Production and Detection of Exotic Nuclei in the EIC

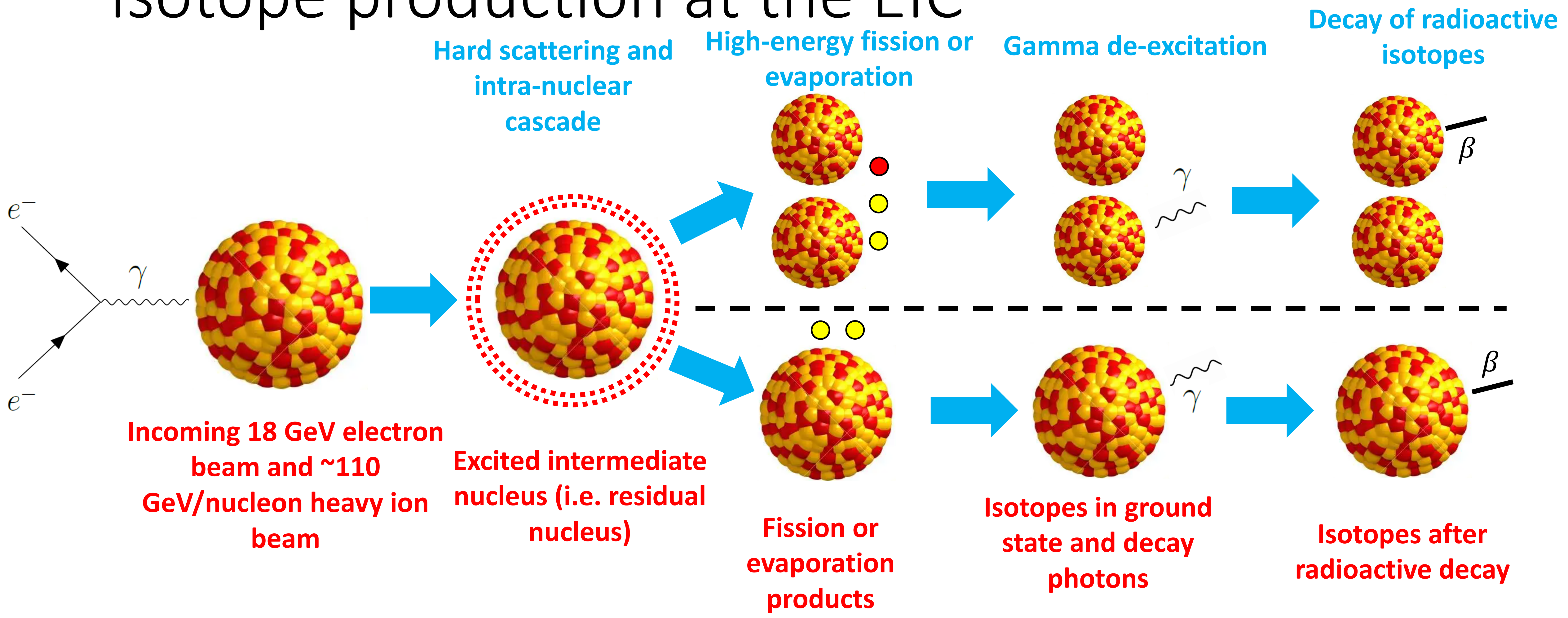
Presented by: brynna Moran

Other Collaborators: Ben Collis, Abhay Deshpande, Zach Finger, Ciprian Gal, Mark Harvey, Isaiah Richardson, Barak Schmookler, Oleg Tarasov, Pawel Nadel-Turonski

Motivating Questions

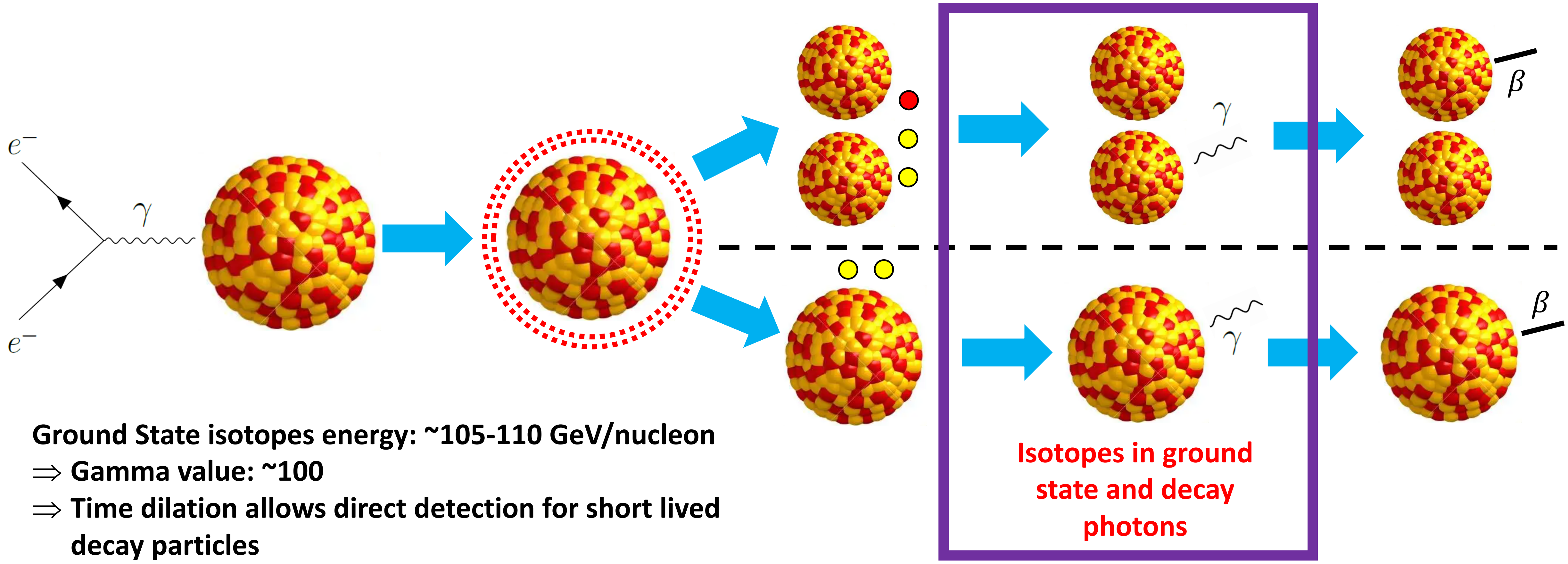
- Would the high-energy electron-heavy nucleus scattering of the future EIC have the capability to produce exotic nuclei?
- Can we go on to detect and correctly identify the produced exotic nuclei?
- Can we also study the level structure of the nuclei by detecting the decay photons? What requirements does this place on the far-forward detection area?

Isotope production at the EIC



t = 0 | t = 10^{-22} s | t = 10^{-20} - 10^{-17} s | t = 10^{-14} s | t = ? – never (stable)

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

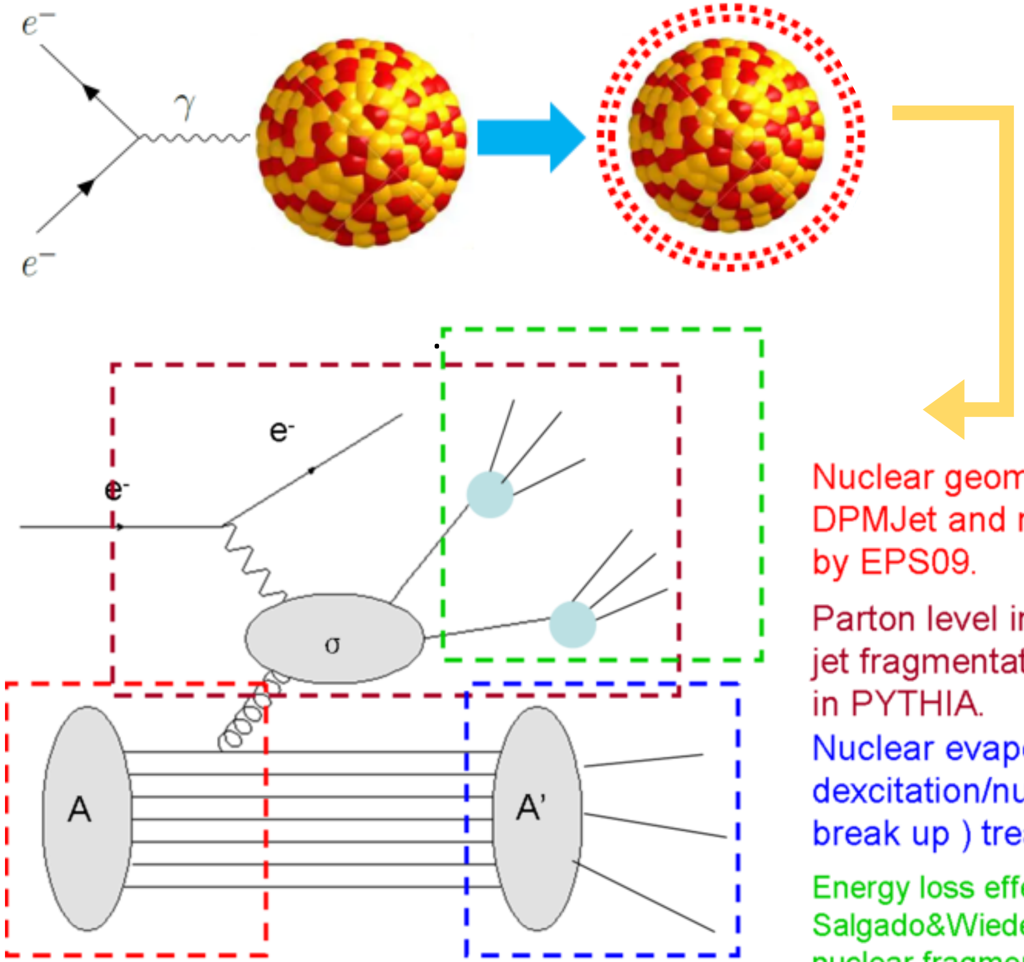
BeAGLE (Benchmark eA Generator for Leptoproduction) is the software we use to simulate the hard scattering and intra-nuclear cascade

Intranuclear Cascade
Hadron Formation Time:

$$T_{Lab} = T_0 \frac{E_S}{m_S} \frac{m_s^2}{m_s^2 + p_{s\perp}^2}$$

Excitation Energy of
Residual Nucleus:

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



Nuclear geometry by DPMJet and nPDF provided by EPS09.

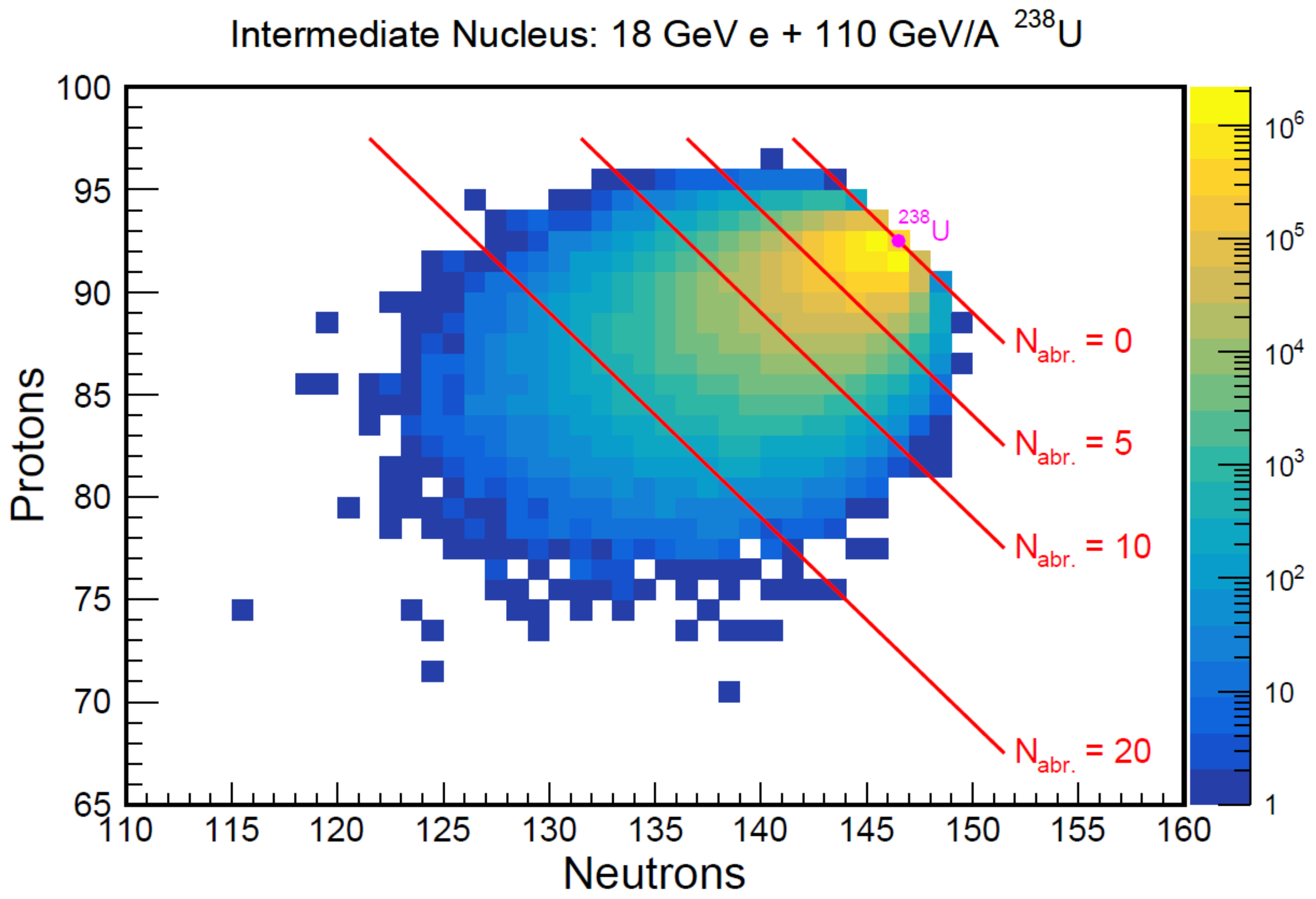
Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

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

Excited Intermediate Nucleus from BeAGLE



The distribution of isotopes created during this stage

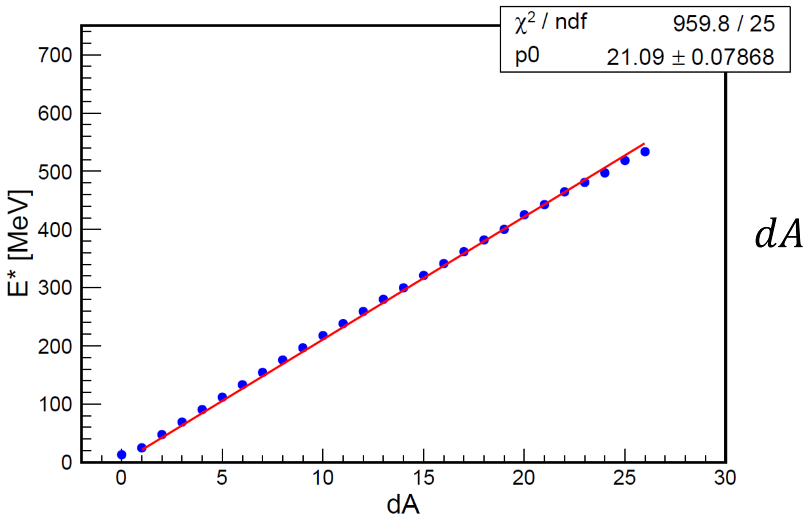
←

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

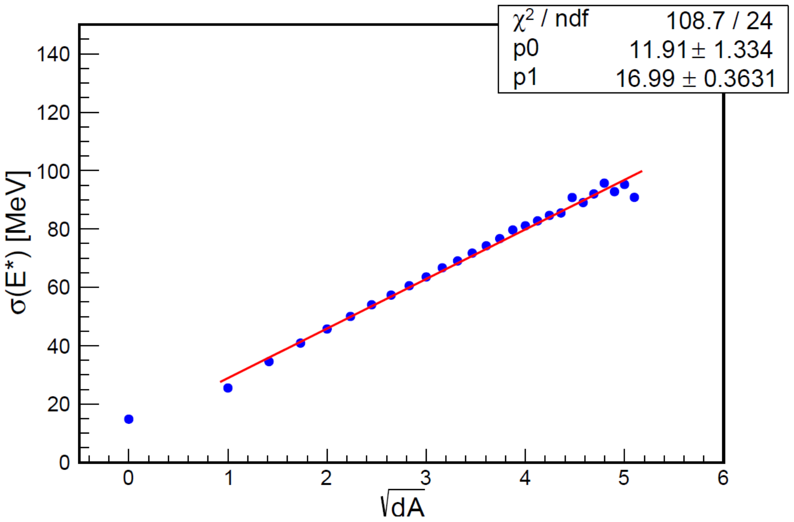
Leaves us with the residual nucleus in an excited state for the next stage of simulations

