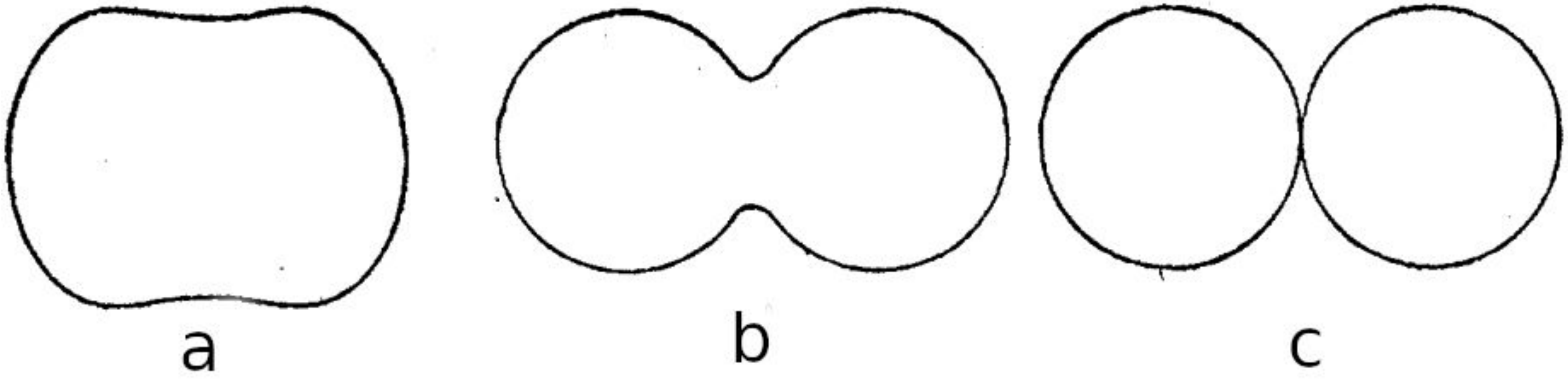
Isotopic fission fragments yields in the Thorium region produced in inverse-kinematics with a ^{232}Th beam

Colloque GANIL 2026

e849 experiment collaboration

Alex Cobo Zarzuelo
22/09/2026

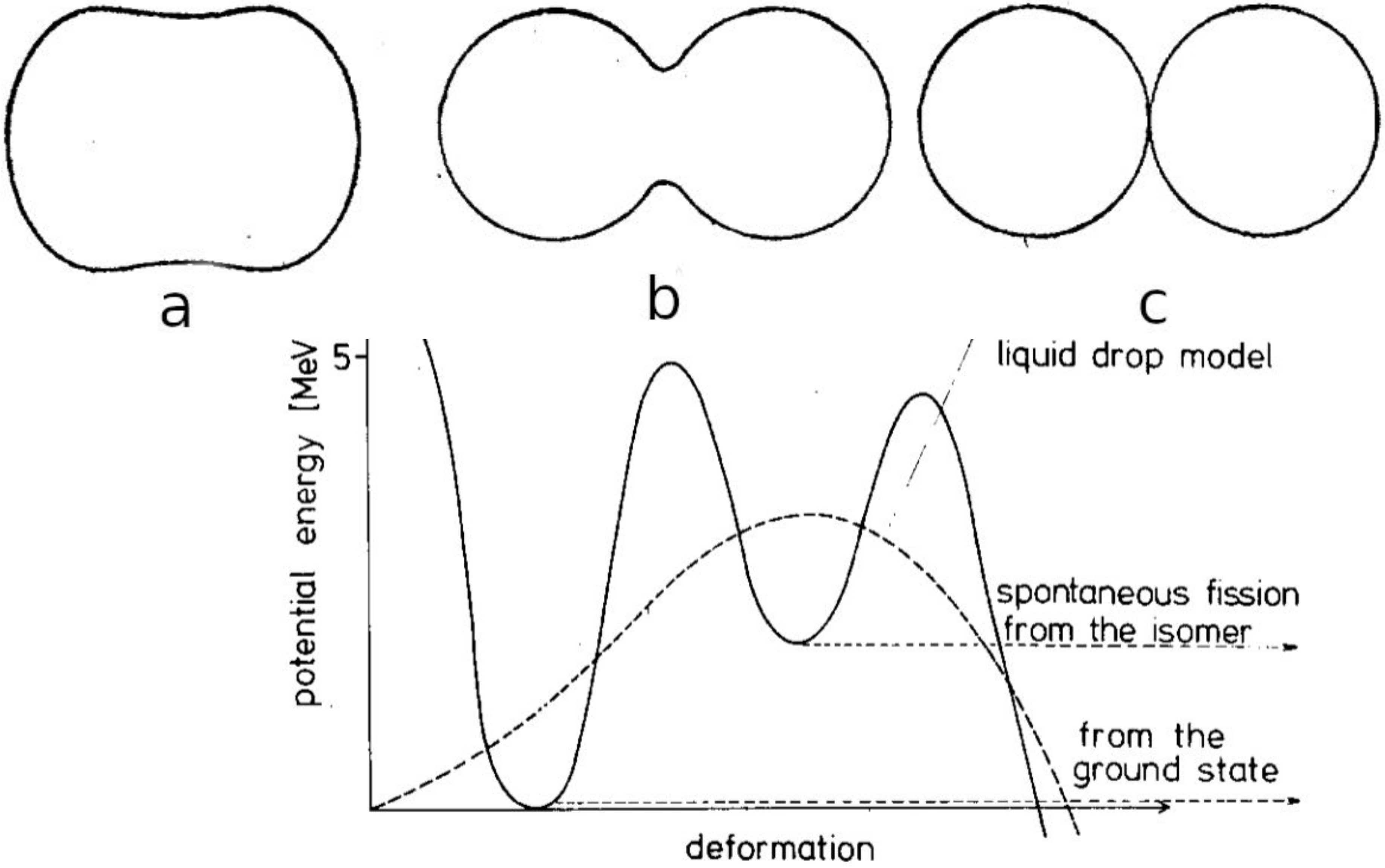
The fission process



Unestable competition between surface tension (Nuclear force) and repulsion (Coulomb) leads to **deformation** and **split** of a heavy nucleus into **2 fragments**

Bohr, N., & Wheeler, J. A. (1939). The mechanism of nuclear fission. Physical Review, 56(5), 426.

The fission process



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The **potential energy surface (PES)** represents the **energy of the system** at a given **deformation**

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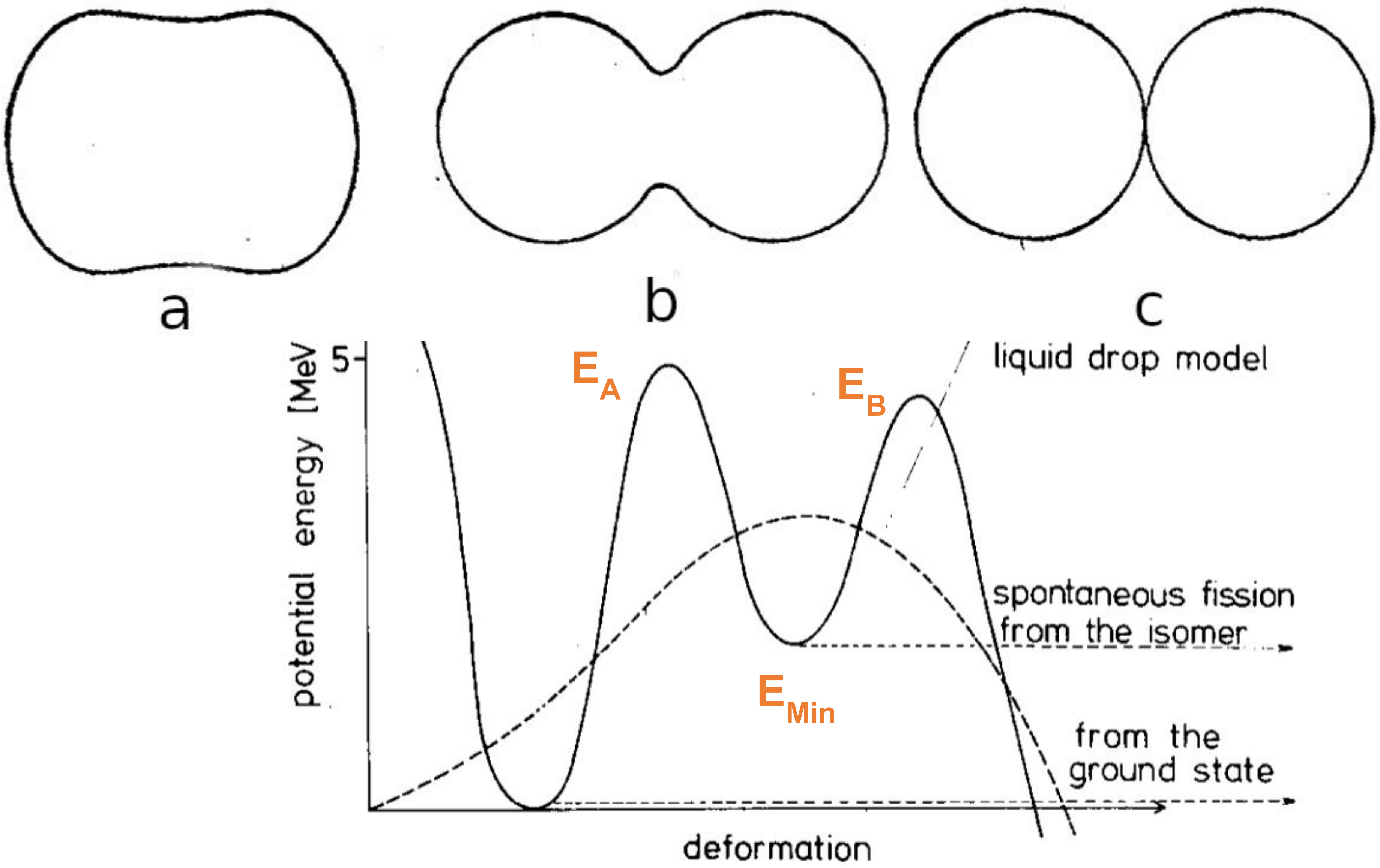

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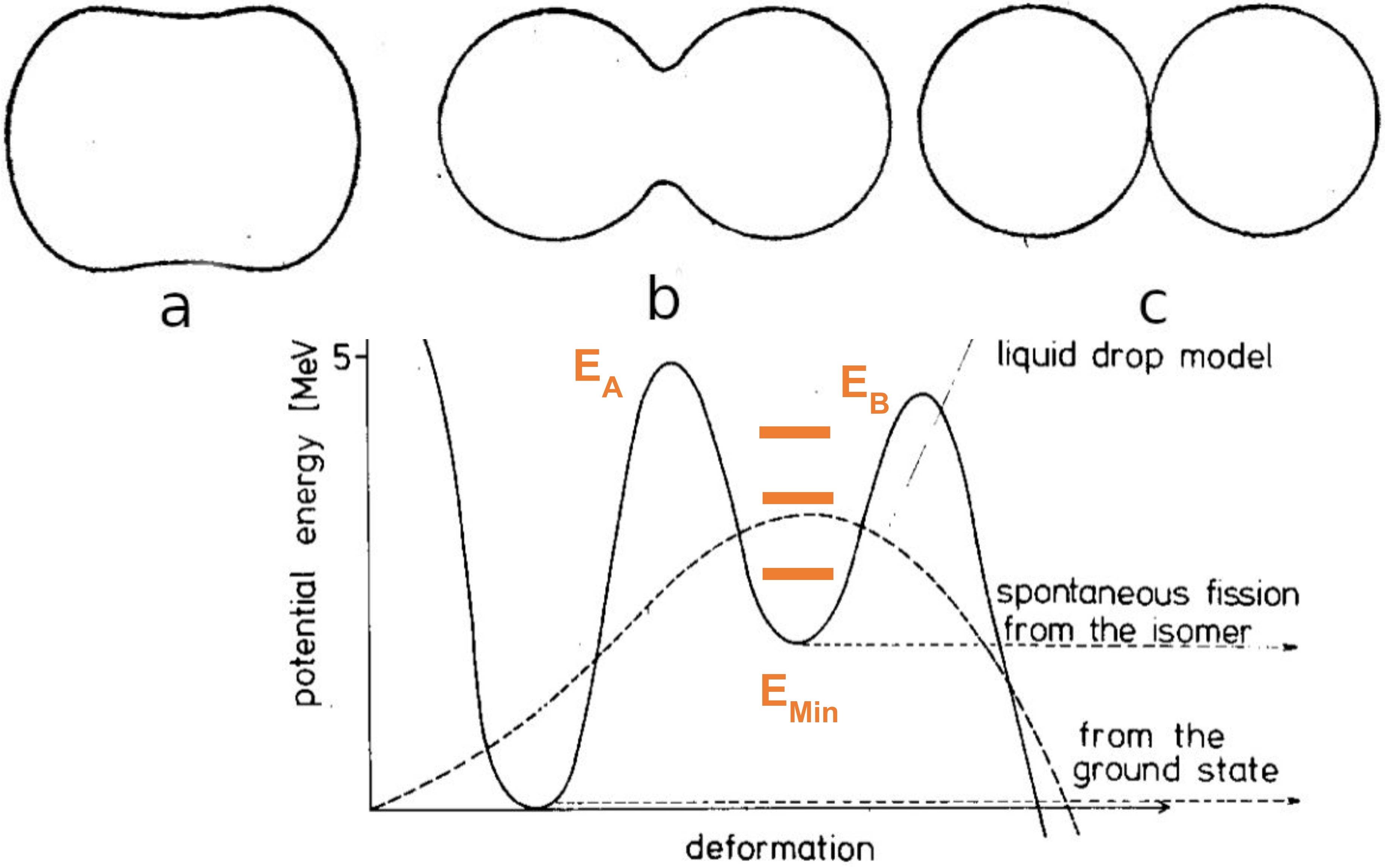
Including **nuclear structure** permits to pass from **single hump (dotted)** to **double humped PES (solid)**

The fission process



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The potential energy surface (PES) represents the energy of the system at a given deformation

Including nuclear structure permits to pass from single hump (dotted) to double humped PES (solid)

↓

- Explain **asymmetric fission in actinides**
- Presence of new **discrete energy levels**

Fission observables

The **PES** can**not** be directly **measured** => **observables related** to it

Fission observables: yields

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The PES cannot be directly measured => observables related to it

The **probability of producing a fission fragment** with
a given A, Z, N, etc. :

$$Y(Z,A) = 200 \cdot \frac{N(Z,A)}{\sum_{Z,A} N(Z,A)}$$

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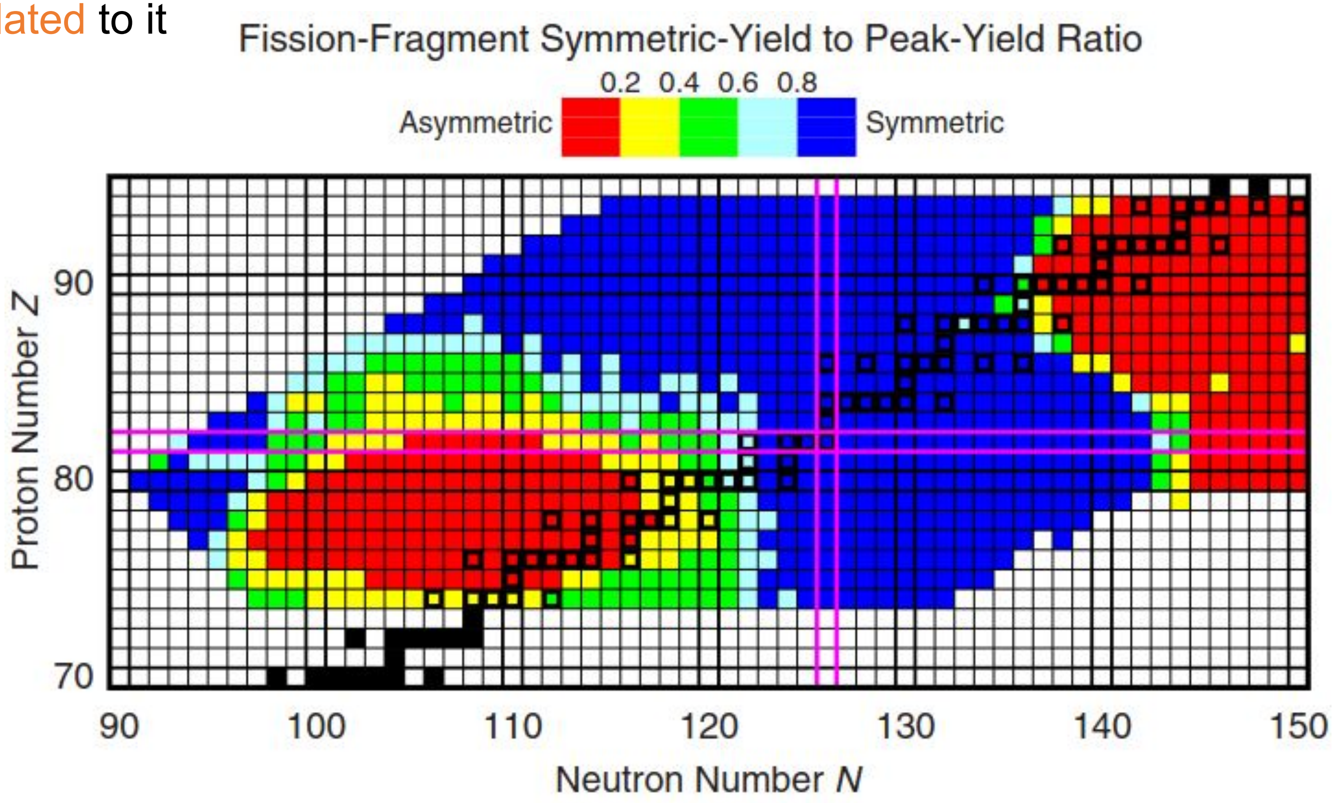
Two groups of **asymmetric fission** driven by **octupolar deformation**



Möller, P., & Randrup, J. (2015). Calculated fission-fragment yield systematics in the region 74≤ Z≤ 94 and 90≤ N≤ 150. Physical Review C, 91(4), 044316.

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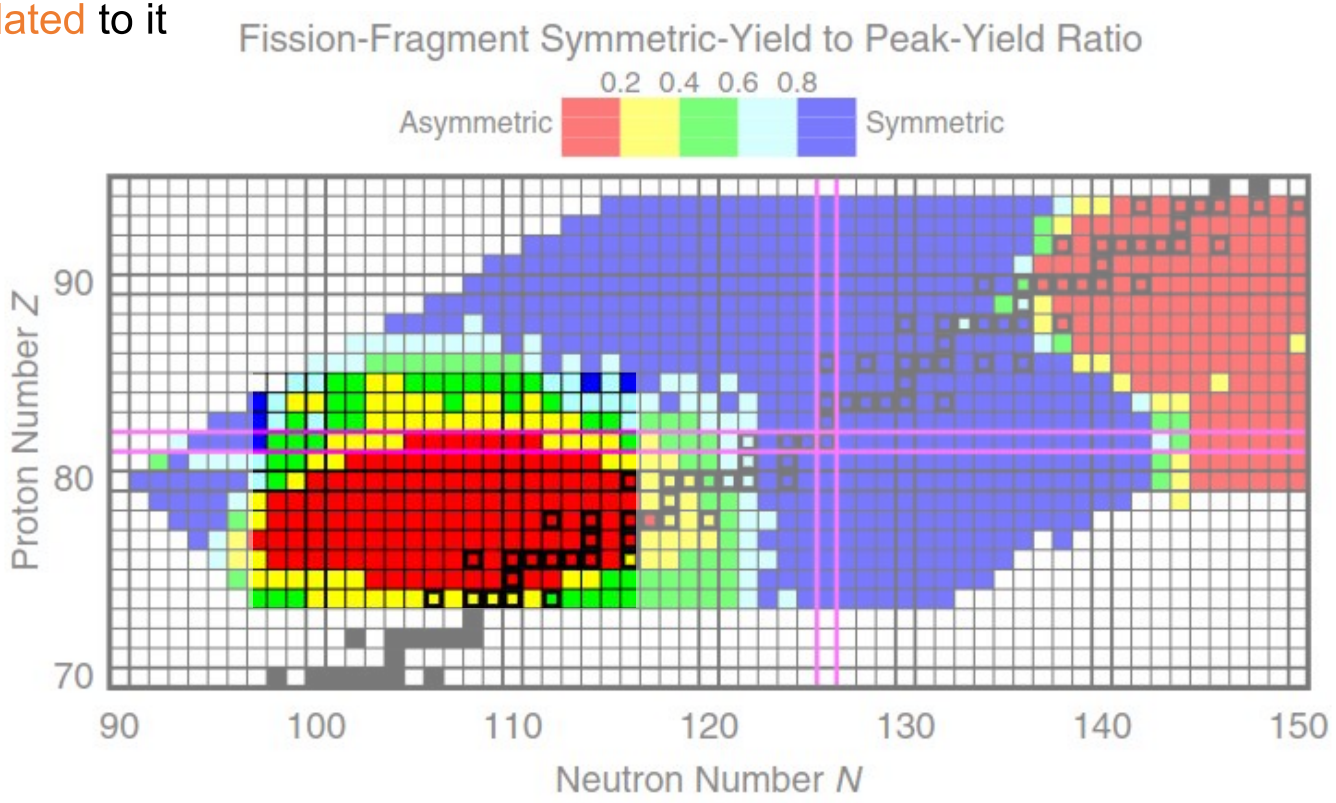
Two groups of **asymmetric fission**:

1) n-deficient sub-Pb -> **governed by Z_L~36**



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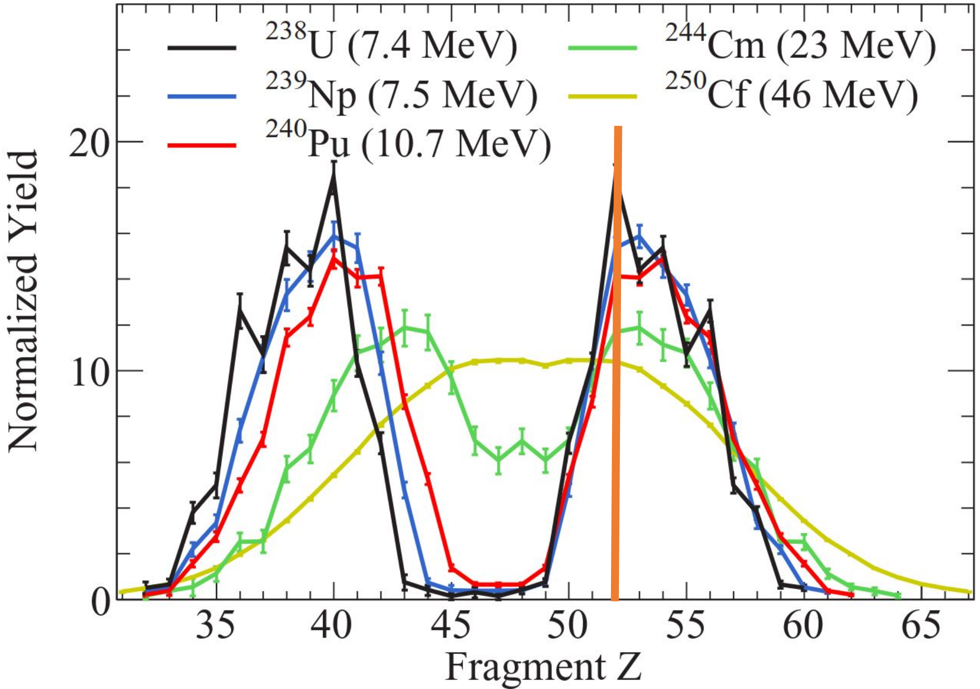
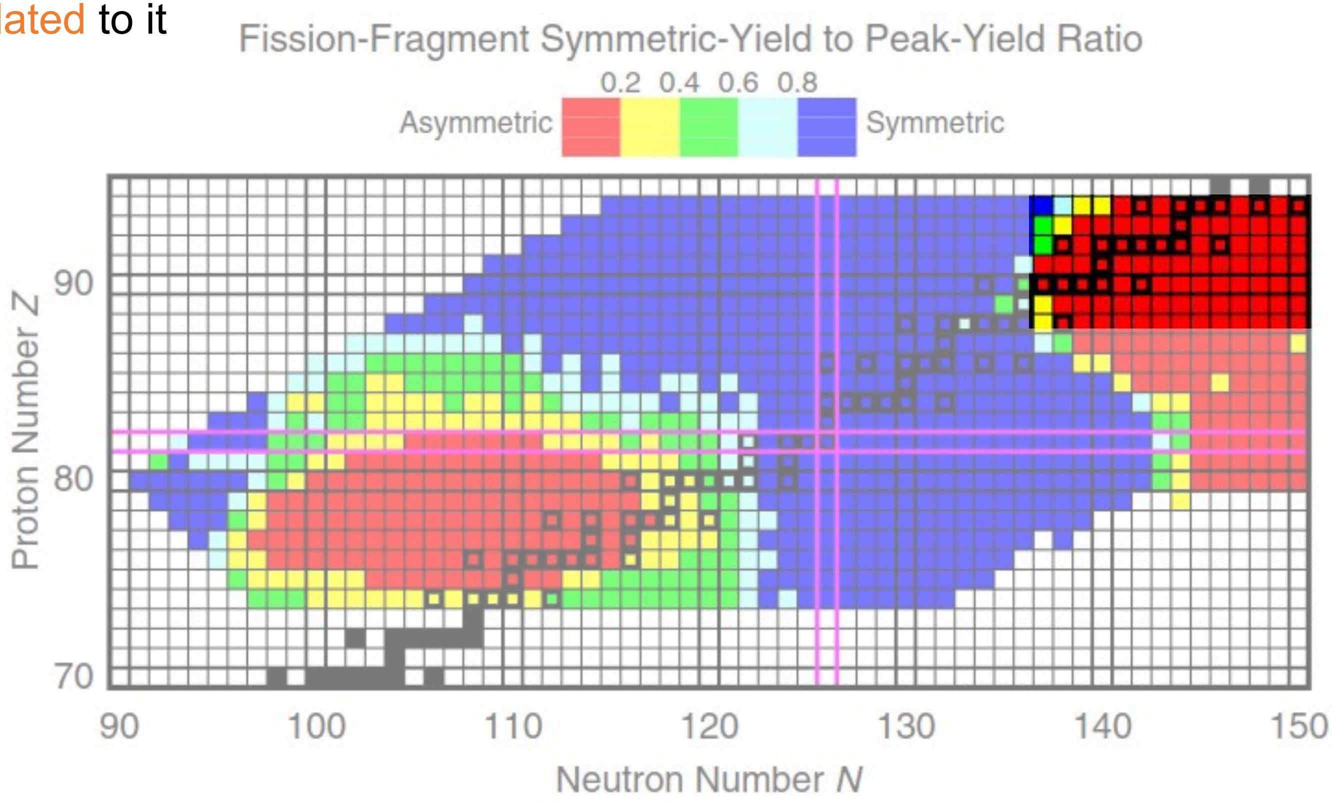
Two groups of **asymmetric fission**:
2) Around ^{238}U -> **driven by Z_H~54**





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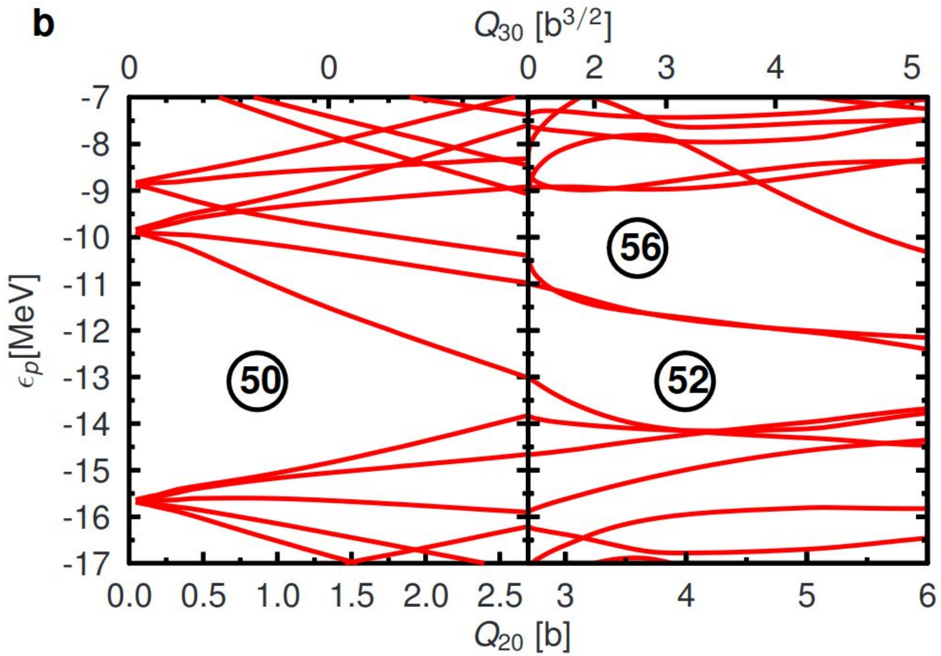

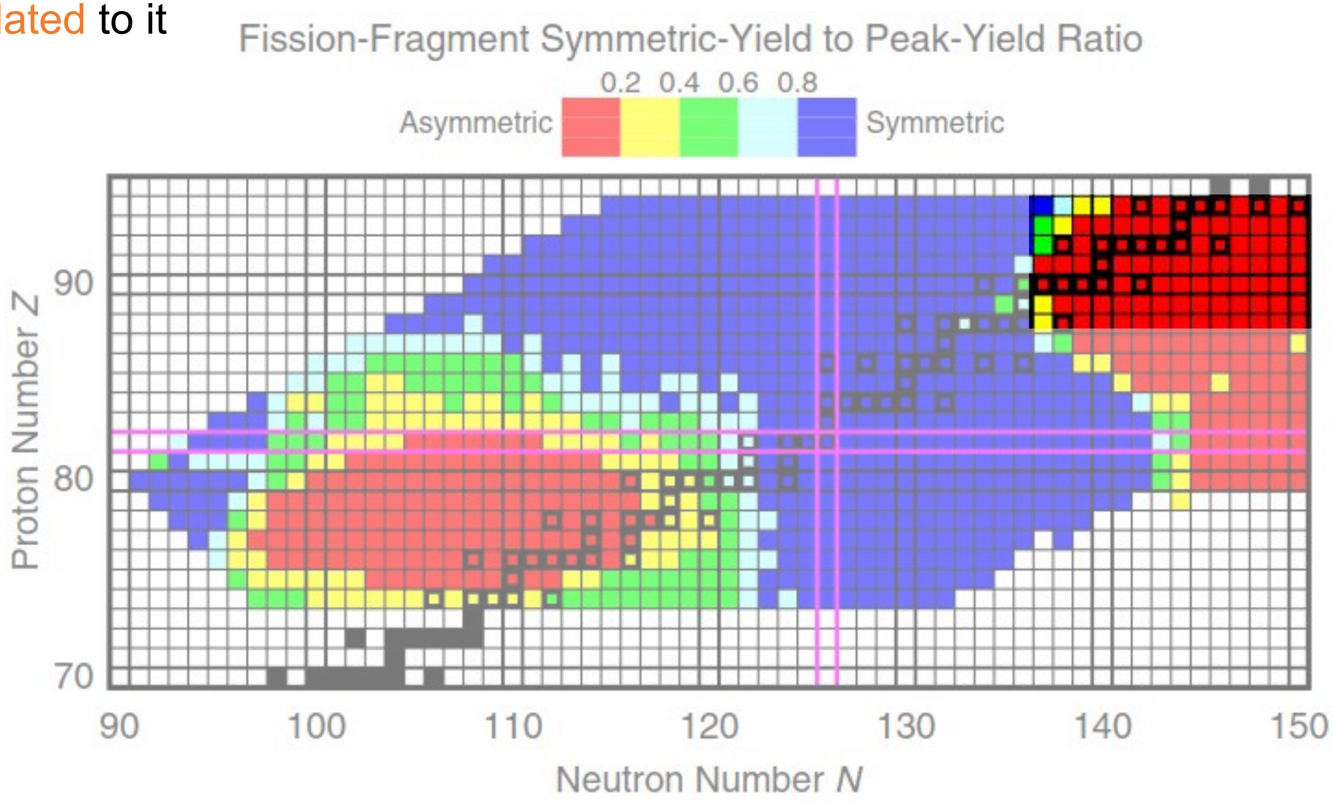

Scamps, G., & Simenel, C. (2018). Impact of pear-shaped fission fragments on mass-asymmetric fission in actinides. Nature, 564(7736), 382-385.

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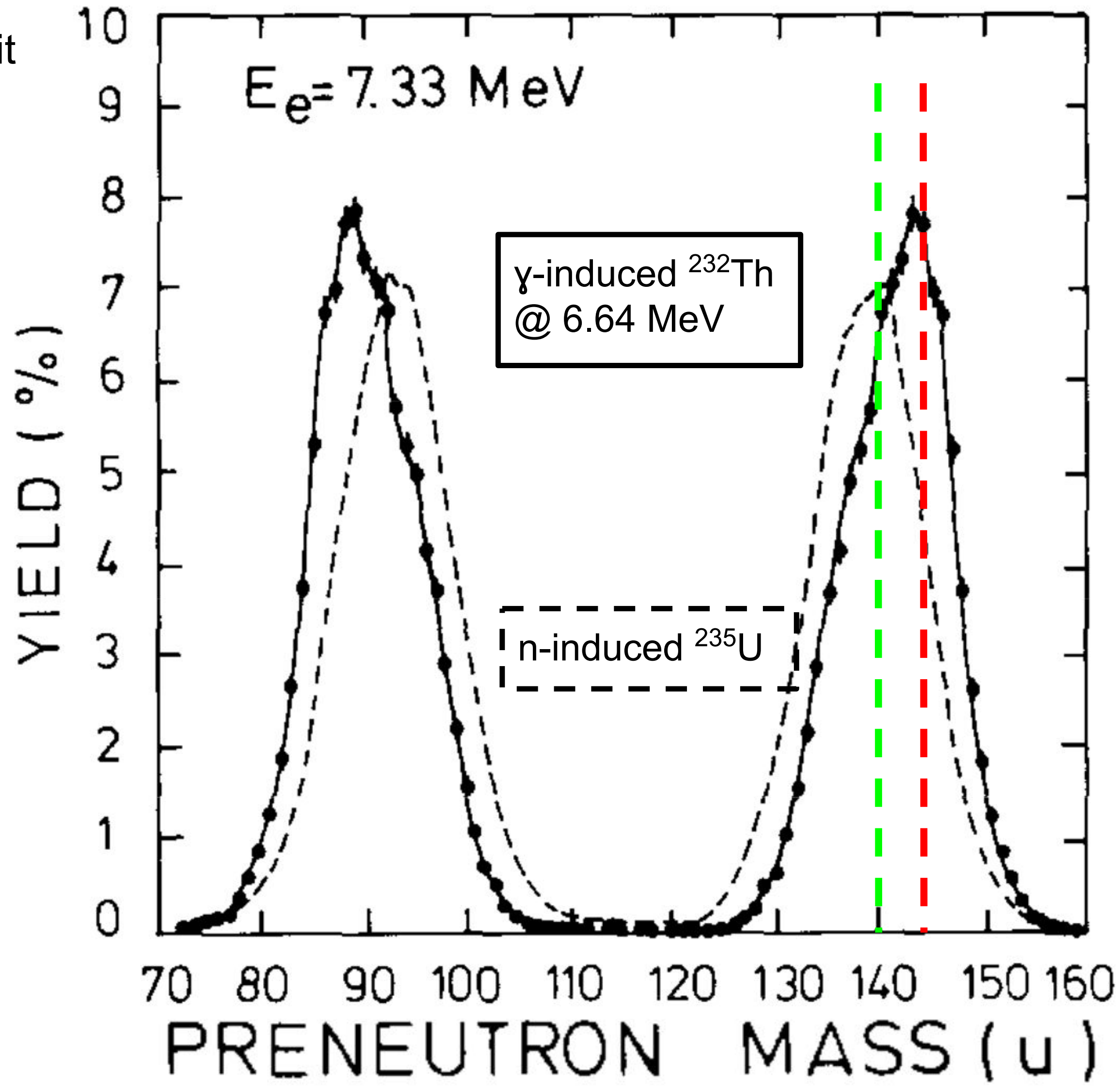
^{232}**Th mass yields** exhibit **more asymmetric** fission than ^{236}U **at low excitation energy** (6.64 MeV)



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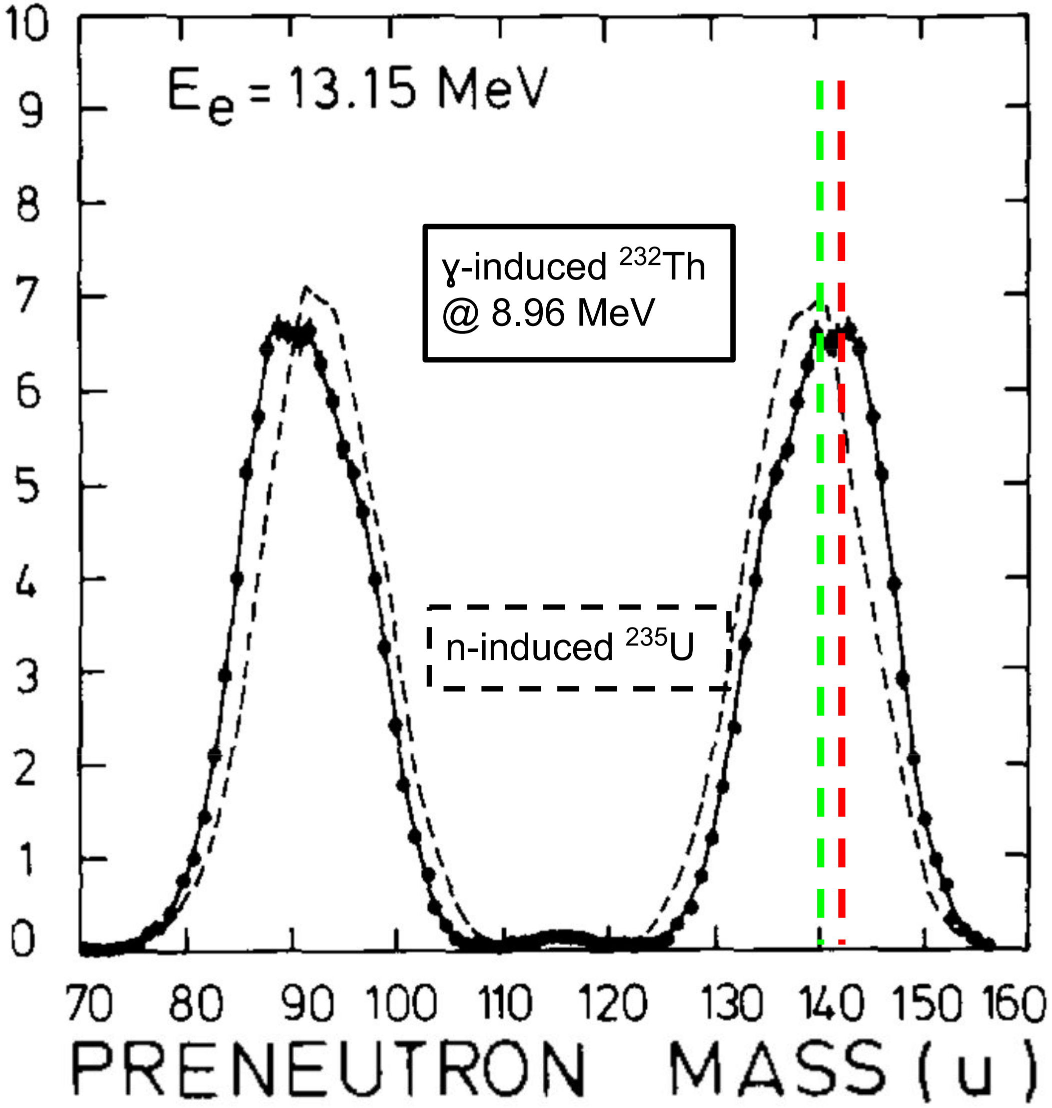
^{232}Th mass yields exhibit more asymmetric fission than ^{236}U at low excitation energy (6.64 MeV)

The **yields get closer to** the "**common** behaviour" when the **excitation energy is increased**

THORIUM ANOMALY



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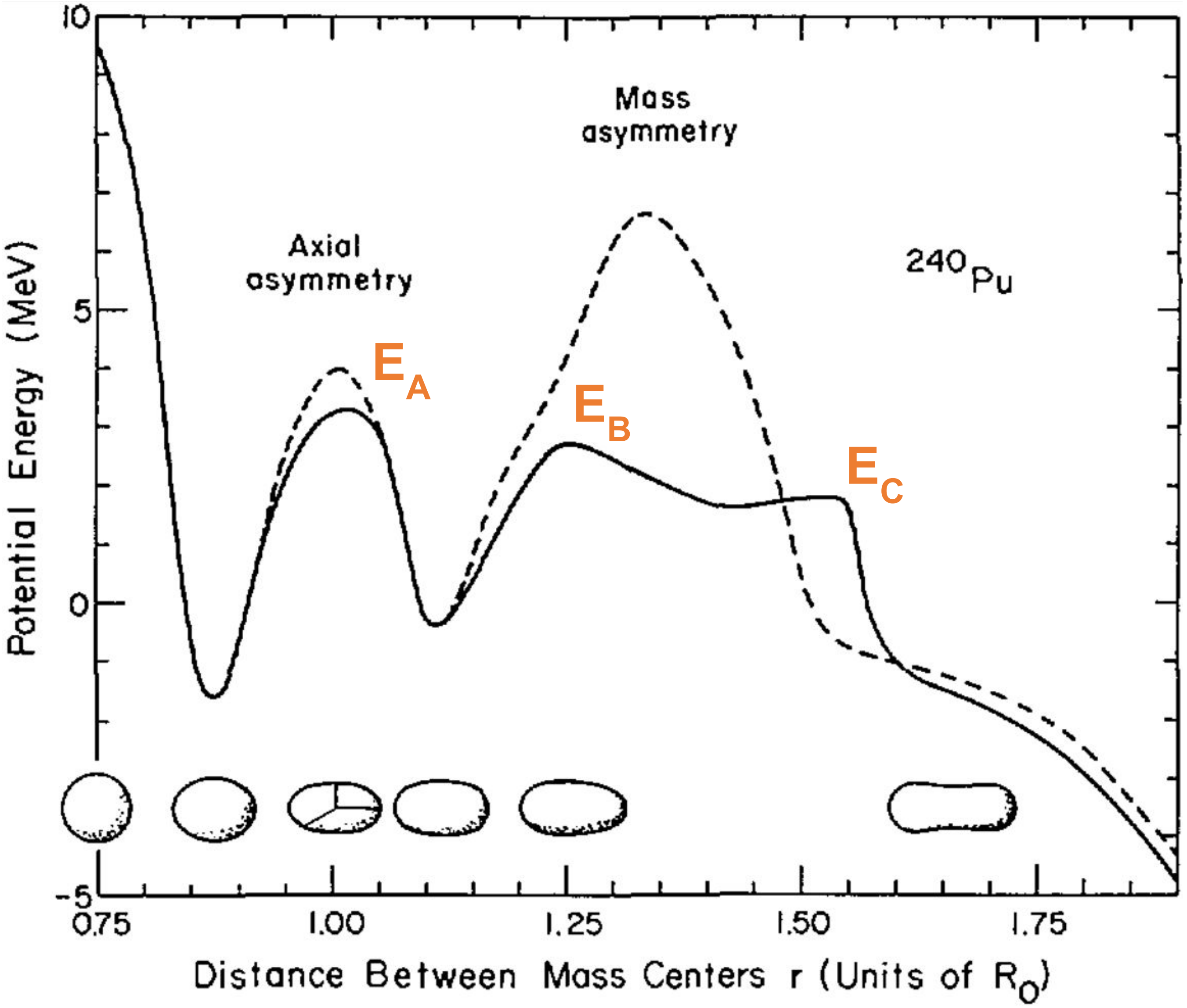
Anomaly explanation: third barrier



A **third fission barrier** was proposed to **explain** these **anomalous** observations

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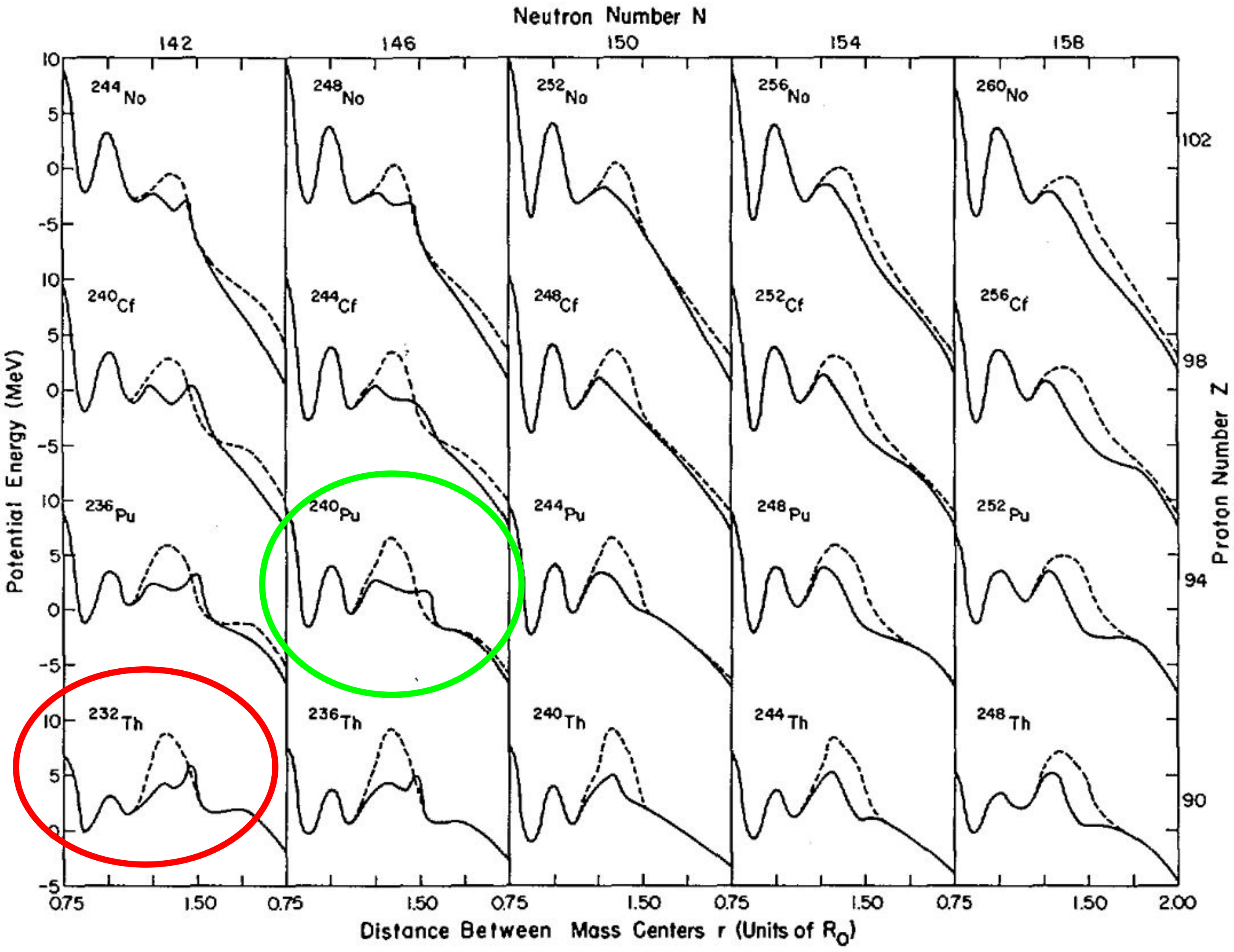

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The **ratio** between the **height of the second and third barrier depends** on **(N,Z)** of the fissioning systems

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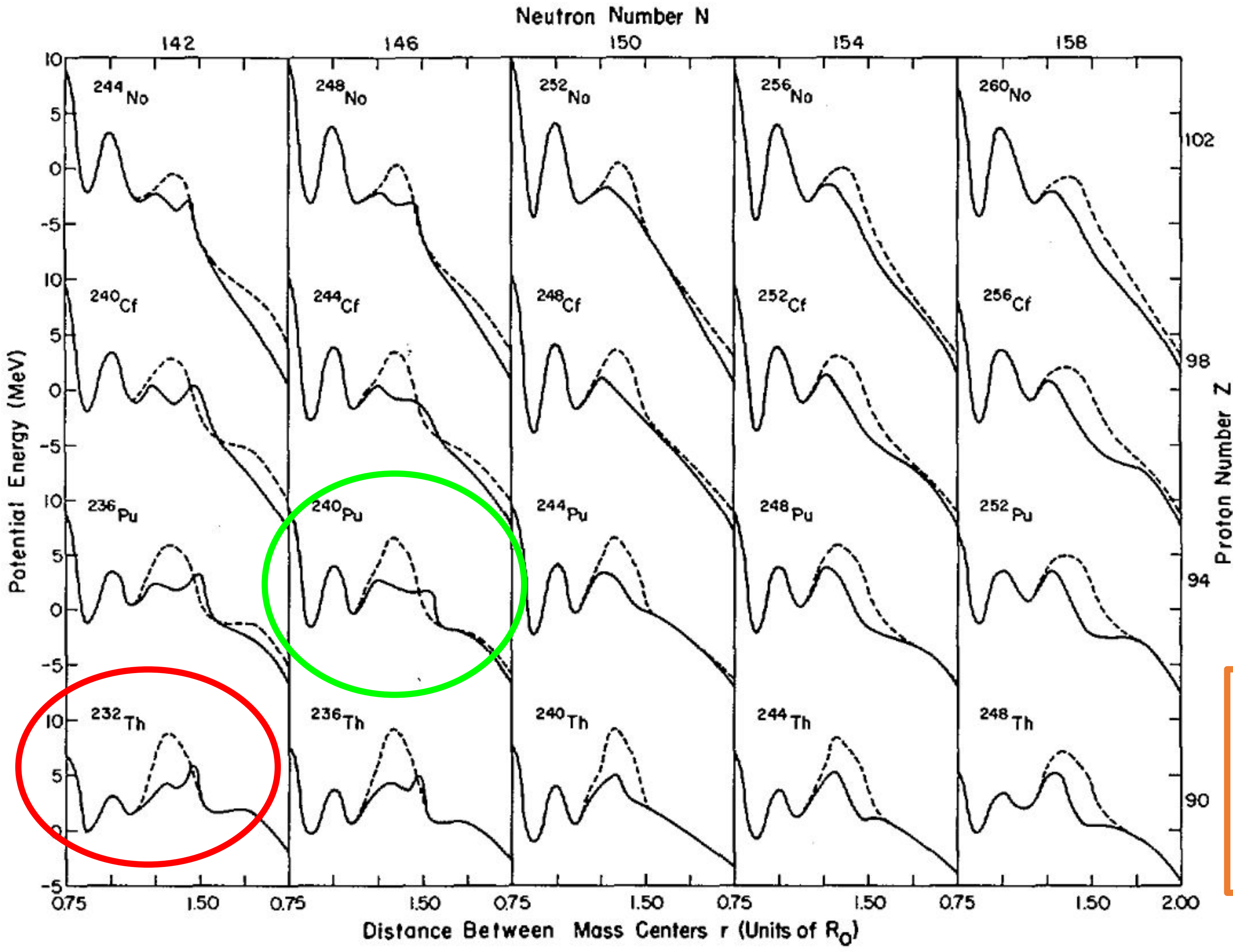

A third fission barrier was proposed to explain these anomalous observations

The ratio between the height of the second and third barrier depends on (N,Z) of the fissioning systems

↓

Only for **N ≤ 146** (in these calculations)

- What **structural effects** (proton/neutron) **drives** this anomaly ?
- **How** do they **vary** with **excitation energy**?
- Is it just an **anomaly?**

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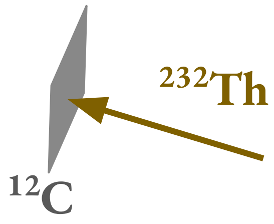
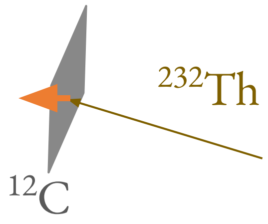
Experimental setup

^{232}Th beam of 6 MeV/u impinging on a ^{12}C target.



