Concepts and challenges in forward ion detection with EIC

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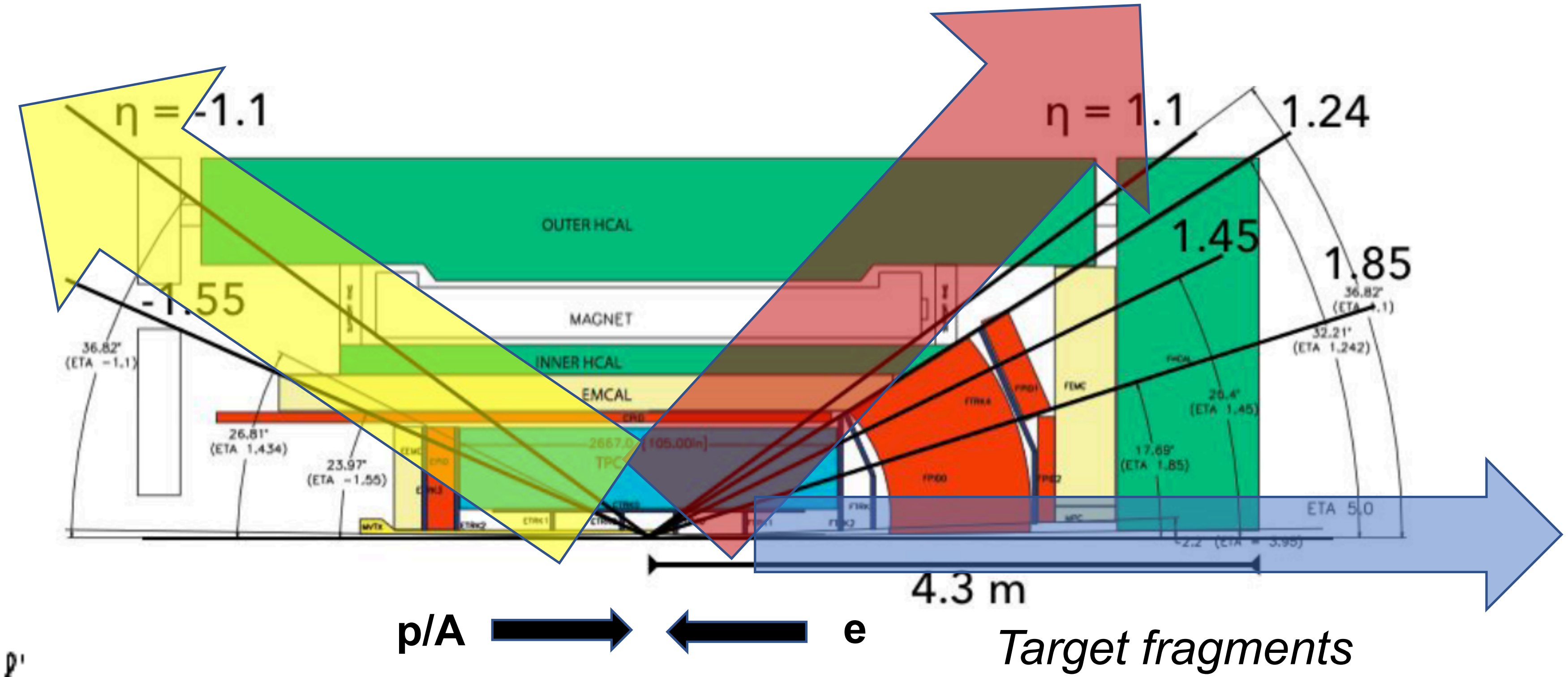
Outline

- Requirements
- Implementation

What do we measure?

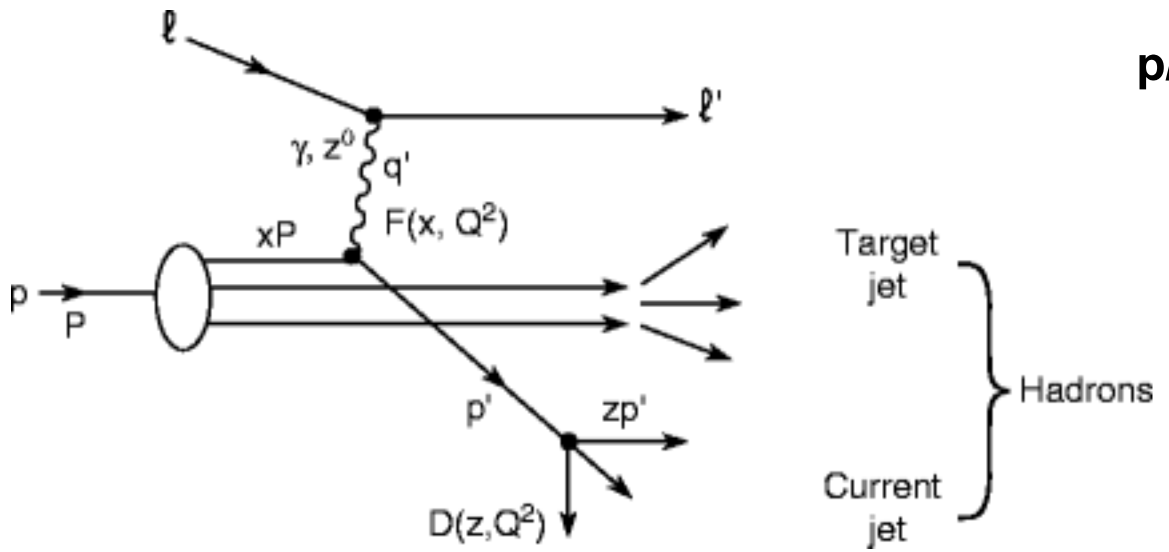
Current jet (or hadron)

Scattered electron



Target fragments

Lepton scattering on a proton



Inclusive DIS: only electron is detected

Semi-Inclusive DIS (SIDIS): electron and current jet (hadron) are detected.

