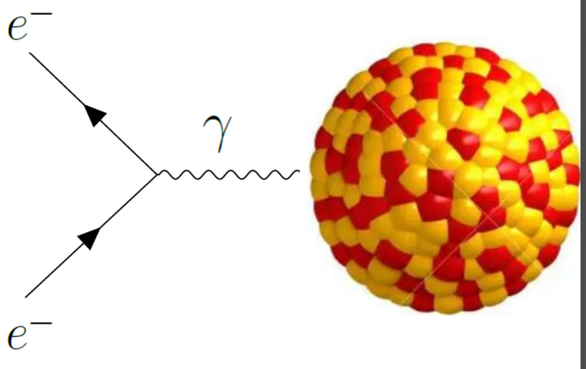
Production and detection of nuclear fragments at the EIC

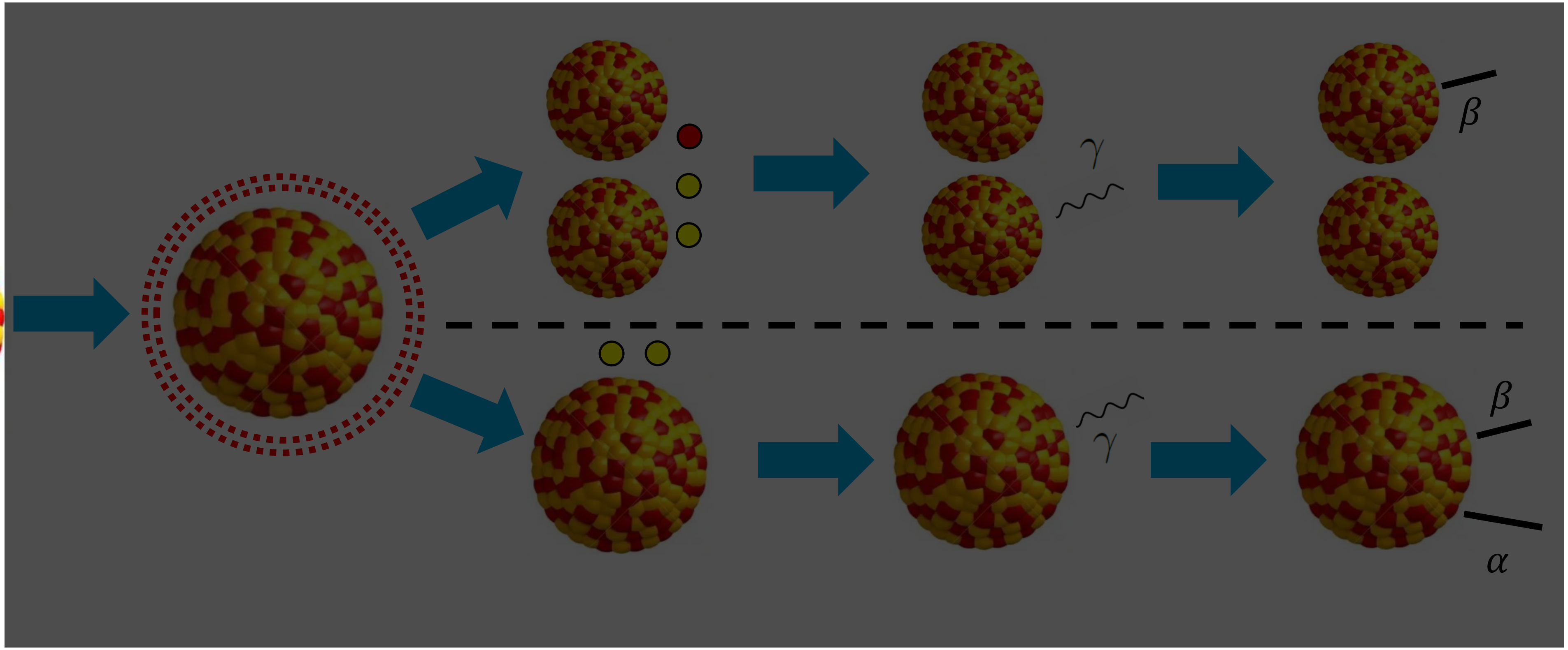
Barak Schmookler

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 the decay photons? 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?

Isotope production at the EIC



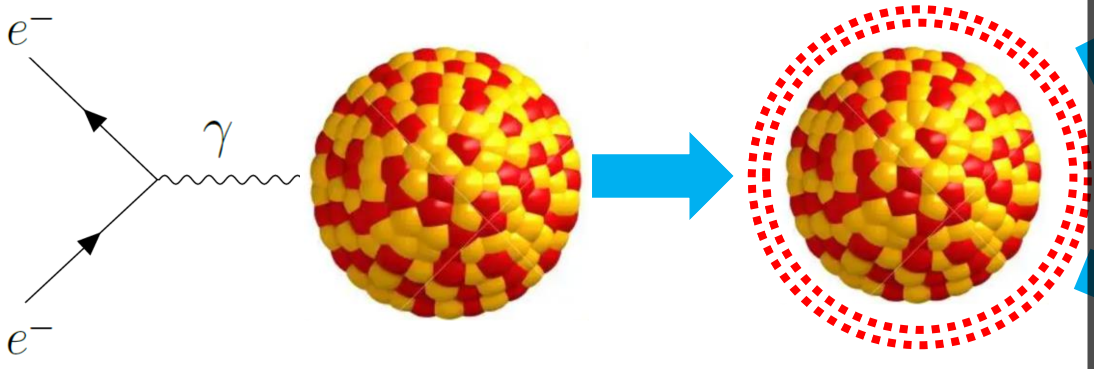


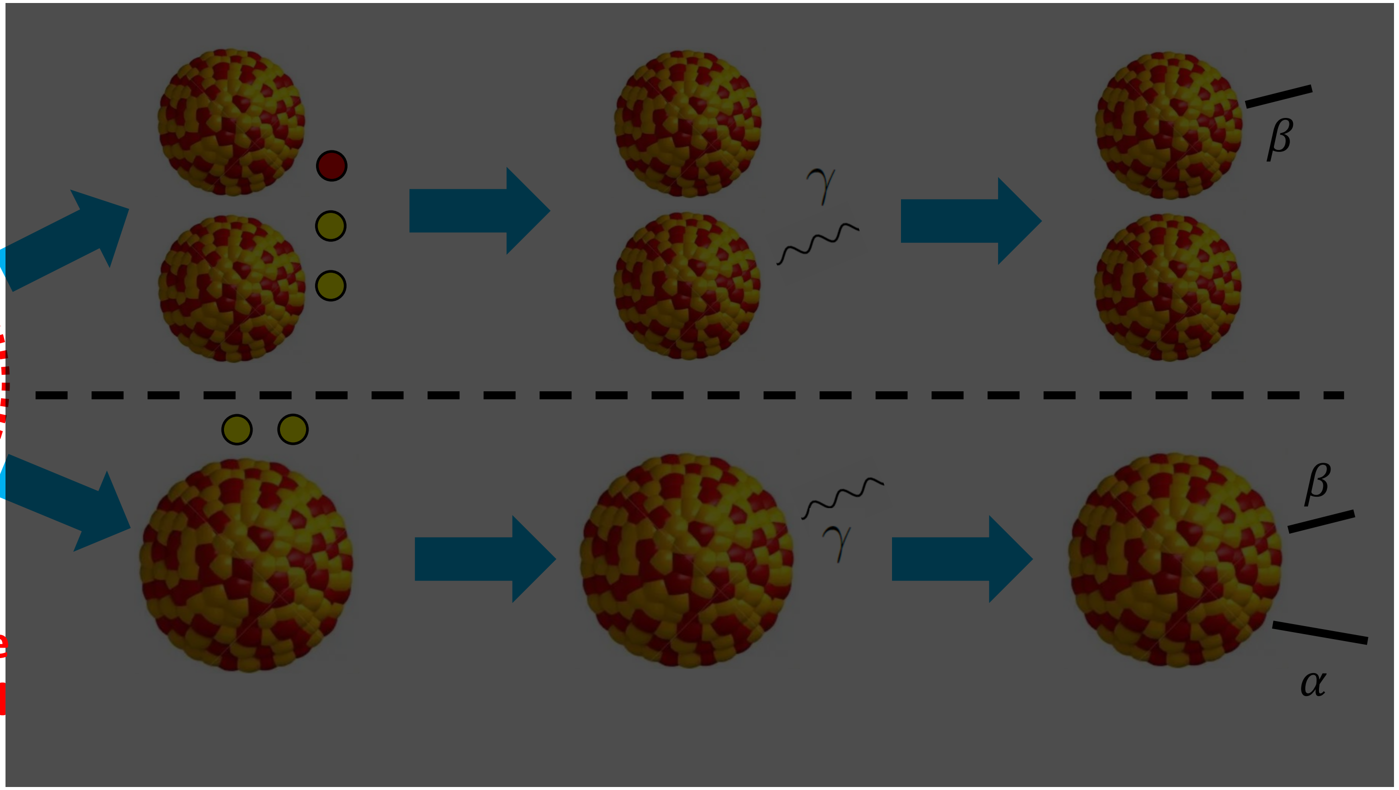
Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

t = 0

Isotope production at the EIC

Hard scattering and
intra-nuclear
cascade





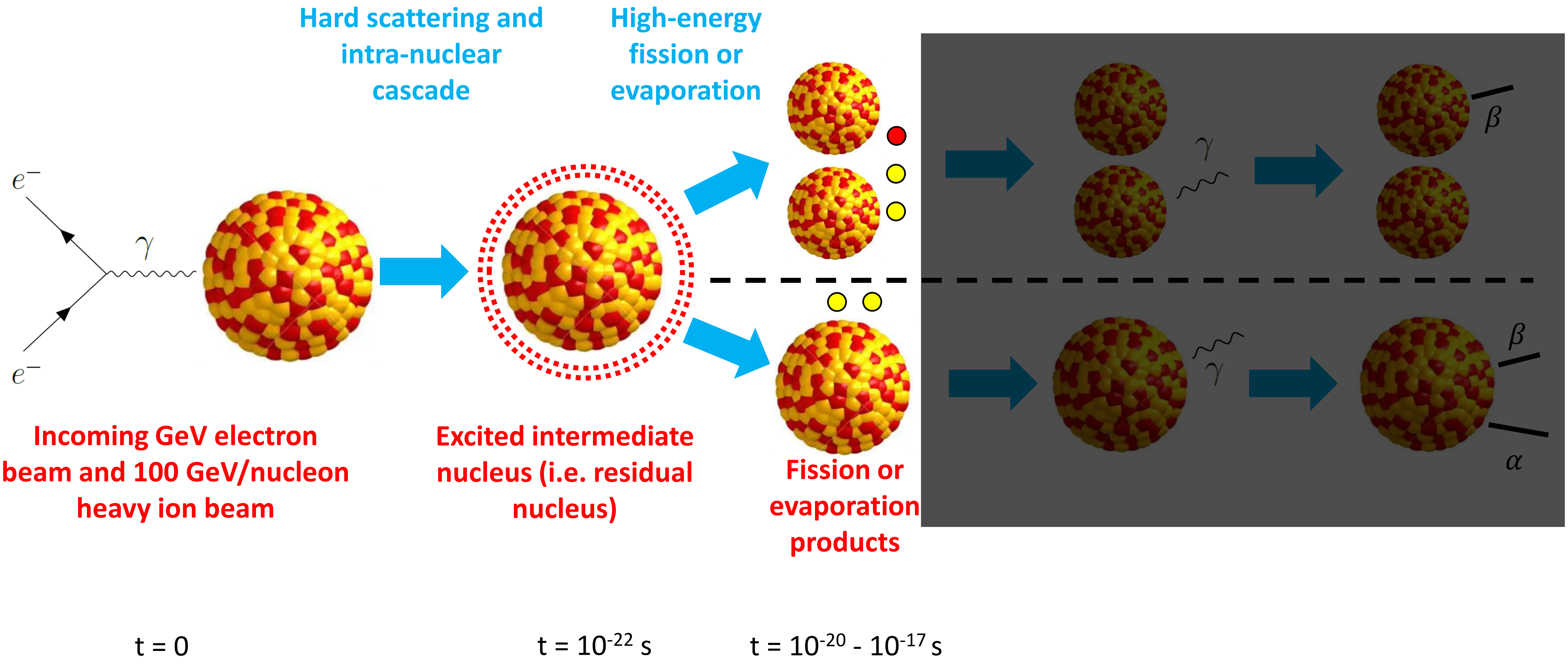
Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

