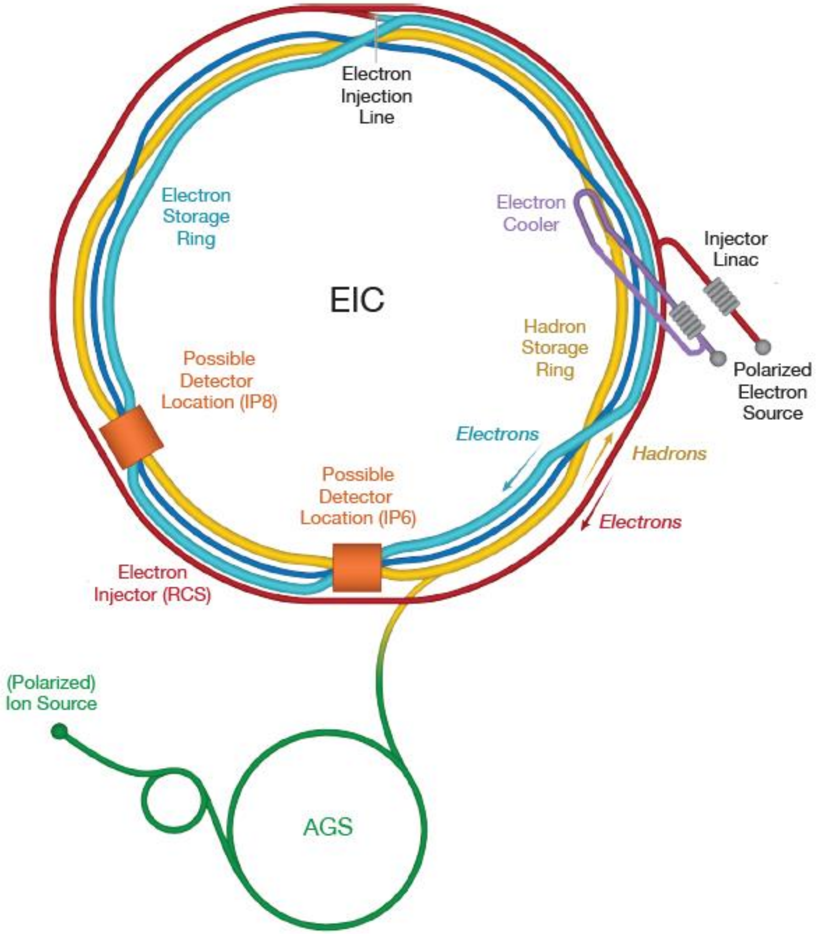
Production and detection of nuclear fragments at the future Electron-Ion Collider (EIC)

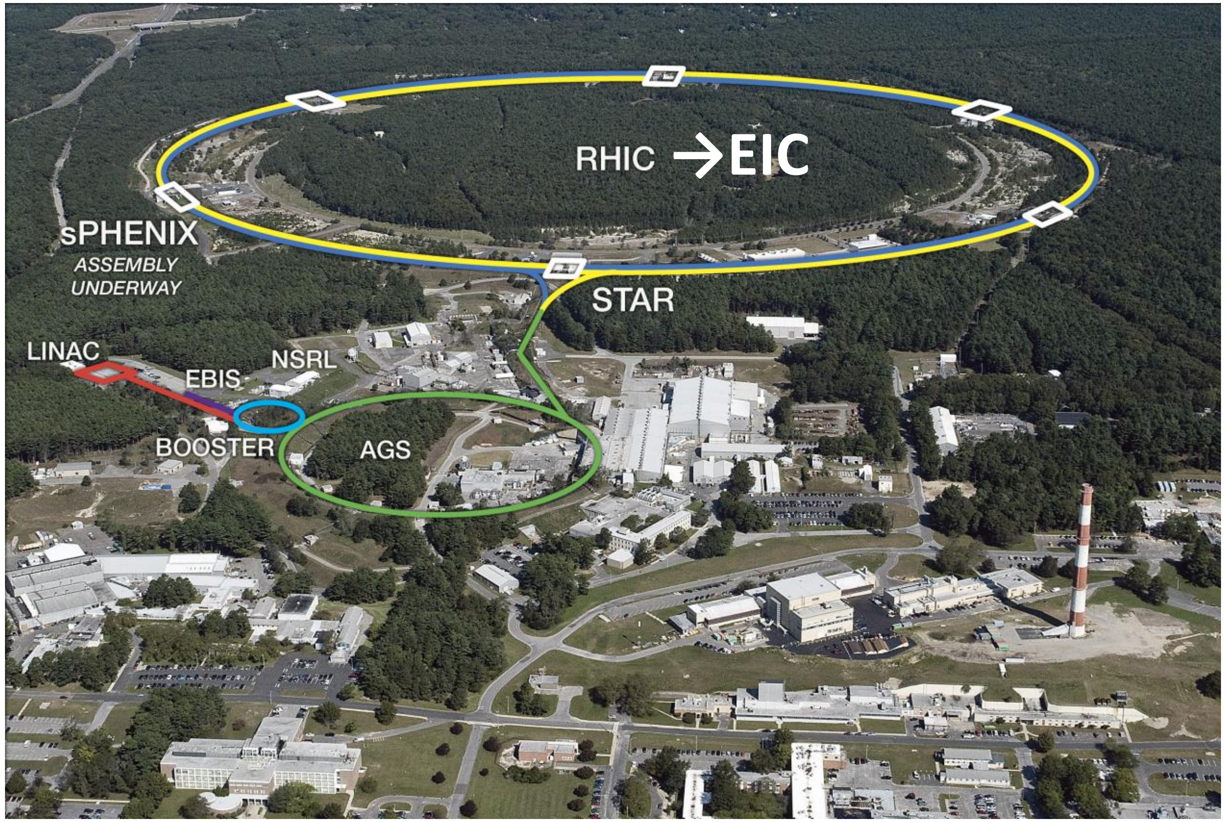
Barak Schmookler

Introduction to the EIC

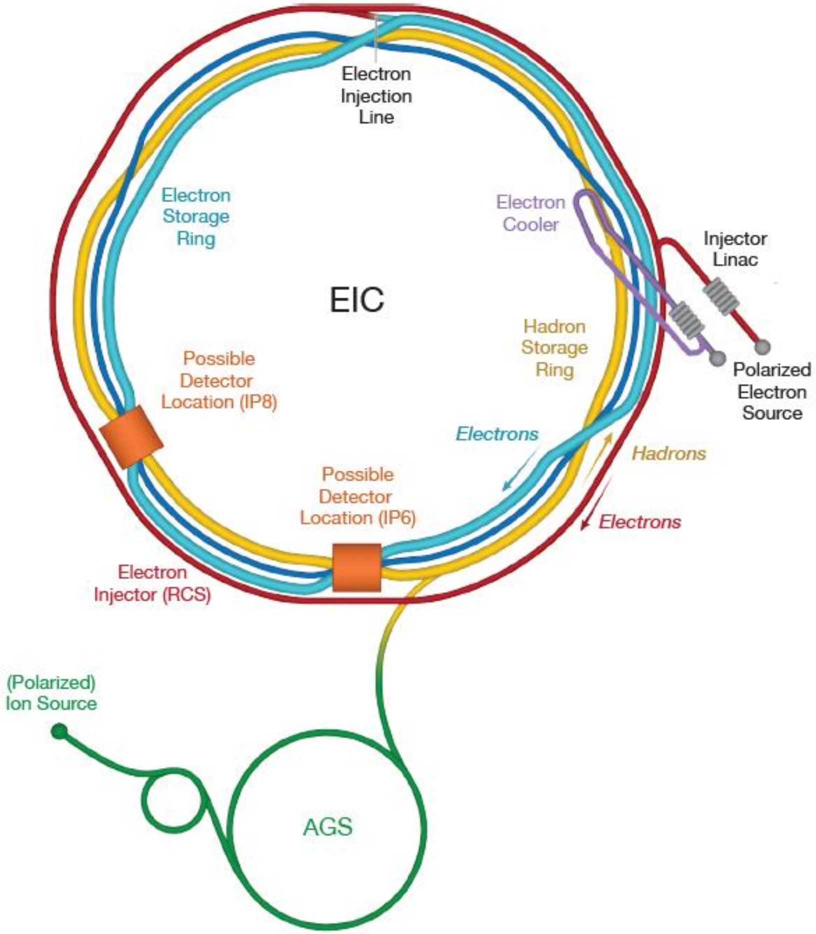
The Electron-Ion Collider (EIC) – The Next QCD Frontier

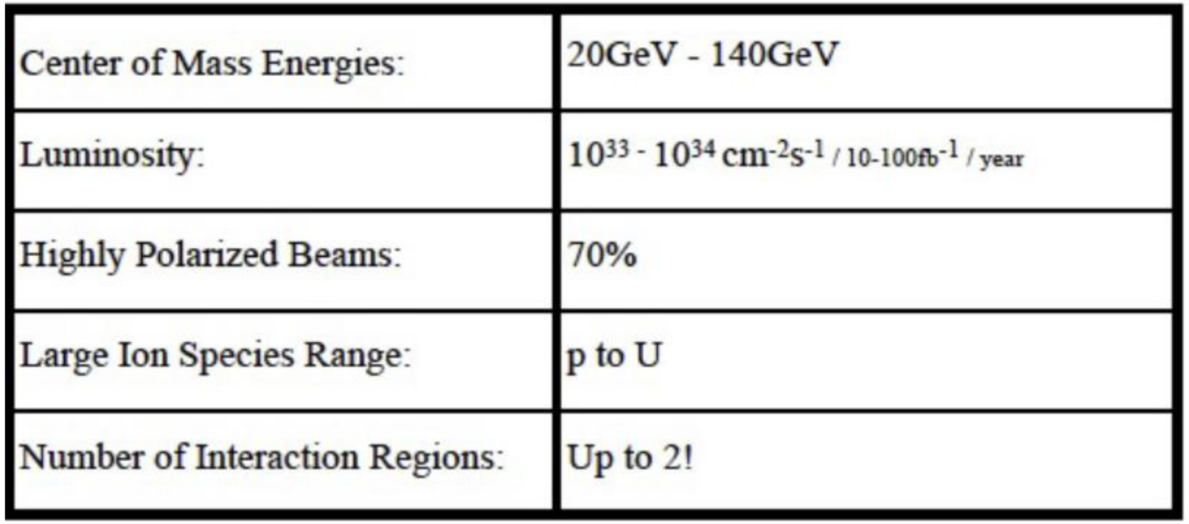


Brookhaven National Laboratory

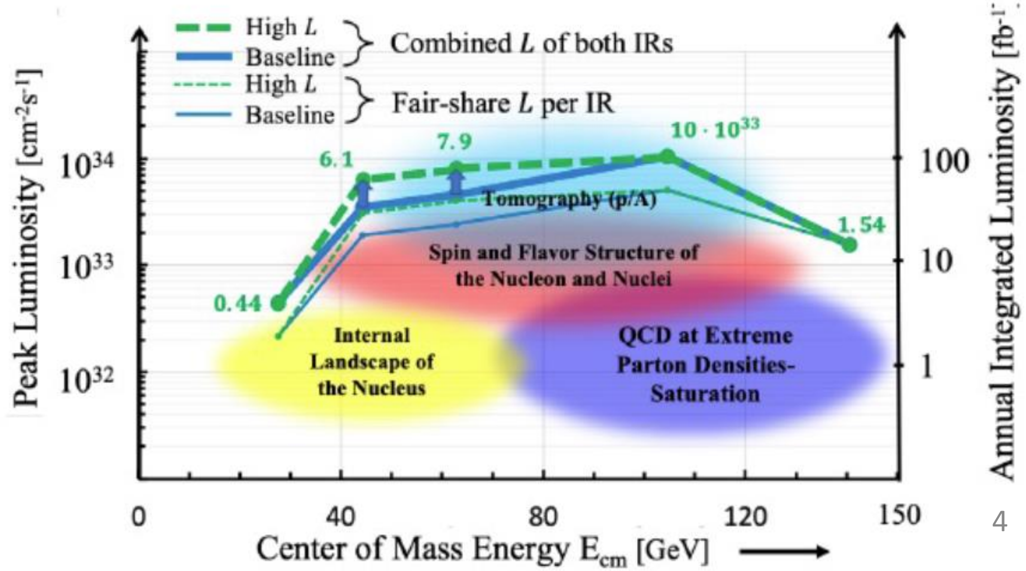


The Electron-Ion Collider (EIC) – The Next QCD Frontier





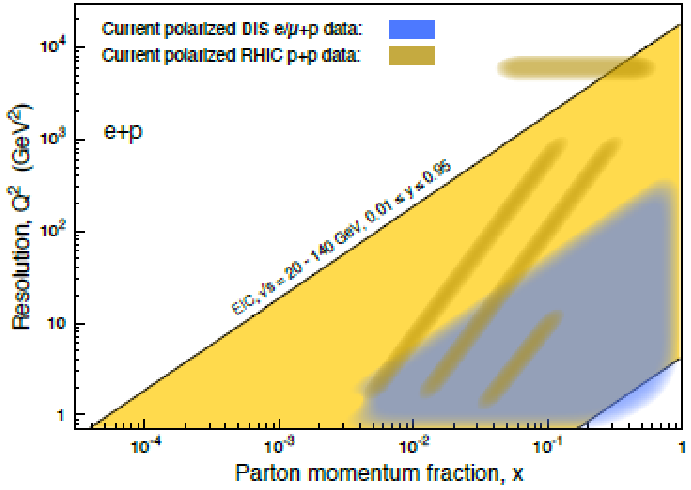
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!

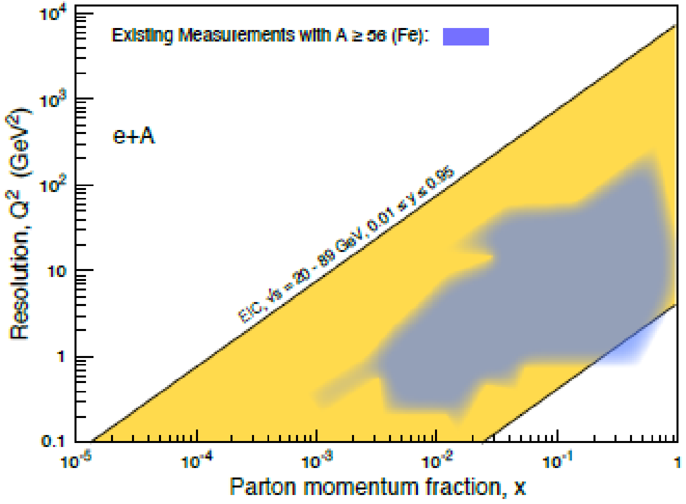


The EIC will make extremely important contributions to our understanding of nucleon structure

Main physics topics to be explored at the EIC:

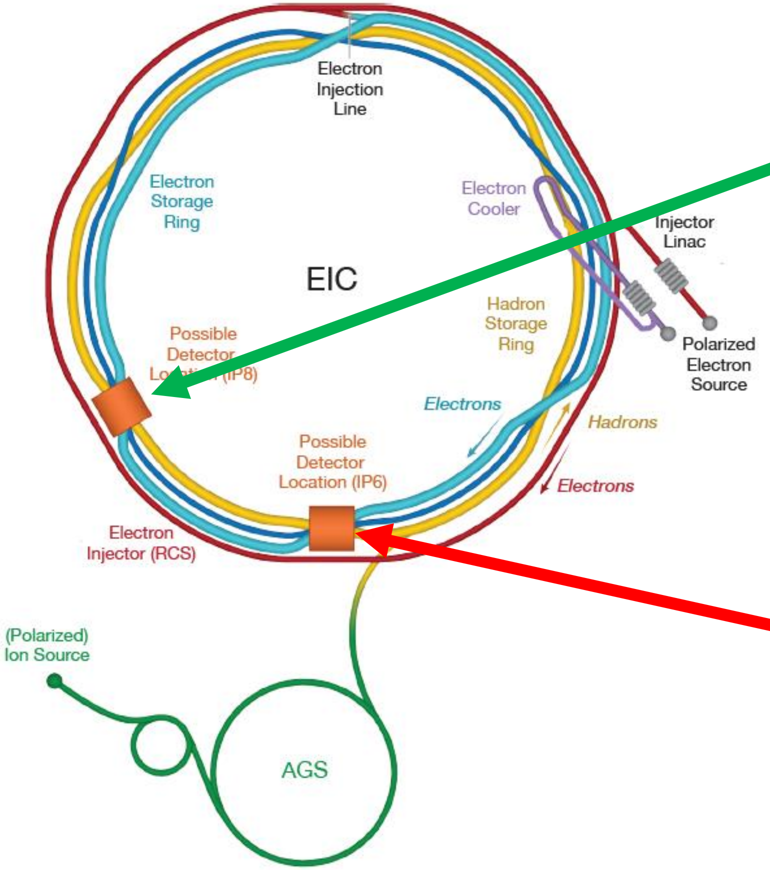
- ❑Nucleon structure – full three-dimensional momentum and spatial structure, as well as spin structure
- ❑Origin of nucleon (hadron) mass – how is the nucleon's mass generated by the underlying internal partonic interactions
- ❑Gluon saturation – at the smallest momentum fractions, the parton density can grow so large that their interactions enter a non-linear regime
- ❑Science beyond the 2018 National Academies of Science (NAS) report





A lot more information coming in Week 5!

EIC current status



- **First second EIC detector will be located here.**
- **There is a conceptual design for the interaction region; and a working group has been formed to develop the detector concept futher.**
- **Data taking would begin a few years later than the first detector.**

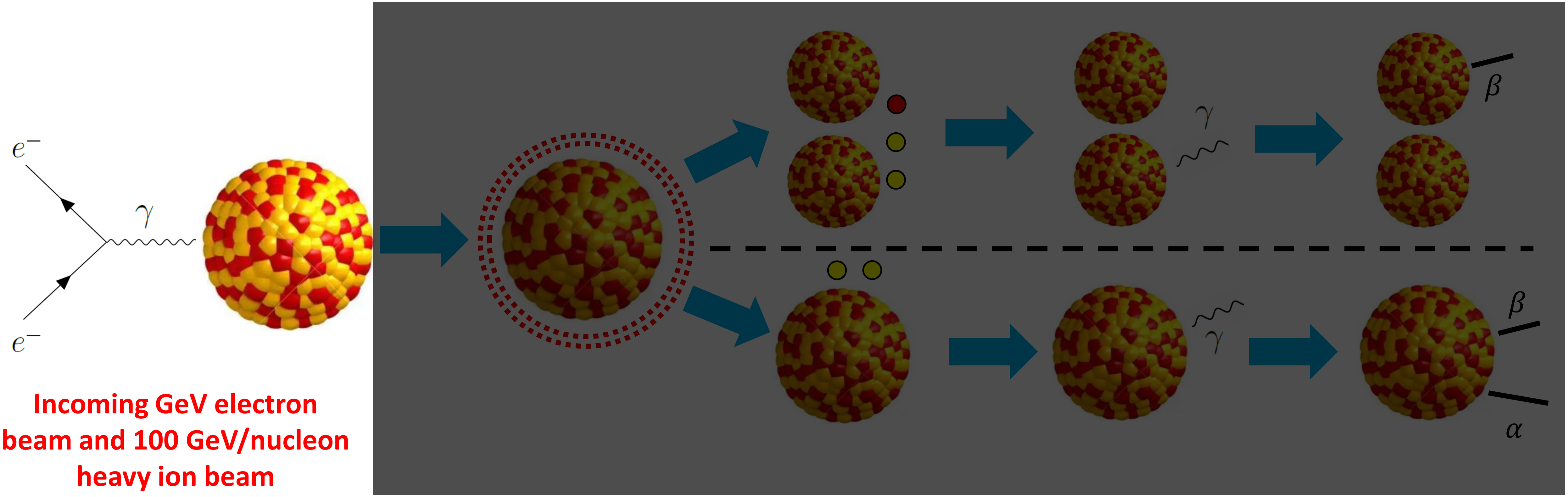
- **The first EIC detector will be located here.**
- **We have a mature design for the interaction region; and a collaboration – ePIC – has been formed.**
- **Data taking should begin in the early 2030's.**

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?

