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New experimental insights into the "Thorium anomaly" from isotopic fission fragment yields of ^{232}Th produced in inverse-kinematics

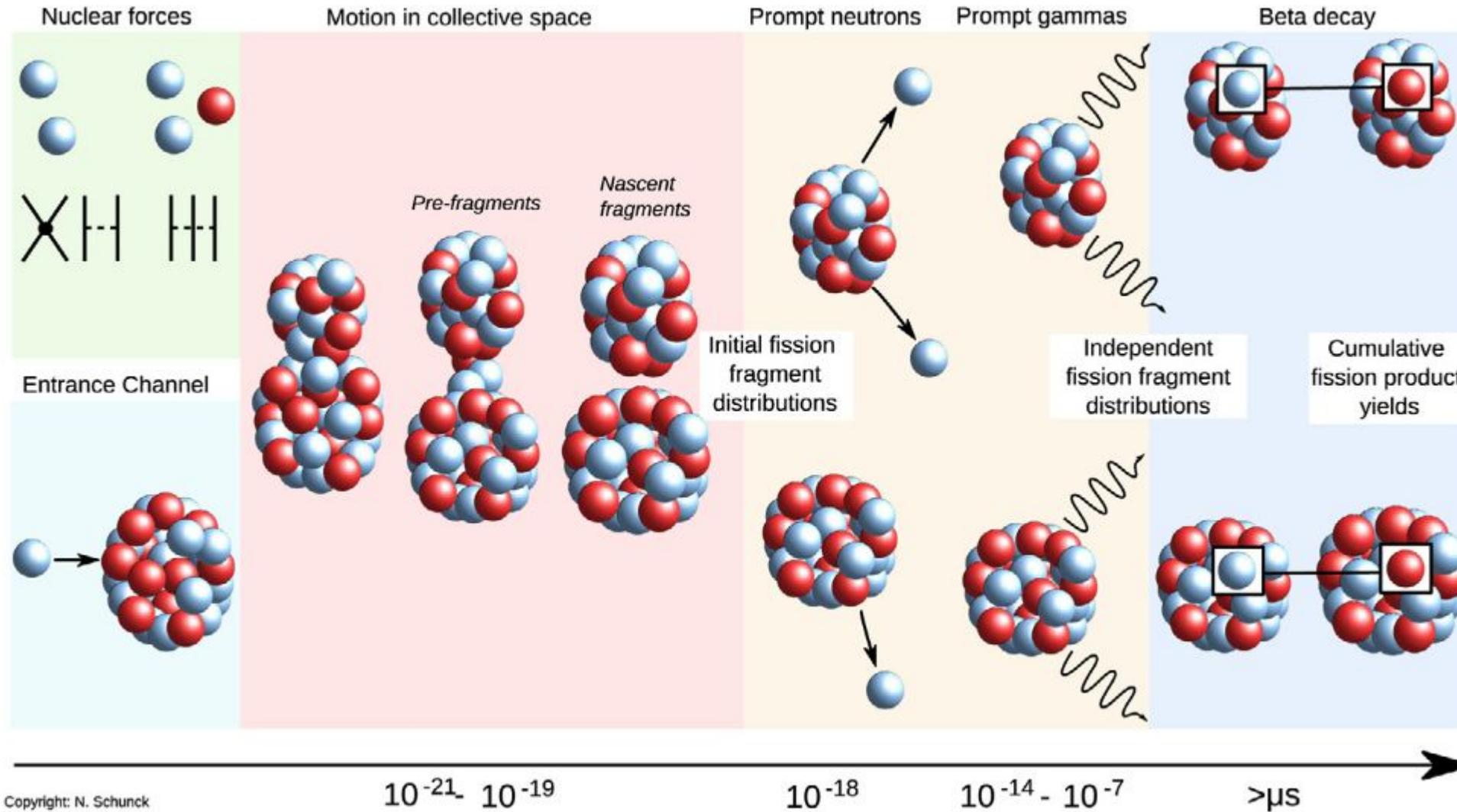
Fission 2026

[e849 experiment collaboration](#)

[Alex Cobo Zarzuelo](#)

10/03/2026

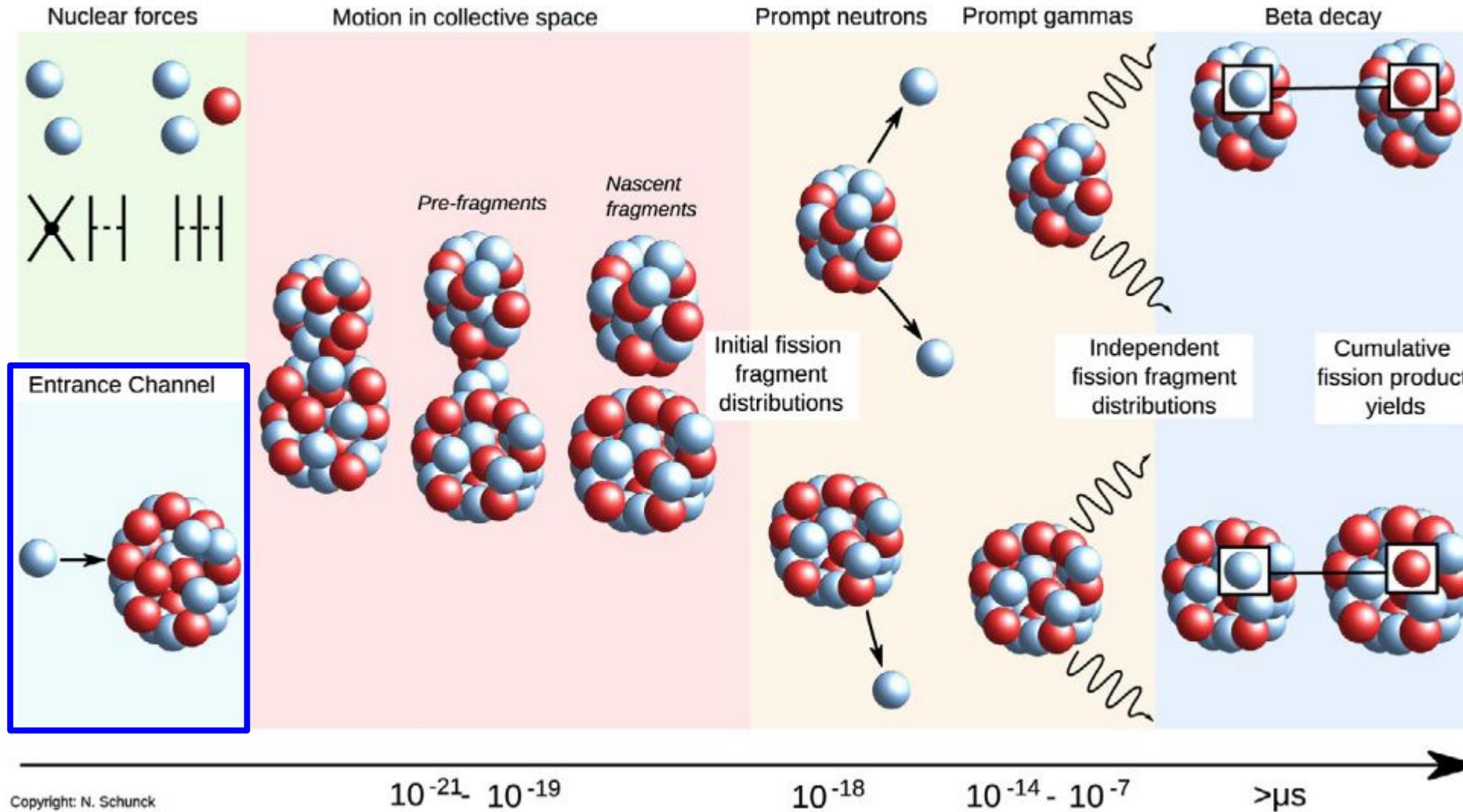
Fission process



Copyright: N. Schunck

[1] Schunck, N., & Regnier, D. (2022). Theory of nuclear fission. Progress in Particle and Nuclear Physics, 125, 103963

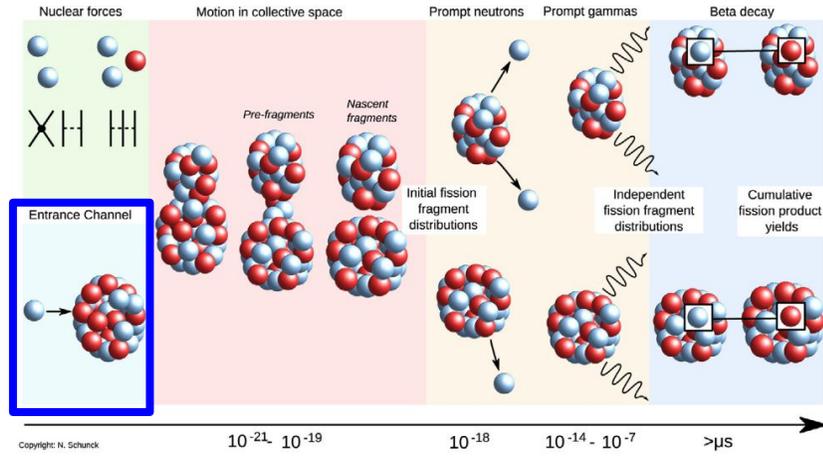
Fission process



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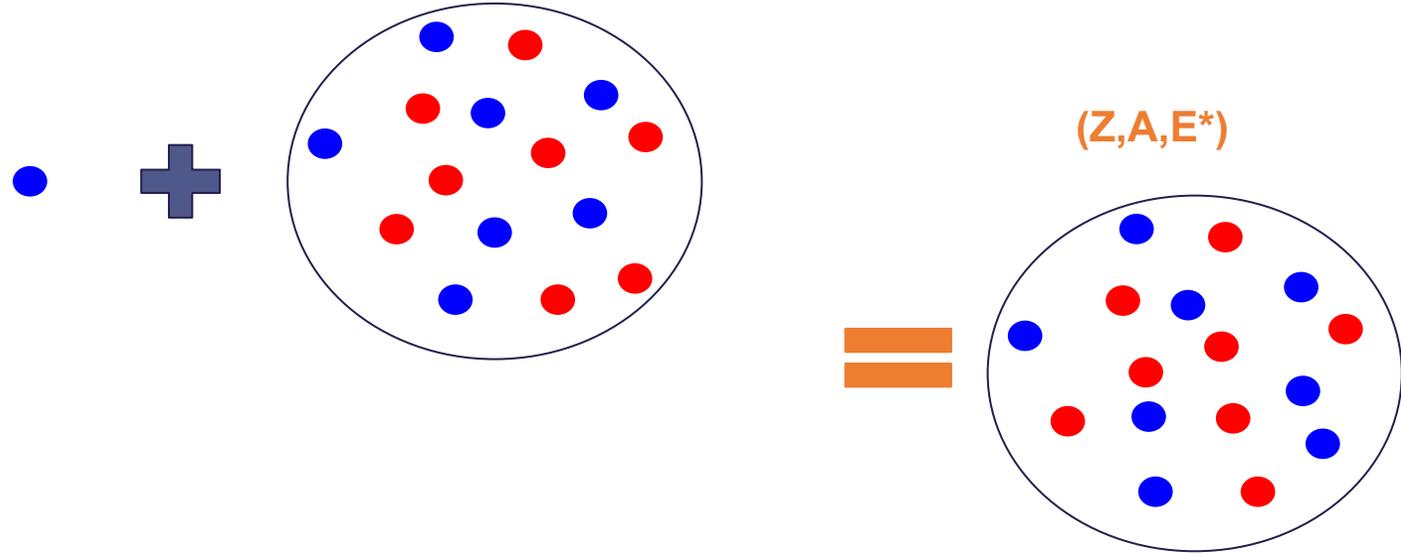
[1] Schunck, N., & Regnier, D. (2022). Theory of nuclear fission. Progress in Particle and Nuclear Physics, 125, 103963

Fission process: Entrance channel

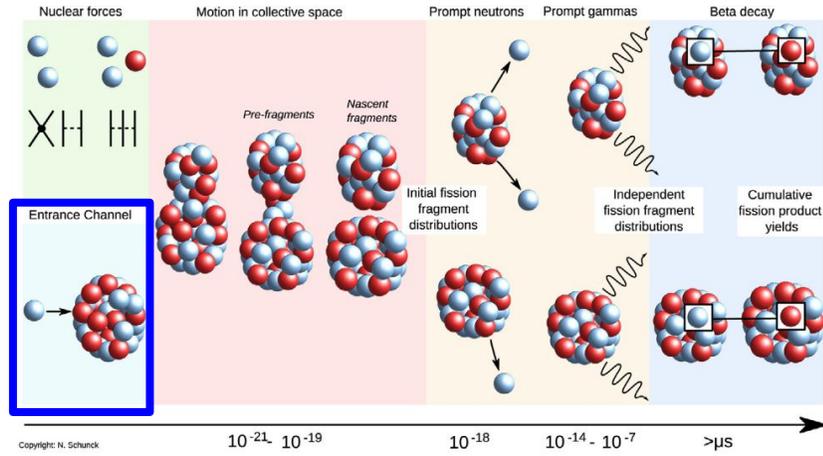


n-induced reaction

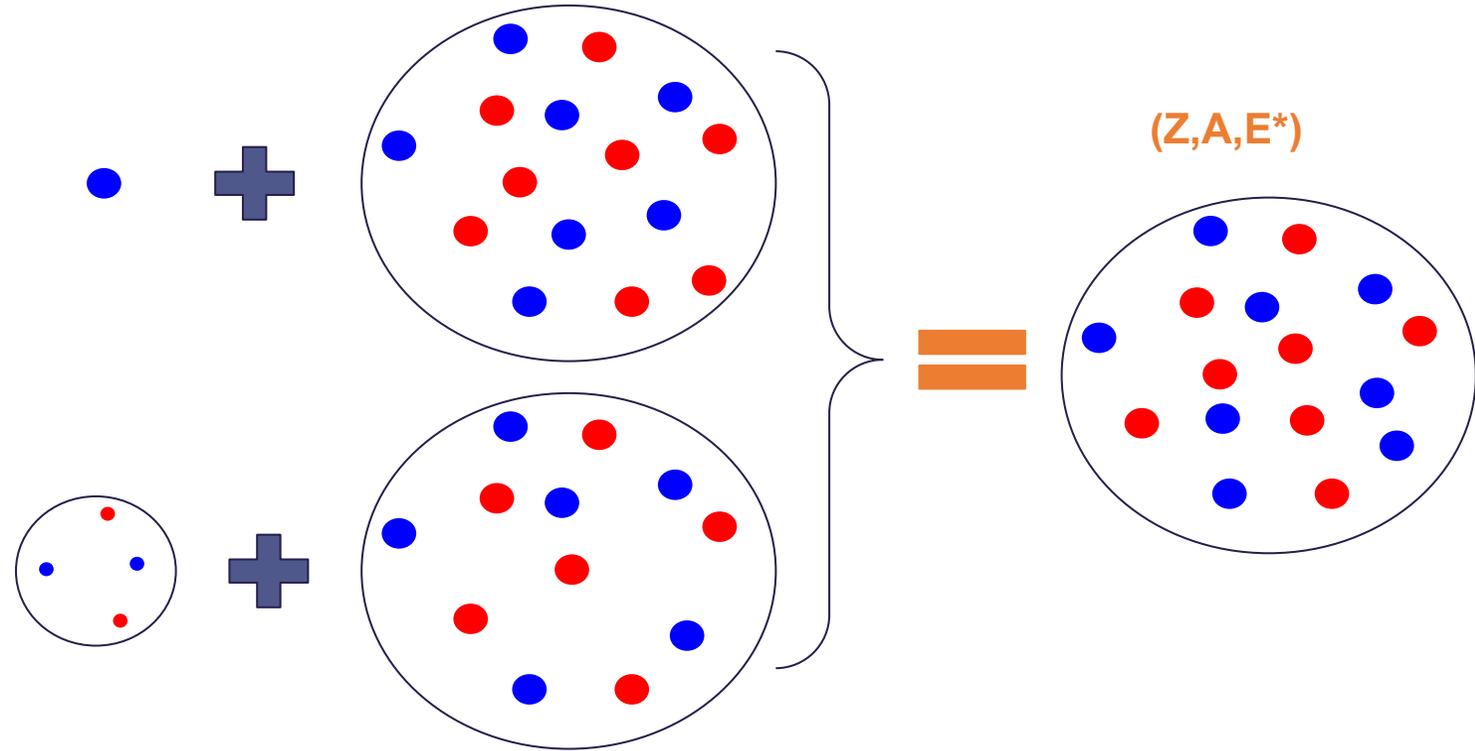
Beam-target combination



Fission process: Entrance channel

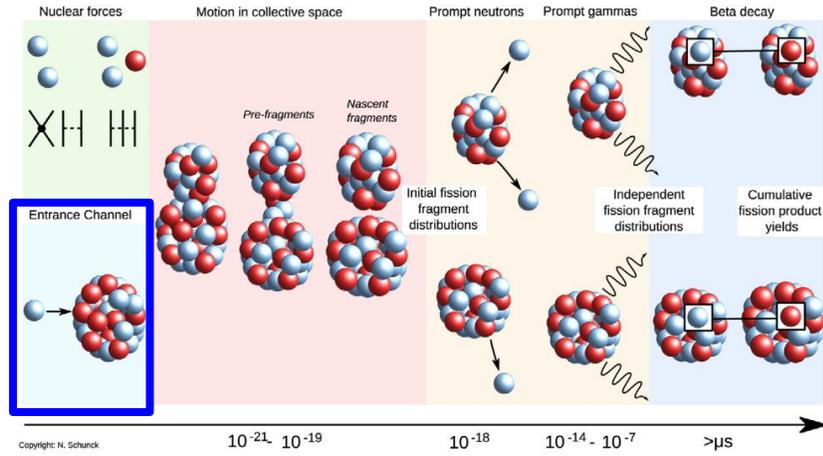


n-induced reaction Beam-target combination

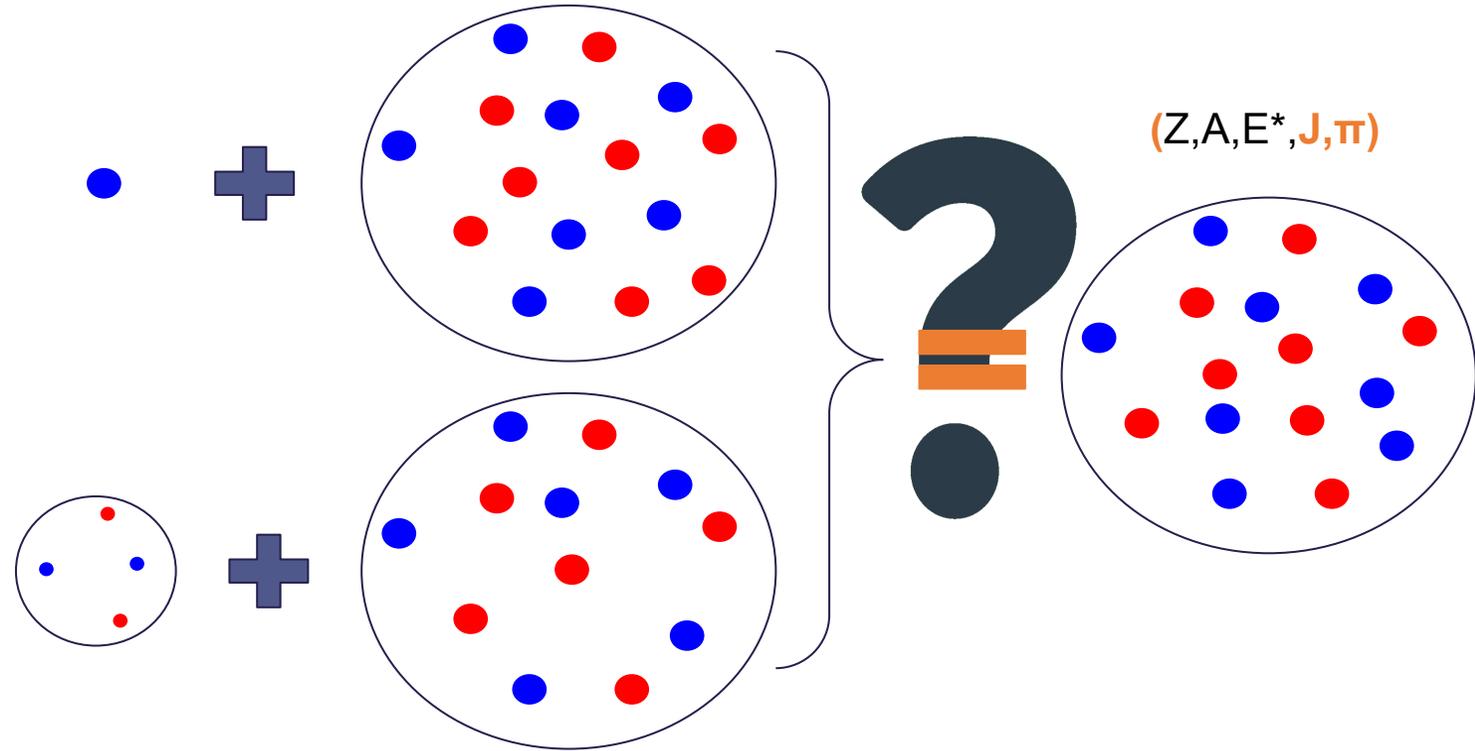


Surrogate reaction

Fission process: Entrance channel

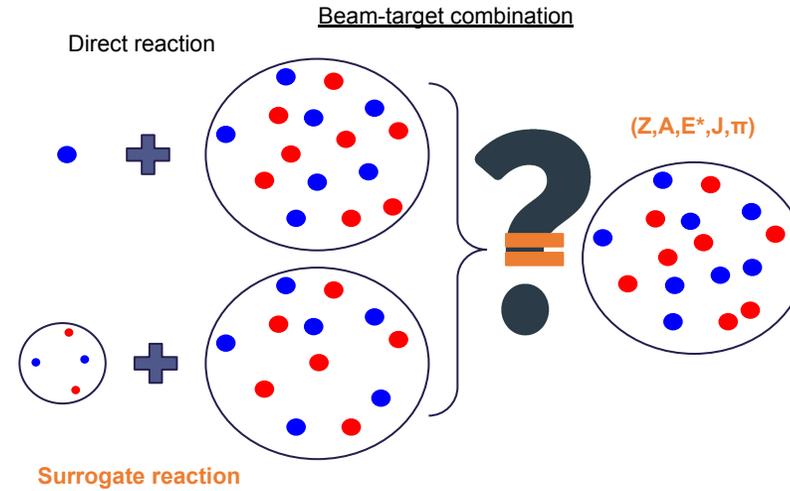
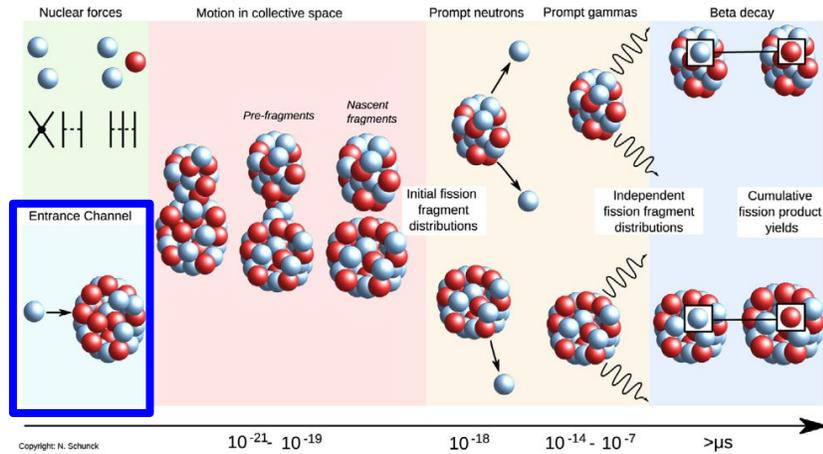


n-induced reaction Beam-target combination



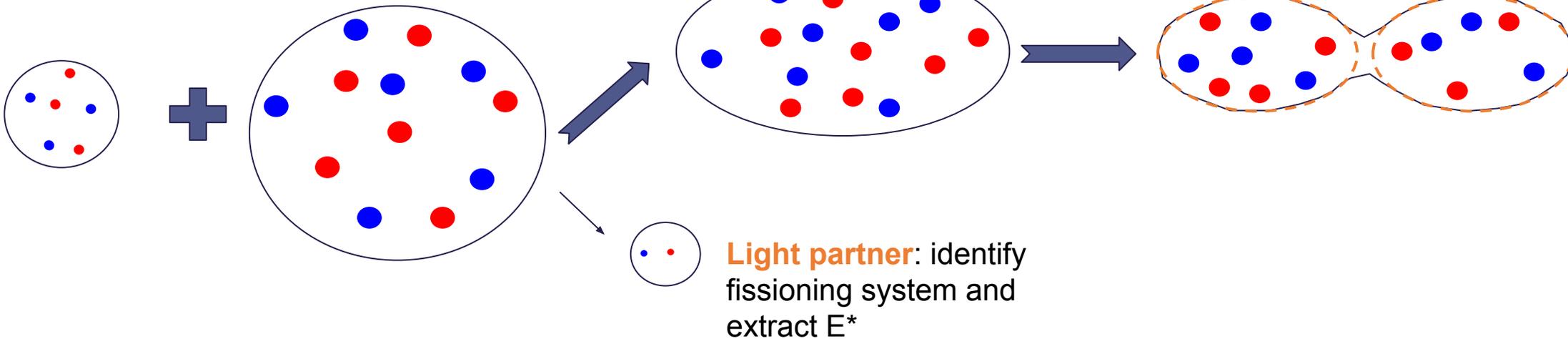
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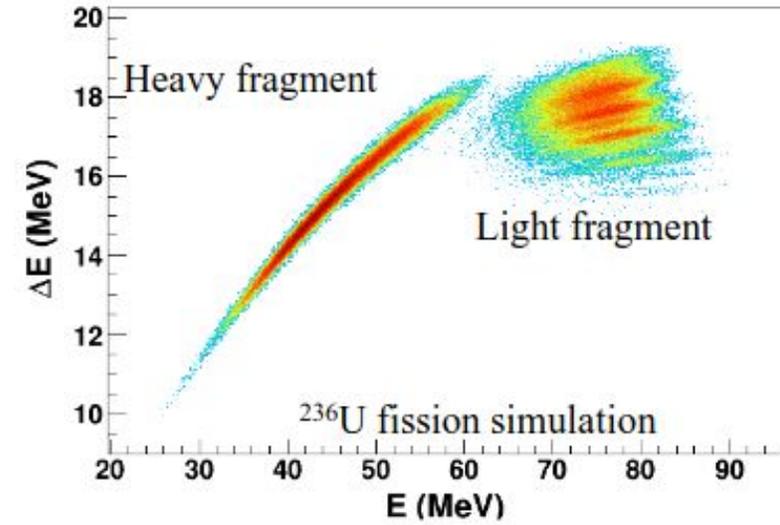
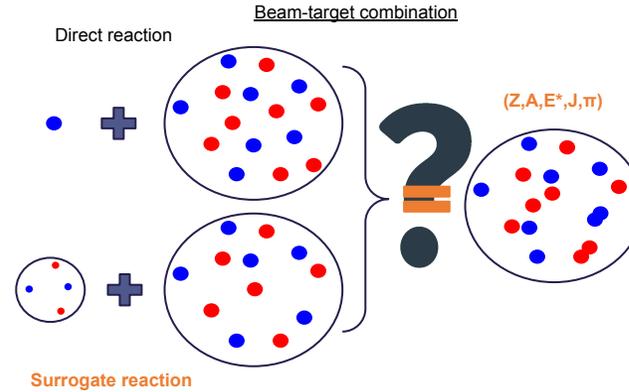
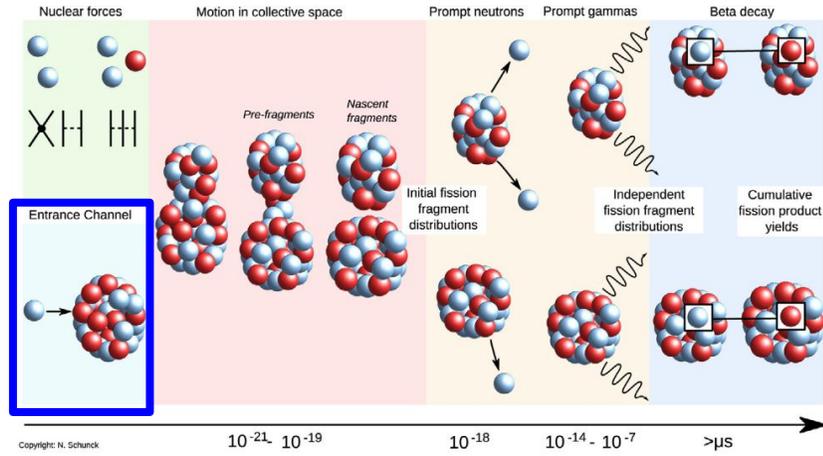