Excited intermediate nucleus (i.e. residual nucleus)

t = 0

t = 10^{-22} s

Isotope production at the EIC



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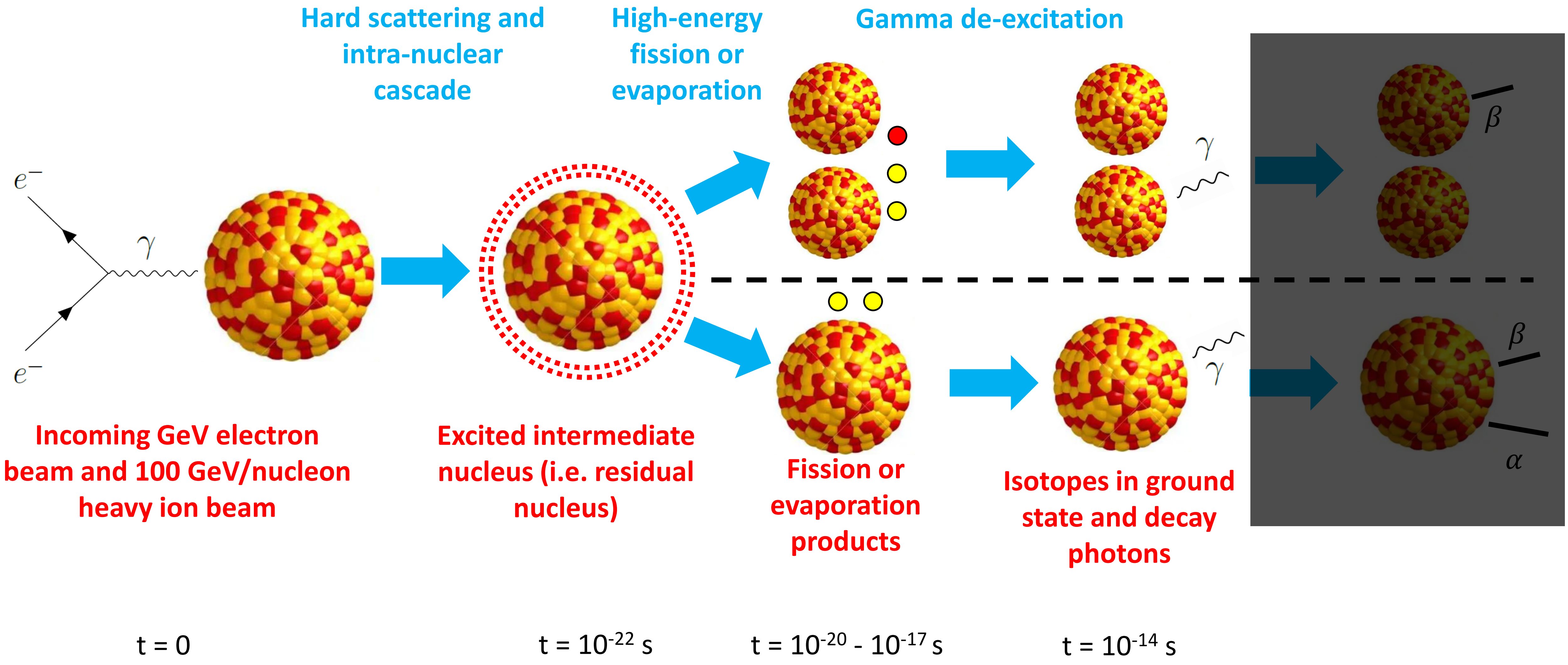

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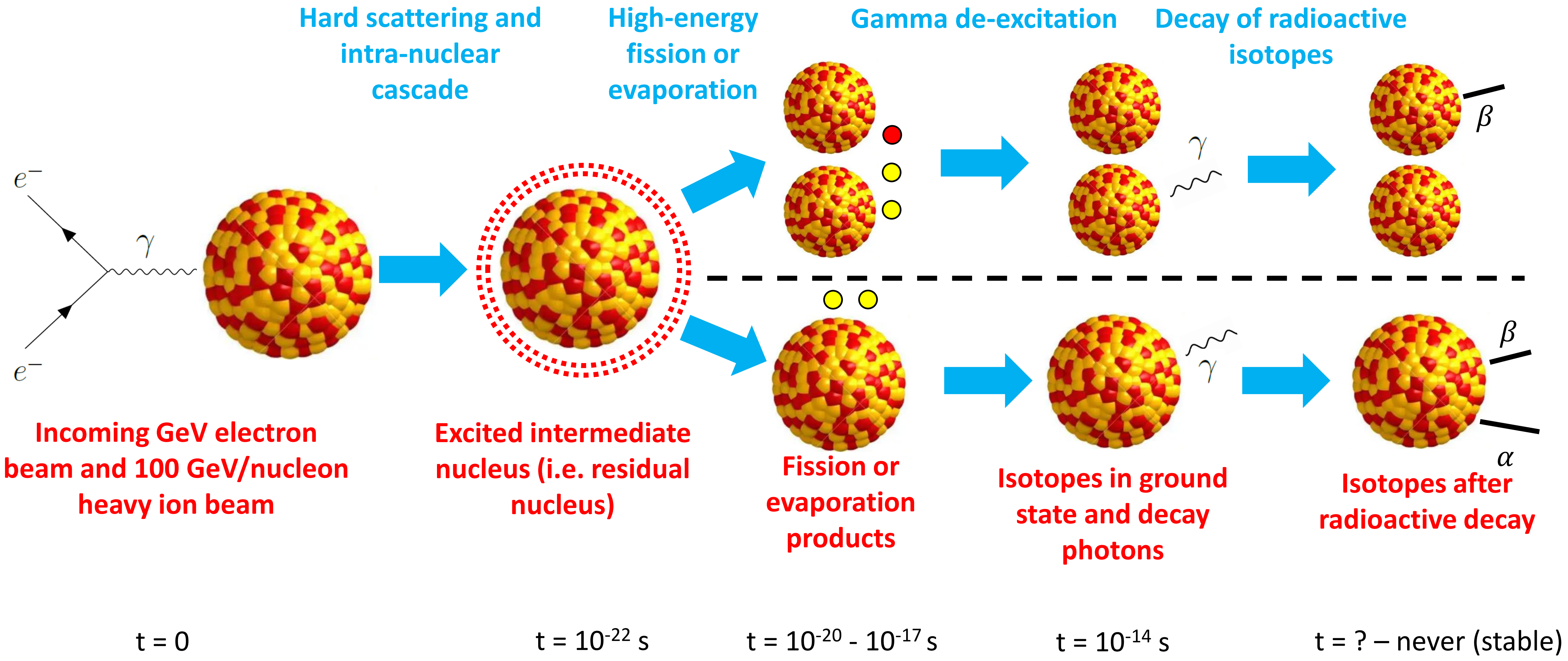
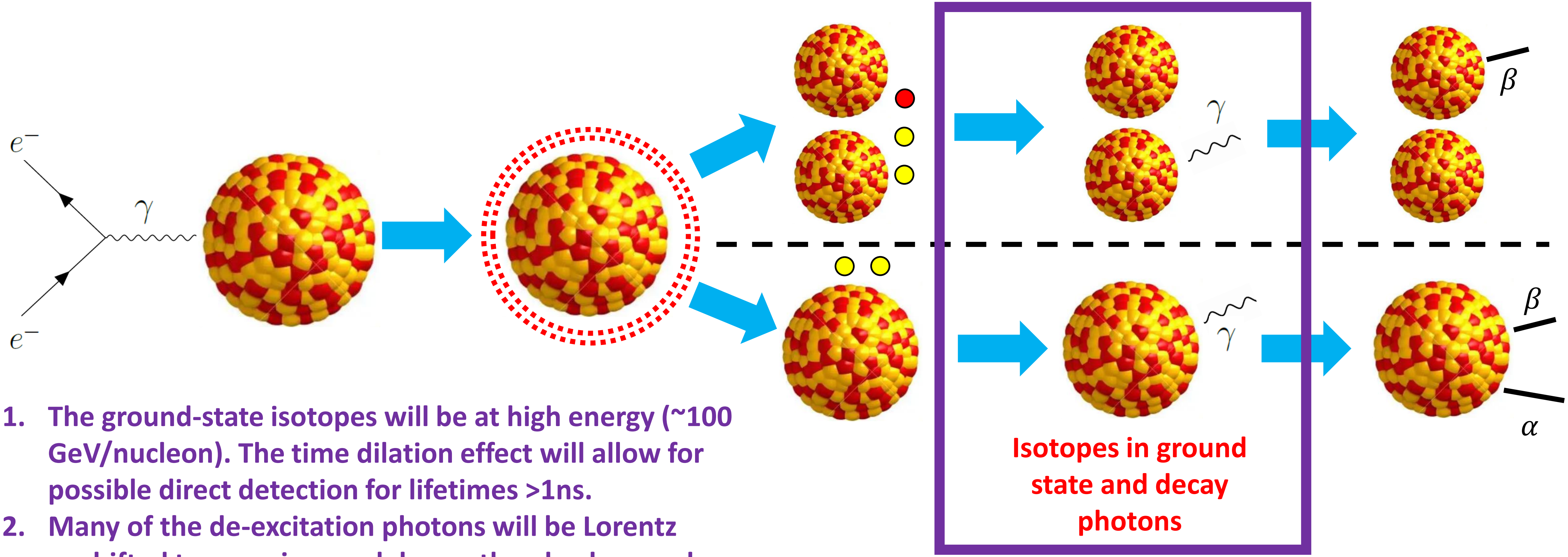


Where the EIC can potentially contribute



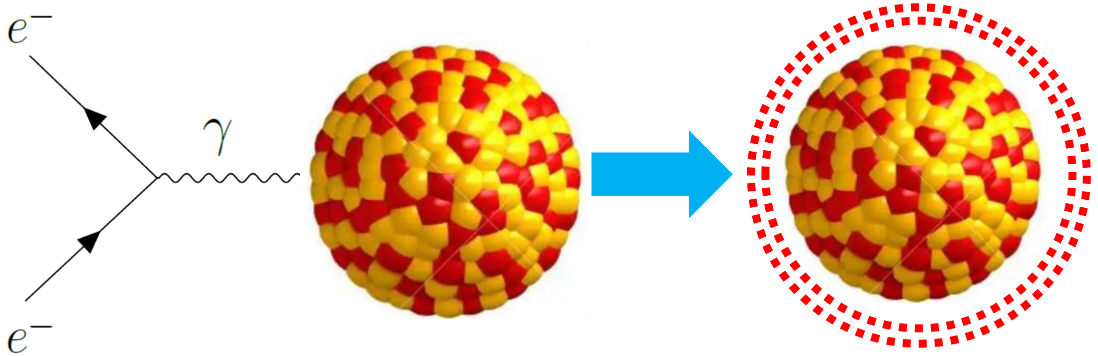
1. The ground-state isotopes will be at high energy (~100 GeV/nucleon). The time dilation effect will allow for possible direct detection for lifetimes >1ns.
2. Many of the de-excitation photons will be Lorentz upshifted to energies much larger than background photons present in the detector area. This will allow for clean detection/identification of these photons, 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 fast Abrasion-Fission model, better understanding of 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 of RIB facilities due to short flight time and possibly higher production cross section
Nuclear structure	Coincidence measurement of isotopes and de-excitation photons
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



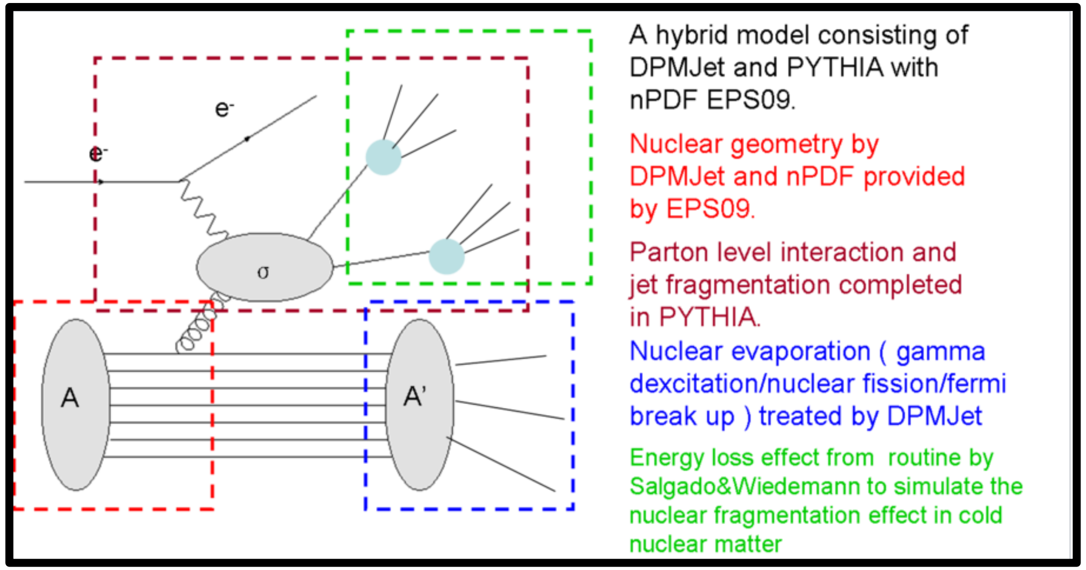
Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

Excited intermediate nucleus (i.e. residual nucleus)

<u>Step 1</u>

The hard scattering and the intra-nuclear cascade are modelled using the *Benchmark eA Generator for Leptoproduction – BeAGLE* (https://eic.github.io/software/beagle.html)

This leaves us with the residual nucleus in an excited state.