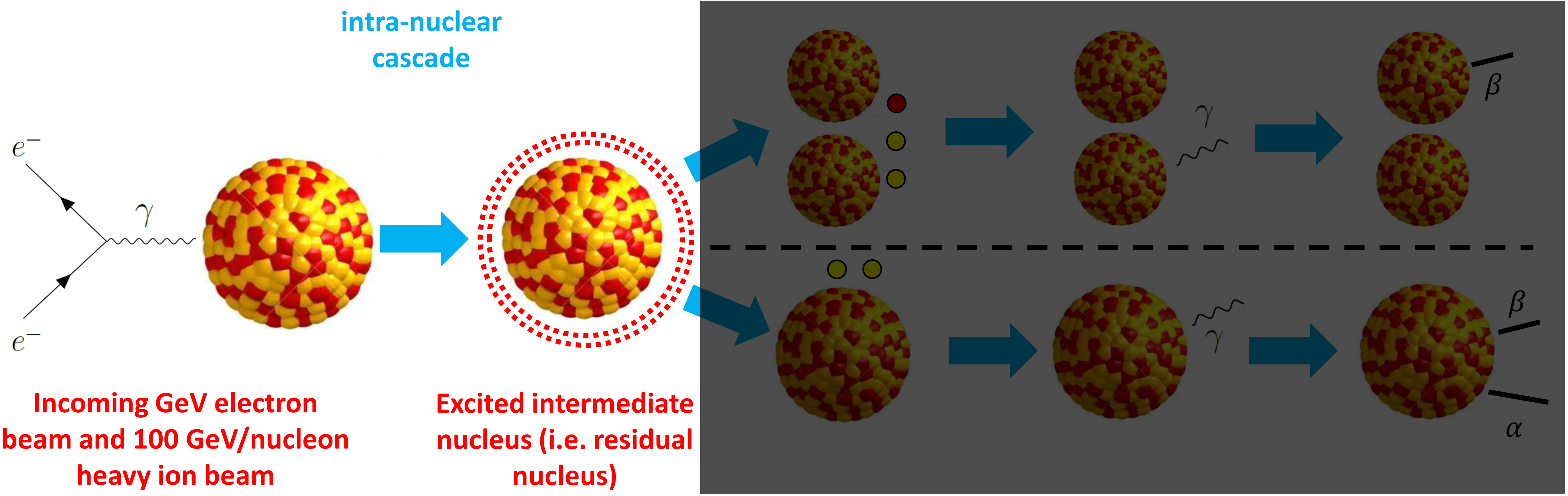
Fragment production at the EIC



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

t = 0

Fragment production at the EIC



Hard scattering and
intra-nuclear
cascade

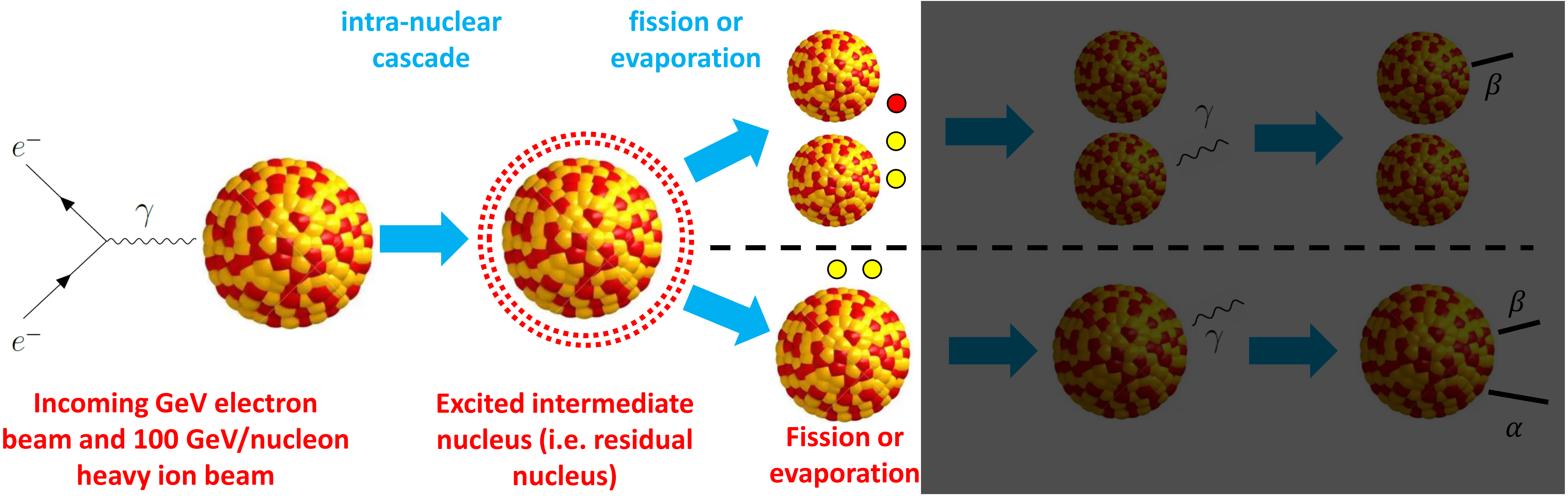
Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

Excited intermediate nucleus (i.e. residual nucleus)

t = 0

t = 10^{-22} s

Fragment production at the EIC



Hard scattering and intra-nuclear cascade

High-energy fission or evaporation

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

Excited intermediate nucleus (i.e. residual nucleus)

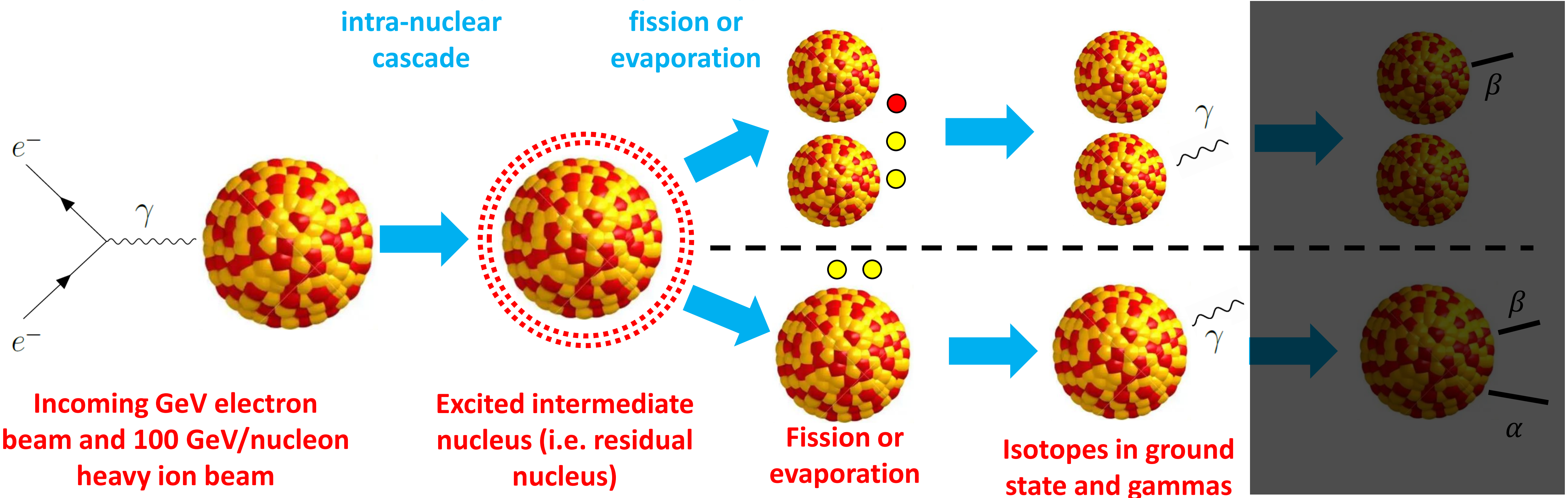
Fission or evaporation products

t = 0

t = 10^{-22} s

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

Fragment production at the EIC



Hard scattering and intra-nuclear cascade

High-energy fission or evaporation

Gamma de-excitation

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

Excited intermediate nucleus (i.e. residual nucleus)

Fission or evaporation products

Isotopes in ground state and gammas

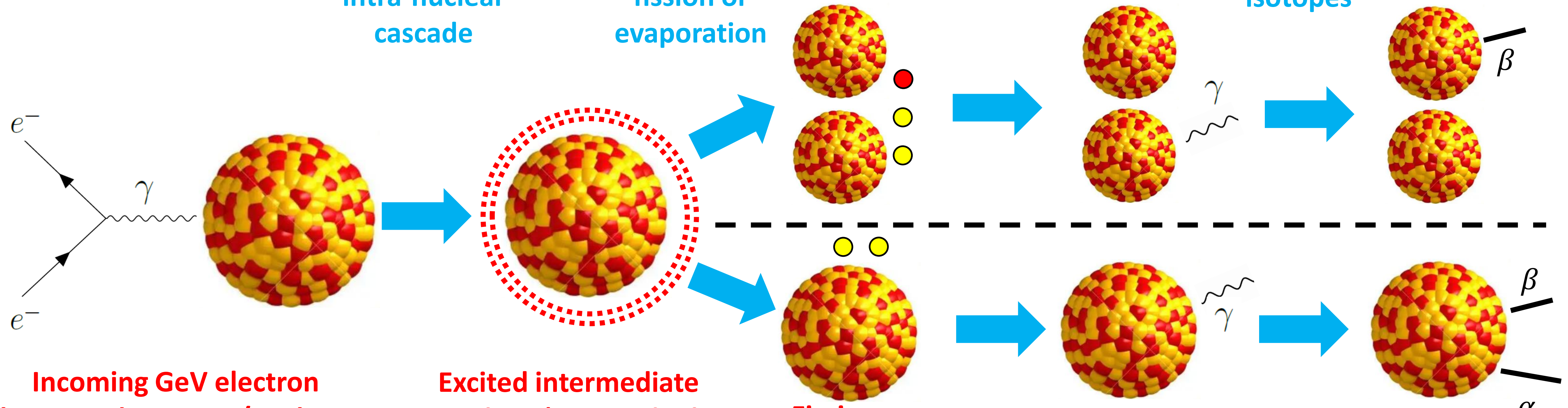
t = 0

t = 10^{-22} s

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

t = 10^{-14} s

Fragment production at the EIC



Hard scattering and intra-nuclear cascade

High-energy fission or evaporation

Gamma de-excitation

Decay of radioactive isotopes

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

Excited intermediate nucleus (i.e. residual nucleus)

Fission or evaporation products

Isotopes in ground state and gammas

Isotopes after radioactive decay

t = 0

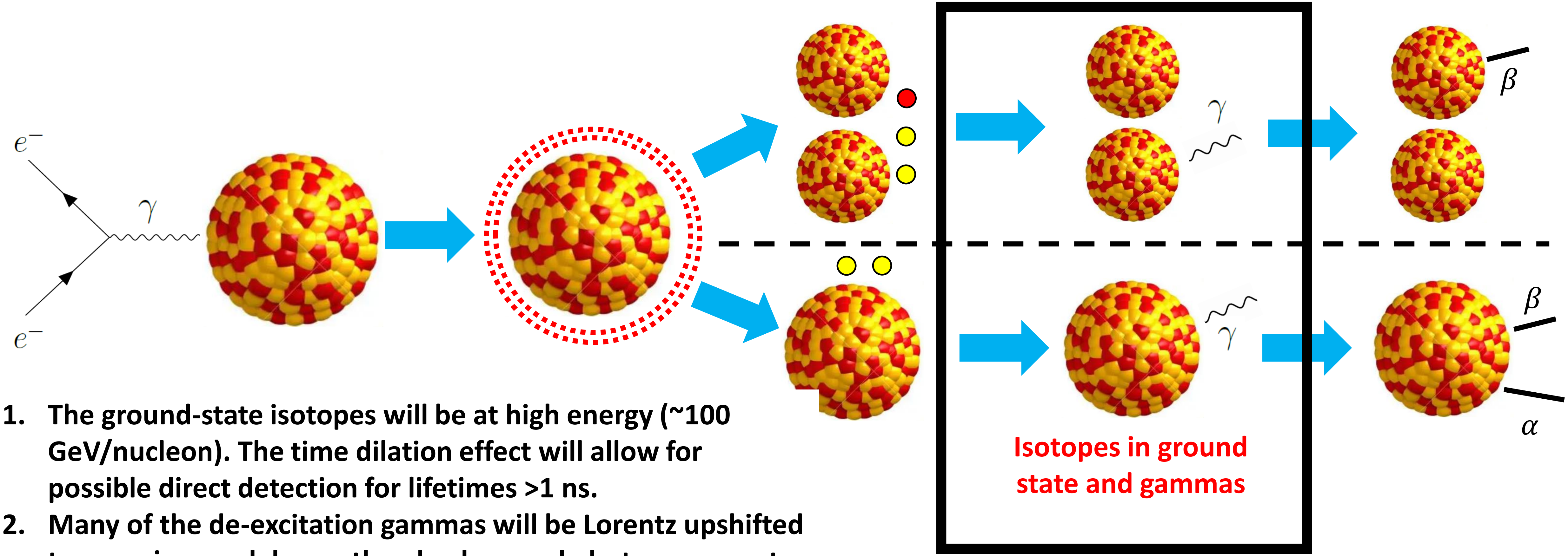
t = 10^{-22} s

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

t = 10^{-14} s

t = ? – never (stable)

Where the EIC can potentially contribute



Isotopes in ground state and gammas

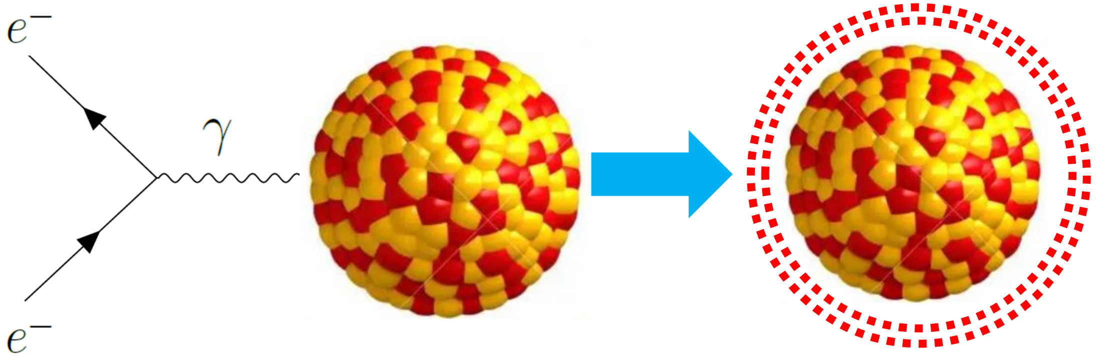
1. **The ground-state isotopes will be at high energy (~100 GeV/nucleon). The time dilation effect will allow for possible direct detection for lifetimes >1 ns.**
2. **Many of the de-excitation gammas will be Lorentz upshifted to energies much larger than background photons present in the detector area. 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 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 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

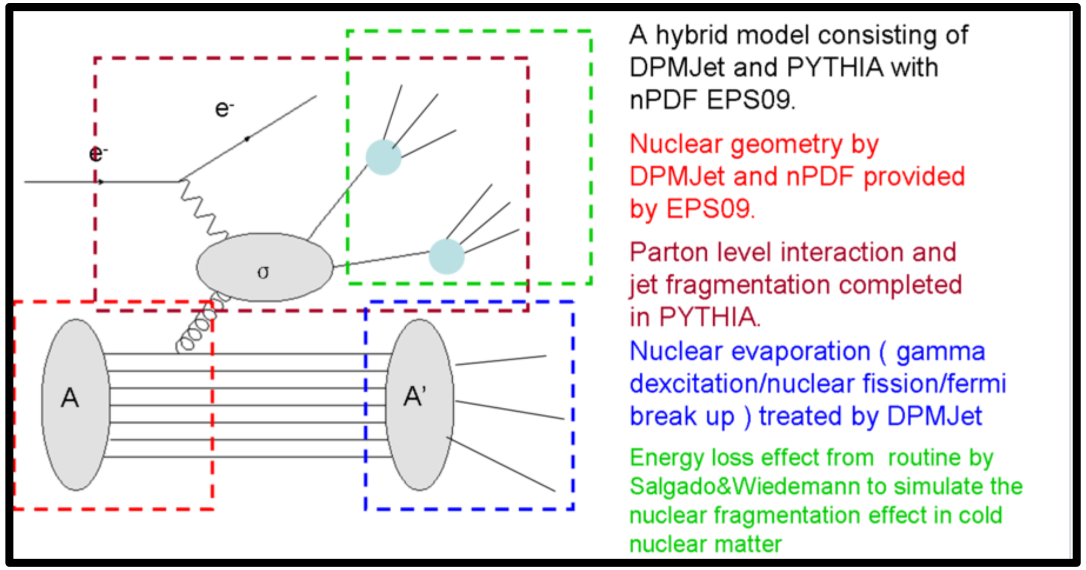


Incoming GeV electron beam and 100 GeV/nucleon heavy ion beam

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.



A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

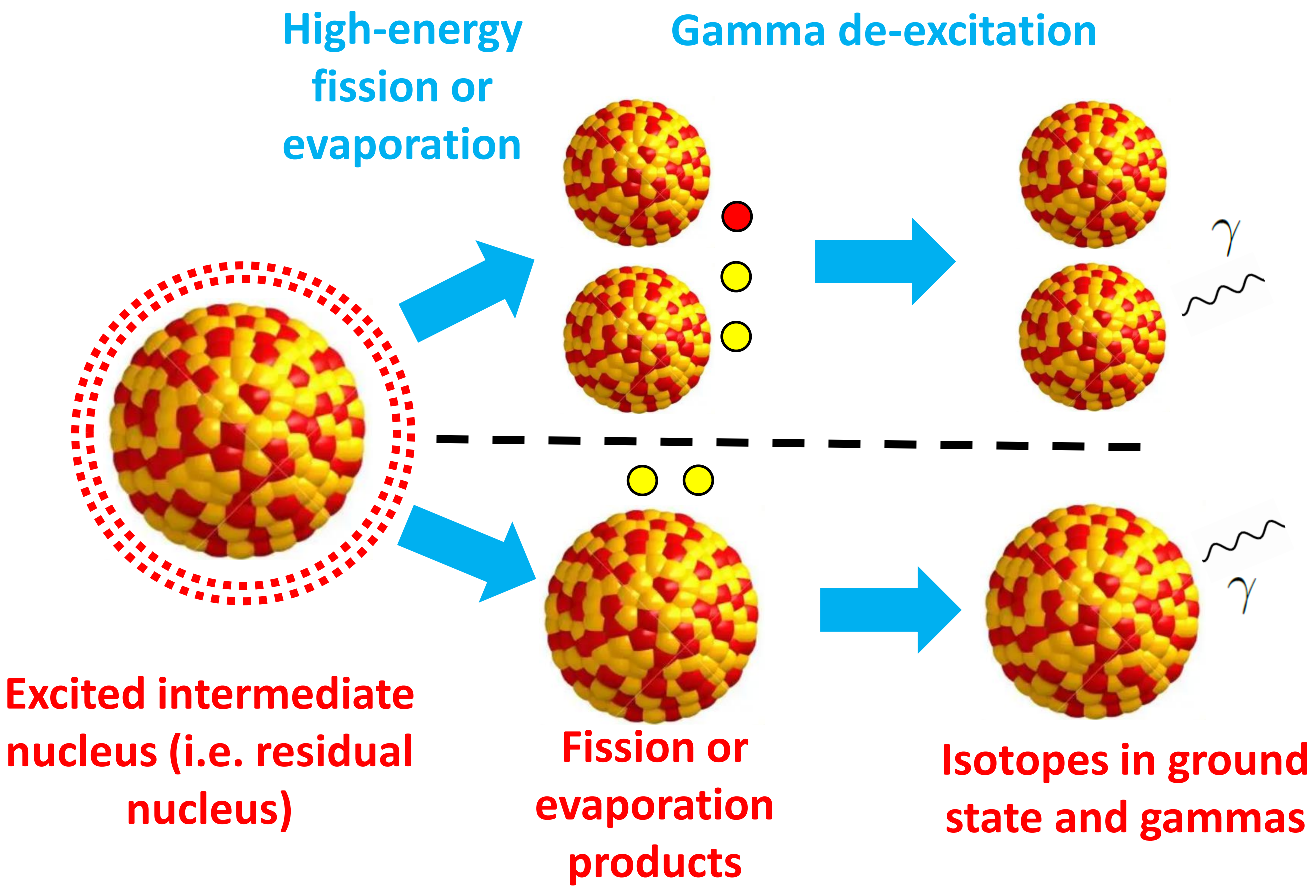
Nuclear geometry by DPMJet and nPDF provided by EPS09.

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

How can we study this?



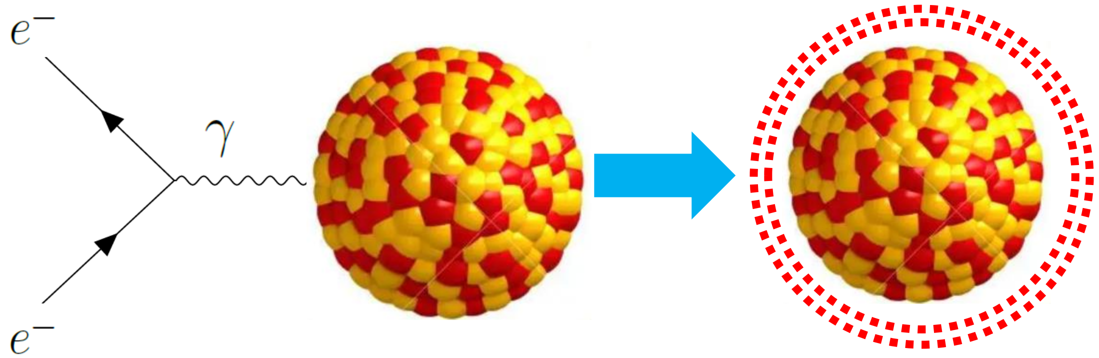
Step 2

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.)