Reaction mechanism:
transfer / inelastic scattering

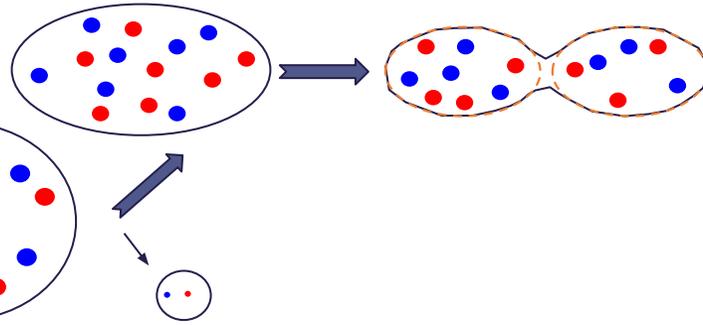
Fissioning system



Fission process: Entrance channel

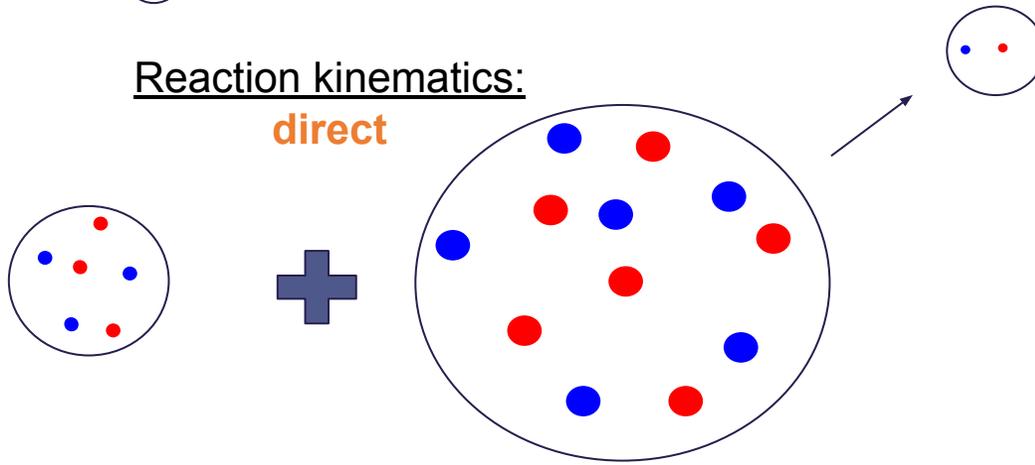


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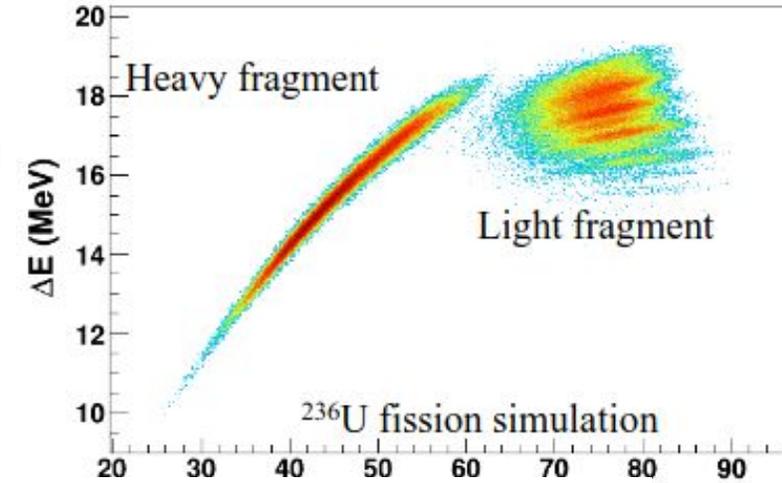
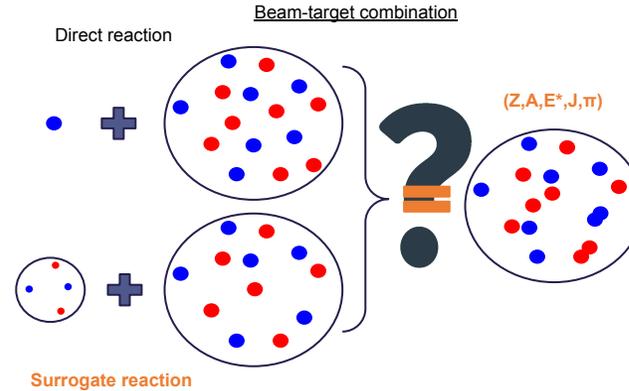
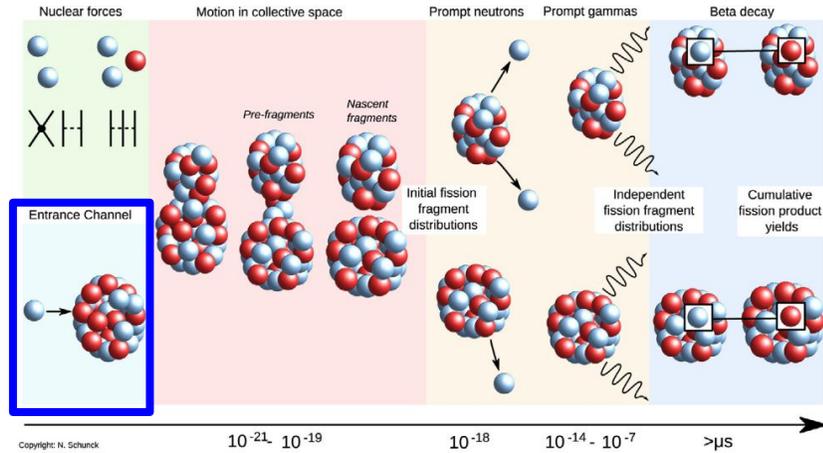


Reaction kinematics:

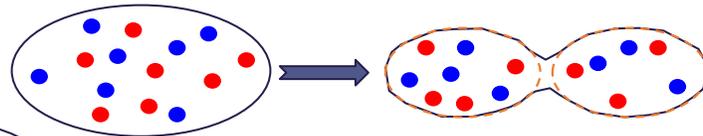
direct



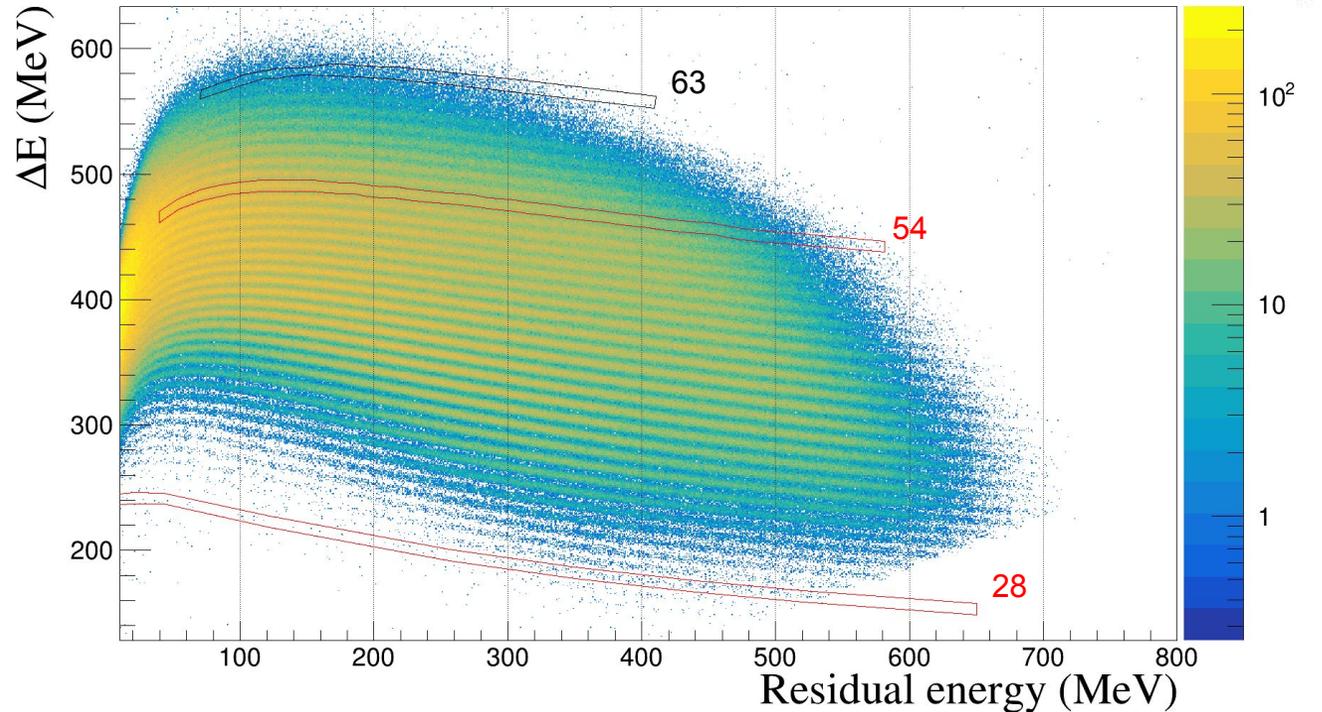
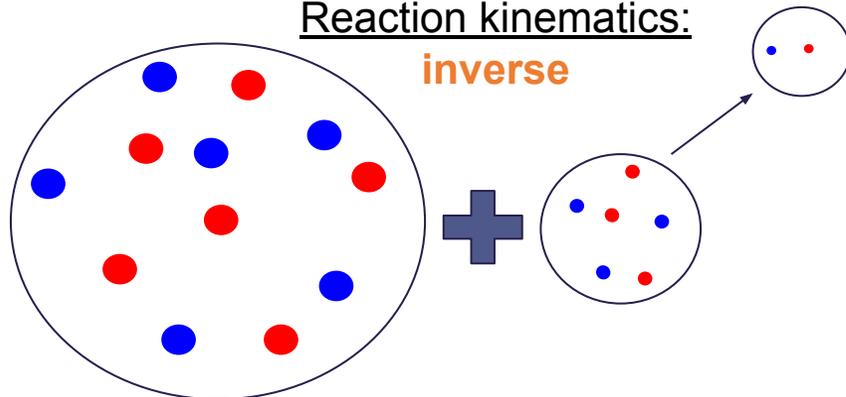
Fission process: Entrance channel



Reaction mechanism:
transfer / inelastic scattering



Reaction kinematics:
inverse



The e849 experiment

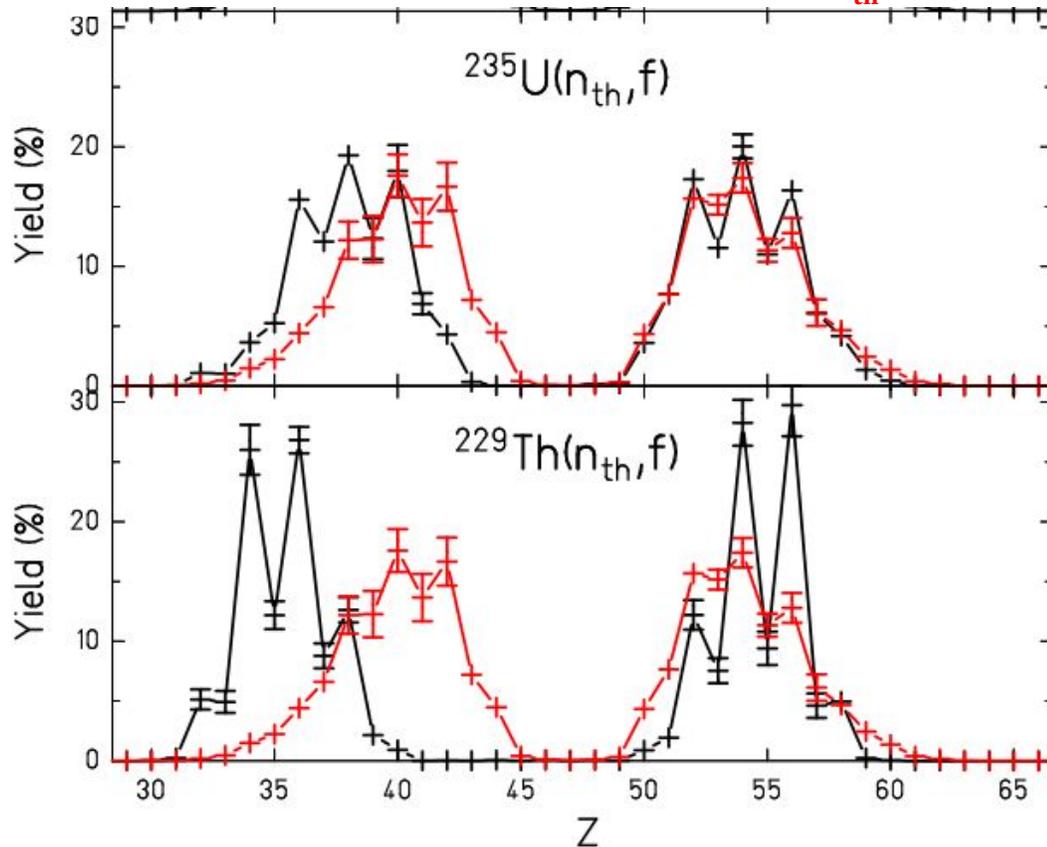
^{232}Th beam of 6 MeV/u impinging on a ^{12}C target.
Produce fissioning **systems through fusion** (^{244}Cm)
, **transfer reactions** (10+ systems like ^{234}U , ^{230}Th ,
 ^{238}Pu , ...) and **inelastic scattering** (^{232}Th)

Motivation to conduct the experiment

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

Produce fissioning systems through fusion (^{244}Cm) and transfer reactions (10+ systems like ^{234}U , ^{230}Th , ^{238}Pu , ...) and inelastic scattering (^{232}Th):

Red: Fission fragment yield of ^{239}Pu (n_{th}, f)



Analyse the origin of the **possible third hump** in the **fission barriers** of **lighter actinides**

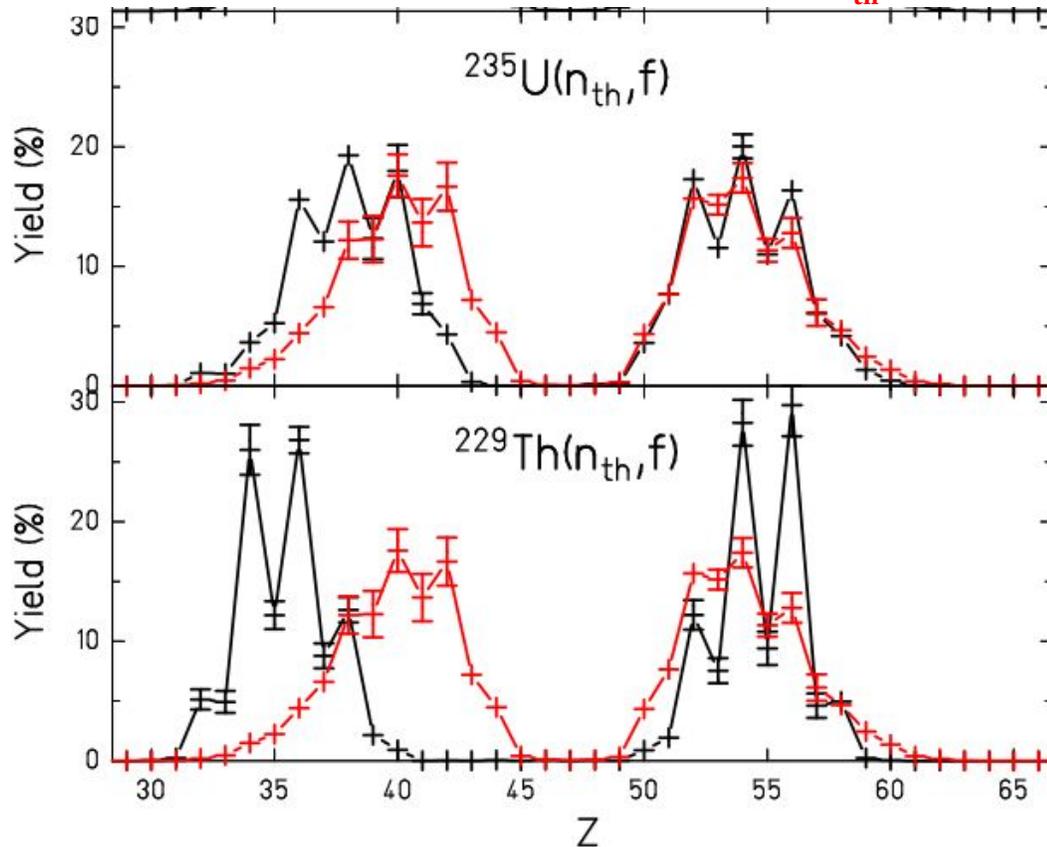
- Yield of **Uranium** and actinides **above** have **similar shape** for **heavy** fragment
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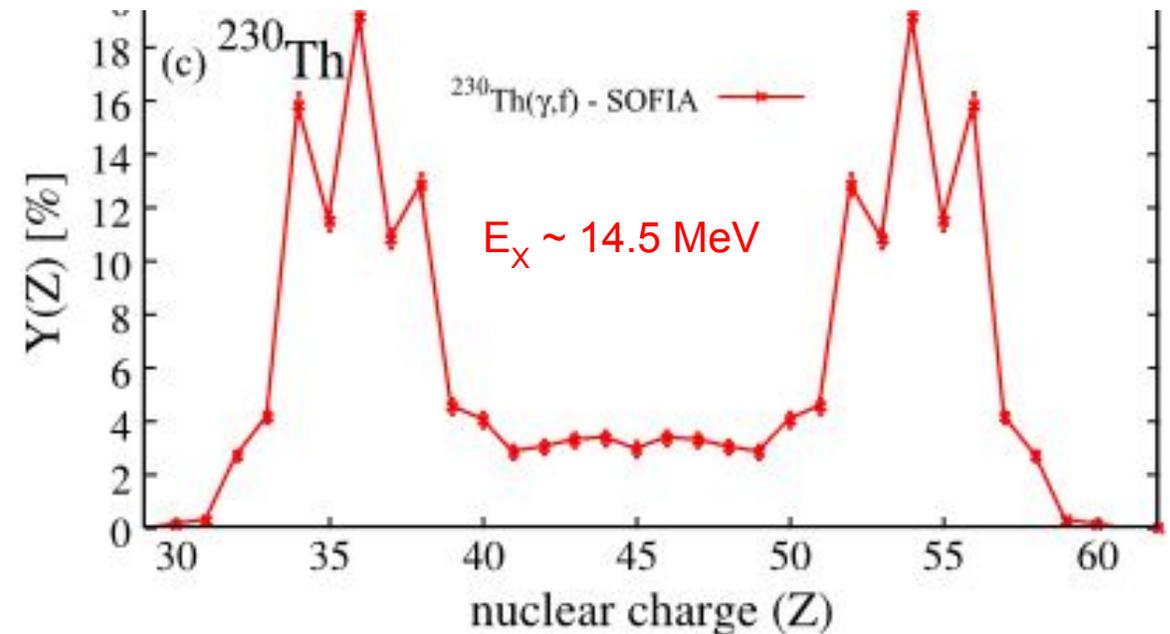
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[2] Schmidt, K. H., Schmitt, C., Heinz, A., & Jurado, B. (2024). Identifying and overcoming deficiencies of nuclear data on the fission of light actinides by use of the GEF code. *Annals of Nuclear Energy*, 208, 110784.

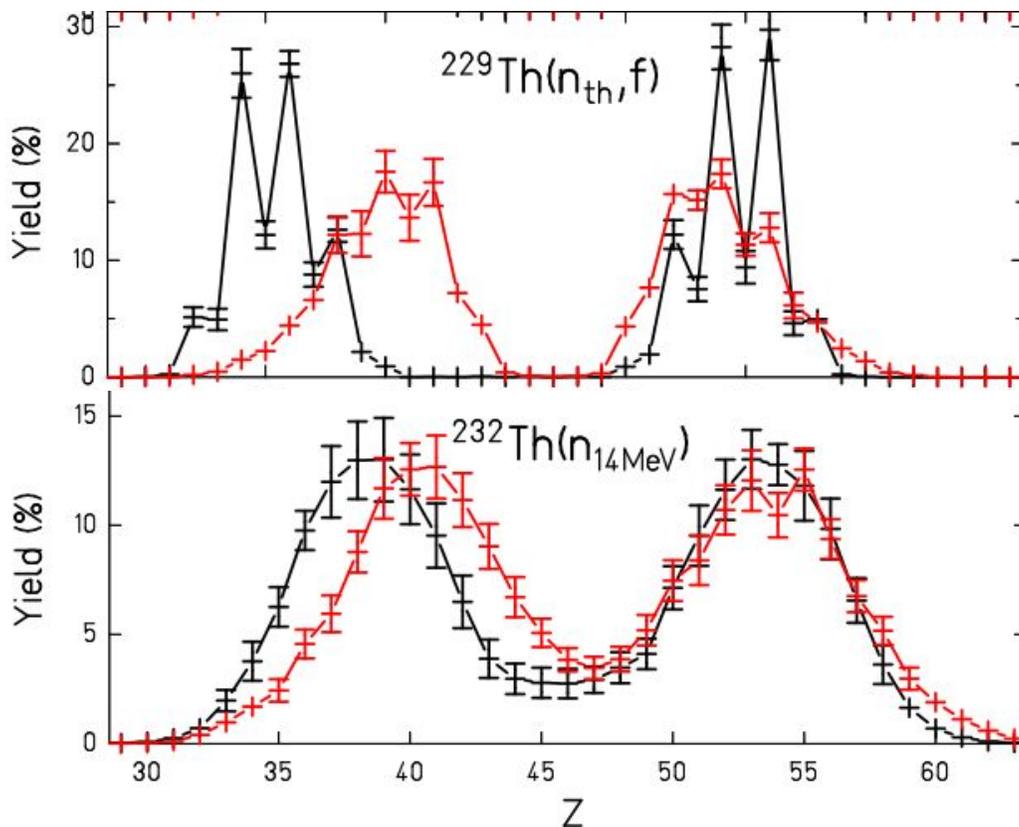
[3] Chatillon, A., Taïeb, J., Alvarez-Pol, H., Audouin, L., Ayyad, Y., Bélier, G., ... & Weick, H. (2020). Evidence for a new compact symmetric fission mode in light thorium isotopes. *Physical Review Letters*, 124(20), 202502.

