Production and detection of nuclear fragments at the Electron-Ion Collider (EIC)

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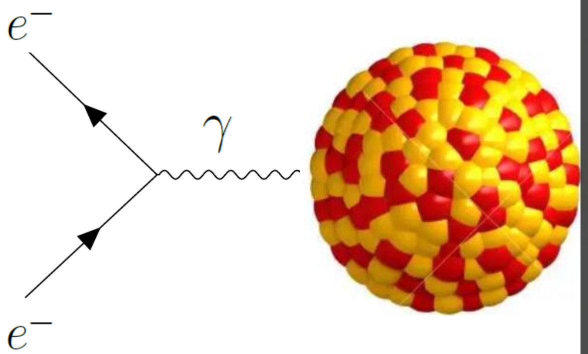
(for the EIC Rare Isotopes team)

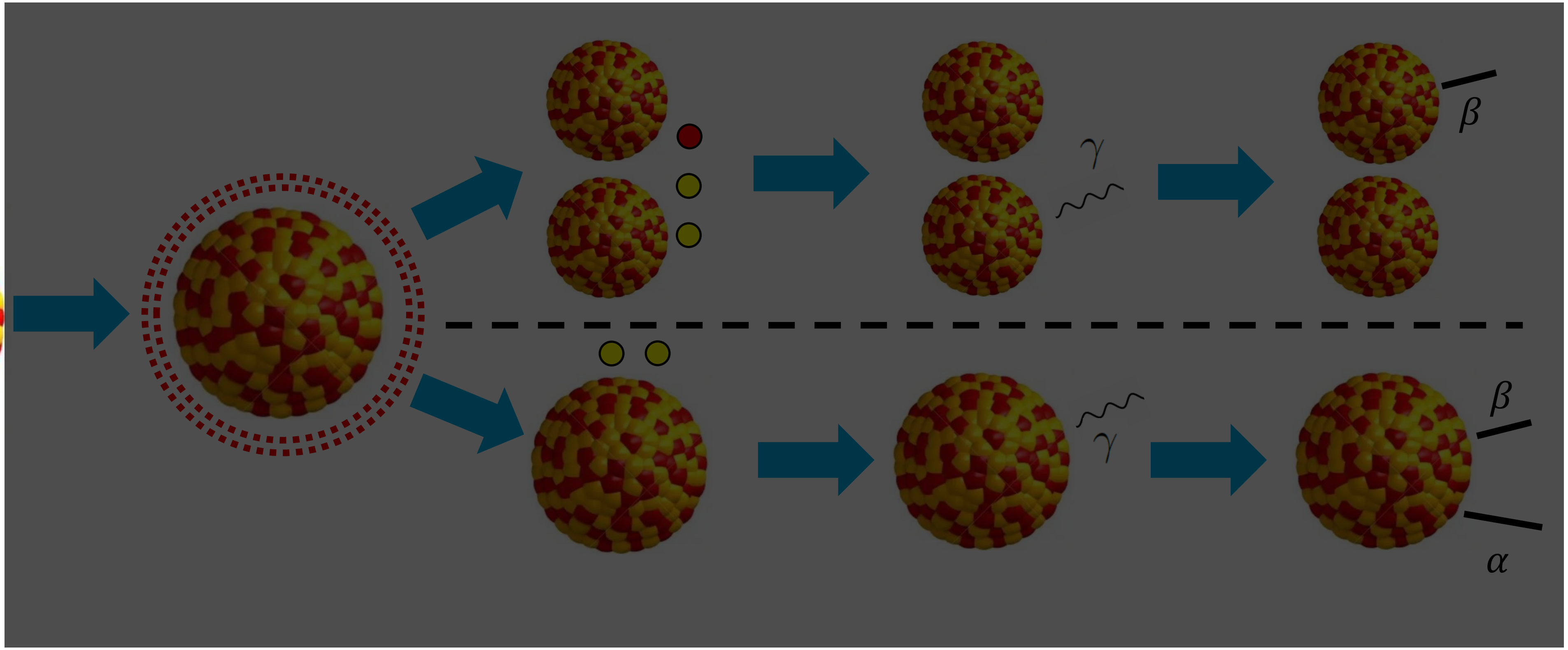
Production of nuclear fragments

Motivating questions

- Can we use high-energy electron-heavy nucleus scattering at the future EIC to produce nuclear fragments, including exotic nuclei (i.e. undiscovered rare isotopes)?
- Can we go on to detect and correctly identify the produced nuclei? Can we also study the level structure of the nuclei by detecting gamma rays? What requirements does this place on the far-forward detection area?
- If we can produce, detect, and identify nuclear fragments at the EIC, how can these results complement the work being done at dedicated rare isotope facilities?

Nuclear fragment production at the EIC



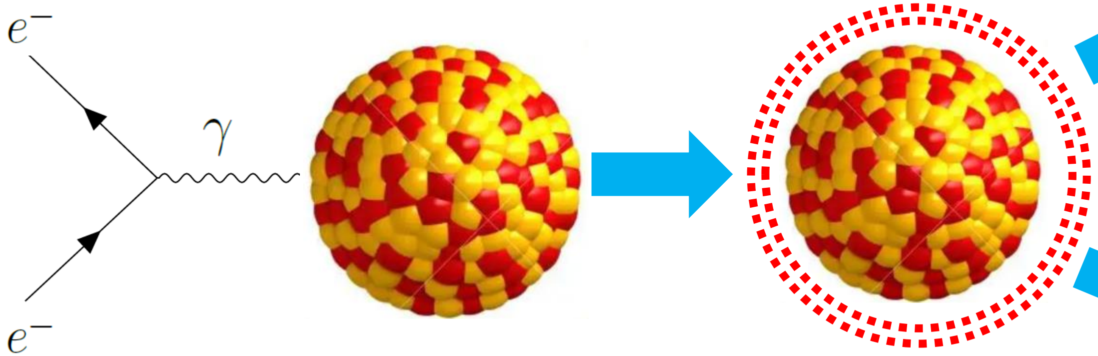


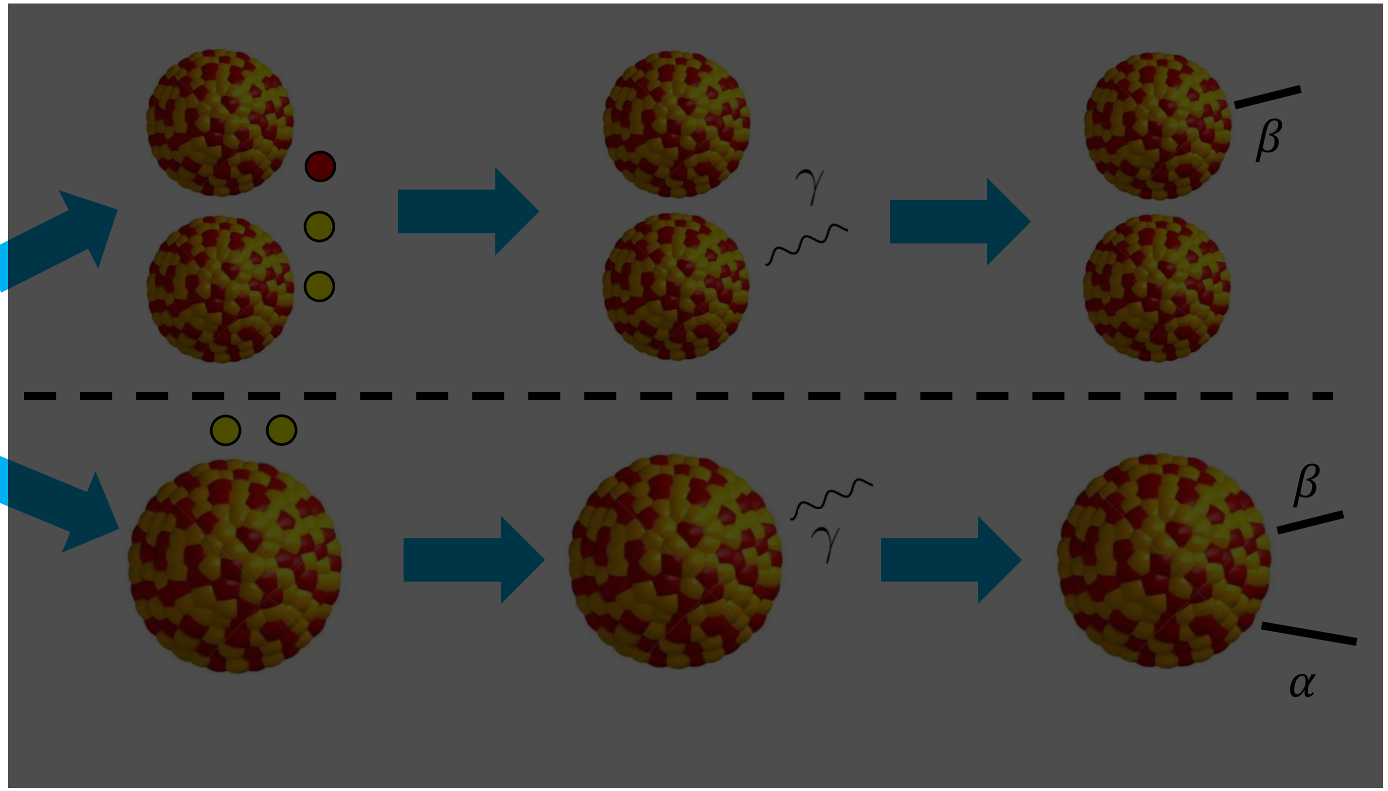
Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

t = 0

Nuclear fragment production at the EIC

Hard scattering and intra-nuclear cascade





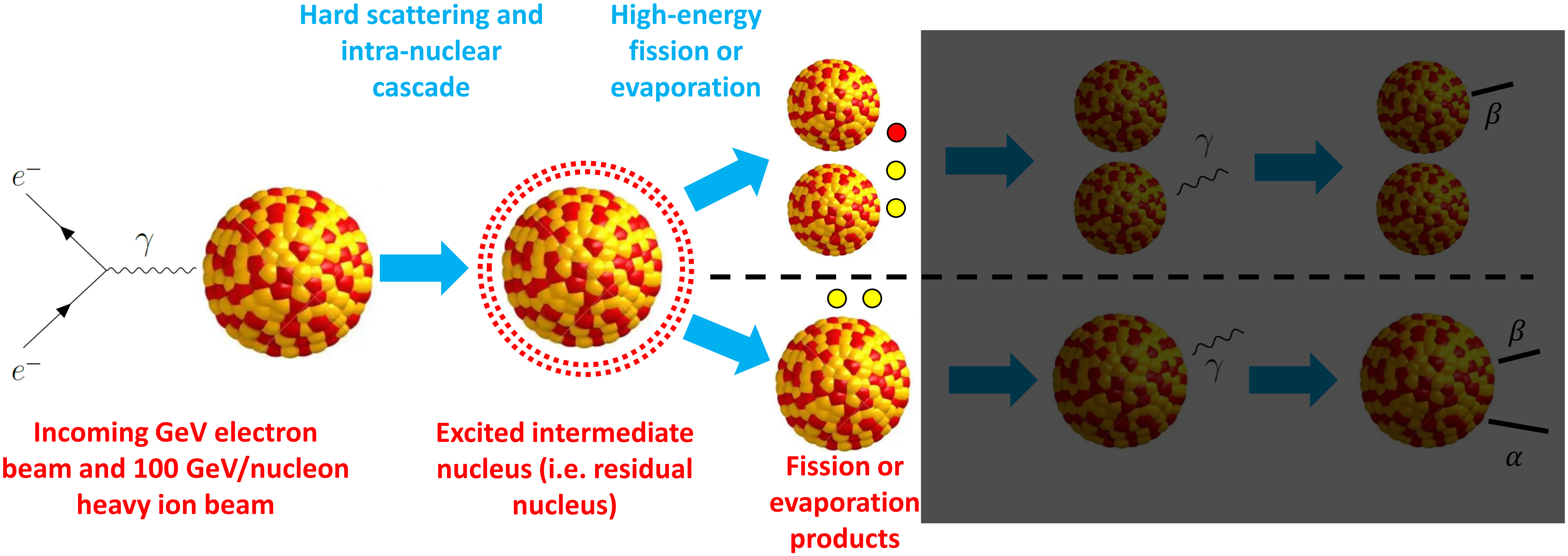
Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

Excited intermediate nucleus (i.e. residual nucleus)