Exclusive reactions: all particles are detected

Forward acceptance requirements for the target and target fragments

Key Challenge: some of the produced particles have angles and momenta (rigidities) very close to that of the beam, and sometimes they they are very different. We need to cover both cases!

- Particles "far" from the beam that have large p_T or very different rigidity
  - High-t exclusive processes on the proton at *low* beam energy
  - Spectator proton tagging in light nuclei
  - Neutron cone limits
  - **Requires** large magnet apertures

- Particles near (or in) the beam that have small p_T and similar rigidity
  - Low-t acceptance for protons and, in particular, coherent scattering on light nuclei
  - Detection and vetoing on residual nuclei in scattering on heavy ions (coherent diffraction, etc)
  - **Requires:** forward spectrometer with large dispersion and focusing optics

Light ions are the perfect benchmark for forward detection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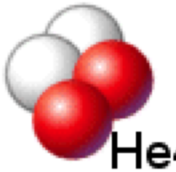
He3


He4

- Spectator tagging in deuterium and coherent scattering on light ions (He, Li, C, etc), are the most demanding processes at the EIC
- Requirements for the proton are a subset of those for light ions
- Heavy ions (coherent diffraction, rare isotopes, etc) would require some additional small pieces of instrumentation, but nothing else
  - Photon detection in front of the ZDC and PID for ion fragments

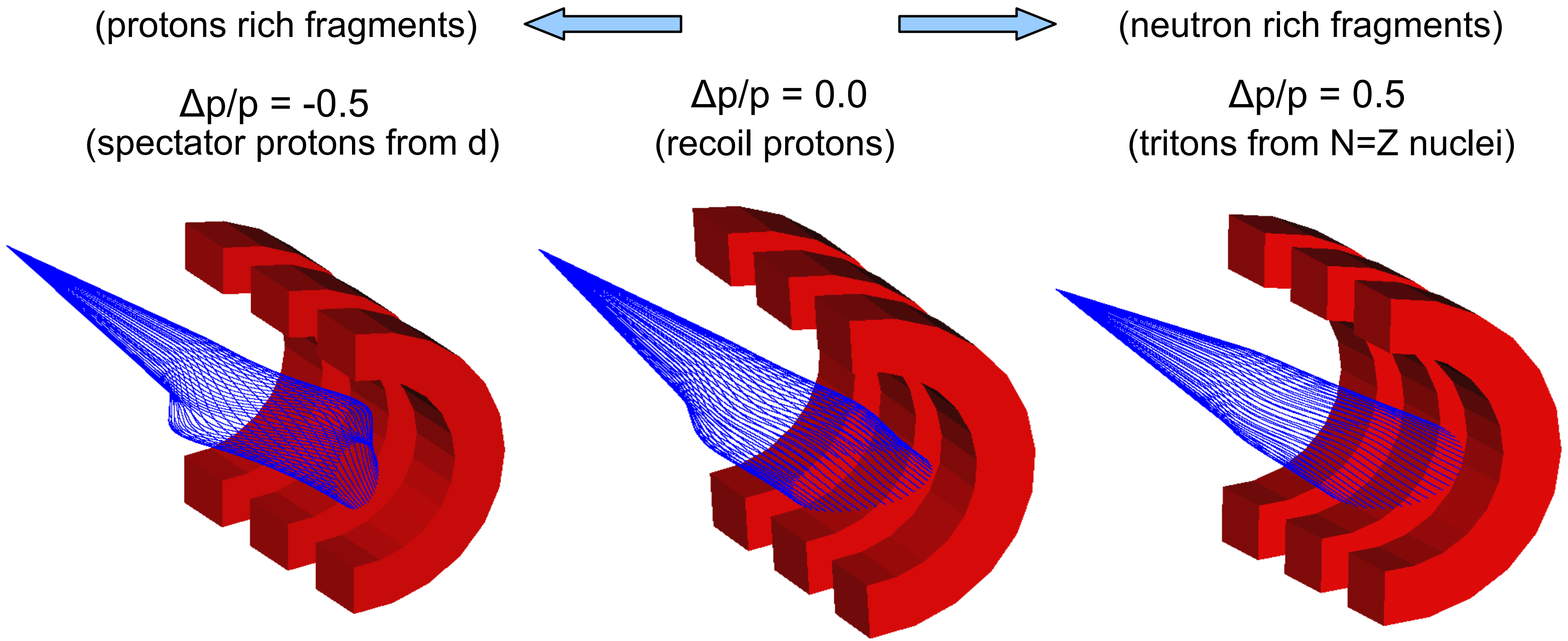
If you design your forward spectrometer for light ions, it will cover *all* EIC forward detection requirements.

Conversely, if the spectrometer is designed for protons, it will only work for protons when beam cooling reaches its nominal values, and will struggle with other parts of the EIC physics program.

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

- The quadrupole magnets are the bottleneck for “large” angle particles.

- The aperture is limited by the “peak” field on the magnet wall.



- The acceptance for neutrons and large-p_T or spectator protons is an almost universal quantity.
  - Both the peak field and lab scattering angle have the same dependence on the beam energy
  - Can be improved through careful design and by using more demanding magnet technologies.

- The “large” angle acceptance will decrease when running below the *maximum* beam energy.
  - The magnet apertures do not change, but the scattering angles do.