Experimental setup

^{232}Th beam of 6 MeV/u impinging on a ^{12}C target.
Produce fissioning systems through fusion (^{244}Cm) , transfer reactions (10+ systems like ^{234}U, ^{230}Th, ^{238}Pu, …) and inelastic scattering (^{232}Th)



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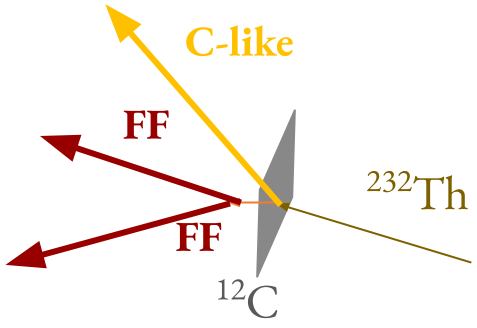
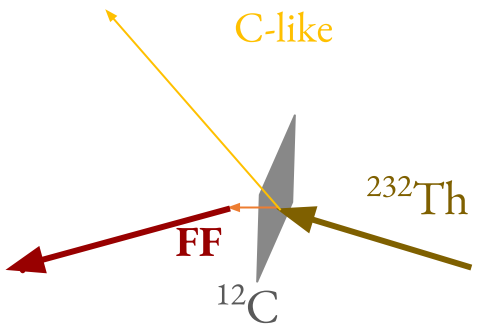
- **Beam-like** at high E* => **fission fragments**
- **Target-like** recoil => **Correlated to the fissioning nucleus**



Experimental setup

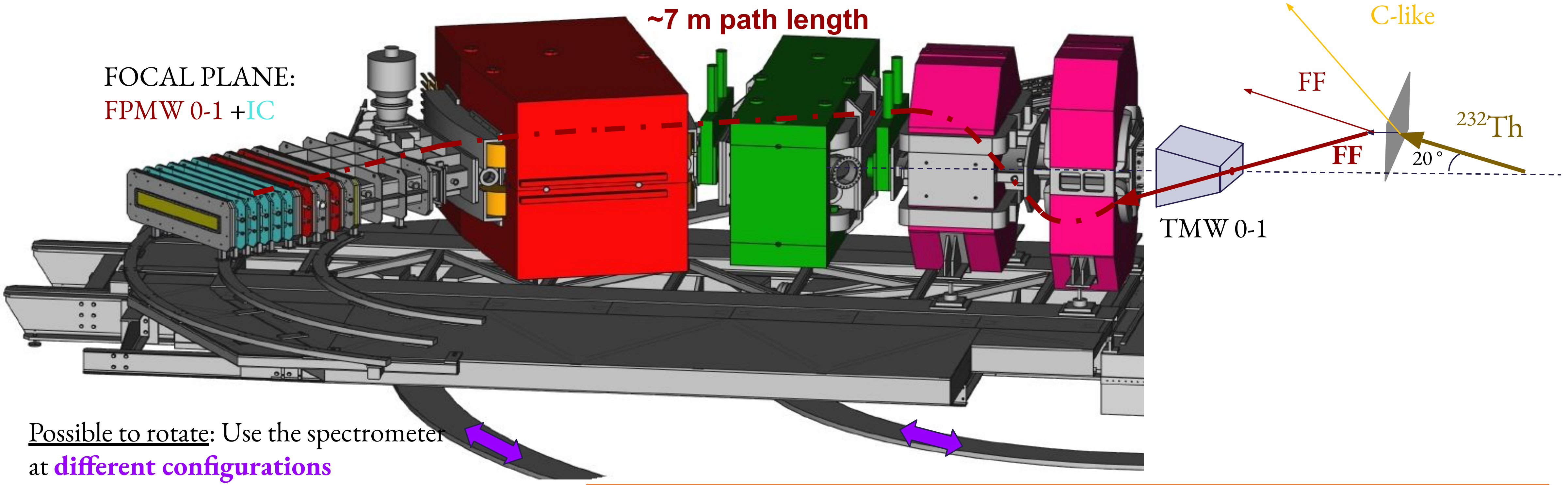
Need to **identify** a **fission fragment mass** event by event
The **mass of the fragments is high** for good resolution through a Energy vs Time-of-Flight (ToF) identification



VAMOS ++ : Exit channel information

Need to identify a fission fragment mass event by event
The mass of the fragments is high for good resolution through a Energy vs Time-of-Flight (ToF) identification
Use a **magnetic spectrometer** => mass **resolution** depends on magnetic rigidity ($B\varrho$) an ToF resolution

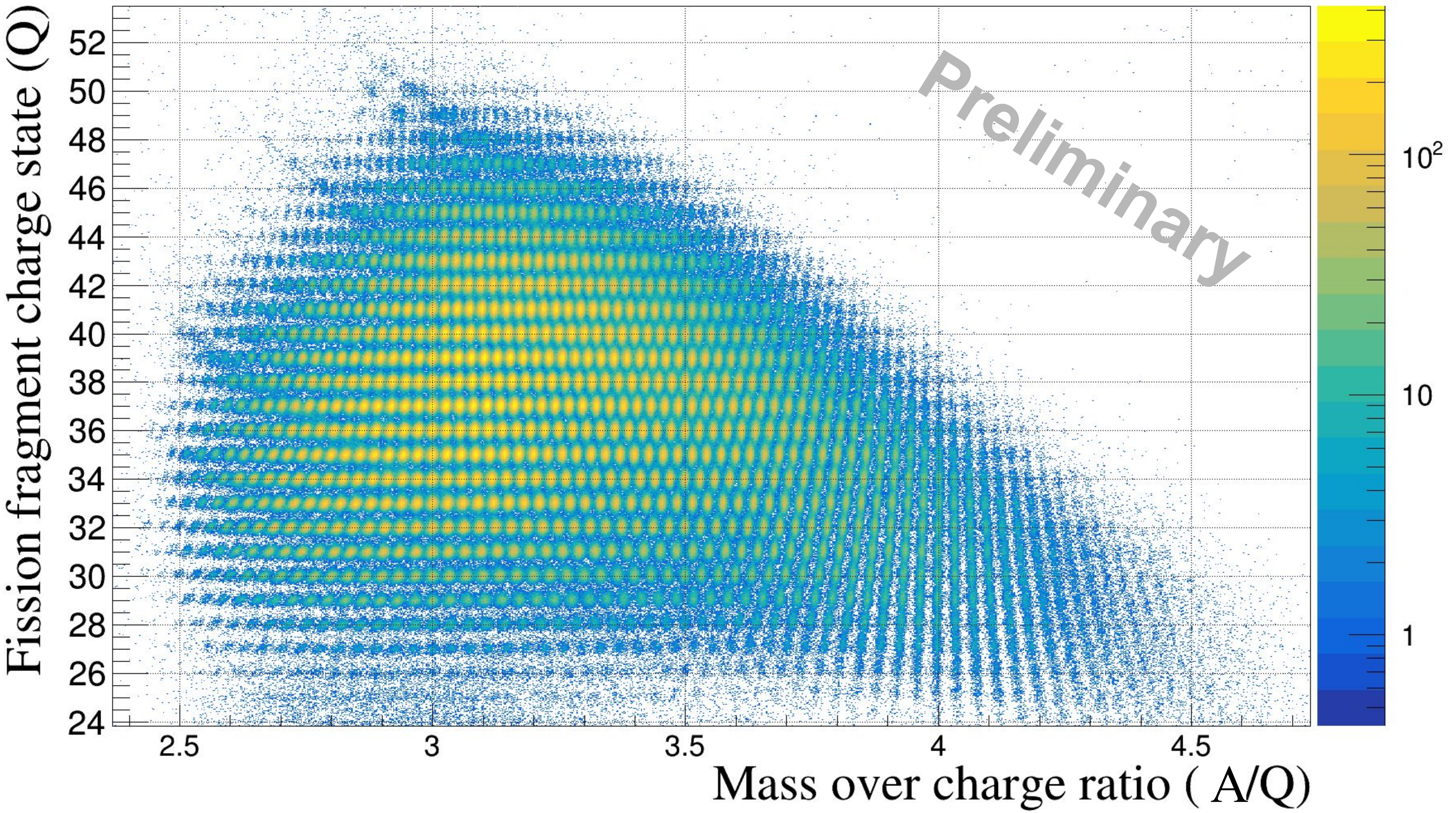
VAMOS: A Dipole, a Wien Filter (not used) and a pair of Quadrupoles



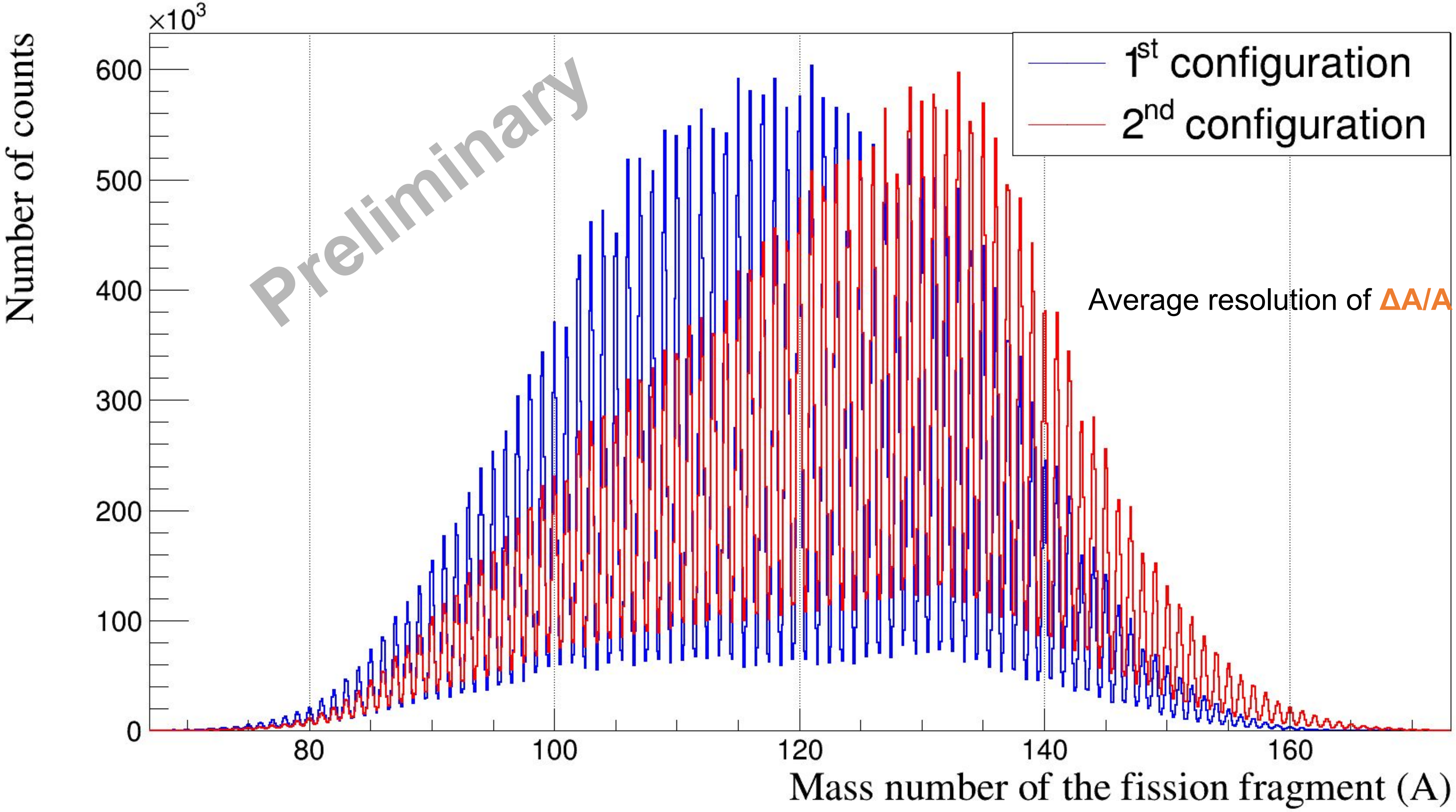
<u>Possible to rotate</u>: Use the spectrometer at **different configurations**

1. **Optics:** $B\varrho$, path, ToF→**A/q**, **velocity** and atomic **charge state (q)**
2. **IC: ΔE - E$_{res.}$** technique to extract the **nuclear charge (Z)**

Fission fragment identification: Q vs A/Q

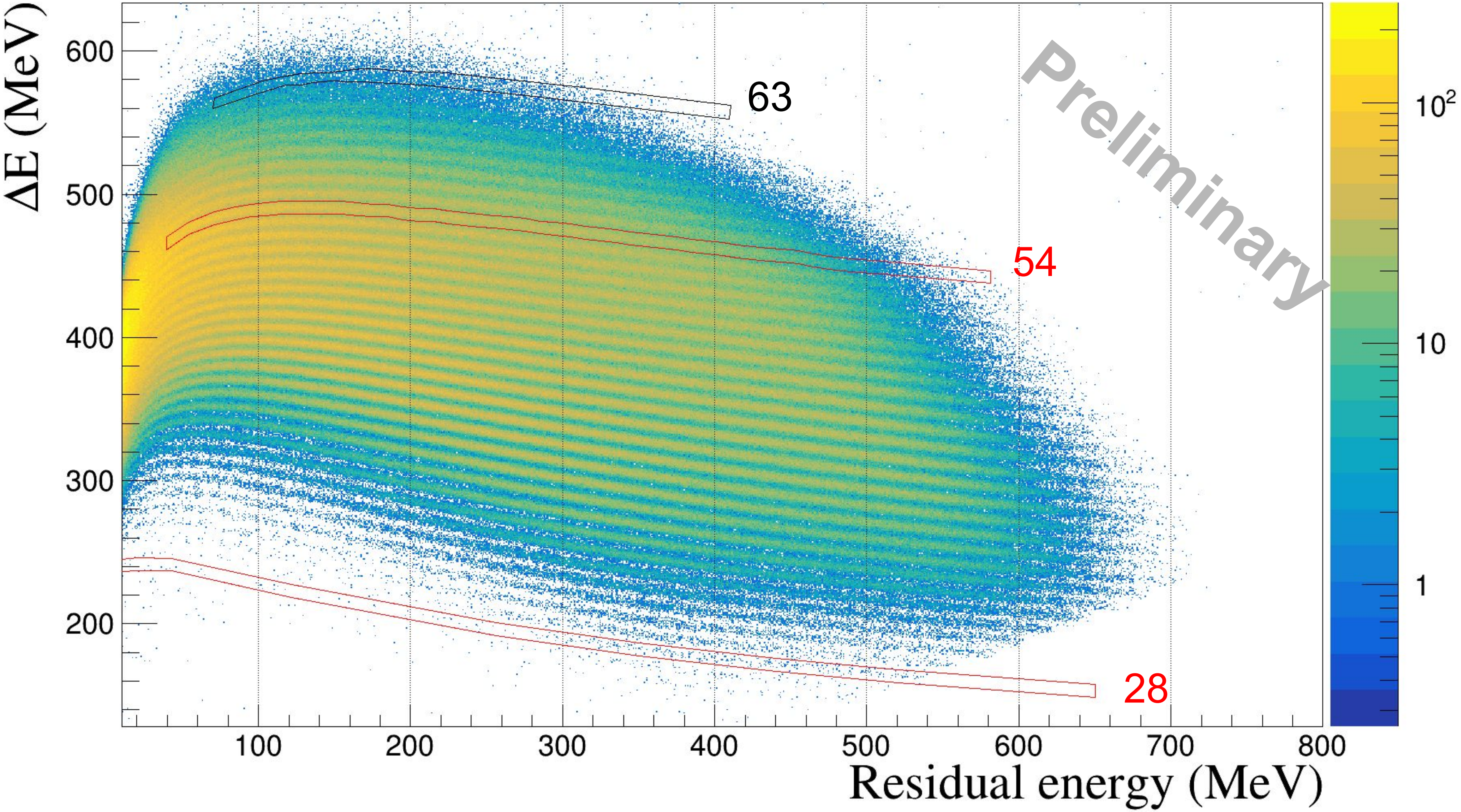


Fission fragment identification: A



Average resolution of **ΔA/A** ~ 1/234 = **4.27 ‰**

Fission fragment identification: Z



Fission fragment identification: Z

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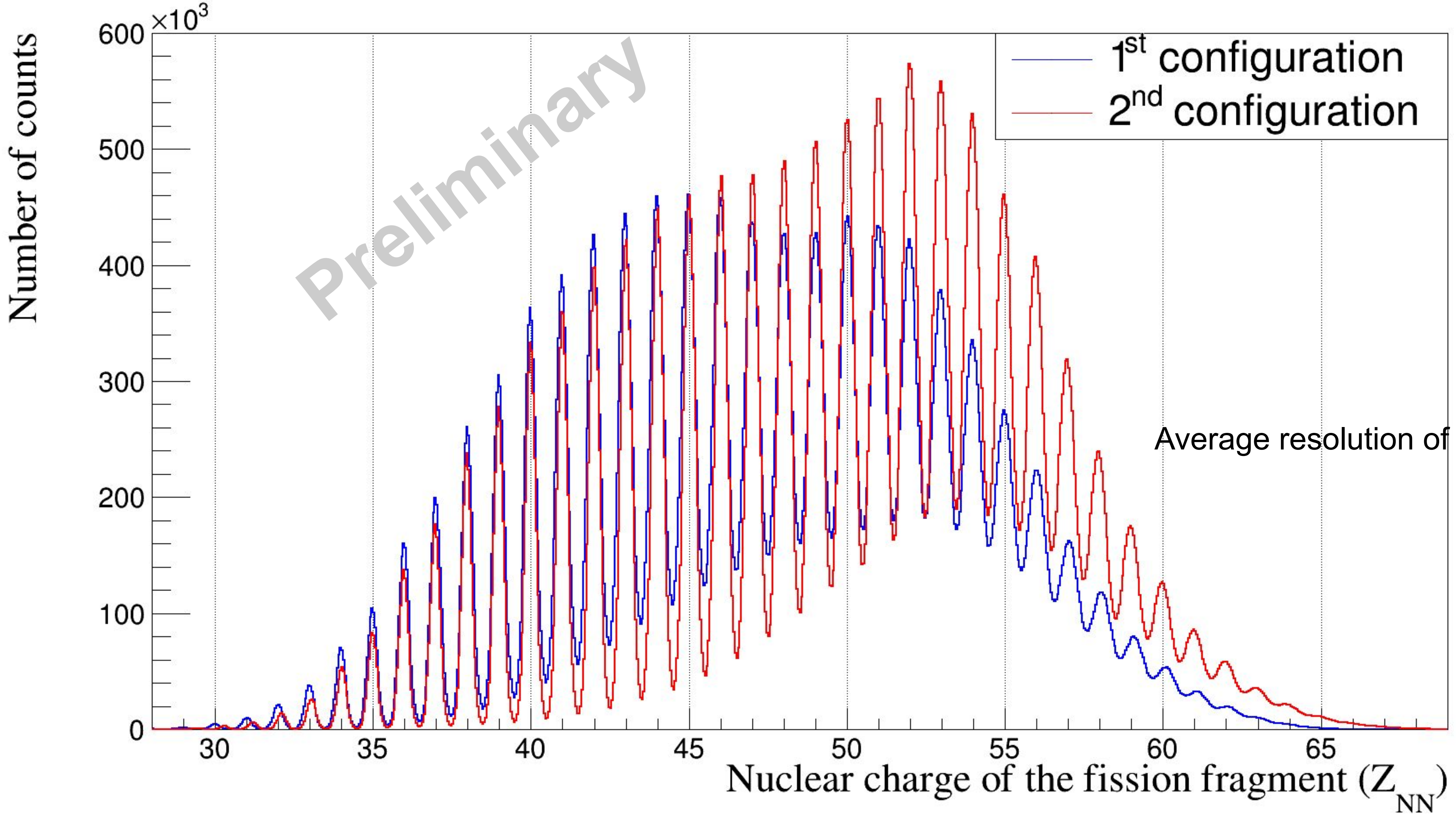
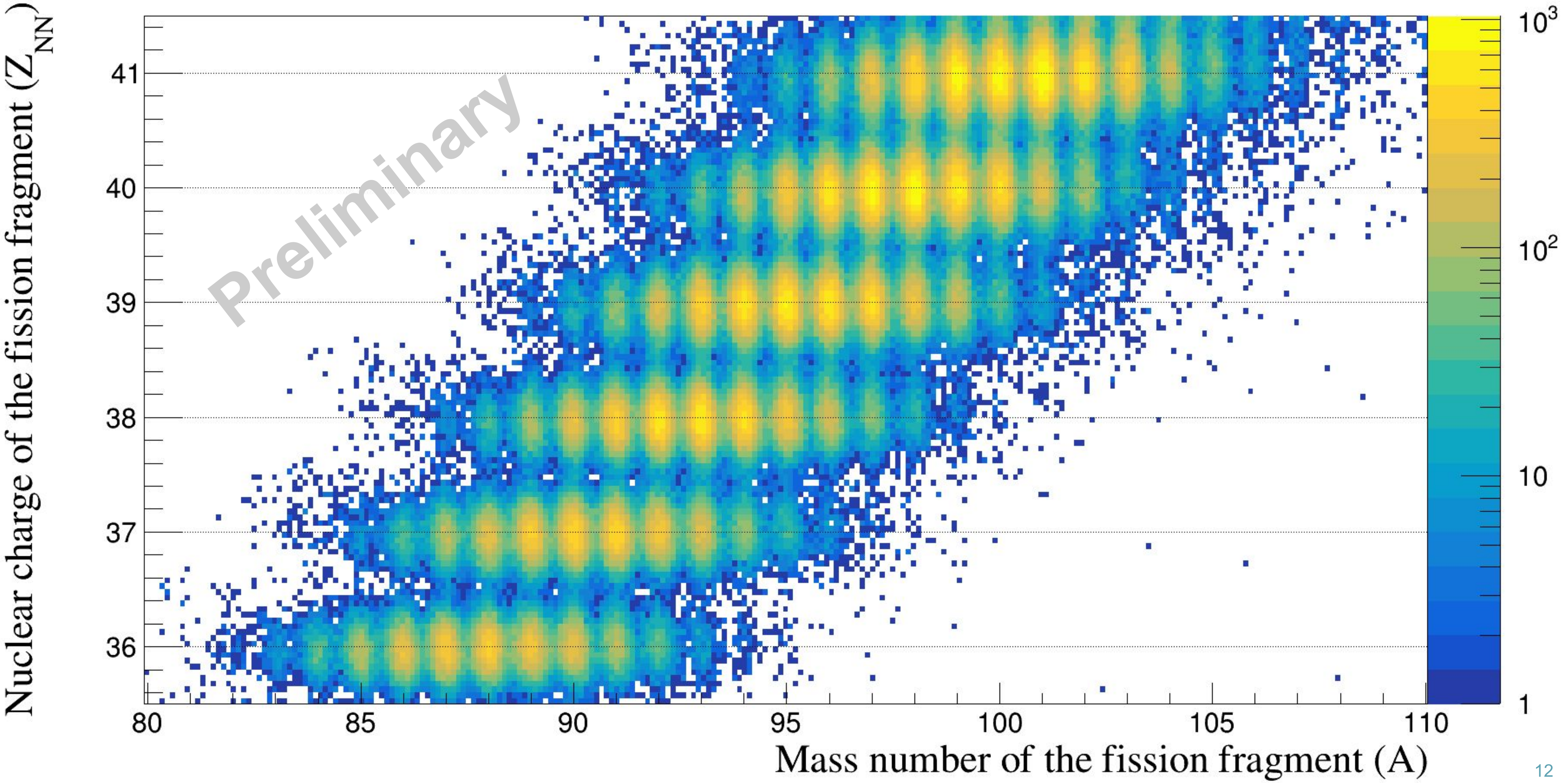


Average resolution of **ΔZ/Z ~** 1/86 = **1.16 %**

Fission fragment isotopic identification



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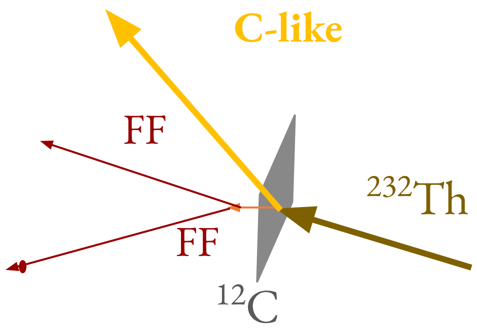

Experimental setup

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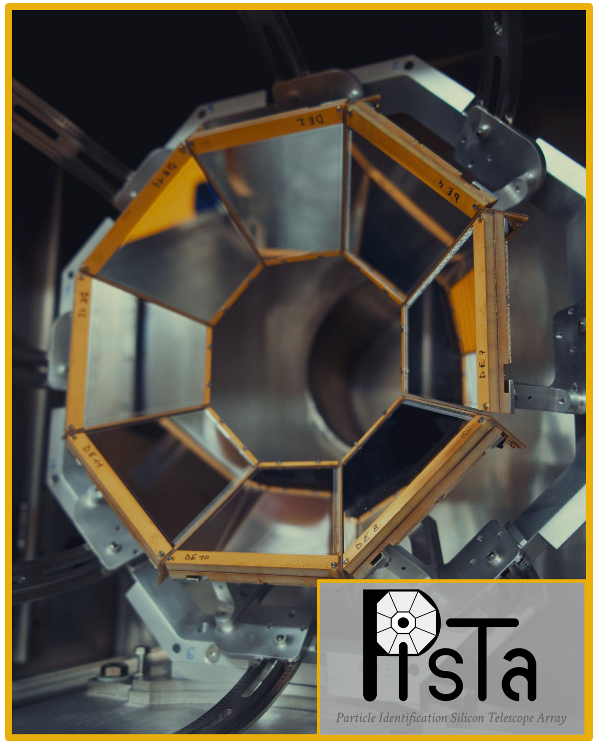
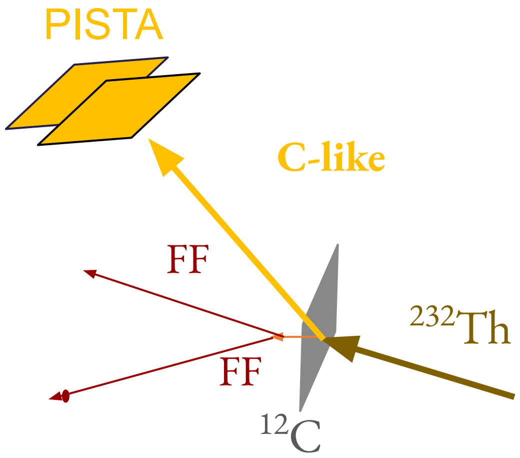
Carbon-like particle identified by **PISTA**: **8 ΔE - E segmented silicon telescopes** => (**E, θ**)

Bégué–Guillou, et al. (2026). Performance of the Particle-Identification Silicon-Telescope Array coupled with the VAMOS++ magnetic spectrometer. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1090, 171671.





PISTA: Entrance channel information

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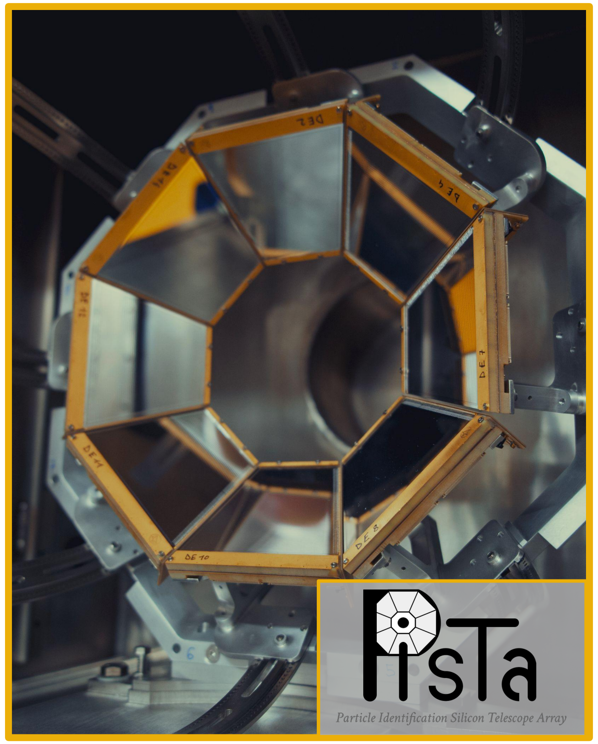
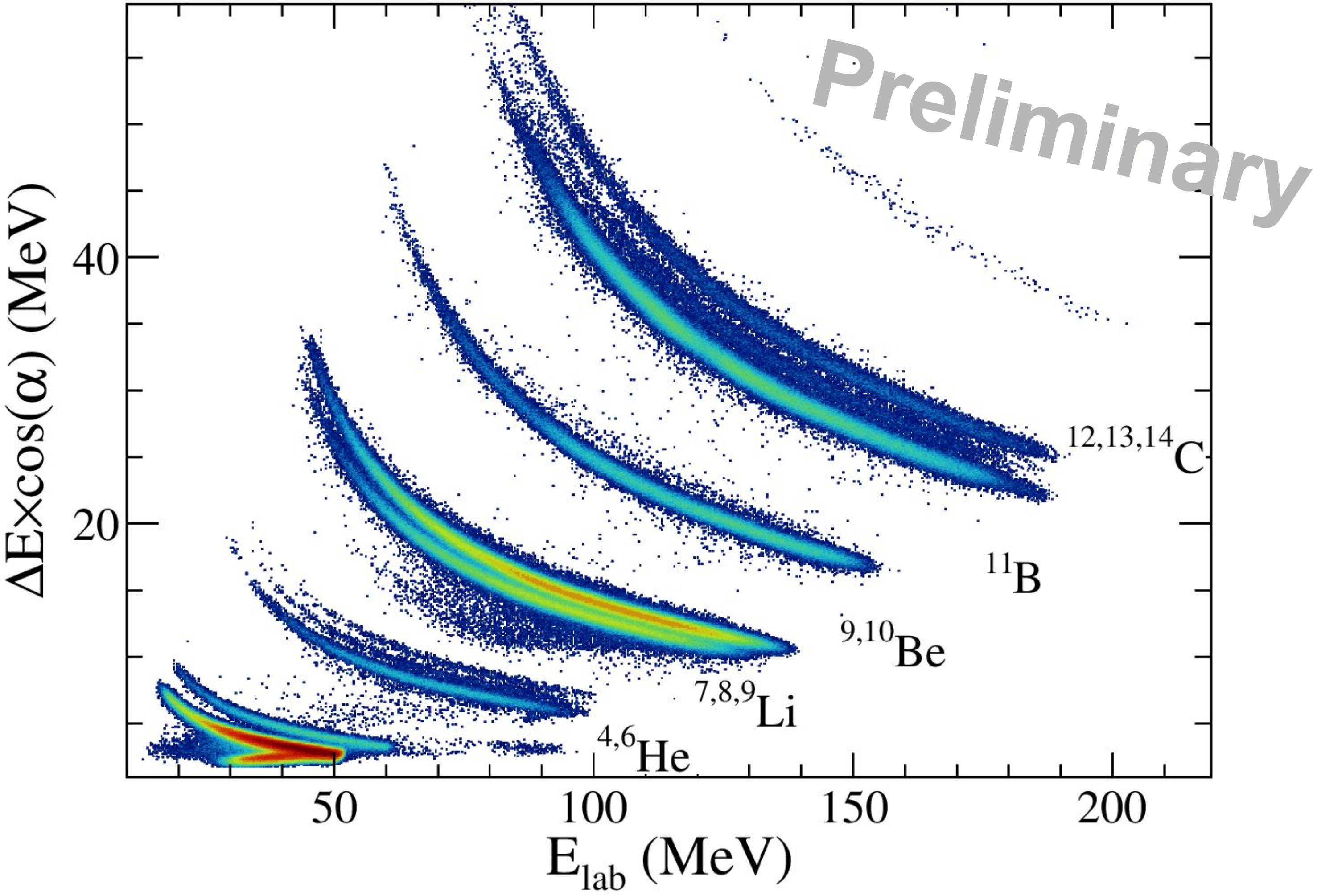
1) What is the fissioning system that was formed (Z,A)





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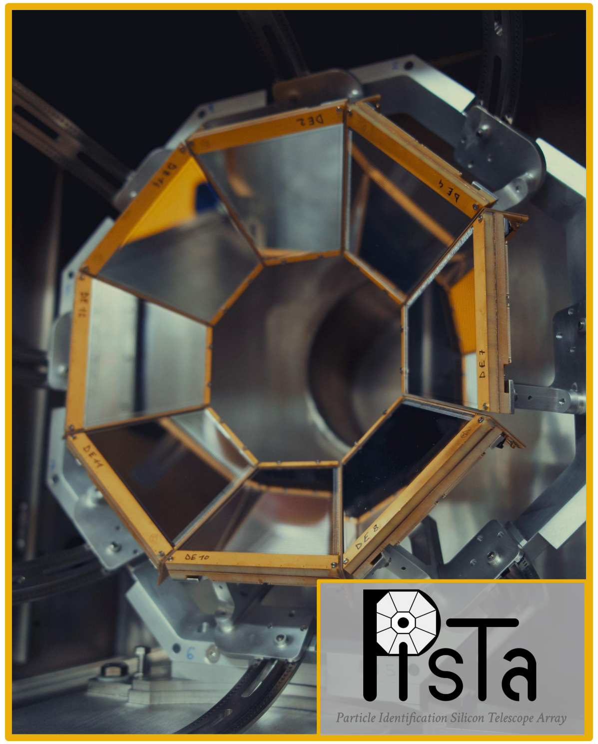

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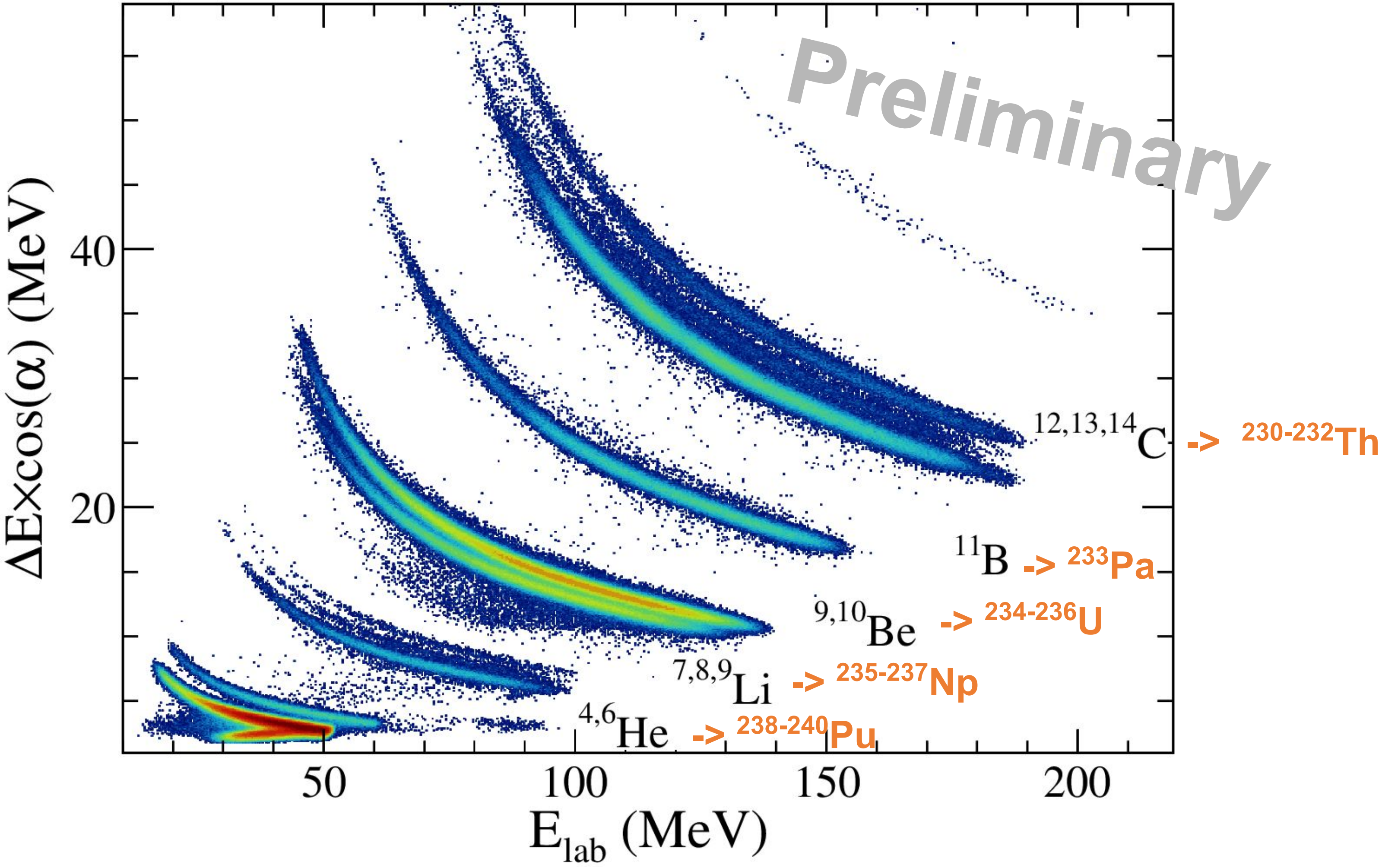

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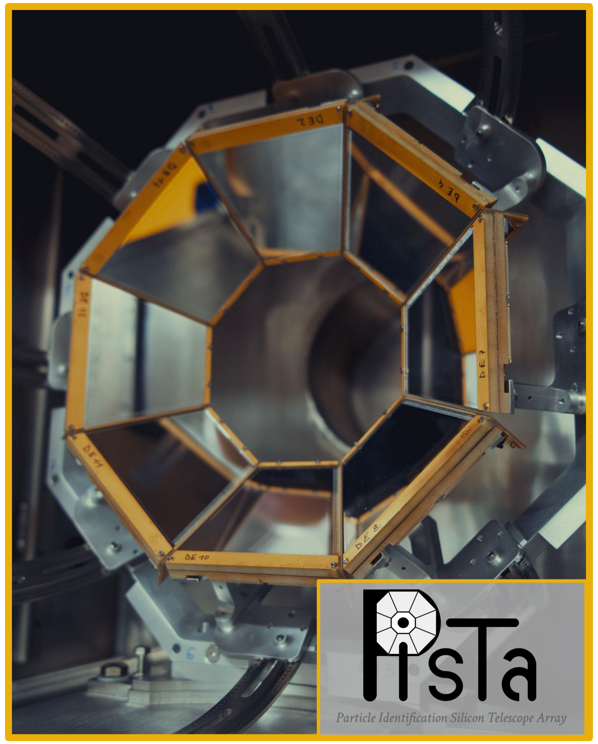
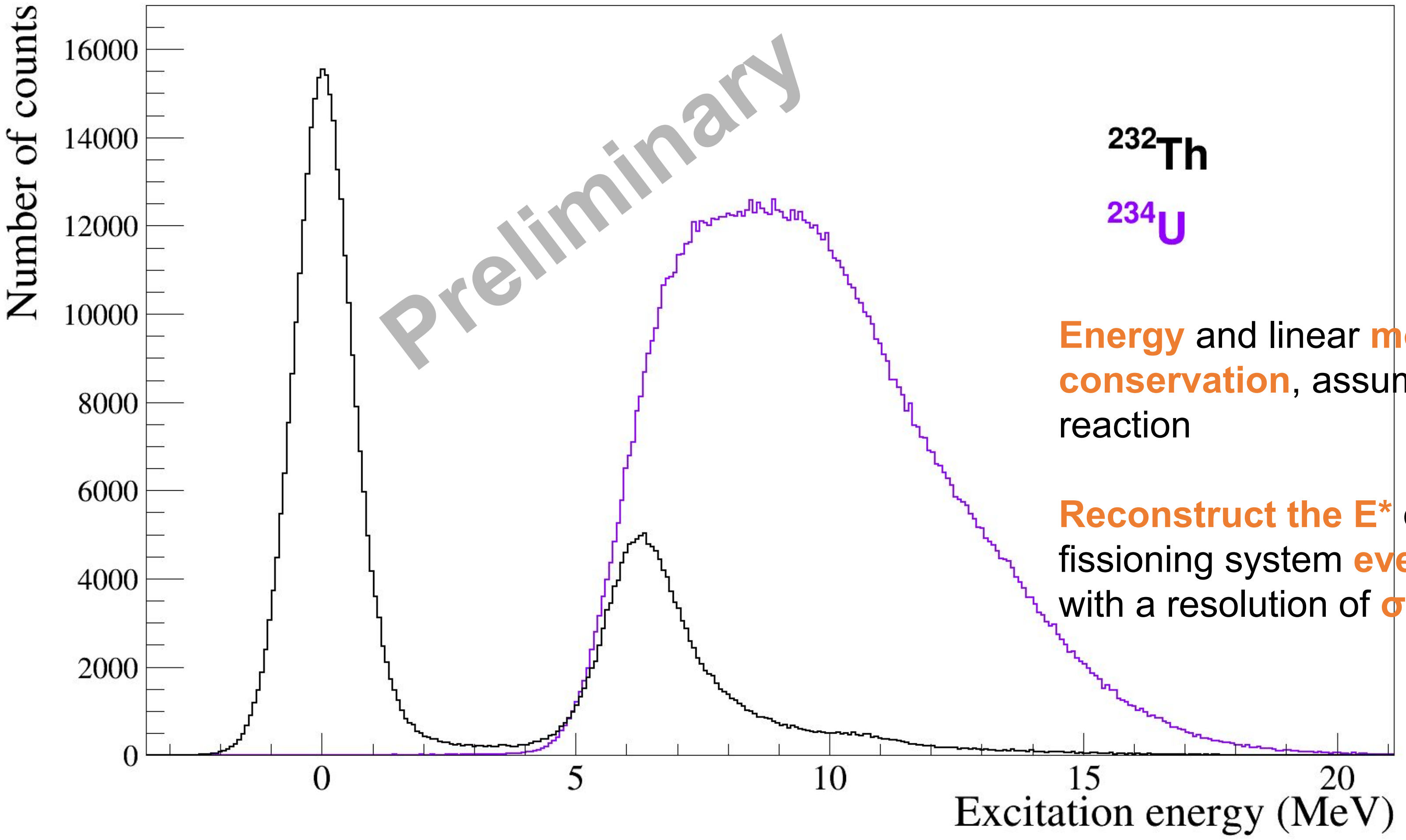
1) What is the fissioning system that was formed (Z,A)
2) **What is the excitation energy (E*)**

