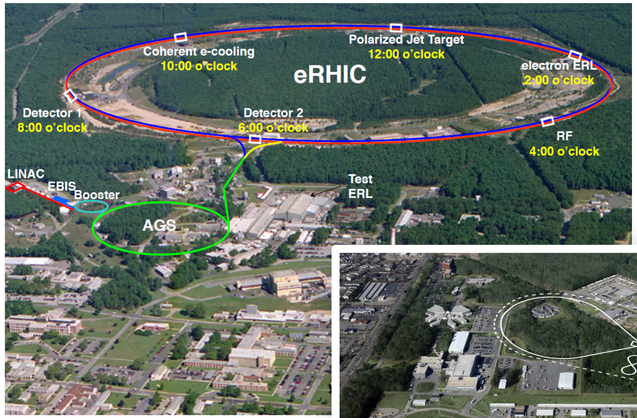
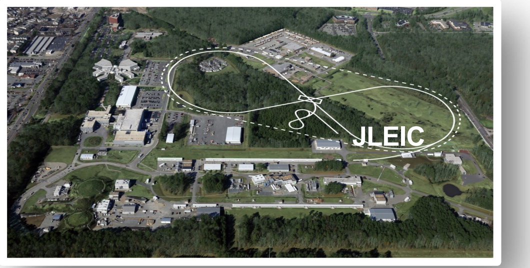
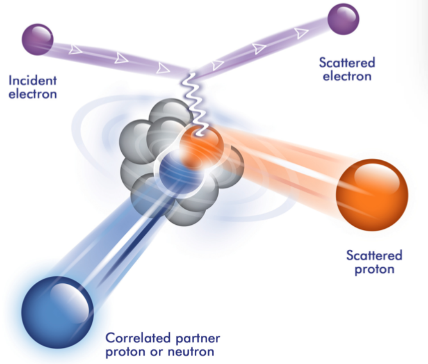
Experimental SRC/EMC Studies: Opportunities and Challenges at EIC

- in a broader context of forward detection requirements







Pawel Nadel-Turonski

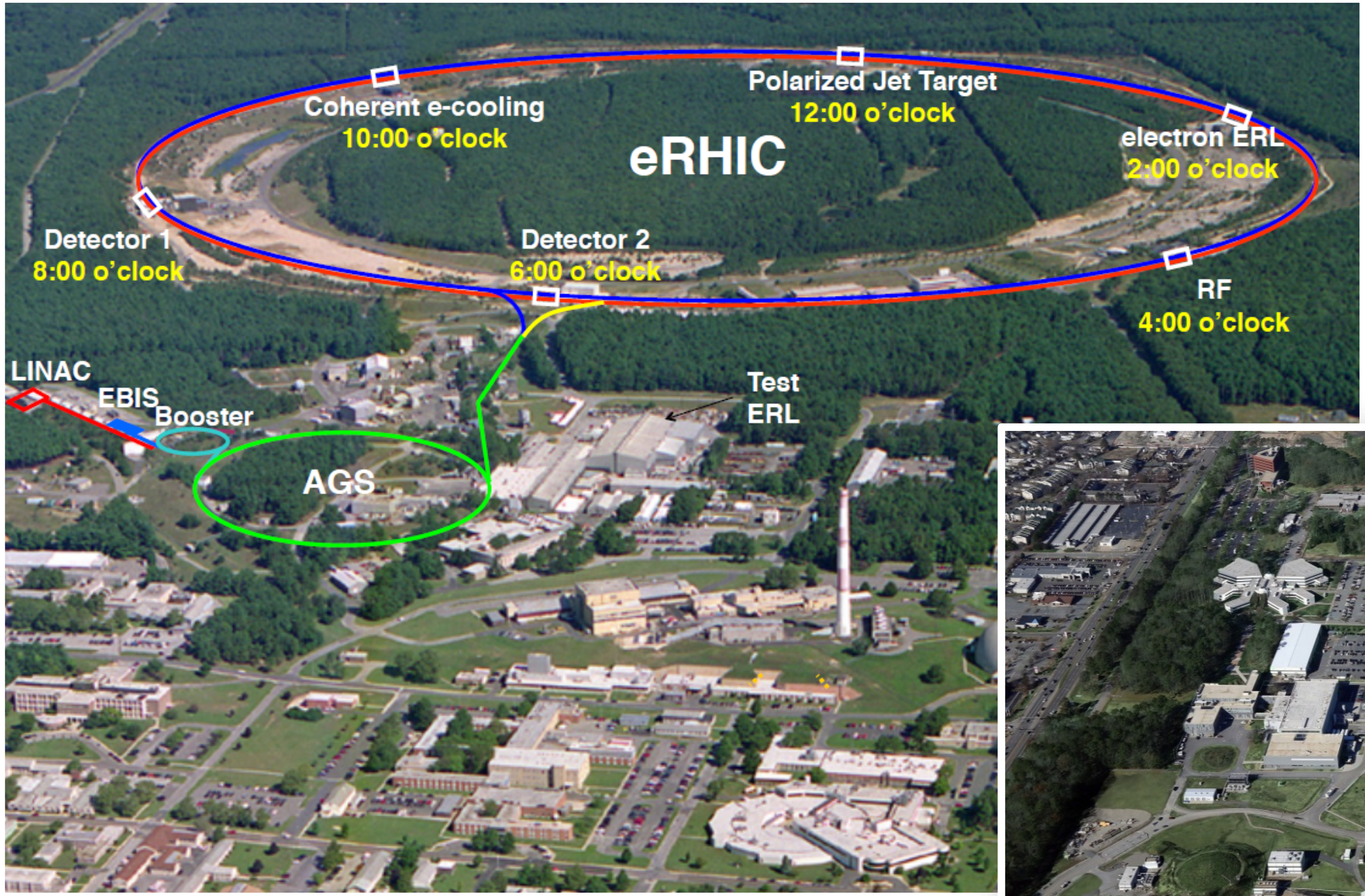
Stony Brook University

Joint CFNS/RBRC on Physics and Detector Requirements at Zero-Degree of Colliders,,
Stony Brook, September 24-26, 2019

Outline

- Forward detection requirements at the EIC
- SRC measurements at the EIC
- Key measurements that have similar requirements

Proposed EIC implementations at JLab and BNL



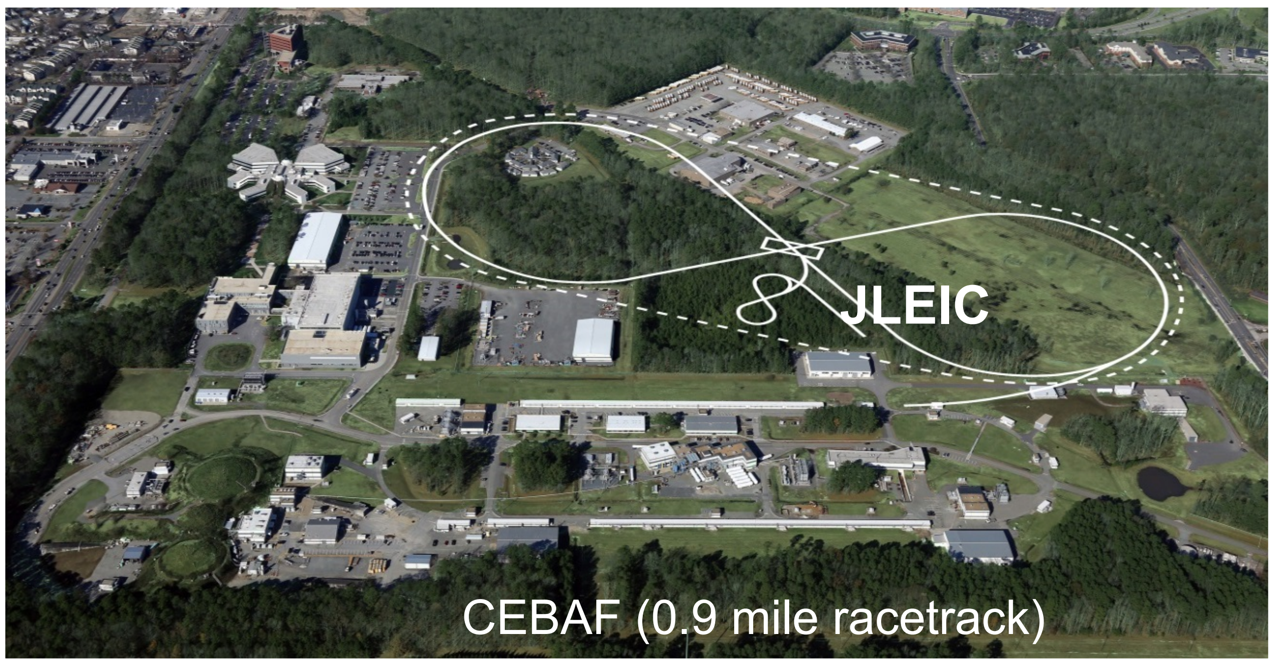
BNL EIC at RHIC (eRHIC)

18 GeV e (10 GeV lumi max) on 275 GeV p

Parameters are similar

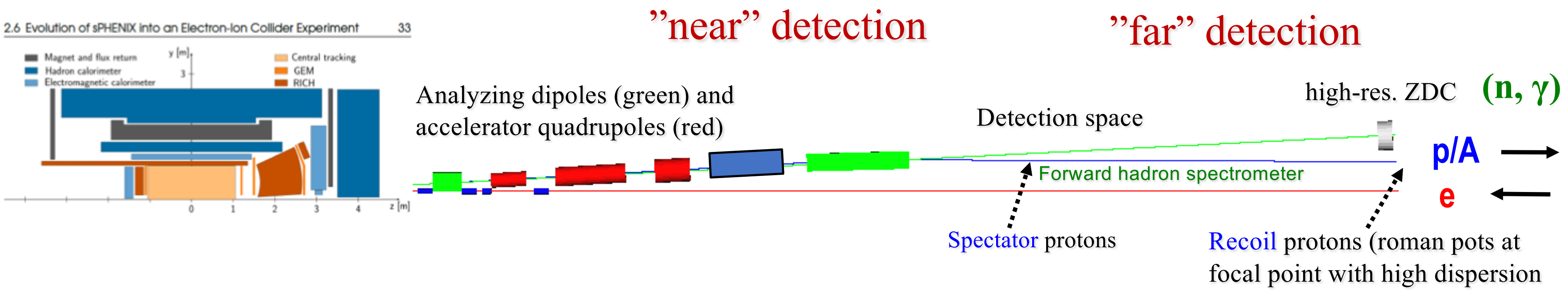
12 GeV e (5 GeV lumi max) on 200 GeV p

JLab EIC (JLEIC)



Near-beam detection could be similar

Detection of target fragments



- A large part of the EIC program relies on detecting recoil baryons and target fragments
  - Spatial imaging through *exclusive* meson/photon production on the proton, and in coherent diffraction on nuclei
  - Neutron structure through spectator tagging in light nuclei
  - Various incoherent processes on heavy nuclei, **including SRC and EMC studies**
- Forward detection requirements for the EIC are very demanding
  - Need to detect particles very near the beam (down to $p_T = 0$ for $p/p_0 < 99\%$)
  - Need to detect protons with p_T up to at least 1 GeV/c and spectators with A/Z very different from that of the beam (*e.g.*, spectator protons from deuterium)
  - Need excellent momentum resolution, detection of neutrals, and PID for ions

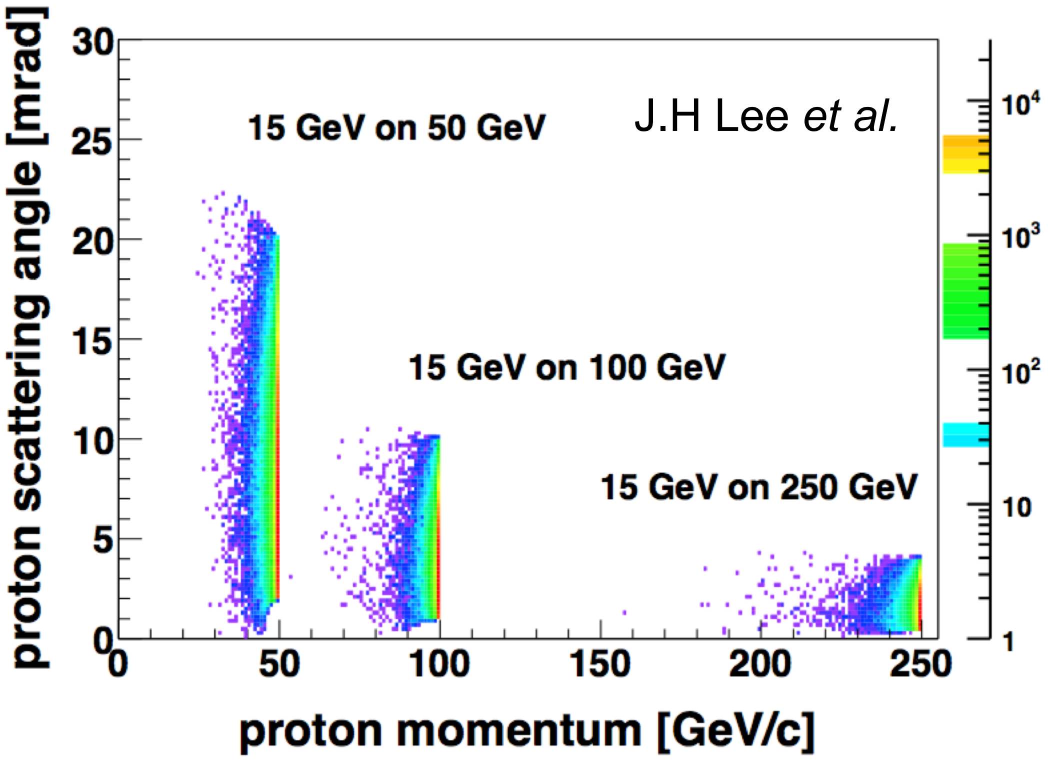
Forward detection – processes and requirements

- 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
  - Exclusive production of photons (DVCS) and mesons (DVMP) on the proton at large t at *low energies*
  - Detection of photons and neutrons from nuclei (cone with line-of-sight)

- Which processes drive the resolution?
  - Magnetic spectrometer: 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)

Near-beam acceptance using a magnetic spectrometer (large dispersion)



- The intrinsic beam momentum spread is on the order of a few x 10^{-4}.

  Insufficient to consider only the beam divergence at the IP

- The target energy loss is typically 1% (DVCS on the proton shown)

- For heavy ions, the momentum 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 even protons scattered at zero degrees or nuclei losing one nucleons.

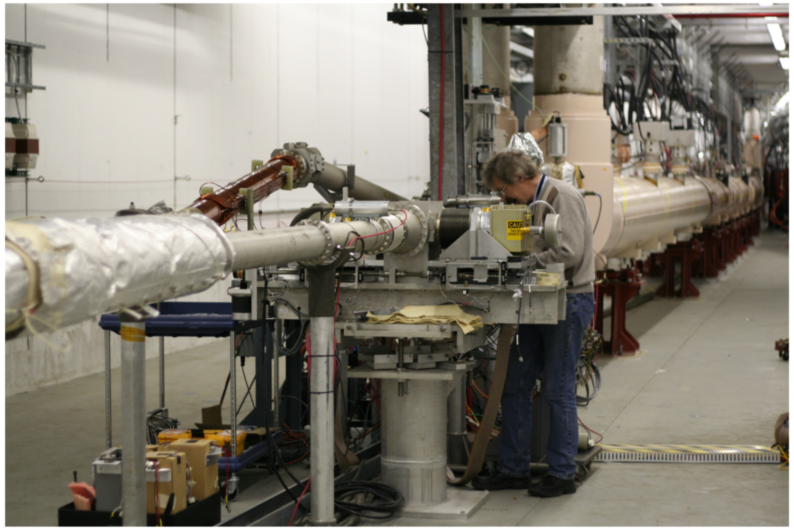
- Detection of intact nuclei is *much* harder than recoil protons, since at fixed t the larger mass implies a smaller change in both longitudinal and transverse momentum (scattering angle)

Near-beam detection at JLab and BNL

- At JLab, a full forward spectrometer was always a key part of the MEIC (now JLEIC) concept since its introduction in 2009.
  - proton acceptance of $E/E_{beam} < 99\%$ for *all* angles and down to 3 mrad for *all* energies

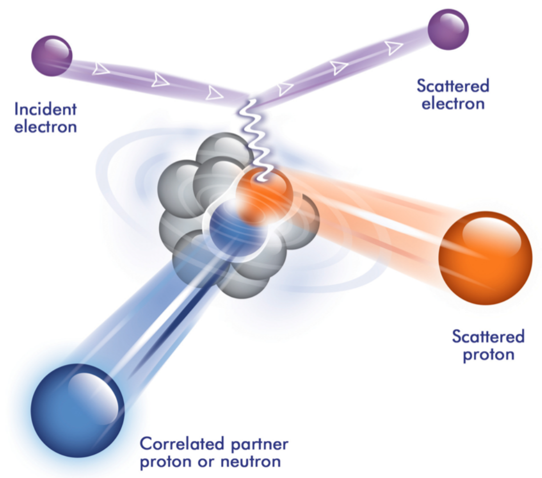
- At BNL, the IR currently lacks a high-dispersion section, limiting its potential for eA.
  - However, nothing prevents BNL to add a forward spectrometer with large dispersion.
  - Implementation easier at BNL since a larger e-ring allows reversing the order of electron and ion quads.

