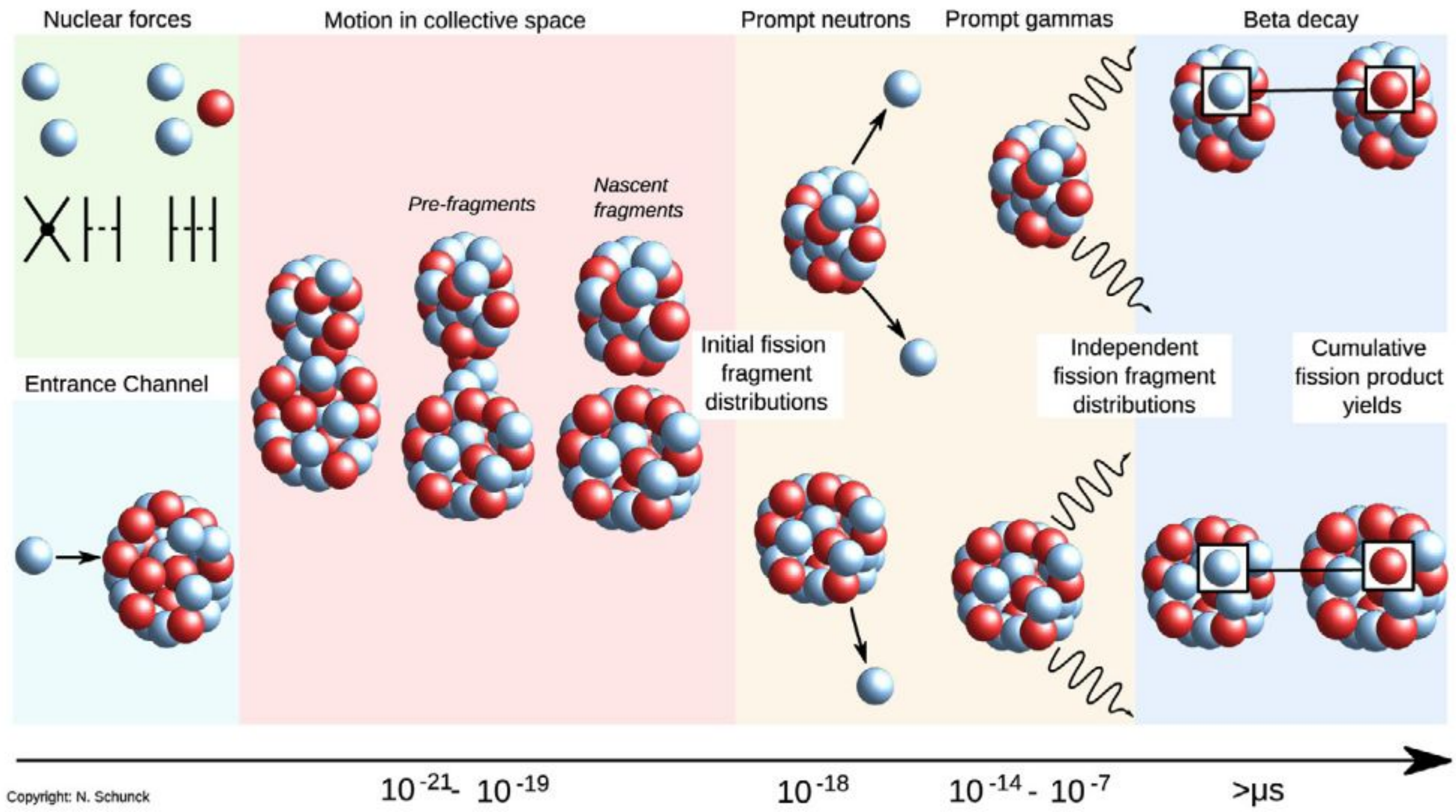
Isotopic fission fragments yields in the Thorium region produced in inverse-kinematics with a 232Th beam

GDR resanet

e849 experiment collaboration

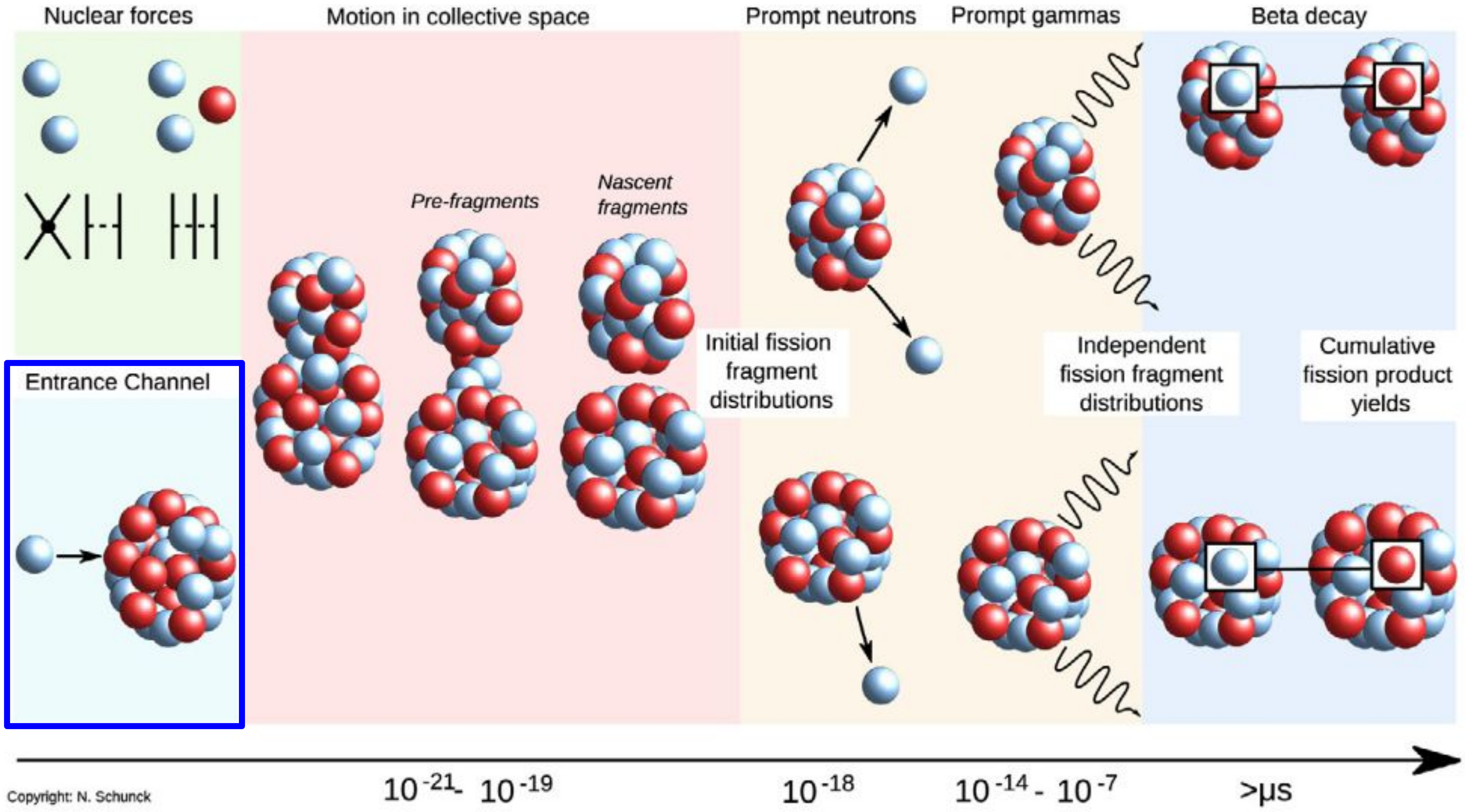
Alex Cobo Zarzuelo
06/11/2025

Fission process



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

Fission process



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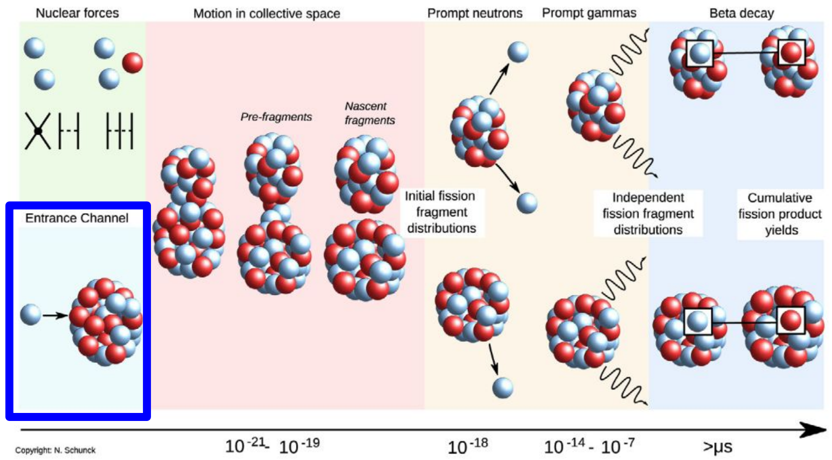
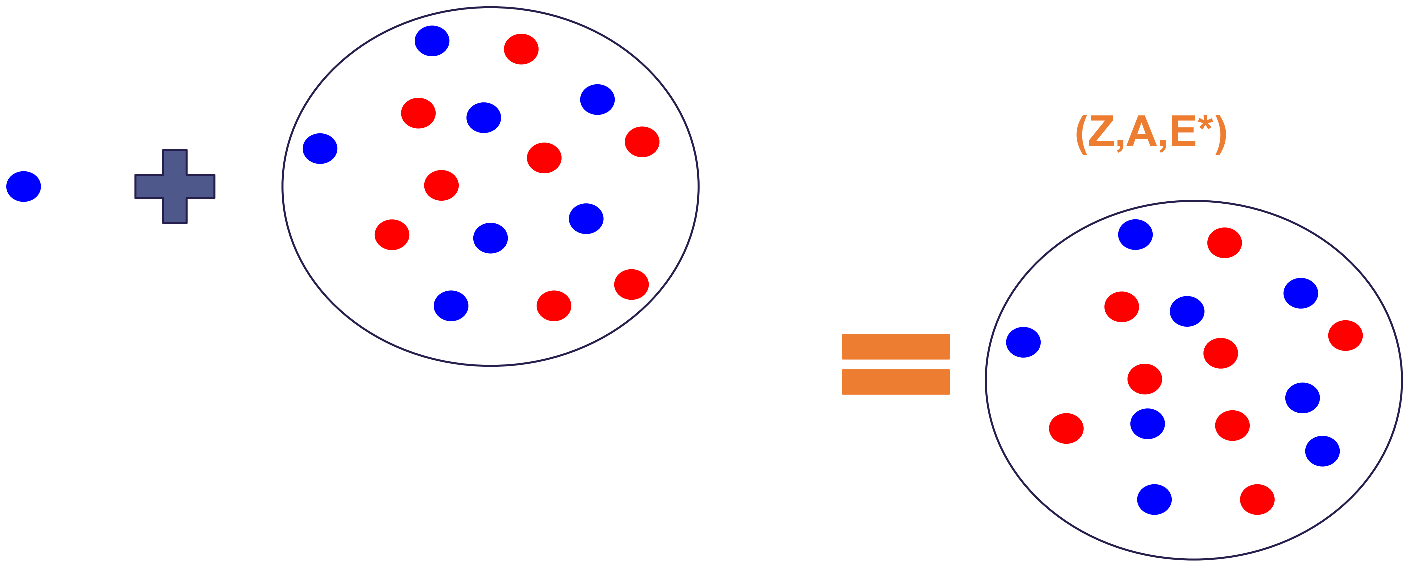
Fission process: Entrance channel

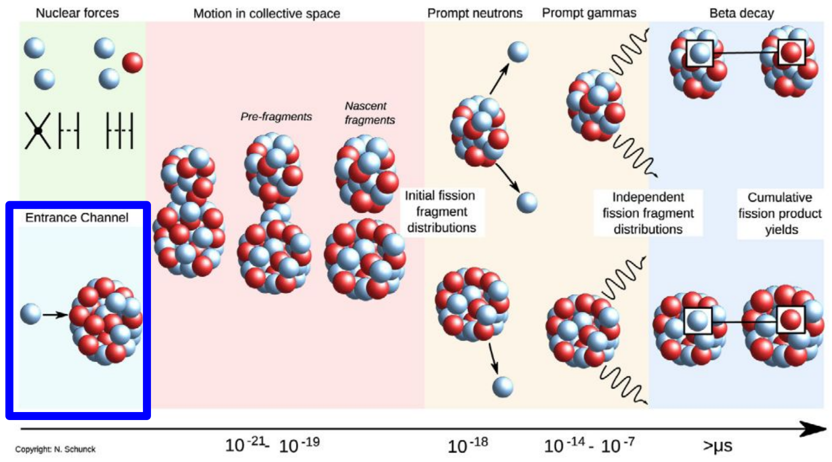


Beam-target combination

n-induced reaction

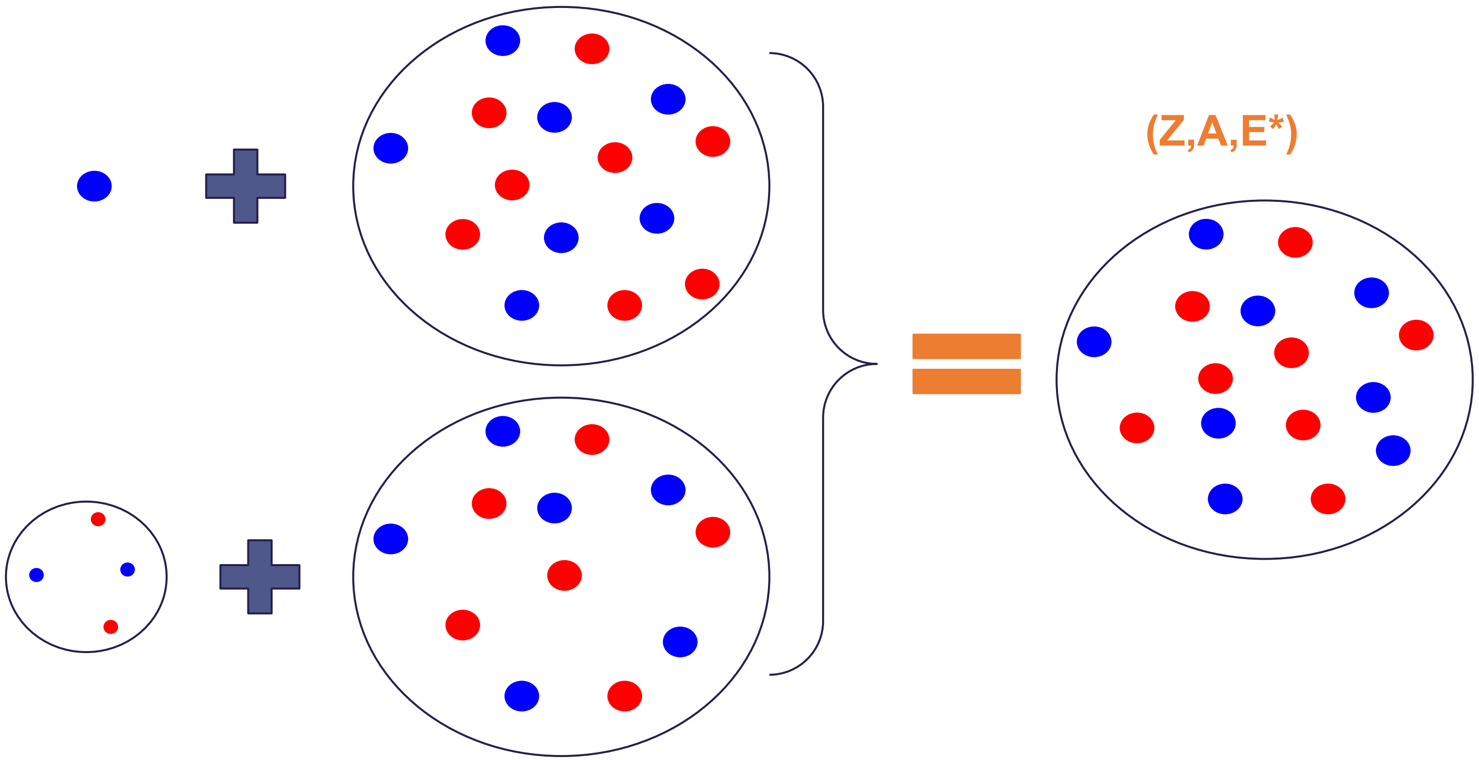


Fission process: Entrance channel



<u>Beam-target combination</u>

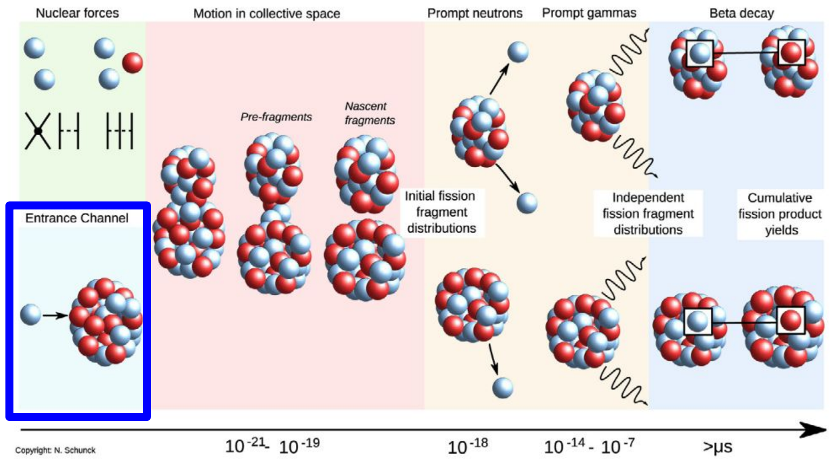
n-induced reaction



(Z,A,E*)

Surrogate reaction

Fission process: Entrance channel



Beam-target combination

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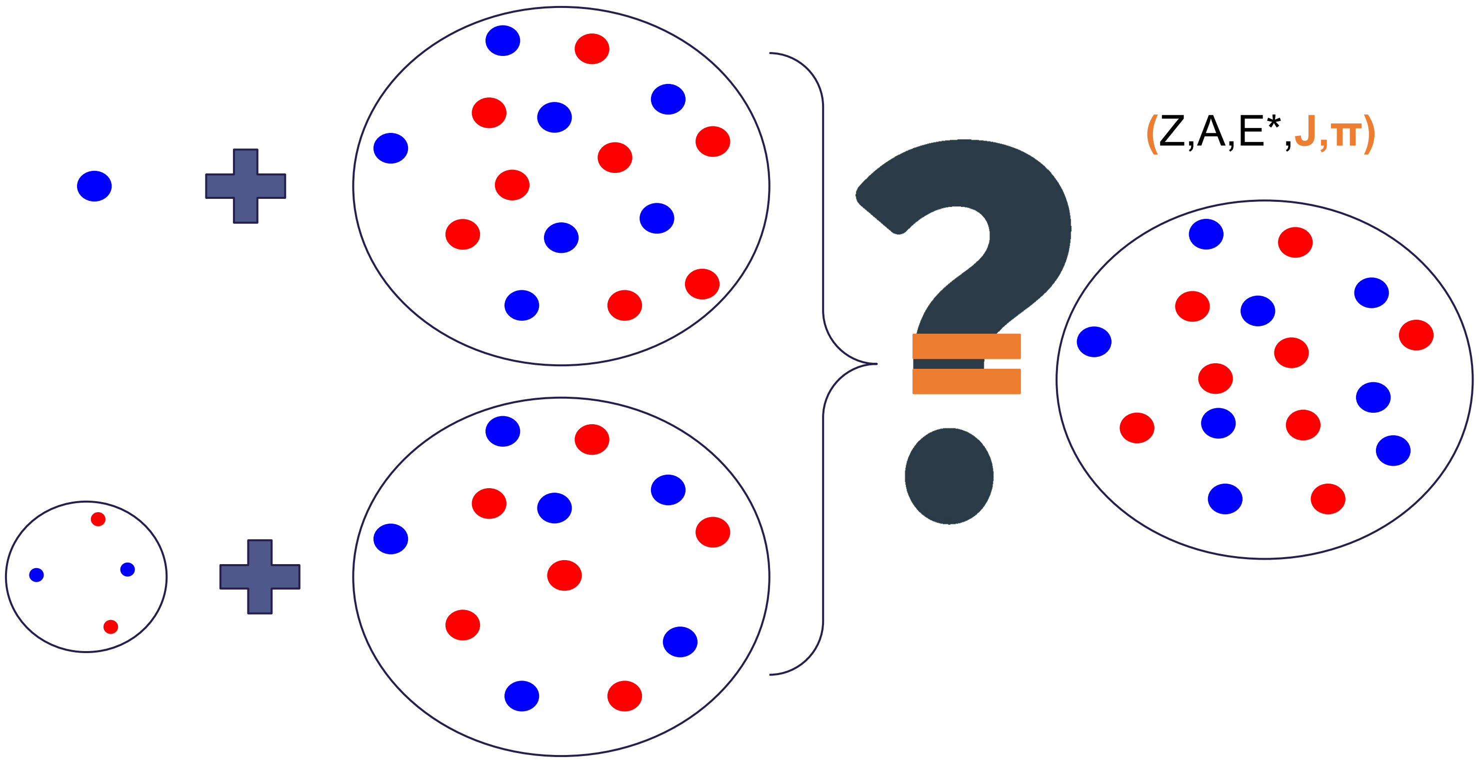

Surrogate reaction

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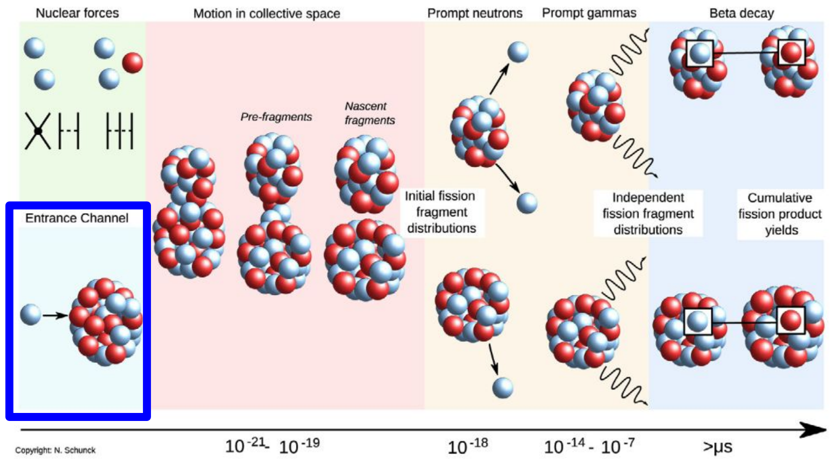
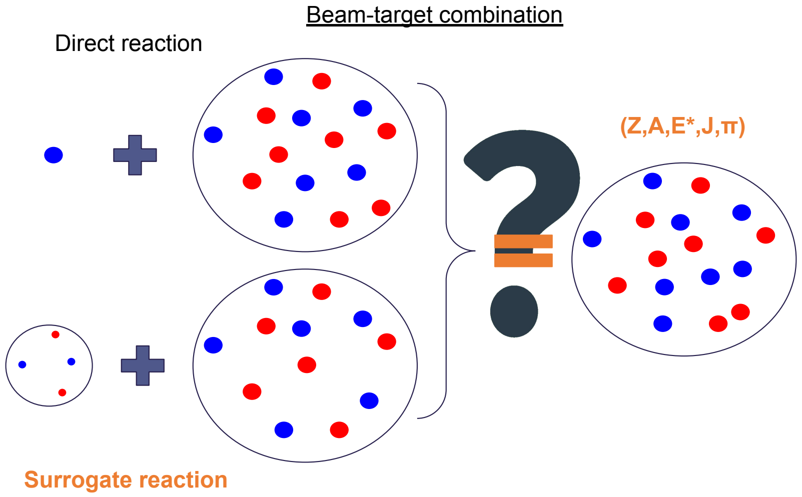
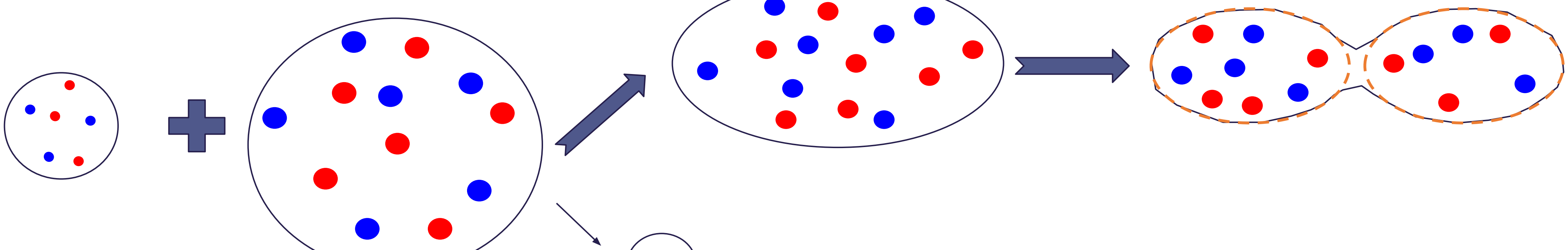
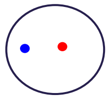