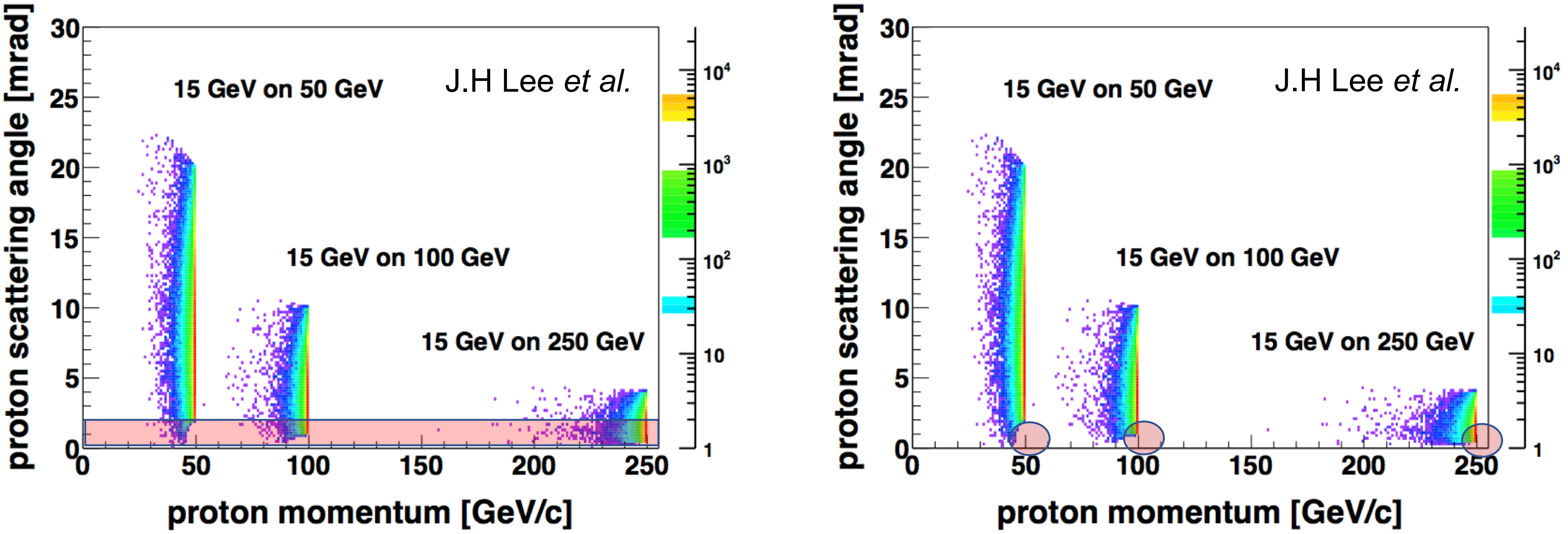
Small-angle (p_T) detection is limited by the presence of the beam

Key Challenge: We need to "peel" off the scattered particles into a region where we can put detectors (*i.e.,* outside of the beam halo). This can be schieved by *combining* two methods.

- Allow the Roman pots to cover smaller angles by reducing the beam size
  - Make the beam smaller globally by *reducing the beam emittance* (cooling)
  - Make the beam smaller at the detection point by *reducing the beta function* (secondary focus).

- *Introduce dispersion* to take advantage of the unique EIC kinematics, where the longitudinal momentum loss is large compared to the intrinsic beam momentum spread
  - Dispersion changes differences in longitudinal momentum into transverse position: dr = D dp/p
  - In DIS, the longitudinal momentum loss dp/p ~ x
  - In EIC kinematics, typical values for x are between 10^{-3} and 10^{-1}
  - The intrinsic longitudinal momentum spread in the beam is a few x 10^{-4}
  - With sufficient dispersion, and leaving an order of magnitude for the halo, we can thus detect *all* protons scattered at zero degrees down to x ~ 10^{-2}, and all x for just slightly larger angles.

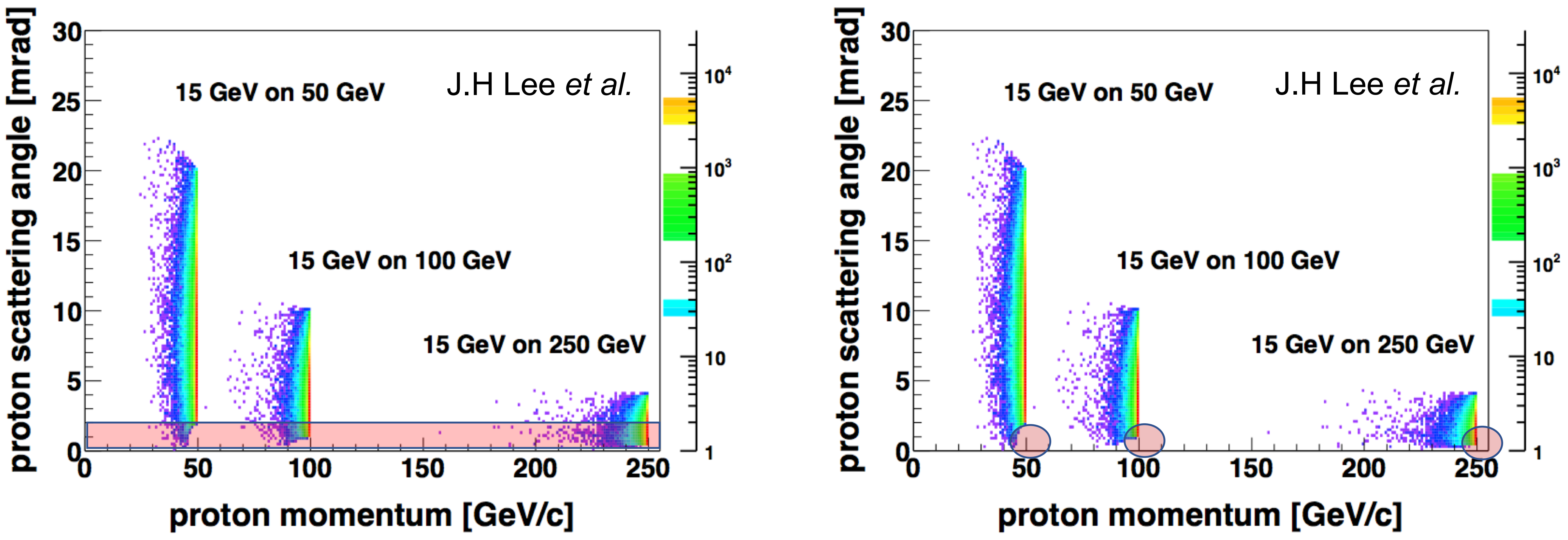
Low-t acceptance for DVCS proton acceptance without and with dispersion



- Near-beam exclusion using an 2 mrad cone due to the angular spread of the beam.
  - The actual cone angle may be larger.
- As on the left, but with dispersion, where the exclusion is shown by a quadrant of a circle
  - The circle size is exaggerated for easier viewing.