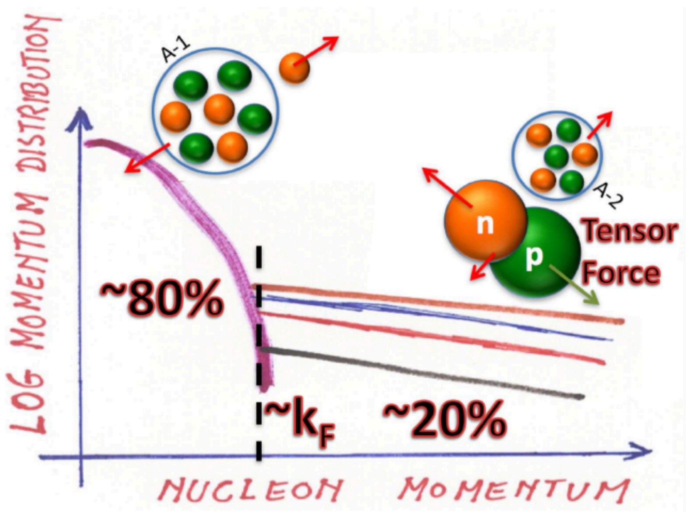
- Input on from the eA community on the detection requirements is thus important and urgent



Roman pots in STAR located ~50 m downstream from the collision point

But SRCs are not a process – so where do they fit in?



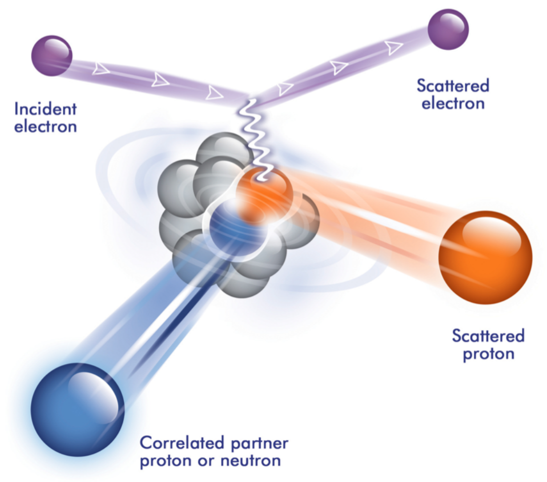


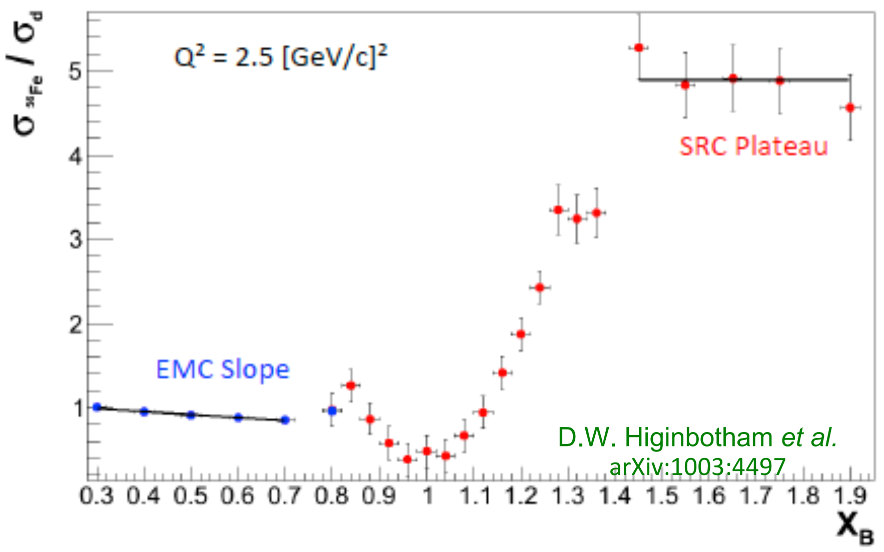
- Deuterium
  - As **spectator tagging on the nucleon** *-> talk by C. Weiss*
    but with sufficient acceptance for high-p_T tail
  - Additional p_T for the struck nucleon will depend on process and kinematics, but can be substantial *-> talk by F. Hauenstein*

- Light ions
  - A-2 fragment(s) easy to detect, except for Z=A/2
  - The latter is, however, a very important case (d, ^{10}B, etc) with detection challenges similar to **coherent processes**

- Heavy ions
  - Tagging and identification of heavy fragments needed.
  - Similar to measurements of **rare isotopes at the EIC** and helpful for **coherent diffraction** on heavy ions.

Traditional SRC measurements at an EIC



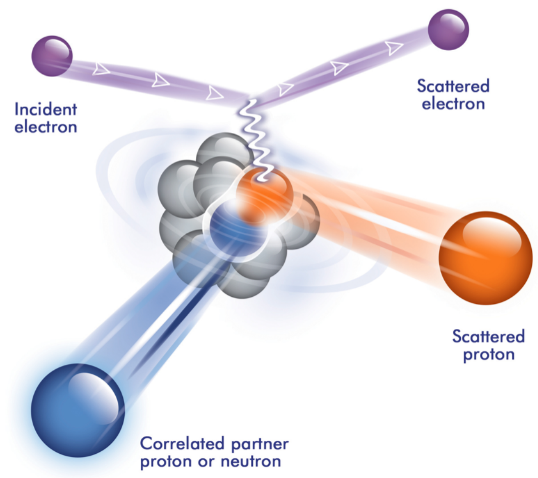


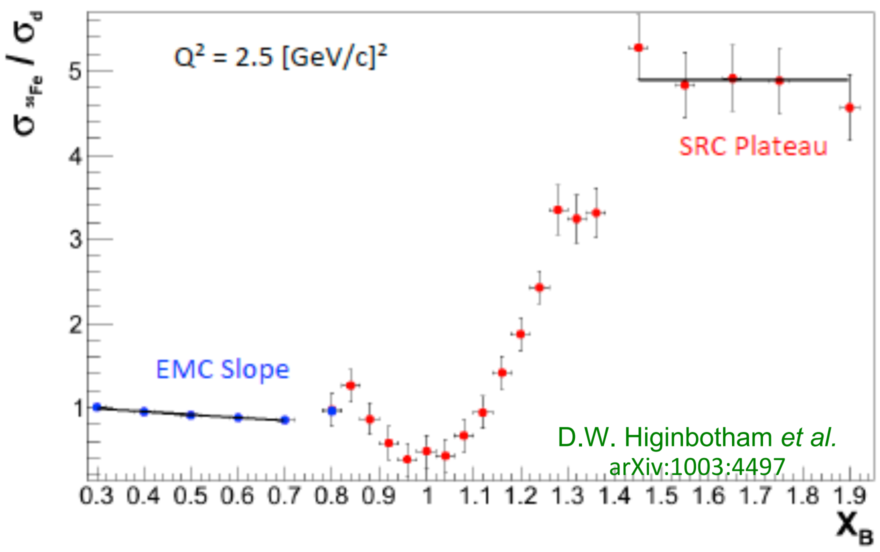
- SRCs have traditionally been studied at high x in quasielastic (QE) reactions in medium- and heavy nuclei.
  - x > 1 ensures participation by more than one nucleon
  - QE process provides straightforward measurement and easier-to-understand final-state interactions

- The EIC can contribute by providing a large lever arm in Q^2 at high x and detection of all target fragments – but there are some challenges.
  - Event rates at high x are much lower than for fixed target
  - Resolutions at large x deteriorate rapidly

-> talk by B. Schmookler

SRCs in DIS at lower x?





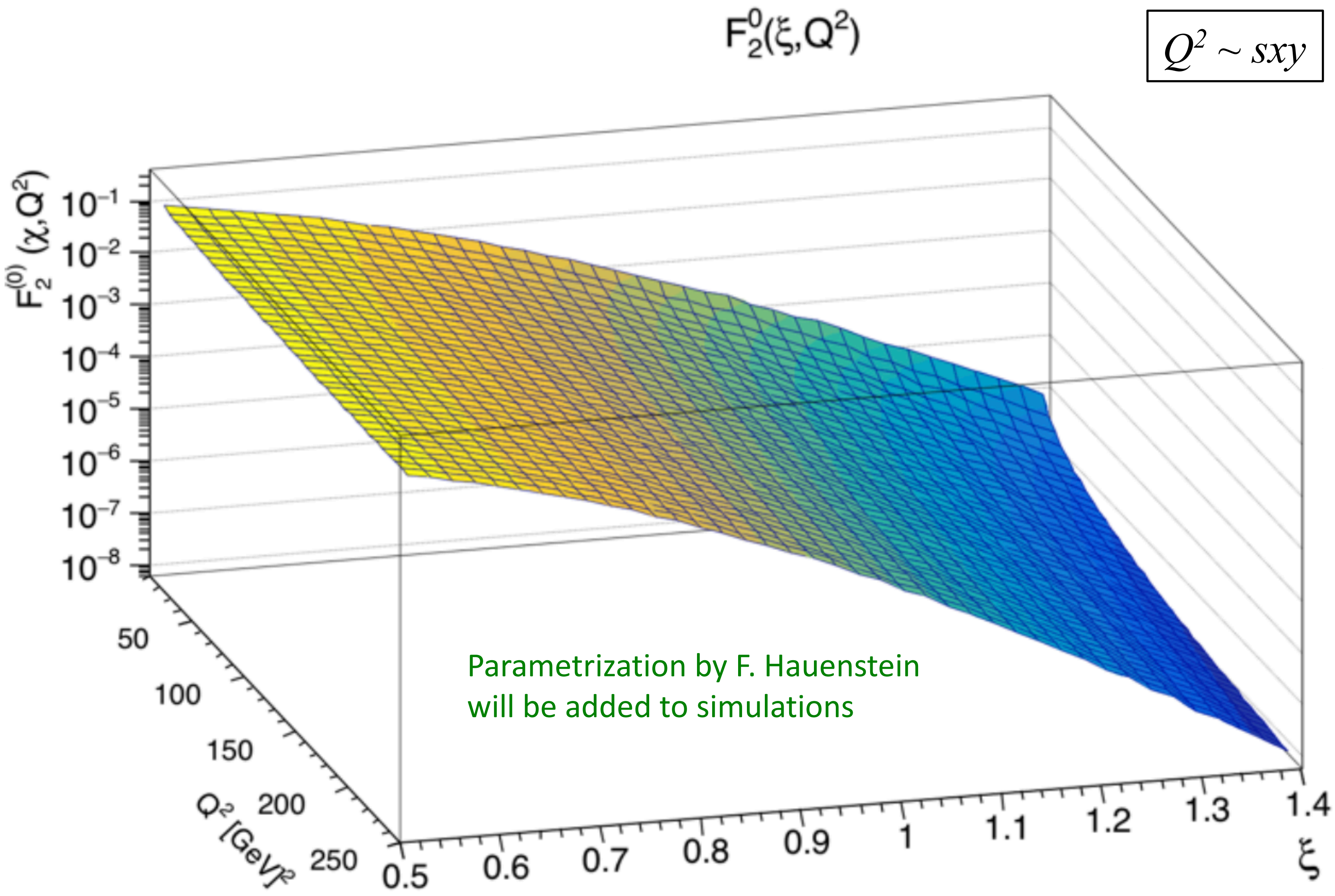
- The EMC effect (x ~ 0.5) is much easier to measure in "typical" EIC kinematics.
- But also for SRC studies at an EIC it would be natural to seek relevant measurements in DIS (or exclusive reactions) at lower x.
  - Can we learn something new about SRCs?
  - Is it important to introduce SRCs into nuclear models (*e.g.,* BeAGLE) for studies of low-x processes?
- Nuclei over the full mass range will provide important input.

JLab LDRD-funded project for SRCs at an EIC

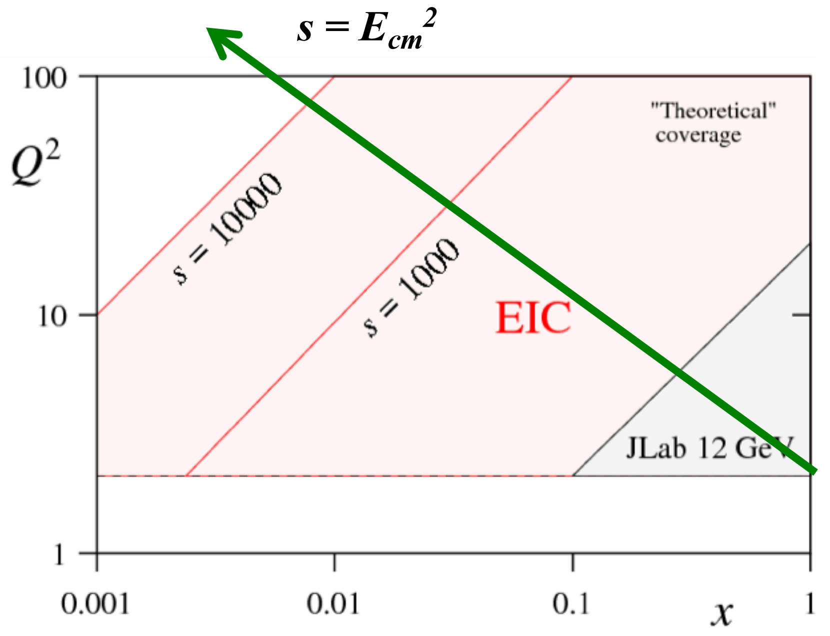
JLab "SRC" LDRD1912: D. Higinbotham, M. Baker, A. Deshpande, F. Hauenstein, O. Hen, C. Hyde, V. Morozov, PNT, A. Schimdt, B. Schmookler, Z. Tu,L. Zheng

- Feasibility studies
  - Rates at high x — *F. Hauenstein*
  - Resolution in x at high x — *B. Schmookler*
- Simulations, modeling, and detection requirements
  - Incorporating SRCs into BeAGLE — *M. Baker*
  - Detection requirements

