Production and Detection of Exotic Nuclei in the EIC

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Motivating Questions

- Would the high-energy electron-heavy nucleus scattering of the future EIC have the capability to produce exotic nuclei?

- Can we go on to detect and correctly identify the produced exotic nuclei?

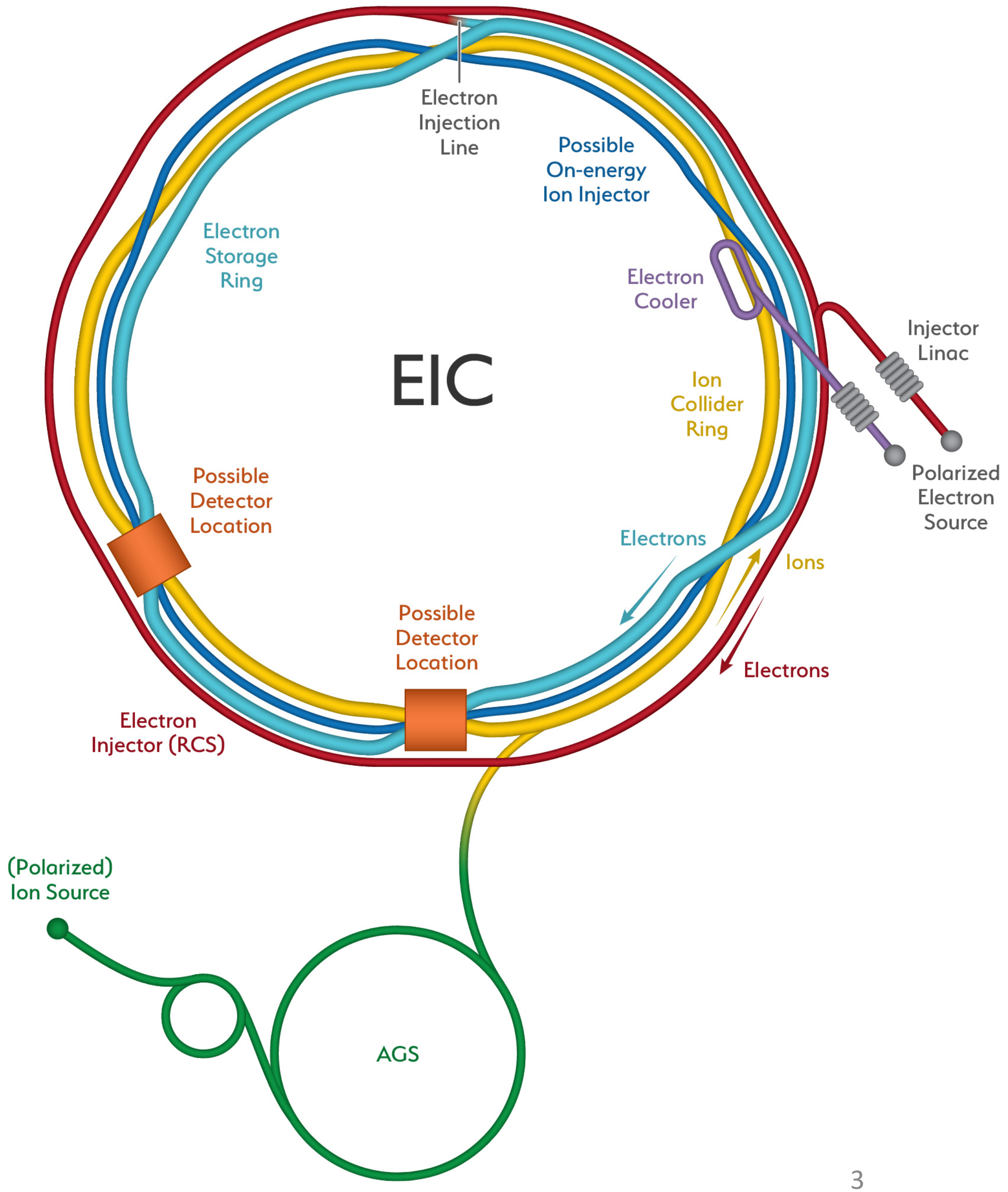
- Can we also study the level structure of the nuclei by detecting the decay photons? What requirements does this place on the far-forward detection area?

Rare Isotopes at EIC

EIC isn't a dedicated rare isotope facility.

Advantages of EIC in Rare Isotope Studies:

- High energy collisions
- Survey-type experiment



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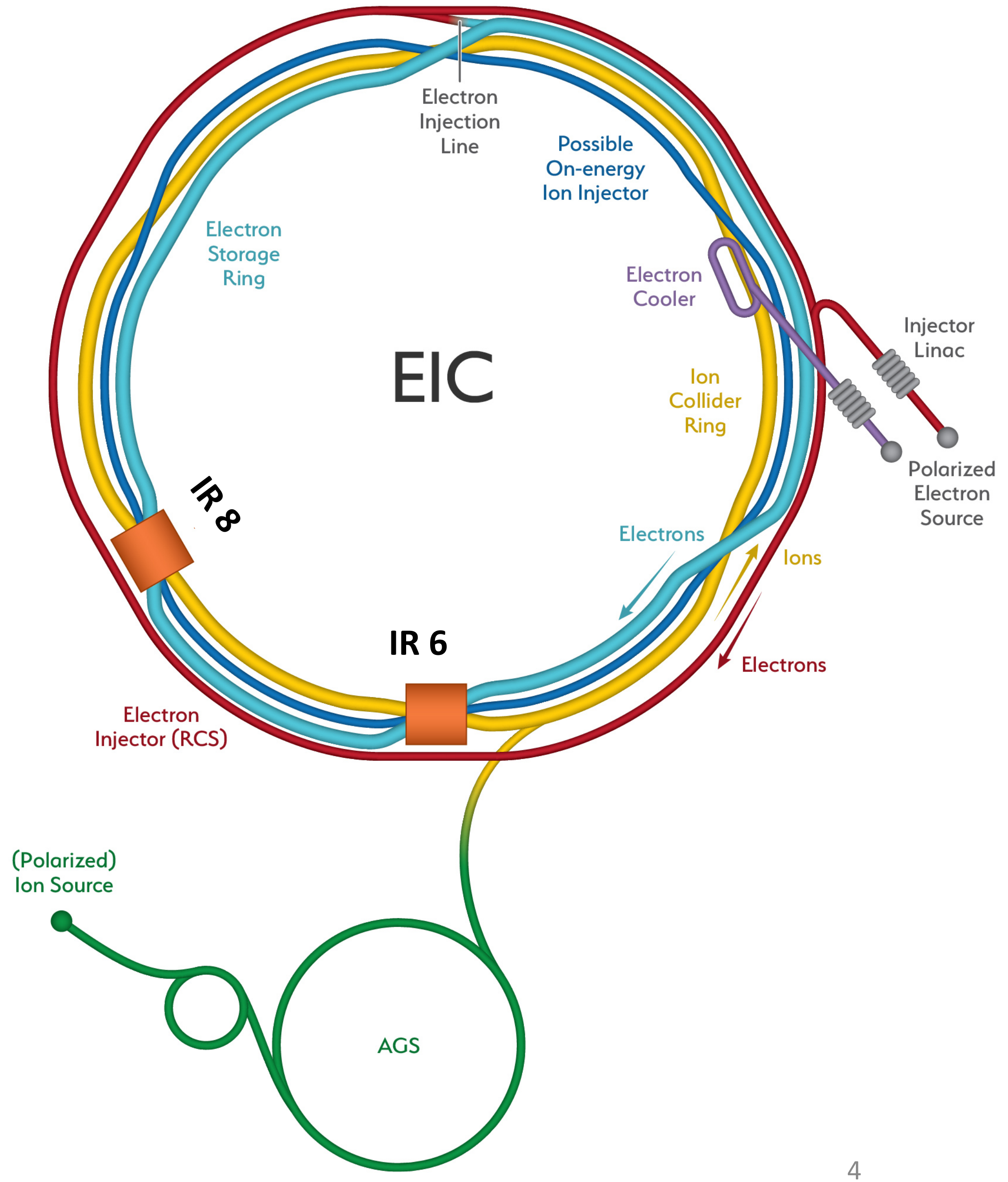
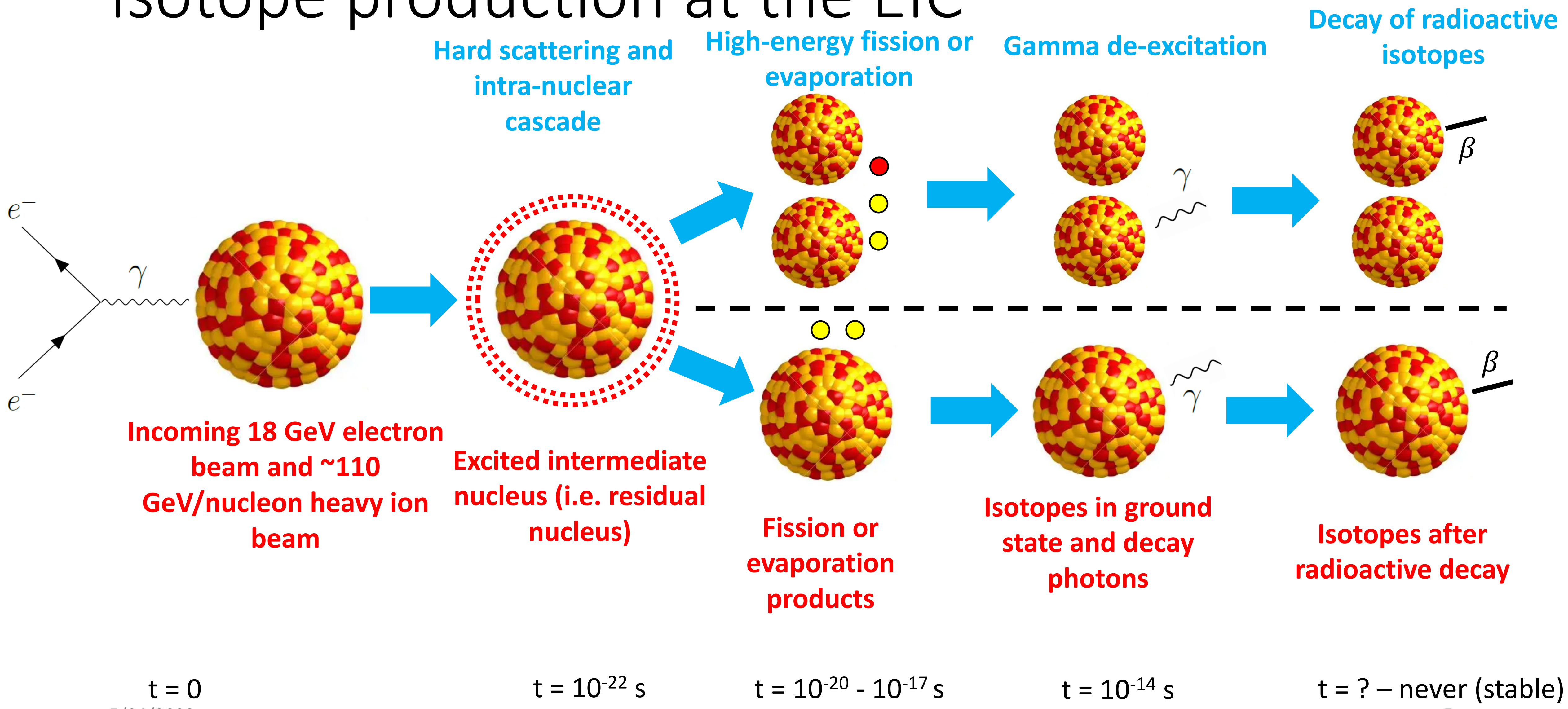
2 Interaction Regions: IR6 and IR8

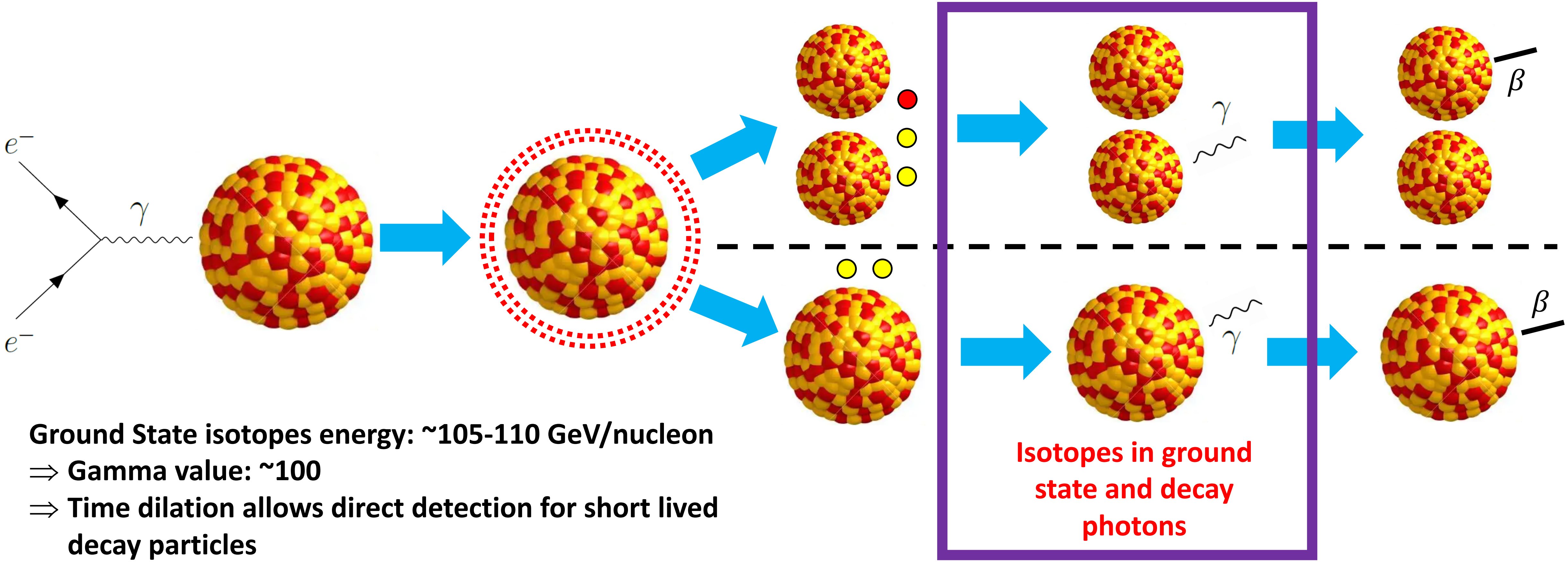
2022 EIC Detector Proposal Advisory Panel report cites these types of studies when discussing potential future experiments.