t = 0

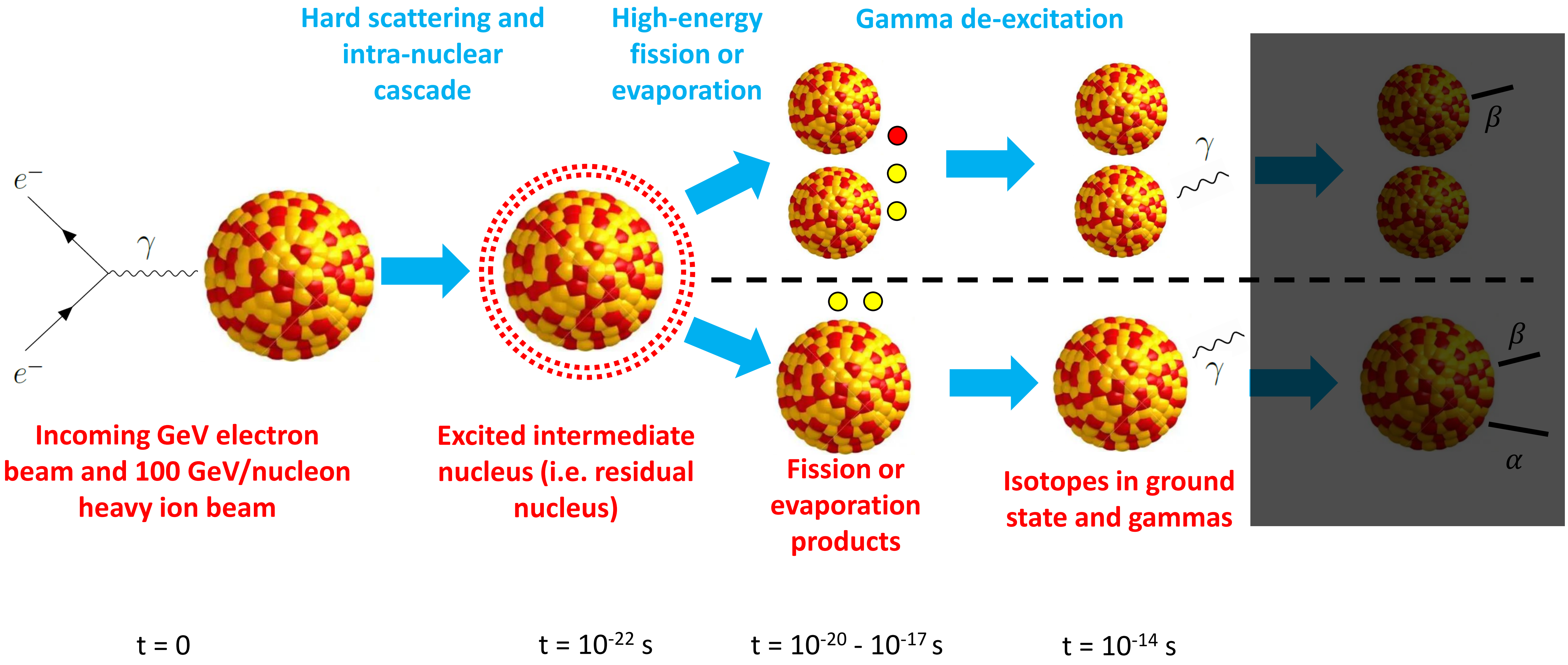
t = 10^{-22} s

Nuclear fragment production at the EIC

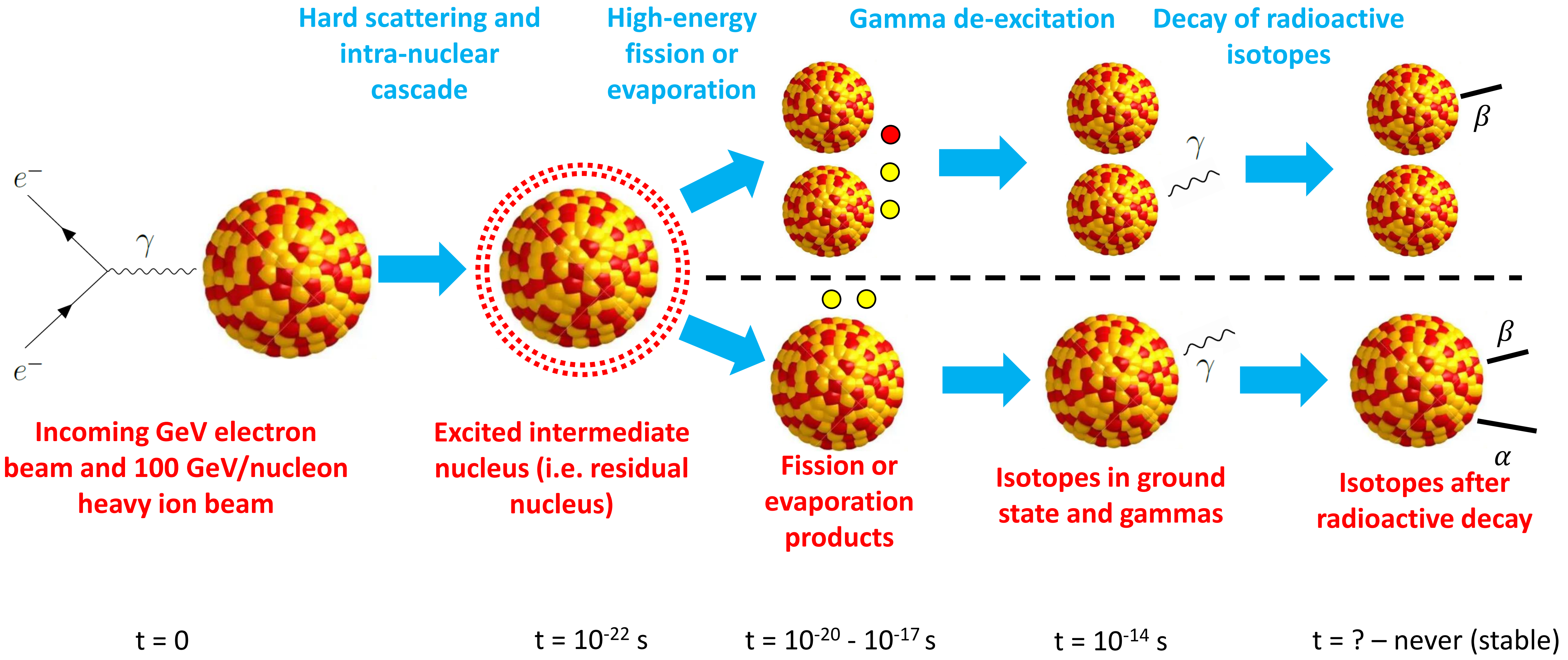


t = 0 t = 10^{-22} s t = 10^{-20} - 10^{-17} s

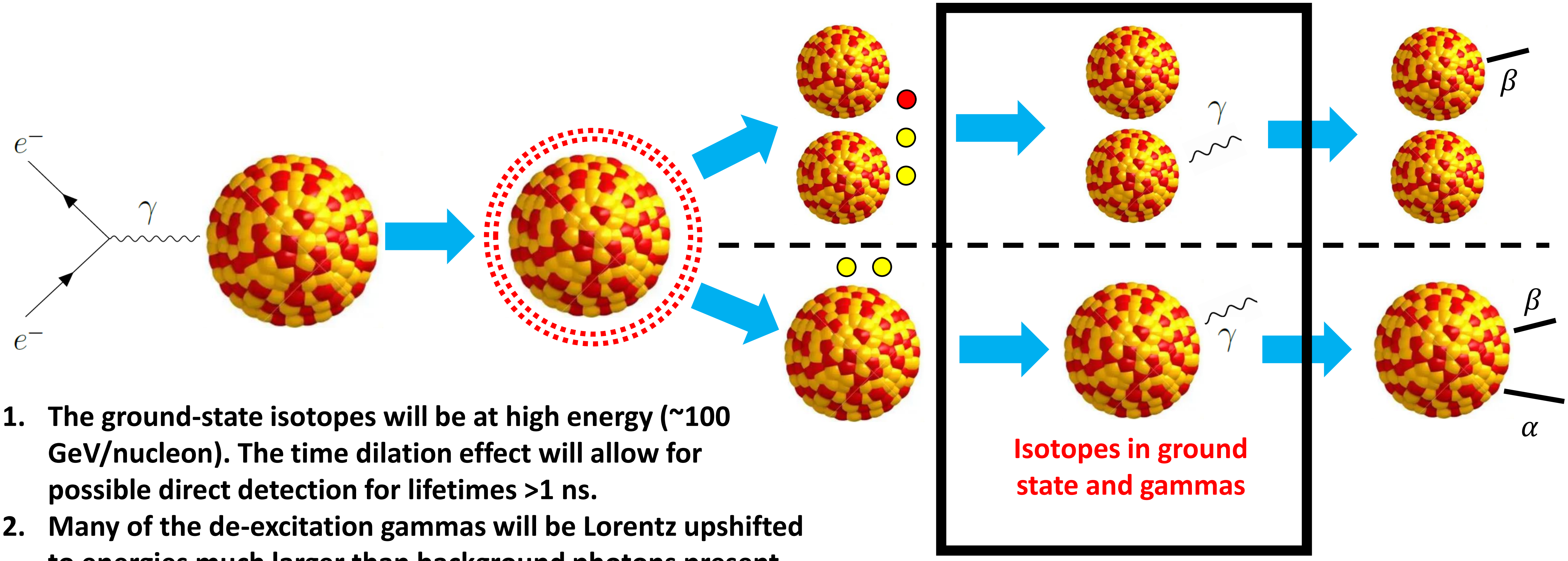
Nuclear fragment production at the EIC



Nuclear fragment production at the EIC



Where the EIC can potentially contribute



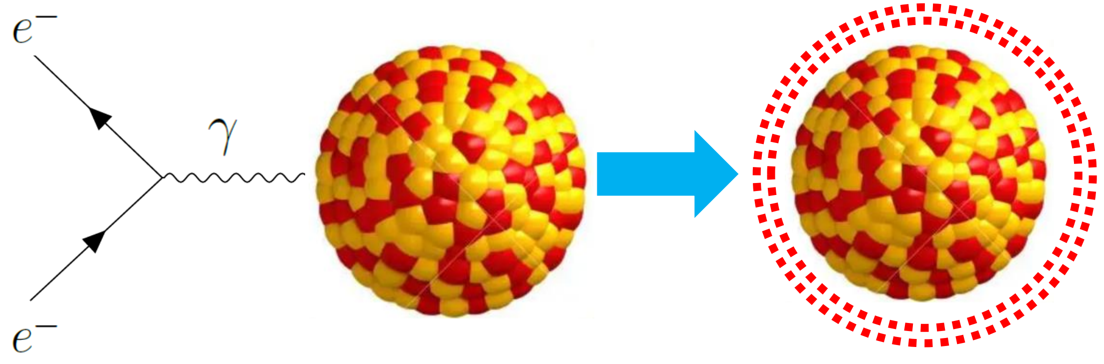
1. The ground-state isotopes will be at high energy (~100 GeV/nucleon). The time dilation effect will allow for possible direct detection for lifetimes >1 ns.
2. Many of the de-excitation gammas will be Lorentz upshifted to energies much larger than background photons present in the detector area. This will allow for clean detection/identification of these gamma rays, which can be used to study the level-structure of the isotopes.

Where the EIC can potentially contribute – specifics

Subject	Details
Reaction mechanism	Excitation energy distribution. Improvement of the fast Abrasion-Fission model and a better understanding of the reaction mechanism. Simultaneous detection of two fission fragments and no target contribution to fragment kinematics. Improvement of production models.
Production of new isotopes	Production of new neutron-deficient isotopes in the Z=89-94 range. Advantages over RIB facilities due to short flight time and possibly higher production cross section.
Nuclear structure	Coincidence measurement of isotopes and de-excitation gammas.
Hadron formation time	Sensitivity of residual nucleus excitation energy distribution to formation time parameters.

How can we study this?

Hard scattering and intra-nuclear cascade

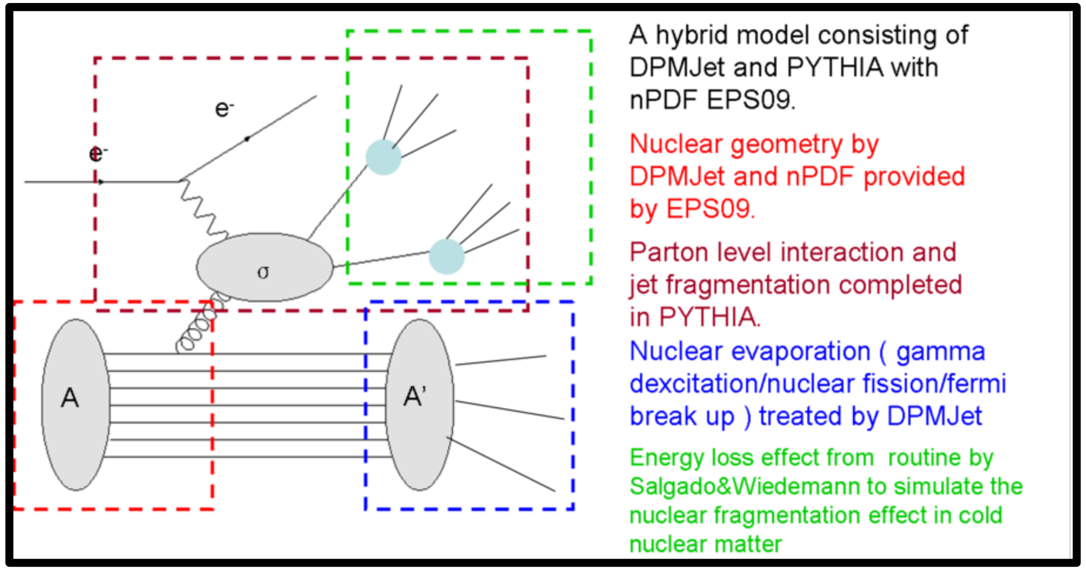


Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

Excited intermediate nucleus (i.e. residual nucleus)

Step 1

The hard scattering (primary interaction) and the intra-nuclear cascade which follows are modelled using the *Benchmark eA Generator for Leptoproduction – BeAGLE* (Phys. Rev. D 106, 012007). This leaves us with the residual nucleus in an excited state.



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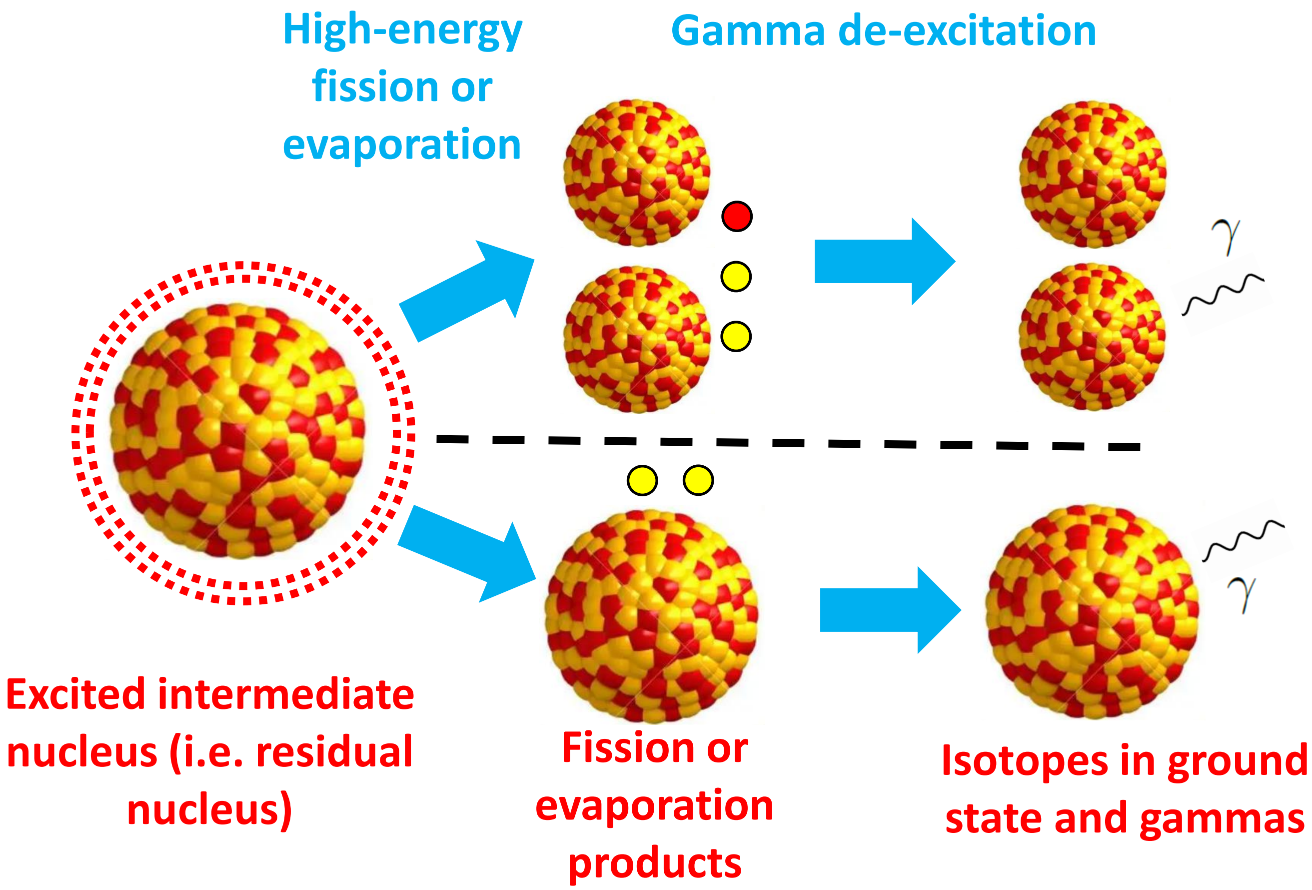


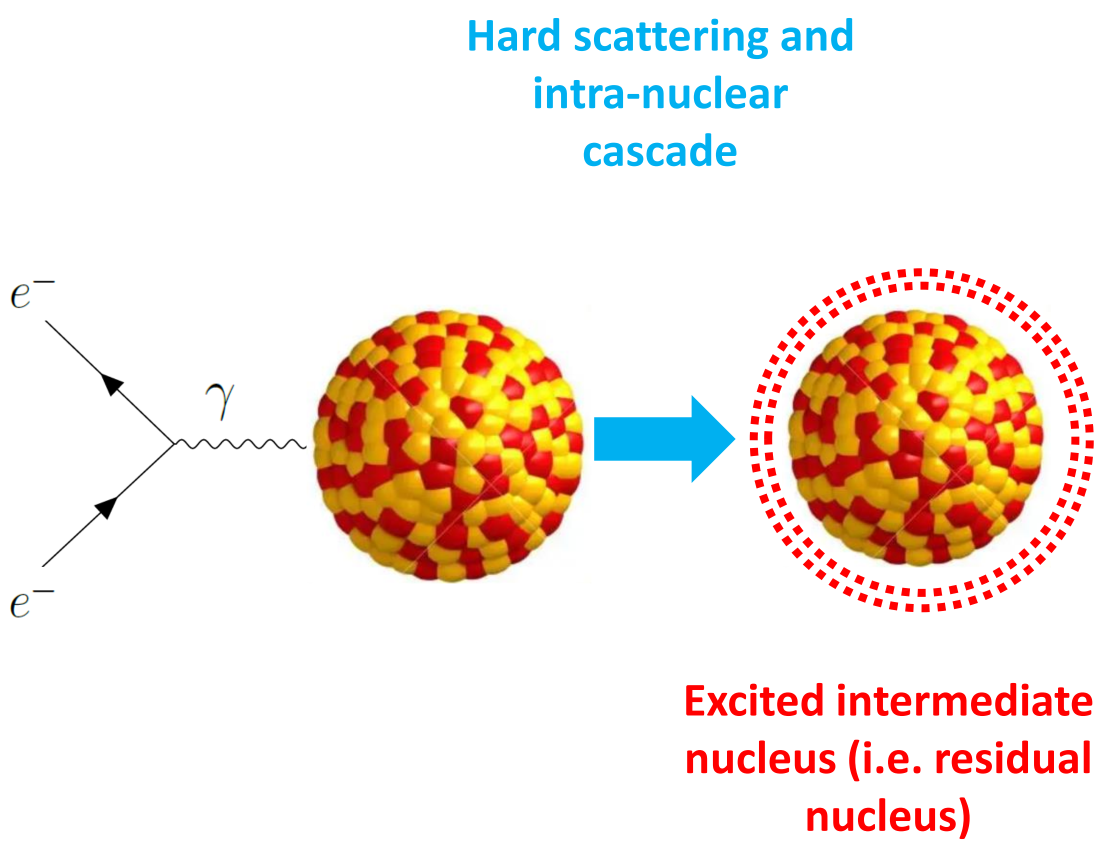
Step 2

For each event, the residual nucleus with a given A, Z, and excitation energy is then handed over to either *FLUKA* (Annals of Nuclear Energy 82, 10-18 (2015)) or ABLA07 for decay (evaporation or fission) followed by gamma de-excitation. We are left with the decay products of the residual nucleus.

FLUKA is used extensively in high-energy physics but has not been used for the study of rare isotope production. *ABLA07* is used extensively in the rare isotope community – and is the second part of the abrasion-ablation code *ABRABLA07*. We run the *BeAGLE* events though both these codes and study the results.

Production of the residual nucleus

- Using *BeAGLE*, we simulate an 18 GeV electron beam colliding with a 110 GeV/nucleon ^{238}U or ^{208}Pb beam.
- We then study the excited residual nucleus that is created following the hard scattering and intra-nuclear cascade.
- The only relevant quantities are the A and Z and excitation energy of the residual nucleus. (The residual nucleus is assumed to have zero angular momentum.)



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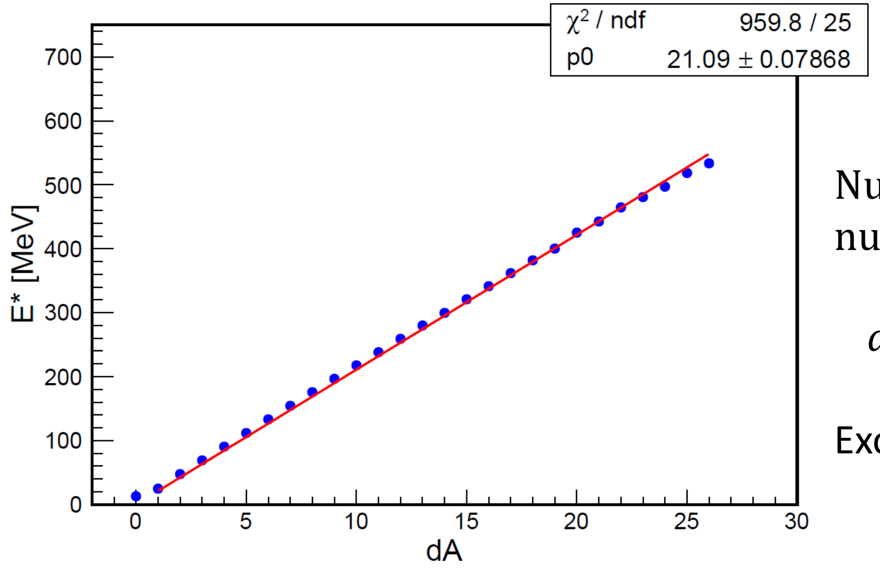
  - The excitation energy shows a linear dependence on the number of abraded nucleons.

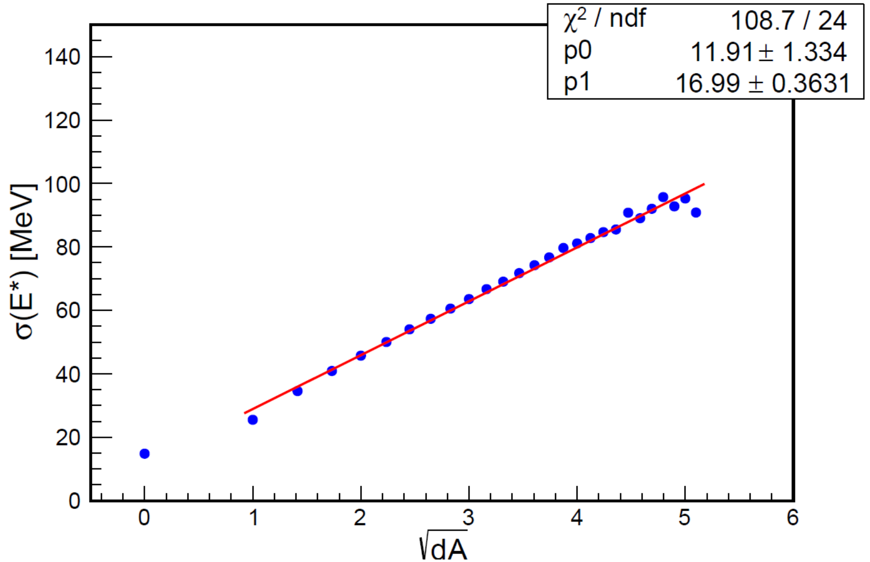
We plot the statistical mean and standard deviation here.



Number of abraded nucleons:

$$dA = A_{beam} - A_{res}$$

Excitation energy: E*



^{238}U beam

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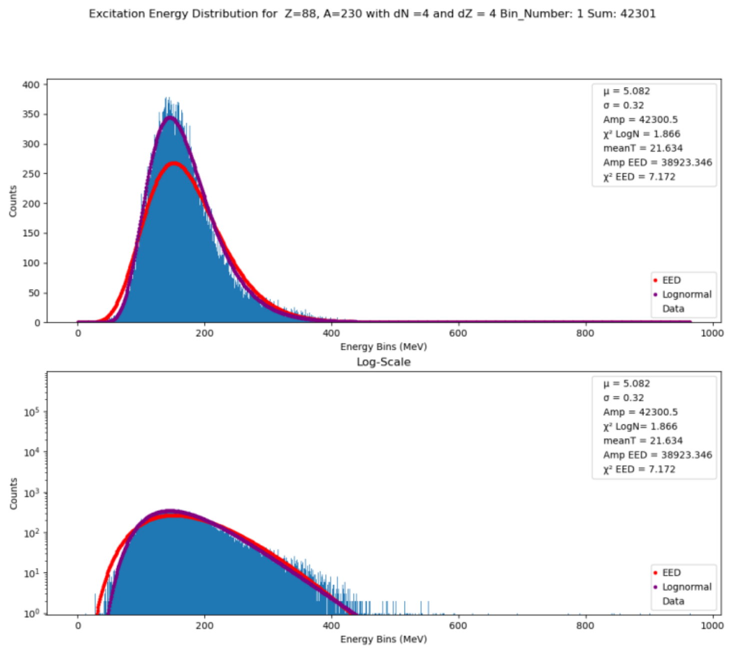

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Excitation energy: E*

The E* distribution at fixed dA may be described with a Log-normal distribution, with some dependence the relative number of protons and neutrons abraded.