Excited Intermediate Nucleus from BeAGLE

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

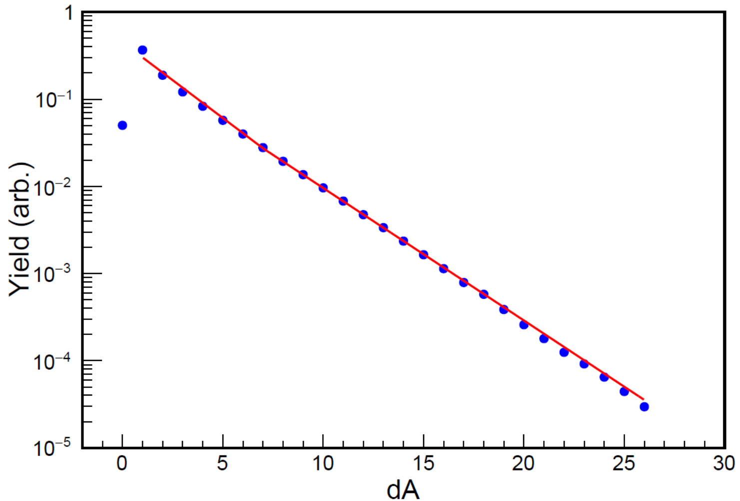


$$dA = A_{beam} - A_{res}$$



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

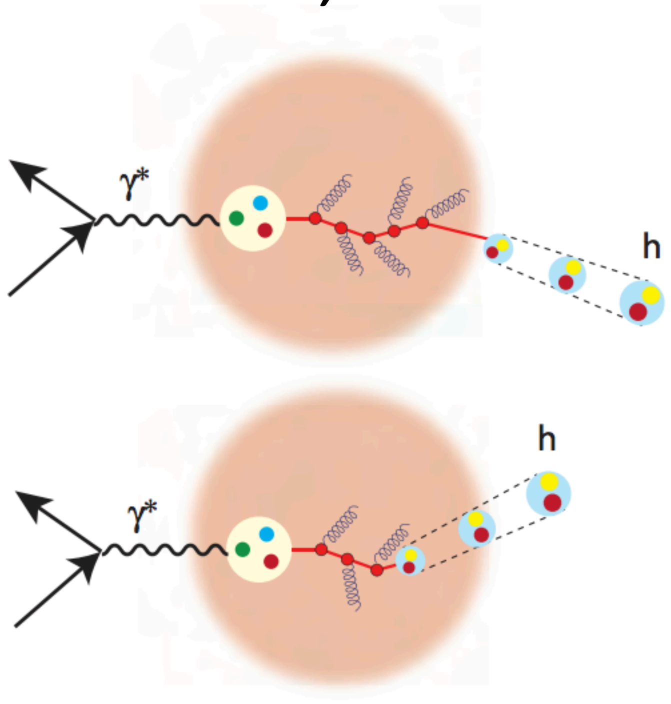
These dependencies are not directly written into BeAGLE, rather arise 'naturally'



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

Initial Parameters-> 10 τ_0, 10 Generations, 3 Shadowing

- **τ_0** → Hadron formation time (in femtoseconds)
- **Generations** →If hadron forms inside nucleon, generation parameter describes how many times we allow for re-interaction
- **Shadowing** →Describes the method software models nuclear shadowing (either models the DIS interaction as point-like or allowing multiple nucleons to be hit)

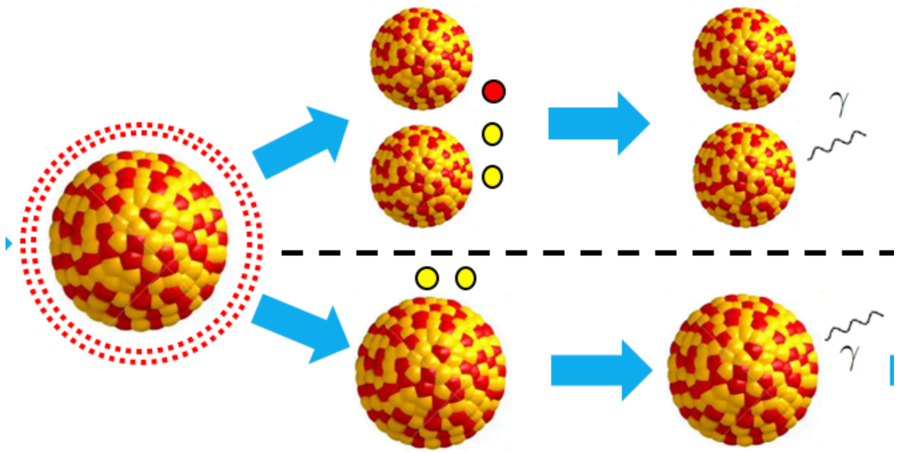


arXiv:1212.1701

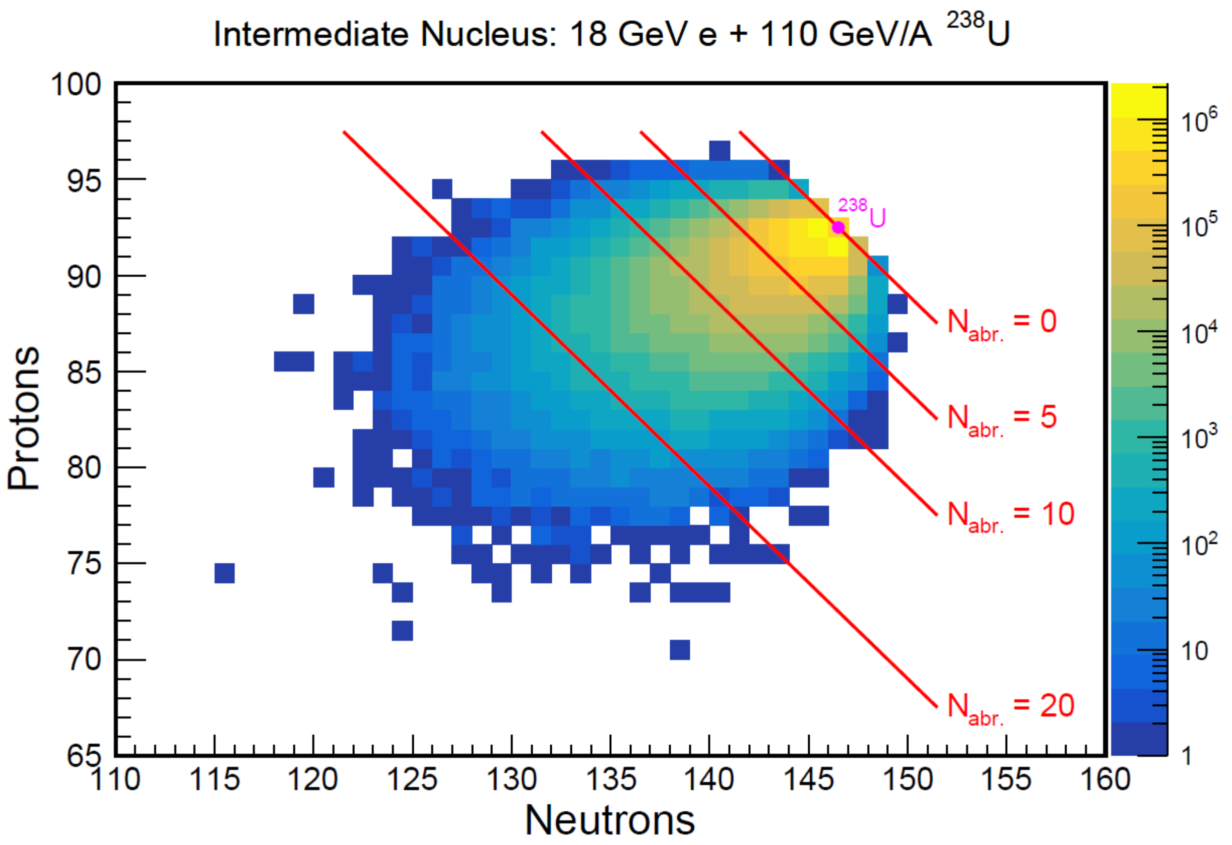
When we looked at how changing these values effected our previous studies, we saw that the **τ_0** parameter had an effect, but not the generation or shadowing parameter!

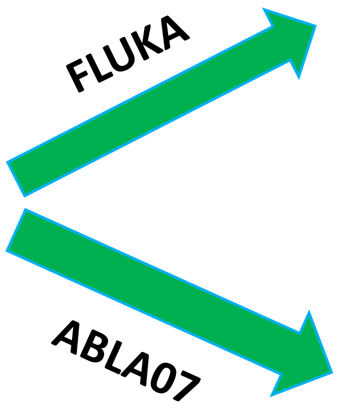
High-energy fission/evaporation and Gamma Decay using FLUKA and ABLA07

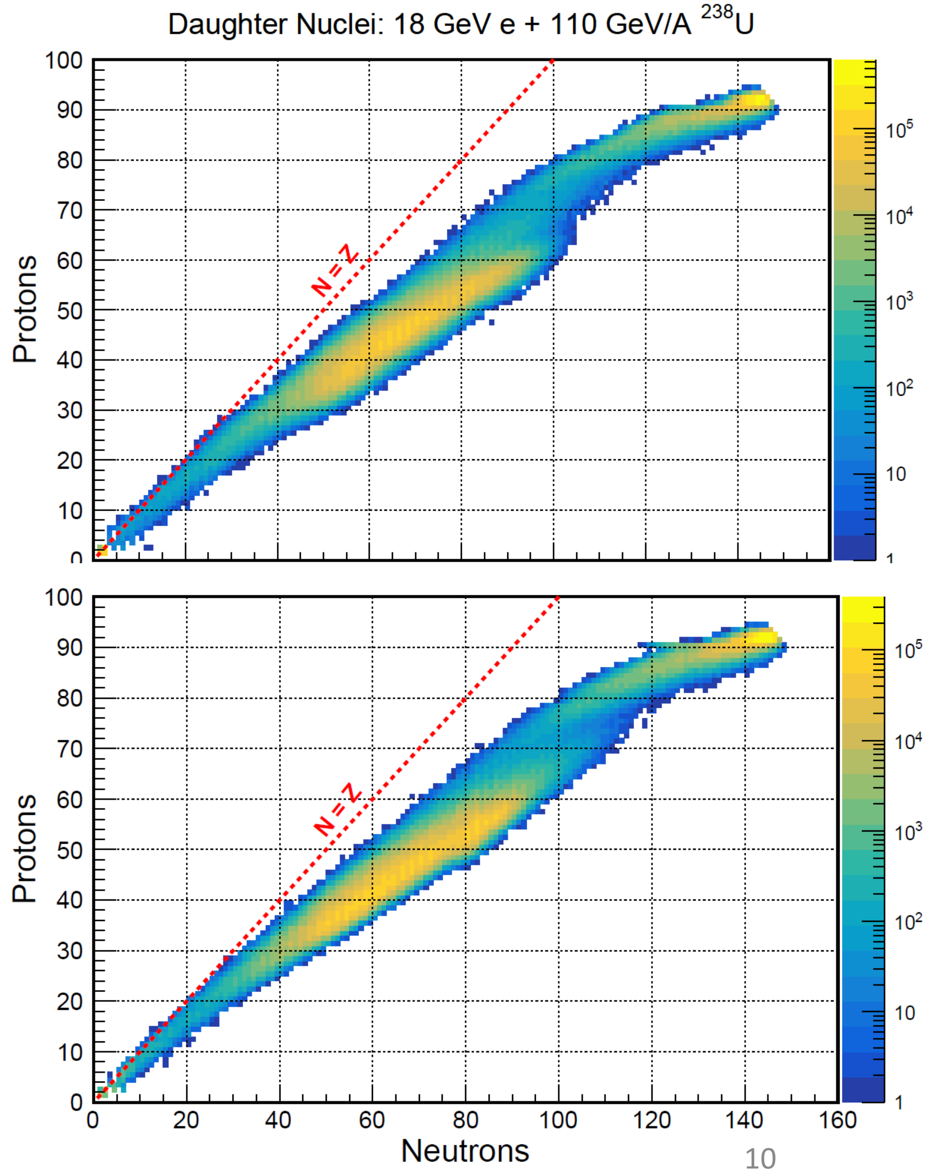
- To simulate the high energy decay and gamma de-excitation, we had 2 good options: FLUKA and ABLA07
- FLUKA:
  - Directly incorporated into the BeAGLE framework, allowing for easier analysis
  - Used extensively in high-energy physics, but not rare isotope production
- ABLA07:
  - The second part of 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