Isotope production at the EIC



Isotope production at the EIC



Ground State isotopes energy: ~105-110 GeV/nucleon
⇒ Gamma value: ~100
⇒ Time dilation allows direct detection for short lived decay particles

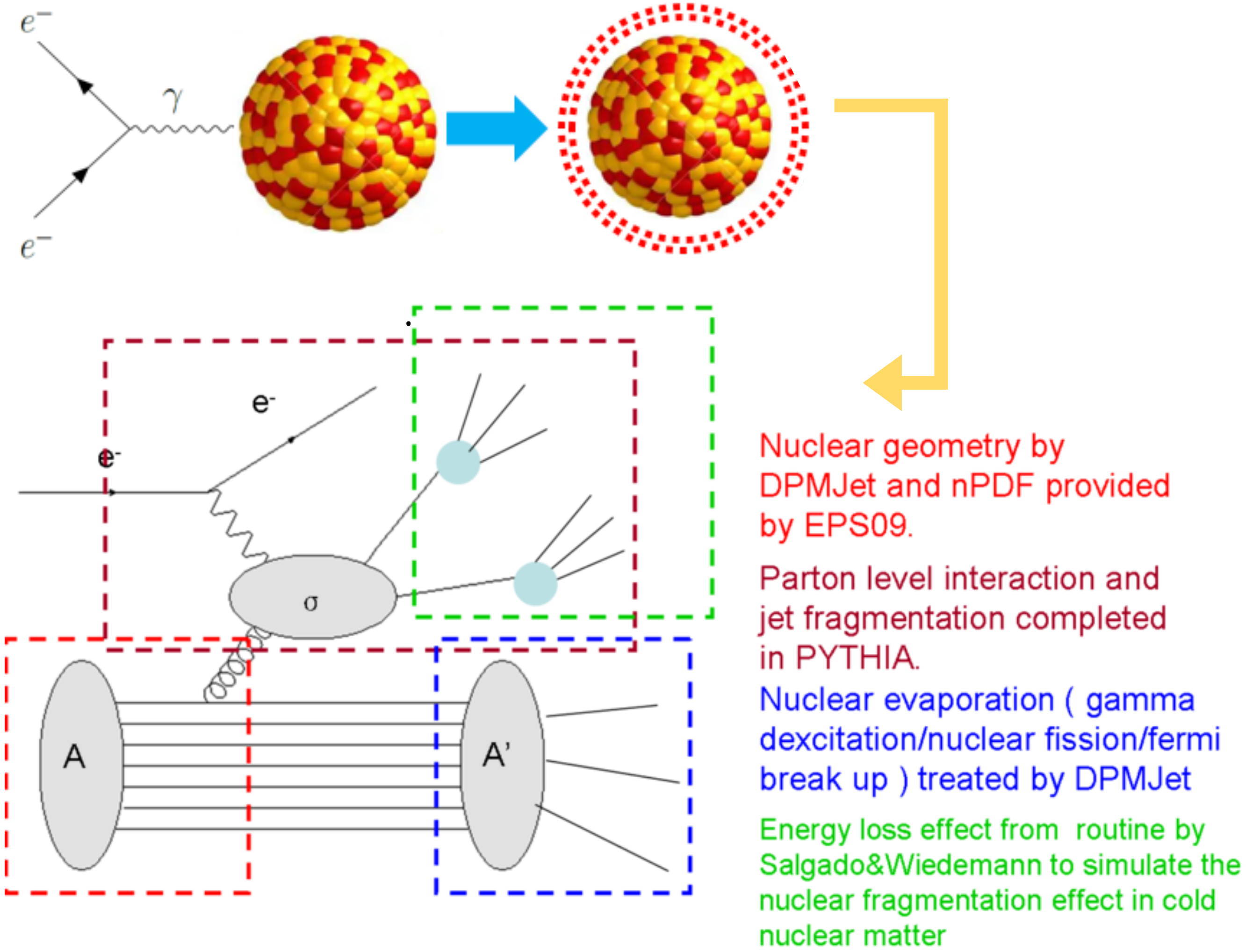
This is primarily where the EIC could potentially contribute

Hard scattering and intra-nuclear cascade using BeAGLE

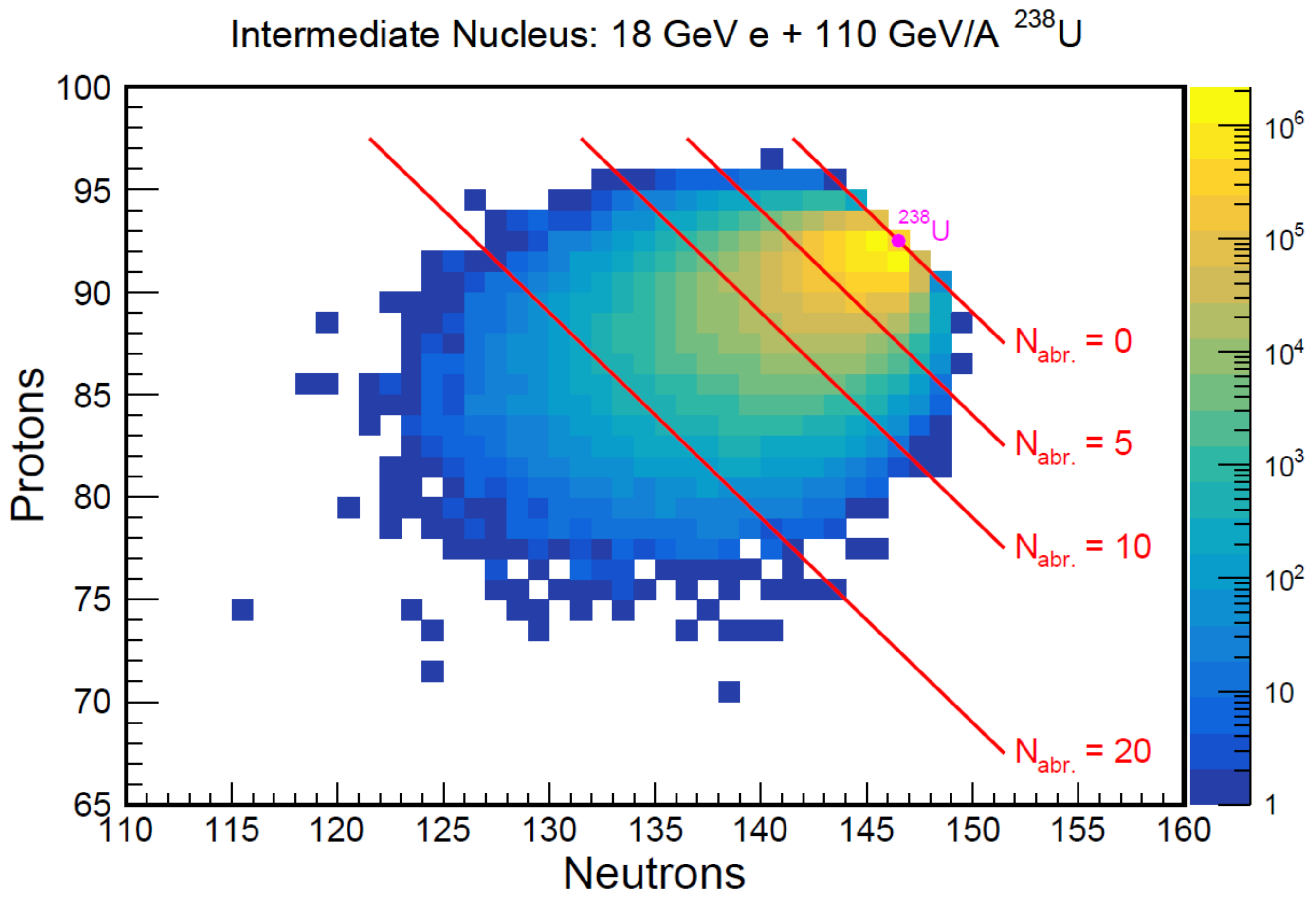
BeAGLE (Benchmark eA Generator for Leptoproduction) is the software we use to simulate the hard scattering and intra-nuclear cascade

Using BeAGLE, we simulated 10 million events to give us the A, Z, and Excitation Energy (E*) of all the excited intermediate nucleii

Leaves us with the residual nucleus in an excited state for the next stage of simulations



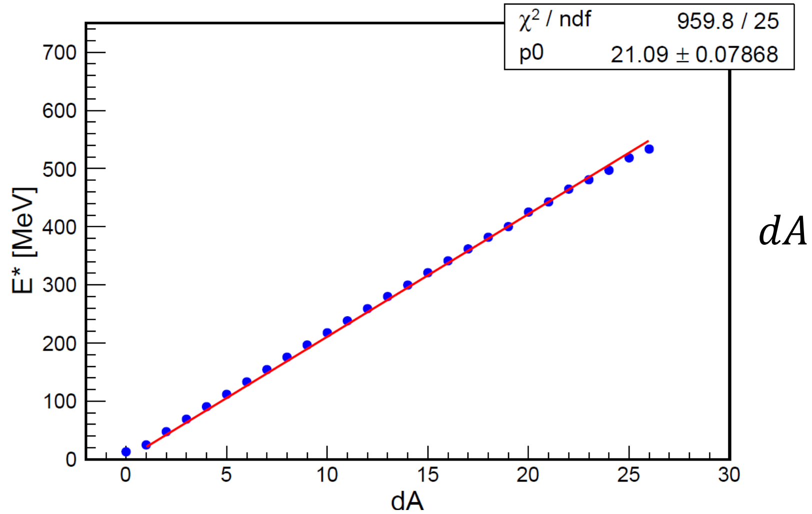
Excited Intermediate Nucleus from BeAGLE



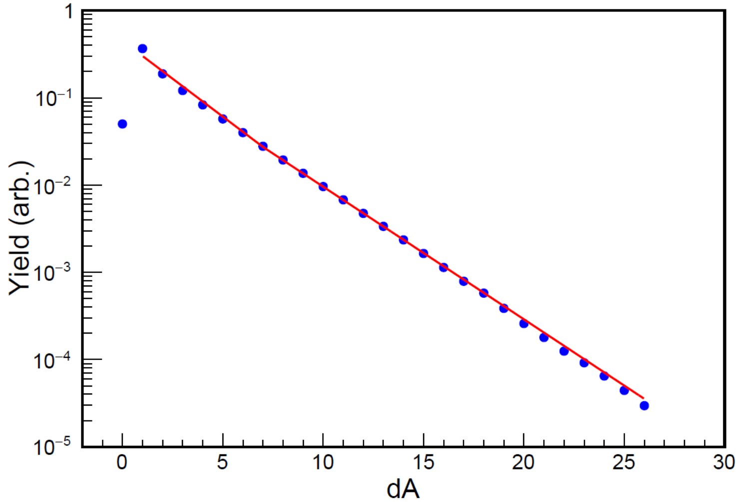
The distribution of isotopes created during this stage
←

Excited Intermediate Nucleus from BeAGLE

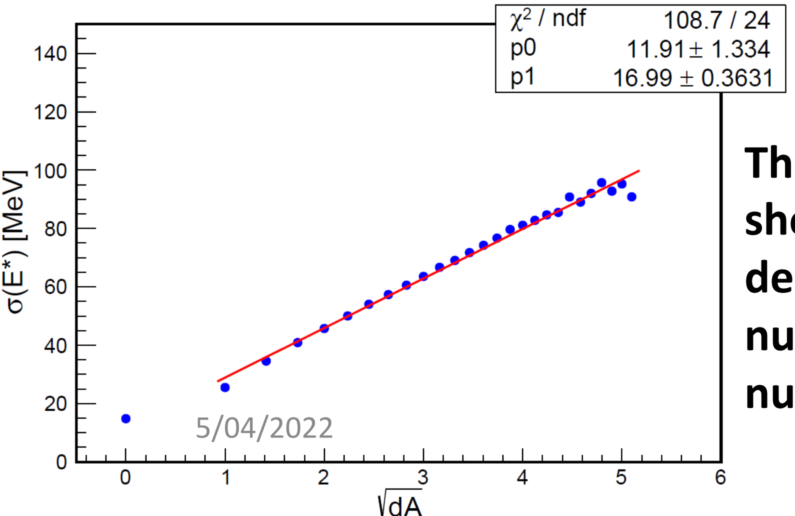
We find that the production of the residual nucleus in *BeAGLE* manifests as a very simple abrasion model:



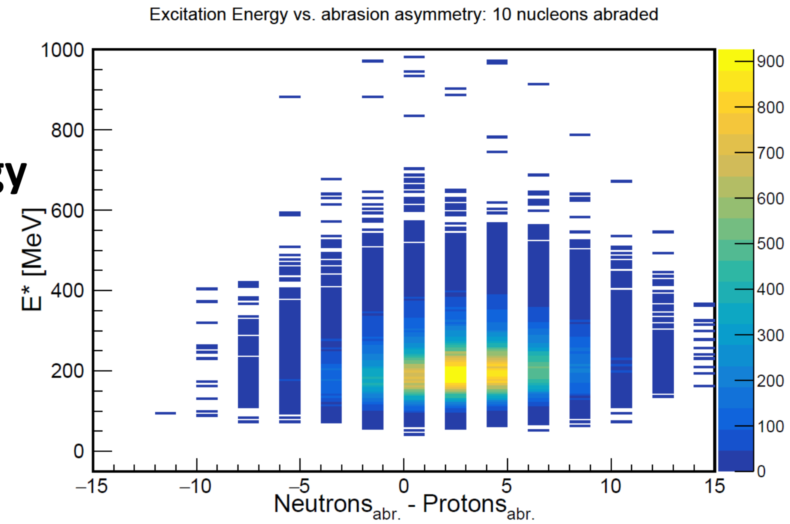
$$dA = A_{beam} - A_{res}$$



The cross section for abrading a given number of nucleons (for dA>1) shows a (piecewise) exponential dependence.