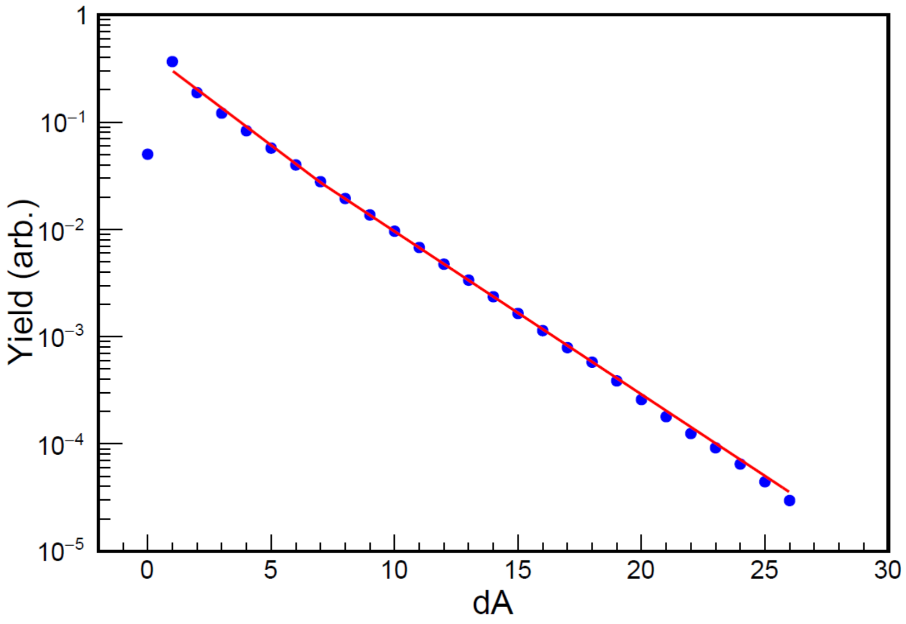
LogNorm Median / dA

Sum of Median / Row Labels	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146
92			21.9	23.4	24.1	23.4	24.4	24.3	22.9	22.9	23.1	22.9	22.9	22.6	22.2	21.5	20.8	18.8	
91		20.4	23.7	22.0	22.6	23.3	23.1	22.1	22.4	22.2	22.0	21.7	21.6	21.2	20.9	20.3	19.8	18.9	16.9
90	21.1	20.1	20.2	22.7	22.4	22.5	22.1	21.4	21.5	21.5	21.5	21.3	21.2	20.8	20.6	20.1	19.7	18.9	18.2
89	22.1	22.0	21.1	21.0	22.3	21.4	21.6	21.1	21.3	21.2	21.0	20.9	20.7	20.4	20.2	19.8	19.4	18.8	18.7
88	20.4	21.6	22.3	21.5	22.0	21.7	21.3	21.0	21.0	20.9	20.8	20.7	20.6	20.3	20.1	19.8	19.5	19.2	19.8
87	21.5	22.2	20.9	21.2	21.3	21.3	20.8	21.0	20.9	20.6	20.4	20.4	20.4	20.0	19.9	19.6	19.4	19.3	19.5
86	19.7	20.3	21.3	21.9	21.3	20.9	21.0	20.7	20.5	20.3	20.5	20.2	20.1	19.8	19.8	19.5	19.4	19.1	19.7
85	20.4	20.4	21.7	20.7	21.3	21.2	20.9	20.7	20.2	20.0	20.1	19.5	20.0	19.7	19.5	19.2	19.1	19.4	20.8
84	21.7	21.2	20.7	21.1	21.1	20.7	21.0	20.2	20.4	20.3	19.9	19.5	19.3	19.3	19.5	19.1	19.1	20.1	21.8
83	23.2	19.8	20.5	20.0	20.6	20.4	20.5	20.5	20.5	20.4	19.6	20.2	19.6	19.6	19.7	20.1	20.4	19.5	18.8
82	19.3	19.1	21.2	20.4	20.6	20.4	20.8	20.2	20.4	20.5	20.5	20.2	20.0	19.8	19.5	20.0	19.1	19.7	
81	20.9	19.3	20.6	19.3	19.4	20.1	19.1	20.2	20.4	20.3	19.7	20.1	19.6	18.3	17.9	18.3	18.1	17.6	
80		21.1	21.3	20.6	19.1	20.3	20.2	19.0	20.5	20.2	19.1	20.5	19.9	20.0	18.4	20.1	18.9		

^{238}U beam

Production of the residual nucleus

- We find that the production of the residual nucleus in *BeAGLE* manifests as a very simple abrasion model:
  - The excitation energy shows a linear dependence on the number of abraded nucleons.
  - The cross section for abrading a given number of nucleons (for dA>1) shows a (piecewise) exponential dependence.



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^{238}U beam

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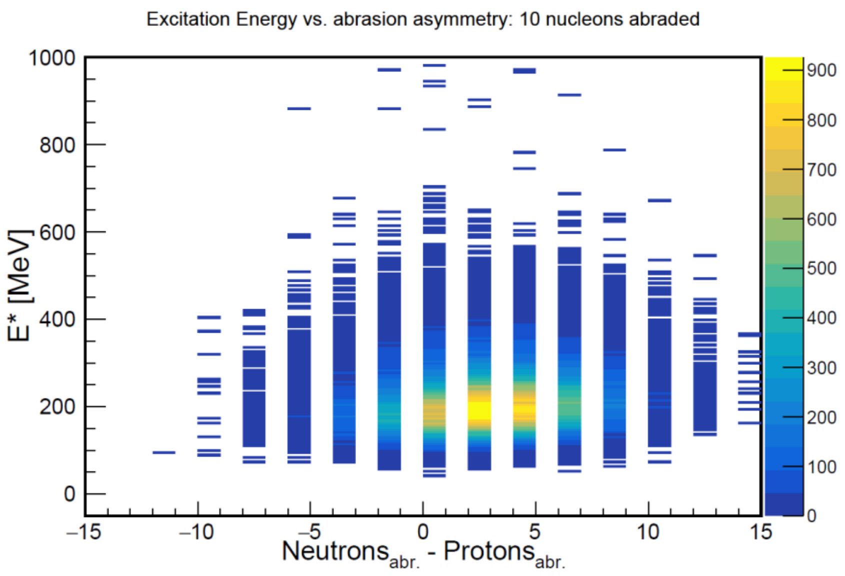
  - For a given number of abraded nucleons, the relative proportion of neutrons and protons abraded is based on simple combinatorics.



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^{238}U beam

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Note: The observed simple abrasion model comes out of *BeAGLE* 'naturally'. The simulation uses an intra-nuclear cascade model and a nuclear potential model to determine the A, Z and excitation energy of the residual nucleus. The ground state mass model comes from *FLUKA*.

Intra-nuclear cascade hadron formation time:

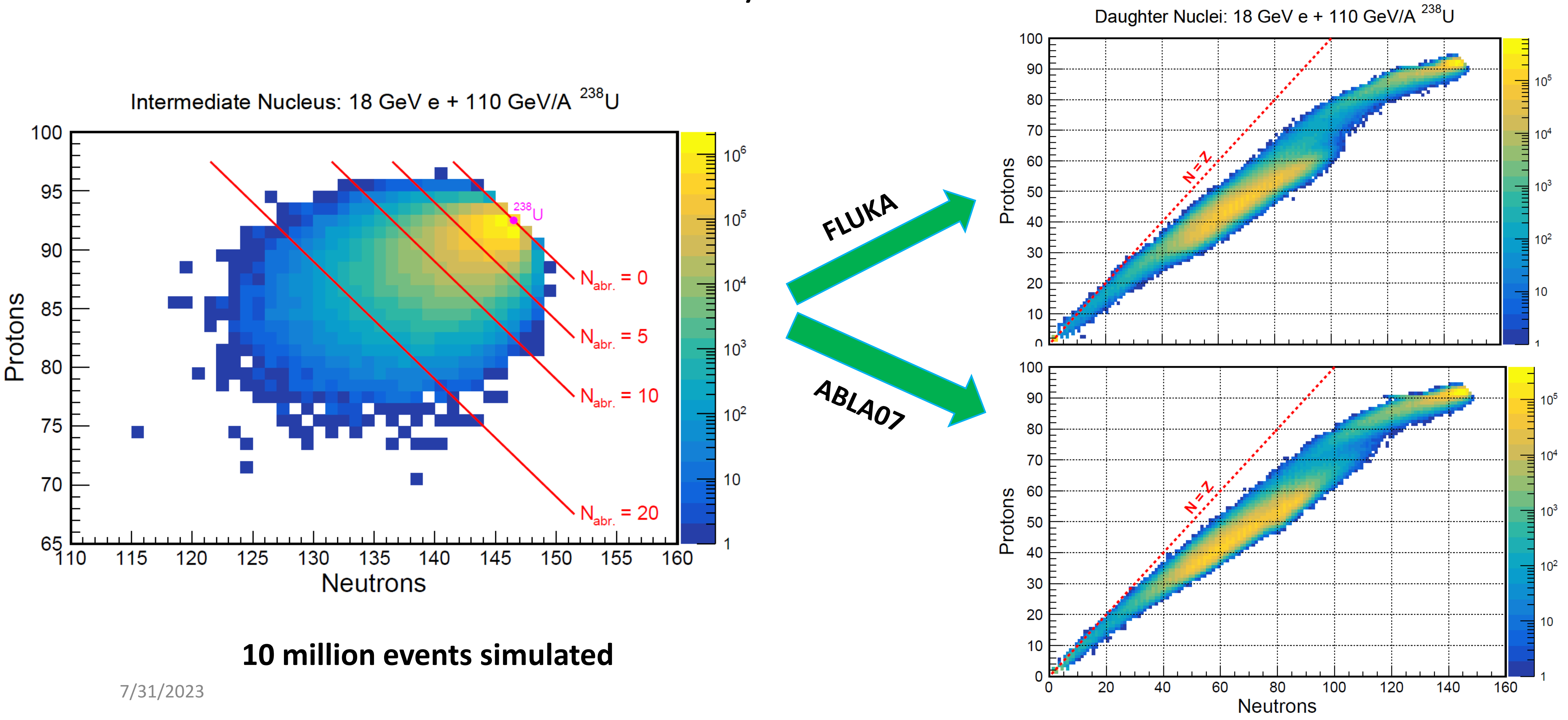
$$\tau_{Lab} = \tau_0 \frac{E_s}{m_s} \frac{m_s^2}{m_s^2 + p_{s\perp}^2}$$

Mass (excitation energy) of the residual nucleus:

$$(E_{res}, \mathbf{p_{res}}) = (M_A, \mathbf{0}) - \sum_{i=1}^{N_w} (E_i^F, \mathbf{p_i^F}) + (E_{rec}, \mathbf{p_{rec}})$$

Z.Phys. C70 (1996) 413-426   Z. Phys. C 71, 75-86 (1996)

We can then decay the residual nucleus



10 million events simulated

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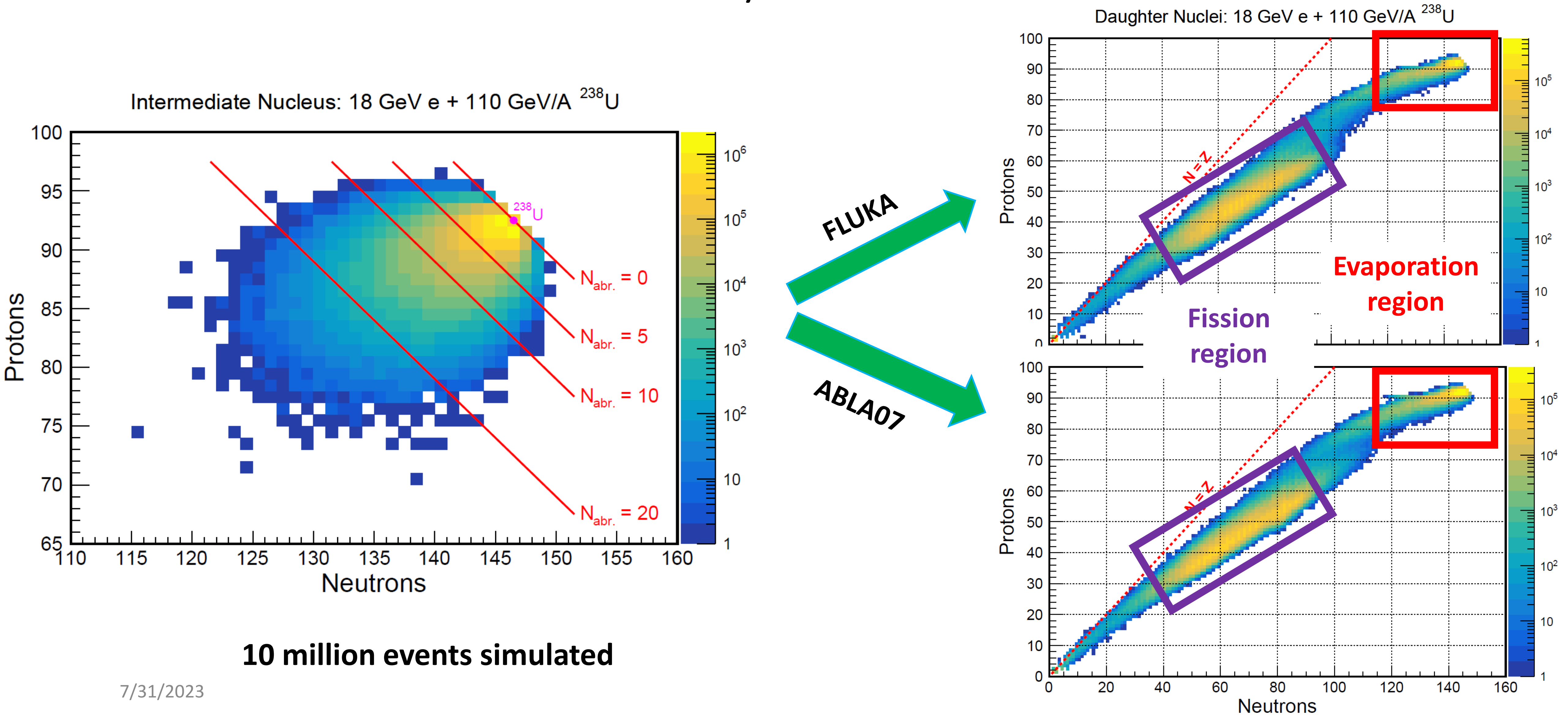
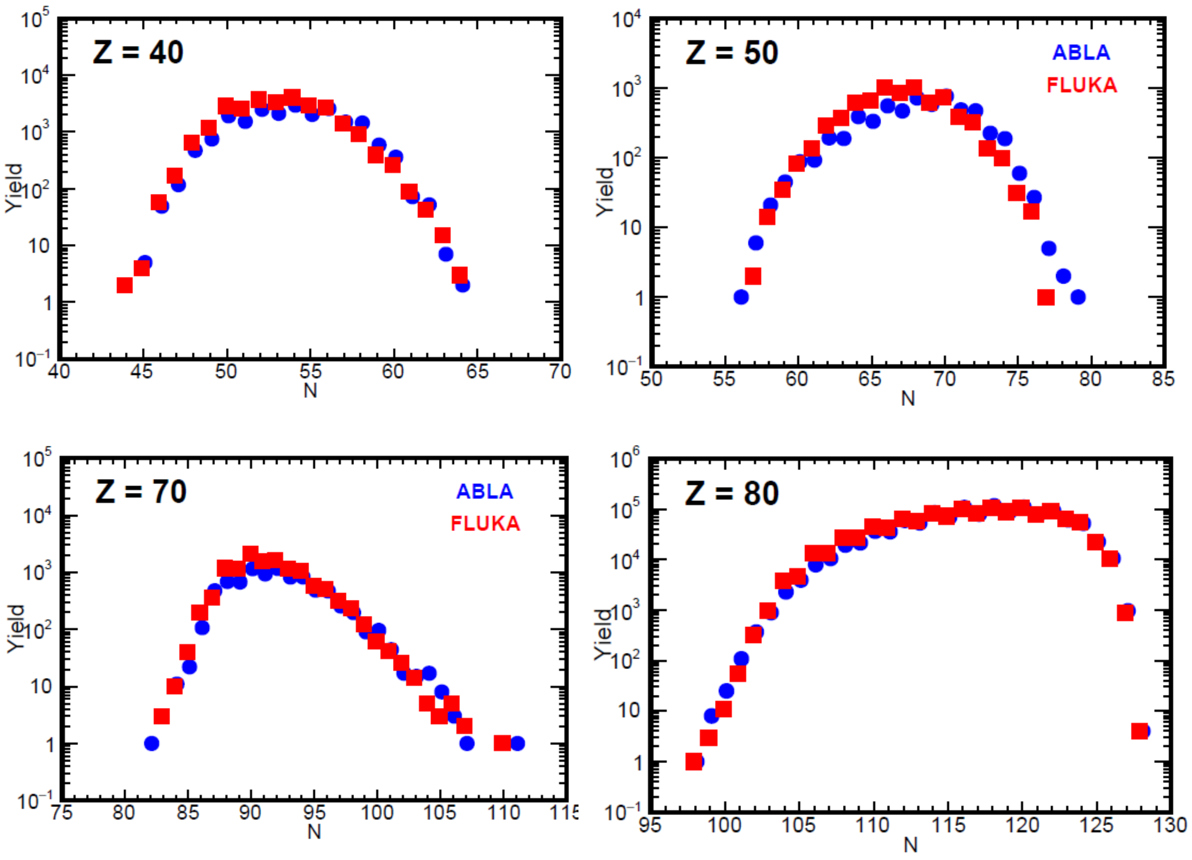


