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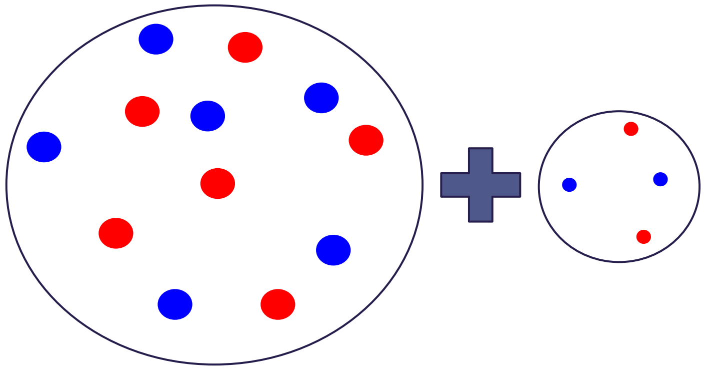
Isotopic fission fragments yields in the Thorium region produced in inverse-kinematics with a 232Th beam

European Nuclear Physics Conference 2025

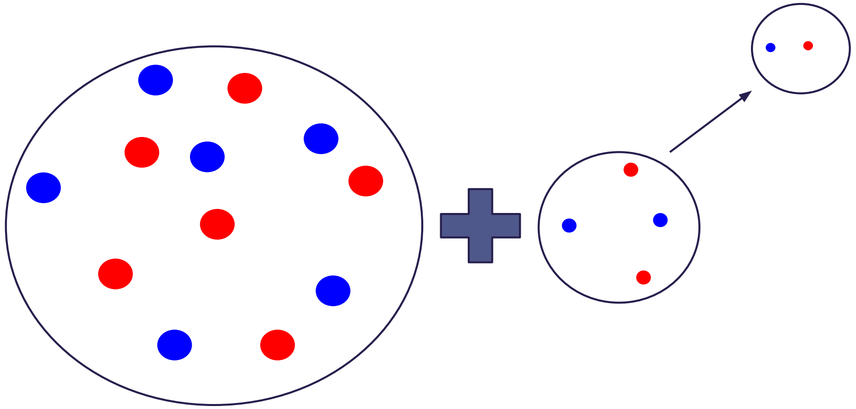
e849 experiment collaboration

Alex Cobo Zarzuelo
23/09/2025

Transfer-induced fission in inverse kinematics

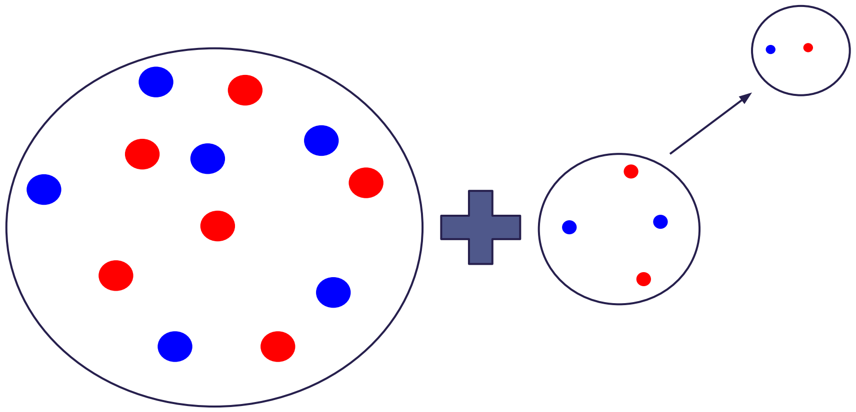


Transfer-induced fission: Entrance channel

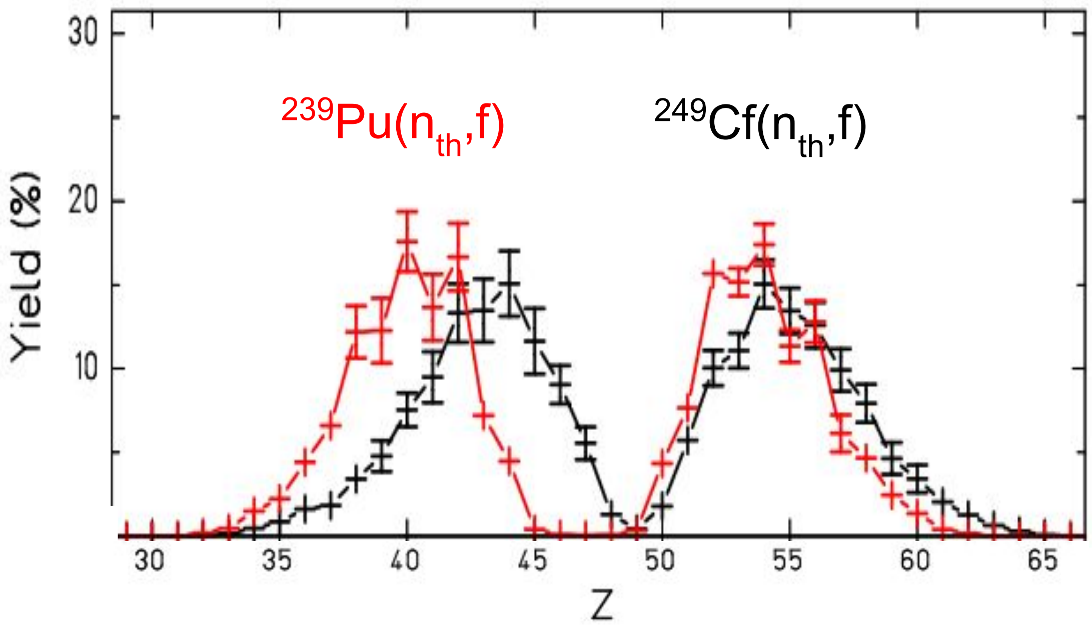