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

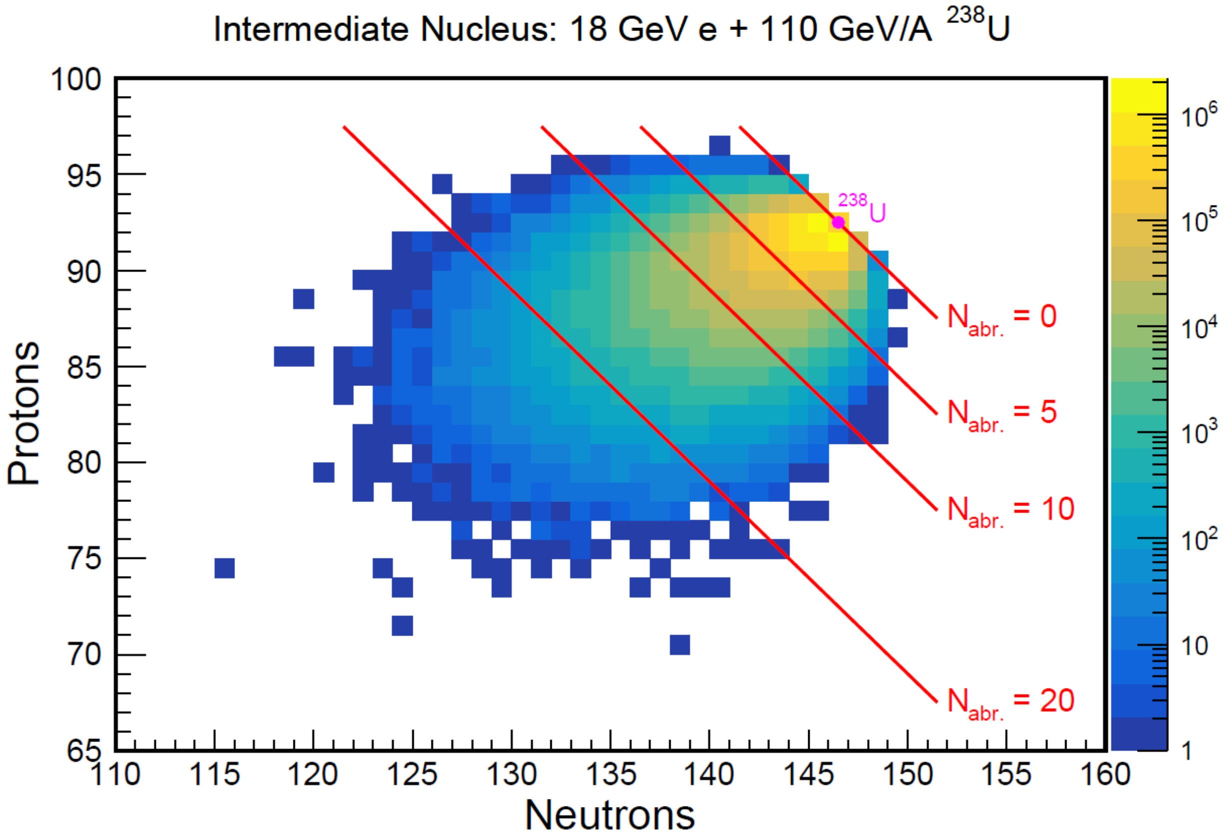


For a given number of abraded nucleons, the relative proportion of neutrons and protons abraded is close to a hypergeometric distribution

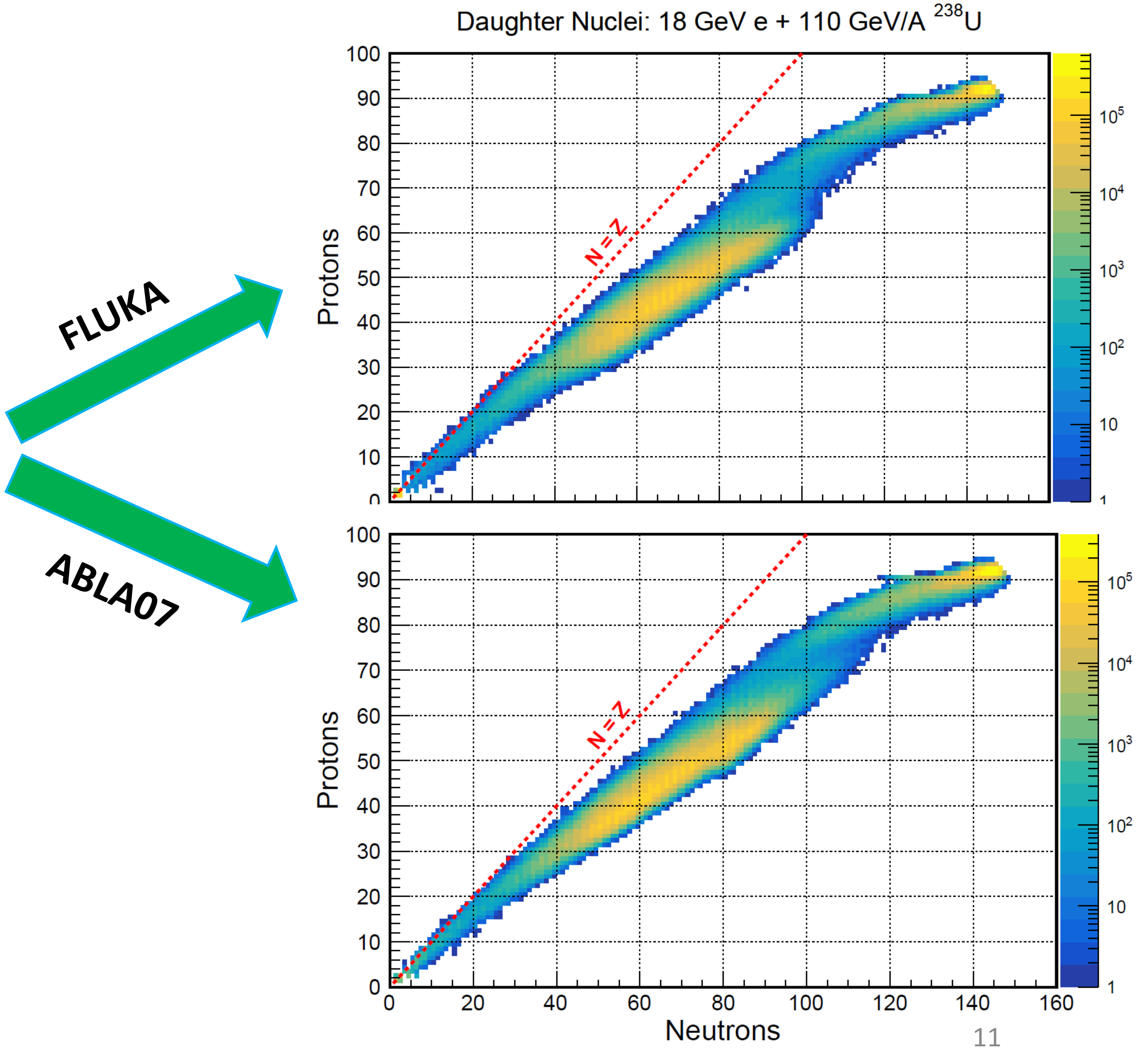
High-energy fission/evaporation and Gamma Decay using FLUKA and ABLA07

- To simulate the high energy decay and gamma de-excitation, we had 2 good options: FLUKA and ABLA07
- FLUKA:
  - Directly incorporated into the BeAGLE framework, allowing for easier analysis
  - Used extensively in high-energy physics, but not rare isotope production
- ABLA07:
  - The second part of the abrasion-ablation code *ABRABLA07*
  - Used extensively in rare isotope community
- We ran the BeAGLE events through both programs and compared the results.

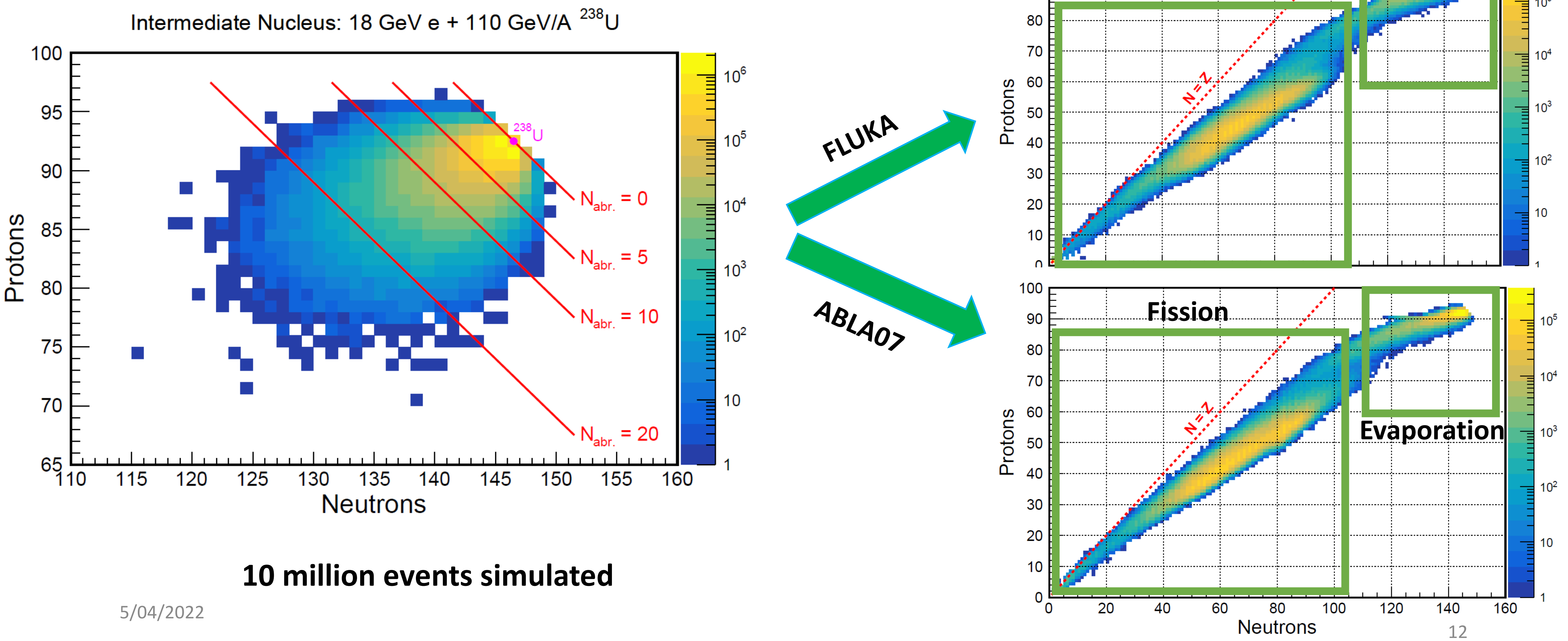
Fission and Evaporation Products in High Energy Decay



10 million events simulated



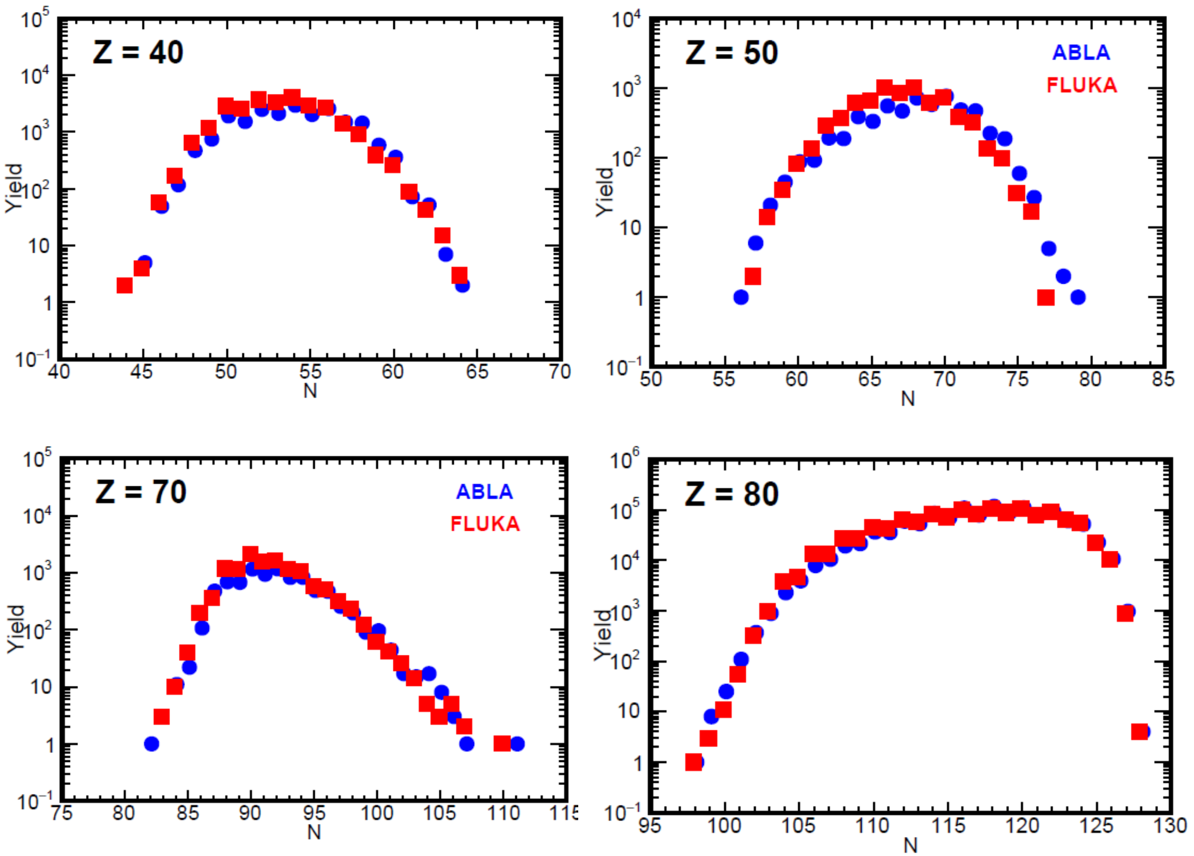
Fission and Evaporation Products in High Energy Decay