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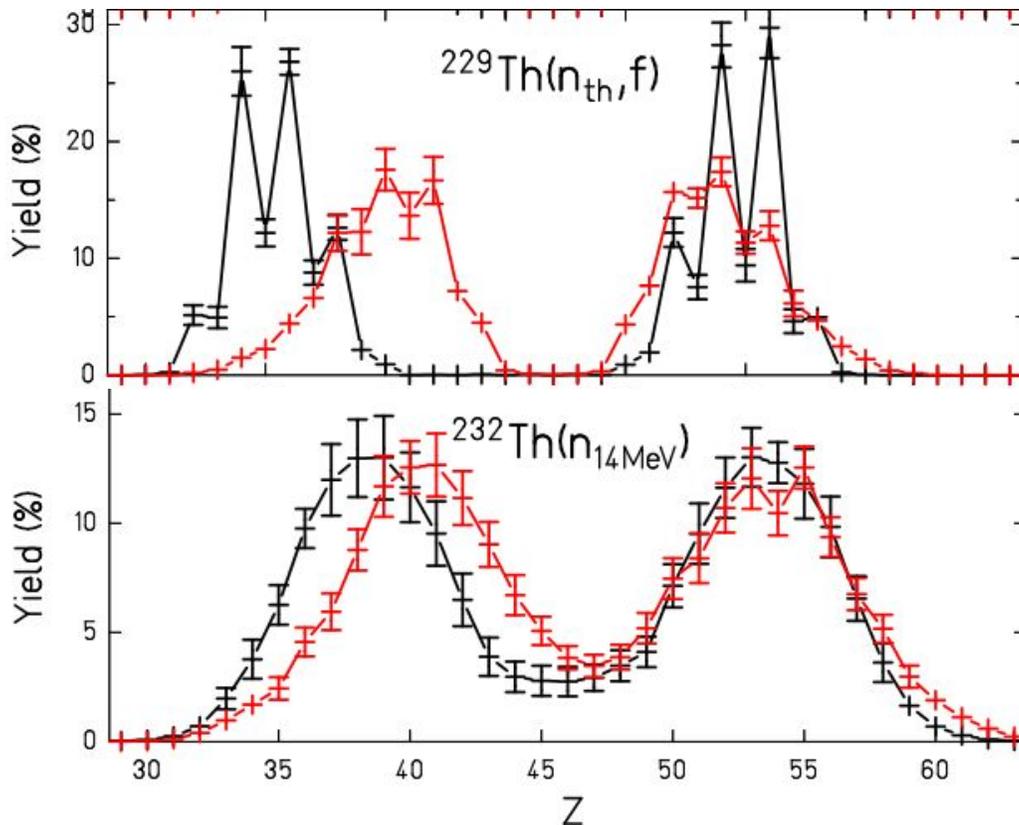
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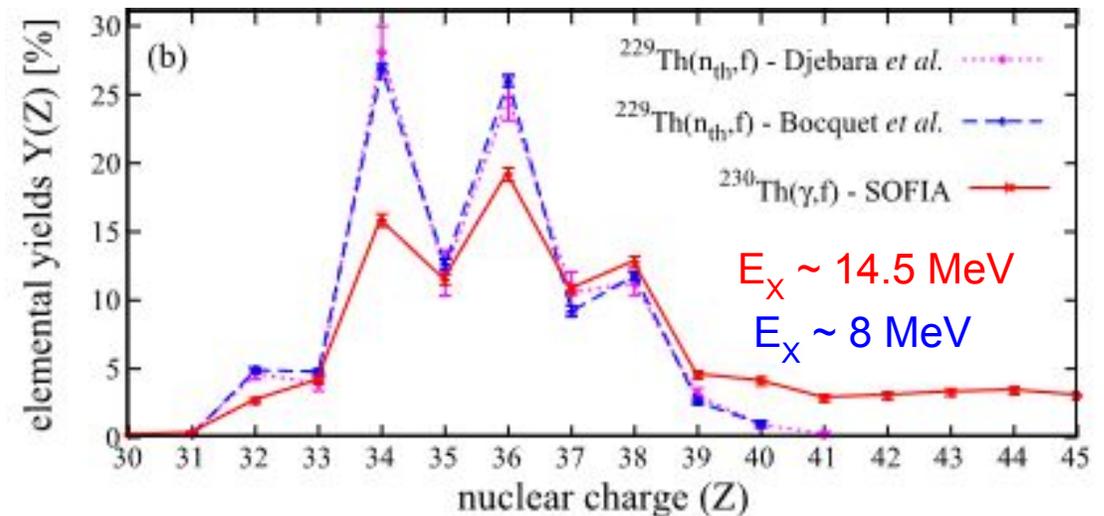
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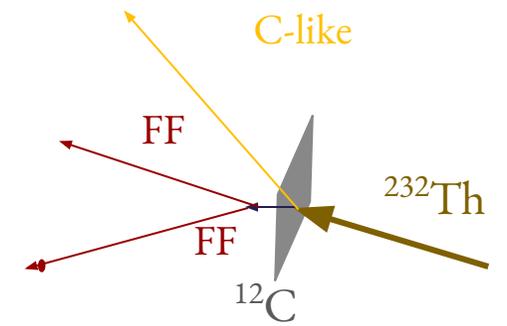
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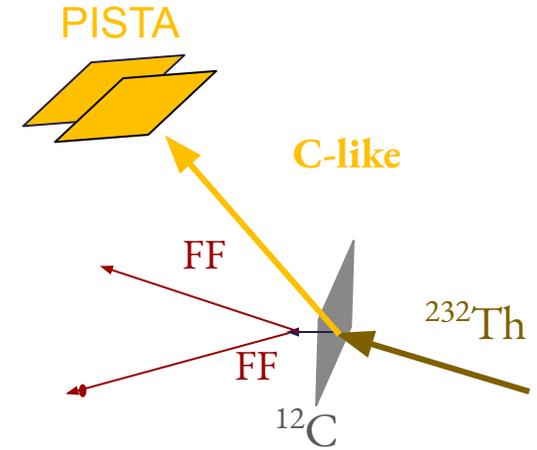
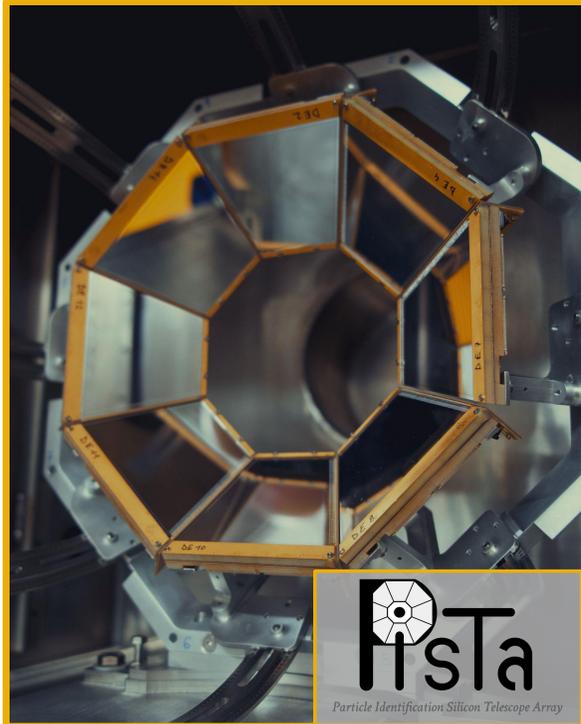
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Experimental setup

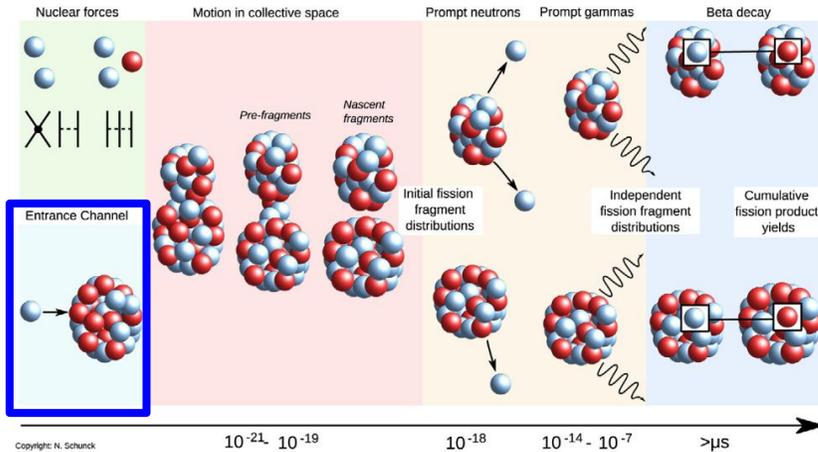


Experimental setup: PISTA

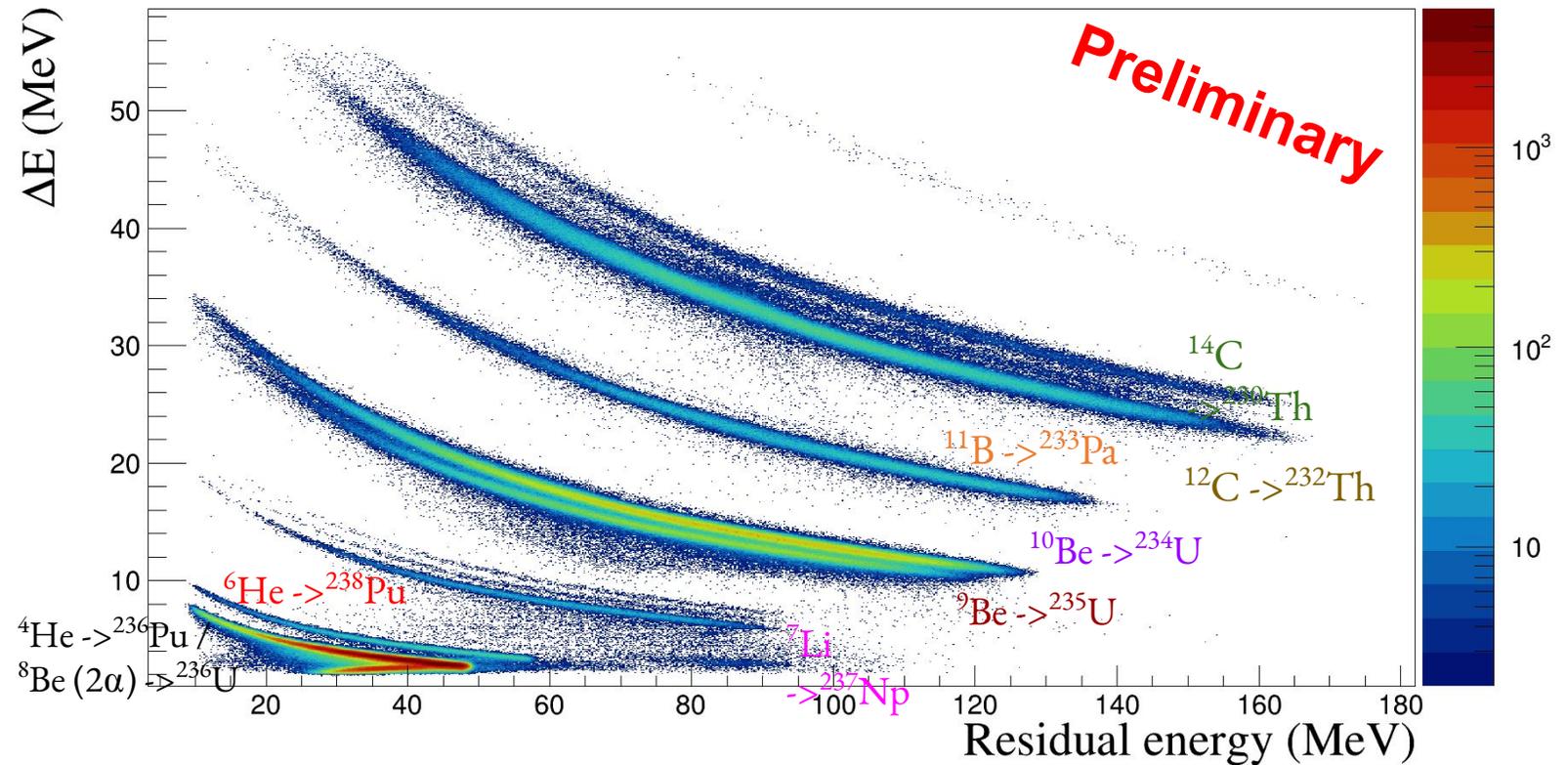
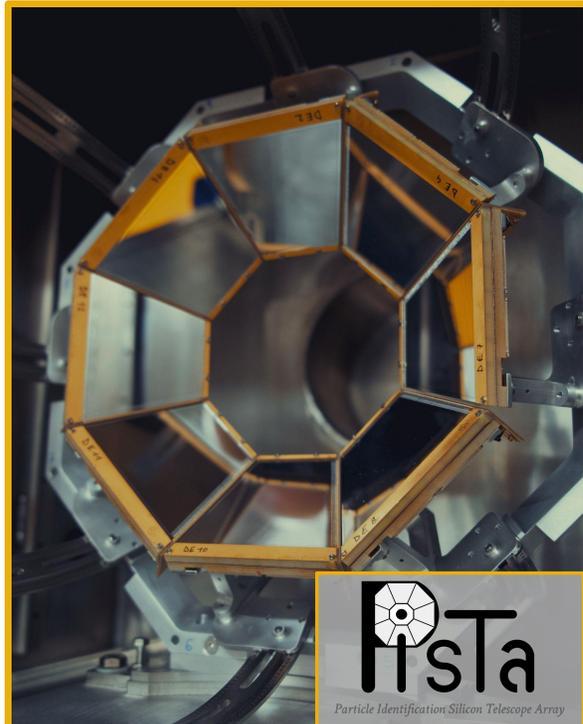
Carbon-like particle identified by PISTA: 8 ΔE - E segmented telescopes => (E, θ)



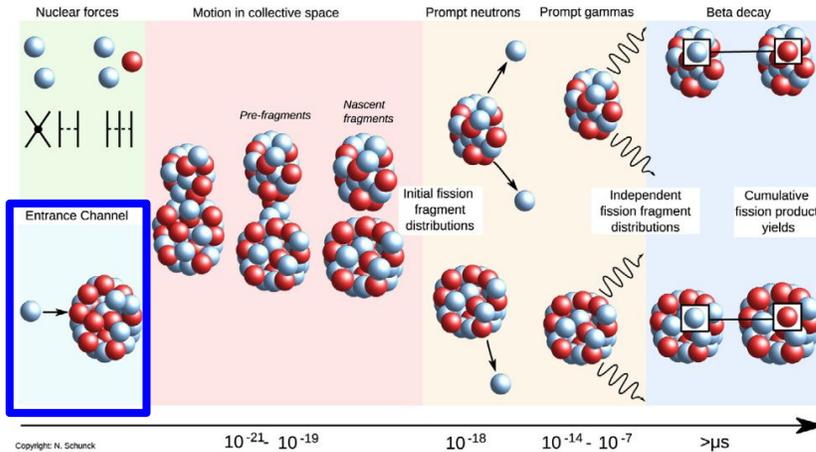
Entrance channel information



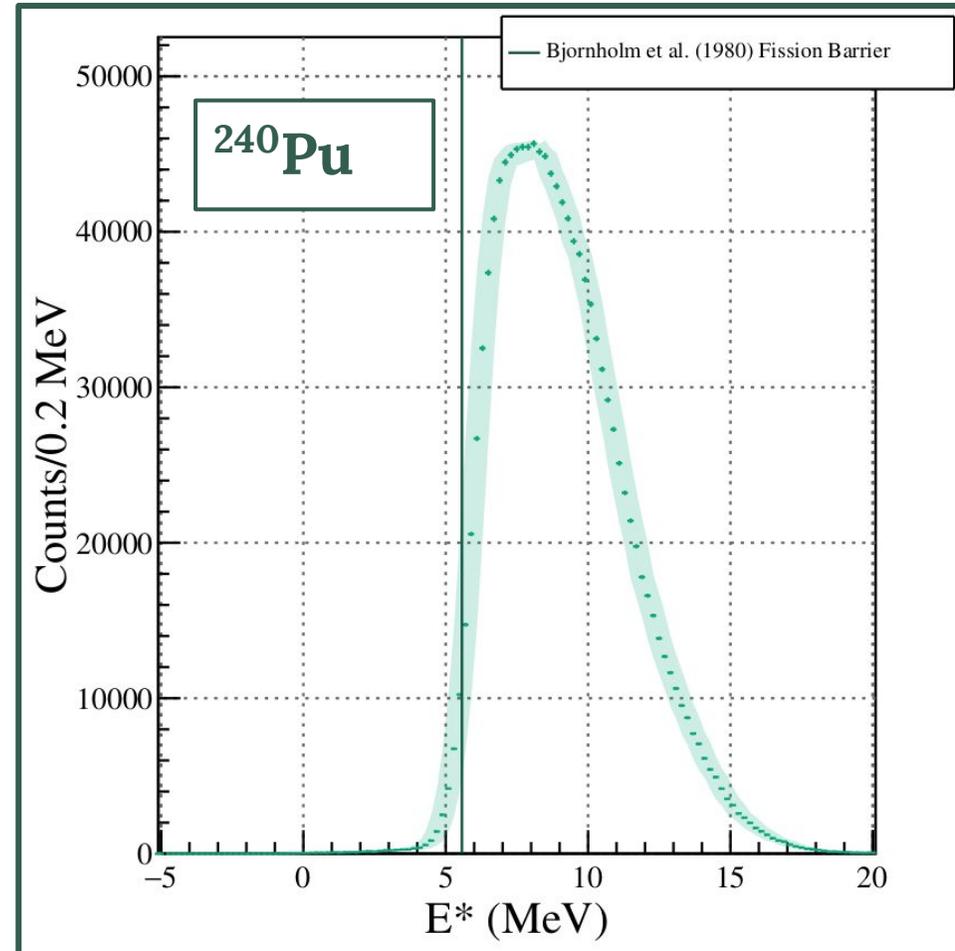
1) What is the fissioning system that was formed (Z,A)



Entrance channel information

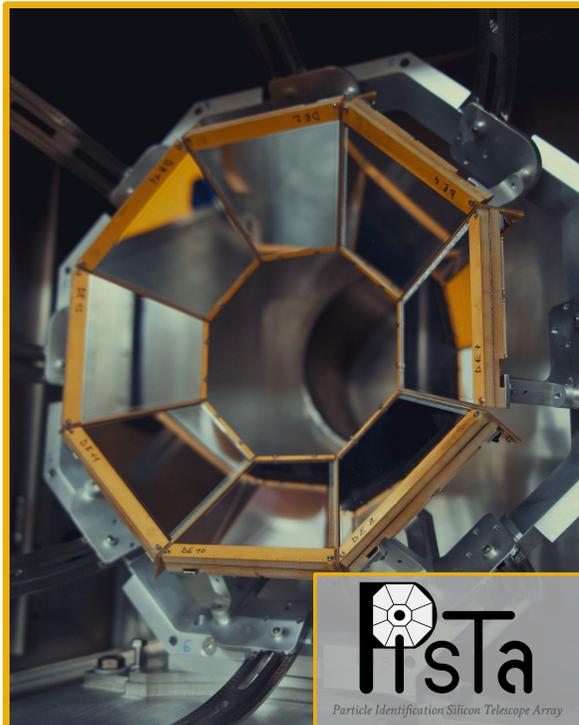


- 1) What is the fissioning system that was formed (Z,A)
- 2) What is the excitation energy (E^*)



Reconstruct the E^* of the fissioning system event-by-event.

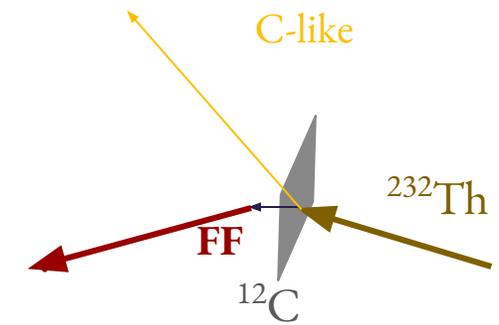
Energy and linear momentum conservation, assuming binary reaction



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



Experimental setup: VAMOS++

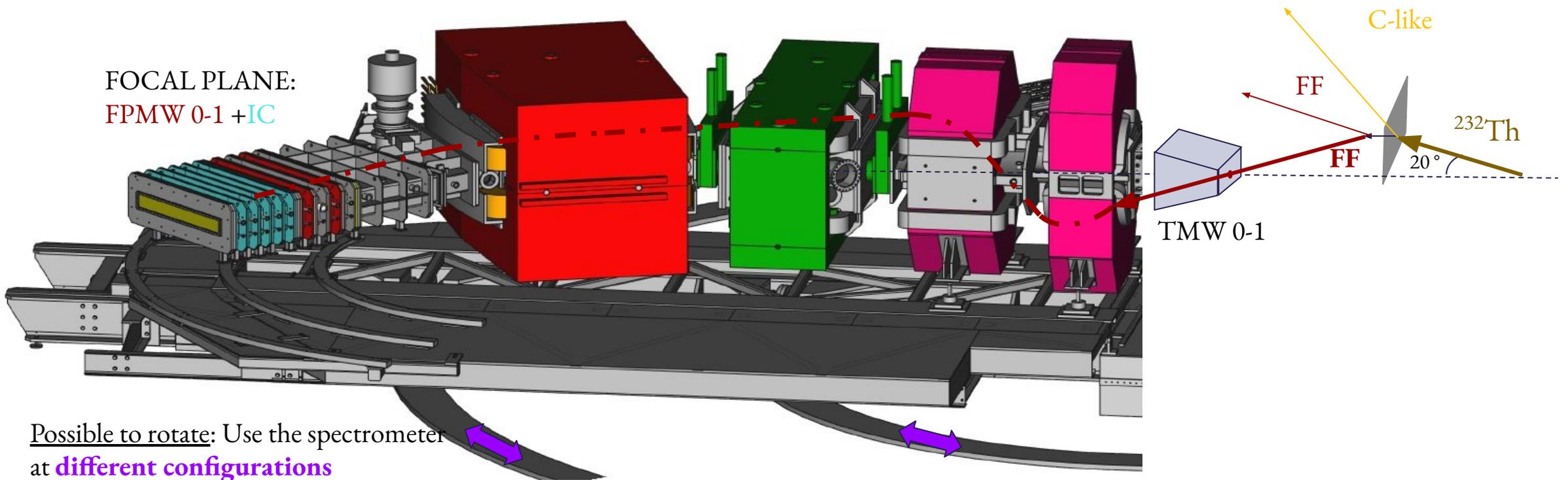
Need to **identify** a **fission fragment mass** event by event

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 ($B\rho$) and ToF resolution

