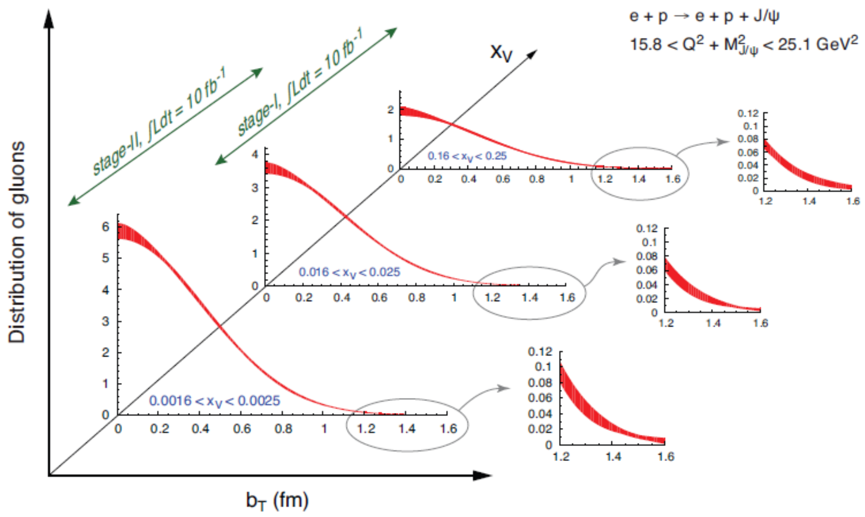


- Understanding the spatial structure of nucleons and nuclei is a key goal of the EIC
- For instance, do the gluons form “clouds” around the quarks, or are they mostly in-between?
- The transverse spatial structure can be probed through exclusive diffractive processes

Generalized Parton Distributions (GPDs) and spatial imaging

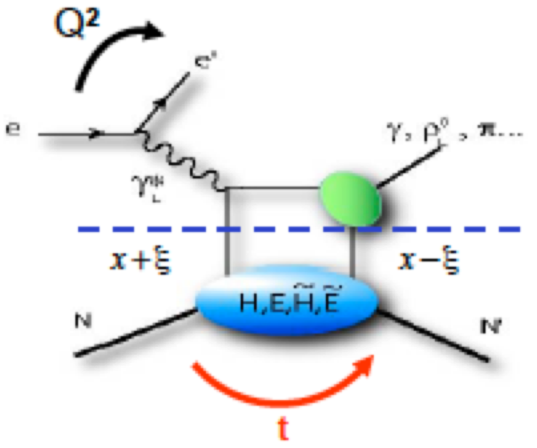


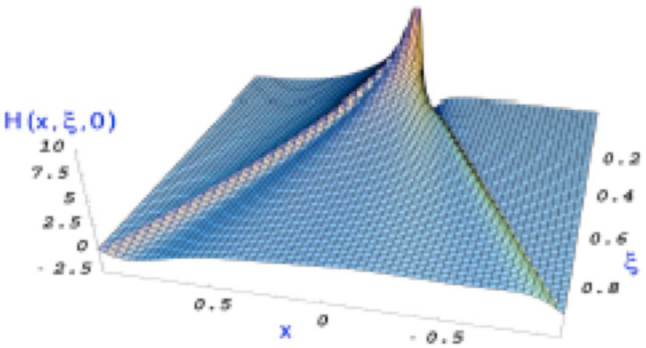


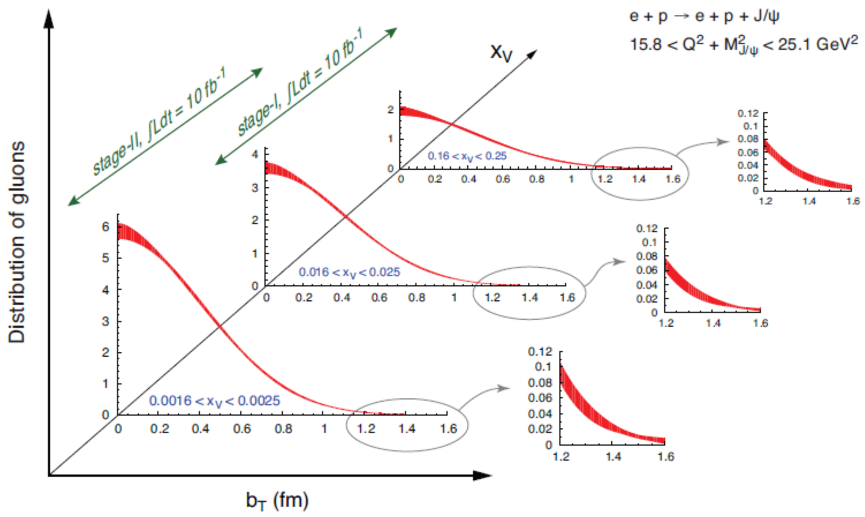


- Exclusive production of a photon or meson is sensitive to GPDs
  - In the limit of small "skewness" xi, the Fourier transform of t, the four-momentum transfer to the nucleon, can be interpreted as a spatial image in impact-parameter space
- The detailed GPD structure depends on the spin of the target
  - Spin-1/2 particles like nucleons or He-3 have four GPDs, whereas the spin-0 He-4 has one
  - In the xi = t = 0 limit, GPDs reduce to the usual PDFs (and integrating over x gives the form factors)

Generalized Parton Distributions (GPDs) and spatial imaging



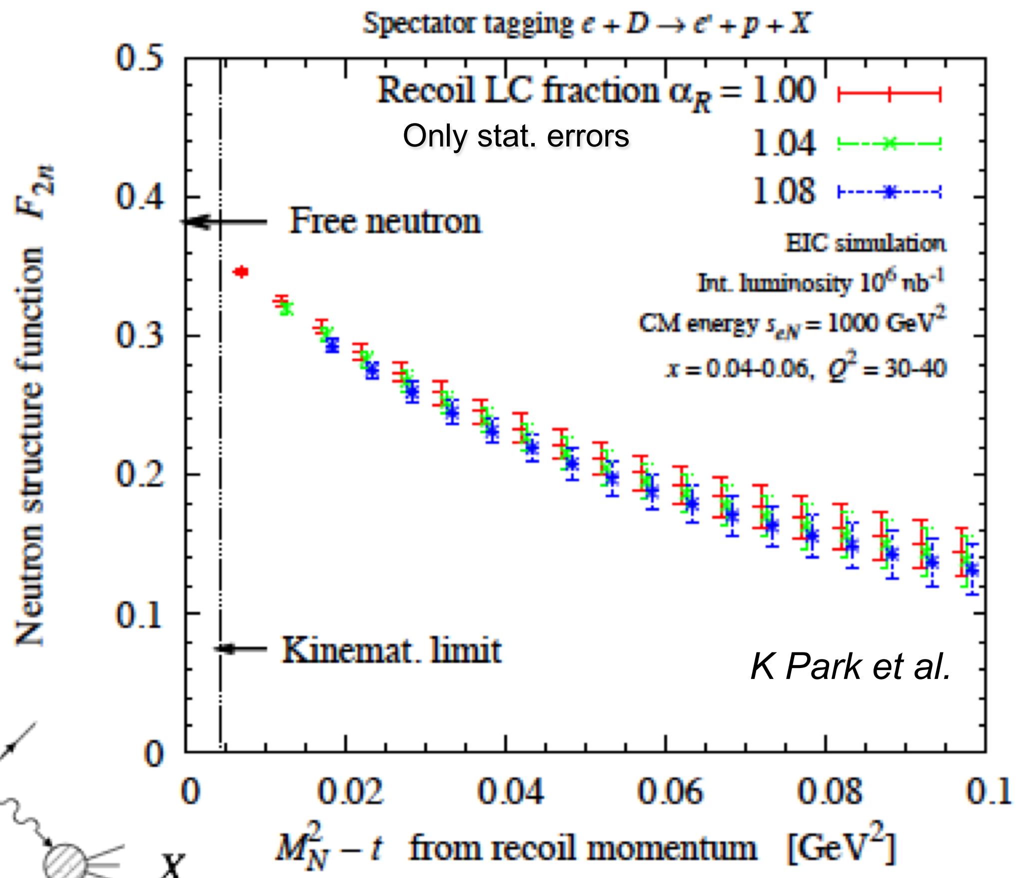


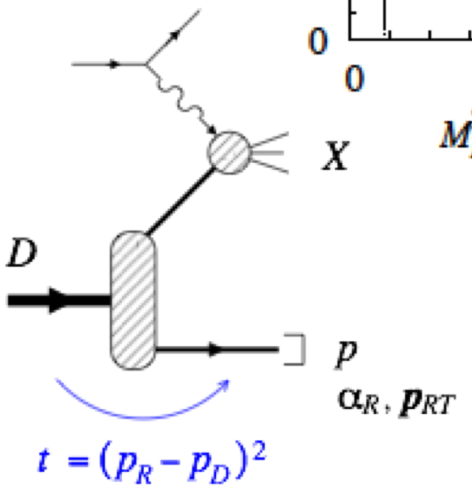


- Different probes are sensitive to different aspects of the spatial distribution
  - Charmonium is sensitive to gluons, while light vector meson production is sensitive to quark flavor
  - Deeply Virtual Compton Scattering (DVCS) is a key process due to its simple structure – but it is insensitive to flavor, making a comparison of proton and neutron targets crucial