Rate estimate: parametrization of modified F_2

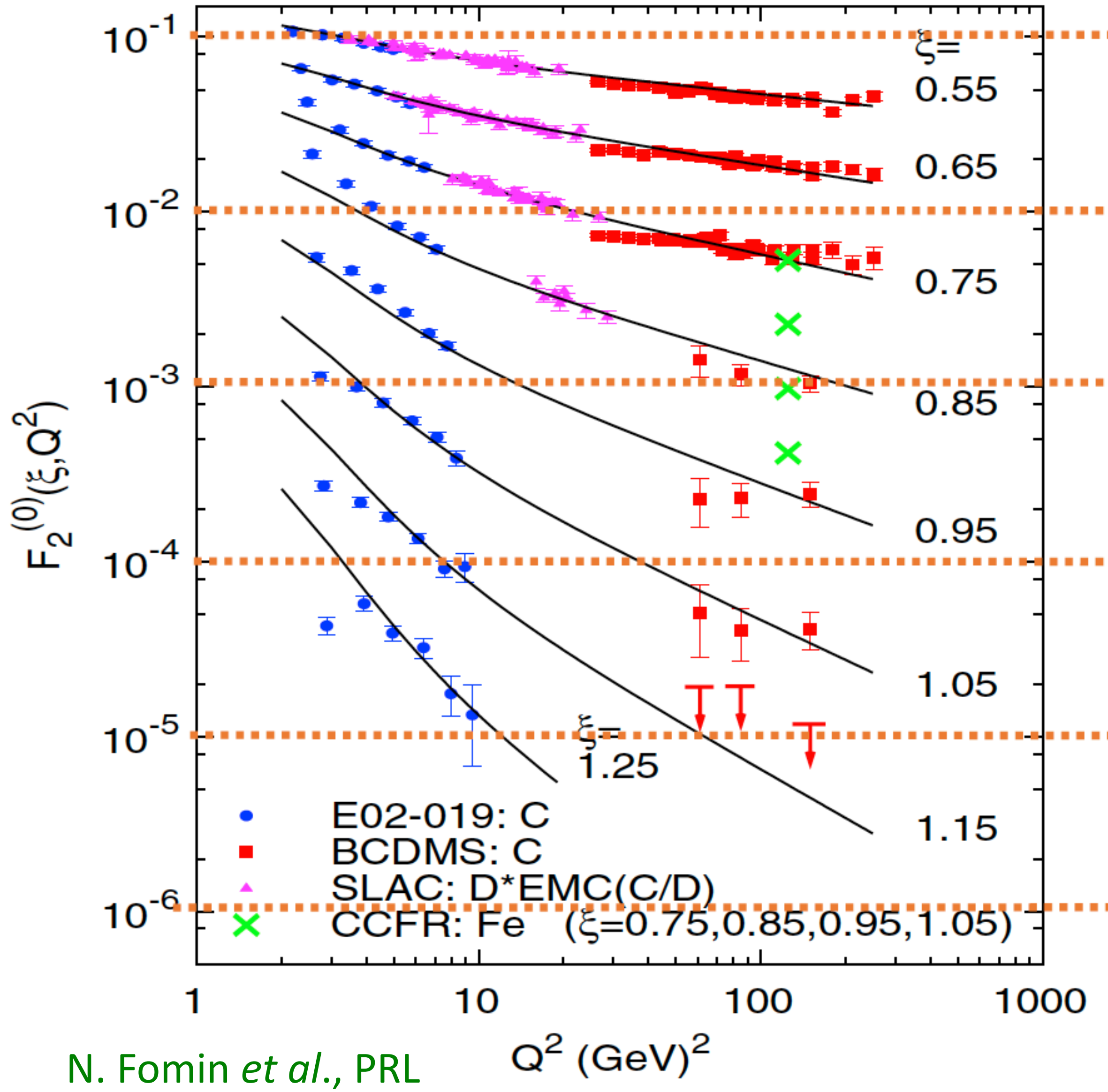


$Q^2 \sim sxy$

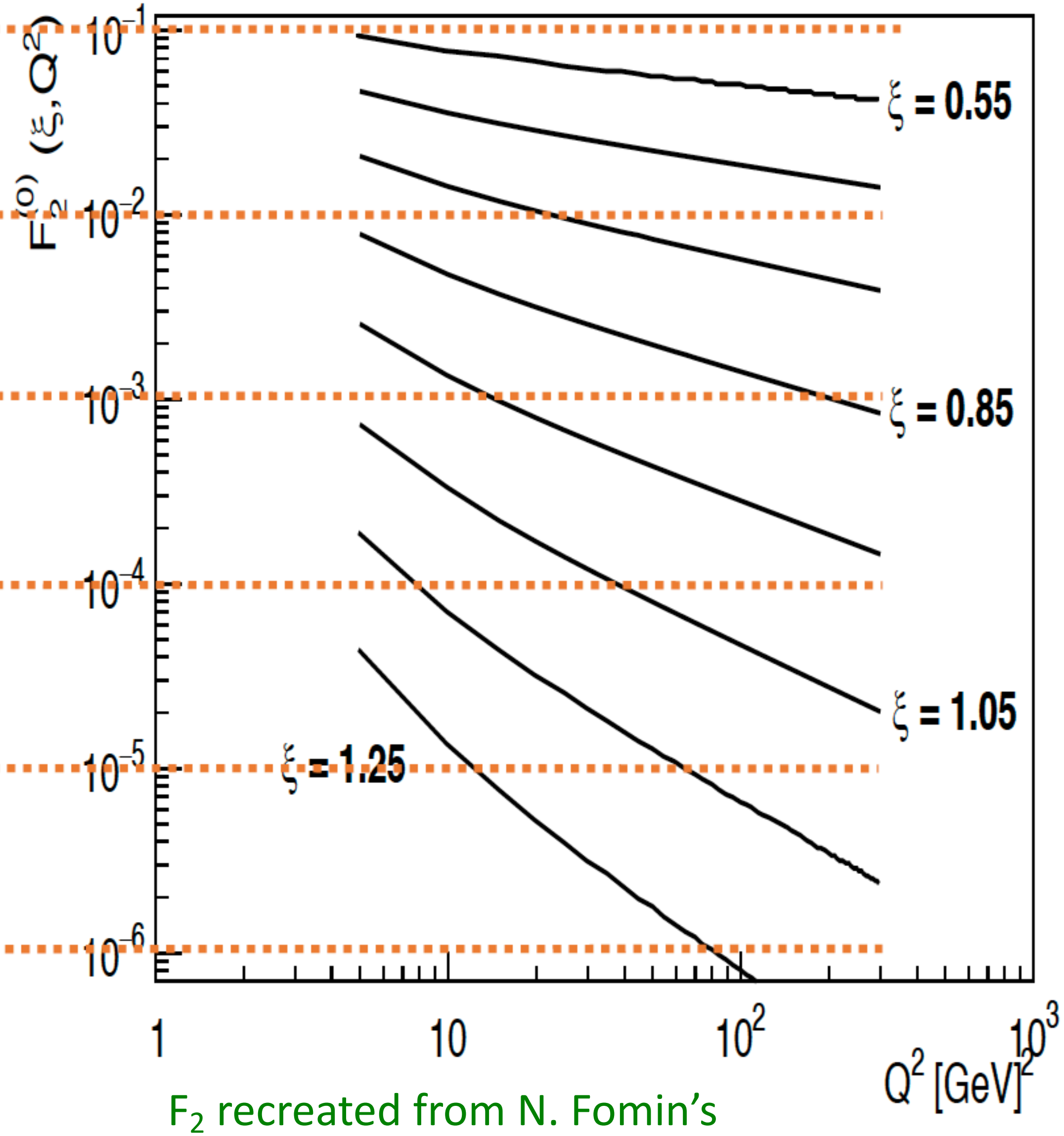


- To reach high x, the EIC would have to operate at low s and low y and/or high Q^2
  - Lower s reduces luminosity
  - Lower y reduces resolution
- At high x and Q^2, the value of F_2 is also low.
  - Rate is challenging
  - Running conditions need to be optimized

A more detailed look at the modified F_2



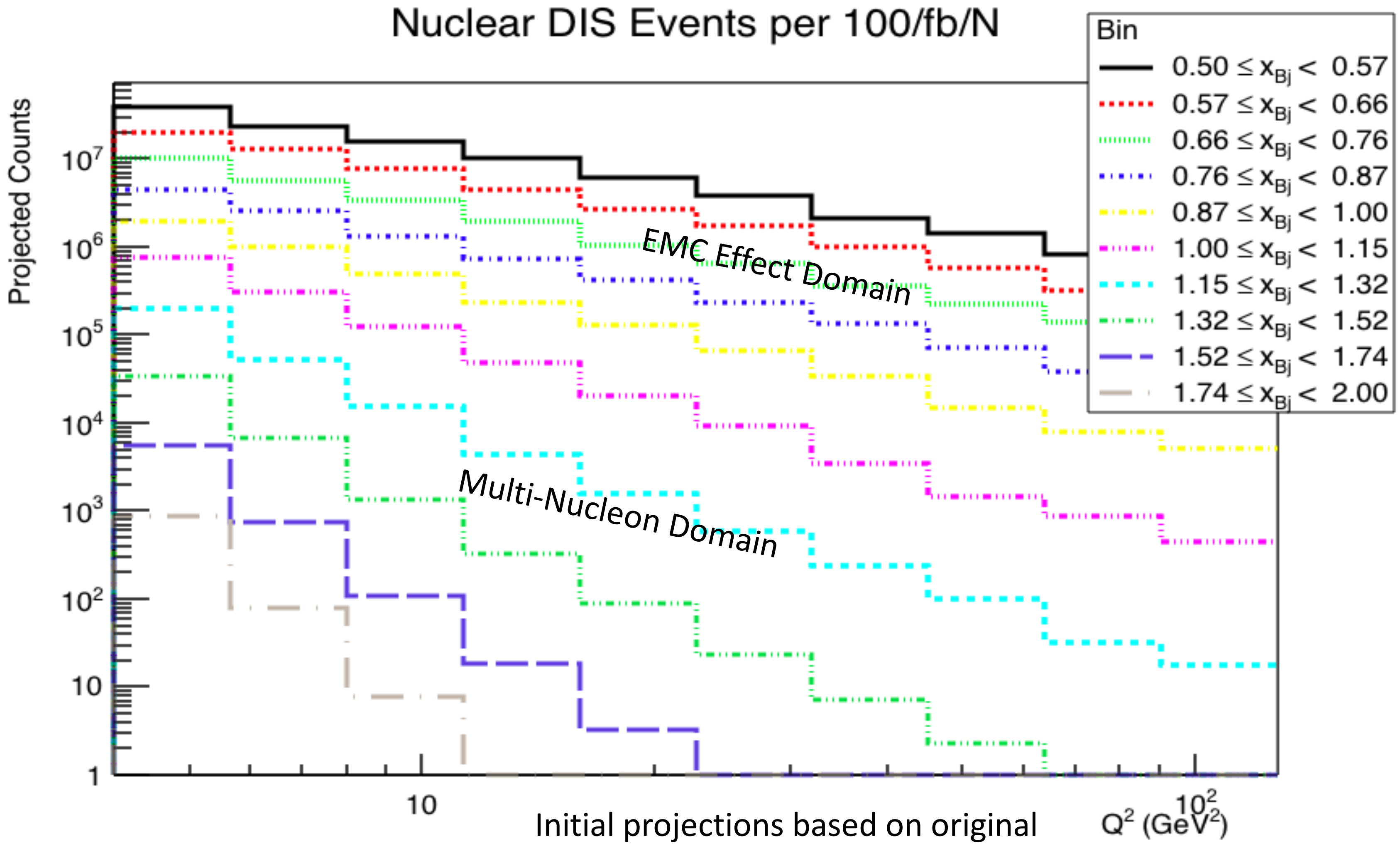
N. Fomin *et al.*, PRL 105, 212502 (2010)



F_2 recreated from N. Fomin's scripts by F. Hauenstein

Initial rate estimates for high x (and Q^2)

5x50 GeV e+C JLEIC with 6 weeks @ 100% eff. (at lower energy rates would be lower)



Initial projections based on original parameterization by N. Fomin et al., PRL **105** (2010) 212502

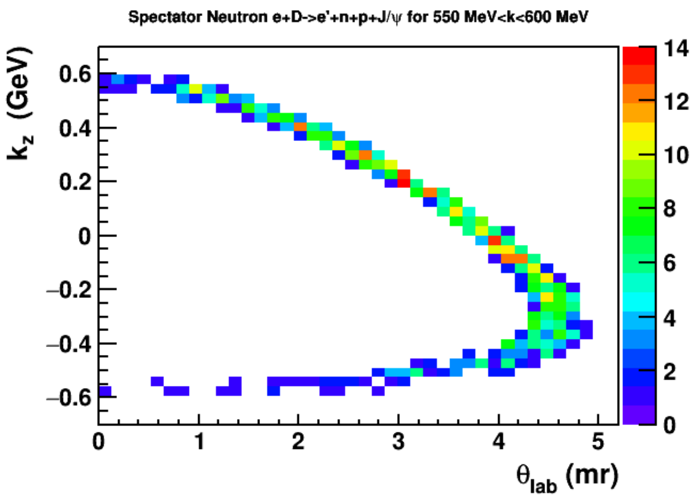
- Measuring the EMC effect at high Q^2 is straightforward
- Measuring SRCs at x>1 is challenging, but there will be some events.

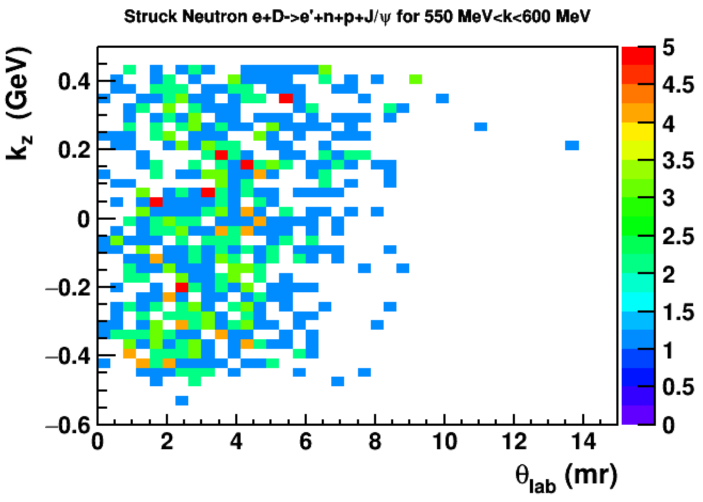
Lab kinematics of spectator and struck neutrons at high energy

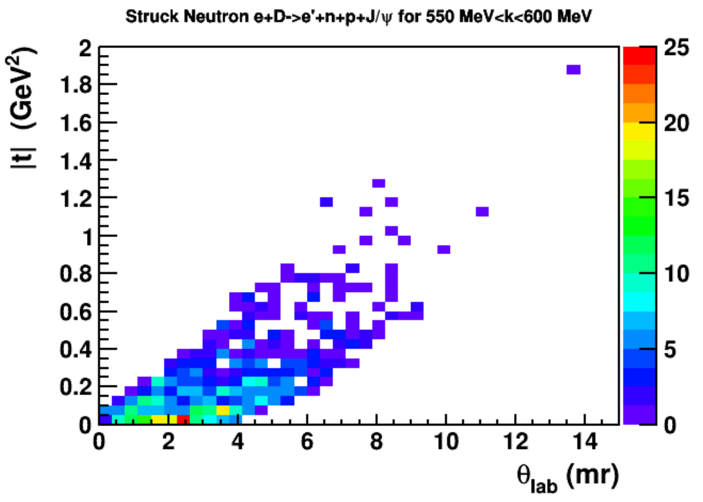
M. Baker

spectator n | struck n | struck n (vs t)

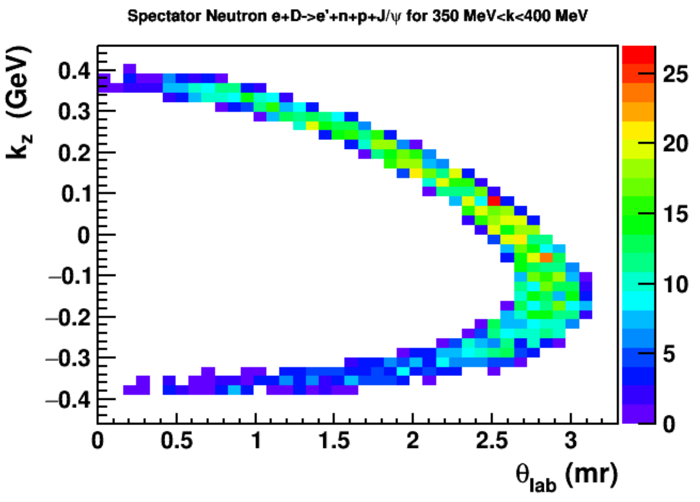
k ~ 575 (MeV)

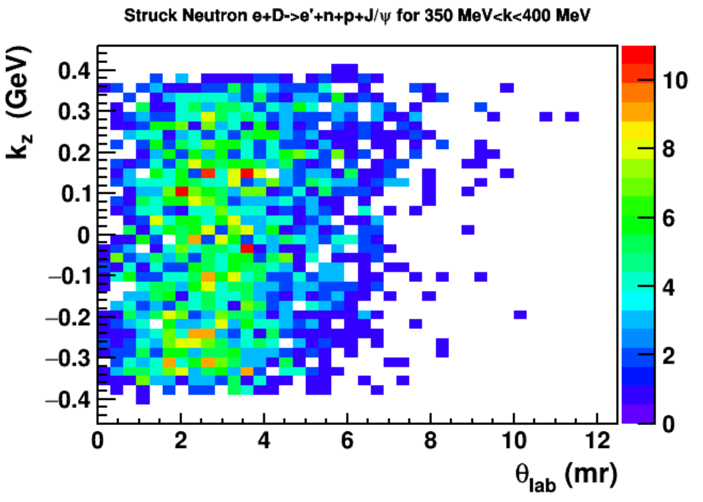


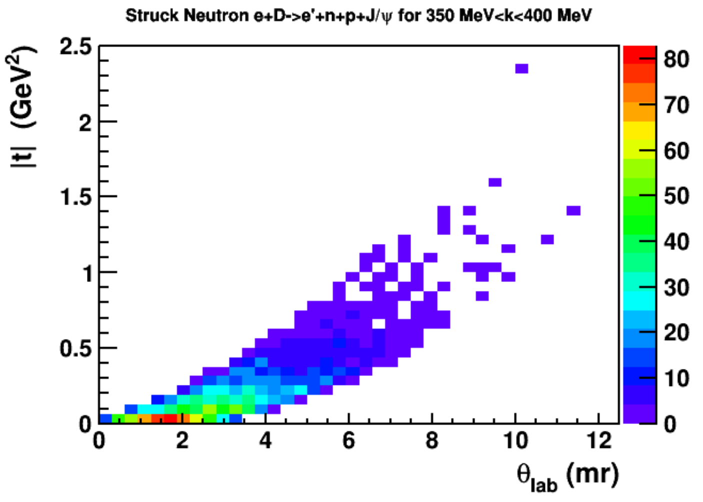




k ~ 375 (MeV)







And protons...