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

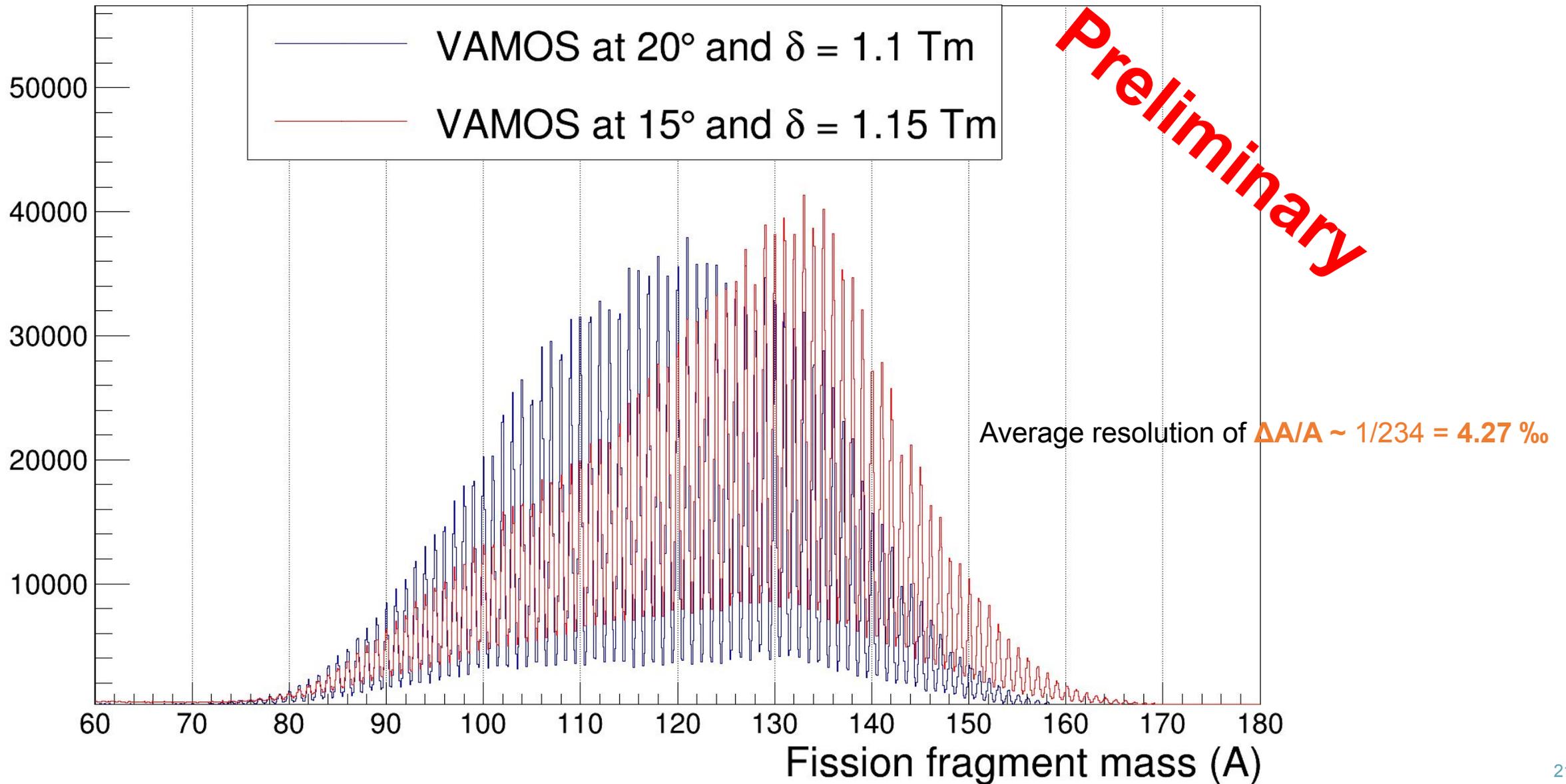
FOCAL PLANE:
FPMW 0-1 + IC



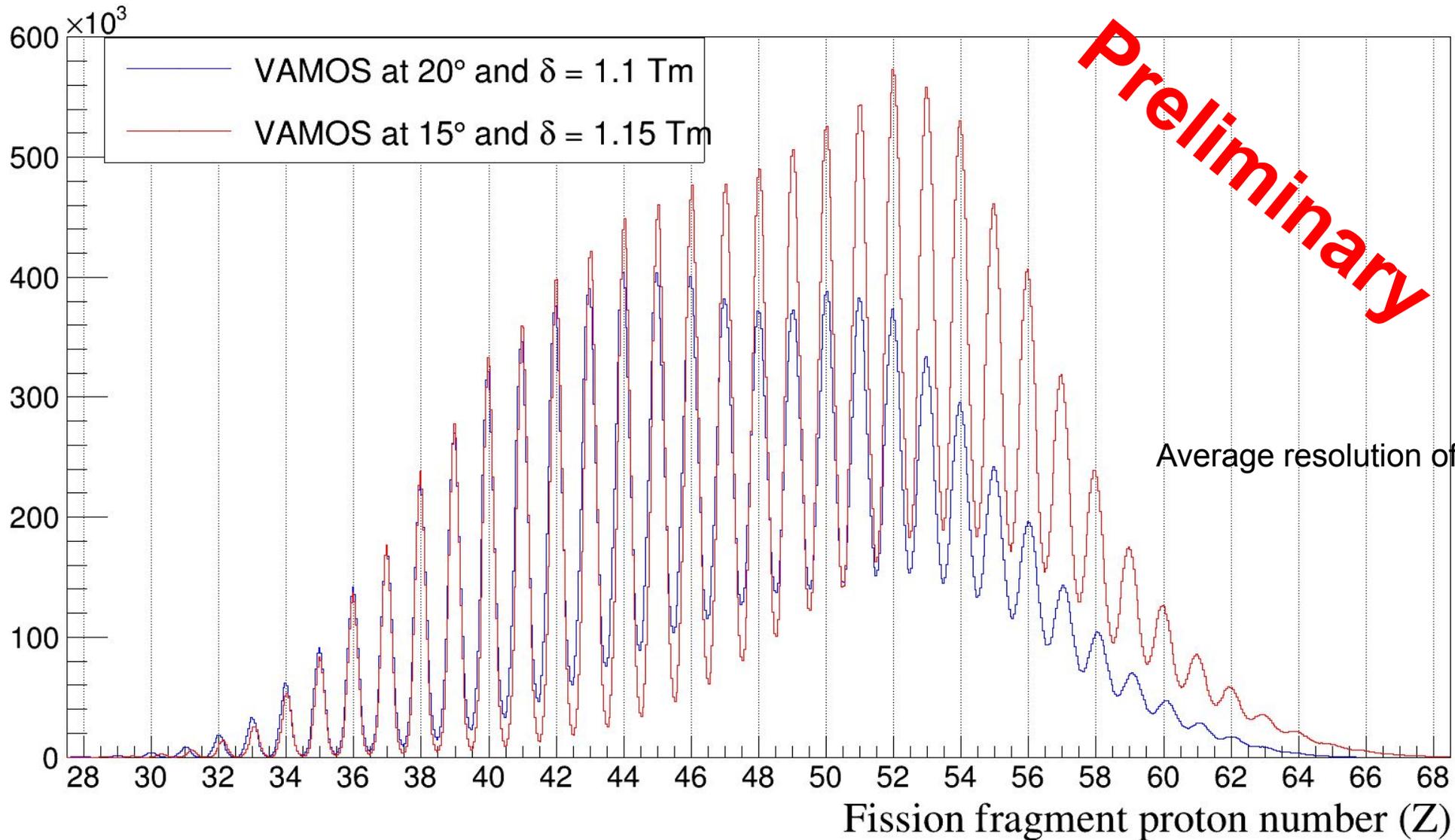
Possible to rotate: Use the spectrometer at **different configurations**

$B\rho = p/q$ → Unique for **one nucleus** of a given **velocity** and **charge state** (q)

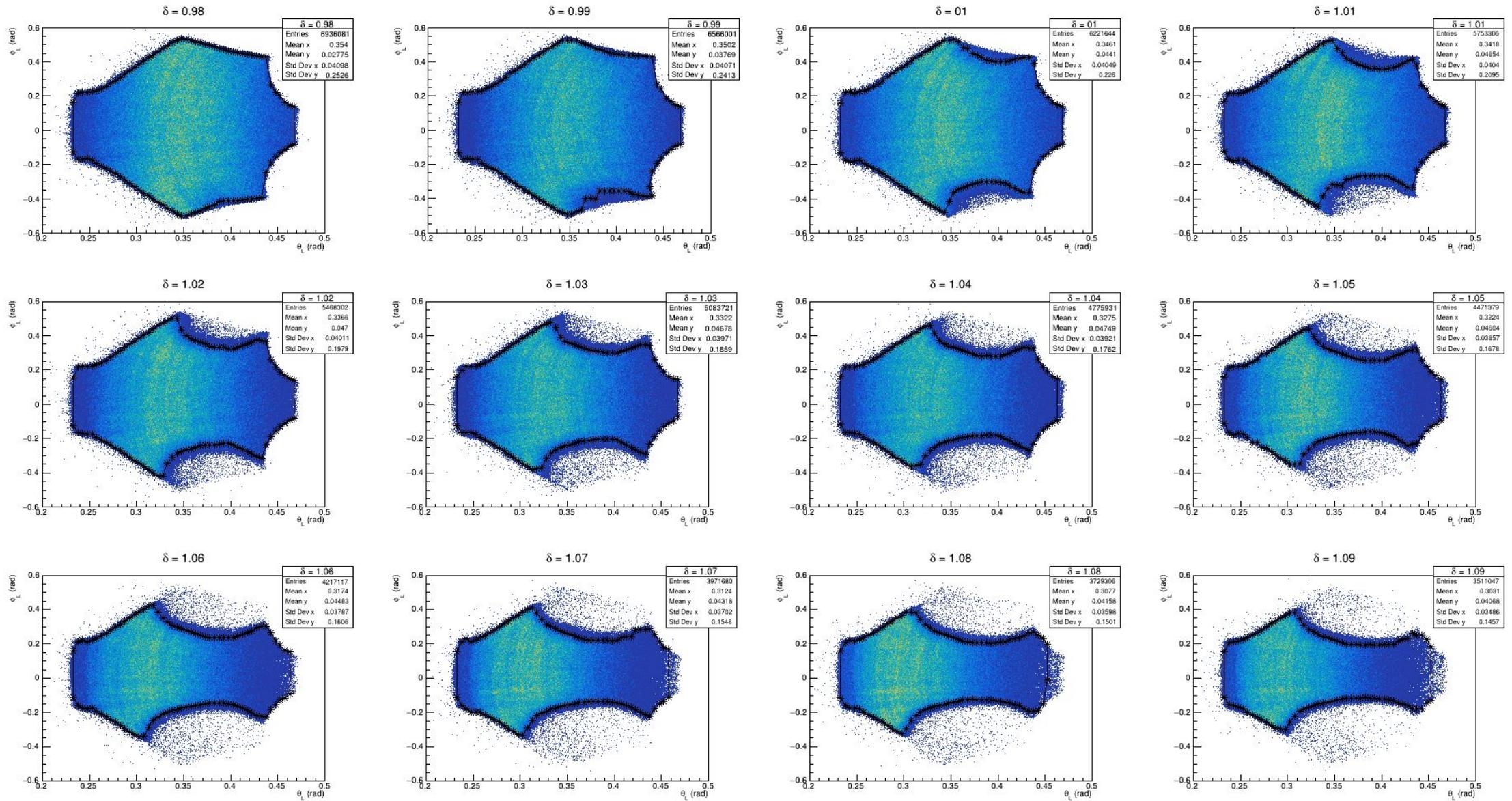
Fission fragment identification: A



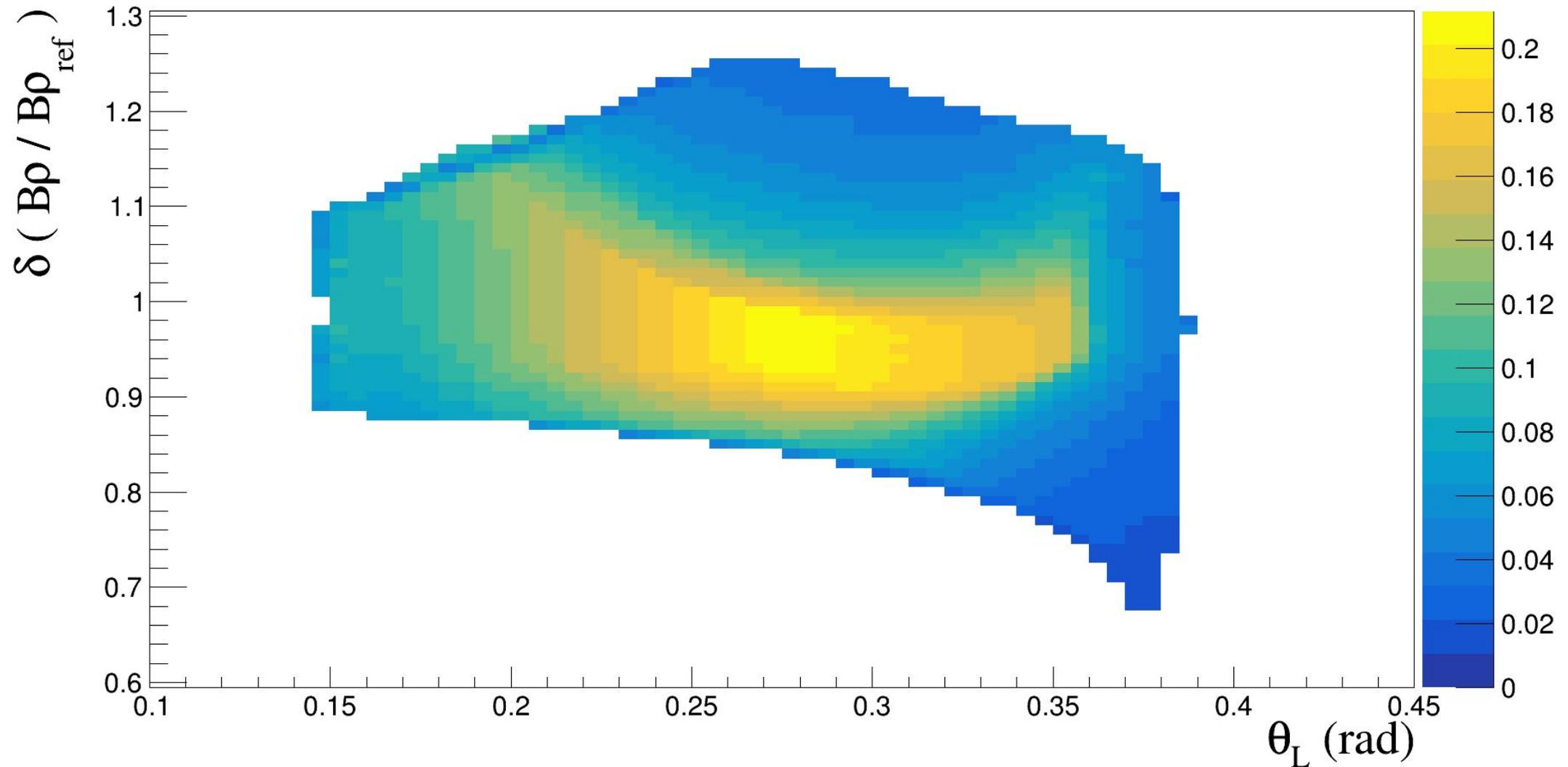
Fission fragment identification: Z



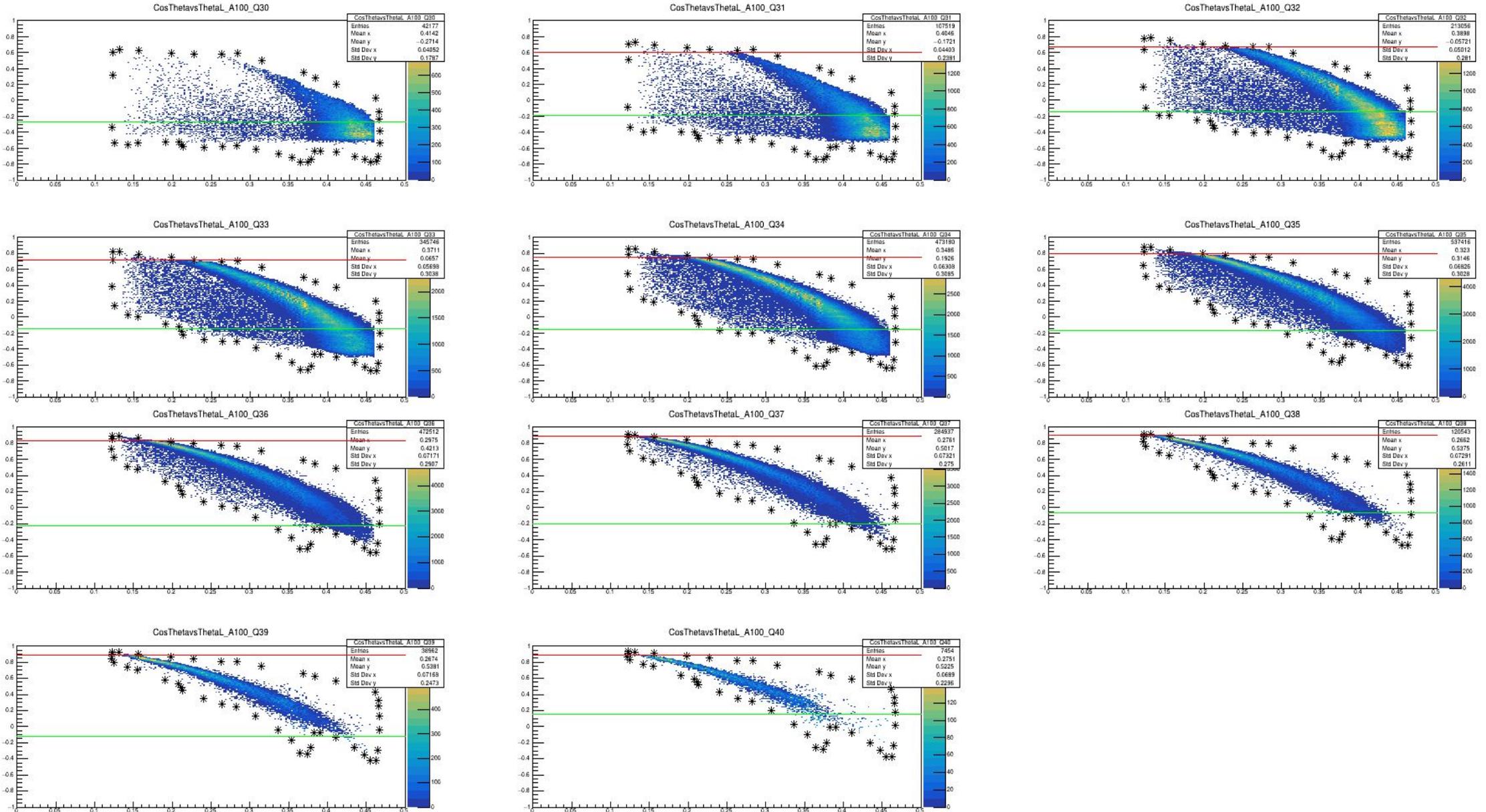
From identification to acceptance: ϕ range



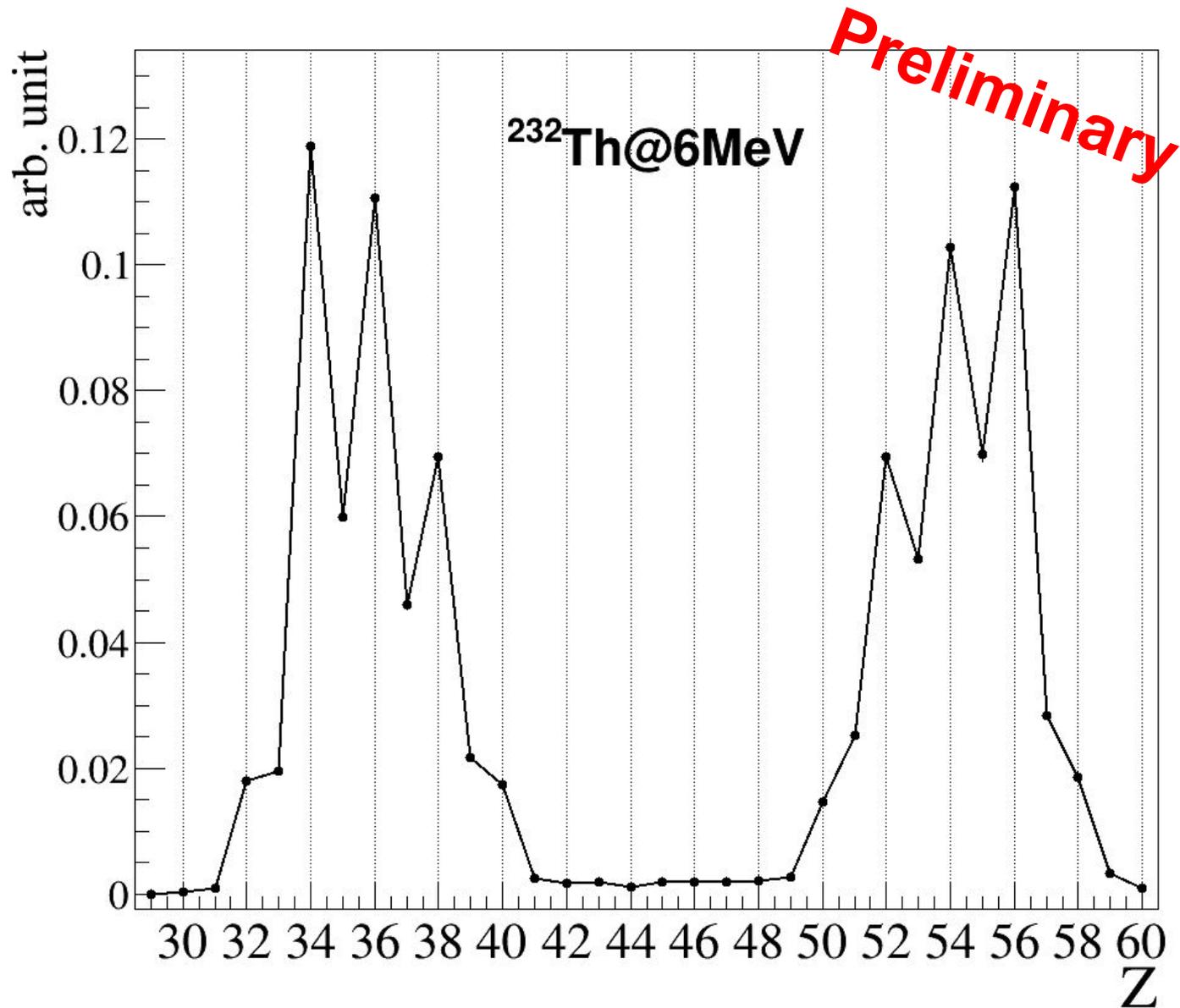
From identification to acceptance: ϕ range



From identification to acceptance: $\cos(\vartheta_{CM})$ range

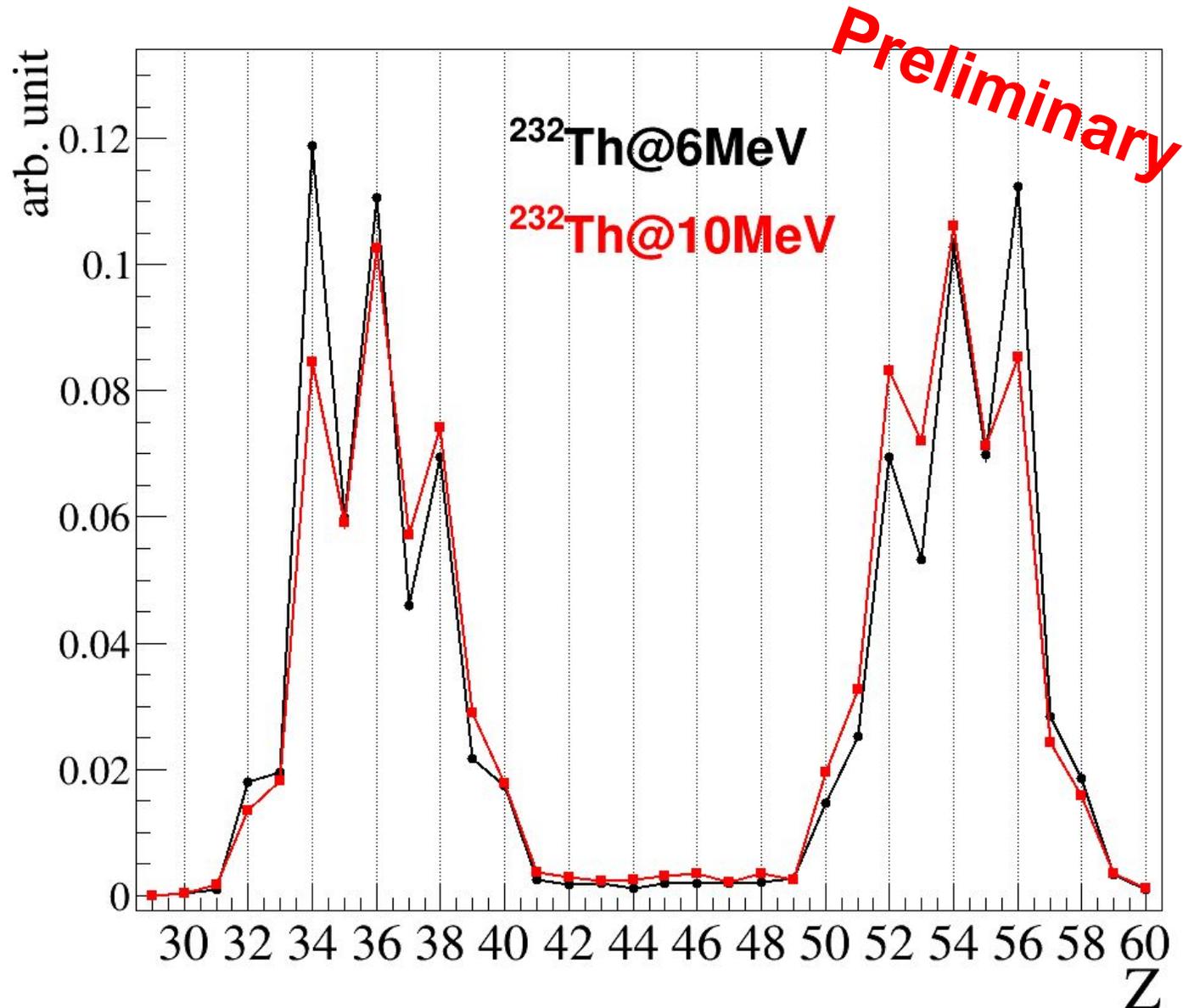


Isotopic yields



^{232}Th at 6 ± 2 MeV of Excitation energy, the isotopic yield peaks at **Z = 56** more than $Z = 52$, following the **Thorium anomaly**

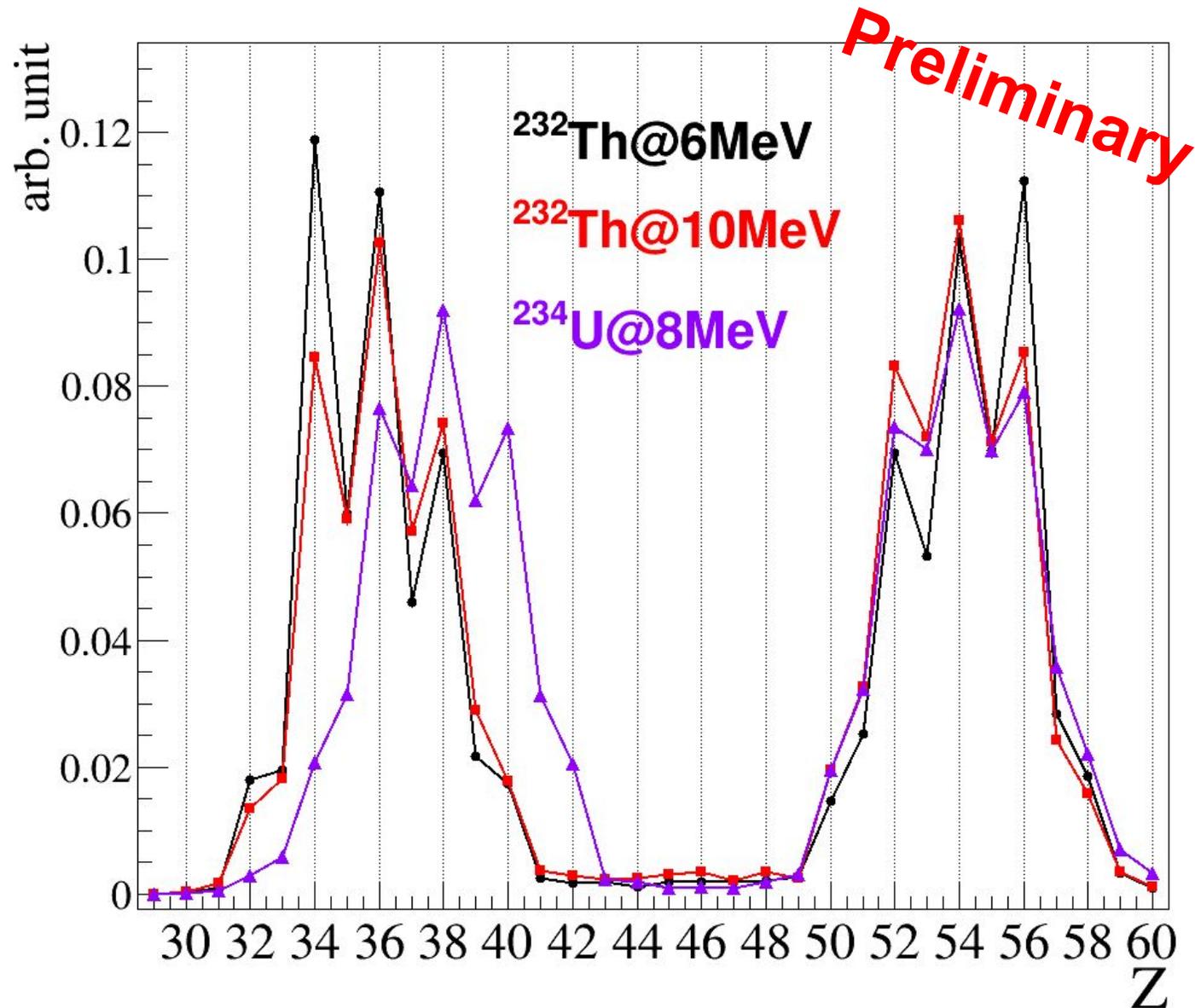
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Increasing the energy by **4 MeV**, the production of $Z = 52$ practically **matches** the one of $Z=56$.