- To create a spatial image in b, data over a sufficient range in t (~ p_T^2) are needed (~ 0-1 GeV^2)
  - Small t <=> large b and vice versa.
  - Note that for nuclei the larger mass means that scattering angle is much smaller for a given t

Neutron structure through spectator tagging





- Simplest case: tagged DIS on neutron
  - Recoil-proton light-cone momentum

$$\alpha_R = (E_R + p_{R||})/(E_D + p_{D||}) \text{ and } \mathbf{p}_{RT}$$

  - Cross section in impulse approximation

$$\frac{d\sigma}{dx\, dQ^2\, (d\alpha_R/\alpha_R)\, d^2 p_{RT}} \propto |\psi_D^{LC}(\alpha_R, p_{RT})|^2 F_{2n}[x/(2-\alpha_R), Q^2]$$

Deuteron LCWF   Neutron SF

Frankfurt, Strikman 1981

talk by C. Weiss

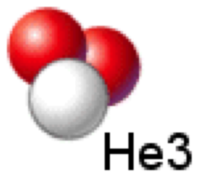
- Free neutron structure at pole
  - Not affected by final-state interactions!
- DVCS can be treated similarly

- Neutron structure can also be accesses by tagging protons in He-3
  - Experimentally straightforward but theoretical treatment more complicated. Deuterium will be needed for comparison.

talk by R. Milner

Coherent exclusive (diffractive) reactions on light nuclei

- In contrast to heavy nuclei, where separating coherent production from a large incoherent background through challenging techniques for efficient vetoing, scattered light nuclei can be detected
  - The momentum transfer t can be determined directly from the ion



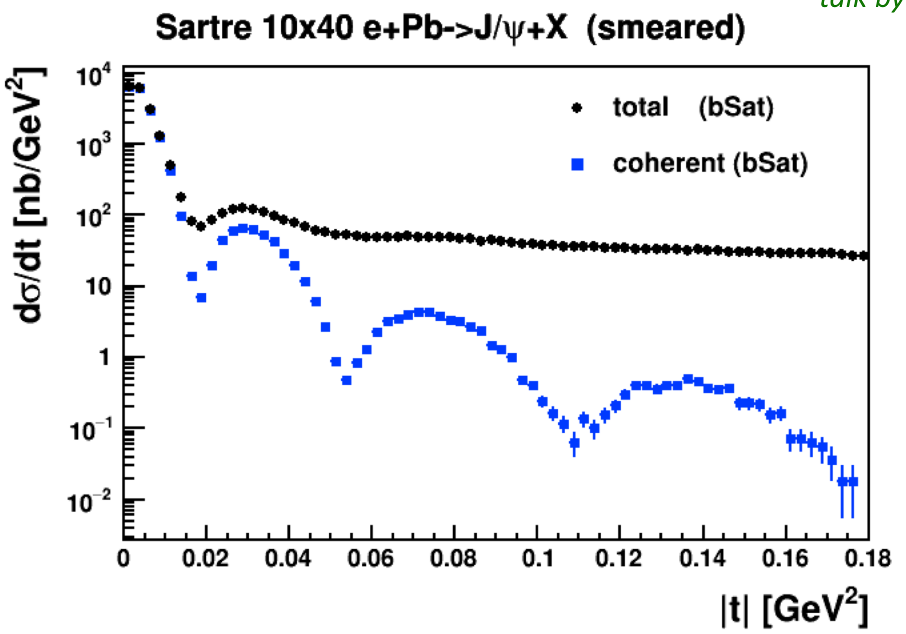
- Light ions span the full range of nuclear densities
  - D is the least dense nucleus unbound, while He-4 is comparable to heavy ions, and He-3 falls in the middle

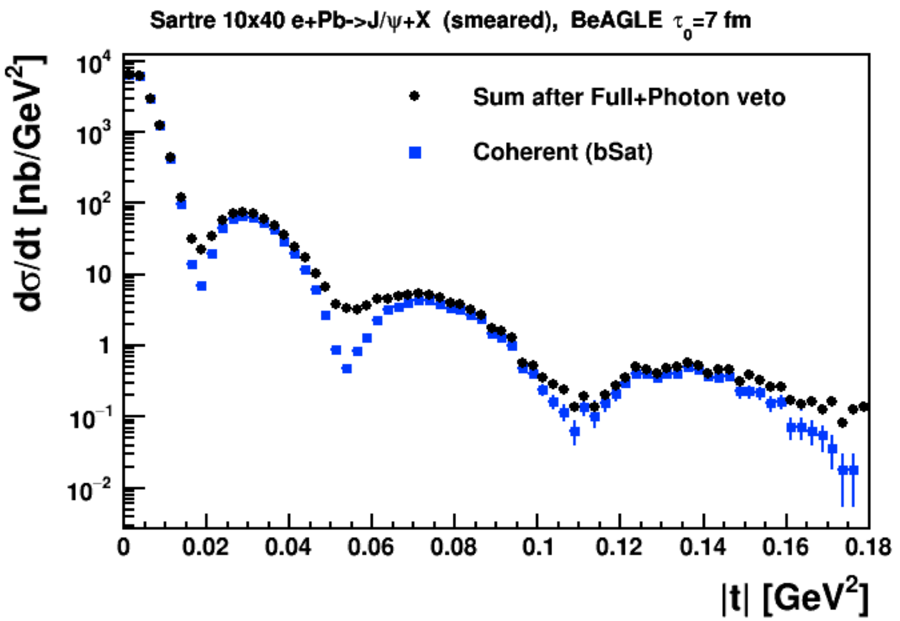
- Polarized He-3 beams will allow for simultaneous measurement of both tagged neutron structure and coherent diffraction on He-3
  - Interesting comparison since spin of He-3 is dominated by the neutron
- He-4 has only one GPD and large asymmetries
  - Easy to measure and interpret

Coherent diffraction on heavy nuclei

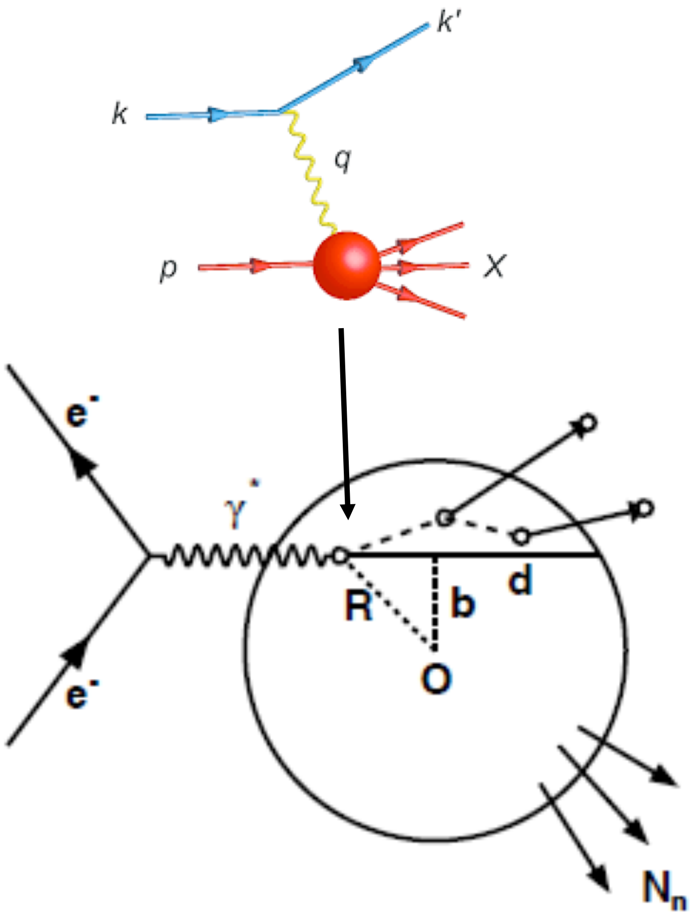
talk by M. Baker

- Sensitive to gluon saturation
  - Comparison of J/psi and phi
- Large incoherent background challenging
  - But interesting in its own right, as it is sensitive to the fluctuations in the spatial distribution
- Efficient veto requires detection of all produced particles: protons, neutrons, light nuclei, and photons from nuclear de-excitations
  - Detection of the residual nucleus is also helpful