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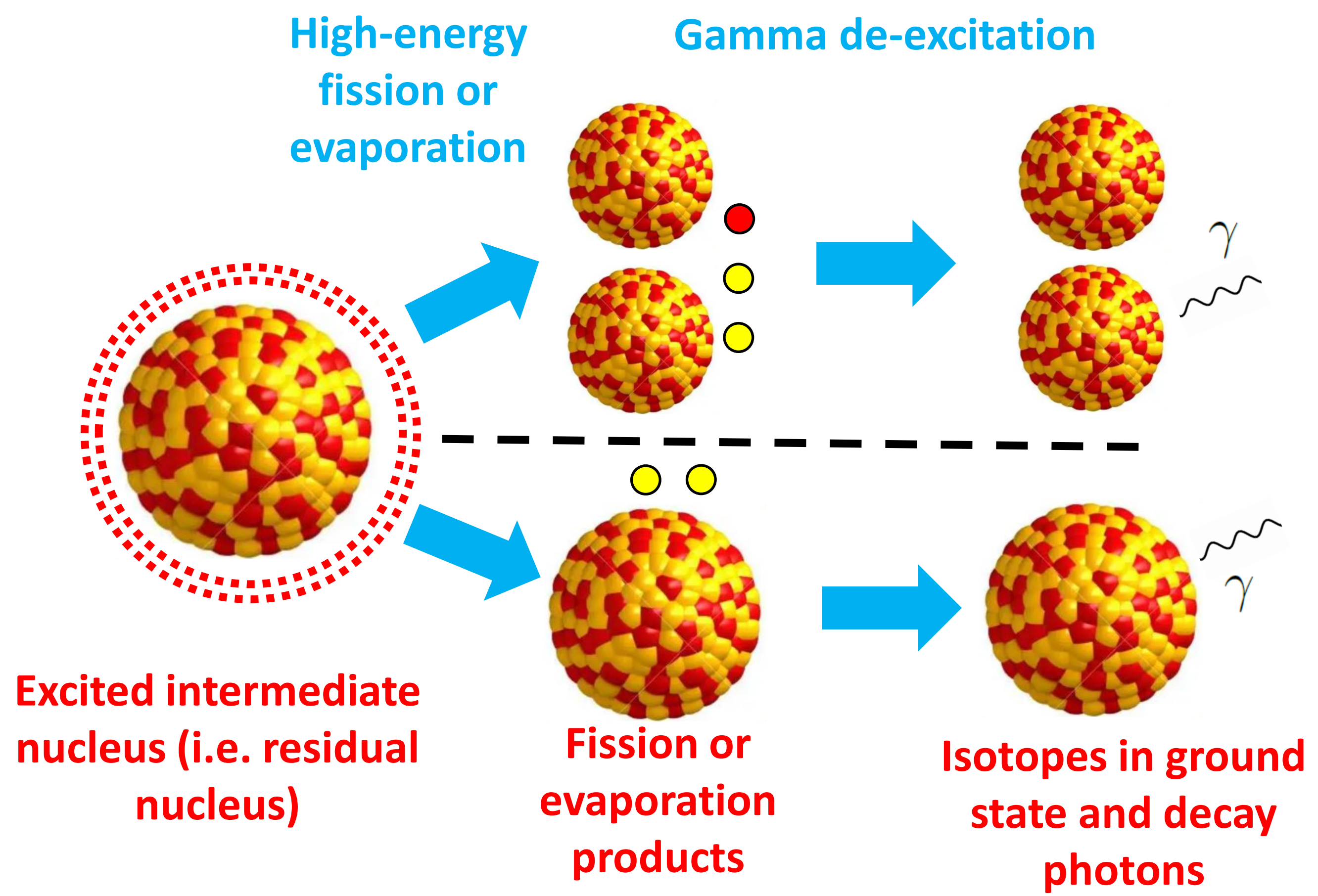


Step 2

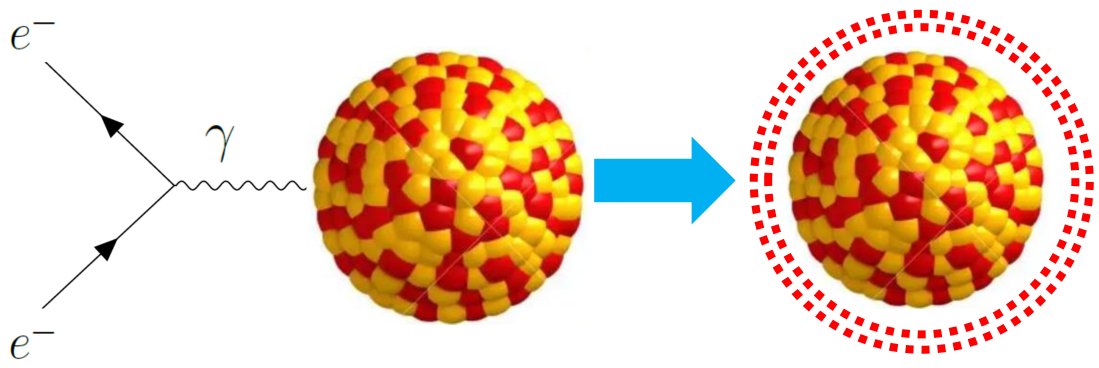
For each event, the residual nucleus with a given A, Z, and excitation energy is then handed over to either *FLUKA* (Annals of Nuclear Energy 82, 10-18 (2015)) or ABLA07 for decay (fission or evaporation) followed by gamma de-excitation. We are left with the decay products of the residual nucleus.

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 compare the results.

(N.B. The *FLUKA* decay of the residual nucleus has been directly incorporated into the *BeAGLE* simulation framework, allowing for easier analysis.

Production of the excited 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 get created following the hard scattering and intra-nuclear cascade.
- The only relevant quantities are the A and Z of the residual, as well as its excitation energy.



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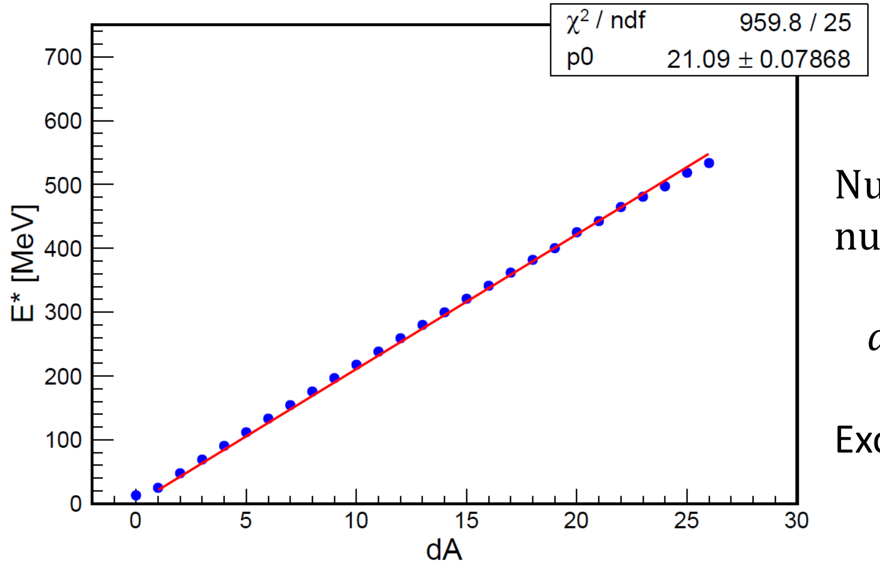
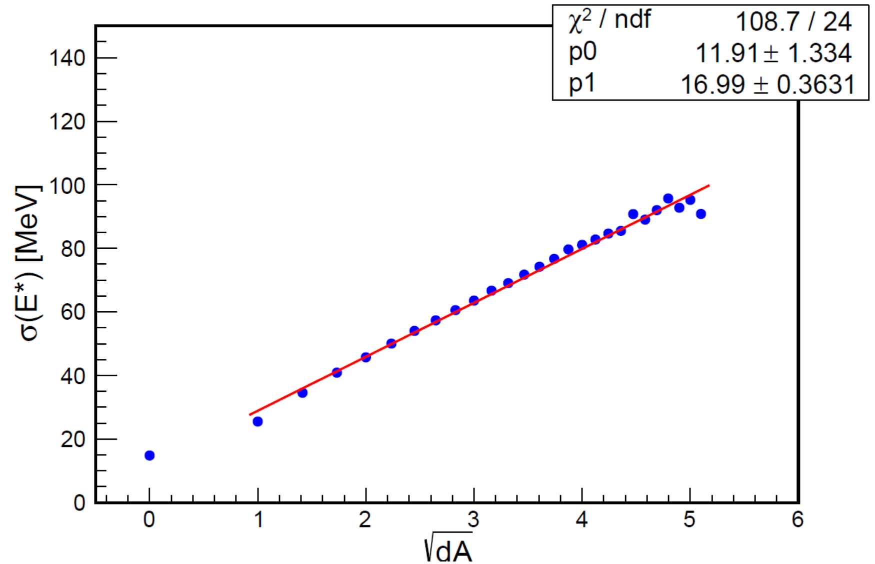


Number of abraded nucleons:

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

Excitation energy: E*



^{238}U

Production of the excited residual nucleus

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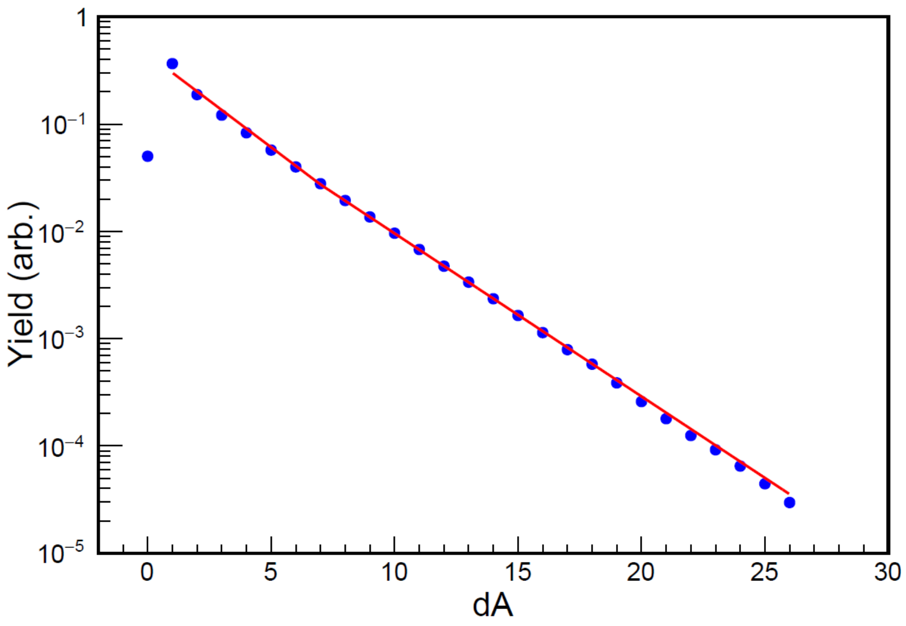
  - The excitation energy shows a simple dependence on the number of abraded nucleons.
  - The cross section for abrading a given number of nucleons (for dA>1) shows a (piecewise) exponential dependence.