Isotopic yields



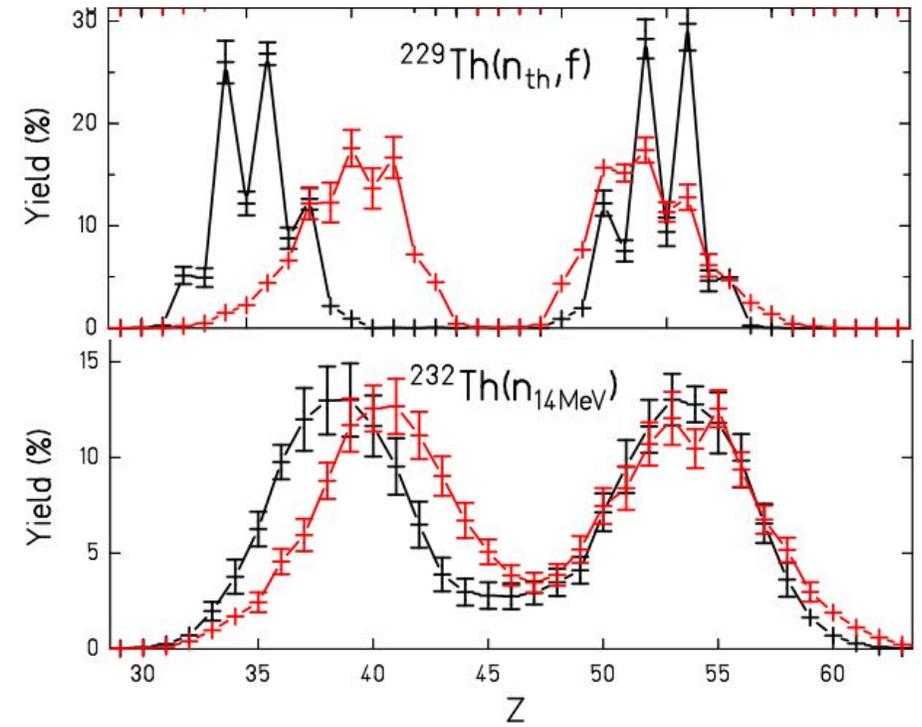
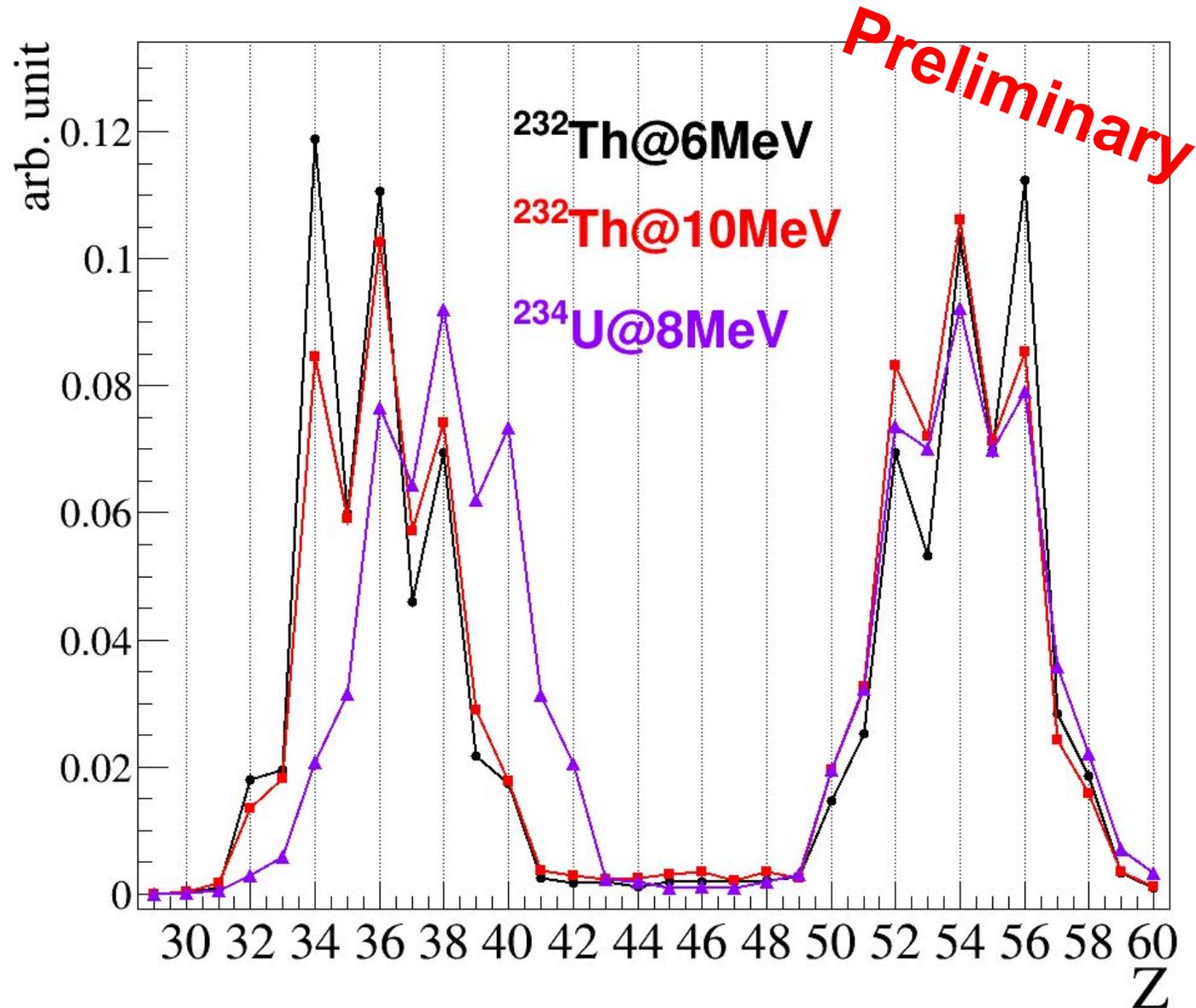
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Similar distribution present in heavier actinides like ^{234}U at 8 ± 2 MeV of E^* .

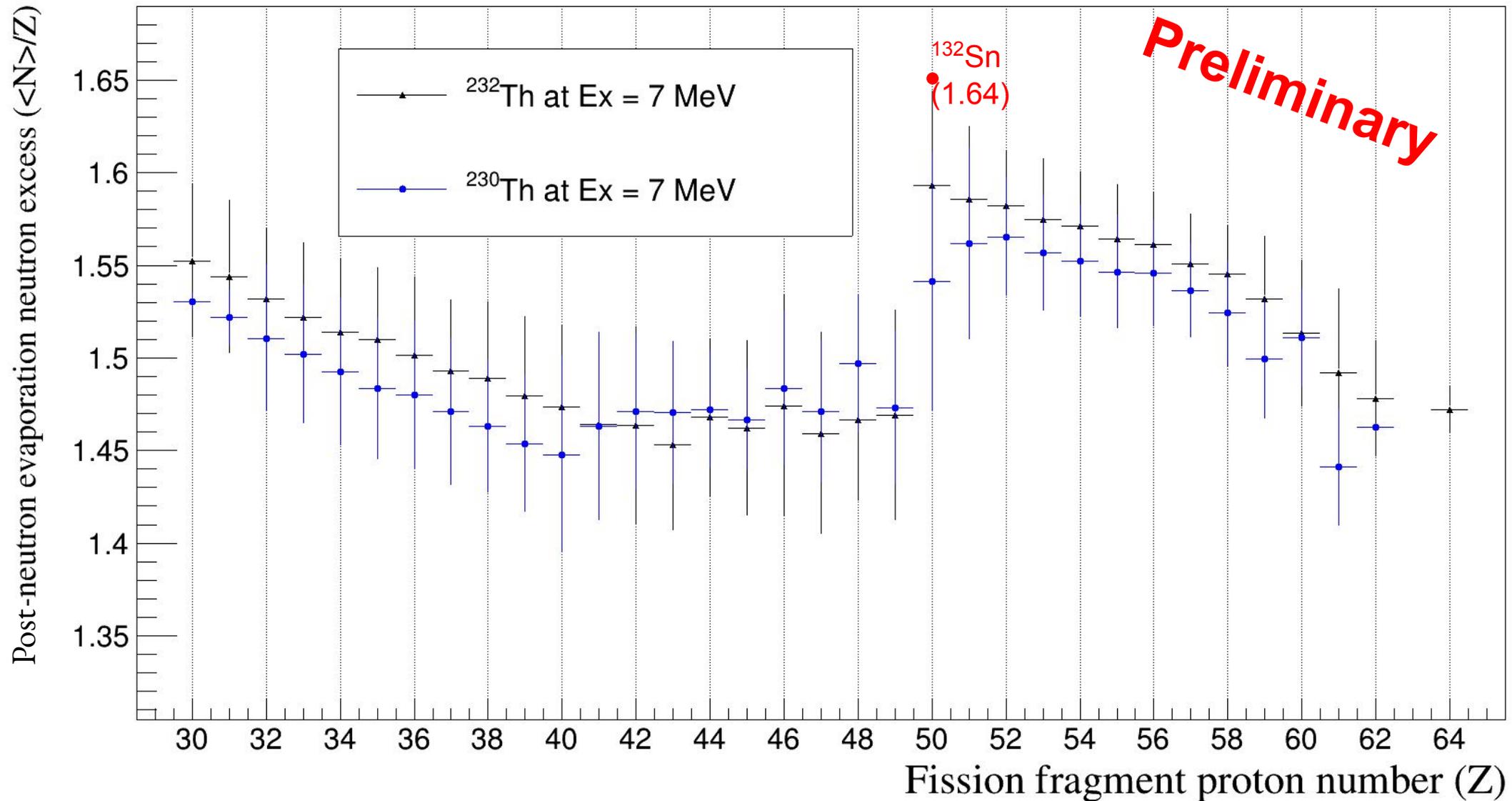
Disappearance of the third barrier effect at moderate Excitation energy increase?

Isotopic yields



Disappearance of the third barrier effect at moderate Excitation energy increase?

Neutron excess @ 7 ± 1 MeV

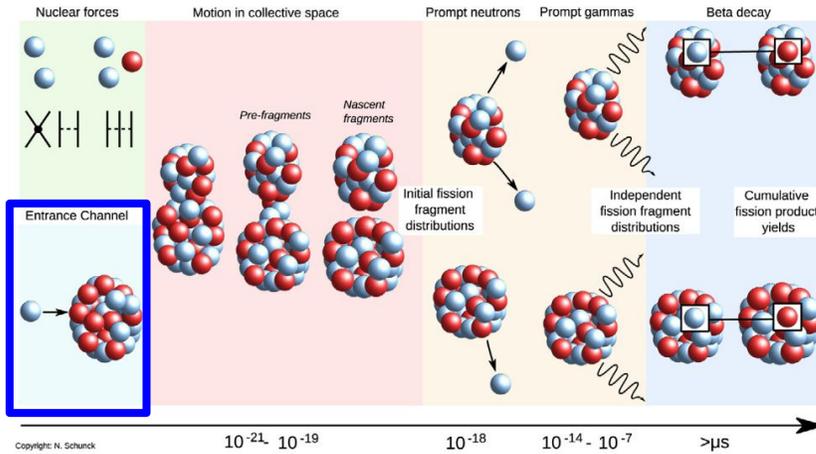


THANK YOU

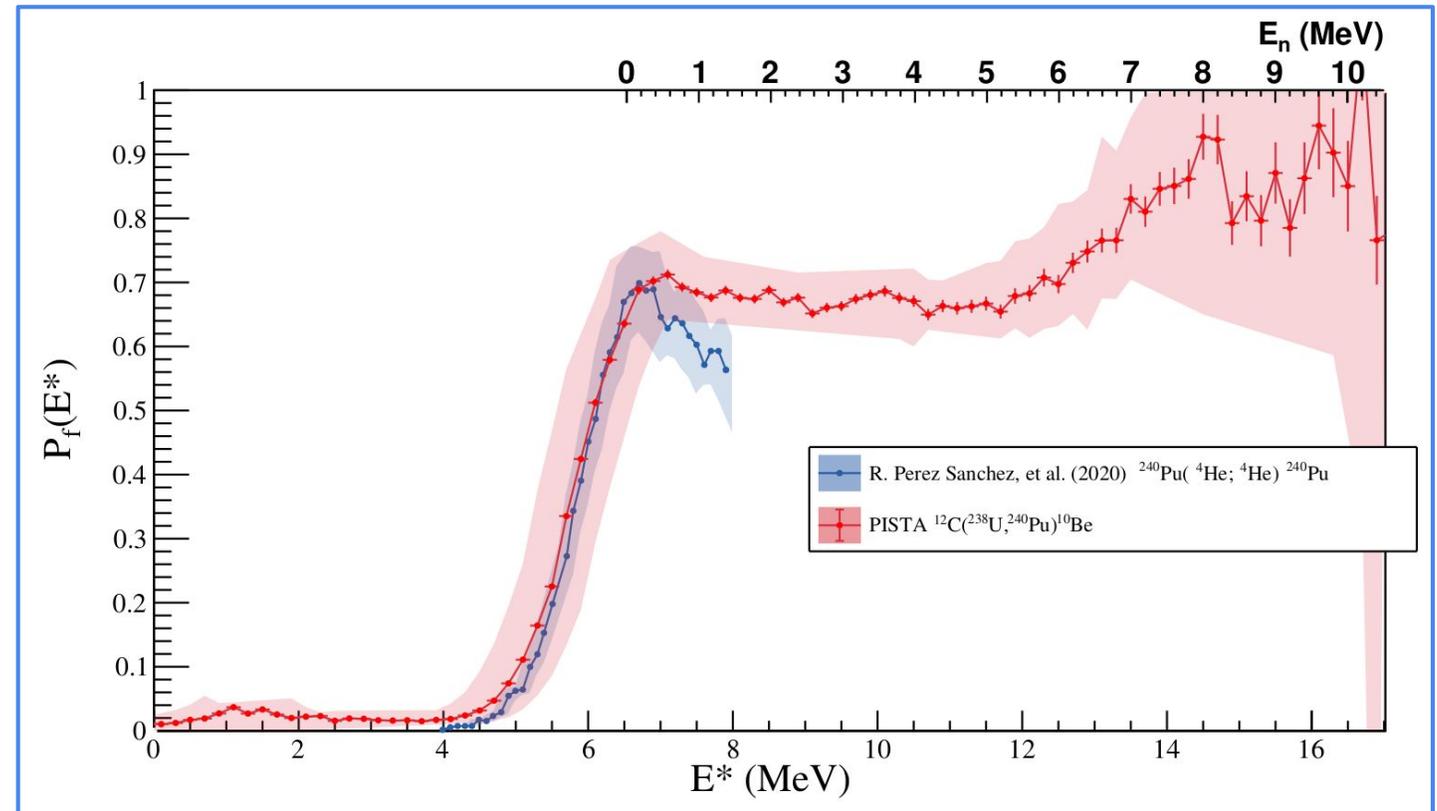
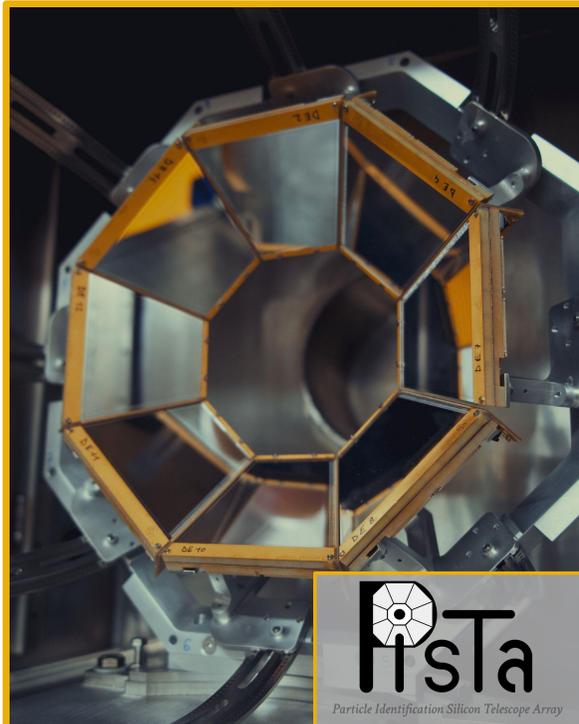
Thanks to VAMOS group and collaborators from e849 experiment

Back up slides

Entrance channel information

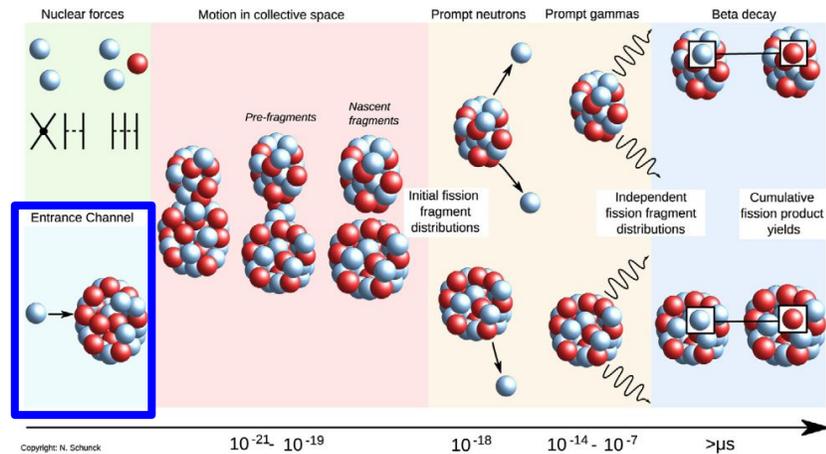


- 1) What is the fissioning system that was formed (Z,A)
- 2) What is the excitation energy (E^*)
- 3) **What is the probability of fissioning for a given excitation energy?**

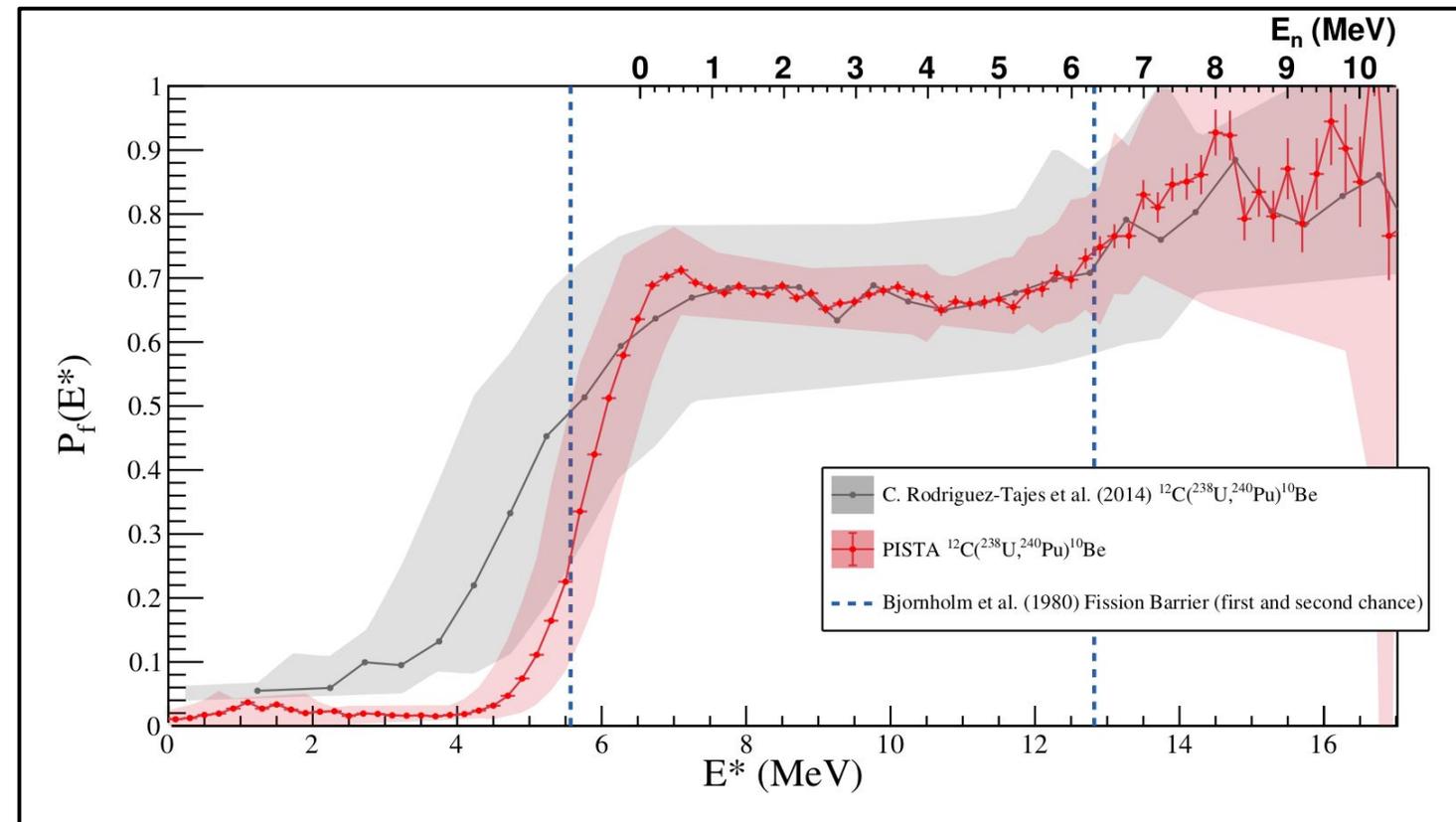
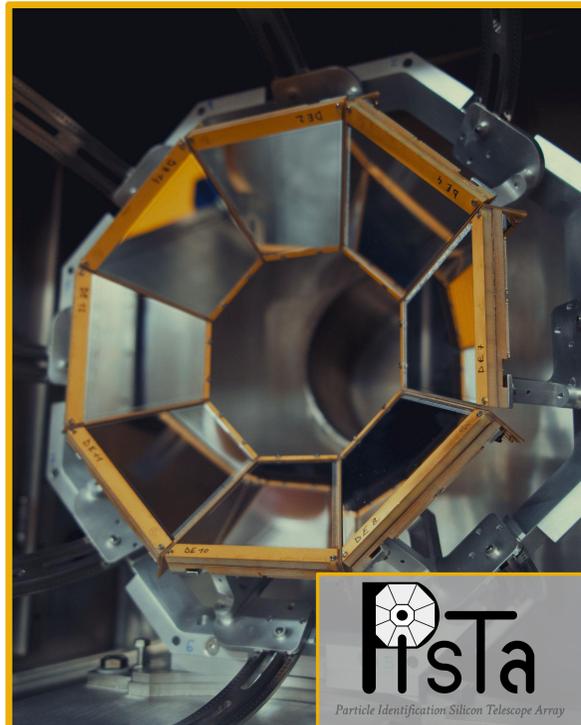