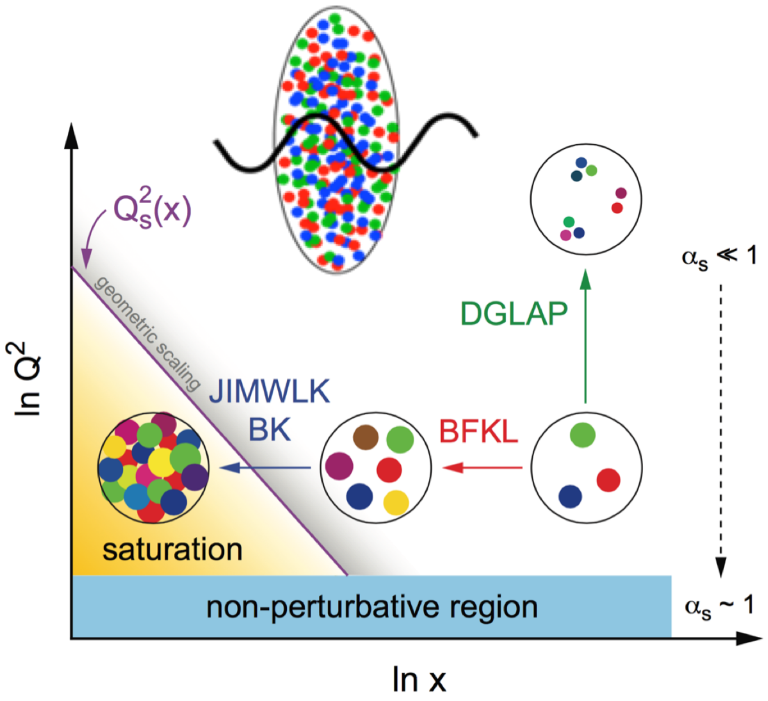


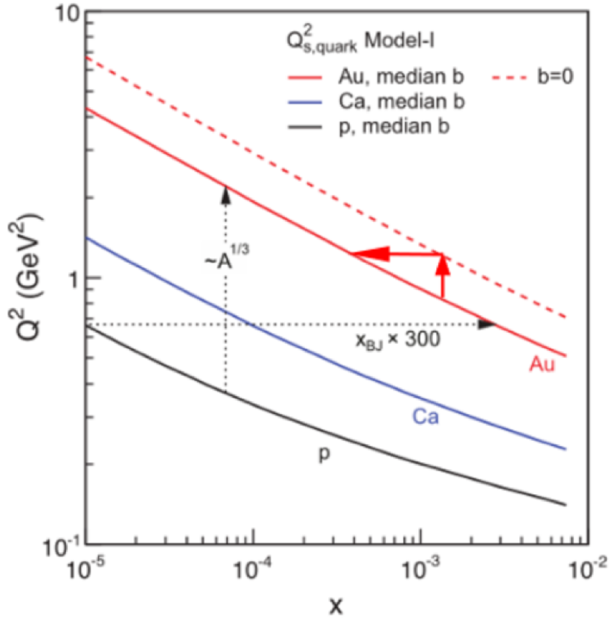
Deep Inelastic Scattering on nuclei

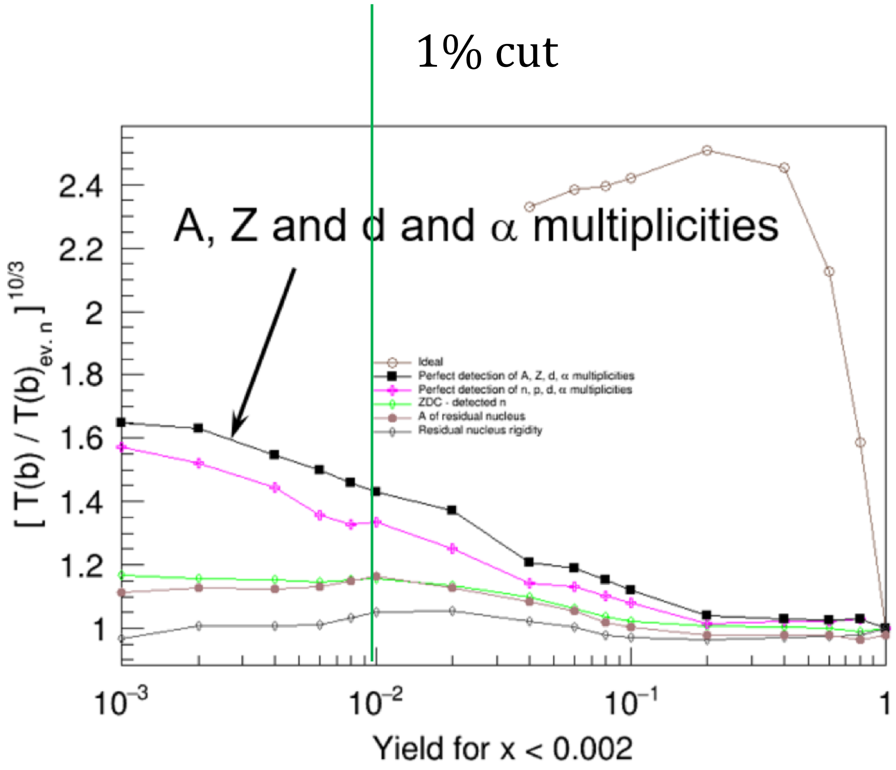


- DIS on nuclei is a multi-stage process.
- First, there is a scattering on a parton
- Debris from the interaction will propagate out of the nucleus, interacting along the way, causing an intra-nuclear cascade typically leading to the knock-out of several nucleons
- The daughter nucleus will usually be left in an excited state, leading to evaporation of nucleons and light nuclei, and sometimes fission.
- At high excitation energies there is no strong preference for emitting charged particles or neutrons, but at low energy neutrons are preferred.
- Finally, when below the nucleon separation energy, the nucleus will emit photons. These transitions between bound states offer detailed insight into the structure of the produced nucleus.

Probing gluon saturation in DIS







- At low x, the photon interacts coherently with the gluons along its path inside a nucleus, allowing the EIC to reach into the saturation regime.
  - Impact parameter tagging selects events with larger average density T(b)

$$Q_s^2 \sim A^{1/3} / x^{0.3} \sim T(b) * (E_e E_A)^{0.3}$$

- A larger thickness T(b) is equivalent to a higher beam energy
  - With a evaporation neutron multiplicities only, this factor is 3.2 at 1%
  - Detecting all final-state particles, this increases to 4.8

$$F_E = \left(\frac{\langle T(b)\rangle_{central}}{\langle T(b)\rangle_{minbias}}\right)^{10/3}$$

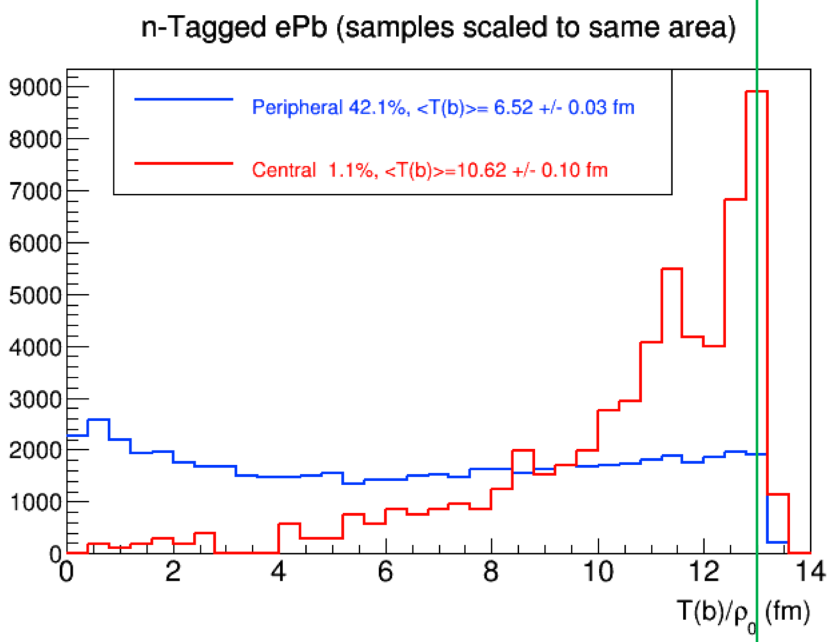
T(b) for ^{208}Pb and ^{238}U

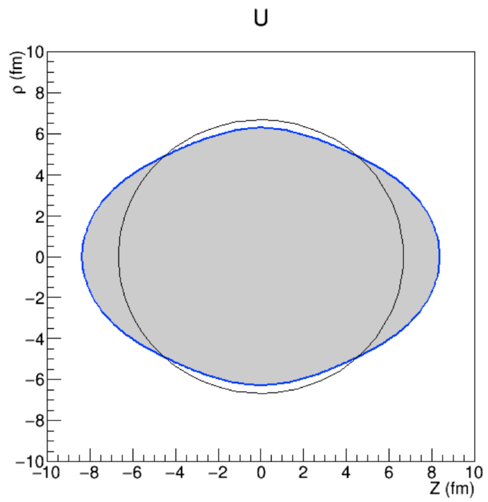
- Using U-238 instead of Au or Pb further increases the equivalent energy, from a factor 4.8 to 6.7 at 1% yield.
  - U has slightly larger A than Pb
  - U is a deformed nucleus. Longer paths along the long axis
  - It is easier to align one axis in eA than two in AA