Hard scattering and intra-nuclear cascade

Excited intermediate nucleus (i.e. residual nucleus)

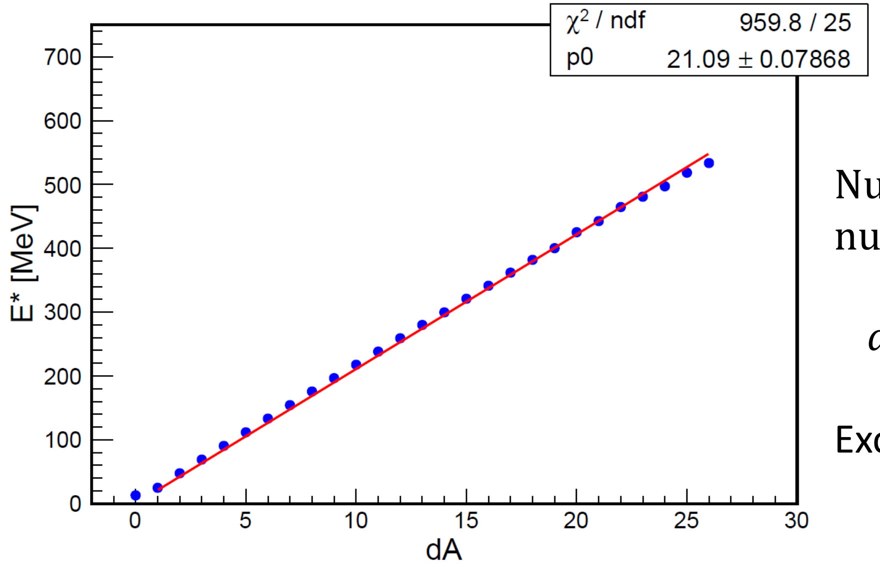
Production of the residual nucleus

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

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.

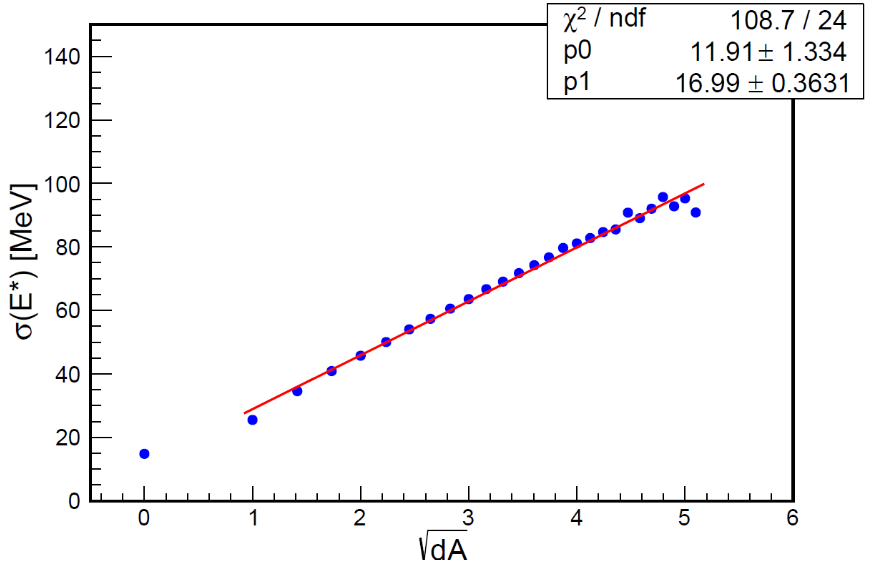
Comment: We plot the statistical mean and standard deviation here, but the E* distribution at fixed dA may be better described with a Log-normal distribution.



Number of abraded nucleons:

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

Excitation energy: E*



^{238}U beam

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  - ➢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.

Number of abraded nucleons:

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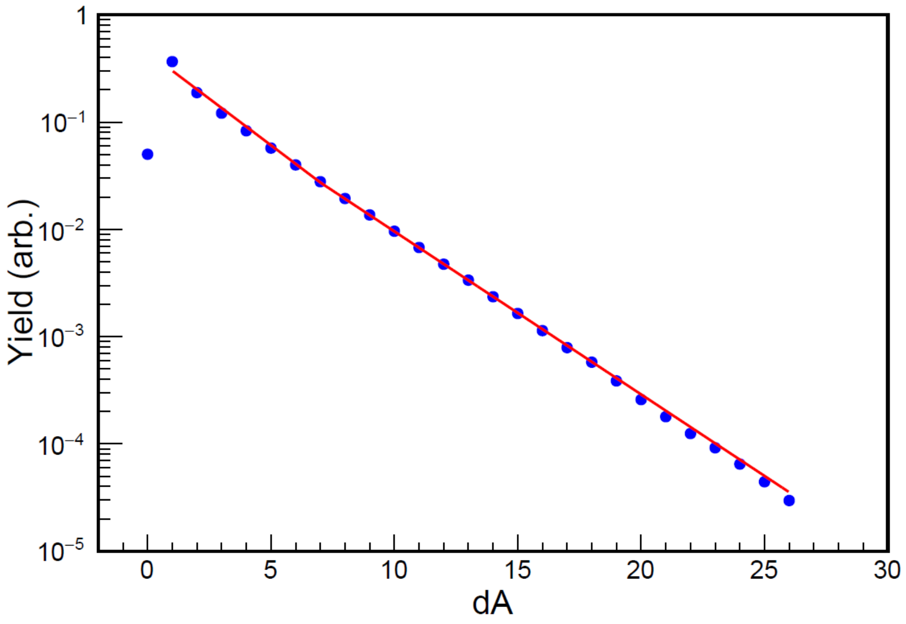

^{238}U beam

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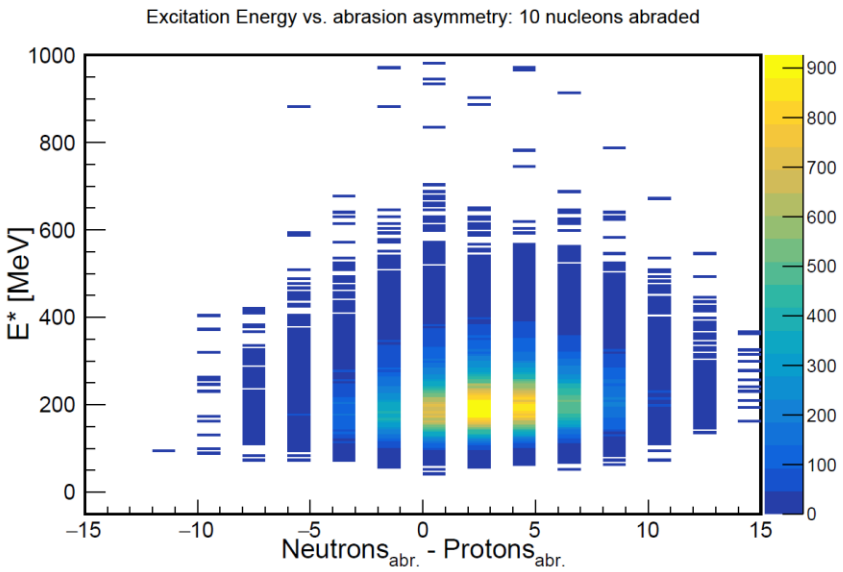
  - For a given number of abraded nucleons, the relative proportion of neutrons and protons abraded is based on simple combinatorics.



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^{238}U beam

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Note: A 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:

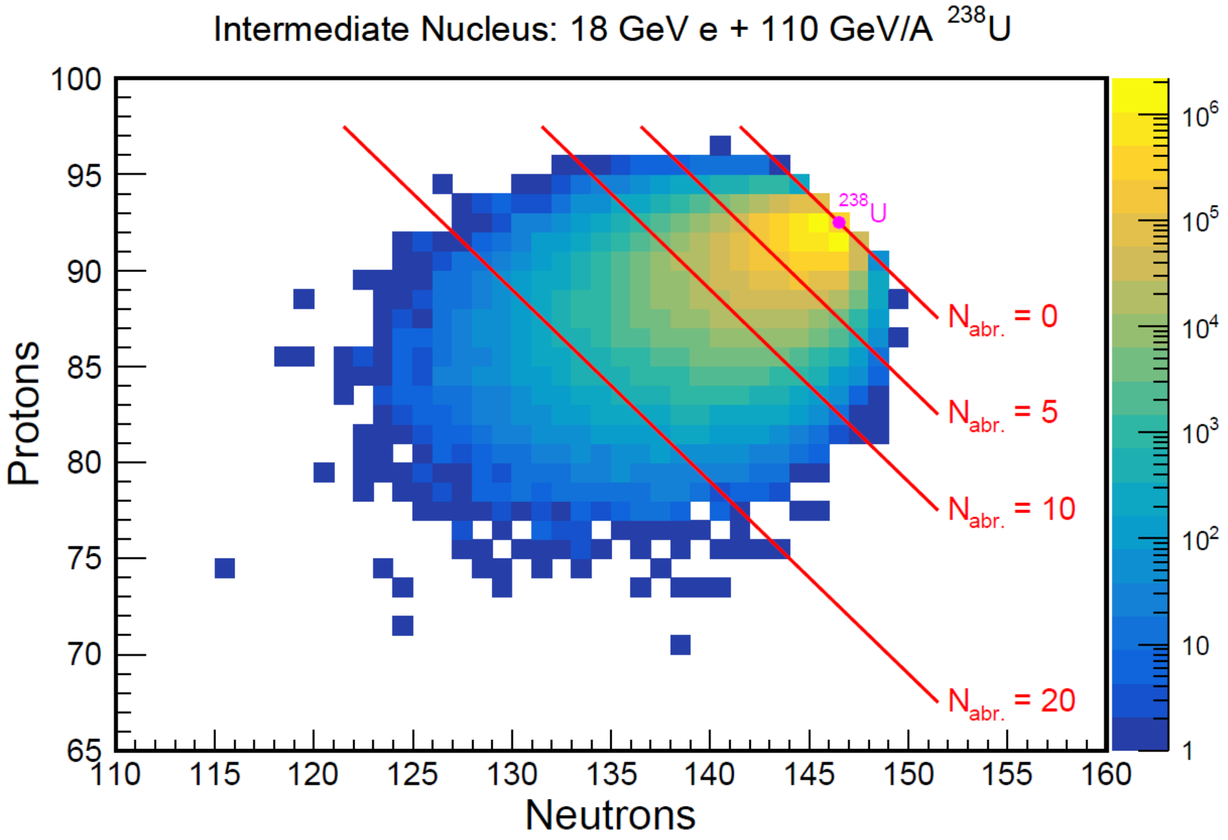
$$\tau_{Lab} = \tau_0 \frac{E_s}{m_s} \frac{m_s^2}{m_s^2 + p_{s\perp}^2}$$

Mass (excitation energy) of the residual nucleus:

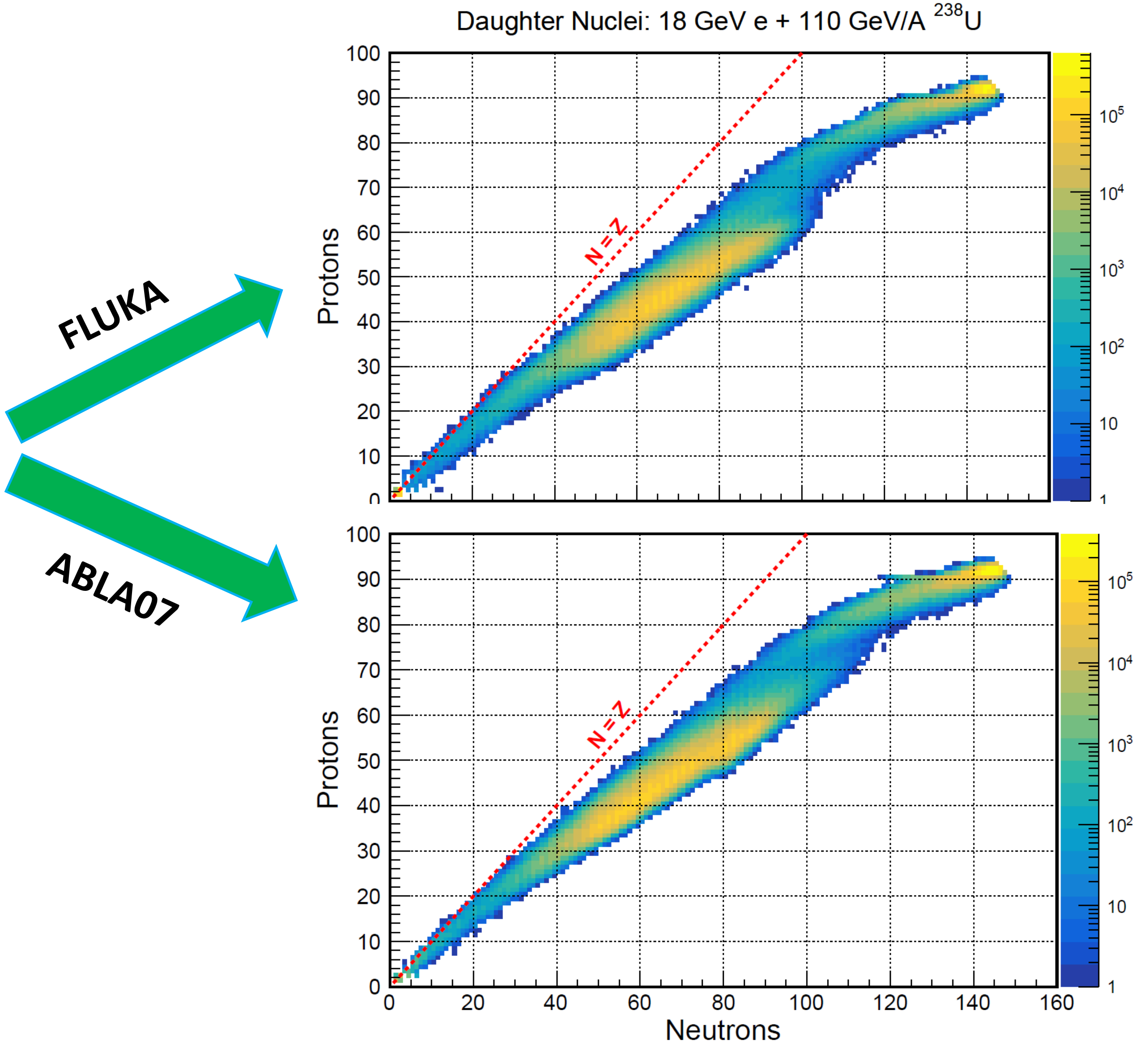
$$(E_{res}, \mathbf{p_{res}}) = (M_A, \mathbf{0}) - \sum_{i=1}^{N_w} (E_i^F, \mathbf{p_i^F}) + (E_{rec}, \mathbf{p_{rec}})$$

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

We can then decay the residual nucleus

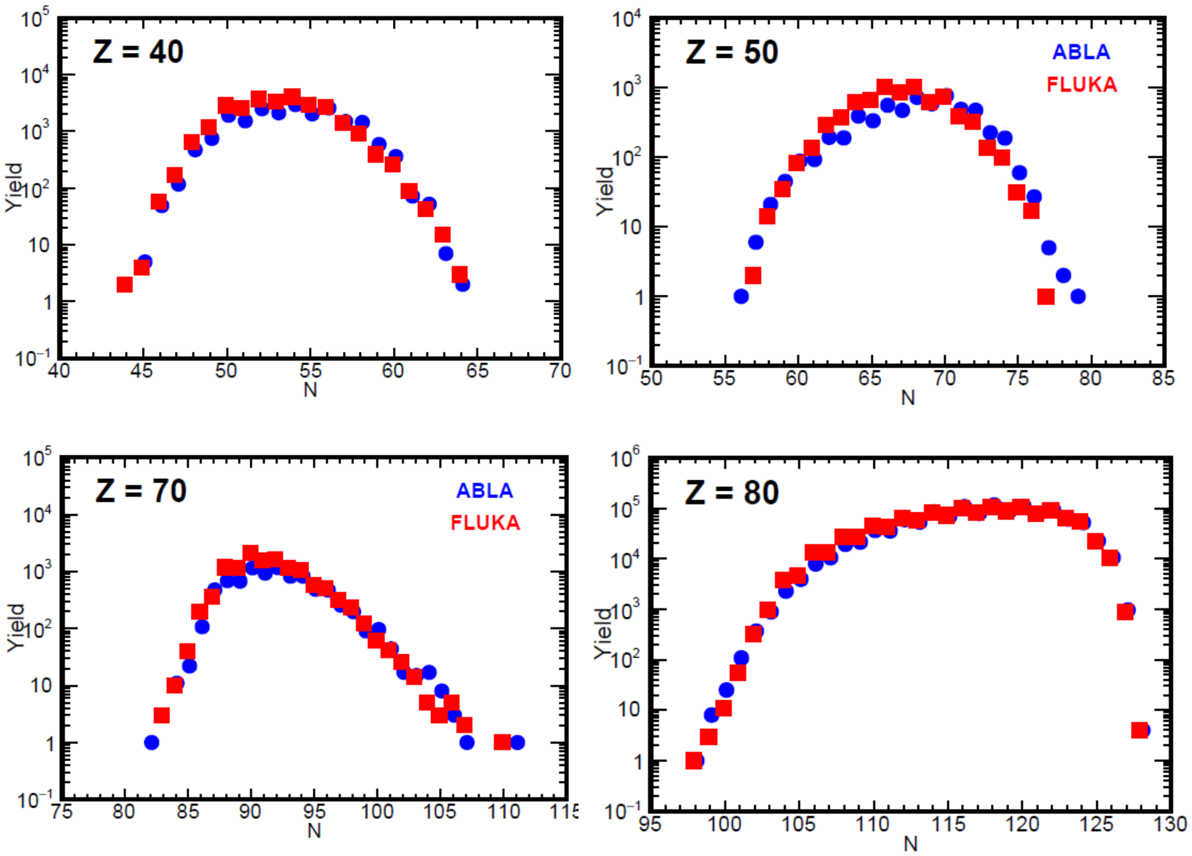


10 million events simulated

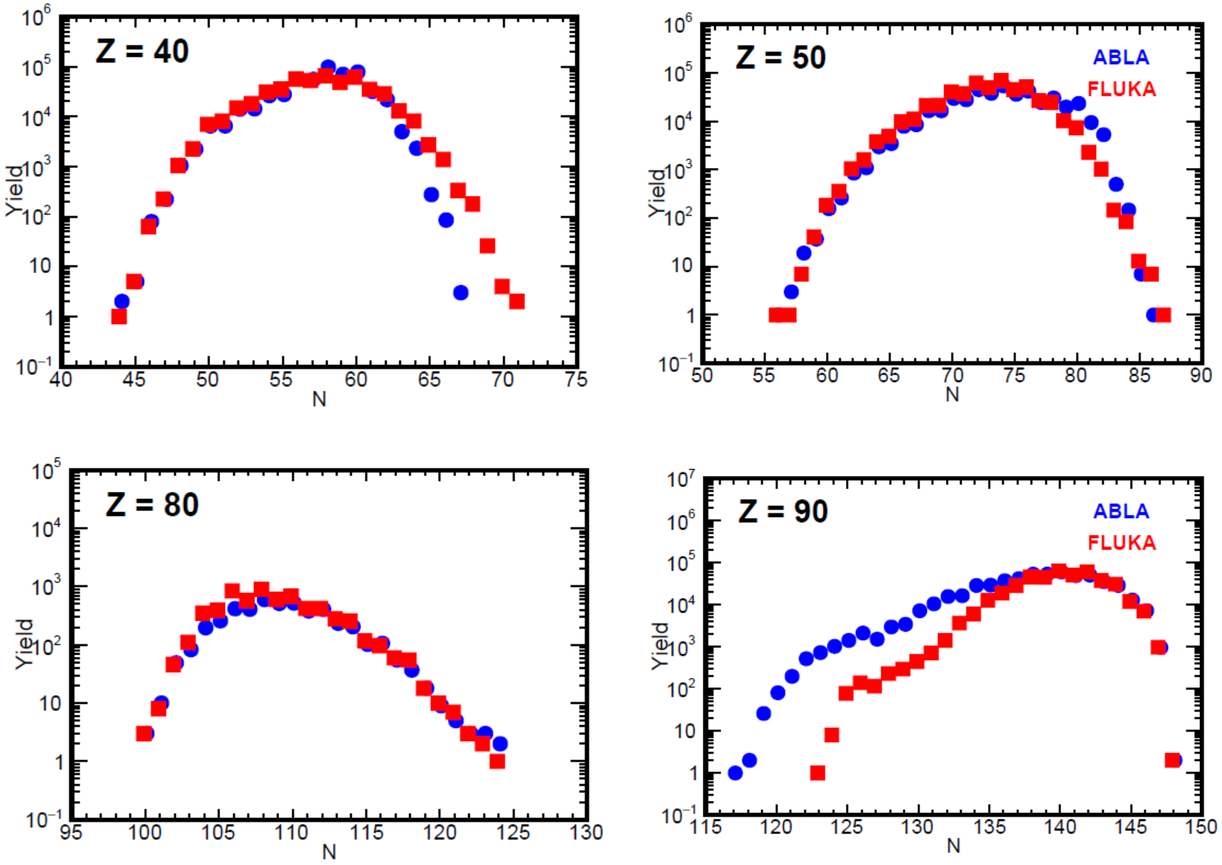


FLUKA and *ABLA07* are largely in agreement about EIC production rates

^{208}Pb

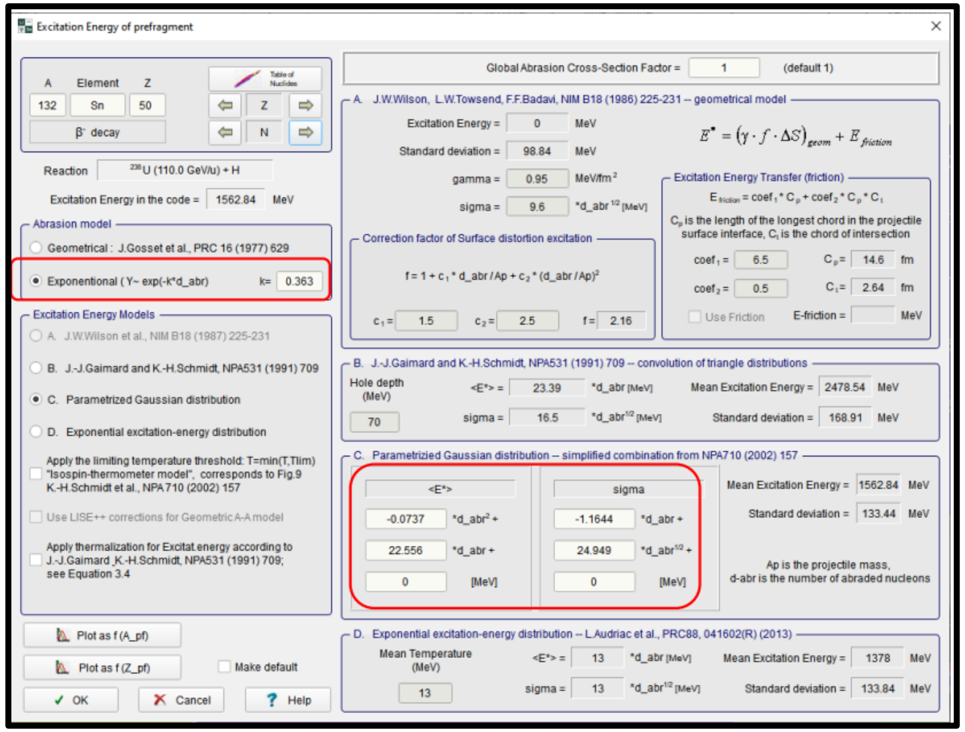


^{238}U



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

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



Excitation Energy of prefragment

A = 132, Element = Sn, Z = 50

β⁻ decay

Reaction: ^{238}U (110.0 GeV/u) + H

Excitation Energy in the code = 1562.84 MeV

Abrasion model
- ○ Geometrical : J.Gosset et al., PRC 16 (1977) 629
- ● Exponentional (Y~ exp(-k*d_abr) k= 0.363