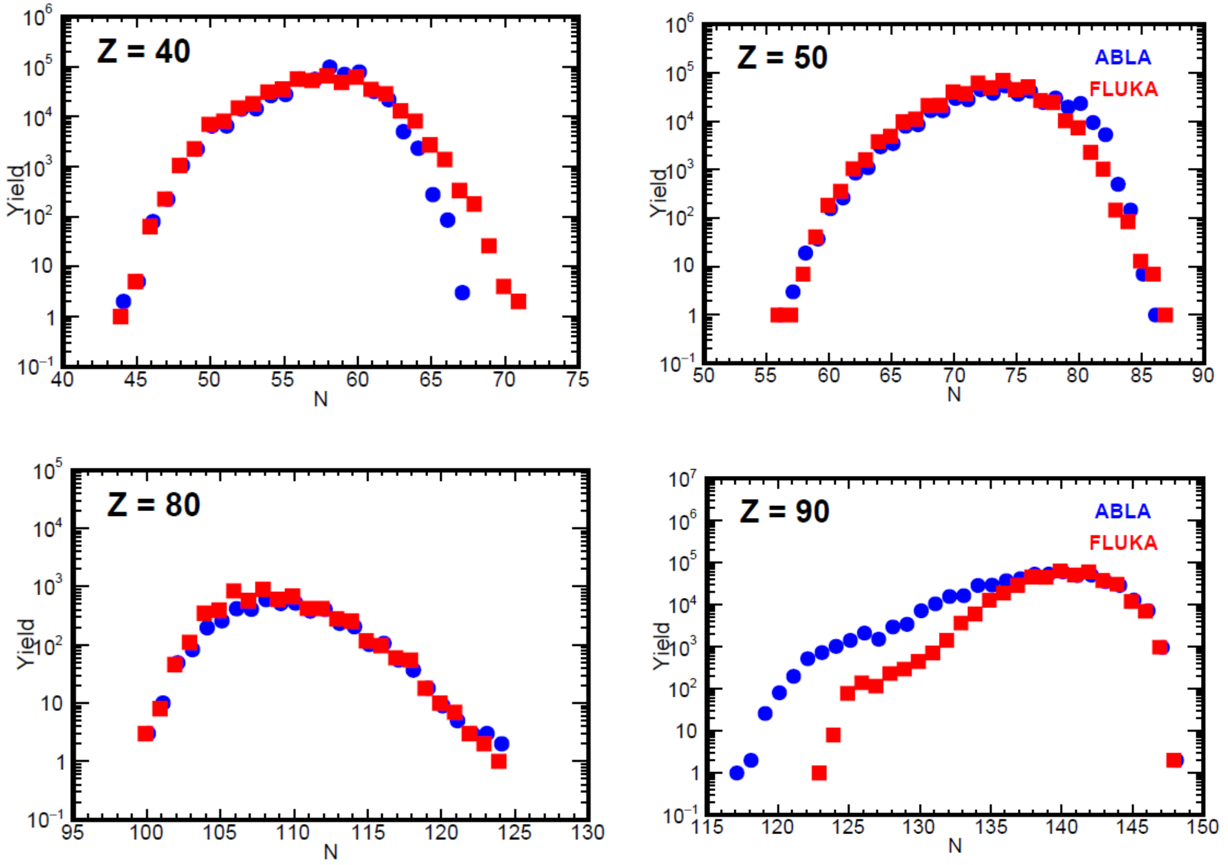
10 million events simulated

We can directly compare the results of FLUKA and ABLA07

^{208}Pb



^{238}U



Running High Statistics for High Scattering and Intra-Nuclear Cascade

- 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),

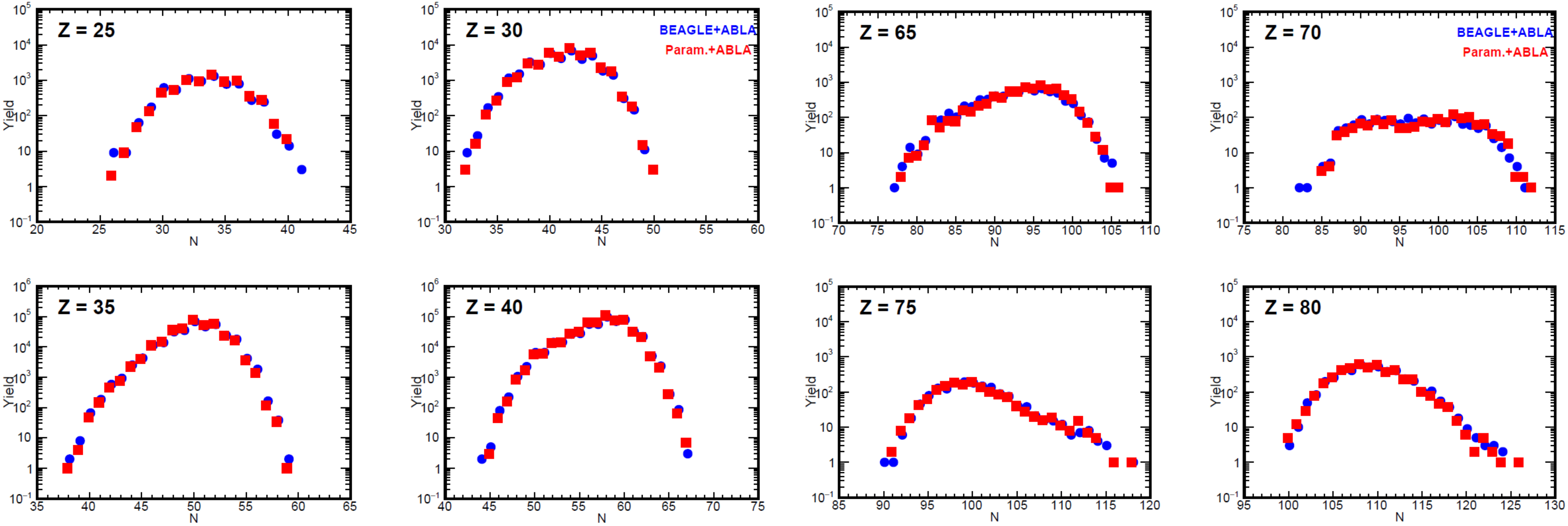
Those 10 million events correspond to ~5 min actual runtime, which isn't enough to get a full understanding of the EIC's capacity to produce rare isotopes.

To get ~1-2 months, that requires simulating ~100 billion events. Very computationally expensive!

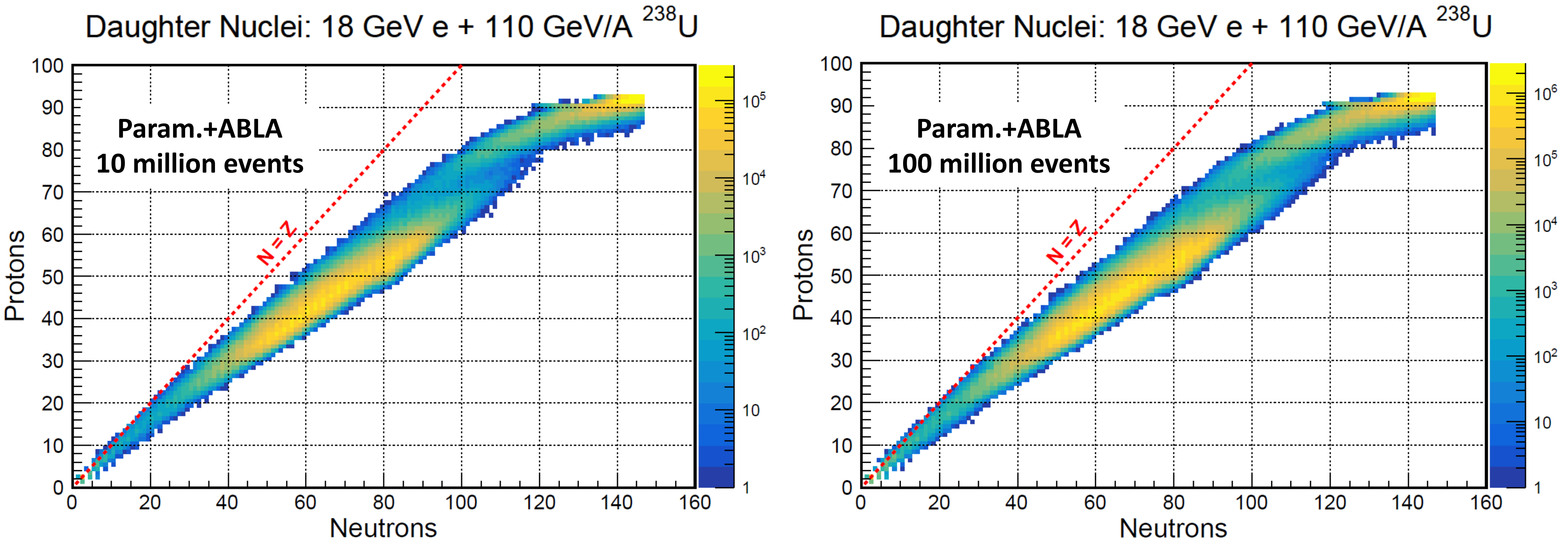
Comparison of *BeAGLE* results and parameterized distribution

Decay isotopes only care about A, Z, and E* of excited residual nucleus. We can create a basic parameterization of the BeAGLE intermediate isotope production and use that.

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



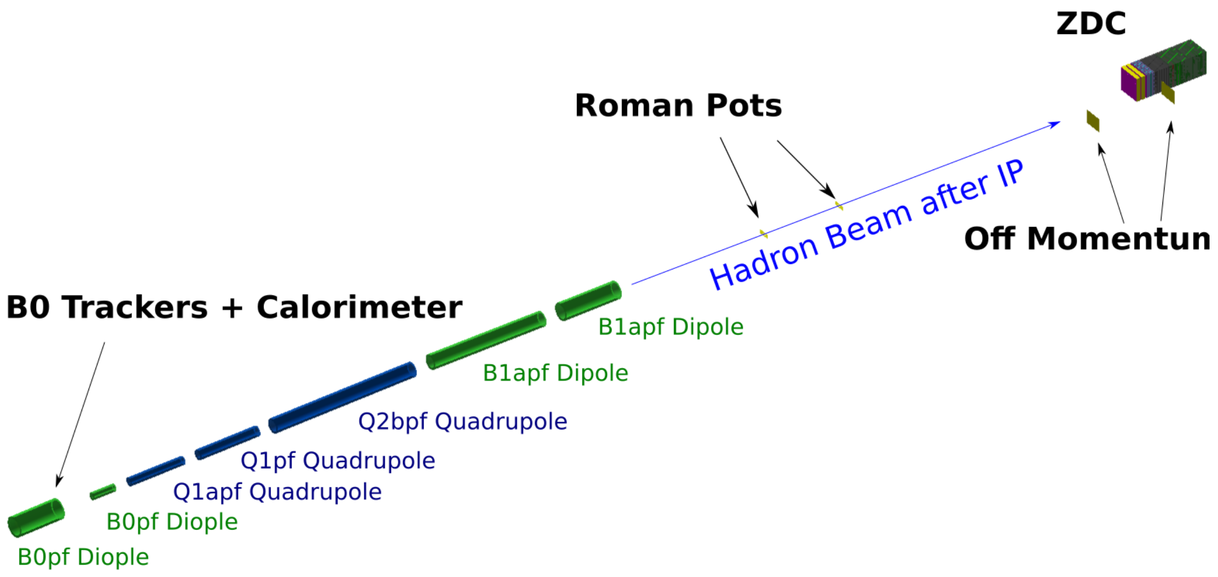
Towards higher statistics simulations

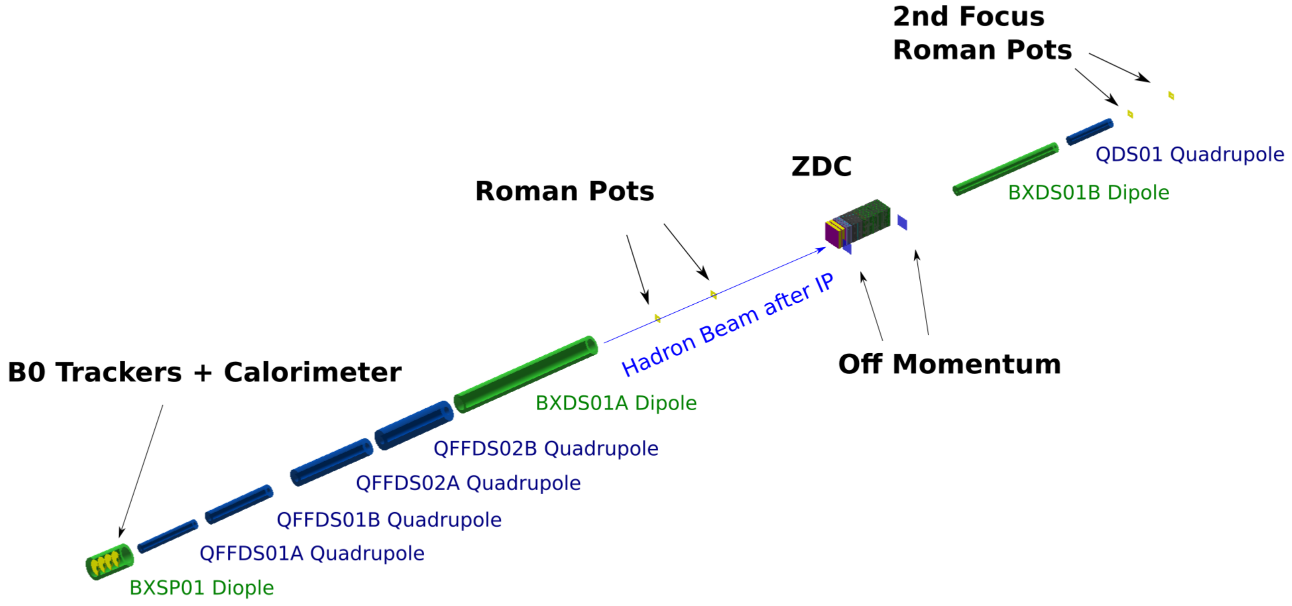


Detection and identification of the nuclear isotopes

IR6

IR8





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

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

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:

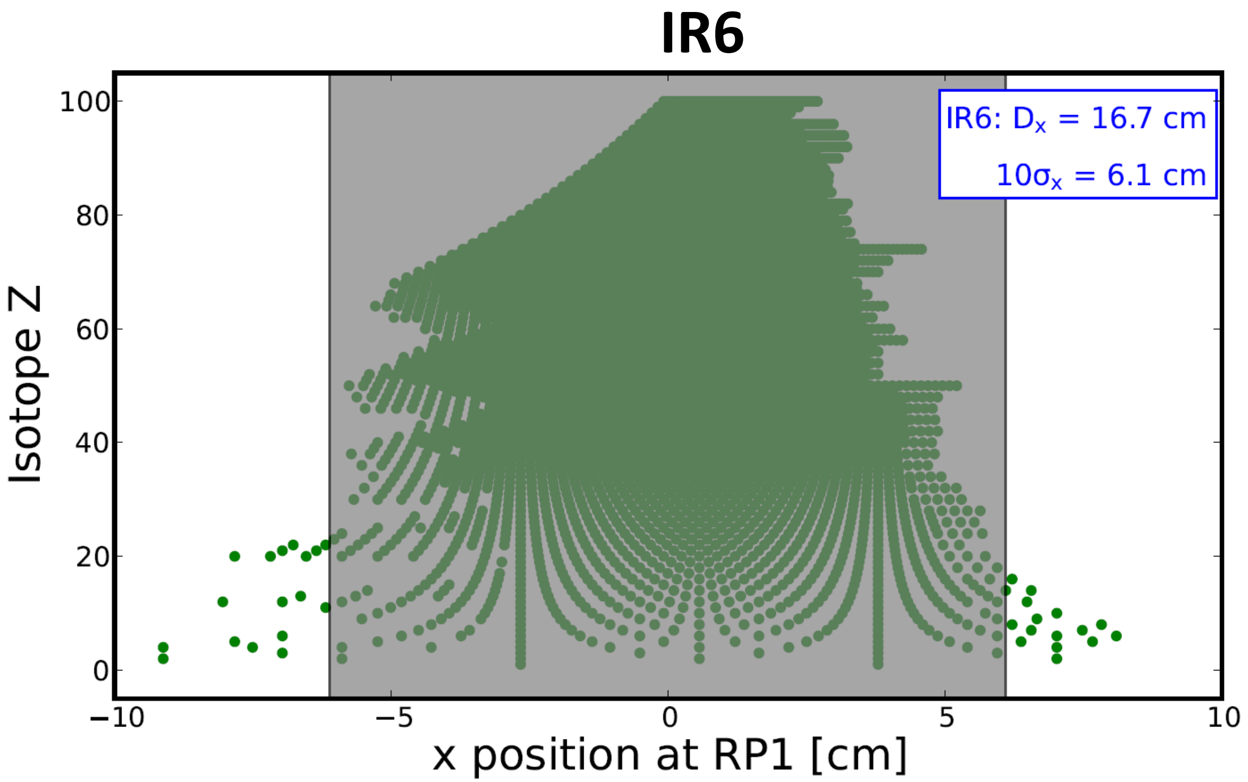
$$\beta_x = 865\ m$$
$$D_x = -16.7\ cm$$
$$\rightarrow x_{min}^{RP1} = 6.11\ cm$$

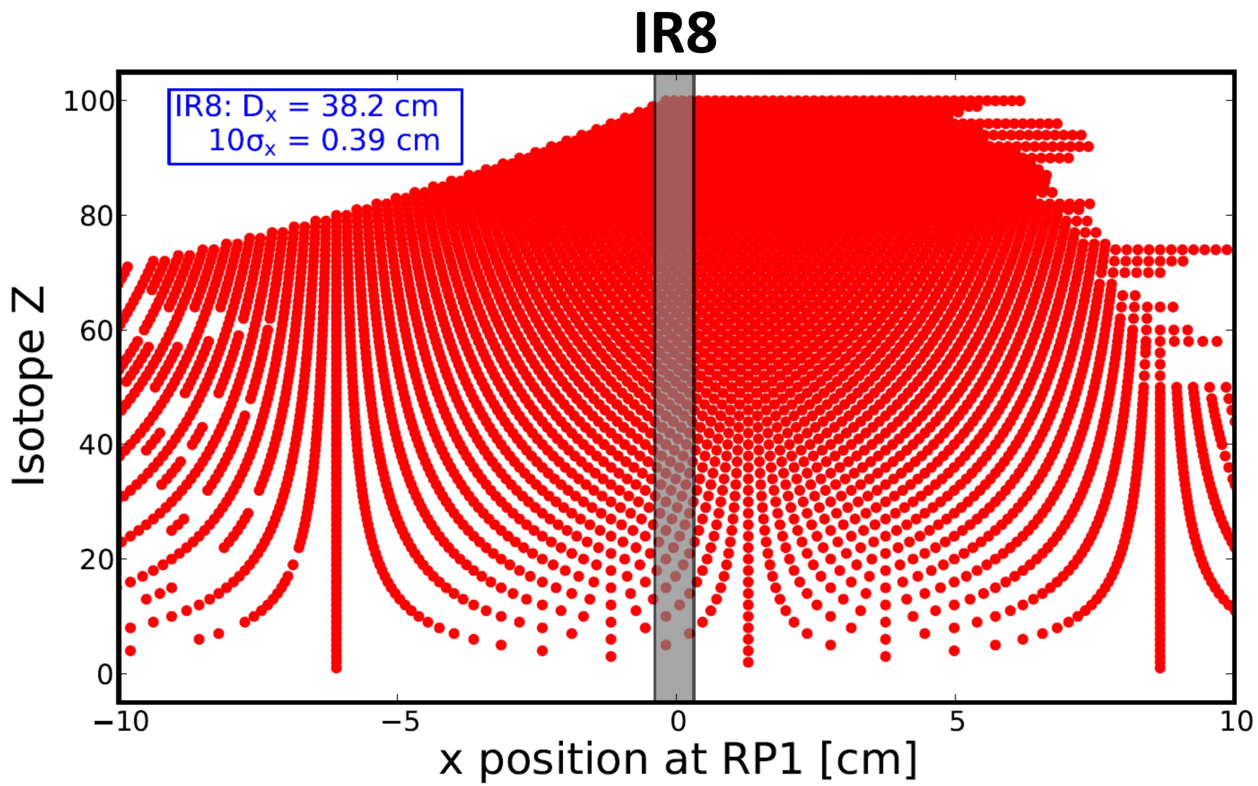
IR8 Parameters at first RP:

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

Big acceptance difference between the two IRs is caused by the second focus at the RPs in the IR8 design

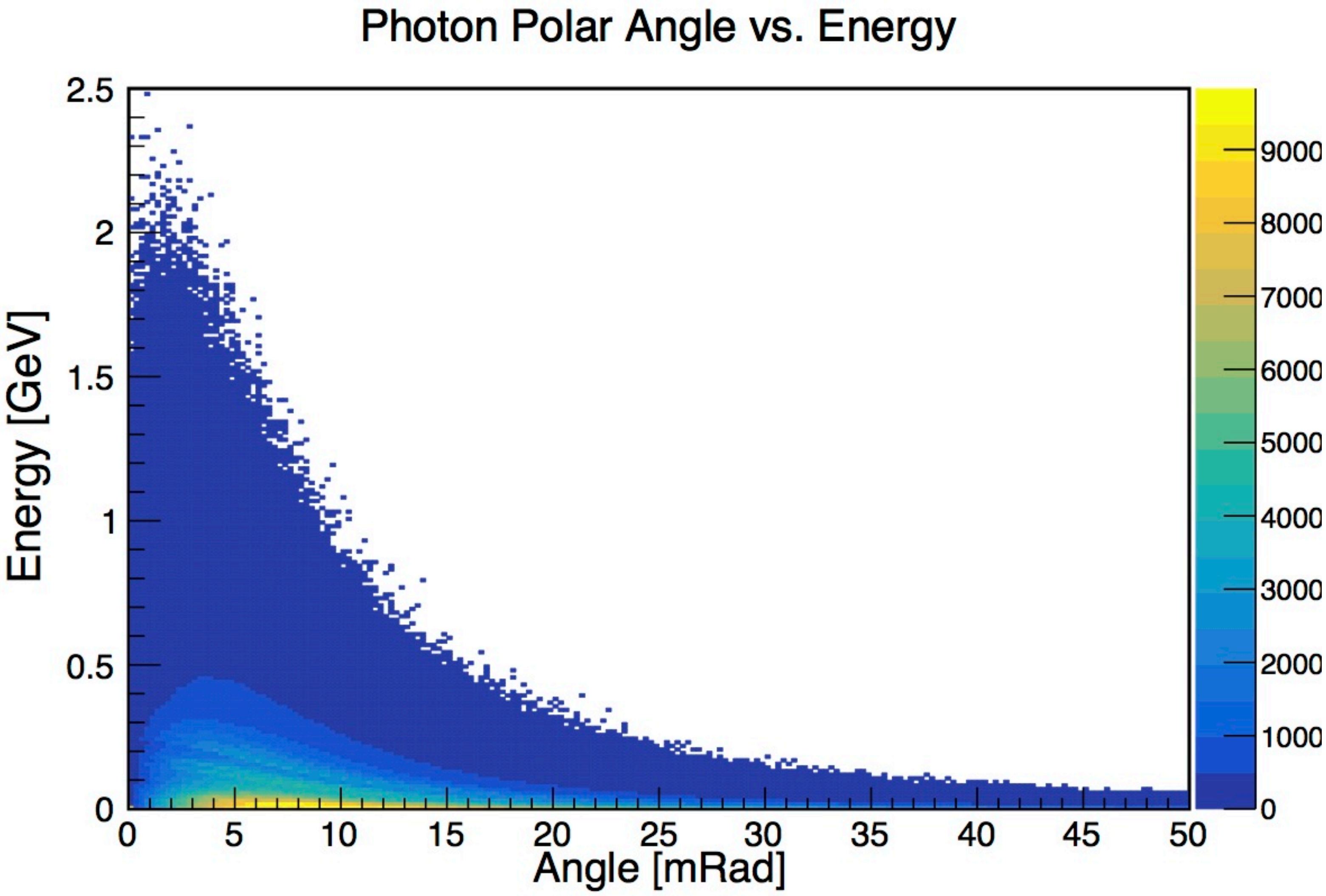
Roman Pot Acceptance



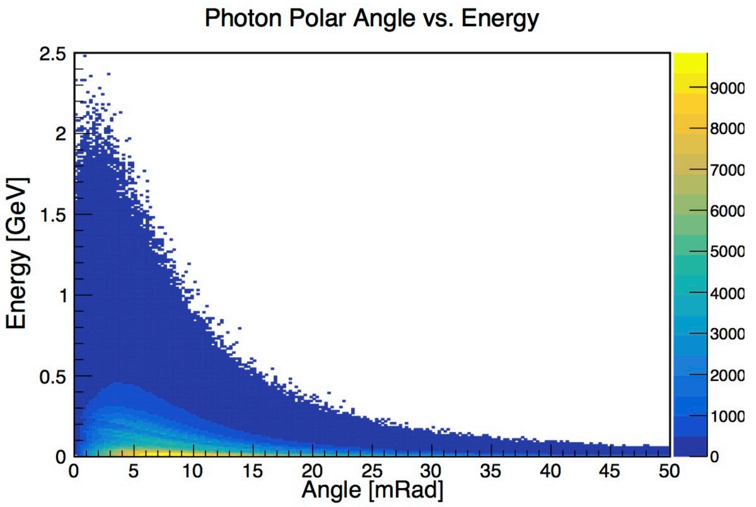


Isotope hit positions at the first RP vs. isotope Z
Includes all isotopes known/potential (NNDC and LISE++ database)
RP Positon Resolution of 10—100 microns