- *Note:* the HERA event generator Milou suggest a very substantial longitudinal momentum loss, making a large dispersion particularly important

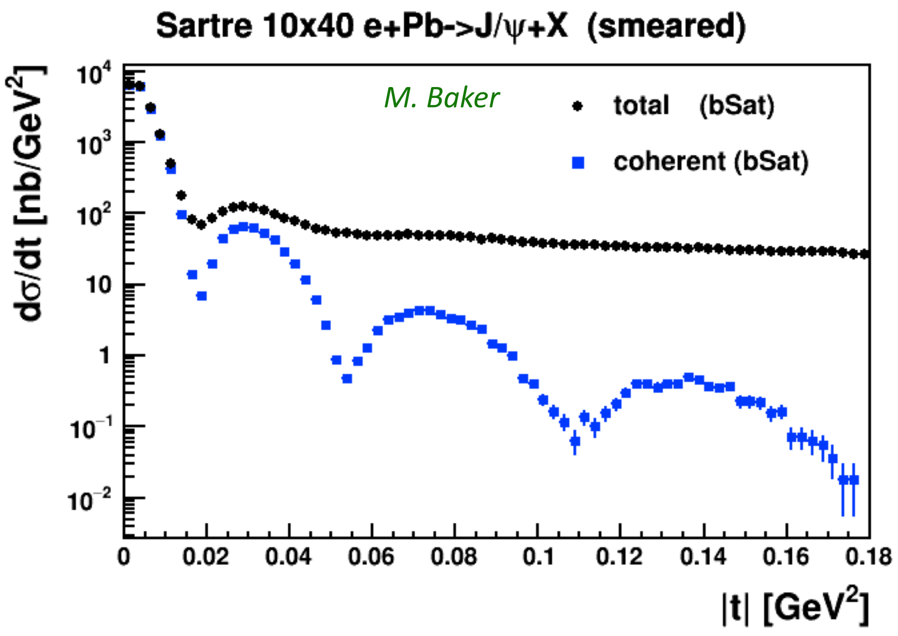
Ion acceptance

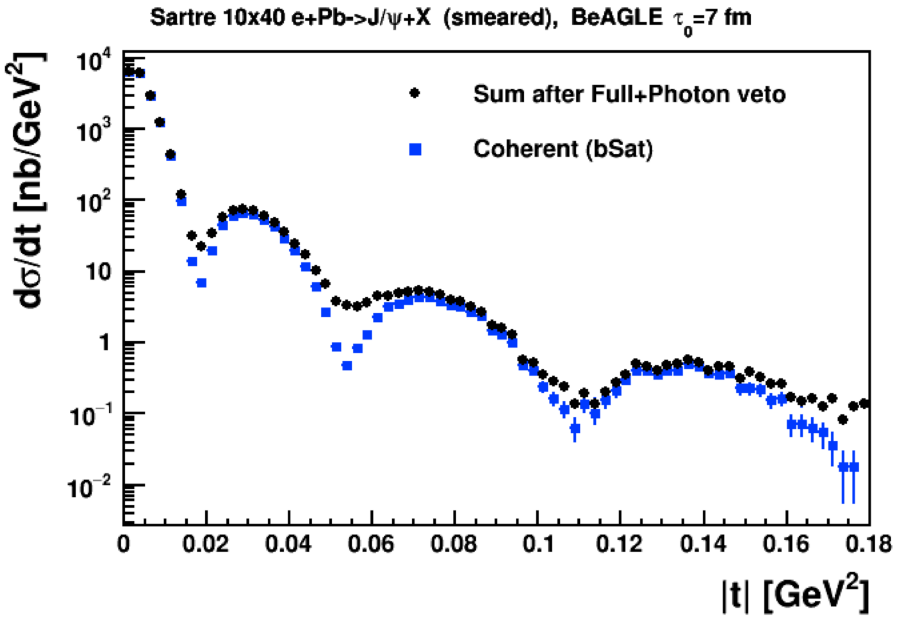


- Since in coherent production both the scattering angle and longitudinal momentum loss scale with pA, to first order ions behave like high-momentum protons.
- Without a large dispersion, protons exhibit large low-t losses at 250 GeV, which would limit coherent measurements on ions to the lowest masses and beam energies.

Synergies between light and heavy ions

- There is considerable interest in the heavy-ion community to study coherent diffraction on heavy nuclei, but it is very challenging experimentally
- The coherent events can only be accessed it the large incoherent background is suppressed
  - The ZDC neutron efficiency is too low to provide the required suppression.
  - A more capable forward detection is required.
  - But even then, interpretation is complicated
- In contrast, coherent scattering on light ions is straightforward if the scattered ion is *detected*.
- Nuclei like ^{12}C would be interesting in their own right, but also important for understanding ^{208}Pb data.
  - Would need to run similar kinematics