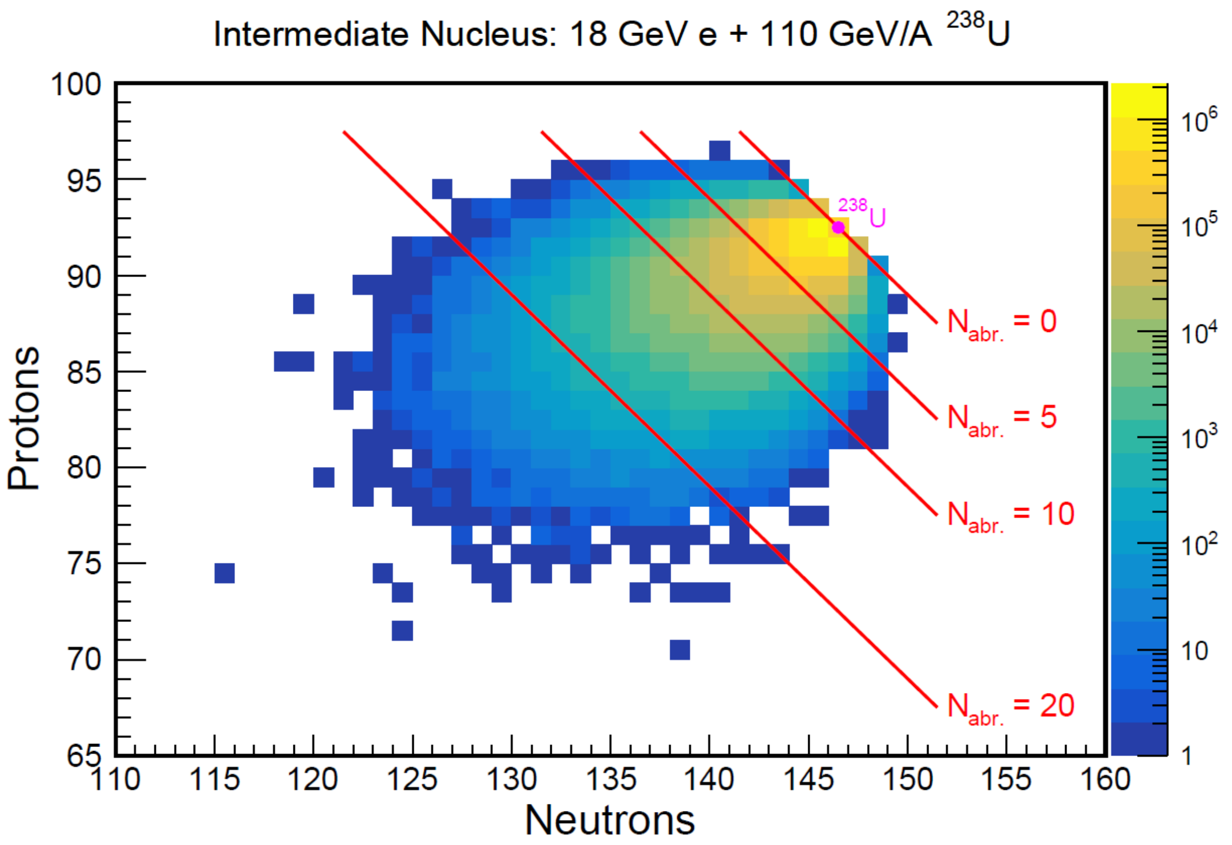


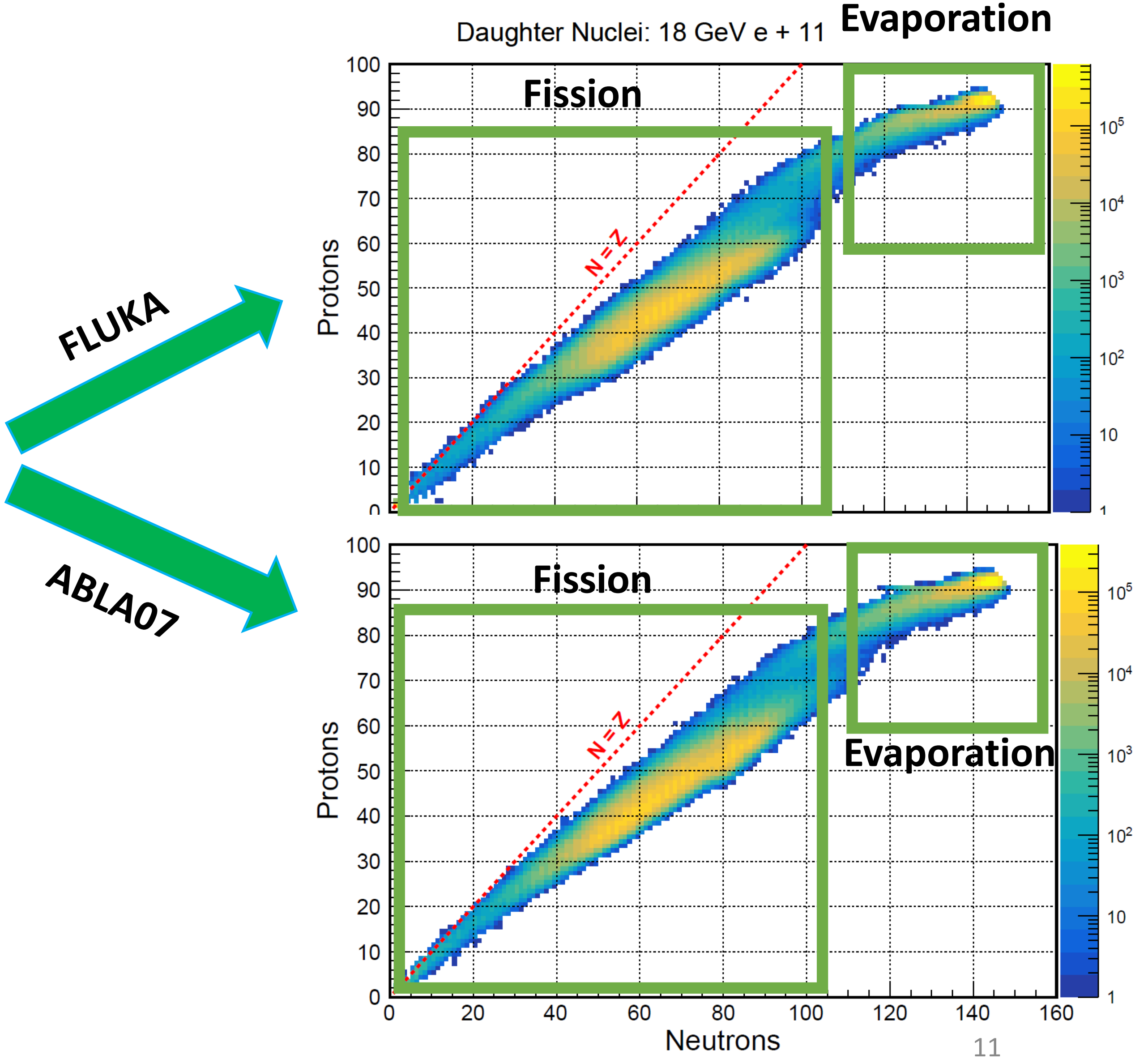




10 million events simulated

Fission and Evaporation Products in High Energy Decay

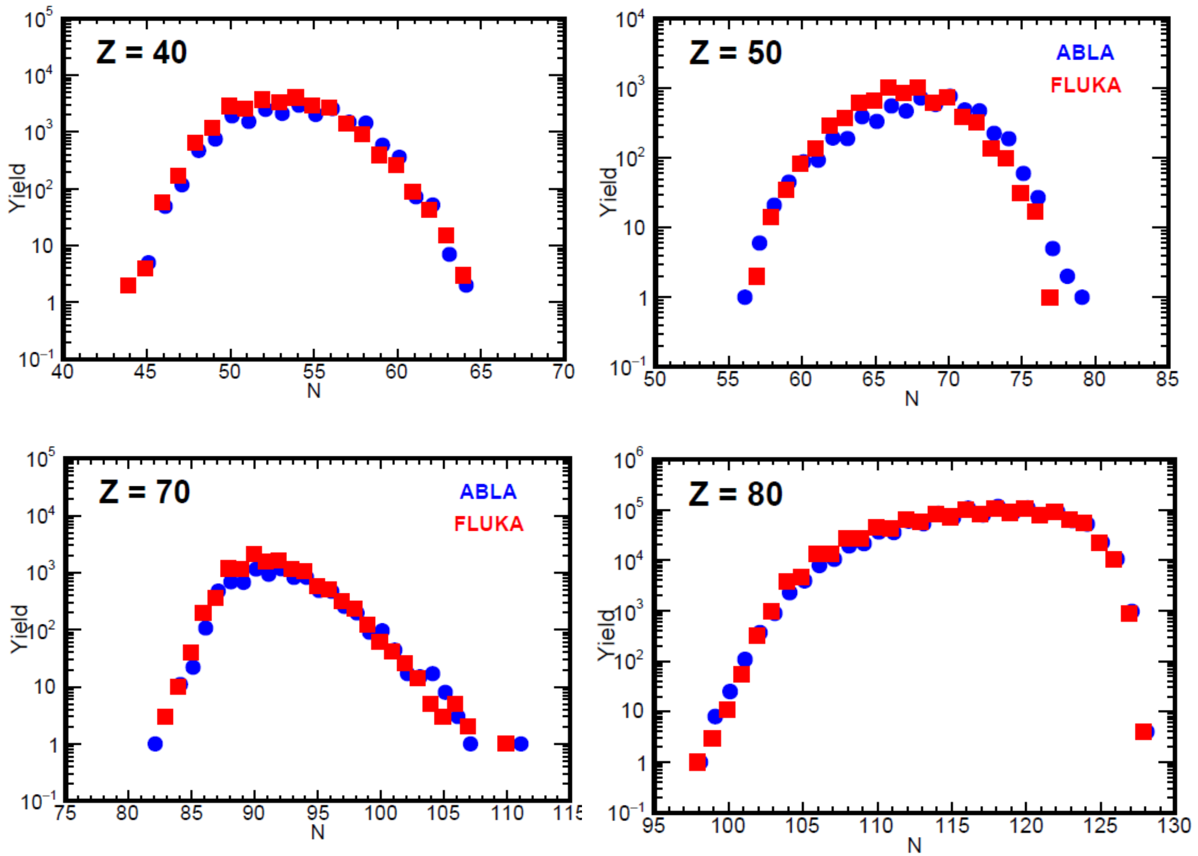




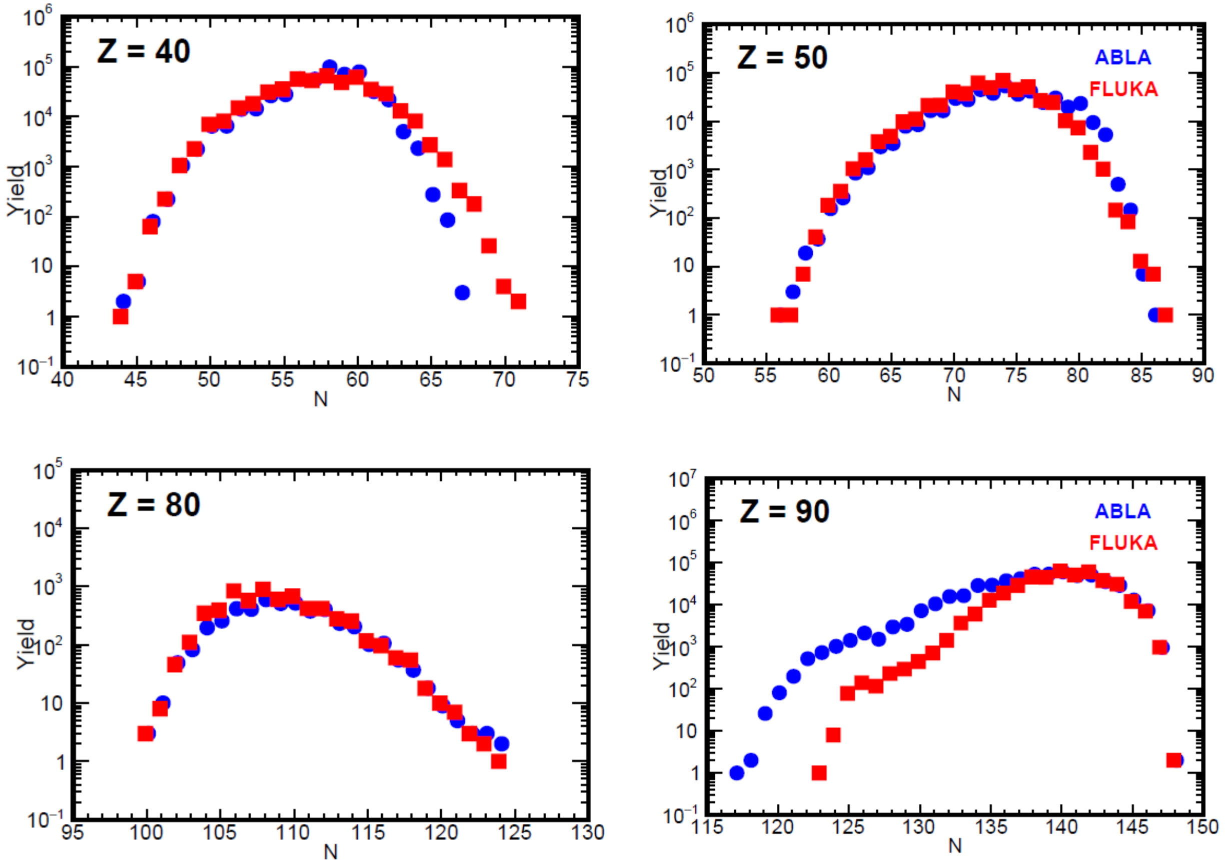
10 million events simulated

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),

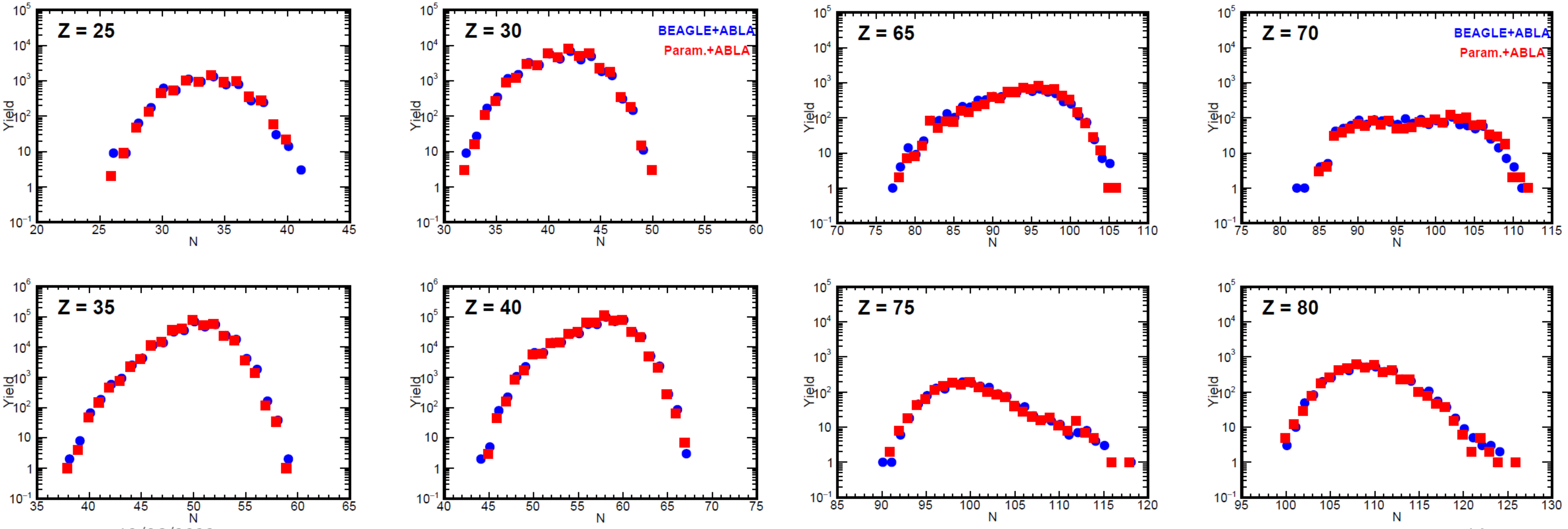
Those 10 million events correspond to ~5 min actual runtime, which isn't enough to get a full understanding of the EIC's capacity to produce rare isotopes.