Excitation Energy Models
- ○ A. J.W.Wilson et al., NIM B18 (1987) 225-231
- ○ B. J.-J.Gaimard and K.-H.Schmidt, NPA531 (1991) 709
- ● C. Parametrized Gaussian distribution
- ○ D. Exponential excitation-energy distribution
- ☐ Apply the limiting temperature threshold: T=min(T,Tlim) "Isospin-thermometer model", corresponds to Fig.9 K.-H.Schmidt et al., NPA710 (2002) 157
- ☐ Use LISE++ corrections for Geometric A-A model
- ☐ Apply thermalization for Excitat.energy according to J.-J.Gaimard_K.-H.Schmidt, NPA531 (1991) 709; see Equation 3.4

☐ Make default

Global Abrasion Cross-Section Factor = 1 (default 1)

A. J.W.Wilson, L.W.Towsend, F.F.Badavi, NIM B18 (1986) 225-231 -- geometrical model

Excitation Energy = 0 MeV

Standard deviation = 98.84 MeV

gamma = 0.95 MeV/fm^2

sigma = 9.6 *d_abr$^{1/2}$ [MeV]

$$E^{*} = (\gamma \cdot f \cdot \Delta S)_{geom} + E_{friction}$$

Correction factor of Surface distortion excitation

$$f = 1 + c_1 * d\_abr/Ap + c_2 * (d\_abr/Ap)^2$$

c_1 = 1.5, c_2 = 2.5, f = 2.16

Excitation Energy Transfer (friction)

$$E_{friction} = coef_1 * C_p + coef_2 * C_p * C_t$$

C_p is the length of the longest chord in the projectile surface interface, C_t is the chord of intersection

$coef_1$ = 6.5, C_p = 14.6 fm

$coef_2$ = 0.5, C_t = 2.64 fm

☐ Use Friction E-friction = MeV

B. J.-J.Gaimard and K.-H.Schmidt, NPA531 (1991) 709 -- convolution of triangle distributions

Hole depth (MeV) 70

<E*> = 23.39 *d_abr [MeV]

sigma = 16.5 *d_abr$^{1/2}$ [MeV]

Mean Excitation Energy = 2478.54 MeV

Standard deviation = 168.91 MeV

C. Parametrizied Gaussian distribution -- simplified combination from NPA710 (2002) 157

<E*>	sigma
-0.0737 *d_abr^2 +	-1.1644 *d_abr +
22.556 *d_abr +	24.949 *d_abr$^{1/2}$ +
0 [MeV]	0 [MeV]

Mean Excitation Energy = 1562.84 MeV

Standard deviation = 133.44 MeV

Ap is the projectile mass, d-abr is the number of abraded nucleons

D. Exponential excitation-energy distribution -- L.Audriac et al., PRC88, 041602(R) (2013)

Mean Temperature (MeV) 13

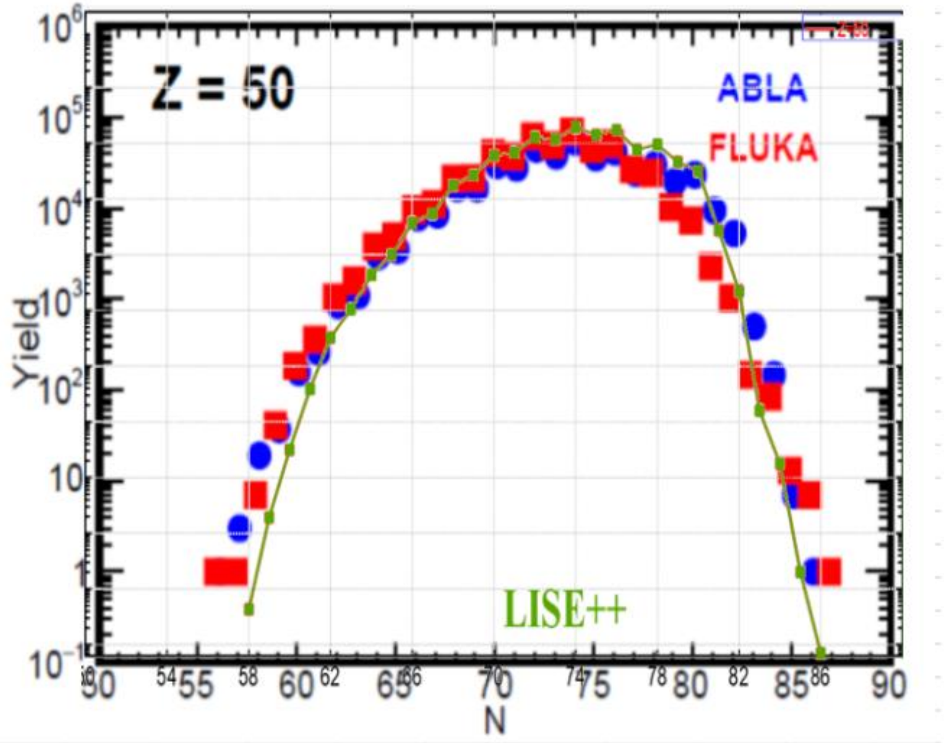
<E*> = 13 *d_abr [MeV]

sigma = 13 *d_abr$^{1/2}$ [MeV]

Mean Excitation Energy = 1378 MeV

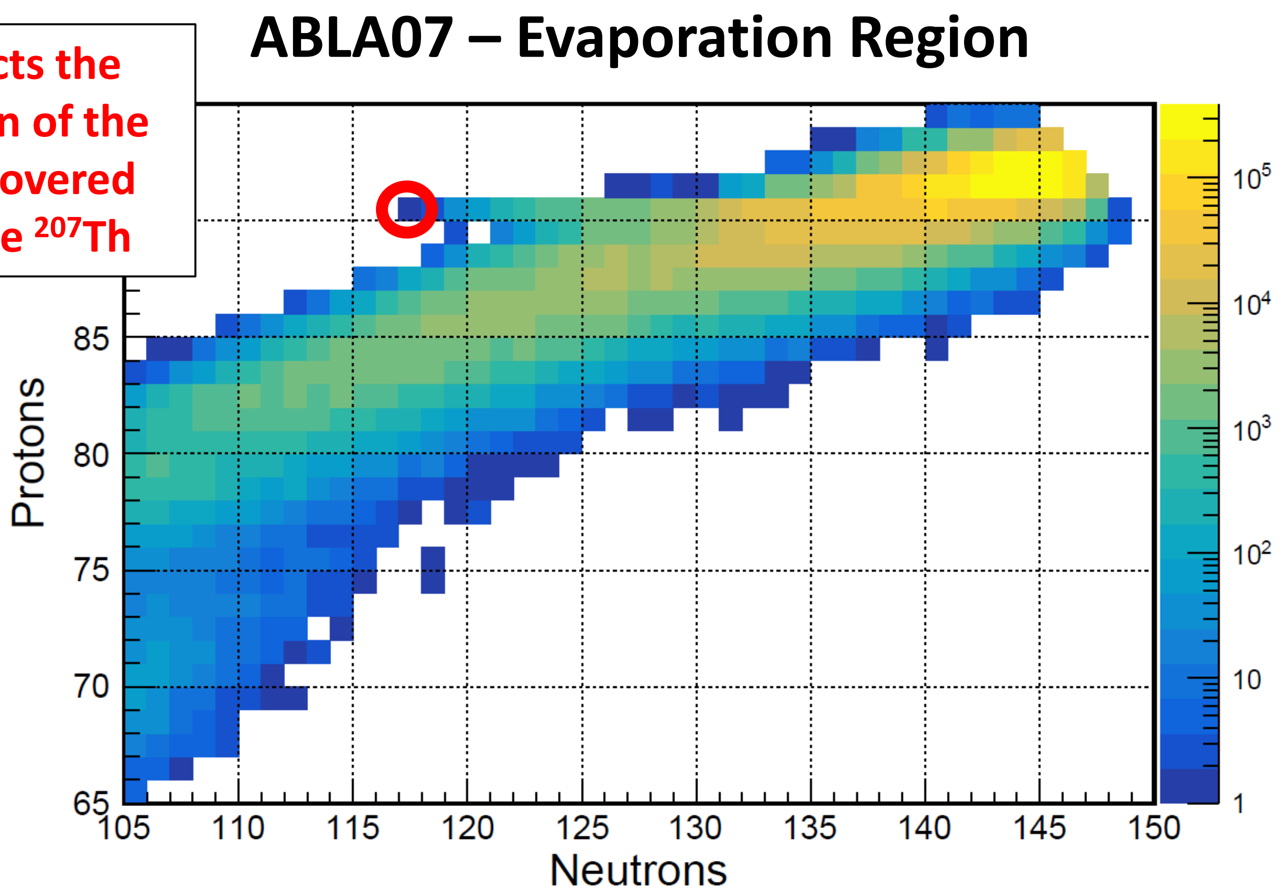
Standard deviation = 133.84 MeV

Comparison of different models:



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

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.

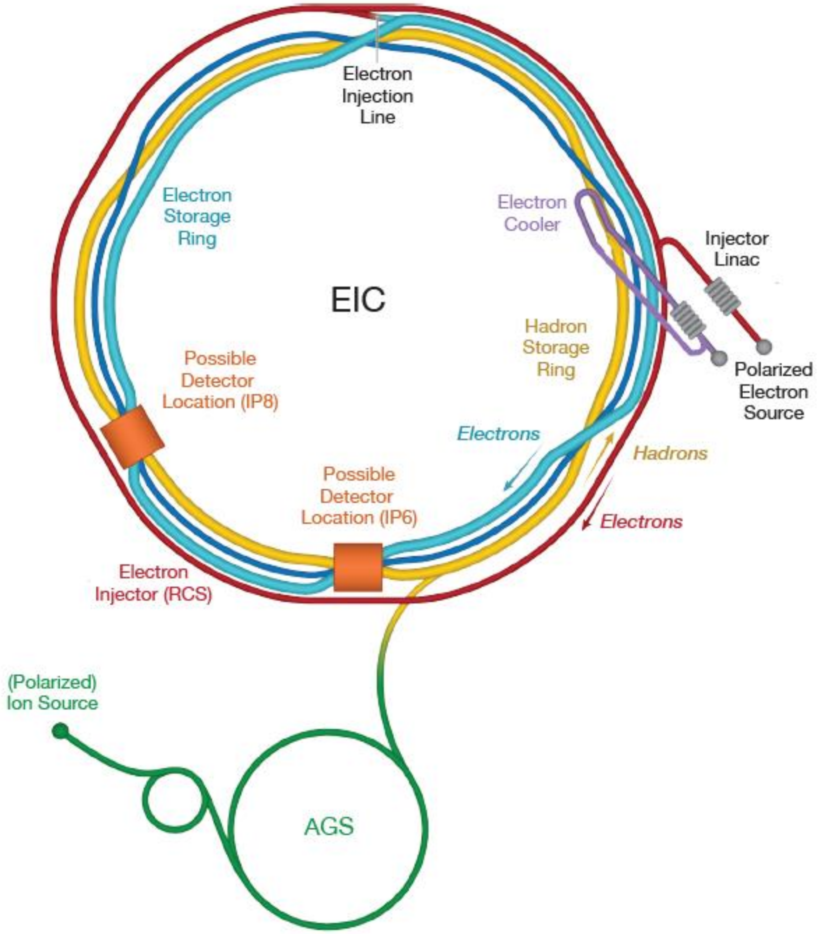

ABLA07 – Evaporation Region

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

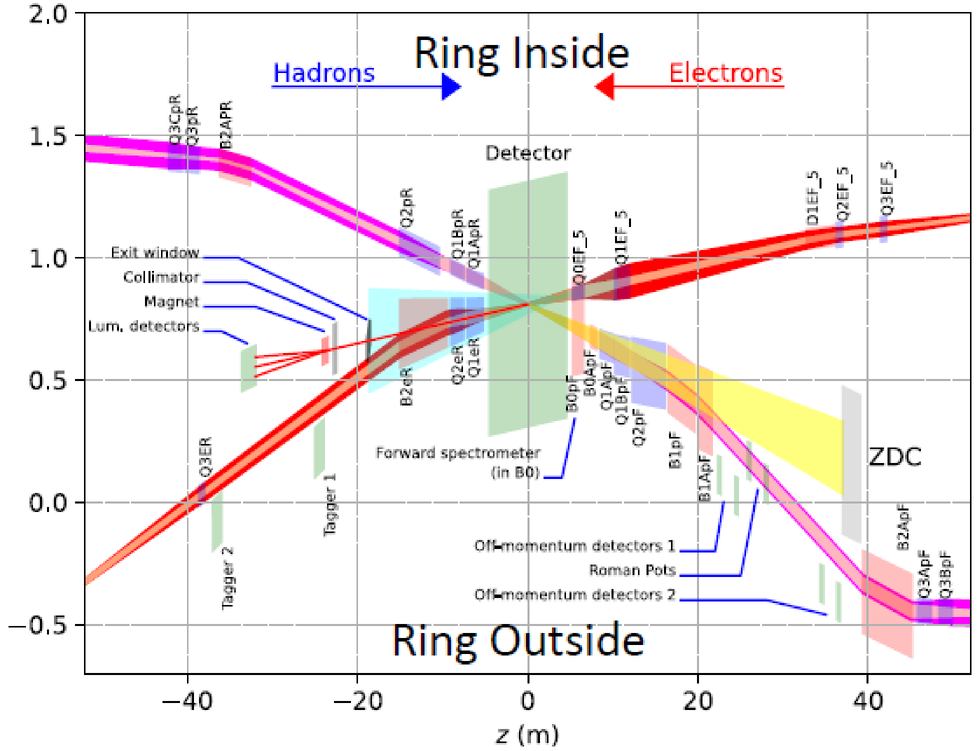
We need to simulate many more events to understand model the production rates at the EIC

Detection of nuclear fragments

EIC Detectors – interaction region



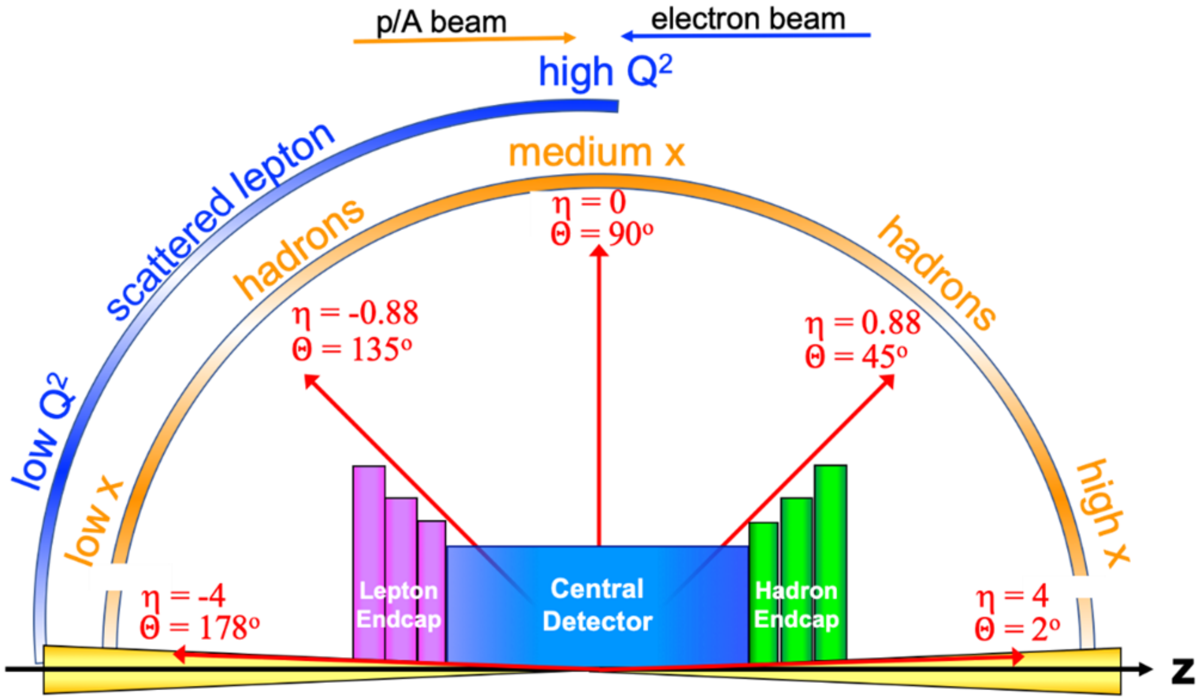
First EIC interaction region – IP6



Three regions will have detectors implemented:

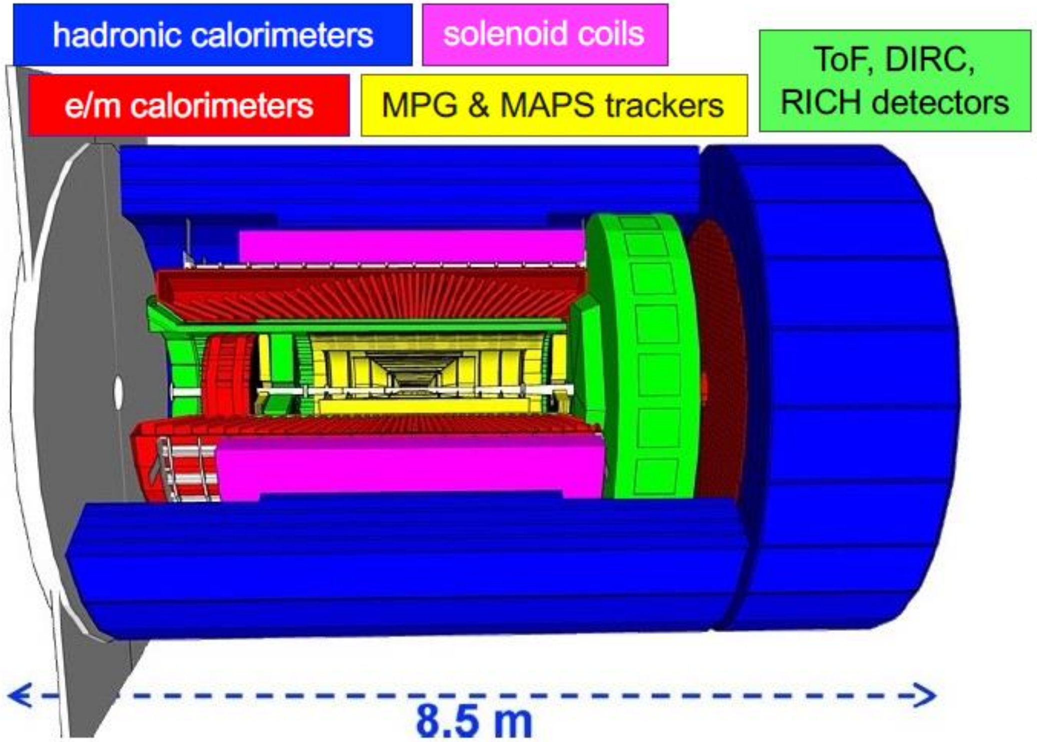
1. Main detector region
2. Far-forward region – **nuclear fragments and de-excitation gamma rays will be measured here**
3. Far-backwards region