<u>Entrance channel</u>: fissioning system **formation**

Transfer-induced fission: Entrance channel

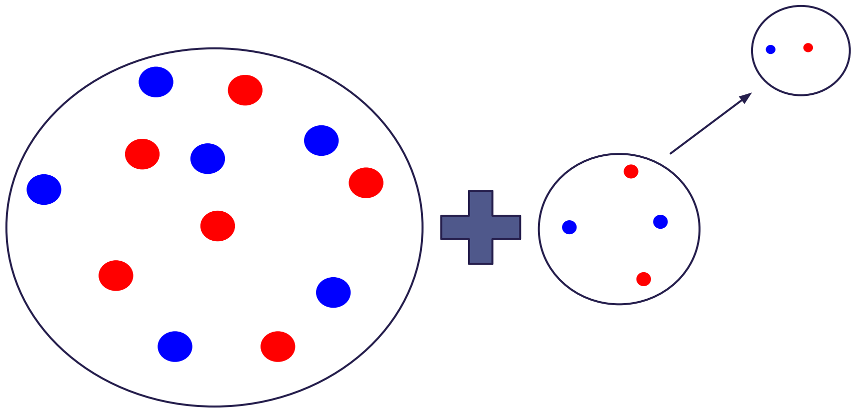


Entrance channel:
1) What is the fissioning system that was formed (Z,A)?

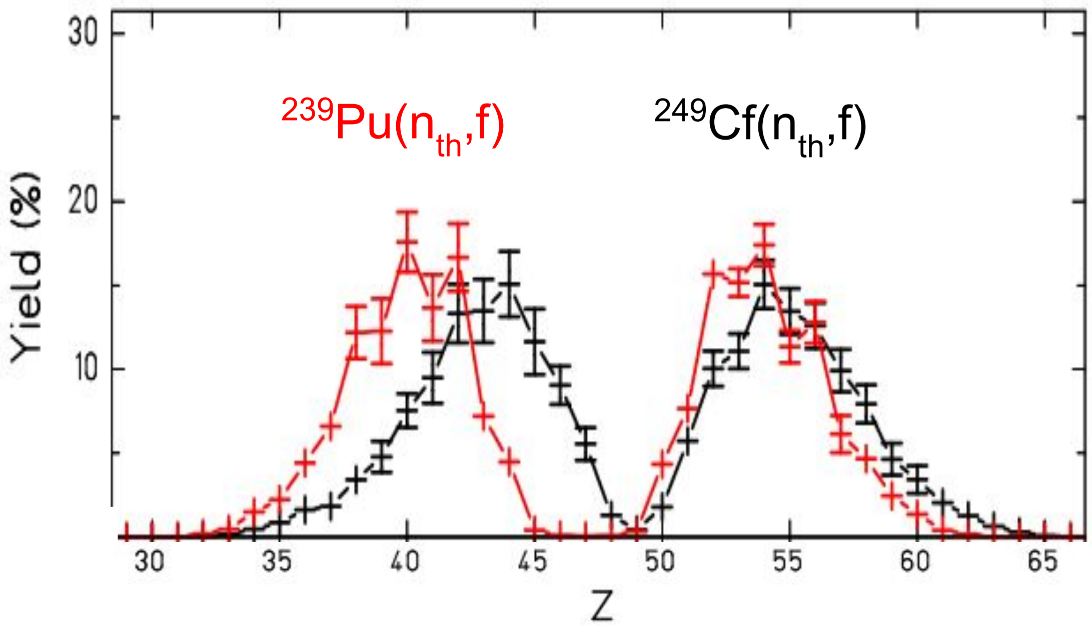


[1] Schmidt, K. H., Schmitt, C., Heinz, A., & Jurado, B. (2024). Identifying and overcoming deficiencies of nuclear data on the fission of light actinides by use of the GEF code. Annals of Nuclear Energy, 208, 110784.