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

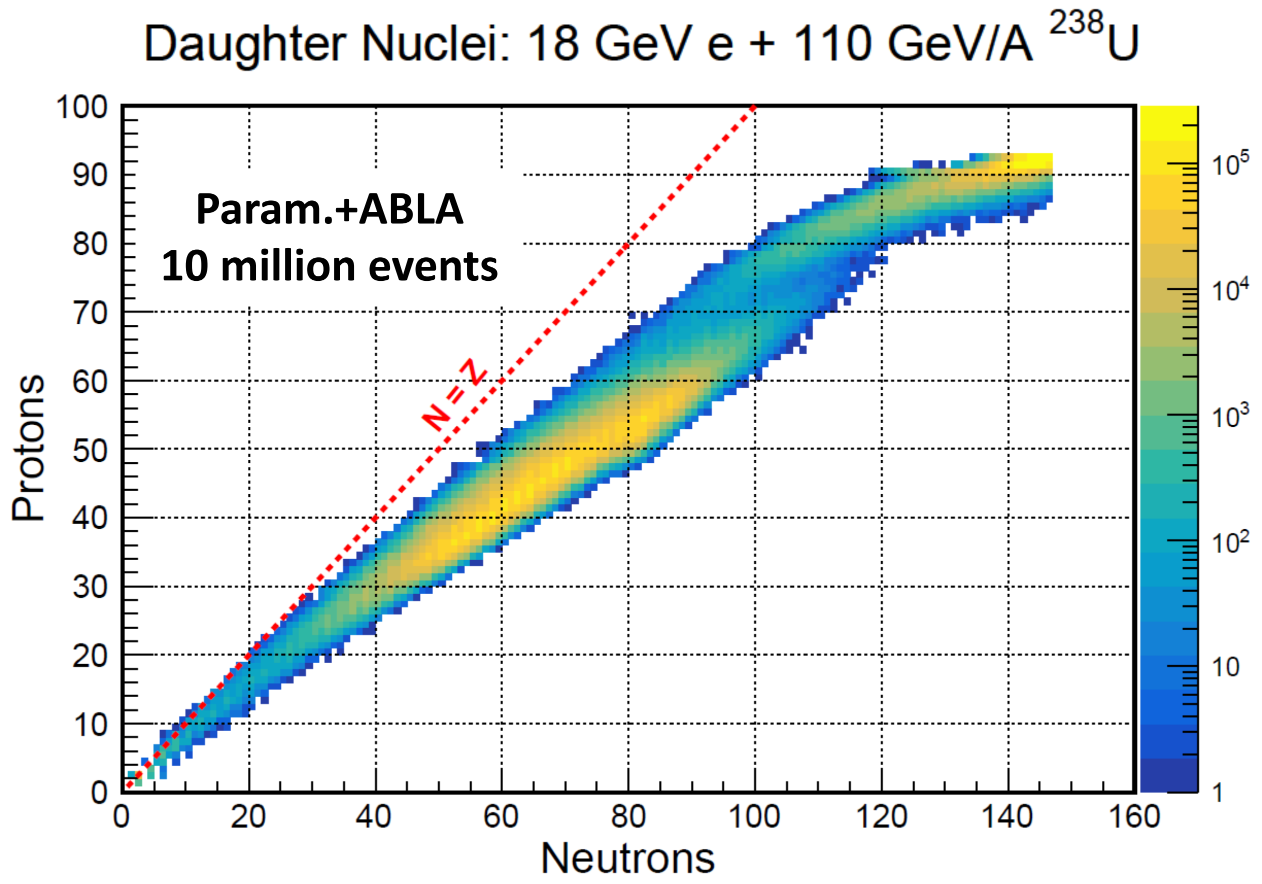
Comparison of *BeAGLE* results and parameterized distribution

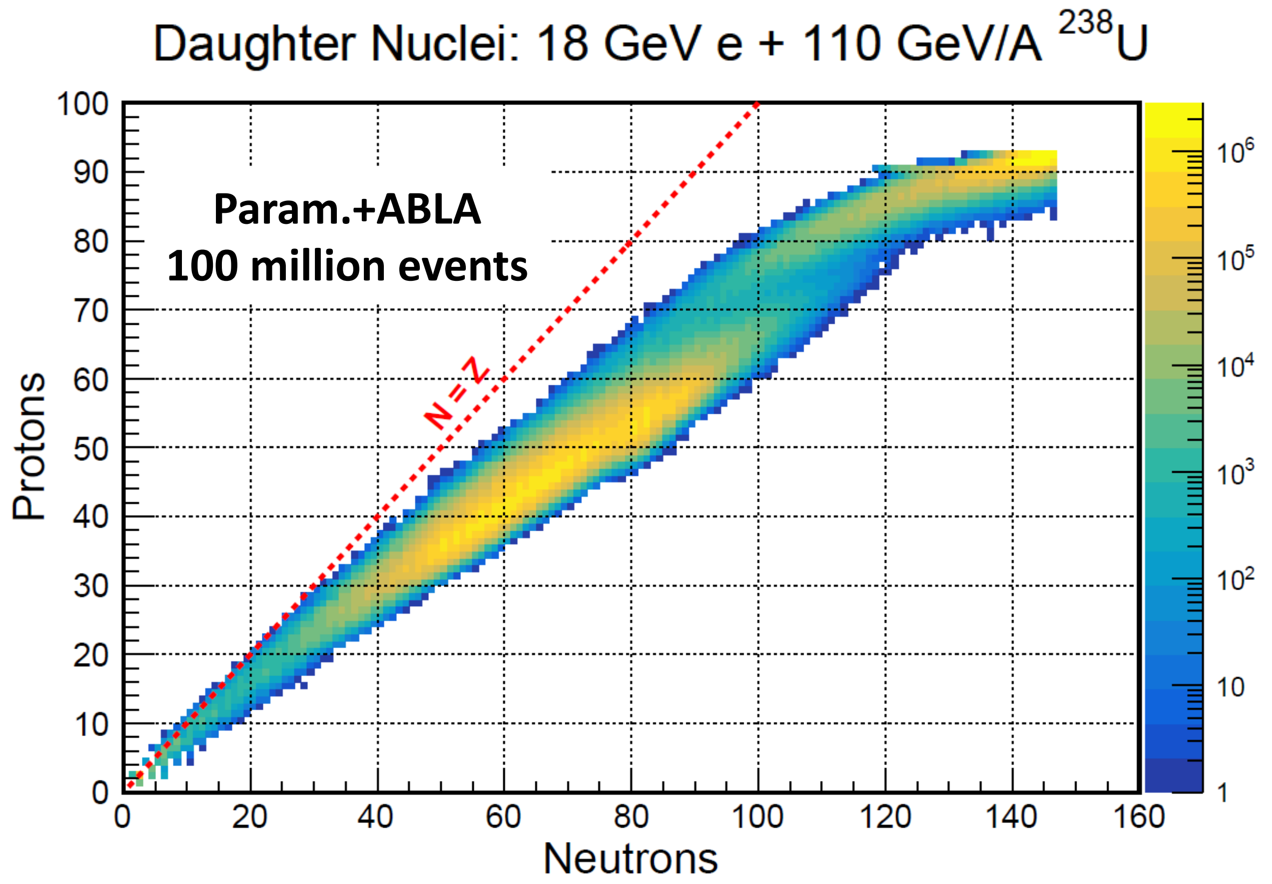
Decay isotopes only care about A, Z, and E* of excited residual nucleus. We can create a basic parameterization of the BeAGLE intermediate isotope production and use that.

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



Towards higher statistics simulations

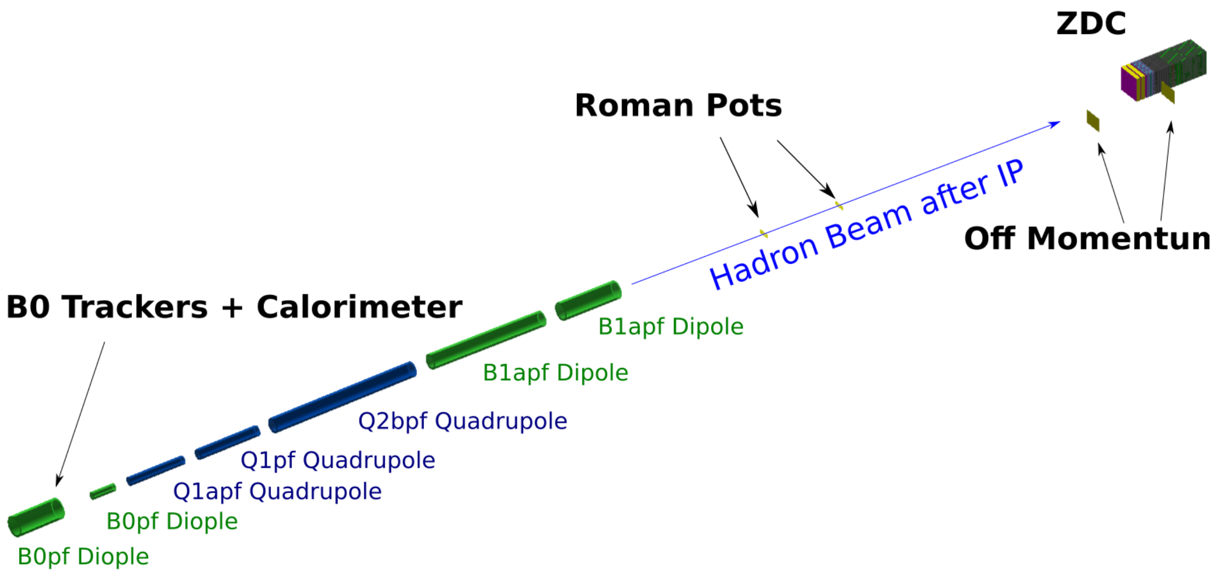




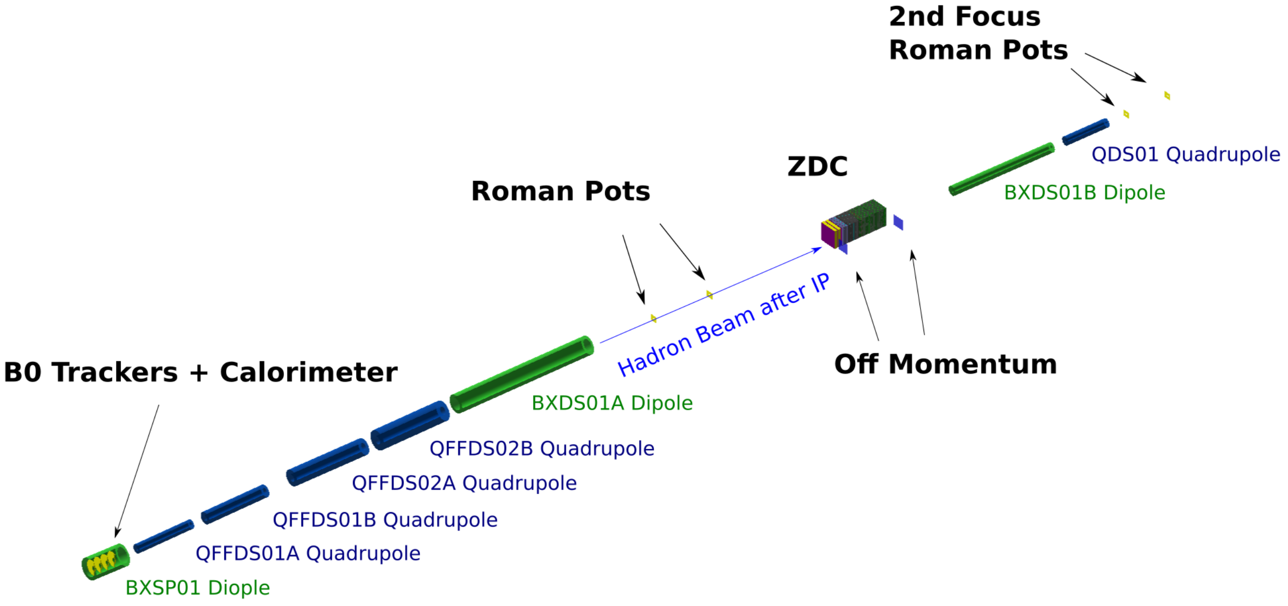
As we increase the number of events generated, the borders expand to give a larger range of unstable isotopes

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:

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

Roman Pots Parameters:

Beta Function β_x

Dispersion D_x

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:

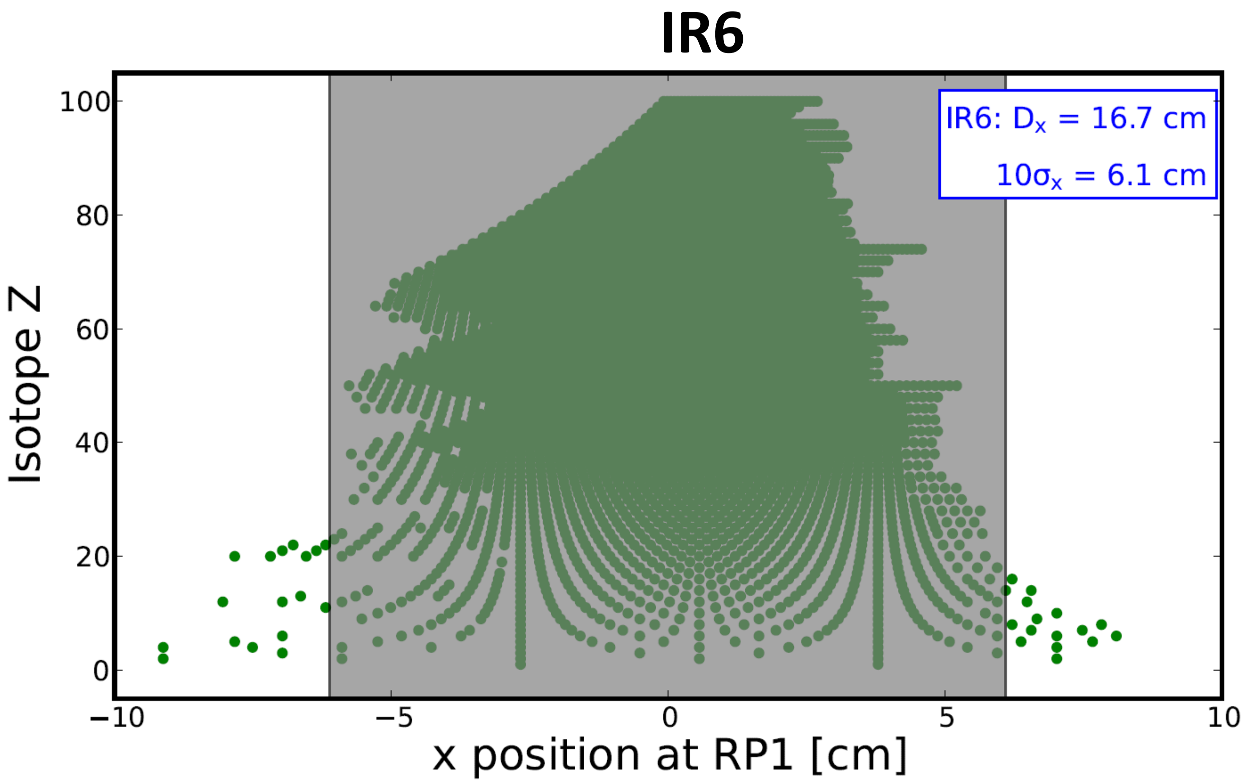
$$\boxed{\beta_x = 865\ m}$$
$$D_x = -16.7\ cm$$
$$\rightarrow \boxed{x_{min}^{RP1} = 6.11\ cm}$$