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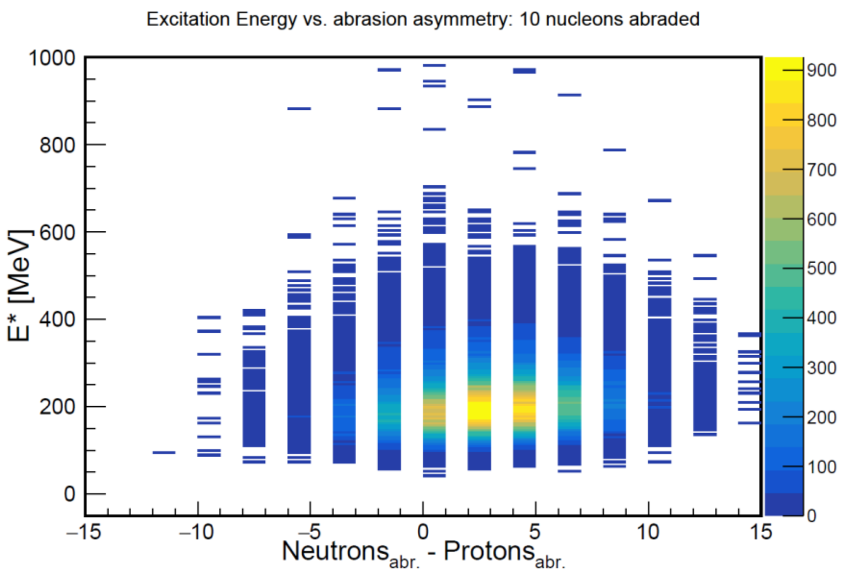
  - ➢ For a given number of abraded nucleons, the relative proportion of neutrons and protons abraded is close to a hypergeometric distribution



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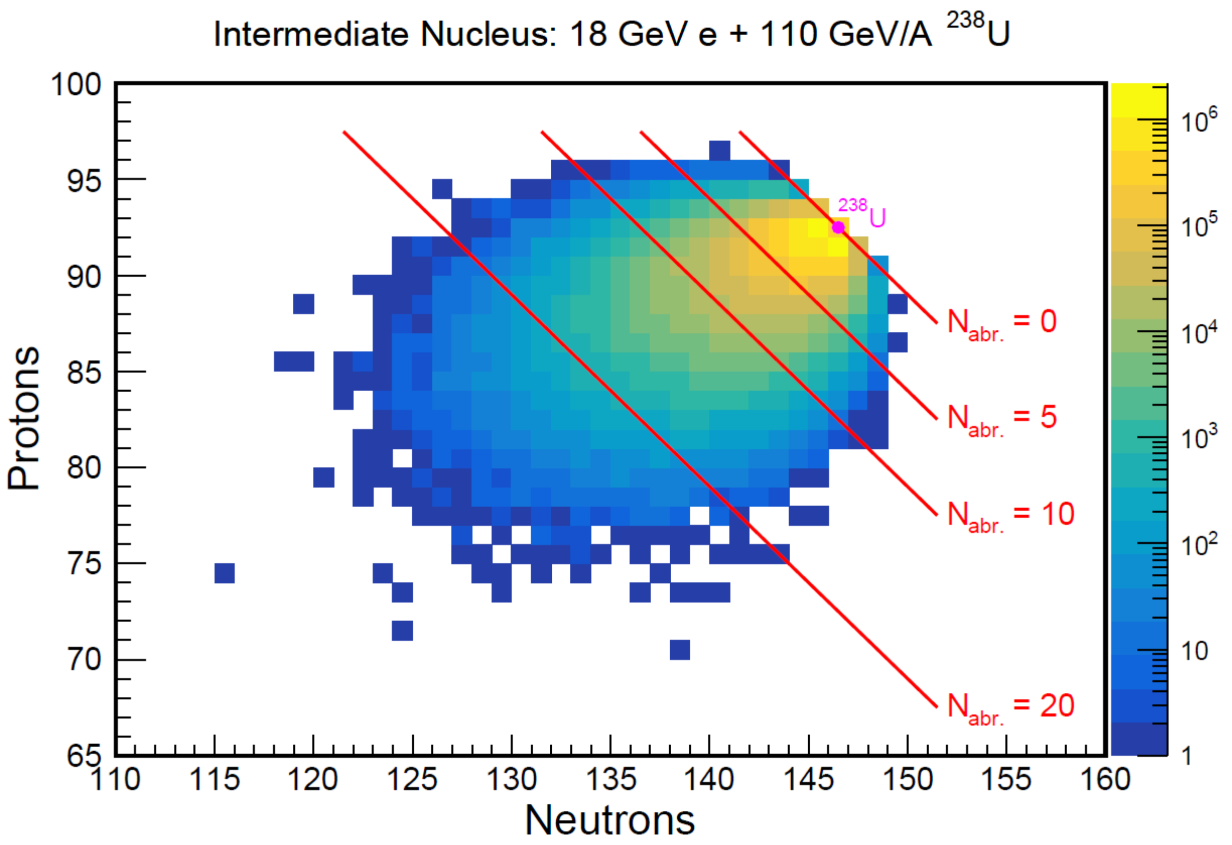
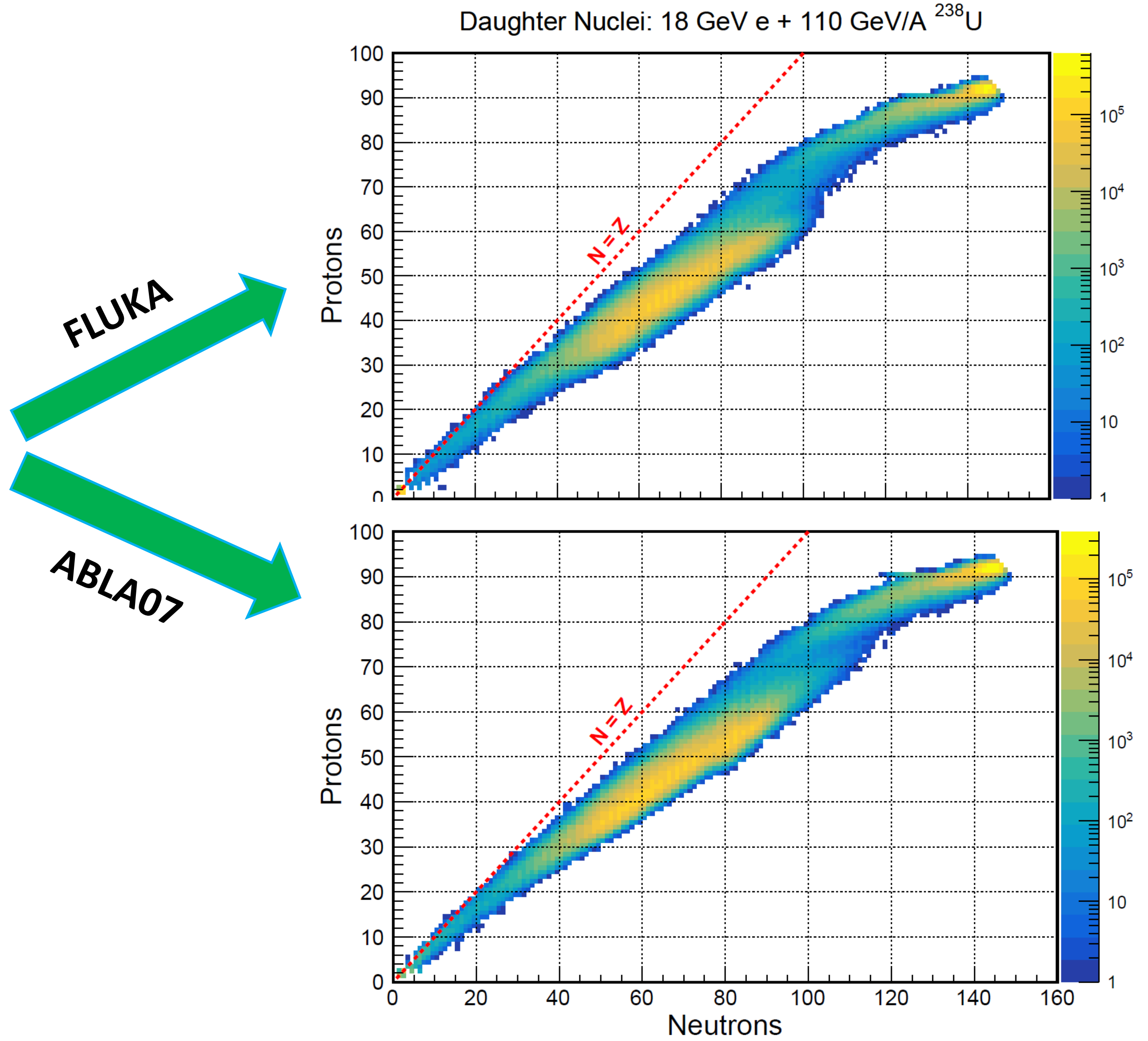
Note: simple abrasion model comes out of *BeAGLE* 'naturally'. Simulation uses intra-nuclear cascade model and nuclear potential model to determine the (A,Z) and excitation energy of the residual nucleus.

$$\tau_s = \tau_0 \frac{m_s^2}{m_s^2 + p_{s\perp}^2} \qquad \tau_{\text{Lab}} \approx \gamma_s \tau_s$$

$$(E_{\text{res}}, \mathbf{p}_{\text{res}}) = (M_{\text{A}}, \mathbf{0}) - \sum_{i=1}^{N_w} (E_i^{\text{F}}, \mathbf{p}_{\text{i}}^{\text{F}}) + (E_{\text{rcl}}, \mathbf{p}_{\text{rcl}})$$

We can then decay the excited residual nucleus

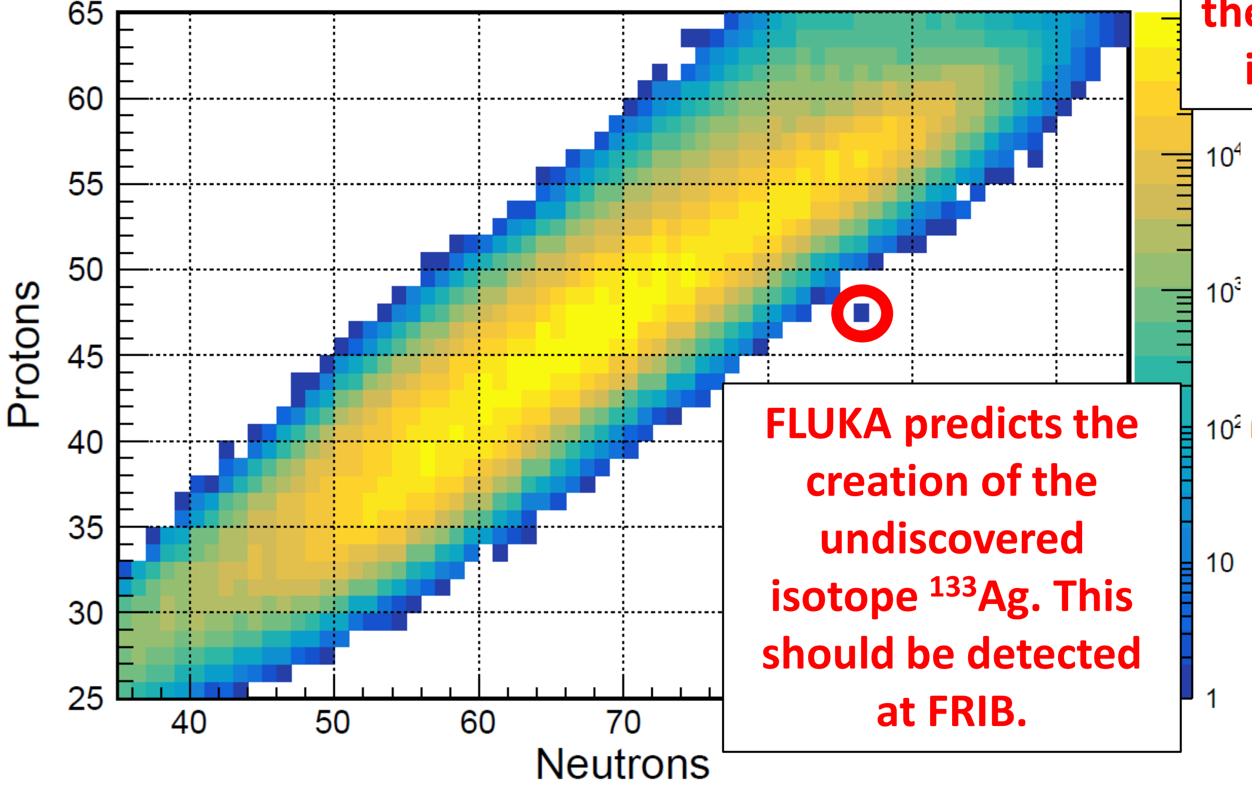




10 million events simulated

Using this 10 million ^{238}U event sample, we see hints of exotic nuclei production