PhD thesis of Lucas Bégué-Guillou ($^{238}\text{U} + ^{12}\text{C}$)

Entrance channel information

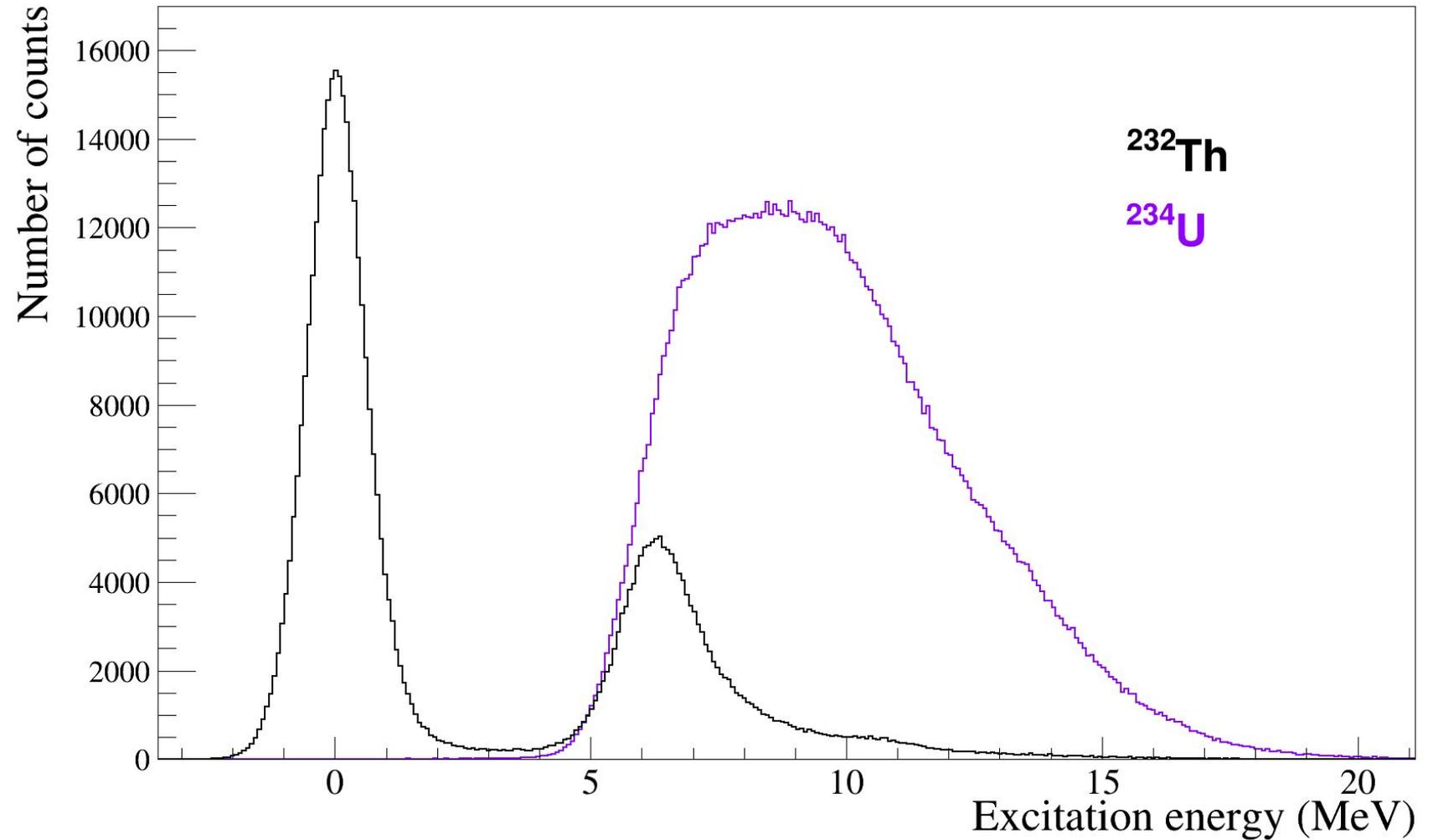
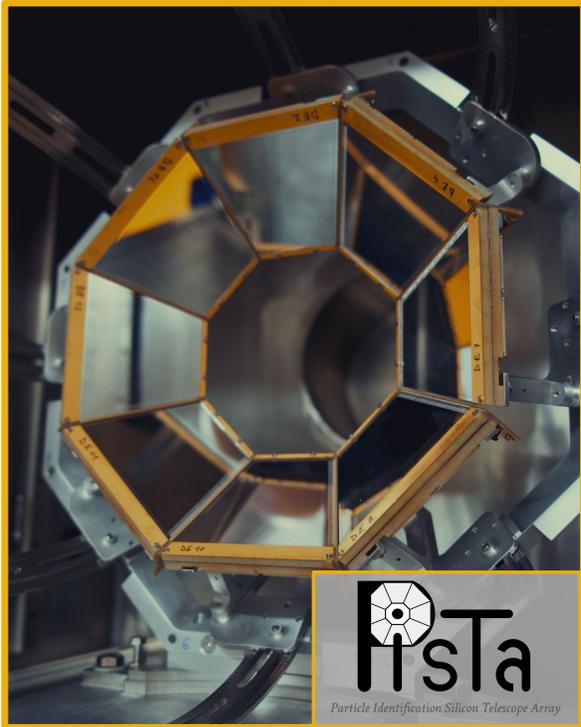


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PhD thesis of Lucas Bégué-Guillou

Excitation energy distributions



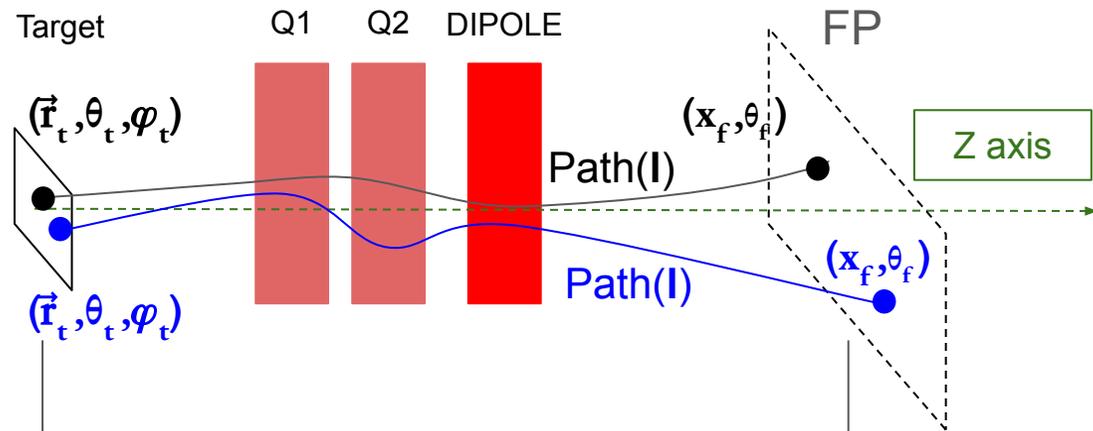
Experimental setup: VAMOS++

Concept basis

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

Particles with different $B\rho$ and entrance coordinates $(\vec{r}_t, \theta_t, \varphi_t)$ will travel a different path (I) 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

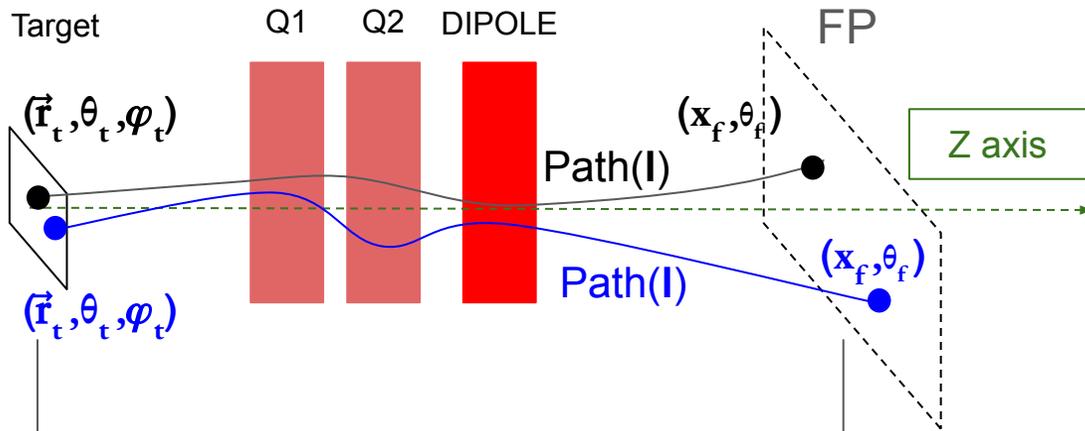
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[7] Rejmund, M., & Lemasson, A. (2025). Seven-dimensional trajectory reconstruction for VAMOS++. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1076, 170445.



Simulation distance: 7.6 m

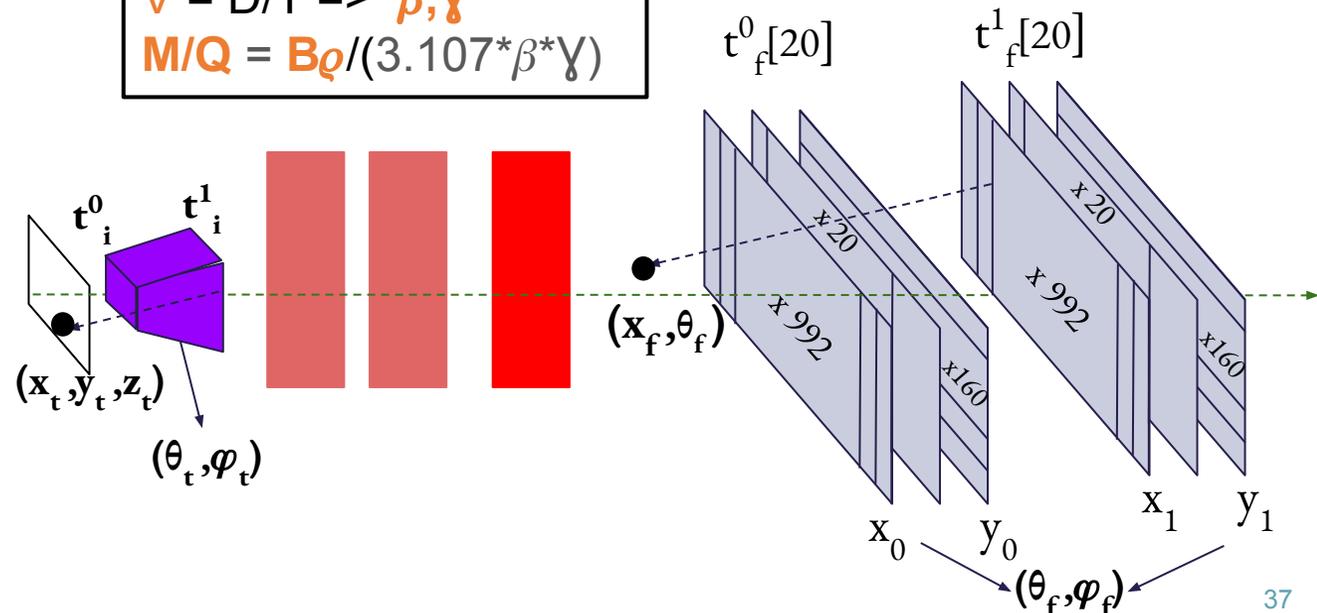
Experimentally

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)

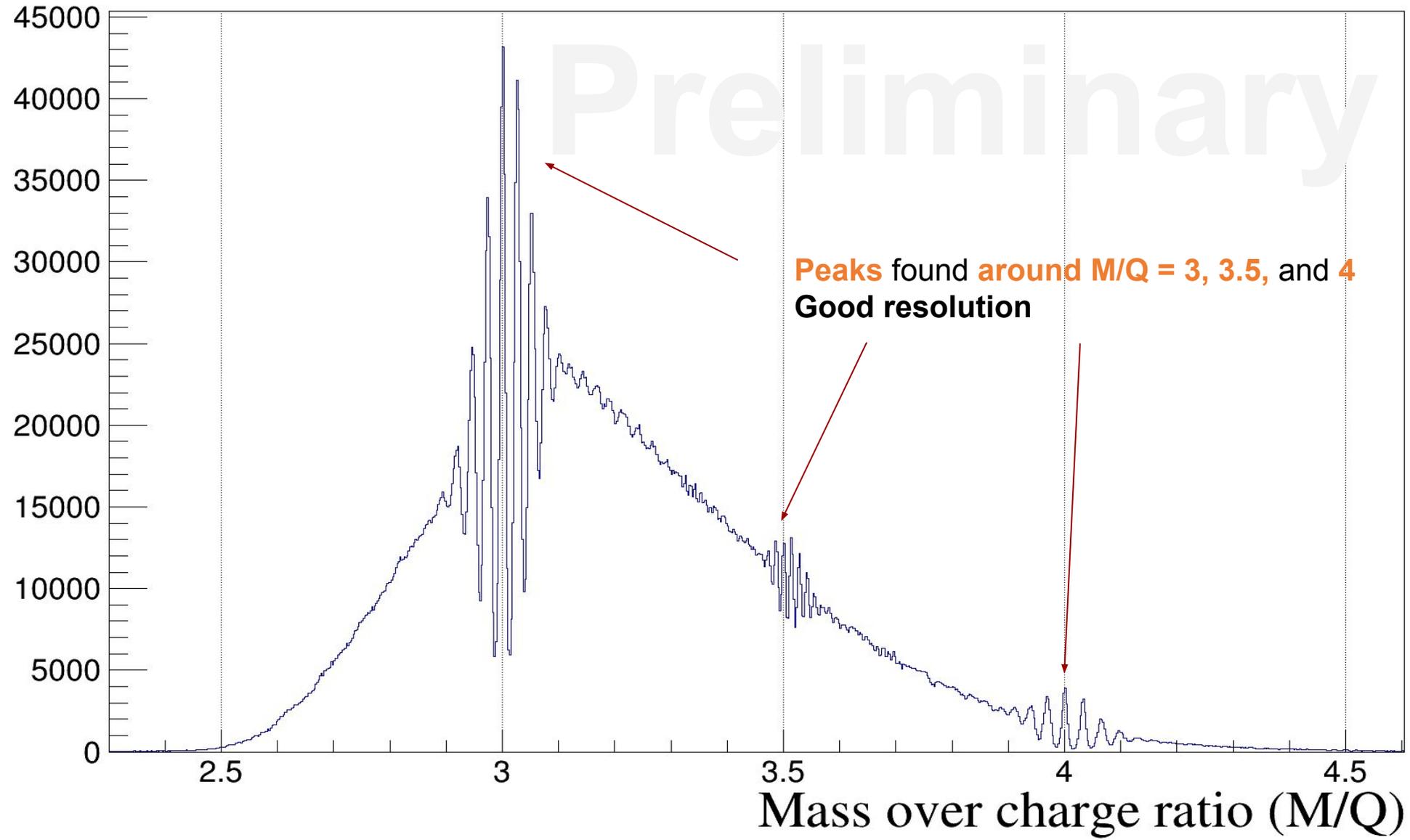
From measured positions, we extract the $B\rho$ and I of a fragment
 Combining it with the ToF ($t_f - t_i$), we get the velocity and M/Q:

$$V = D/T \Rightarrow \beta, \gamma$$

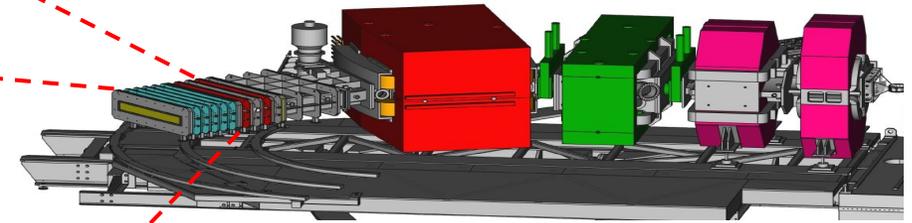
$$M/Q = B\rho / (3.107 \cdot \beta \cdot \gamma)$$



Experimental result: M/Q



Experimental setup: Ionization Chamber (Q)

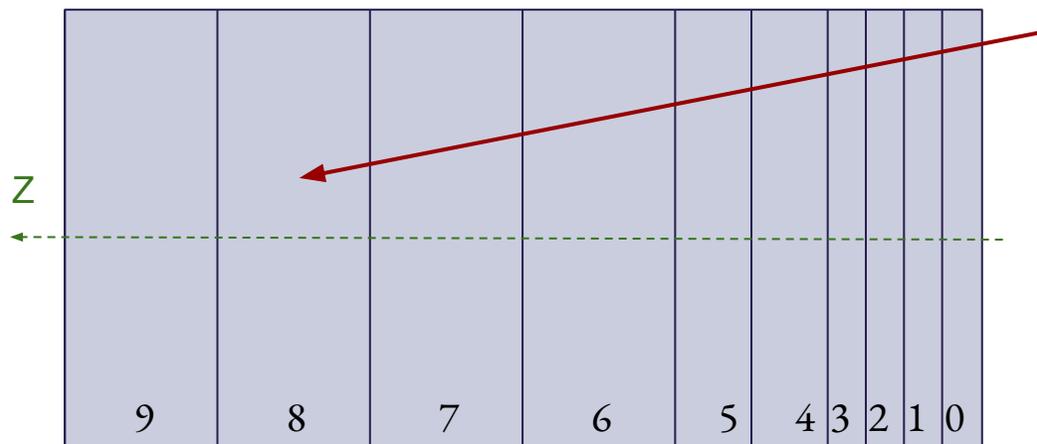


The **kinetic energy** (E_{kin}) of the fragment is proportional to the **mass** and the **velocity** (γ)

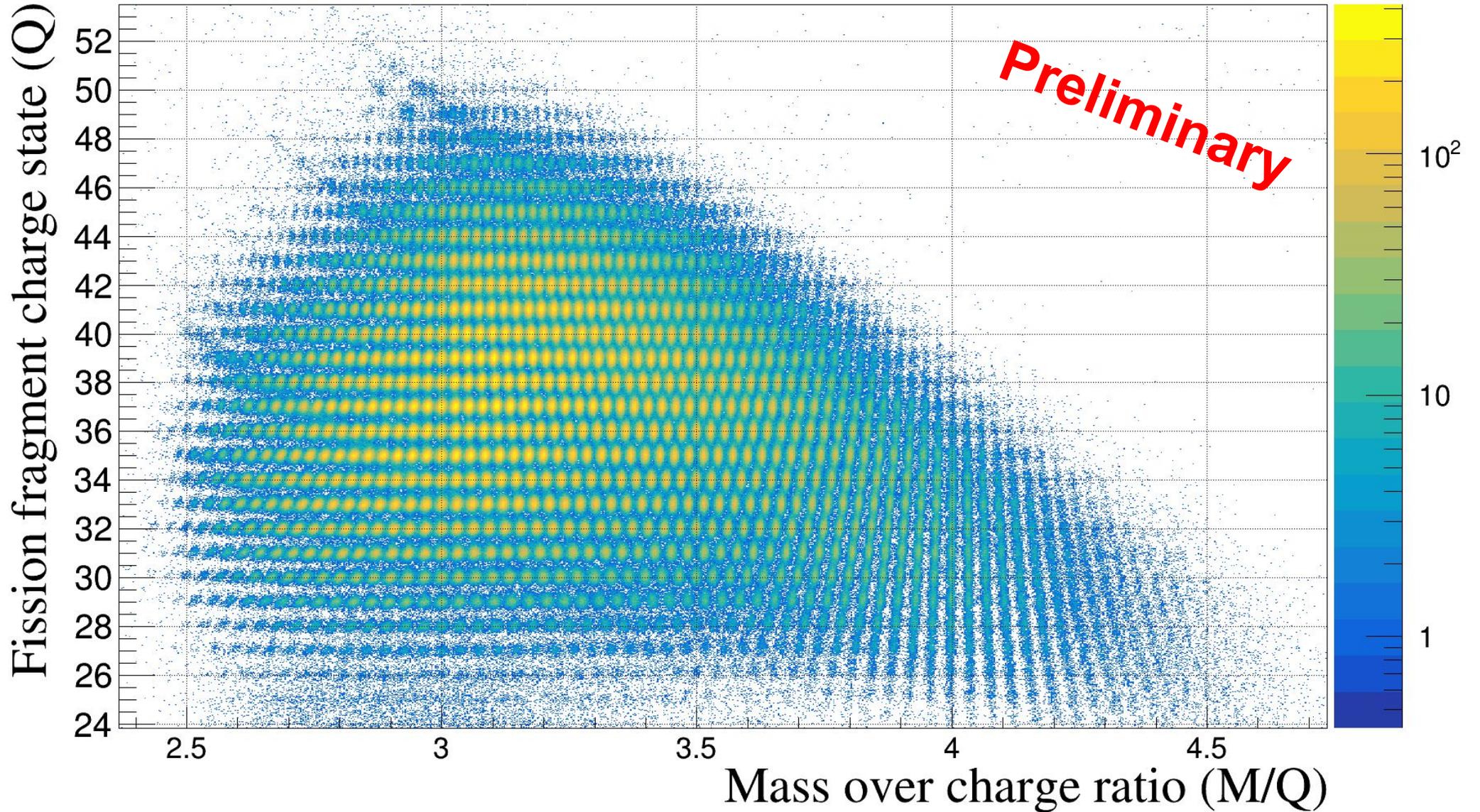
Through a **minimization method**, **scale** the contribution of **each IC** section for every time section

$$E_{\text{kin}} = \sum a_i \cdot IC_i + b_0$$
$$M_{\text{IC}} = E_{\text{kin}} / (\gamma_{\text{VAMOS}}^{-1})$$

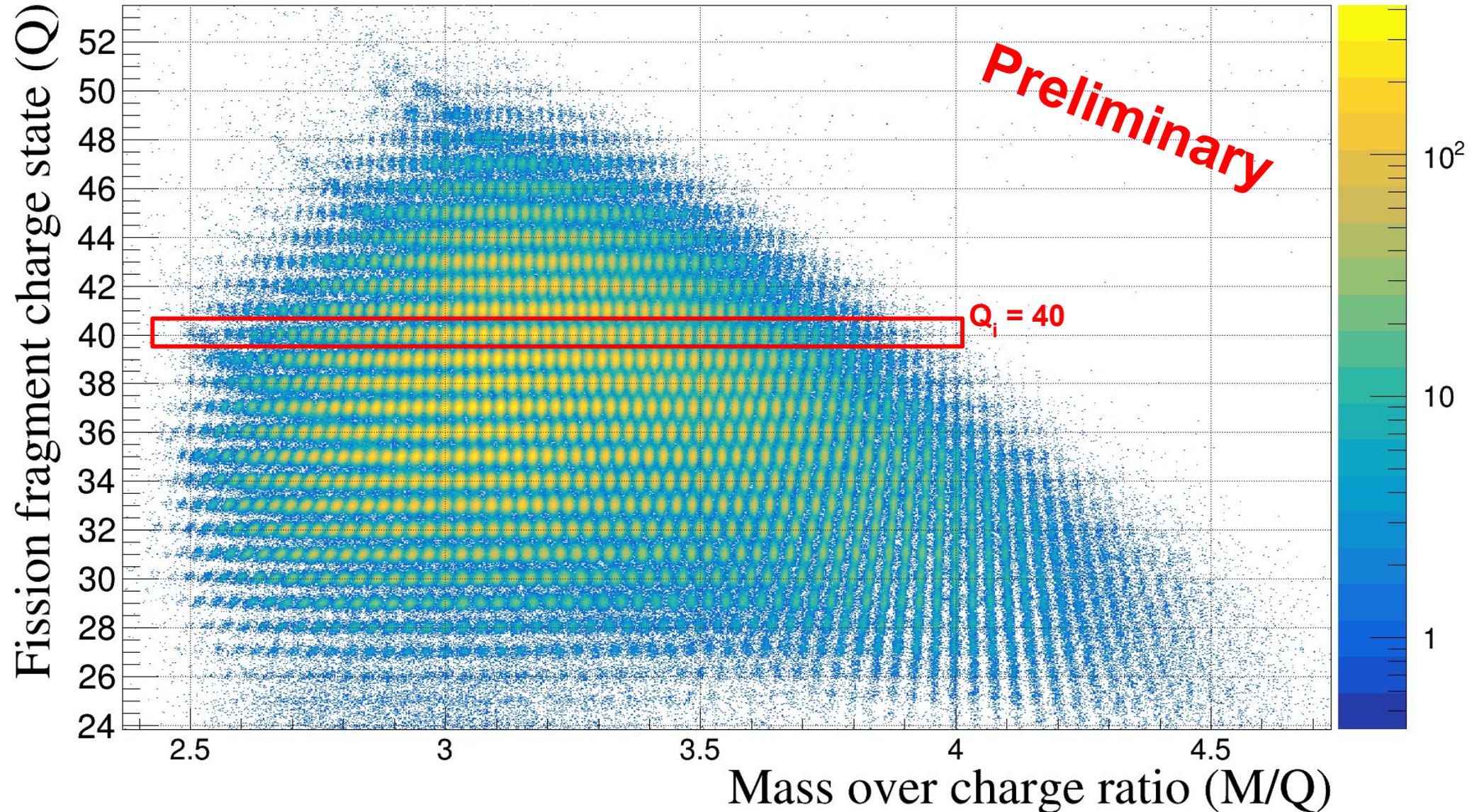
The M_{IC} is **not enough** ($\sim 1\%$) for our goal :
 $Q = M_{\text{IC}} / (M/Q)$