ZDC Acceptance



ZDC Acceptance



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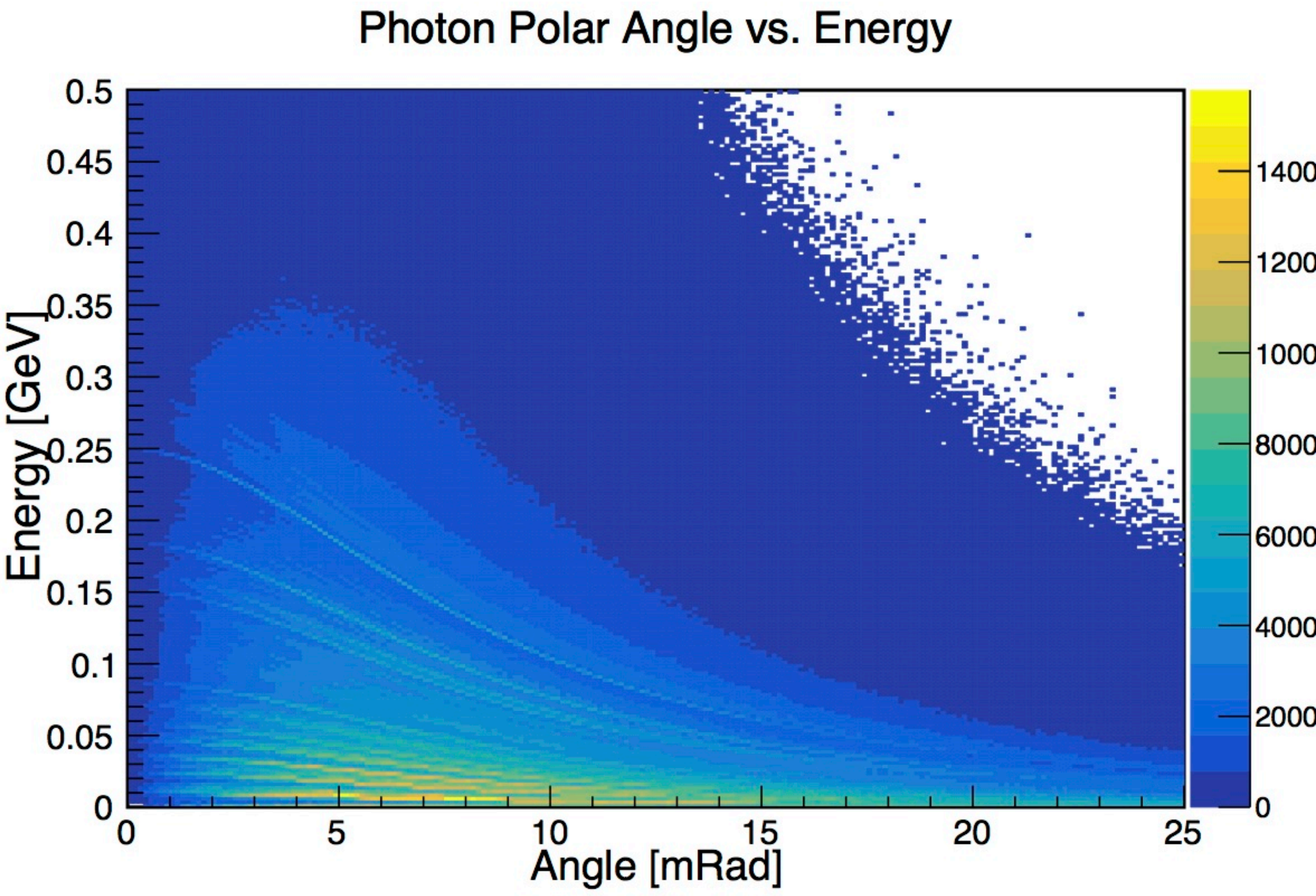
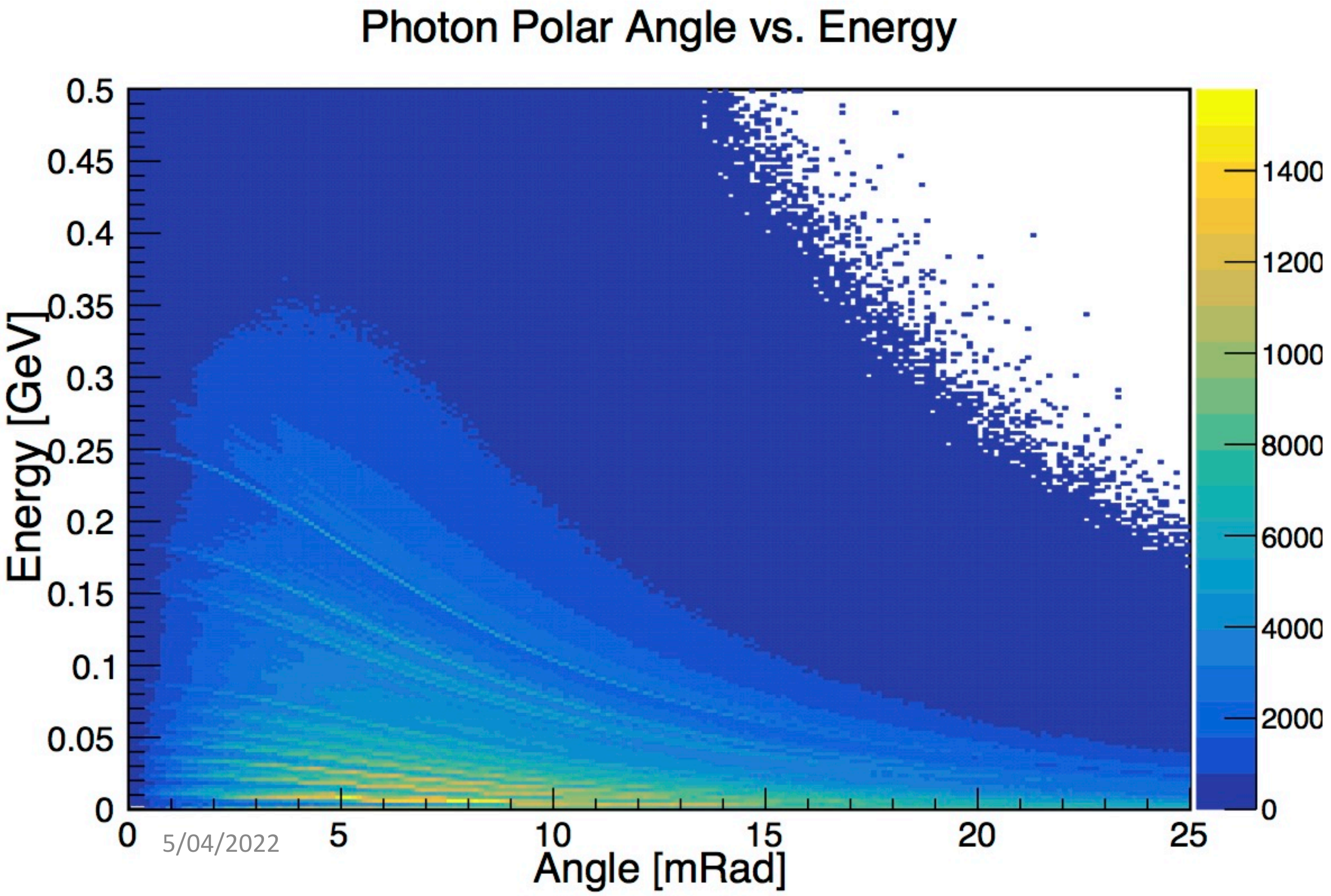
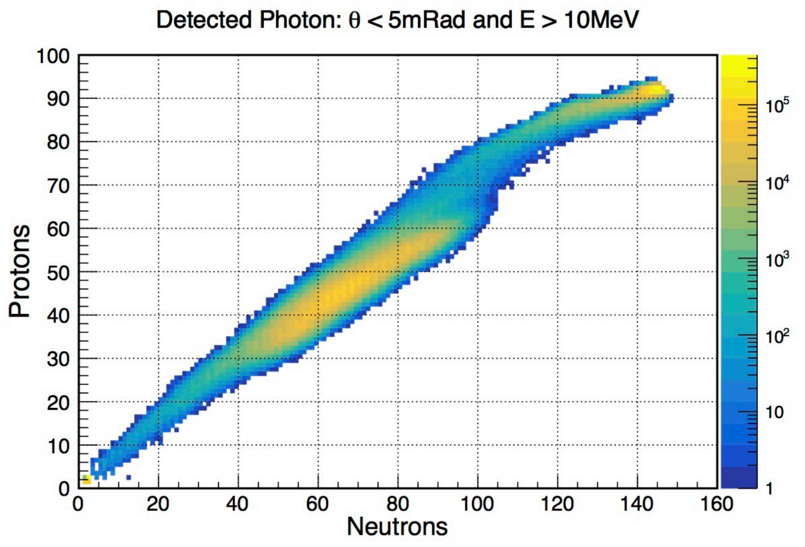


ZDC Acceptance



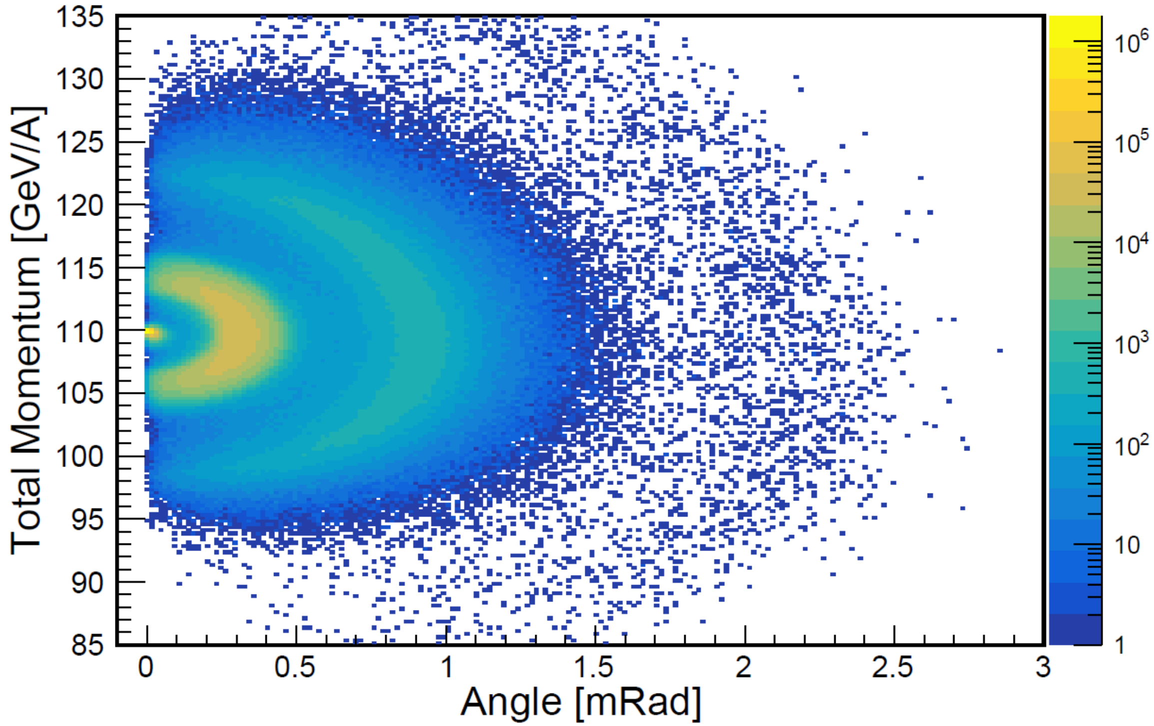
If we zoom in, we can see that most isotopes are within the acceptance region



Identification of Isotopes in IR6

To determine initial kinematics:

$$\begin{bmatrix}\theta_{x,ip}\\ \theta_{x,ip}\\ R_{rel}\end{bmatrix} = \begin{bmatrix}0.387 & -0.428 & 0\\ 0 & 0 & 1.95\\ -0.359 & 5.89 & 0\end{bmatrix}\begin{bmatrix}x_{rp2}\\ \theta_{x,rp}\\ y_{rp2}\end{bmatrix}$$



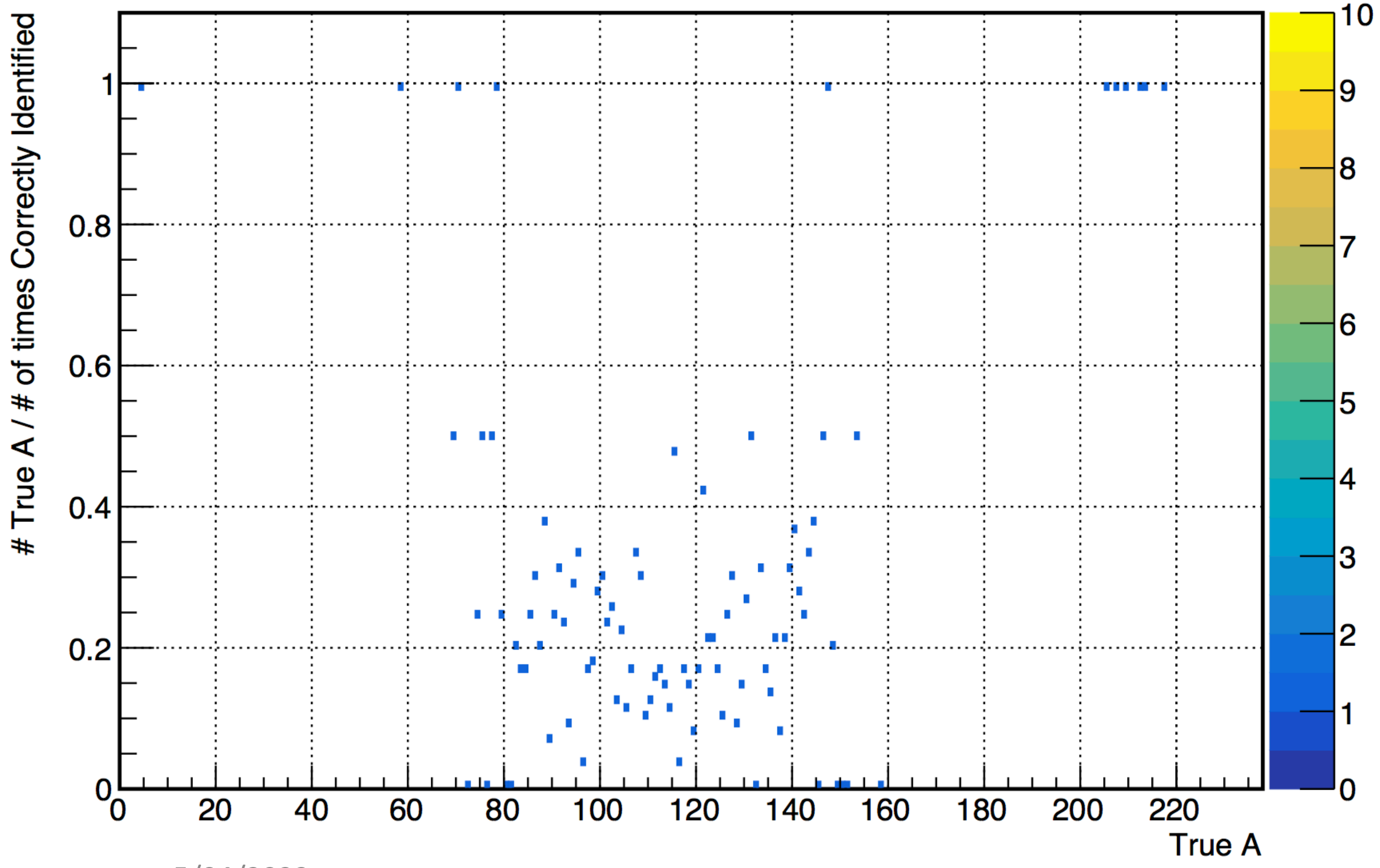
To identify isotopes, we use the relationship