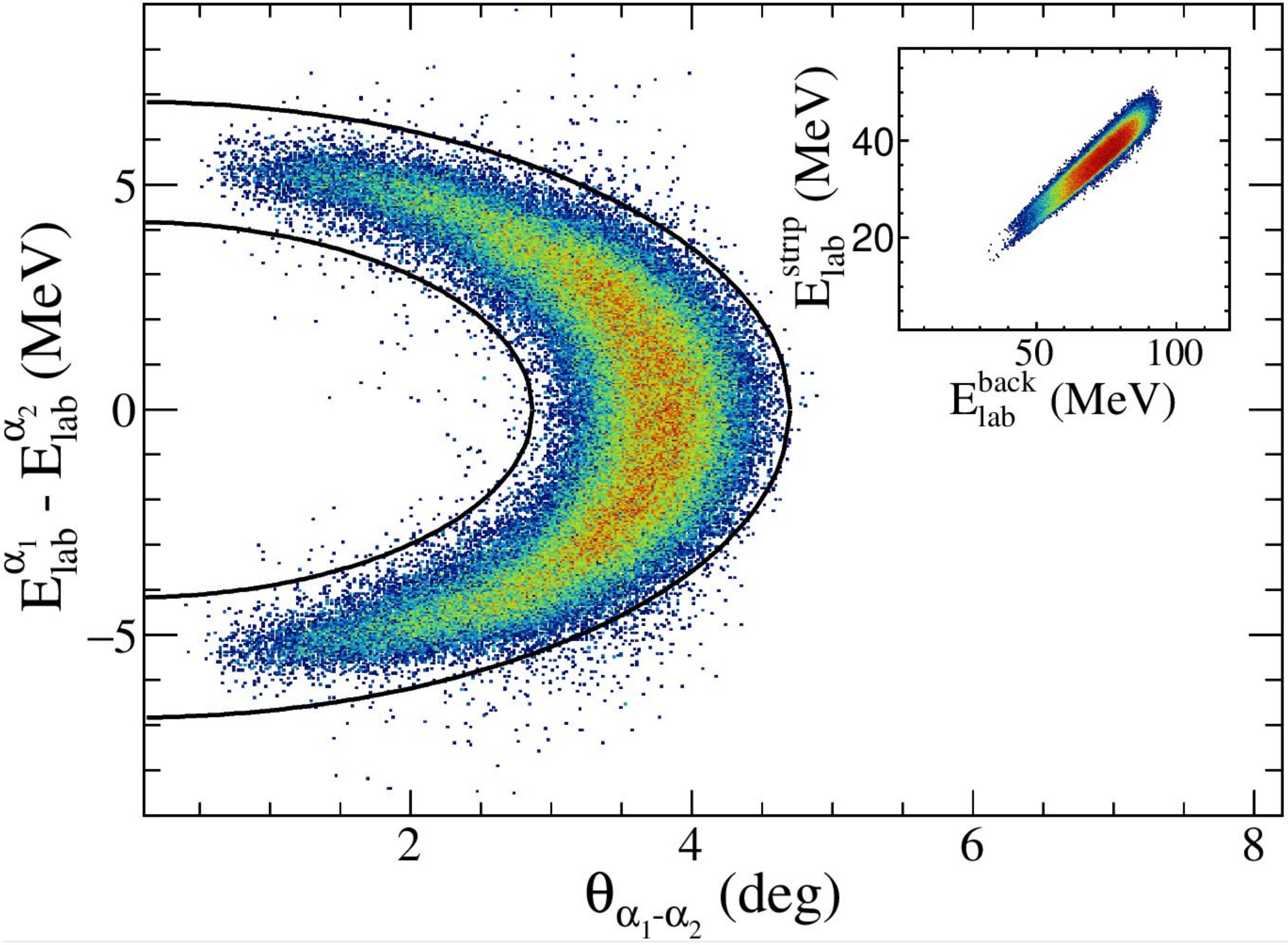




Energy and linear **momentum conservation**, assuming binary reaction

Reconstruct the E* of the fissioning system **event-by-event** with a resolution of **σ ~ 500 keV**

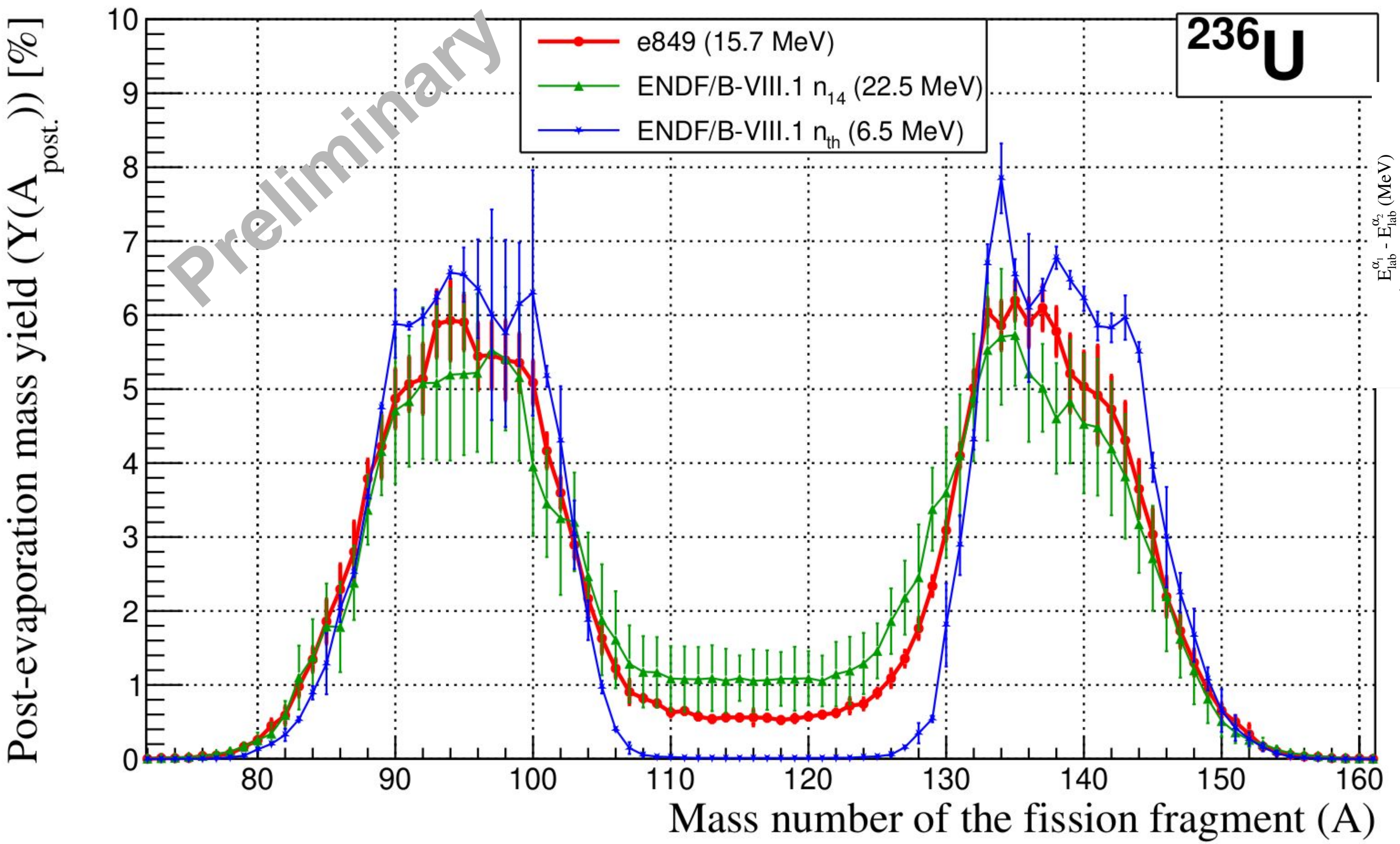
Choose fissioning system: ^{236}U

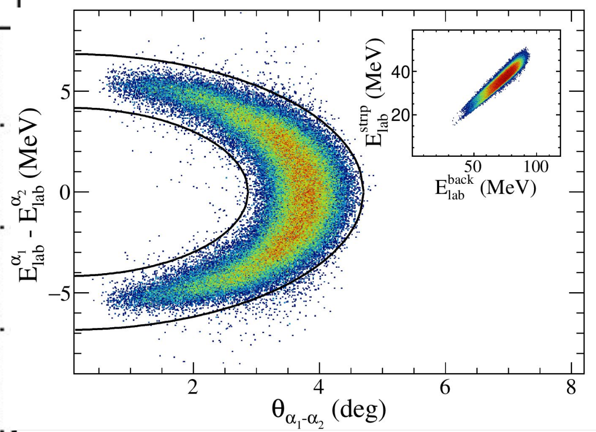


^{8}Be -> 2-α

Surrogate reaction to **neutron-induced** fission of ^{235}U

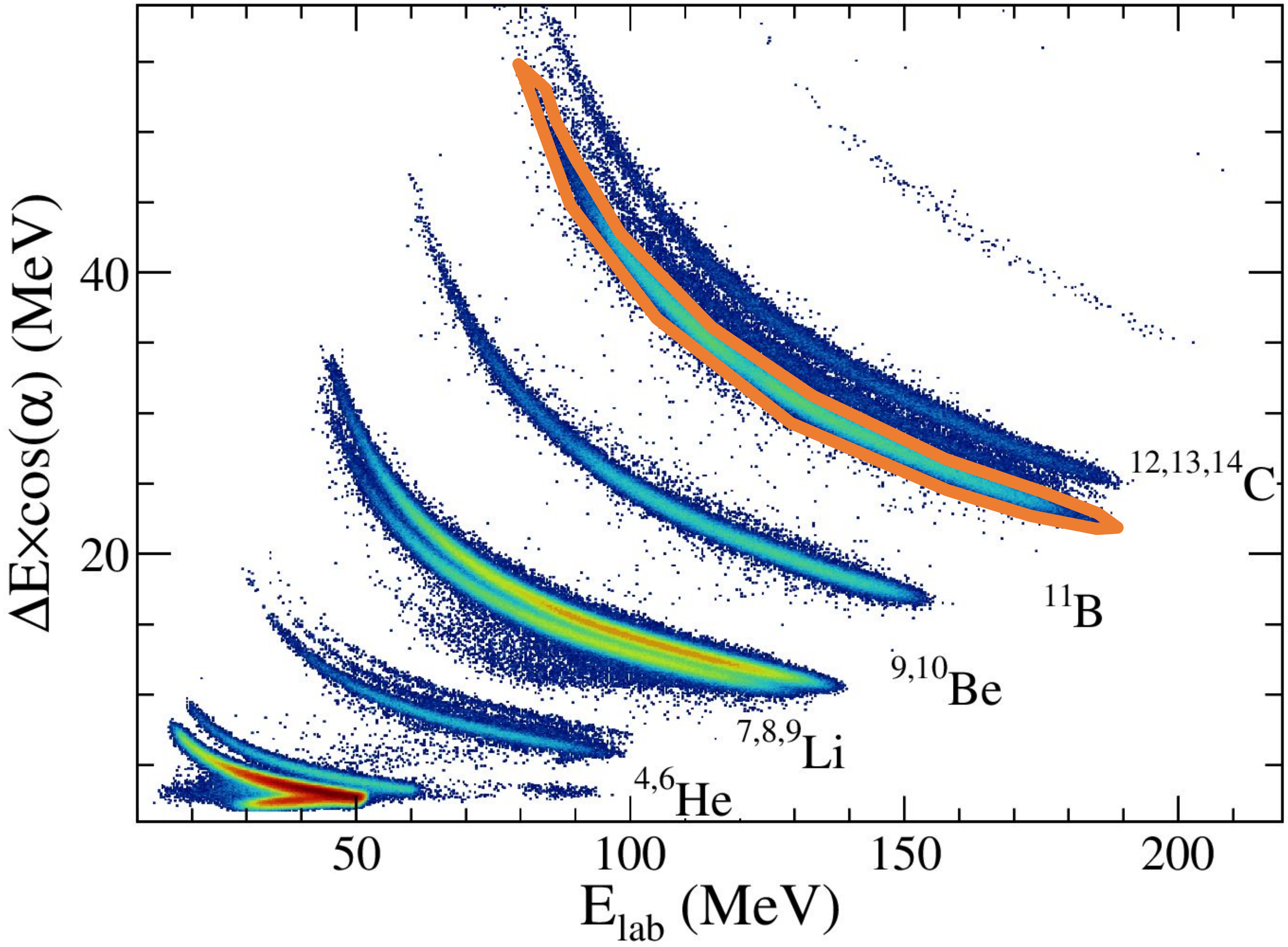
Mass yields of ^{236}U





e849 data lies between **thermal neutron** induced fission **(6.5 MeV)** and **fast neutron** induced fission **(22.5 MeV)**

Choose fissioning system: ^{232}Th



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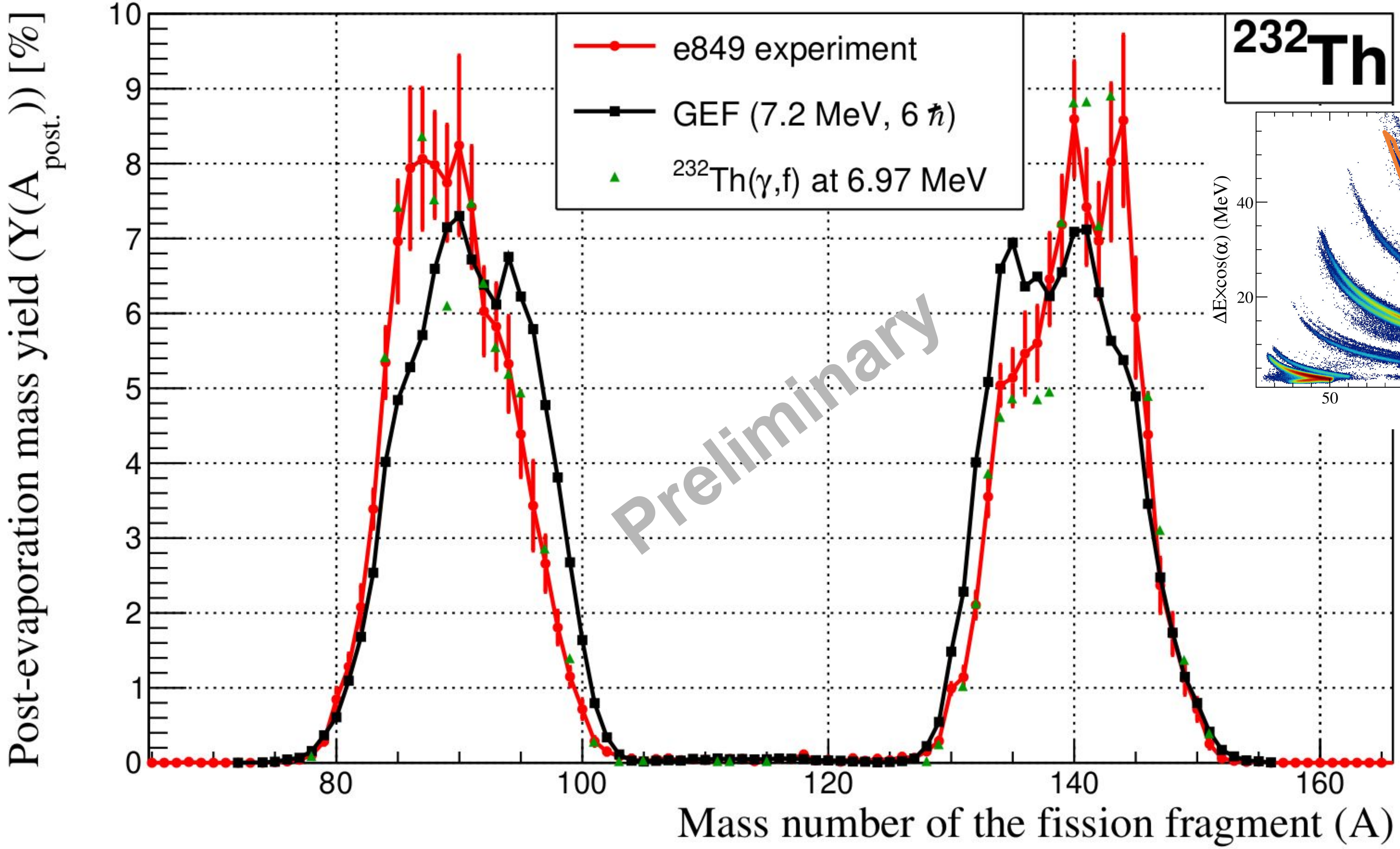
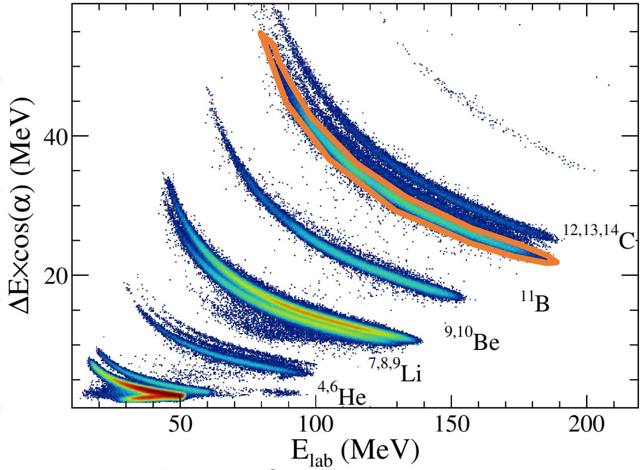
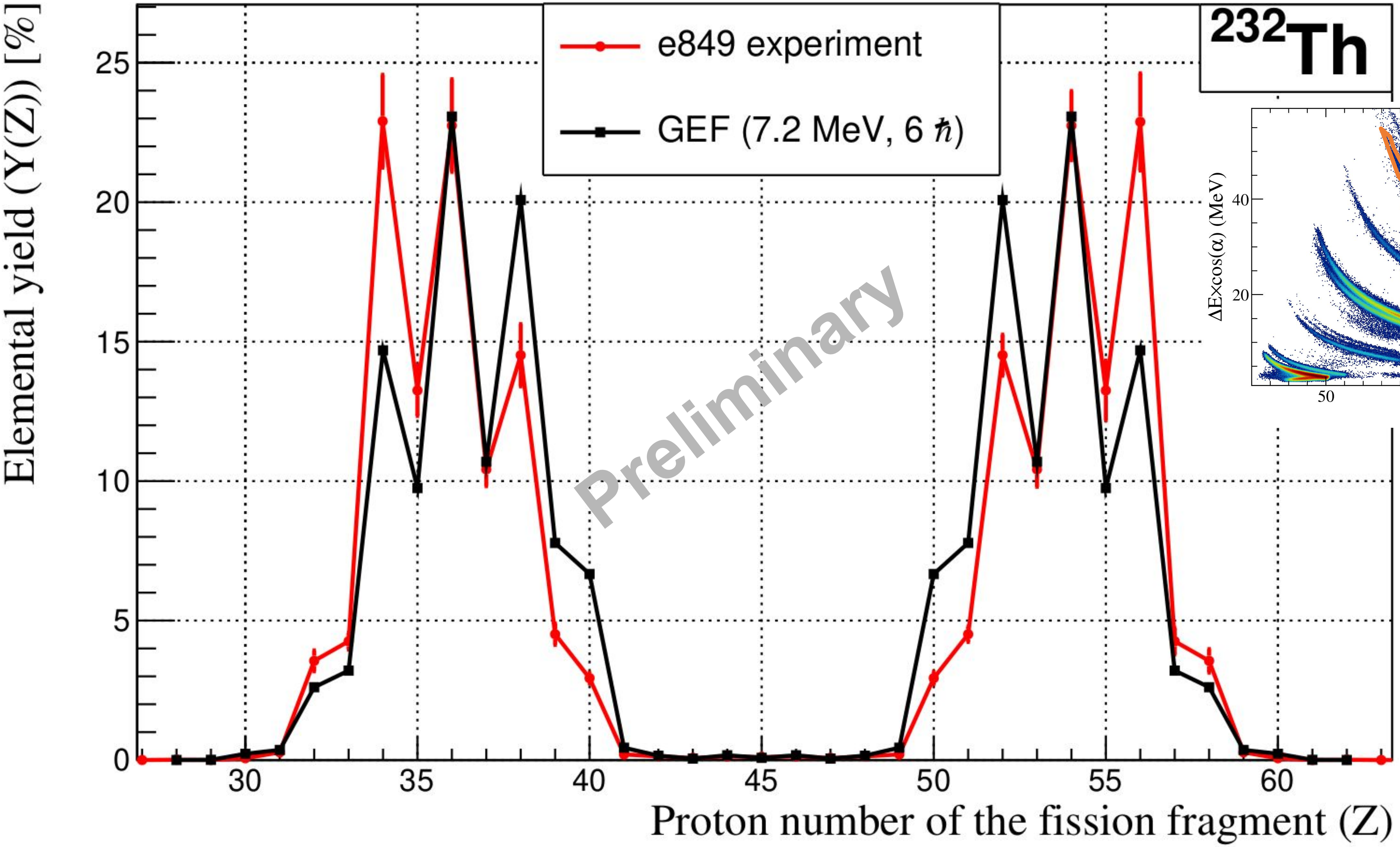


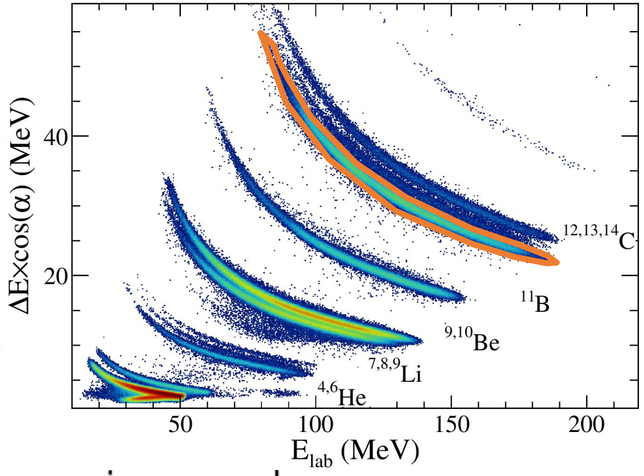


Experimental result is more asymmetric than the **GEF prediction**

Similar yields than the **results** from **γ-fission**

Elemental yields of ^{232}Th





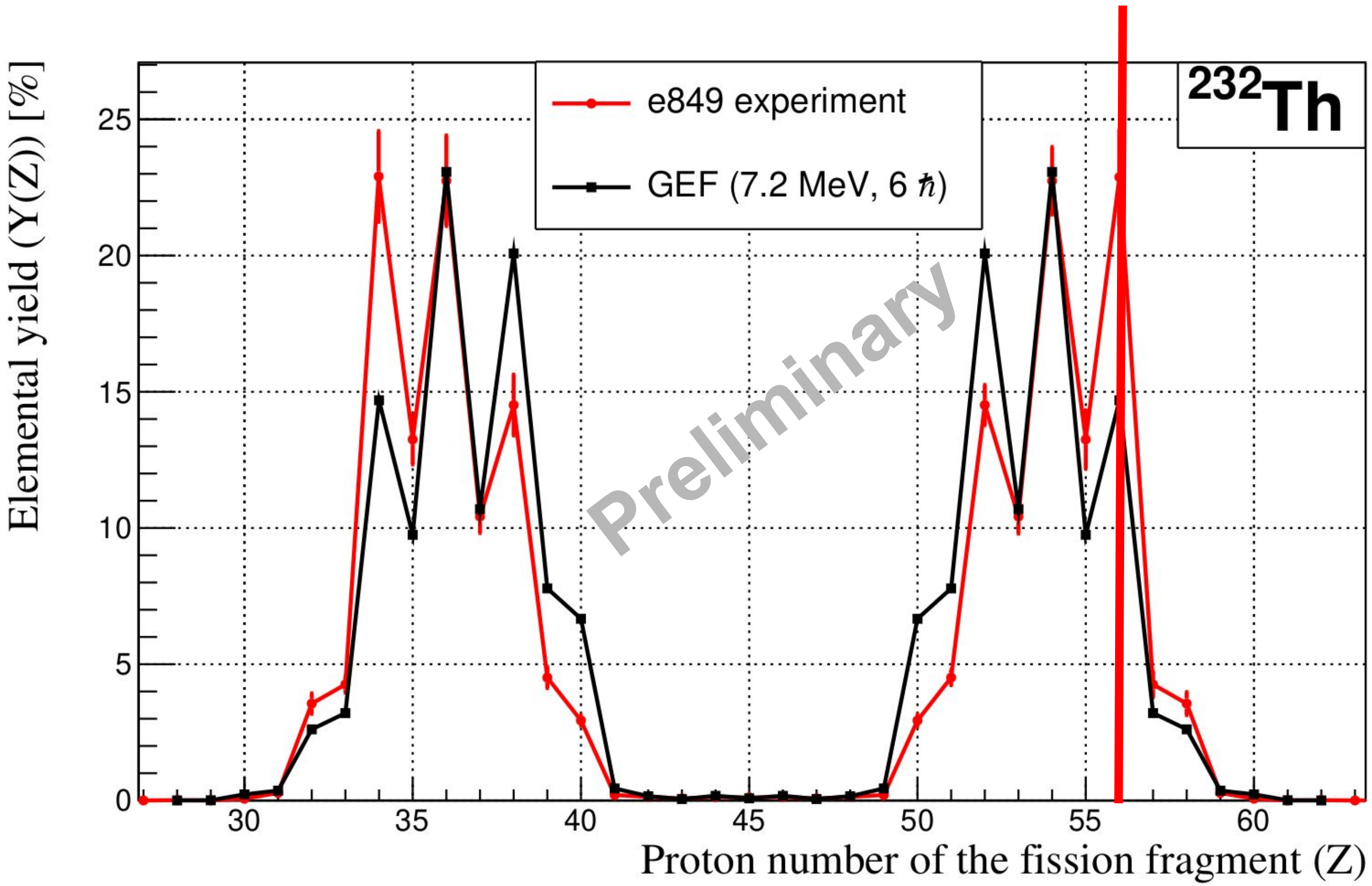
Access **also** to the **nuclear charge (Z)**

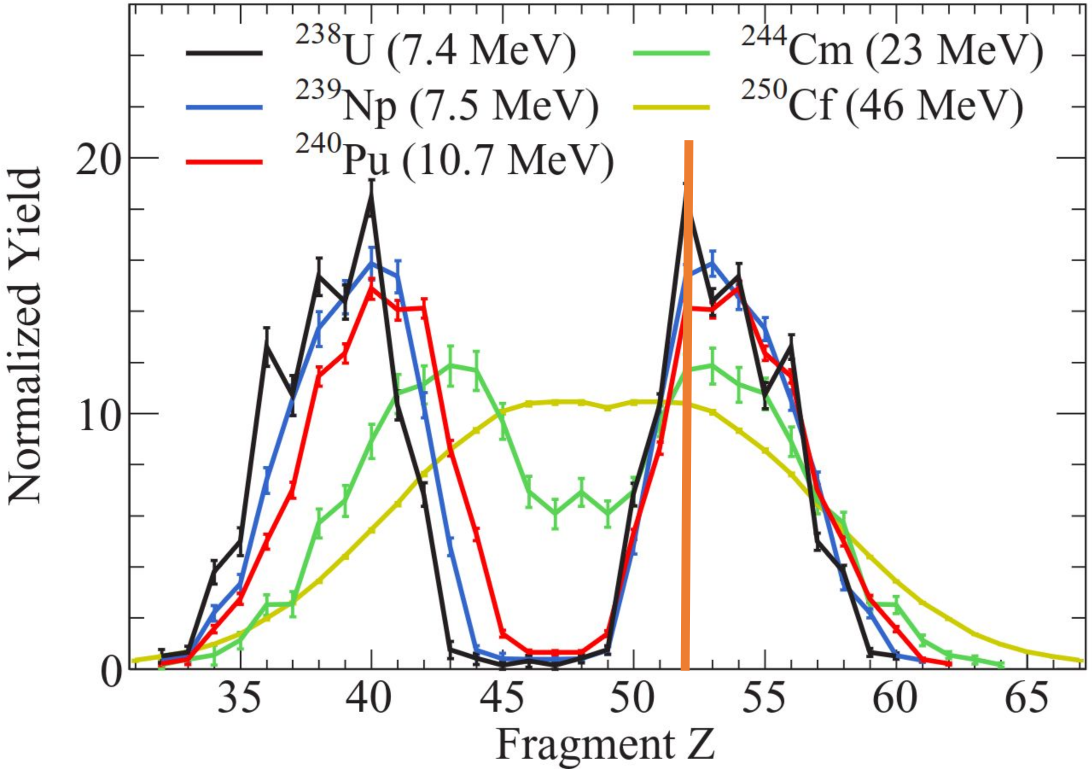
The **elemental** yields predominantly **peak at Z=56**

Elemental yields of ^{232}Th

The yields around ^{238}U peak at Z=52, while the yields of ^{232}Th peak at Z=56

- Another observable related to the **anomaly**
- **What drives** this more stable **proton shell**?





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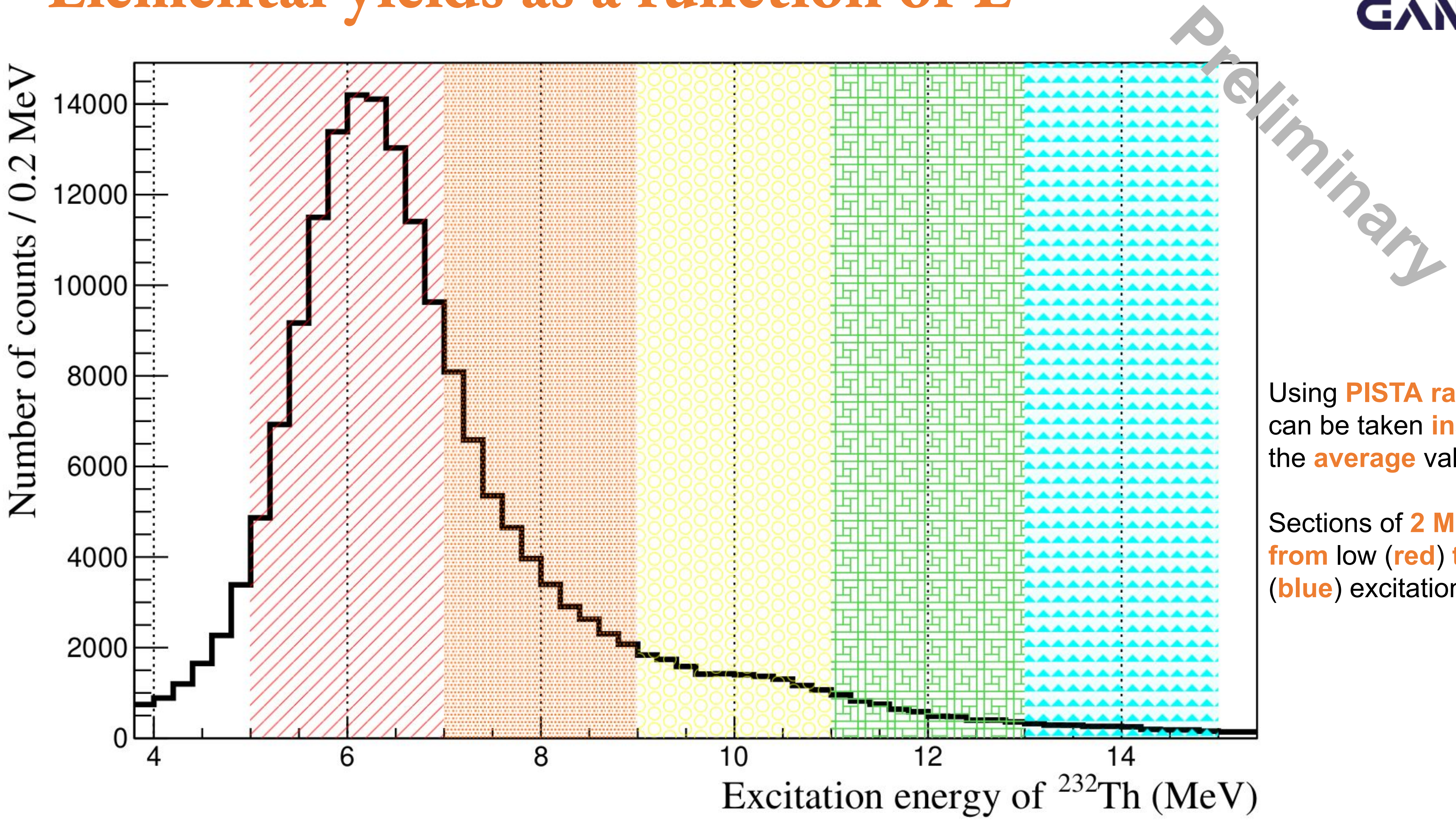
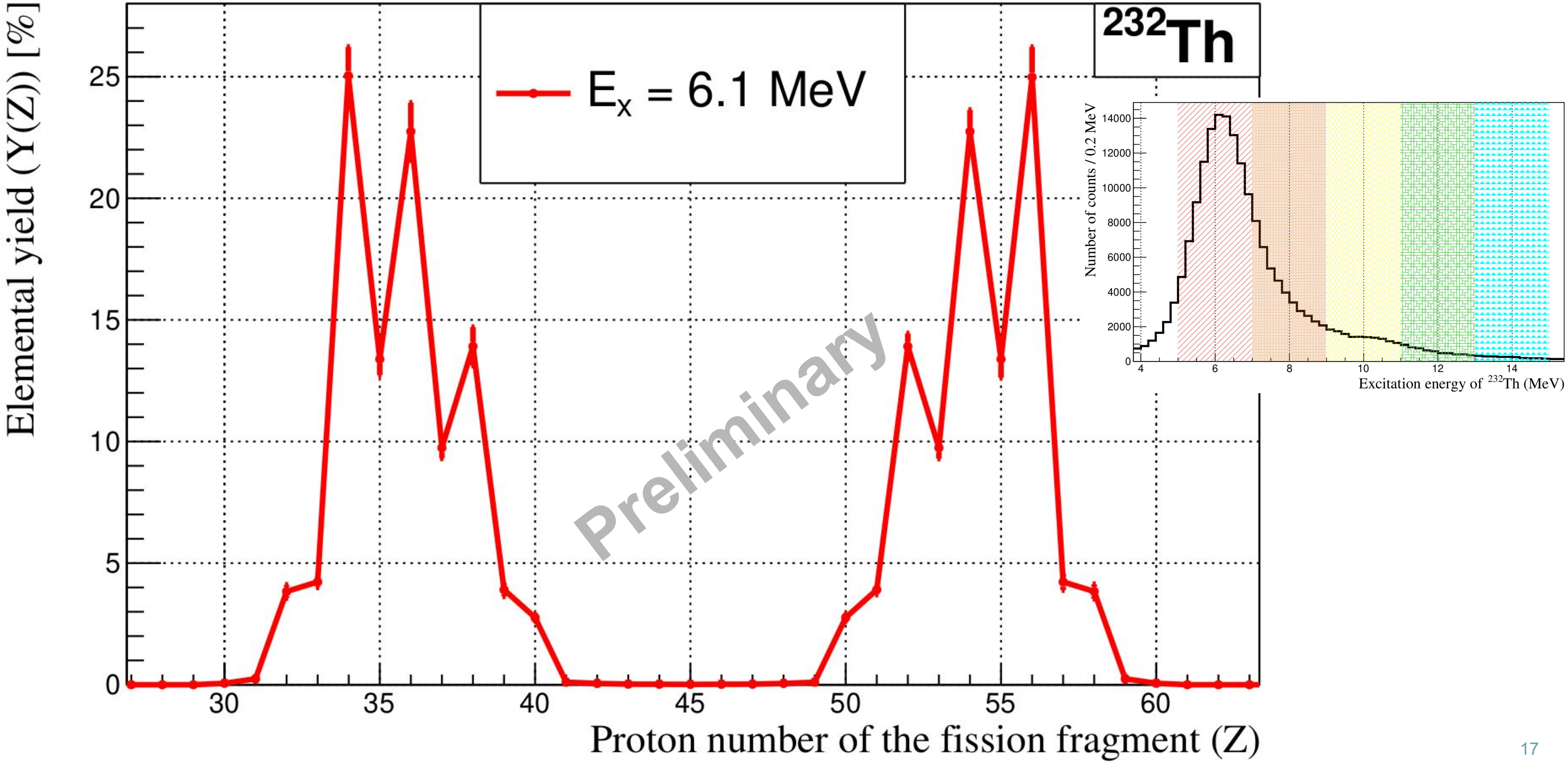
Elemental yields as a function of E*



Using **PISTA ranges of E*** can be taken **instead of** the **average** value

Sections of **2 MeV** going **from** low (**red**) **to** high (**blue**) excitation energy

Elemental yields of ^{232}Th as a function of E*



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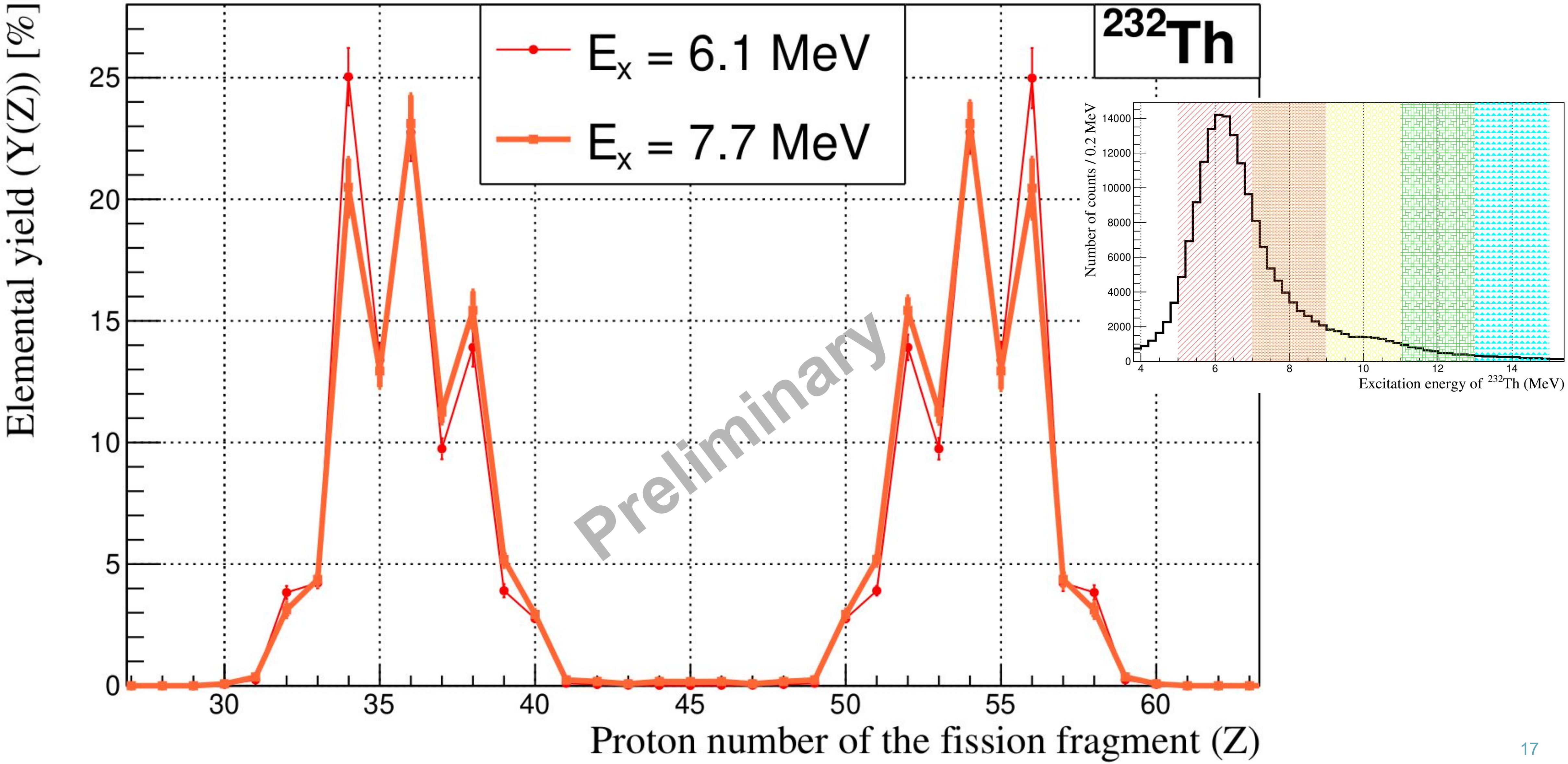

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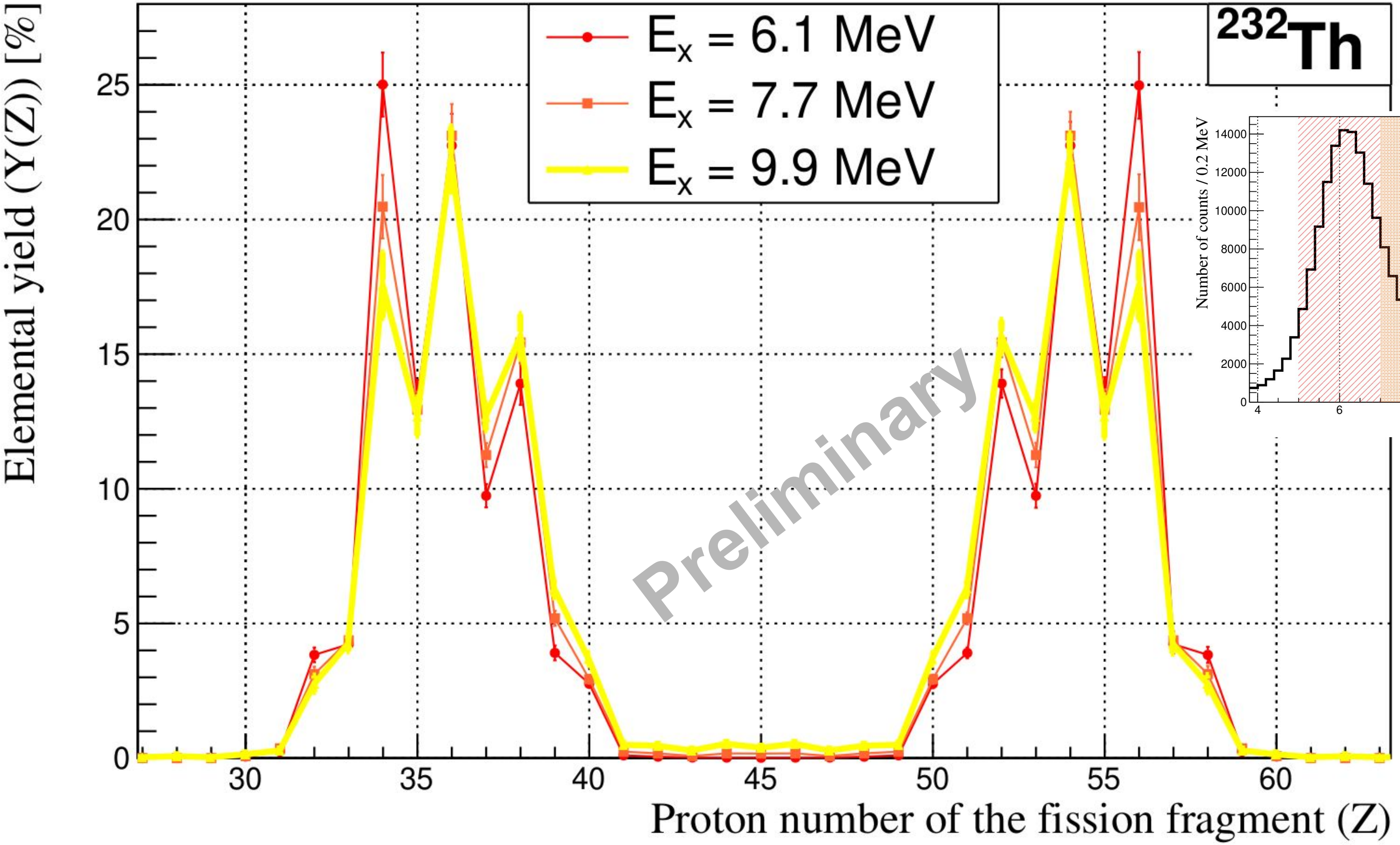