Half-time summary

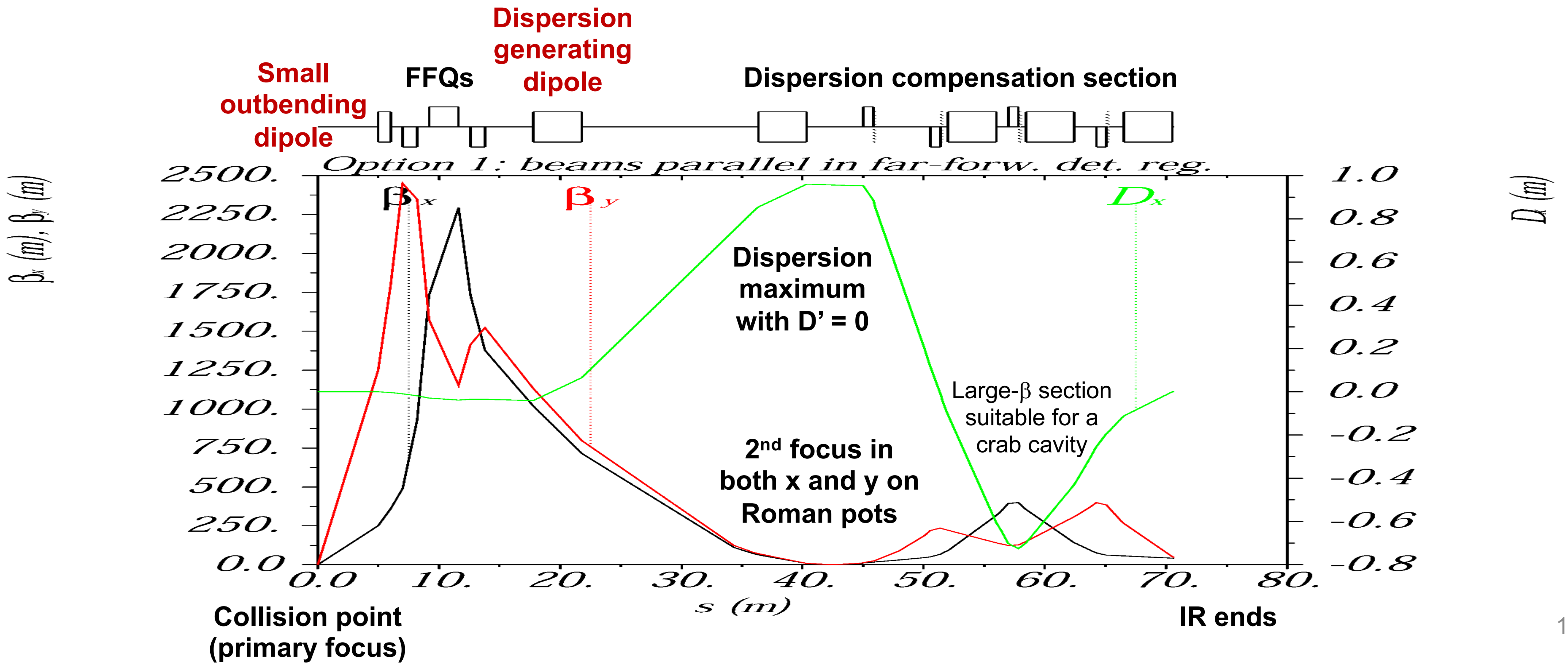
- With careful design and advanced magnets, a good large-t acceptance for low-energy protons and off-rigidity particles (spectator protons from deuterium) can be achieved.
  - Also true for neutron cone / ZDC acceptance

- With a large dispersion, it is straightforward to build a forward detection system covering the full t-range for protons in one setting in one IR.
  - This is also true during early running with limited cooling (poor beam emittance).

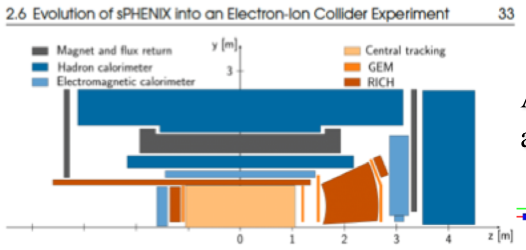
- A large dispersion is *essential* for measuring coherent processes on light nuclei.
  - Without it one is limited to the lowest masses and energies
  - Energy range needed, for instance to extract real part in DVCS

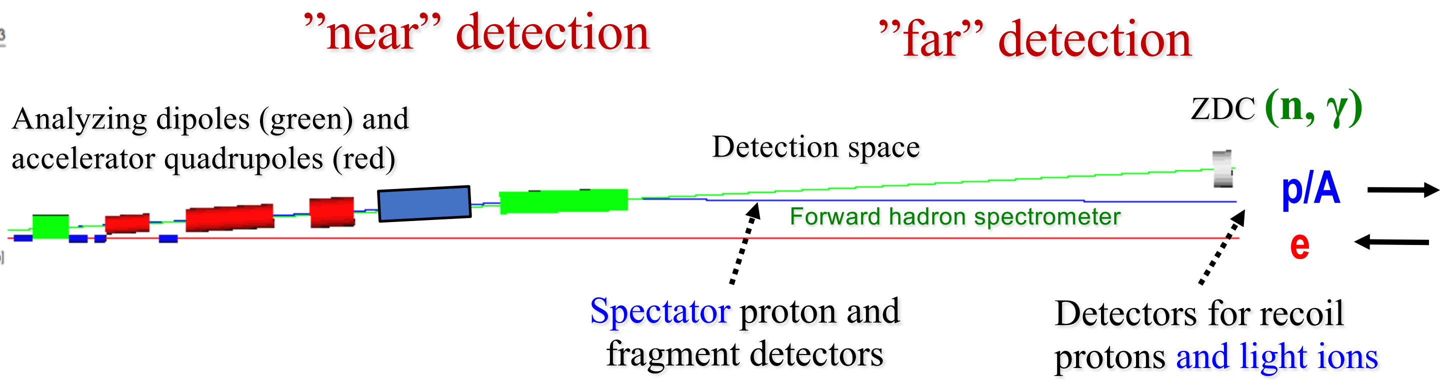
Maximally compact high-dispersion forward spectrometer - optics