Reaction mechanism:
transfer / inselastic scattering

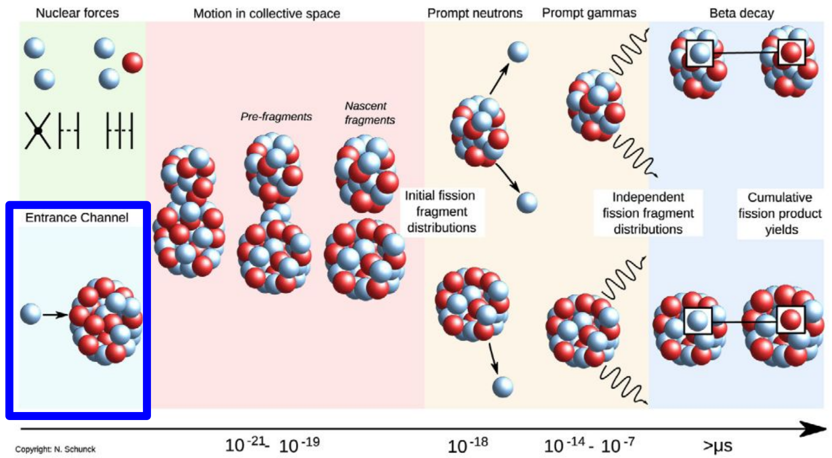
Fissioning system

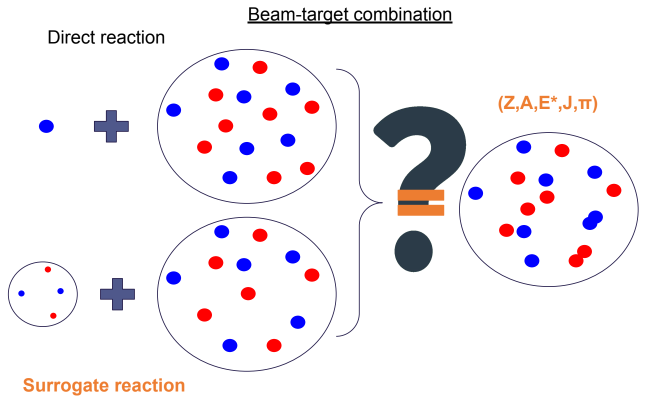


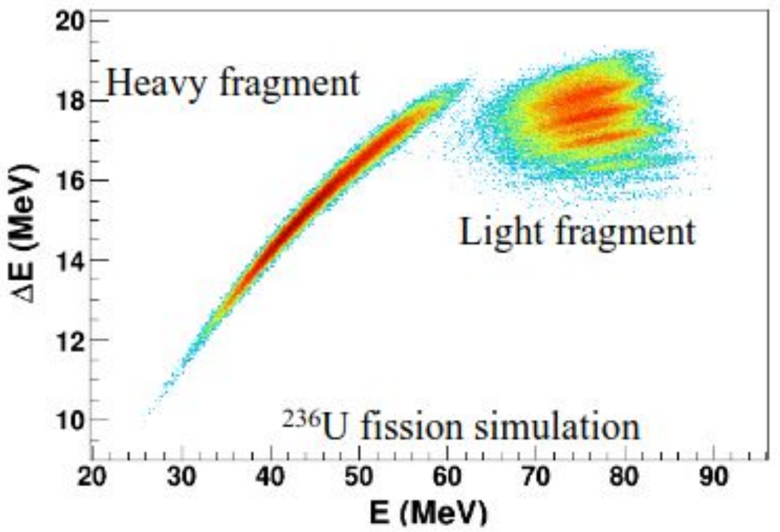


Light partner: identify fissioning system and extract E*

Fission process: Entrance channel







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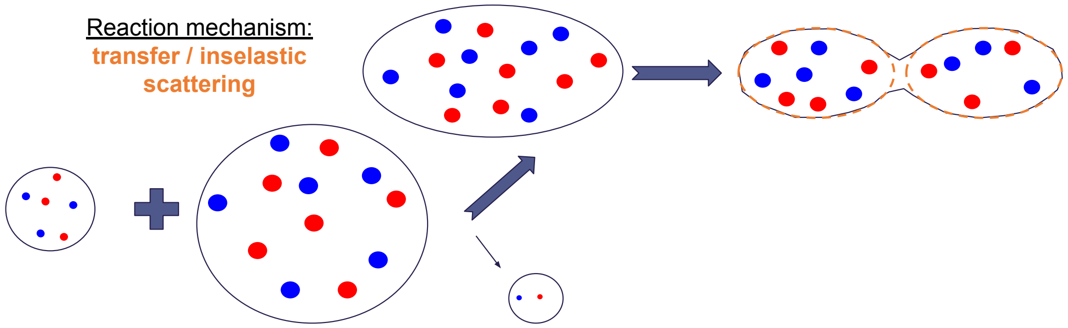
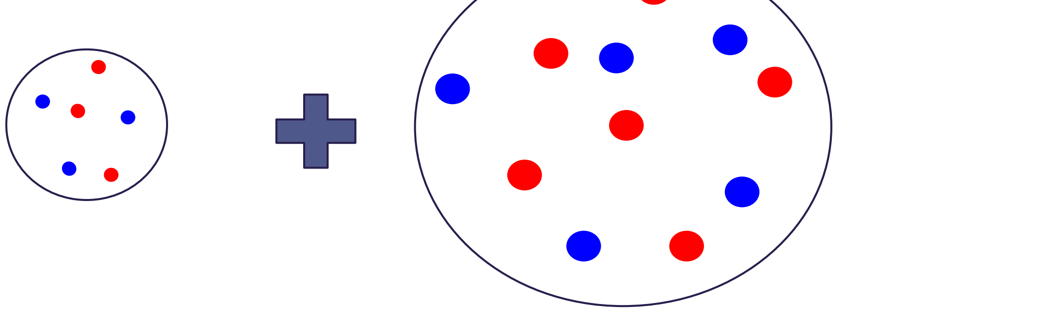
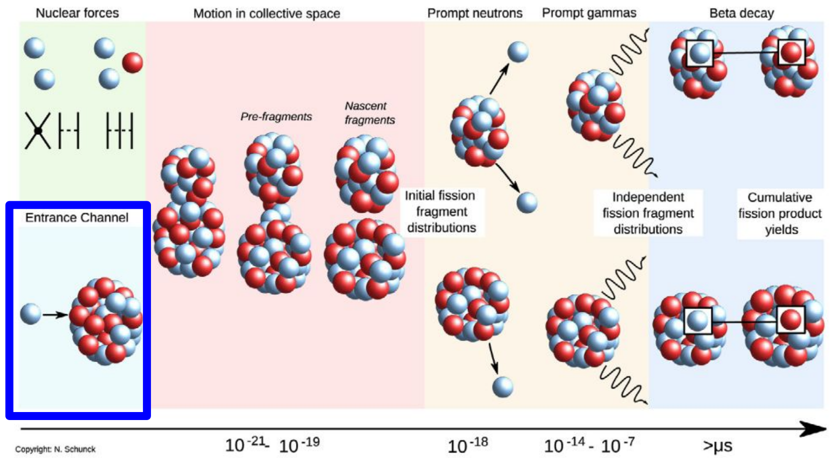
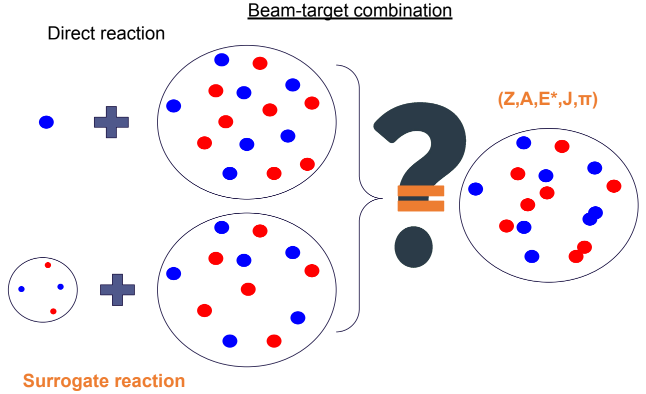


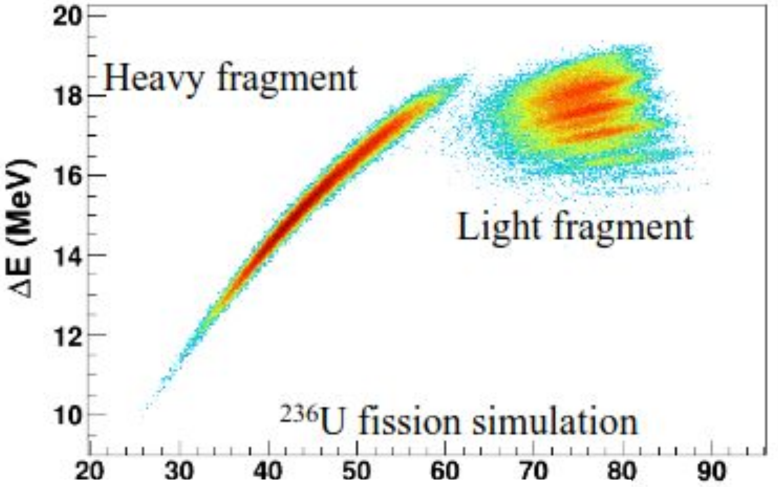
Reaction kinematics:
direct



Fission process: Entrance channel







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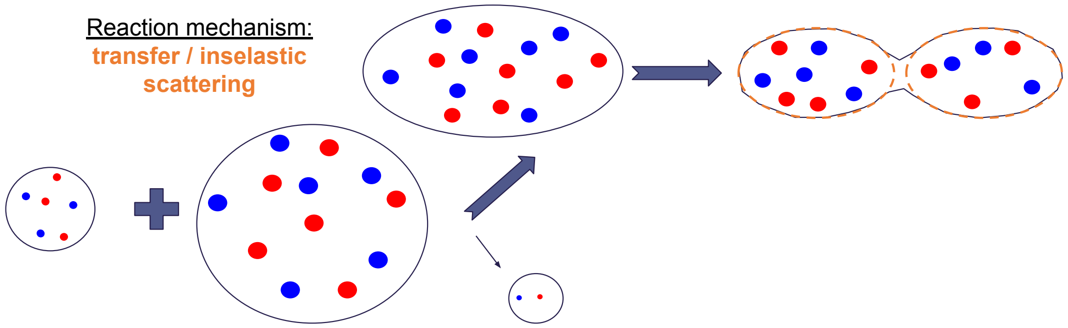
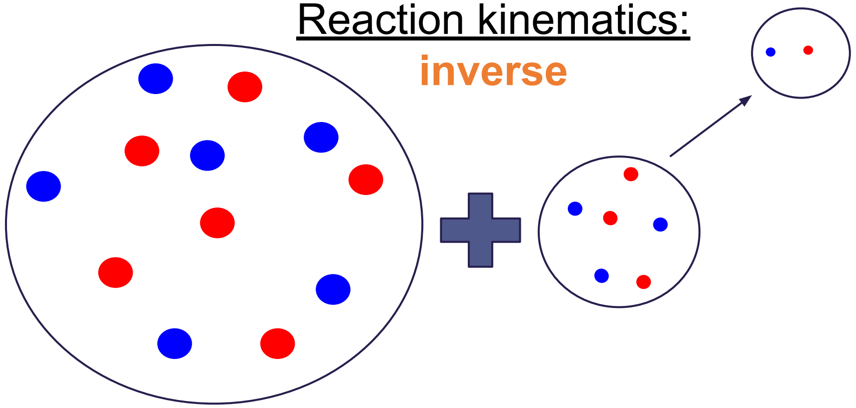
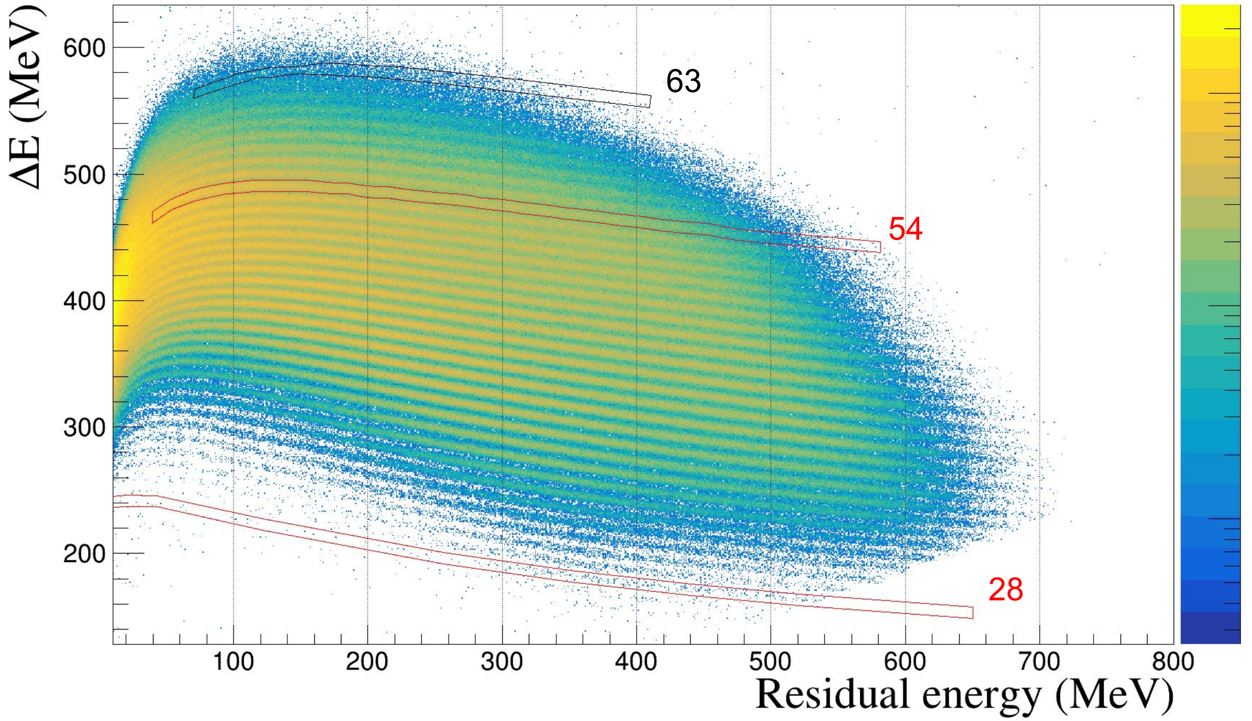
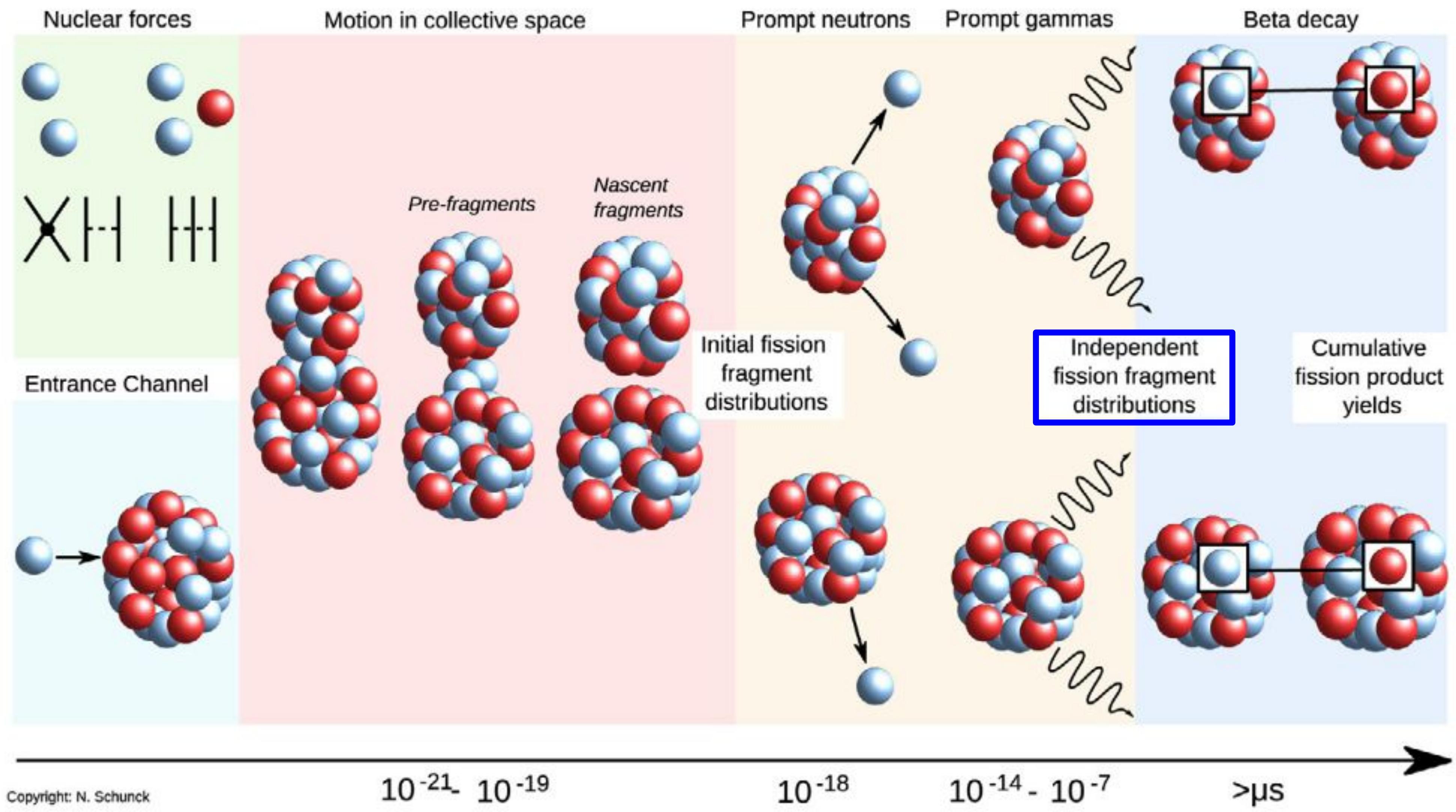


Reaction kinematics:
inverse



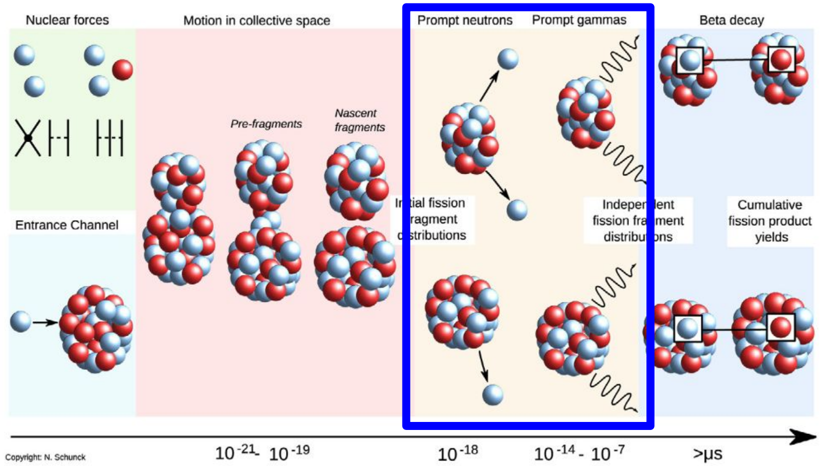


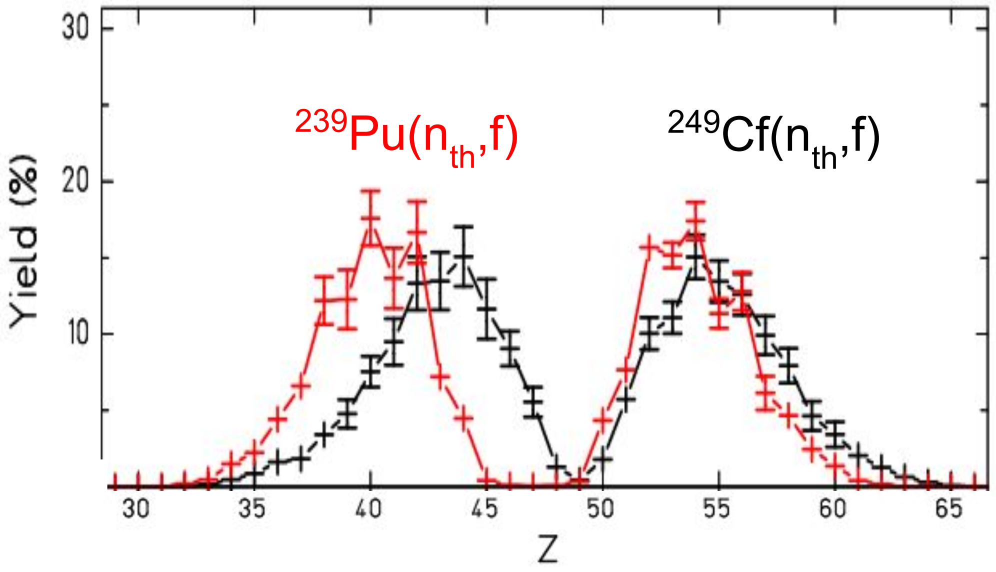
Fission process



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

Fission process: Exit channel

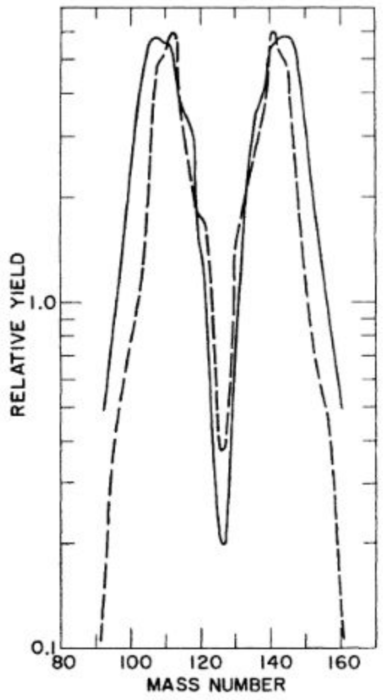




[2] Schmidt, K. H., Schmitt, C., Heinz, A., & Jurado, B. (2024). *Identifying and overcoming deficiencies of nuclear data on the fission of light actinides by use of the GEF code. Annals of Nuclear Energy, 208, 110784.*

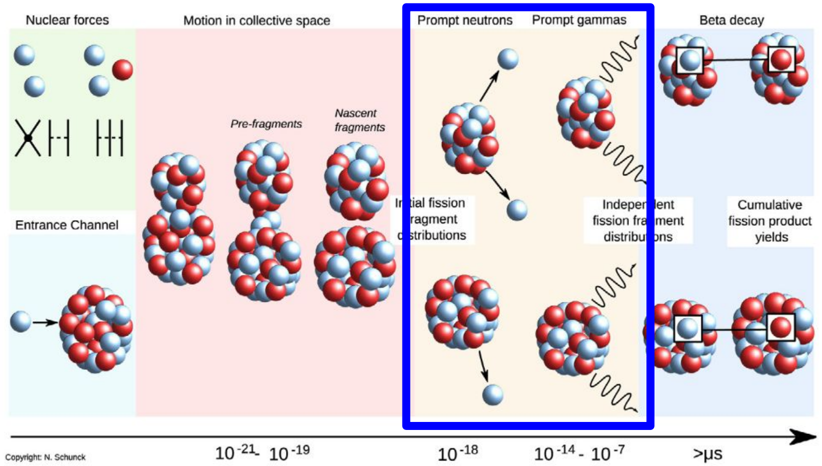
1. **How are the protons and neutrons distributed in the fragments (modes)?**

^{252}Cf (spontaneous fission)

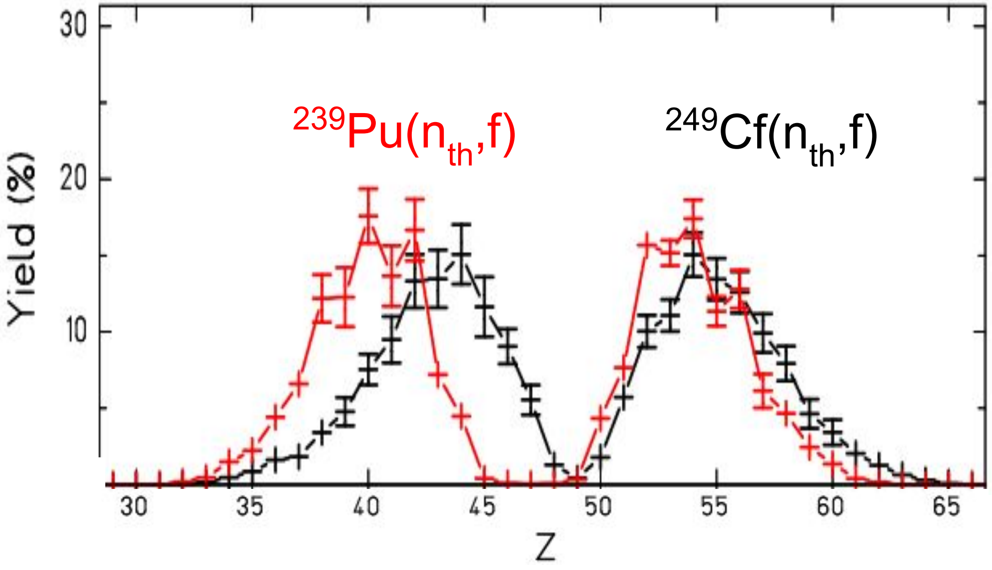


[3] Wilkins, B. D., Steinberg, E. P., & Chasman, R. R. (1976). Scission-point model of nuclear fission based on deformed-shell effects. Physical Review C, 14(5), 1832

Fission process: Exit channel



1. How are the protons and neutrons distributed in the fragments (modes), **as a function of E*?**



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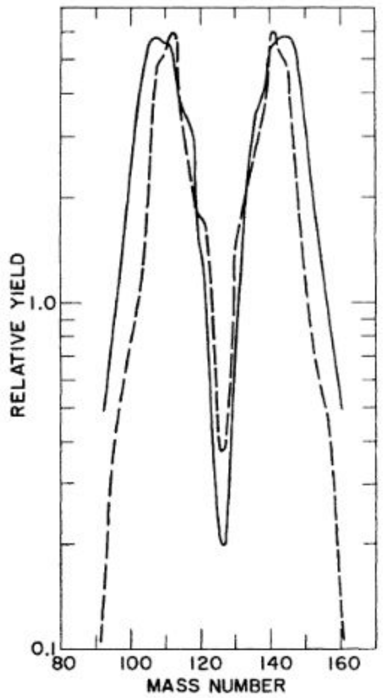