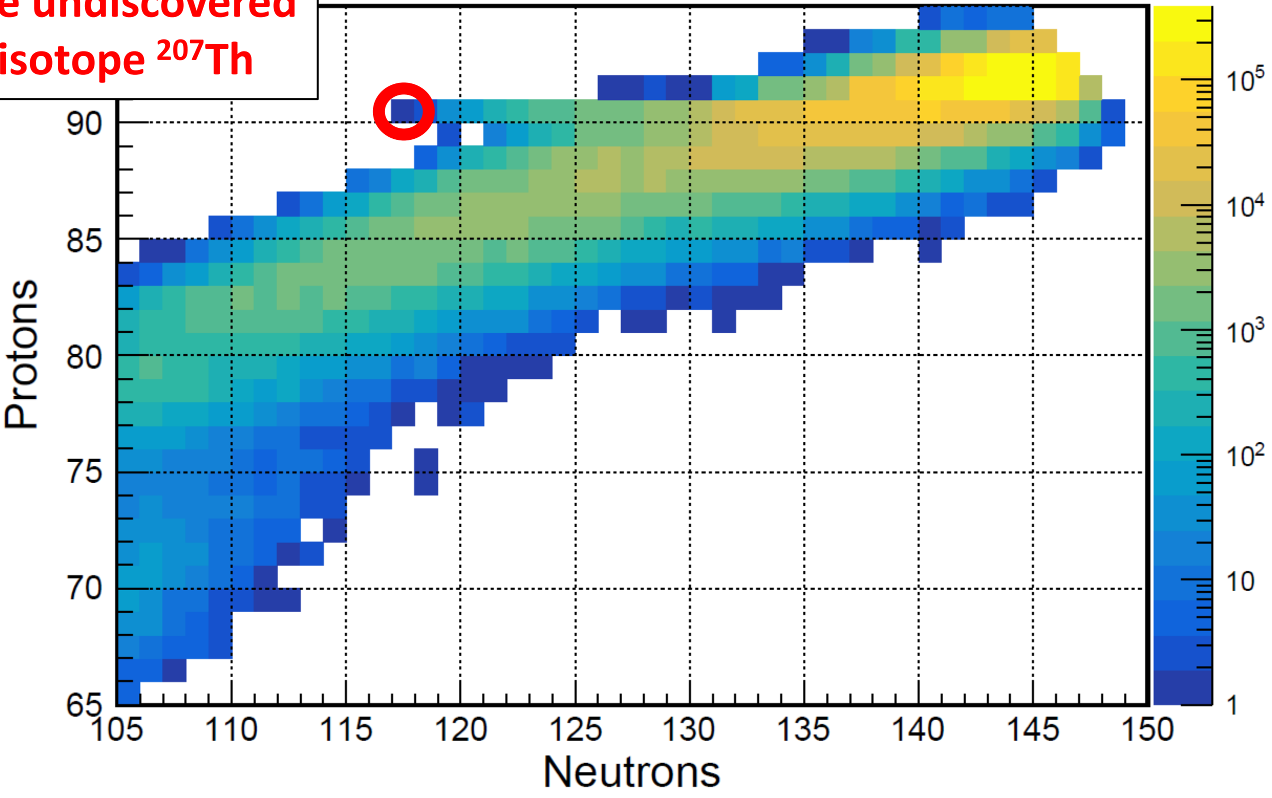
FLUKA – Fission Region



FLUKA predicts the creation of the undiscovered isotope ^{133}Ag. This should be detected at FRIB.

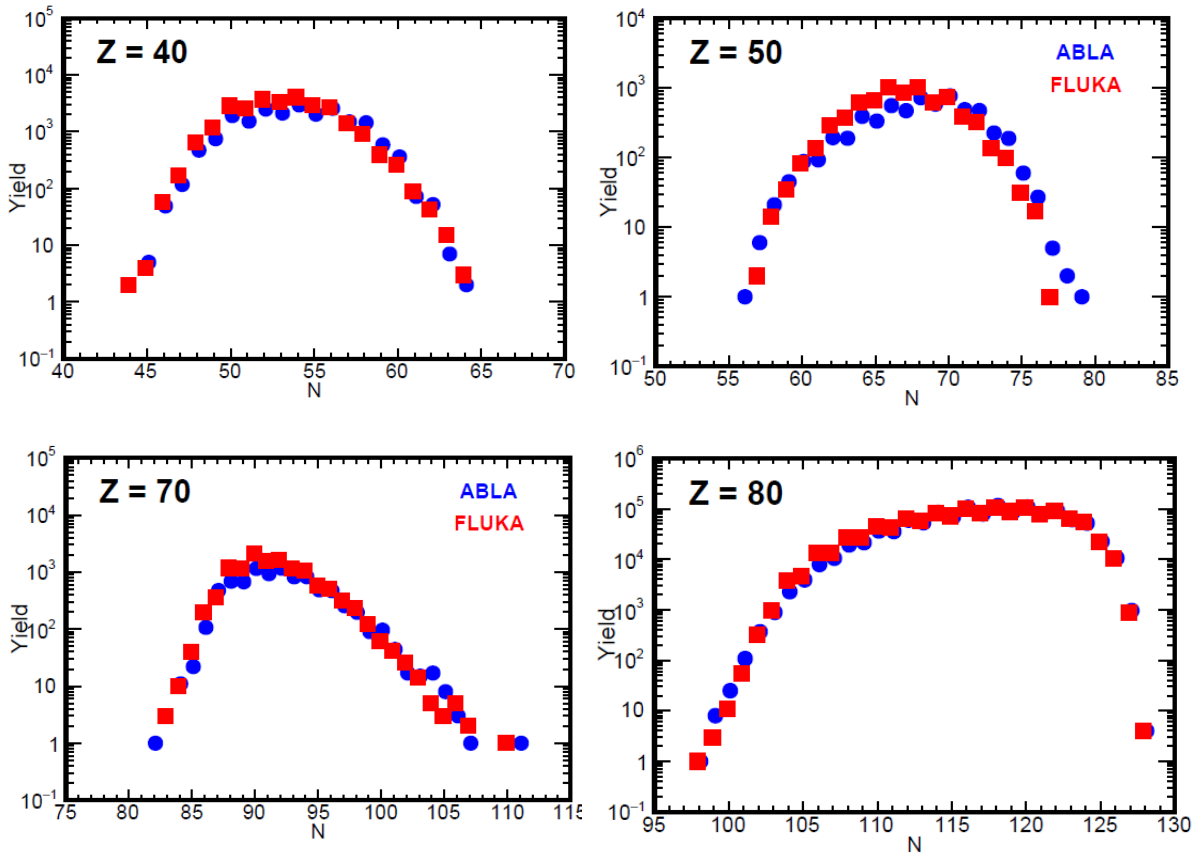
ABLA07 predicts the creation of the undiscovered isotope ^{207}Th

ABLA07 – Evaporation Region

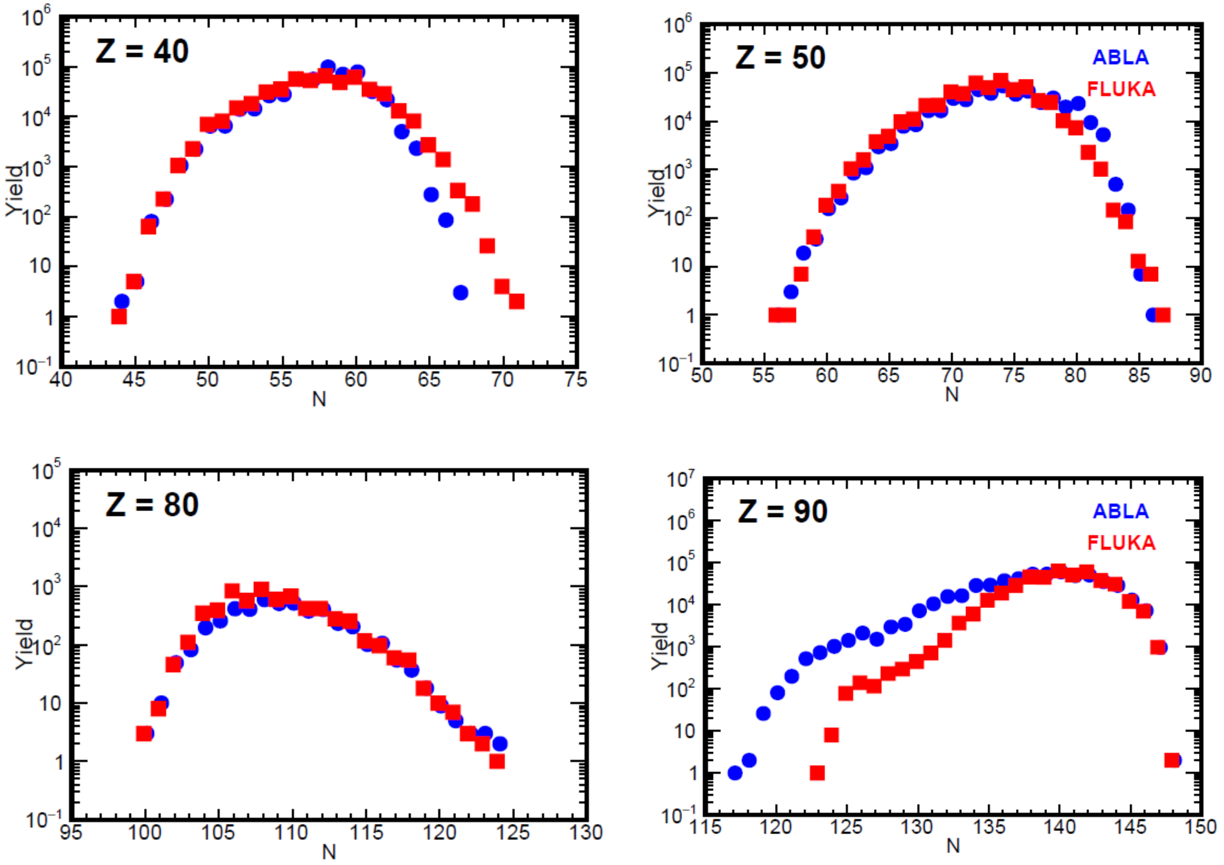


FLUKA and *ABLA07* are largely in agreement about EIC production rates

^{208}Pb



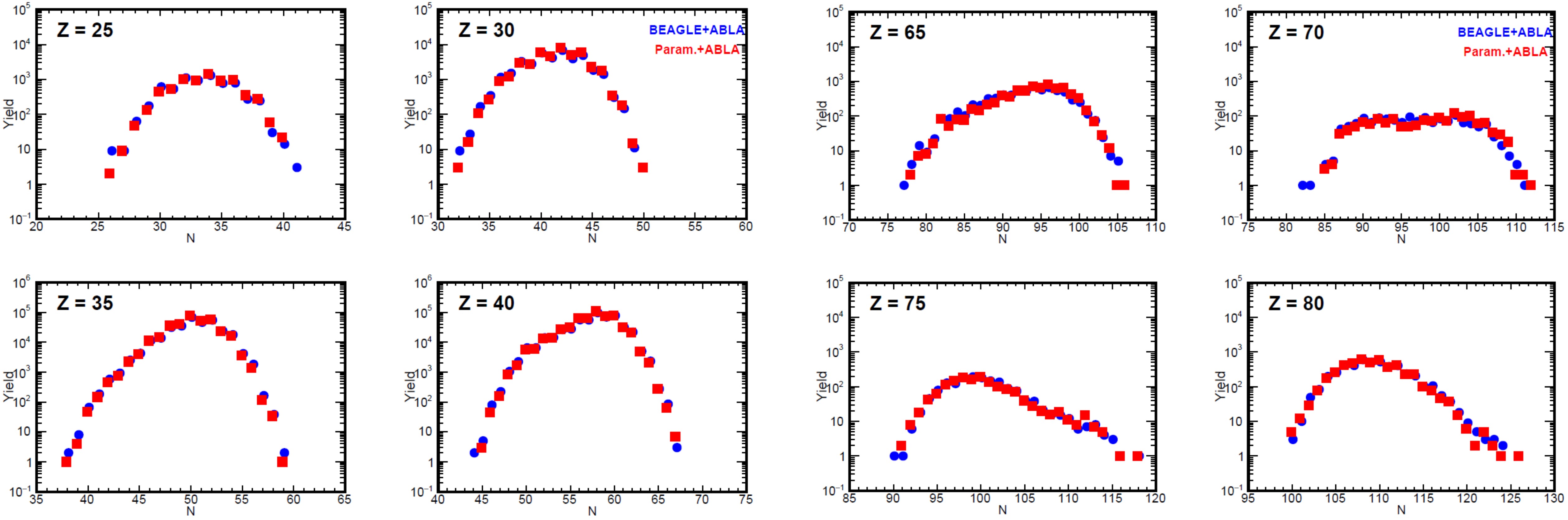
^{238}U



We need to simulate much more than 10 million events

- Using a *Pythia6* simulation where we generate over the entire allowed kinematic phase space (i.e. all the way down to photoproduction), we see that the total scattering cross section is about 100 μb.
- If we make the assumptions that 1) we collect 10 fb^{-1} integrated luminosity per year and 2) the production of nuclear isotopes is independent of the kinematics (i.e. Q^2 and x), we can estimate than 10 million events will correspond to about 5 minutes of running.
- Even though the above calculation is very rough, it clearly shows that we need to generate much larger quantities of events in order to study the EIC's capacity to produce rare isotopes.
- Generating larger number of events with *BeAGLE* becomes computationally expensive. Fortunately for us, all we care about is the production of the excited residual nucleus. And we can create a simple parameterization of the residual nucleus production based on the *BeAGLE* model.