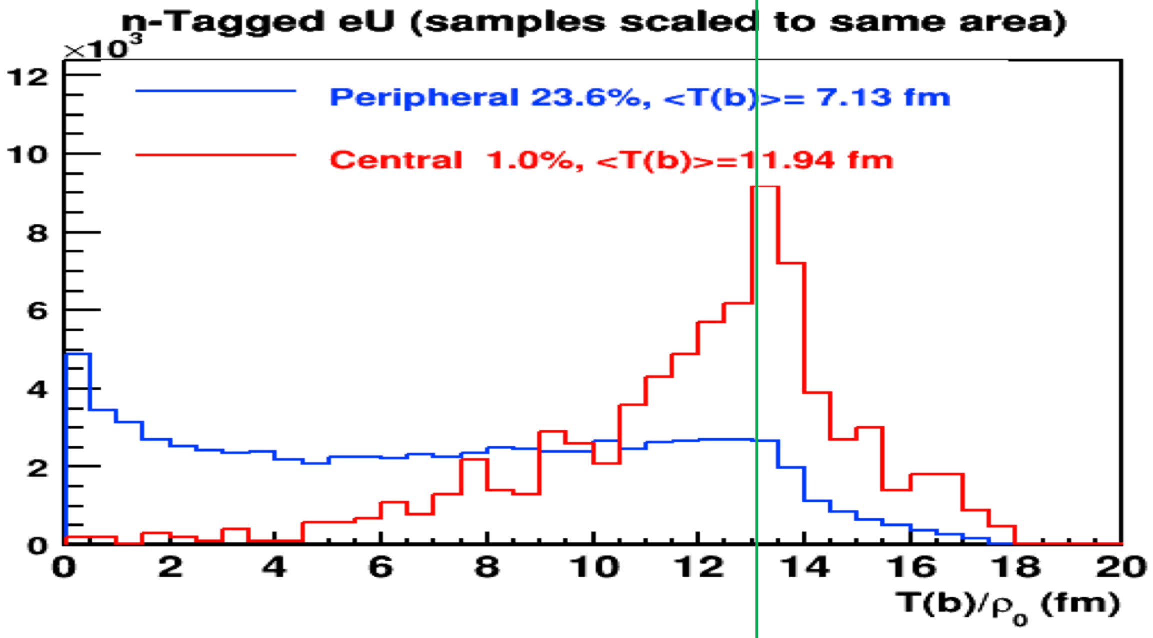
- A factor 6.7 is equivalent to running untagged Pb at 740 GeV/A

- Note that detection of all nuclear fragments, including spectator protons, is crucial