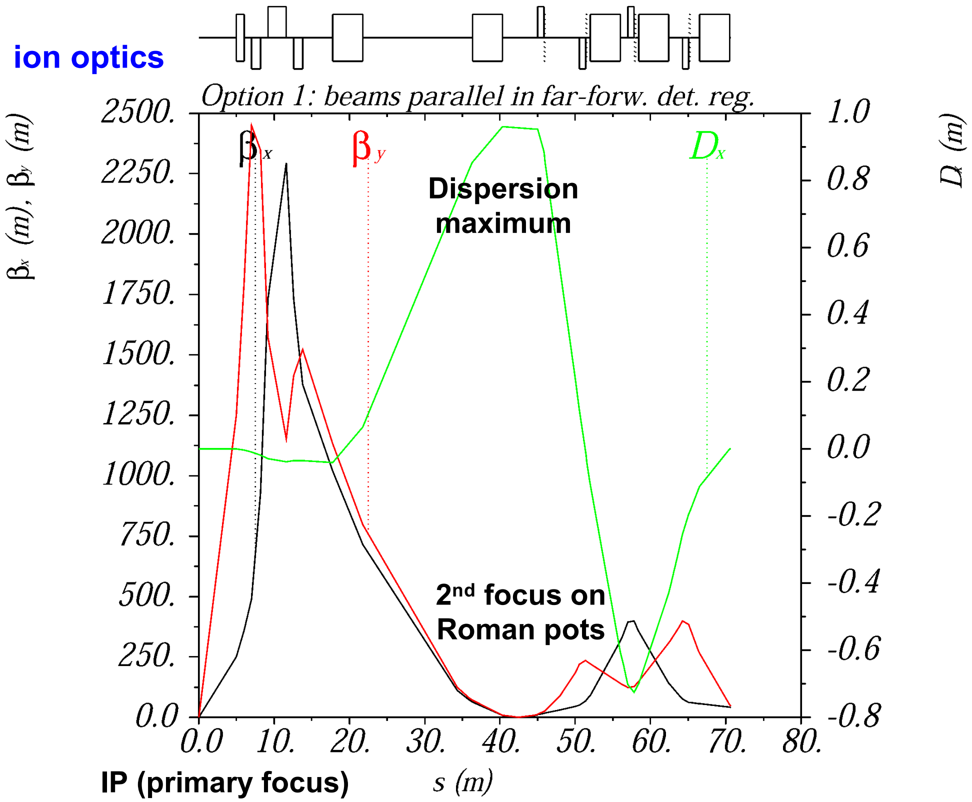
- Same quadrupoles create both the strong primary focus and the weak secondary focus.
- The near-beam Roman pots are integrated into the dispersion compensation section.
  - (Flat) dispersion maximum at secondary focus
  - With D = 1 m, dp/p = 1% @ 0º => dr = 1 cm



Maximally compact high-dispersion spectrometer - instrumentation







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

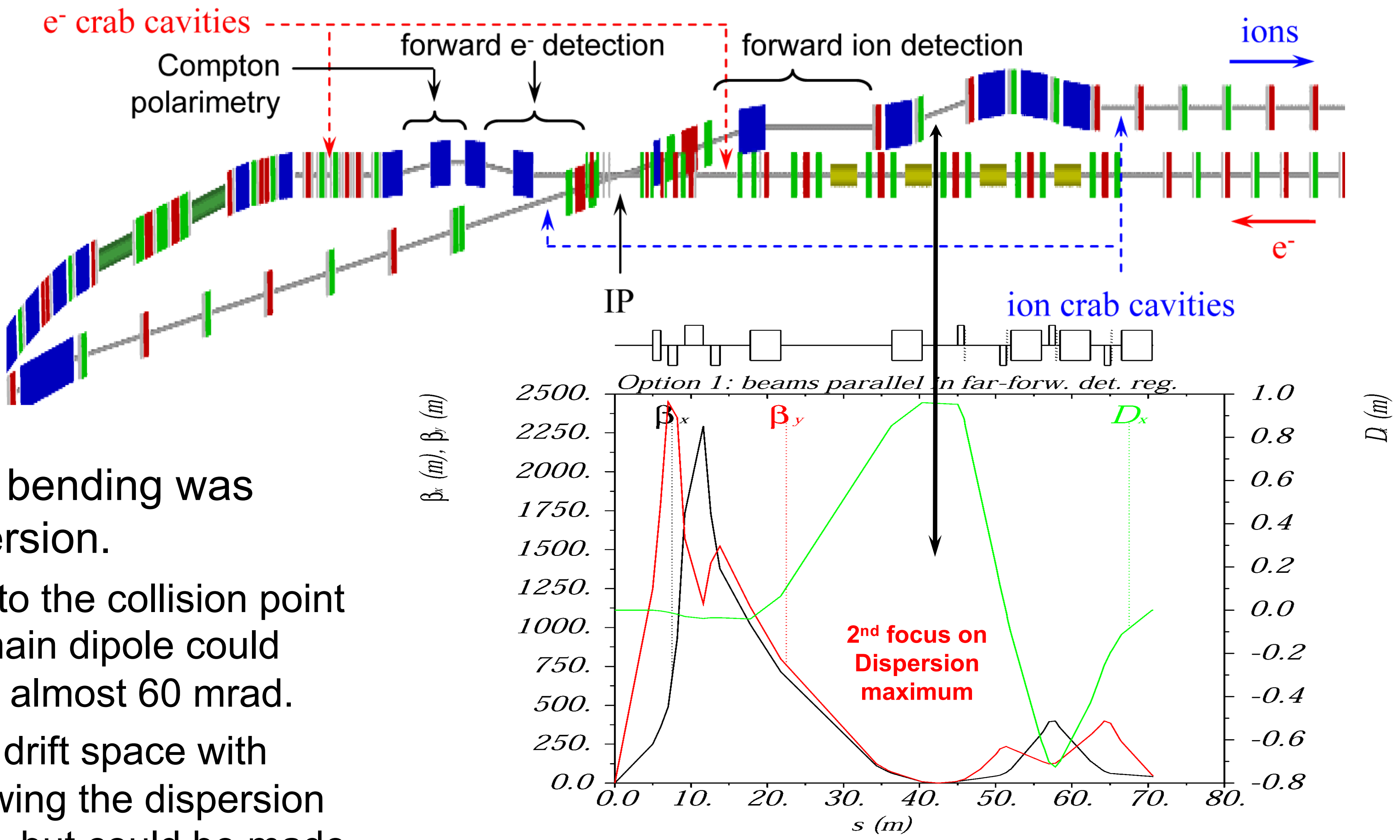
Can the compact forward spectrometer be used for the EIC (at BNL)?