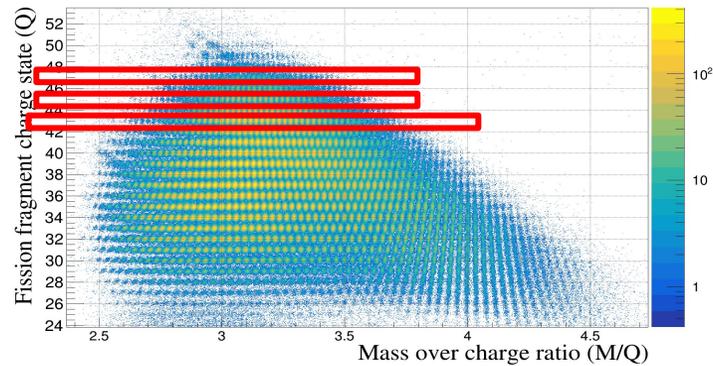
Experimental result: Q



Experimental result: Q and M

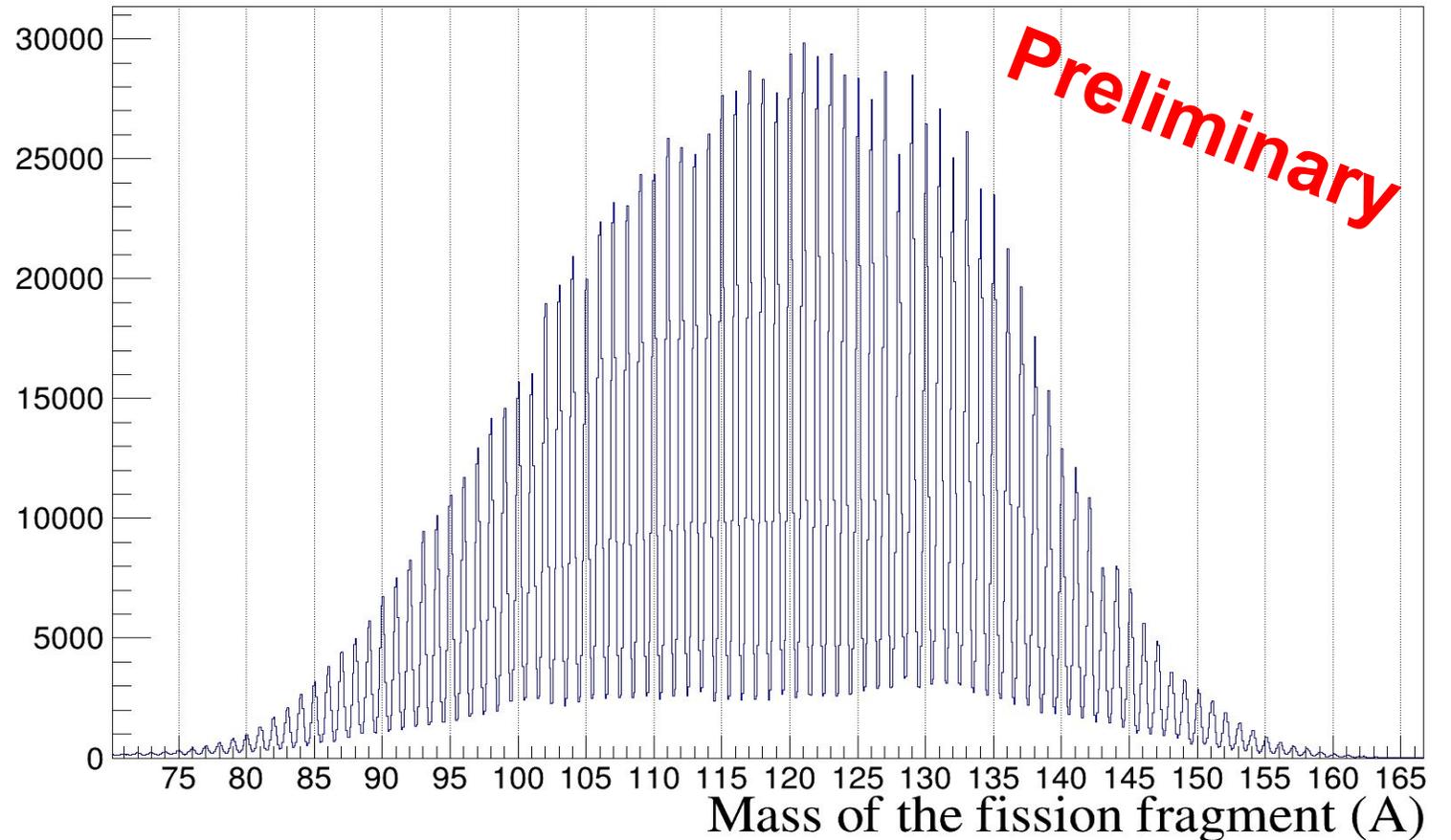


Experimental result: Q and M

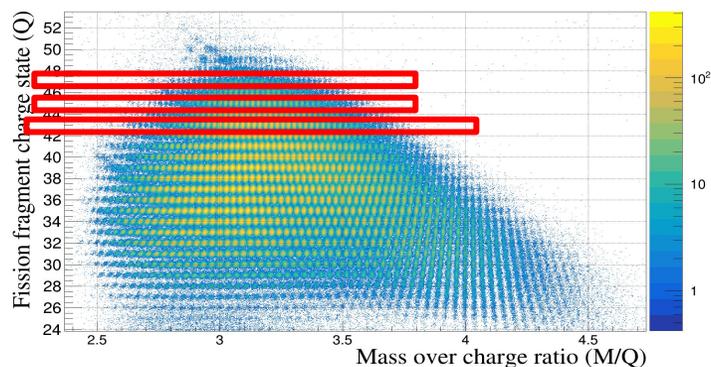


$$M = Q_i * M/Q$$

Average resolution of $\Delta A/A \sim 1/234 = 4.27 \%$

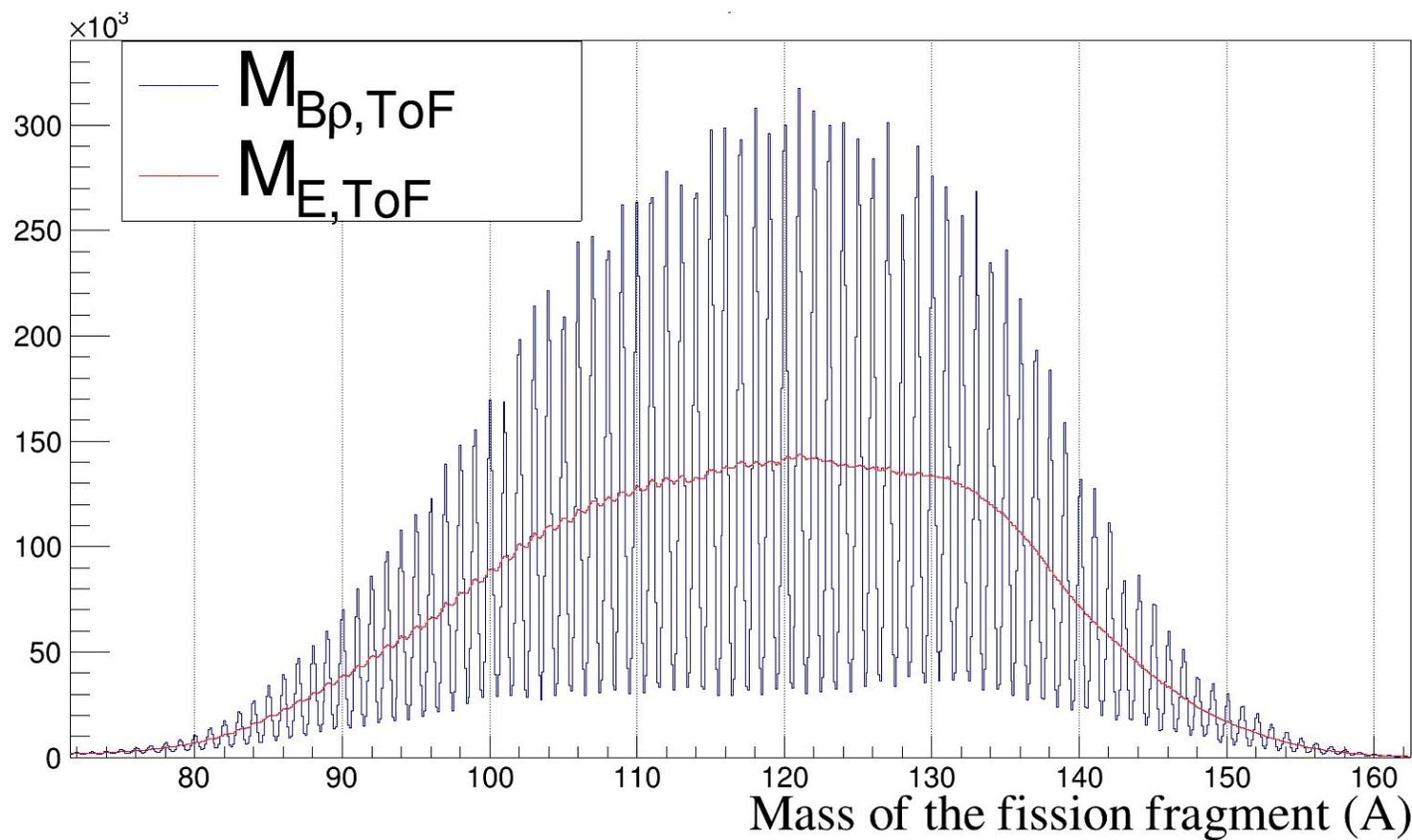


Experimental result: Q and M



$$M = Q_i * M/Q$$

Average resolution of $\Delta A/A \sim 1/234 = 4.27 \text{ ‰}$

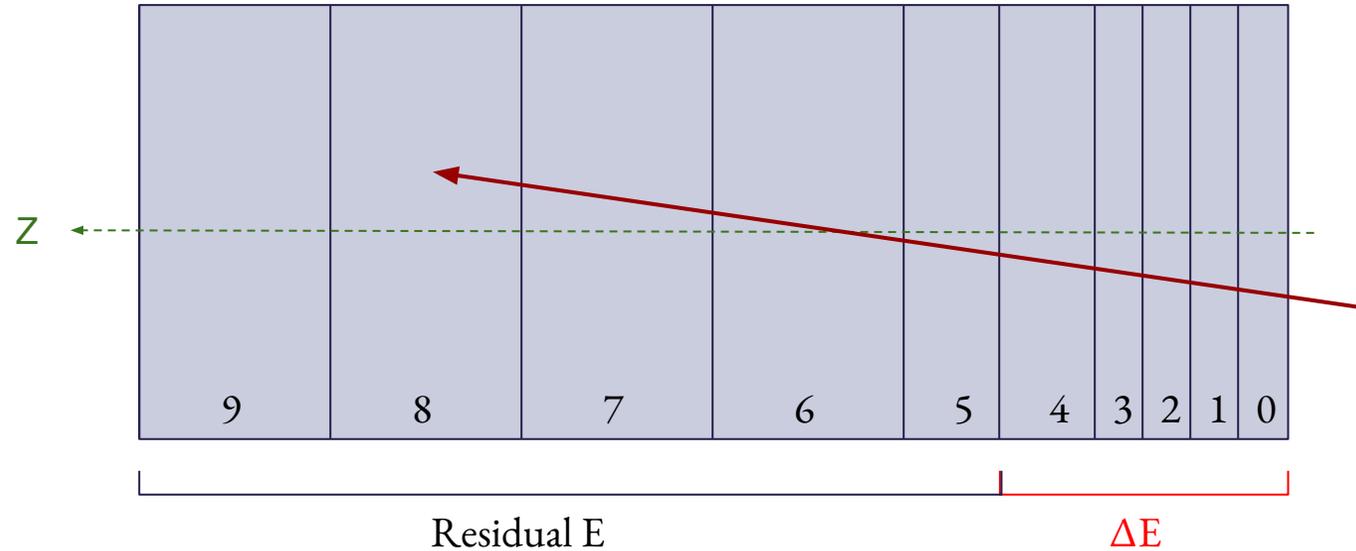


Preliminary

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

Experimental setup: Segmented IC

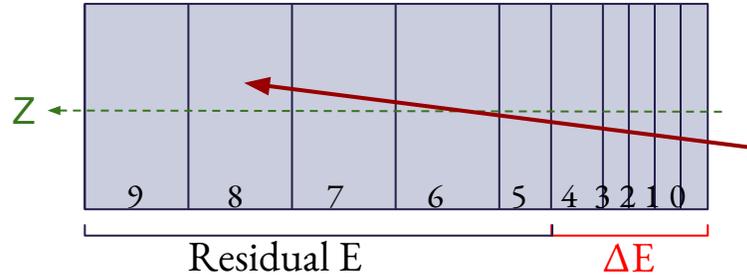
We can also use the **sections** of the **IC** to get the **proton content** of the fission fragment
Several combinations possible, best in our case: ΔE = sections 0-4 , E_{Res} = sections 5-9



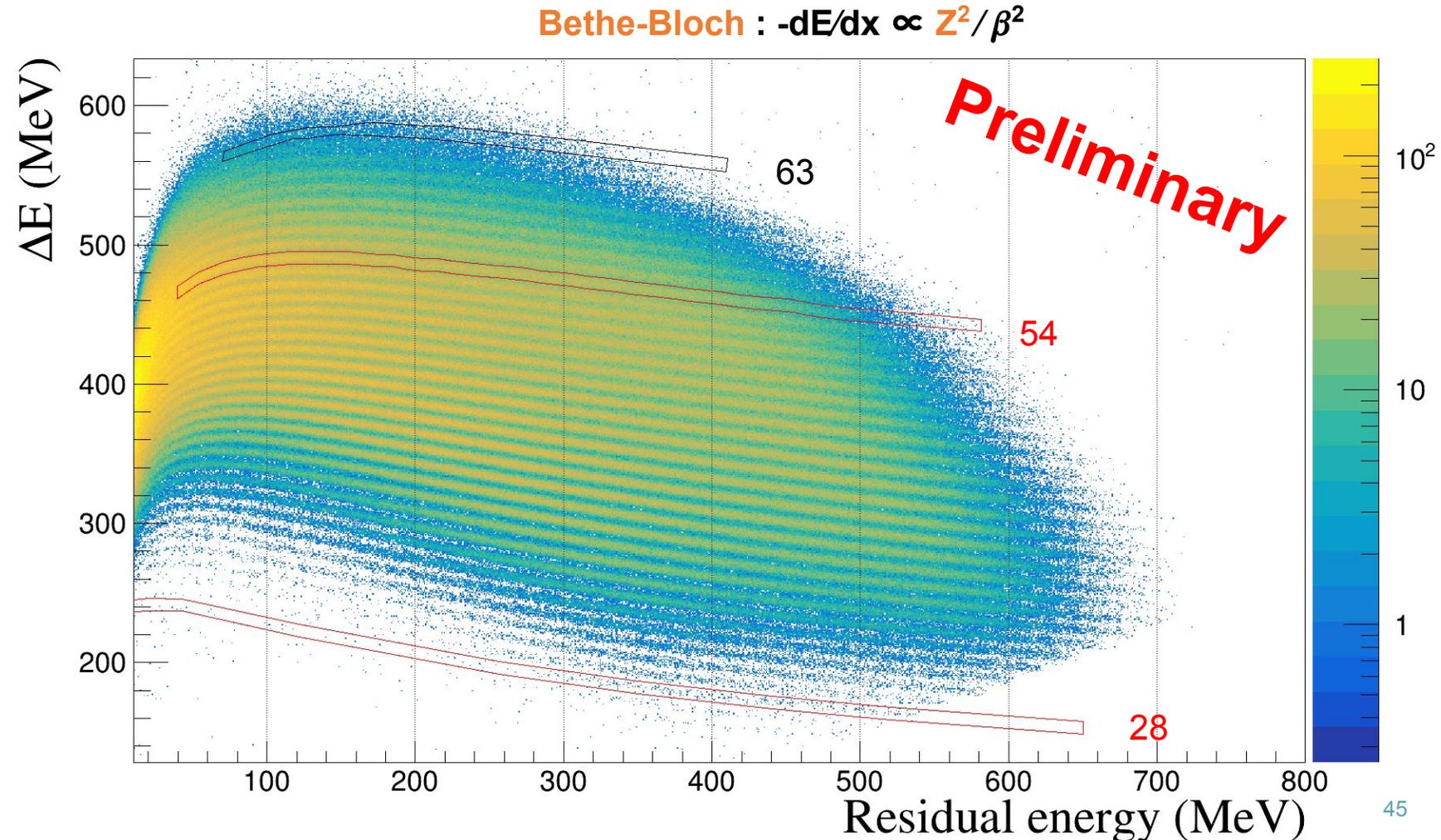
Bethe-Bloch : $-dE/dx \propto Z^2/\beta^2$

Experimental result: Z

We can also use the **sections** of the **IC** to get the **proton content** of the fission fragment
Several combinations possible, best in our case: ΔE = sections 0-4 , E_{Res} = sections 5-9



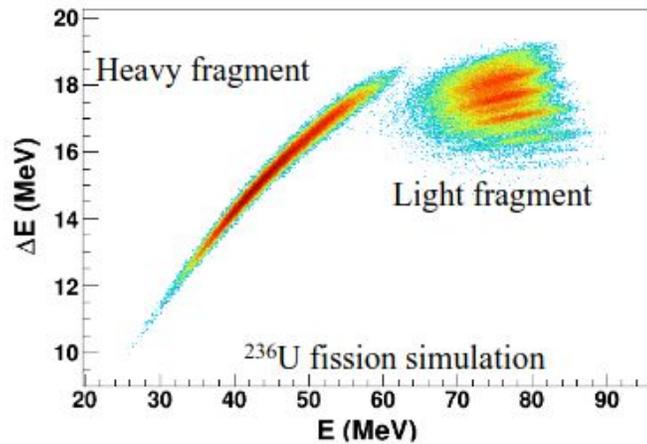
Each **line** corresponds to **one Z**
A resolution of $\Delta Z/Z \sim 1/70$



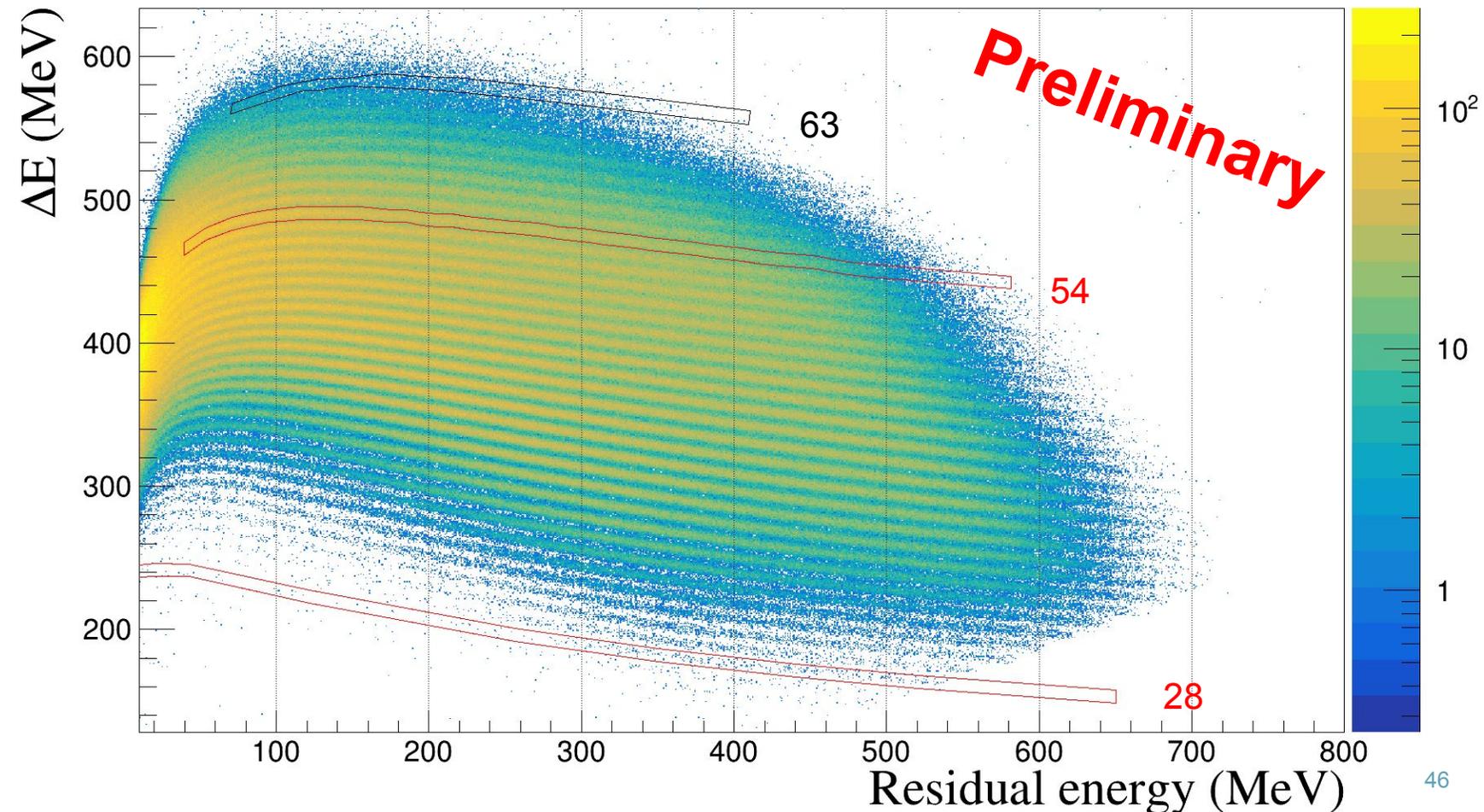
Experimental result: Z

We can also use the **sections of the IC** to get the **proton content** of the fission fragment
Several combinations possible, best in our case: ΔE = sections 0-4 , E_{Res} = sections 5-9