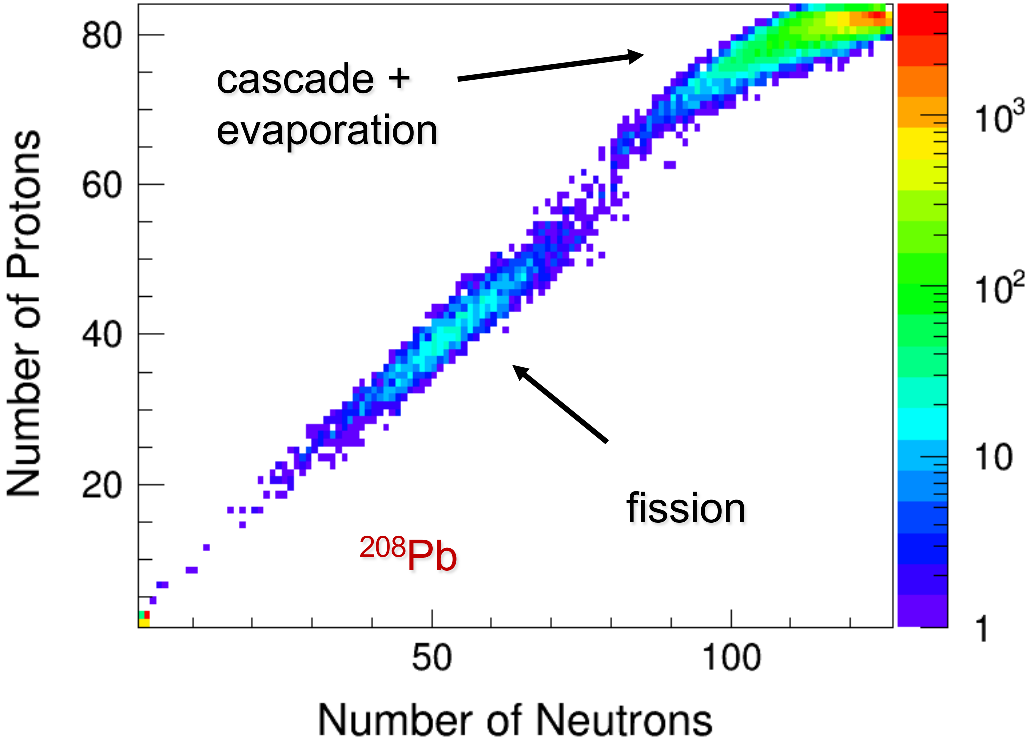
M. Baker, 2018

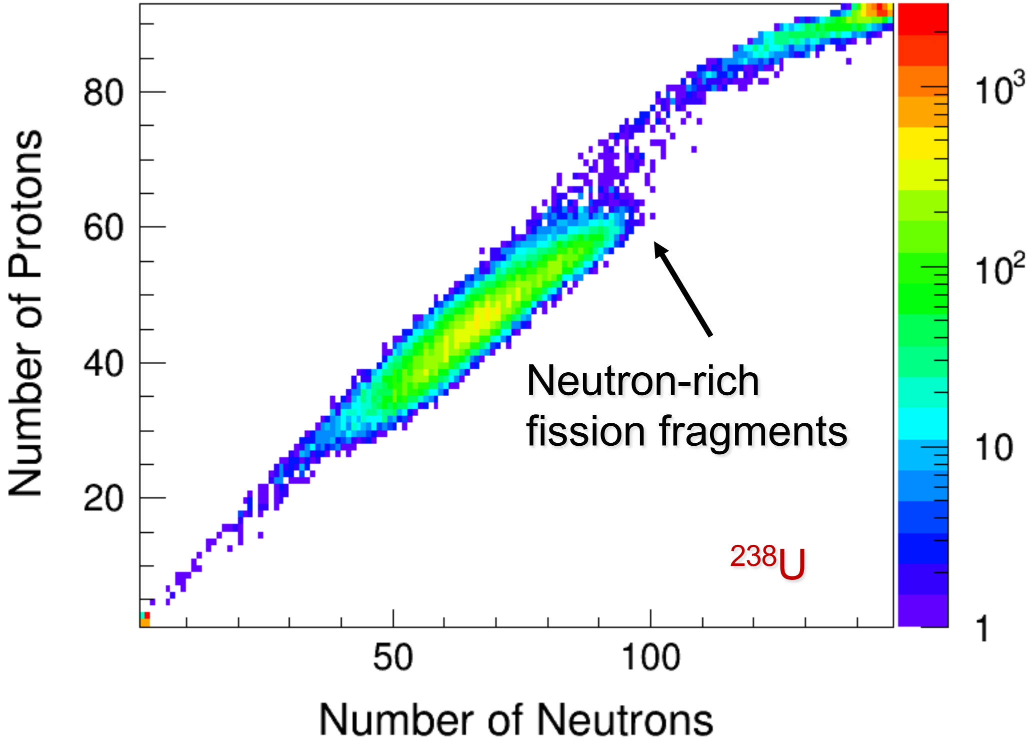






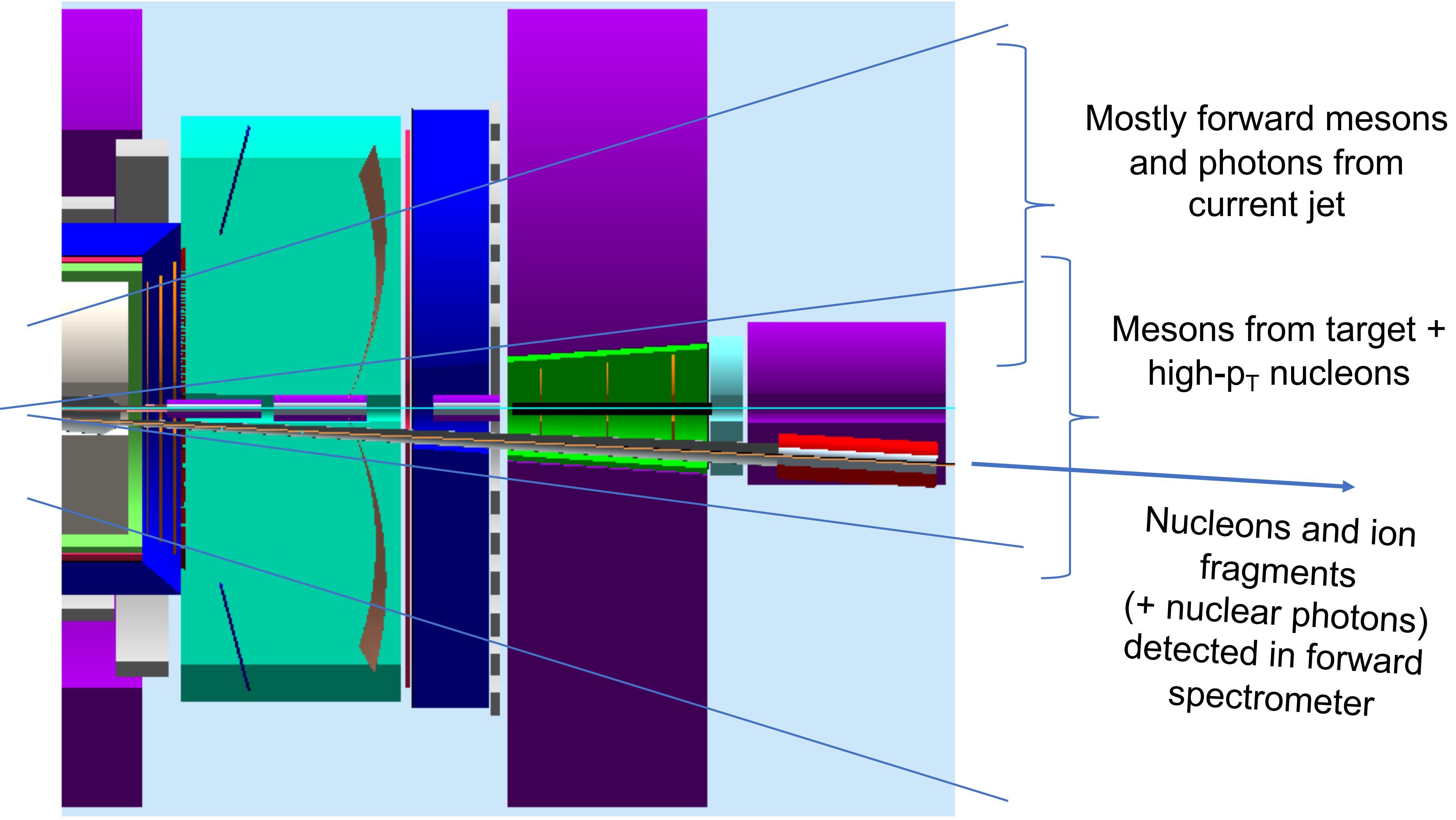
Rare isotopes at the EIC?





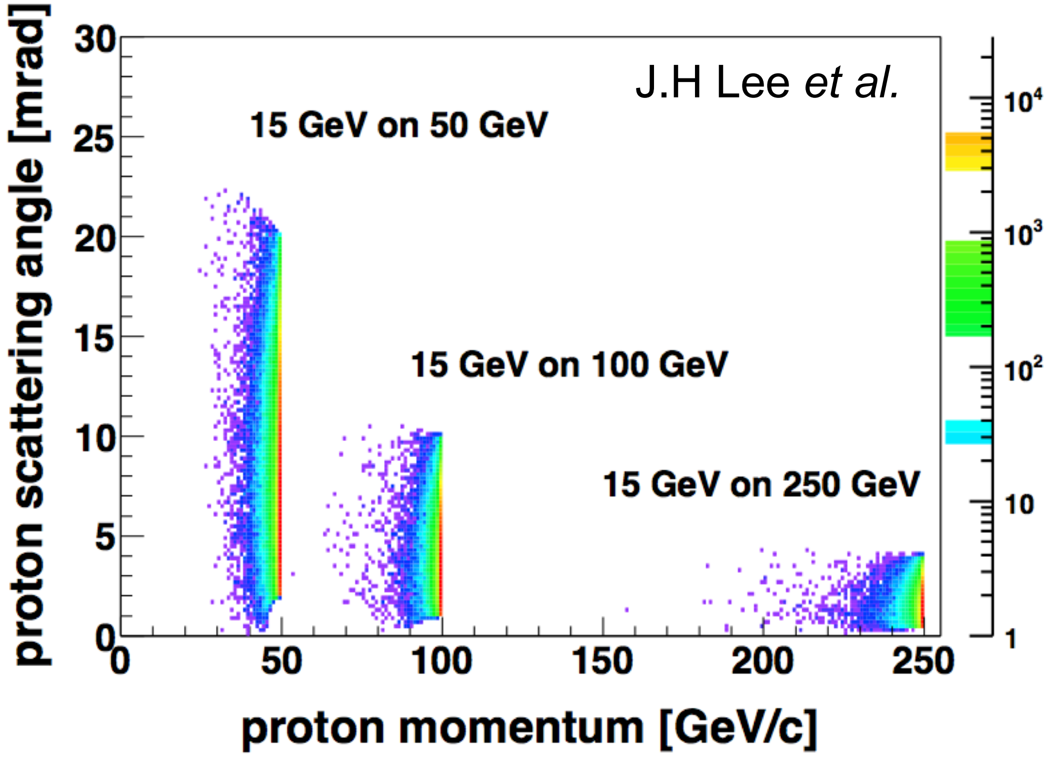
- The EIC will produce a large number of exotic isotopes
- The long lifetime in the lab frame will allow detection in the forward spectrometer
- Complementary to measurements at FRIB

Detection of forward hadrons (and photons) - nomenclature



- Forward endcap of central detector
- Transition region
- Forward detection

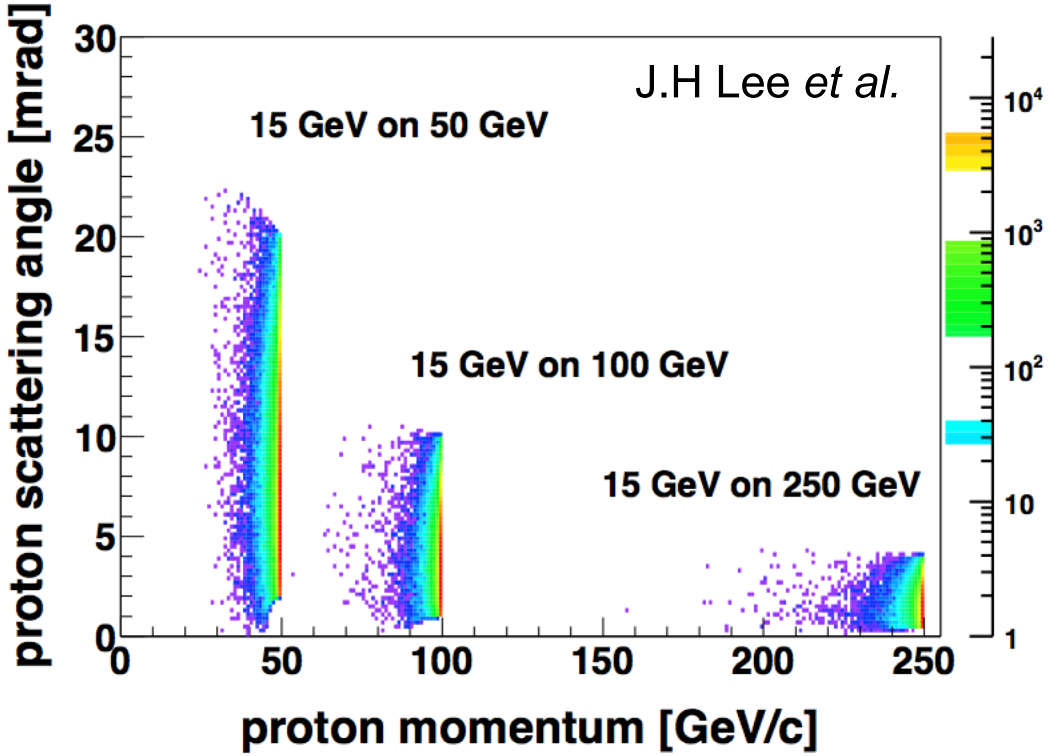
Near-beam detection using the forward magnetic spectrometer