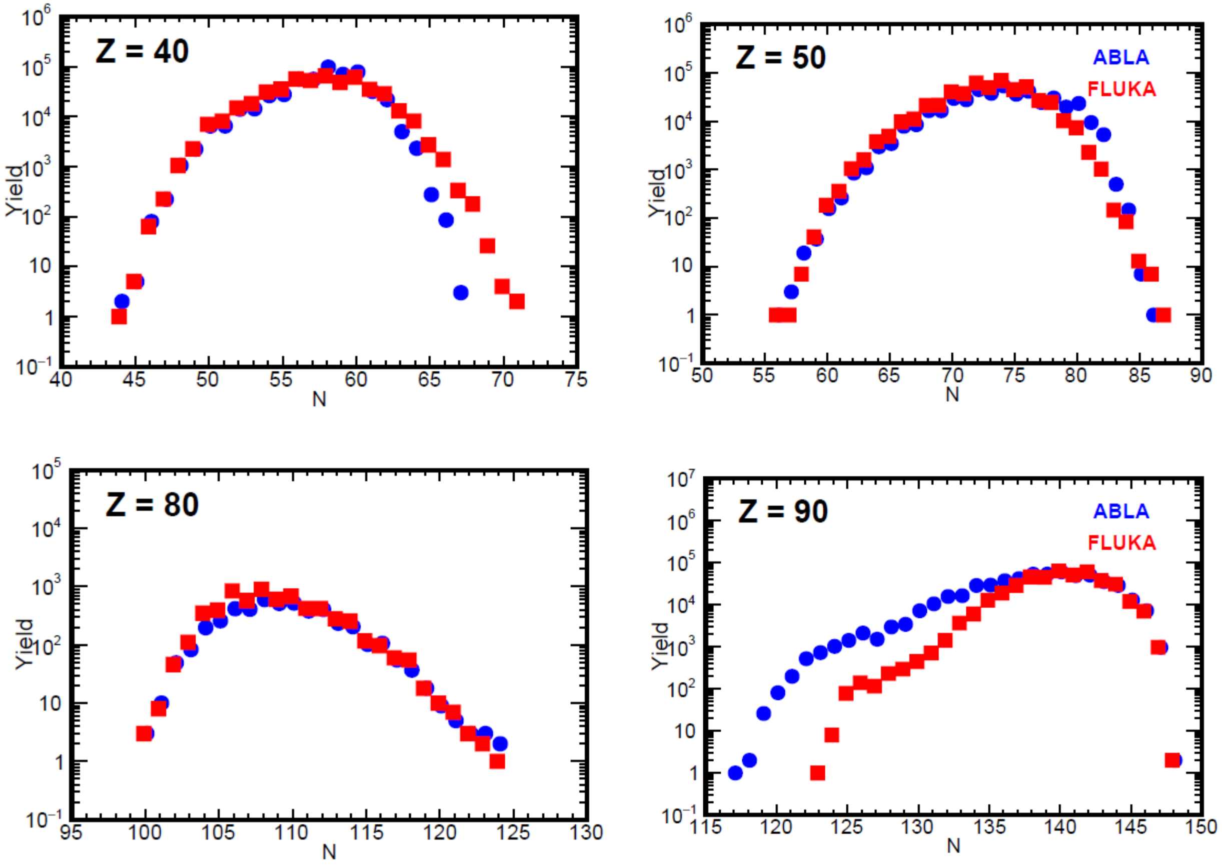
10 million events simulated

FLUKA and *ABLA07* are largely in agreement about EIC production rates

^{208}Pb

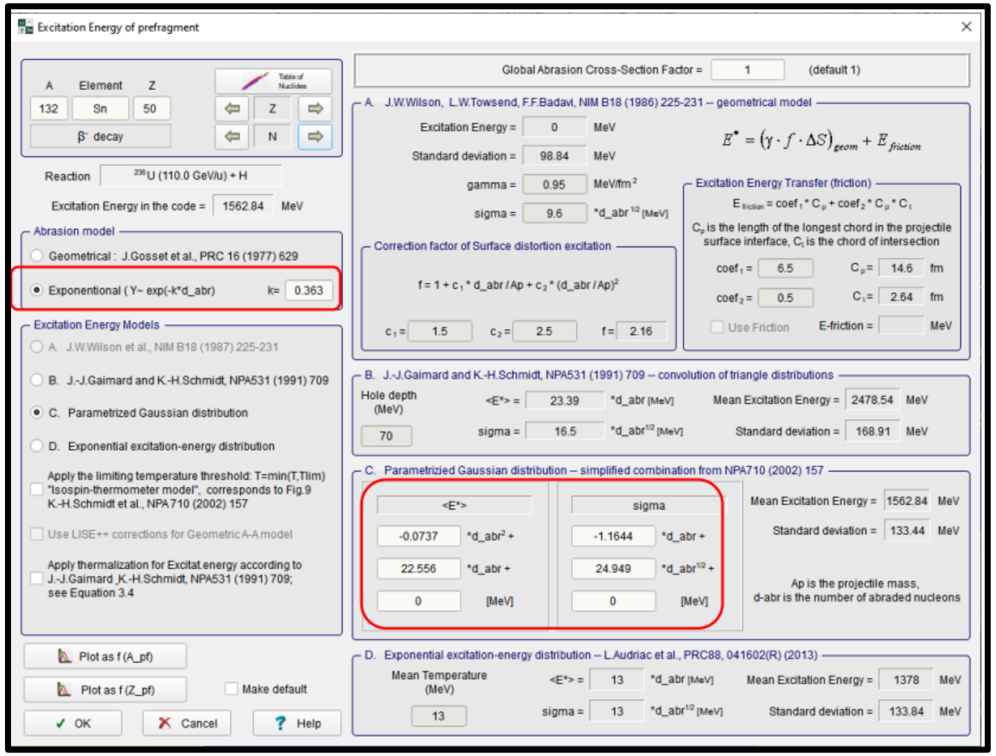


^{238}U



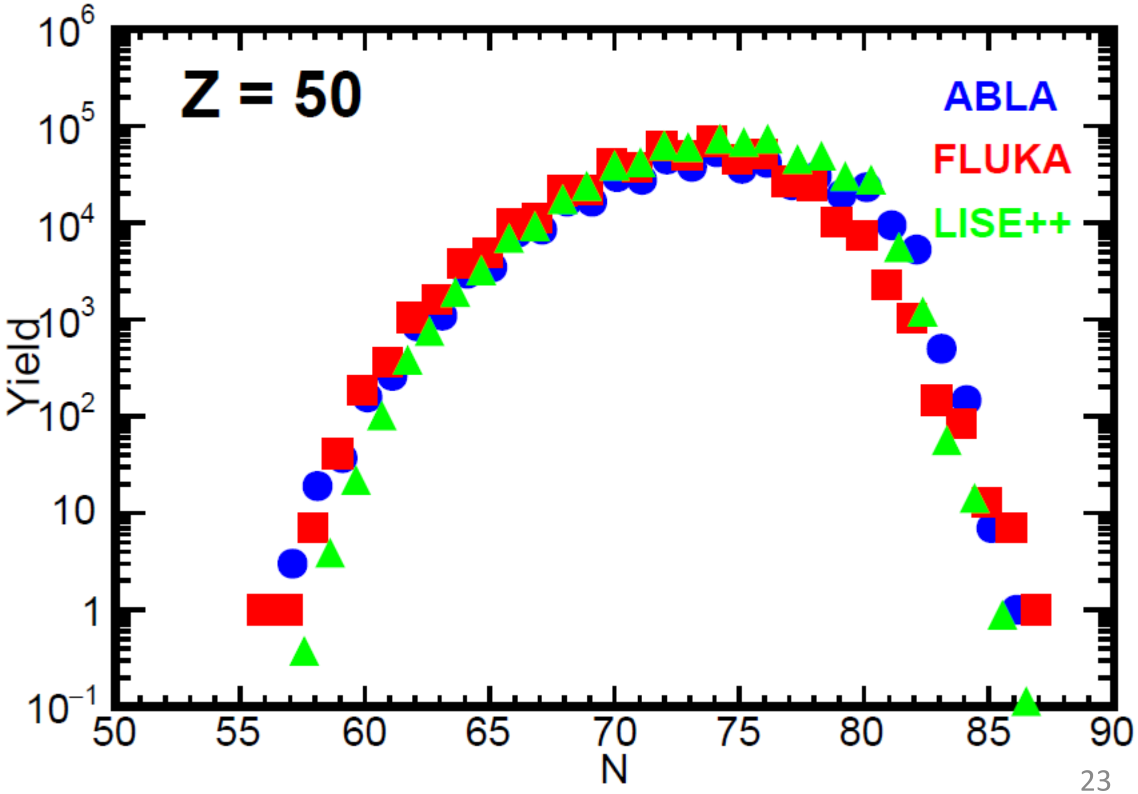
Fission fragment production can also be studied with *LISE++*

Based on *BeAGLE* findings above, an Exponential Abrasion Model has been implemented in *LISE++*:



Comparison of different models:

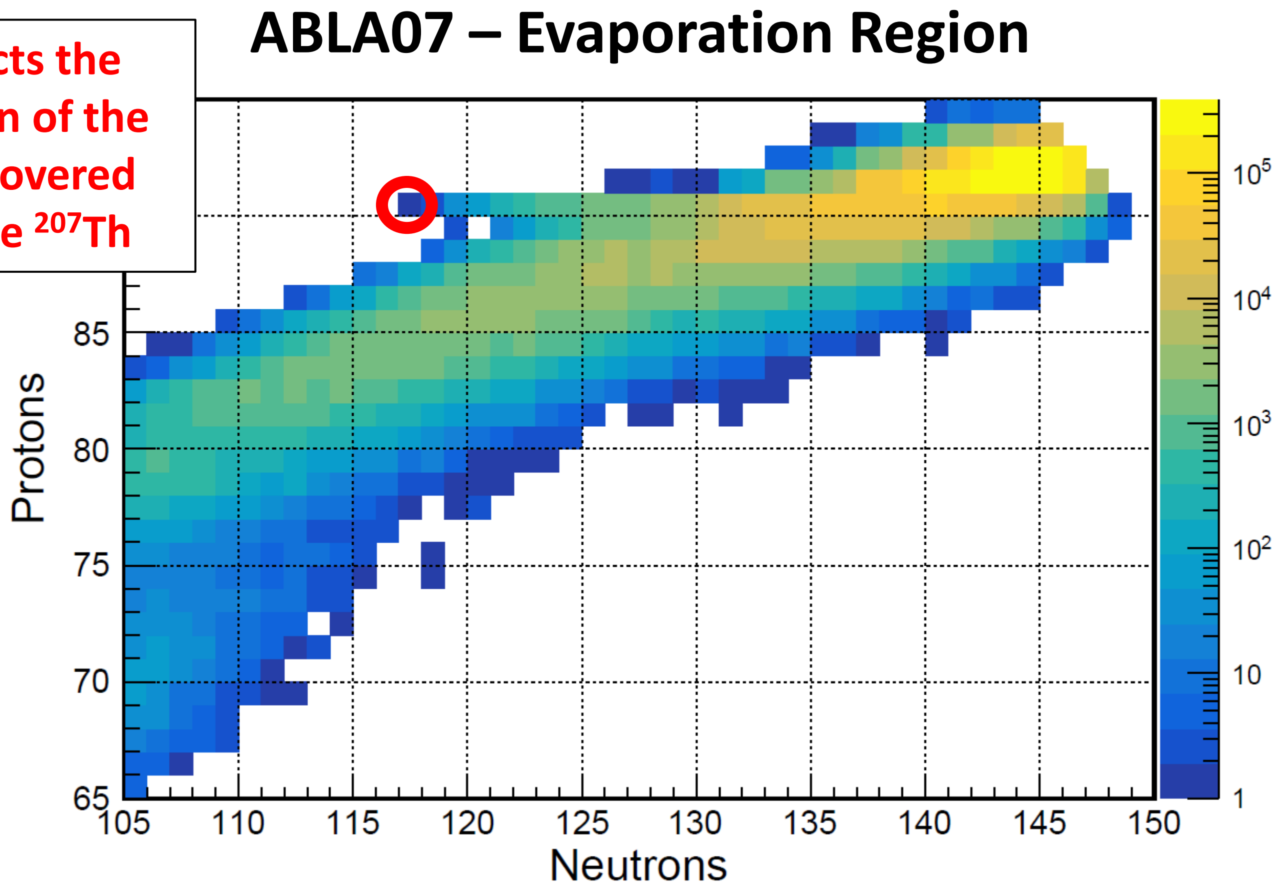
^{238}U beam



Using our small simulation sample, we see hints of interesting physics

Production of new neutron-deficient isotopes in the Z=89-94 range. Advantages over RIB facilities due to short flight time and possibly higher production cross section.

Predicts the creation of the undiscovered isotope ^{207}Th



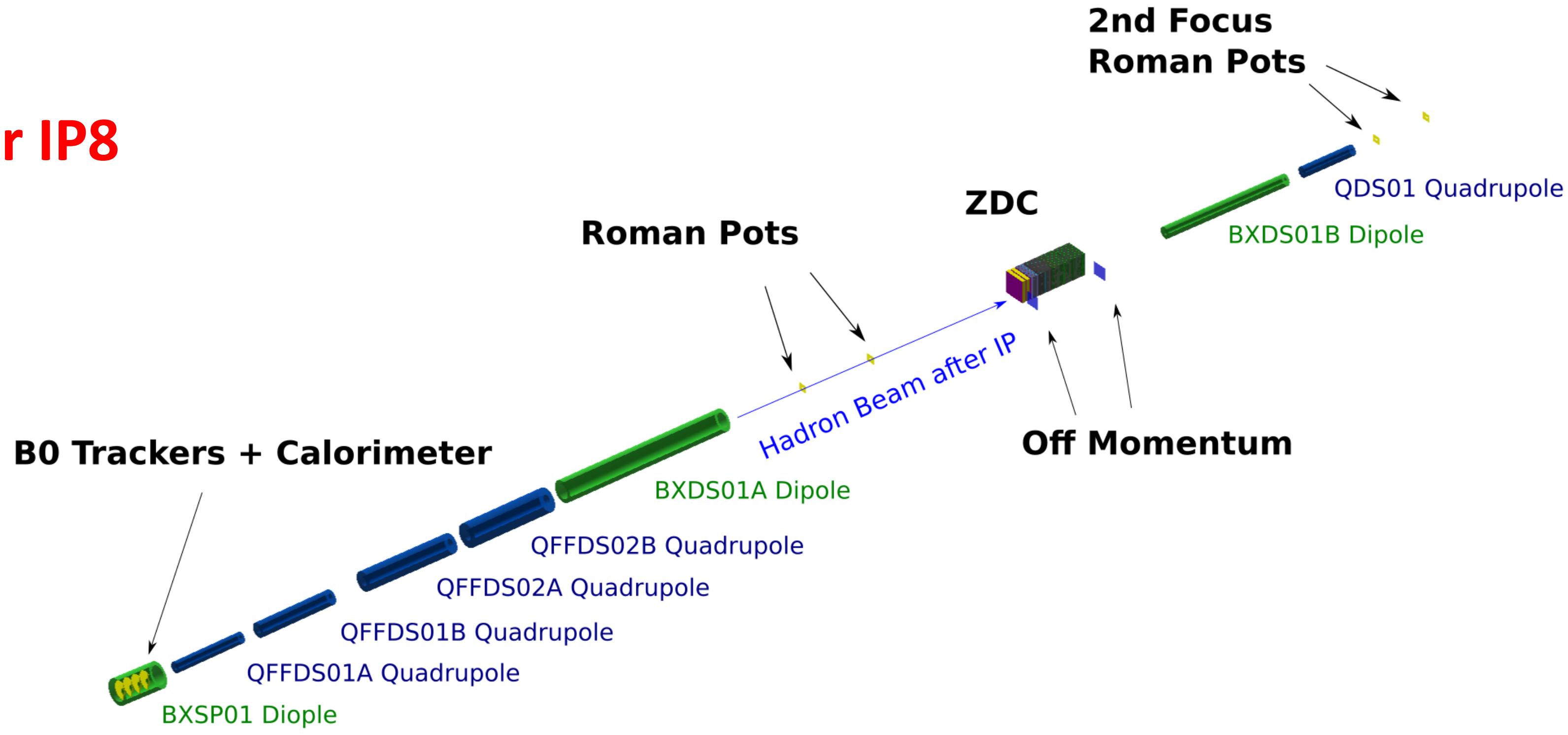
We need to simulate many more events to model the production rates at the EIC; or use LISE++ for an analytical approach

Detection of nuclear fragments

EIC Detectors – far-forward region

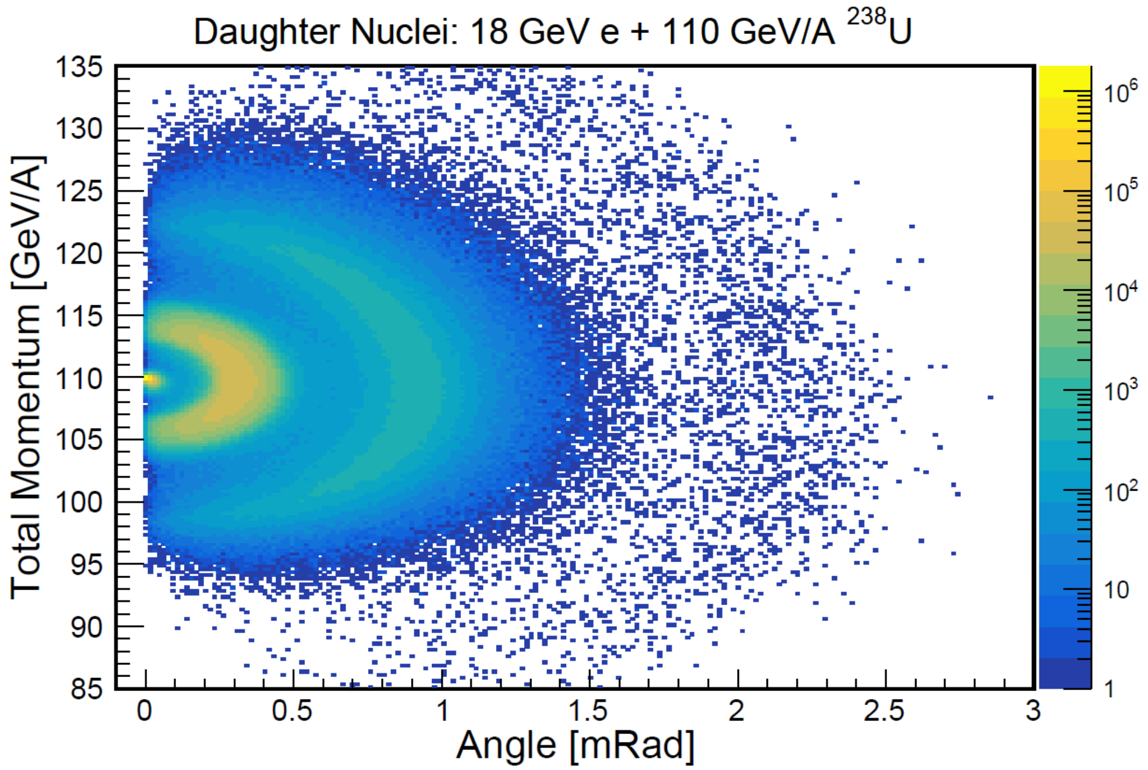
Conceptual design for IP8

doi:10.2172/1765663

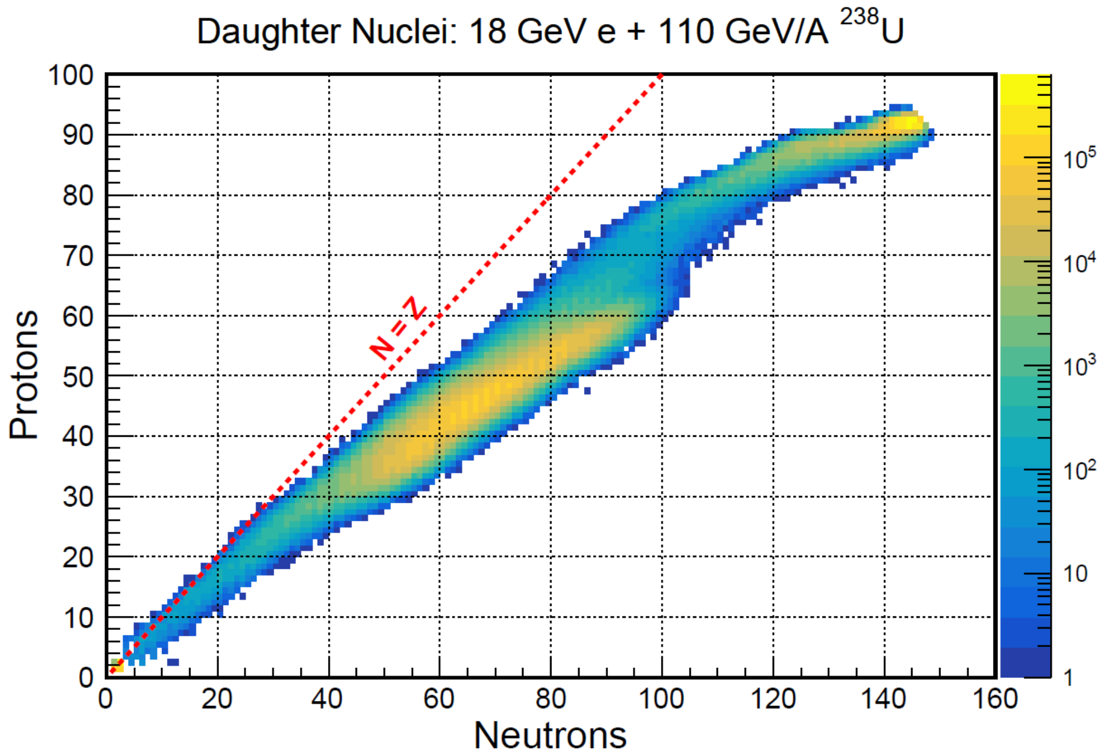


- ❑ The nuclear fragments can be measured using detectors in the (second set of) Roman Pots (RP) – two tracking planes to measure local positions and angles.
- ❑ Gamma rays can be detected using the Zero-Degree Calorimeter (ZDC).