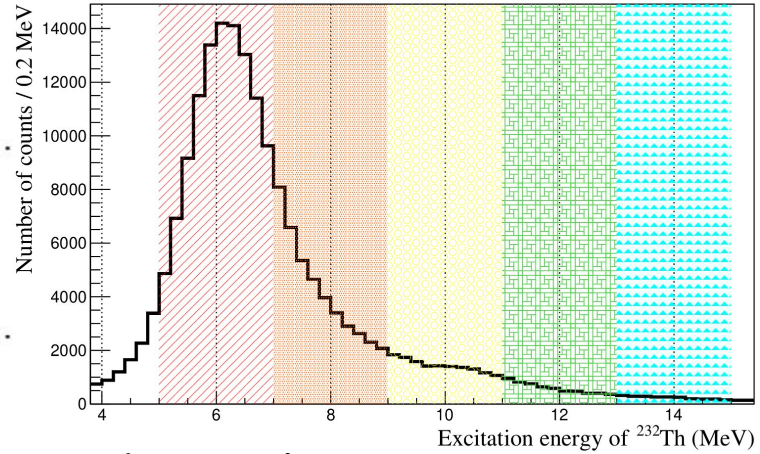

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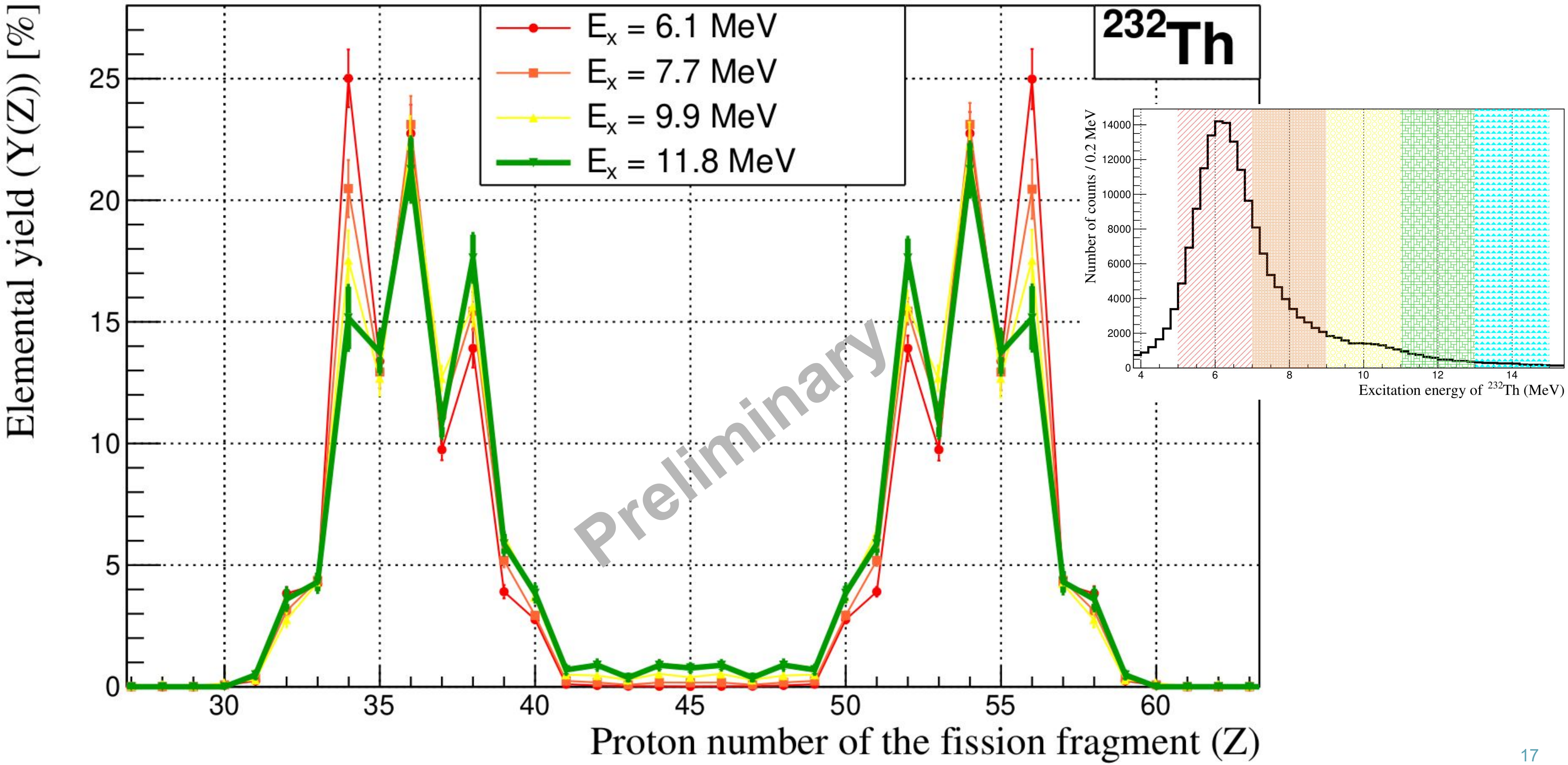

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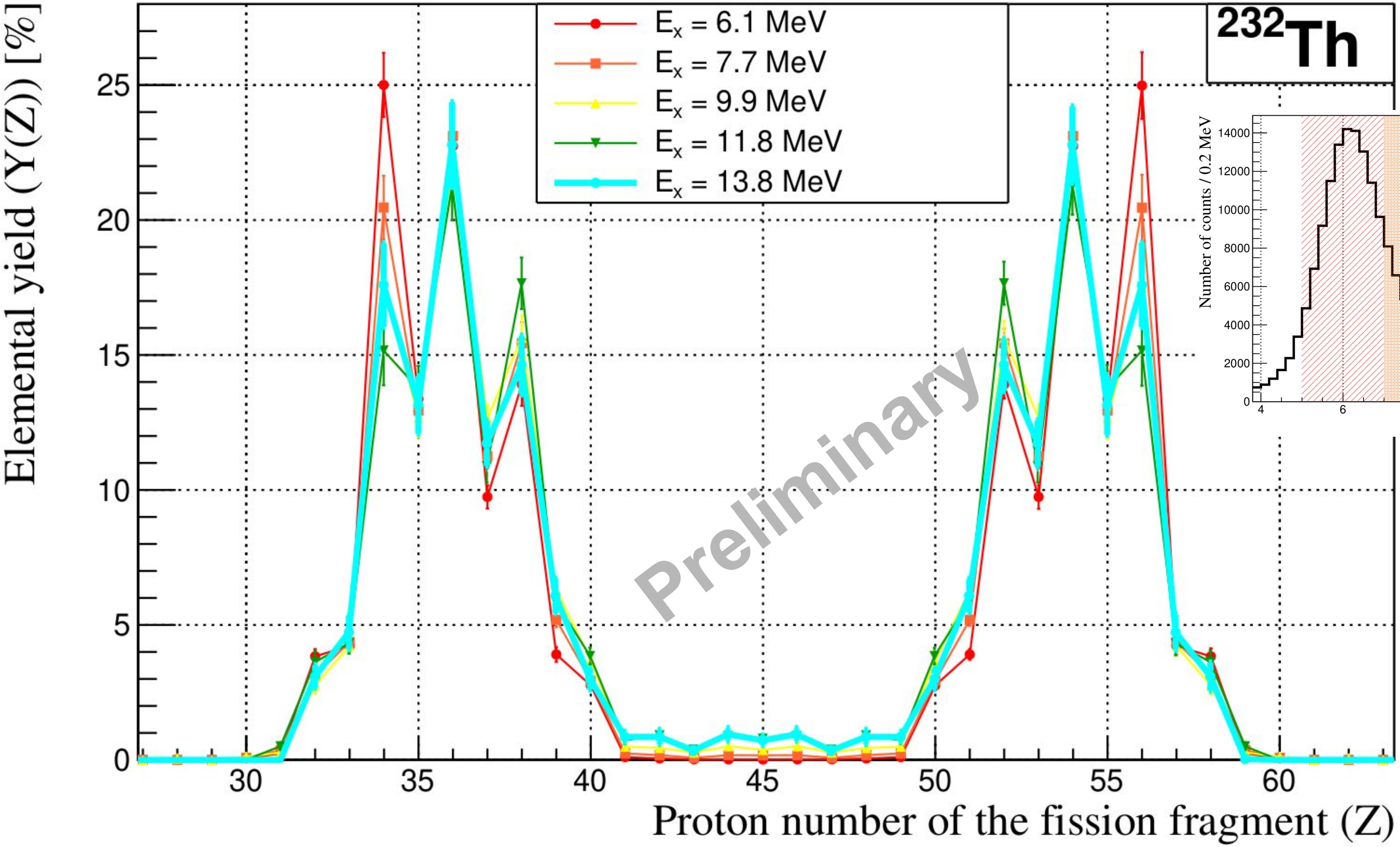

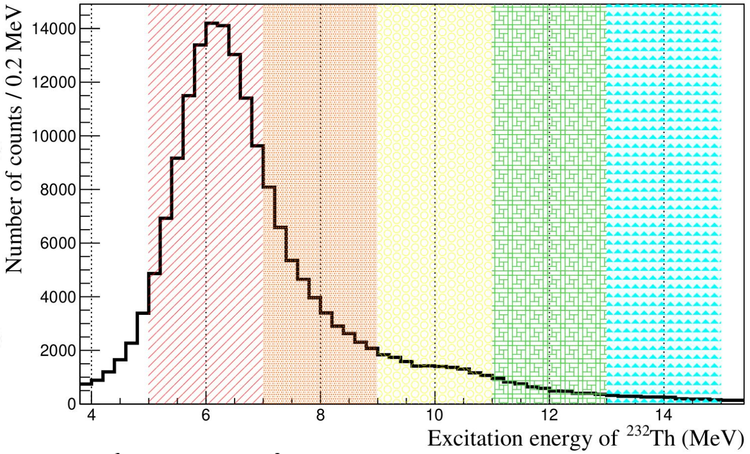

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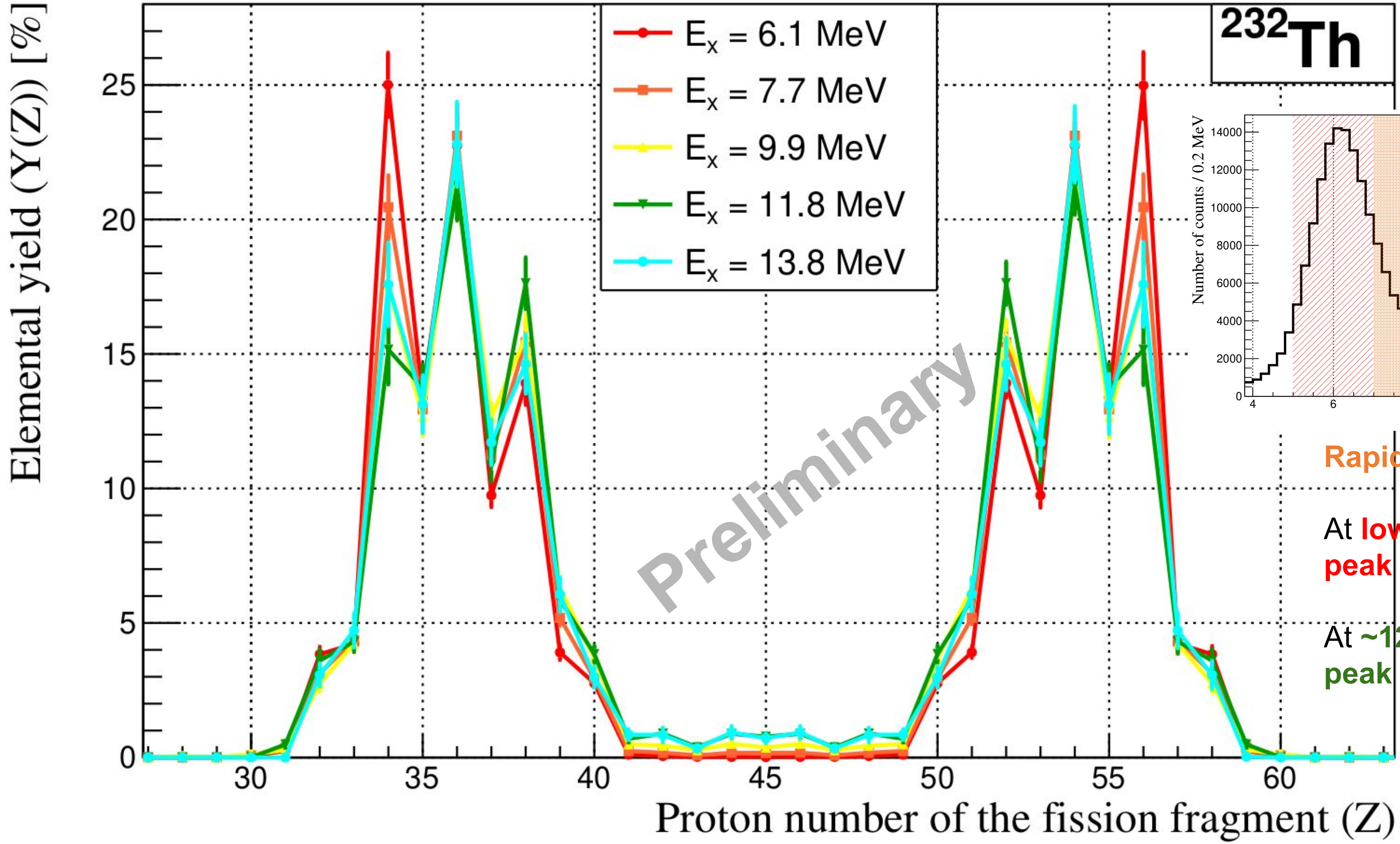
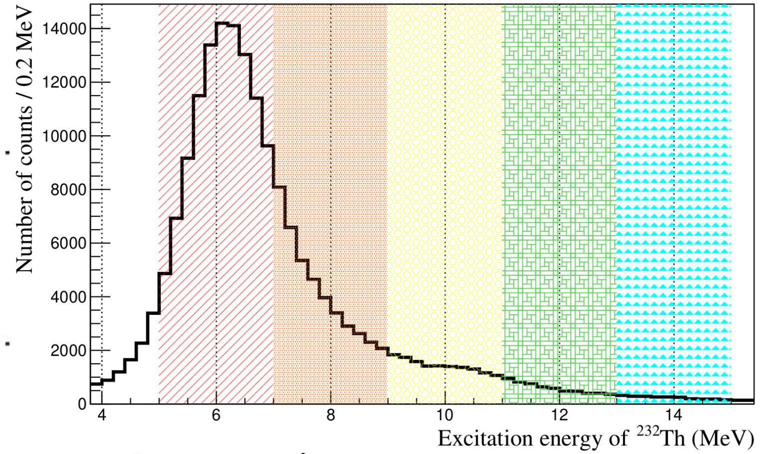


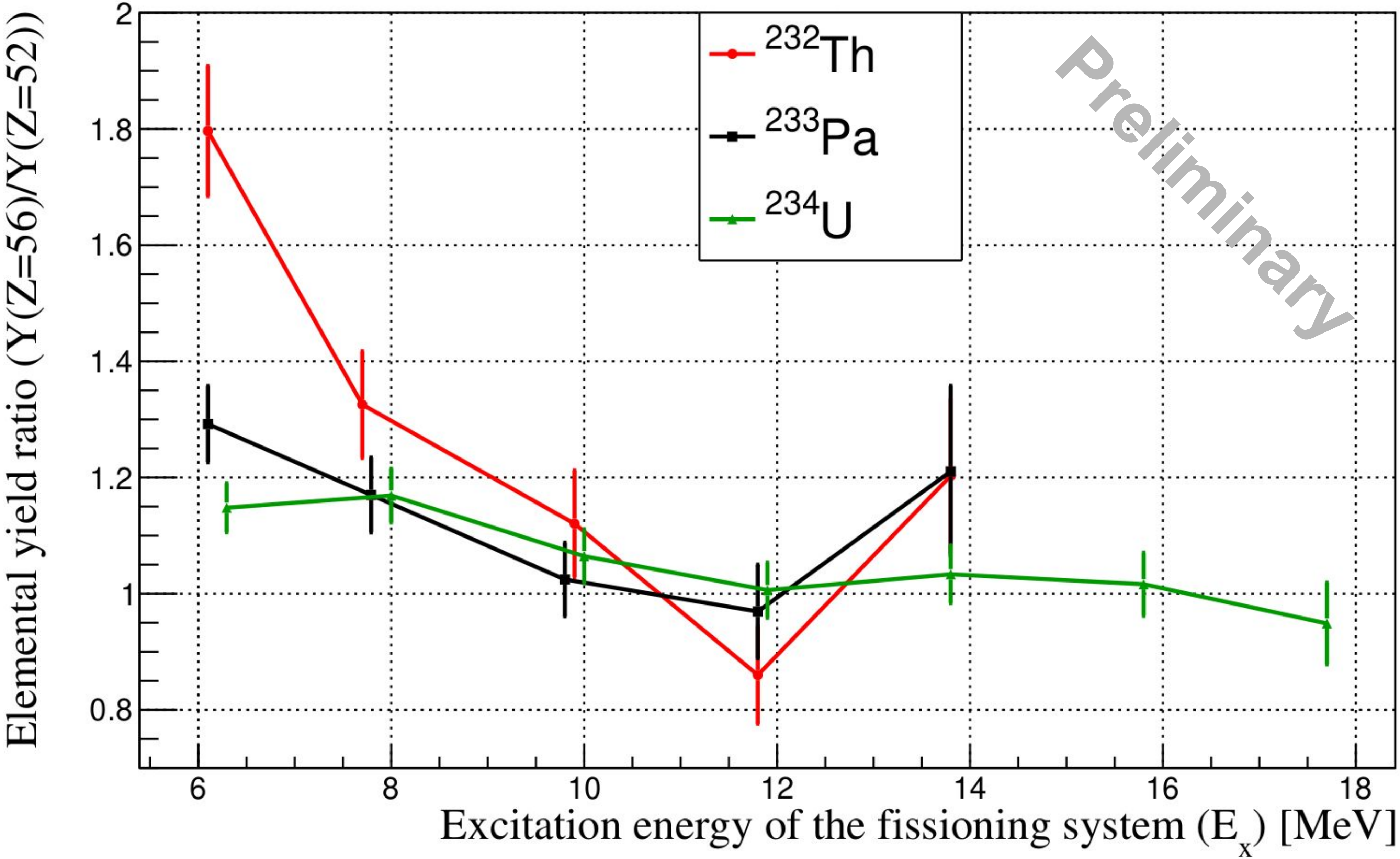


Rapid yields evolution

At **low E*** (red) the yields **peak at Z=56**

At **~12 MeV** the yields **peak more at Z=52**

Elemental yields ratio as a function of E*



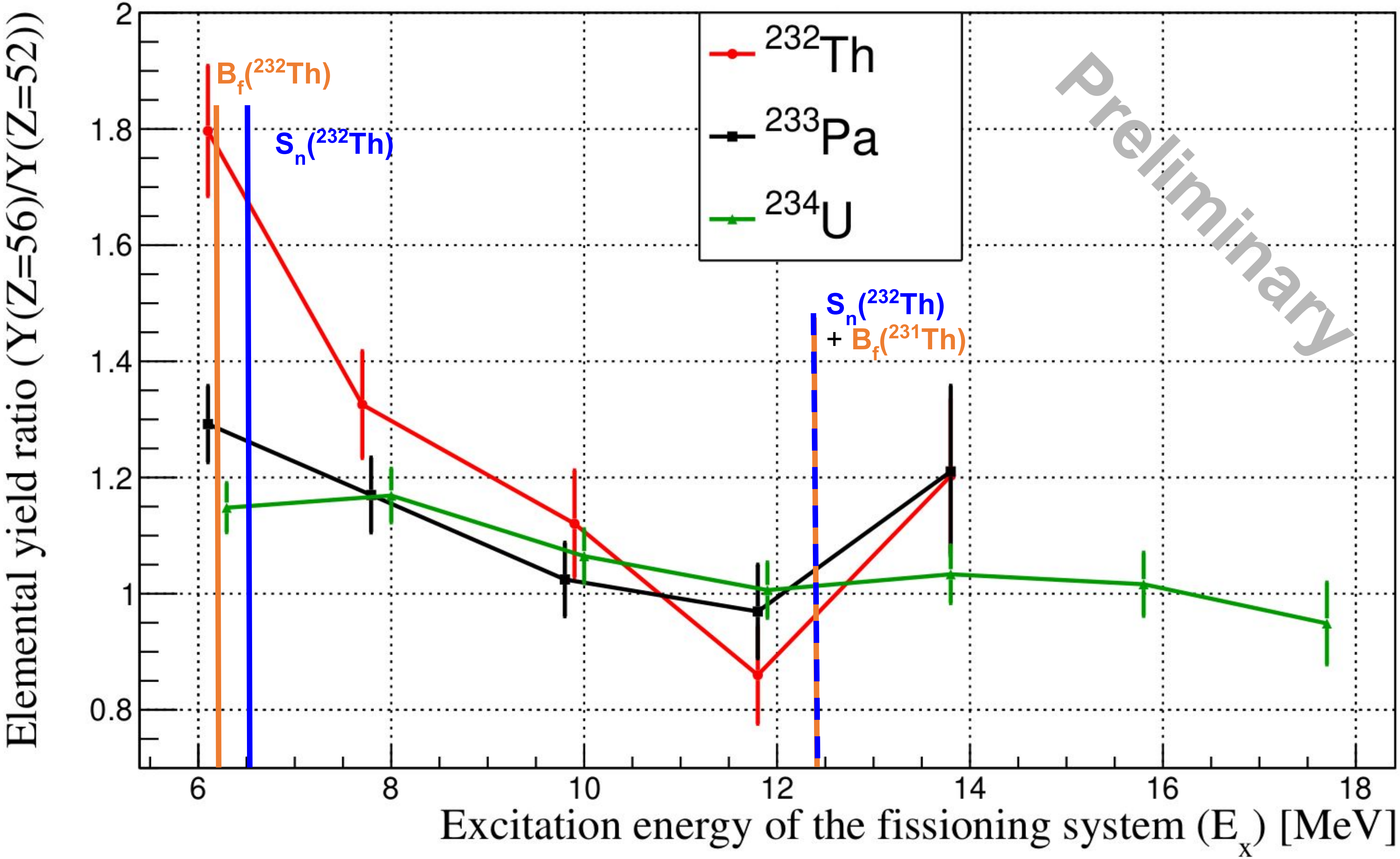
The **evolution** can be **"followed"** using:

Y(Z=56)/Y(Z=52)

^{233}Pa and **^{234}U** show a **similar evolution**:

The **anomaly is** a **more general** behaviour

Elemental yields ratio as a function of E*

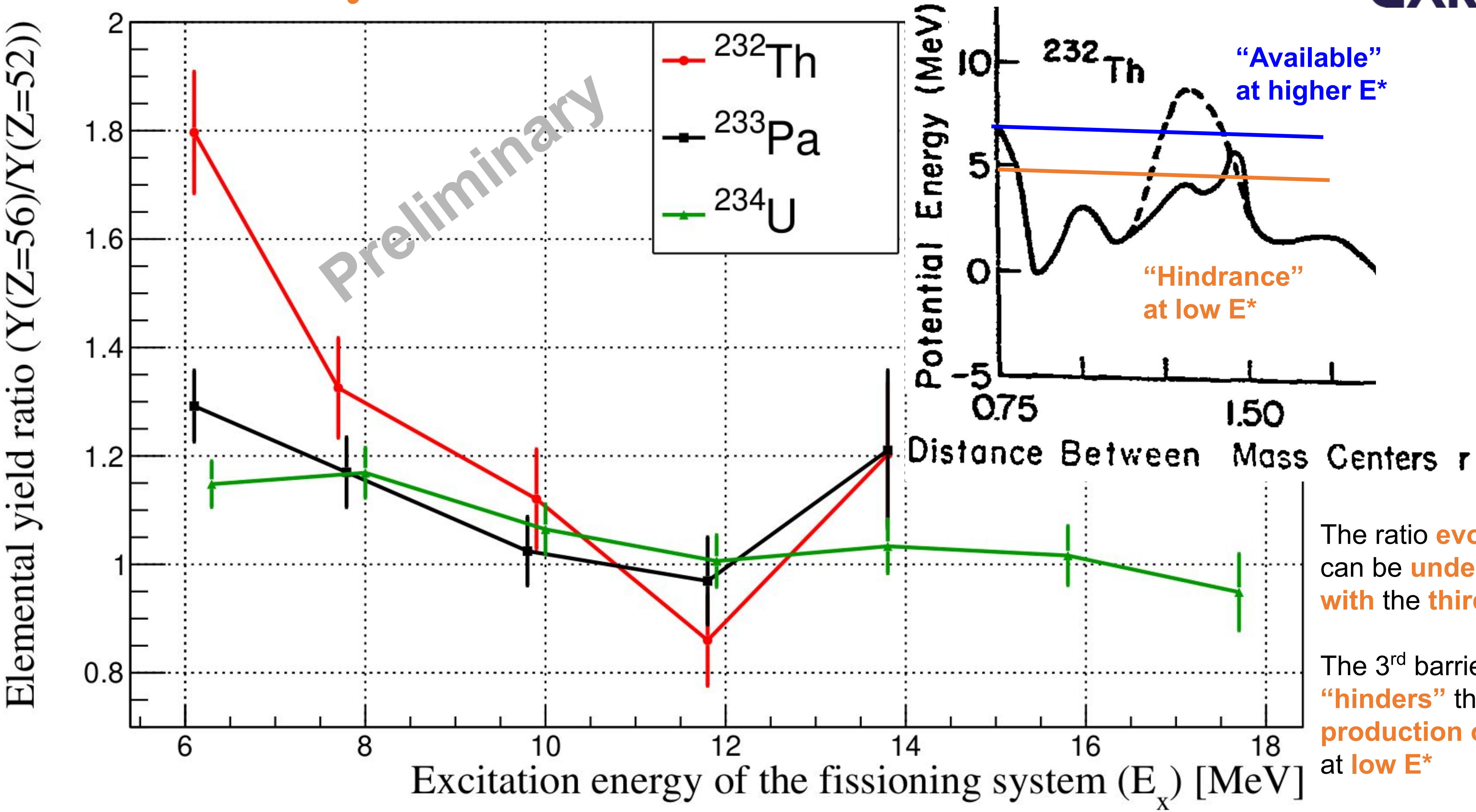


The **rise at E*~12 MeV** is due to the **second-chance** fission:

The system **emits a neutron** and the **daughter** nucleus **fissions**

The **daughter** is **also anomalous**

Elemental yields ratio as a function of E*



The ratio **evolution** can be **understood with** the **third barrier**

The 3rd barrier **"hinders"** the **production of Z=52** at **low E***

Summary and future perspectives

GANIL

SUMMARY

1. Successfully populated 10+ fissioning **systems around ^{232}Th** via transfer reactions with a ^{12}C target and the **newly** produced **^{232}Th beam at GANIL**
2. The post-neutron evaporation mass and elemental **yields** of **^{232}Th** are observed to be **more asymmetric than** the **yields** of the **heavier actinides: Th ANOMALY**
3. The ratio of the yields Z = 56 and Z=52 **^{232}Th, ^{233}Pa and ^{234}U decrease** with **increasing excitation energy** of the fissioning system
4. These observations can be **related to** a **third** fission **barrier in the PES**

FUTURE

1. Analyse the **pre-evaporation mass distributions** and the **neutron evaporation**
2. Study the **kinetic energy evolution** as a function of the excitation energy: **infer** the **shape** of the system **at scission**
3. **Extend the study** to more fissioning systems: **ANOMALY**

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THANK YOU

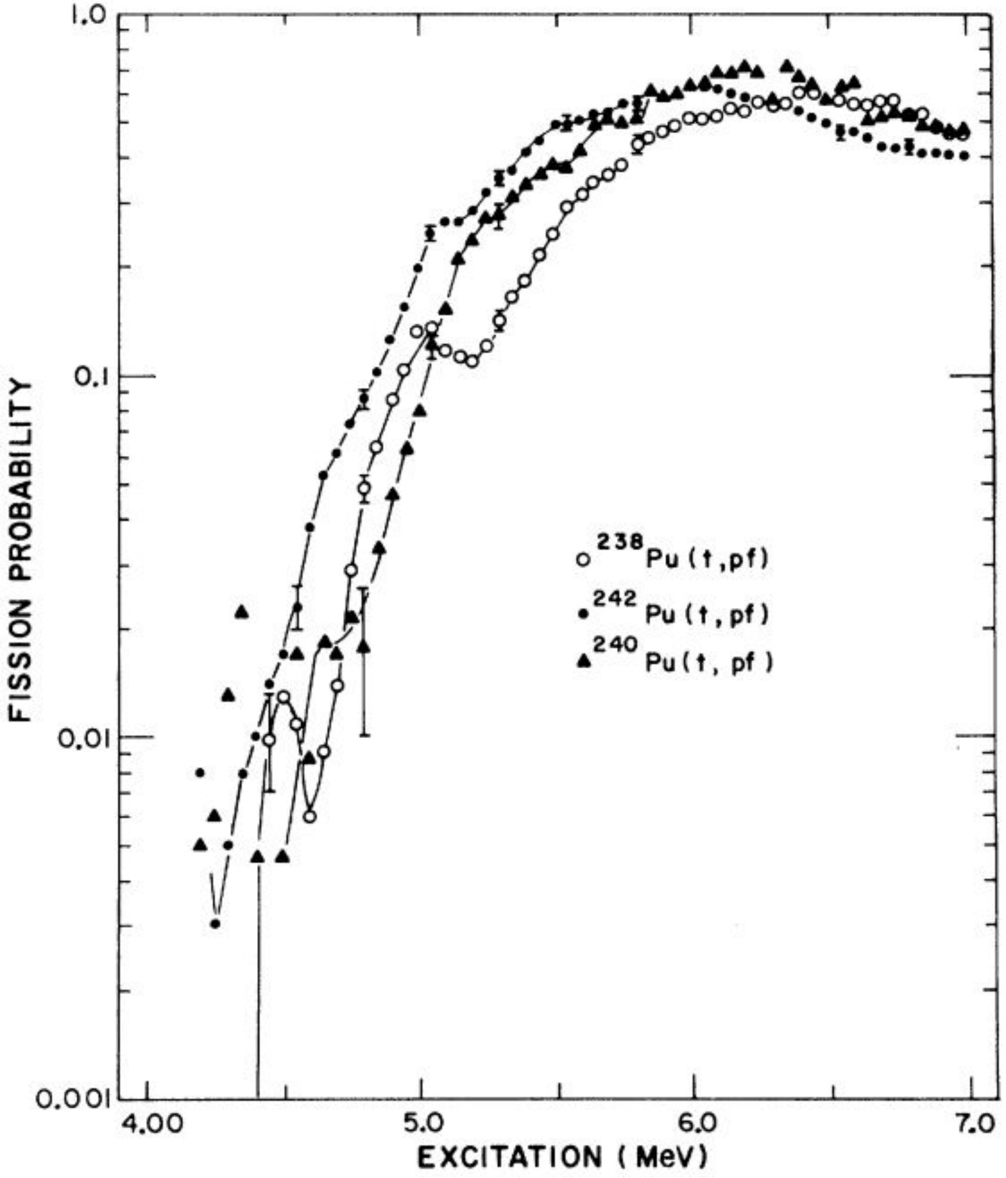
Thanks to VAMOS group and collaborators from e849 experiment

Back up slides

Fission observables

The **PES** can**not** be directly **measured** => **observables related** to it

Fission observables: fission probability



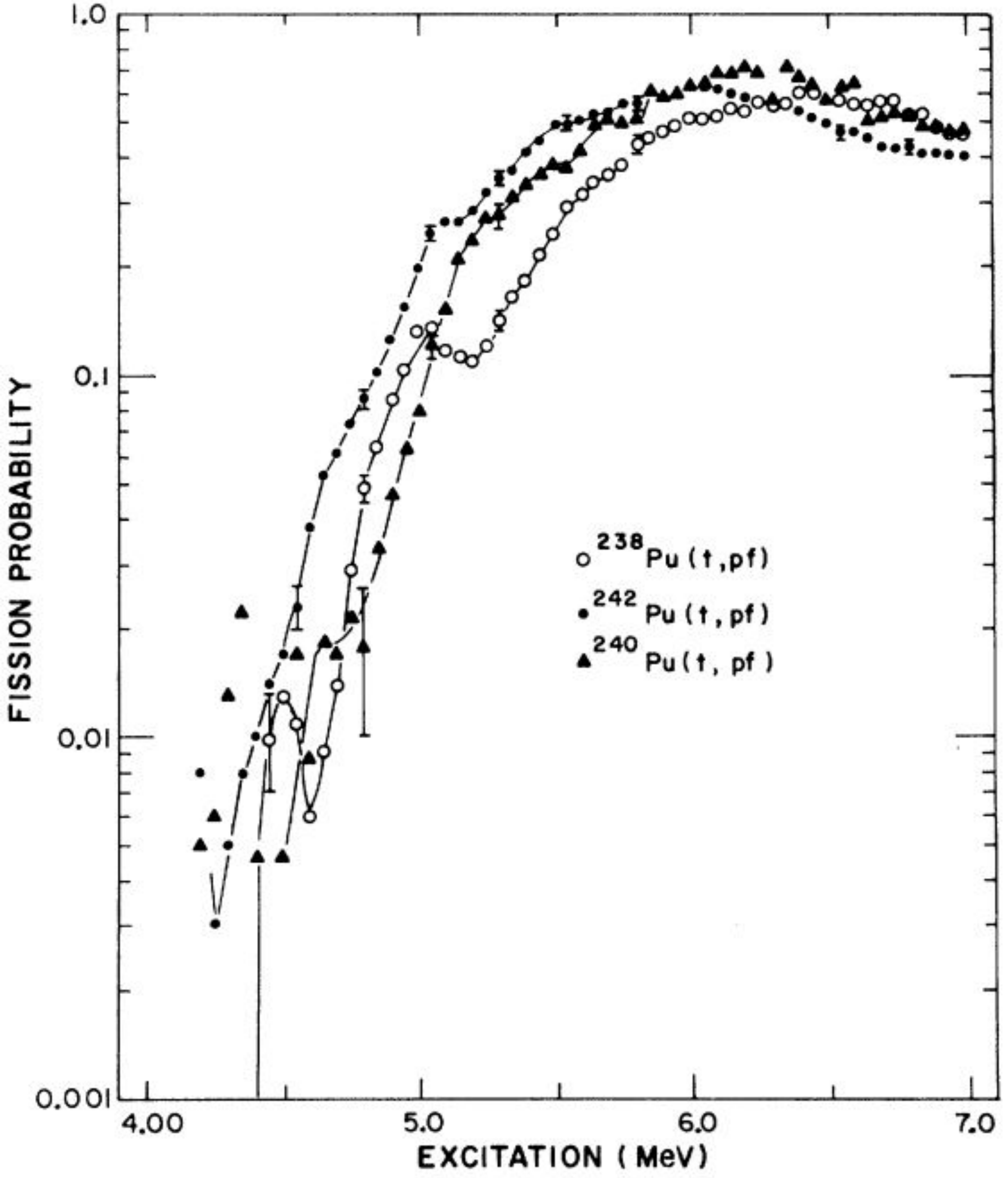
The PES cannot be directly measured => observables related to it

After forming a **fissioning system**, the nucleus can **decay through various channels**: n-, ɣ- emission, **fission**, …

- **No fission** probability **below** the fission **barrier**
- The **peaks** represent **resonances in** the **PES pocket**

Cramer, J. D., & Britt, H. C. (1970). Fission studies of thorium, uranium, and plutonium isotopes with (t, pf) reactions. Physical Review C, 2(6), 2350.

Fission observables: fission probability



The PES cannot be directly measured => observables related to it

After forming a fissioning system, the nucleus can decay through various channels: n-, ɣ- emission, fission, …

- No fission probability below the fission barrier
- The peaks represent resonances in the PES pocket

The **PES** shapes and **barrier penetrability** calculations are used to **extract barrier heights**:

Nucleus	Ref	E_A MeV	$\hbar\omega_A$ MeV	E_{IS} MeV	E_{Min} MeV	$\hbar\omega_{Min}$ MeV	E_B MeV	$\hbar\omega_B$ MeV	E_B-E_A MeV
Theory:									
^{240}Pu	a	6.3	-	2.5	-	-	5.3	-	-1.0
	e	5.8	-	2.7	-	-	5.6	-	-0.20
	c	5.2	-	2.3	1.8	-	5.5	-	0.30
Experiment:									
^{240}Pu	f	6.05	1.00	2.95	2.35	1.20	5.55	0.70	-0.50

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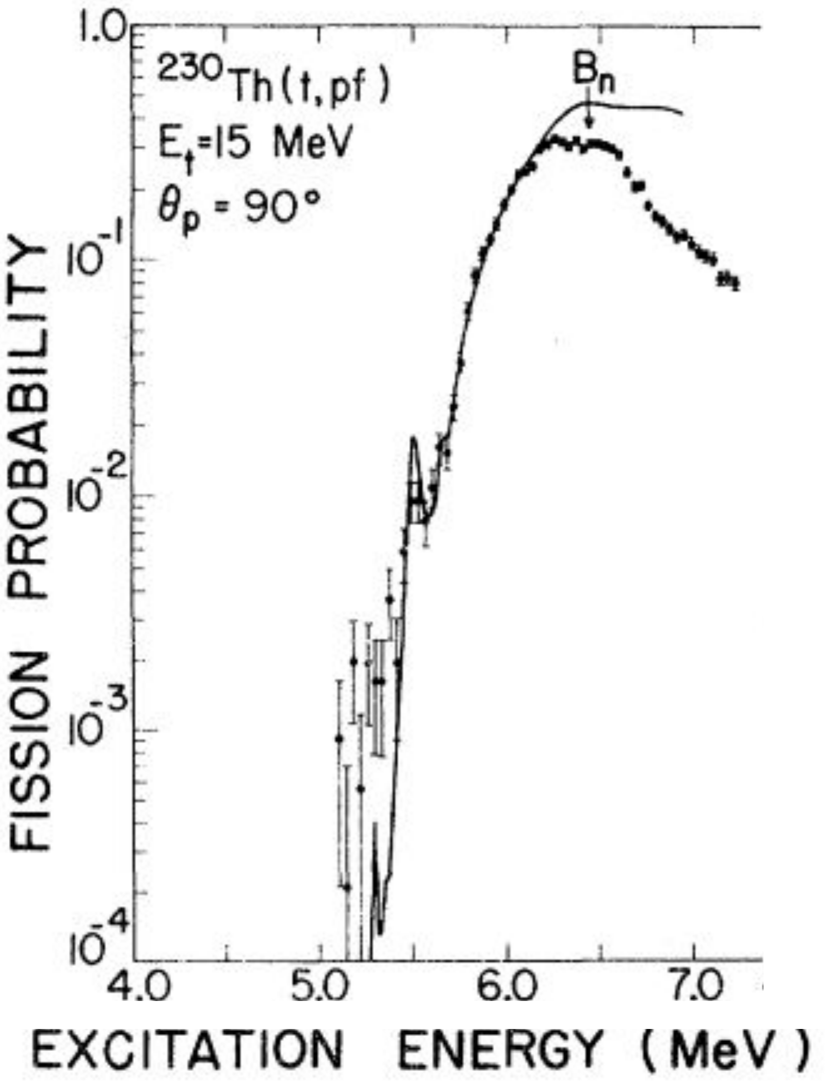
Fission observables: fission probability



Back, B. B., Britt, H. C., Garrett, J. D., & Hansen, O. (1972). Subbarrier fission resonances in Th isotopes. Physical Review Letters, 28(26), 1707.

Nucleus	Ref	E_A MeV	$\hbar\omega_A$ MeV	E_{IS} MeV	E_{Min} MeV	$\hbar\omega_{Min}$ MeV	E_B MeV	$\hbar\omega_B$ MeV	E_B-E_A MeV
Theory:									
^{232}Th	a	4.8	-	2.8	-	-	7.3	-	2.5
	b	4.3	-	1.9	1.4	-	8.6	-	4.3
	c	3.4	-	2.3	1.8	-	6.6	-	3.2
Experiment:									
^{232}Th	Present	5.50	0.90	4.43	4.25	0.36	6.18	0.47	0.68

The **theoretical models** can**not reproduce** the **observations** for the **Thorium isotopes**

THORIUM ANOMALY (1)

Anomaly explanation: third barrier

GANIL

Nucleus	Ref	E_A MeV	$\hbar\omega_A$ MeV	E_{IS} MeV	E_{Min} MeV	$\hbar\omega_{Min}$ MeV	E_B MeV	$\hbar\omega_B$ MeV	E_B-E_A MeV
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A third fission barrier was proposed to explain these anomalous observations

The ratio between the height of the second and third barrier depends on (N,Z) of the fissioning systems

↓

Only for N ≤ 146 (in these calculations)

(1) The observed **height difference** would be E_C-E_B instead of E_B-E_A

Back, B. B., Britt, H. C., Garrett, J. D., & Hansen, O. (1972). Subbarrier fission resonances in Th isotopes. Physical Review Letters, 28(26), 1707.

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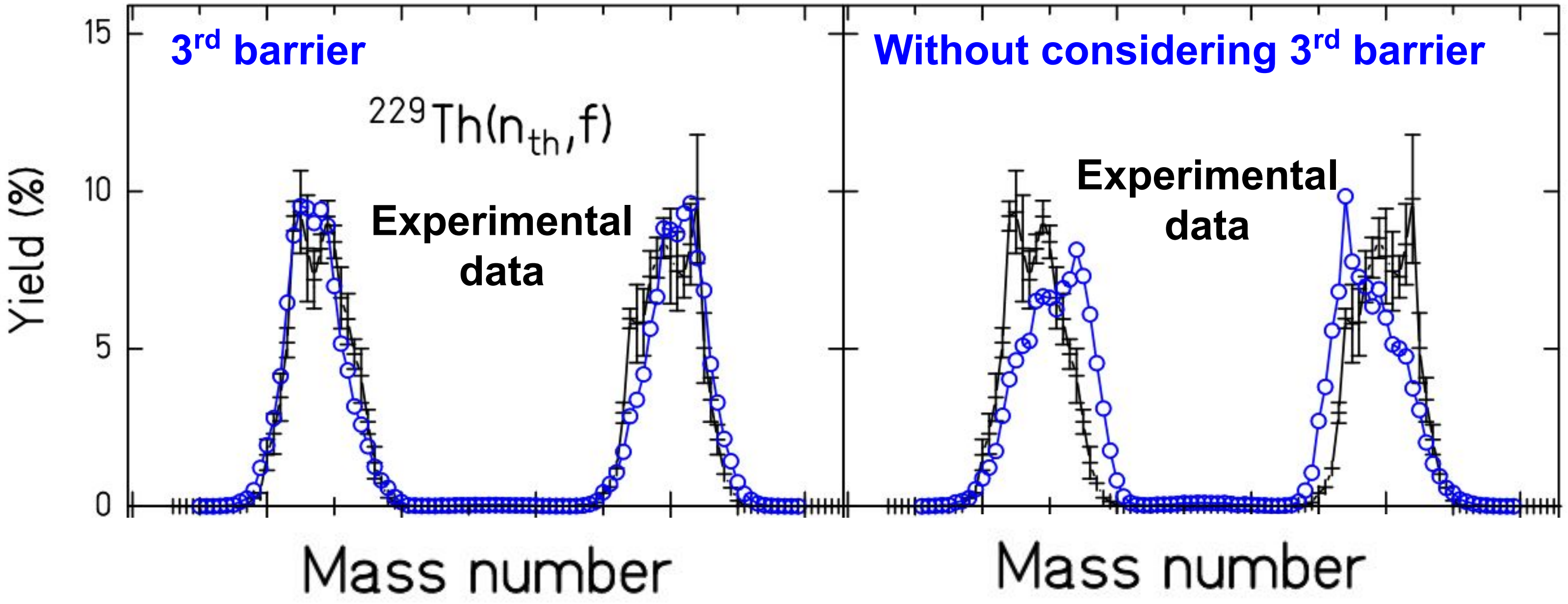

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The **mass yields** are **better reproduced** by the **semi-empirical model (GEF)** **when** the **third barrier** is included

Schmidt, K. H., Schmitt, C., Heinz, A., & Jurado, B. (2024). Identifying and overcoming deficiencies of nuclear data on the fission of light actinides by use of the GEF code. Annals of Nuclear Energy, 208, 110784.