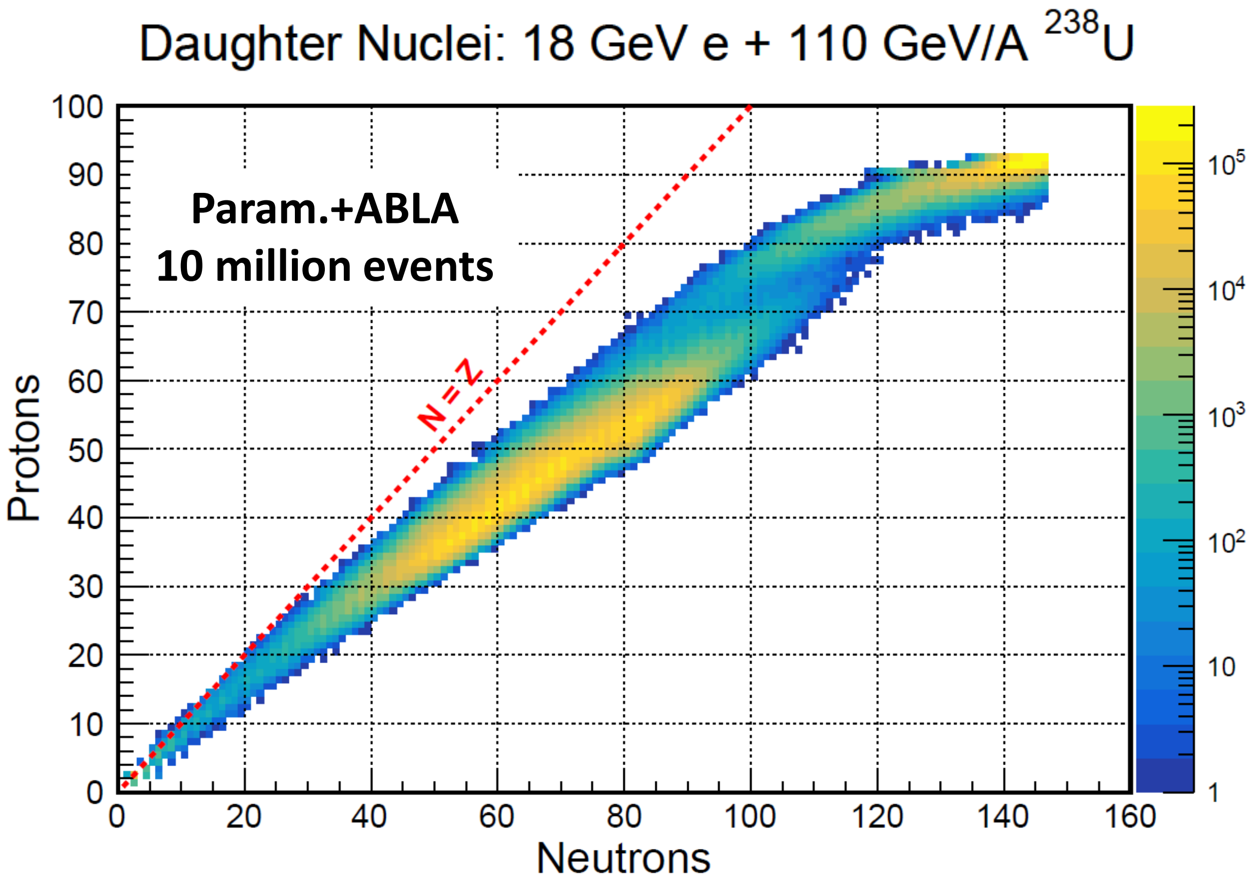
Comparison of *BeAGLE* results and parameterized distribution

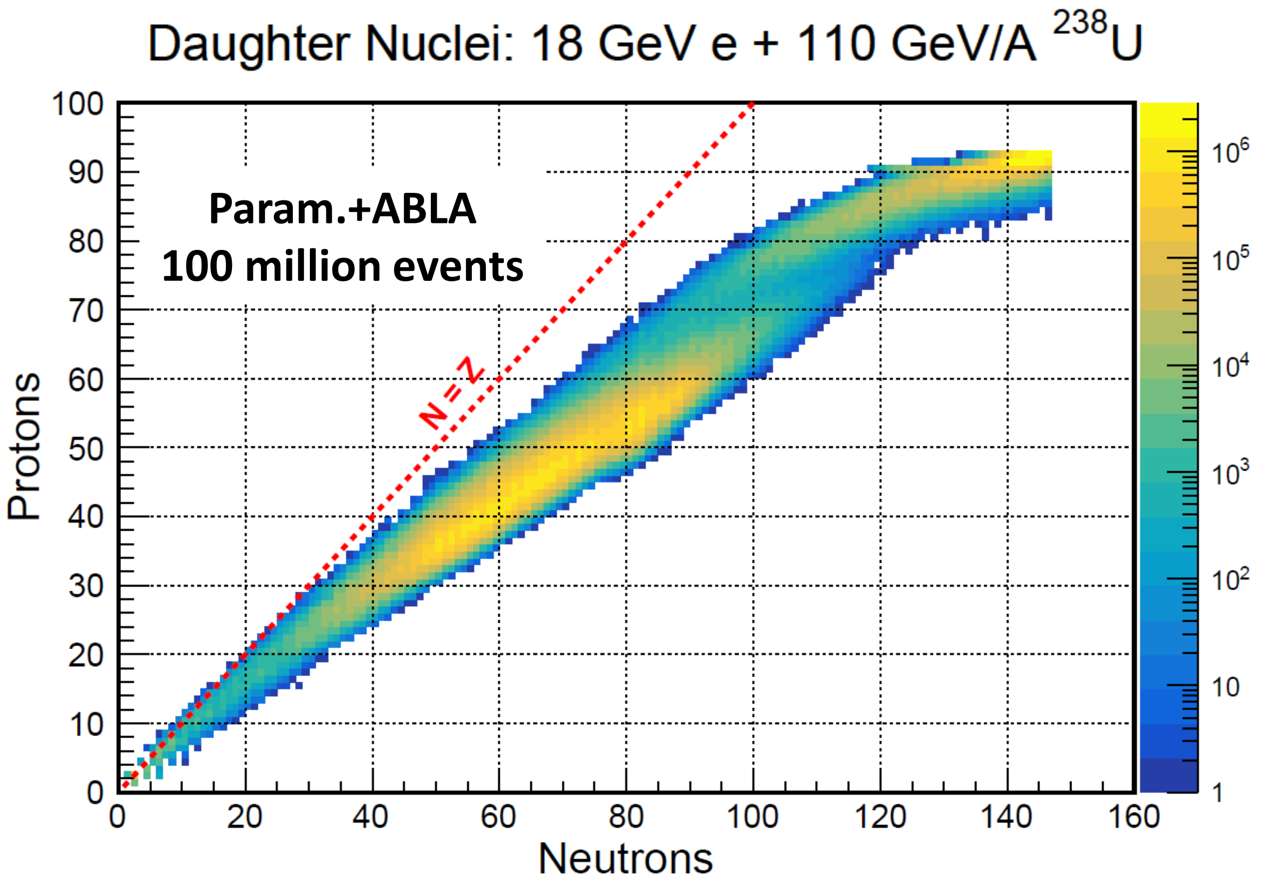


Using our parameterized model for the excited residual nucleus, we can generate 10 million events in 15 minutes.

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

Towards higher statistics simulations





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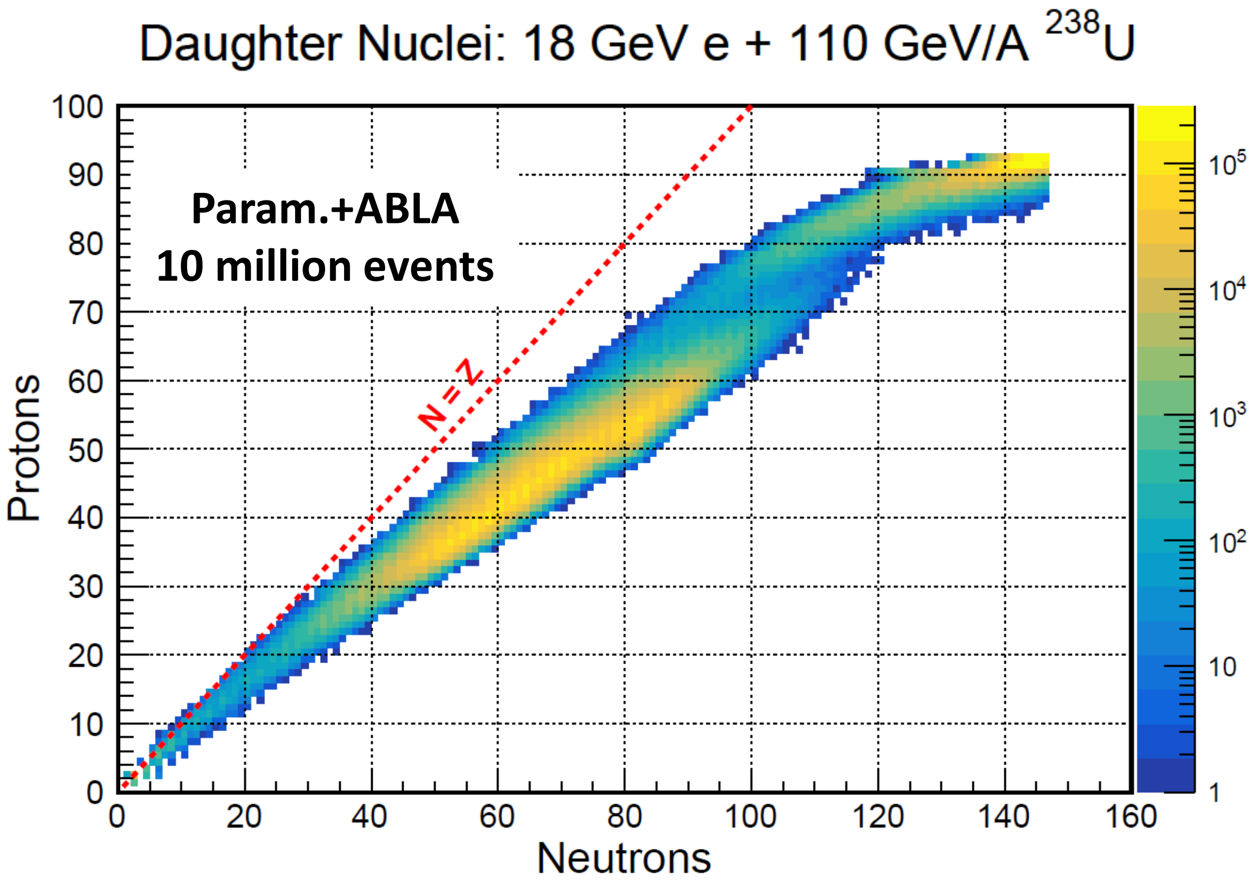
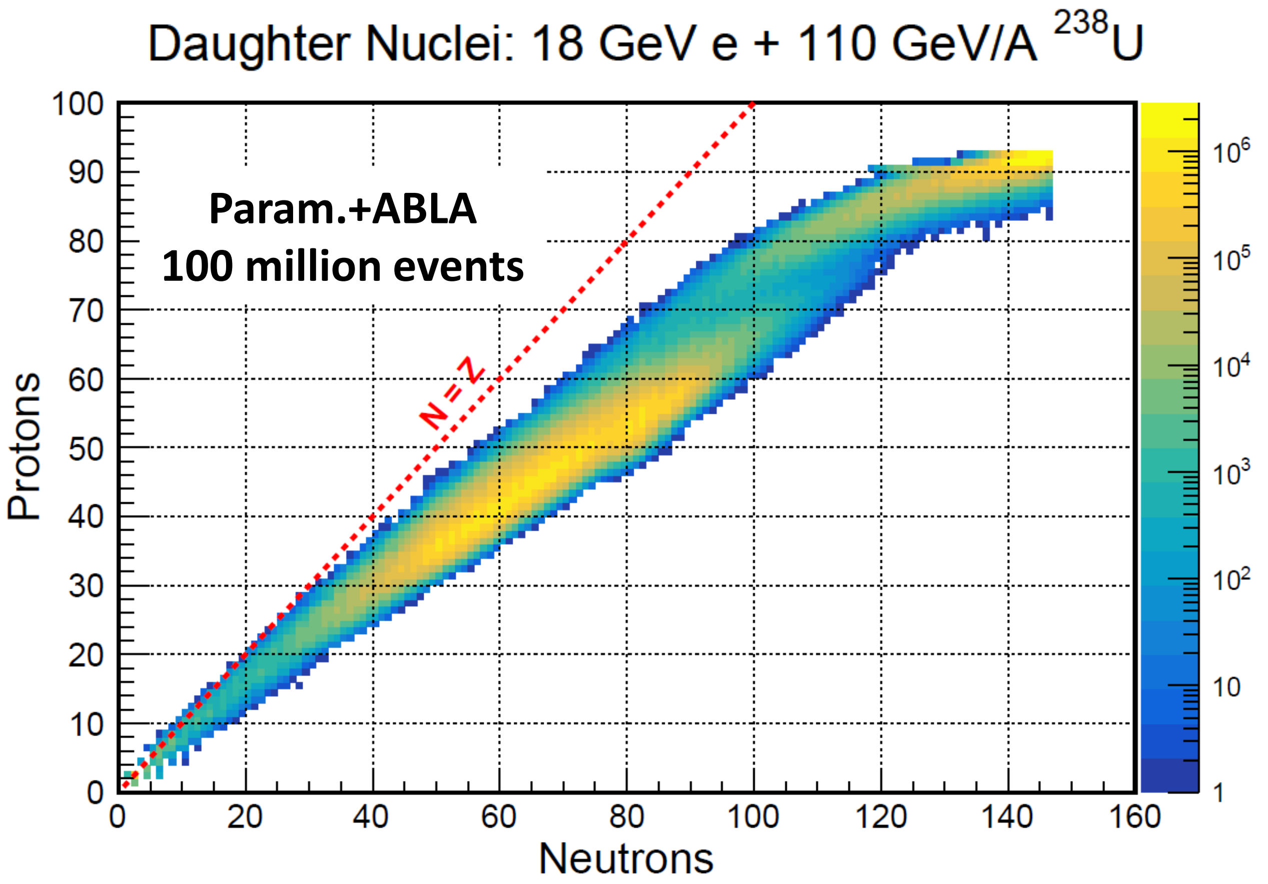
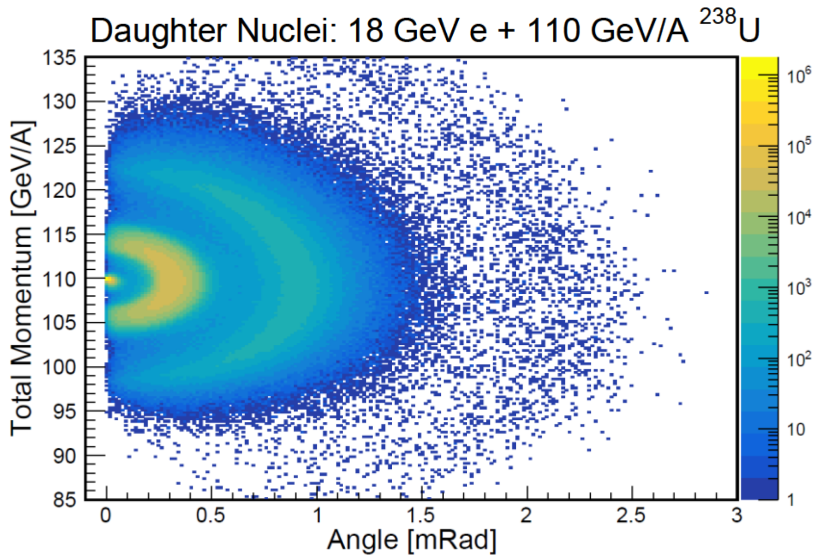