Kinematics of produced nuclear fragments

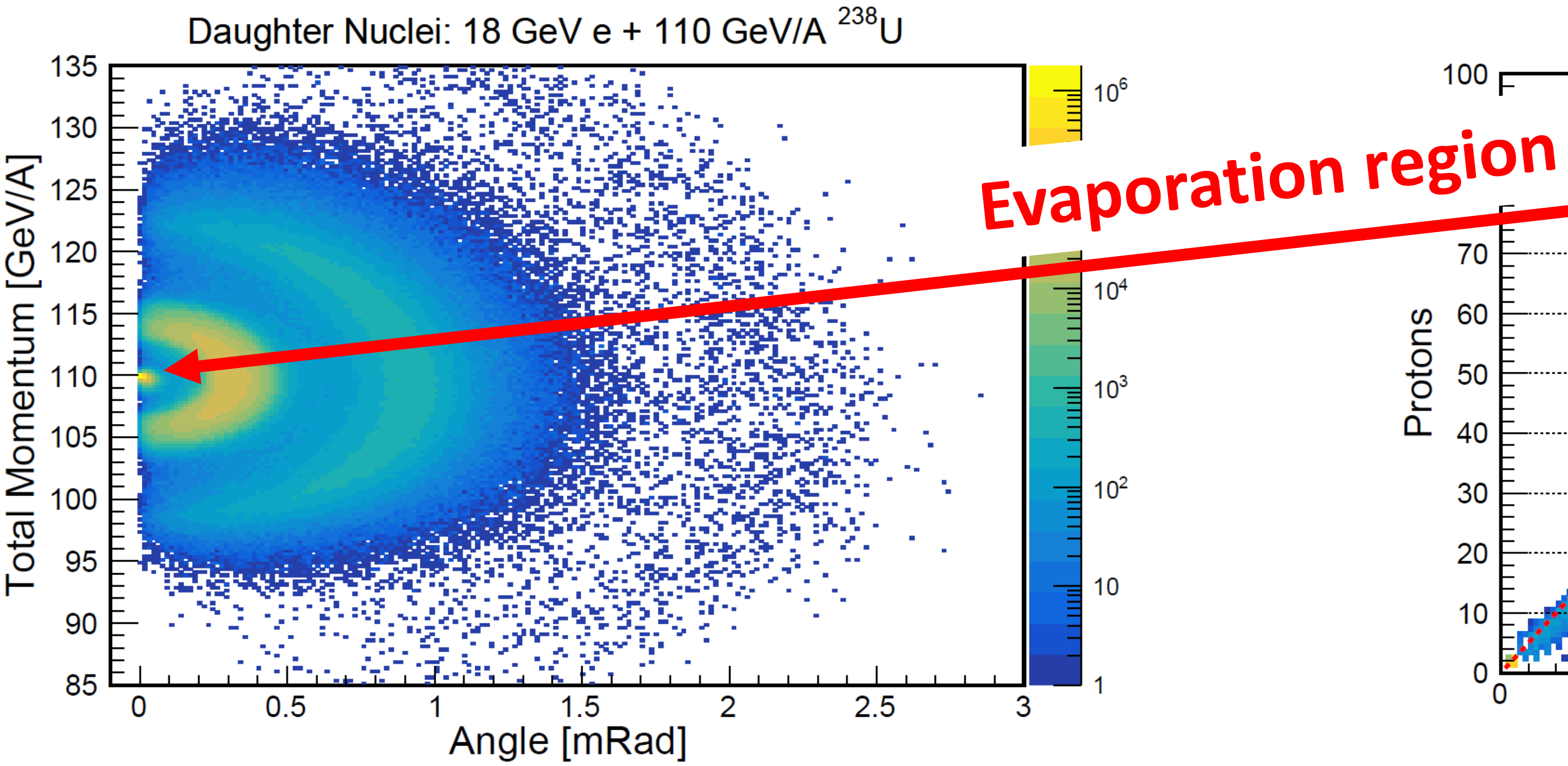


(with respect to incoming ^{238}U beam)



BeAGLE + FLUKA

Kinematics of produced nuclear fragments



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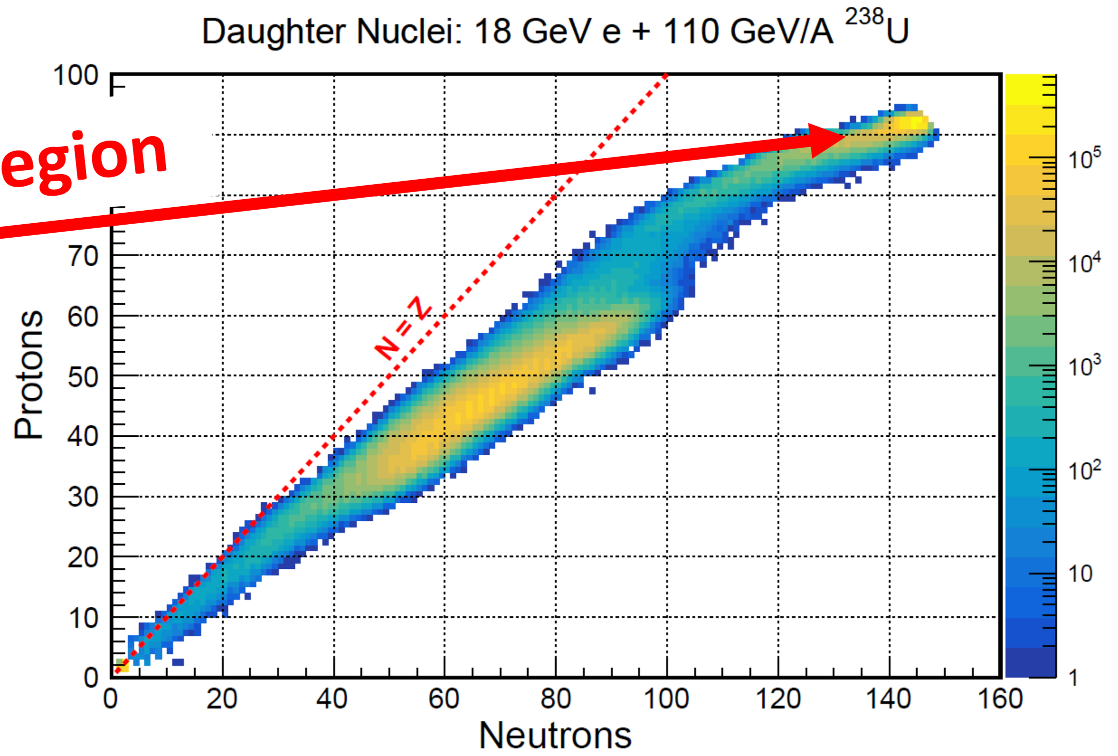
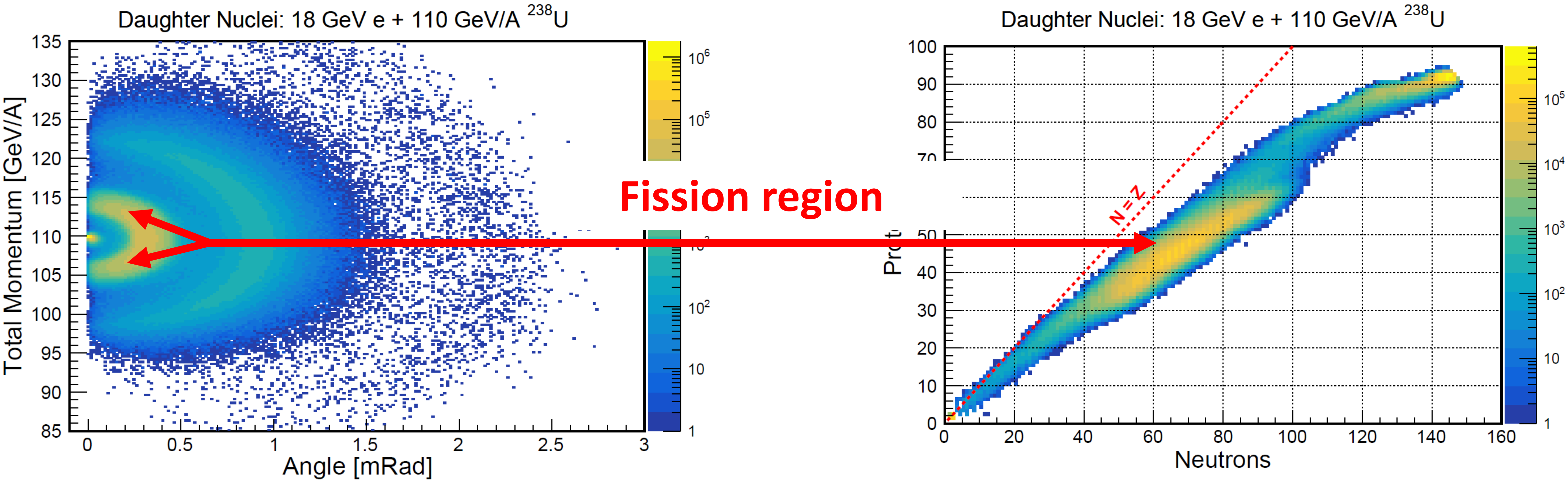


Fragments are produced parallel to beam with same momentum per nucleon.

BeAGLE + FLUKA

Kinematics of produced nuclear fragments

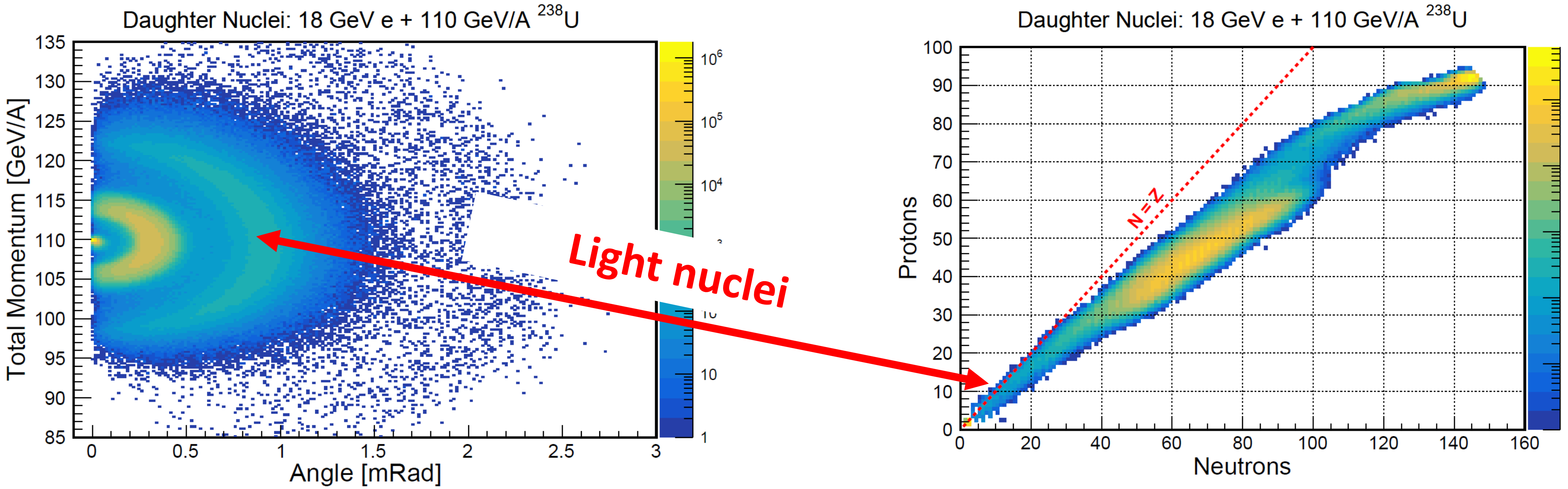


(with respect to incoming ^{238}U beam)

One fragment will be ‘upshifted’ and the other ‘downshifted’. Both fission fragments can be registered in coincidence.

BeAGLE + FLUKA

Kinematics of produced nuclear fragments



(with respect to incoming ^{238}U beam)

Fermi breakup and light nuclei from evaporation

BeAGLE + FLUKA

Principle of detection – rigidity measurement

At first approximation the momentum-per-nucleon of the outgoing fragment (p_N) is the same as the momentum-per-nucleon of the incoming beam ($p_{N,beam}$).

$$x_L = \frac{R}{R_{beam}} = \left[\left(\frac{A p_N}{z}\right) \Big/ \left(\frac{A_{beam} p_{N,beam}}{z_{beam}}\right) \right]$$

$$= \left[\left(\frac{A}{z}\right) \Big/ \left(\frac{A_{beam}}{z_{beam}}\right) \right]$$

Measurement of rigidity (x_L) determines the fragment A/Z ratio

Some definitions

- $Fragment\ Rigidity\ (R) = \frac{p}{Z}$
- $x_L = \frac{R}{R_{beam}}$
- $Relative\ Rigidity\ (R_{Rel}) = \frac{R - R_{beam}}{R_{beam}} = x_L - 1$

Principle of detection – rigidity measurement

The hit position at the Roman Pot (RP) detectors in the dispersive direction:

$$x_{RP} = D_x(-R_{Rel}) = D_x(1 - x_L)$$

Minimum allowed hit position at the RPs to exclude beam envelope:

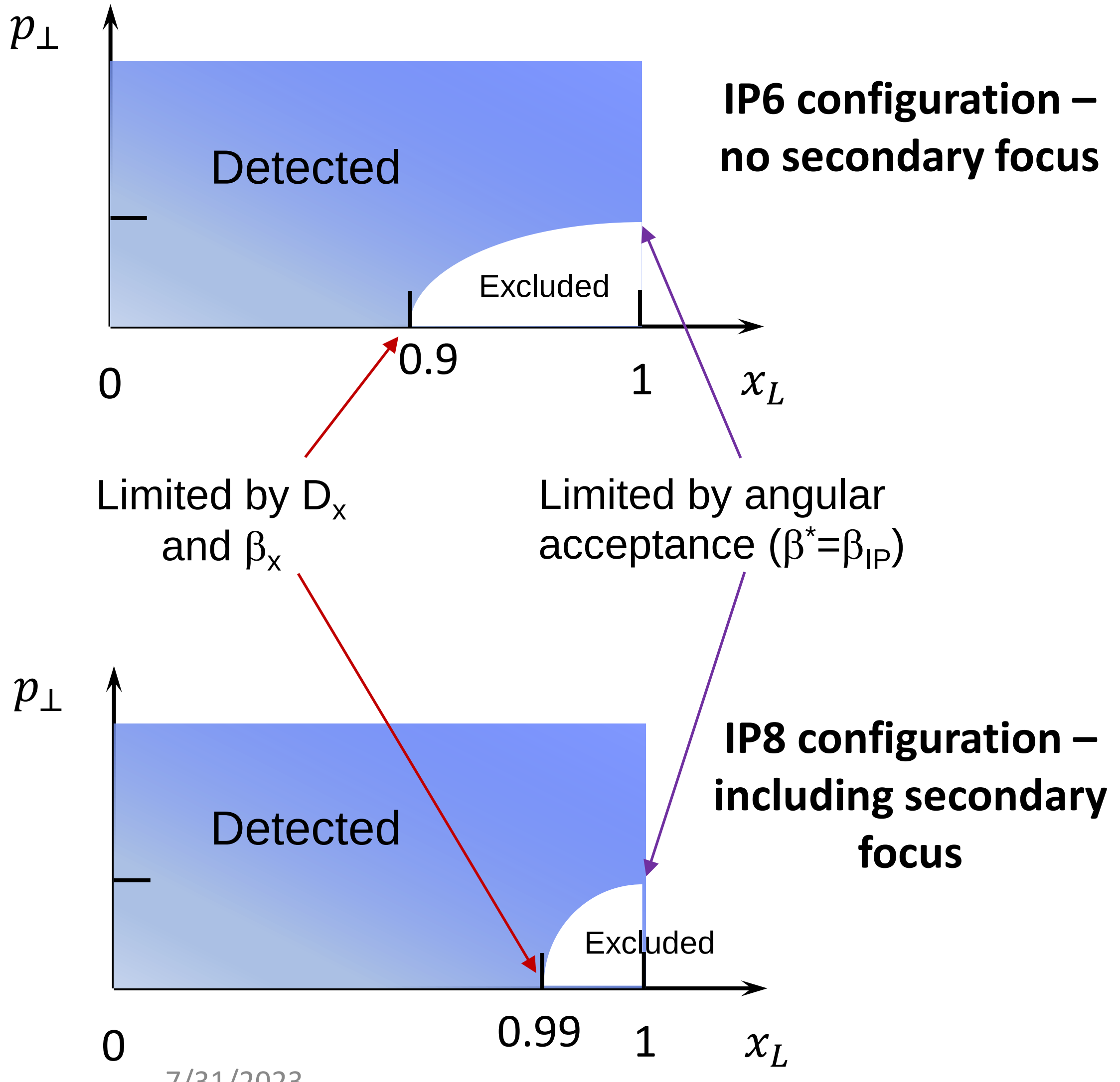
$$x_{RP}^{min} = 10\sigma_x = 10\sqrt{\beta_x \varepsilon_x + D_x^2 \sigma_p^2}$$

Additional definitions

- At Roman Pots:
  - Dispersion (D_x)
  - Beta Function (β_x)
- Accelerator parameters (EIC CDR Table 3.5):
  - Beam Emittance (ε_x) $= 43.2\ nm$
  - Momentum spread (σ_p) $= 6.2 \times 10^{-4}$

doi:10.2172/1765663

Acceptance for fragments in IP6 and IP8



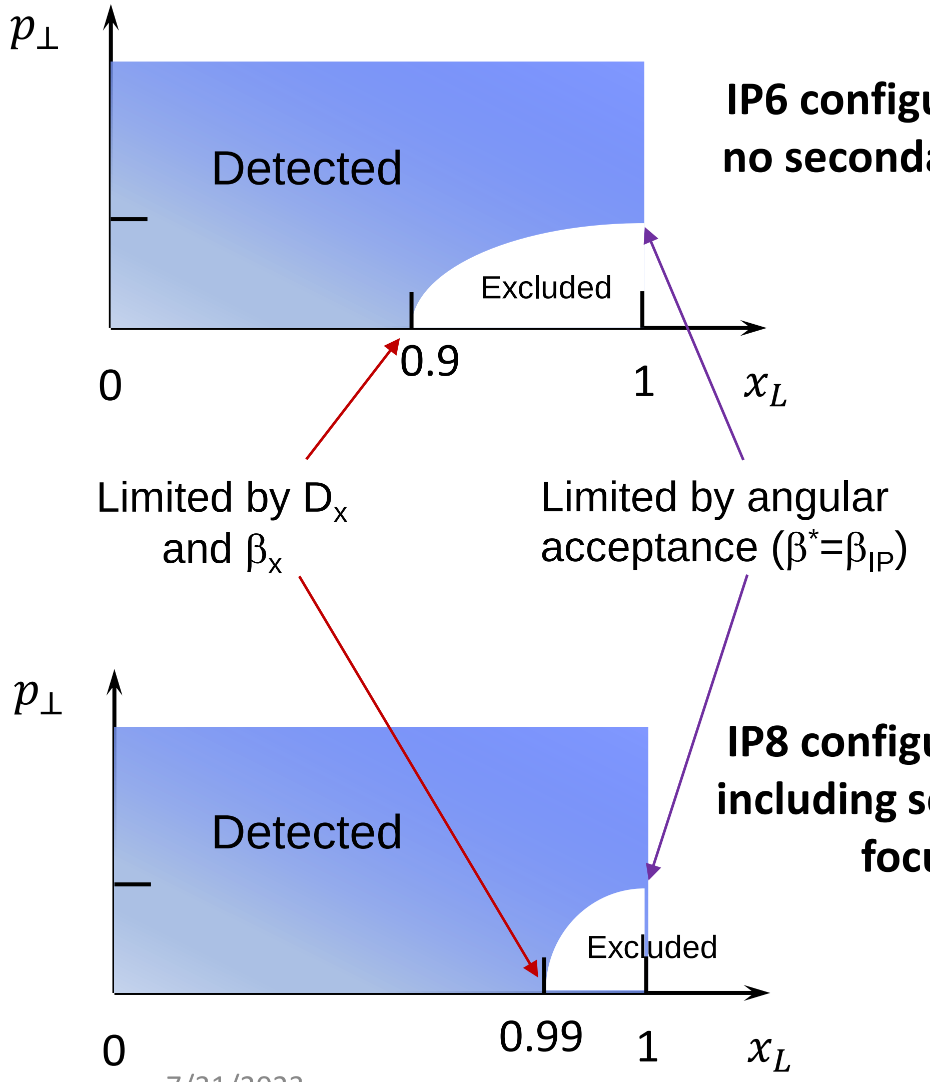
IP6 acceptance at first RP (using the high-divergence 10x100 GeV shifted lattice):

$$\beta_x = 865\ m$$
$$D_x = 16.7\ cm$$
$$\rightarrow\ x_{RP1}^{min} = 6.11\ cm$$