- It was originally incorporated into the JLab EIC, but the concepts are universal.
  However, the detailed implementation also included workarounds which were necessary at JLab, but might not be beneficial at BNL.

- In particular, the poor emittance in the small-radius electron ring combined with a small β^* made it necessary place the electron quadrupoles very close to the collision point. In general, this is not a desirable feature
  - Quads created lots of synchrotron radiation at the IP
  - The crossing angle had to be sufficiently large (50 mrad) to avoid having the cryostat of the electron quads in the acceptance of the forward spectrometer.

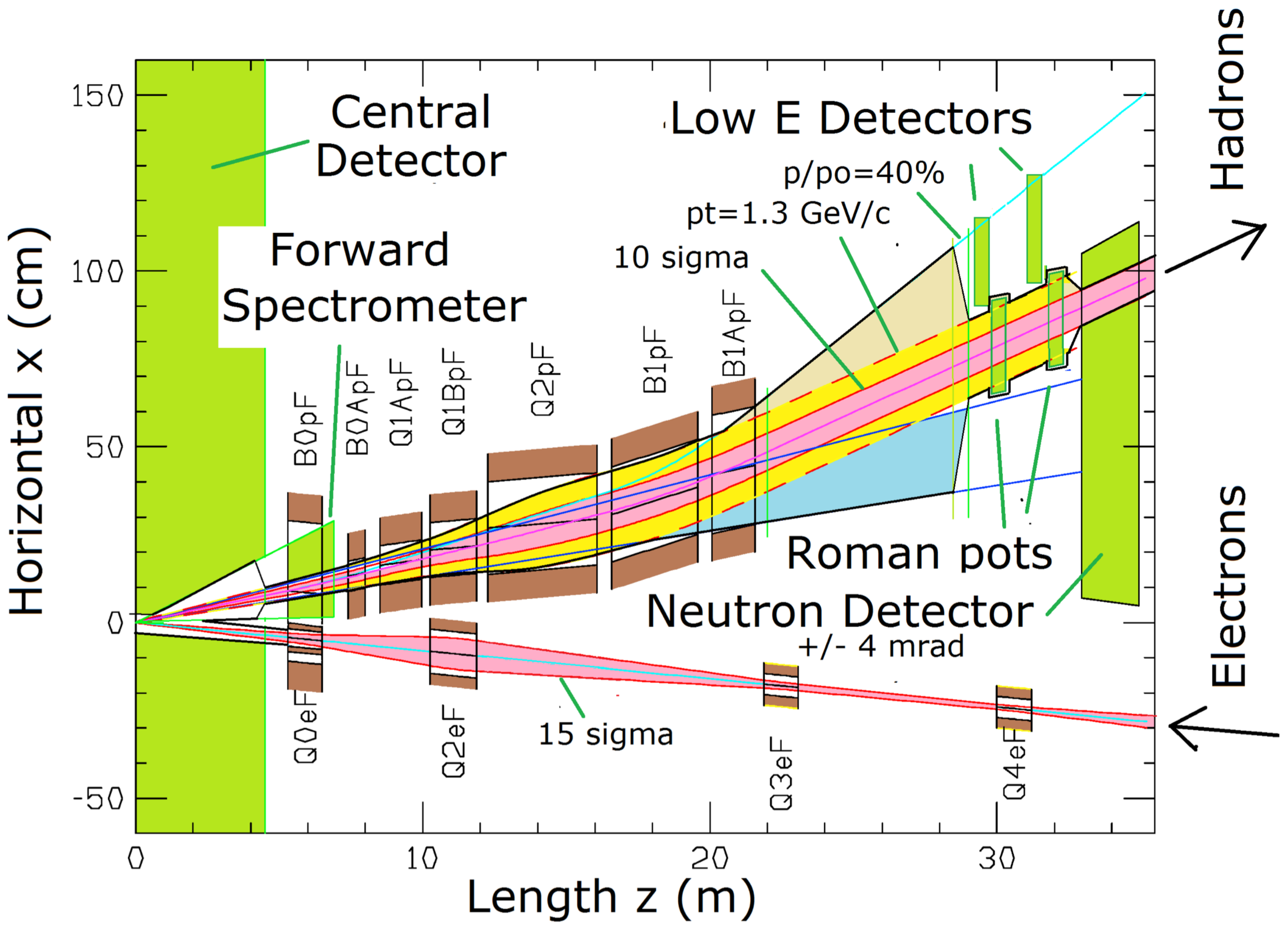
- There were, however, some benefits to a large crossing angle
  - Beamlines separated quickly making room for instrumentation.
  - It was easy to accommodate the bending beam lines caused by strong dipoles

Impact of crossing angle on dispersion generation



- In lab space, all possible bending was utilized to generate dispersion.
  - The small dipole close to the collision point was outbending. The main dipole could then bend the beam by almost 60 mrad.
  - This was followed by a drift space with parallel beamlines allowing the dispersion to grow. This was 25 m, but could be made as long as needed.