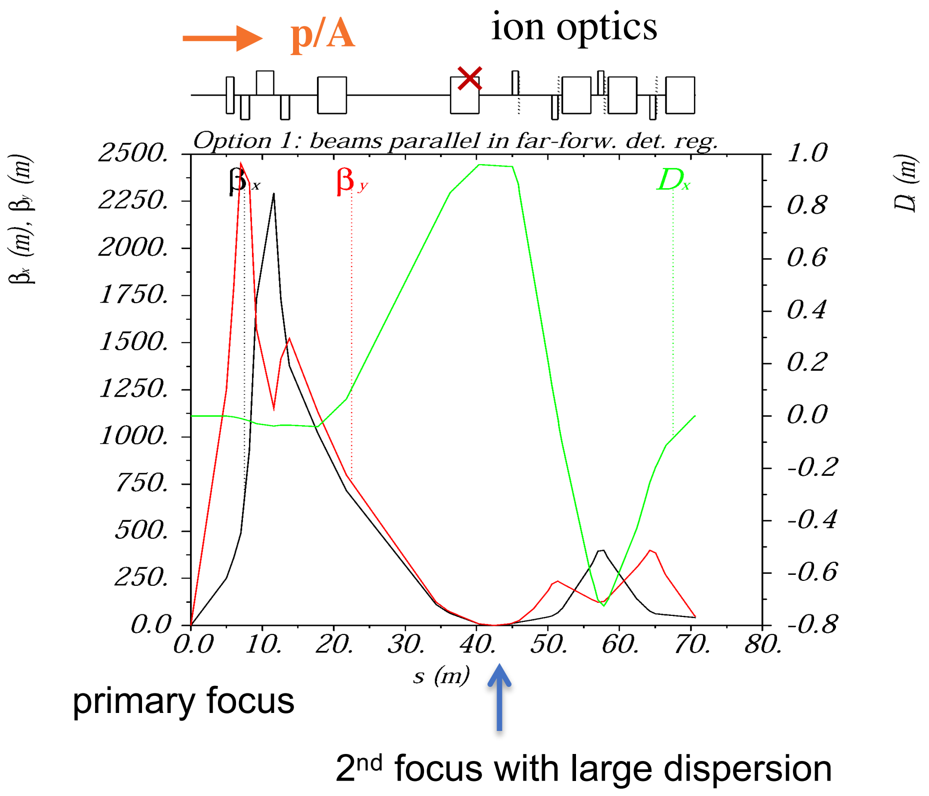


- The intrinsic beam energy spread is on the order of a few x 10^{-4}.
- In contrast, the target energy loss is typically >1% (DVCS on the proton shown)
- For heavy ions, the energy change is small, but losing a single proton changes the rigidity (~A/Z) by about 1%

- With sufficiently large dispersion (which separates off-momentum particles from the beam), it is possible to detect all target particles, even protons scattered at zero degrees or nuclei losing only one or two nucleons.

Near-beam detection using the forward magnetic spectrometer



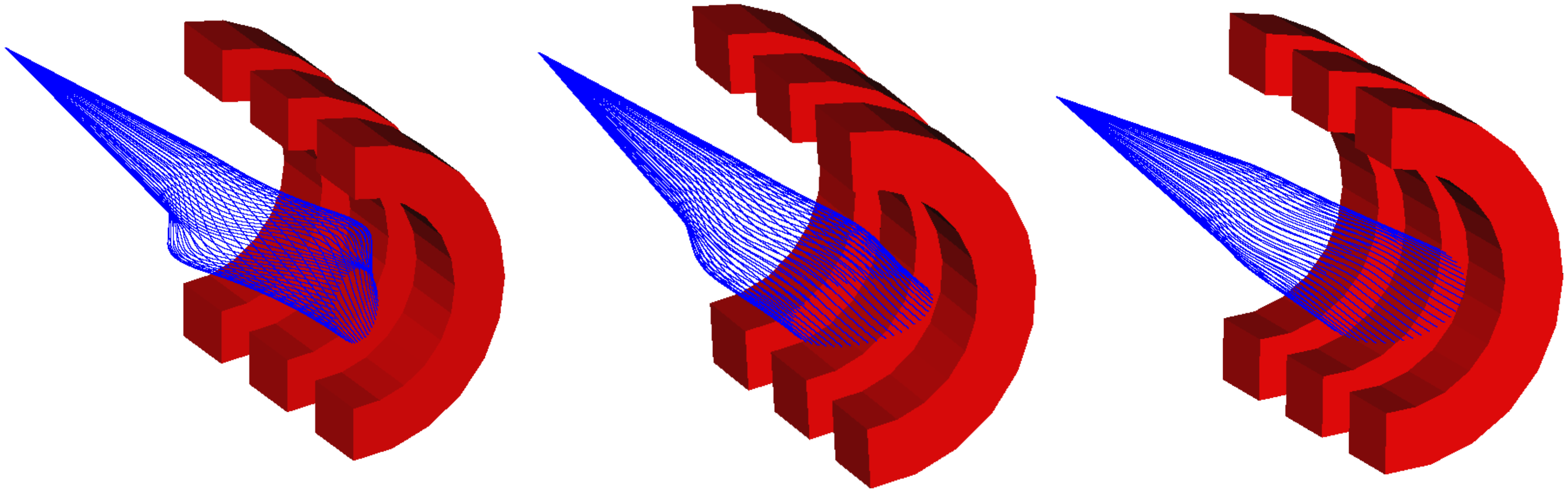


- A (weaker) secondary focus where the dispersion is large makes the beam smaller, allows the Roman pots to go closer, thereby reducing the dispersion requirement
  - Note that only the beam size and not the angular spread at the collision point is relevant here
- The optimal combination of dispersion and beam size (focusing and cooling) will be site dependent

“Large” angle (p_T) detection is determined by accelerator magnet apertures

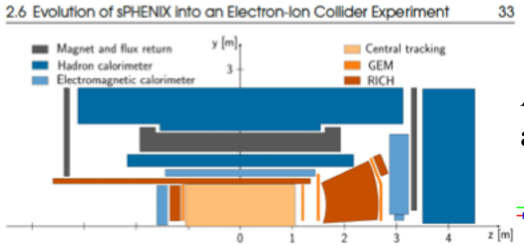
(protons rich fragments) ← → (neutron rich fragments)

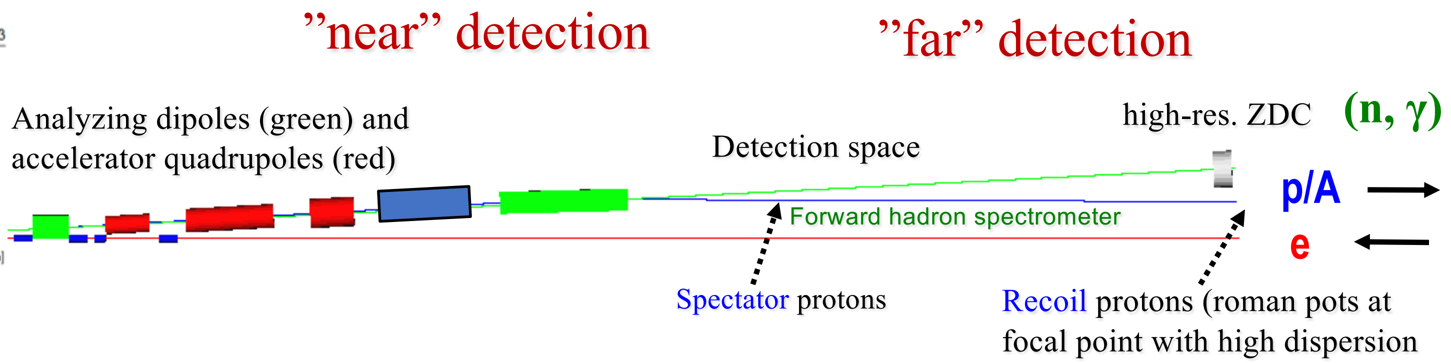
$\Delta p/p = -0.5$	$\Delta p/p = 0.0$	$\Delta p/p = 0.5$
(spectator protons from deuterium)	(exclusive / diffractive recoil protons)	(tritons from N=Z nuclei)