IP8 acceptance at first RP:

$$\beta_x = 2.28\ m$$
$$D_x = 38.2\ cm$$
$$\rightarrow\ x_{RP1}^{min} = 0.39\ cm$$

Acceptance for fragments in IP6 and IP8



IP6 configuration – no secondary focus

IP8 configuration – including secondary focus

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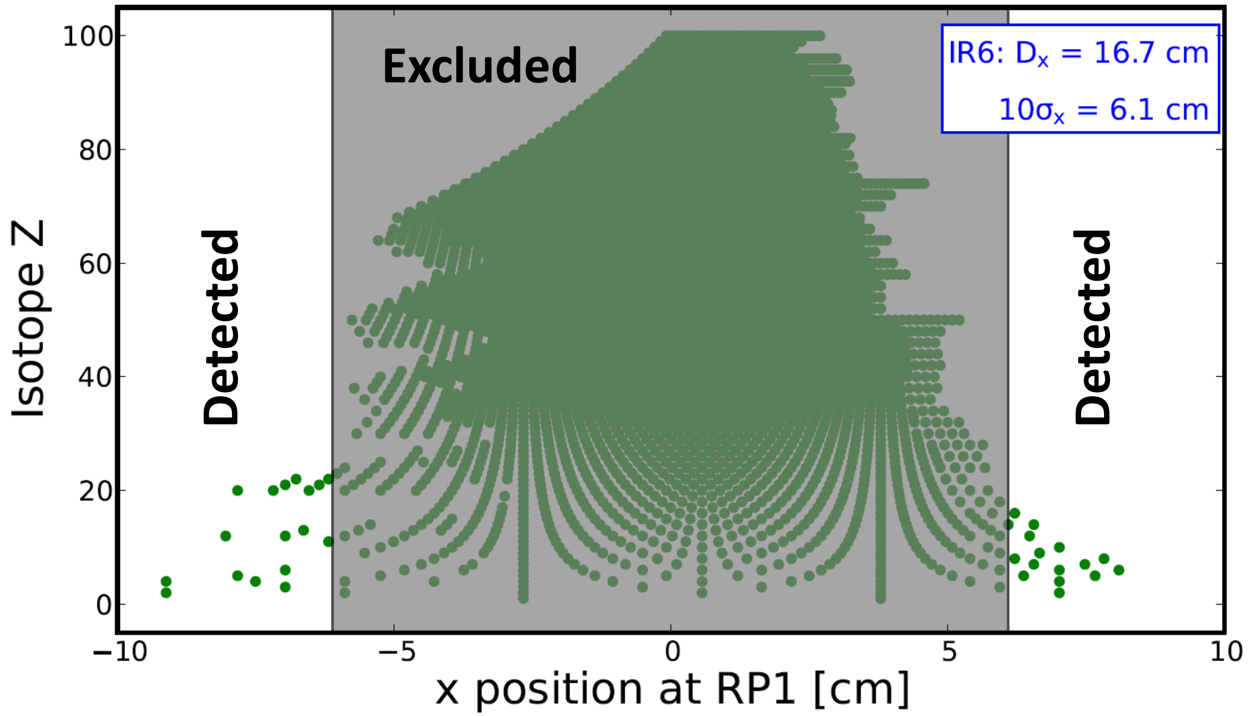
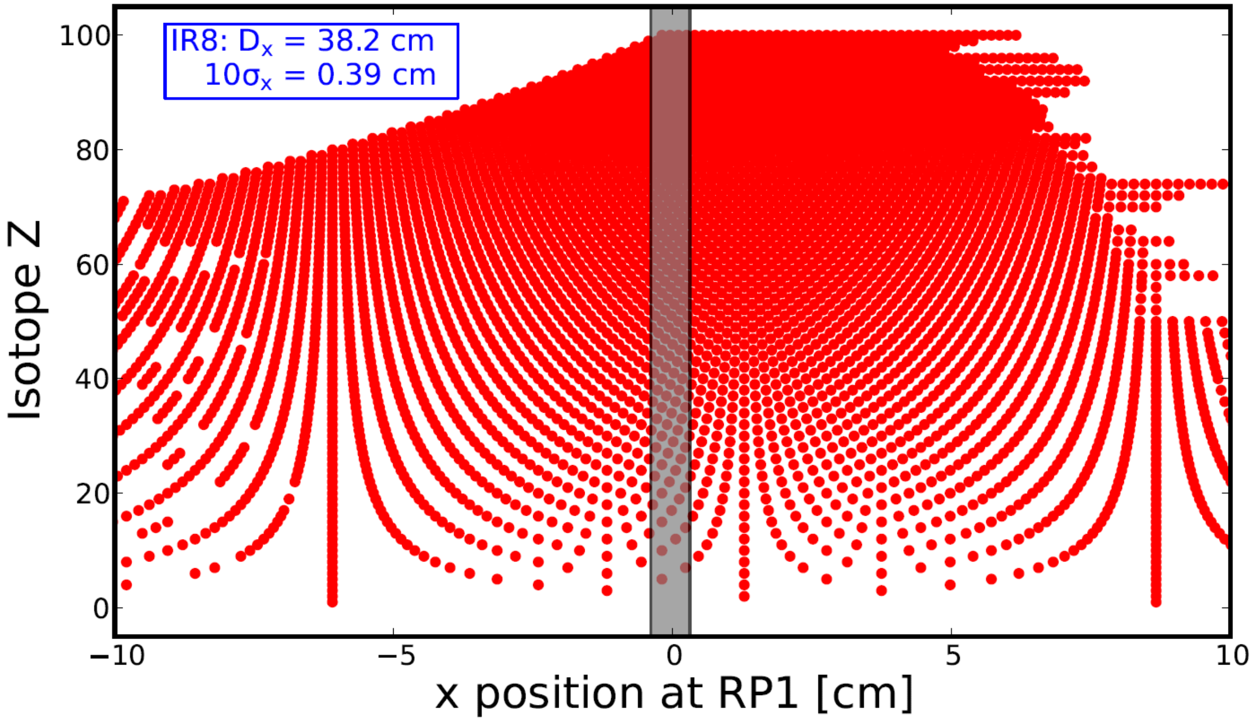
Acceptance for fragments in IP6 and IP8

IP6



IP8

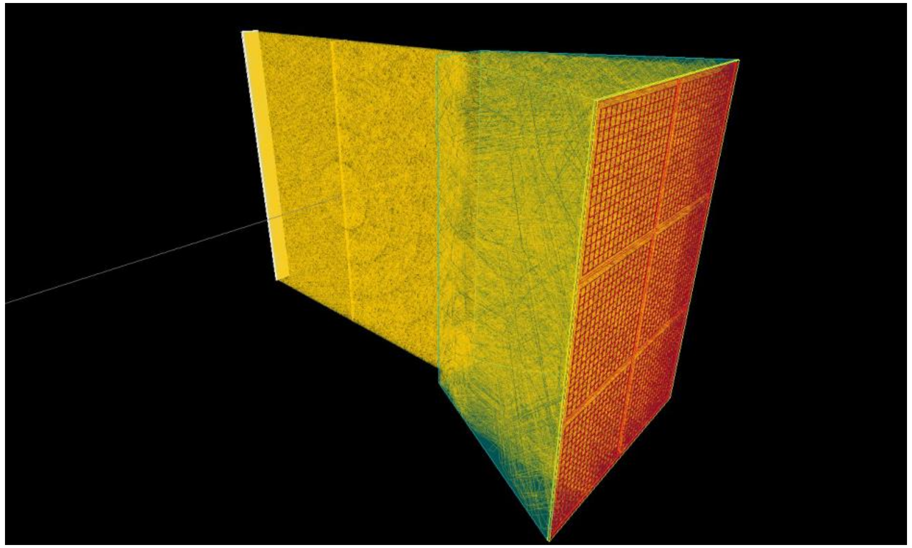


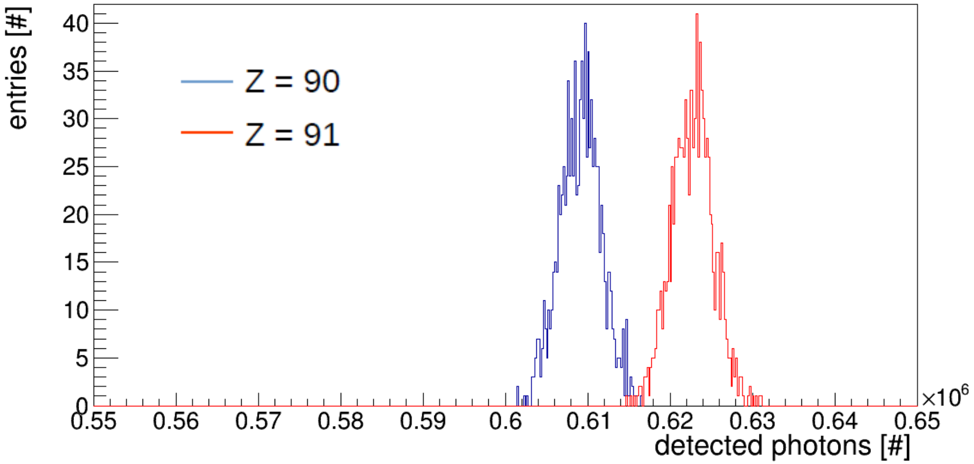
Each point is an individual isotope. All known and potential isotopes which come from a combined *NNDC* and *LISE++* database are included.

Assuming a RP position resolution of 10-100 microns, isotopes with the same Z are well separated.

Full reconstruction of the fragments

1. **The charge of the isotope (Z) must be determined.** This can potentially be done using a thin (few mm thick) quartz bar placed inside the RP (behind the tracker) at the second focus. The quartz bar would be perpendicular to the beam, extended along the dispersive (x) direction. The number of Cherenkov photons produced will be quite large (proportional to Z^2).
2. **In the fission region, the outgoing isotopes do not have the same momentum-per-nucleon as the ion beam.** This can be corrected for by measuring the angles at the RP detectors and registering both fission fragments in coincidence.

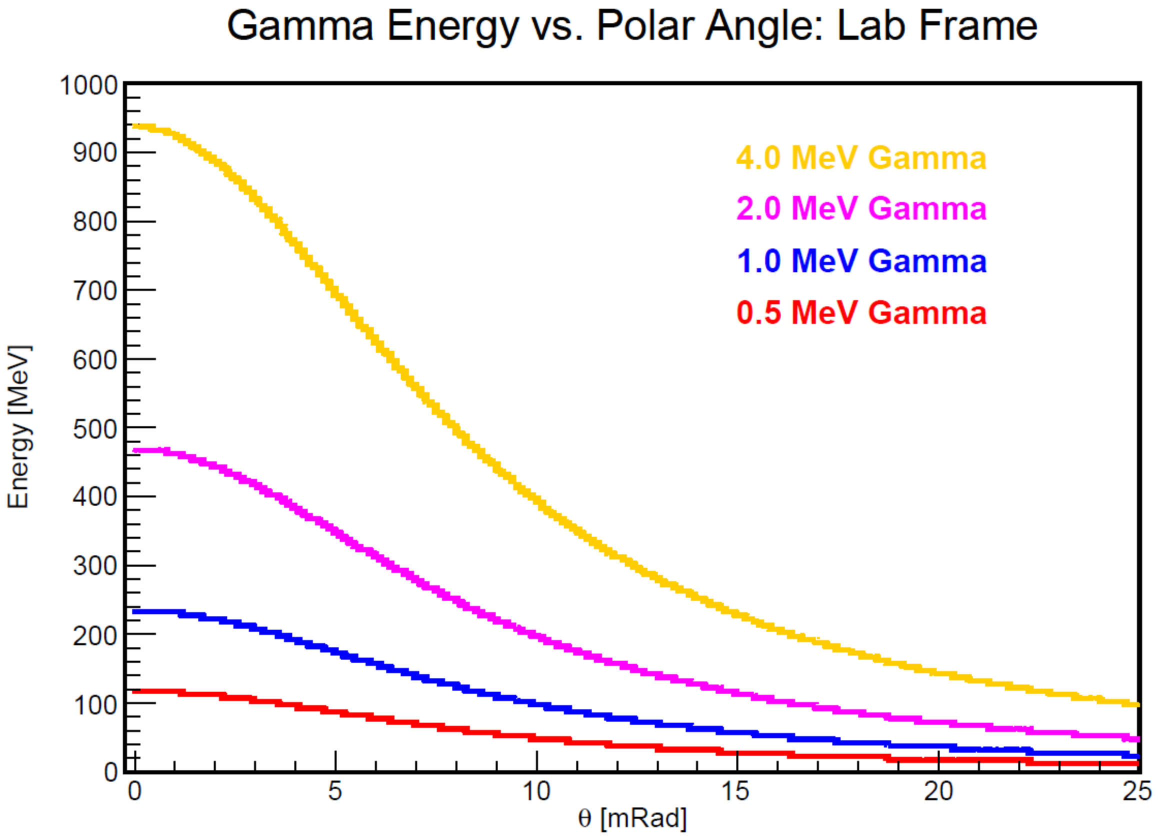




Simulation by Roman Dzhygadlo

Detection of gamma rays

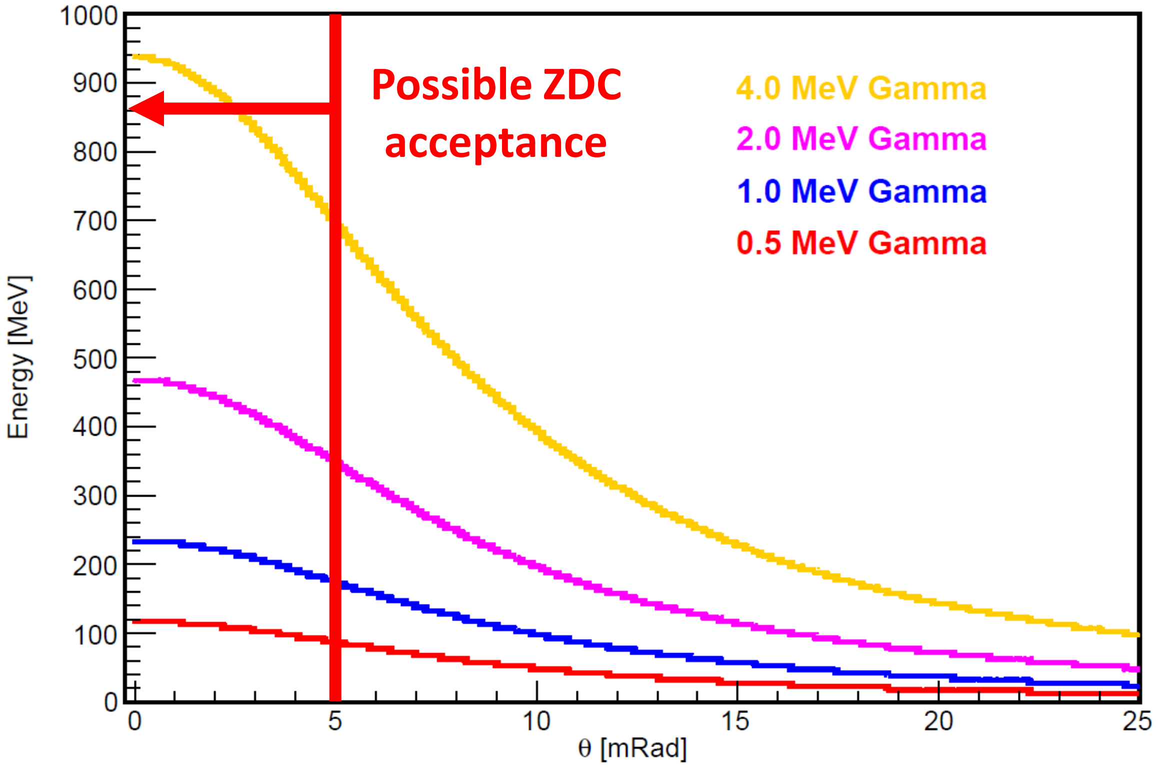
Single gamma simulation – 110 GeV/A beam



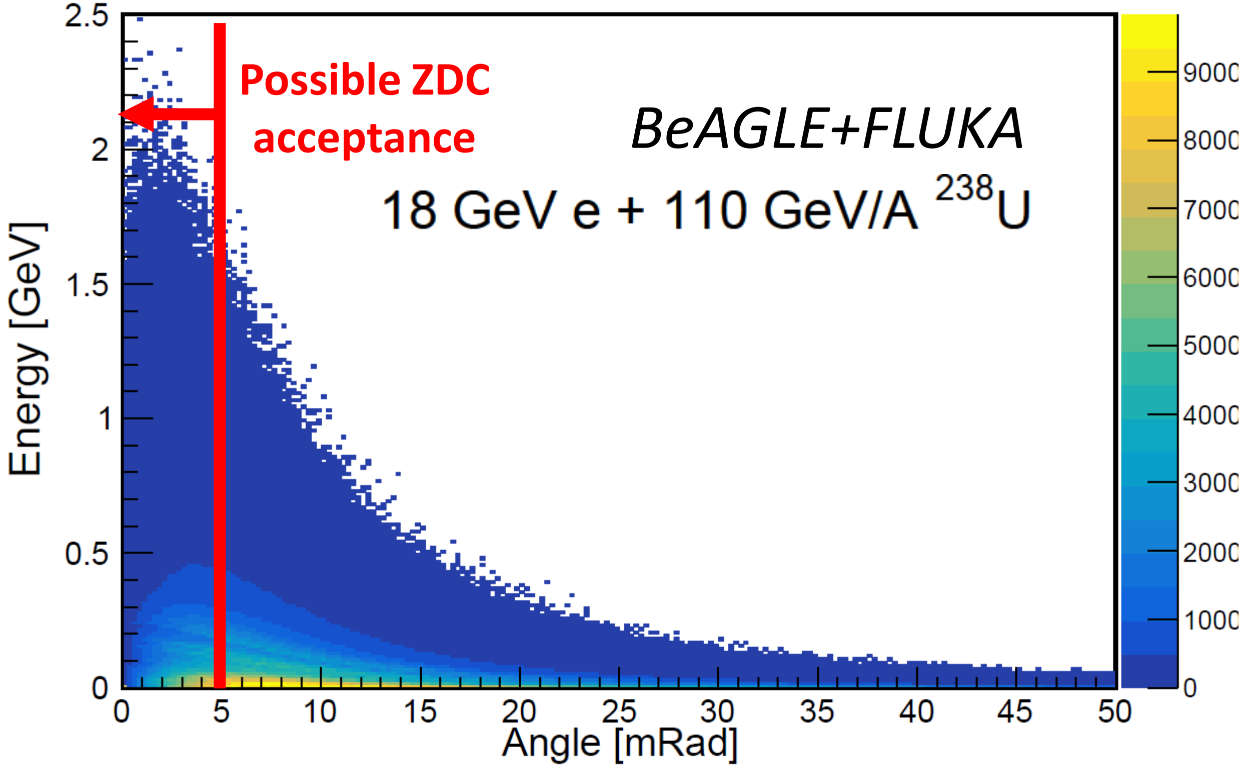
- Gamma rays from nuclear de-excitations can be detected in the Zero-Degree Calorimeter (ZDC). The ZDC acceptance range will be approximately 0-5 mRad.
- The energy resolution of the ZDC for photon detection may be as good as $2\%/\sqrt{E\ (GeV)}$ if a material such as LYSO crystals are used.
- We will therefore be able to measure gamma rays which are Lorentz upshifted and moving very close to the ion beam direction.
- A 1 MeV gamma will have an energy of ~240 MeV at zero degrees in the lab frame. For the ZDC resolution above, this gamma will have its energy measured to 4% in the lab frame. At first approximation, the energy resolution in the nucleus' rest frame is equivalent – that is, a 40 keV resolution for a 1 MeV gamma.