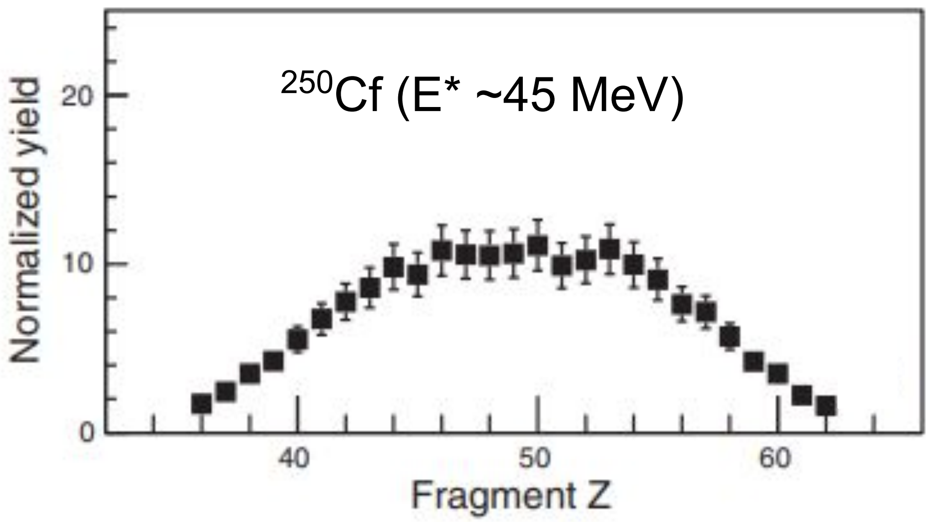
Transfer-induced fission: Entrance channel



Entrance channel:
1) What is the fissioning system that was formed (Z,A)?
2) At which state was it formed? (E*)

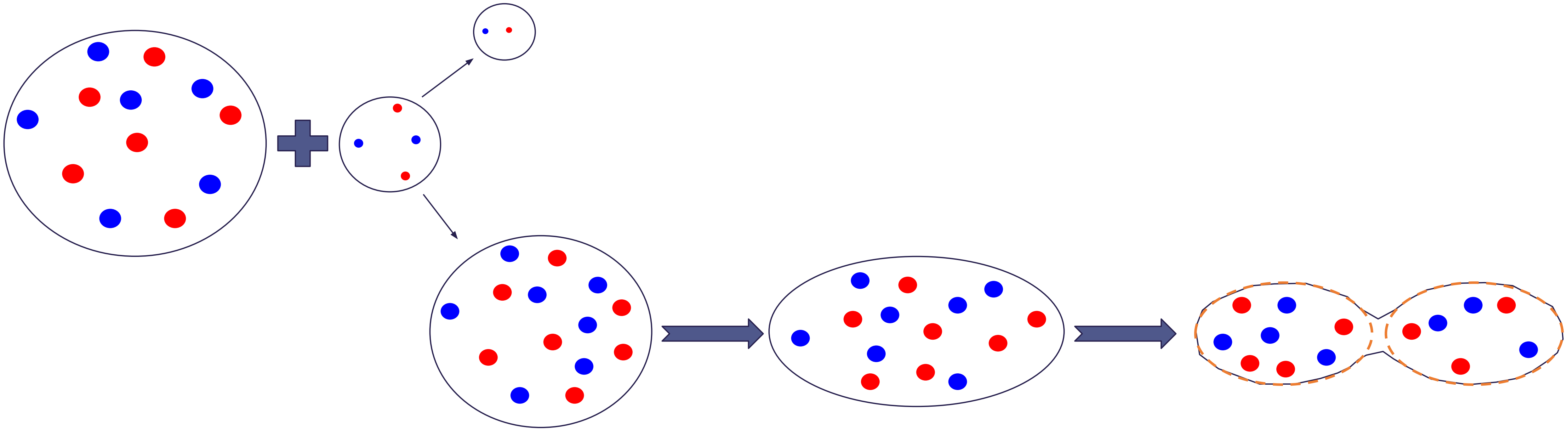


[1] Schmidt, K. H., Schmitt, C., Heinz, A., & Jurado, B. (2024). Identifying and overcoming deficiencies of nuclear data on the fission of light actinides by use of the GEF code. Annals of Nuclear Energy, 208, 110784.



[2] 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.