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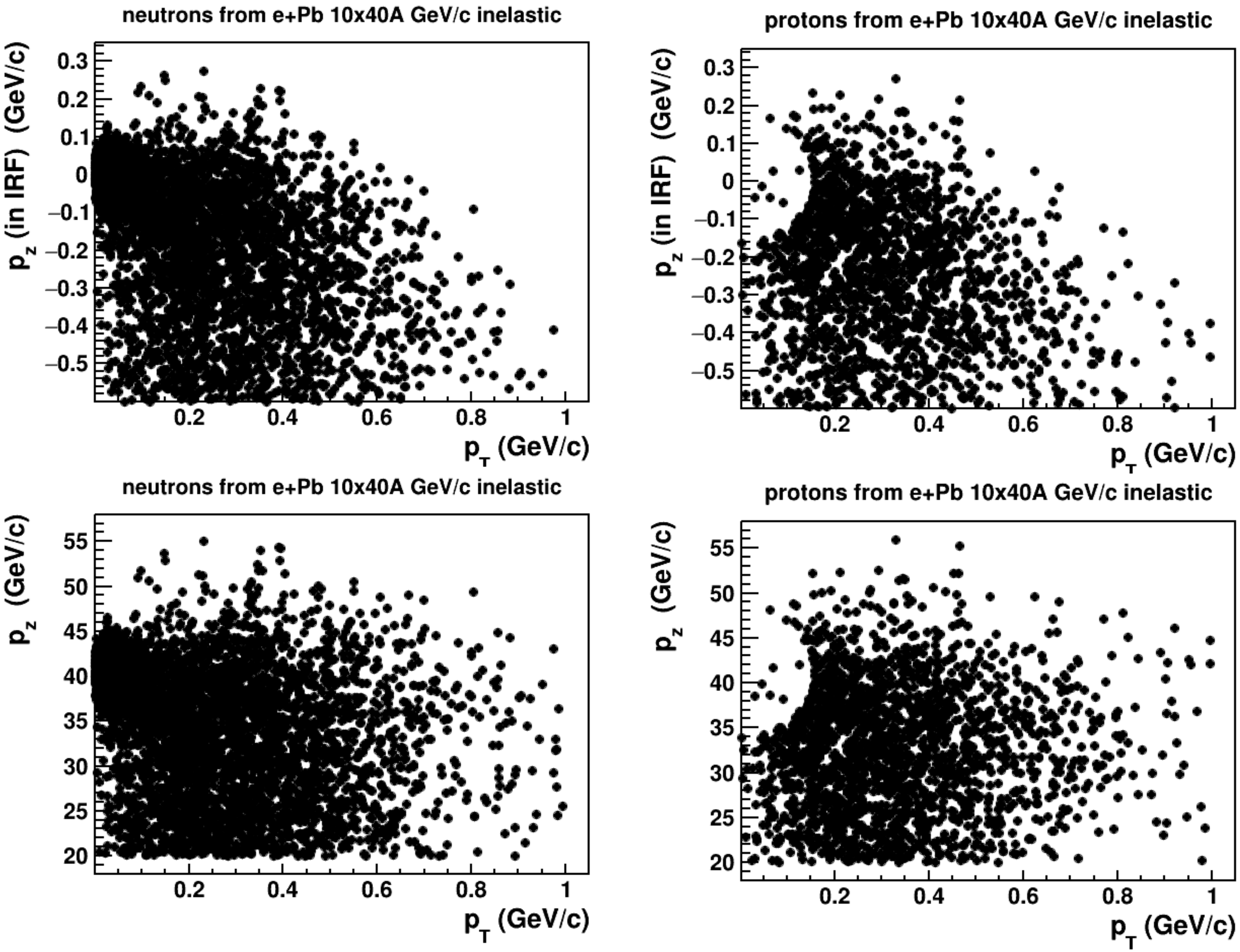
- For protons, Coulomb effects are not negligible.
- We need to merge the primary process with a detailed simulation of the nuclear response (BeAGLE) to understand the measurements

struck n | struck p



IRF = ion rest frame

And correlations (deuteron breakup)...

struck neutron, spectator proton
$|t|<0.1$ GeV^2, $550 < k < 600$ MeV

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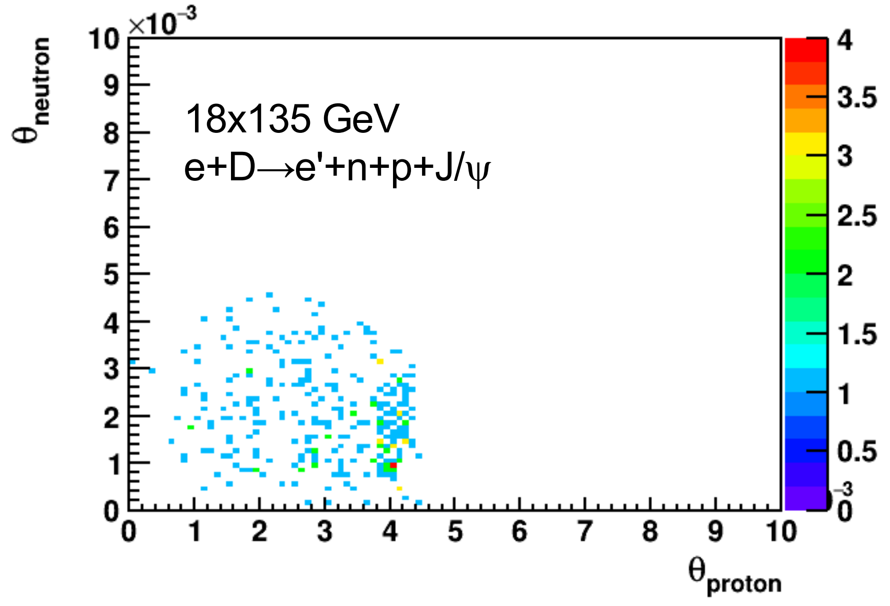
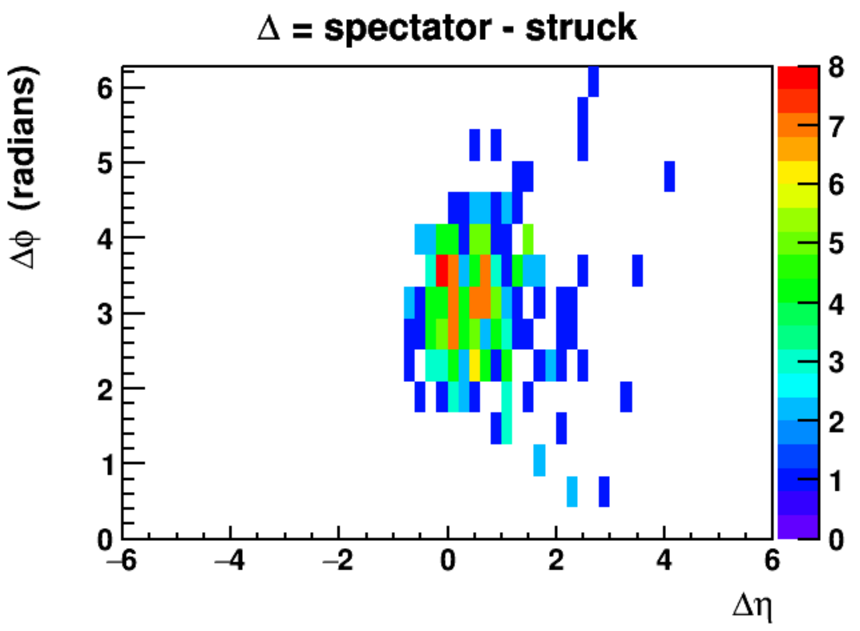
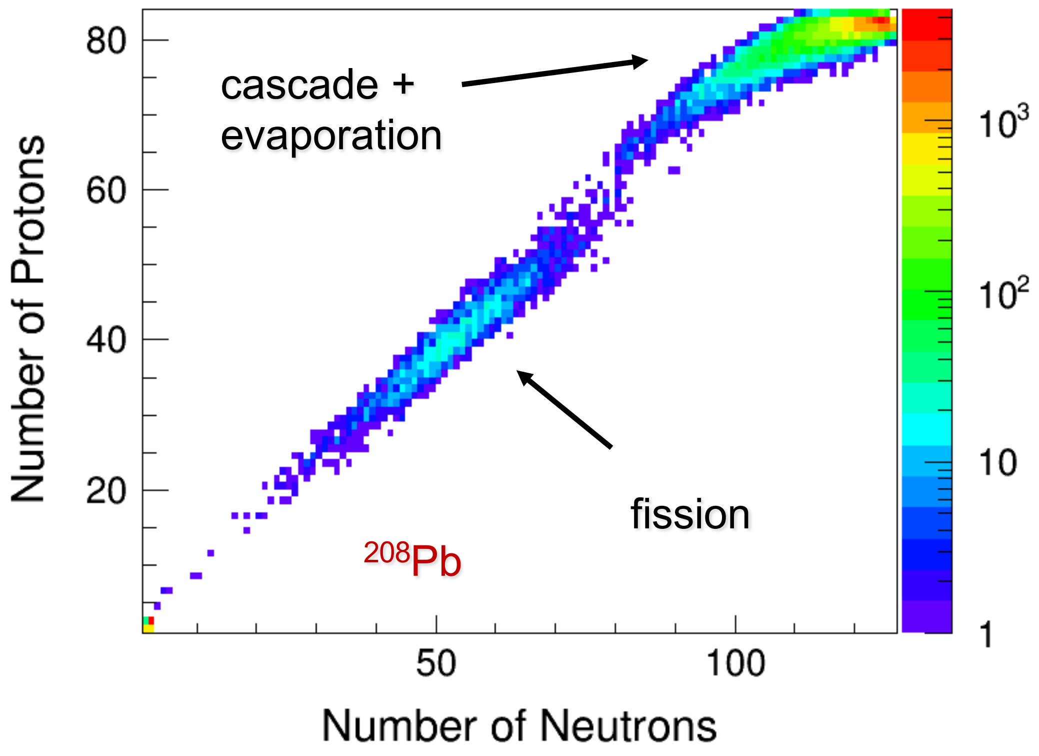
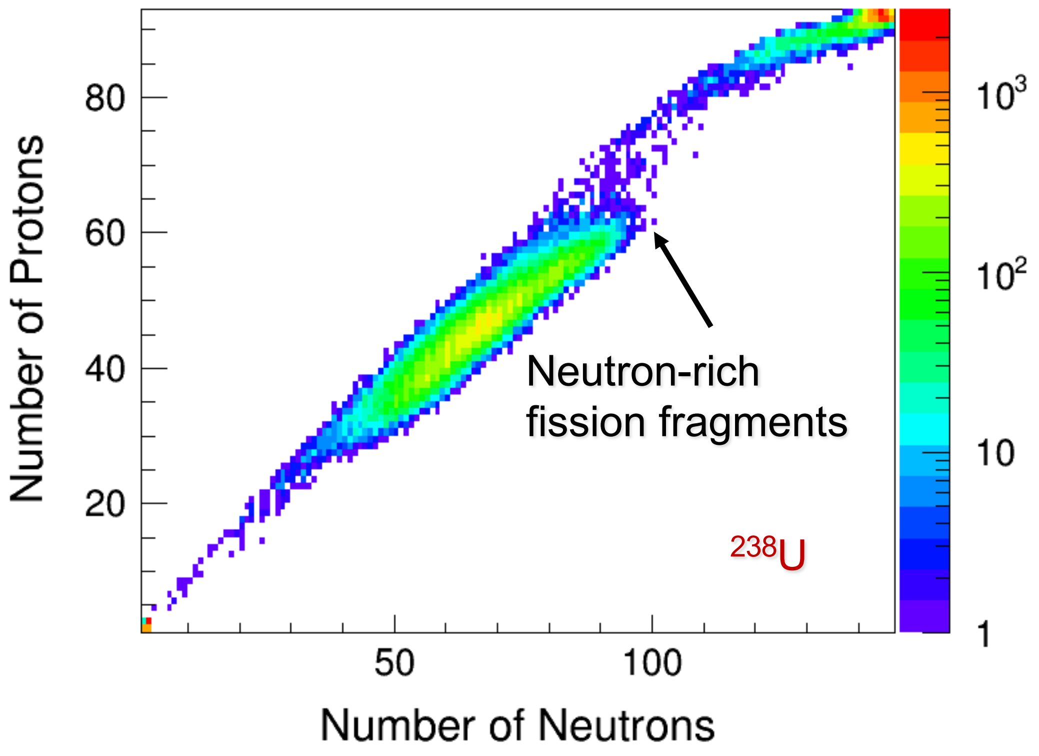




$\eta = -\ln\tan(\theta/2)$

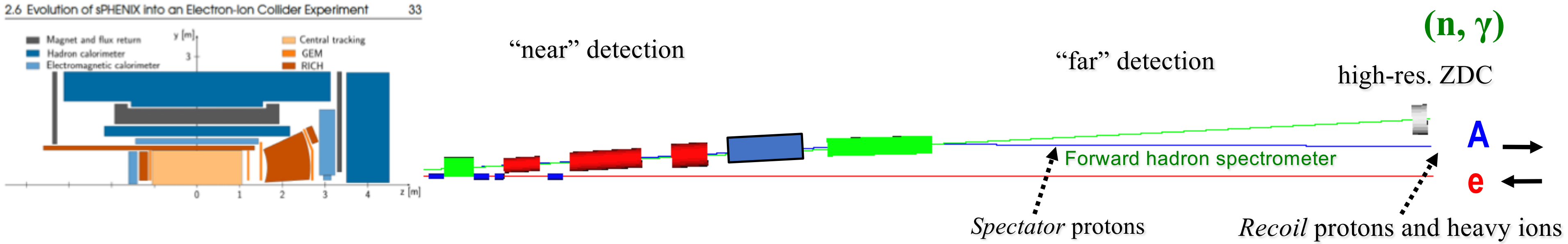
Nuclear fragments produced in eA reactions at the EIC



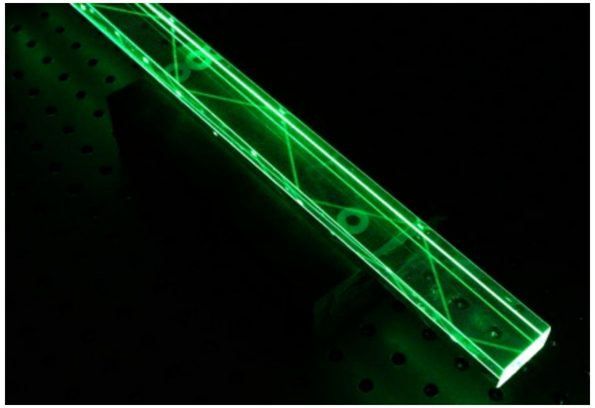


- Fragment detection ("tagging") is needed to, for instance, reconstruct the Fermi momentum of the struck nucleon

Detection and identification of the produced nuclei

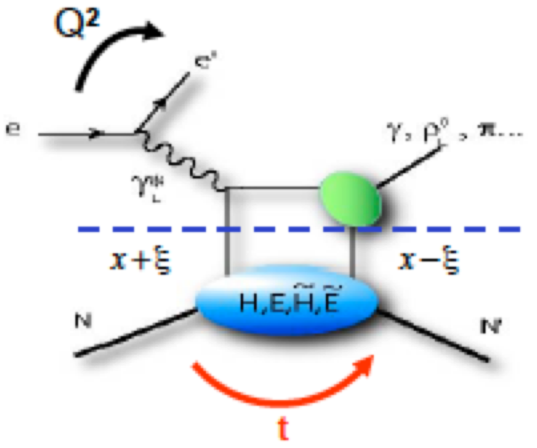


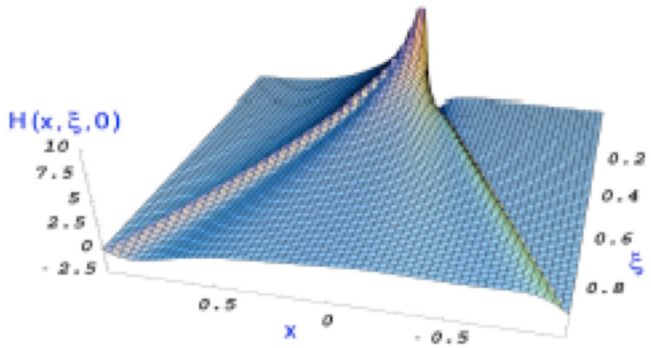
- Detection of nuclei with rigidities (A/Z) close to that the beam require a dedicated "far" spectrometer where the beam is small and dispersion large.
- But to identify the ion we need both A/Z and an independent measurement of Z. The requirement for sensitivity in Z^2 is 2% in order to identify heavy residual nuclei down to A-1.
- A "mini-DIRC" can produce 100,000 photons (<< 1% error) in a few mm of fused silica.
- R&D in progress (Generic Detector R&D for an EIC program).