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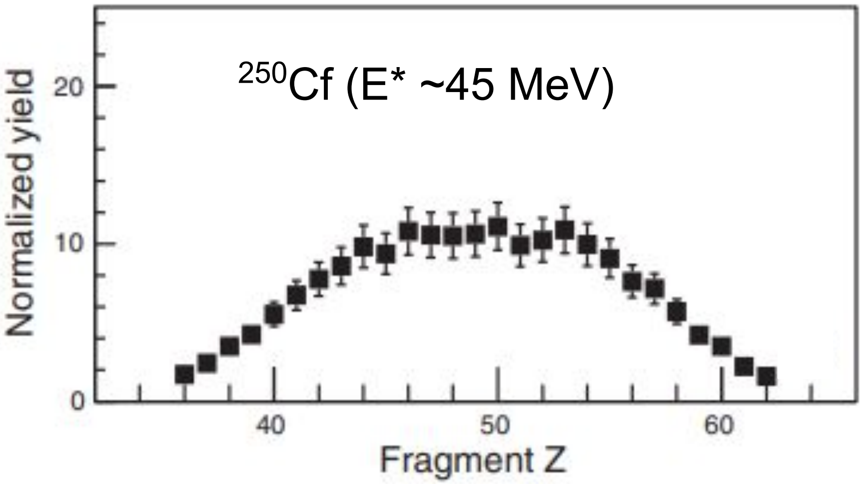
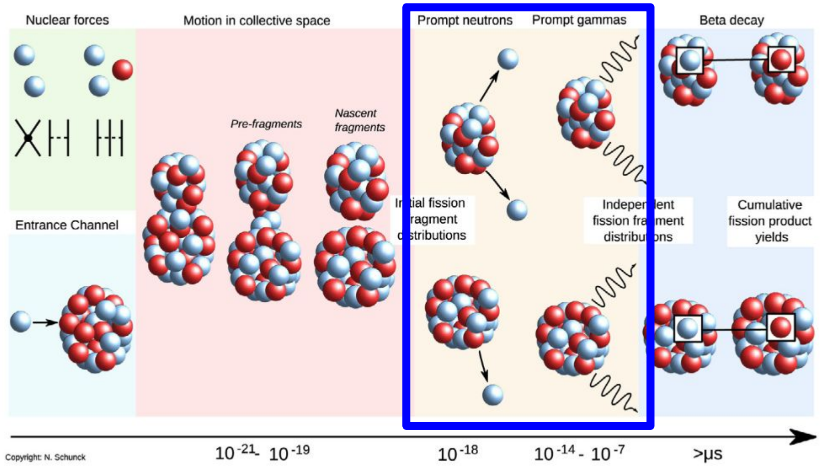


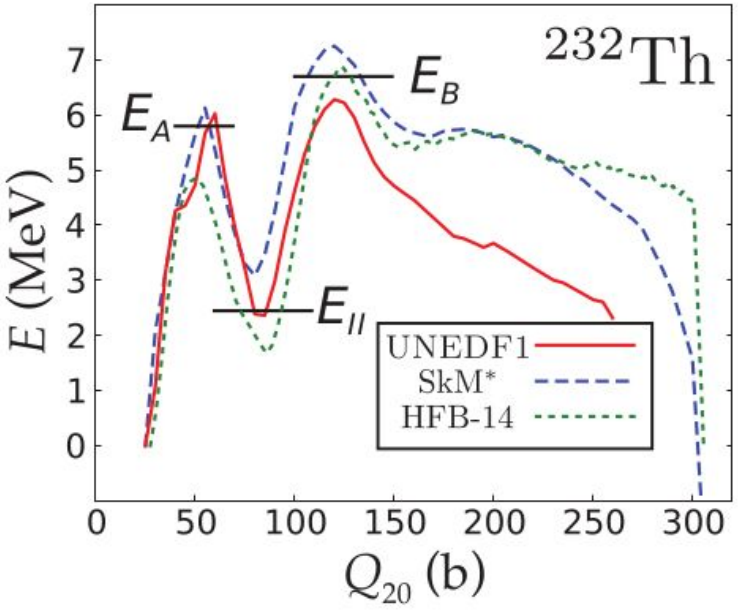
[4] Caamaño, M., Farget, F., Delaune, O., Schmidt, K. H., Schmitt, C., Audouin, L., ... & Shrivastava, A. (2015). *Characterization of the scission point from fission-fragment velocities. Physical Review C, 92(3), 034606.*

Fission process: Exit channel



1. How are the protons and neutrons distributed in the fragments (modes)?
2. **What are the characteristics of the fission fragments (TKE, $\nu_{mult.}$, $\gamma_{mult.}$, Y(A,Z), …)** : signatures of the PES

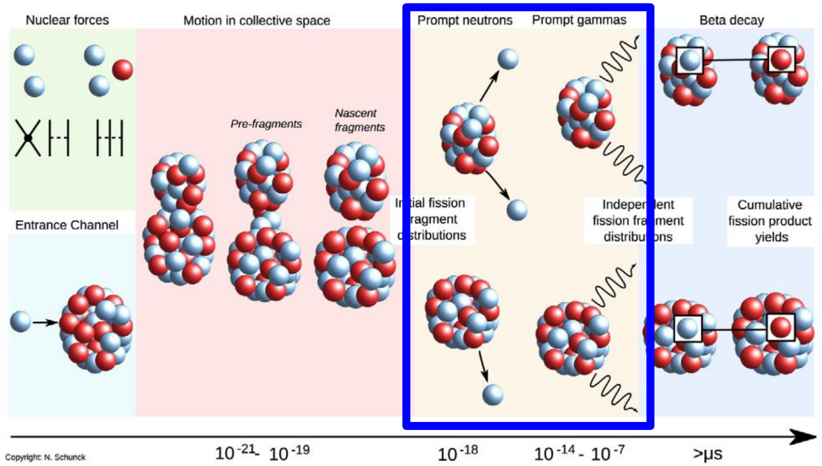
Minimal **energy for a given deformation** (i.e. quadrupole Q_{20})



1st barrier(E_A)
2nd barrier(E_B)

[5] N Schunck and L M Robledo 2016 Rep. Prog. Phys. 79 116301

Fission process: Exit channel



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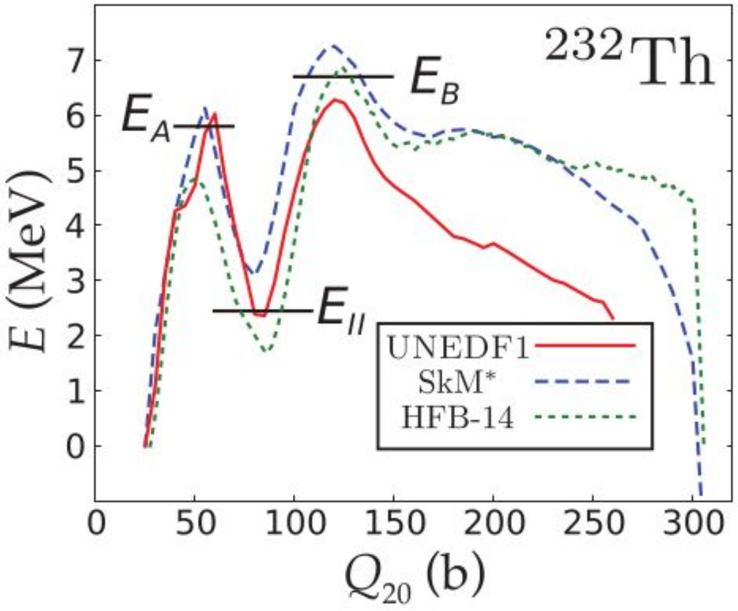
Extend to **several simultaneous deformations**



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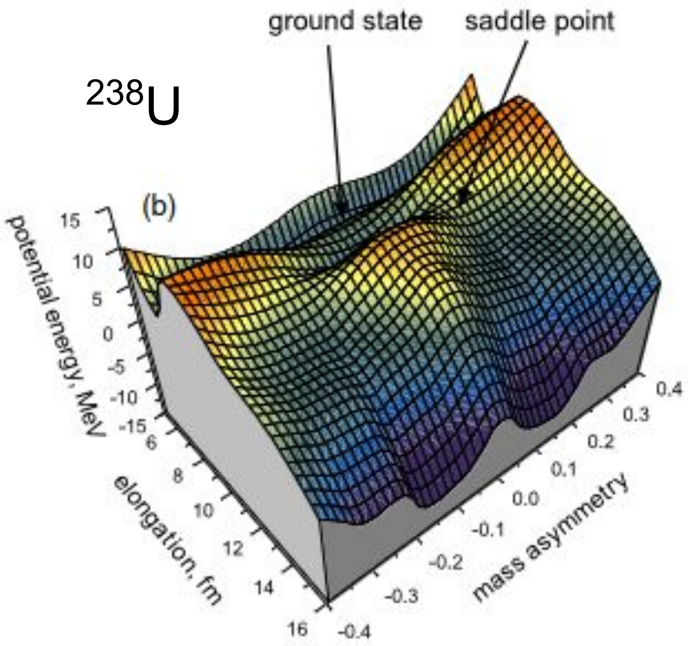
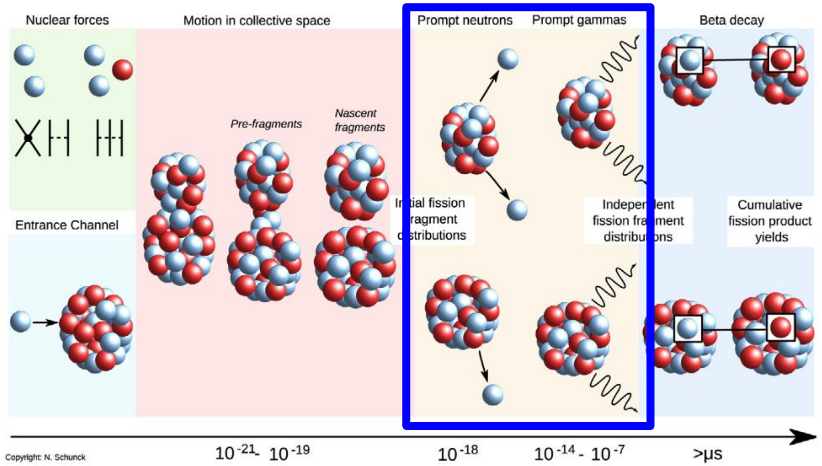


[6] A V Karpov et al 2008 J. Phys. G: Nucl. Part. Phys. 35 035104

Fission process: Exit channel



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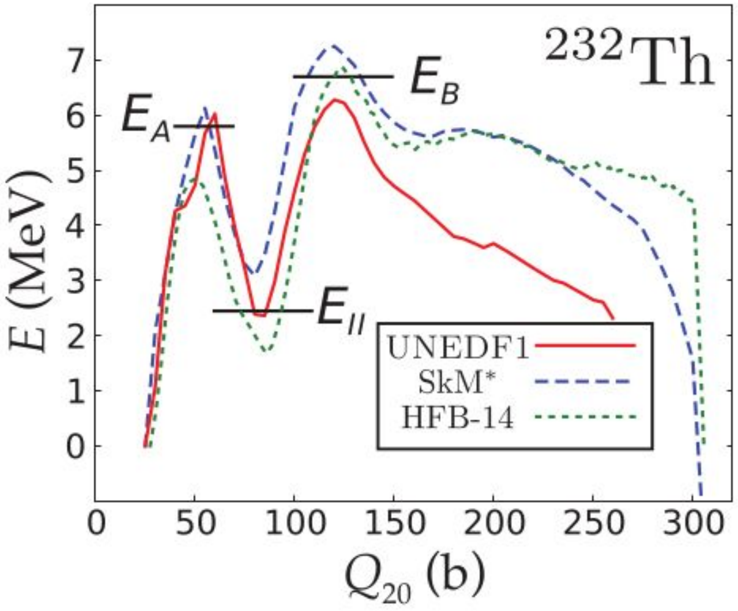
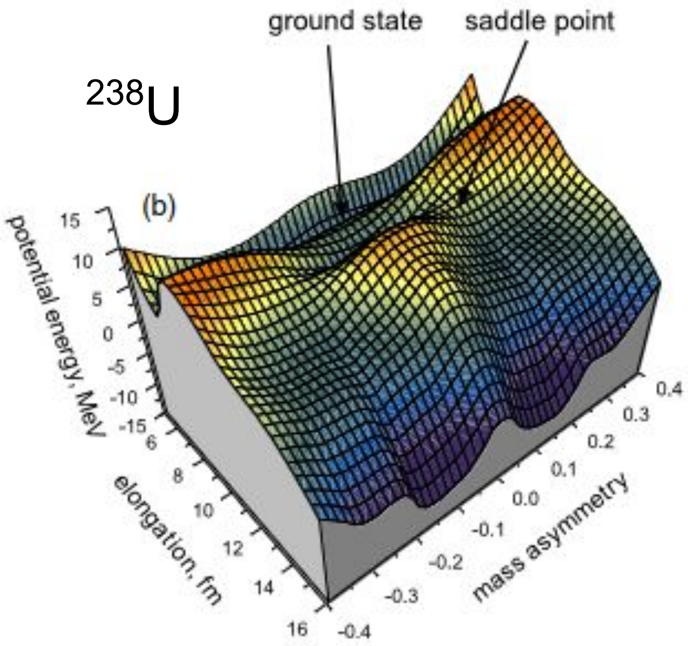
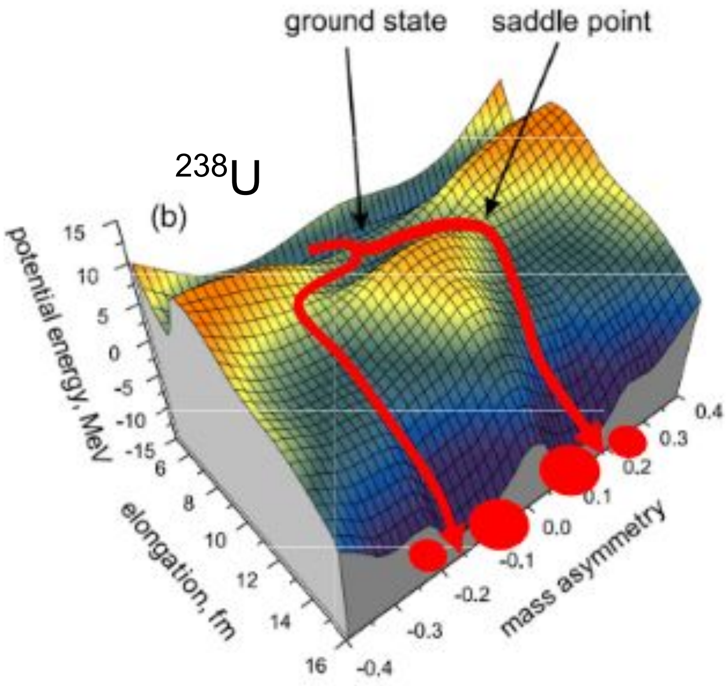
The **path** travelled **through the surface** results in the final **characteristics**







[5] N Schunck and L M Robledo 2016 Rep. Prog. Phys. 79 116301

[6] A V Karpov et al 2008 J. Phys. G: Nucl. Part. Phys. 35 035104

[7] A N Andreyev et al 2018 Rep. Prog. Phys. 81 016301

Motivation to conduct the experiment

GANIL

^{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, …)

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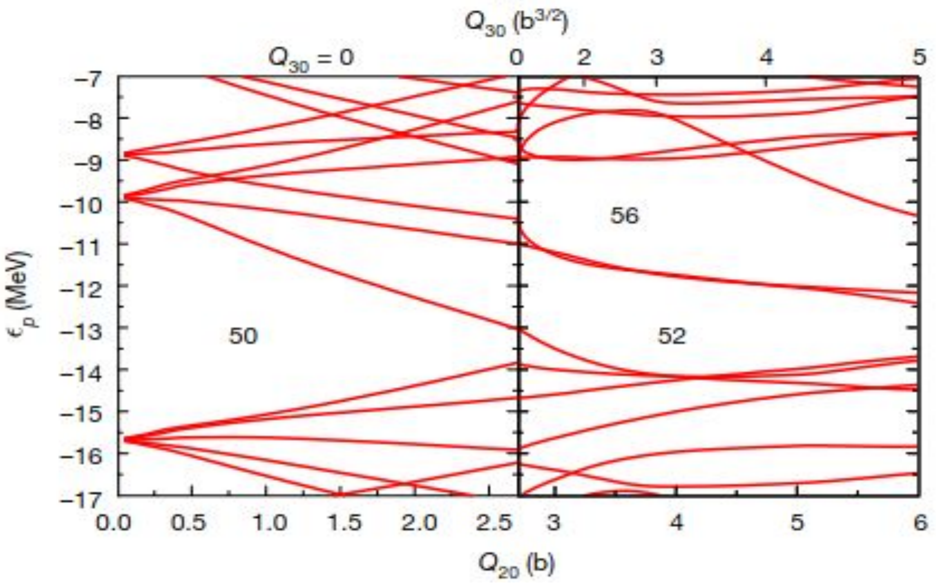
- Study the effect of the **shell-closure at octupole deformation**
    - Shown to **drive the asymmetric** fission modes



[8] 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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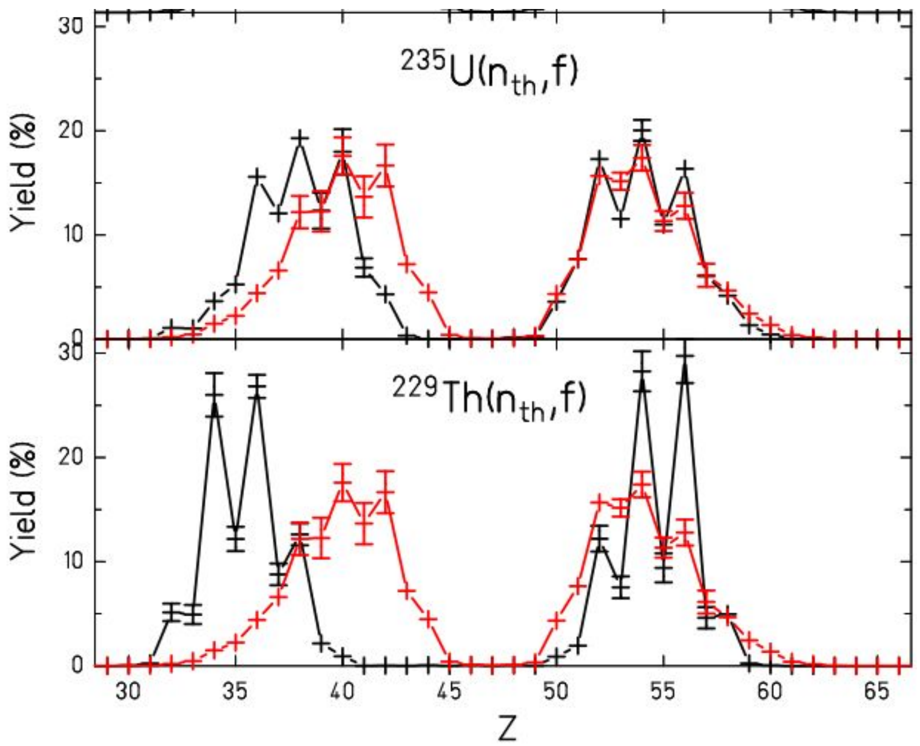
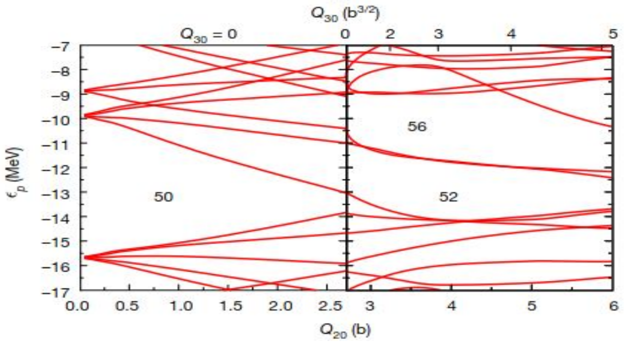
- Study the effect of the shell-closure at octupole deformation
- Analyse the origin of the **possible third hump** in the **fission barriers** of **lighter actinides**
    - Yield of **Uranium** and actinides **above** have **similar shape** for **heavy** fragment
    - **Thorium and lower** mass actinides exhibit a different shape, **peaking around Z=56**



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

[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.



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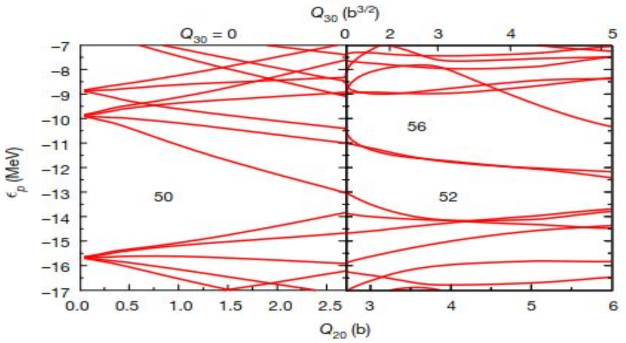
- Study the effect of the shell-closure at octupole deformation
- Analyse the origin of the possible third hump in the fission barriers of lighter actinides
  - Yield of Uranium and actinides above have similar shape for heavy fragment
  - Thorium and lower mass actinides exhibit a different shape, peaking around Z=56
  - The effect **disappears** at **moderate Excitation** energy



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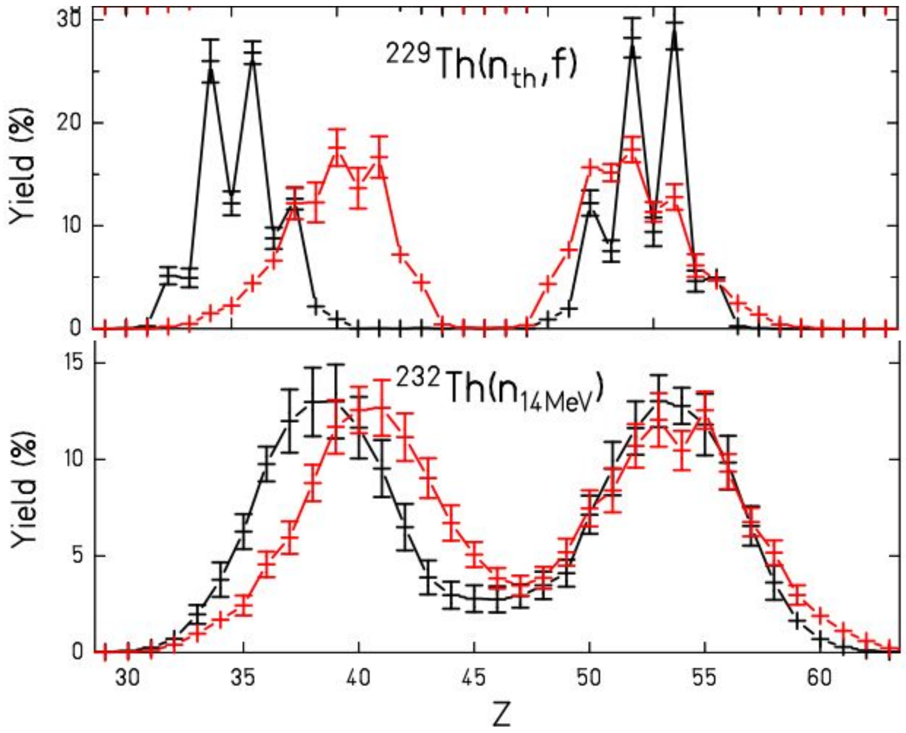

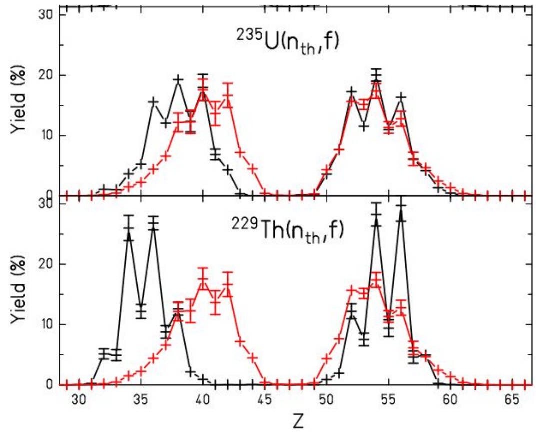

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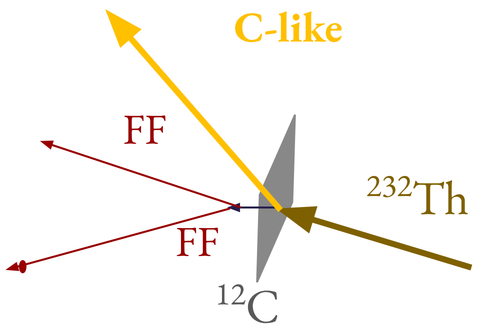
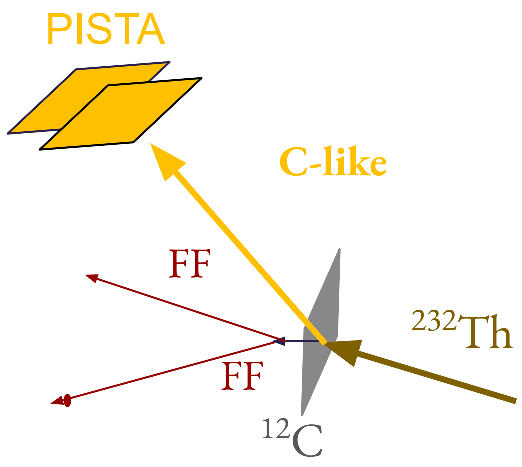
Experimental setup: VAMOS++