Transfer-induced fission: Entrance and exit channel



<u>Exit channel</u>: fissioning system **decay**

Transfer-induced fission: Entrance and exit channel

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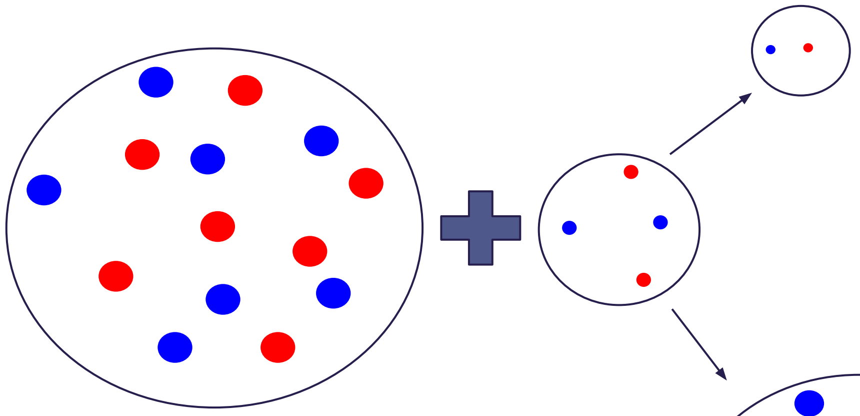
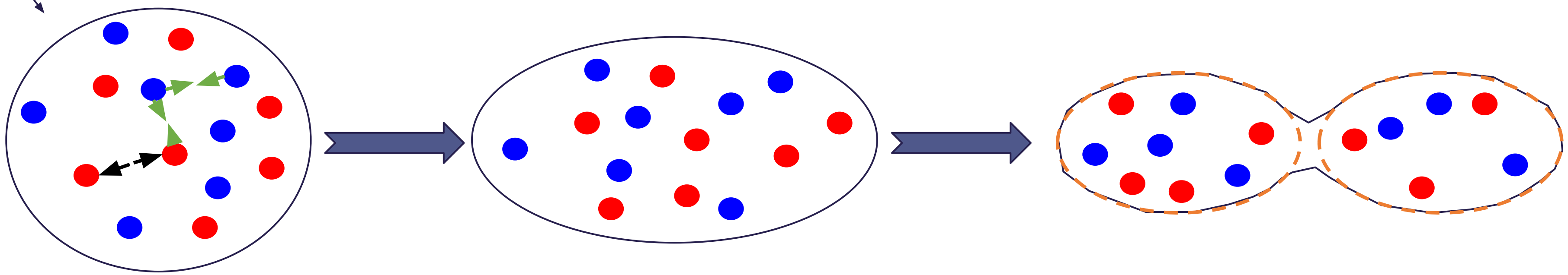
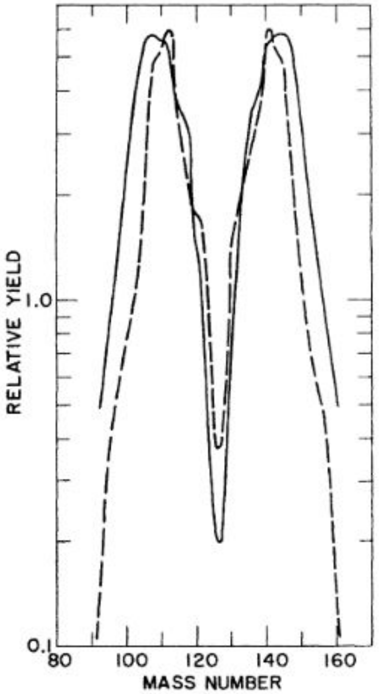


The competition on the **attractive nuclear force** and the **repulsive Coulomb interaction** make a **nucleus (Z,A,E*) deform** and **break into 2 fragments**





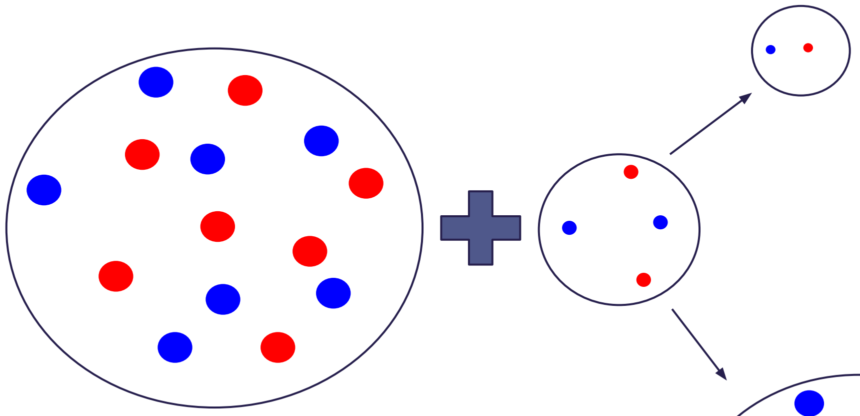
^{252}Cf (spontaneous fission)

Exit channel:

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

[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

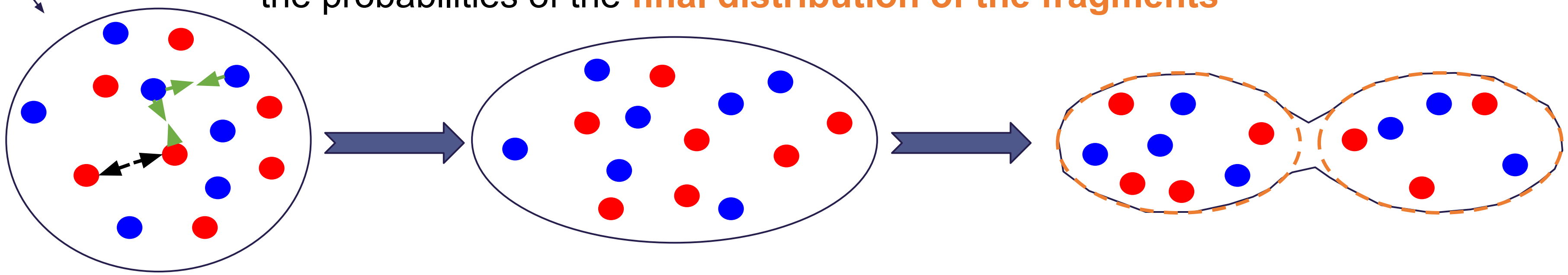
Transfer-induced fission: Entrance and exit channel