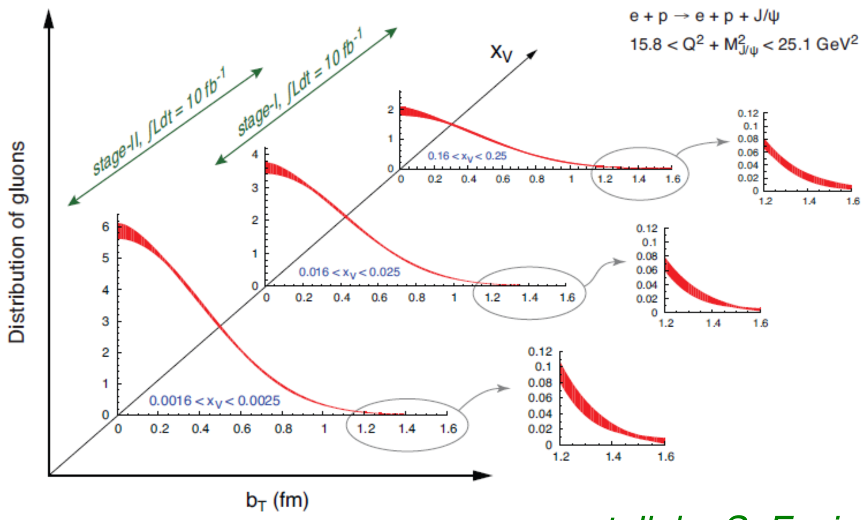


A "mini-DIRC" inside a Roman pot at the downstream focus can identify ions to ~1% in Z^2

Generalized Parton Distributions (GPDs) and 3D spatial imaging







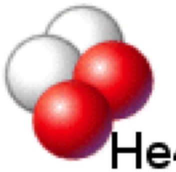
-> talk by S. Fazio

- 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 at different values of x
- 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.
  - For nuclei with A > 1, that scattering angle is much smaller for a given t, cutting the low t acceptance

Coherent exclusive (diffractive) reactions on light nuclei

D

He3

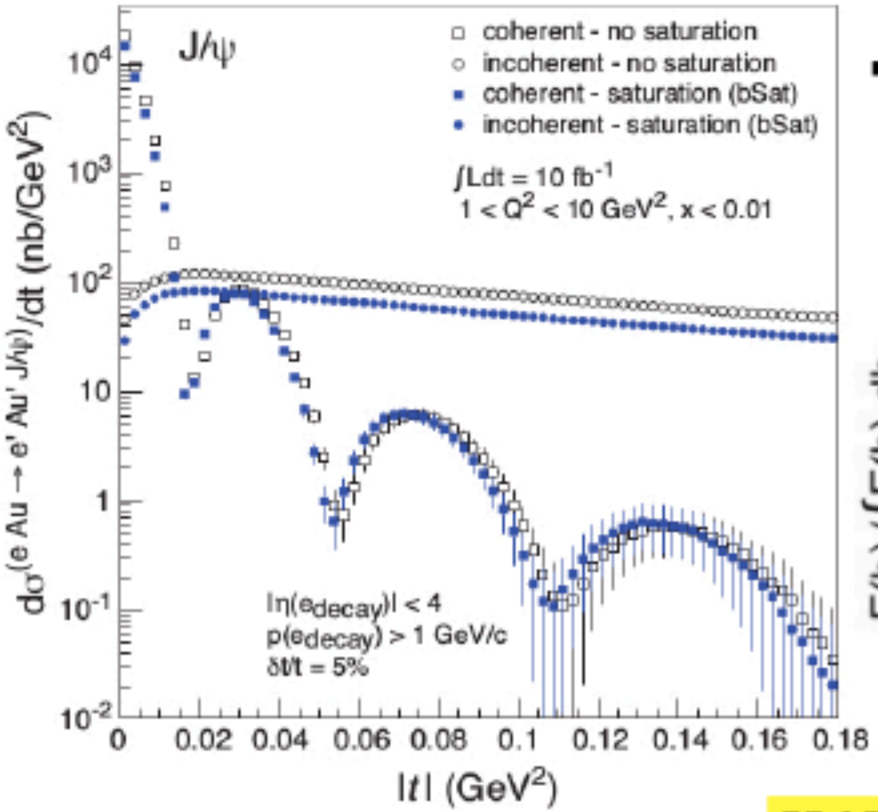


He4

- Coherent exclusive reactions on light ions give *unique* access to the 3D structure of *nuclei*.
- In contrast to heavy nuclei, 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

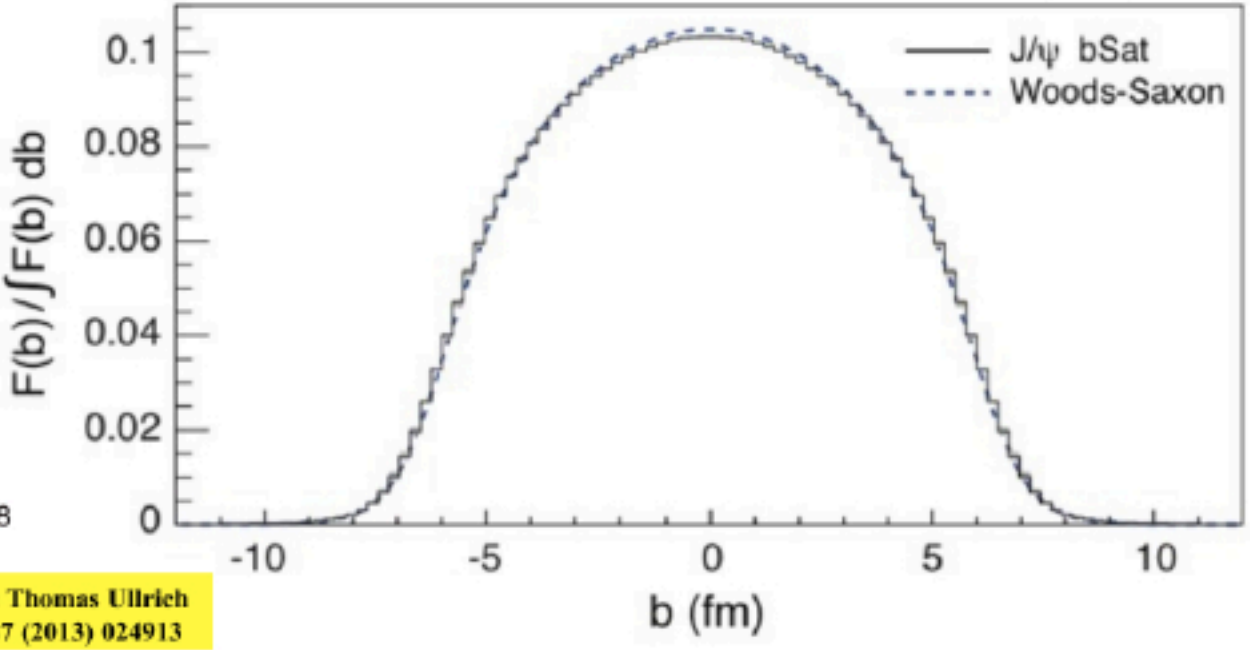
2D spatial gluon imaging in heavy nuclei through coherent diffraction

Momentum transfer t conjugate to transverse coordinate b



$$F(b) \propto \int \mathrm{d}\Delta \Delta J_0(\Delta b) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$

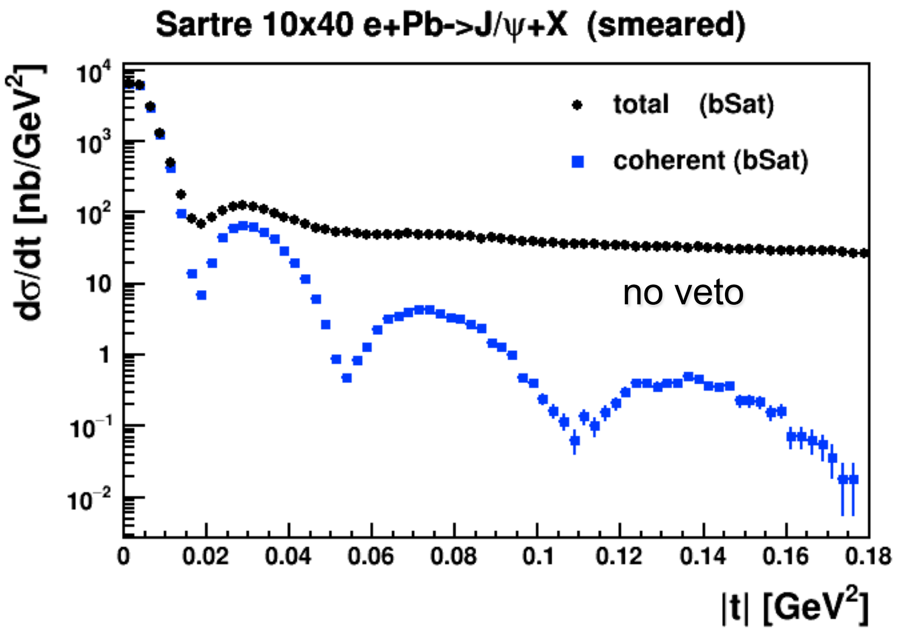


T.T. & Thomas Ullrich
PRC 87 (2013) 024913

- Experimental challenge: veto the large incoherent background.

Evaluate the veto efficiency of target fragment detection

- Intact heavy ions cannot be detected directly
  - The momentum transfer is too small to kick intact heavy ions out of the beam envelope
- Need high-efficiency veto of incoherent events
  - Detection of *all* produced particles is required: protons, neutrons, light nuclei, and photons from nuclear de-excitations *-> talk by C. Hyde*
  - Detection of the residual nucleus (from incoherent diffraction) is also helpful
- BeAGLE was used to simulate the incoherent part – in this case the background
  - The coherent simulation used Sartre



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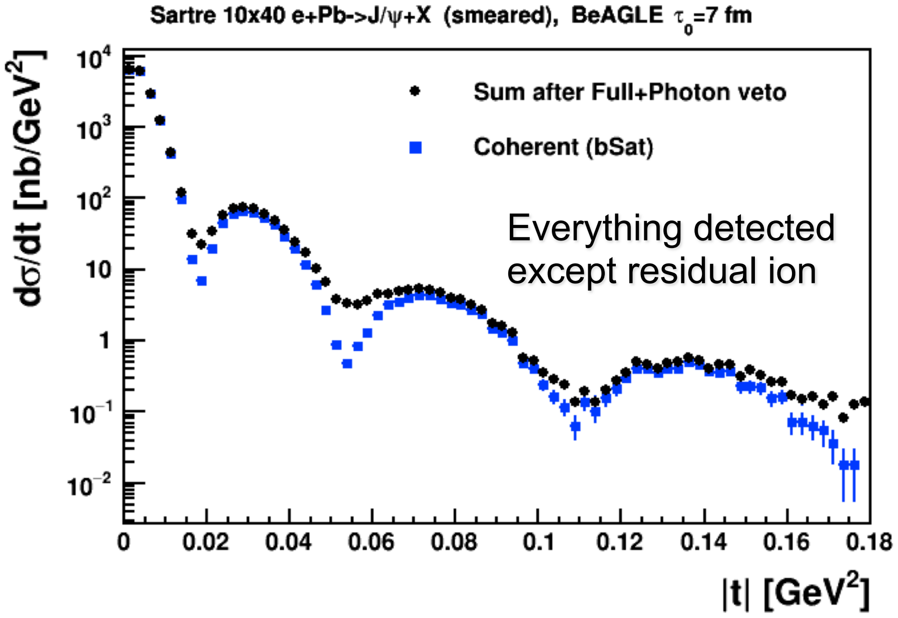
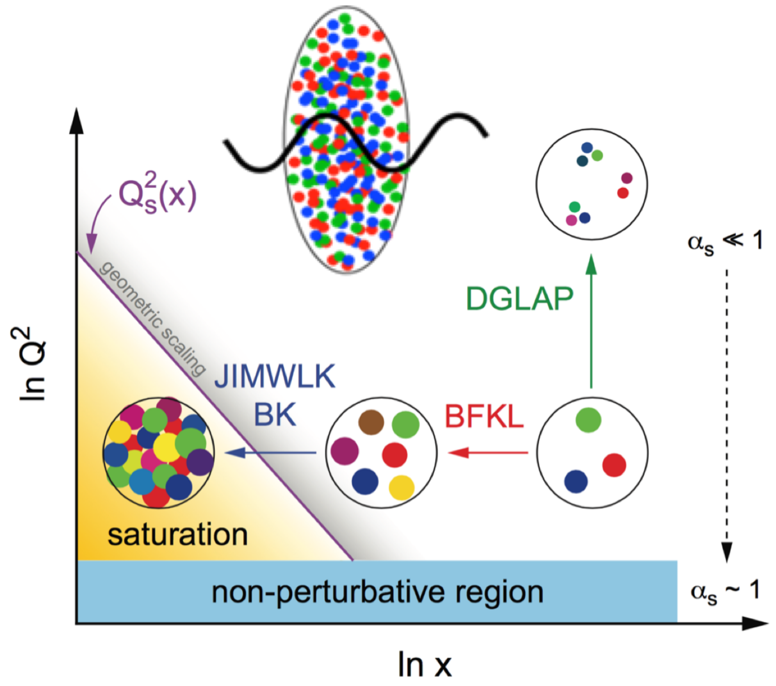
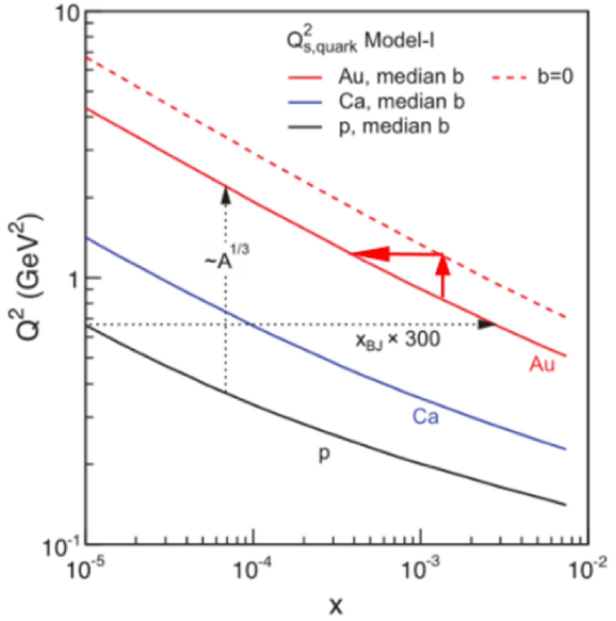
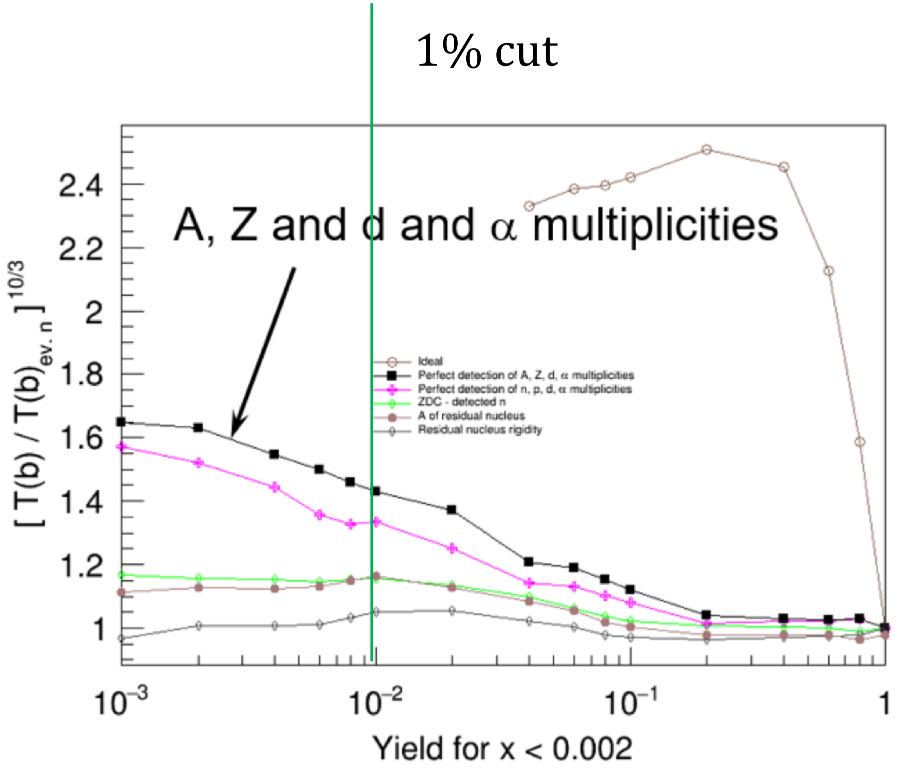


Kinematic reach for probing gluon saturation in DIS







- 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)

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

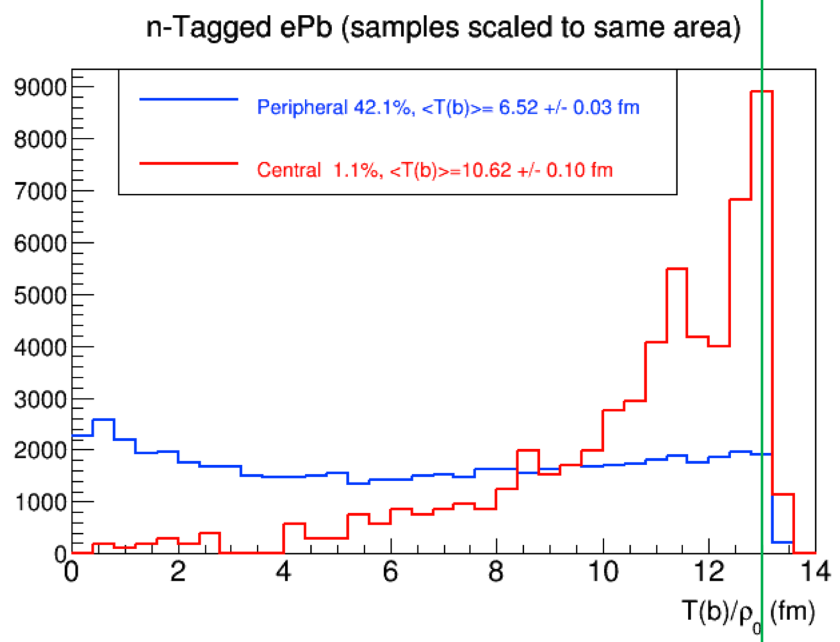
- A larger thickness T(b) is equivalent to a higher beam energy
  - With a evaporation neutron multiplicities only, this factor is 3.2 at 1%
  - Detecting all final-state particles, this increases to 4.8