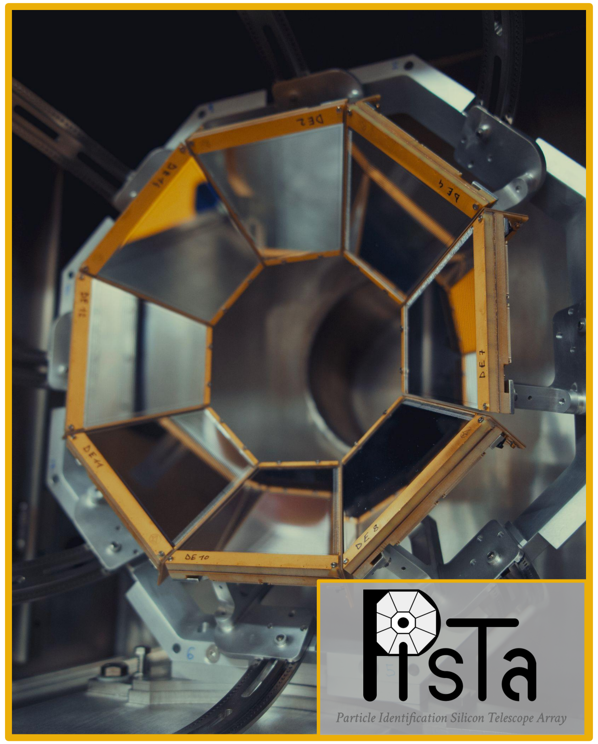
Carbon-like particle identification



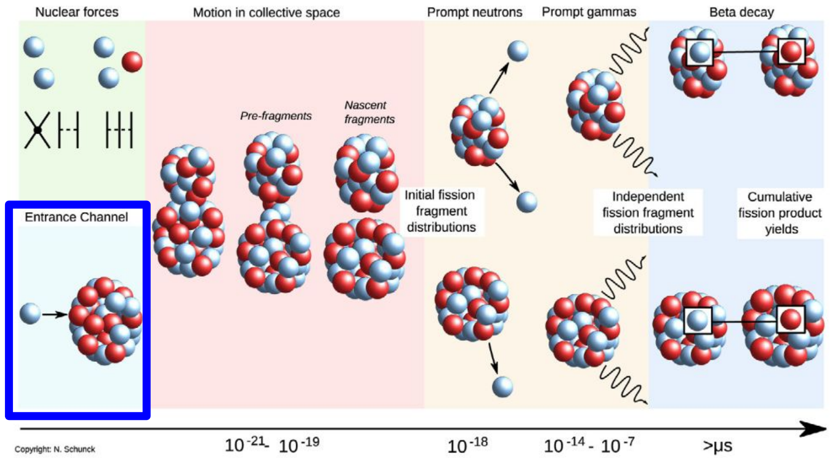
Experimental setup: VAMOS++

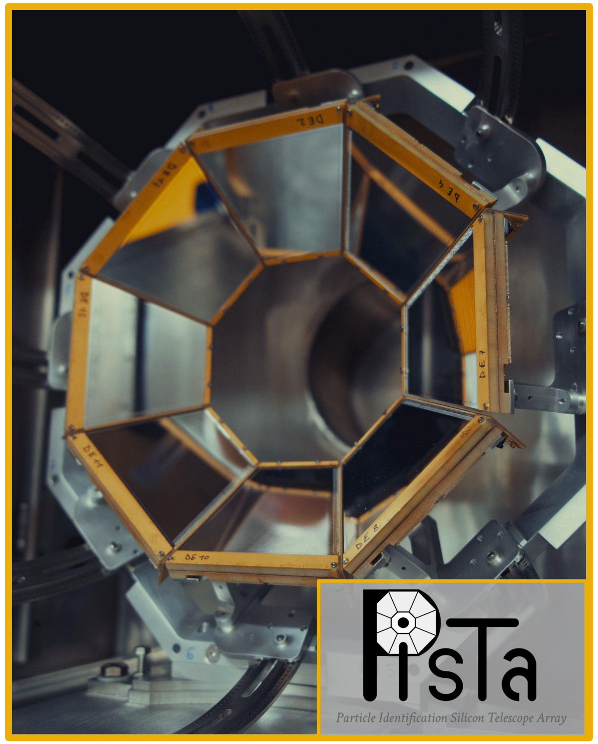
Carbon-like particle identified by **PISTA**: **8 ΔE - E segmented telescopes** => (**E, θ**)



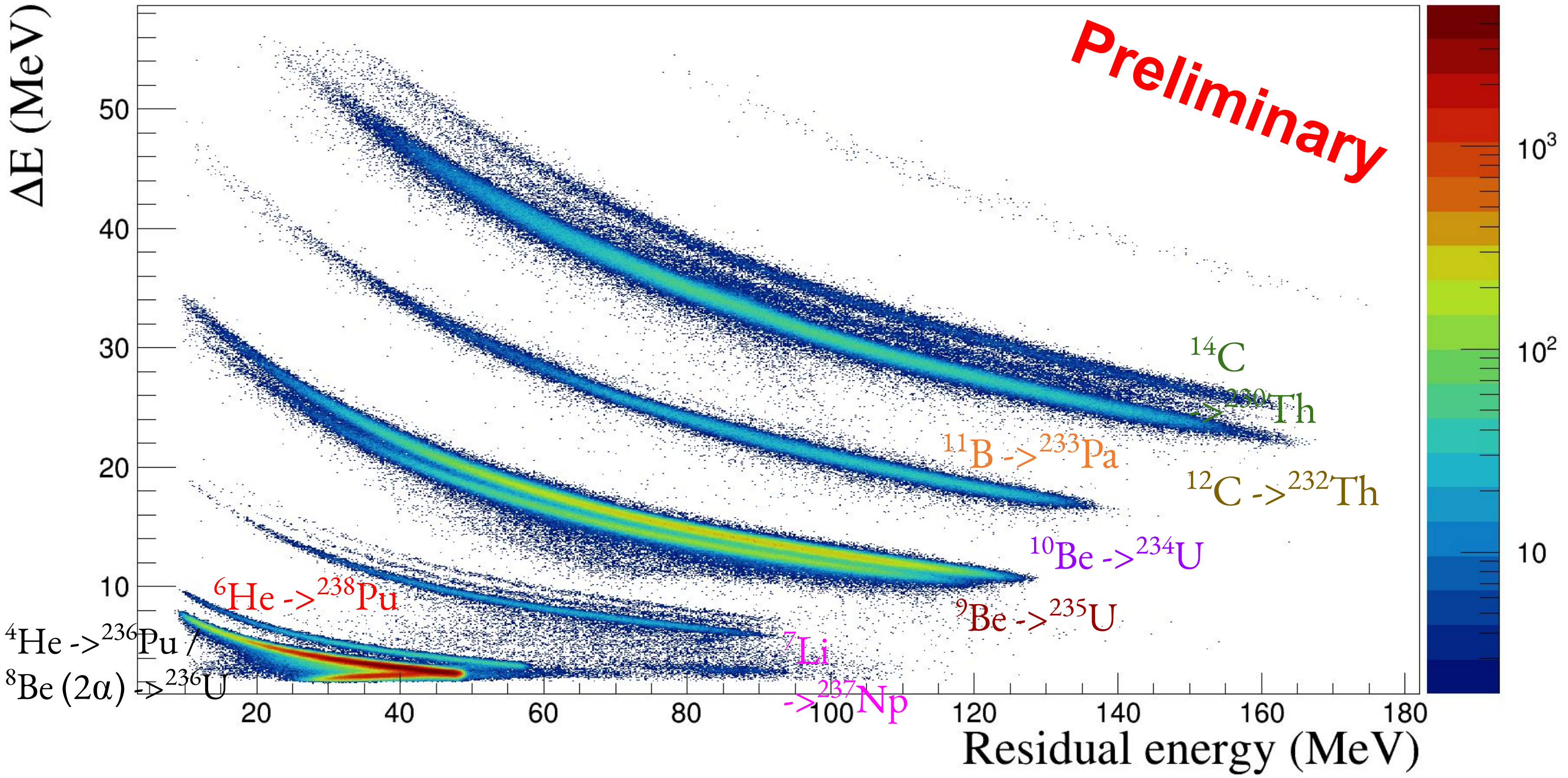


Entrance channel information





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



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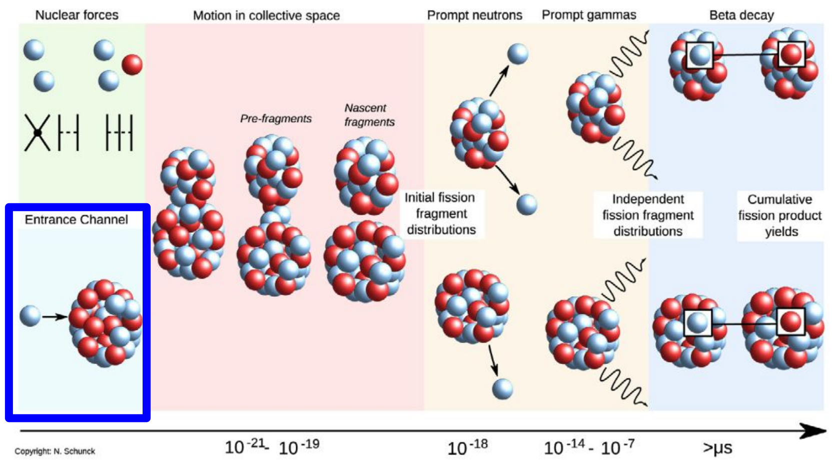
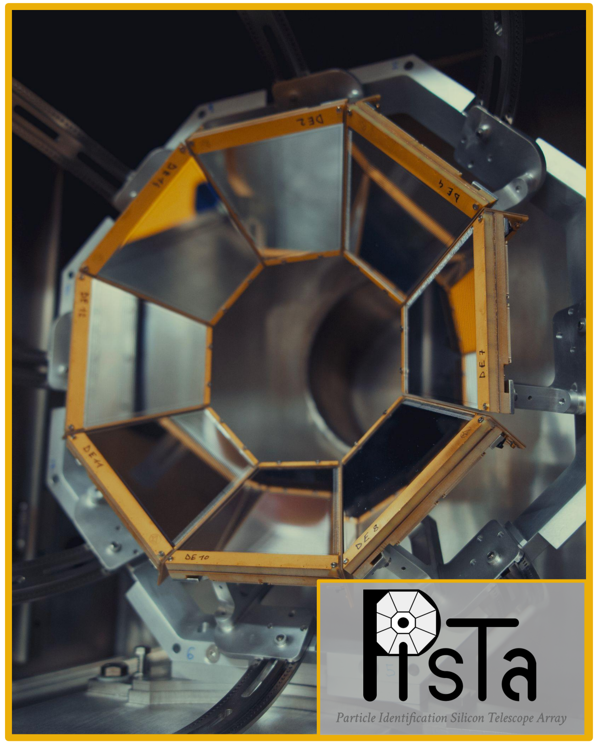
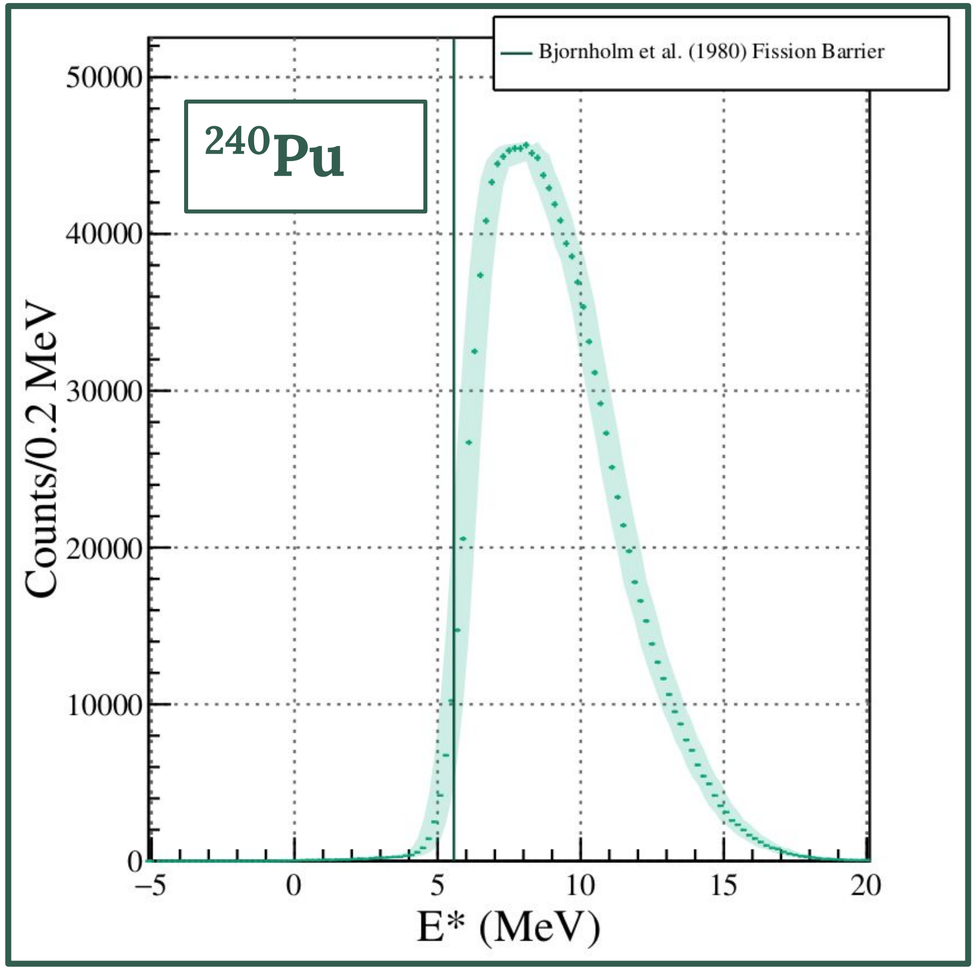




1) What is the fissioning system that was formed (Z,A)
2) **What is the excitation energy (E*)**

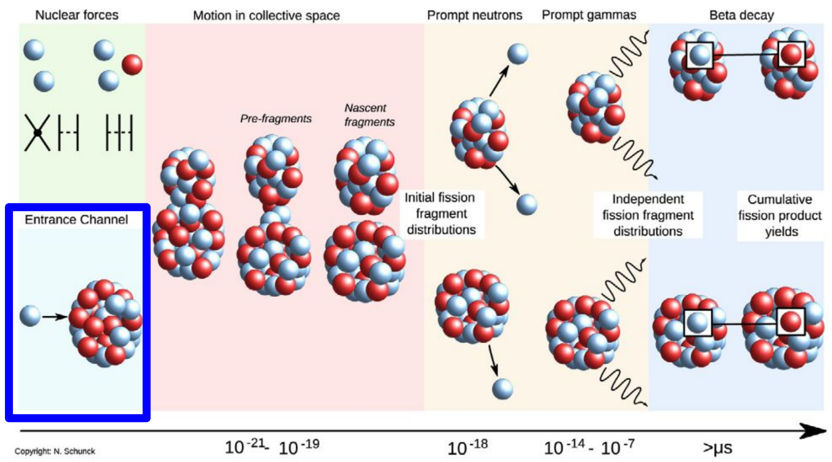


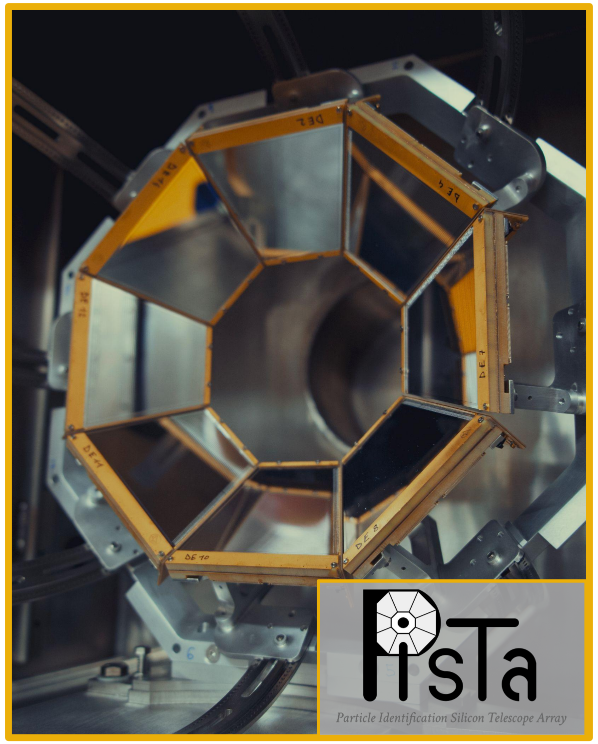
PhD thesis of Lucas Bégué-Guillou (^{238}U + ^{12}C)

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

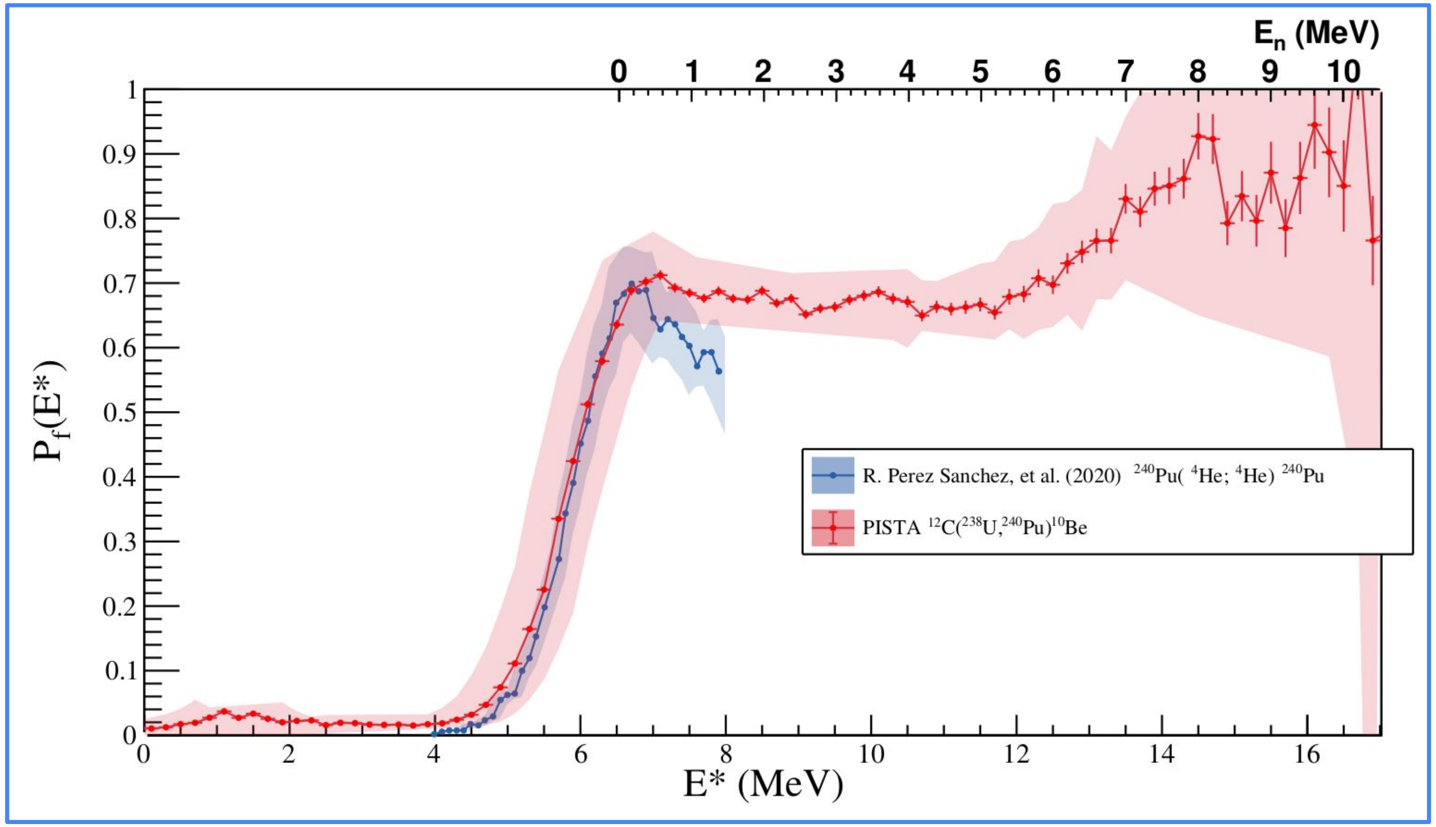
Energy and linear **momentum conservation**, assuming binary reaction

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?**

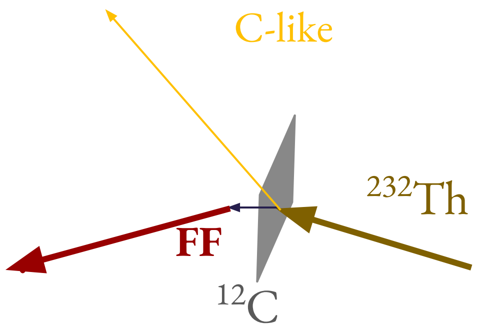


PhD thesis of Lucas Bégué-Guillou (^{238}U + ^{12}C)

Experimental setup: VAMOS++

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

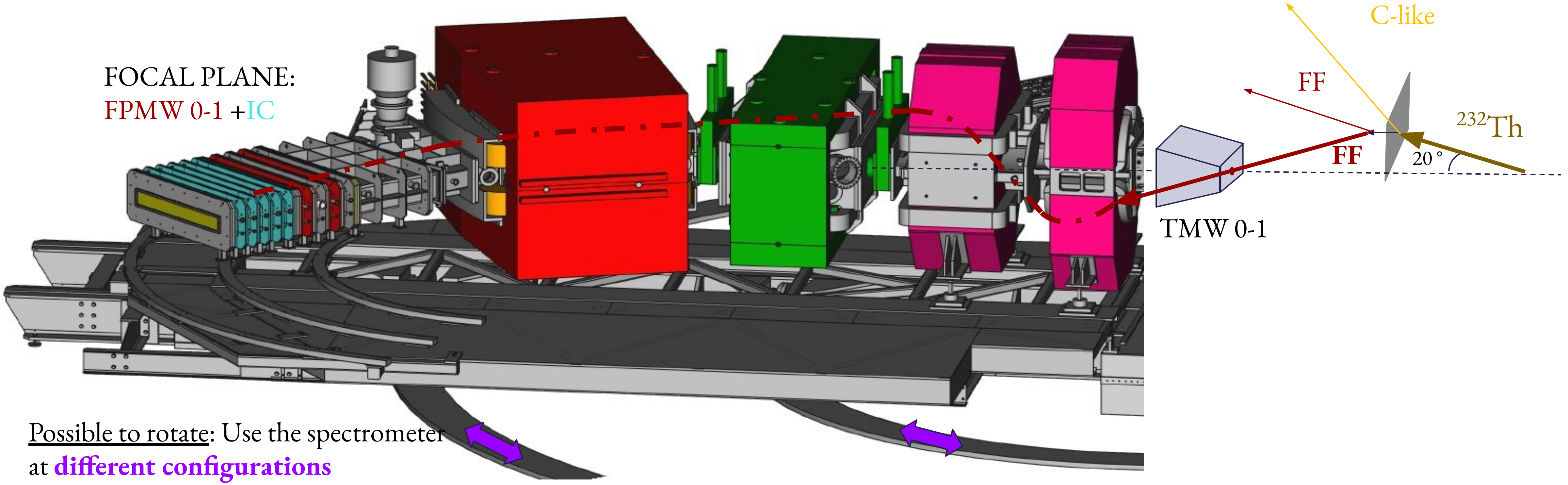
The **mass of the fragments is high** for good resolution through a Energy vs Time-of-Flight (ToF) identification



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 ($B\varrho$) an ToF resolution