EIC Detectors – main detector



doi:10.2172/1765663

Proposed IP6 detector design

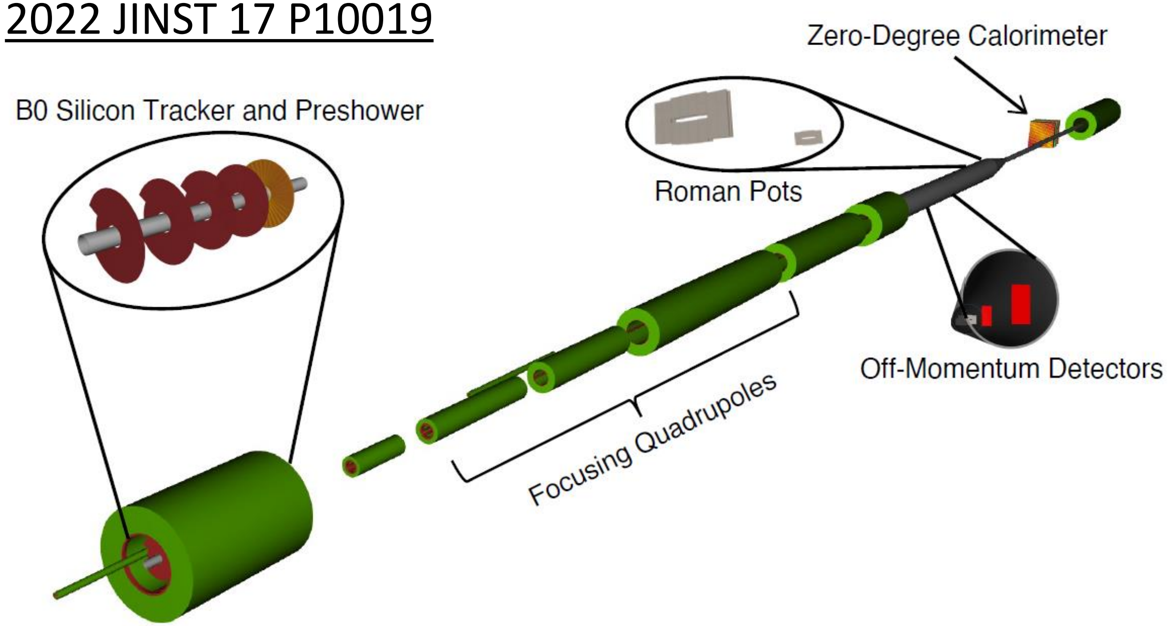


10.5281/zenodo.6537588

EIC Detectors – far-forward region

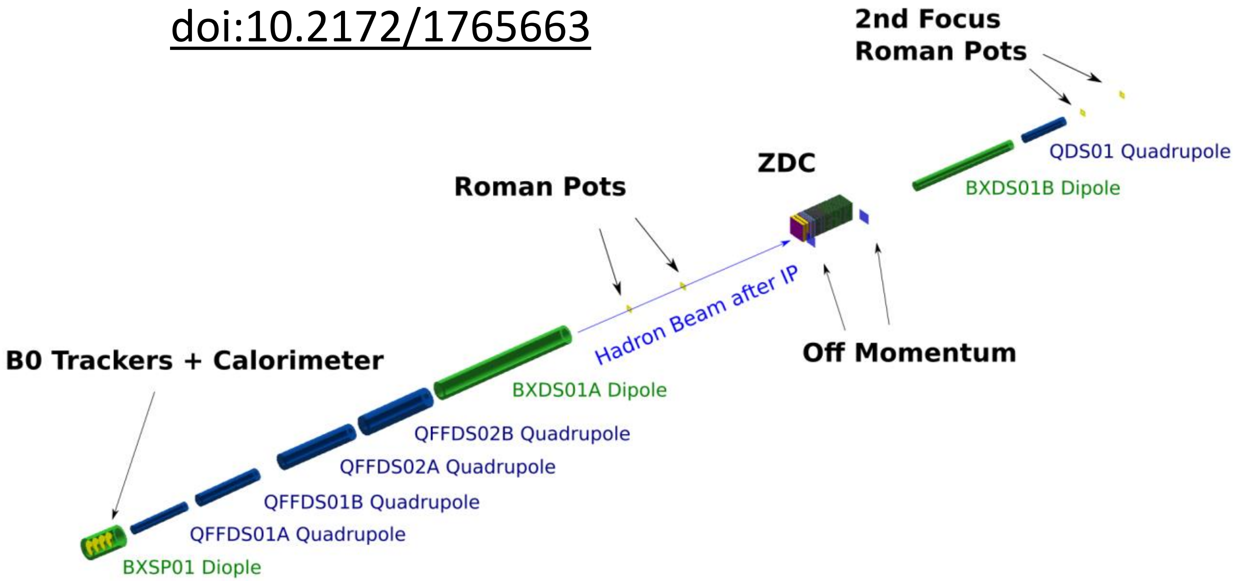
Current design for IP6

<u>2022 JINST 17 P10019</u>



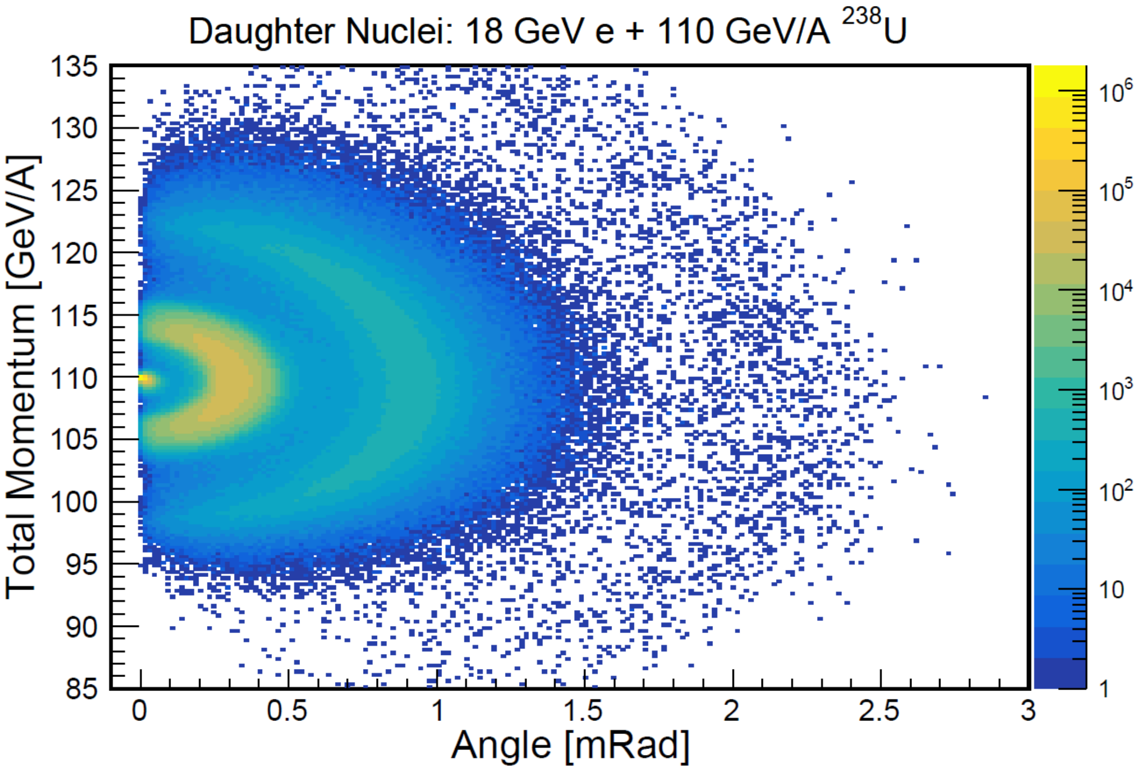
Conceptual design for IP8

<u>doi:10.2172/1765663</u>

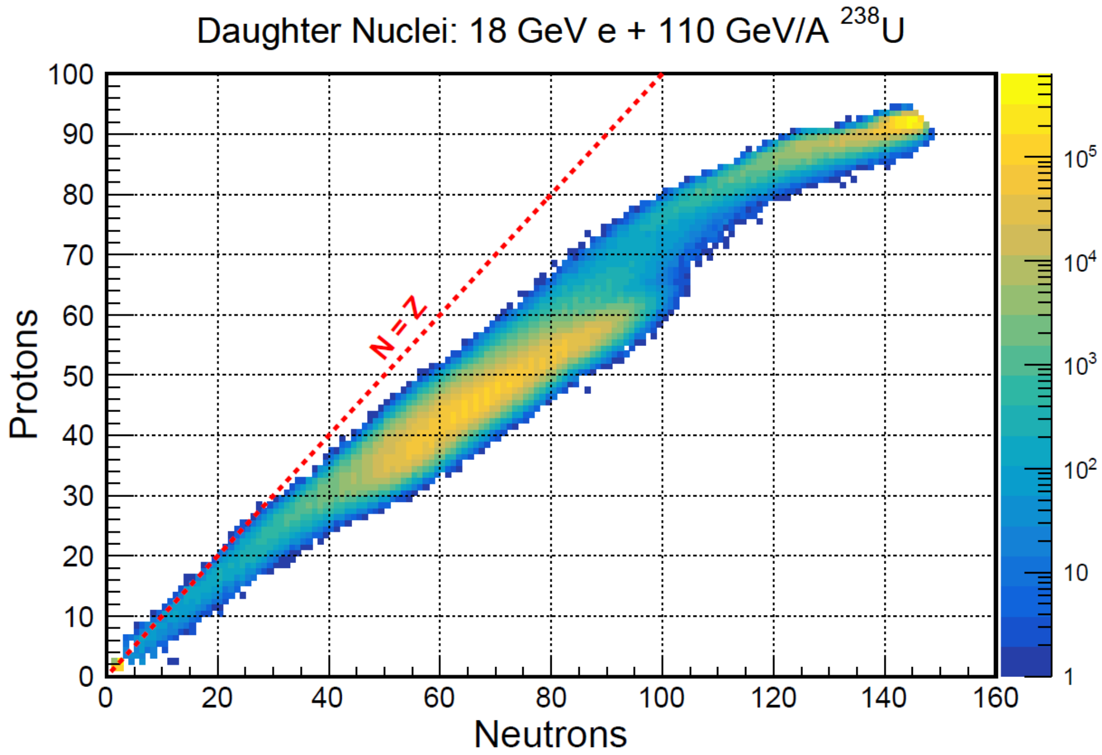


- The nuclear fragments can be measured using detectors in the Roman Pots (RP) – two tracking planes to measure local positions and angles.
- Gamma rays can be detected using the Zero-Degree Calorimeter (ZDC).

Kinematics of produced nuclear fragments

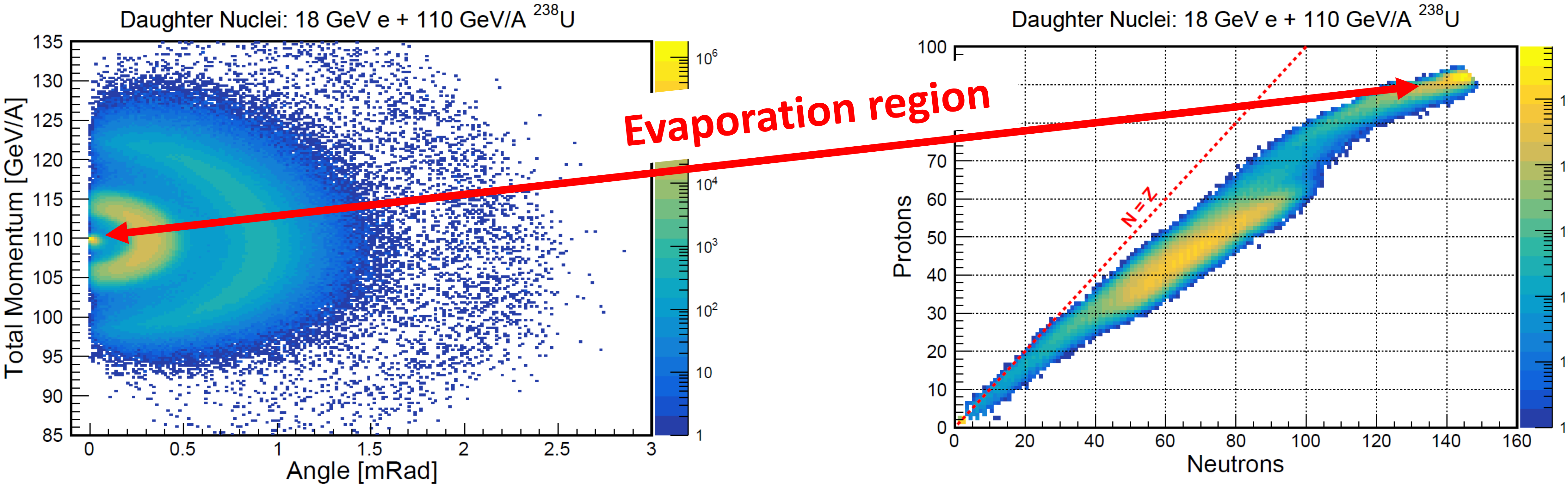


(with respect to incoming ^{238}U beam)



BeAGLE + FLUKA

Kinematics of produced nuclear fragments

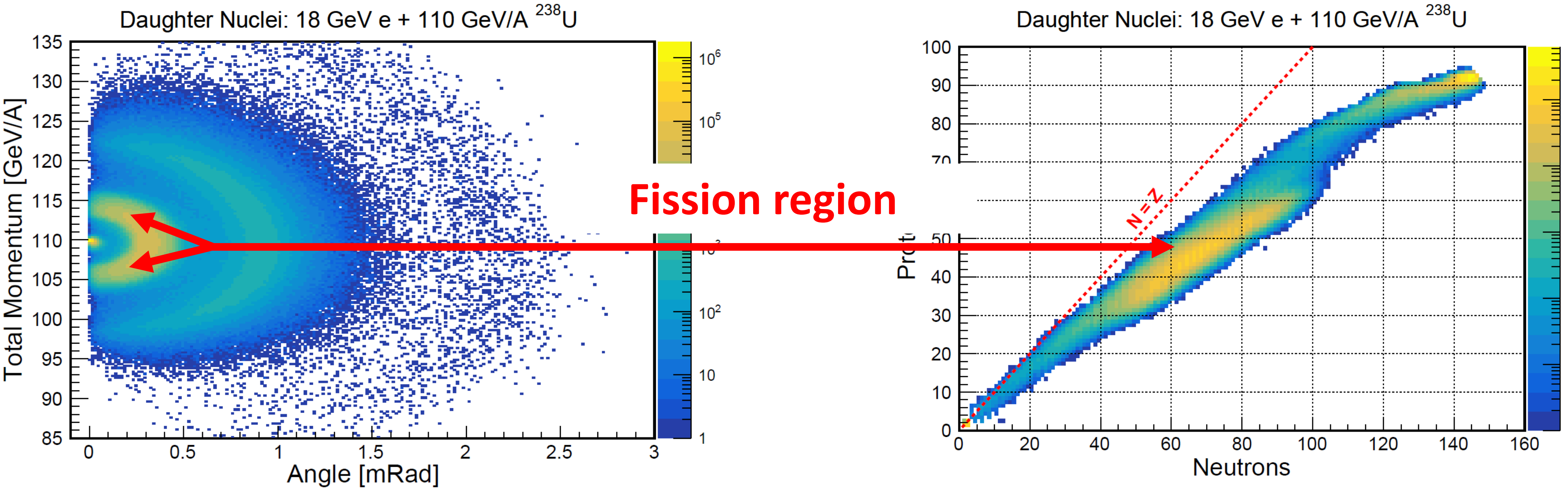


(with respect to incoming ^{238}U beam)

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

BeAGLE + FLUKA

Kinematics of produced nuclear fragments



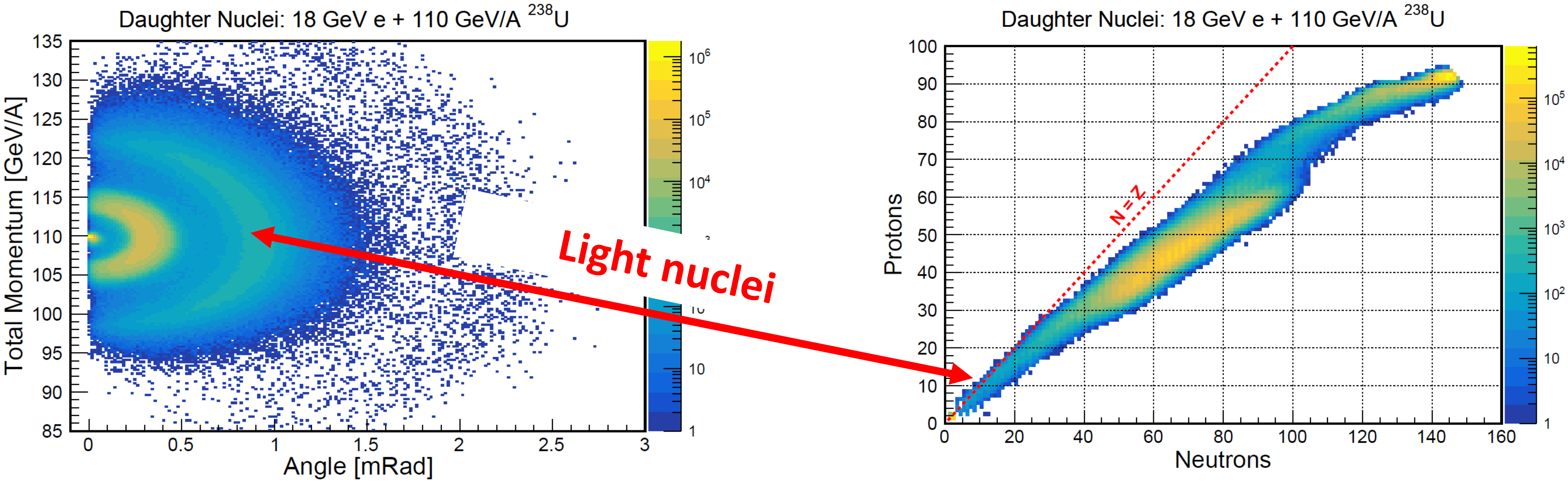
Fission region

(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)

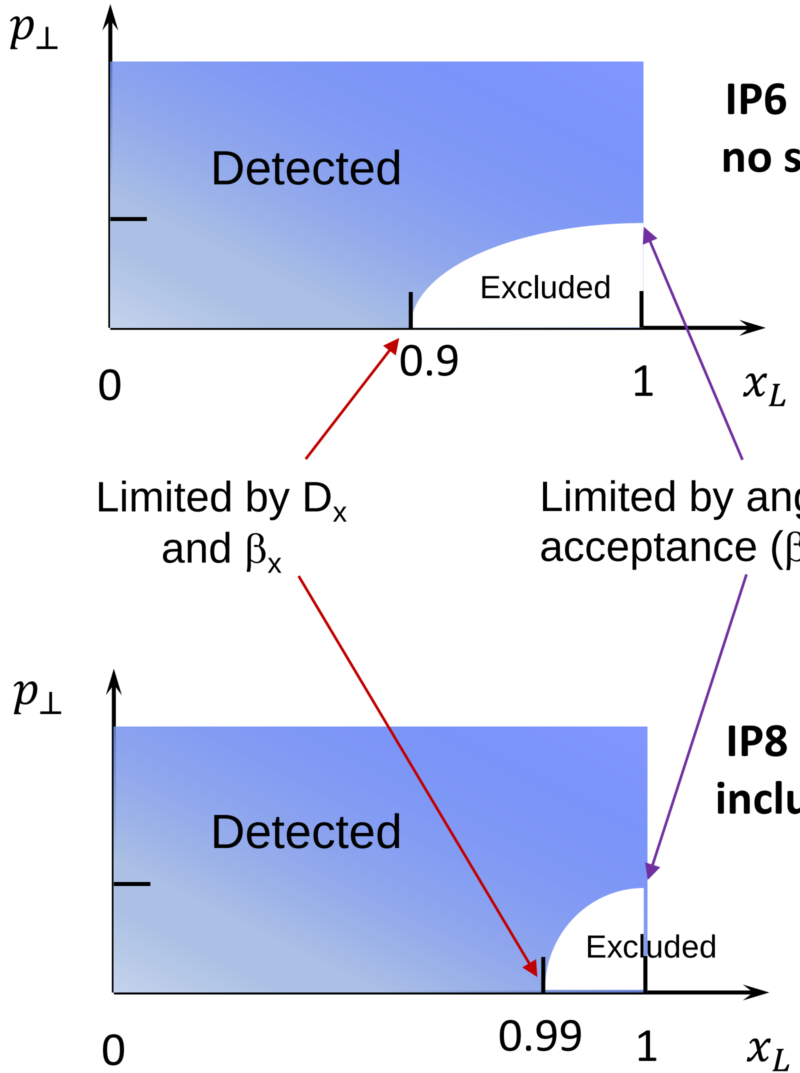
☑ Accelerator parameters (EIC CDR Table 3.5):