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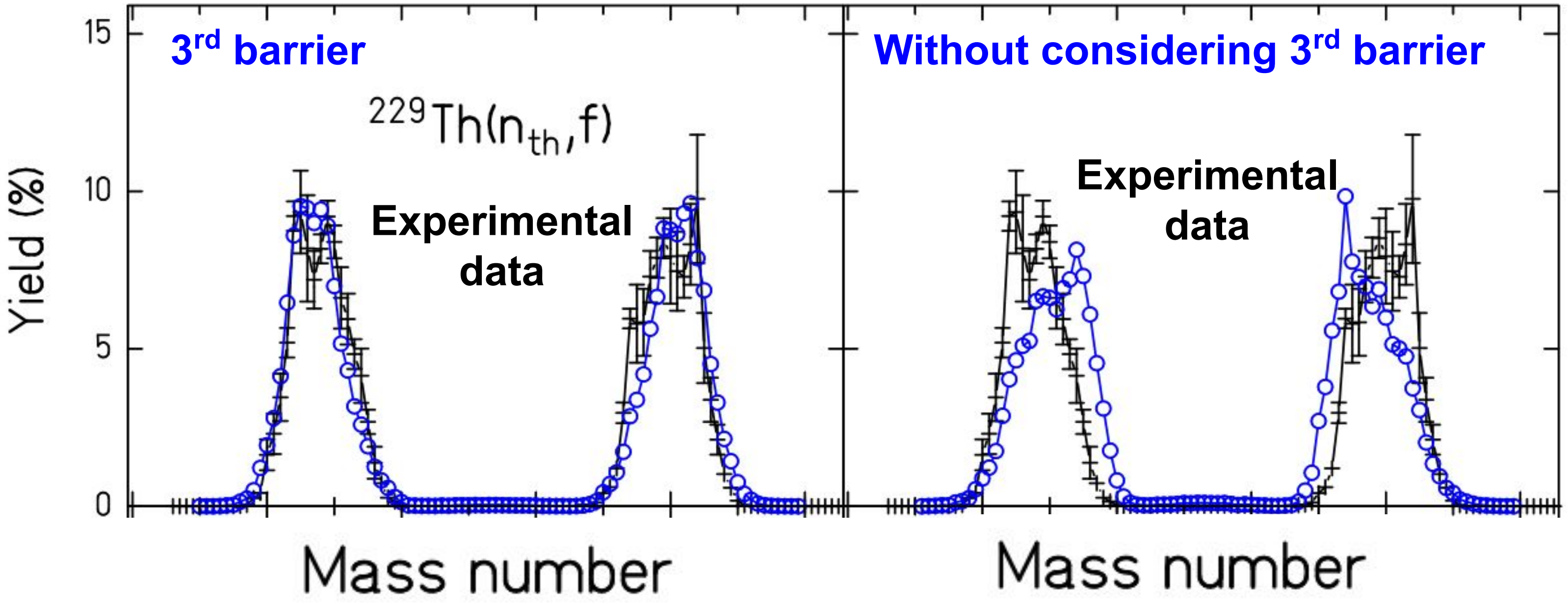

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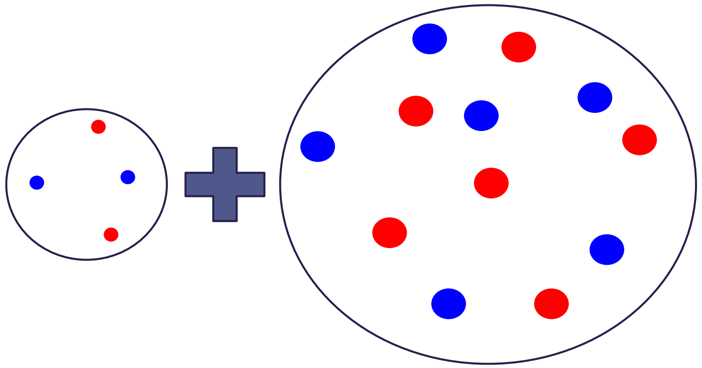
- What **structural effects** (proton/neutron) **drives** this anomaly ?
- **How** do they **vary** with **excitation energy**?
- Is it just an **anomaly?**

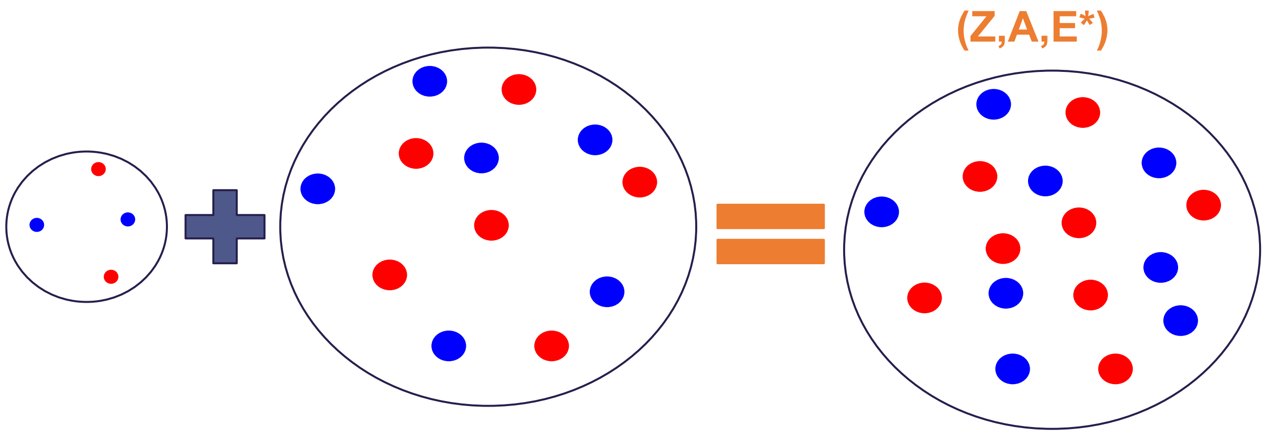
Schmidt, K. H., Schmitt, C., Heinz, A., & Jurado, B. (2024). Identifying and overcoming deficiencies of nuclear data on the fission of light actinides by use of the GEF code. Annals of Nuclear Energy, 208, 110784.

Experimental technique: inverse-kinematics



Reaction kinematics:
direct

Experimental technique: inverse-kinematics



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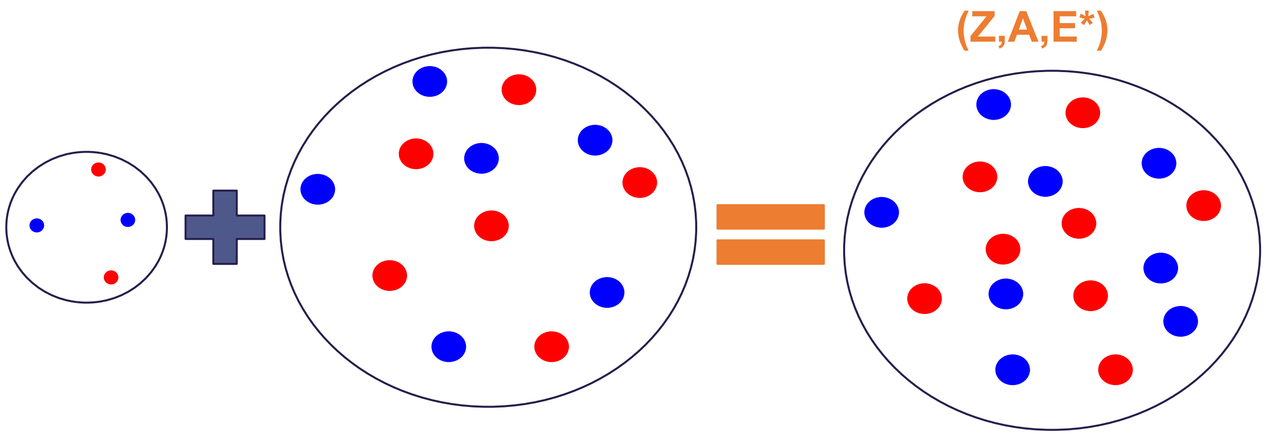

Reaction kinematics:
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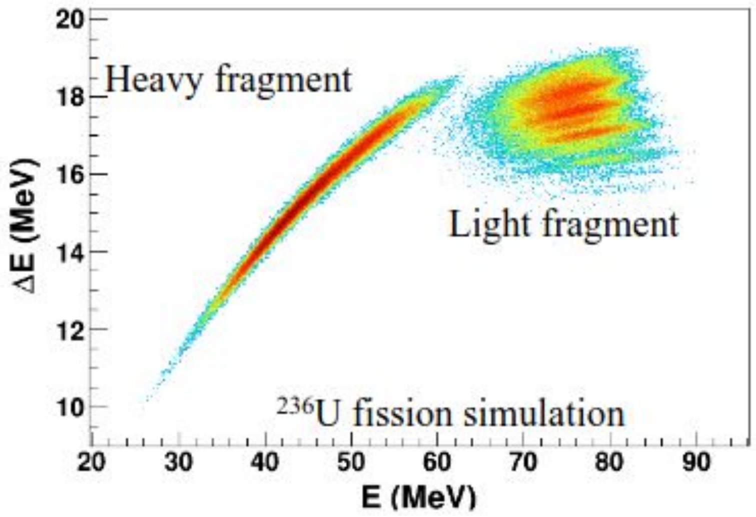
In fission, Total Kinetic Energy (TKE) ~ 200 MeV



Bethe-Bloch : $-dE/dx \propto Z^2/\beta^2$

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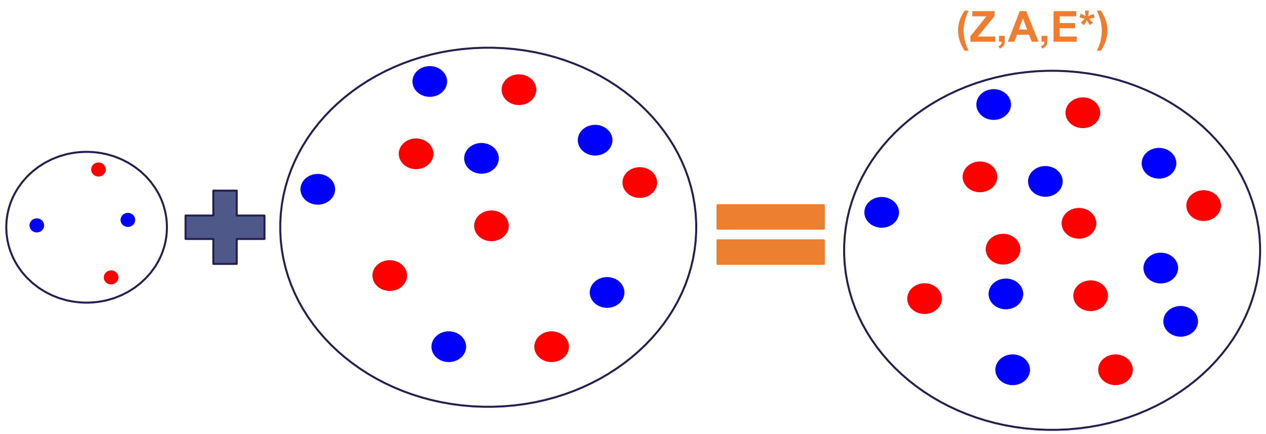

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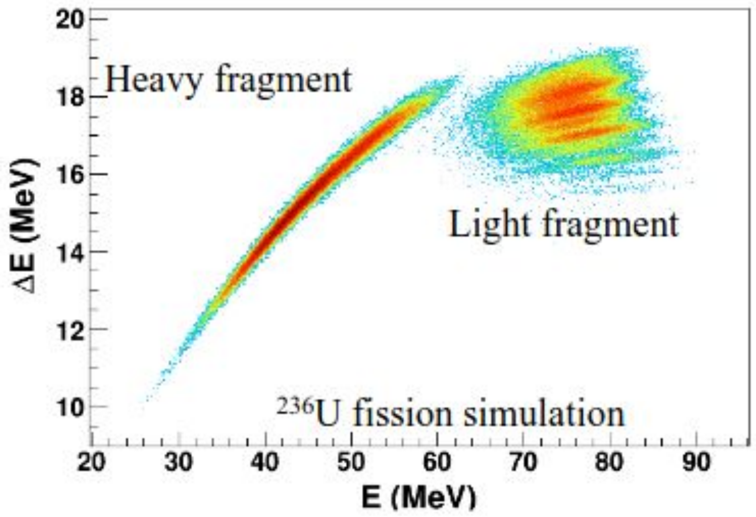

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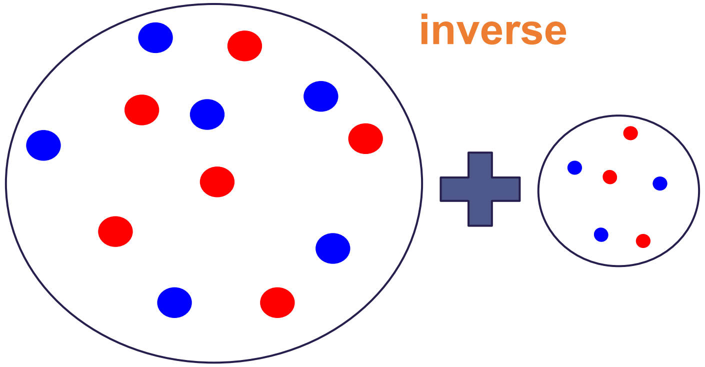

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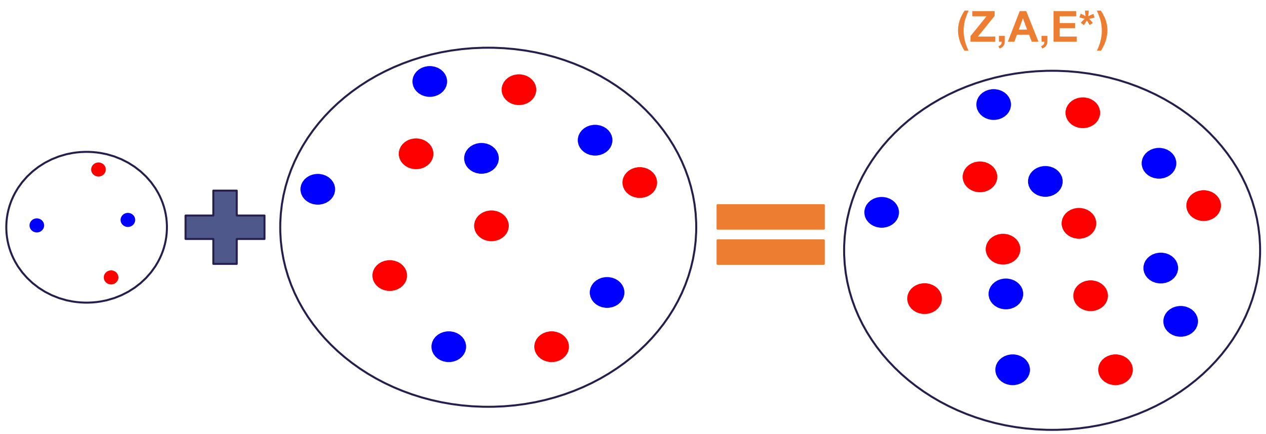

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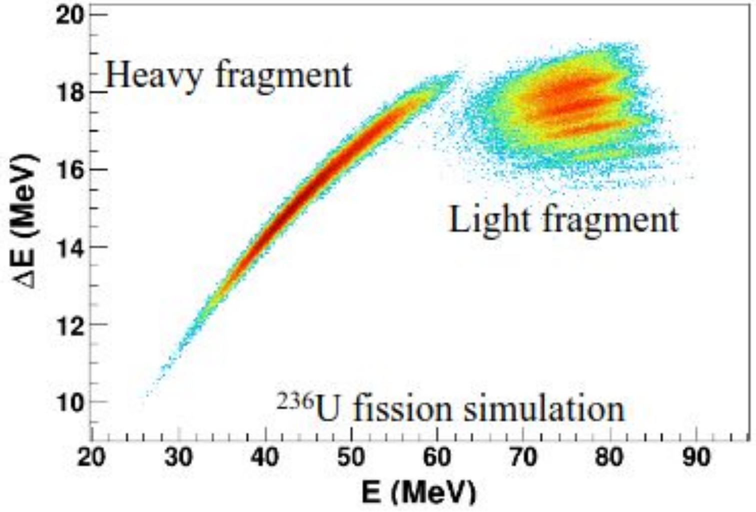

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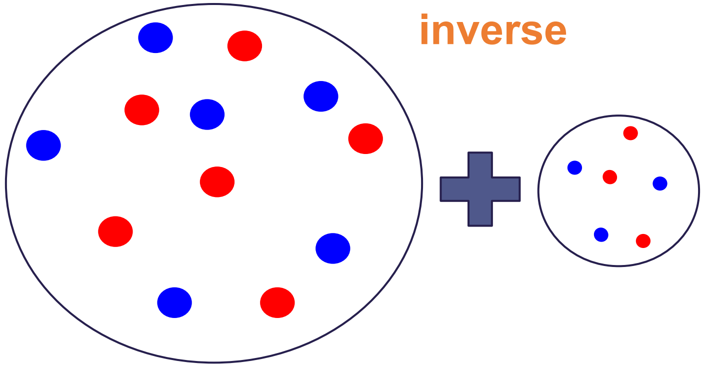
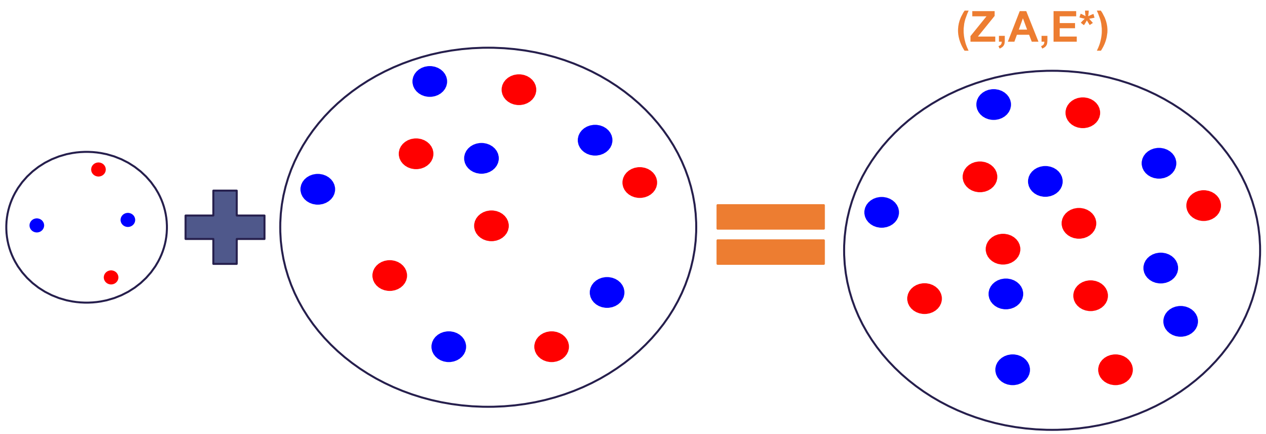


Kinematic boost:

TKE up to ~1000 MeV

Experimental technique: inverse-kinematics



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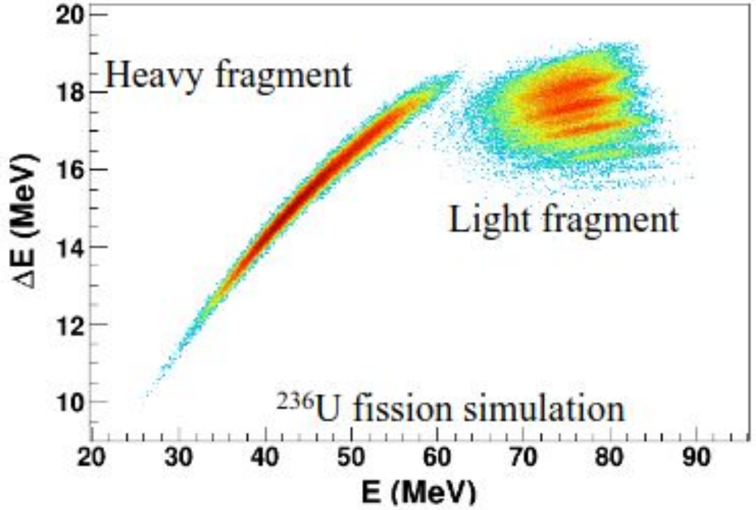

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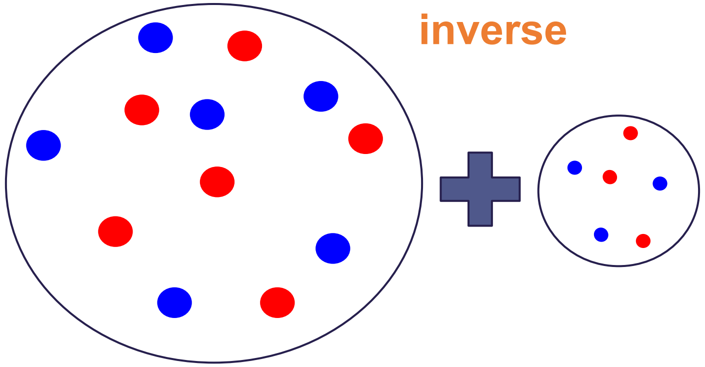
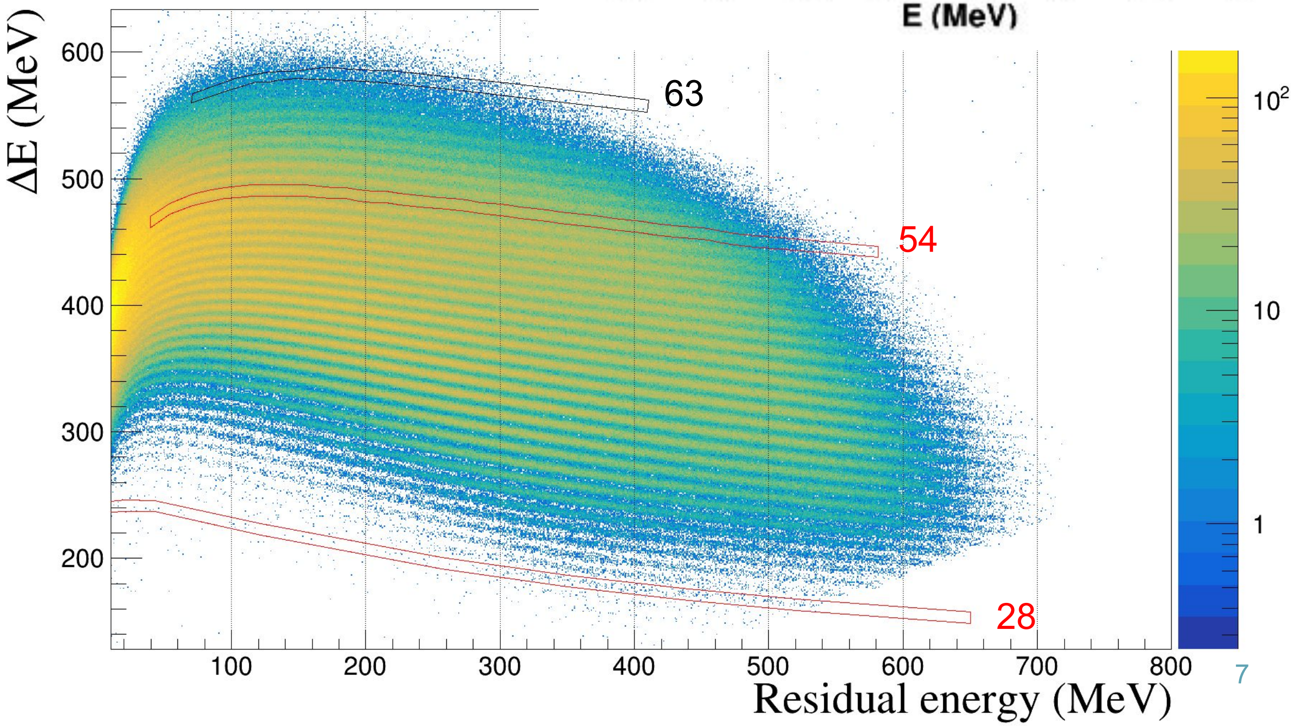


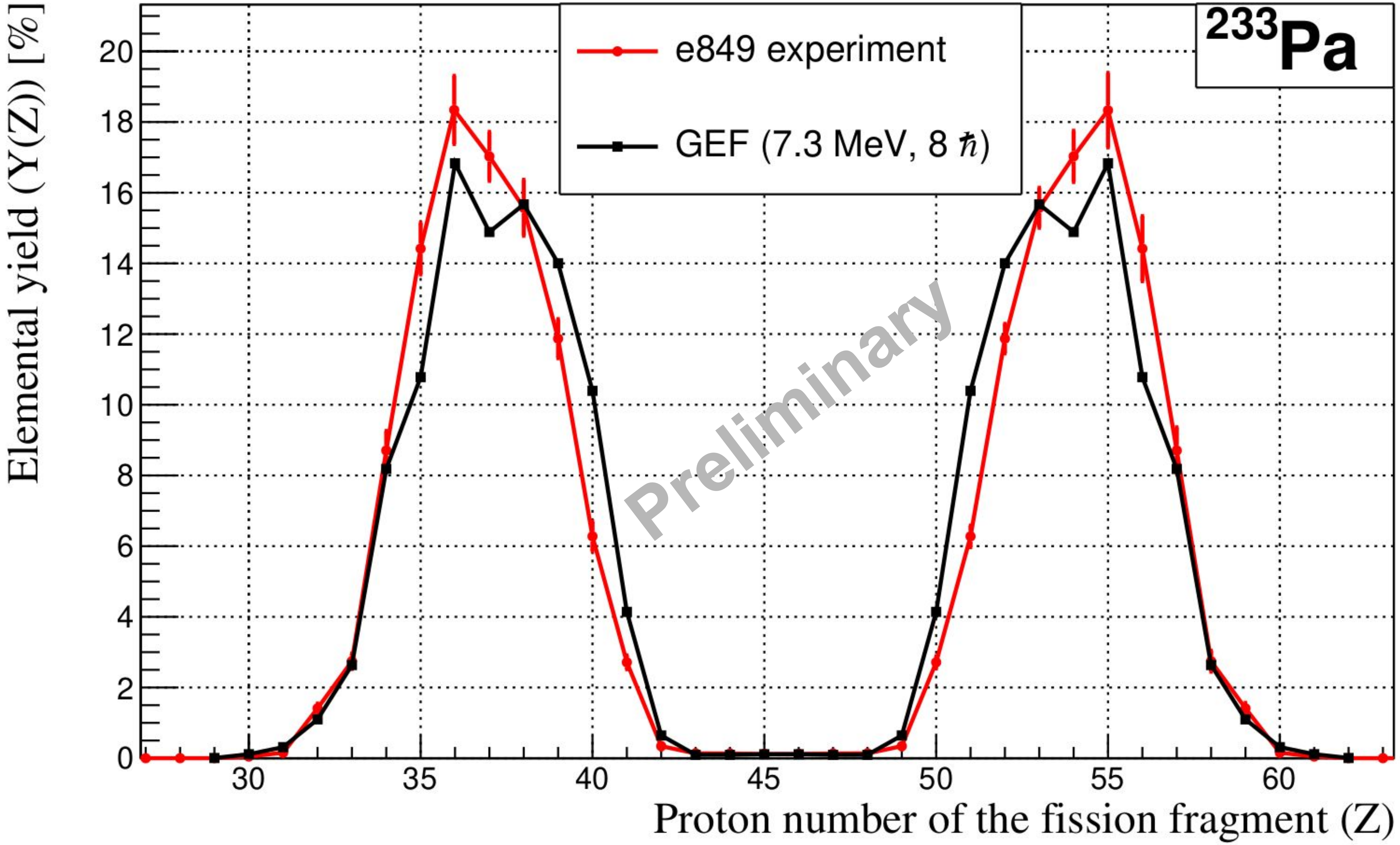
Kinematic boost:

TKE up to ~1000 MeV

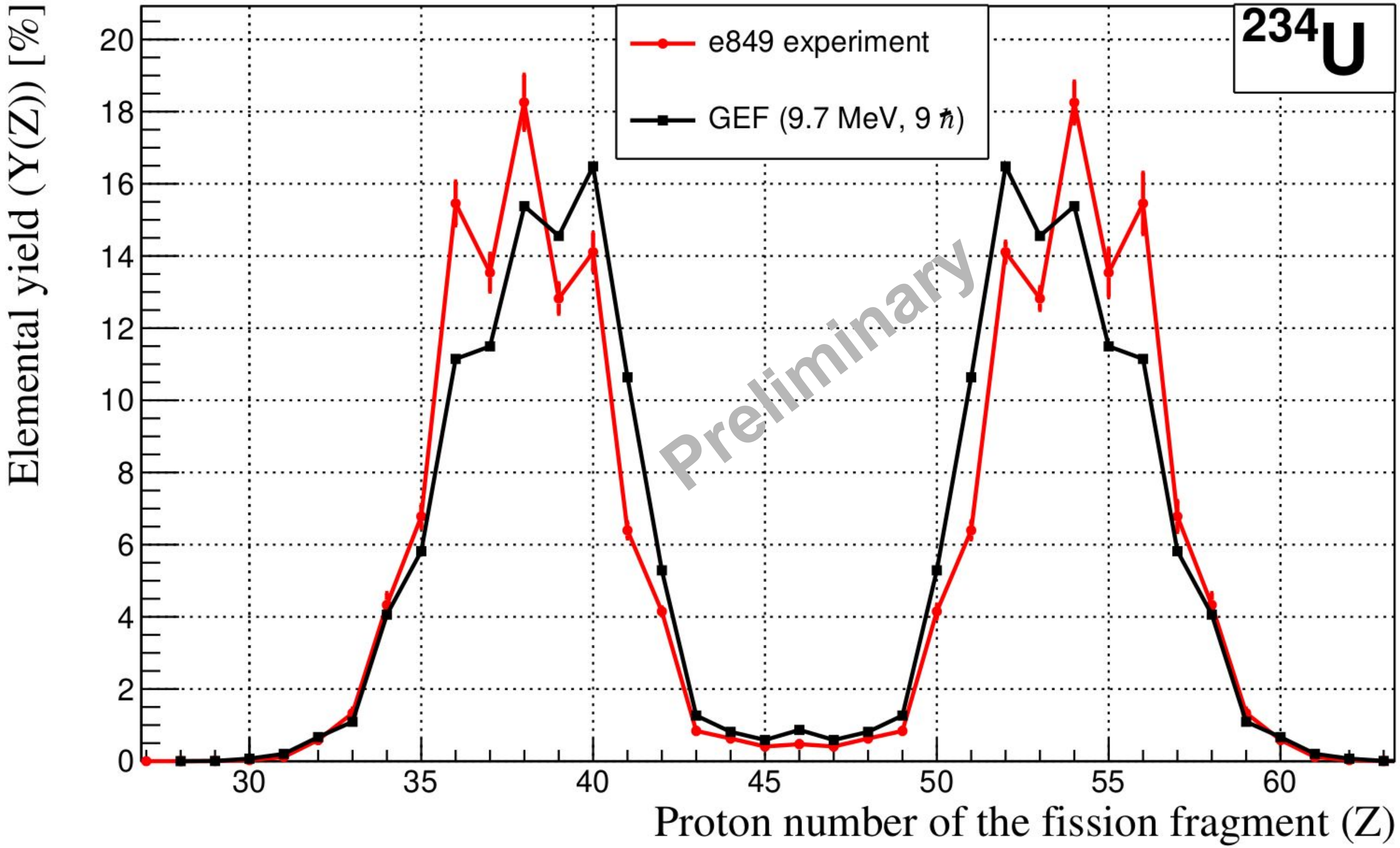
-dE/dx ∝ Z^2/β^2



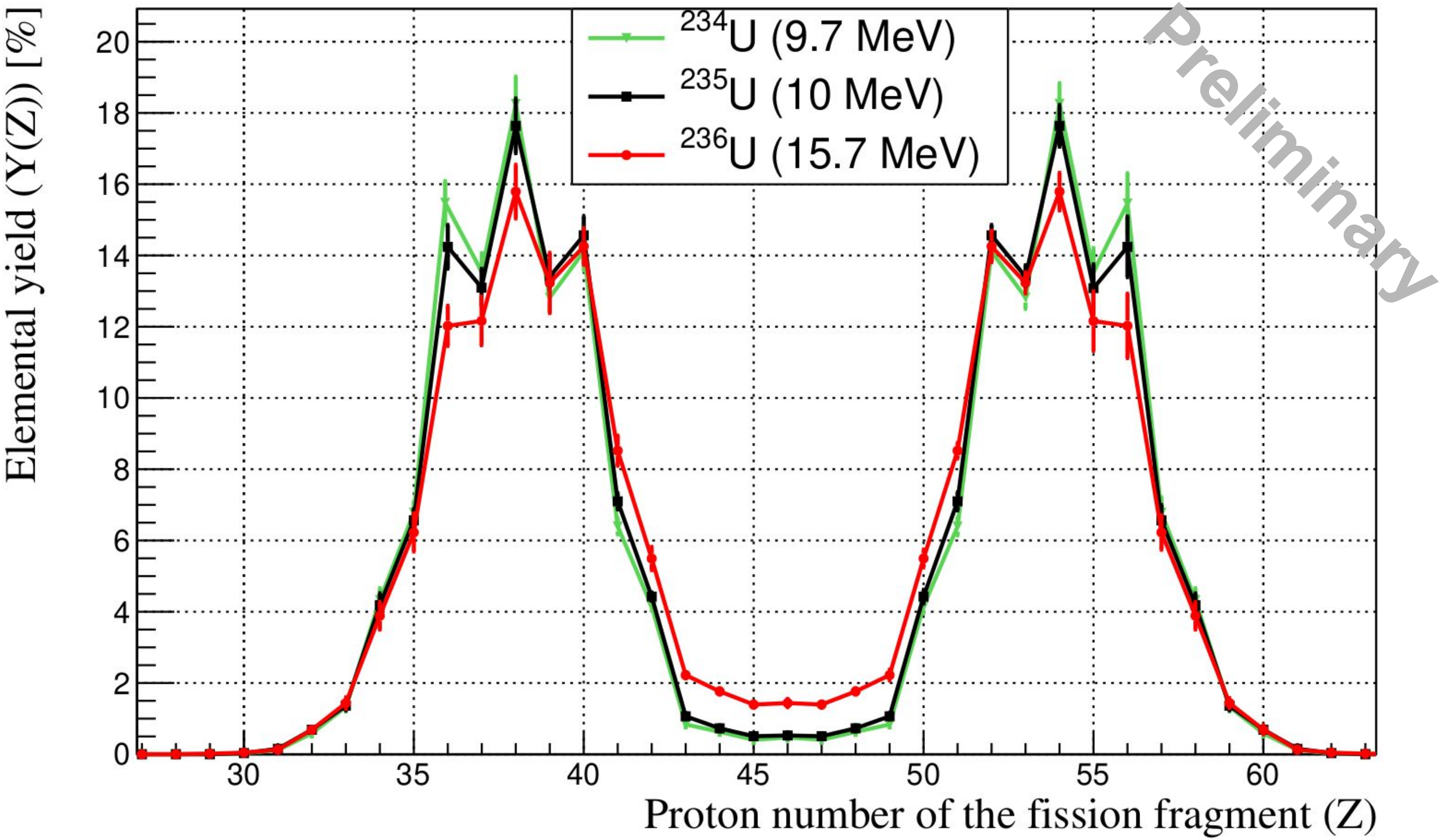
Elemental yields of ^{233}Pa



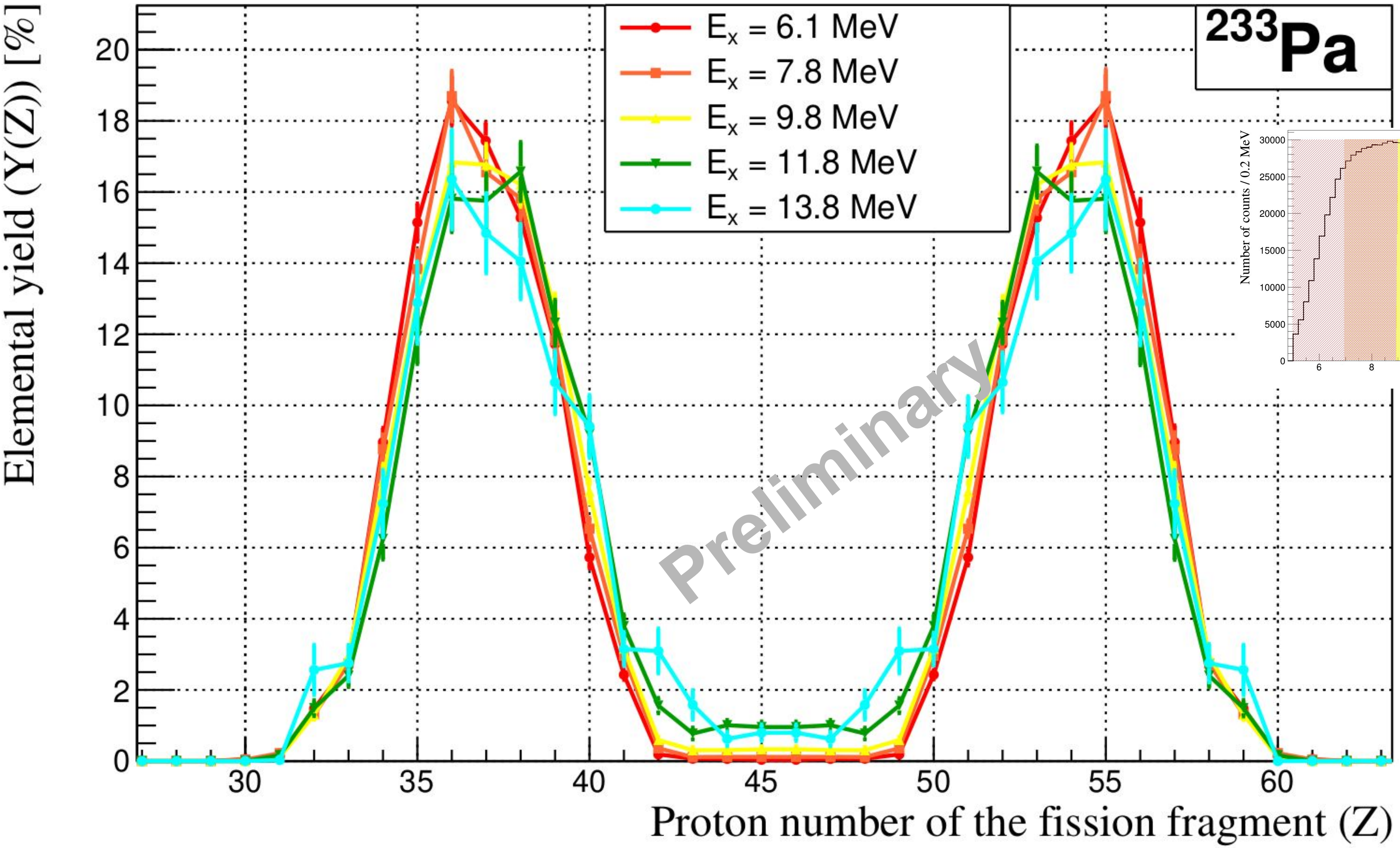
Elemental yields of ^{234}U

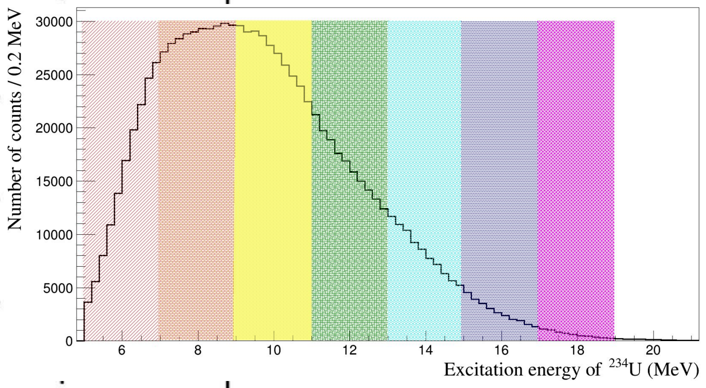


Elemental yields of $^{234-236}U$

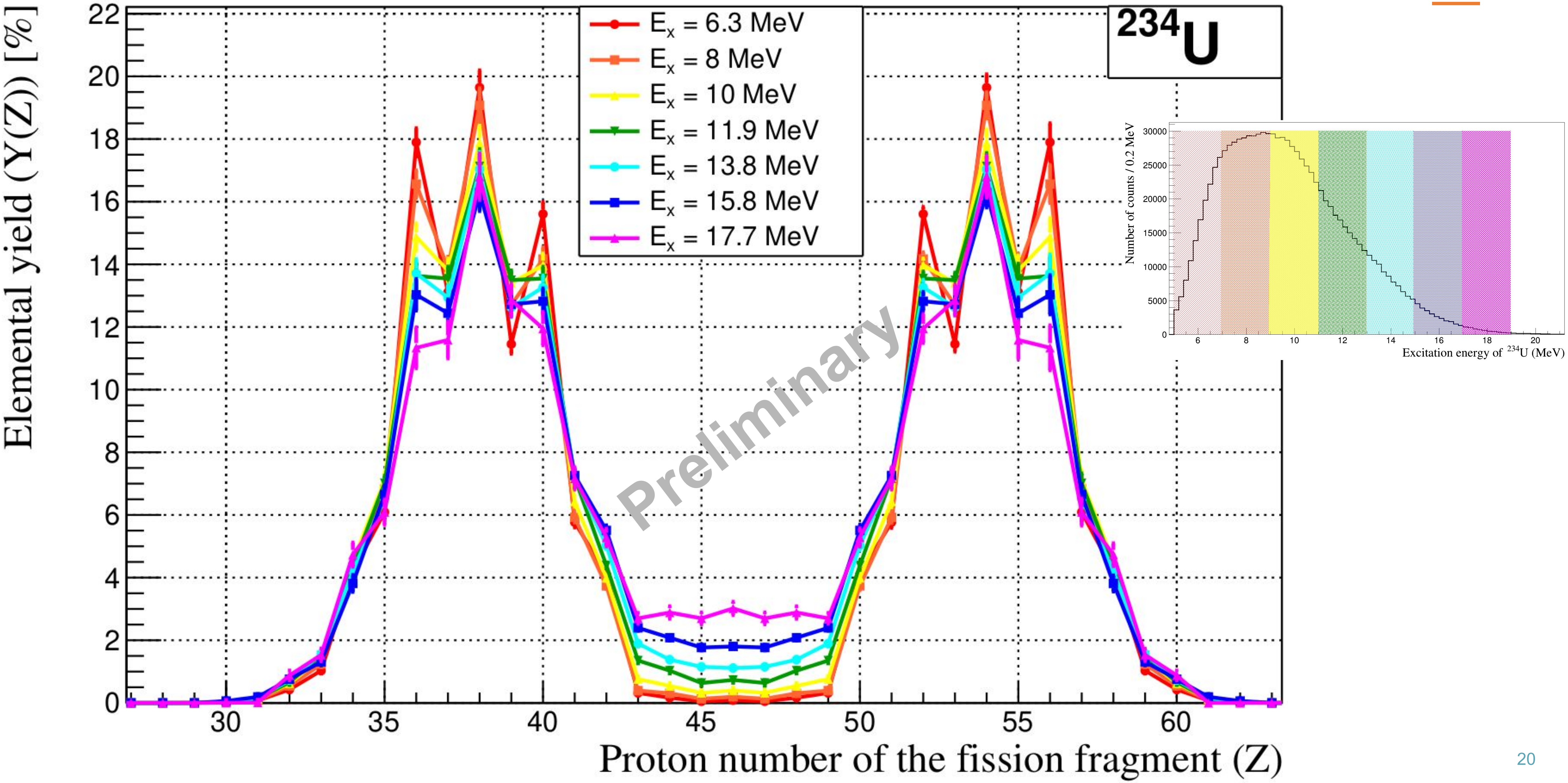


Elemental yields of ^{233}Pa as a function of E*

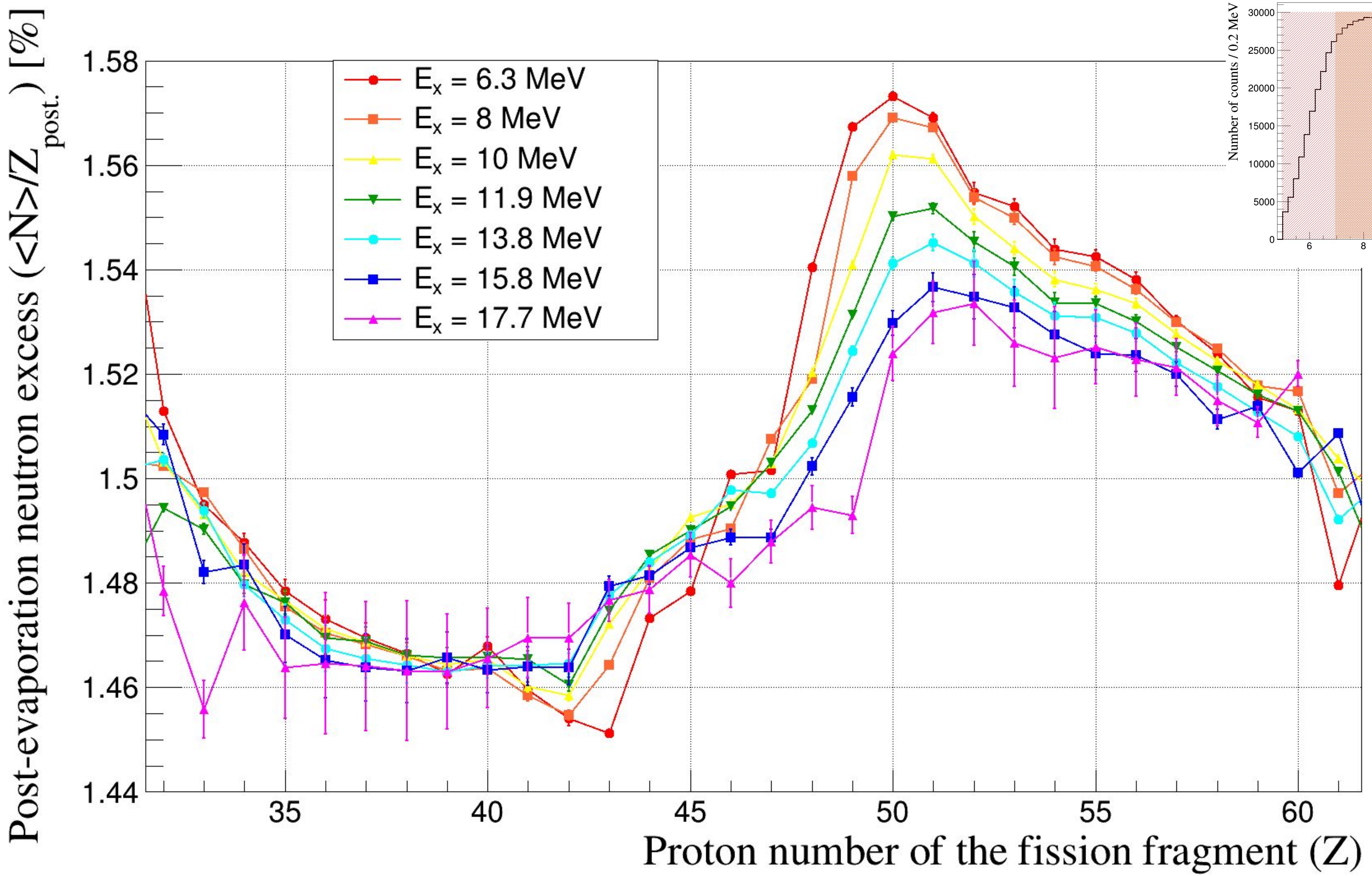


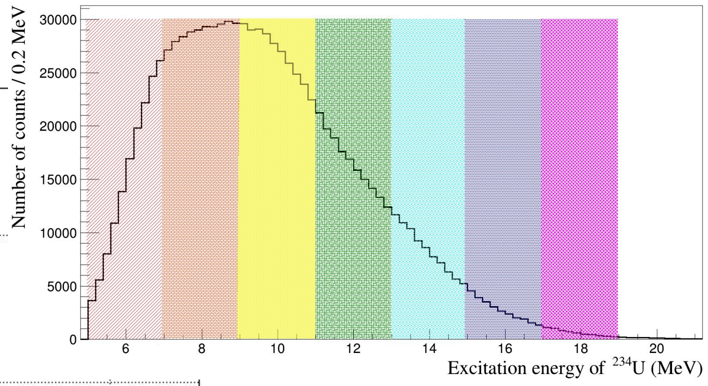


Elemental yields of ^{234}U as a function of E*

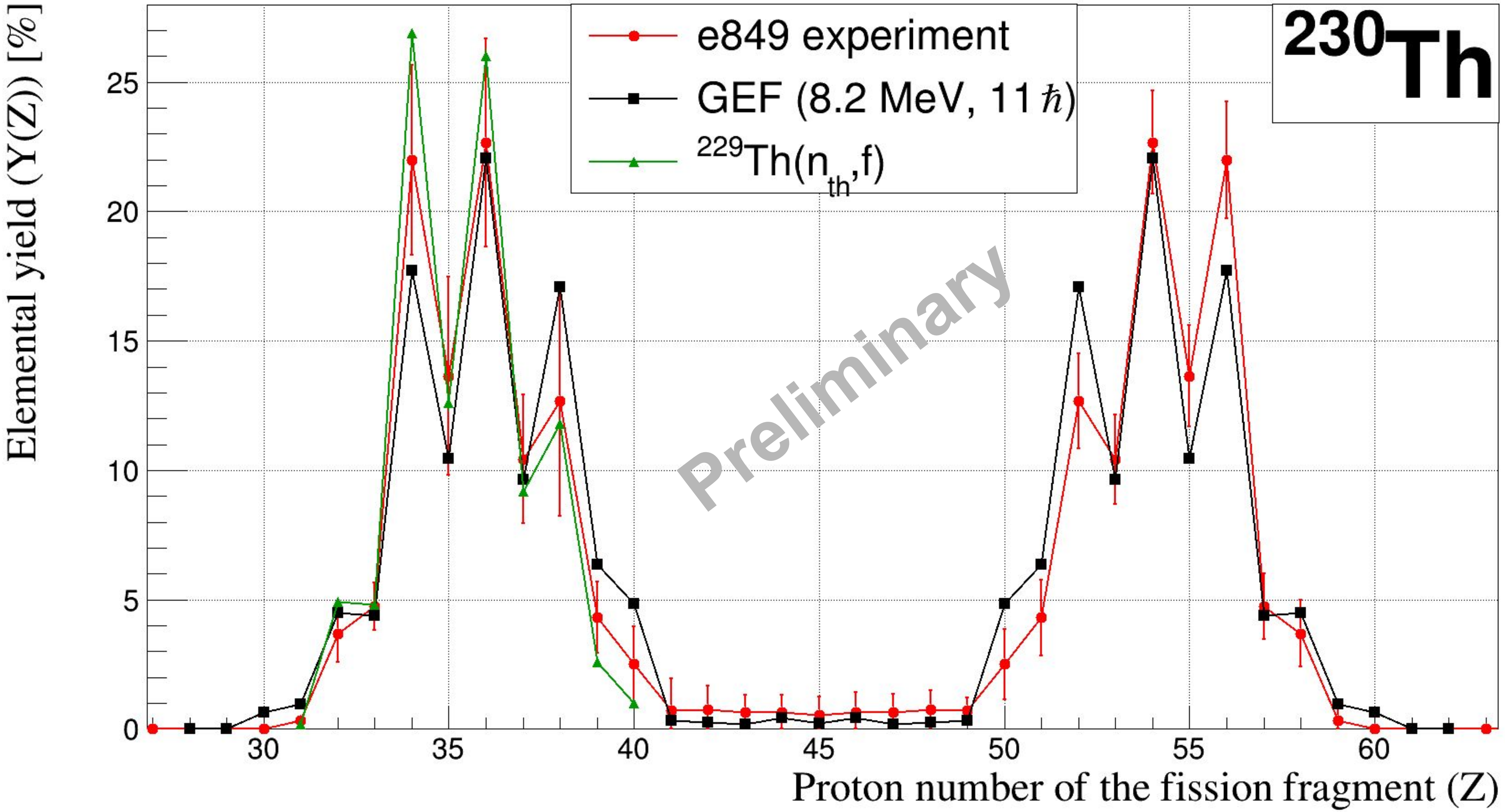


Neutron excess of ^{234}U as a function of E*

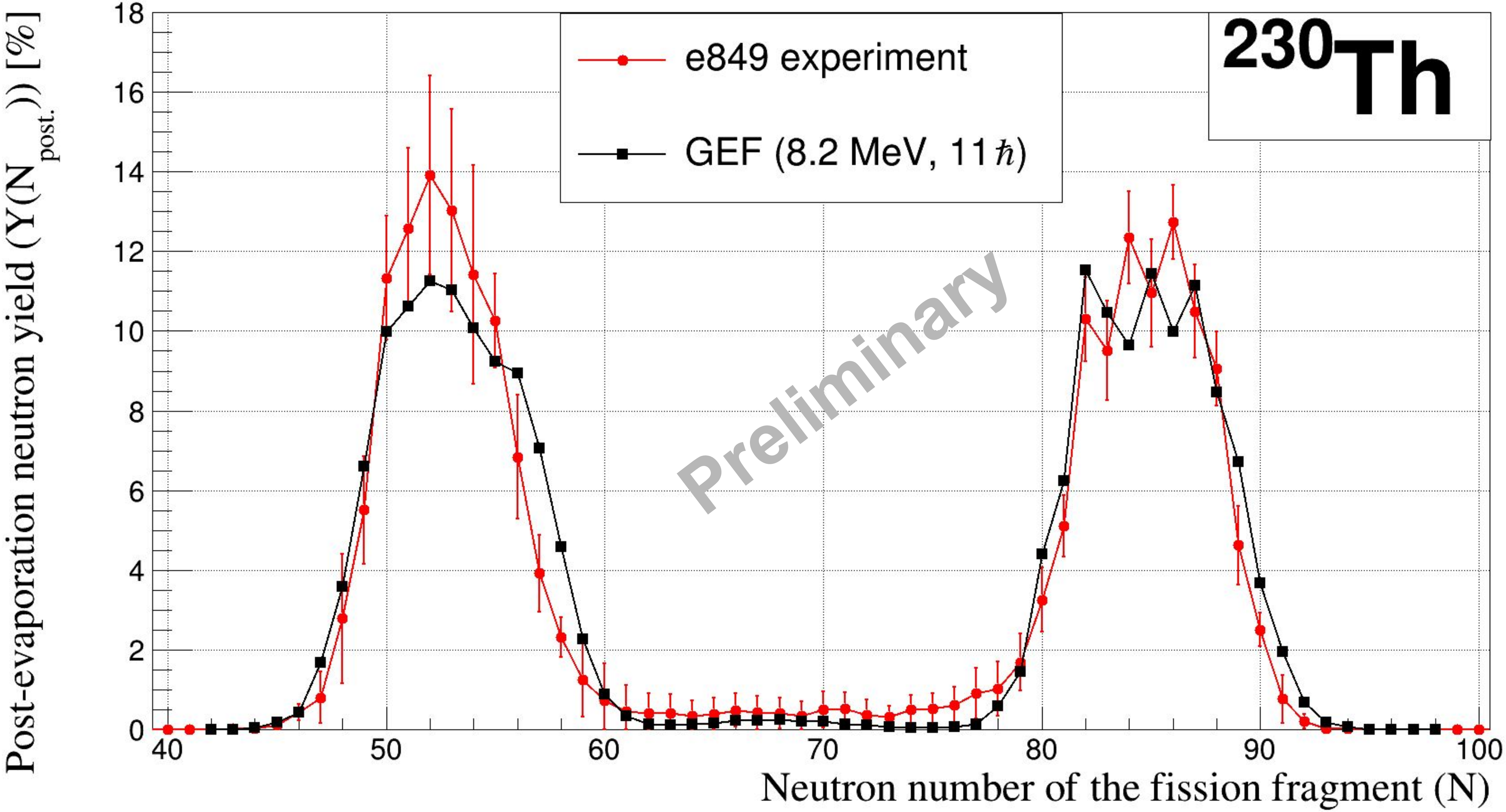




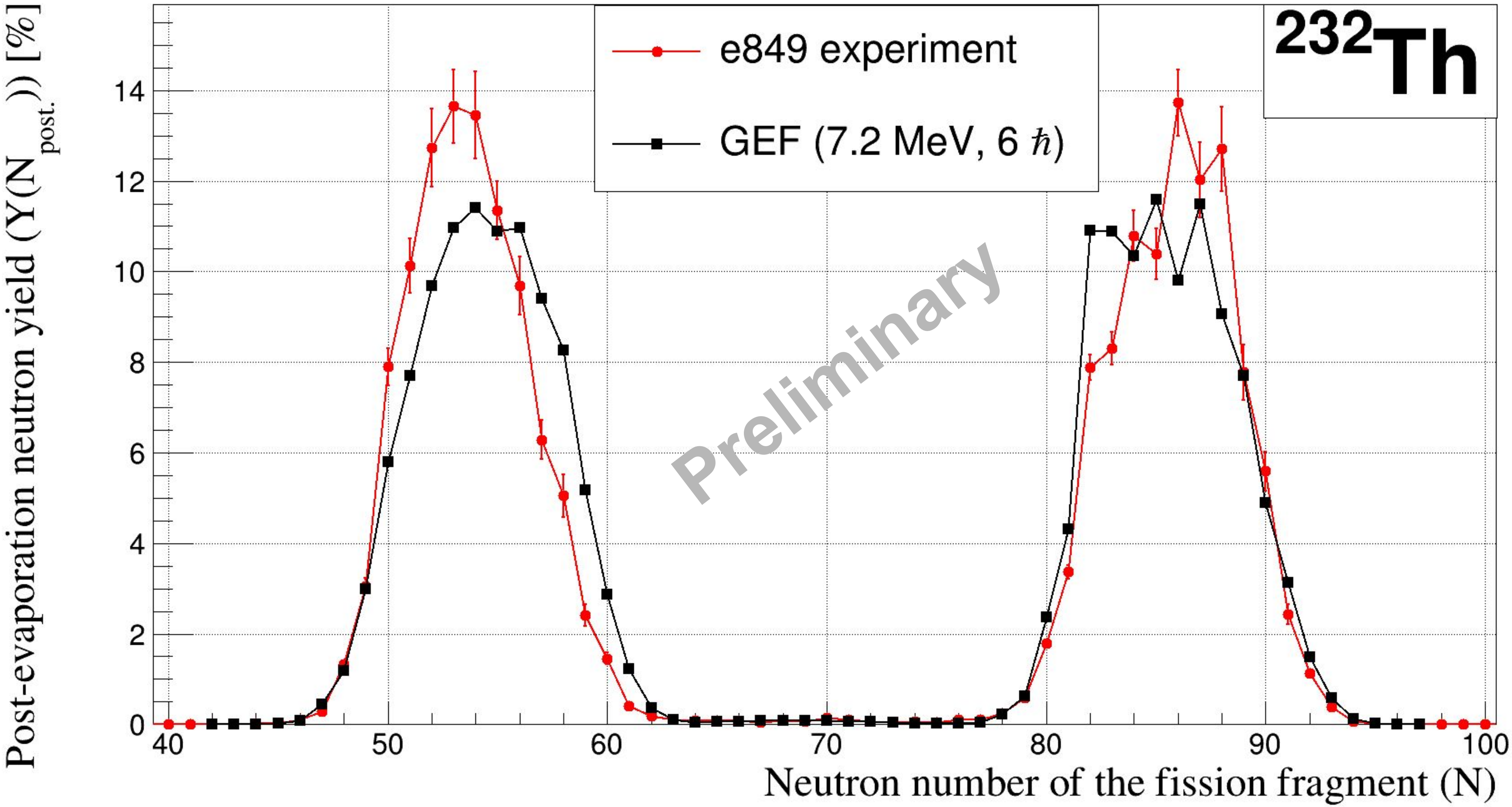
Elemental yields of ^{230}Th



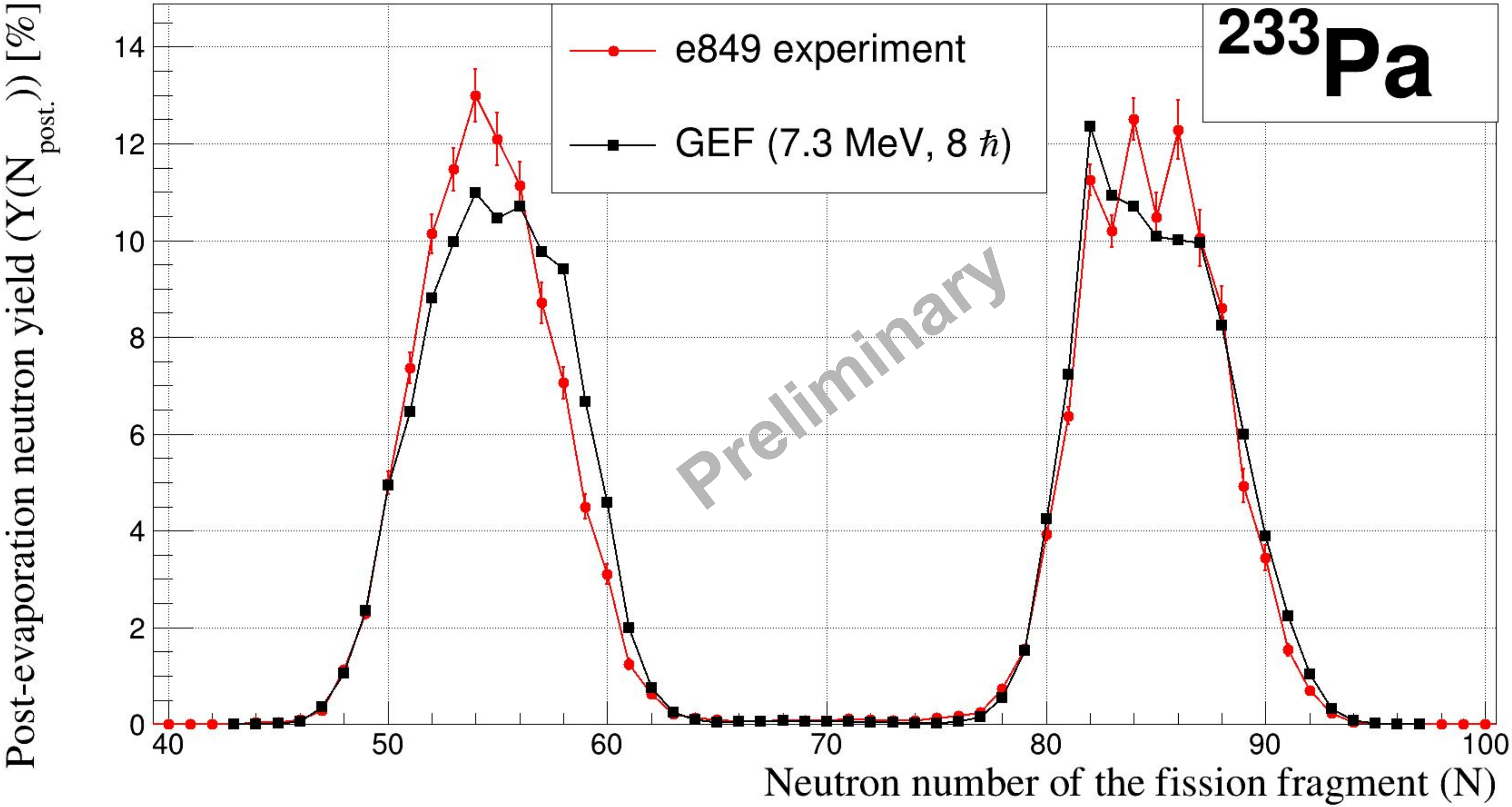
Neutron yields of ^{230}Th



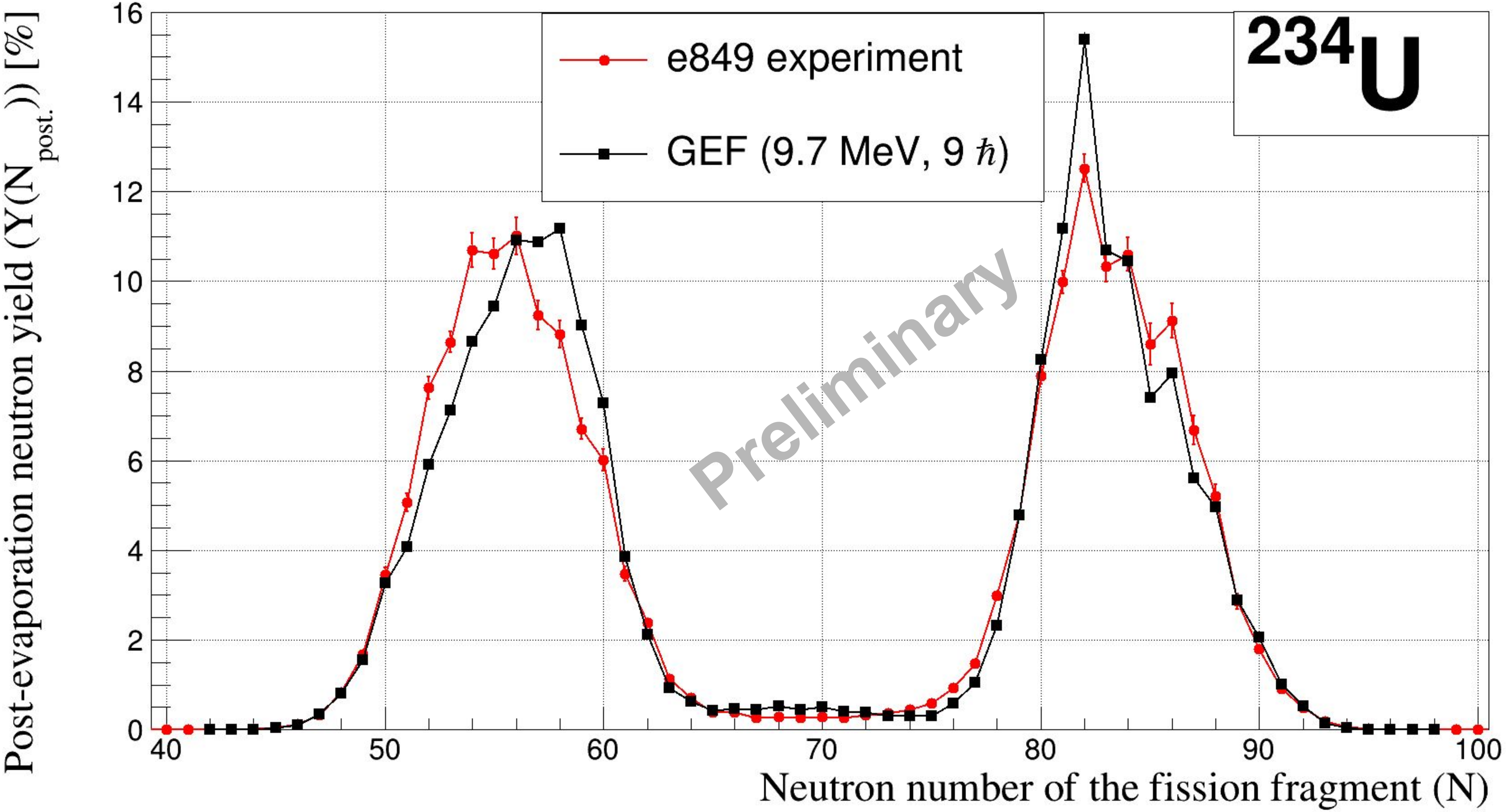
Neutron yields of ^{232}Th



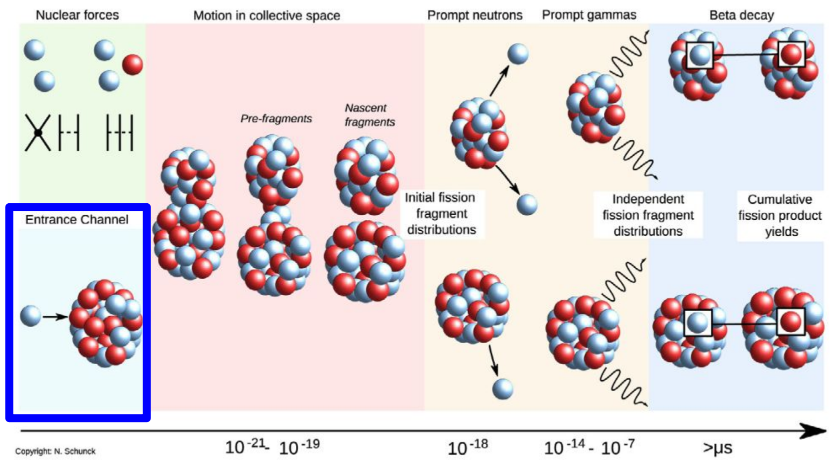
Neutron yields of ^{233}Pa

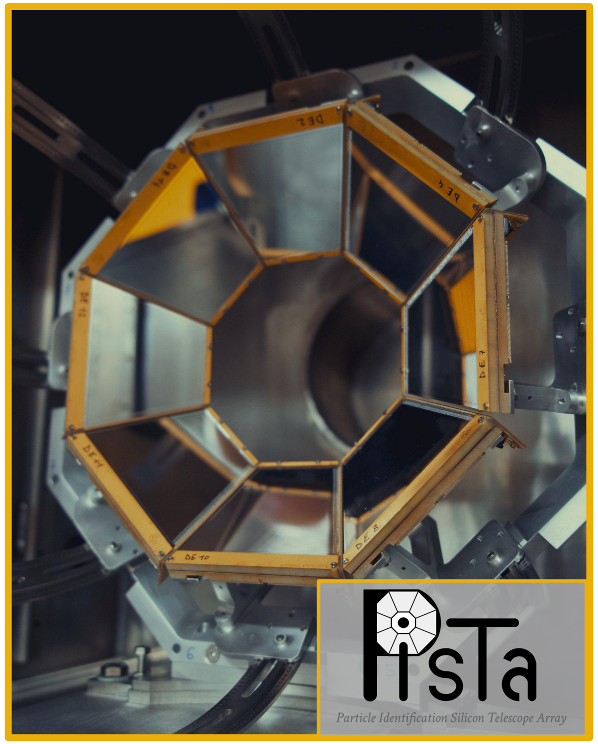


Neutron yields of ^{234}U

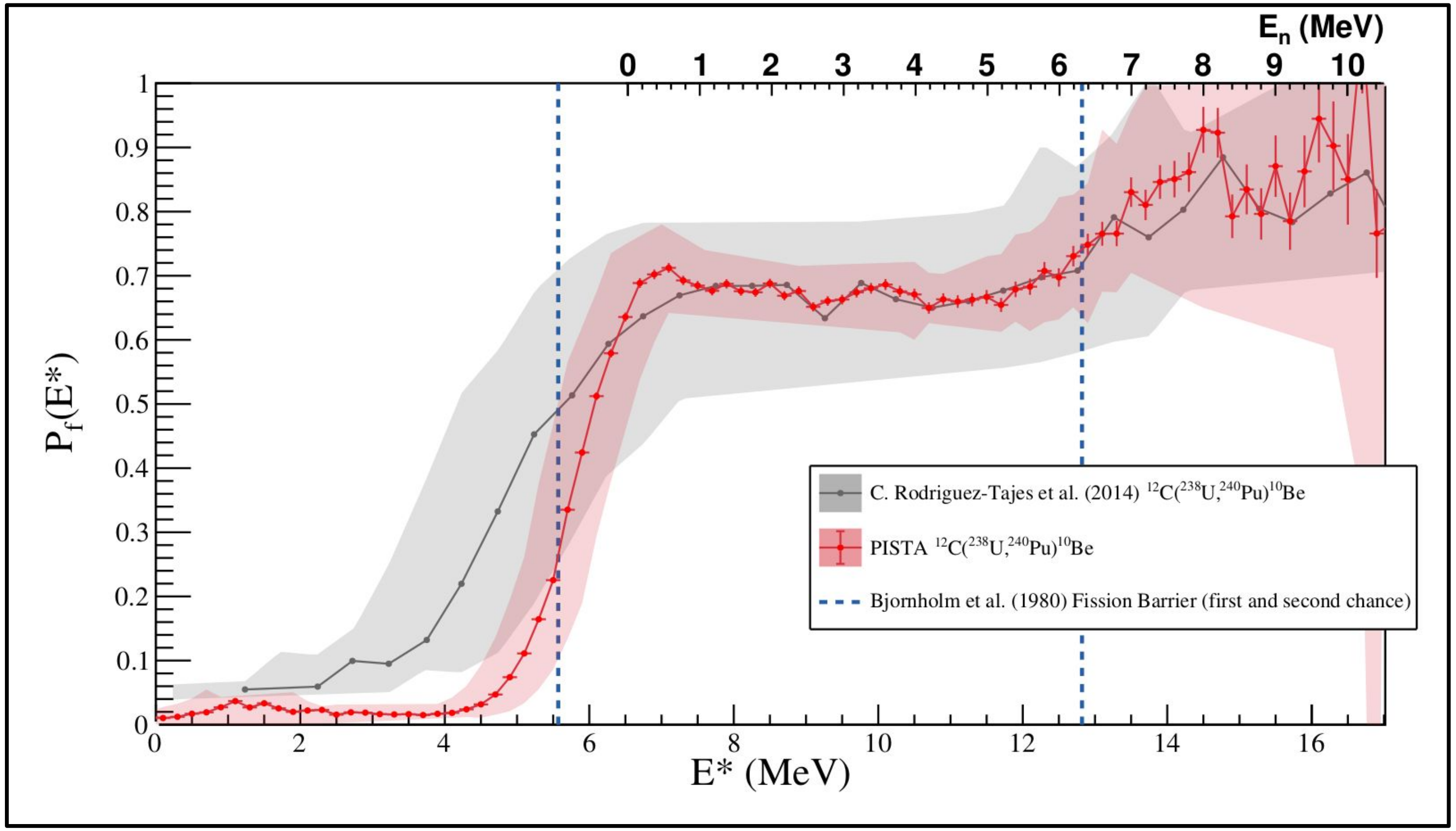


Entrance channel information





1) What is the fissioning system that was formed (Z,A)?
2) **What is the probability of fissioning for a given excitation energy?**



PhD thesis of Lucas Bégué-Guillou

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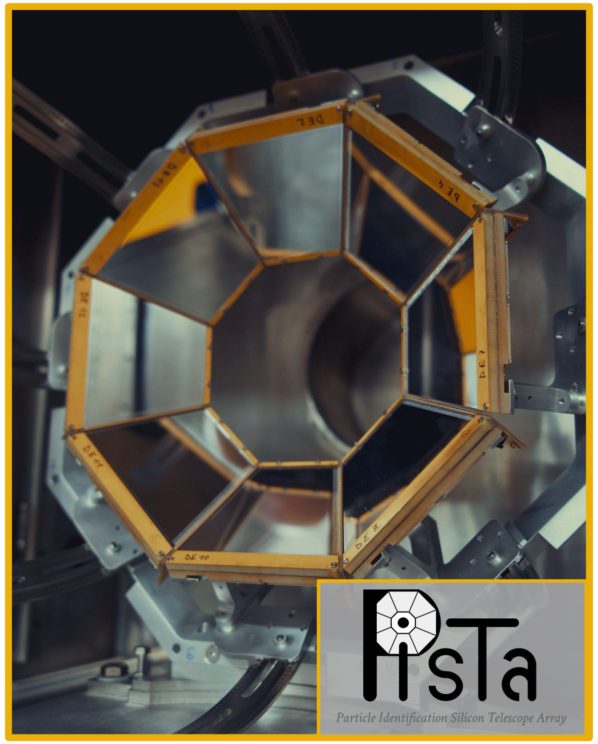
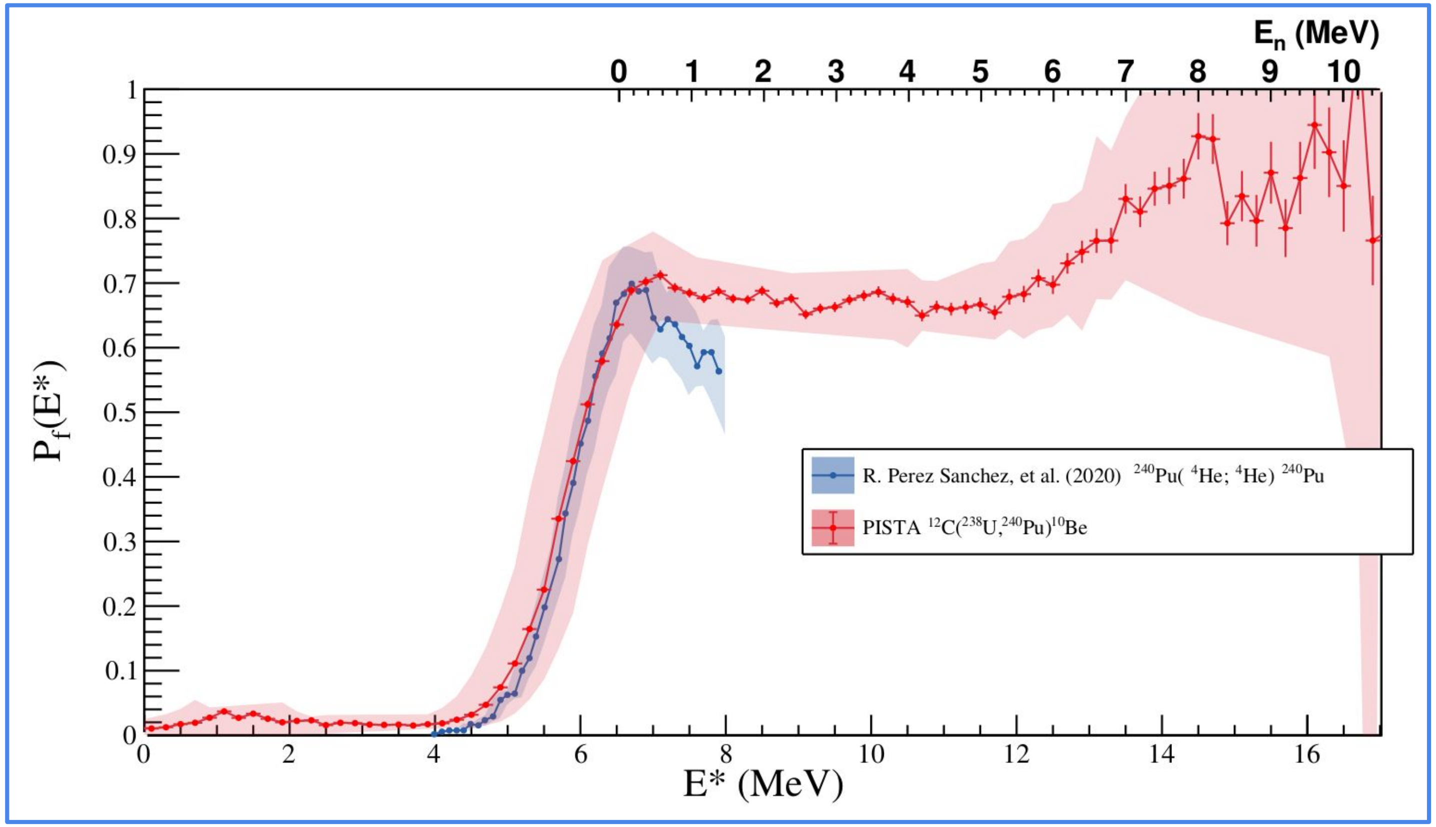
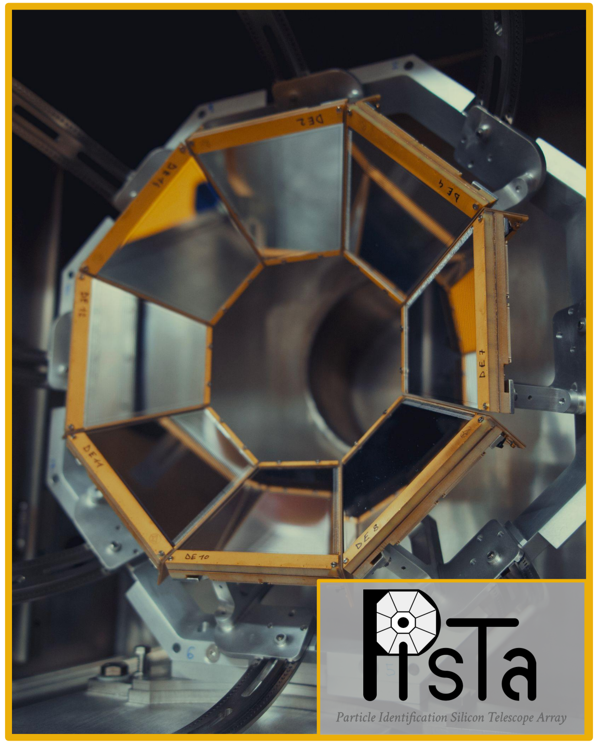
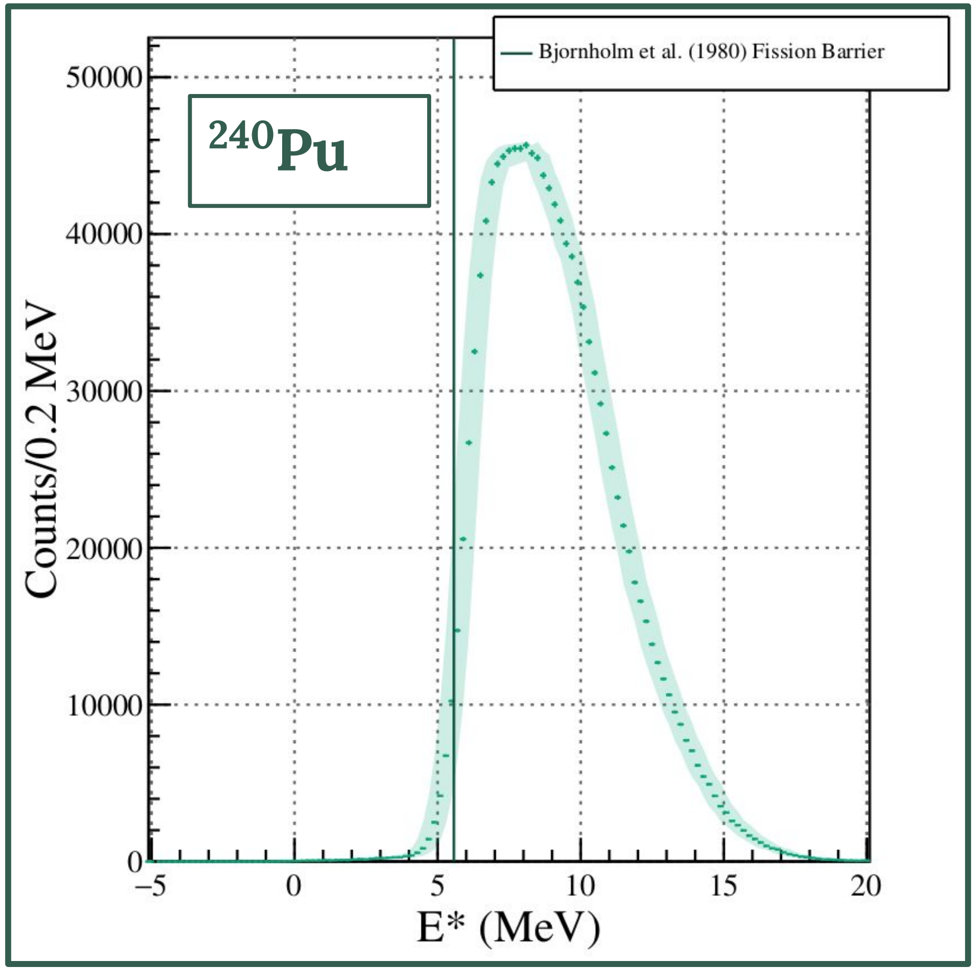




PhD thesis of Lucas Bégué-Guillou (^{238}U + ^{12}C)

Excitation energy distributions





PhD thesis of Lucas Bégué-Guillou (^{238}U + ^{12}C)

Experimental setup: VAMOS++

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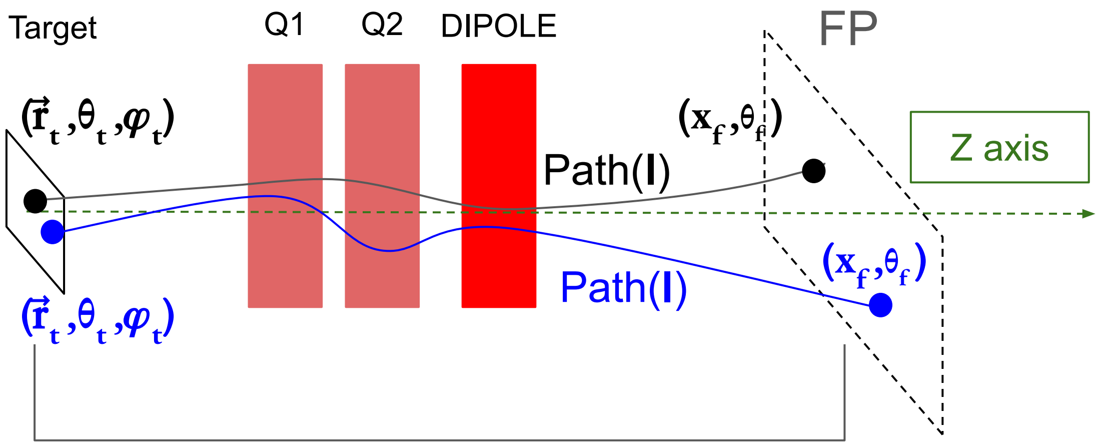
Concept basis

Simulations of trajectories propagating particles through the spectrometer from the target until the focal plane.

Particles with **different Bϱ and entrance coordinates** ($\vec{r}_t$, θ_t, φ_t) will travel a **different path (l)** and arrive at **different position** (x_f, θ_f) at the Focal Plane (FP)

[7] Rejmund, M., & Lemasson, A. (2025). Seven-dimensional trajectory reconstruction for VAMOS++. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1076, 170445.



Simulation distance: 7.6 m

Experimental setup: VAMOS++

Concept basis

Simulations of trajectories propagating particles through the spectrometer from the target until the focal plane.

Particles with **different Bρ and entrance coordinates** ($\vec{r}_t$,θ_t ,φ_t) will travel a **different path (l)** and arrive at **different position** (x_f ,θ_f) at the Focal Plane (FP)

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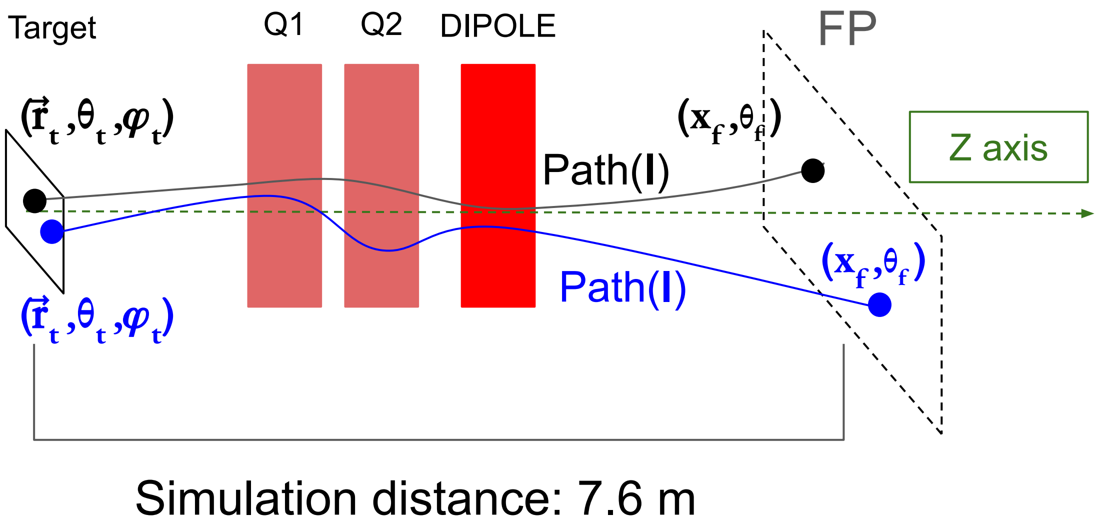
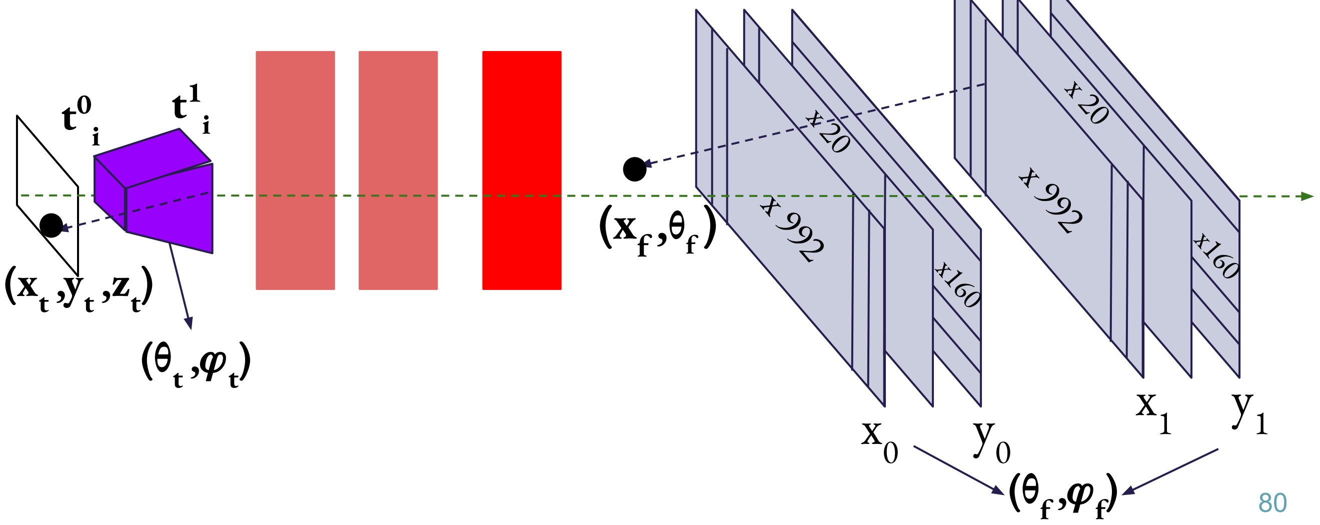


Experimentally

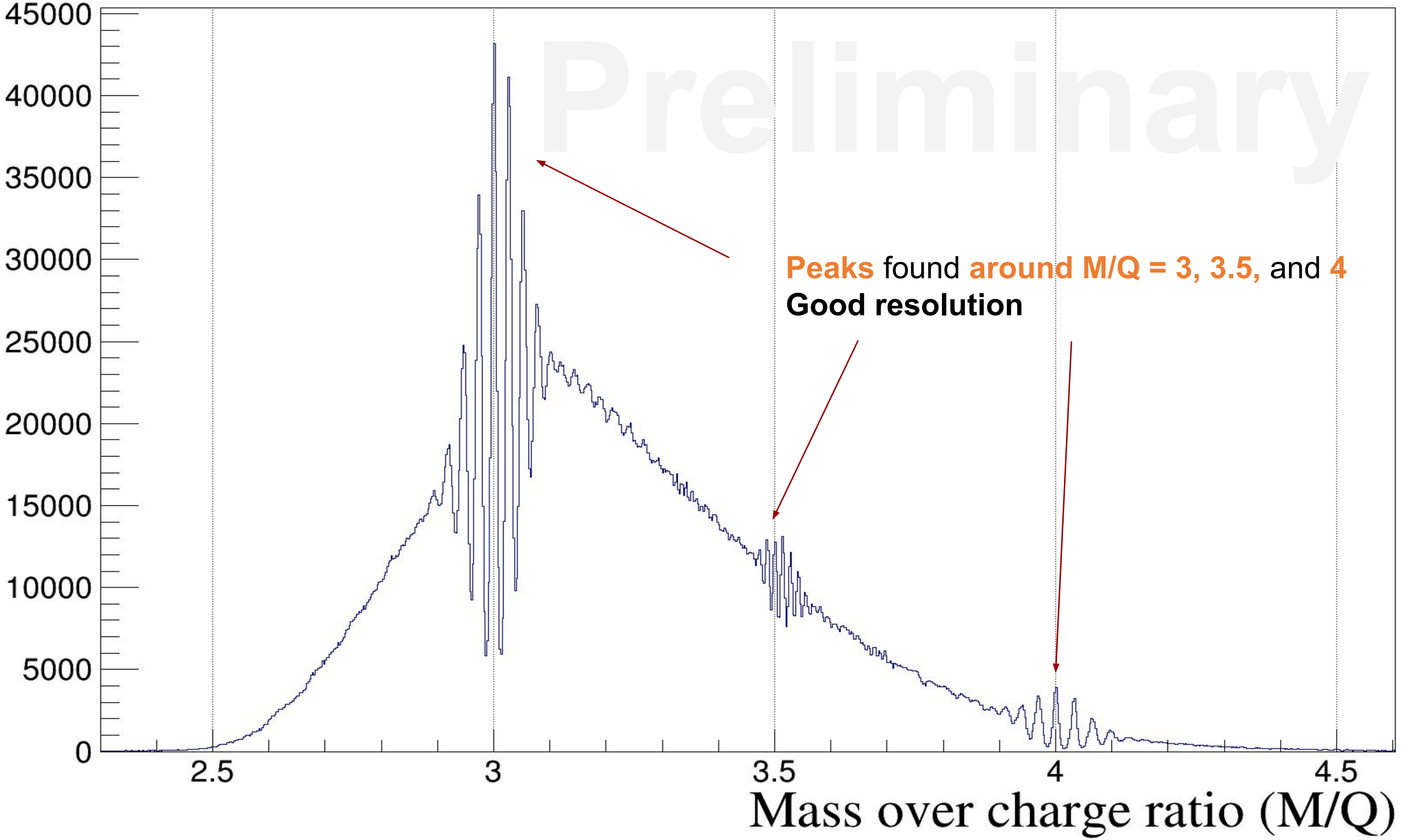
A pair of Multi-Wire Proportional counters (MWPC) at the target determine the **entrance coordinates** and **start time** (t_i)
A pair of MWPCs at the exit determine the **focal plane coordinates** and **20 stop times** (t_f)

From measured positions, we extract the **Bρ and l** of a fragment
Combining it with the **ToF (t_f - t_i)**, we get the **velocity and M/Q**:

V = D/T => β,γ
M/Q = **Bρ**/(3.107*β*γ)



Experimental result: M/Q



VAMOS ++ : Ionization Chamber

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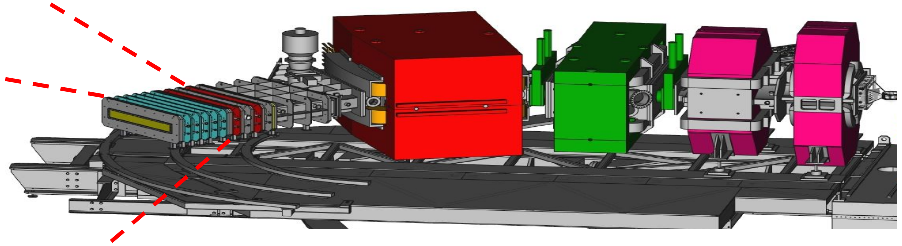