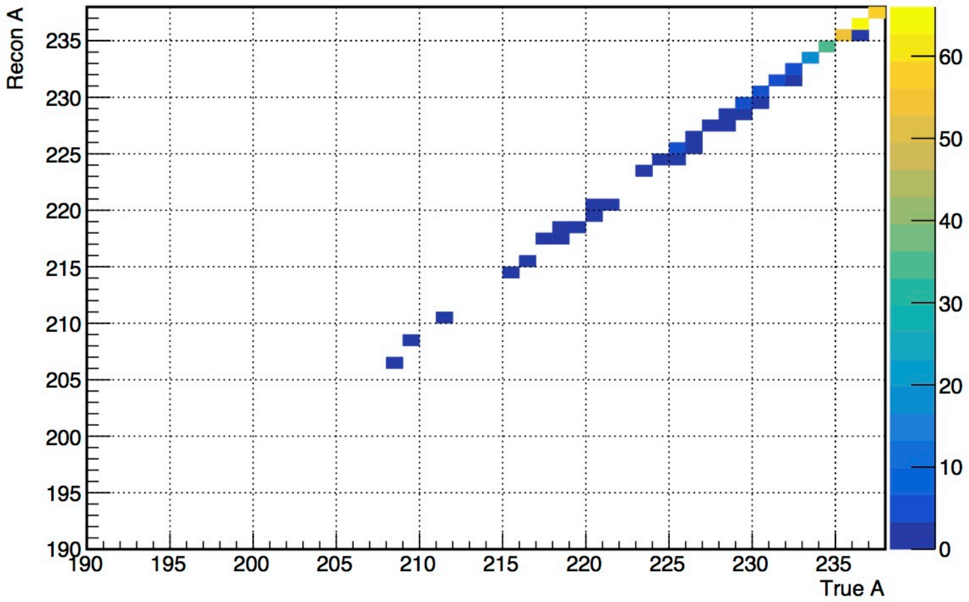
$$xL = \frac{R}{R_{Beam}} = \left[\left(\frac{Ap_N}{Z}\right) \Big/ \left(\frac{A_{beam}p_{N,beam}}{z_{beam}}\right)\right]$$

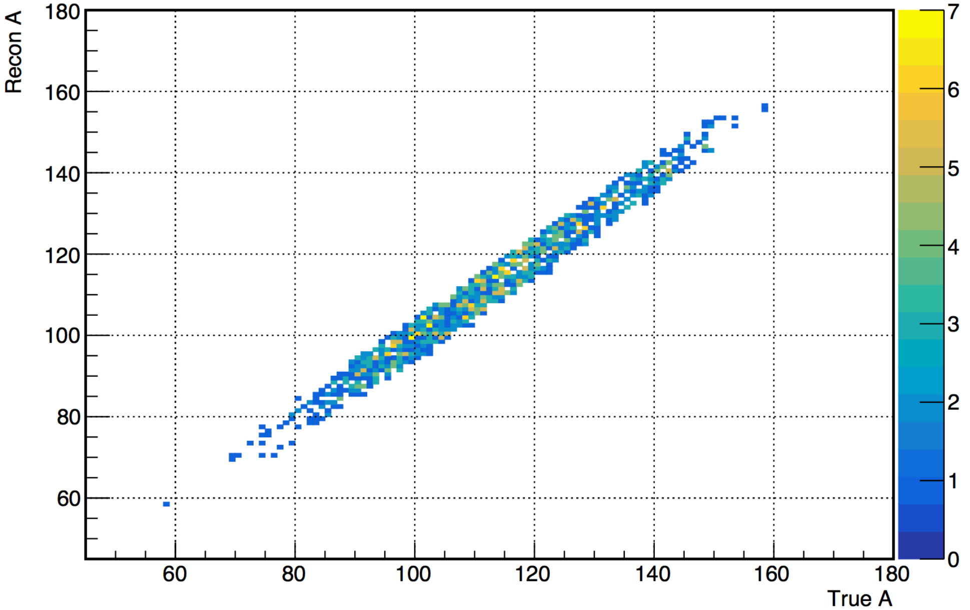
Using the assumption $P_N = P_{N,Beam}$ **:**

$$=> \frac{A}{Z} = (R_{rel} + 1)\left[\frac{A_{Beam}}{Z_{Beam}}\right]$$

A Reconstruction in IR6







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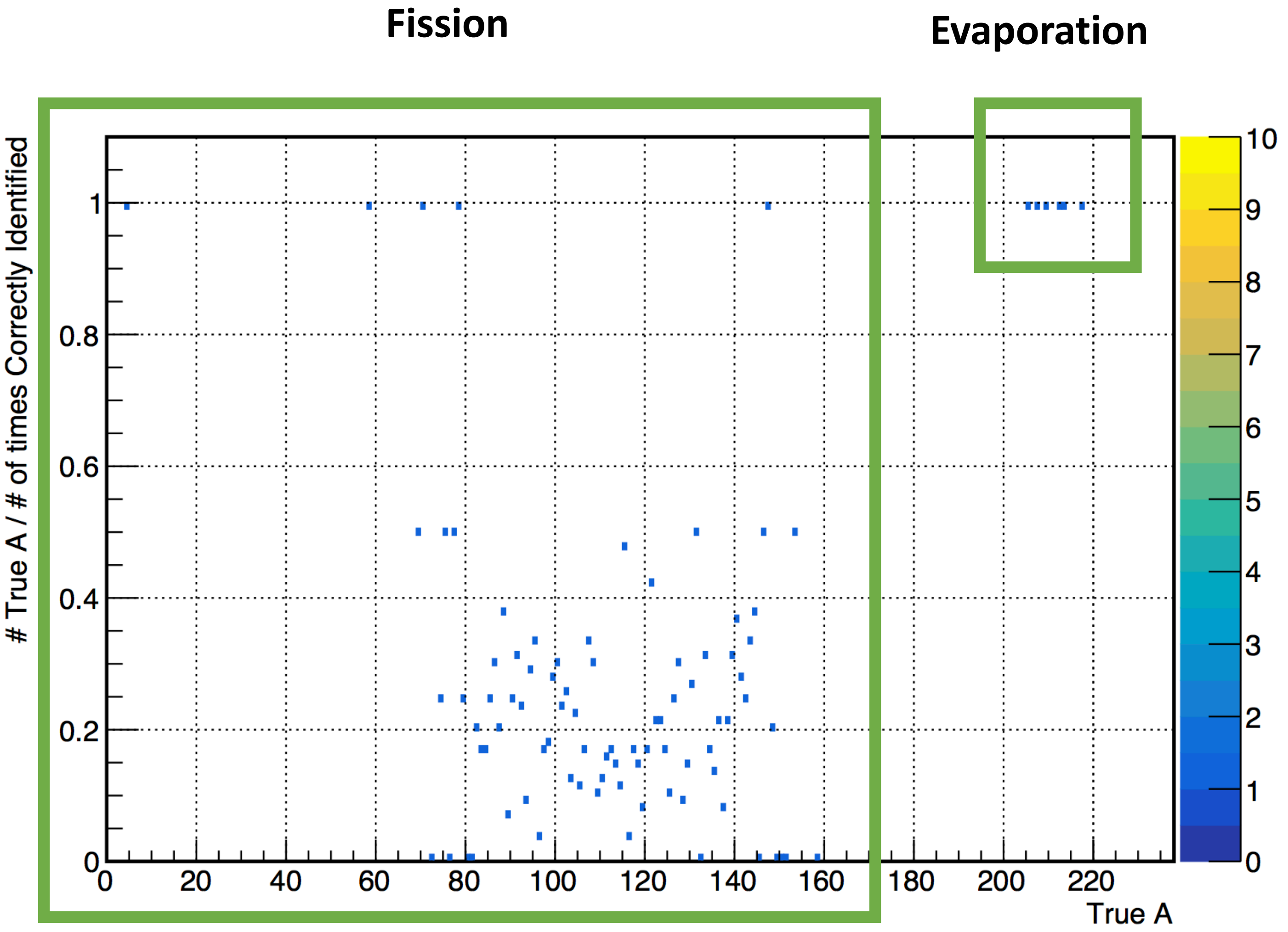
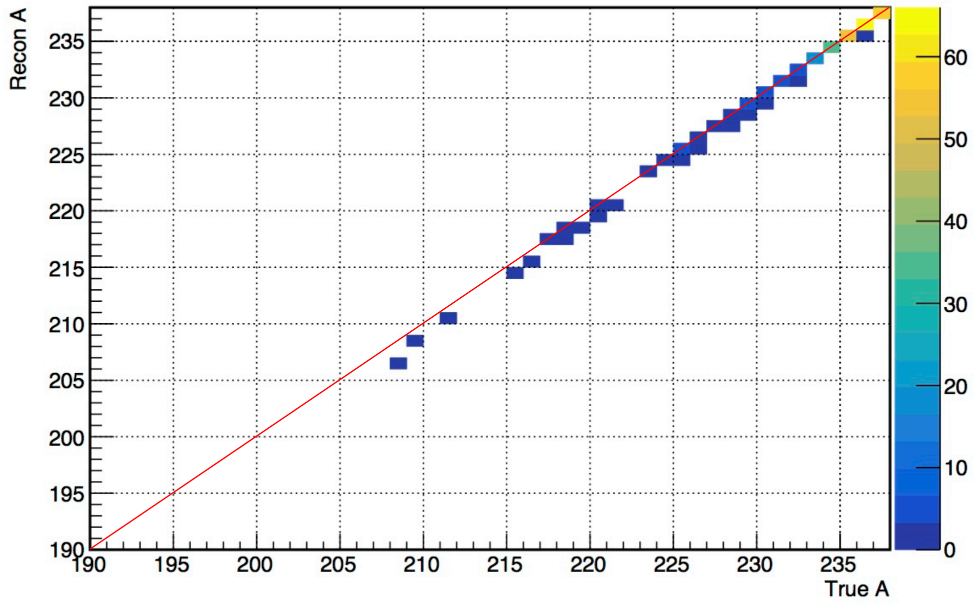
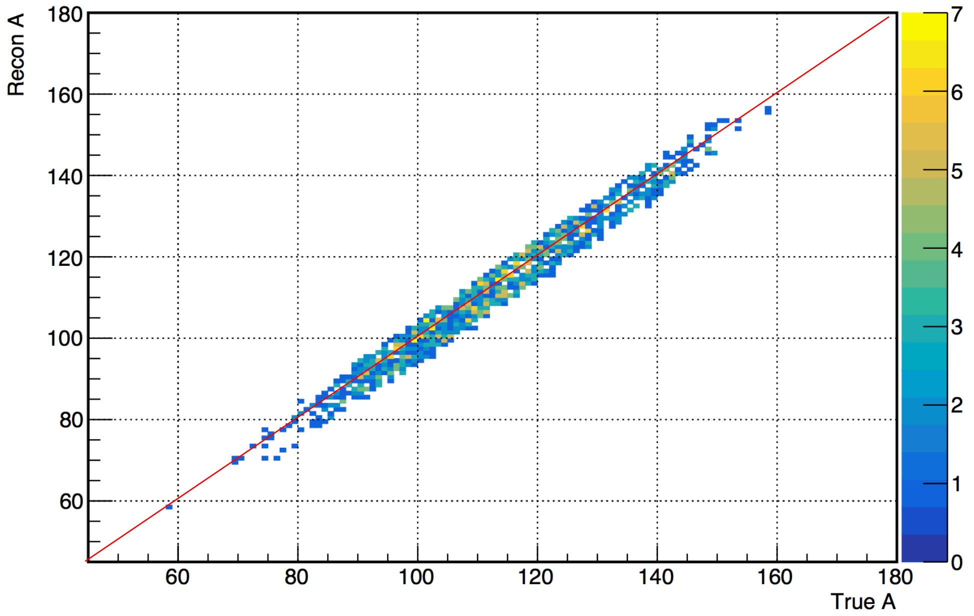
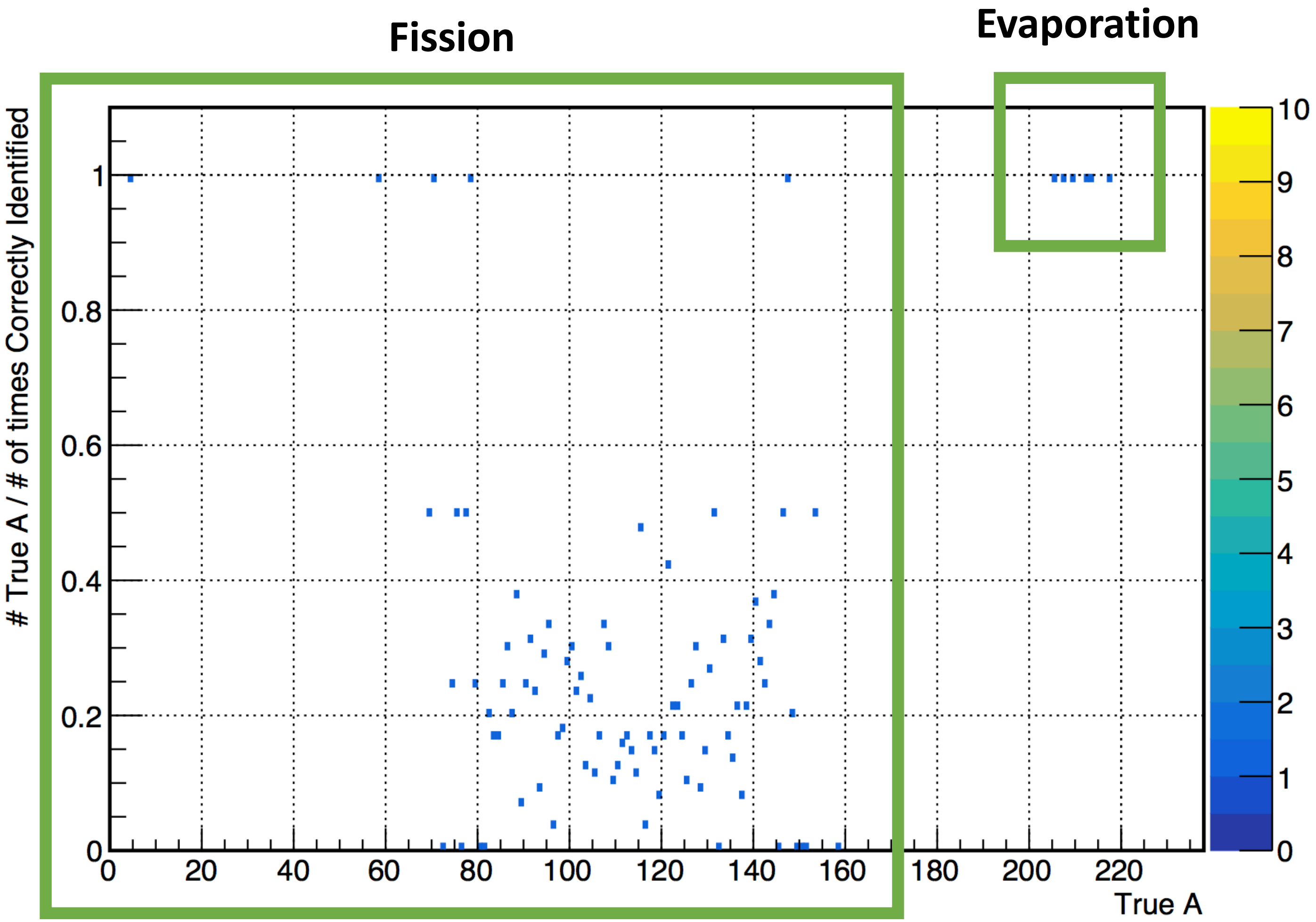
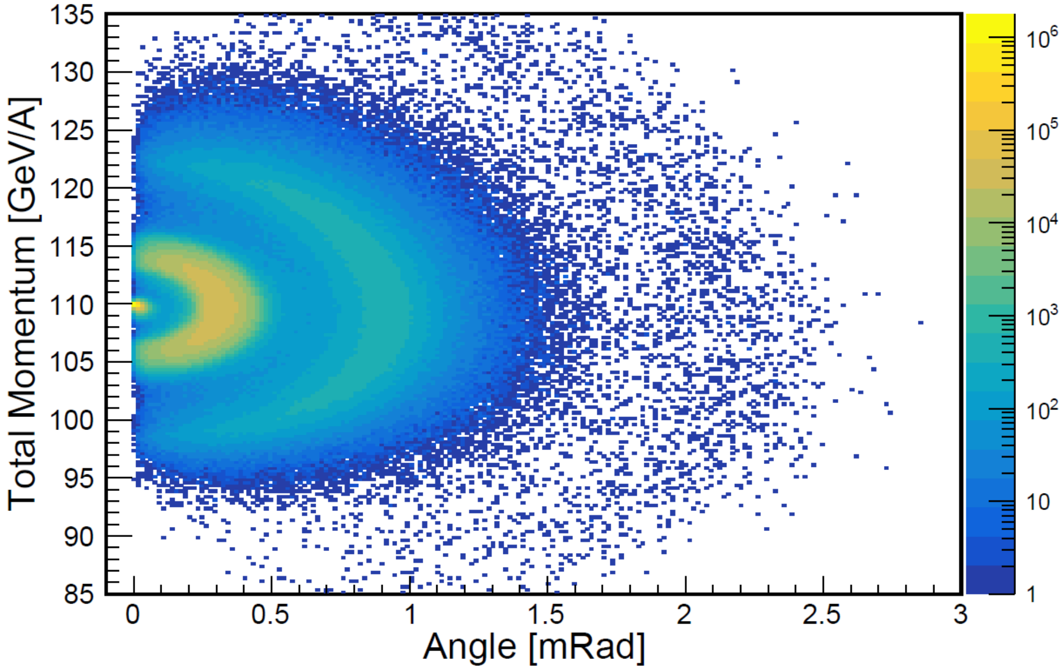