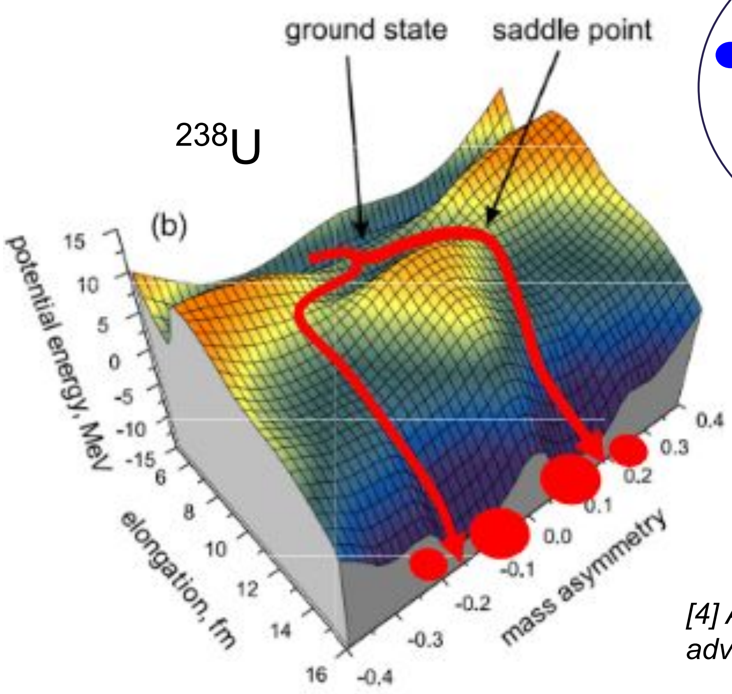


We can calculate the **energy of the system** for a **given deformation (q)** value (quadrupole, octupole…)

The **Potential Energy Surface (PES)** shows the configuration of the nucleus from the ground state to the **breakup point (scission)**

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





<u>Exit channel</u>:

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), …)

[4] Andreyev, A. N., Nishio, K., & Schmidt, K. H. (2017). Nuclear fission: a review of experimental advances and phenomenology. Reports on Progress in Physics, 81(1), 016301.

Region of interest

^{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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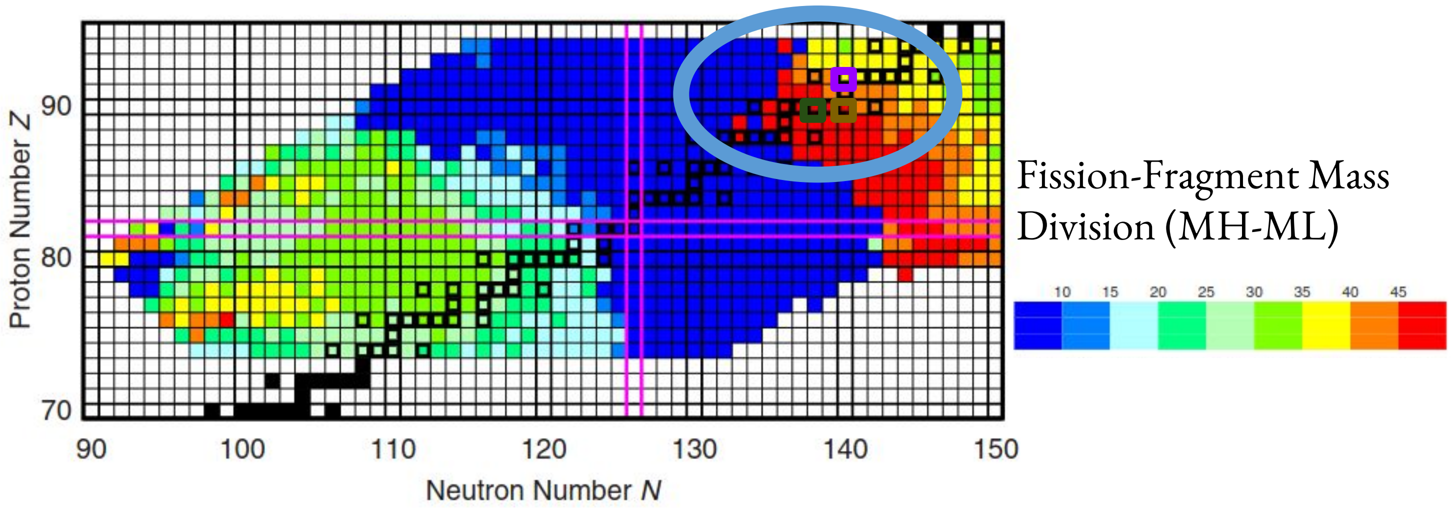
- Access a region where there is a **transition from symmetric to asymmetric** fission.