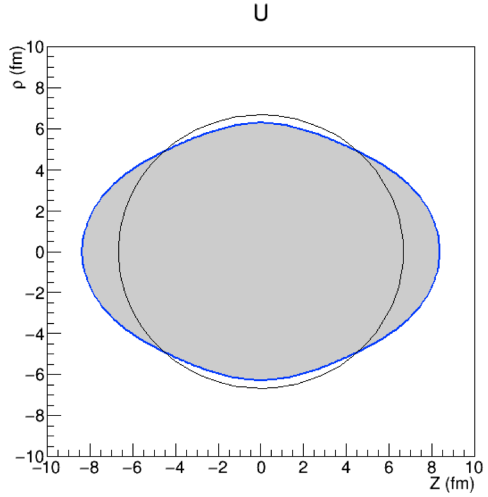
$$F_E = \left(\frac{\langle T(b)\rangle_{central}}{\langle T(b)\rangle_{minbias}}\right)^{10/3}$$

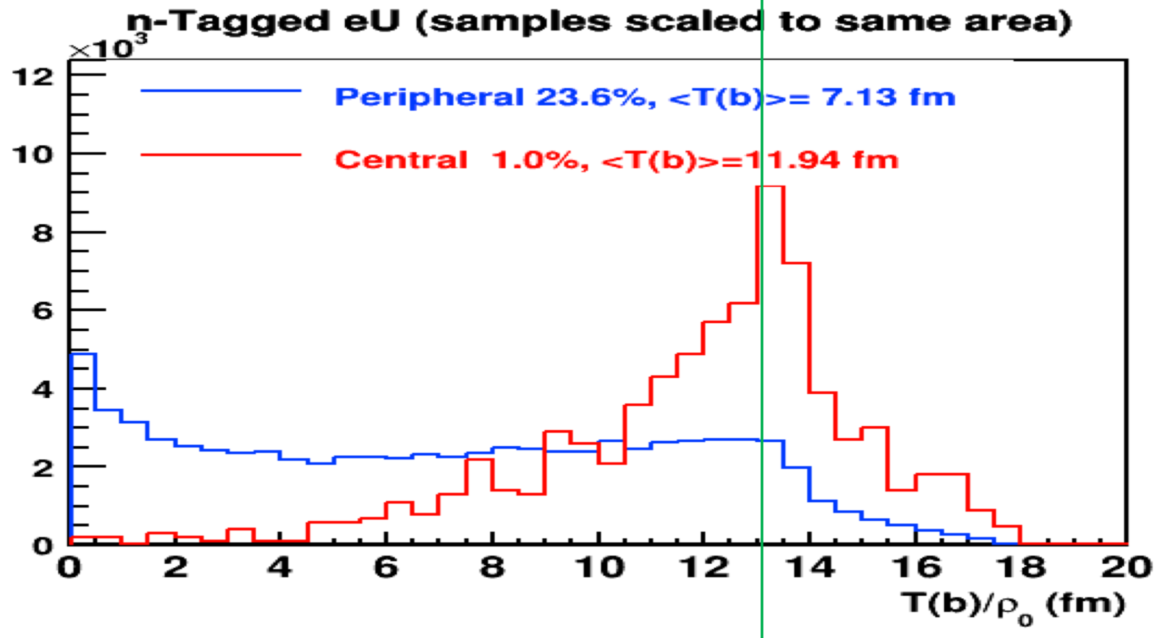
T(b) for ^{208}Pb and ^{238}U

- 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

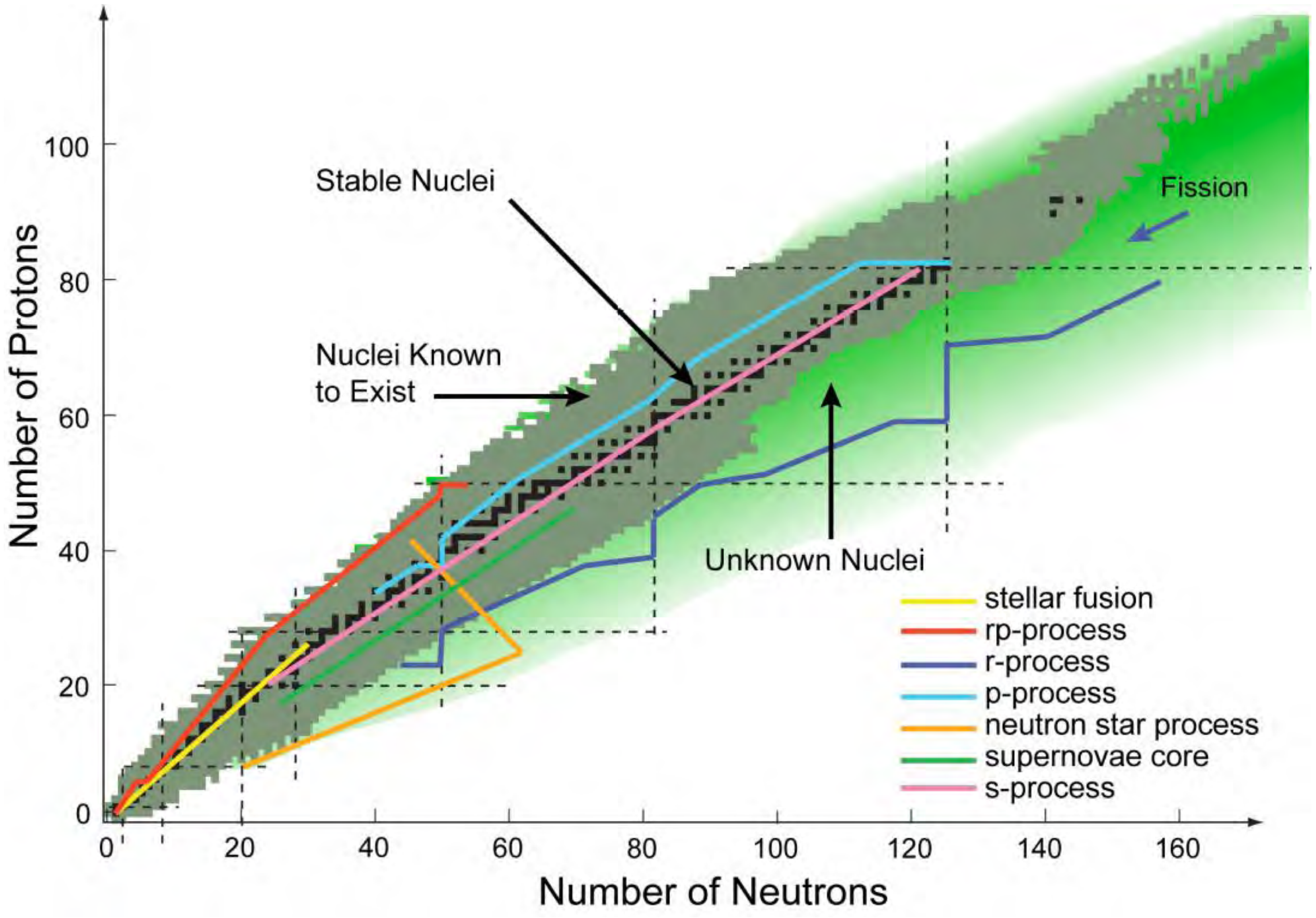
M. Baker, 2018

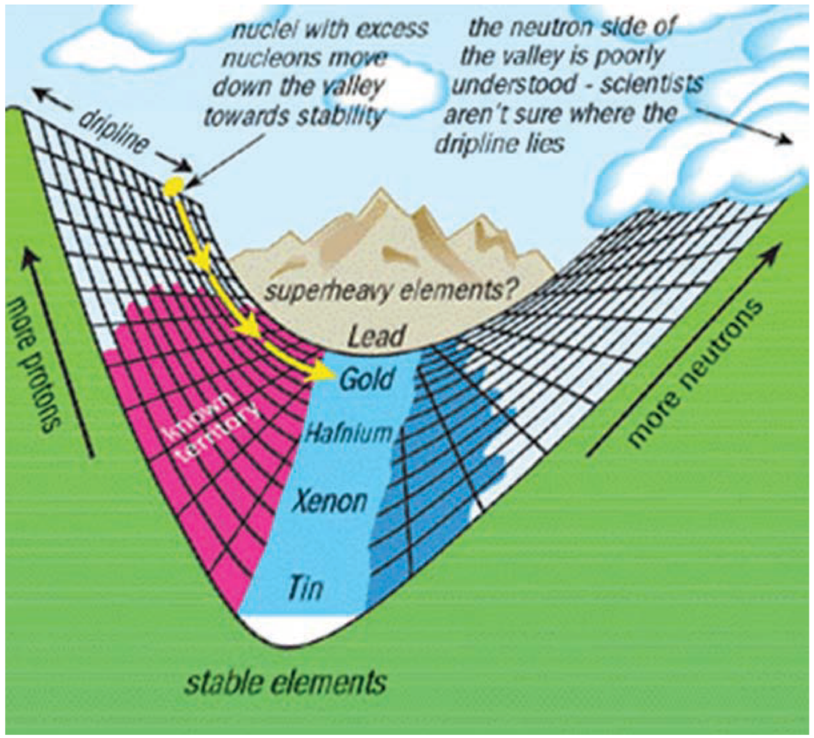


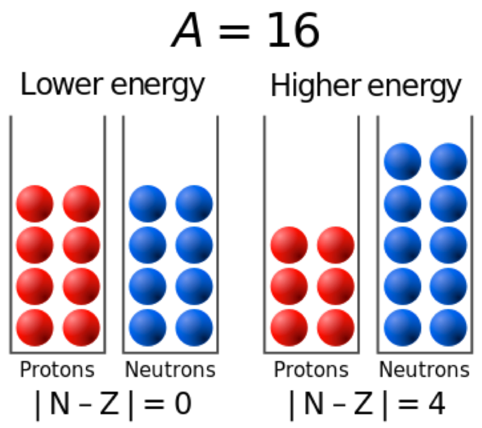




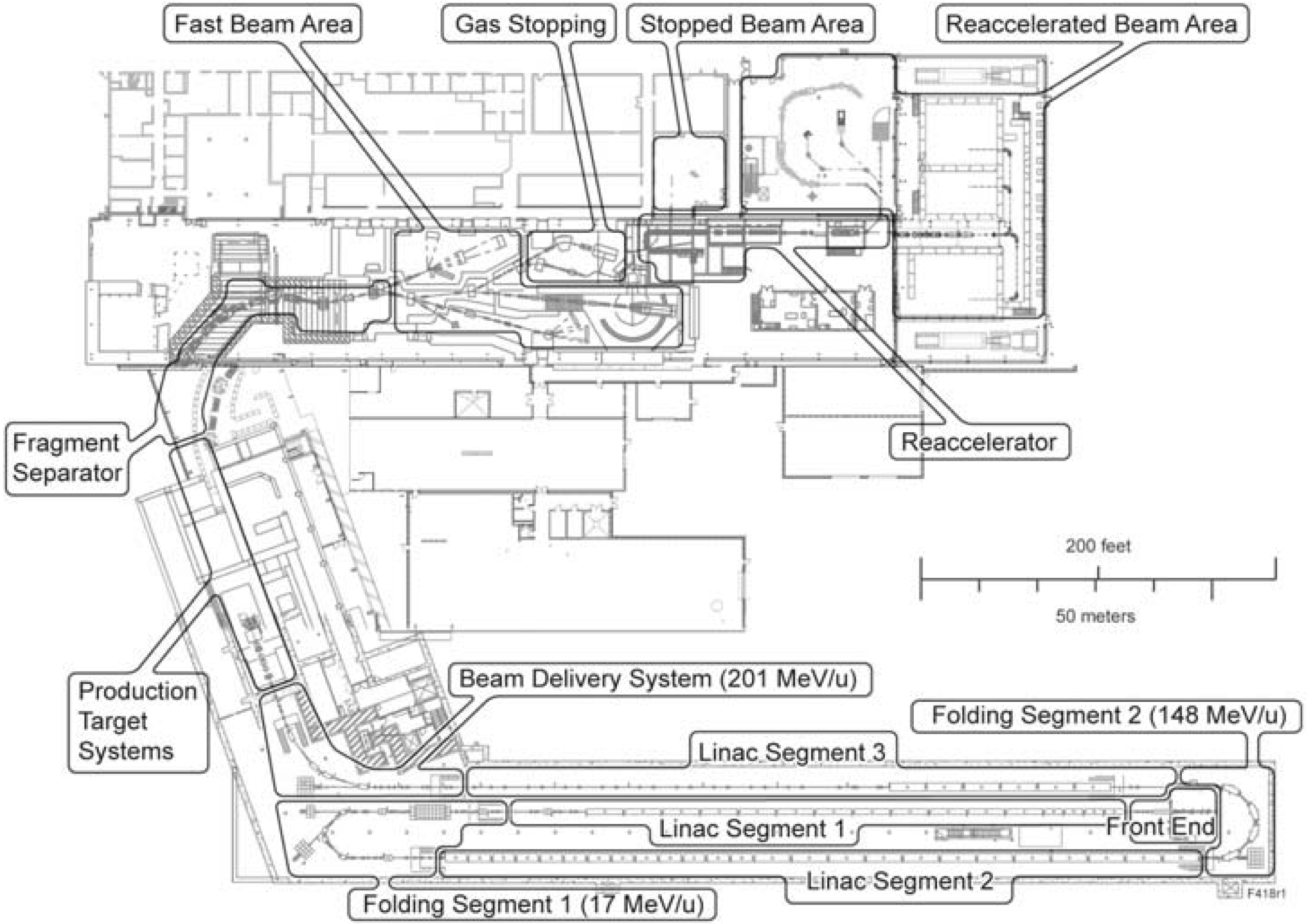
Rare isotopes at an EIC





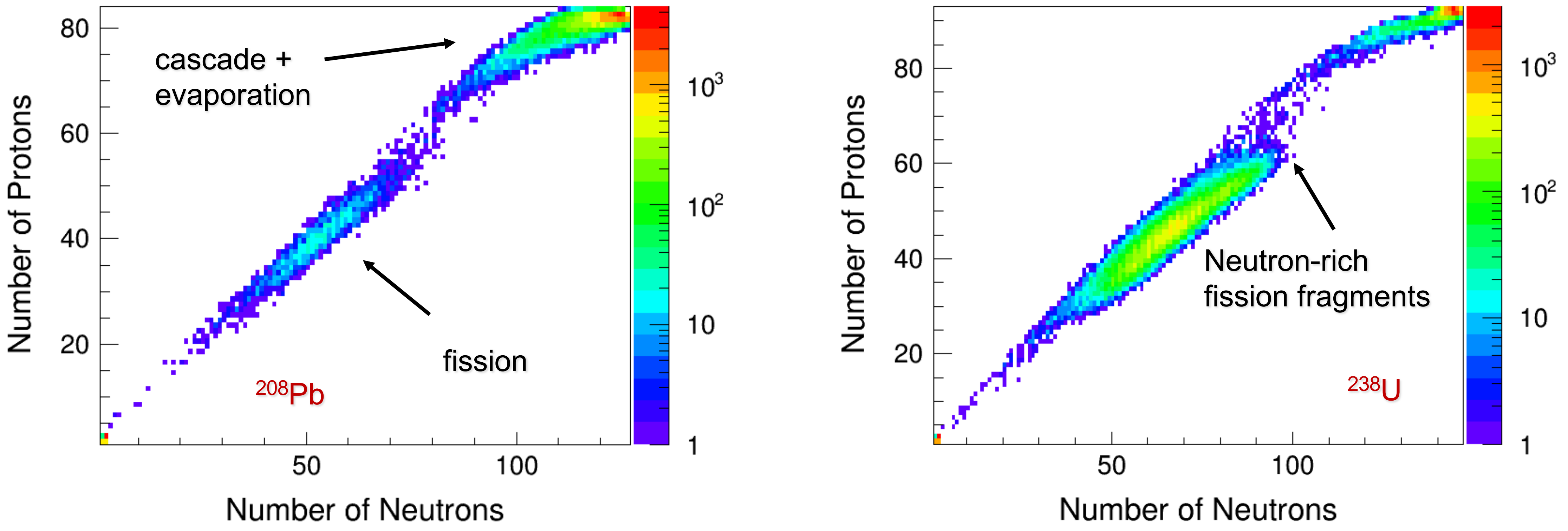


Facility for Rare Isotope Beams (FRIB)



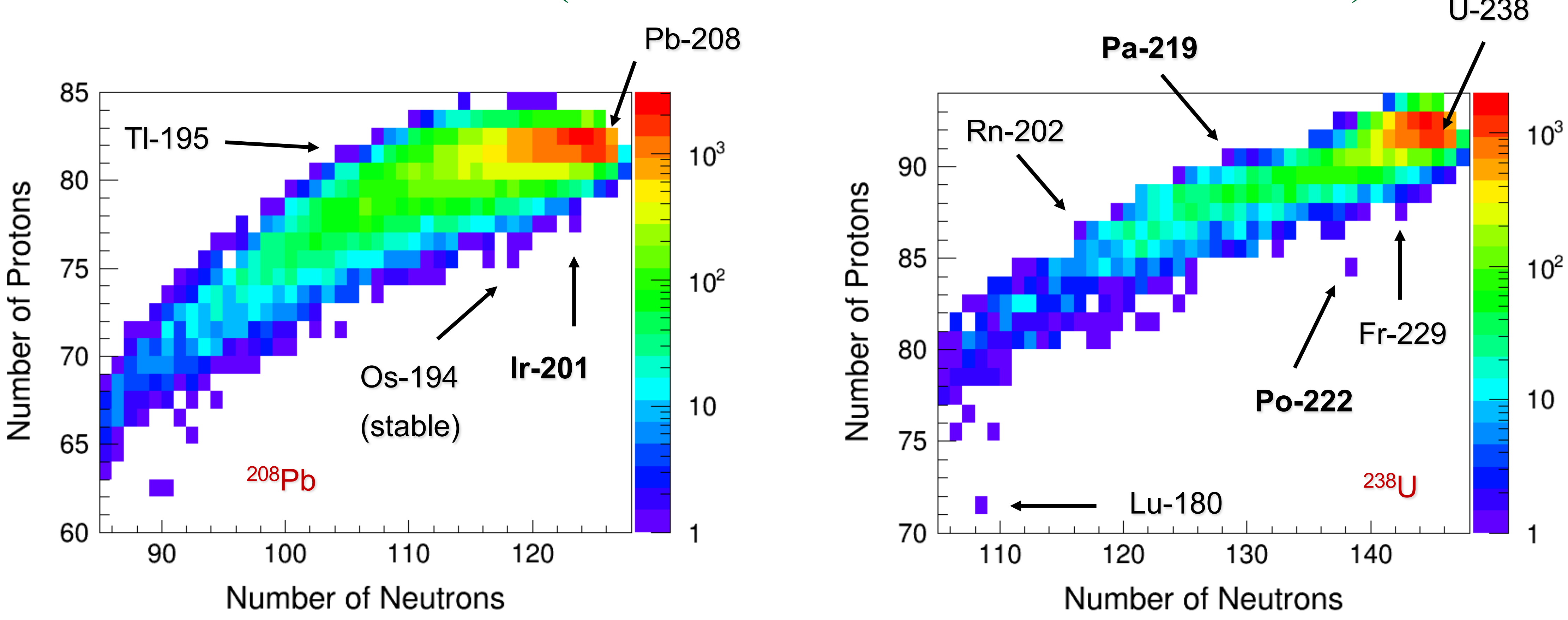
- Close to completion at MSU
- Will produce radioactive beams through in-flight projectile fragmentation followed by fragment separation in a downstream spectrometer
- Focus in on neutron-rich nuclei

Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time at the EIC)



- ^{208}Pb (left) produces mainly heavy isotopes from evaporation
- ^{238}U (right) produces fewer, but heavier isotopes from evaporation. It also produces very neutron-rich fission fragments (medium-mass nuclei have fewer neutrons).

Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time at the EIC)



- ^{208}Pb (left) produces mainly heavy isotopes from evaporation
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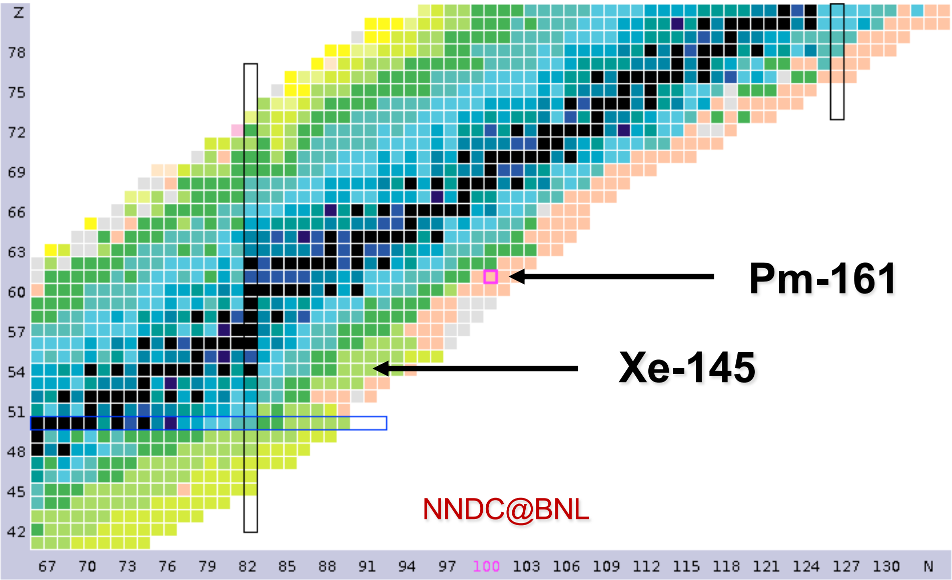
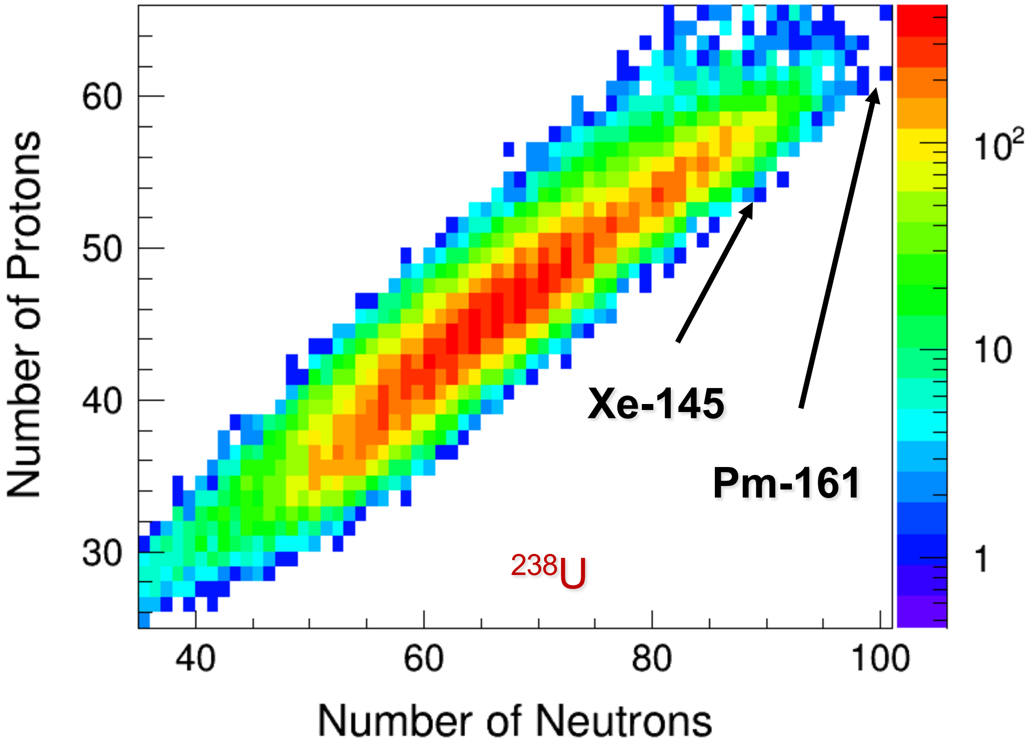
How “exotic” are ^{161}Pm and ^{145}Xe (produced in 1s of simulated beam time)?

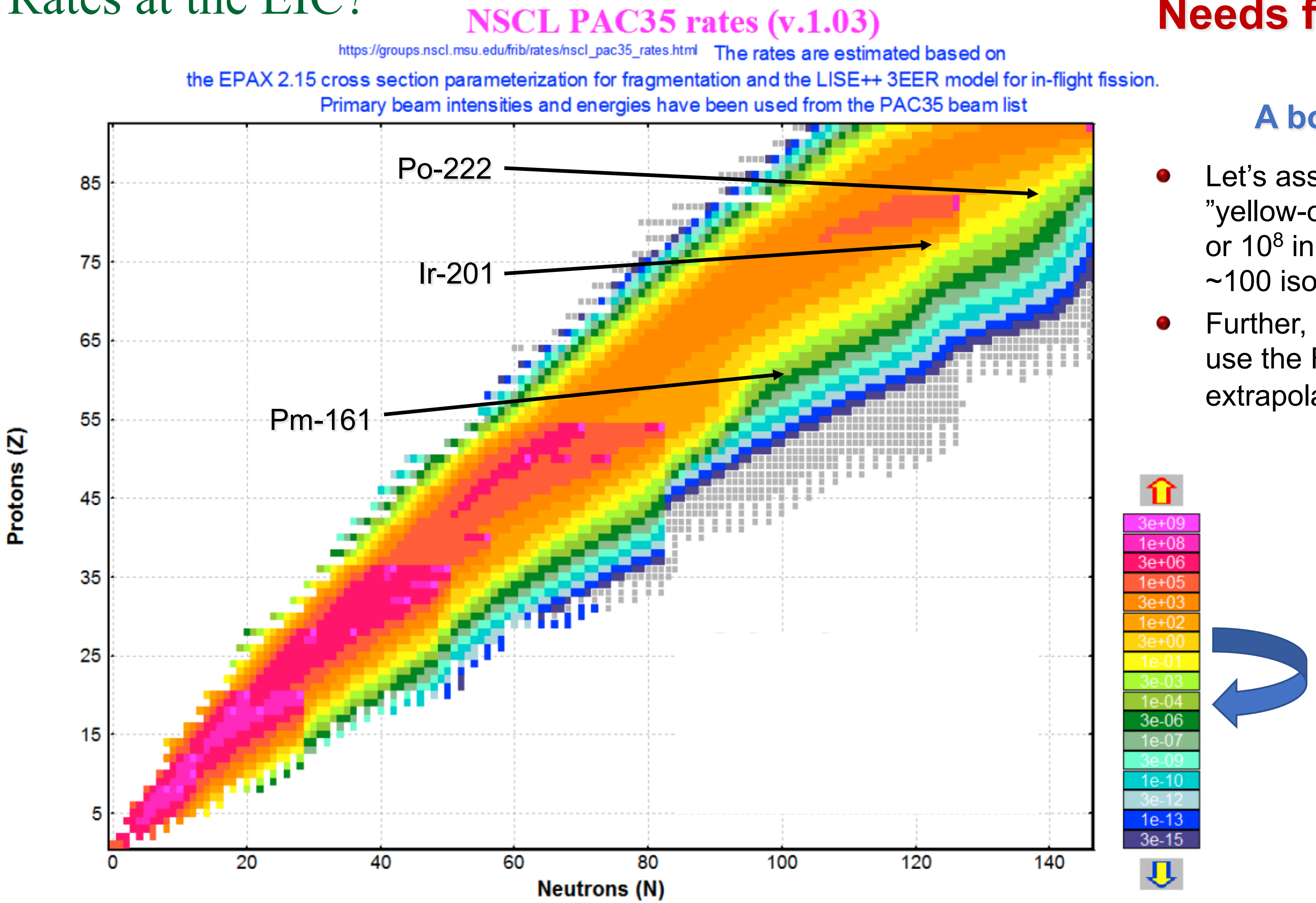




- Lifetime for ^{161}Pm: >130 ns
- Lifetime for ^{145}Xe: 188 ms
- Both nuclei are very close to the most neutron-rich nuclei currently known – and in a spot where rates at FRIB are relatively low

Rates at the EIC?

Needs further studies!



A bold extrapolation

- Let's assume that we have one "yellow-orange" event per second, or 10^8 in a year, distributed over ~100 isotopes of interest
- Further, lets assume that we can use the FRIB rate estimates for the extrapolation.

- Then, if we want to accumulate a total of 10,000 events for the isotopes of interest, in a year we can move from the orange-yellow to light green (although for ^{161}Pm we are there in 1 minute)

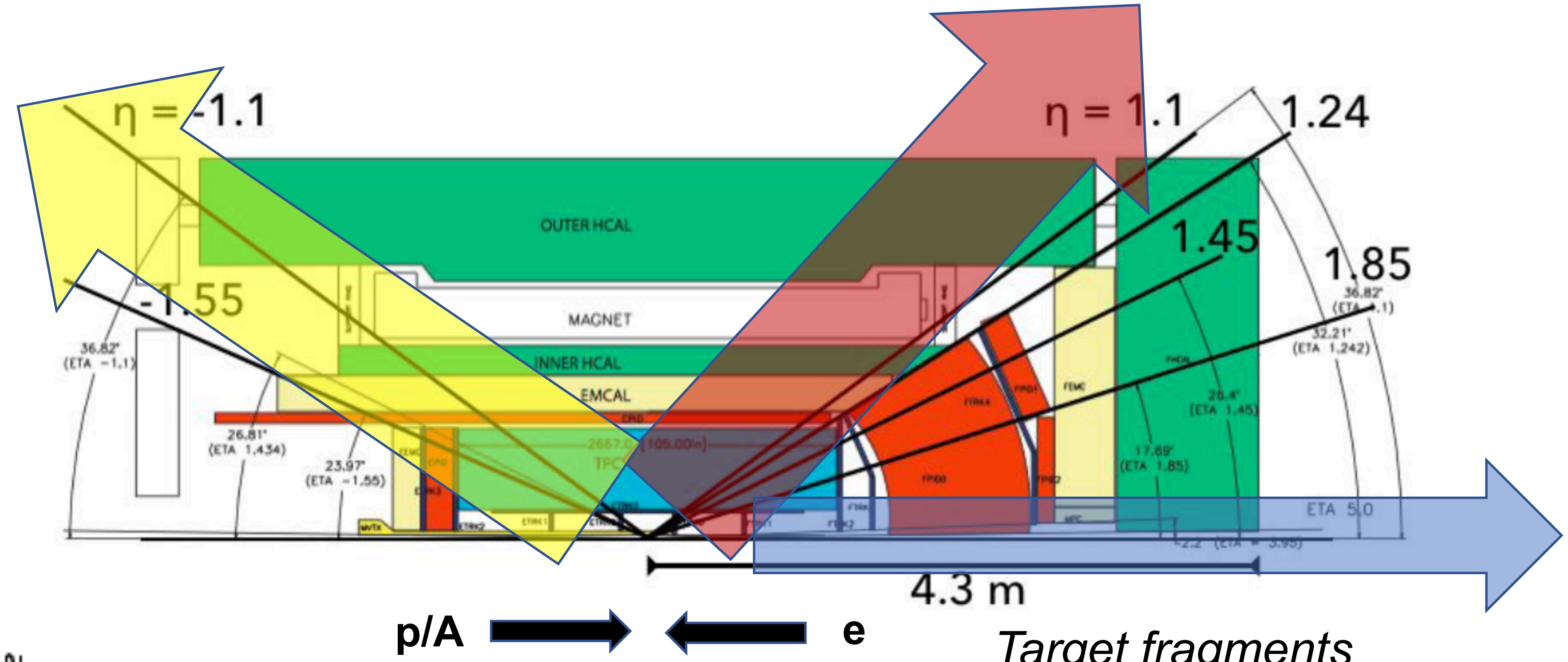
Thank you!

Backup

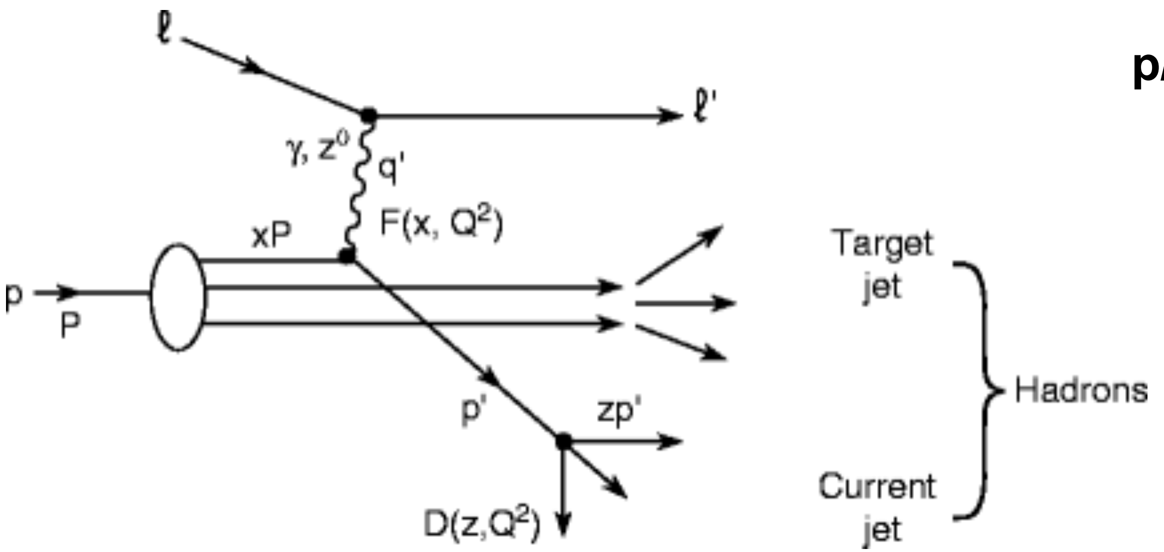
What do we measure?