Detection of gamma rays

Single gamma simulation – 110 GeV/A beam



De-excitation gammas: full simulation results



Z.Phys. C70 (1996) 413-426

Z. Phys. C 71, 75-86 (1996)

Summary and ongoing work

- Our simulation studies suggest the EIC has the potential to produce nuclear fragments using various heavy-ion beams. We believe that measuring these fragments can complement current and future work being done at dedicated rare isotope facilities.
- We are working to implement the current official IR8 lattice (see https://wiki.bnl.gov/eic-detector-2/index.php?title=Project_Information) into *Geant4* to conduct some detailed simulation studies. We are conducting additional simulations with BeAGLE and working to compare the residual nucleus results to published data.
- With the right combination of detectors, these nuclei can be reconstructed using the proposed optics design of the 2nd interaction point using detectors located at a secondary focus.
- Our studies also suggest that de-excitation gamma rays can be measured in coincidence with the nuclear fragments to quite high resolution.
- Given the time scales for the EIC project – and the 2nd interaction region in particular – there is sufficient time to conduct further studies on the potential of the EIC to contribute to this physics, as well as place requirements on the far-forward spectrometer optics and detector design.

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Thanks!

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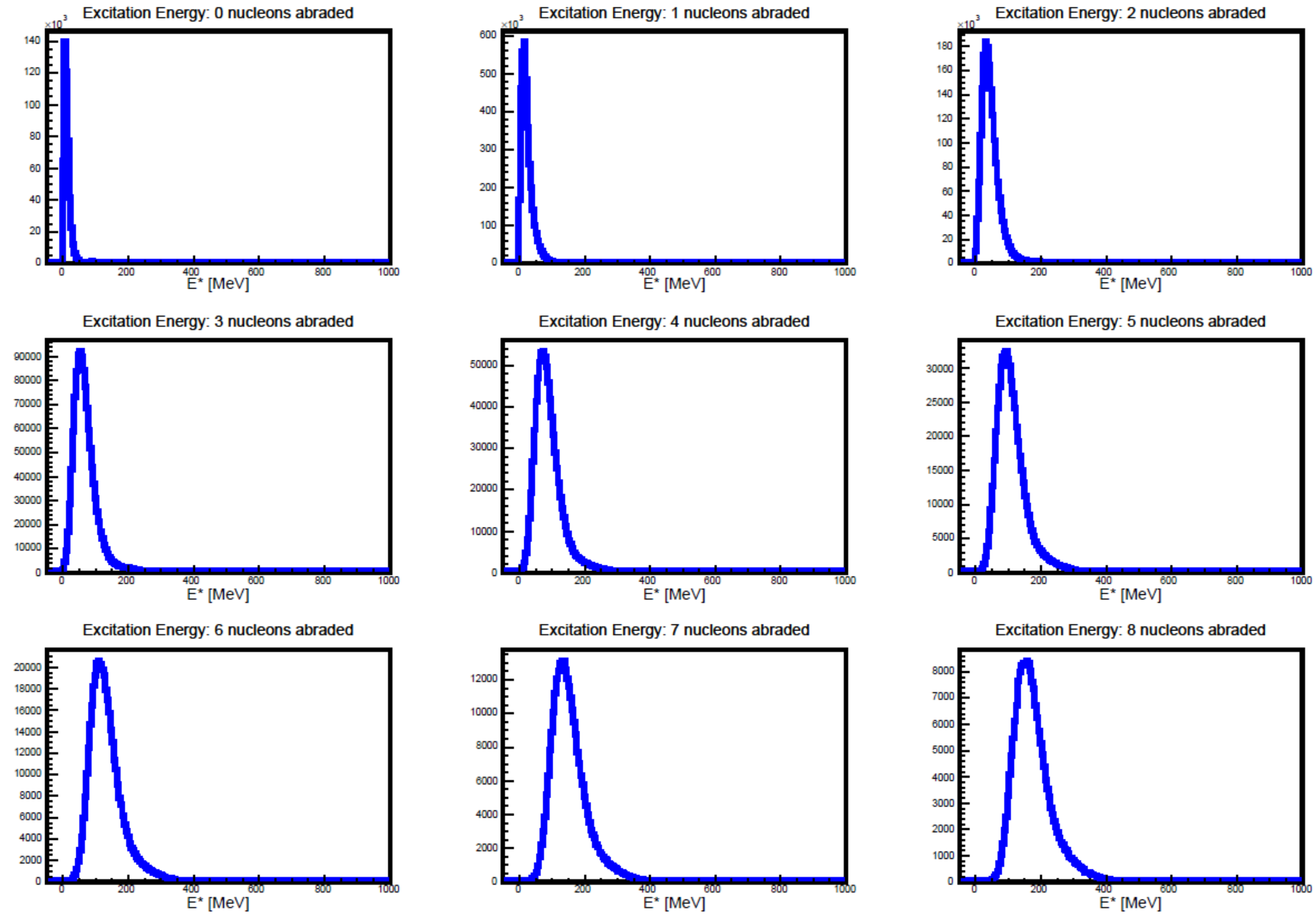
- ❑Thanks to Aleksandra Kelic-Heil for providing access to the *ABRABLA07* code, as well as instructions on running the ablation portion!

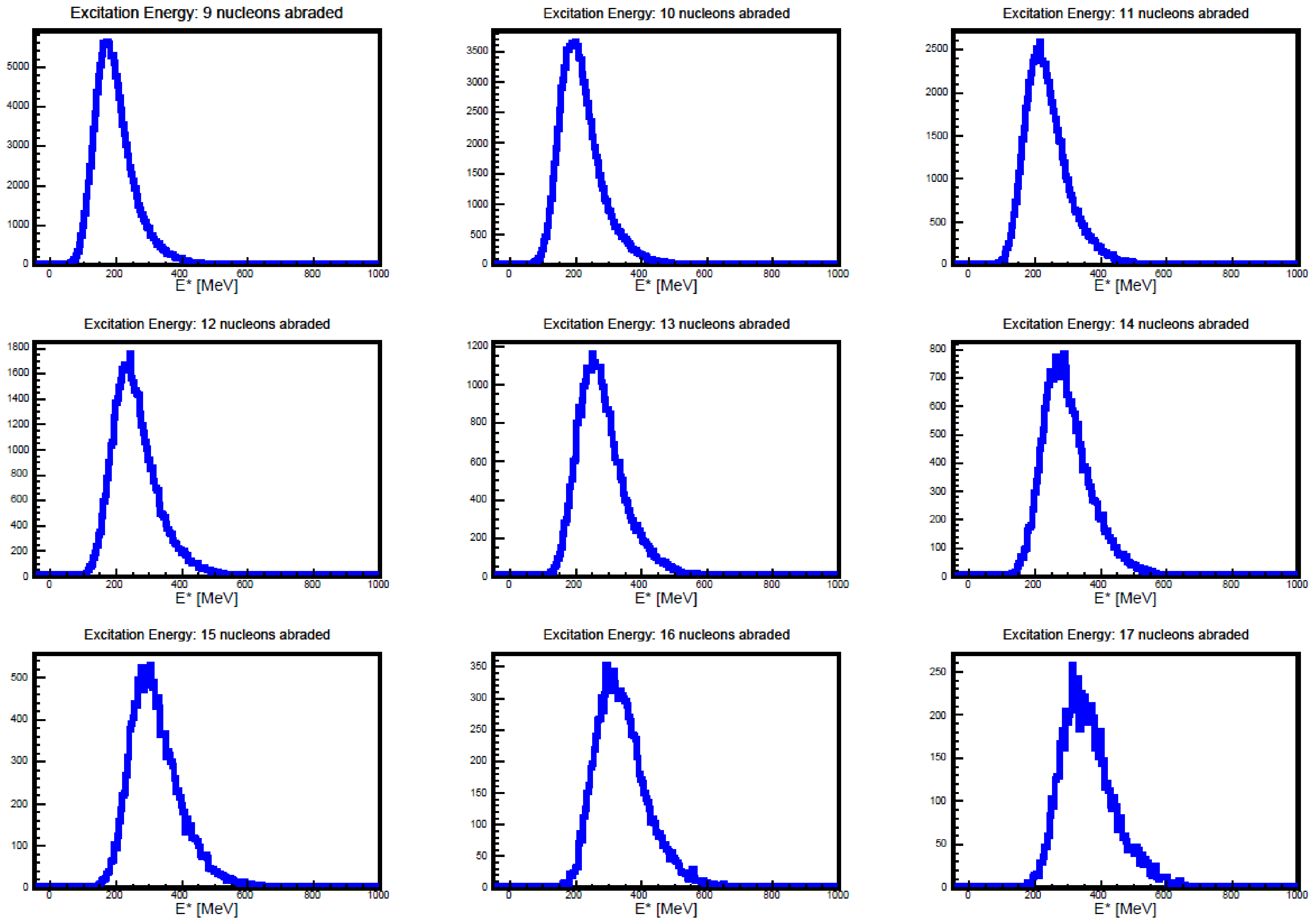
Backup Slides

Residual nucleus excitation energy distributions

18 GeV e + 110 GeV/A ^{238}U

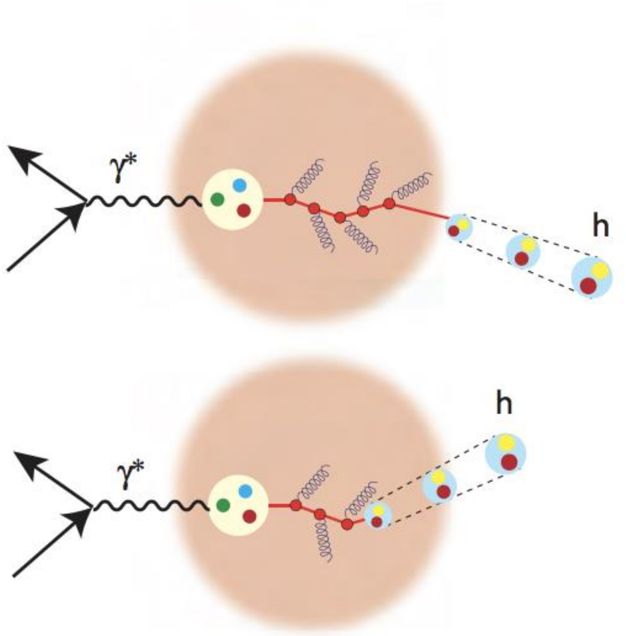


Residual nucleus excitation energy distributions

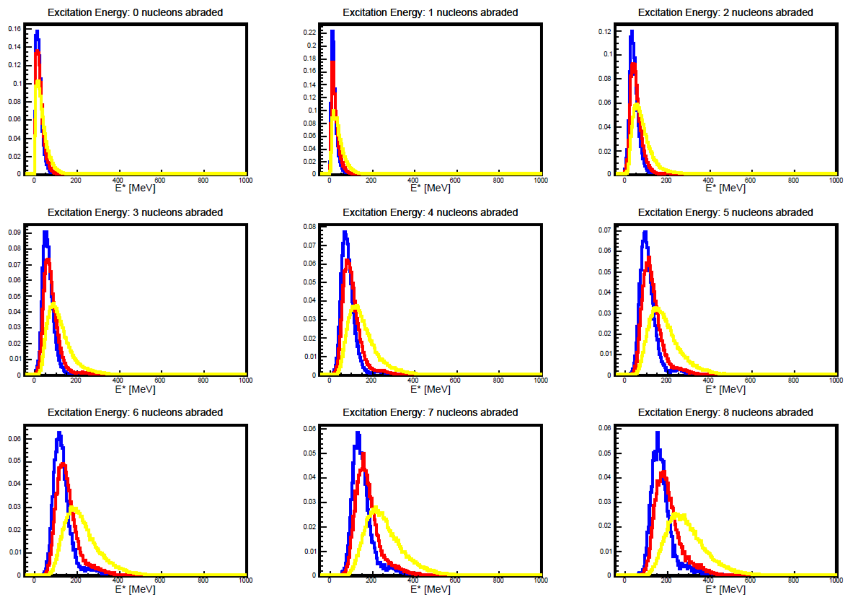


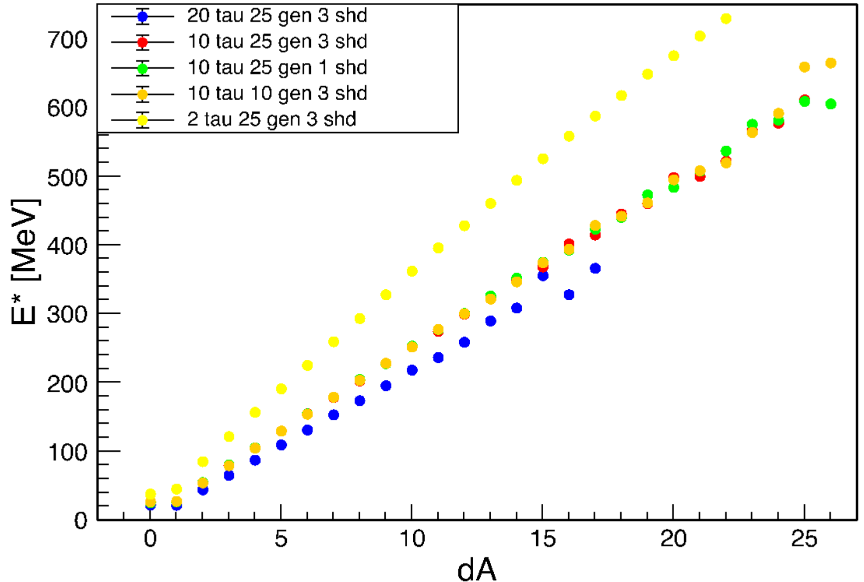
18 GeV e + 110 GeV/A ^{238}U

Residual nucleus sensitivity to formation time parameter



$$\tau_{Lab} = \tau_0 \frac{E_s}{m_s} \frac{m_s^2}{m_s^2 + p_{s\perp}^2}$$



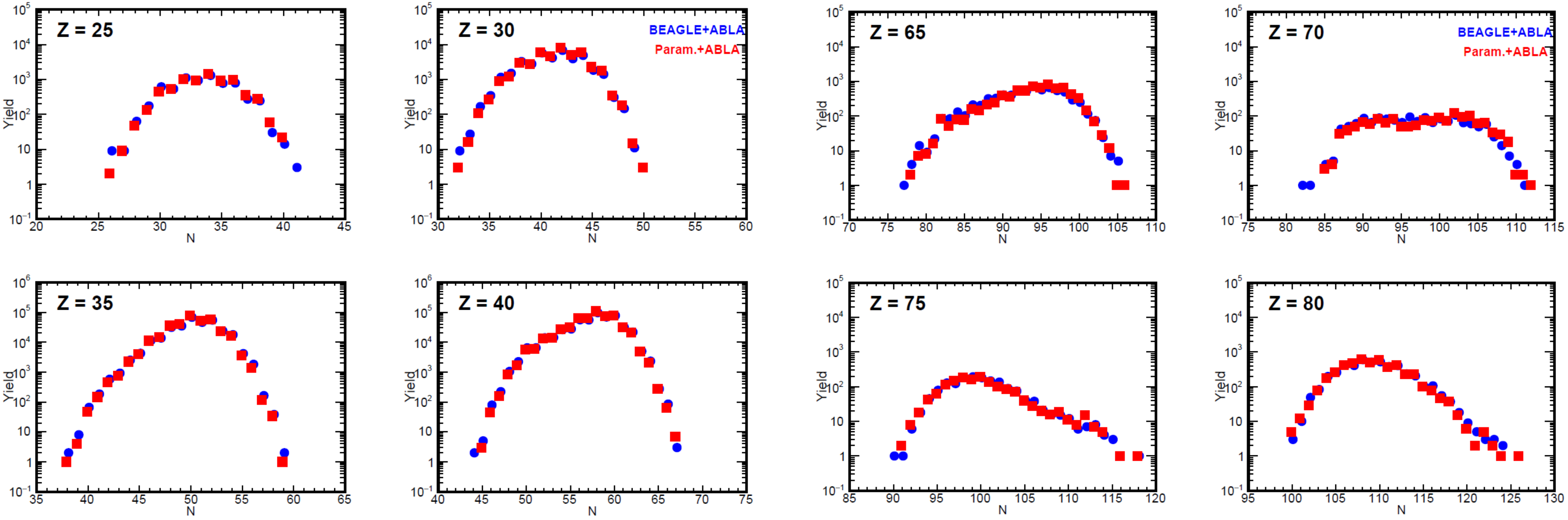


Expected EIC event counts

- Event rates at the EIC will be on the order of 10,000 events per second. Most of these events are at very low Q^2 (the photoproduction region of the e-p/A total cross section), but nuclear fragments can still be produced and detected in for these kinematics.
- The 10 million event sample which we generated may correspond to less than an hour of EIC running. Generating a larger number of events with *BeAGLE* becomes computationally expensive.
- Since all we care about here is the production of the residual nucleus, we can create a simple empirical parameterization of the abrasion model observed in *BeAGLE*.