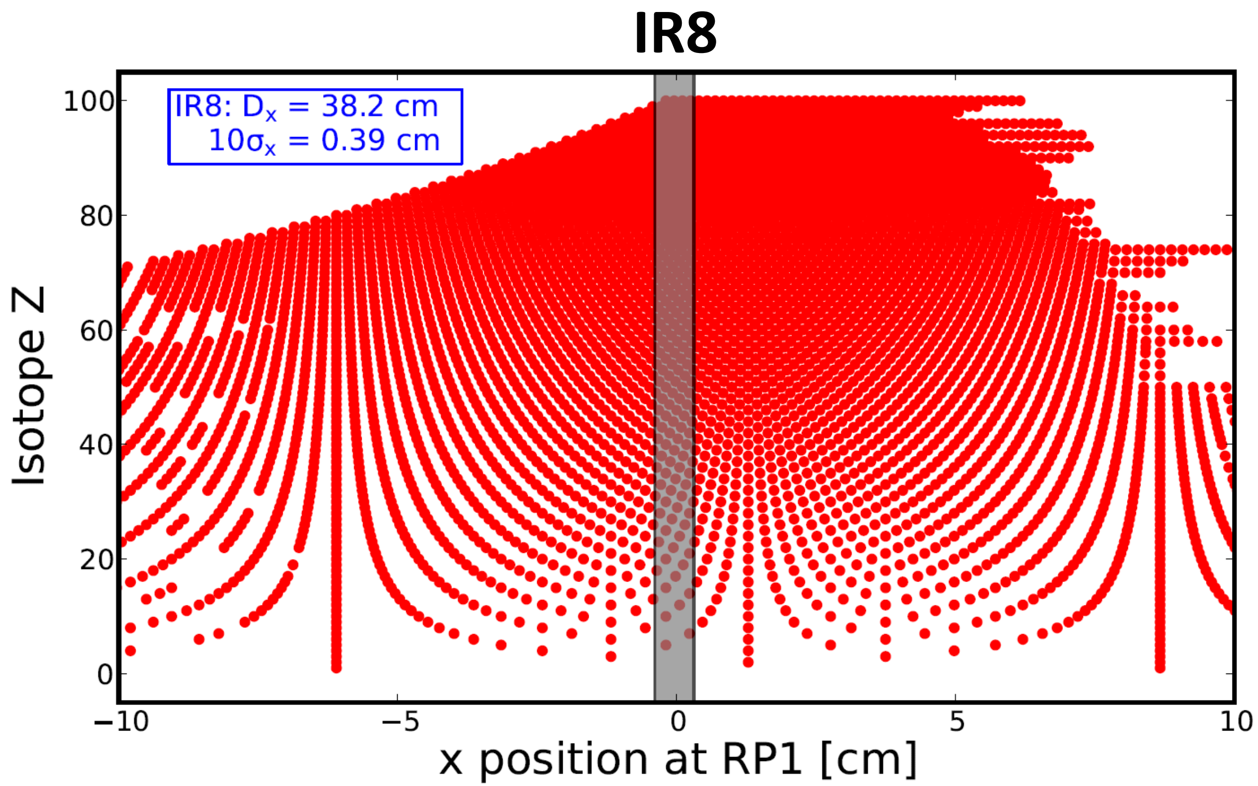
IR8 Parameters at first RP:

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

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

Roman Pot Acceptance





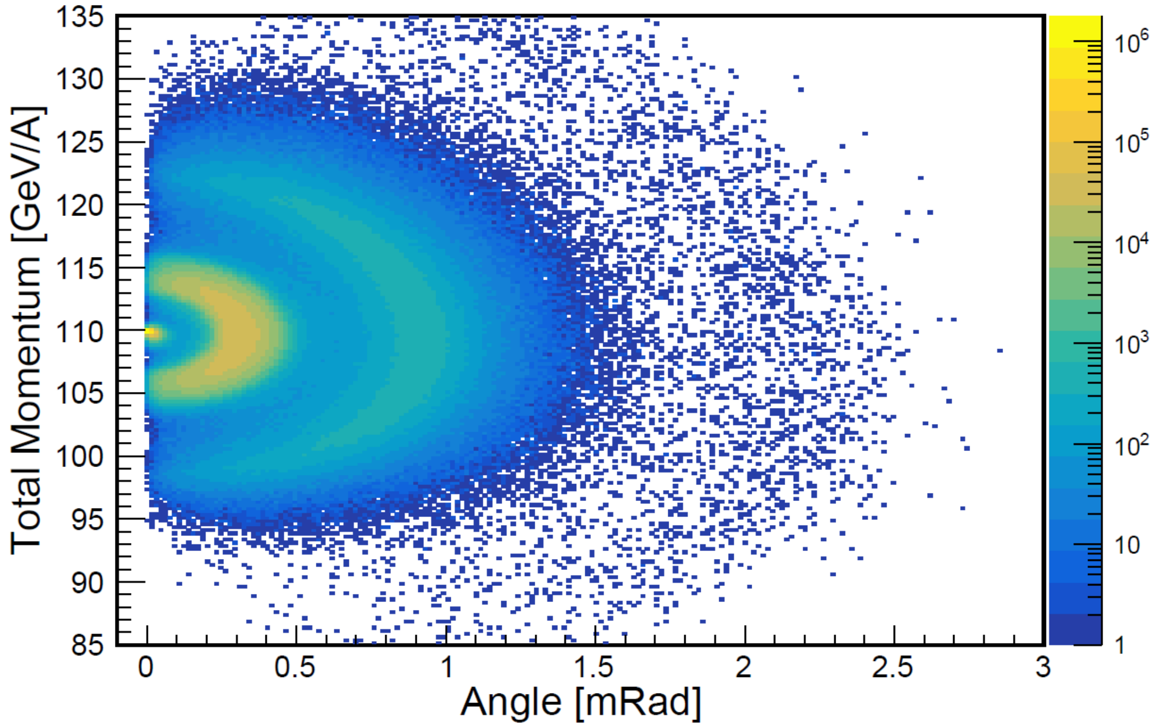
Isotope hit positions at the first RP vs. isotope Z
Includes all isotopes known/potential (NNDC and LISE++ database)
RP Positon Resolution of 10—100 microns

arXiv:2209.00496

Identification of Isotopes in IR6

To determine initial kinematics:

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



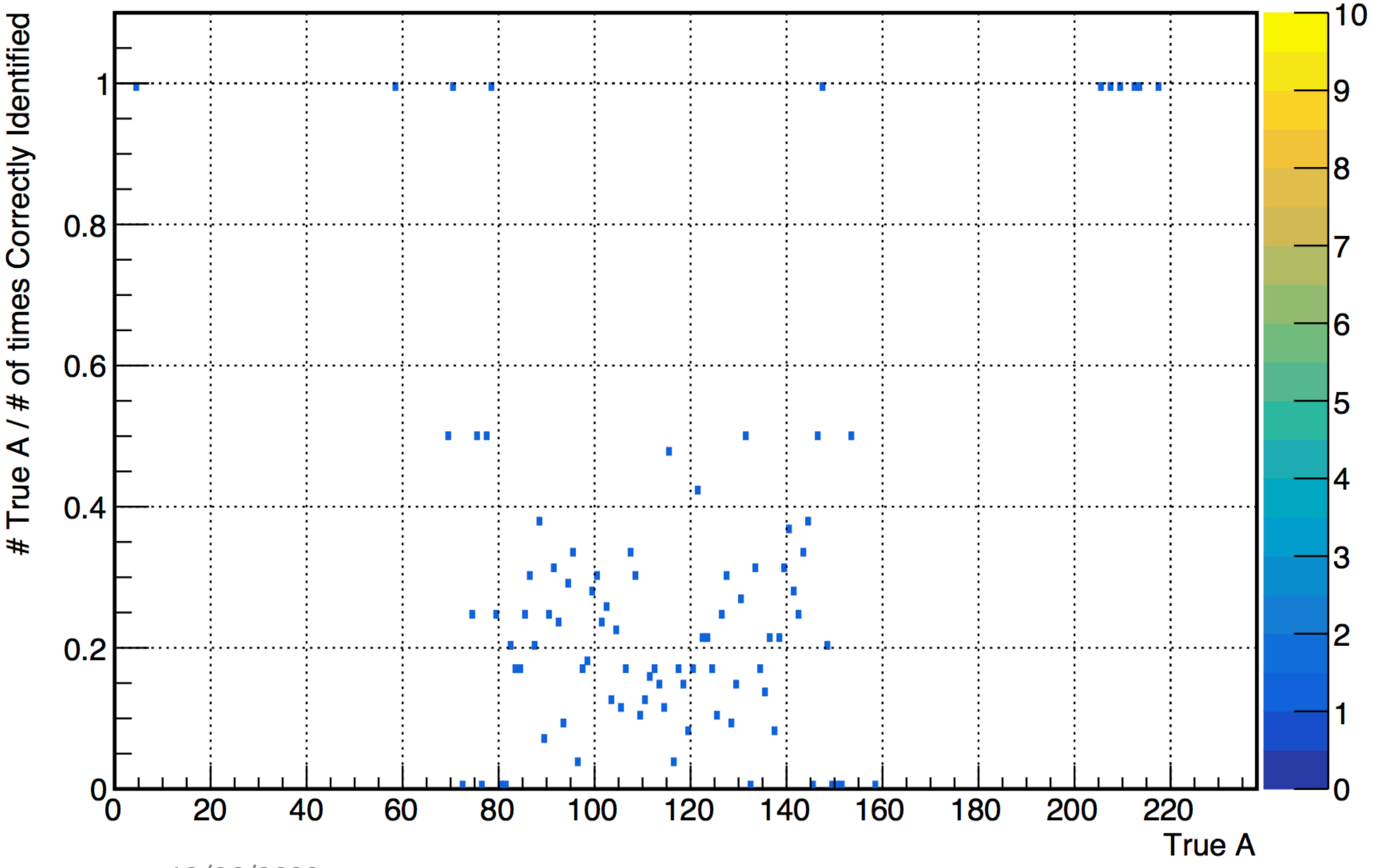
To identify isotopes, we use the relationship

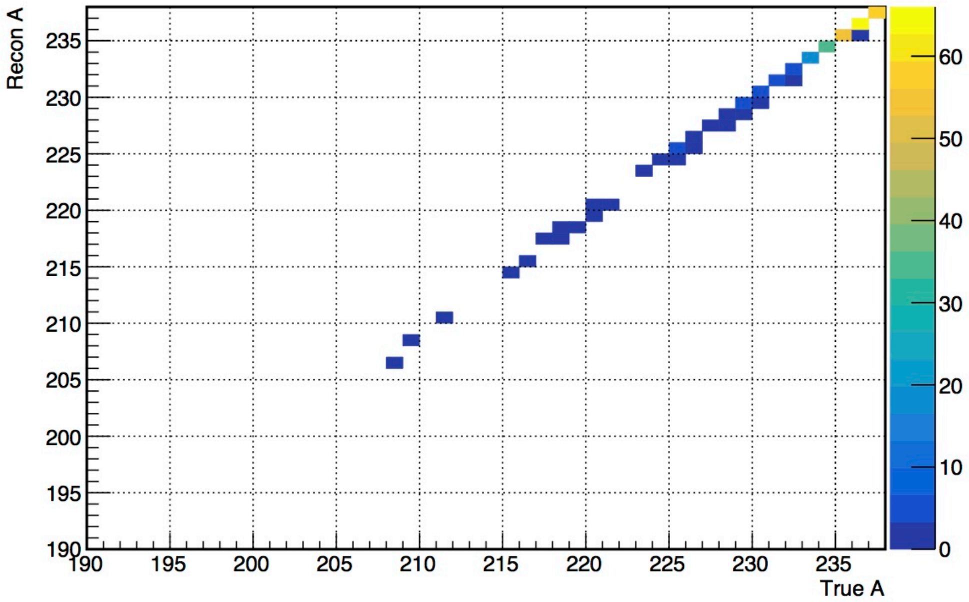
$$xL = \frac{R}{R_{Beam}} = \left[\left(\frac{Ap_N}{Z}\right) \Big/ \left(\frac{A_{beam}p_{N,beam}}{z_{beam}}\right)\right]$$

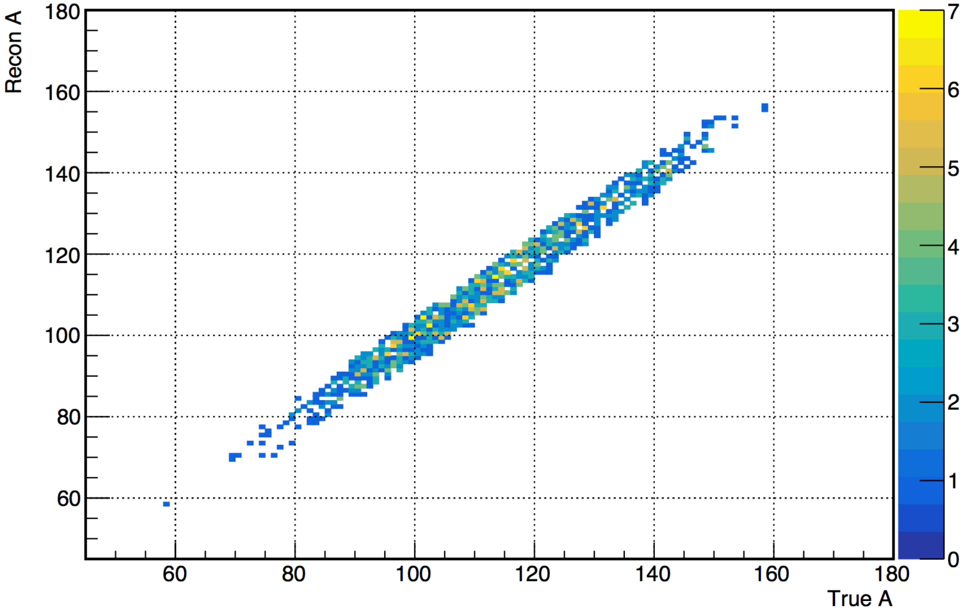
Using the assumption $P_N = P_{N,Beam}$:

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

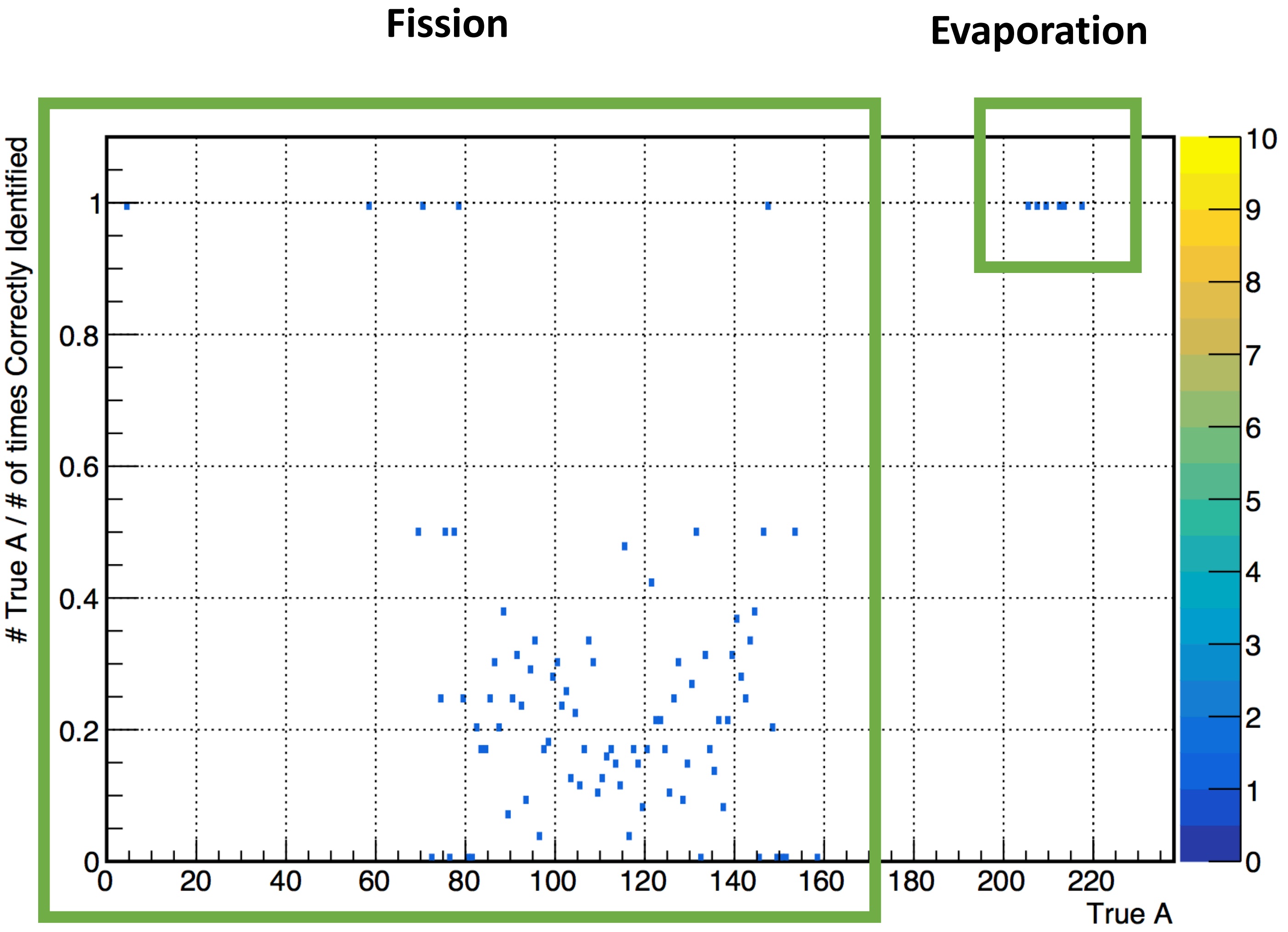
A Reconstruction in IR6

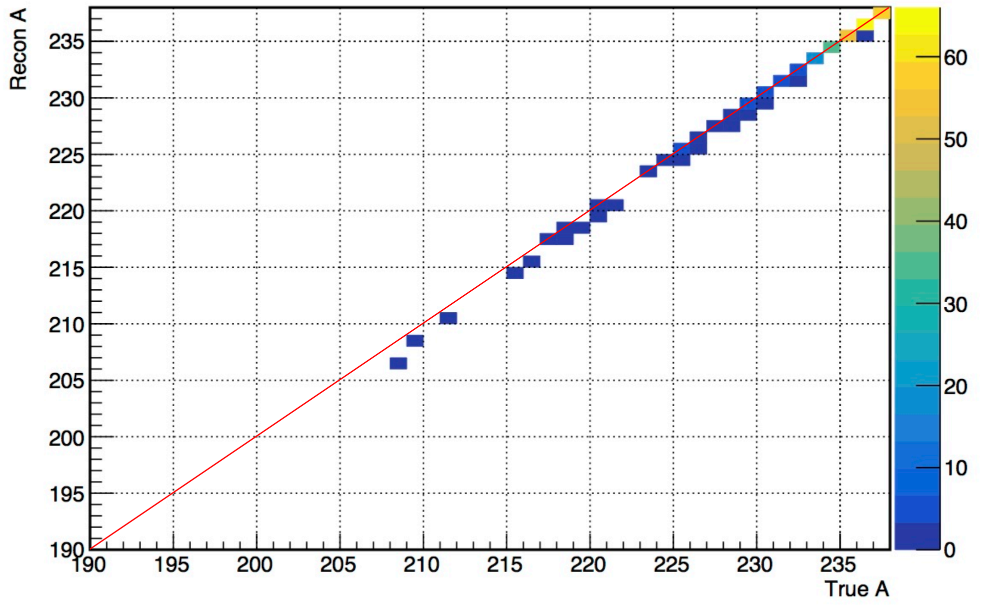


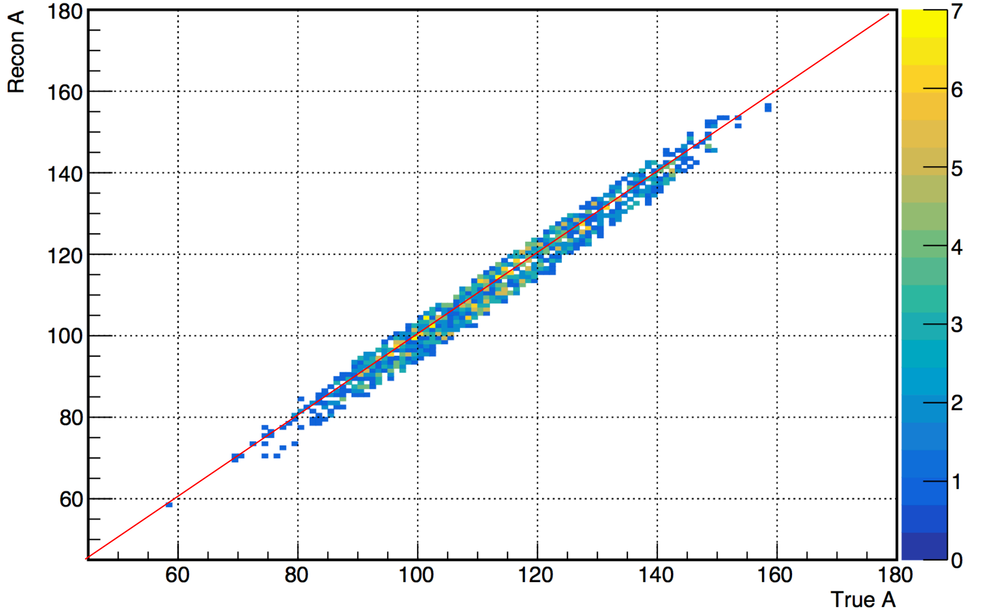




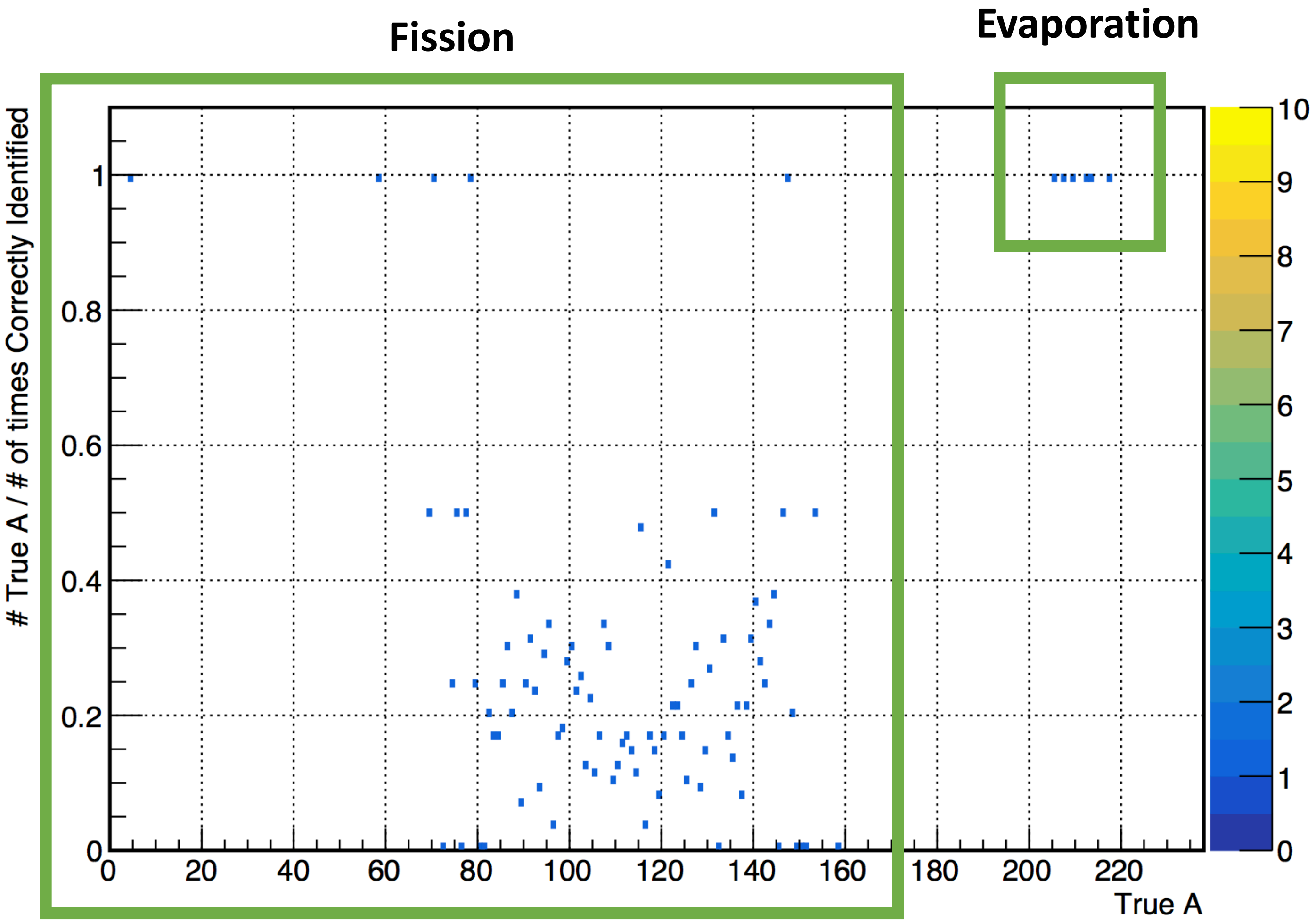
A Reconstruction in IR6

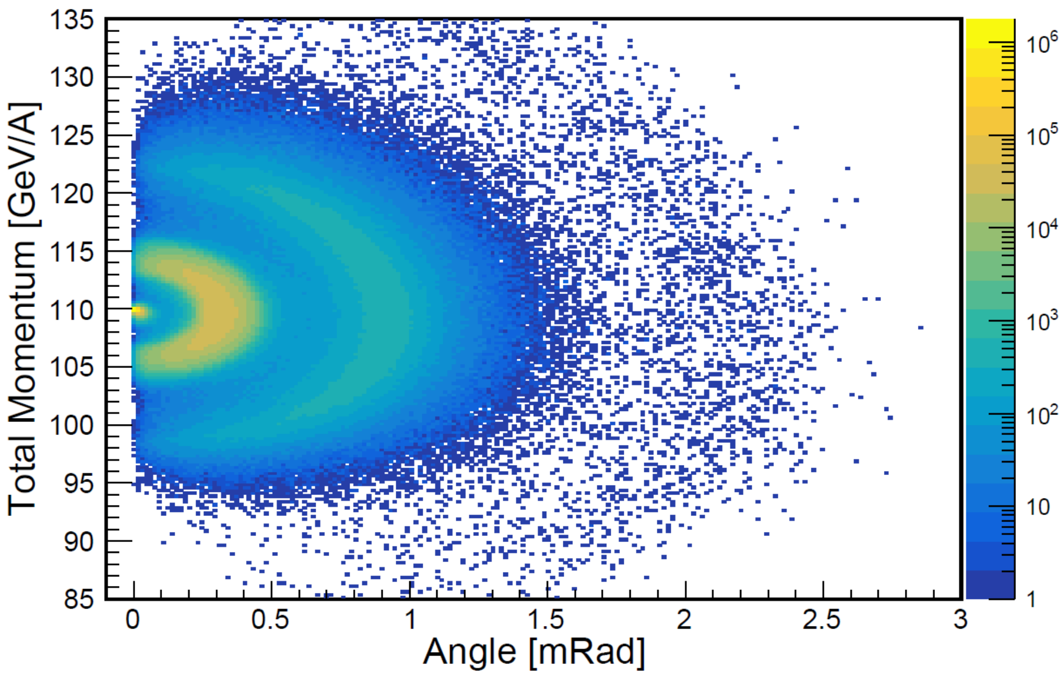






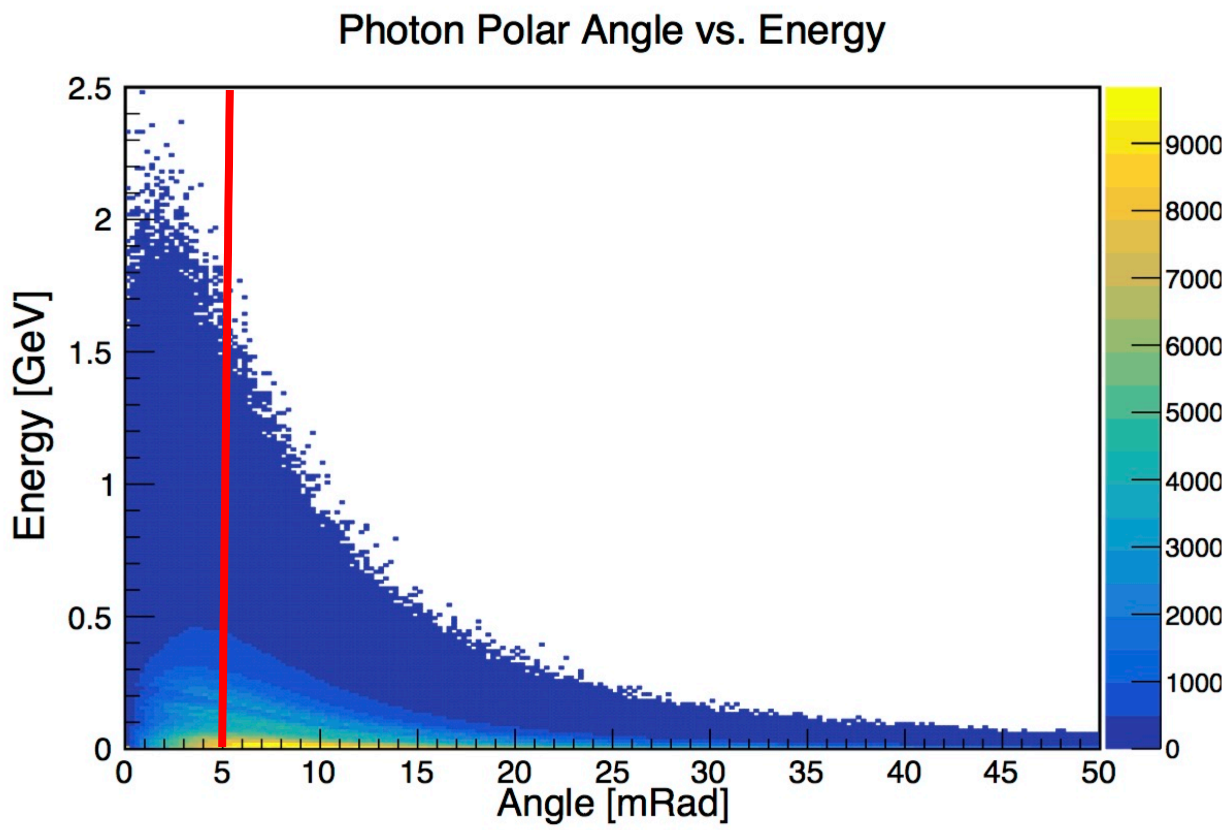
A Reconstruction

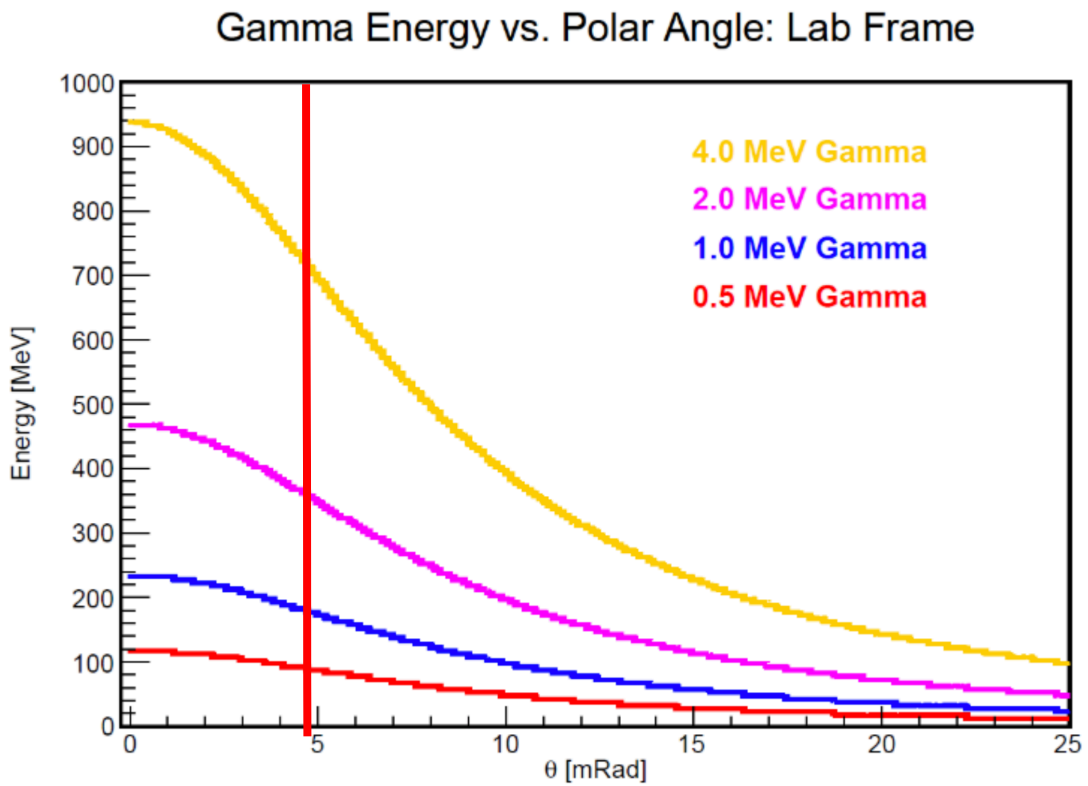




Our initial assumption about the momentum doesn't hold for isotopes with larger scattering angles (mostly fission products)
However, we can use this relationship to improve reconstruction!