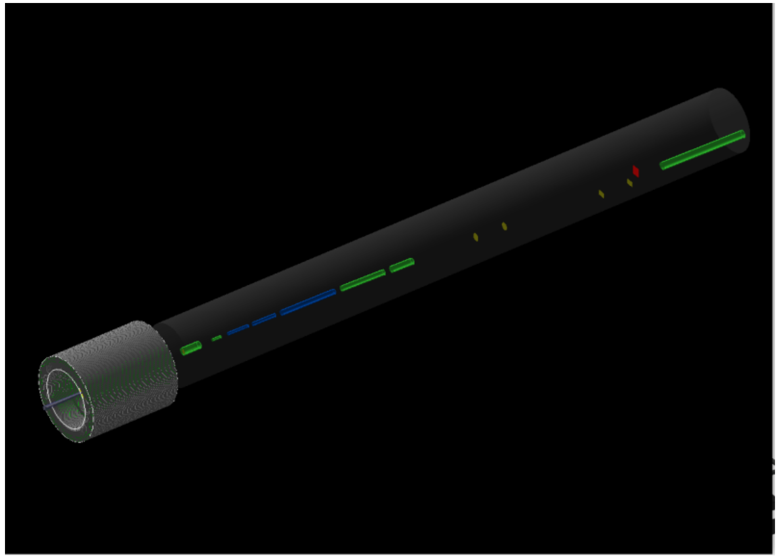
Note how borders expand as more events are generated. Also working with *LISE++* software for production cross section estimates.

Detection and identification of the nuclear isotopes

- Our simulation studies suggest that the daughter isotopes of the residual nucleus will be produced with (per-nucleon) momenta close the incoming ion beam momentum and with a very small scattering angles with respect to the ion beam.
- In order to detect these produced isotopes, we will need to use the far-forward part of the interaction region.



BeAGLE
+
FLUKA



Far-forward magnets and detectors of IR6 in the *Fun4All* simulation framework

Isotope detection under a simple assumption

In the simplest assumption, the momentum per-nucleon of the outgoing isotope (p_N) is the same as the momentum per-nucleon of the incoming beam ($p_{N,beam}$).

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

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

We can calculate various quantities – such as the isotope hit position at a Roman Pot (RP) and whether the isotope is within the RP acceptance – using the above equation.

Some definitions:

$$Rigidity = R = \frac{p}{Z}$$

$$x_L = \frac{R}{R_{beam}}$$

$$Relative\ Rigidity = R_{Rel} = \frac{R - R_{beam}}{R_{beam}} = x_L - 1$$

We can then calculate the isotope hit position at a RP and the acceptance

Hit position:

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

Minimum allowed hit position:

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

Accelerator Parameters:

$\varepsilon_x = 43.2\ nm$ (EIC CDR Table 3.5)

$\sigma_p = 6.2 \times 10^{-4}$ (EIC CDR Table 3.5)

IR6 parameters at first RP:

High-divergence setting (may be slightly out-of-date).

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

IR8 parameters at first RP:

$$\beta_x = 2.28\ m$$
$$D_x = 38.2\ cm$$
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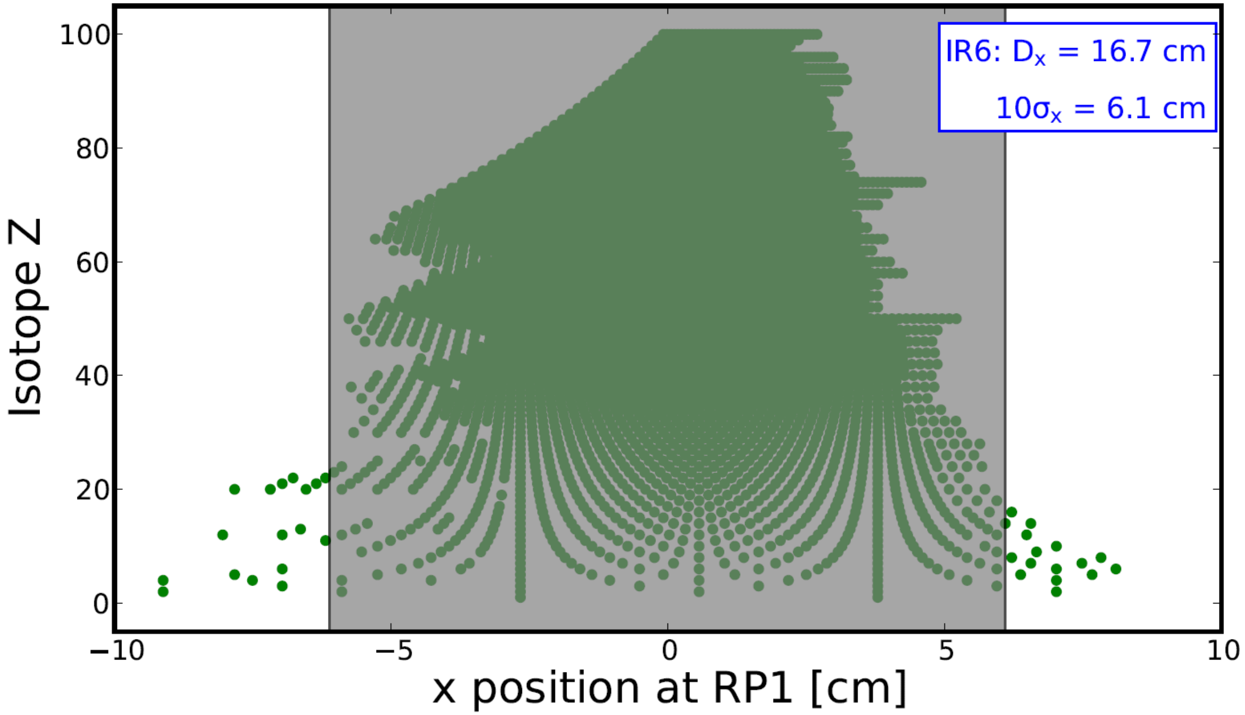
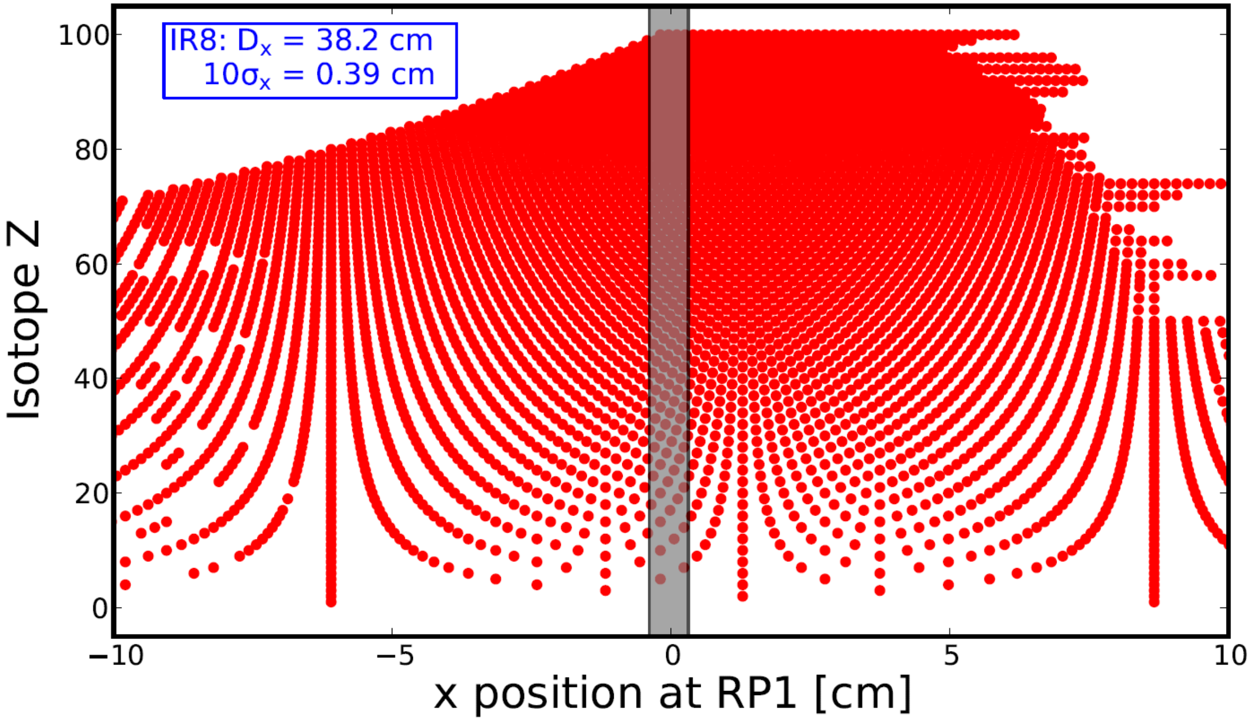
Big acceptance difference between the two IRs is caused by the second focus at the RPs in the IR8 design

Isotope hit positions at the first RP vs. isotope Z

IR6



IR8



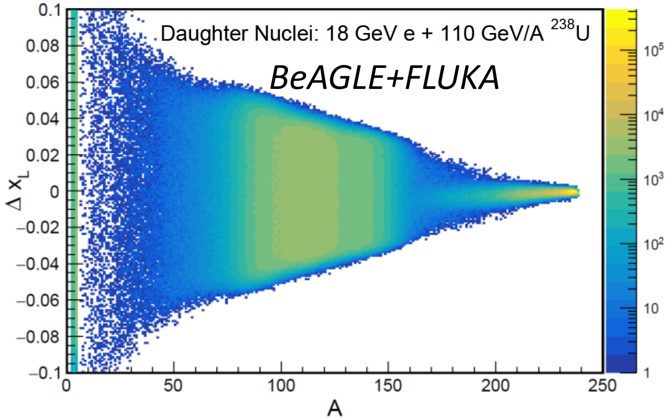
Each point is an individual isotope. All known and potential isotopes which come from a combined NNDC and LISE++ database are included.