[5] 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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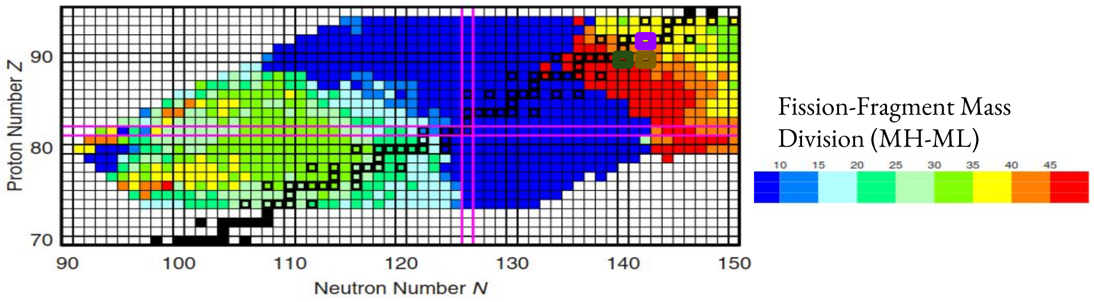
- Access a region where there is a transition from symmetric to asymmetric fission.
- Study the effect of the **shell-closure at octupole deformation**
  - Shown to **drive the asymmetric** fission modes



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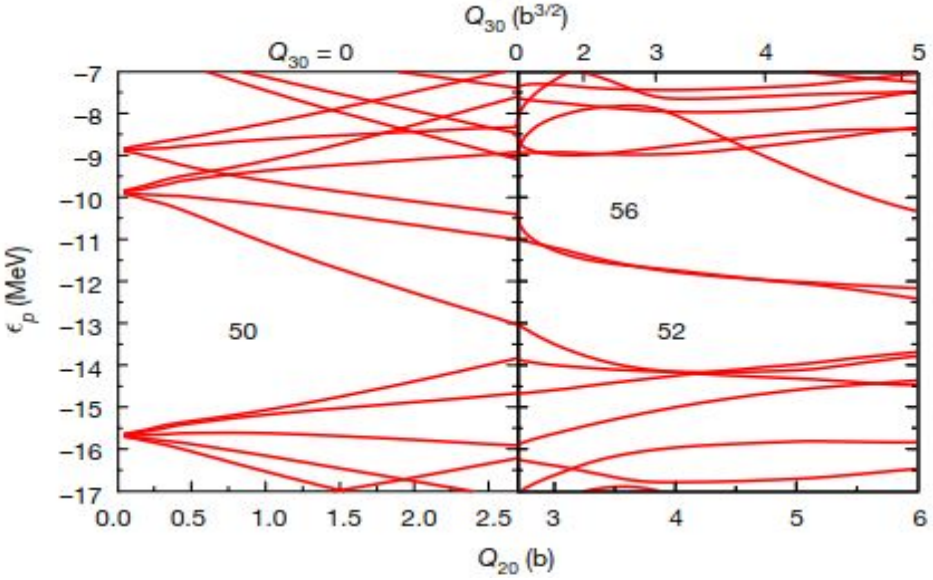

[6] Scamps, G., & Simenel, C. (2018). Impact of pear-shaped fission fragments on mass-asymmetric fission in actinides. Nature, 564(7736), 382-385.

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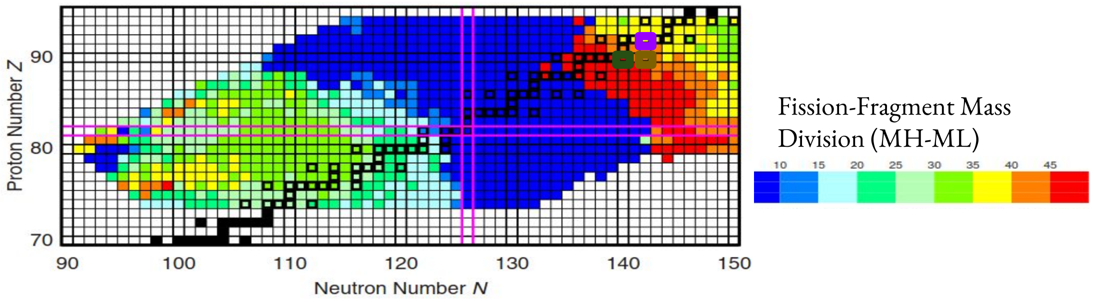
Produce fissioning systems through fusion (^{244}Cm) and transfer reactions (10+ systems like ^{234}U, ^{230}Th, ^{238}Pu, …) :