ZDC Acceptance of de-excitation Gamma





Zero-Degree Calorimeter (ZDC) will have an acceptance range of ~0-5 mRad, and an energy resolution that could potentially be as good as $2\%/\sqrt{E(GeV)}$.

In Summary

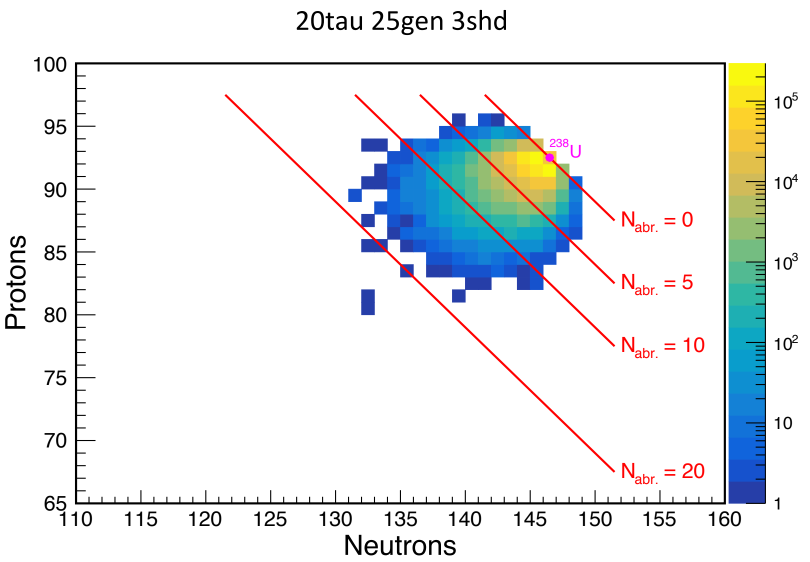
- Our studies suggest that the EIC has the potential to produce exotic nuclei, as well as the potential to be detected and identified using the proposed optics of the second interaction point with a second focus.
- We have the opportunity to simultaneously measure the de-excitation gammas of these rare isotopes, as well as improve current Abrasion-Fission models.
- This study is still in the early stages, however given the time scale for the project there’s still time to conduct further studies on how the EIC has the potential contribute to this field!

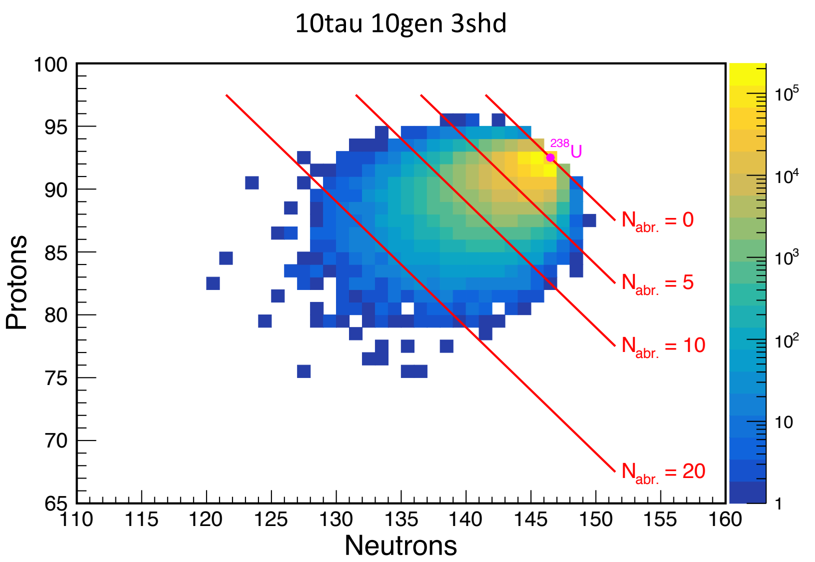
Thank you for listening!

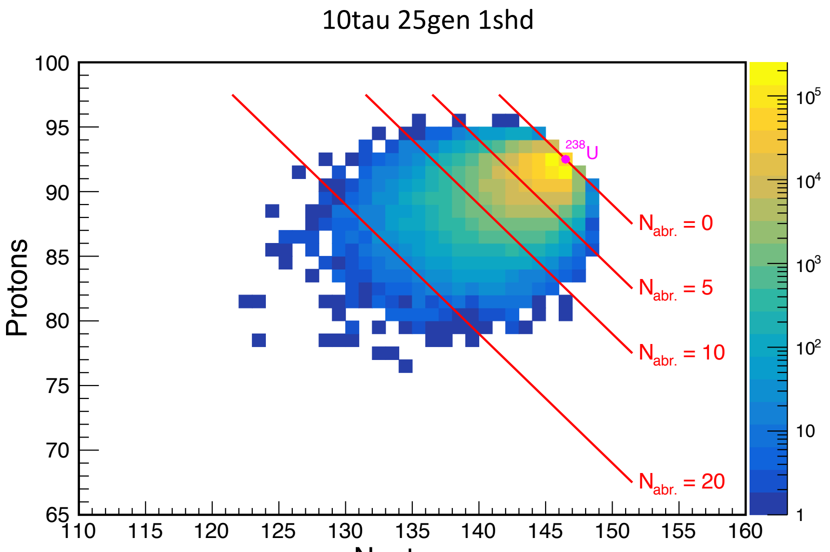
Backup Slides

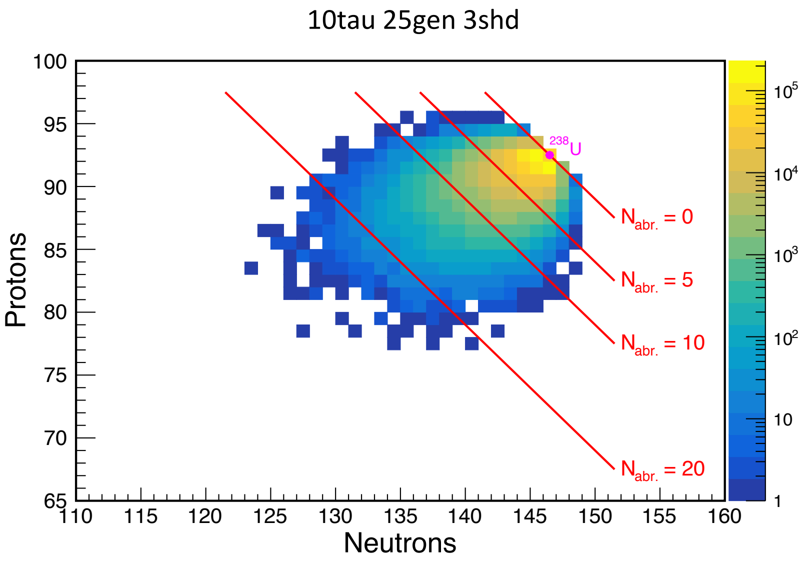
Residual Nucleus N vs Z

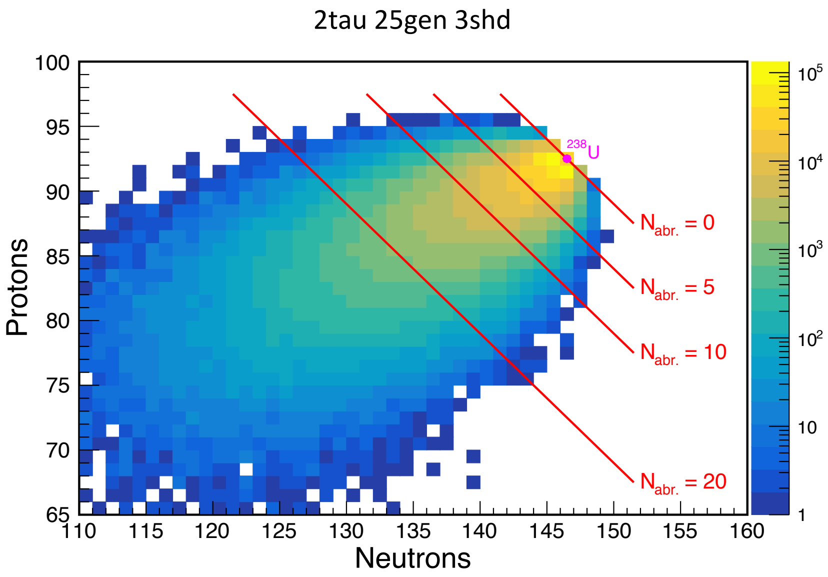
We can see that varying τ_0 has a greater impact than the gen or shd parameter



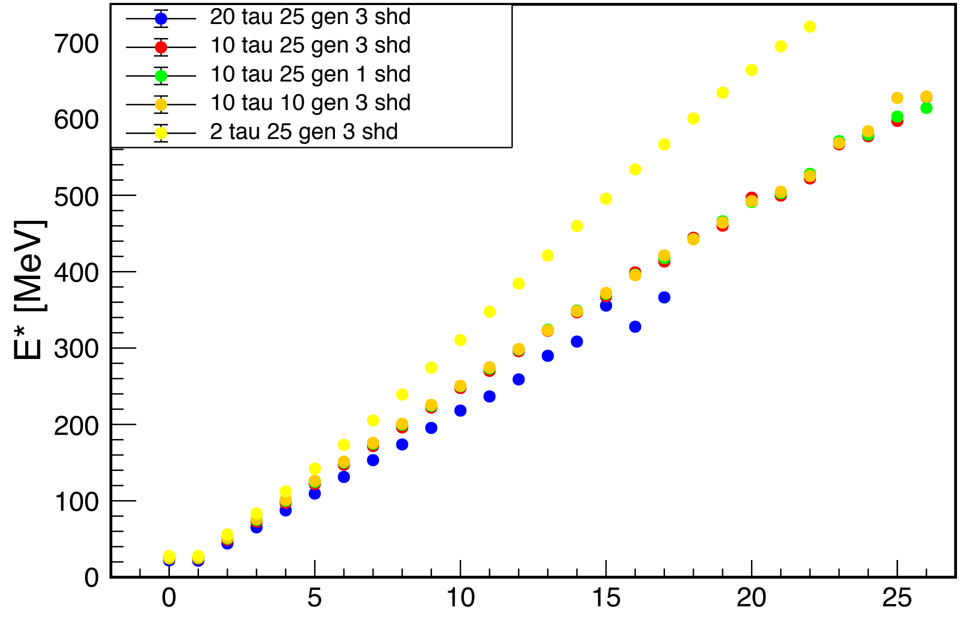


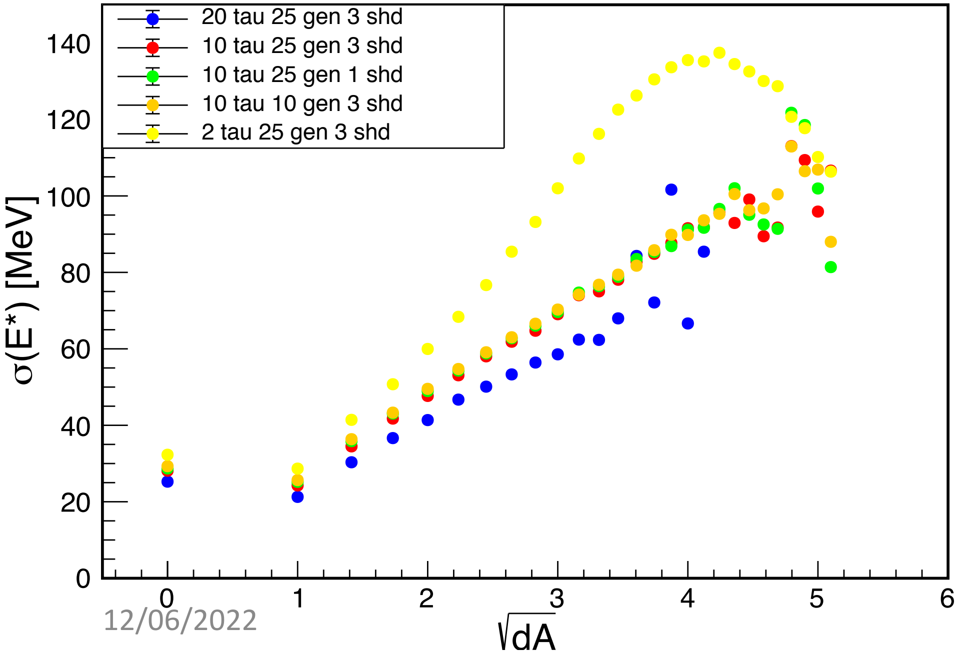


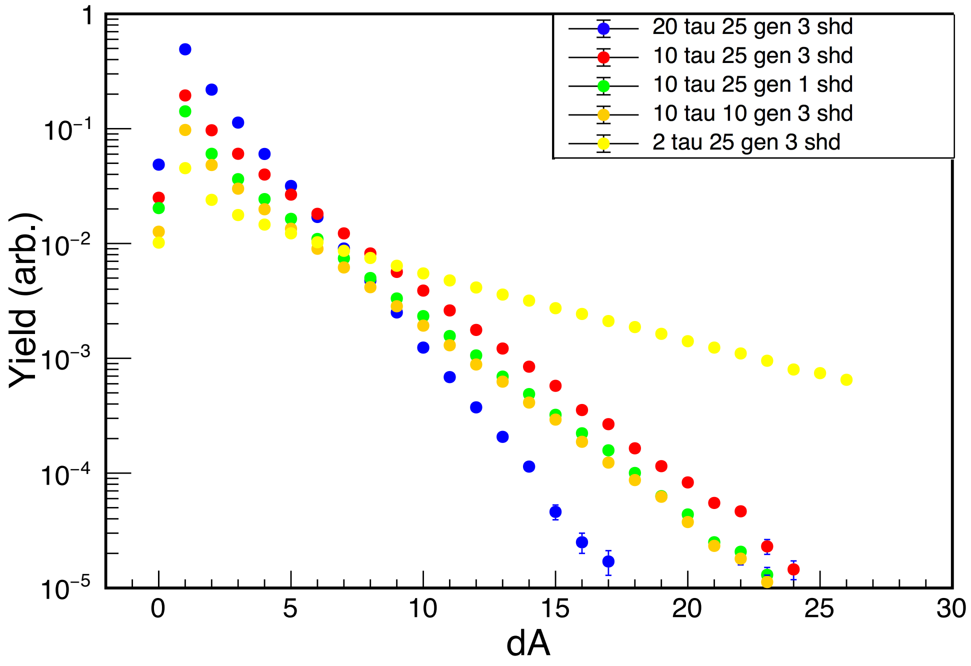




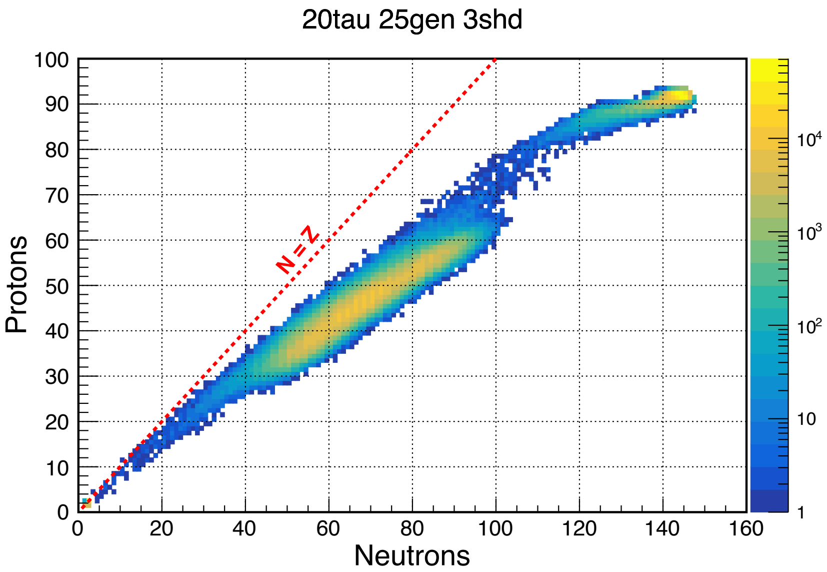
Excited Intermediate Nucleus from BeAGLE