The current IR and forward detection at BNL

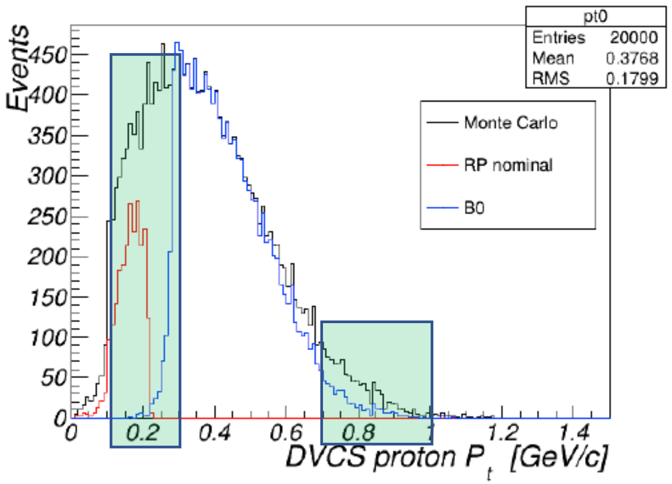


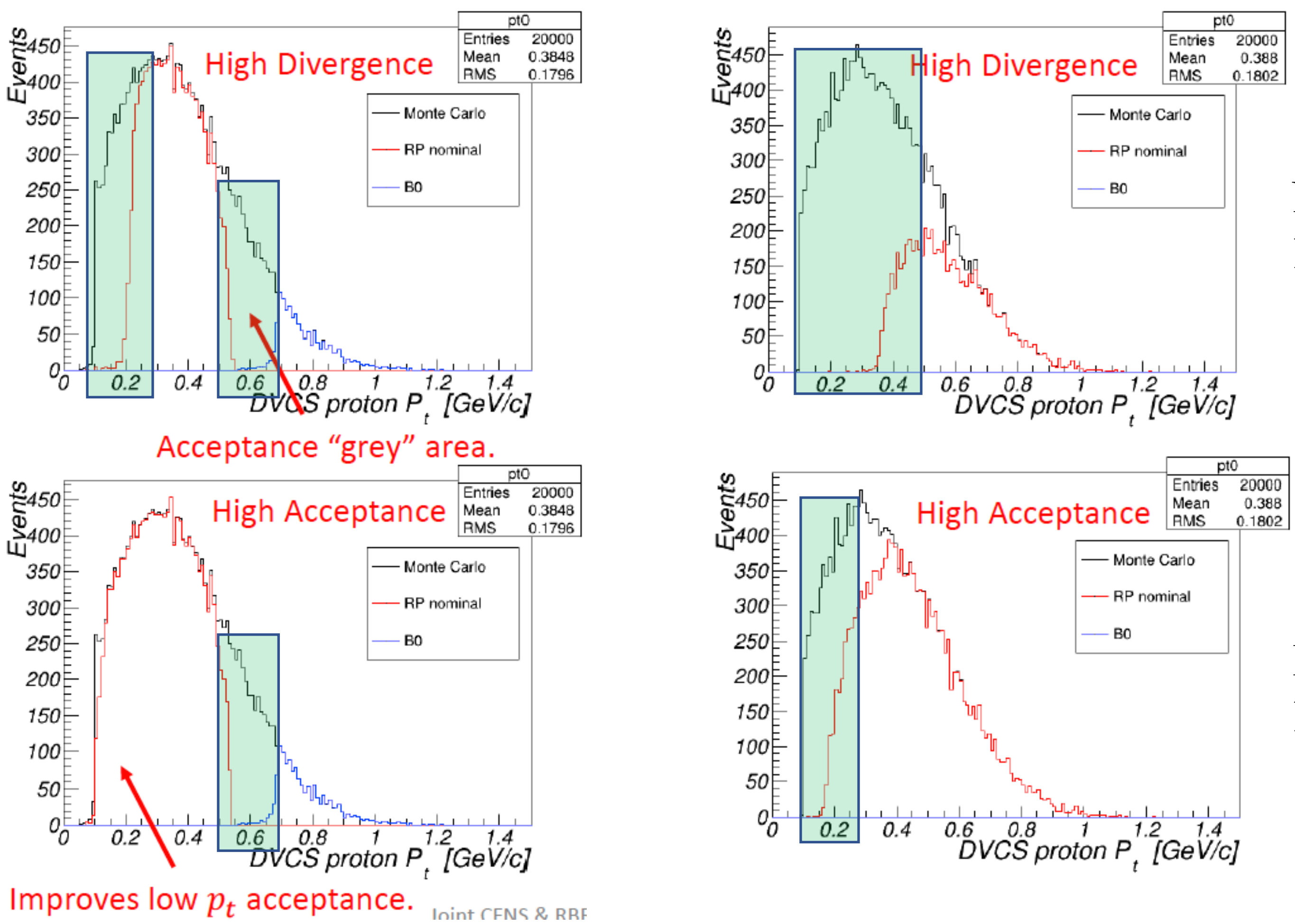
The ions quads are integrated with the electrons quads, which is accelerator friendly

- This IR is not designed to generate a large dispersion.
- The main dipole is outbending. Thus, despite being rather weak, it creates very divergent beamlines.
  - The size of the tunnel then also limits the following drift space.
  - In this configuration, the crossing angle adds to the divergence
- Eventually, the beamlines have to be brought to parallel, but this is not part of the spectrometer.
- The quadrupoles also do not generate a 2nd focus on the Roman pots, further limiting low-p_T acceptance.

Recoil baryon detection

A. Jentsch et al.





Nominal luminosity

Reduced luminosity

- The lack of dispersion and focusing causes challenges
- Low-t protons are cut both at 275 GeV and 41 GeV
- High-t protons hit the apertures at 100 GeV
- Despite using two IR “settings,” combining data taken at different energies, and using multiple detector locations, the acceptance for DVCS protons is somewhat limited, and insufficient for light ions.

Can we draw on ideas from both implementations to create an excellent forward detection solution for the EIC?

- **Absolutely**, in particular we can use
  - The overall layout with a large dispersion and a secondary focus
  - The advanced "accelerator friendly" magnets allowing large apertures

- One could, however, also consider less compact designs if there is space available.
  - For instance, one could use different magnets to create the primary and secondary focus

- Also, if one wants to build an IR with a geometry compatible with a large dispersion but using a modest crossing angle, there may be a more optimal layout of magnets and drift spaces than one based on a large crossing angle.
  - An optics study taking into account constraints from. available space, including tunnel width, can be done relatively quickly.

Thank you!