- Access a region where there is a transition from symmetric to asymmetric fission.
- 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**



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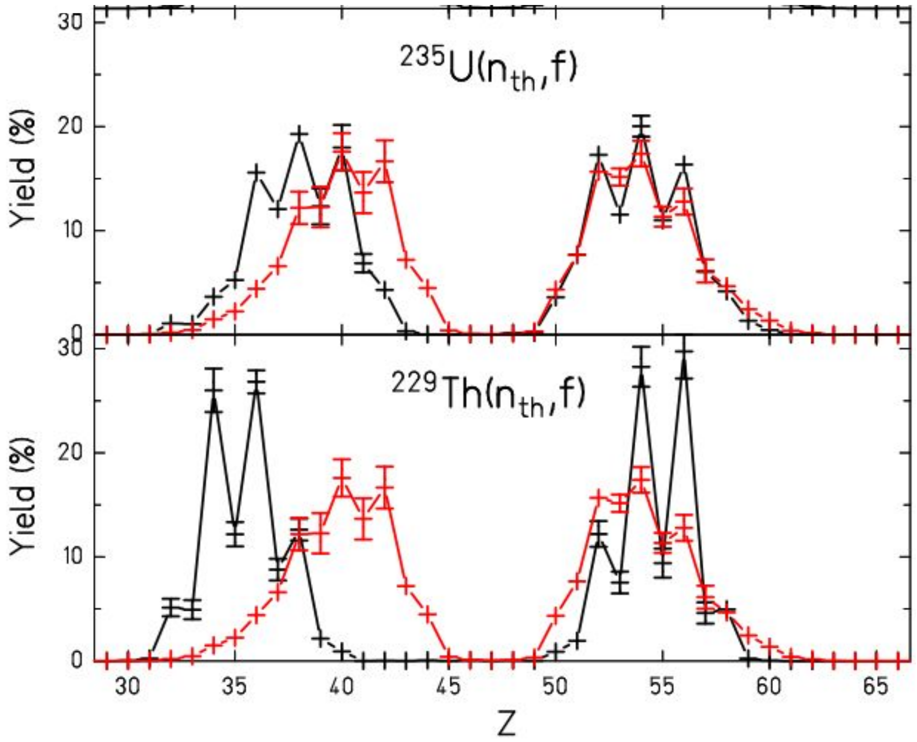
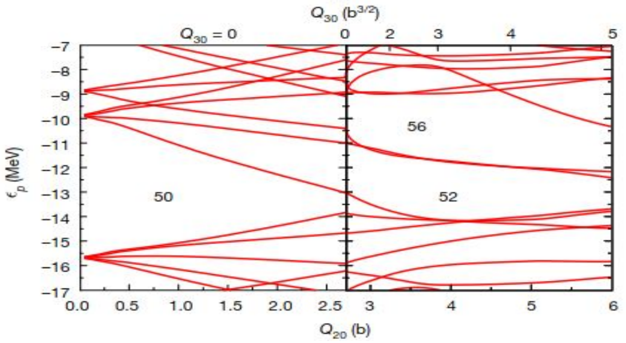


Red: Fission fragment yield of ^{239}Pu (n_{th},f)

[1] 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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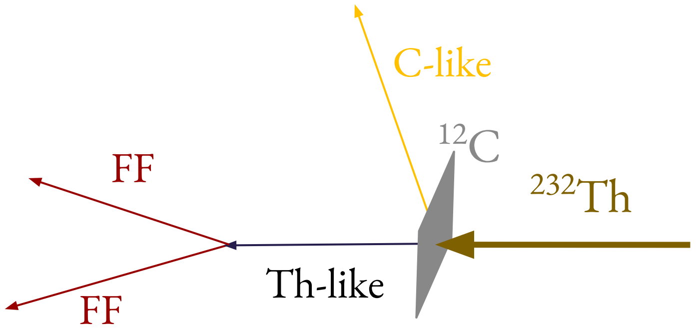
Experimental setup: VAMOS ++