Beam Emittance $(\varepsilon_x) = 43.2\, nm$

Momentum spread $(\sigma_p) = 6.2 \times 10^{-4}$

doi:10.2172/1765663

Acceptance for fragments in IP6 and IP8



IP6 configuration – no secondary focus

IP8 configuration – including secondary focus

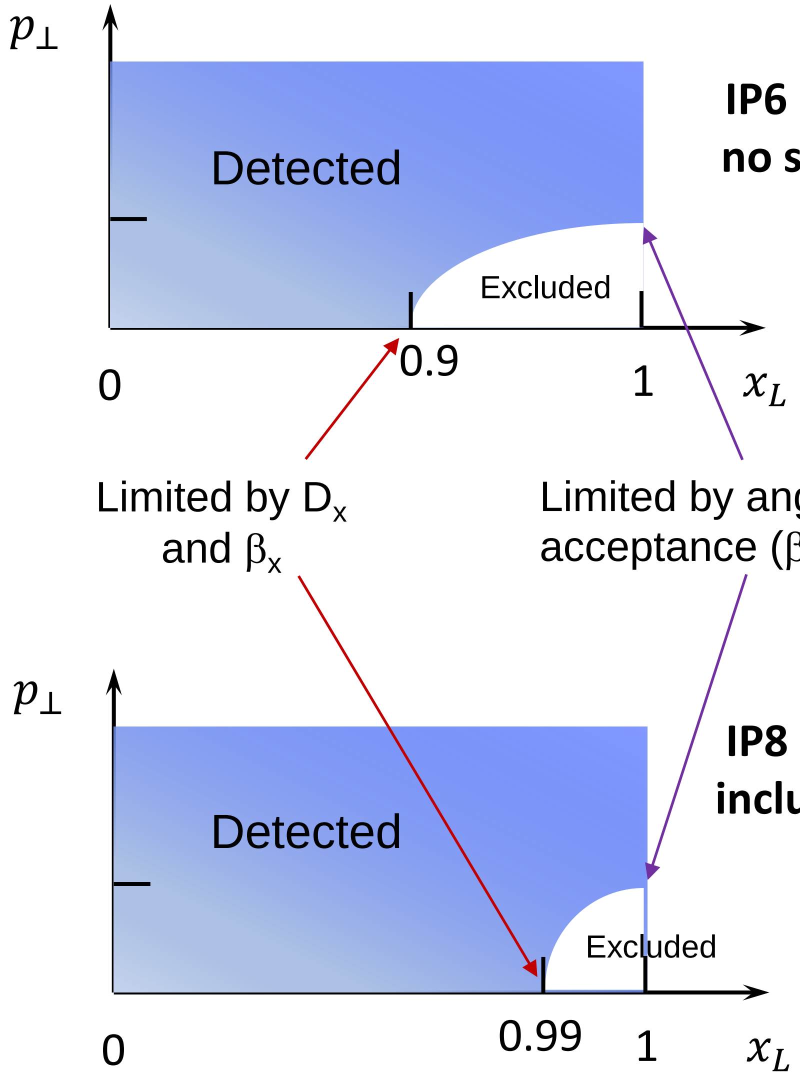
IP6 acceptance at first RP (using the high-divergence 10x100 GeV shifted lattice):

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

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

Limited by D_x and β_x

Limited by angular acceptance ($\beta^*=\beta_{IP}$)

IP8 configuration – including secondary focus

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

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

IP8 acceptance at first RP:

$$\boxed{\beta_x = 2.28\ m}$$
$$D_x = 38.2\ cm$$
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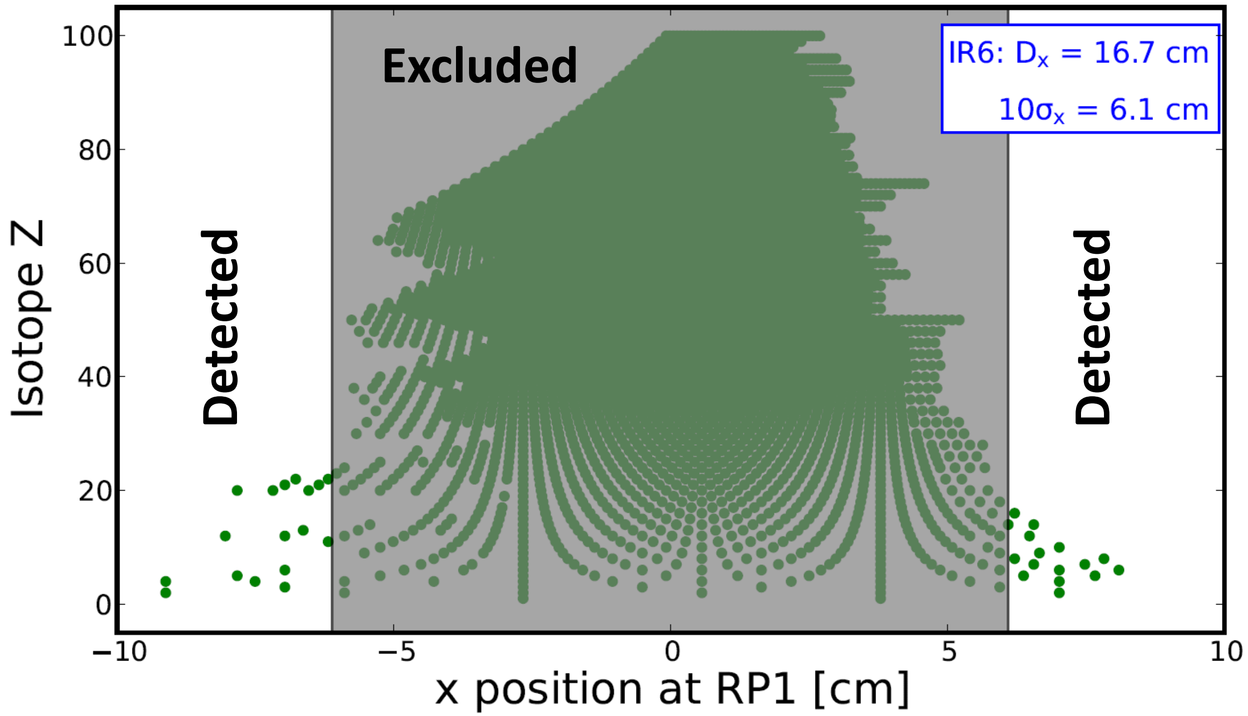
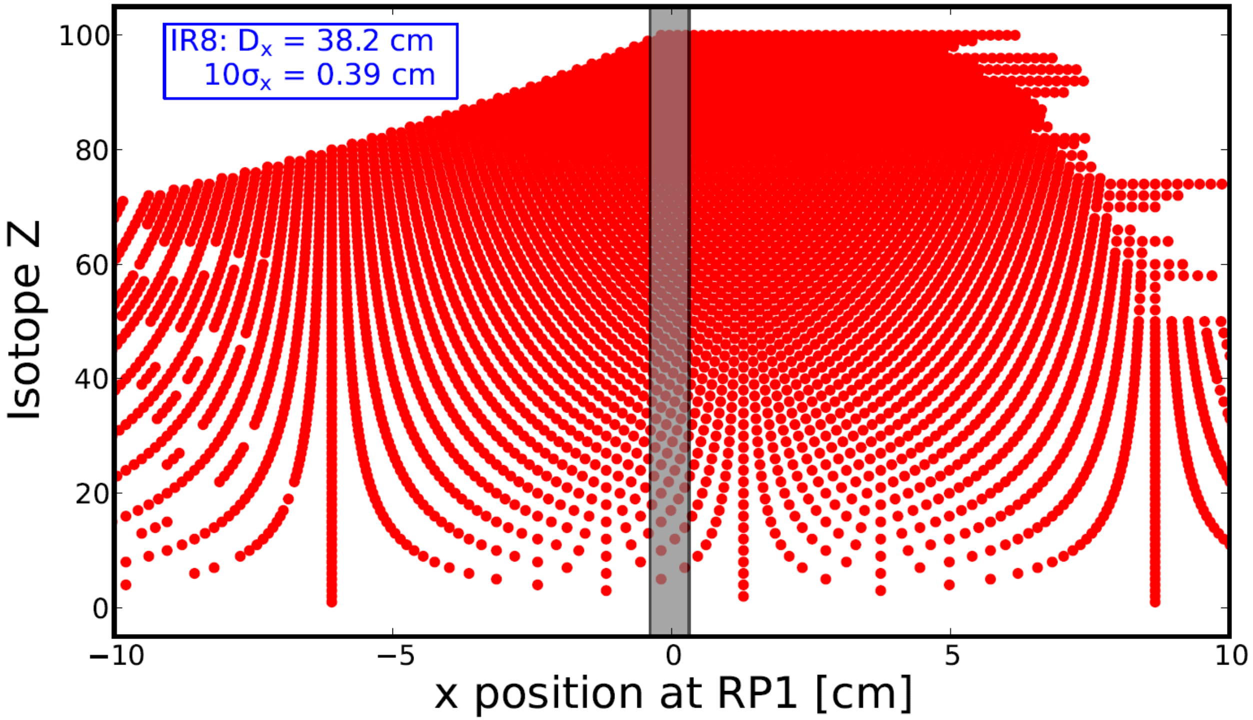
Acceptance for fragments in IP6 and IP8

IP6



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

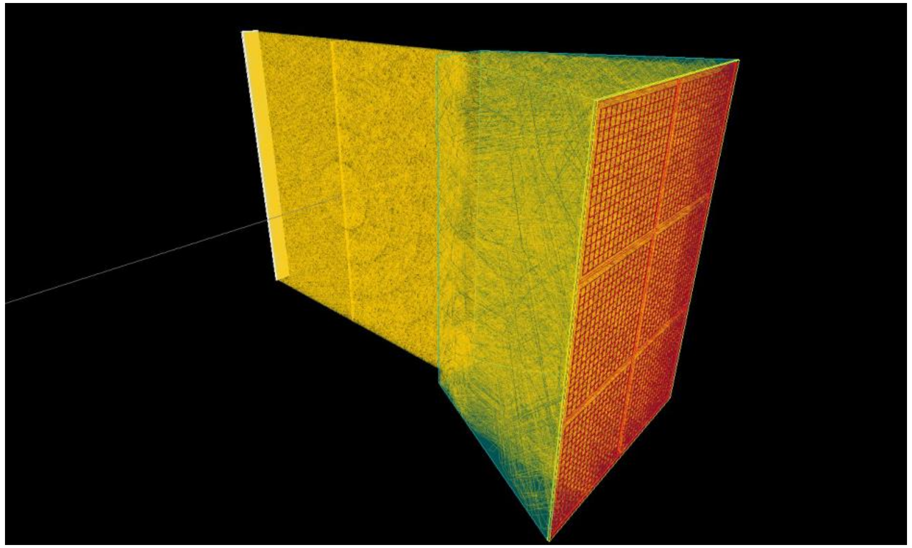
IP8

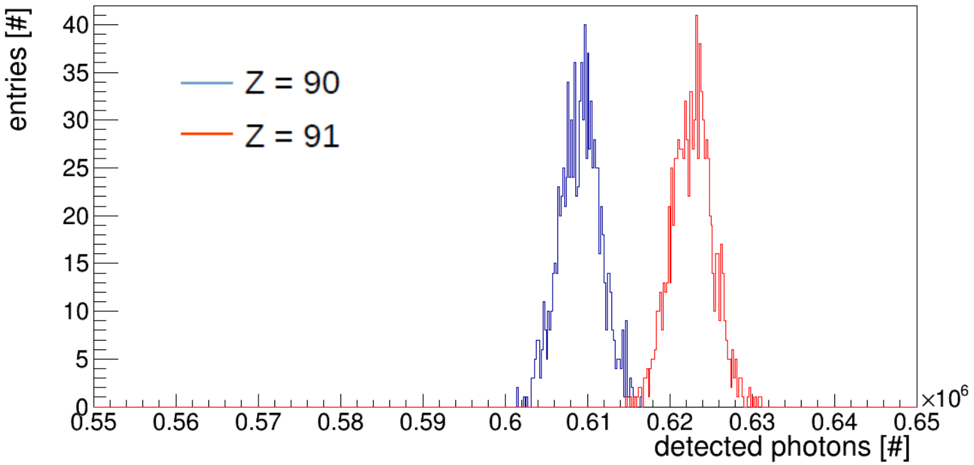


Assuming a RP position resolution of 10-100 microns, isotopes with the same Z are well separated.

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.

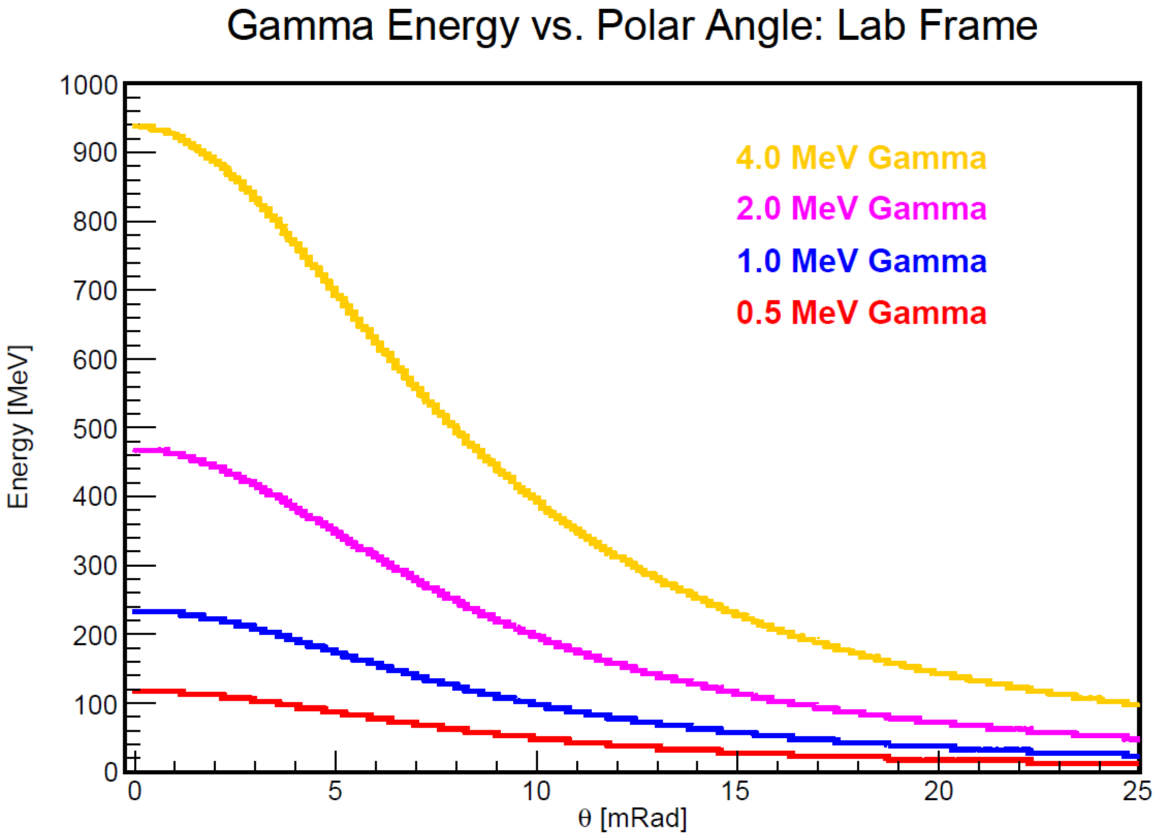




Simulation by Roman Dzhygadlo

Detection of gamma rays

Single gamma simulation – 110 GeV/A beam

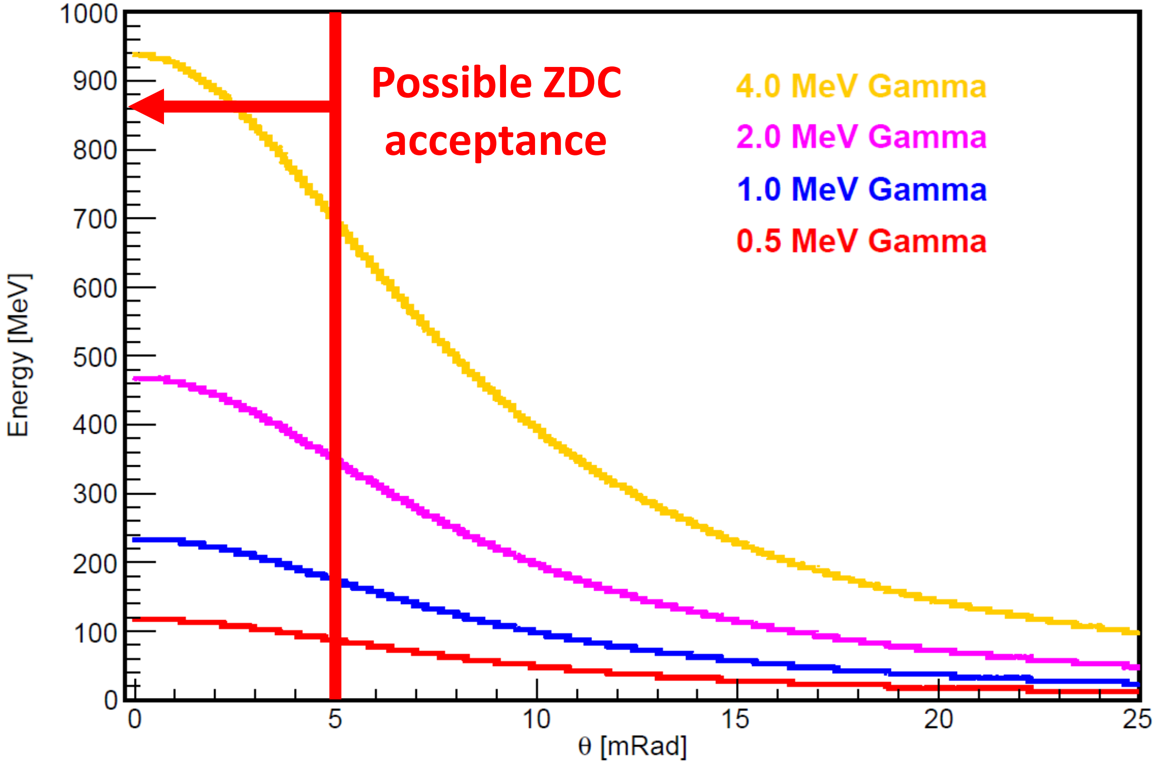


- ☐ Gamma rays from nuclear de-excitations can be detected in the Zero-Degree Calorimeter (ZDC). The ZDC acceptance range will be approximately 0-5 mRad.
- ☐ The energy resolution of the ZDC for photon detection may be as good as $2\%/\sqrt{E\ (GeV)}$ if a material such as LYSO crystals are used.
- ☐ 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.

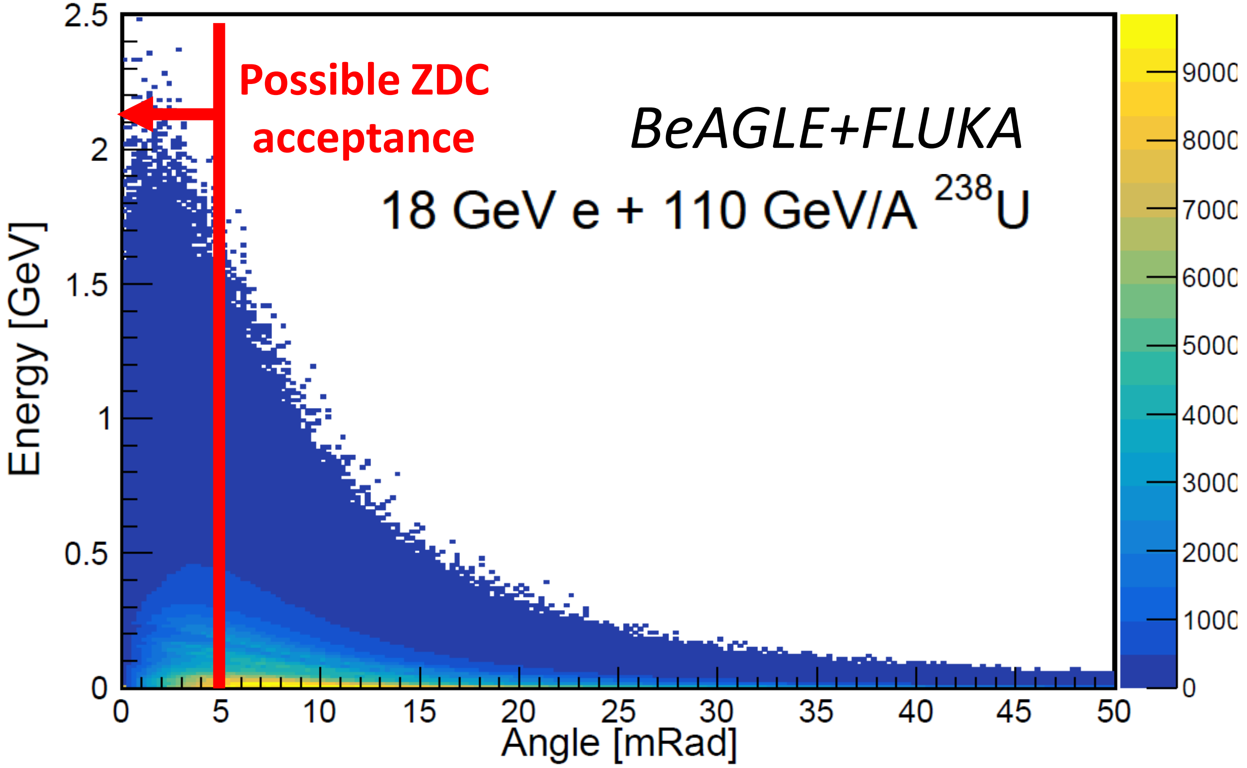
Detection of gamma rays

Single gamma simulation – 110 GeV/A beam

Gamma Energy vs. Polar Angle: Lab Frame



De-excitation gammas: full simulation results



Z.Phys. C70 (1996) 413-426

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

Summary

- ❑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.
- ❑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.