Current jet (or hadron)

Scattered electron



Lepton scattering on a proton

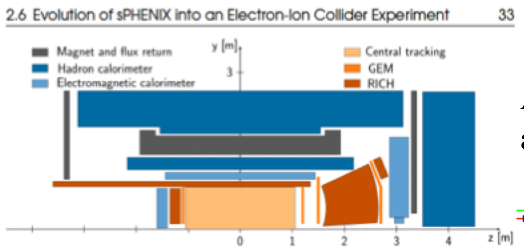


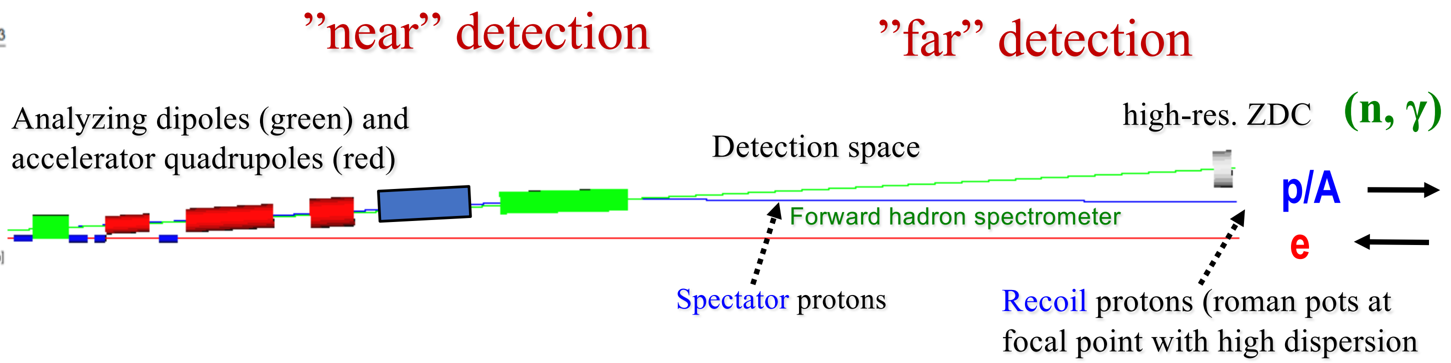
Inclusive DIS: only electron is detected

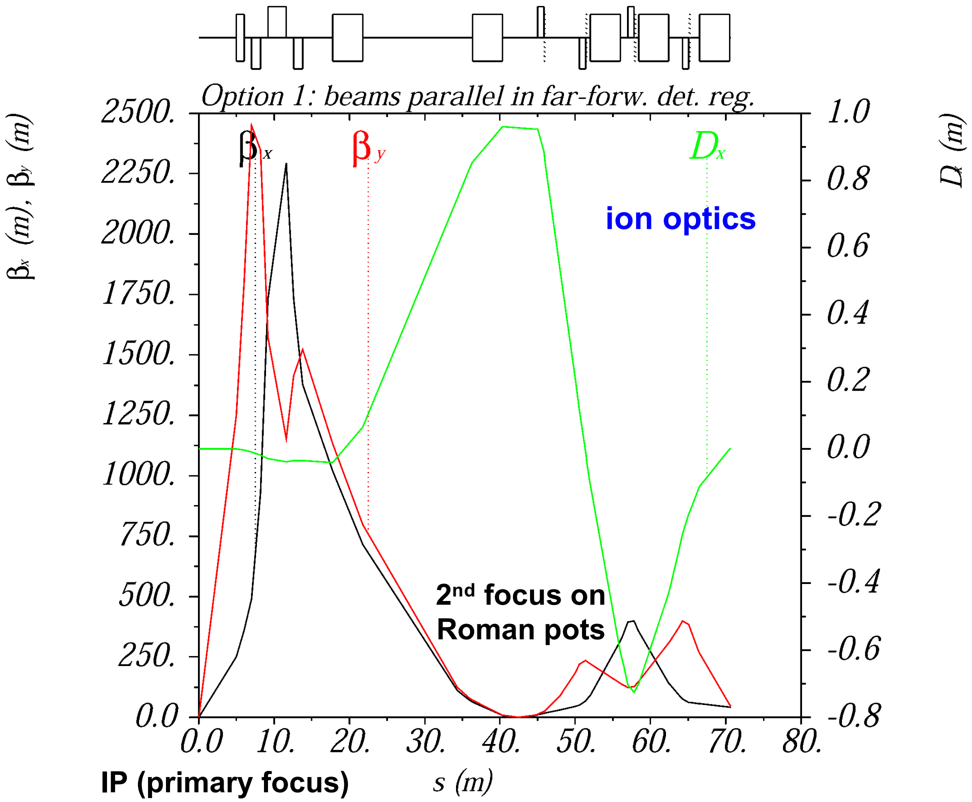
Semi-Inclusive DIS (SIDIS): electron and current jet (hadron) are detected.

Exclusive reactions: all particles are detected

Detection of target fragments – forward spectrometer

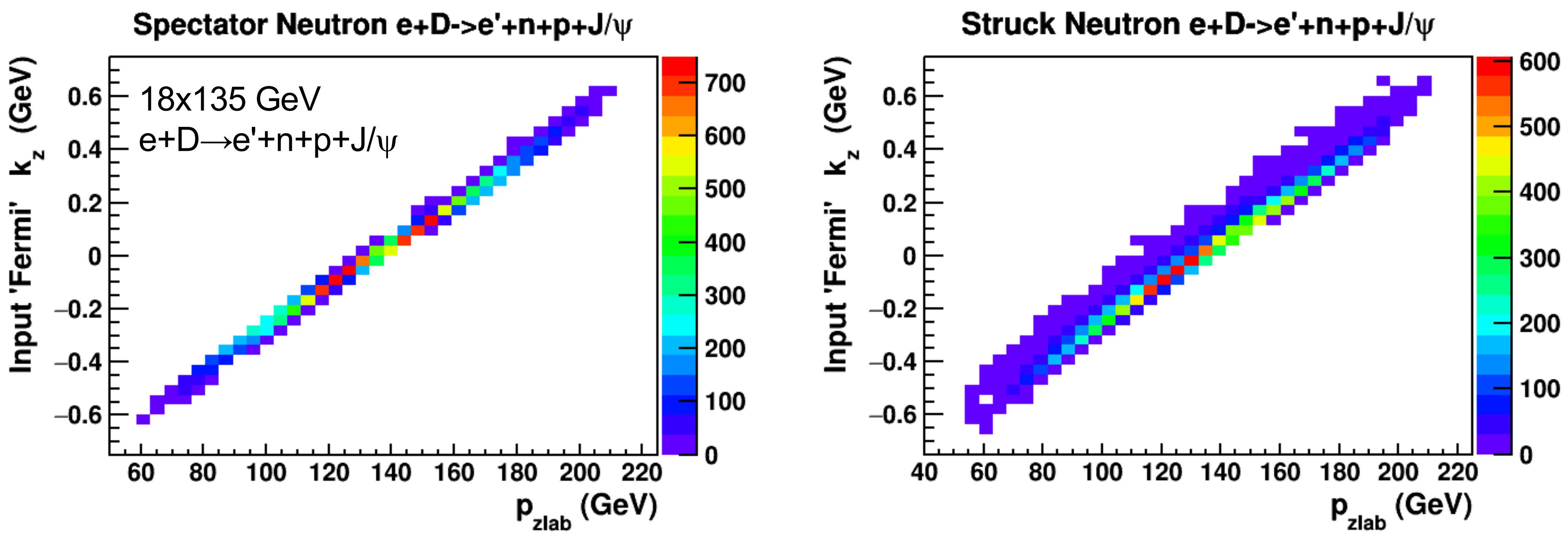






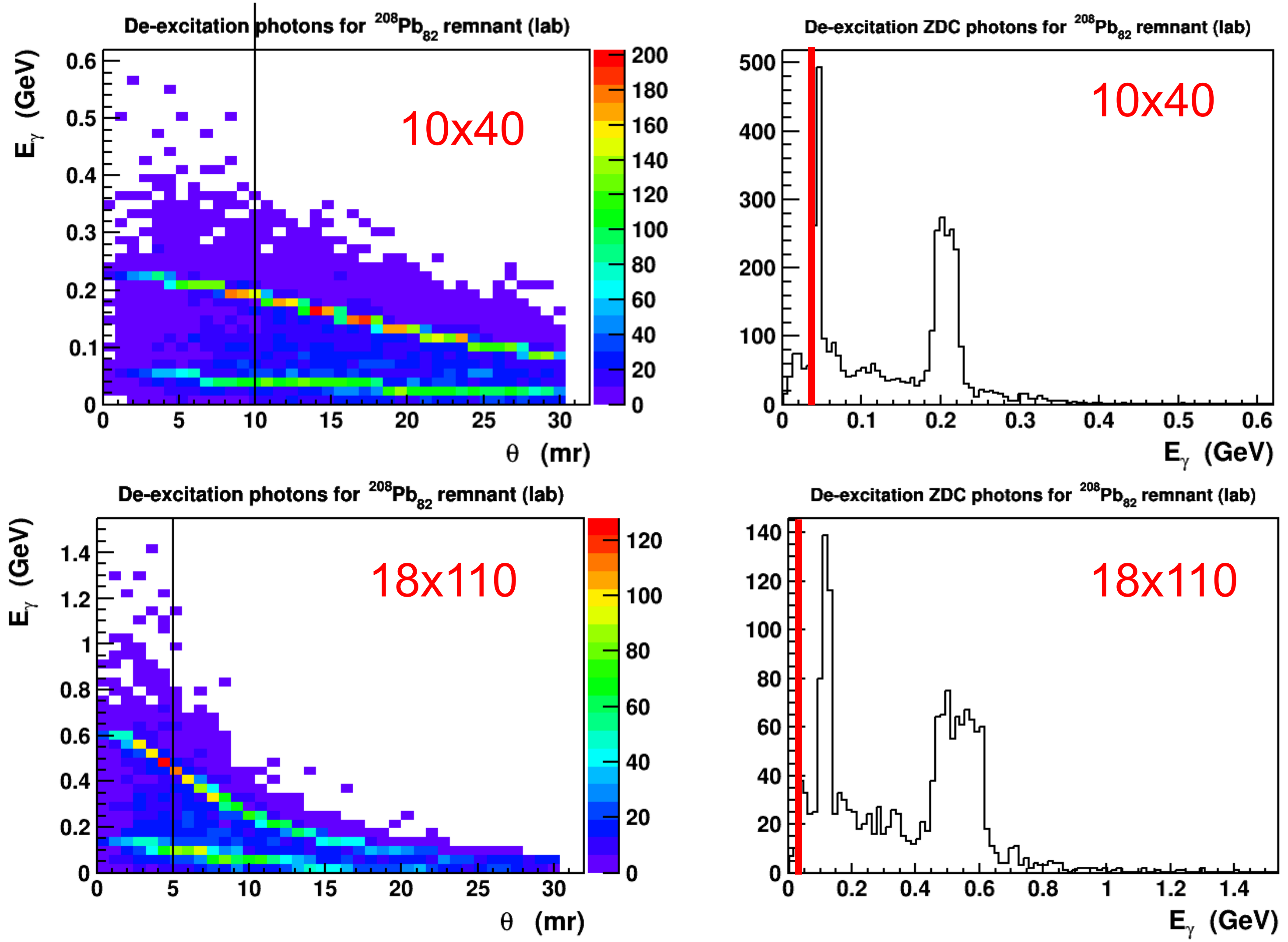
- Functionally, the forward detection is naturally separated into a ”near” and “far” parts
- “Near” detection:
  - *Goal*: off-momentum/rigidity particles or ones scattered at ”large” angles (high p_T)
  - *Requirement*: large magnet apertures
- “Far” detection (can be after a crab cavity):
  - *Goal*: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

Effect of boosting k_z to the lab frame



- The boost makes precision measurements of nucleons moving along the z-axis easier
  - It also makes precision gamma spectroscopy of photons from nuclear de-excitations in heavier nuclei possible.
- However, as noted earlier, this is also the reason why hadronic reconstruction methods do not work as well for eA as they do for pA.

Photons from $^{208}Pb_{82}$ in lab frame



Detailed studies ongoing.

It is clear that γ's will be needed for low |t|!

w/ Morozov, Hyde, Turonski et al.

Density fluctuations from incoherent diffraction

- Incoherent diffraction probes the variance of the density
  - Calculations at x ~ 10^{-3} show ”lumpiness” in the gluon distribution and suggest sensitivity to model assumptions

- Could we in the future see the imprint of correlations from nucleonic degrees of freedom at the partonic level?
  - Experimentally straightforward, but a clear interpretation needs much more progress on the theory side

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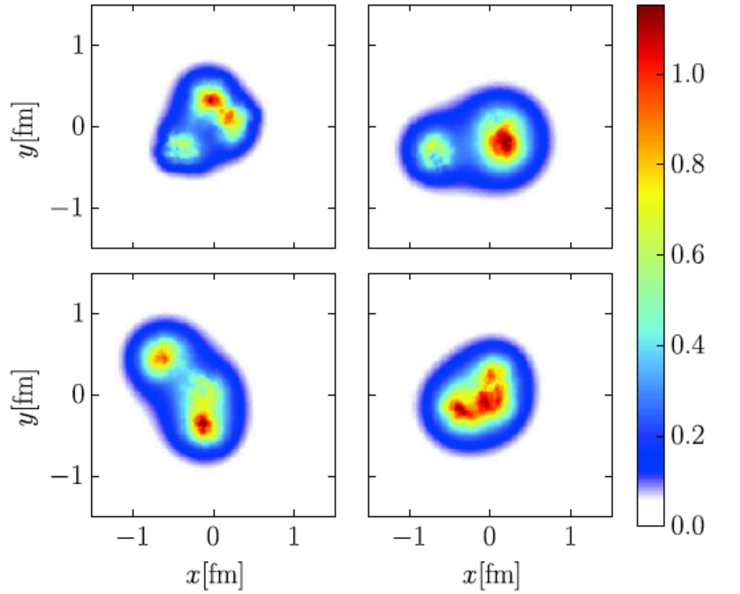
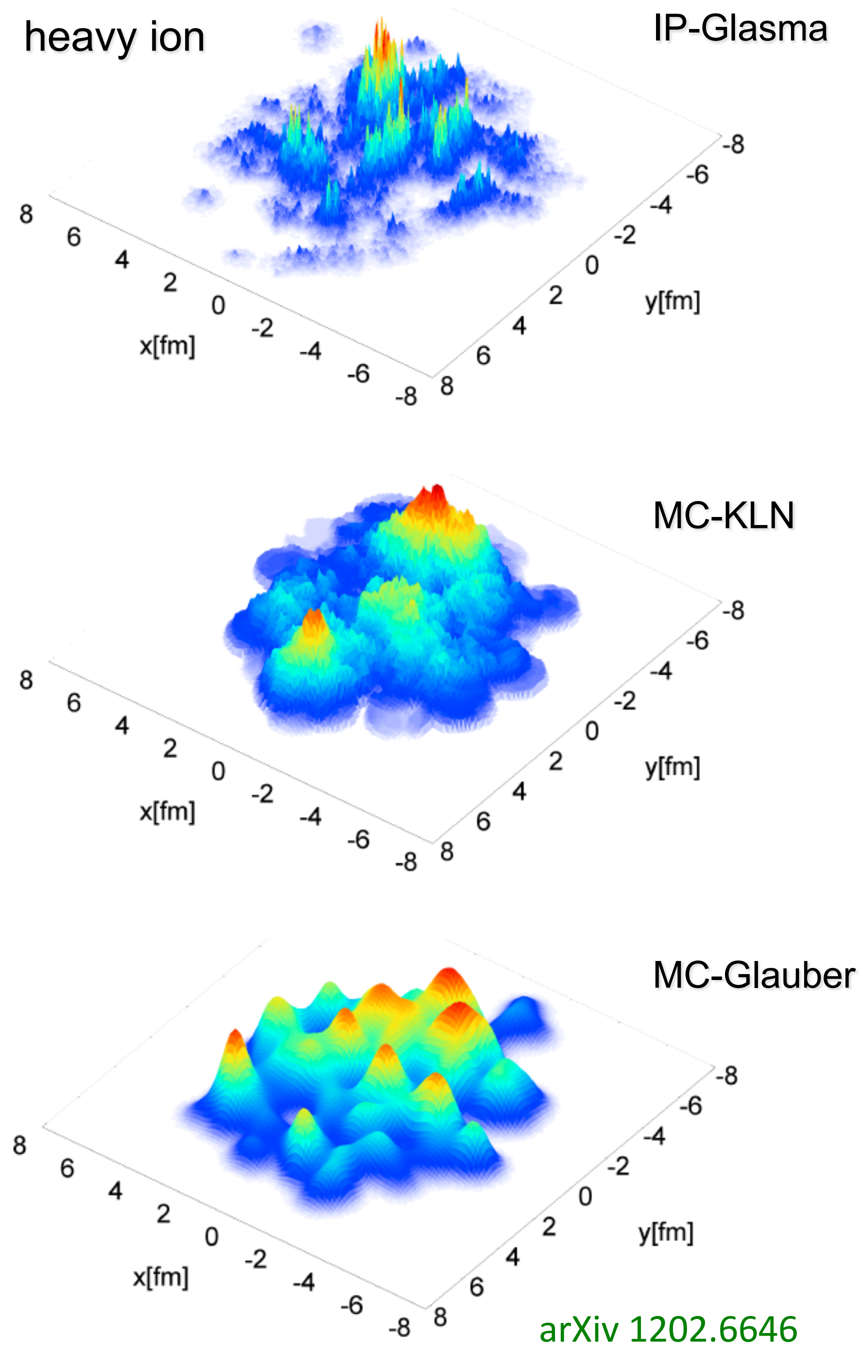


proton



arXiv 1202.6646