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

Some comments on above results

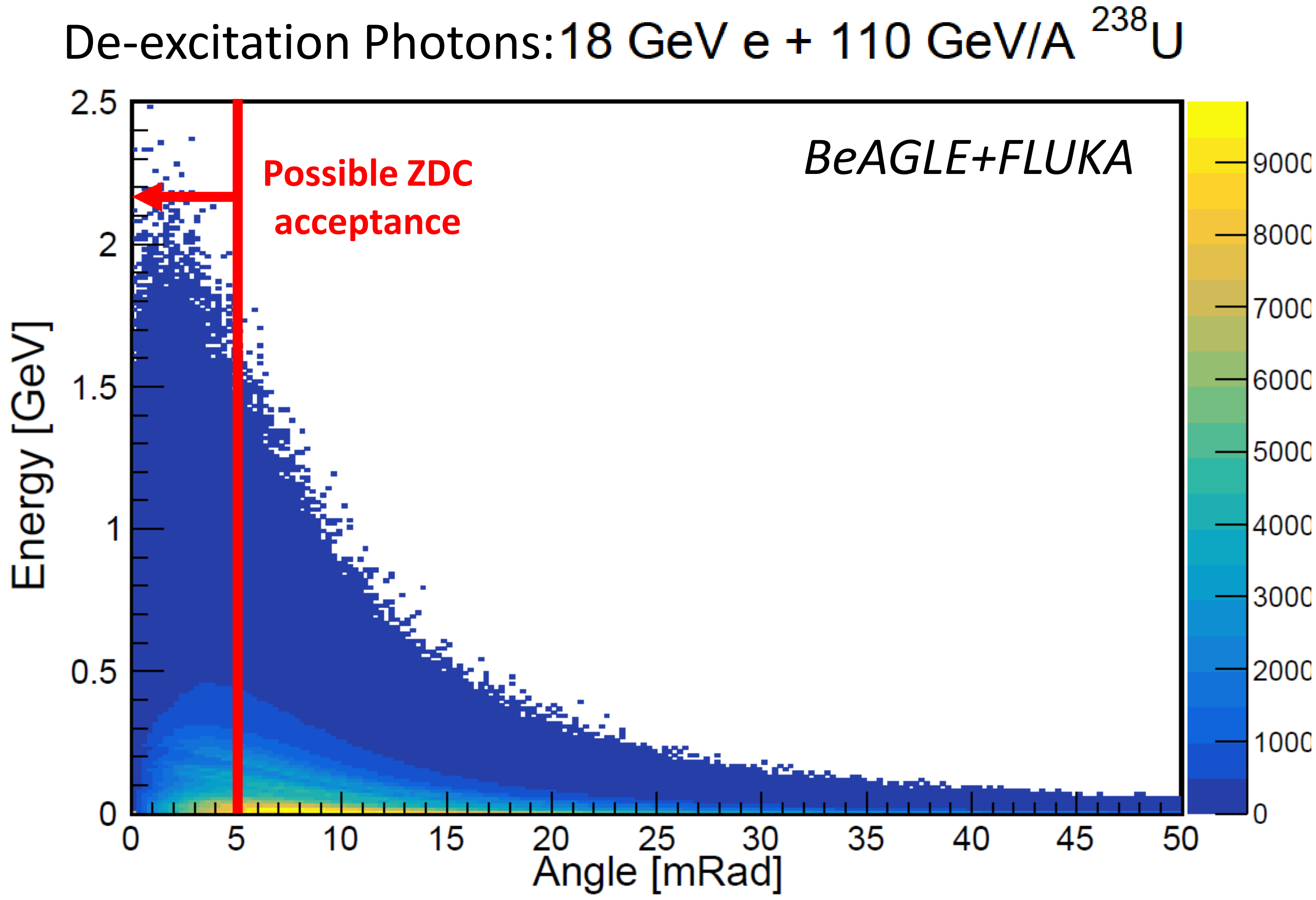
- The above plots show that a large fraction of the potential isotopes can be accepted and correctly identified using the position at the RP.
- This assumes that the charge of the isotope (Z) has already been determined.
- A thin (few mm thick) quartz bar can be placed in the RPs at the second focus behind the tracker to determine Z^2. 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, and the challenge will be to measure the photons with high enough precision.

- The assumption made in the plots on the previous slide is that the outgoing isotope has the same momentum-per-nucleon as the ion beam and no angle with respect to the ion beam. Under this assumption, the isotope hit position at the RPs is just a function of (A/Z).
- This assumption works well in the evaporation region; but less well in the fission region – where the kinetic energy in the excited residual nucleus rest frame can be 1 MeV/nucleon.



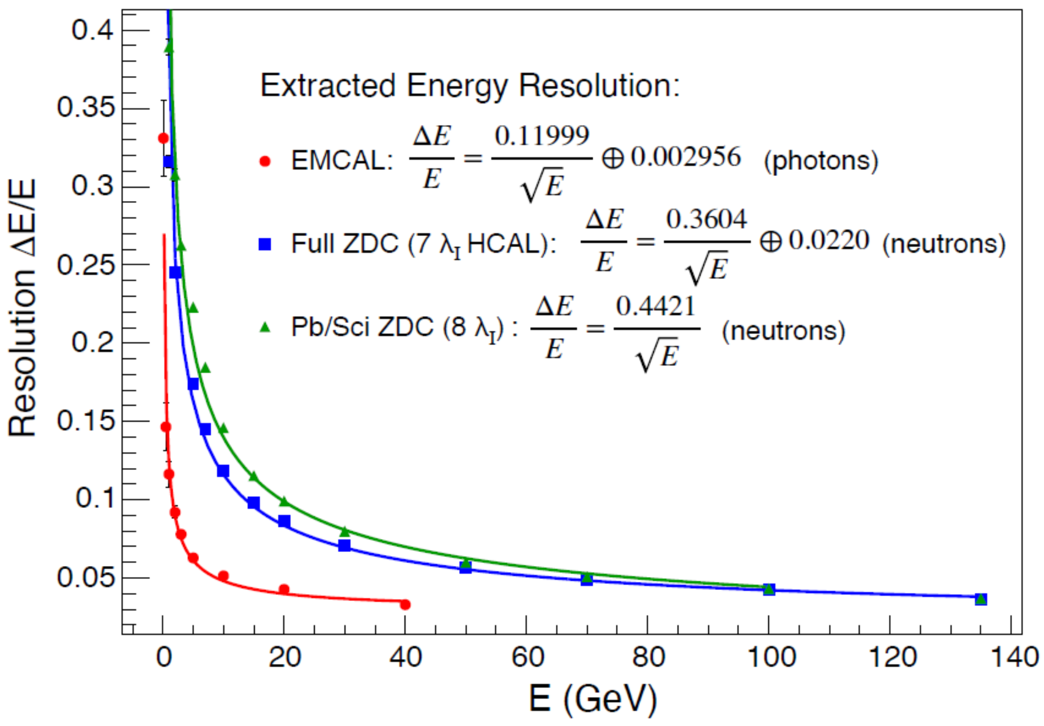
$$\Delta x_L = x_L - \left[\left(\frac{A}{Z}\right) \Big/ \left(\frac{A_{beam}}{Z_{beam}}\right) \right]$$

Detection of the de-excitation photons



Detection of the de-excitation photons

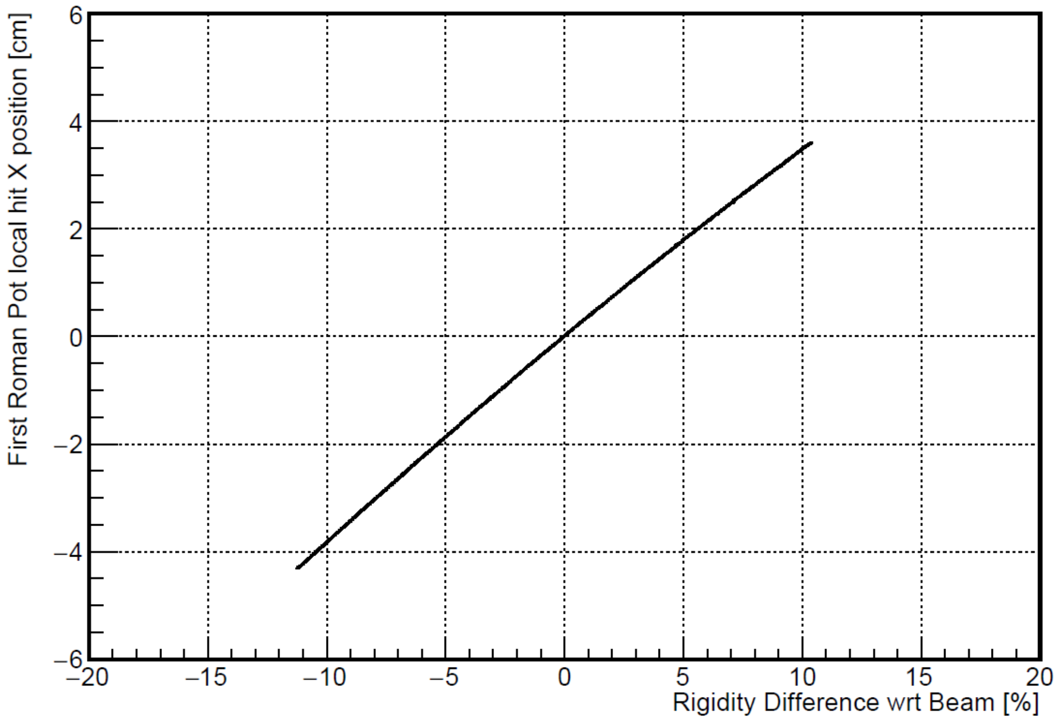
- We will not need to detect all photons (since they are not serving as a veto). But some photons will be at small energies.
- For example, consider the 2.6MeV photon from ^{208}Pb de-excitation, for a 100 GeV/A beam.
- If the photon decays in the direction of the beam, it's energy in the lab will be 558 MeV. If it decays in the opposite direction, it will have an energy of 0.01 MeV. If it decays backwards, at an angle of 120^{o} in the rest frame relative to the beam direction, it will have an energy of 140 MeV in the lab frame and a small angle w.r.t the beam.



ZDC for detector 1. Taken from ATHENA proposal. ZDC EmCal is W/SciFi. Expected resolution is ~40% for 100 MeV photons.

Ongoing work

- ❑Discussion with experts at RIB facilities on opportunities at the EIC. Ongoing collaboration with Oleg Tarasov, who is the *LISE++* developer.
- ❑Higher statistics simulations.
- ❑Simulation studies of the 'baseline' IR8 far-forward region in *Fun4All*. See plot on right.
- ❑Improvement of *BeAGLE* model
- ❑Determination of ZDC resolution requirements for detection of de-excitation photons.



Protons transported to first RP near 2nd focus in IR8 'baseline' *Fun4All* simulation.

Summary

- We have shown that the EIC has the potential to produce nuclear fragments.
- These nuclei can be detected and identified using the proposed optics of the second interaction point with its secondary focus.
- Studying these fragments and the associated de-excitation photons will allow the EIC to complement the work done at dedicated rare isotope facilities.