Comparison of *BeAGLE* results and parameterized distribution

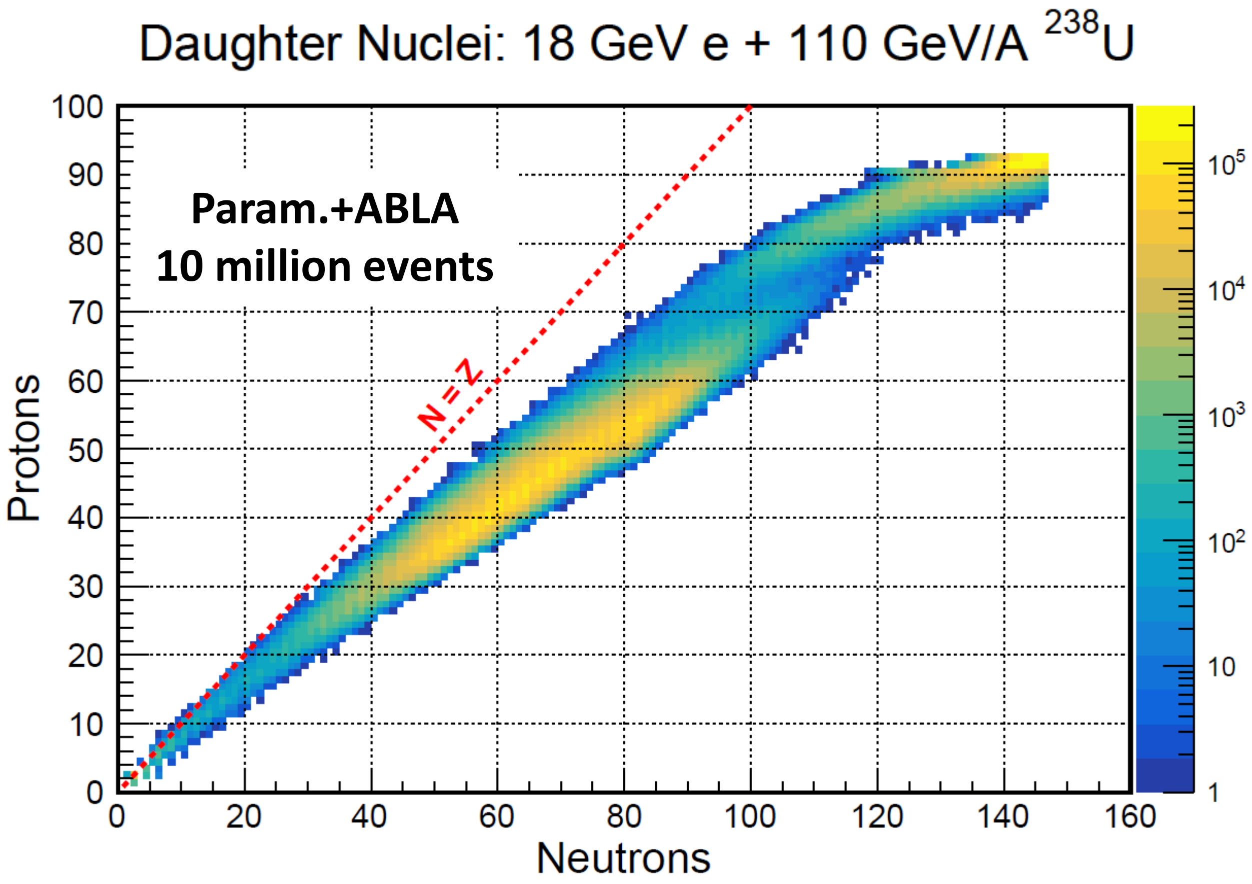
^{238}U

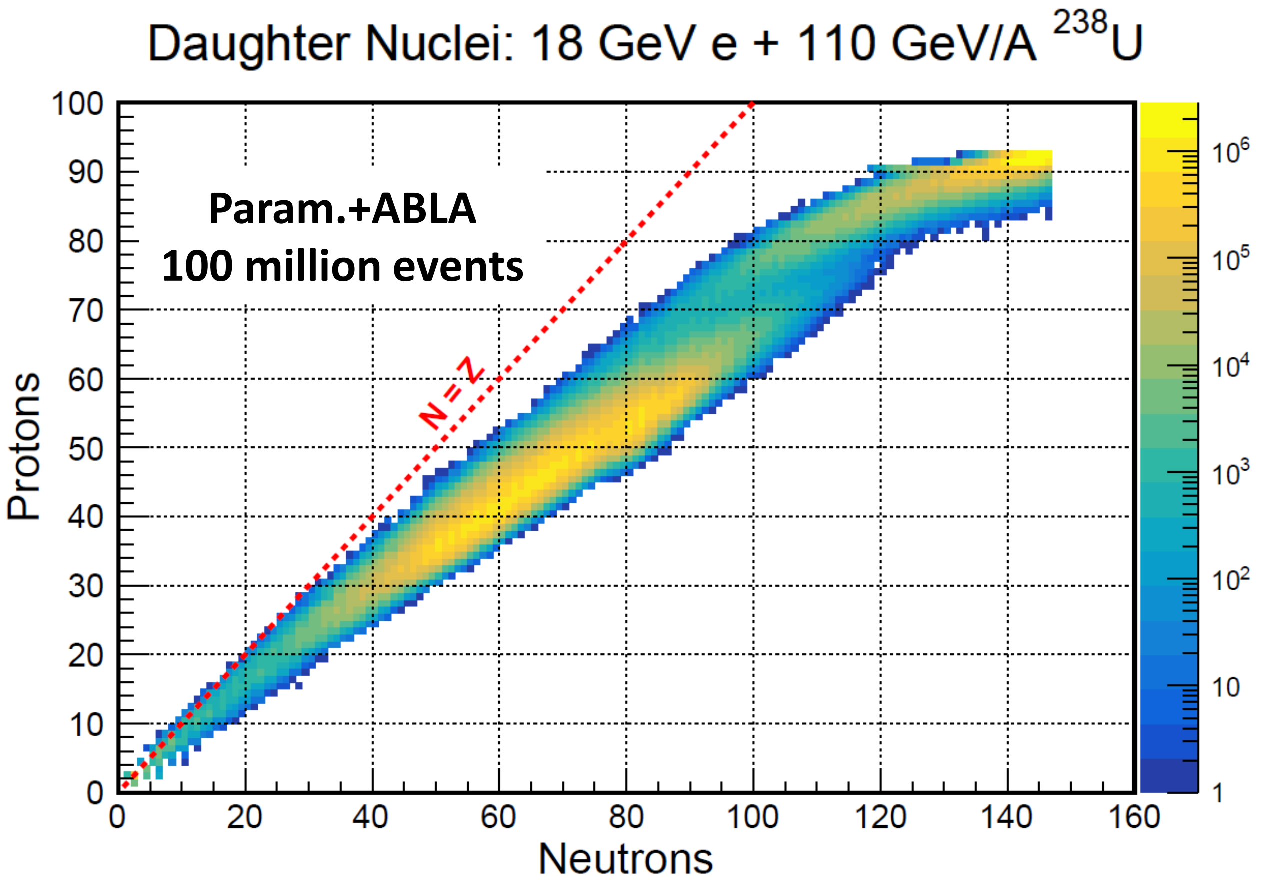


Using our parameterized model for the residual nucleus, we can simulate 10 million events in a few minutes.

The results are very consistent with using the full *BeAGLE* simulation.

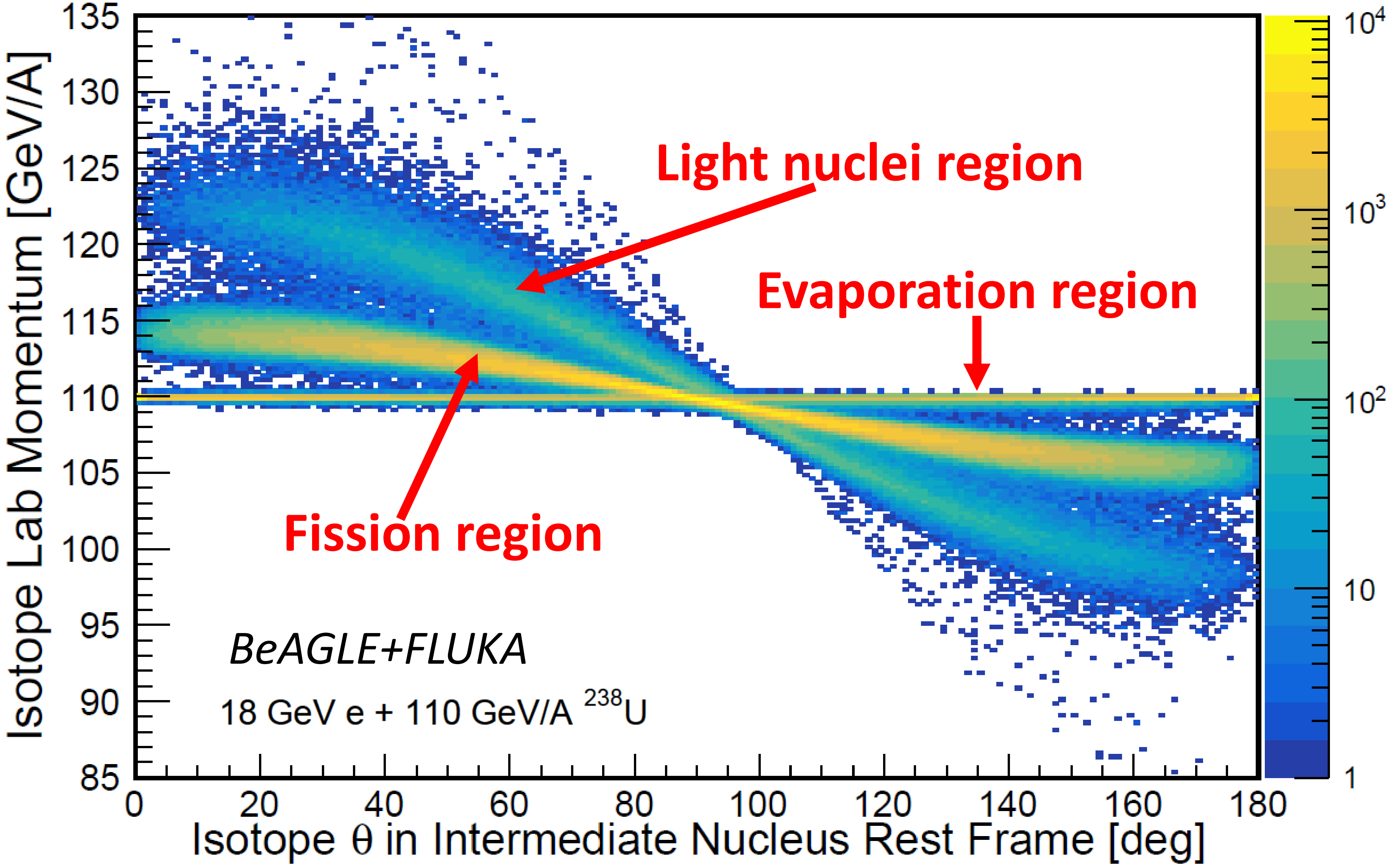
Towards higher statistics simulations



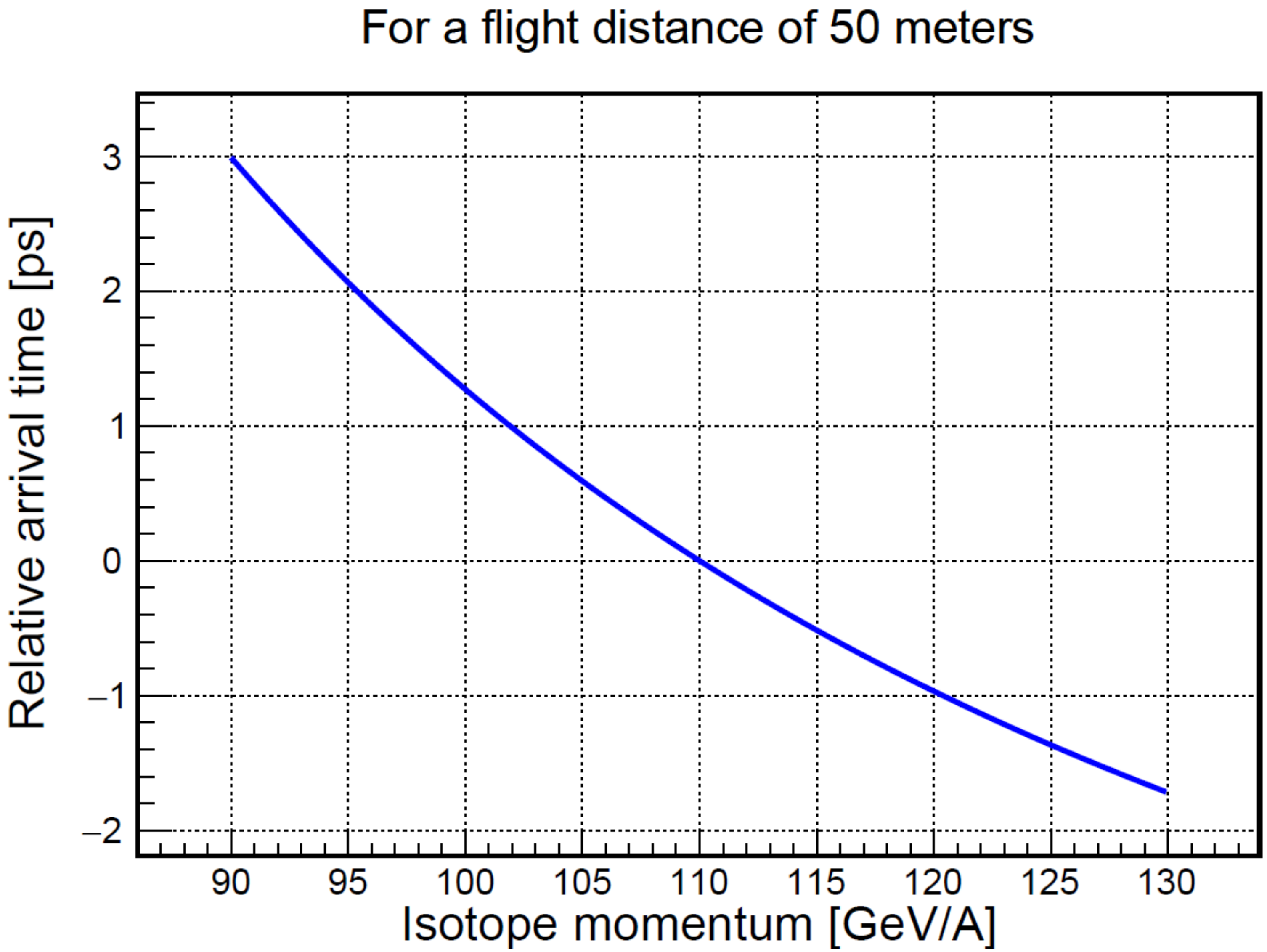


Note how borders expand towards more unstable isotopes as additional events are generated.

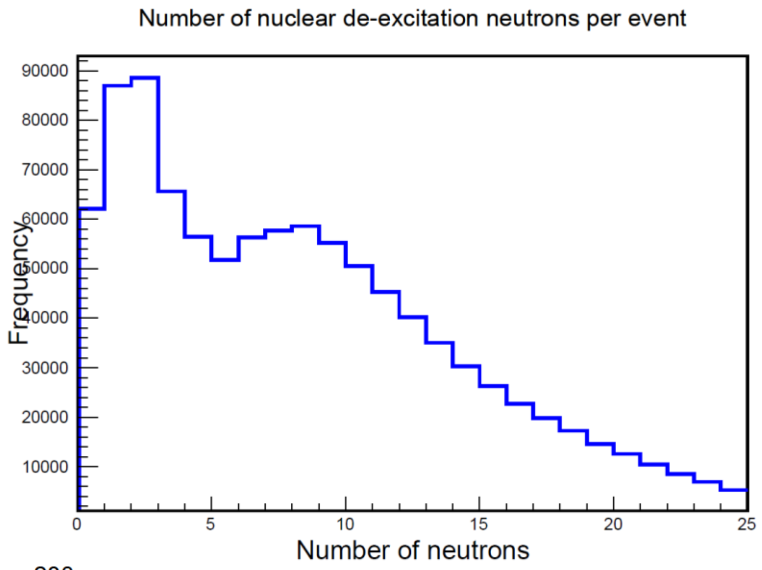
Fragment kinematics

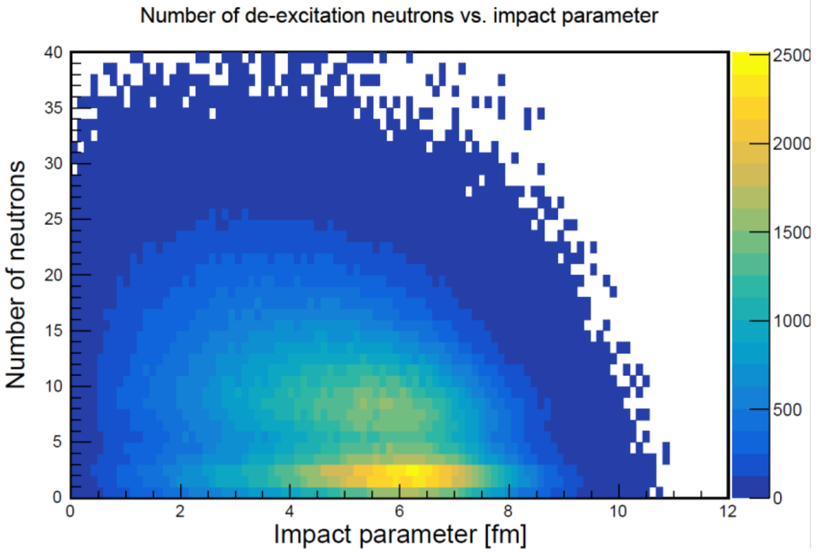


Time-of-flight measurements would require picosecond resolution



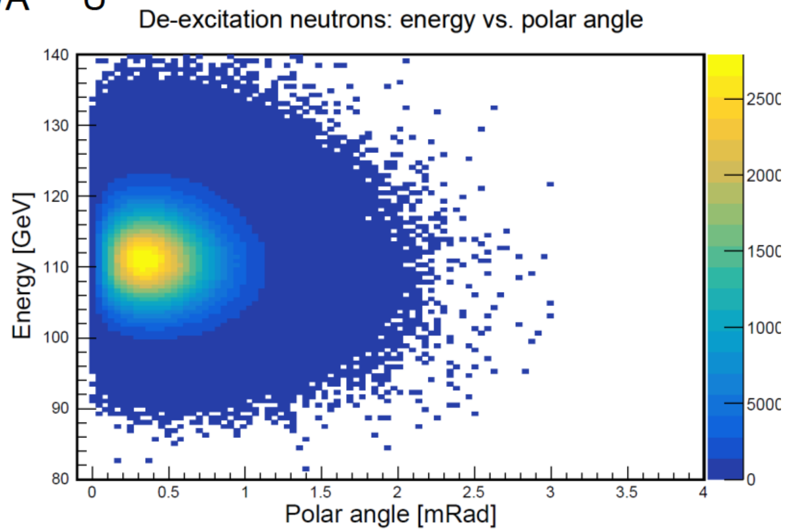
Centrality determination

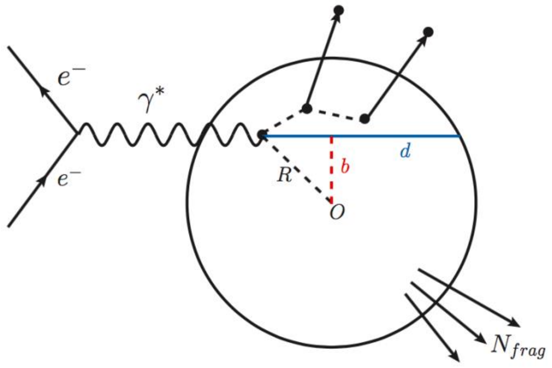


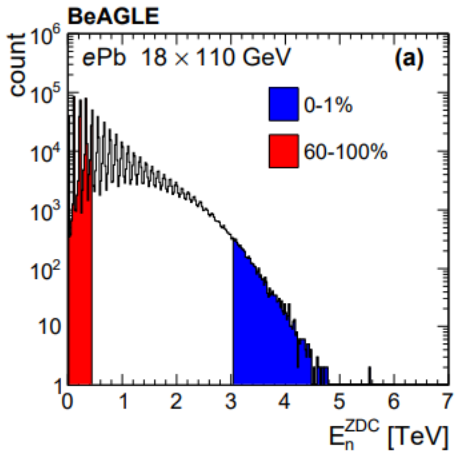


18 GeV e + 110 GeV/A ^{238}U

BeAGLE+FLUKA







Phys. Rev. D 106, 012007

Centrality determination – model sensitivity

18 GeV e + 110 GeV/A ^{238}U

BeAGLE+FLUKA