The EIC Rare Isotopes Team

TSU
TEXAS SOUTHERN UNIVERSITY

I. **Mark Harvey**

Facility for Rare Isotope Beams
at Michigan State University

I. **Oleg Tarasov**
II. **Isaiah Richardson – graduate student**

Stony Brook
University

I. **Abhay Deshpande**
II. **Pawel Nadel-Turonski**
III. **Ciprian Gal**
IV. **Brynna Moran – graduate student**
V. **Benjamin Collis – undergraduate student (2021)**
VI. **Zach Finger – high school student (2022)**

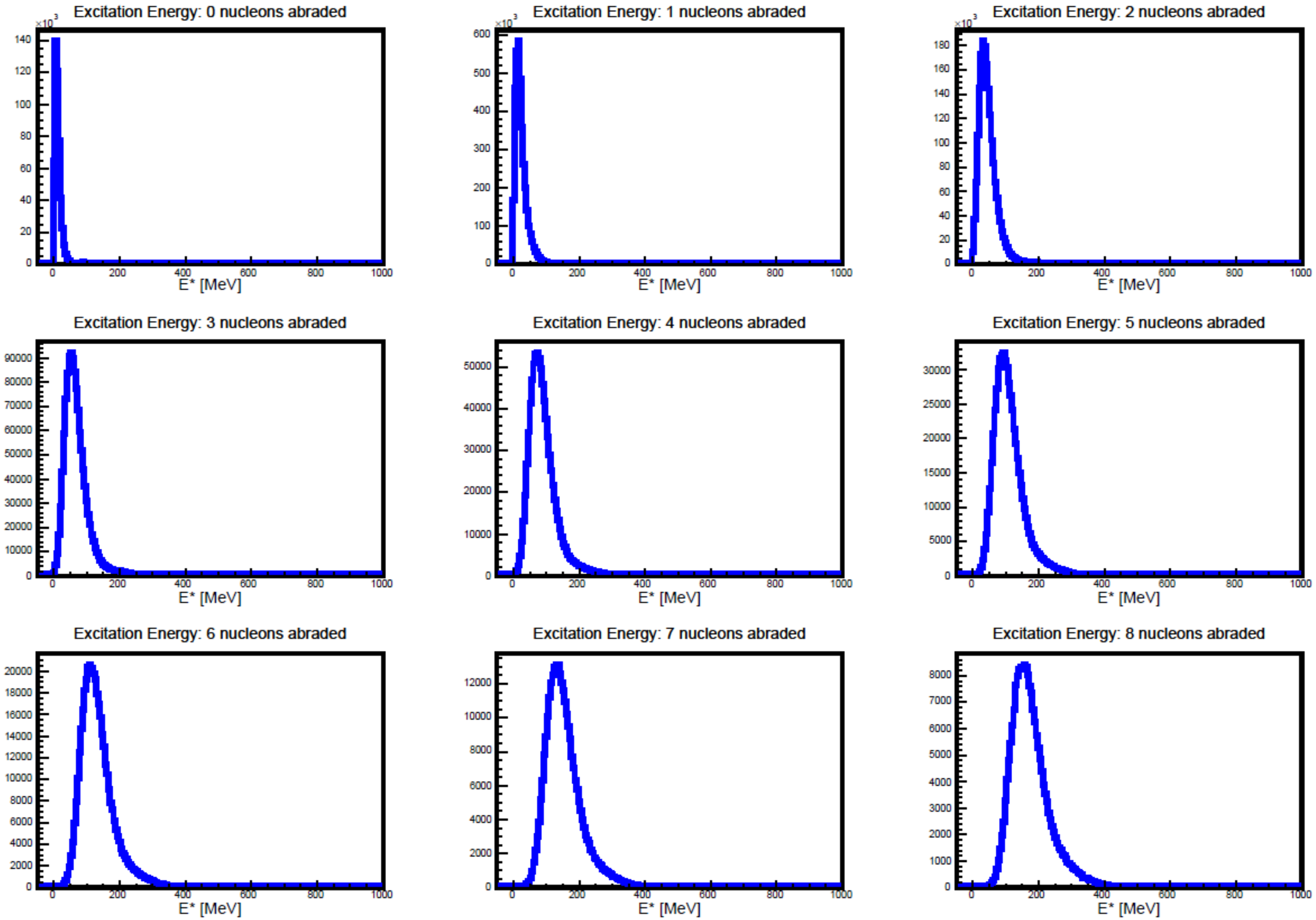
Thanks!

Acknowledgements

- Thanks to Mark Baker and Kong Tu for help with the *BeAGLE* event generator!
- Thanks to Aleksandra Kelic-Heil for providing access to the *ABRABLA07* code, as well as instructions on running the ablation portion!

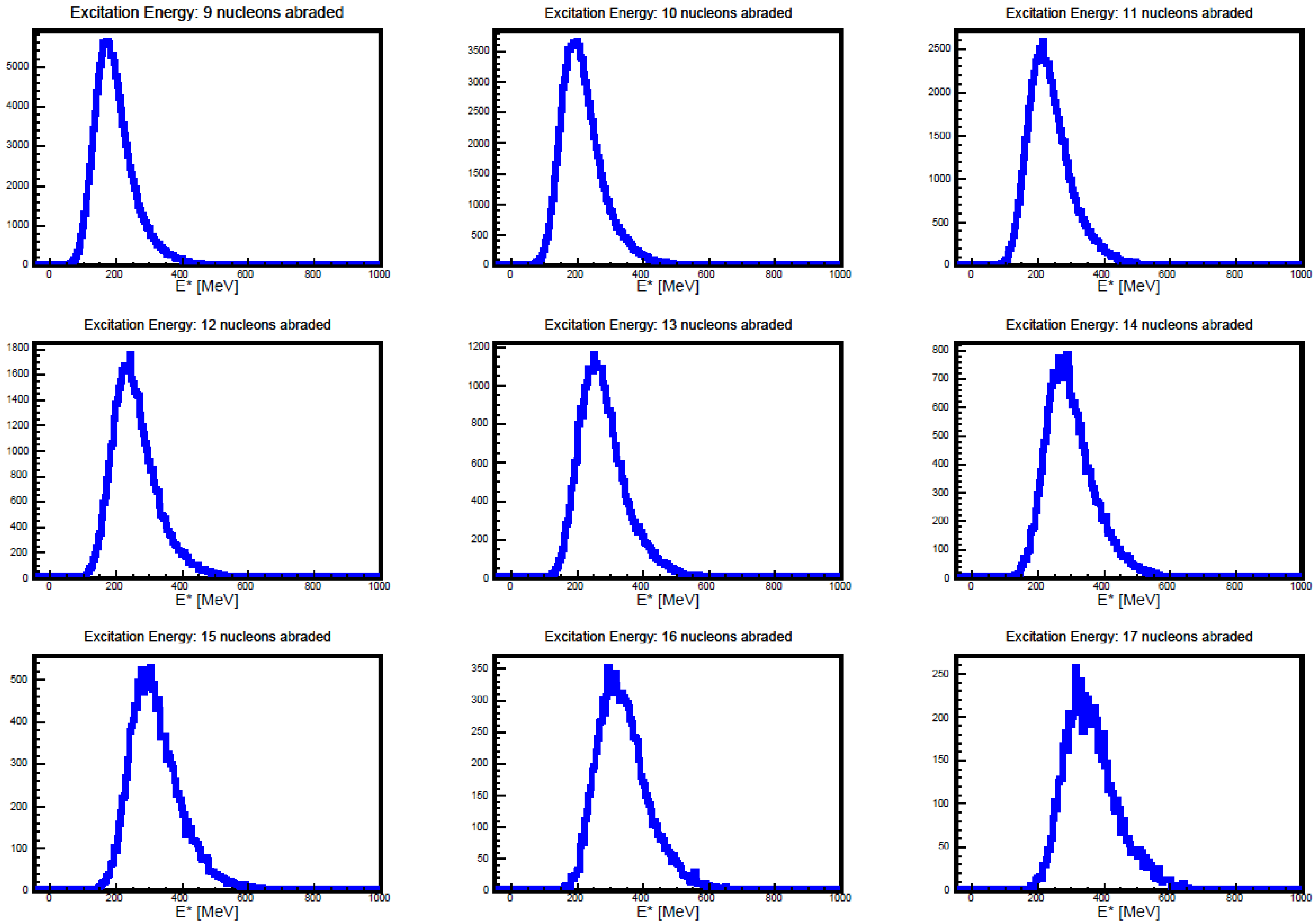
Backup Slides

Residual nucleus excitation energy distributions



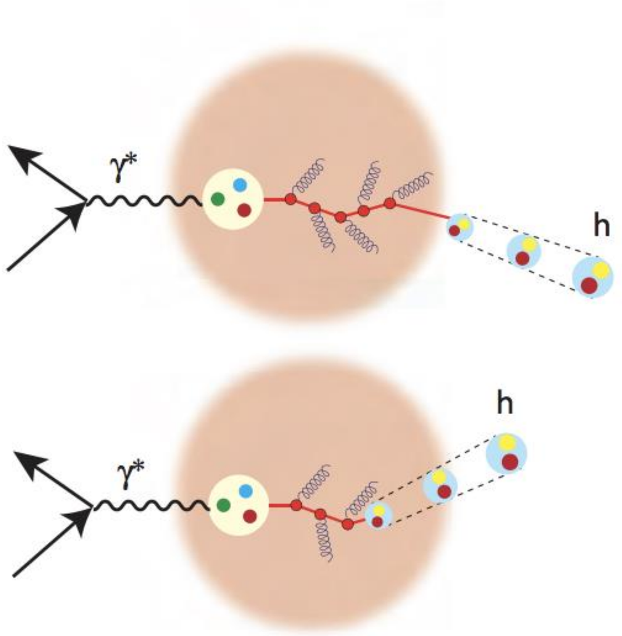
18 GeV e + 110 GeV/A ^{238}U

Residual nucleus excitation energy distributions

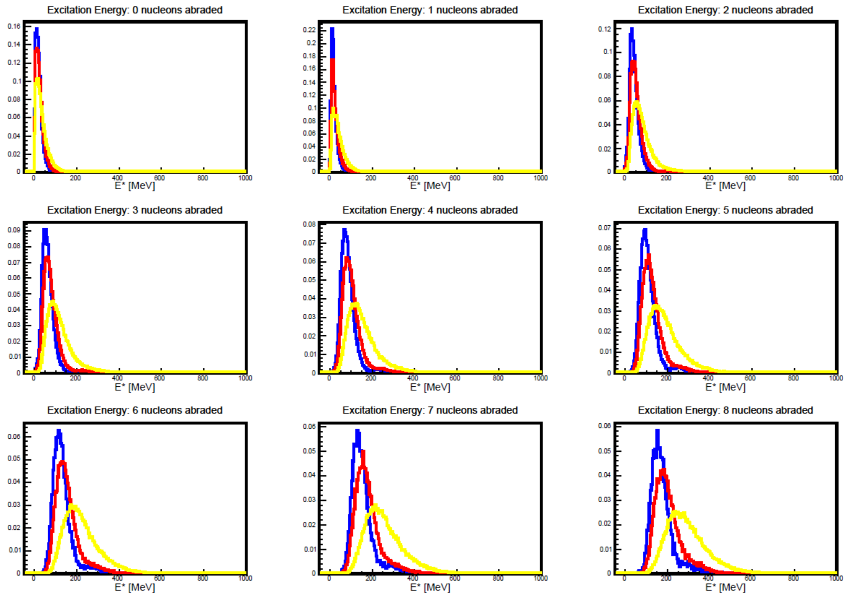


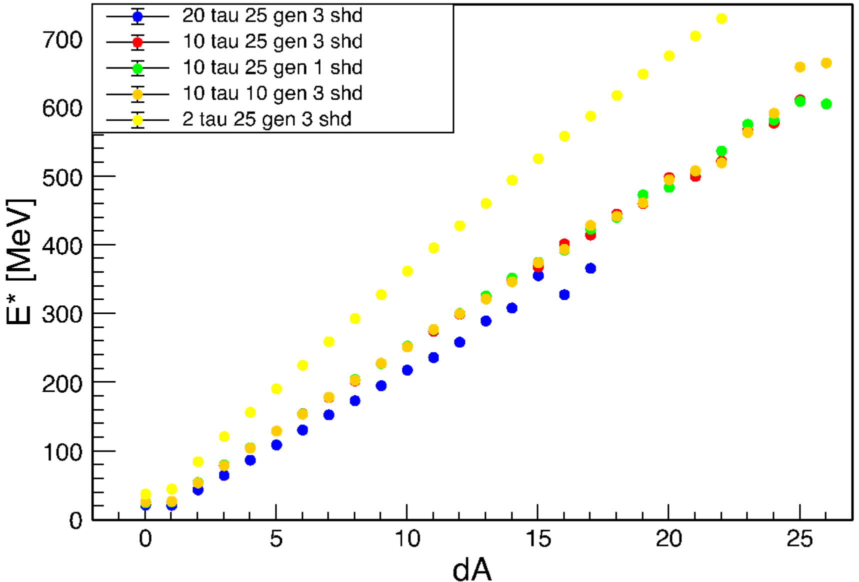
18 GeV e + 110 GeV/A ^{238}U

Residual nucleus sensitivity to formation time parameter



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



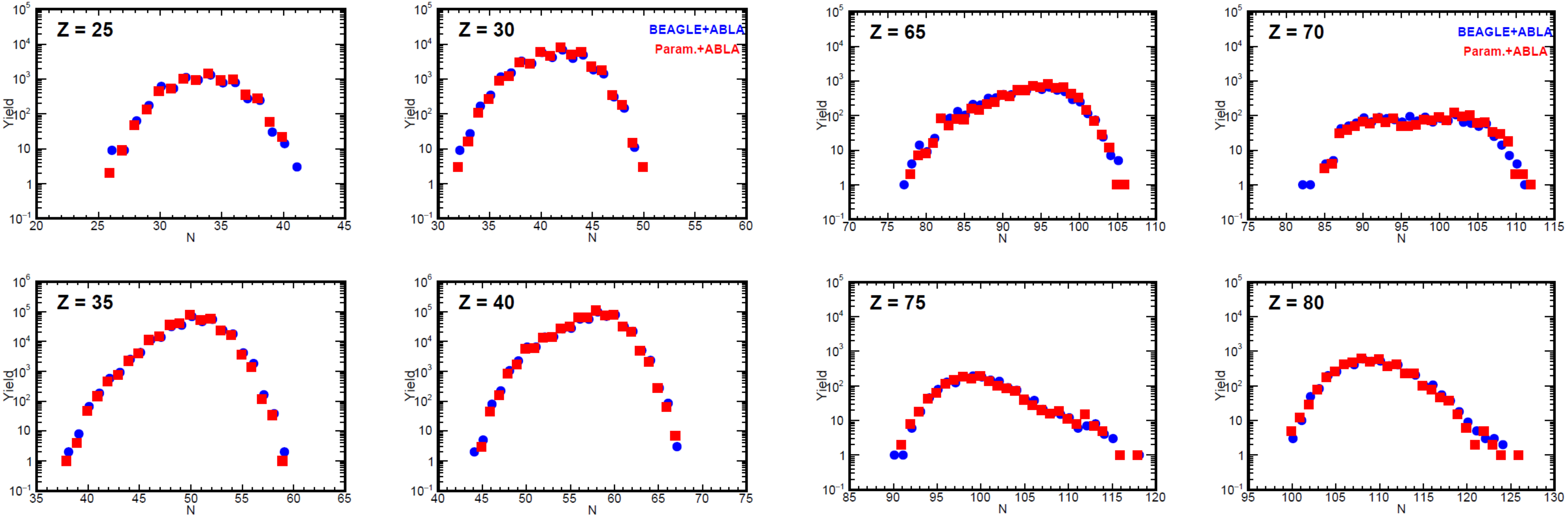


Expected EIC event counts

- ❑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

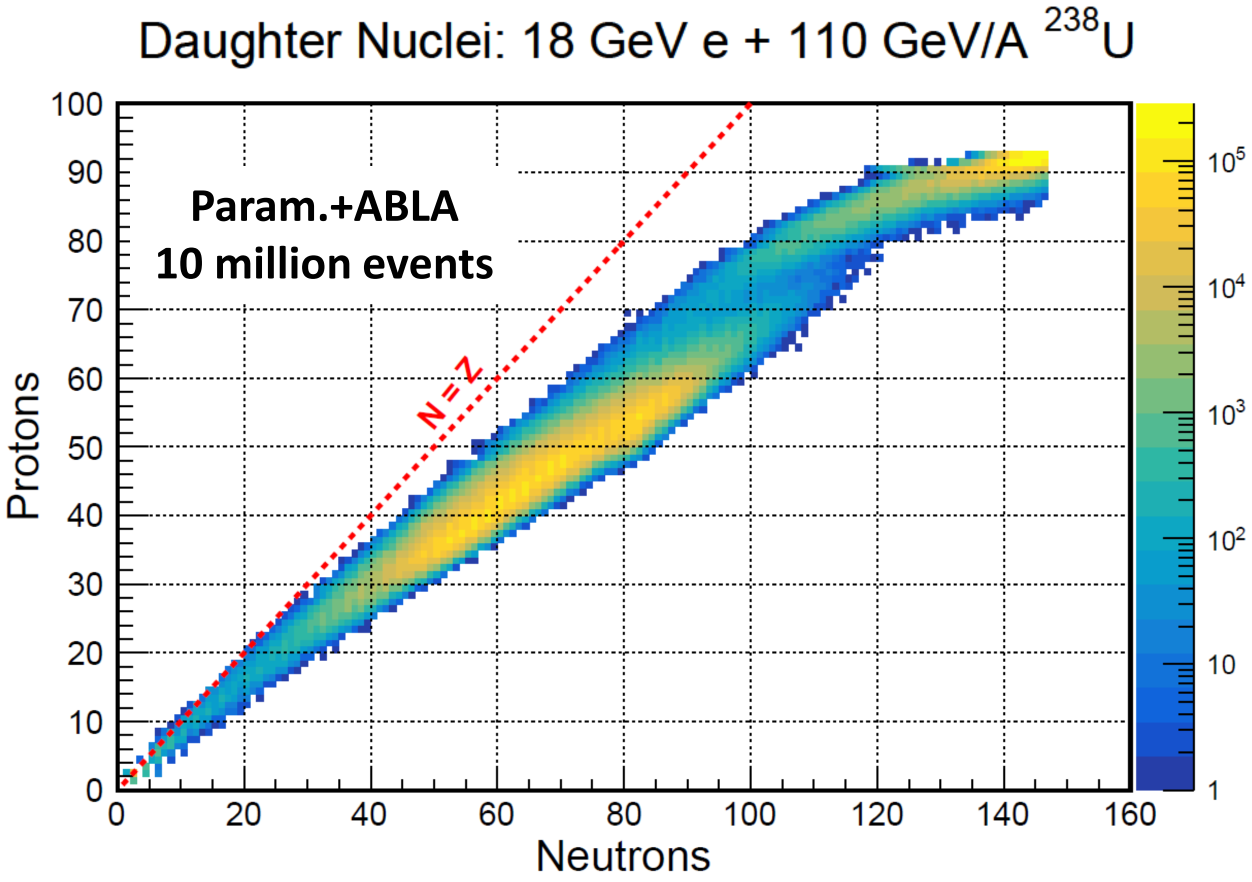
^{238}U

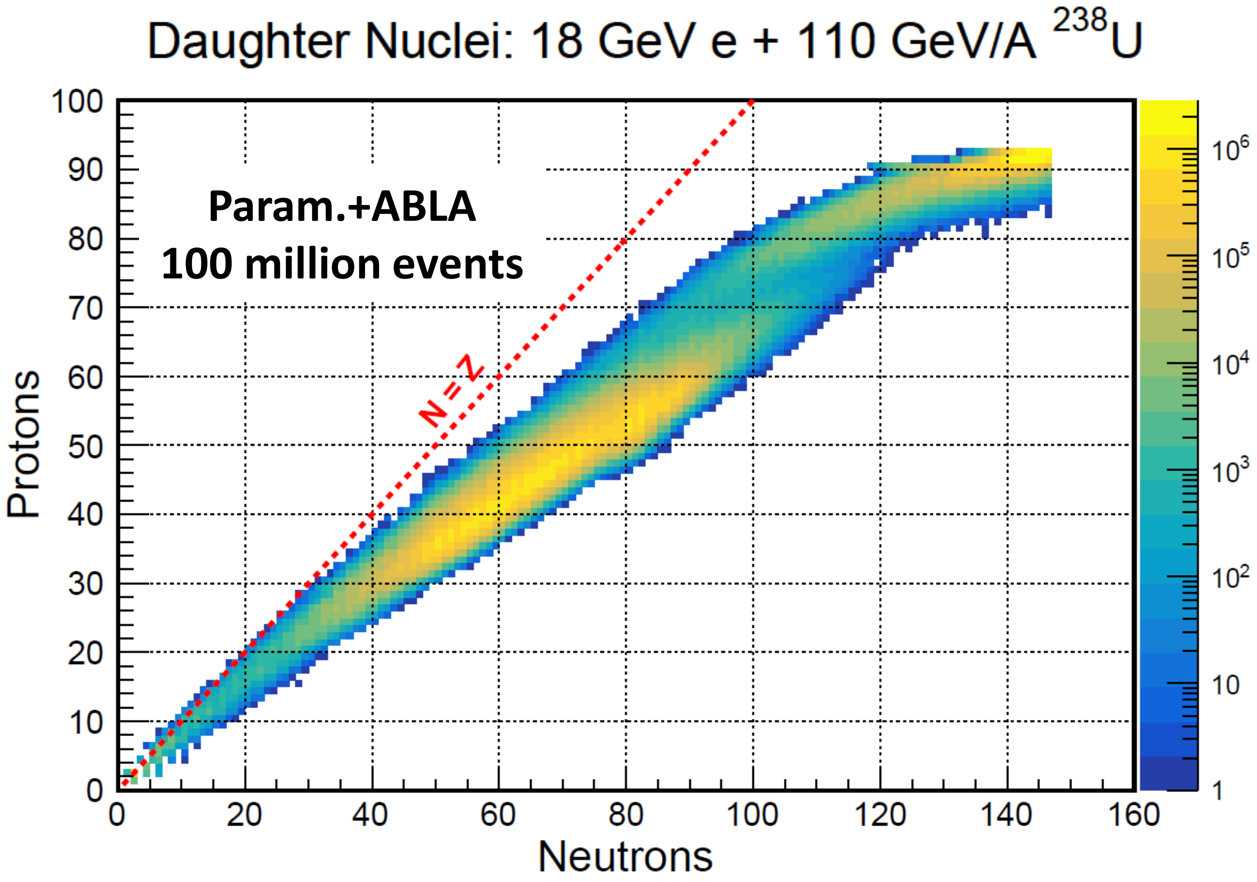


Using our parameterized model for the residual nucleus, we can simulate 10 million events in a few minutes.