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

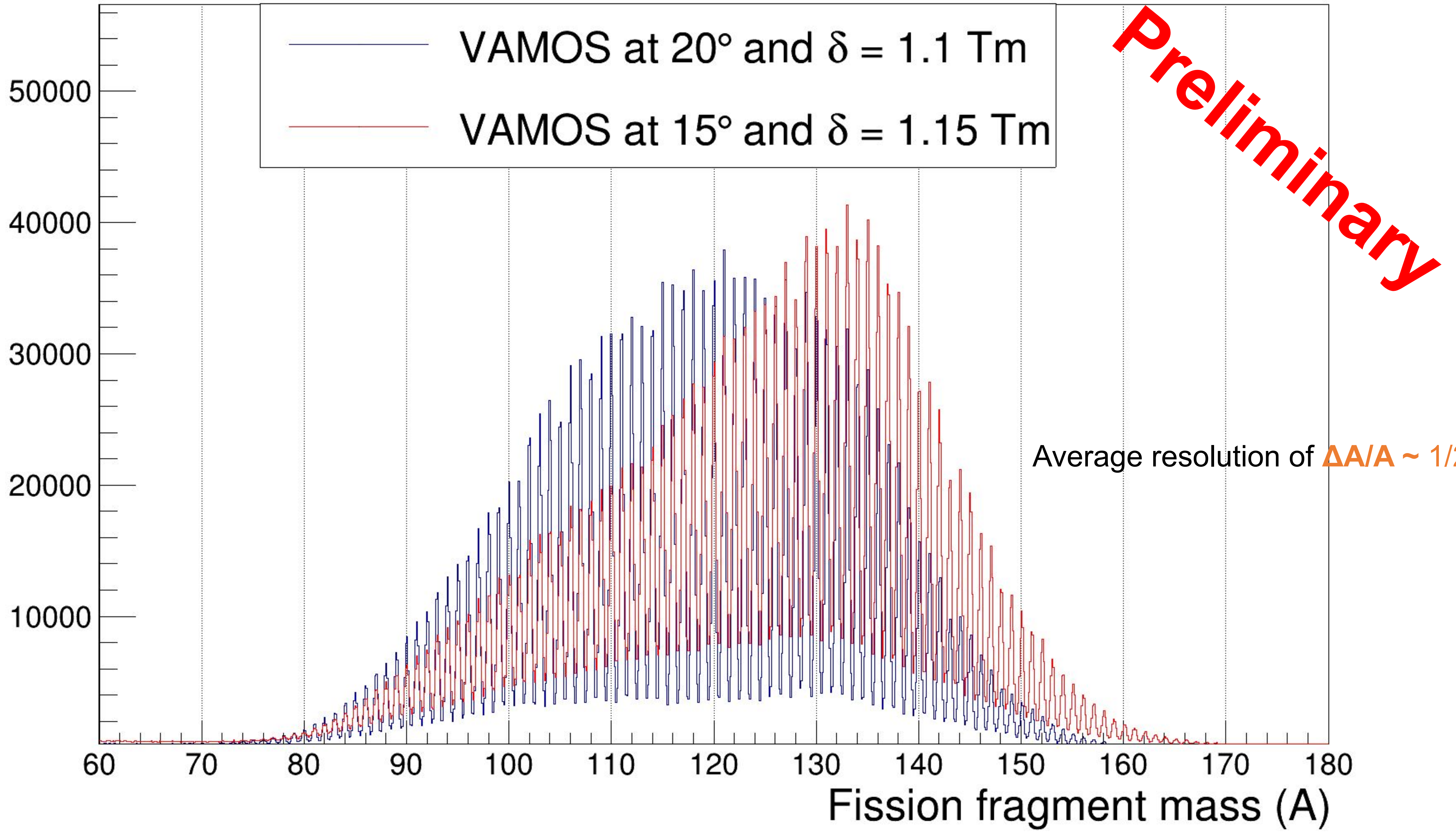


Possible to rotate: Use the spectrometer at **different configurations**

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

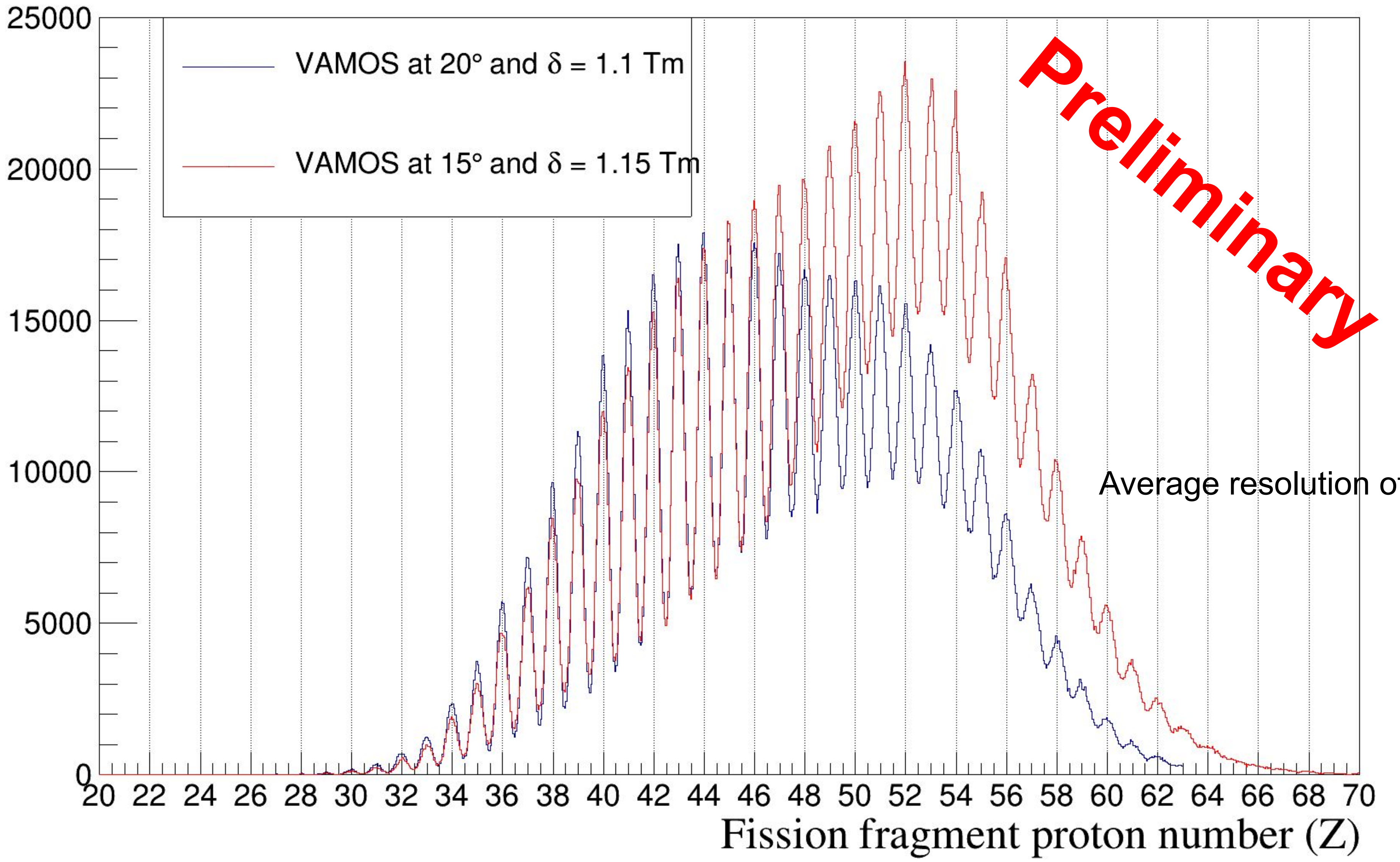
Fission fragment identification: A

GANIL



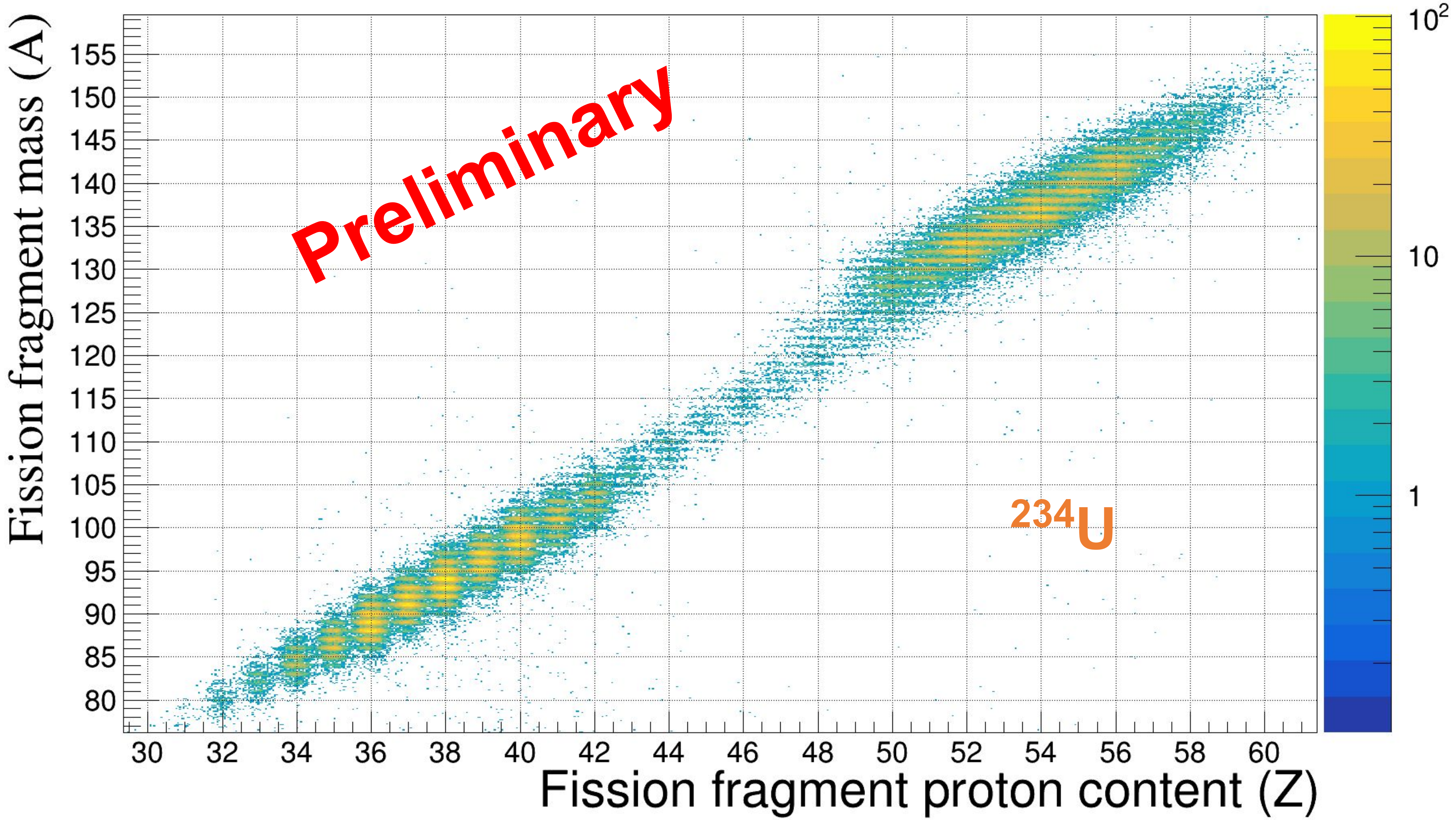
Average resolution of **ΔA/A ~** 1/234 = **4.27 ‰**

Fission fragment identification: Z

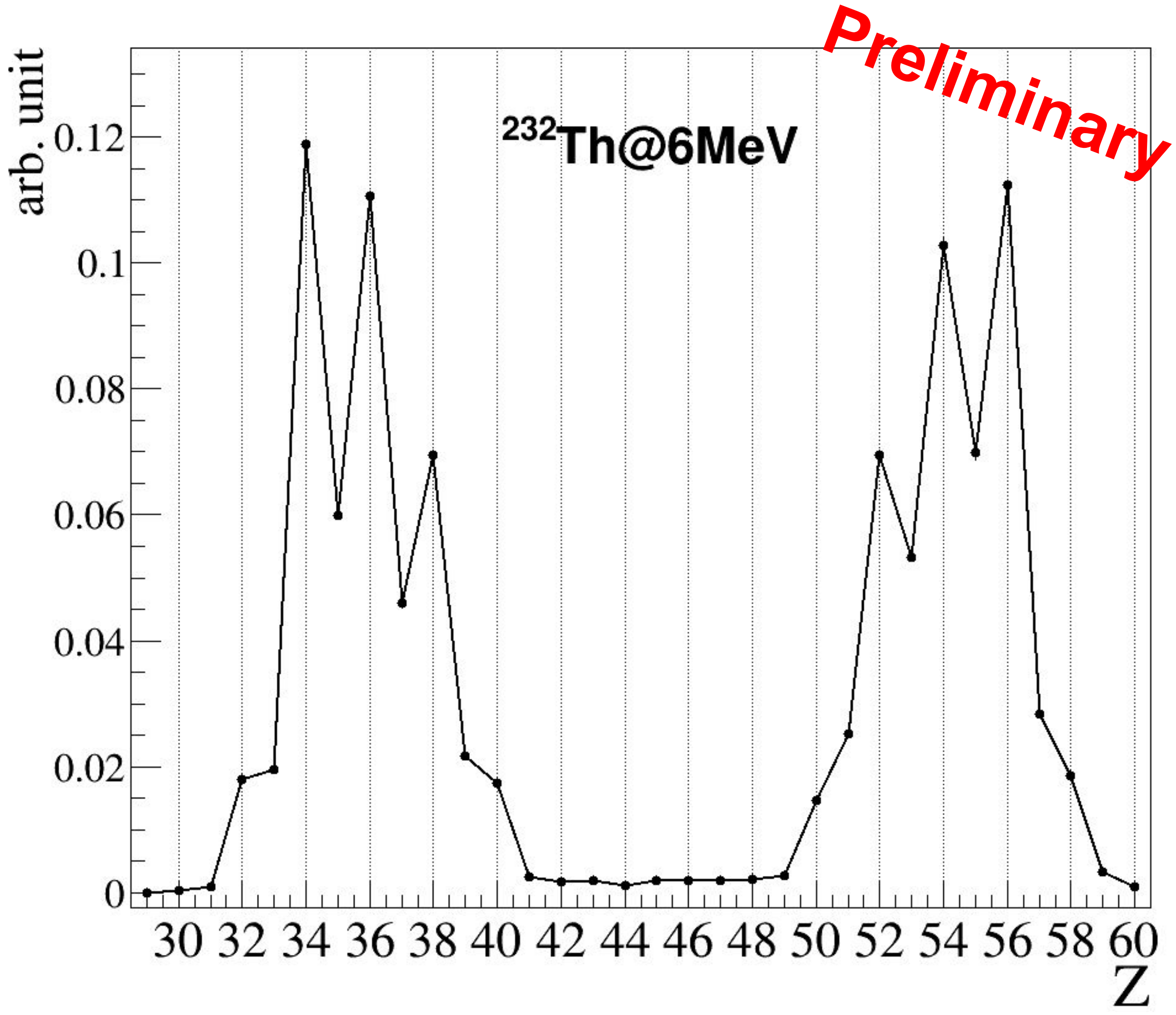


Average resolution of **ΔZ/Z ~** 1/70 = **1.42 %**

Fission fragment identification: A and Z

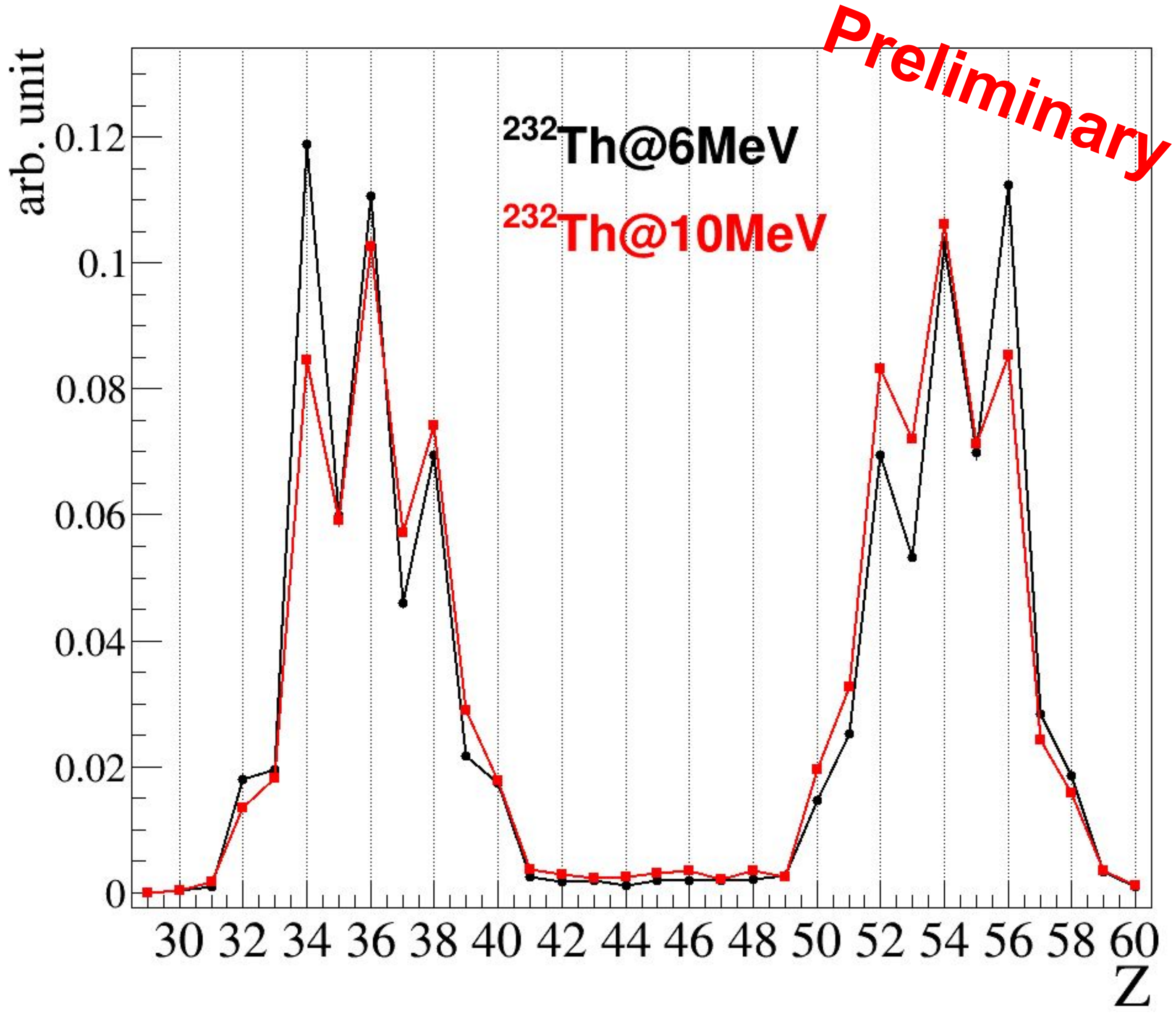


Isotopic yields



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

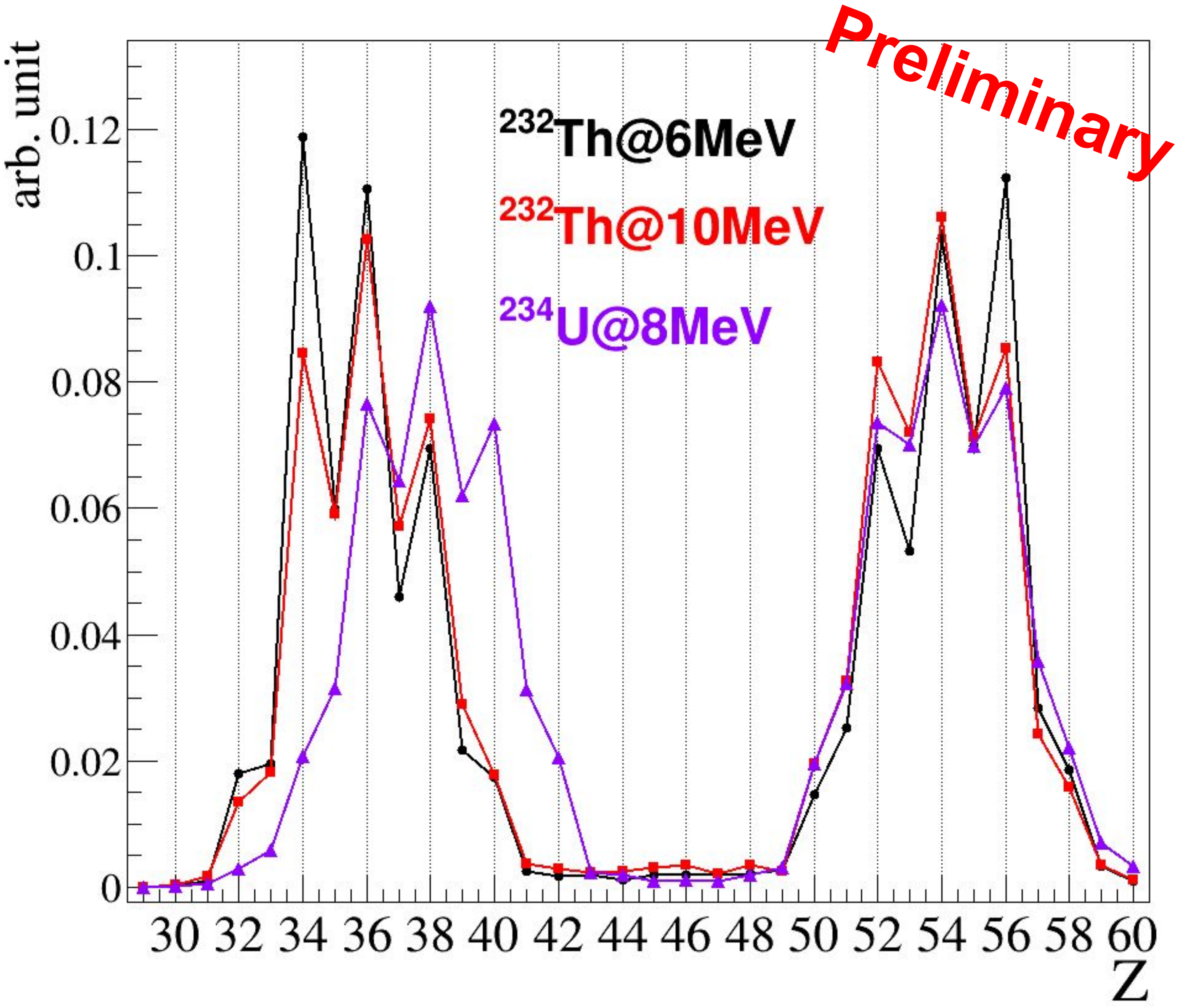
Isotopic yields



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

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

Isotopic yields



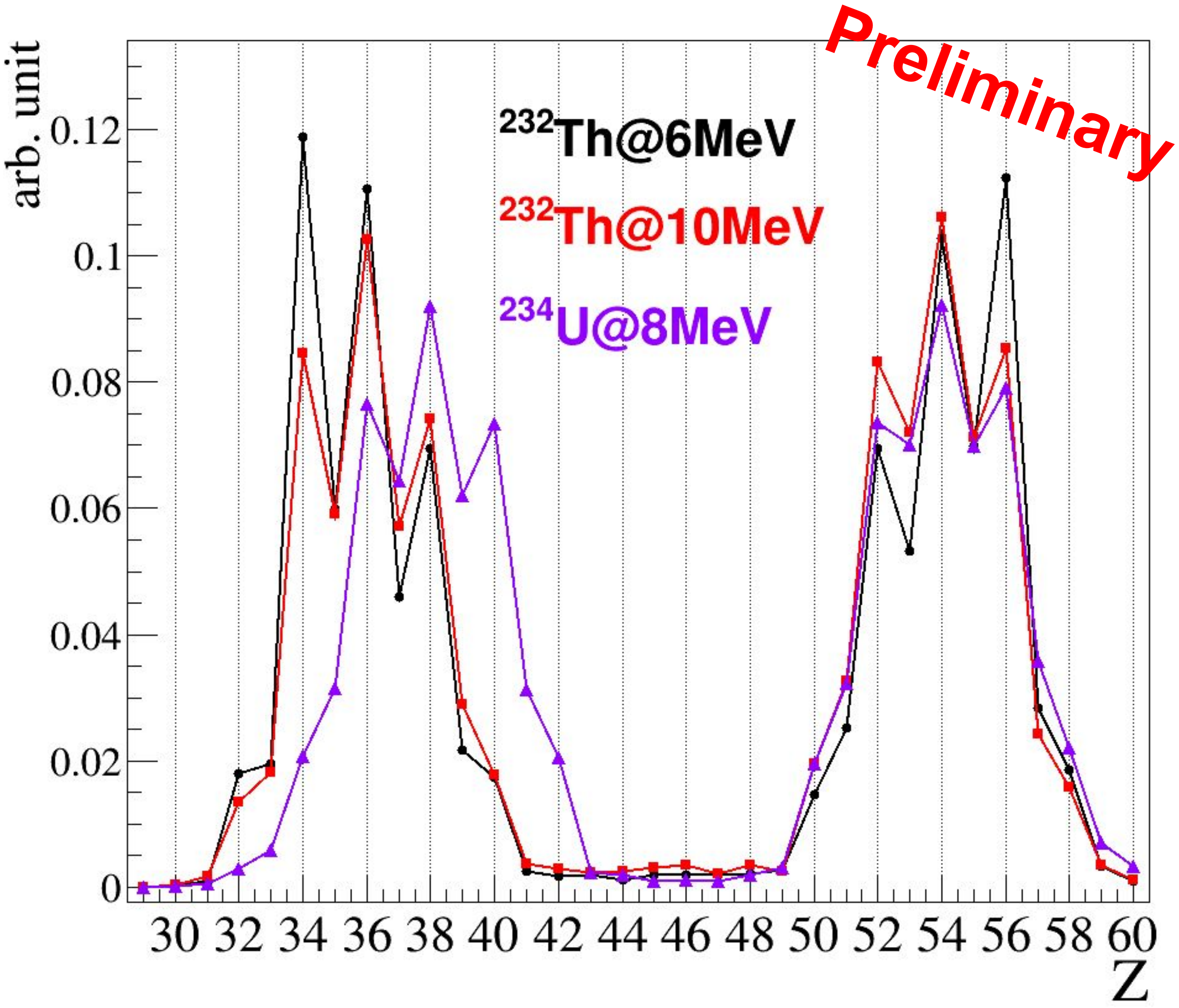
^{232}Th at 6 ± 2 MeV of Excitation energy, the isotopic yield peaks at **Z = 56** more than Z = 52, following the **Thorium anomaly**

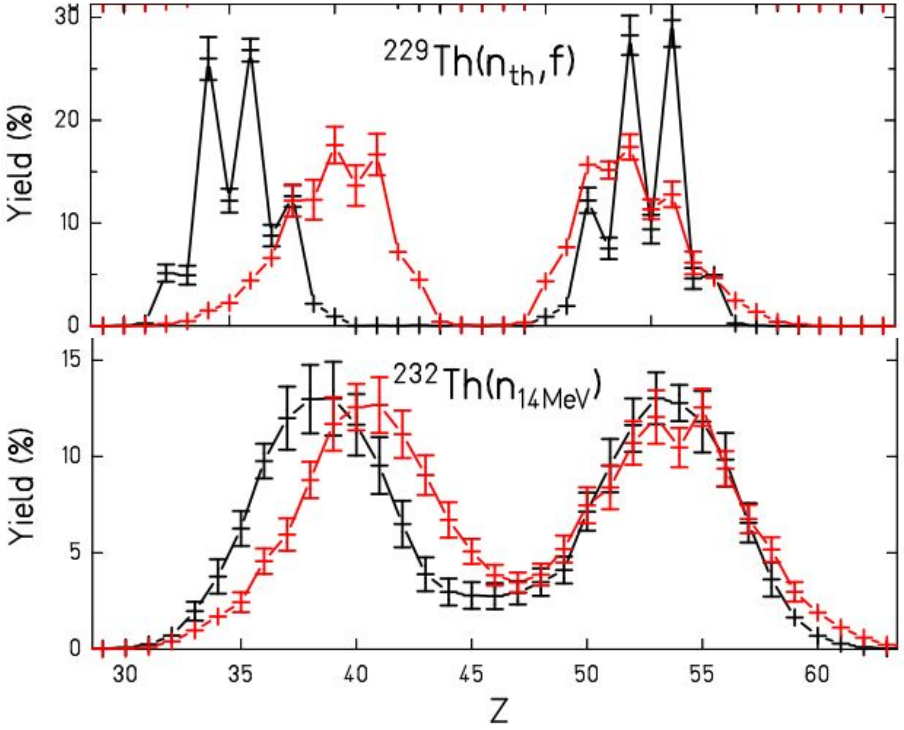
Increasing the energy by **4 MeV**, the production of **Z = 52** practically **matches** the one of **Z=56**.