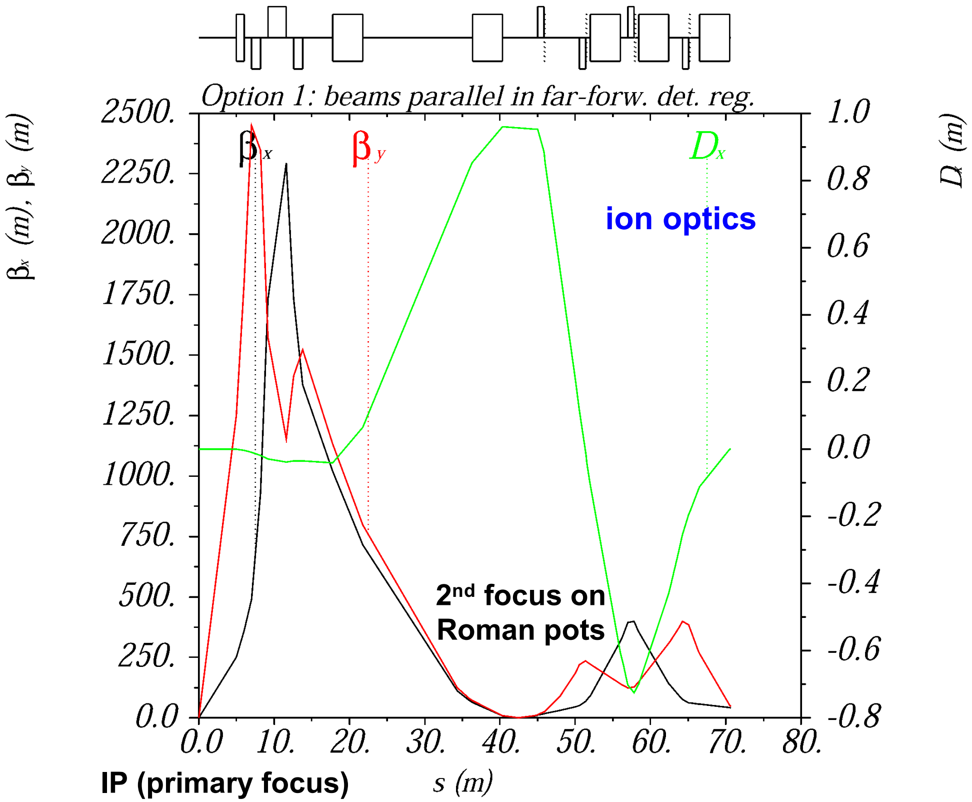


- The ion quadruoples are the bottleneck for transporting particles scattered “far” from the beam
  - Larger apertures can be achieved by using technologies allowing for higher peak fields
  - Peak fields can be reduced by optimizing field gradients (lengths and positions of focusing magnets)

Detection of fragments and nuclei



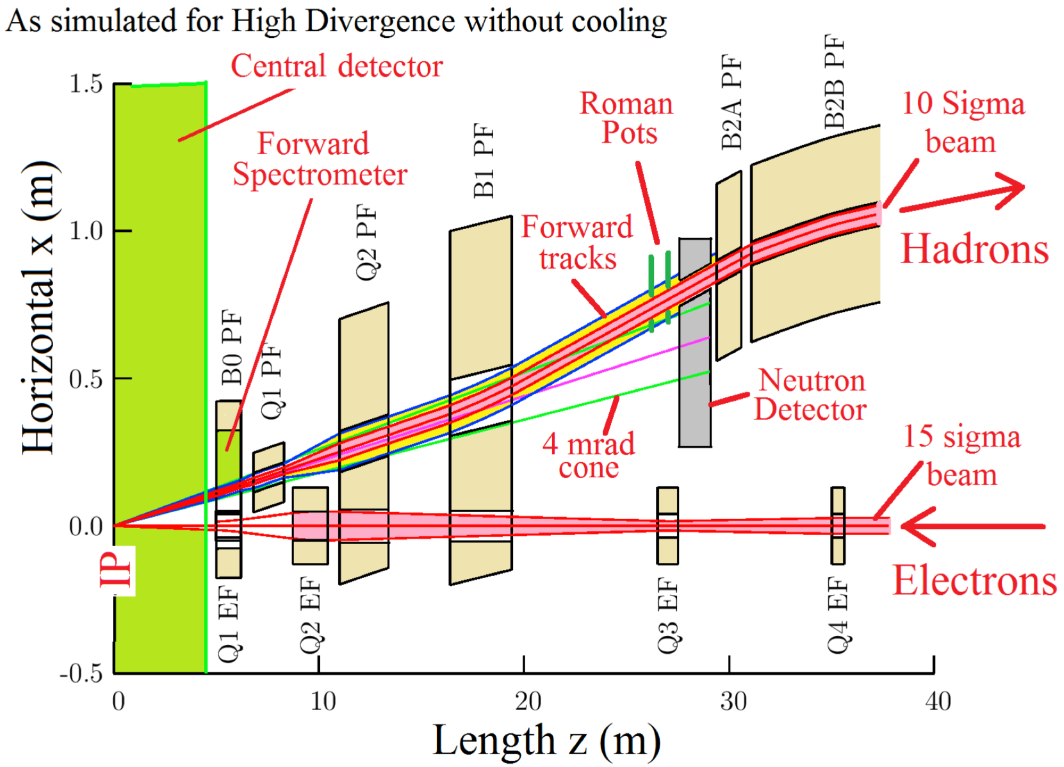


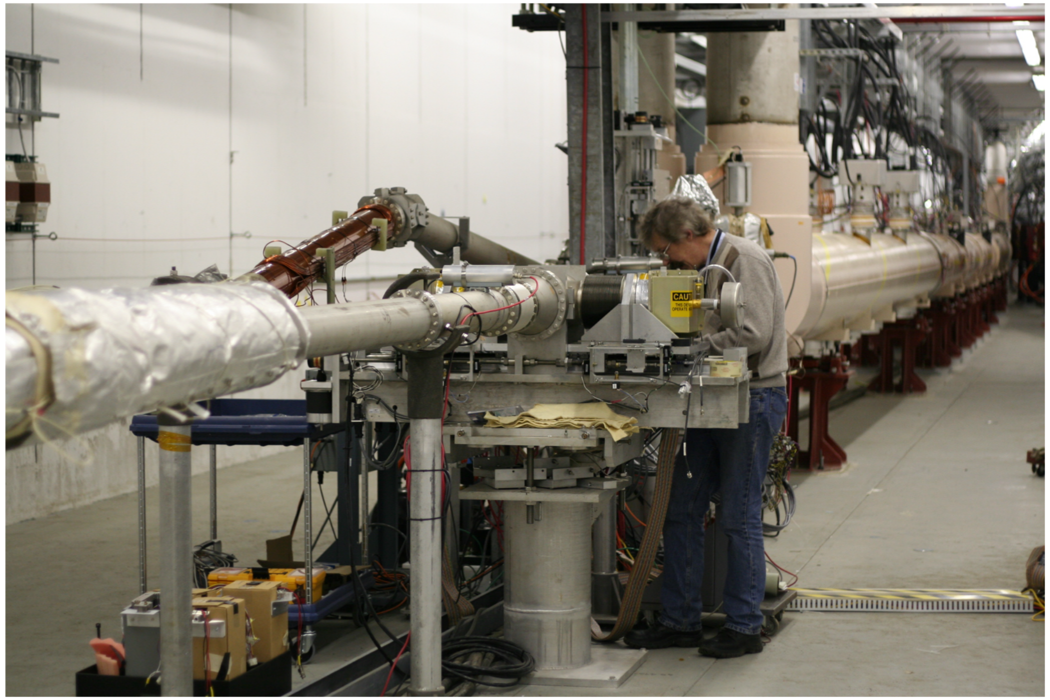


- Functionally, the forward detection is naturally separated into a "near" and "far" parts
- "Near" detection:
  - *Goal*: off-momentum/rigidity particles or ones scattered at "large" angles (high p_T)
  - *Requirement*: large magnet apertures
- "Far" detection (can be after crab cavity):
  - *Goal*: small-angle particles with momentum/rigidity close to that of the beam
  - *Requirement*: large dispersion and small beam size