A Reconstruction





Our initial assumption about the momentum doesn't hold for isotopes with larger scattering angles (mostly fission products)

In Summary

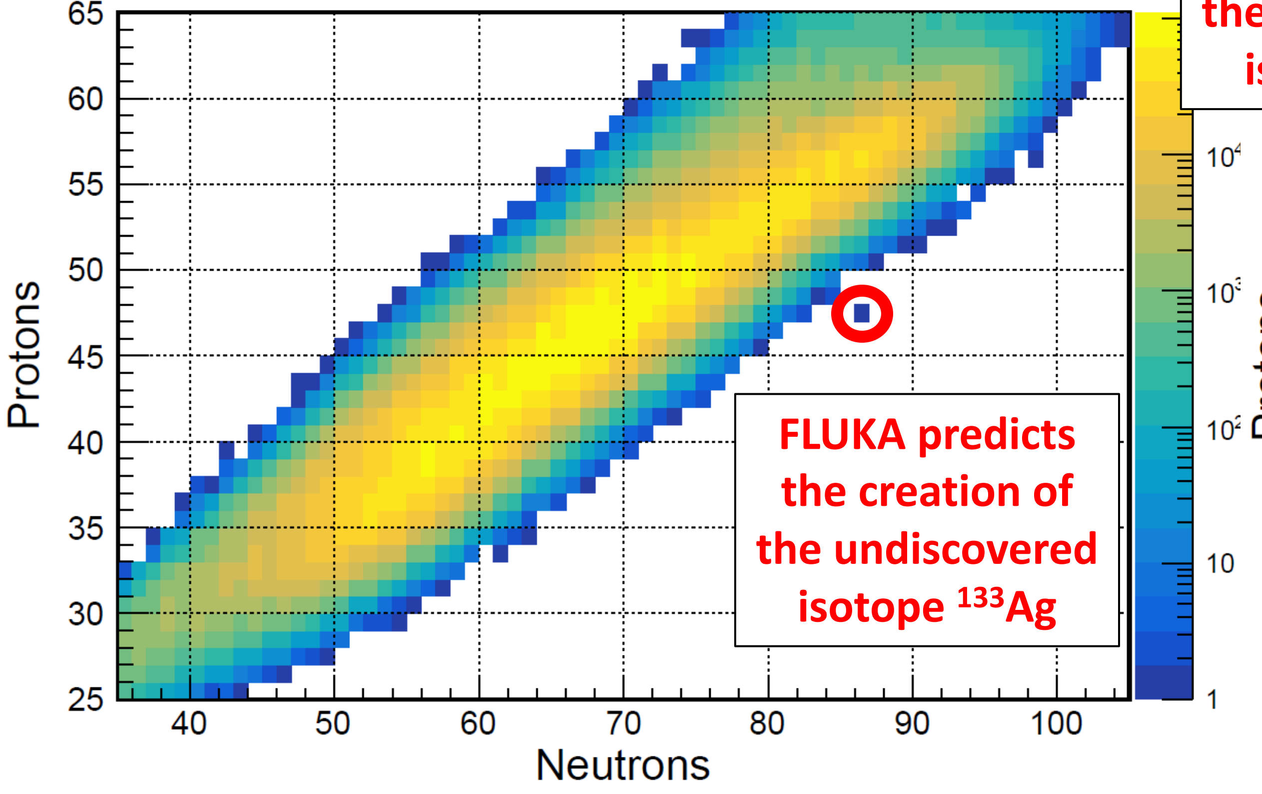
- We have shown that the EIC has the potential to produce exotic nuclei.
- These nuclei can be detected and identified using the proposed optics of the second interaction point with its secondary focus.
- Studying the level structure of the produced isotopes will be possible through the detection of the de-excitation photons.

Thank you for listening!

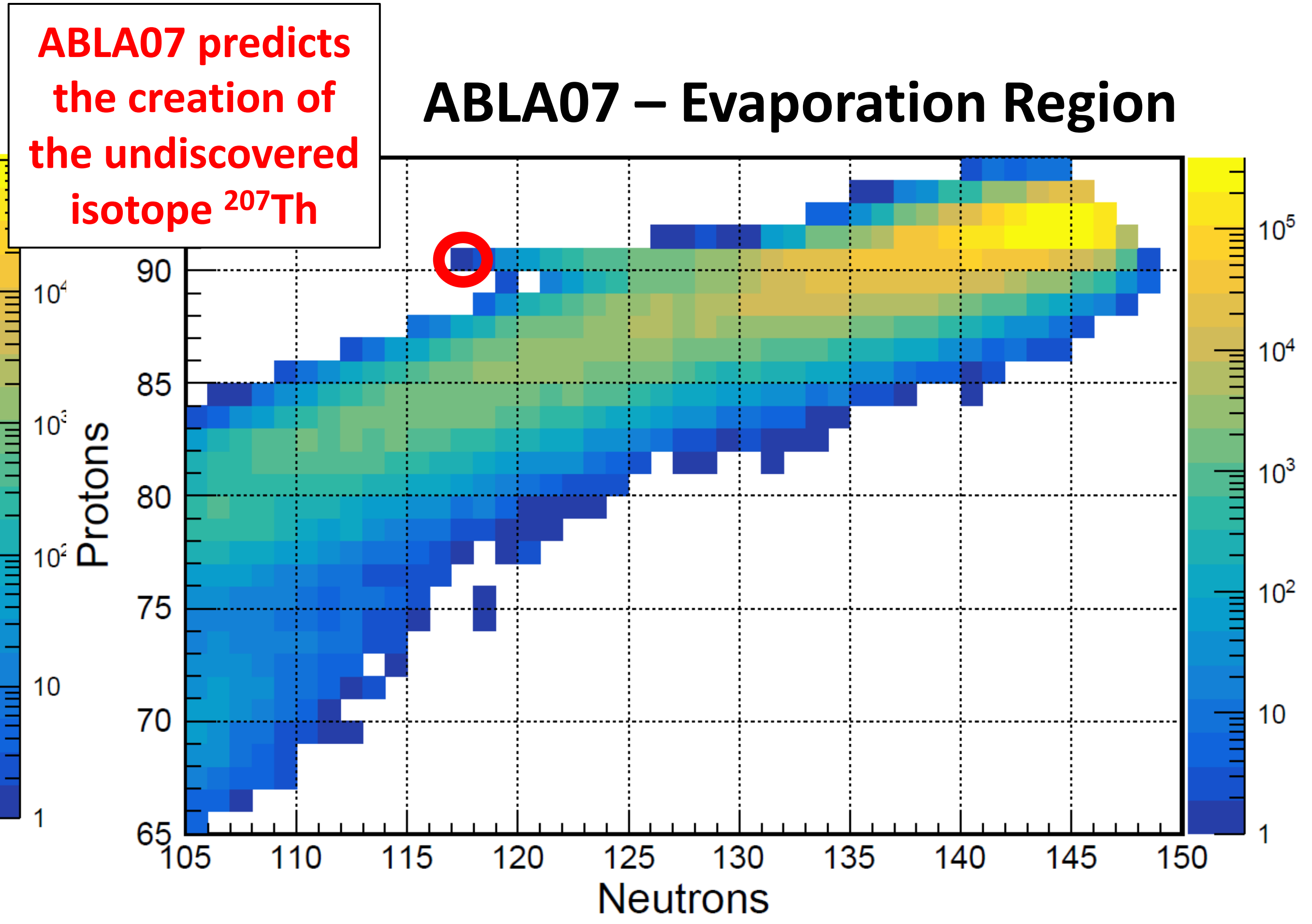
Backup Slides

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

FLUKA – Fission Region



ABLA07 – Evaporation Region



Detection and Reconstruction

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

$$xL = \frac{R}{R_{Beam}} = \left[\left(\frac{Ap_N}{Z}\right) \Big/ \left(\frac{A_{beam}p_{N,beam}}{z_{beam}}\right) \right]$$

$$Relative\ Rigidity = R_{Rel} = \frac{R - R_{Beam}}{R_{Beam}} = xL - 1$$

Using the assumption $P_N = P_{N,Beam}$:

$$xL = Rrel + 1 = \left(\frac{A}{Z} \Big/ \frac{A_{Beam}}{Z_{Beam}} \right) \Rightarrow \frac{A}{Z} = (R_{rel} + 1) \left[\frac{A_{Beam}}{Z_{Beam}}\right]$$

To do:

LISE++ Plots

ZDC Acceptance of de-excitation photons

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