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





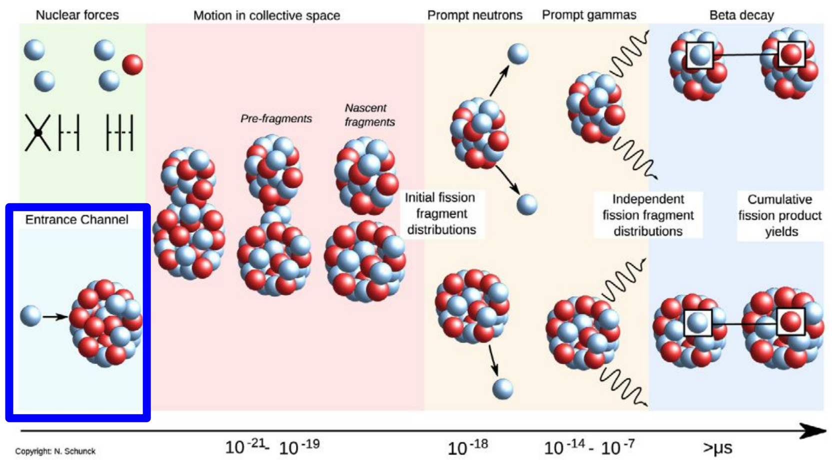
Disappearance of the third barrier effect at moderate Excitation energy increase?

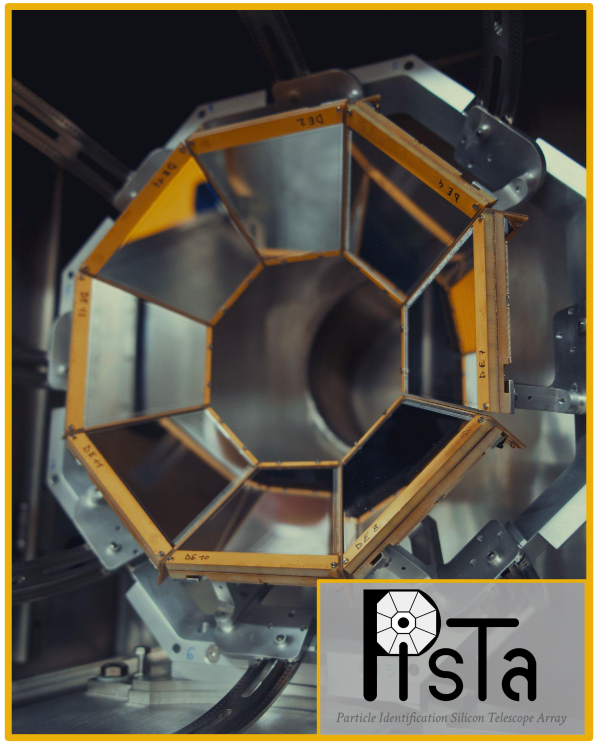
THANK YOU

Thanks to VAMOS group and collaborators from e849 experiment

Back up slides

Entrance channel information





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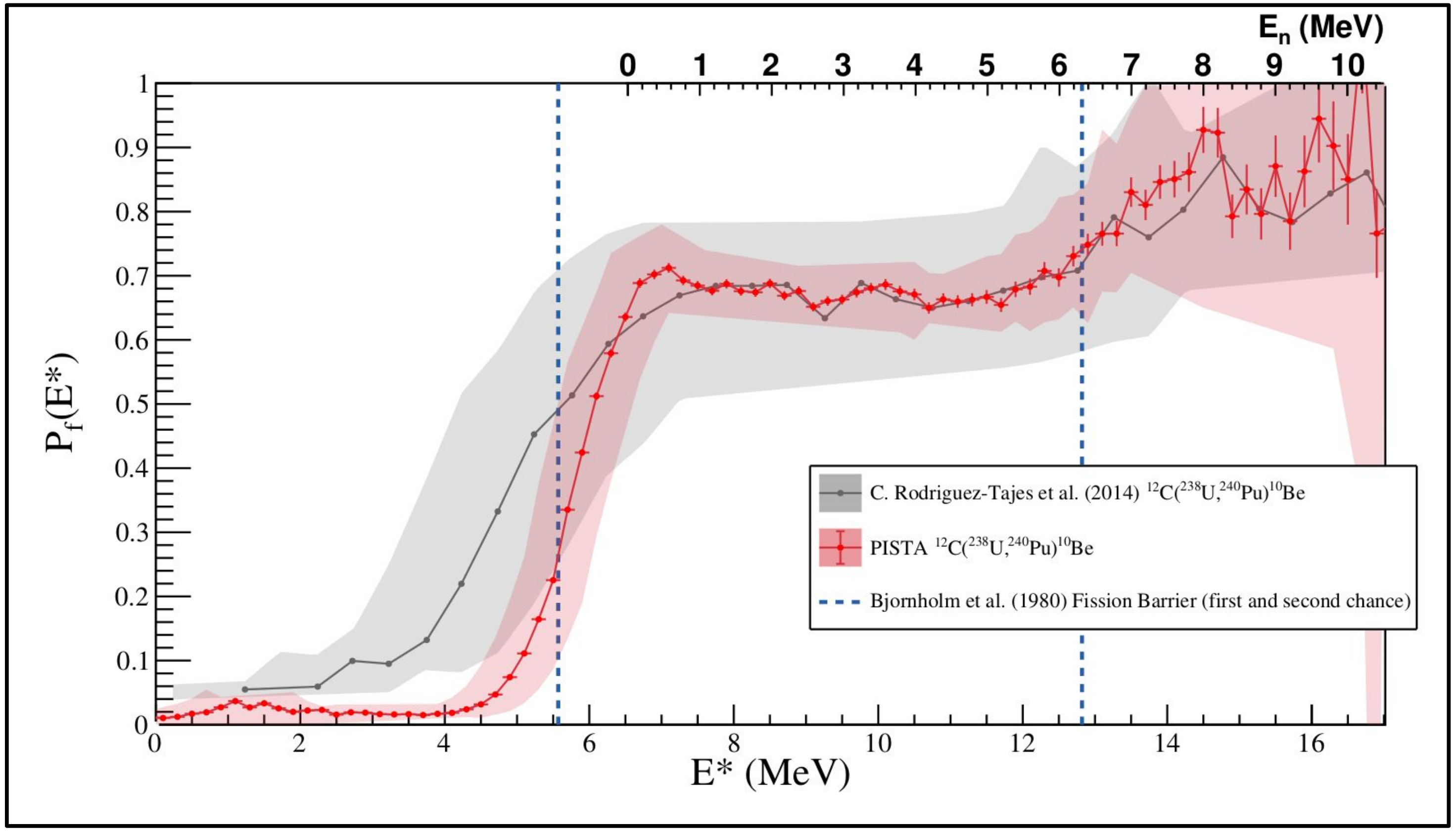
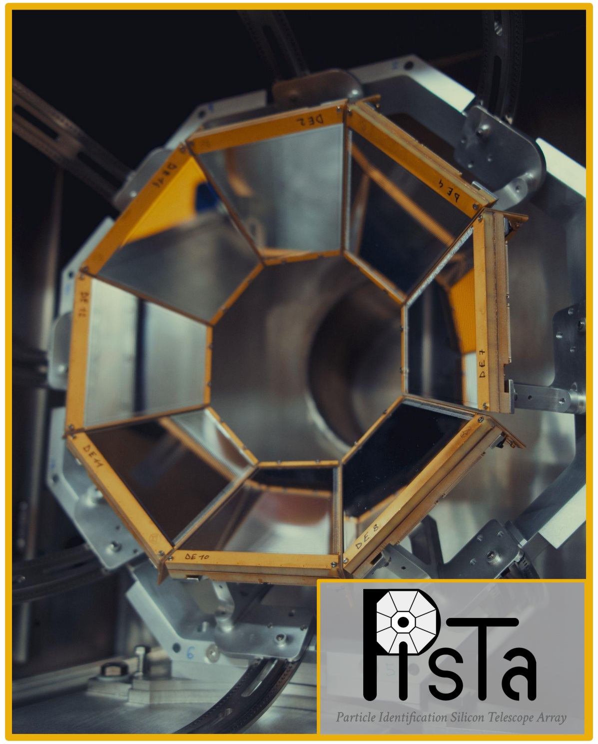
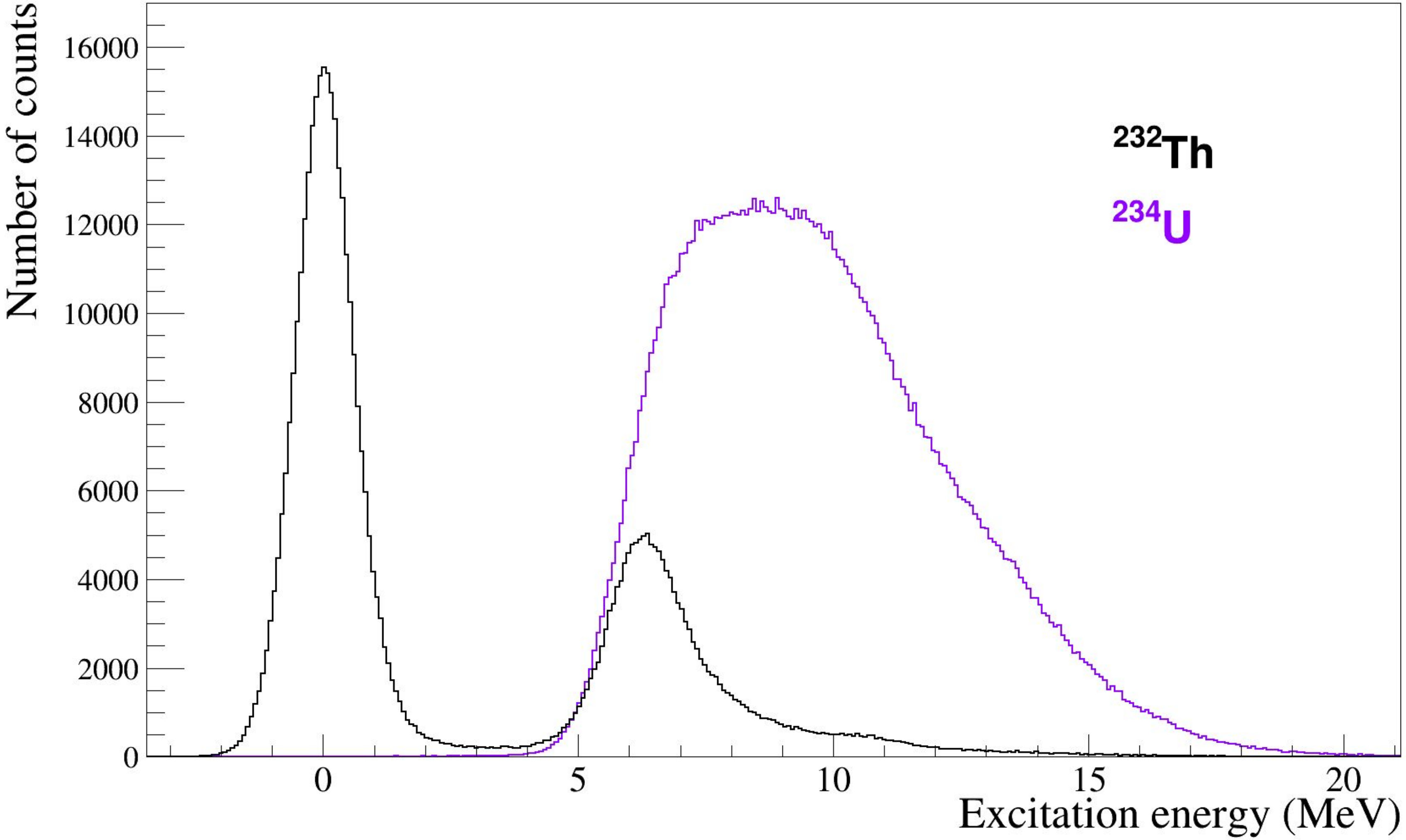


PhD thesis of Lucas Bégué-Guillou

Excitation energy distributions





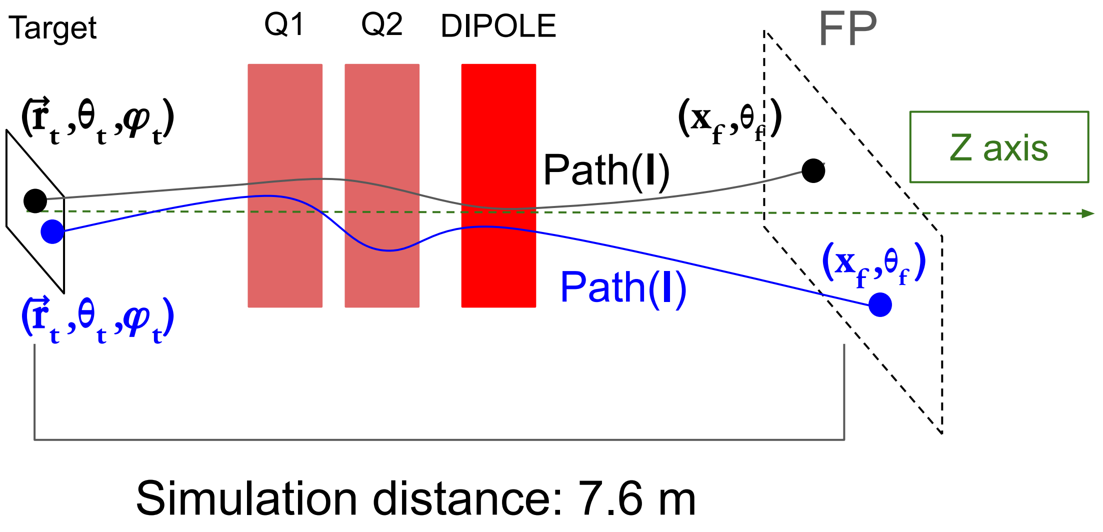
Experimental setup: VAMOS++

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 (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.



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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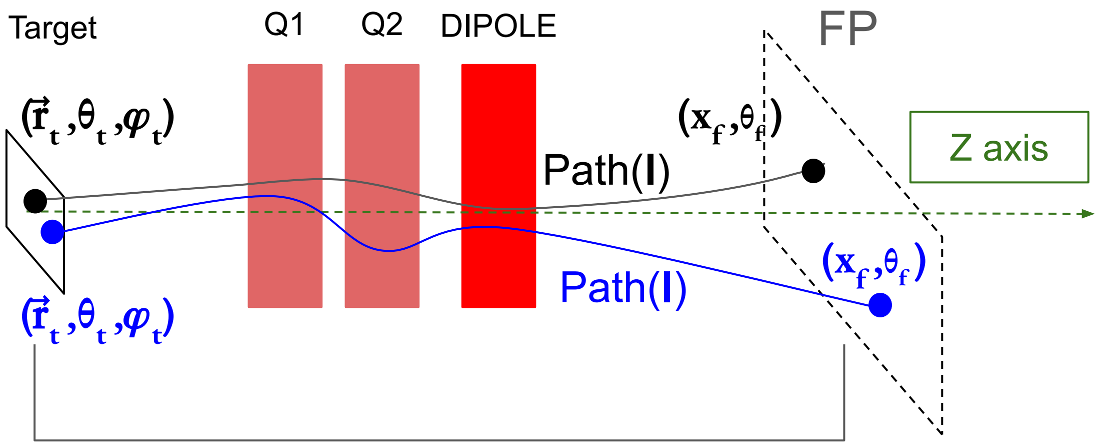


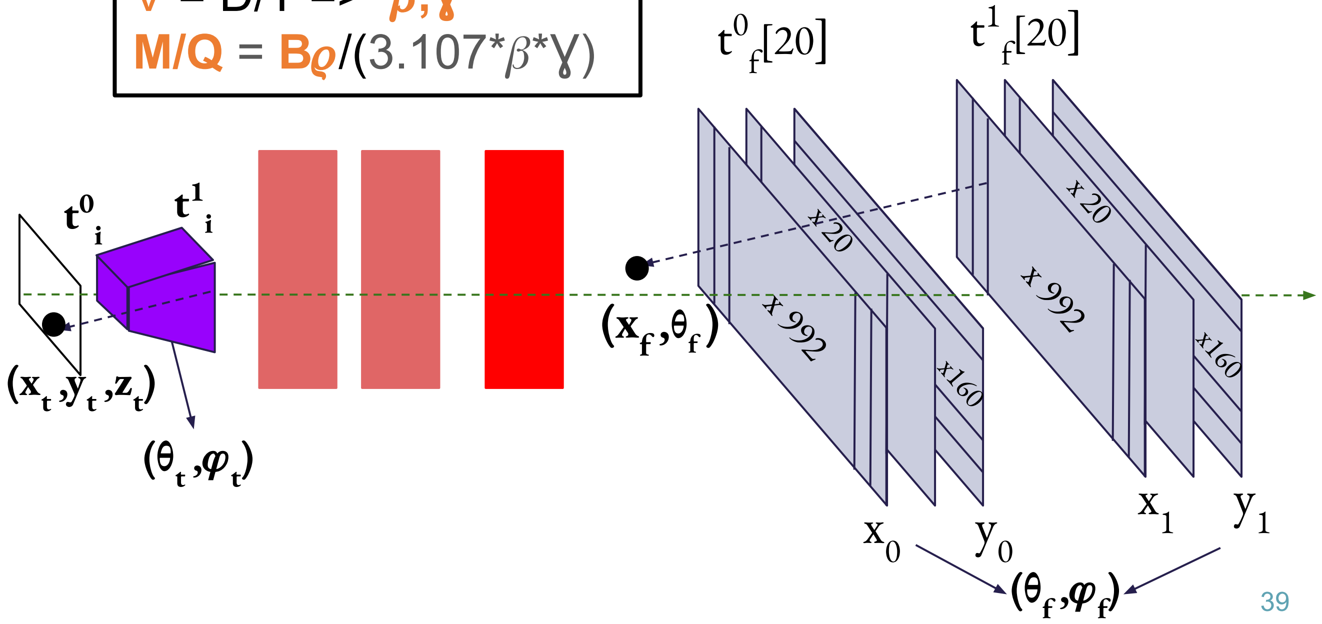
Simulation distance: 7.6 m

Experimentally

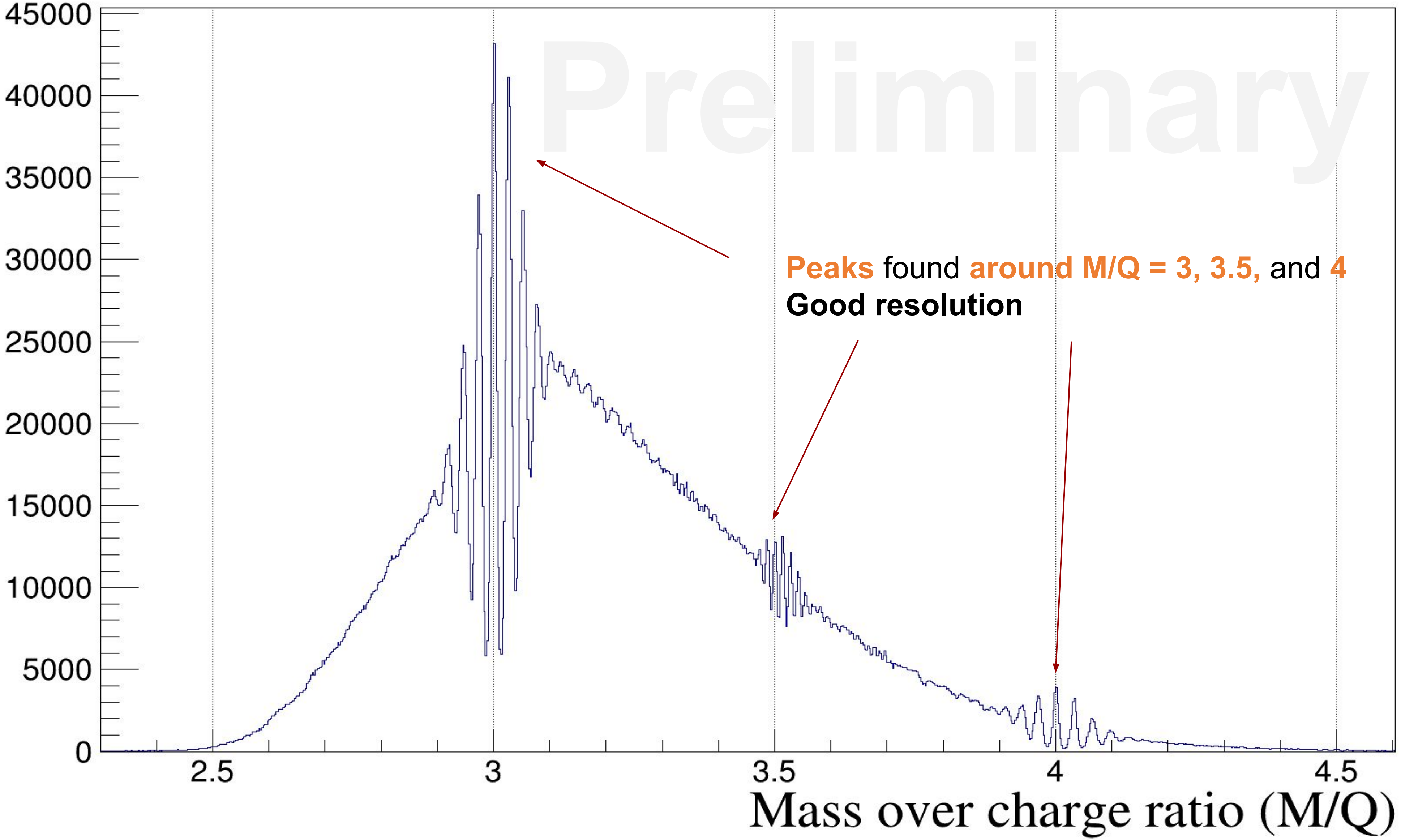
A pair of Multi-Wire Proportional counters (MWPC) at the target determine the **entrance coordinates** and **start time** (t_i)
A pair of MWPCs at the exit determine the **focal plane coordinates** and **20 stop times** (t_f)

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

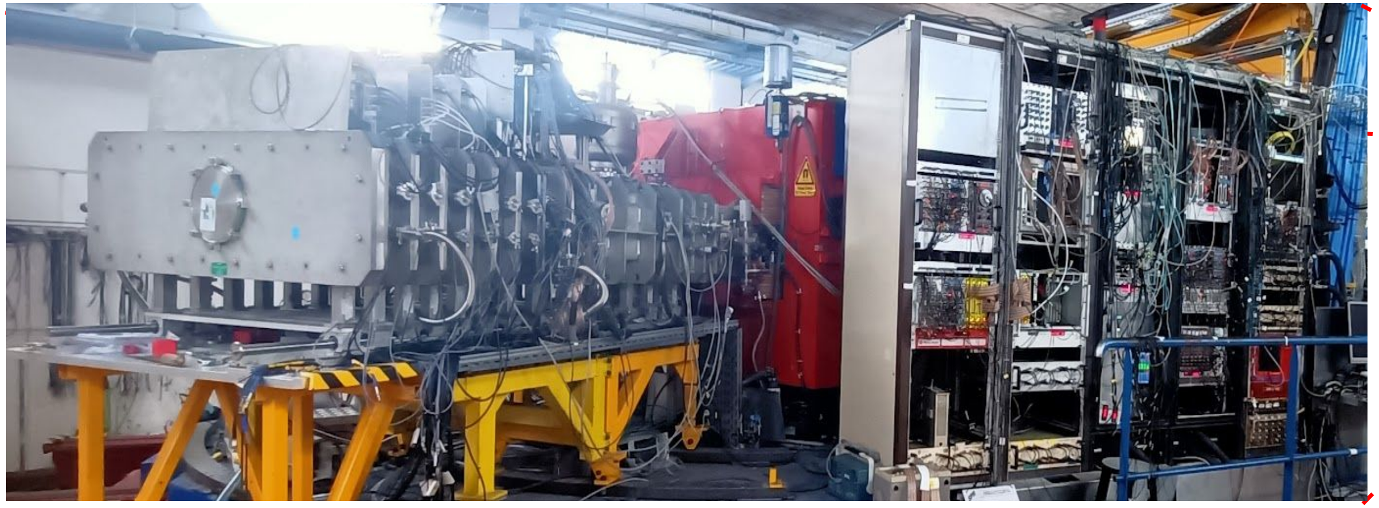
V = D/T => β,γ
M/Q = **Bϱ**/(3.107*β*γ)