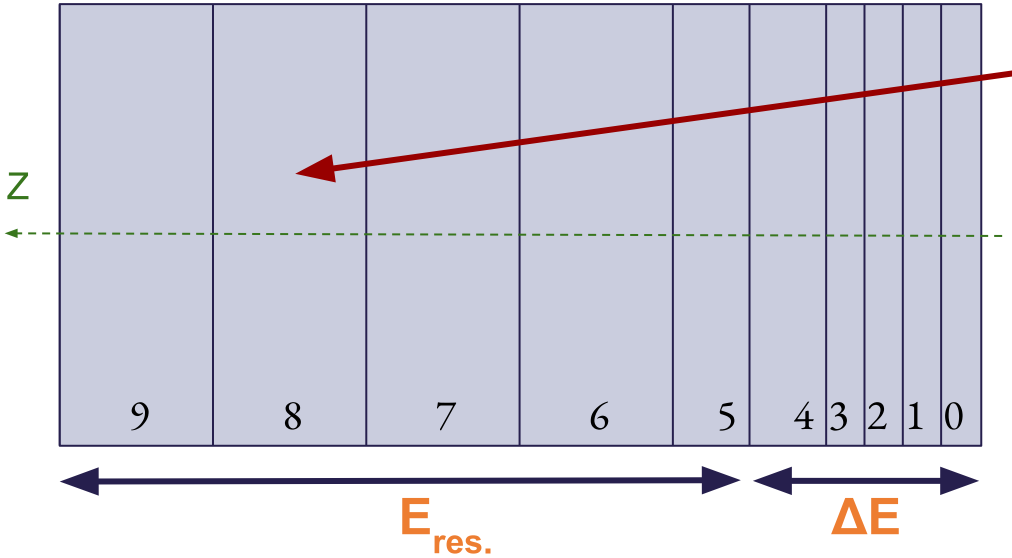

ΔE - $E_{res.}$ technique to extract the **nuclear charge (Z)**

The **kinetic energy (E_{Kin})** of the fragment is proportional to the **mass** and the **velocity (γ)**

Through a **minimization method**, **scale** the contribution of **each IC** section for every time section

$E_{Kin} = \Sigma a_i * IC_i + b_0$
$A_{IC} = E_{Kin} / (\gamma_{VAMOS} - 1)$

The **A_{IC} is not enough** (~1%) for our goal :
$Q = A_{IC}/(A/Q)$

Experimental result: Q

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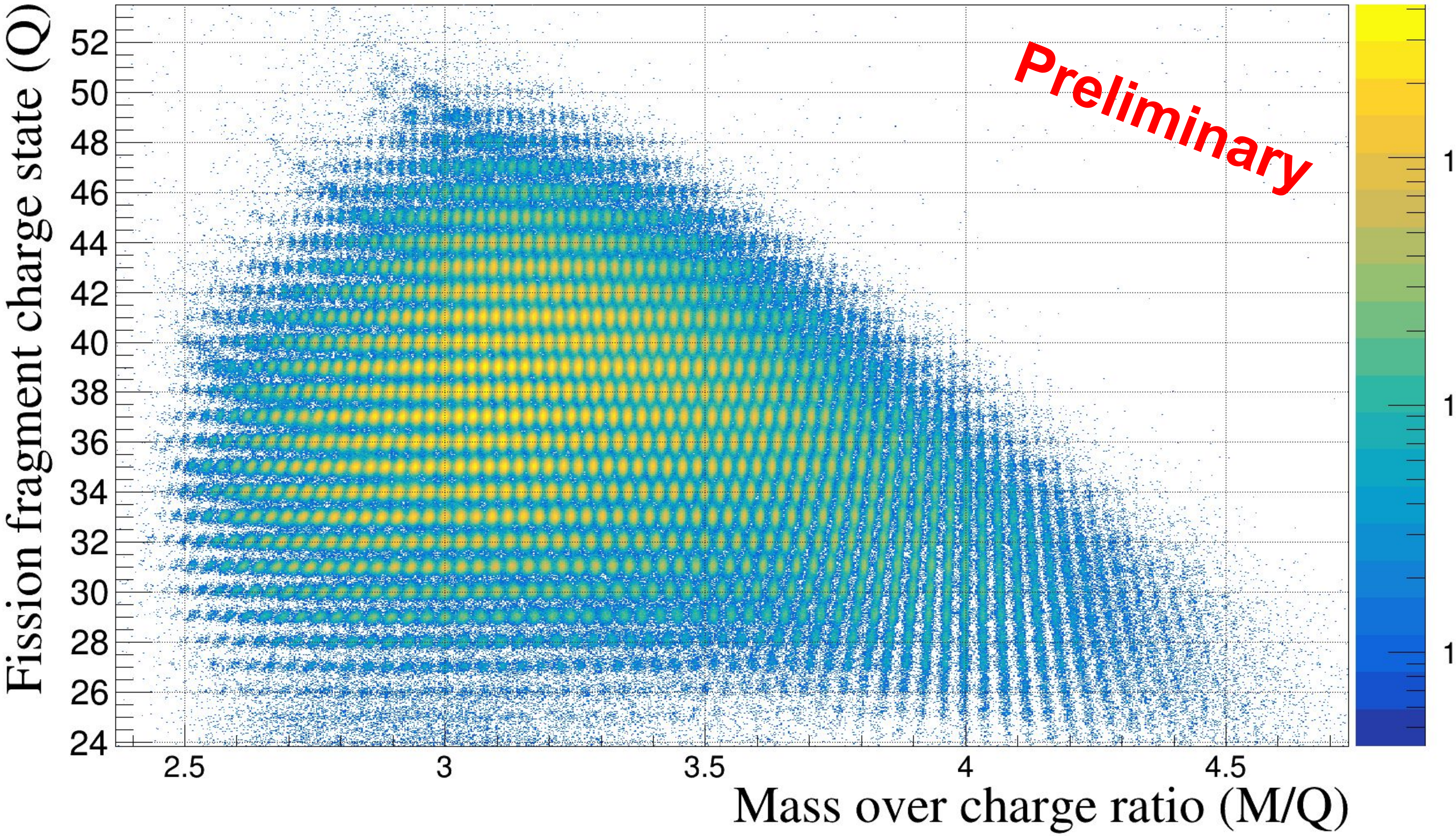
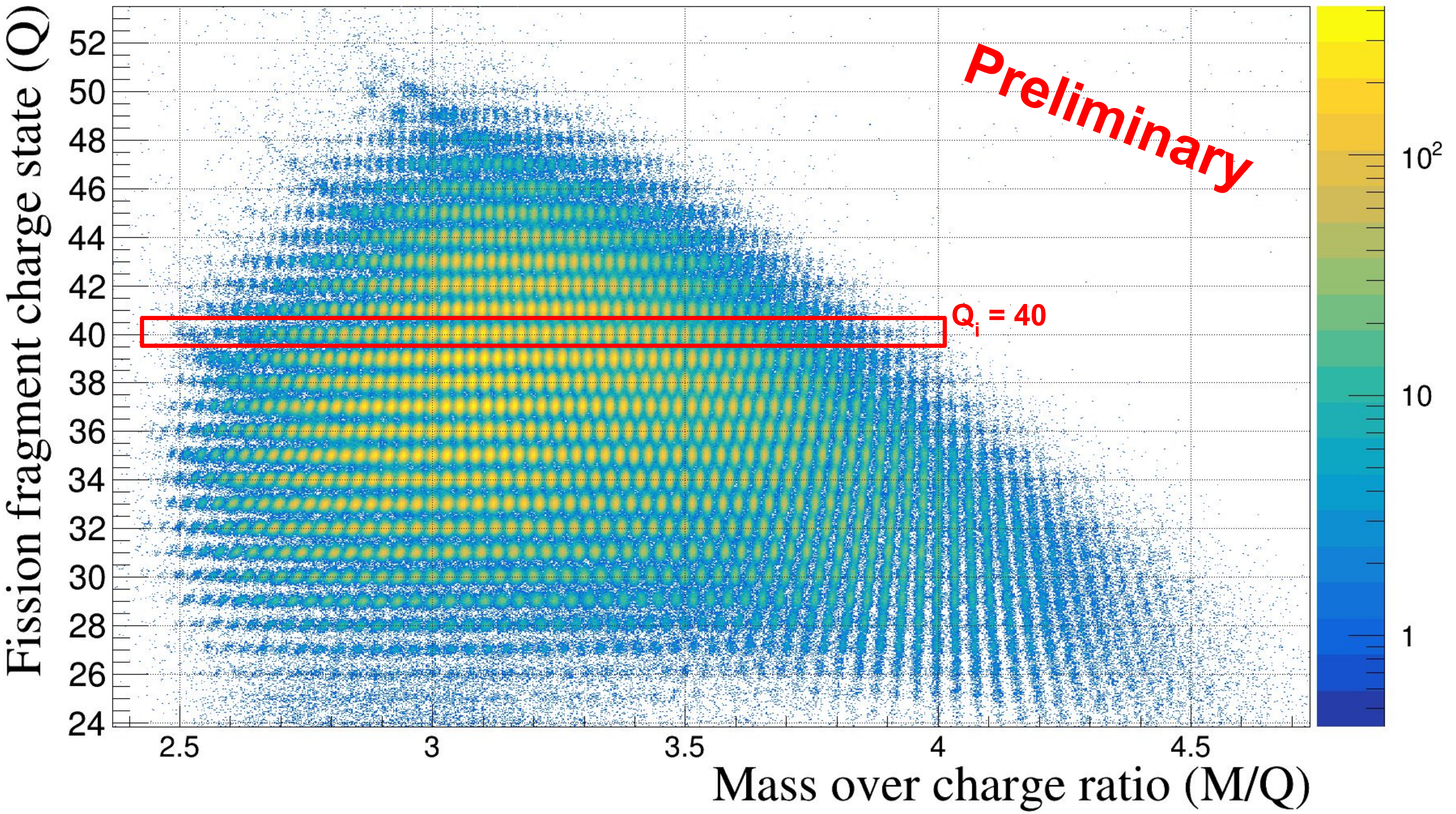


Experimental result: Q and M



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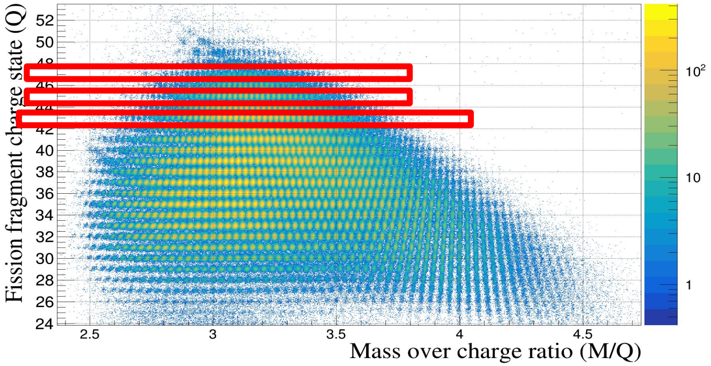
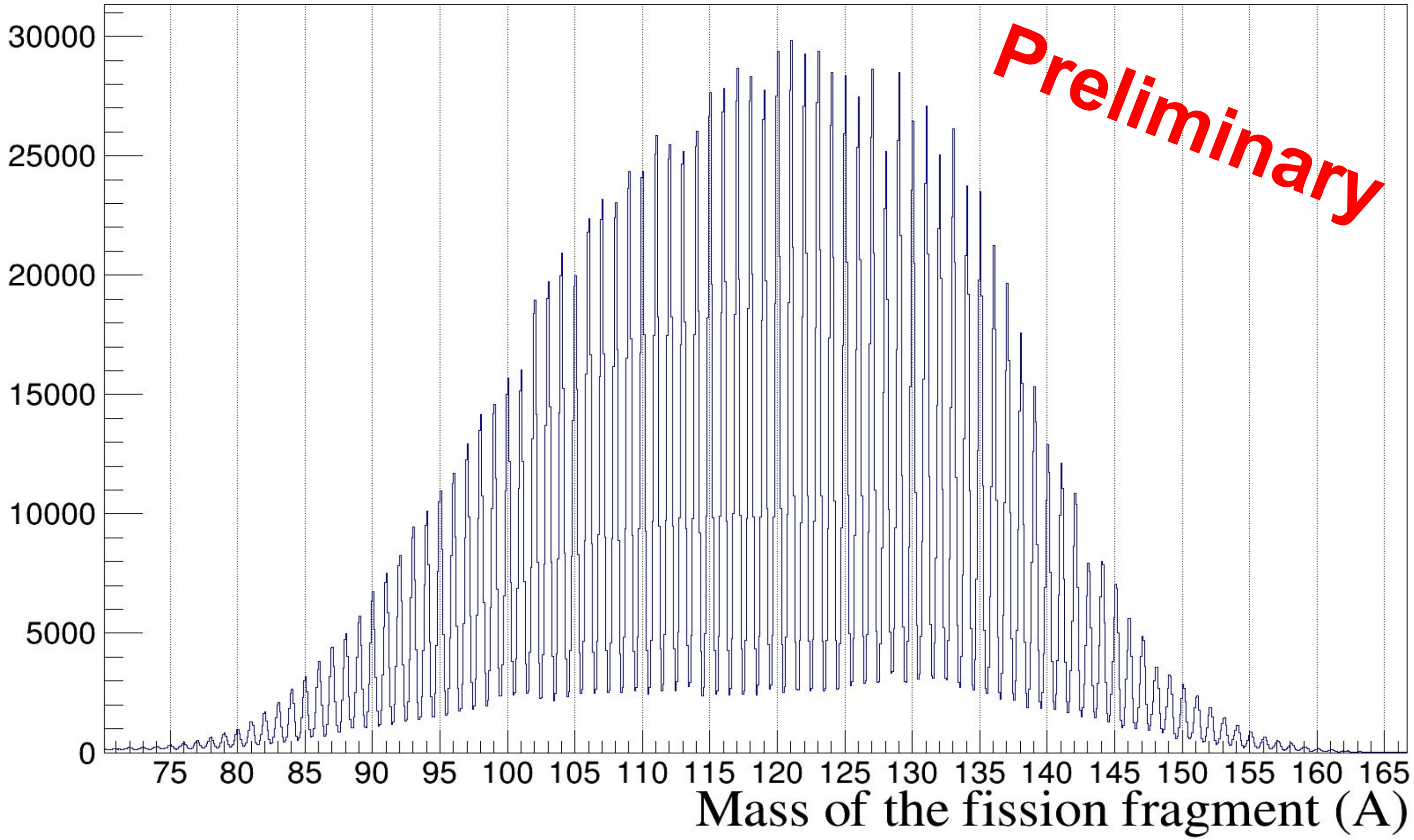


M = Q_i * M/Q

Average resolution of **ΔA/A ~** 1/234 = **4.27 ‰**



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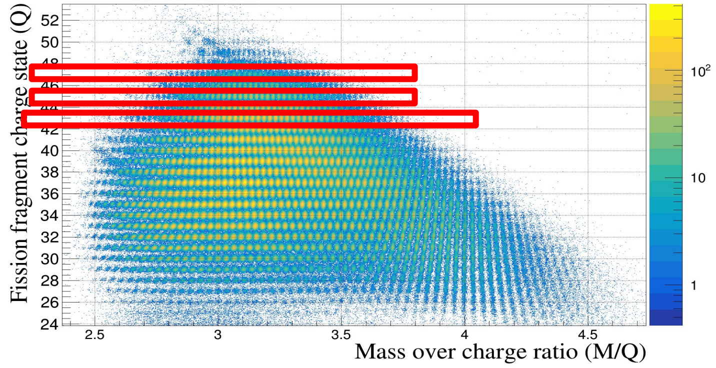
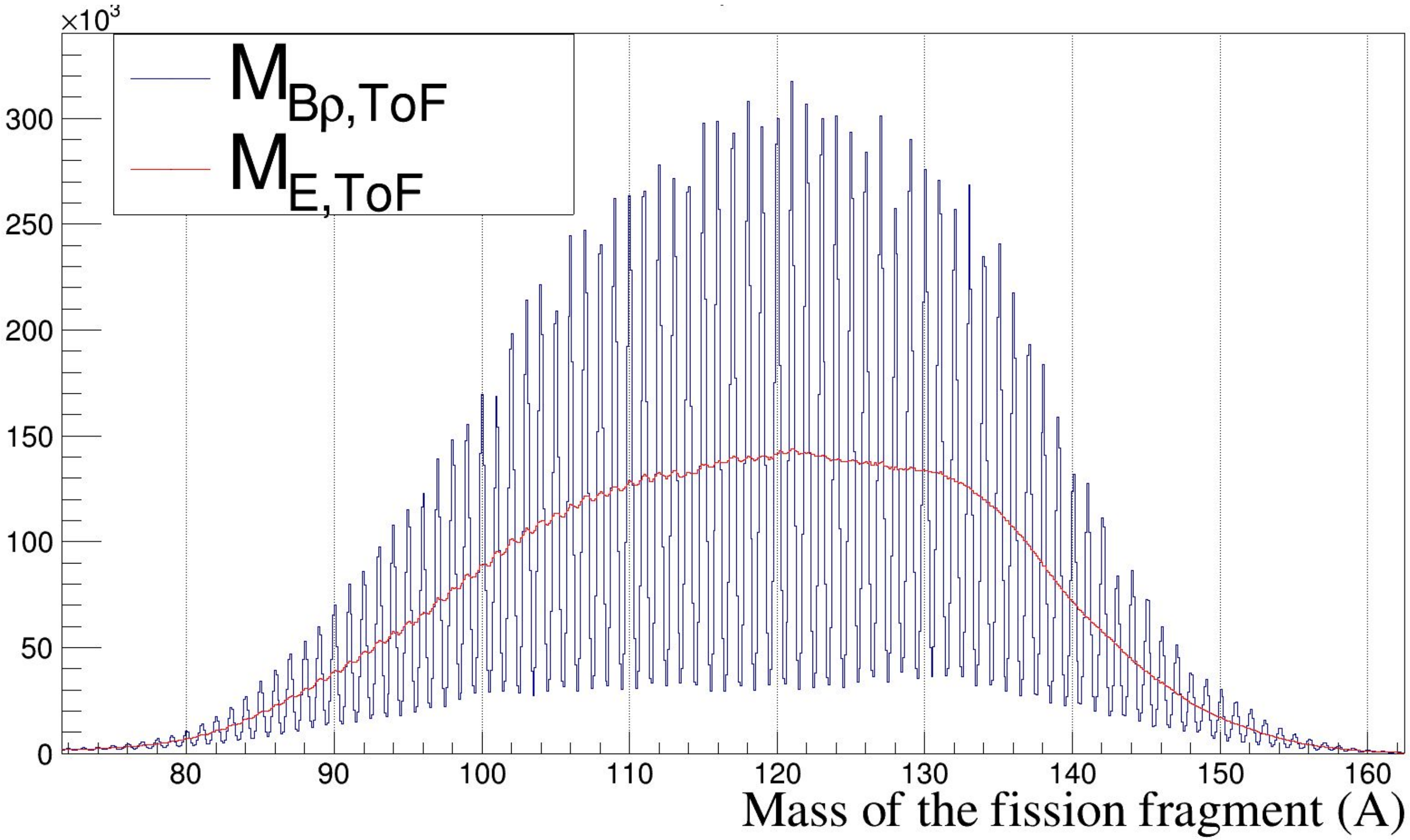


Preliminary

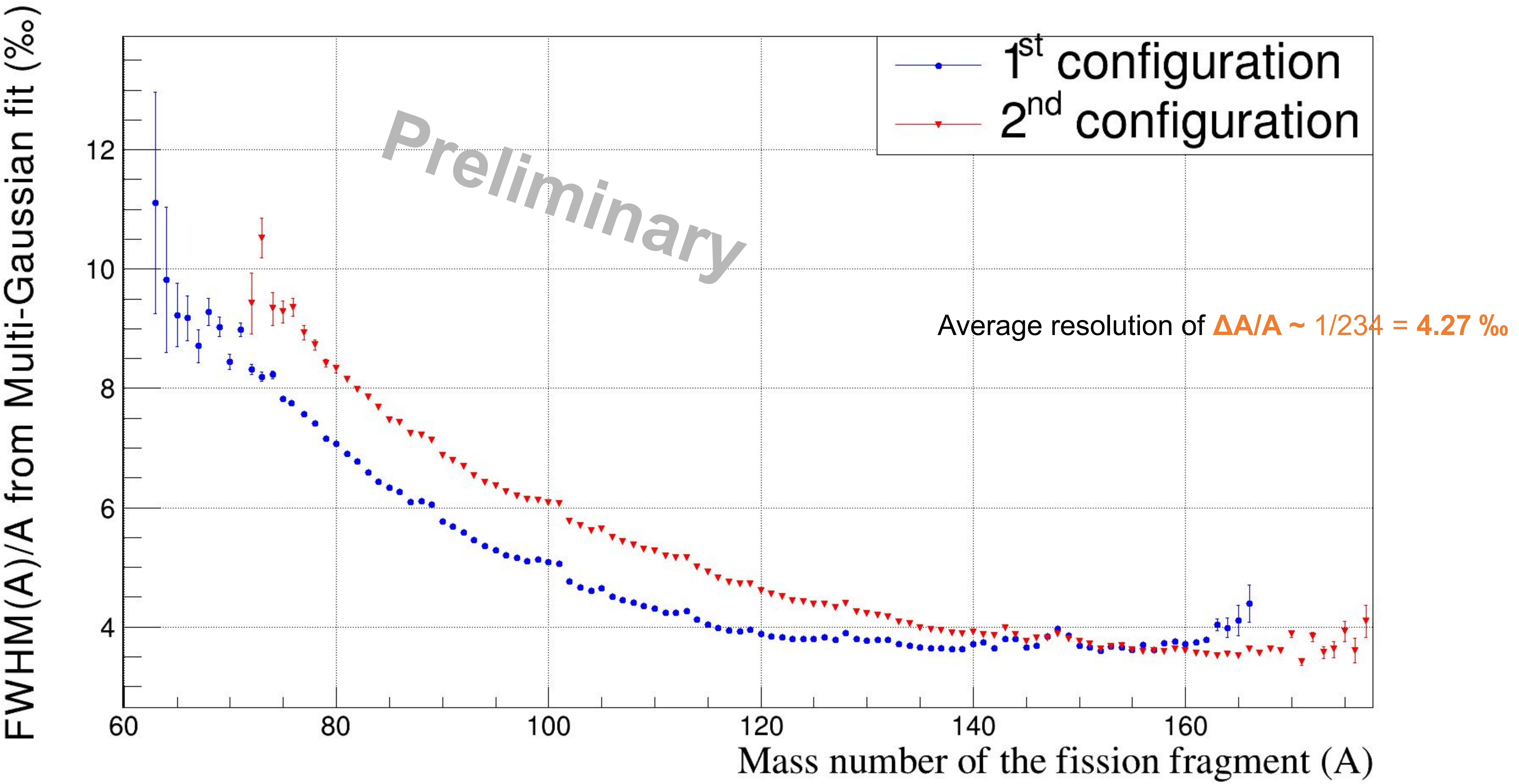
Mass resolution improvement thanks to the **VAMOS++ spectrometer**

$M = Q_i * M/Q$

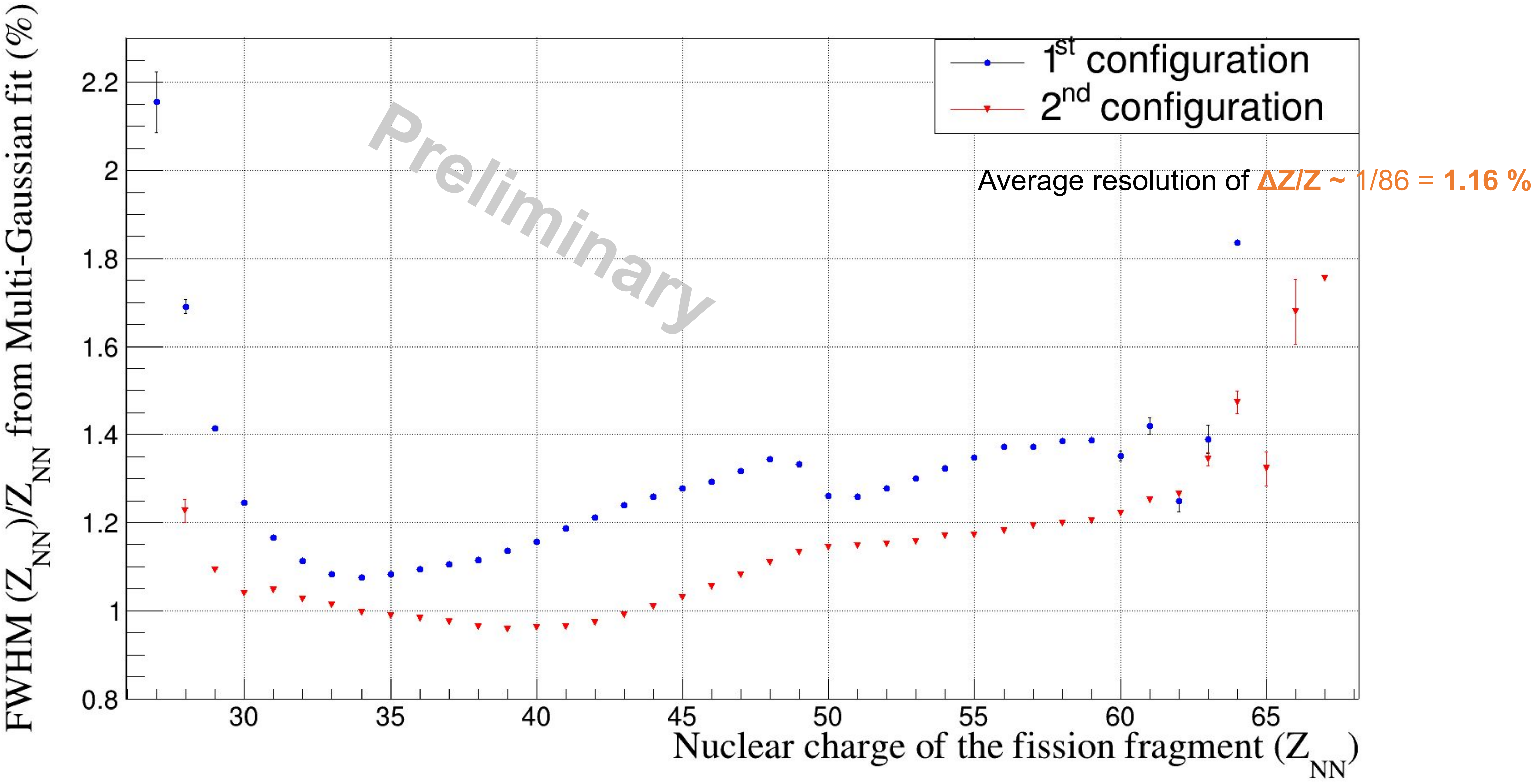
Average resolution of **ΔA/A ~** 1/234 = **4.27 ‰**



Fission fragment identification: A



Fission fragment identification: Z



Experimental identification confirmation

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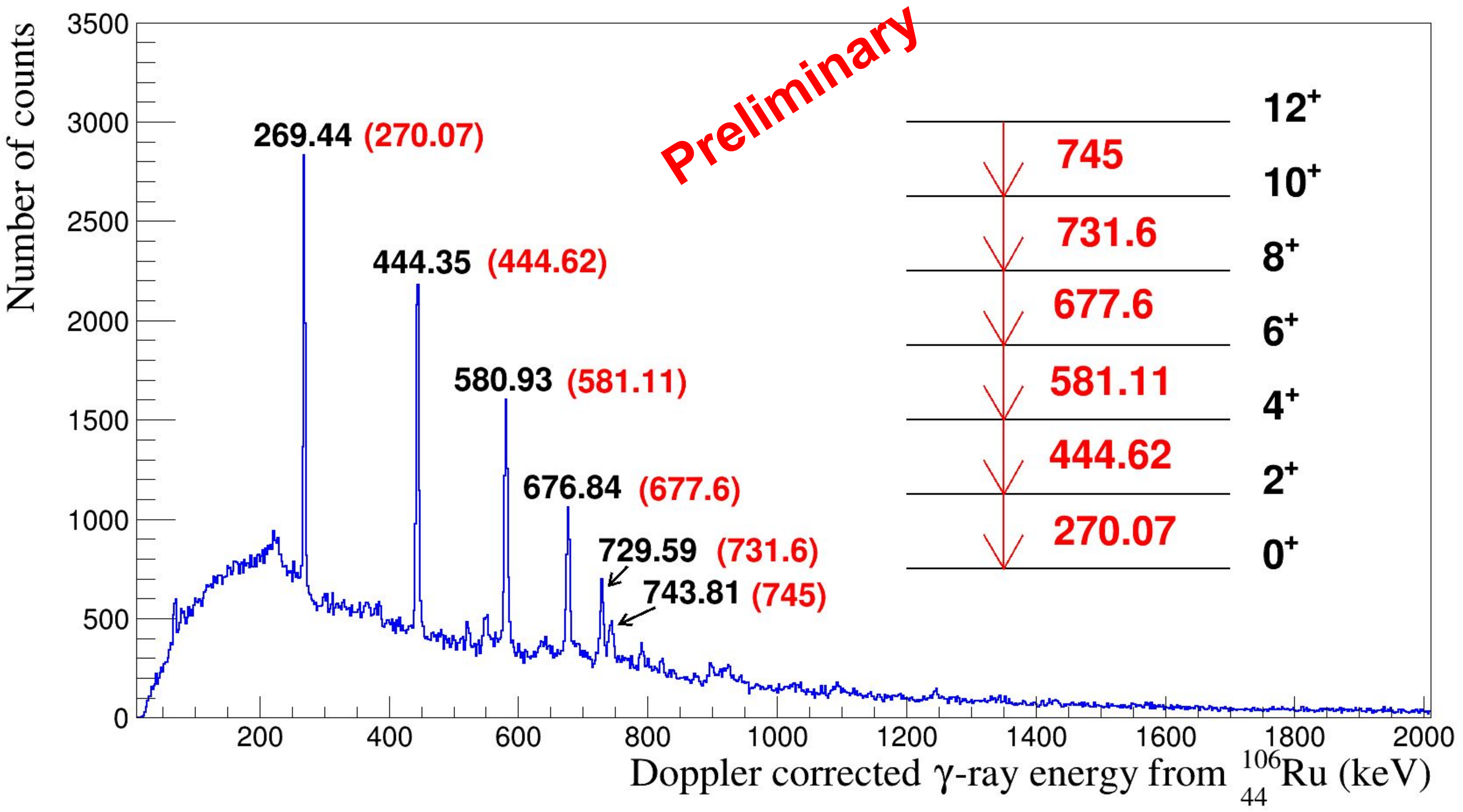
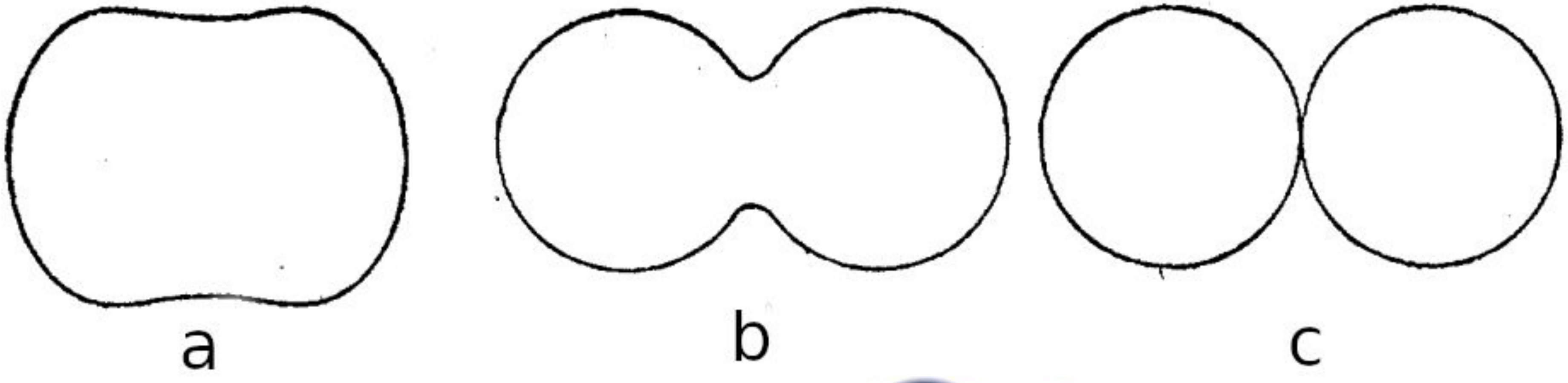
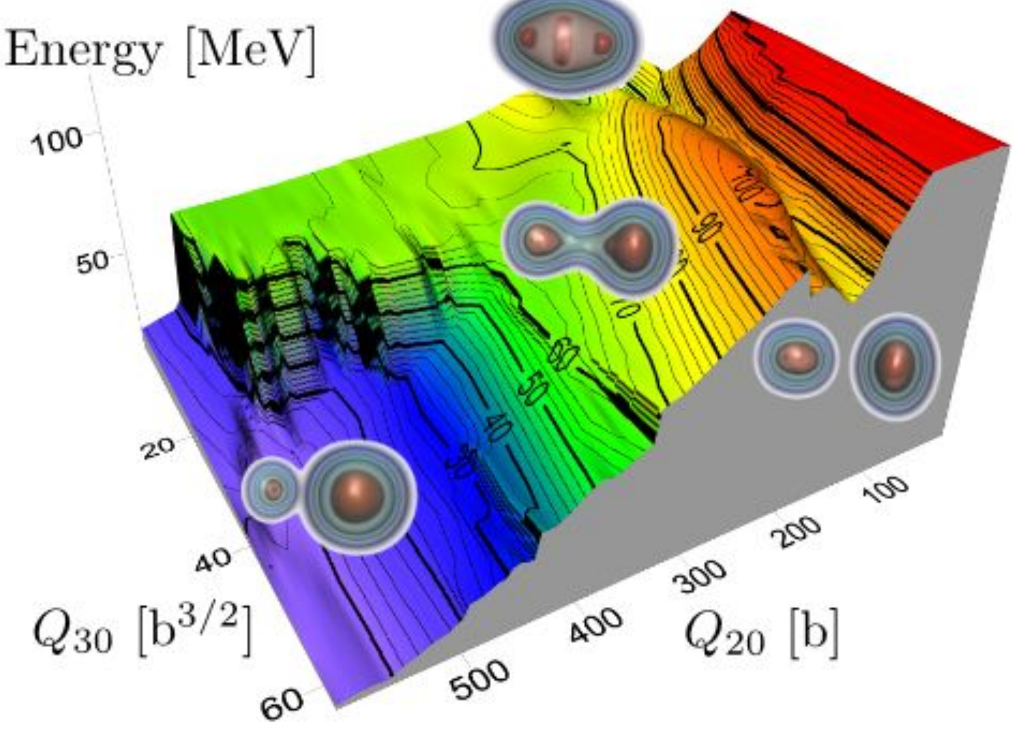


The fission process





Unestable competition between surface tension (Nuclear force) and repulsion (Coulomb) leads to deformation and split of a heavy nucleus into 2 fragments

The potential energy surface (PES) represents the energy of the system at a given deformation

More **complex PES** can be calculated for **2, 3, etc. deformation parameters**

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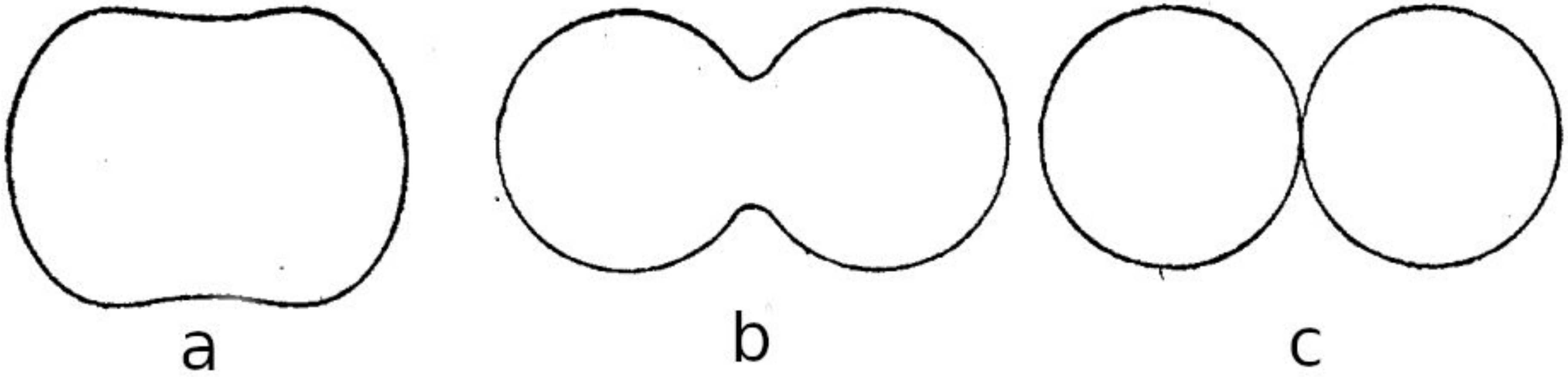

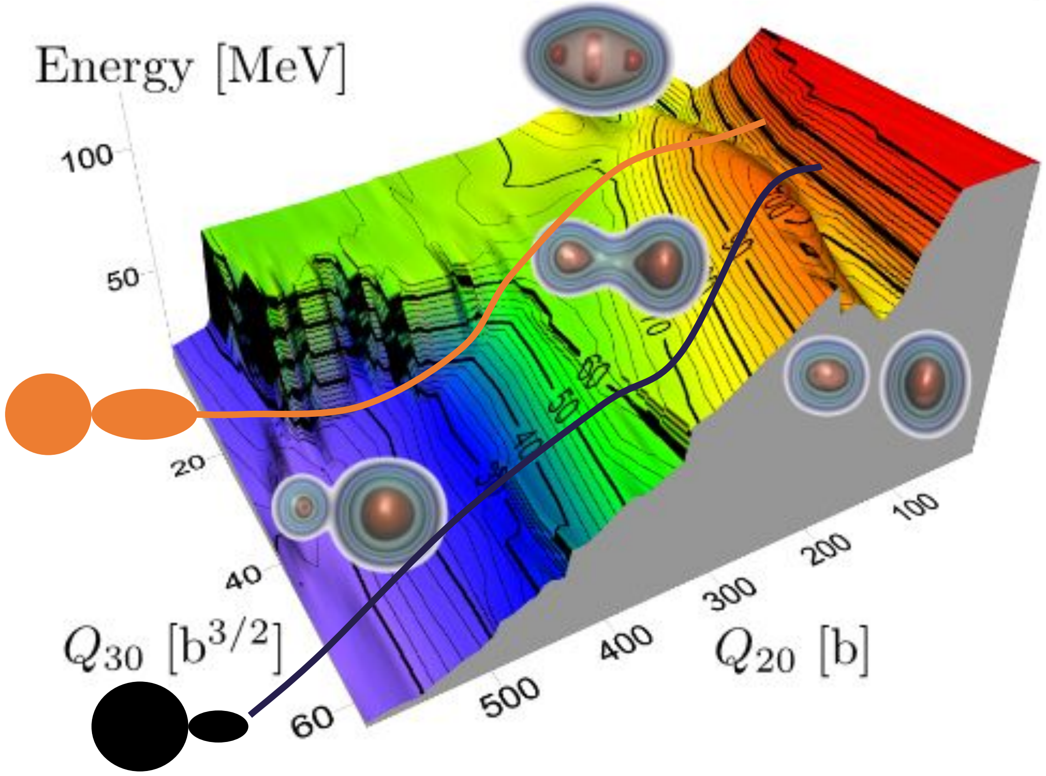

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↓

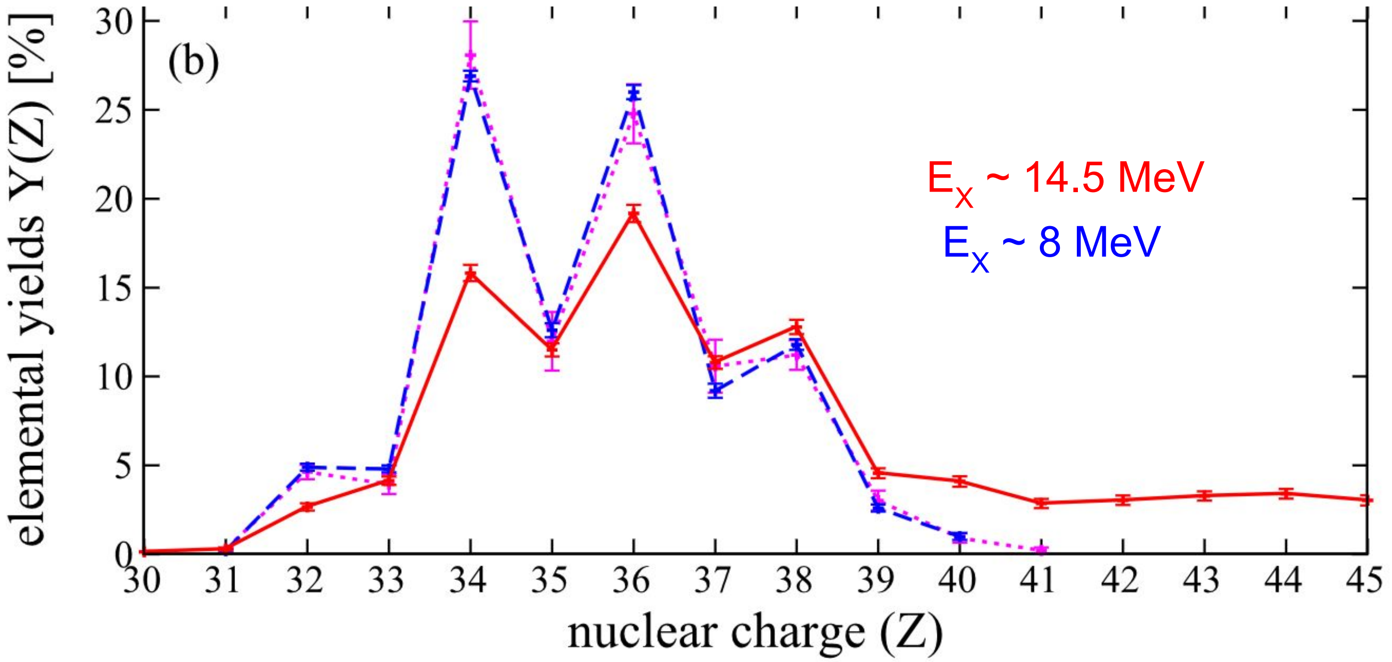
The **possible paths** the system can have through the surface define the probabilities of the **final configurations of the fragments**

Fission observables: yields

The **probability of producing a fission fragment** with a given A, Z, N, etc. :

$$Y(Z,A) = 200 \cdot \frac{N(Z,A)}{\sum_{Z,A} N(Z,A)}$$

^{230}**Th elemental yields also** show this **evolution** as a function of **excitation energy**



Chatillon, A., Taïeb, J., Alvarez-Pol, H., Audouin, L., Ayyad, Y., Bélier, G., ... & Weick, H. (2020). Evidence for a new compact symmetric fission mode in light thorium isotopes. *Physical Review Letters, 124(20), 202502.*

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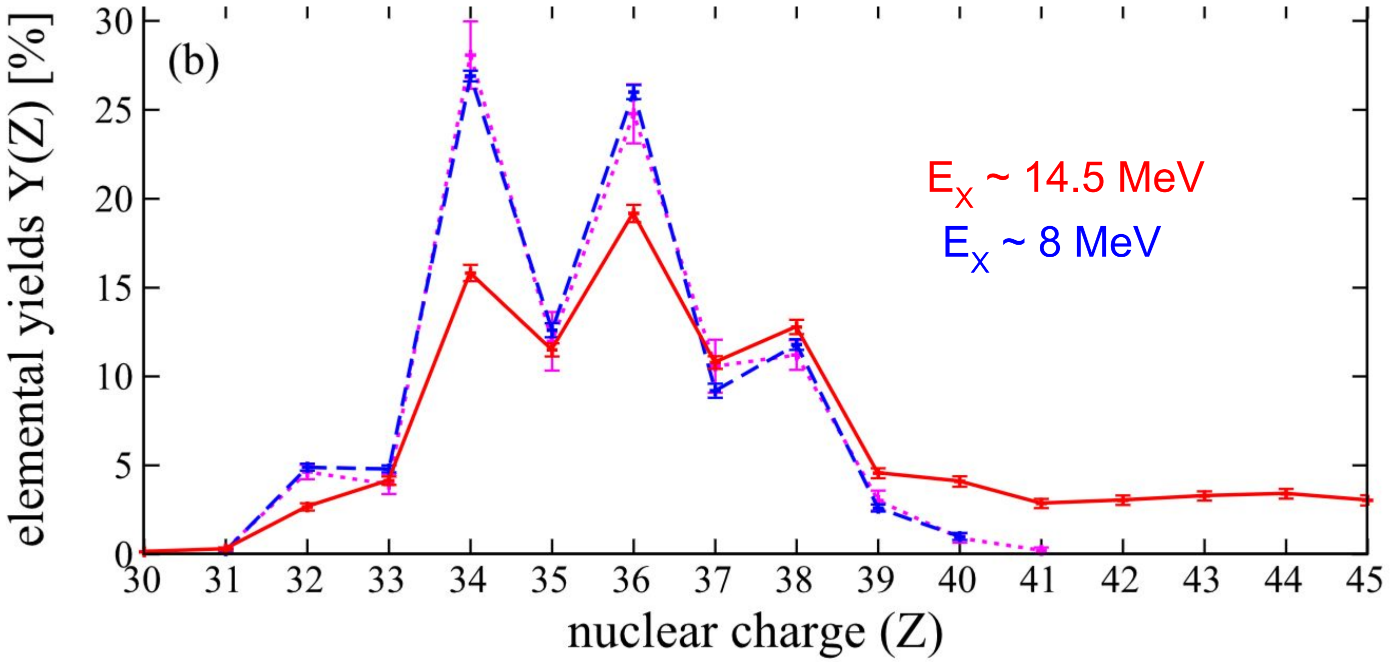
THORIUM ANOMALY (2)