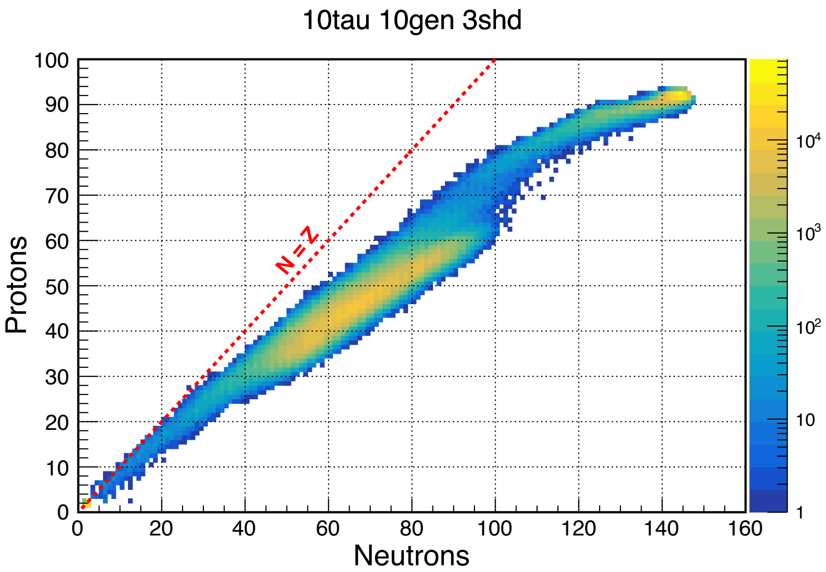


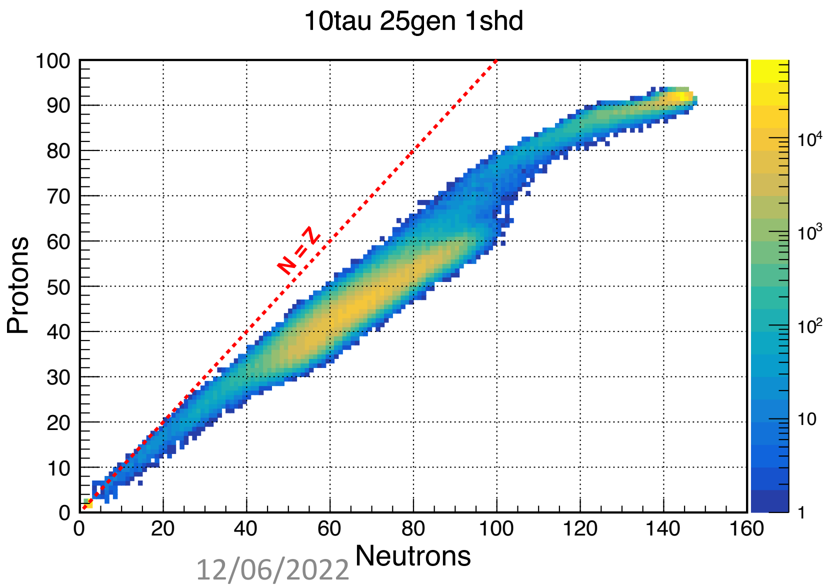


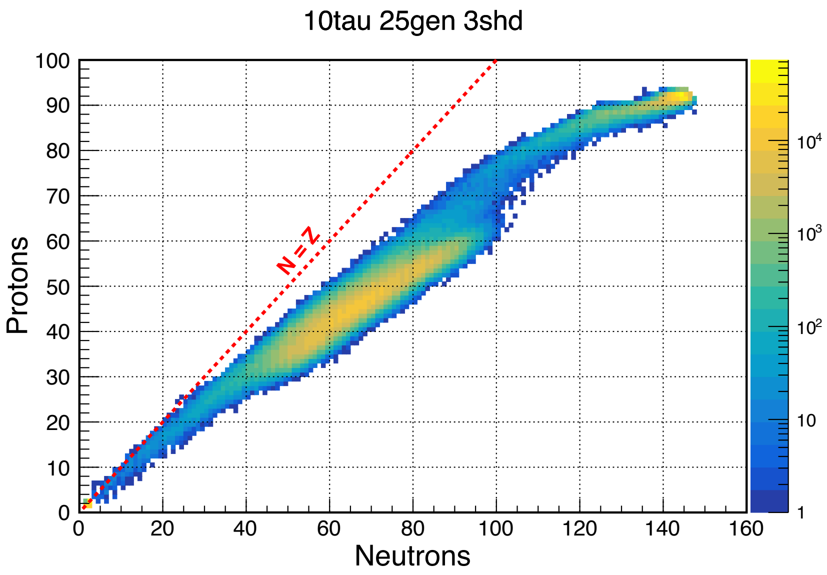


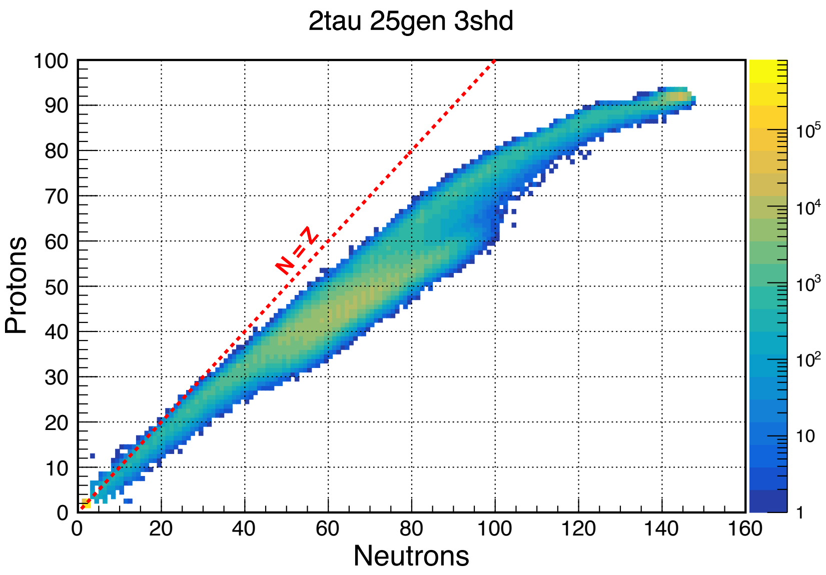
Daughter Products N vs Z



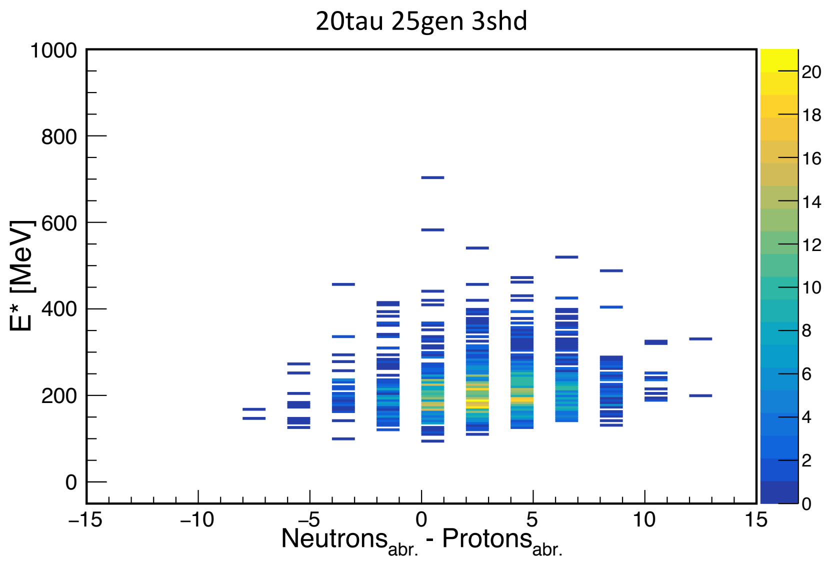


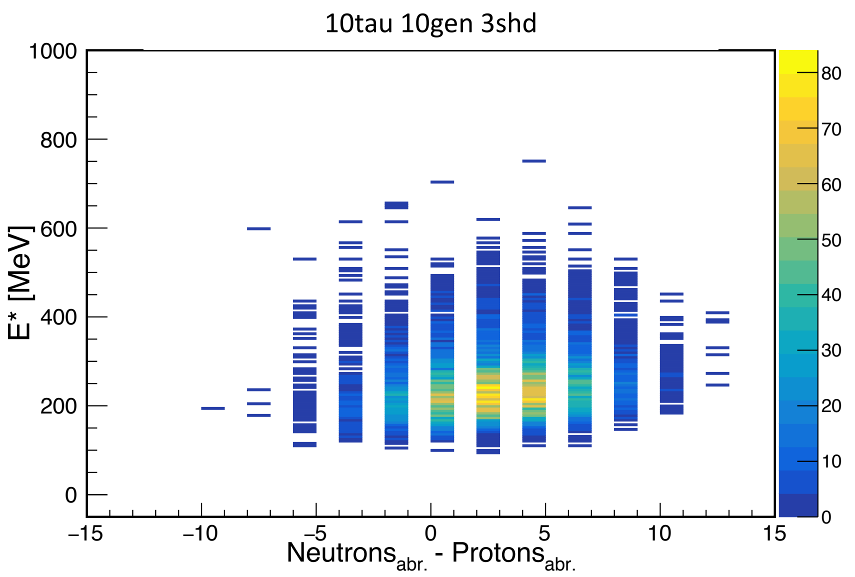


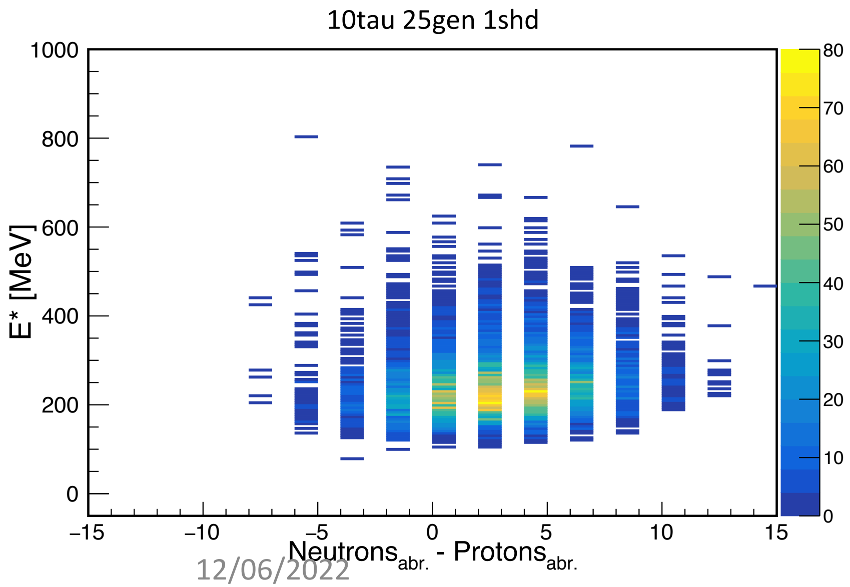


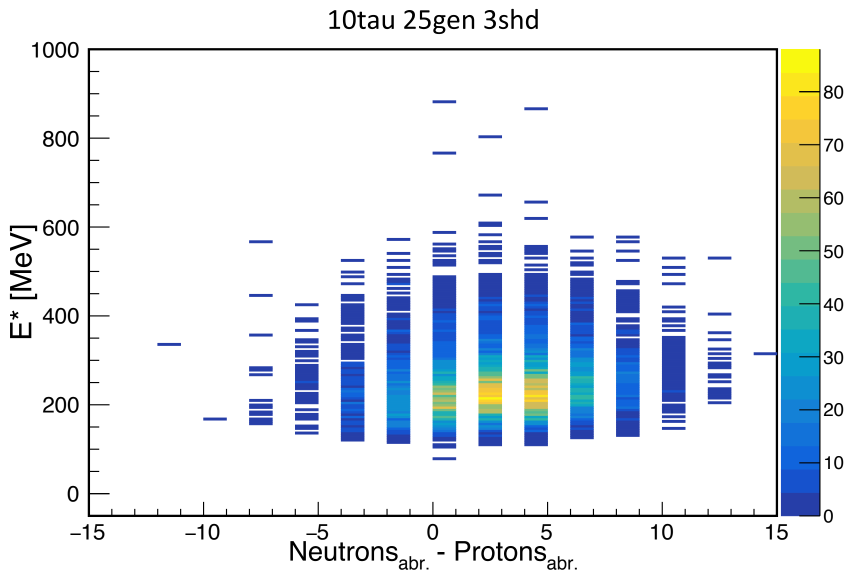


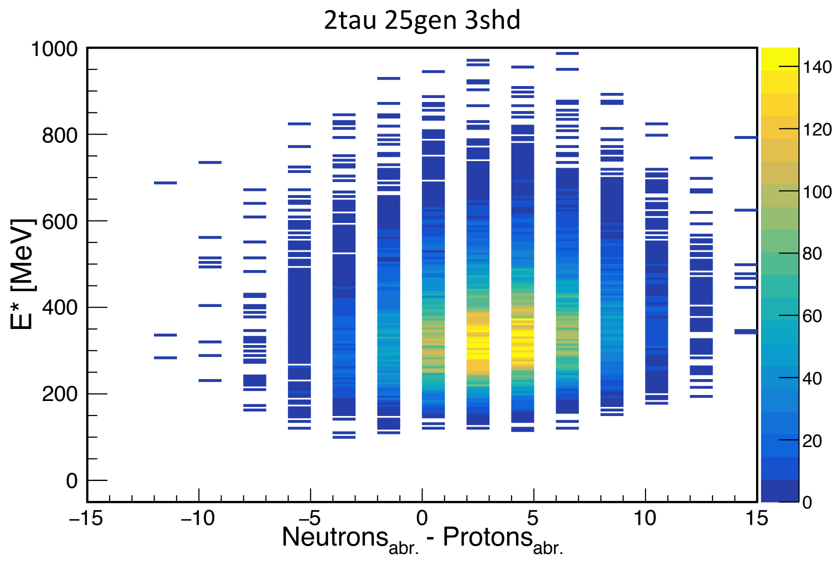
Abrasion asymmetry for 10 nucleon abraded events











ZDC Reconstruction of the Level Structure