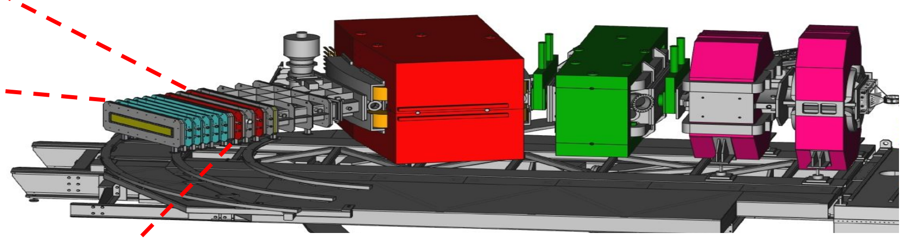


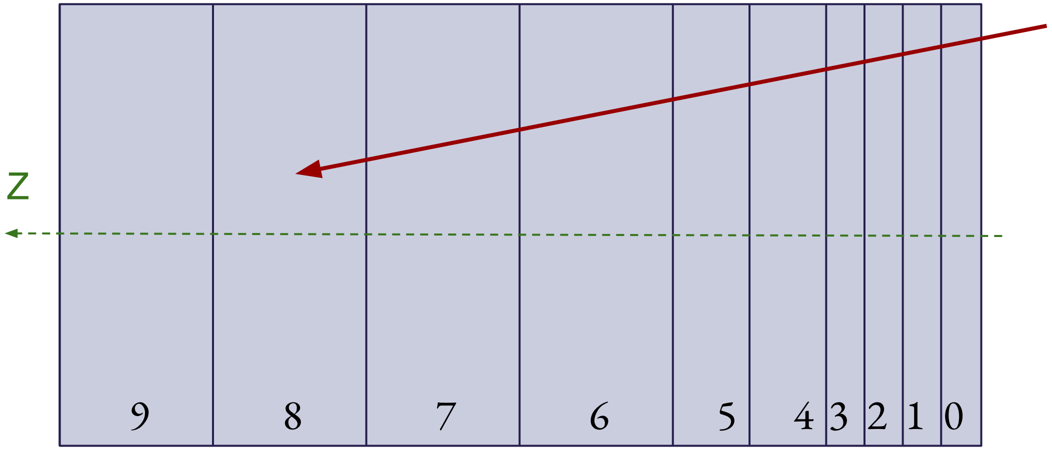
Experimental result: M/Q



Experimental setup: Ionization Chamber (Q)







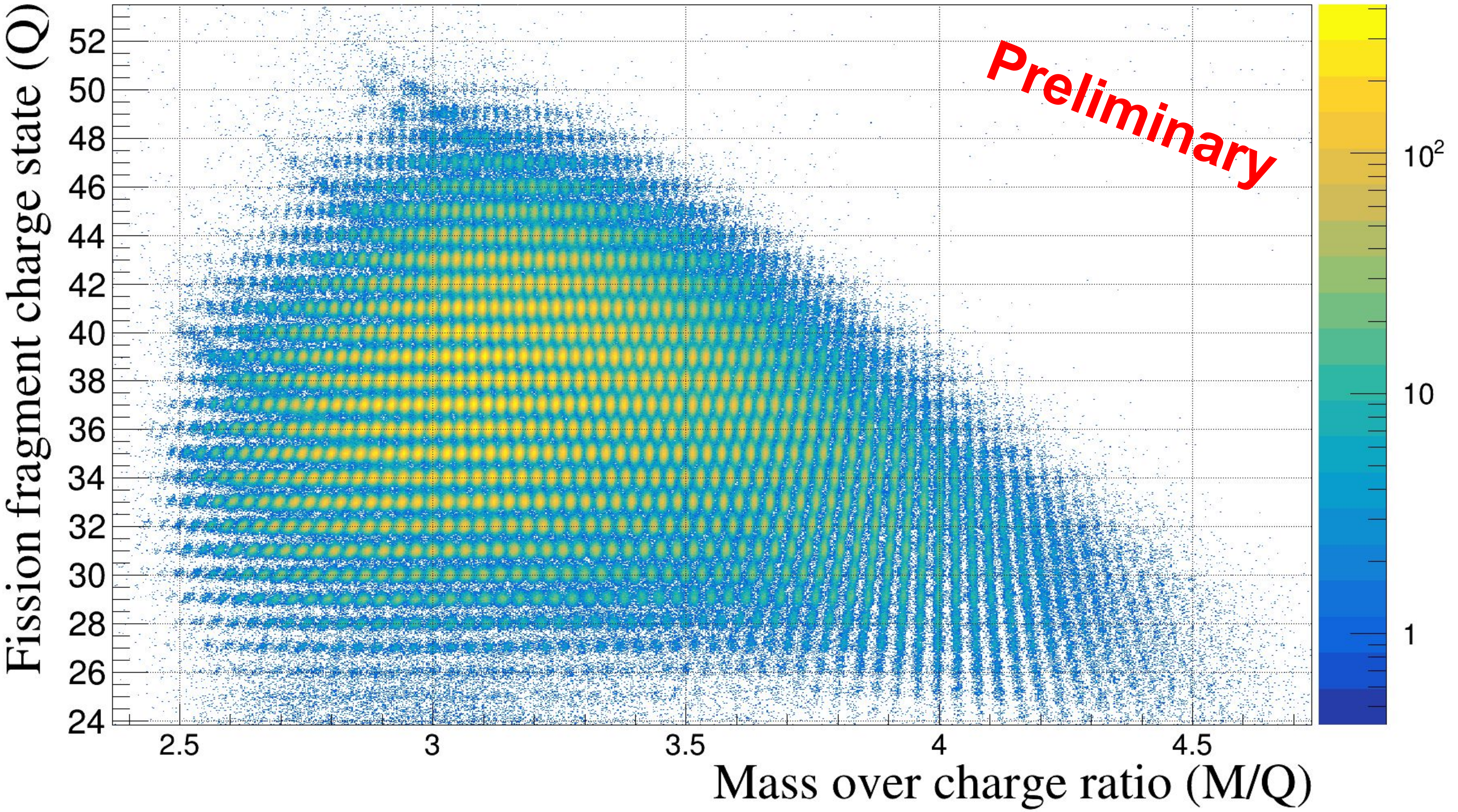
The **kinetic energy (E_{Kin})** of the fragment is proportional to the **mass** and the **velocity (γ)**

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

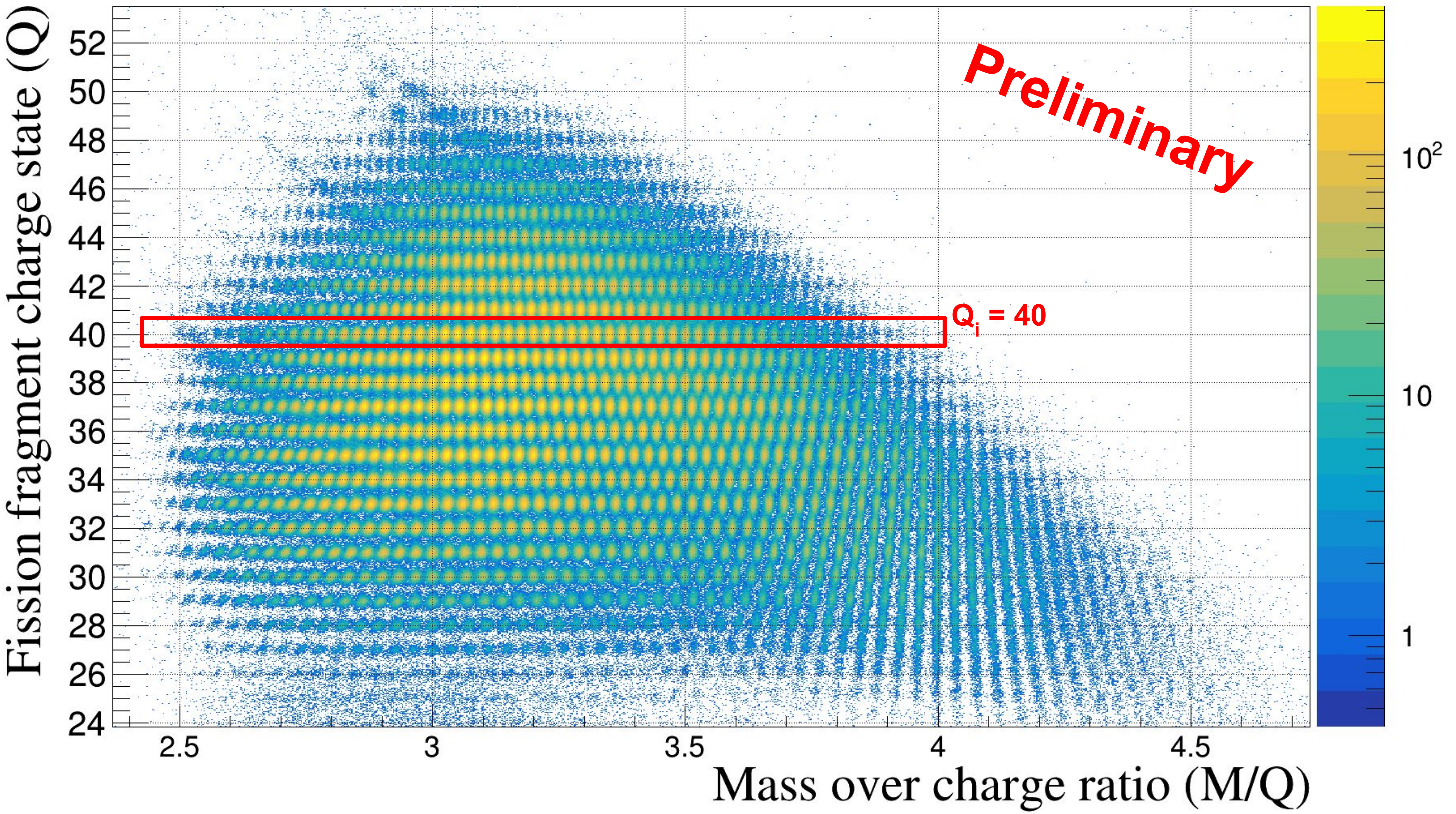
$$E_{Kin} = \Sigma a_i * IC_i + b_0$$
$$M_{IC} = E_{Kin} / (\gamma_{VAMOS} - 1)$$

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

Experimental result: Q



Experimental result: Q and M



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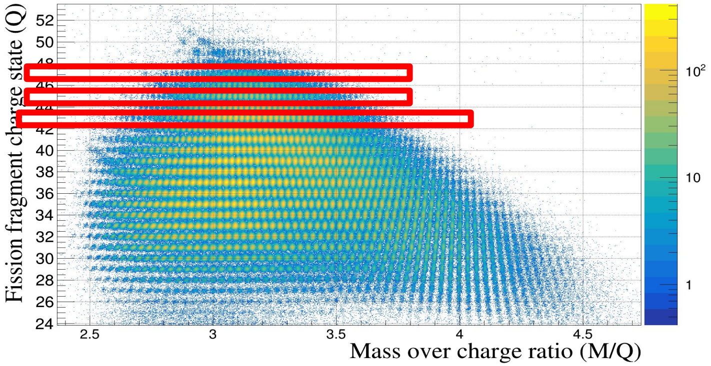
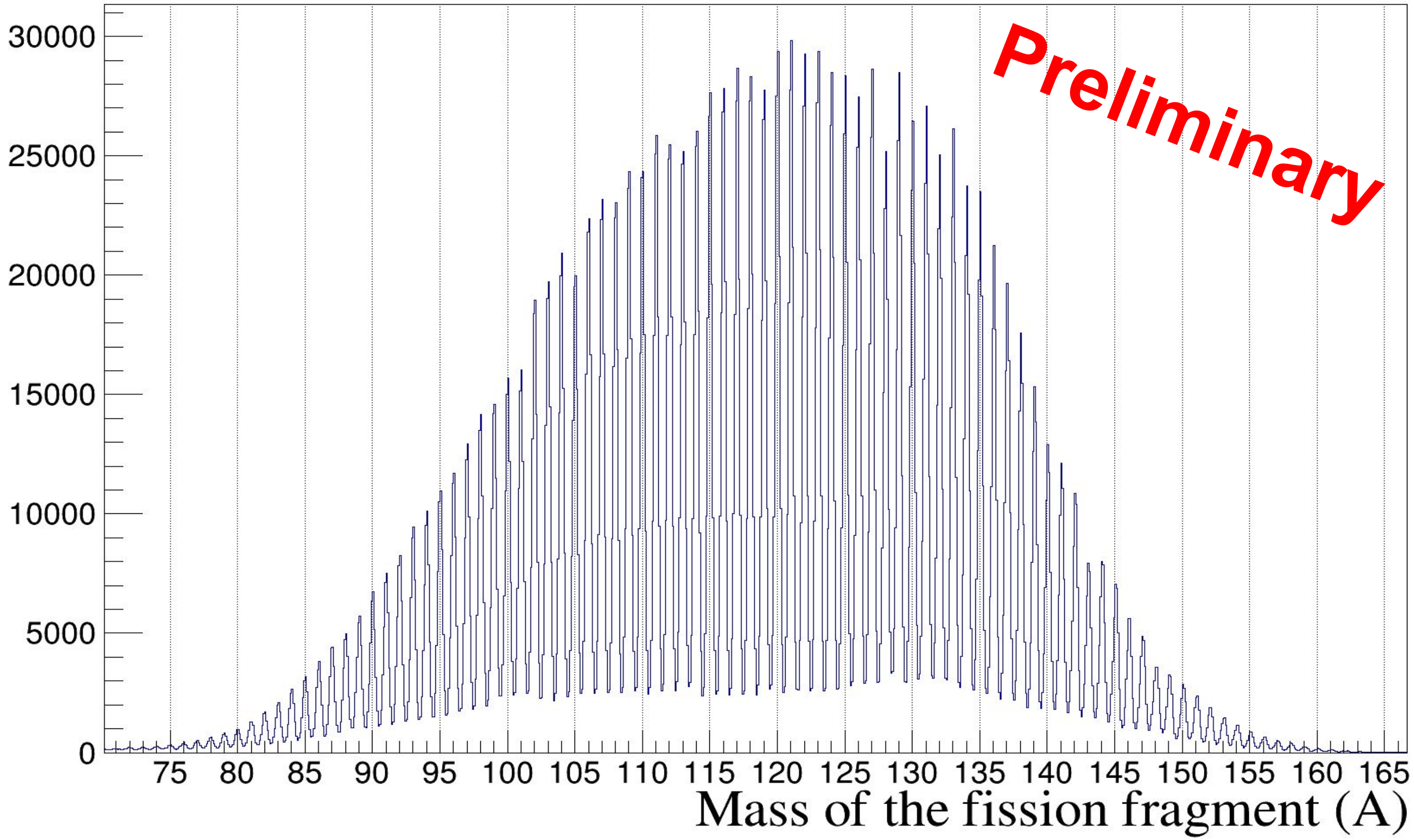


$M = Q_i * M/Q$

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



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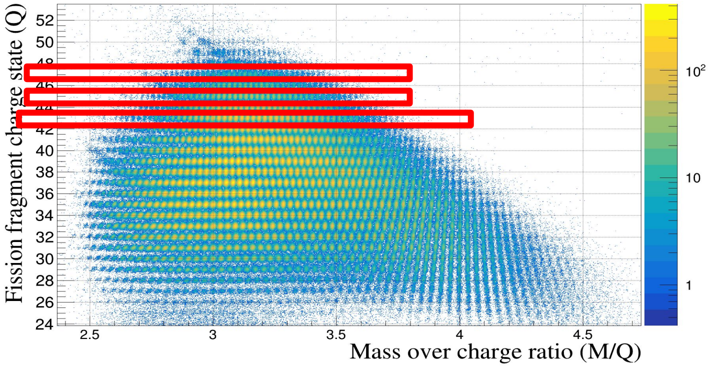

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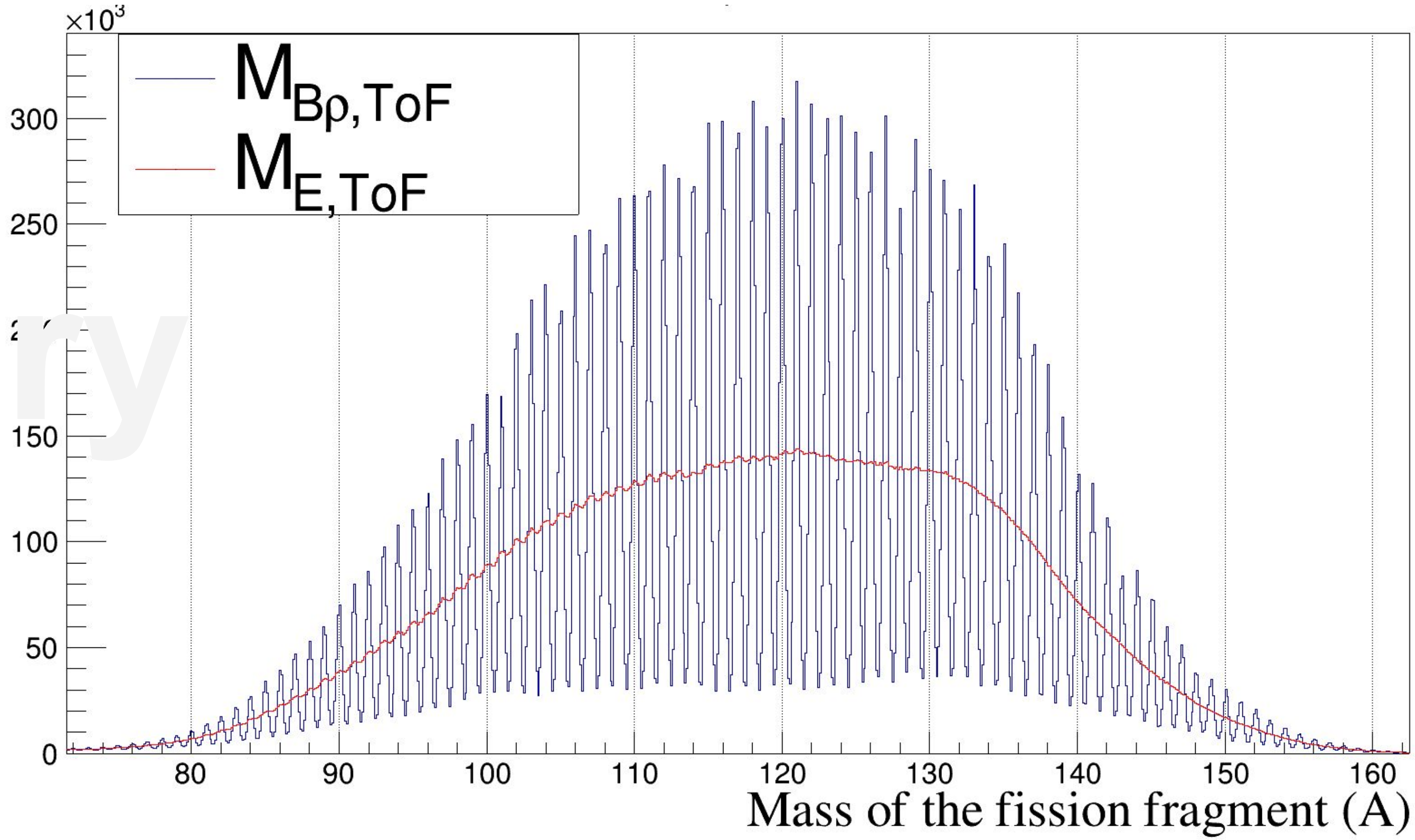
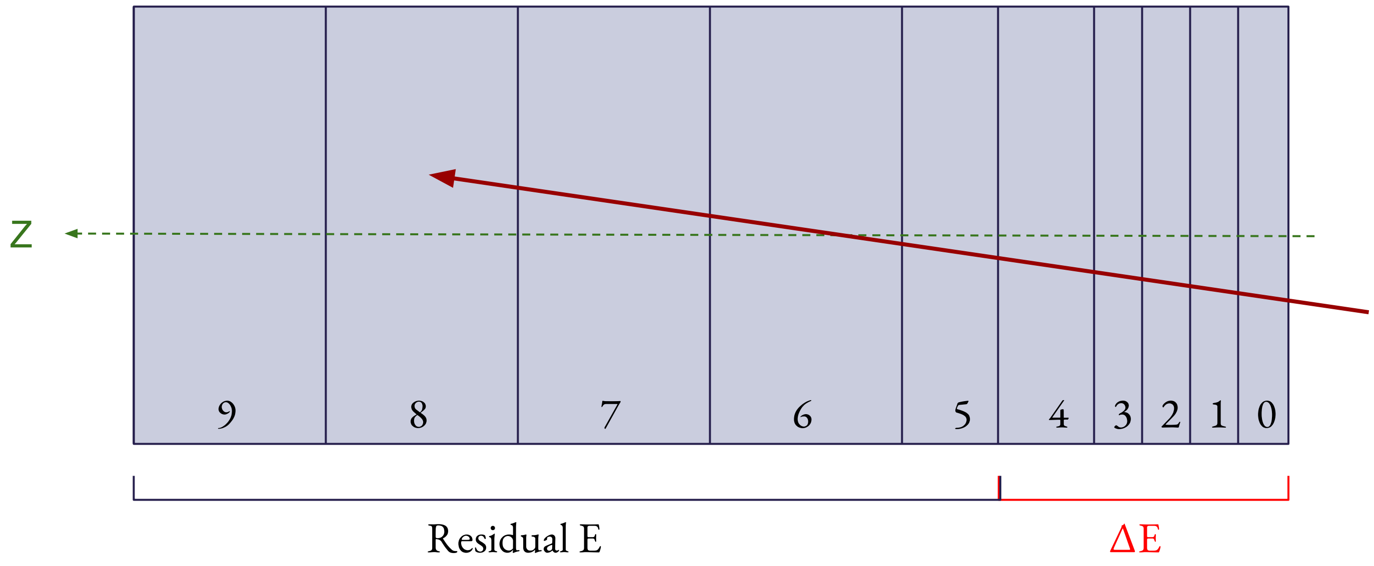


Preliminary

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

Experimental setup: Segmented IC

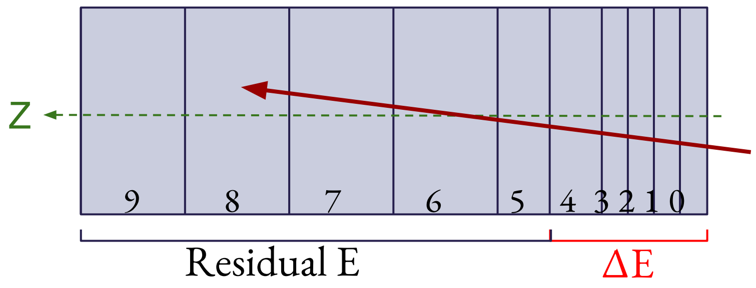
We can also use the **sections of** the **IC** to get the **proton content** of the fission fragment
Several combinations possible, best in our case: **ΔE** = sections 0-4 , **E_{Res}** = sections 5-9



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

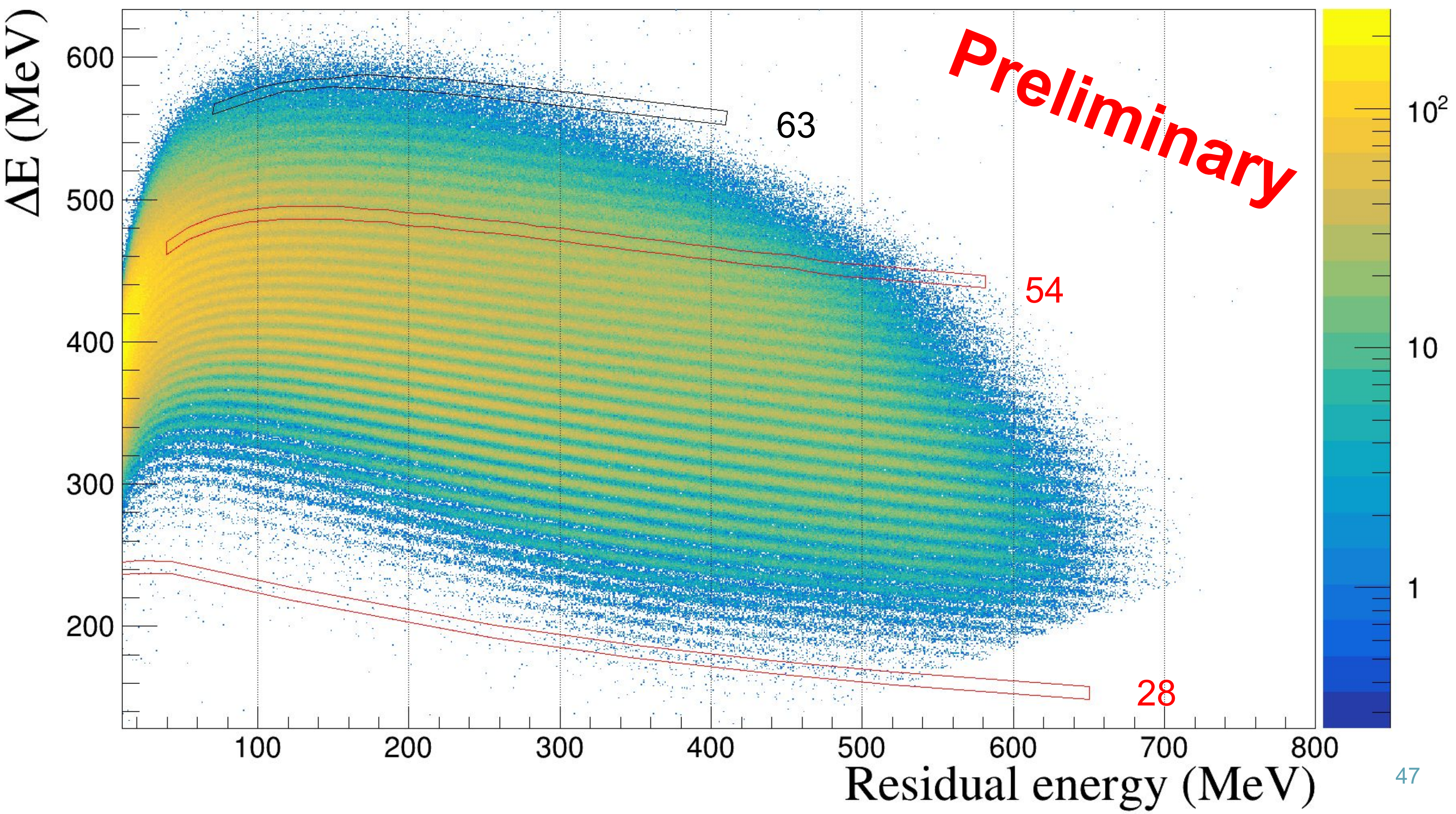
Experimental result: Z

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 **ΔZ/Z ~ 1/70**

Bethe-Bloch : **-dE/dx ∝ Z^2/β^2**



Experimental result: Z

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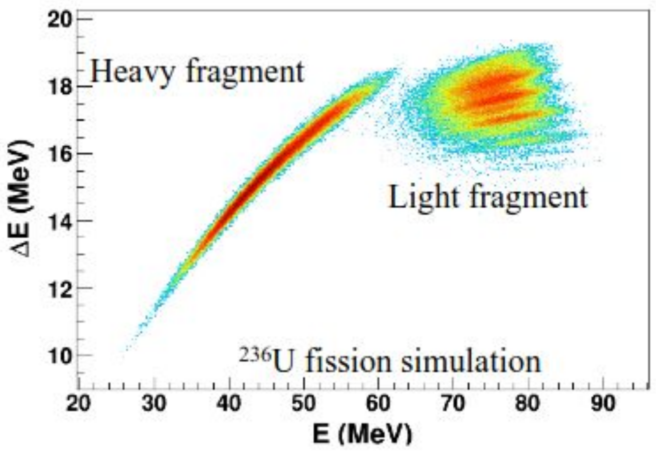
Direct-kinematics