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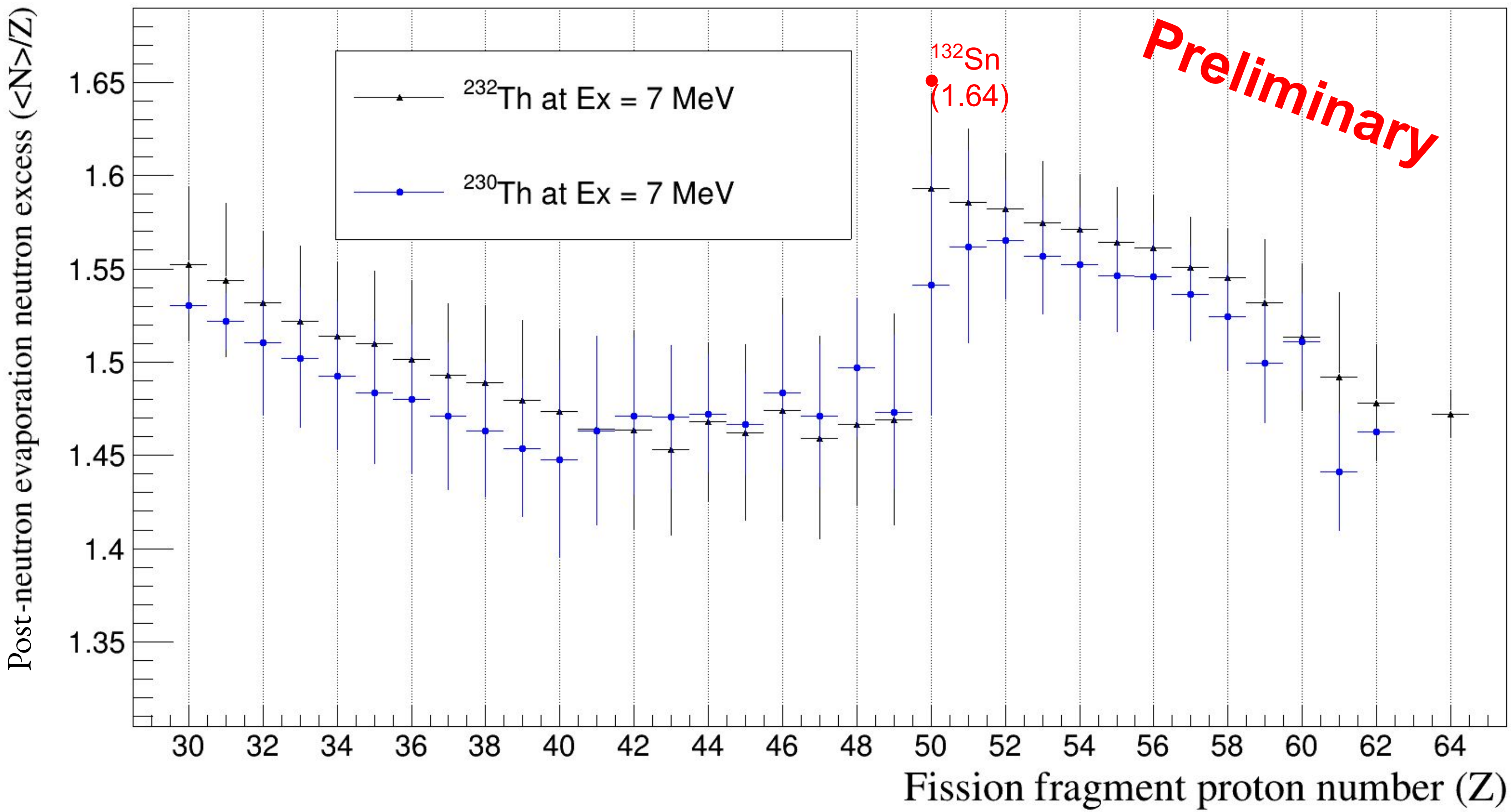
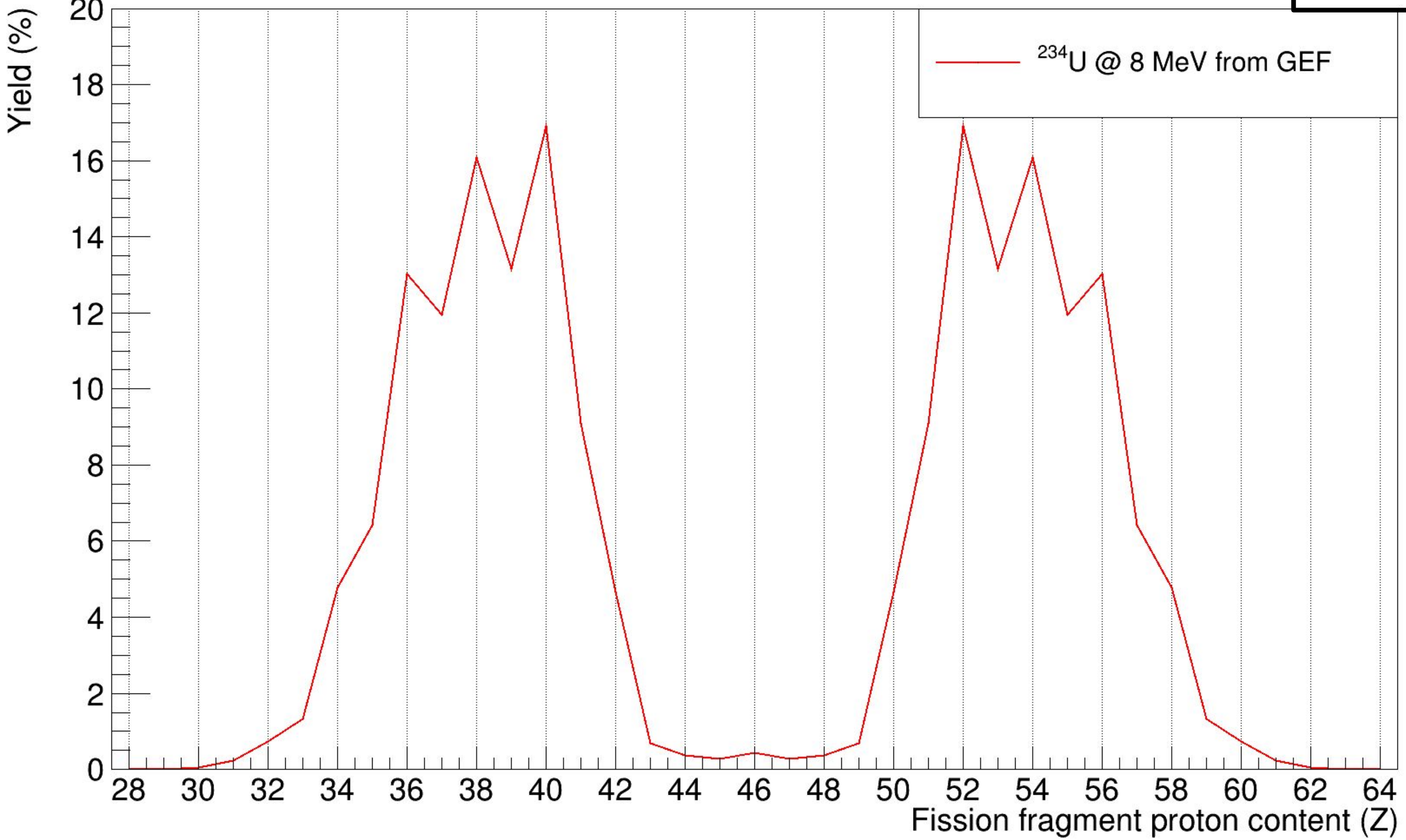
Neutron excess @ 7 ± 1 MeV



Elemental yields of ^{234}U



Yield: $Y(Z,A) = 200 * N(Z,A) / \sum_i N(Z_i, A_i)$

1. Choose your fissioning system
1. **Get the Z from VAMOS**

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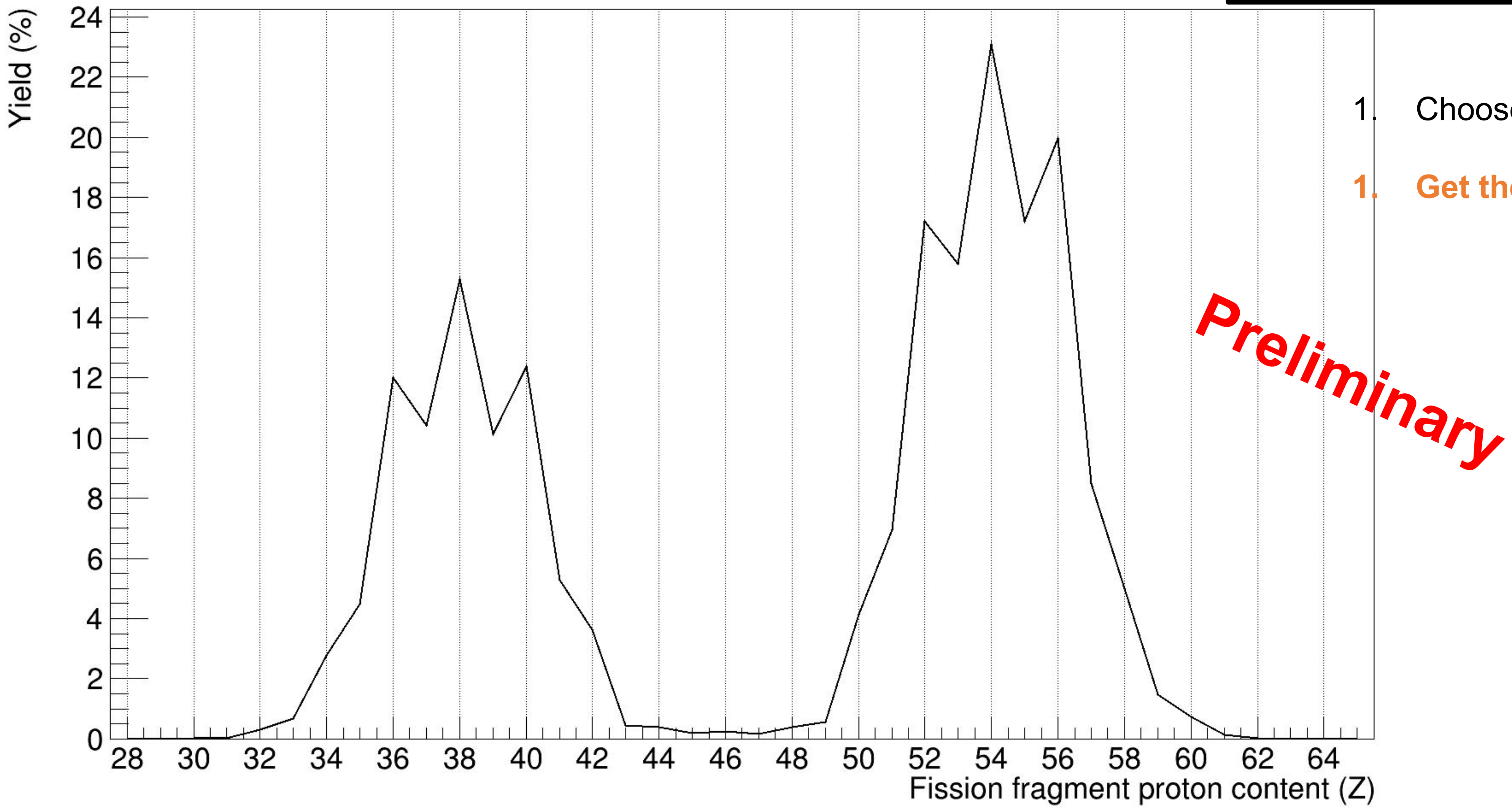

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Elemental yields of ^{234}U

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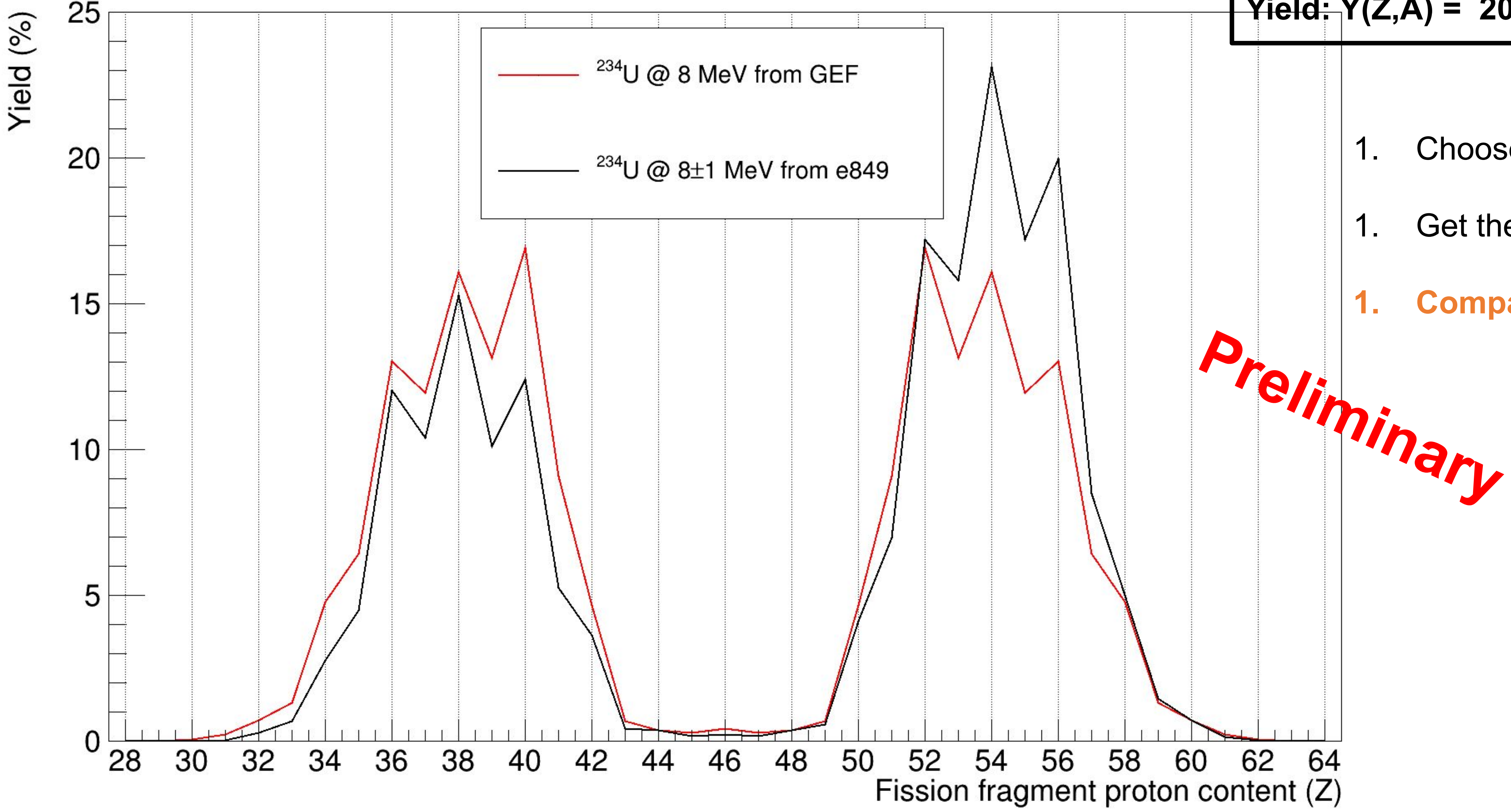

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1. **Compare with data/model**

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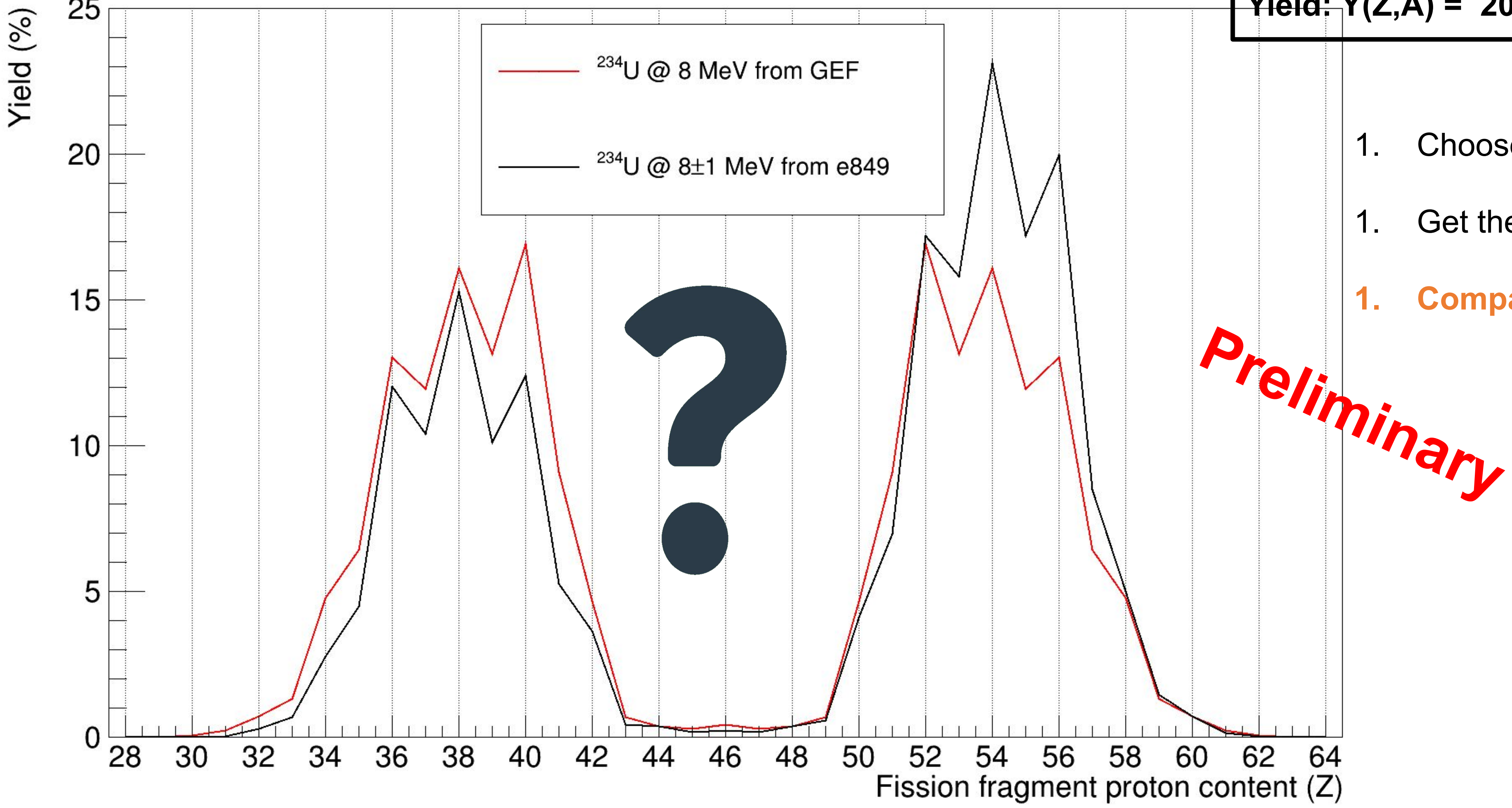

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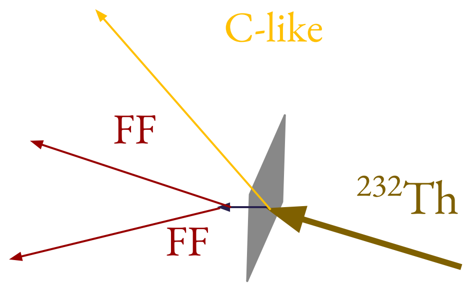
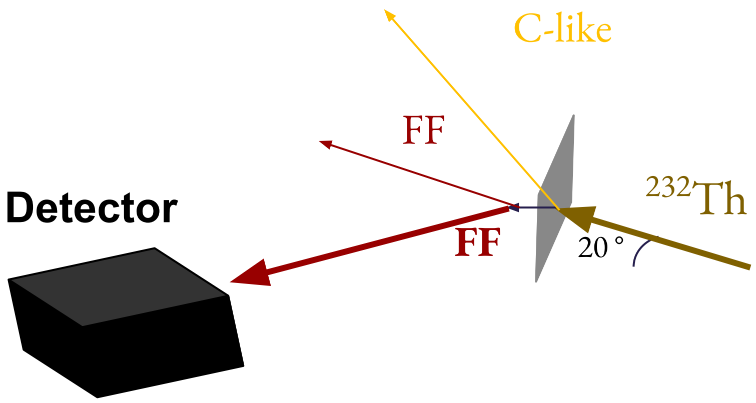
Spectrometer acceptance

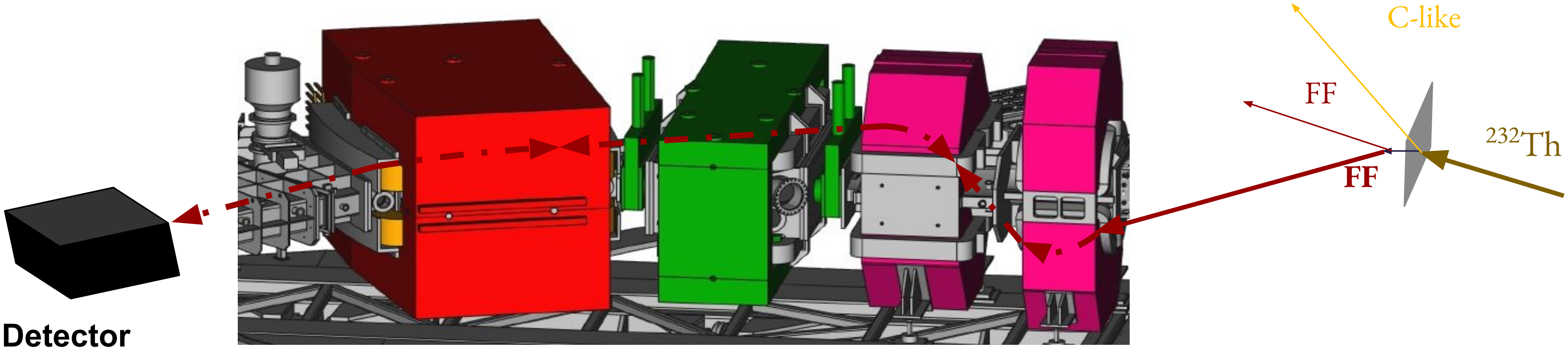


Spectrometer acceptance



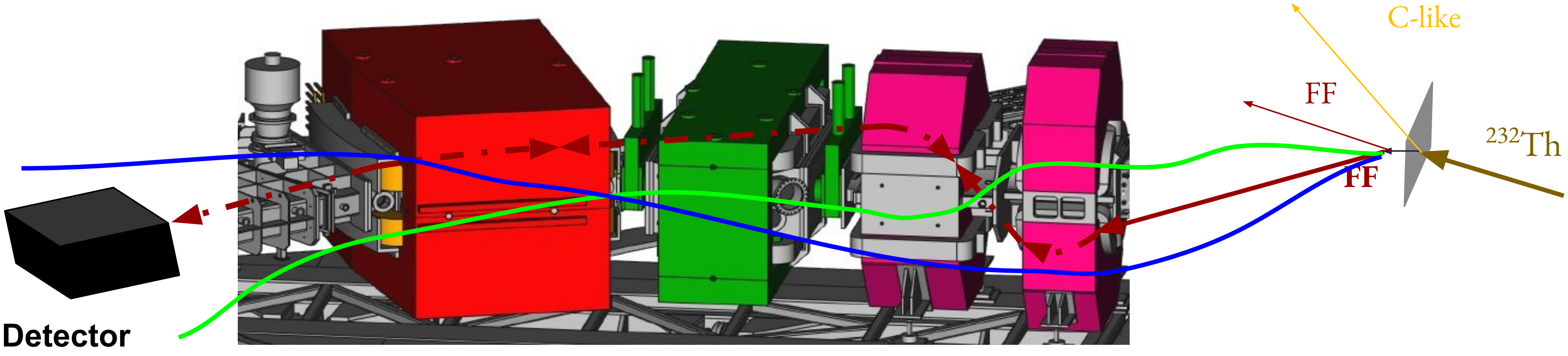
Direct measurement

Spectrometer acceptance

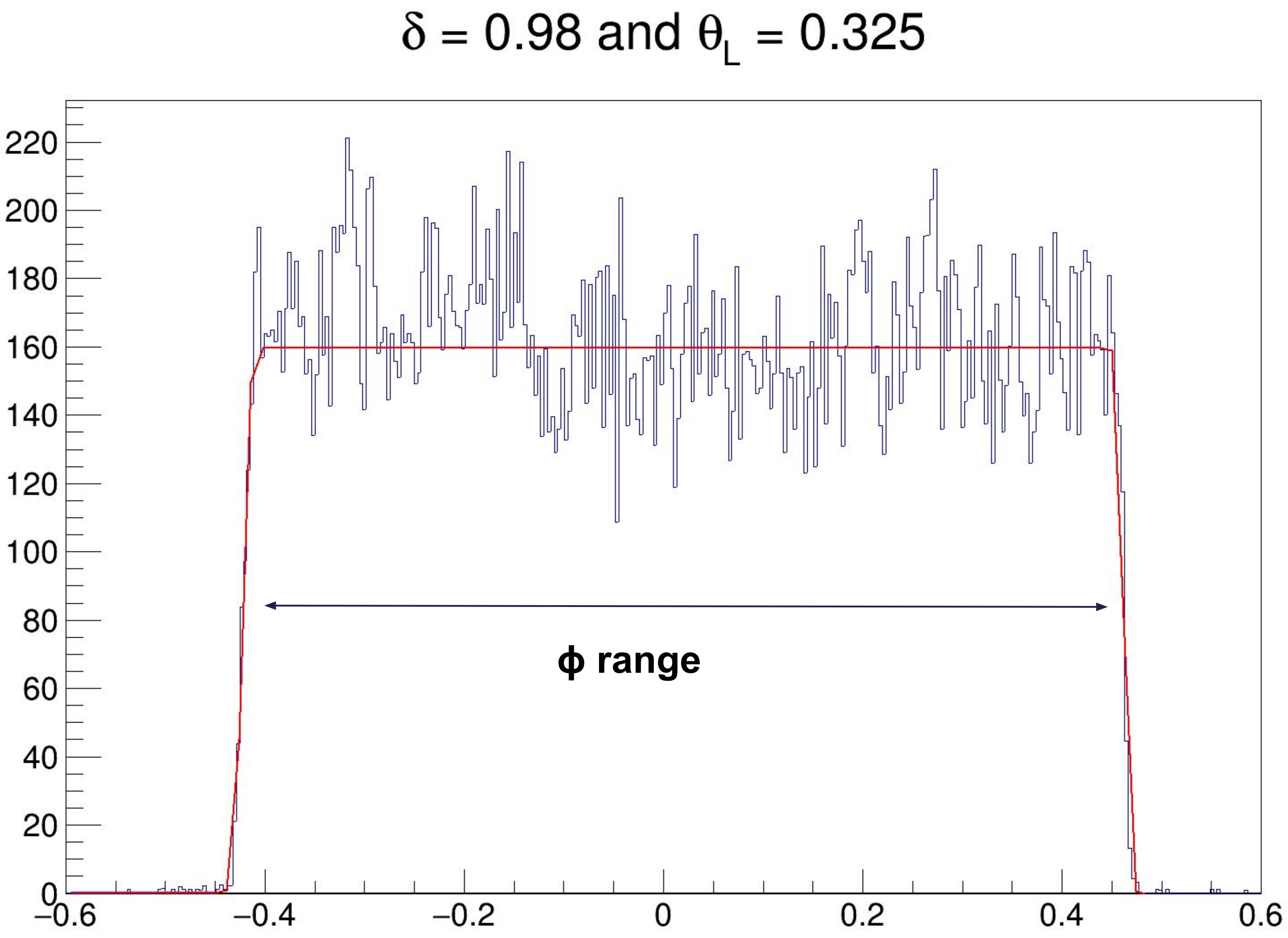


Spectrometer acceptance

We need to account for the trajectories that were not measured due to the different kinematics of the particle



From identification to acceptance: ϕ range



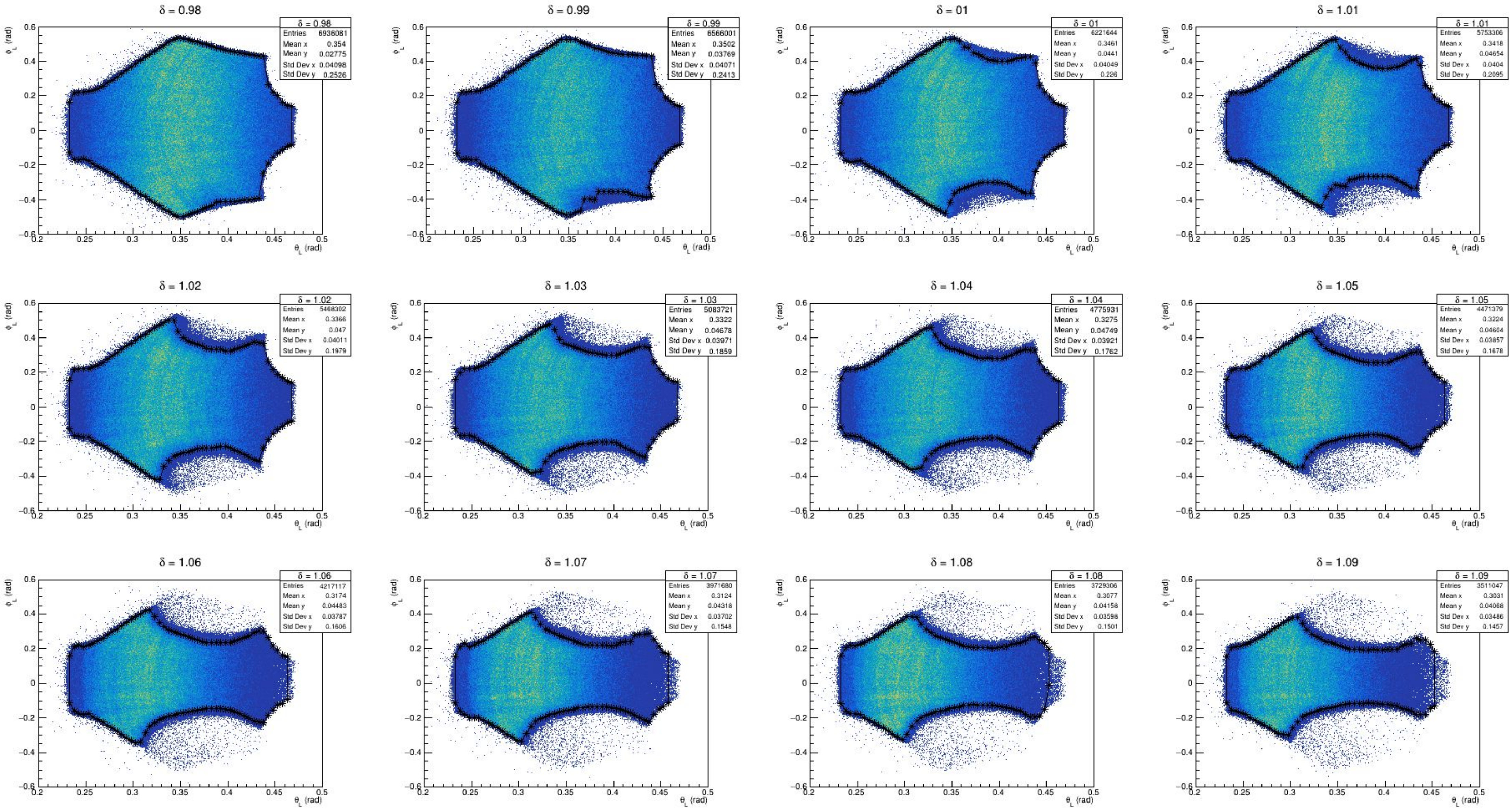
δ : Relative magnetic rigidity with respect to the central value

θ_L : polar angle in the laboratory frame

Get the ϕ range for a given δ ($B\varrho/B\varrho_{REF}$)

Fission fragments are emitted isotropically:
f_ϕ = 2π /(ϕ range)

From identification to acceptance: ϕ range



From identification to acceptance: ϕ range

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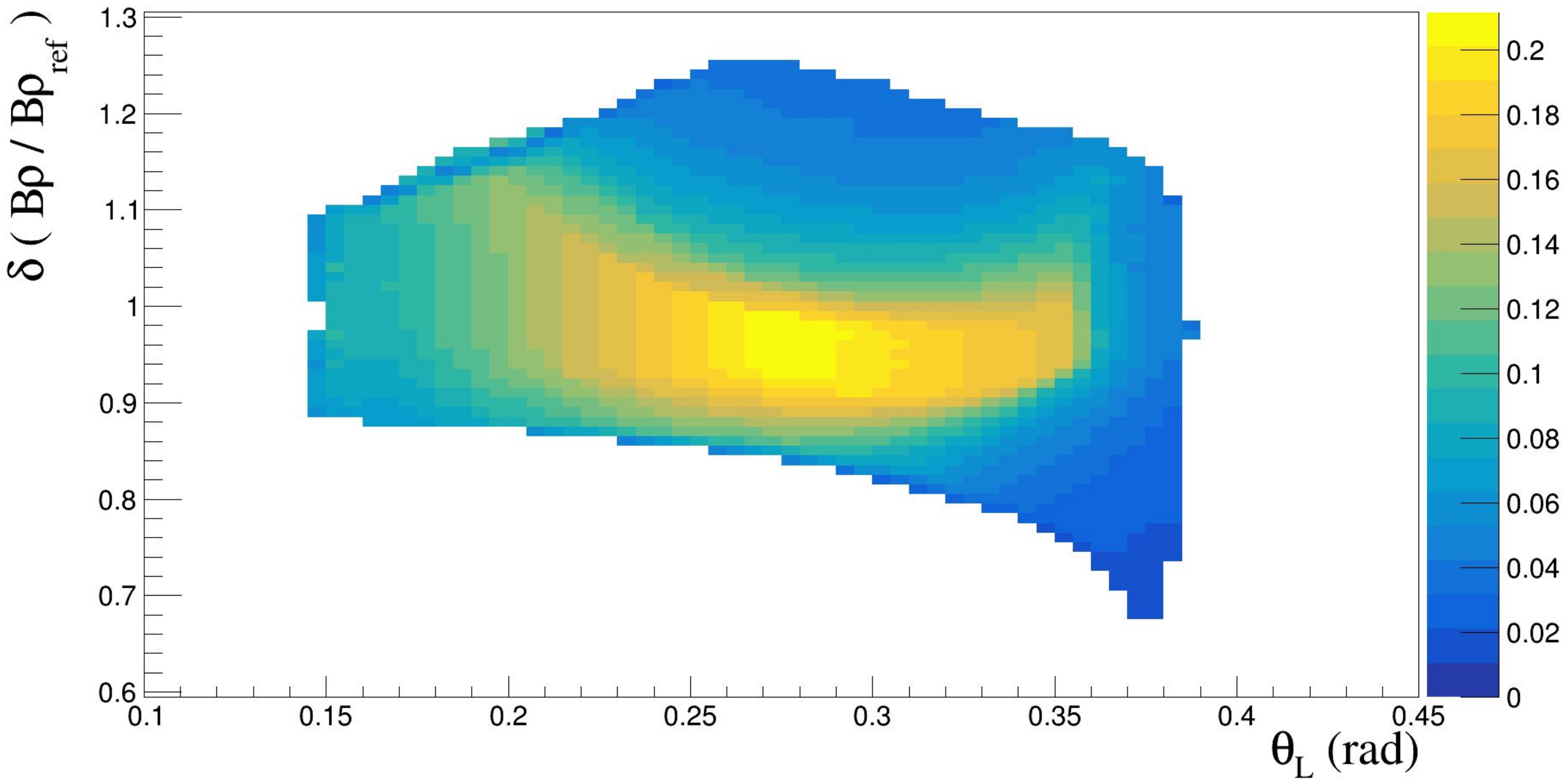
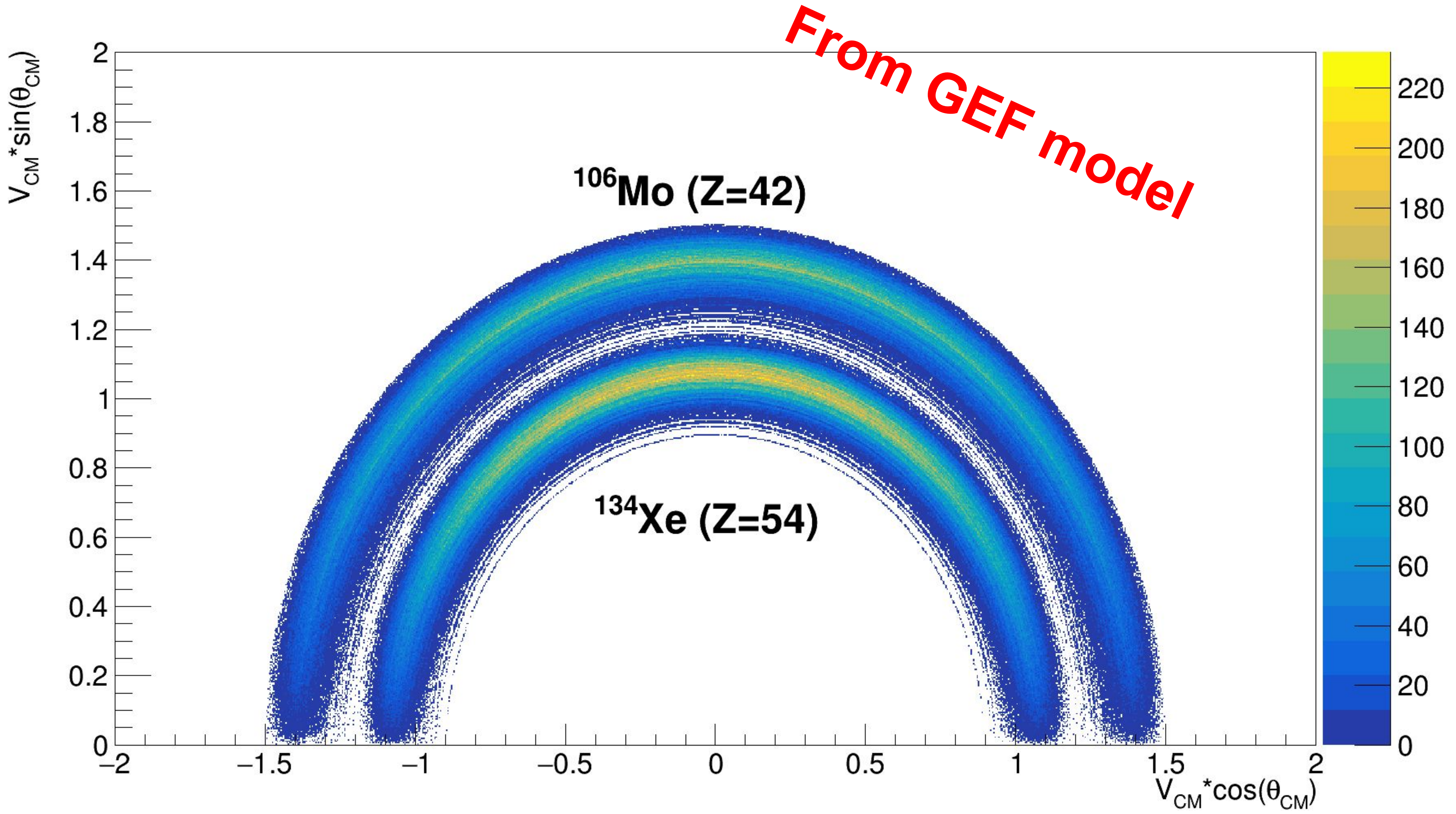


From identification to acceptance: cos(ϑ_{CM})range



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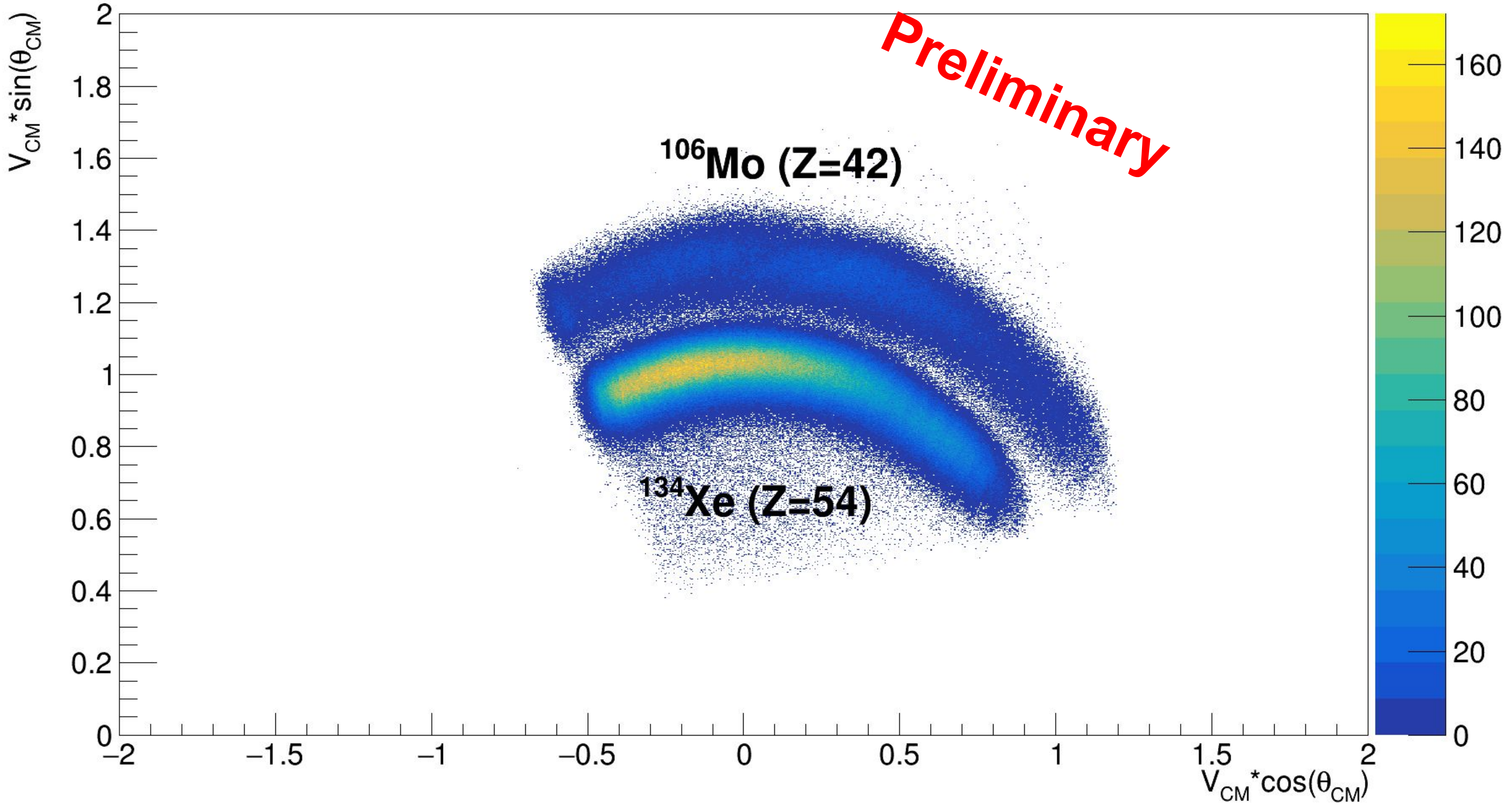

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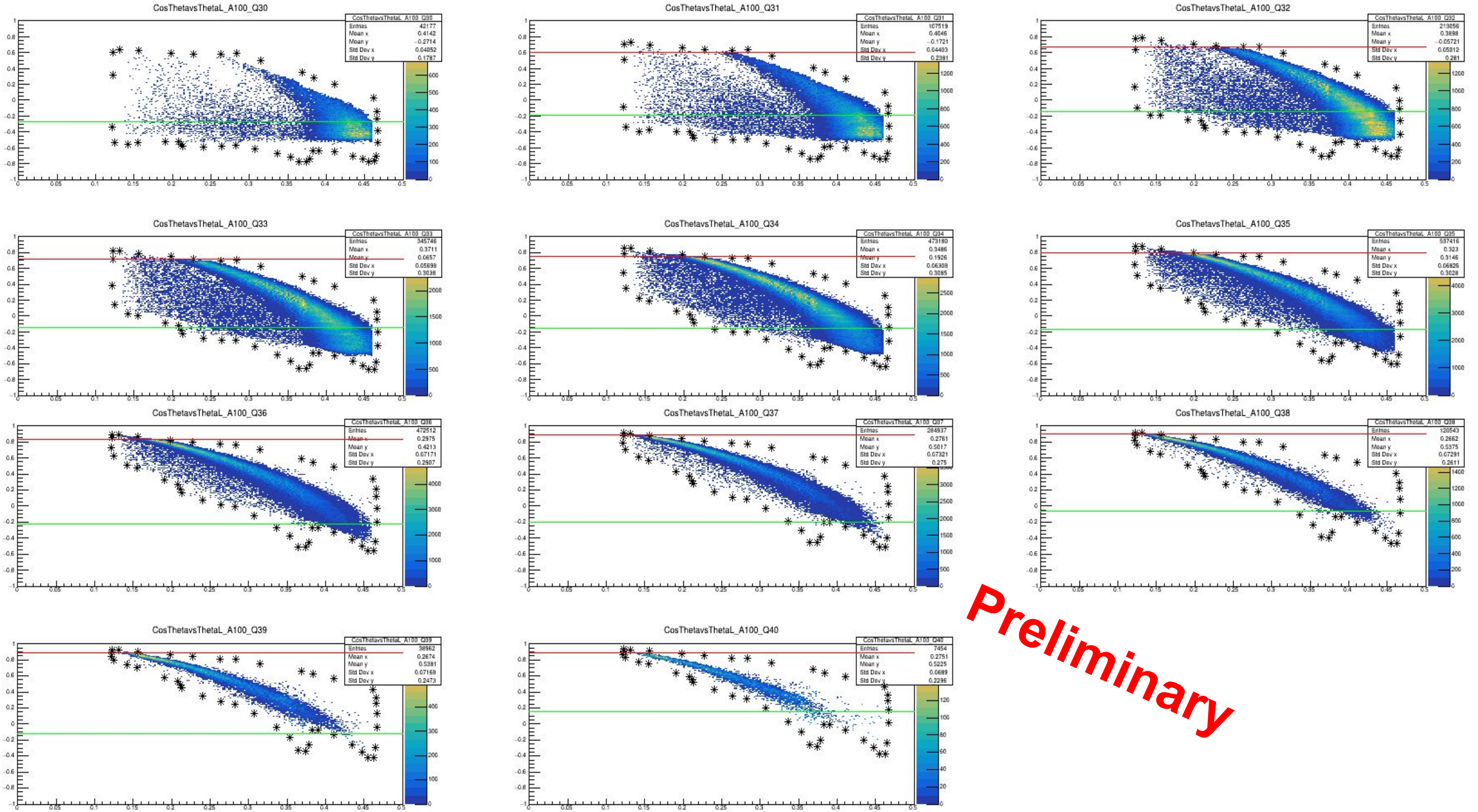

Preliminary