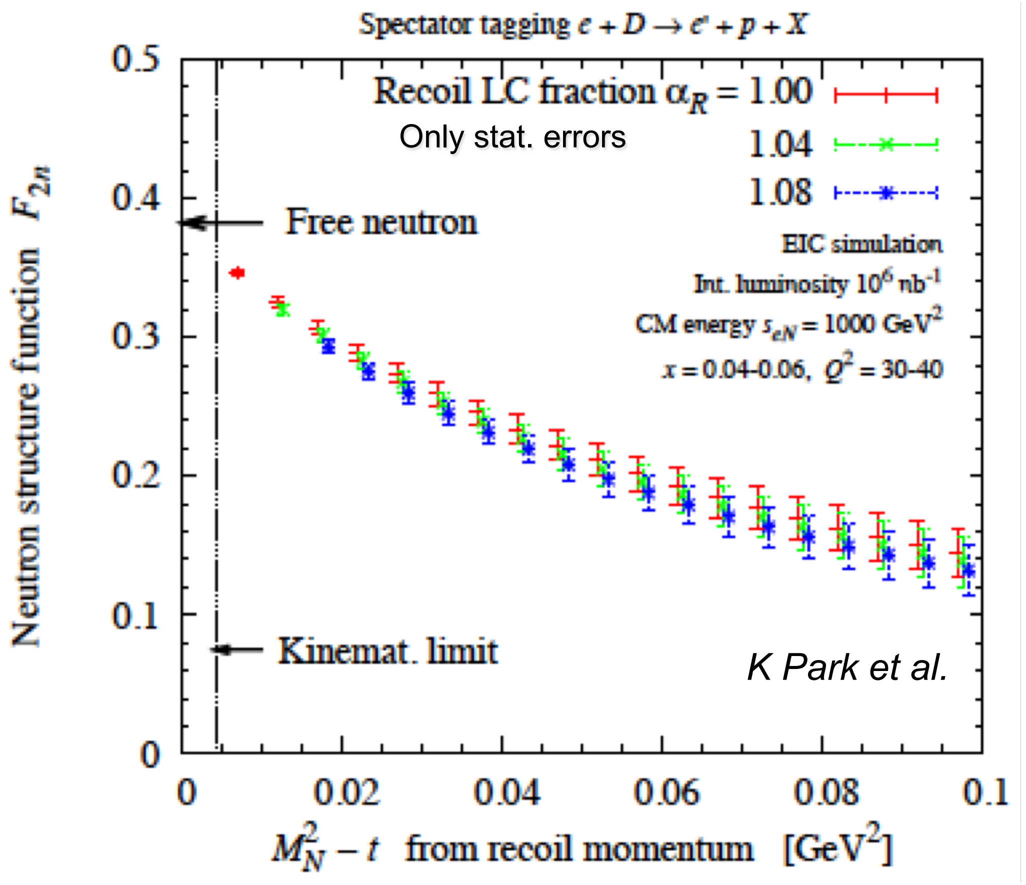
Near-beam detection at JLab and BNL

- At JLab, a full forward spectrometer was always a key requirement for the MEIC (now JLEIC)
  - Recoil proton acceptance up to 99.8% of the E_{beam} for *all* angles and down to 2 mrad for *all* energies
- At BNL, the focus has been on the "near" part, but a "far" part can be added
  - In STAR, Roman pots are located 50 m downstream – a good location for a second focus for the EIC





Resolution



- The measured resolution has two components
  - Intrinsic spectrometer resolution
  - Beam momentum spread - an initial-state smearing that cannot be avoided
- For physics, the transverse beam momentum spread is most important
  - Depends on focusing (~ luminosity)
  - Strong focusing (small beta*) creates large transverse momentum spread
  - Proportional to angular spread at IP
- The spectrometer resolution needs to be at least as good as the beam momentum spread at the largest beta* (lowest luminosity)
  - Beyond that unfolding is possible, but complicated

Forward detection – processes and requirements revisited

- Which processes drive the near-beam (small p_T) acceptance?
  - Coherent diffraction on light nuclei (detecting recoiling ion for clean signal)
  - DIS and (in)coherent diffraction on medium- and heavy nuclei (detecting residual nucleus)

Benchmarks for the ”far” detection

- Which processes drive the “large” angle (p_T) acceptance?
  - Tagging of spectator protons from nuclei (heavy ions and deuterium is most challenging)
  - Exclusive production of photons (DVCS) and mesons (DVMP) on the proton at large t at lower energies
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Benchmarks for the ”near” detection

- Which processes drive the resolution?
  - Magnetic: tagging of protons from nuclei (spectators have p ~ Fermi momentum)
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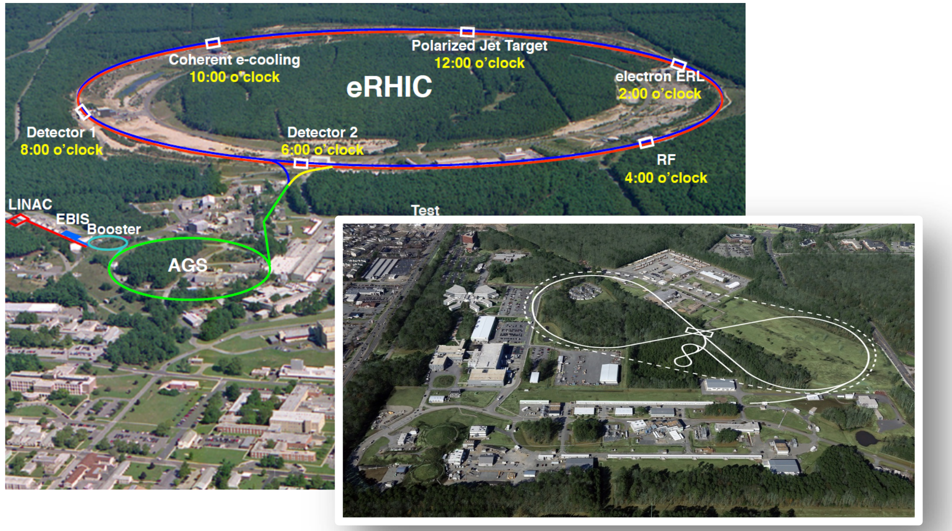
  - EMcal: Photons from nuclear de-excitations (coherent diffraction and rare isotopes)

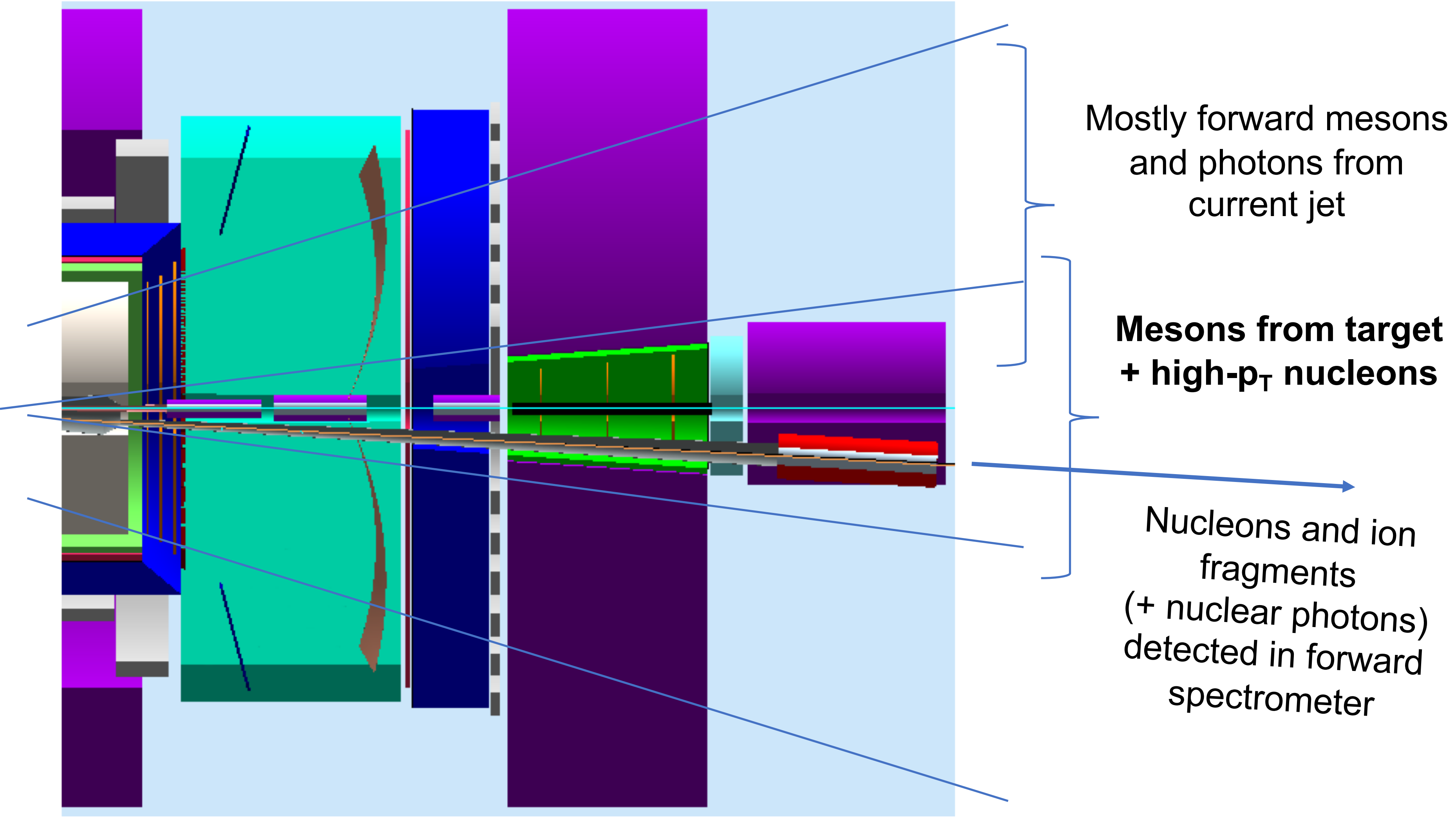
Forward detection – two IRs

- Both EIC concepts currently under consideration offer the possibility of more than one detector.
- With two complementary detectors, one could also consider two complementary IRs
- A natural choice would be to have one focus on the “near” and one on the “far” detection, with both being able to do less demanding measurements like DVCS on the proton.



- However, since the availability of “far” detection relaxes the constraints for the “near” detection, it would probably be advantageous to include full spectrometer in any detection scenario.

Transition between central and forward detectors



- Not the focus of this talk, but also important
  - Hermeticity
  - Photon detection
  - Small-angle tracking vs Hcal coverage
- Two main options
- Dipole integrated with endcap Hcal
  - Small-angle tracking
  - Higher luminosity
- Dipole behind Hcal
  - Uniform small-angle Hcal coverage

Thank you!