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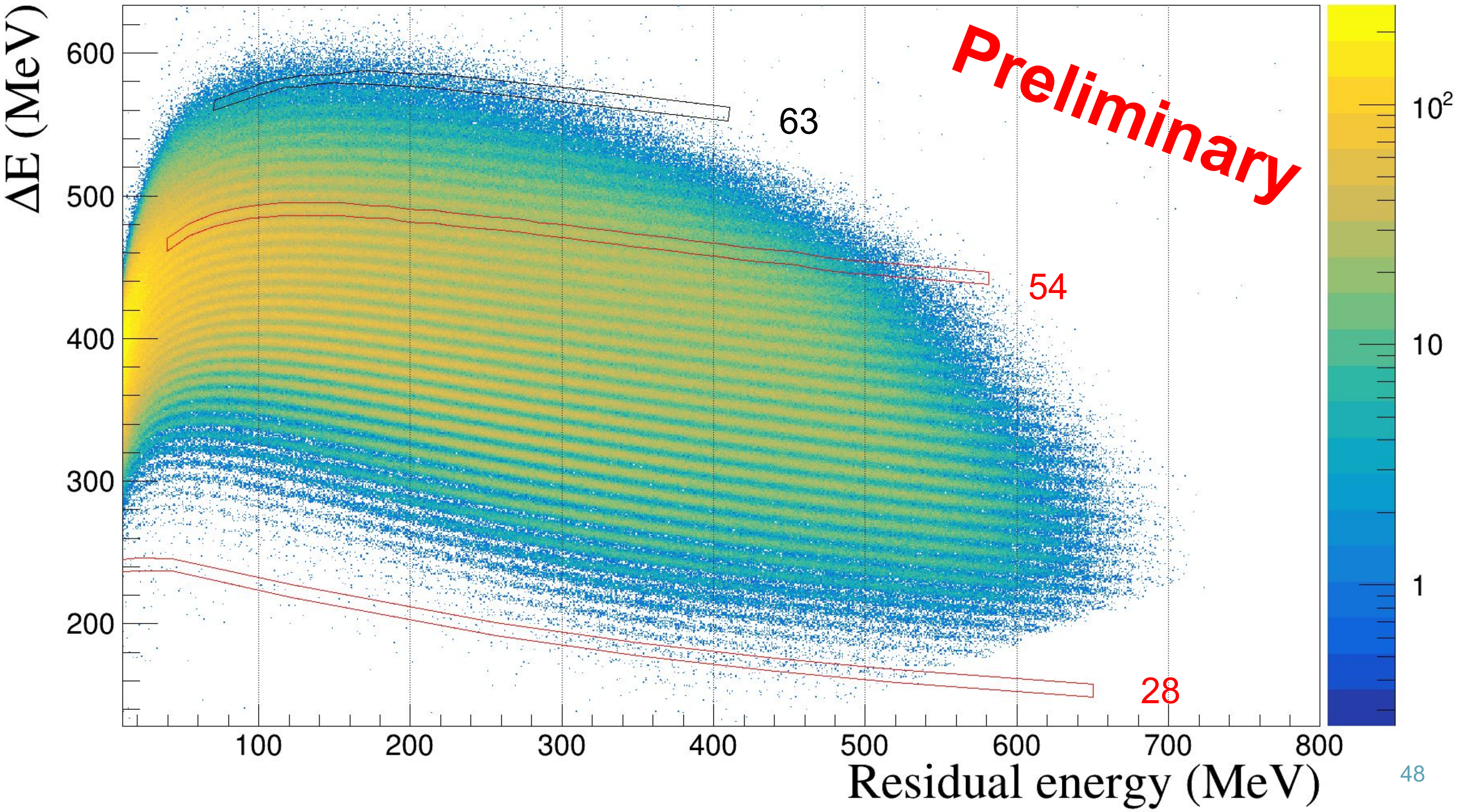
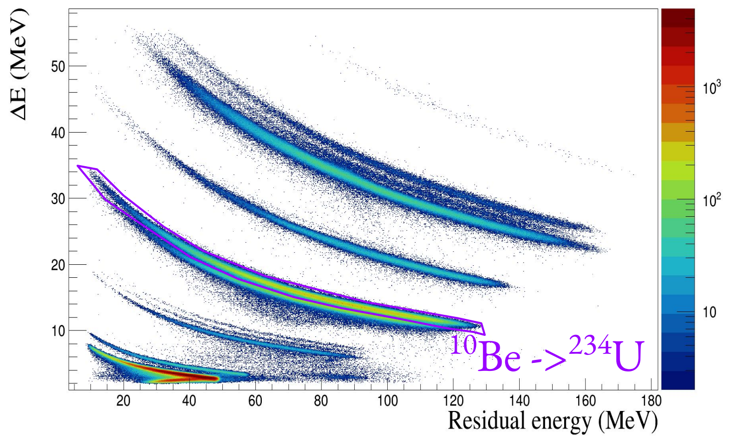
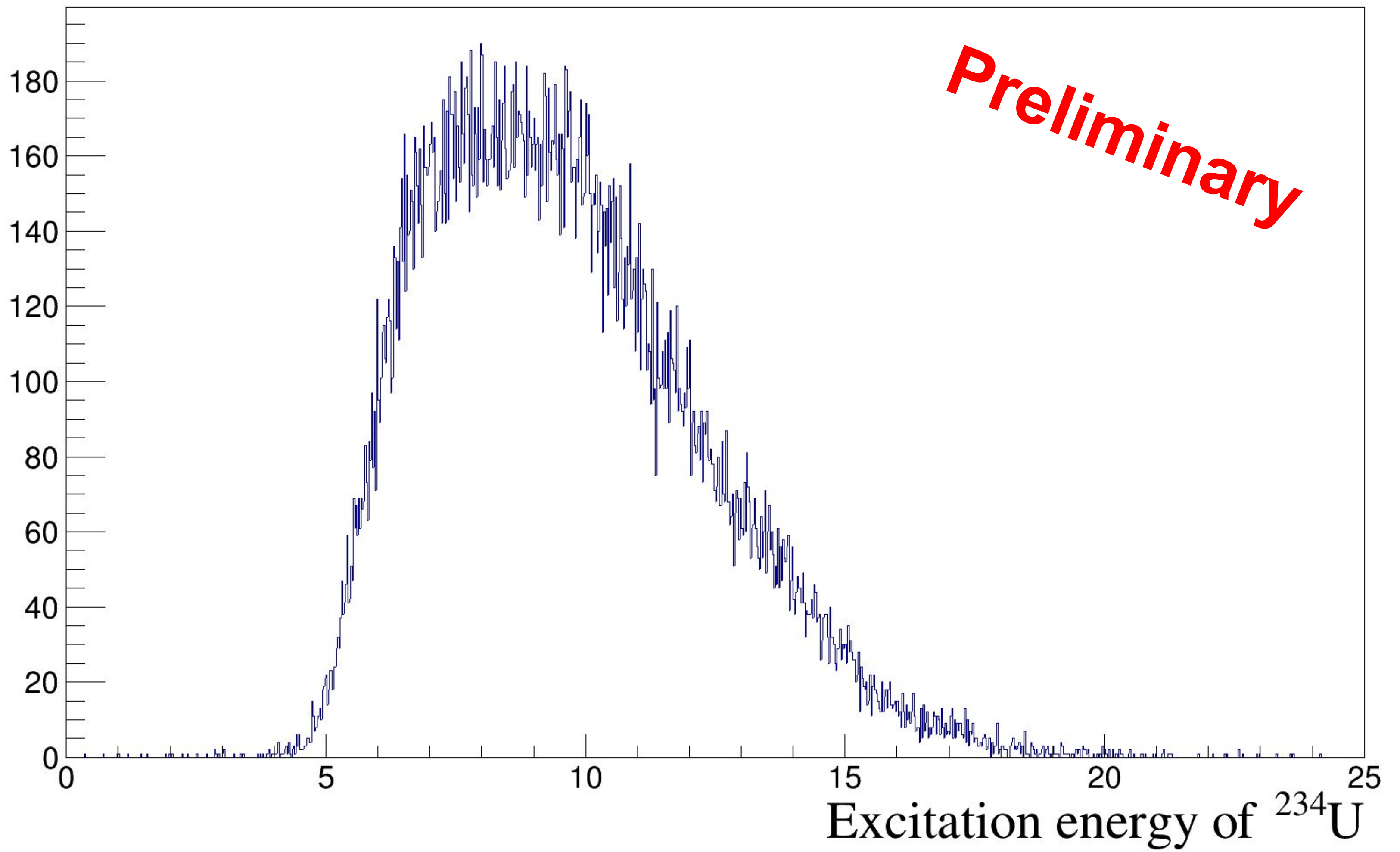


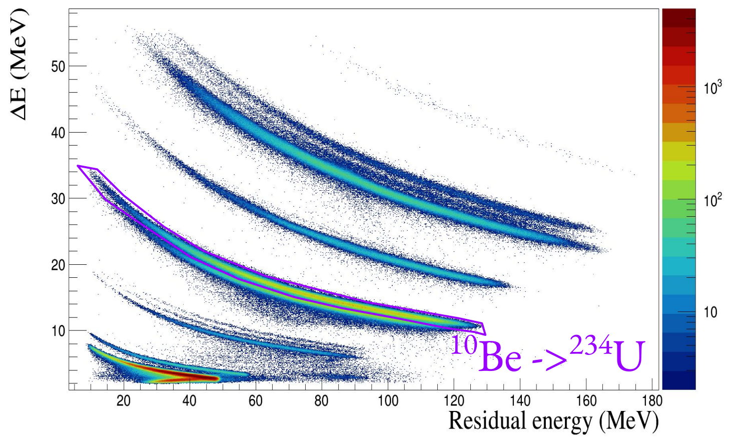
Identify Z from ~26 to ~65
Thanks to inverse-kinematics

Experimental result: Fissioning system E*

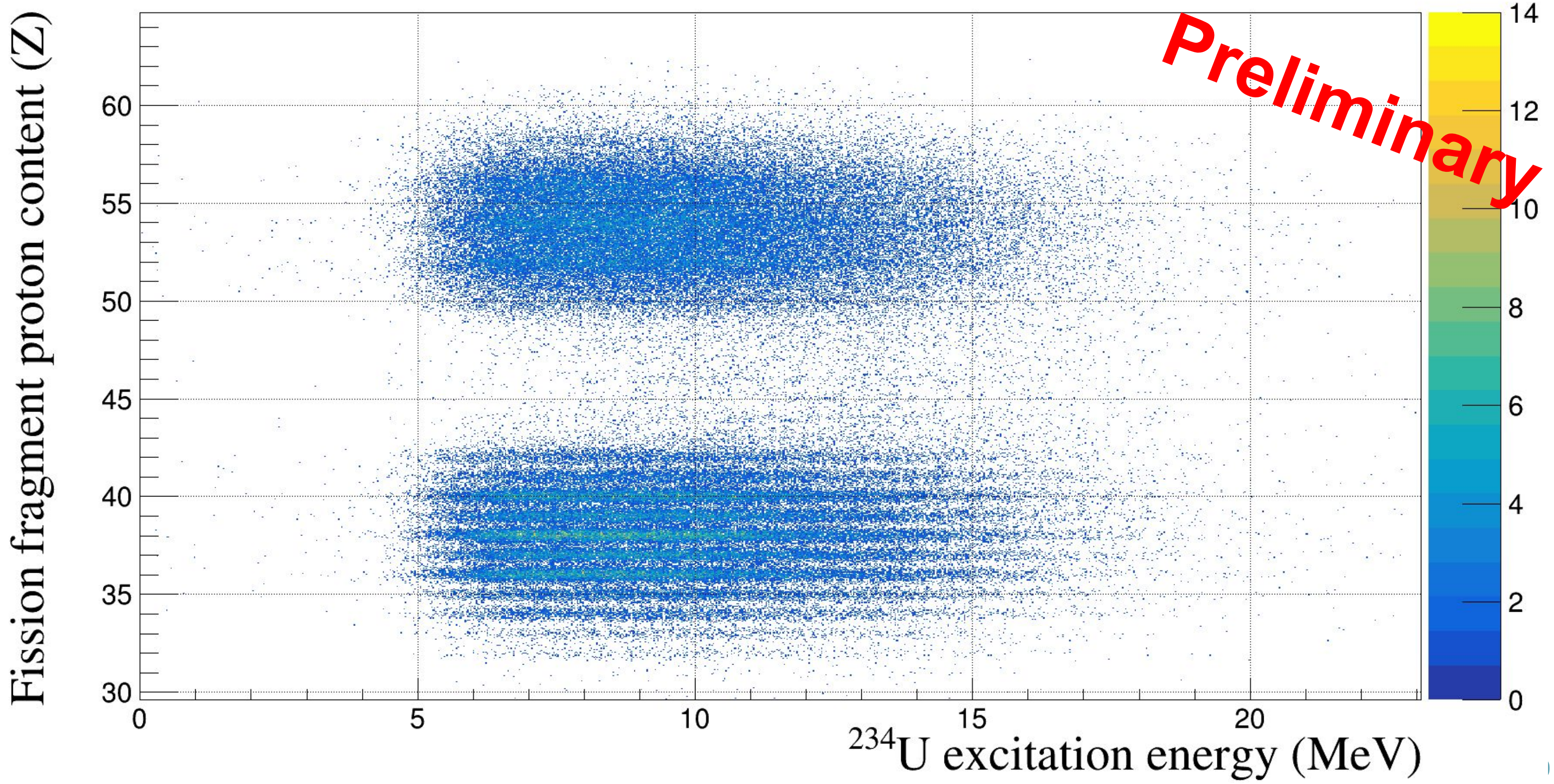




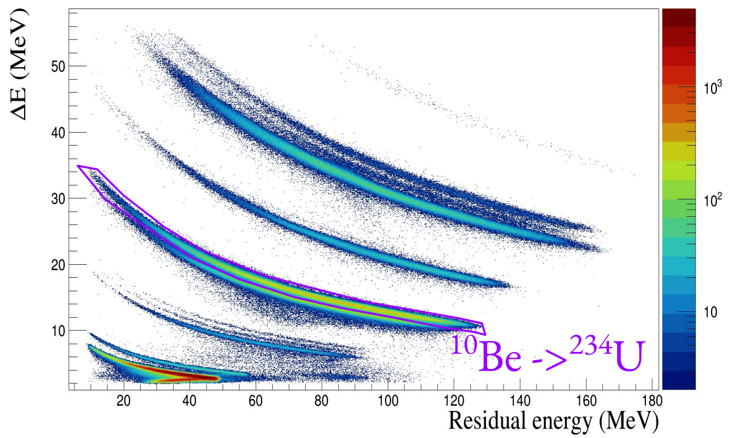
Experimental result: Fissioning system E*



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



Experimental result: Z evolution with E*



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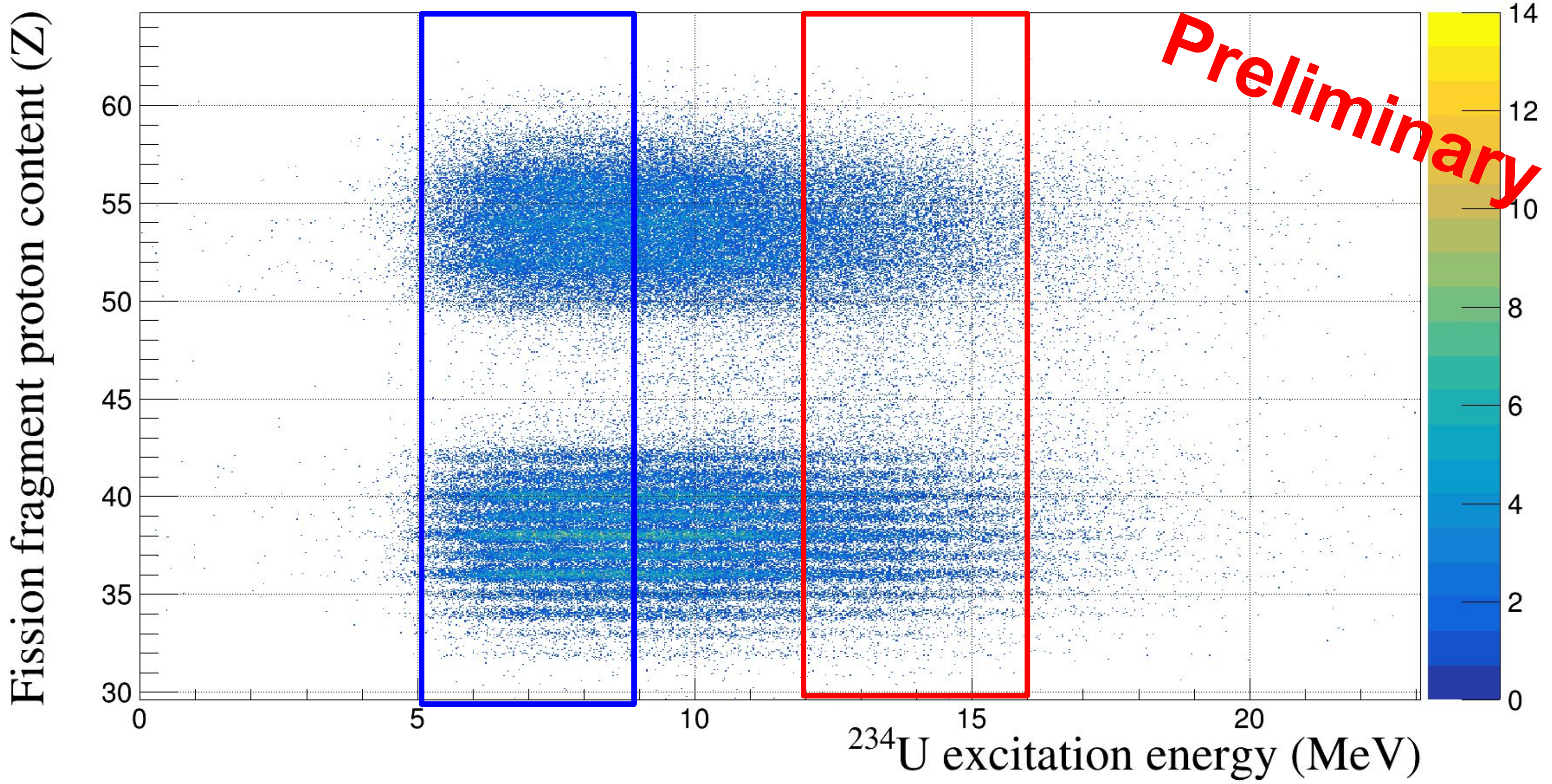
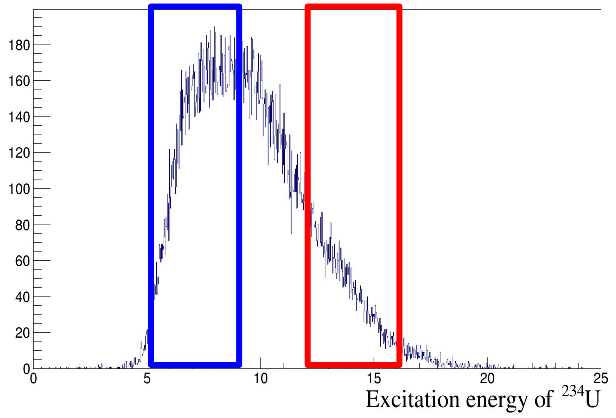
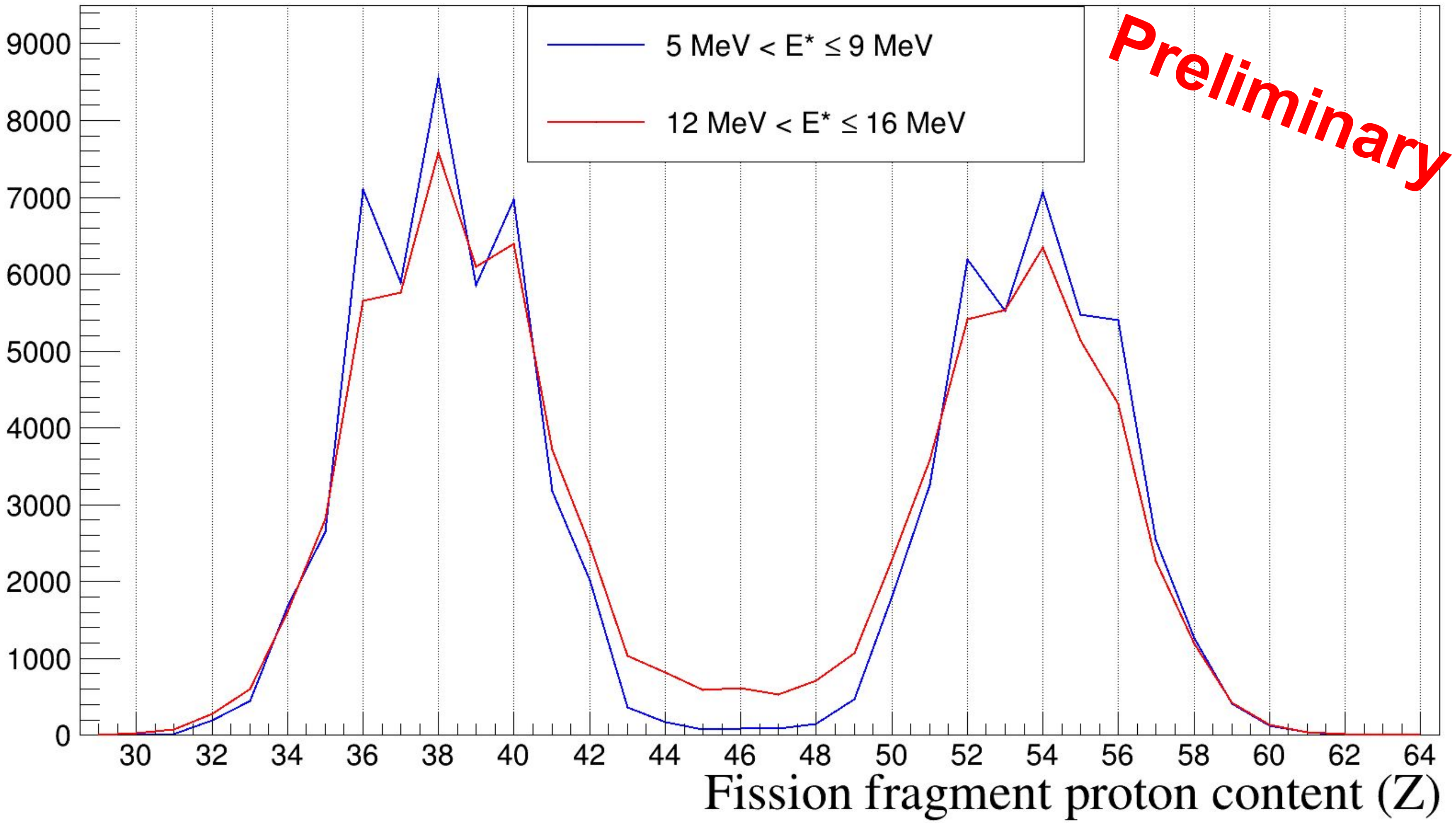


Experimental result: Z evolution with E*

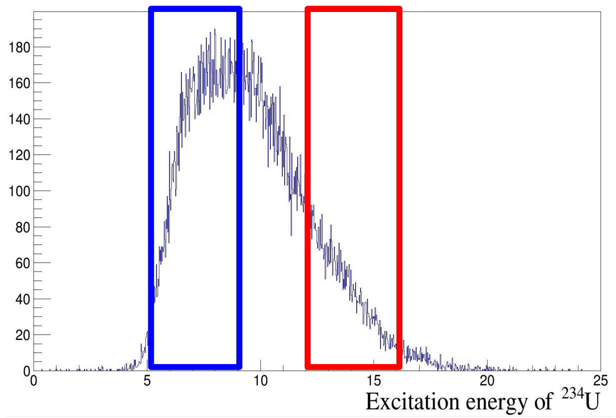


Odd-even staggering effect in the **light** and **heavy** fragment
Less notorious for **higher Ex**

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



Experimental result: N/Z evolution with E*



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

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