Direct-kinematics

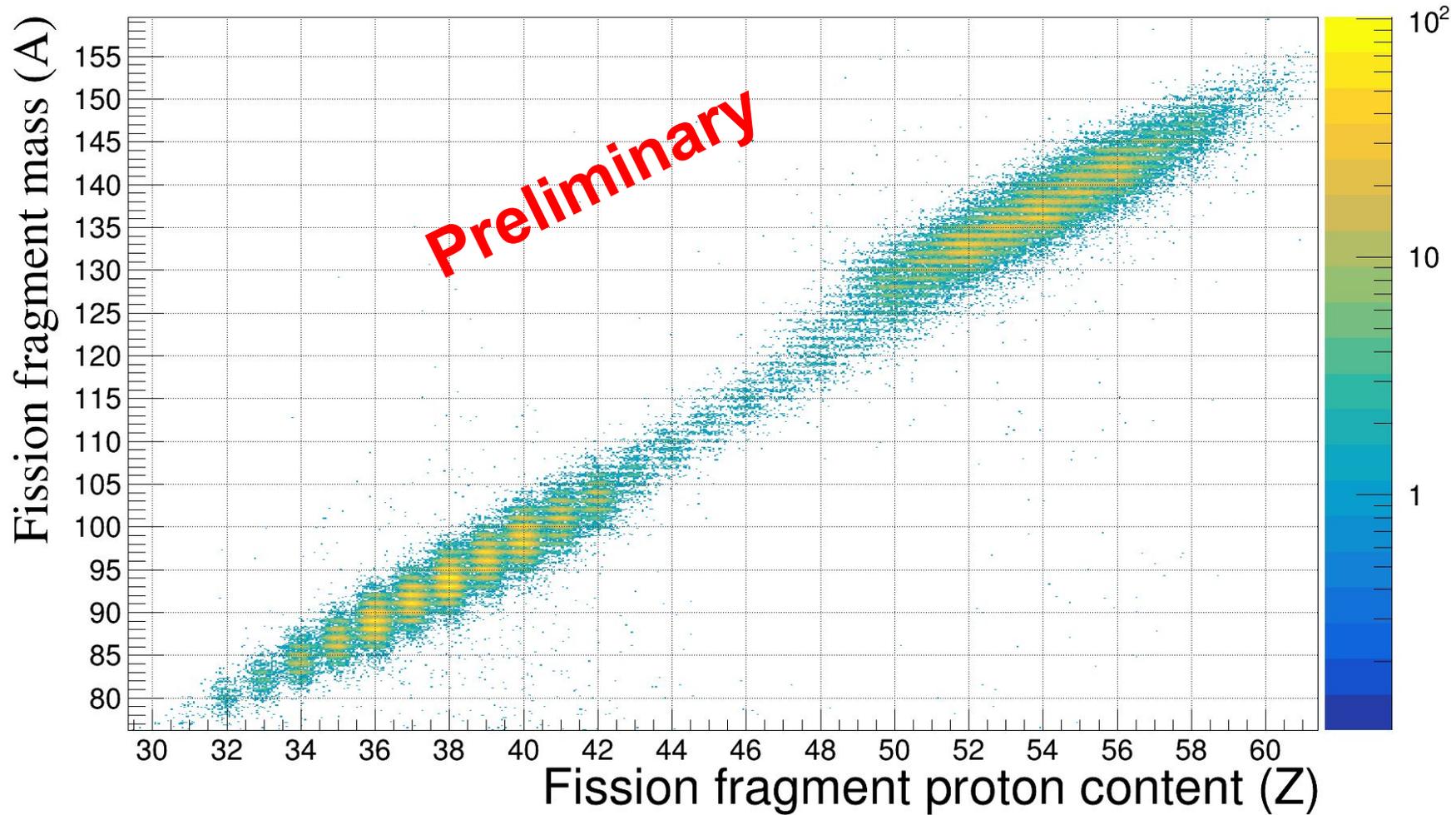


Bethe-Bloch : $-dE/dx \propto Z^2/\beta^2$

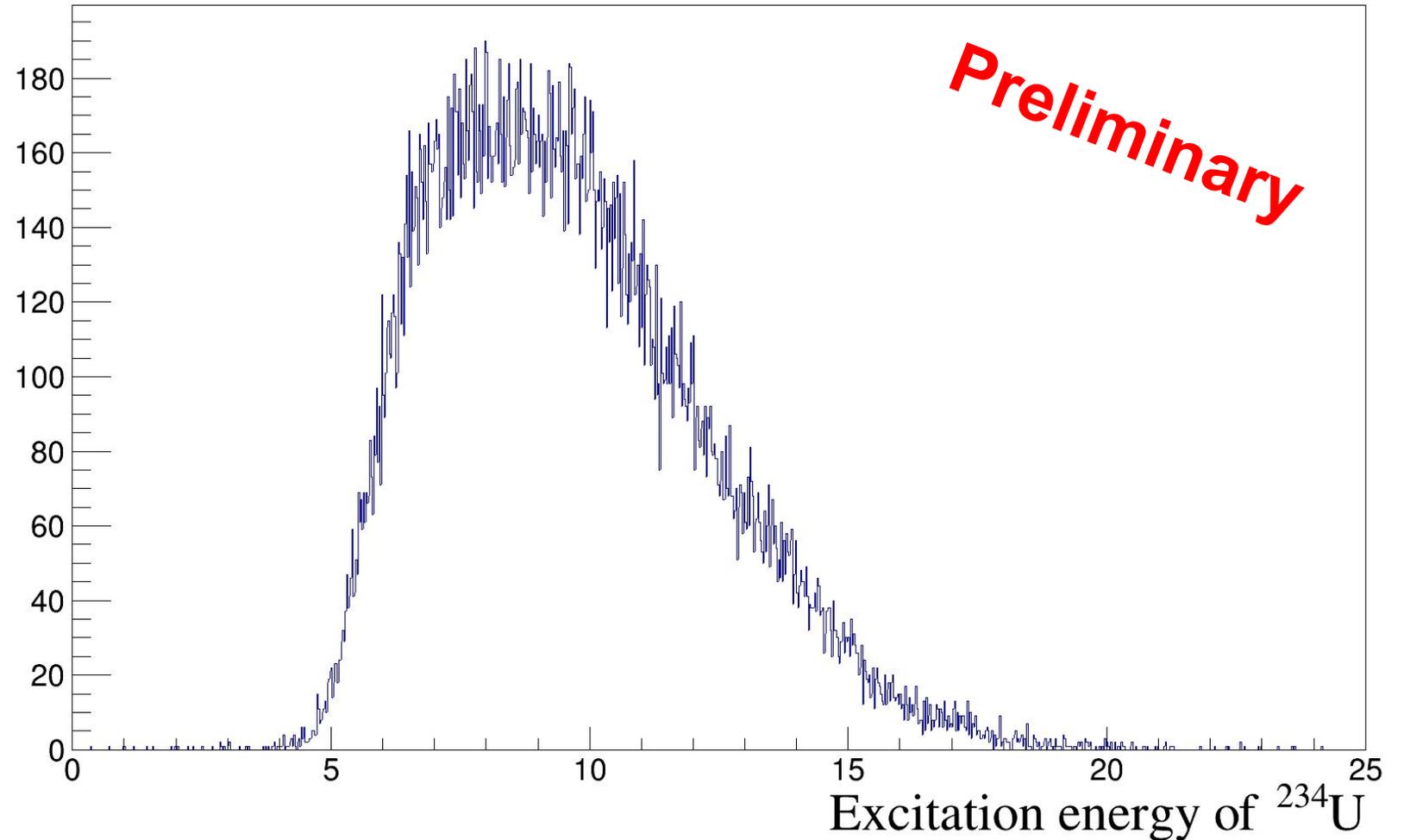
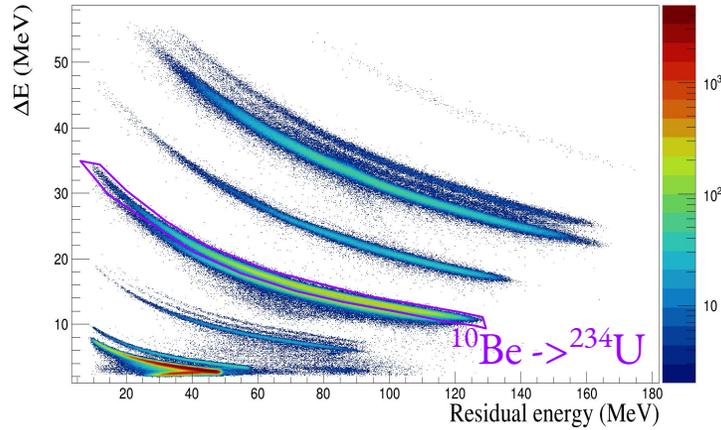


Identify Z from ~26 to ~65
Thanks to inverse-kinematics

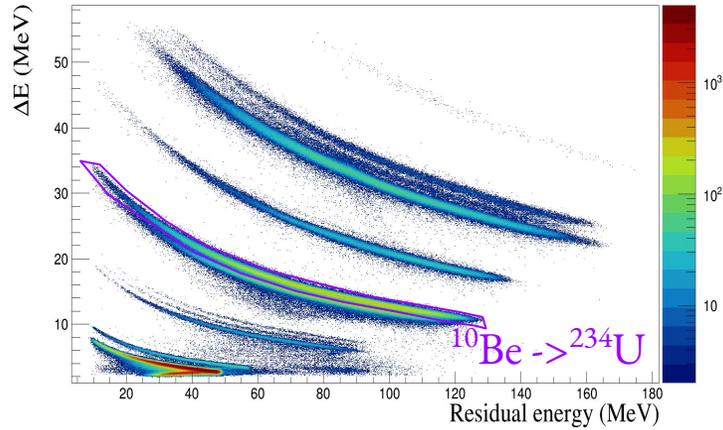
Experimental result: Fissioning system E*



Experimental result: Fissioning system E^*

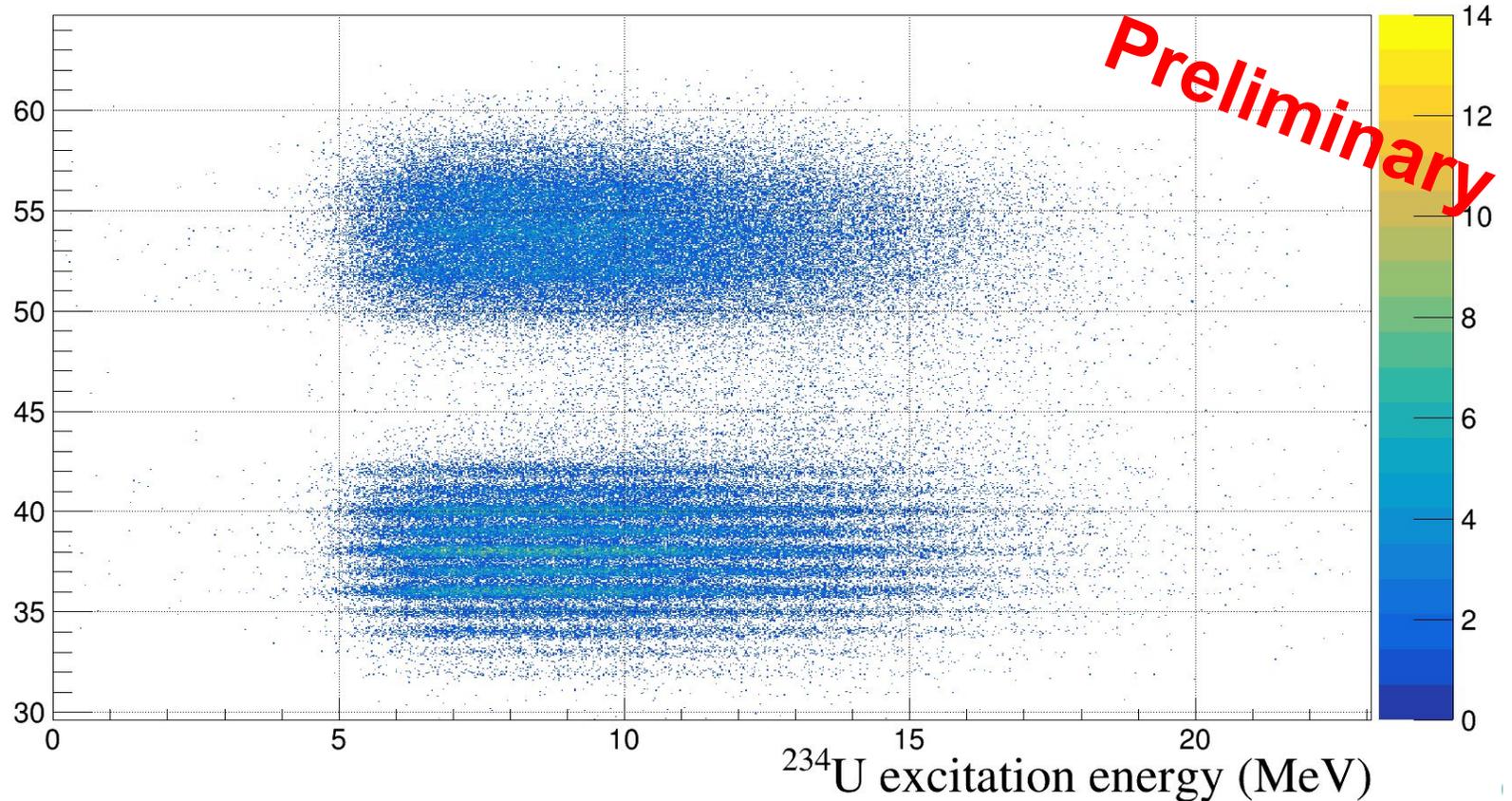


Experimental result: Fissioning system E^*

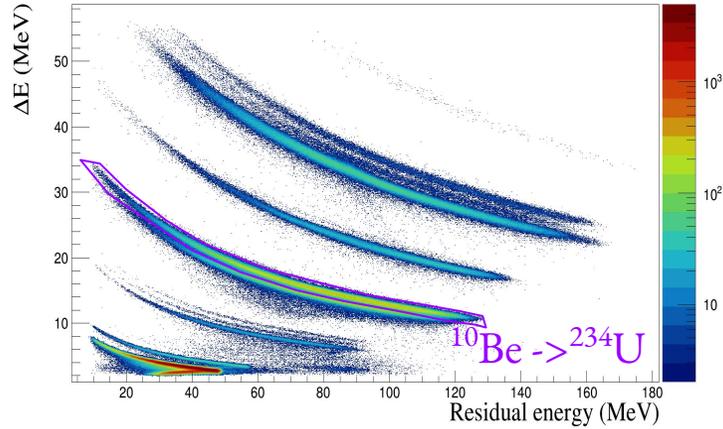


We can see the **evolution** of the distribution as a **function of the excitation energy**

Fission fragment proton content (Z)

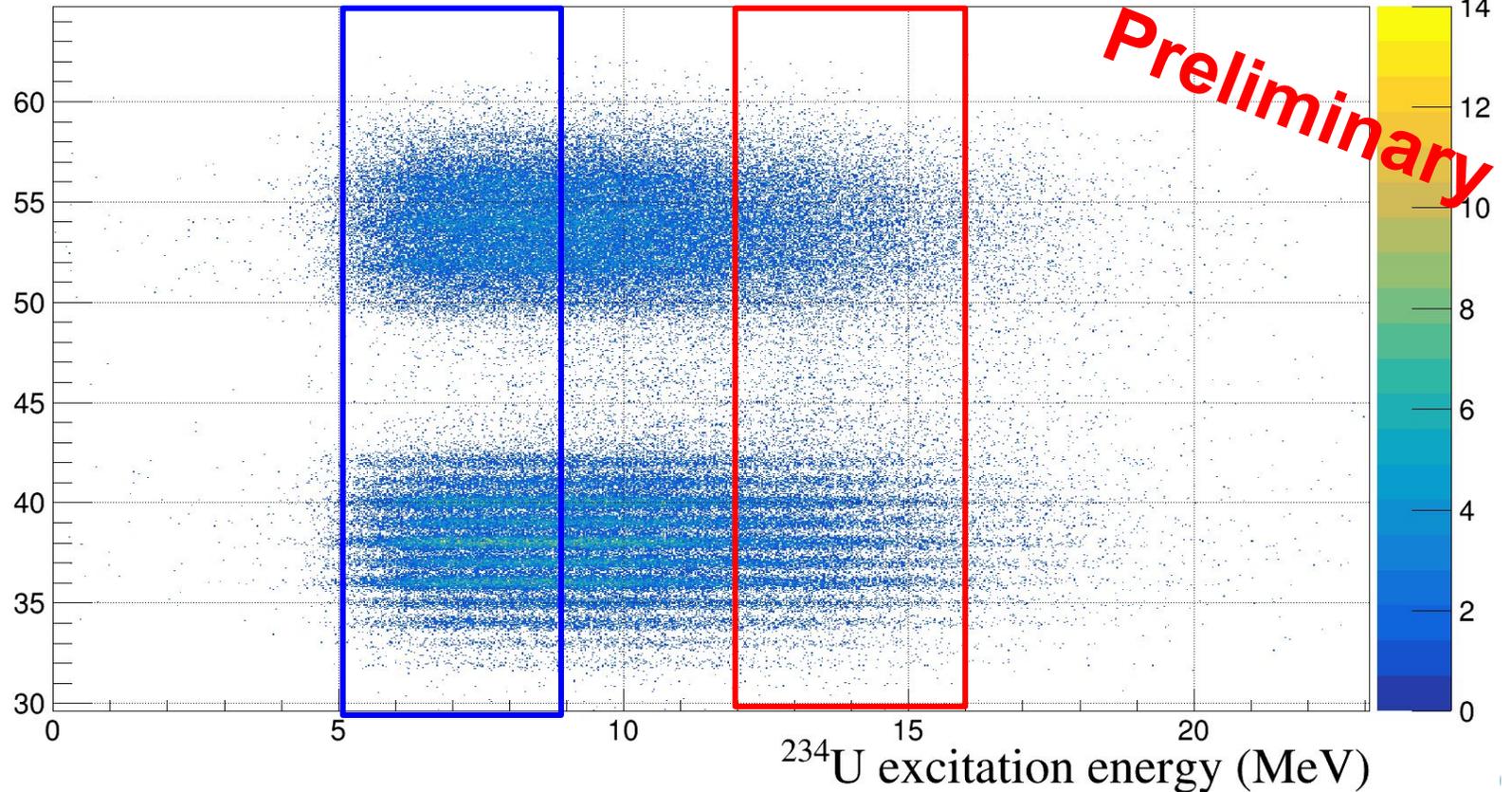


Experimental result: Z evolution with E^*

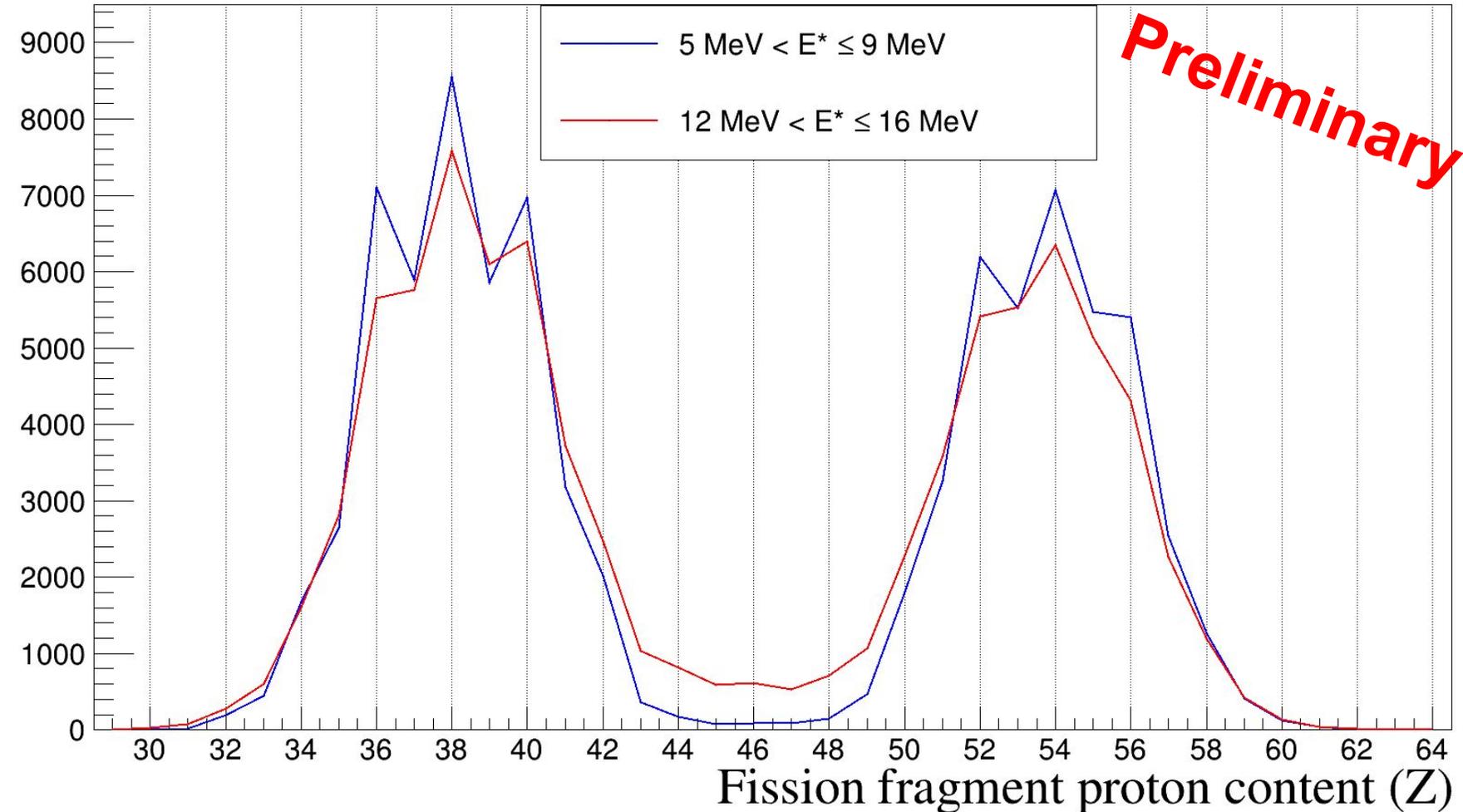
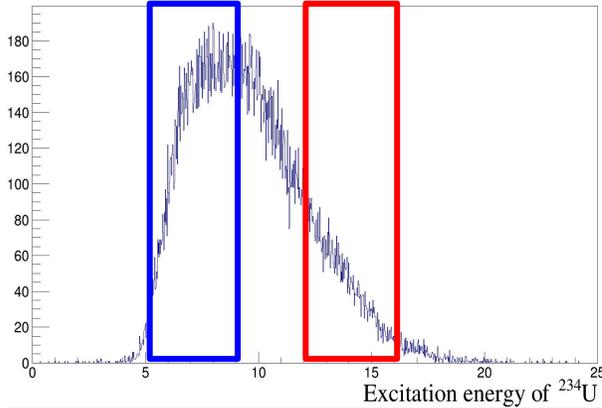


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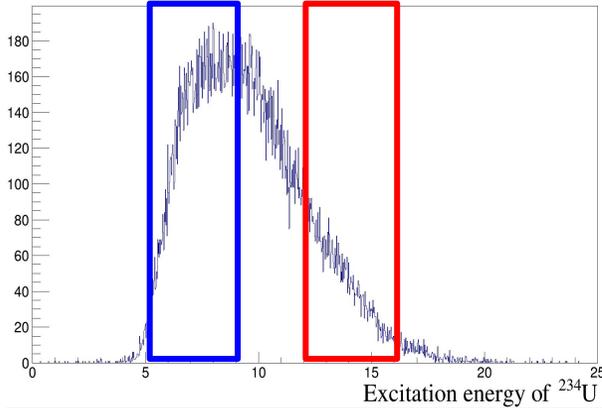
Experimental result: Z evolution with E^*



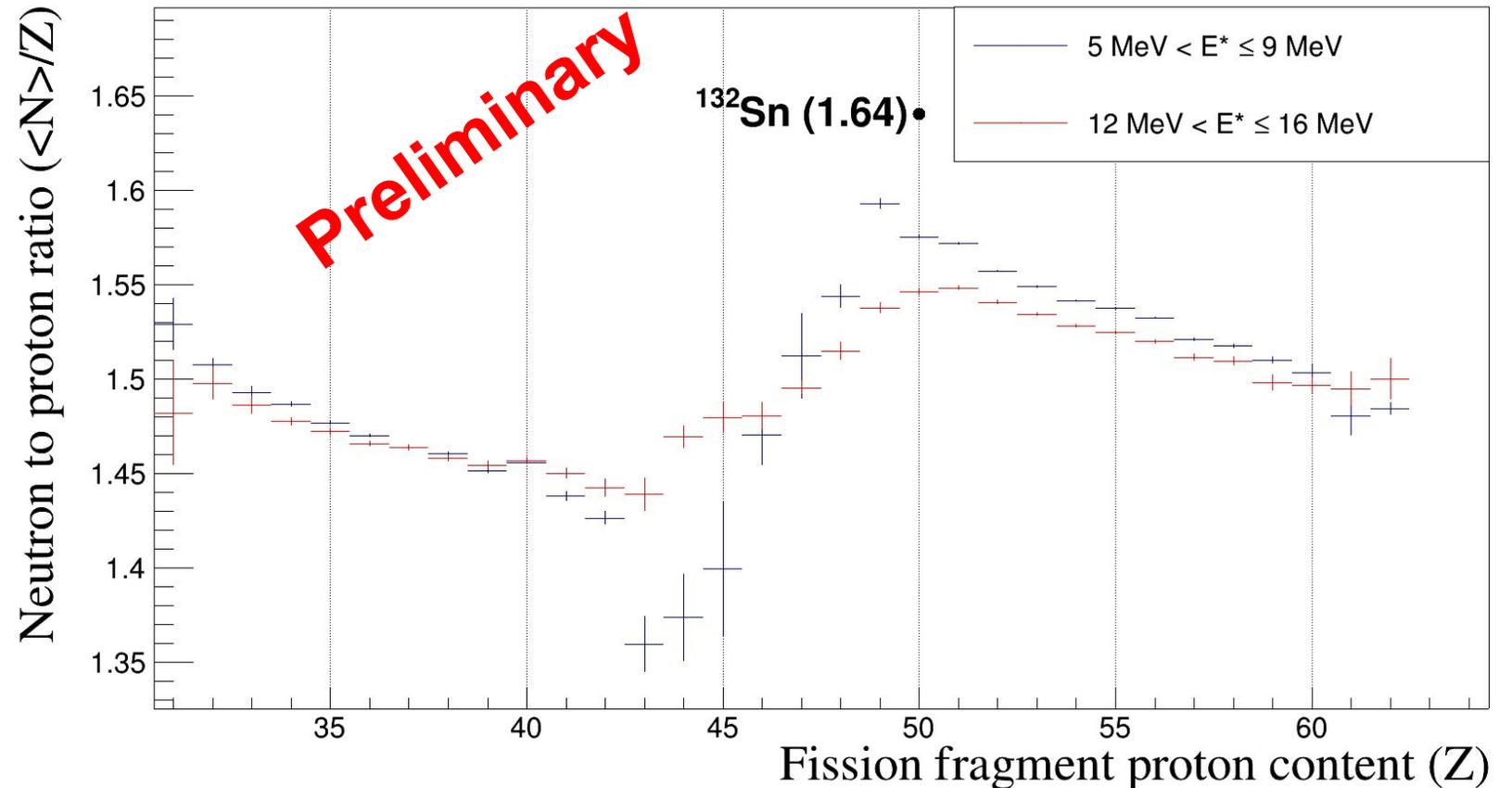
Odd-even staggering effect in the light and heavy fragment
Less notorious for **higher E_x**

Symmetric configuration **increases** with increasing **Excitation energy**

Experimental result: N/Z evolution with E^*



Post-neutron evaporation



Highest N/Z ratio for Z around 50
(corresponding to ^{132}Sn)

Less evaporation of neutrons in
the heavy fragment for lower
excitation energy