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

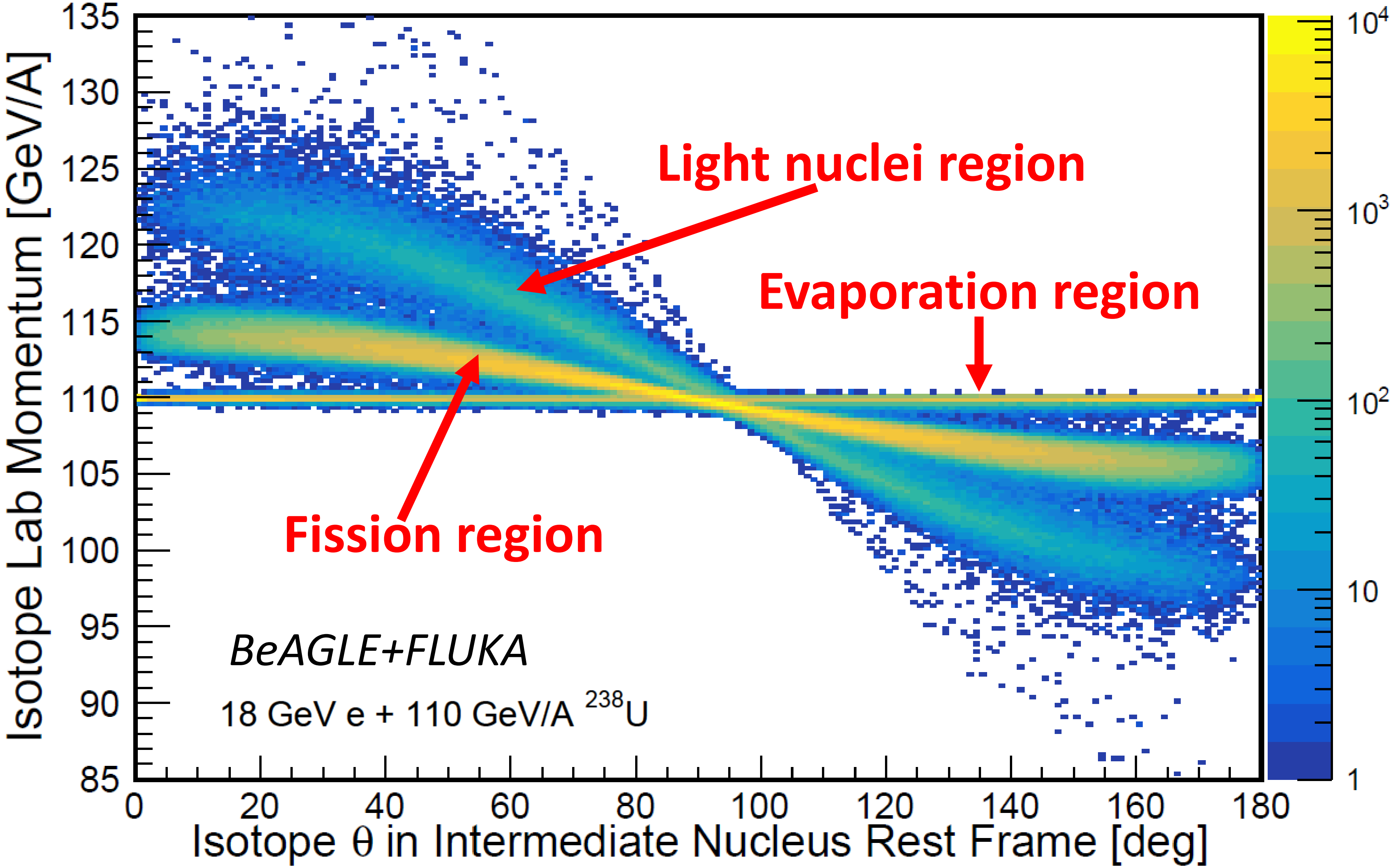
Towards higher statistics simulations



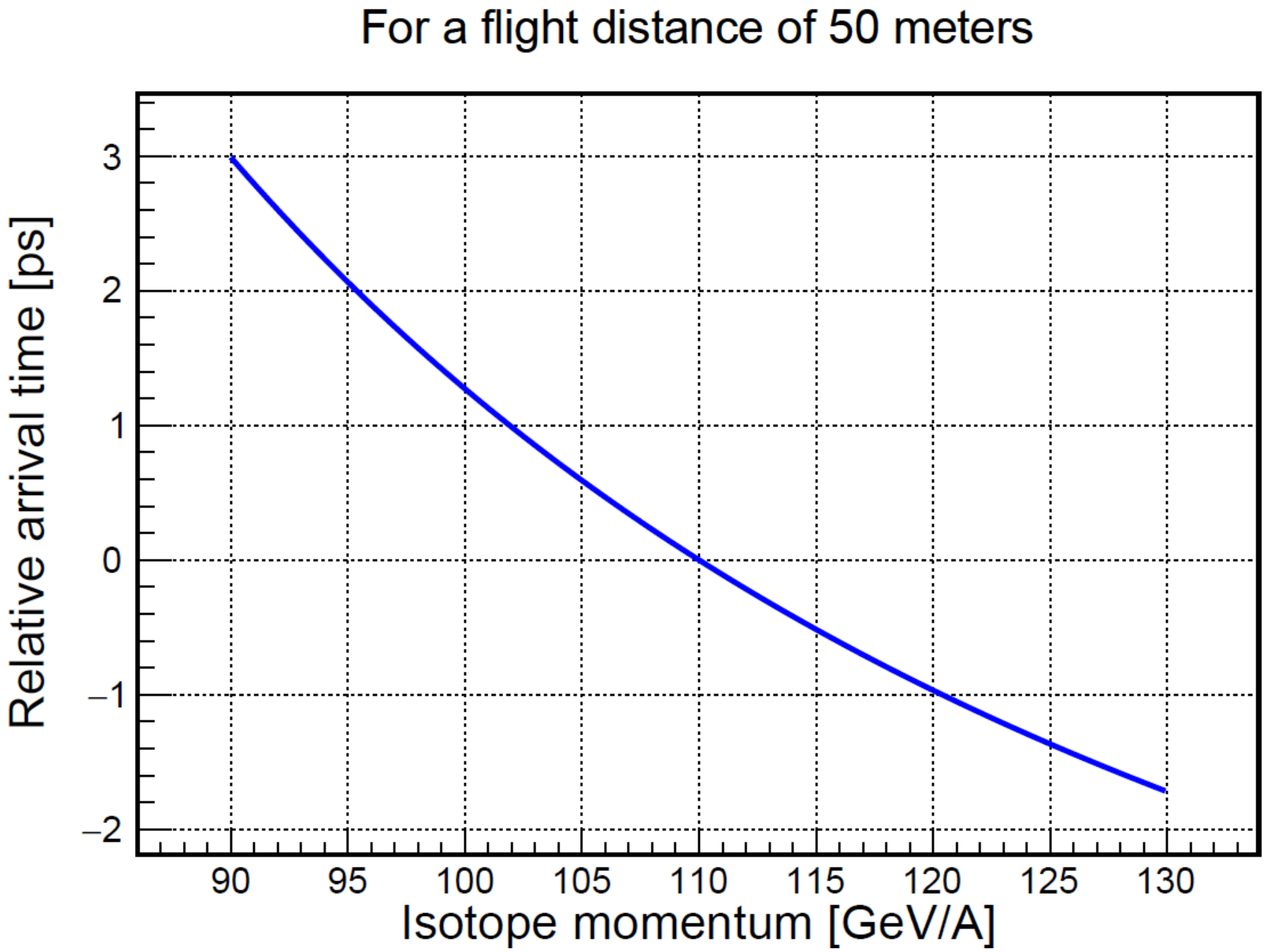


Note how borders expand towards more unstable isotopes as additional events are generated.

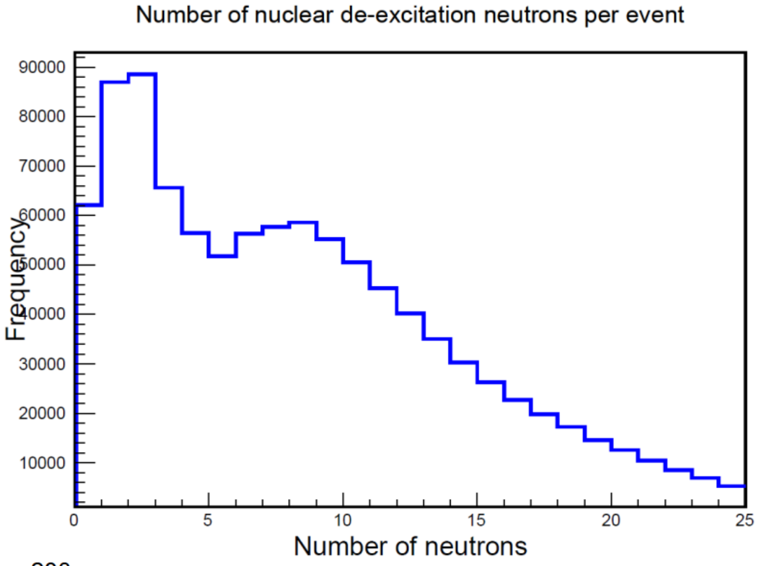
Fragment kinematics

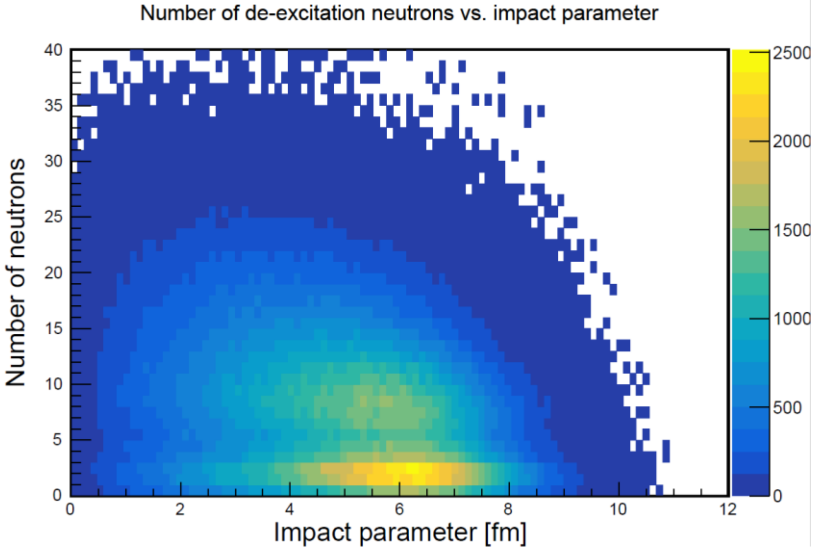


Time-of-flight measurements would require picosecond resolution



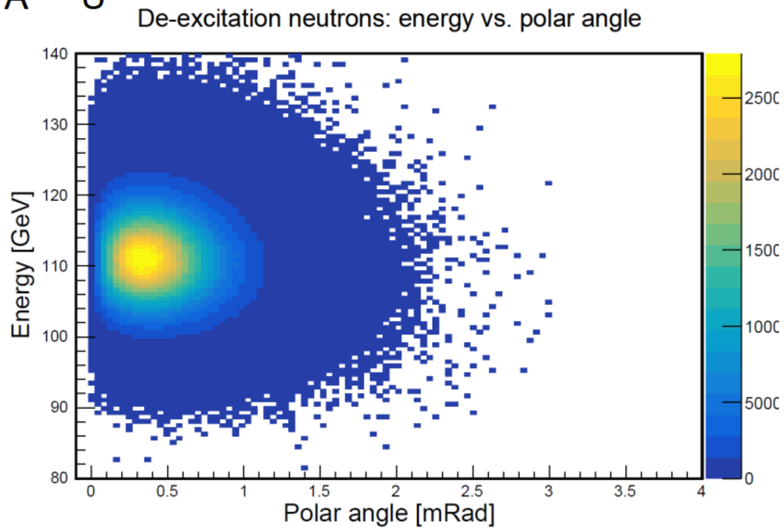
Centrality determination

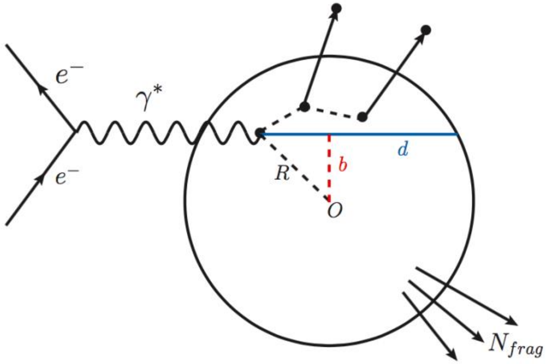


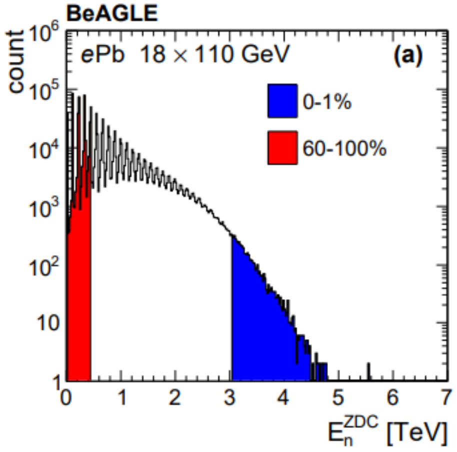


18 GeV e + 110 GeV/A ^{238}U

BeAGLE+FLUKA

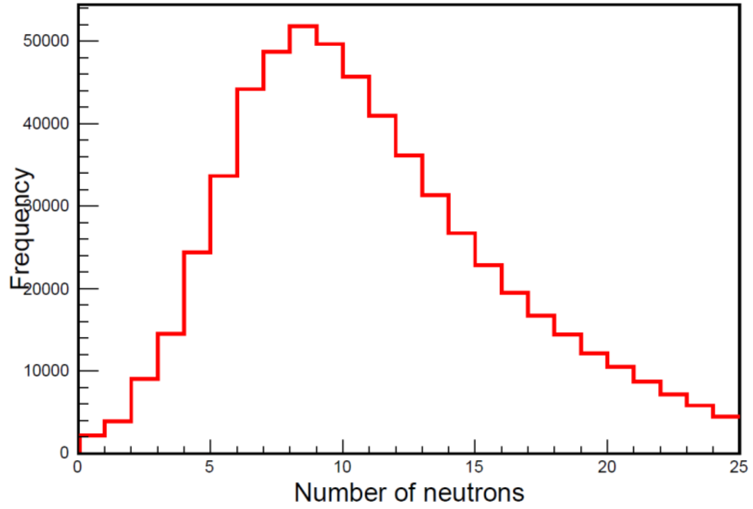


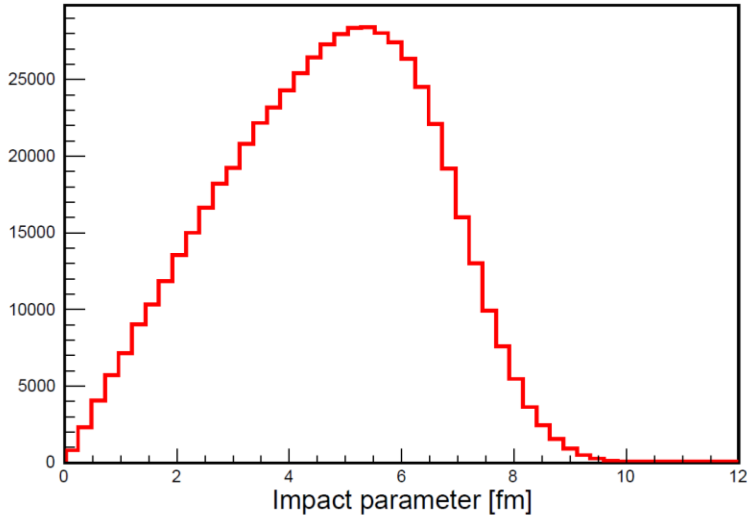




Phys. Rev. D 106, 012007

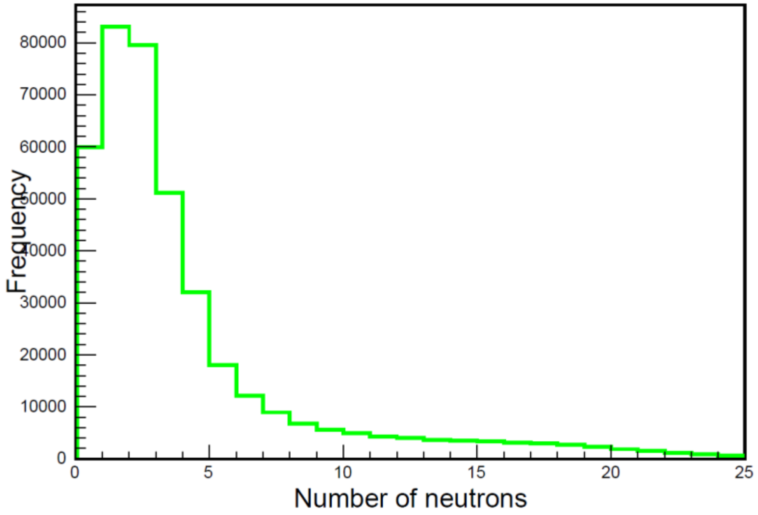
Centrality determination – model sensitivity

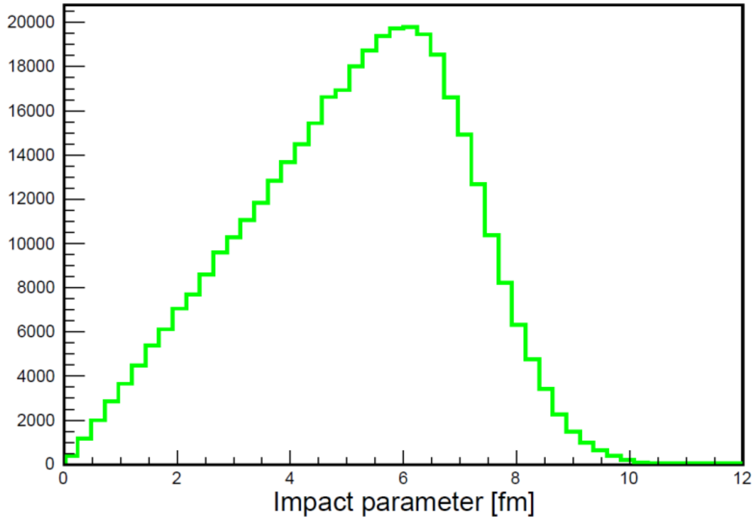

Number of de-excitation Neutrons -- fission region


Impact parameter -- fission region

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

BeAGLE+FLUKA


Number of de-excitation Neutrons -- evaporation region


Impact parameter -- evaporation region