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



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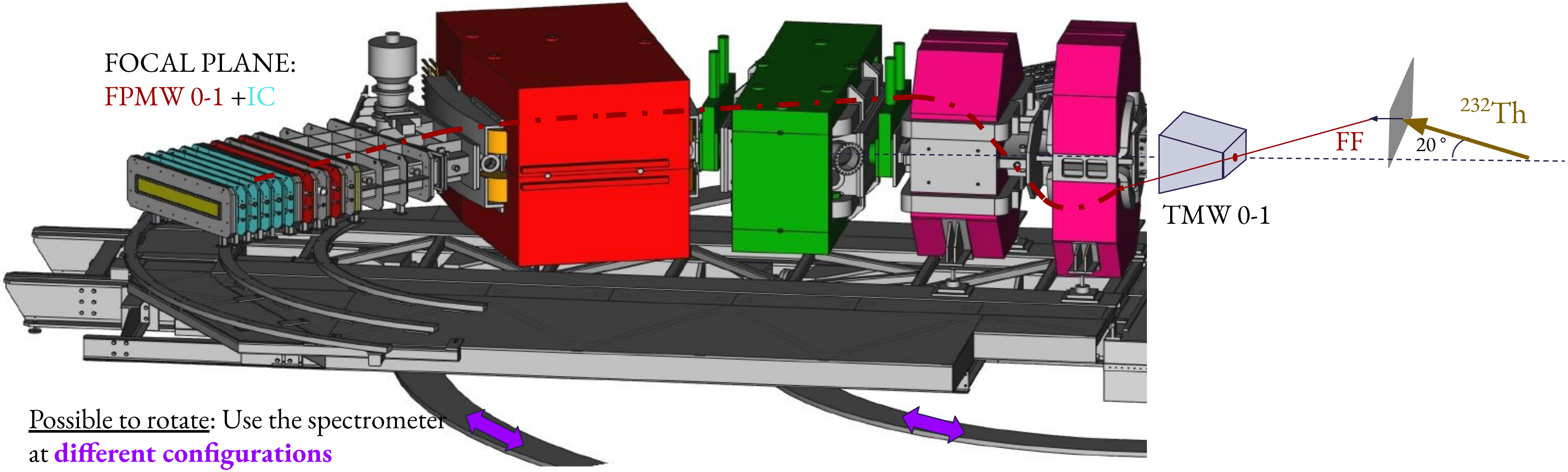
The **mass of the fragments is high** for good resolution through a Energy vs Time-of-Flight (ToF) identification
Use a **magnetic spectrometer** => mass **resolution** depends on magnetic rigidity (Bϱ) an ToF resolution

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



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

Bϱ = p/q →Unique for one nucleus of a given velocity and charge state (q)

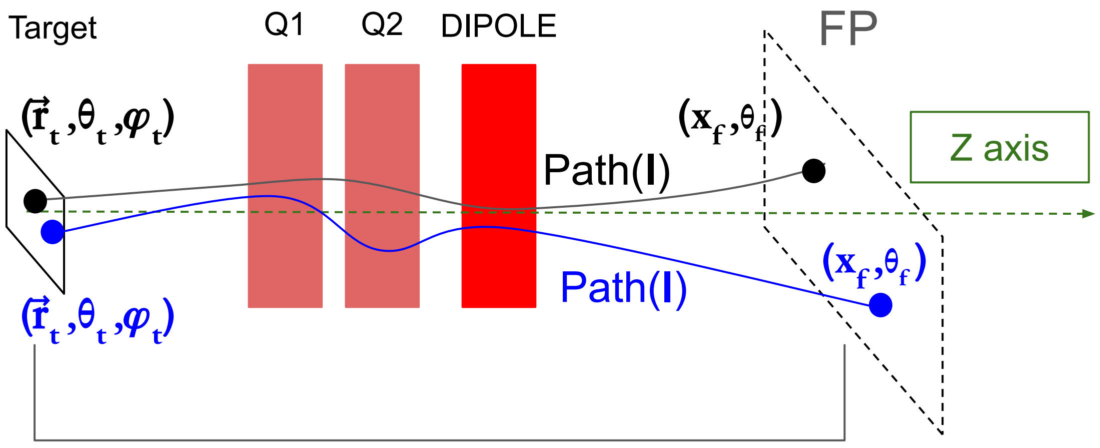
Experimental setup: VAMOS++

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)

[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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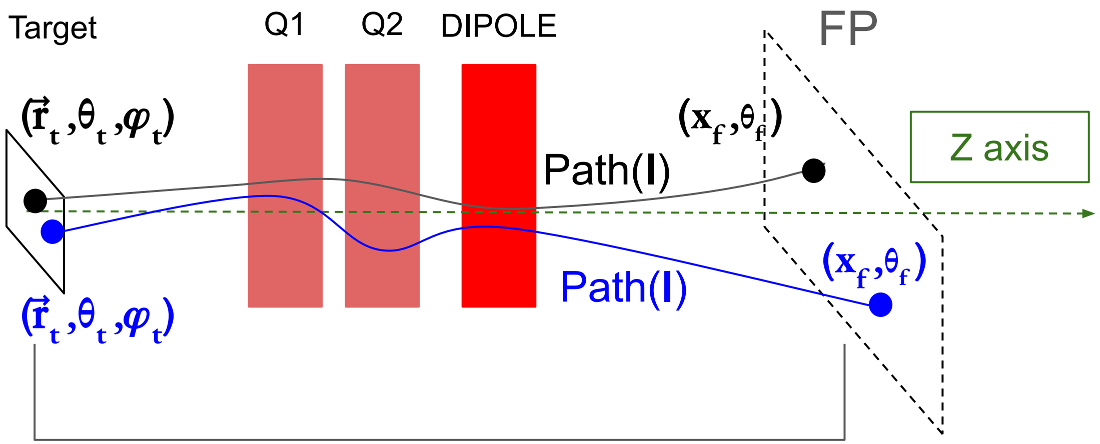


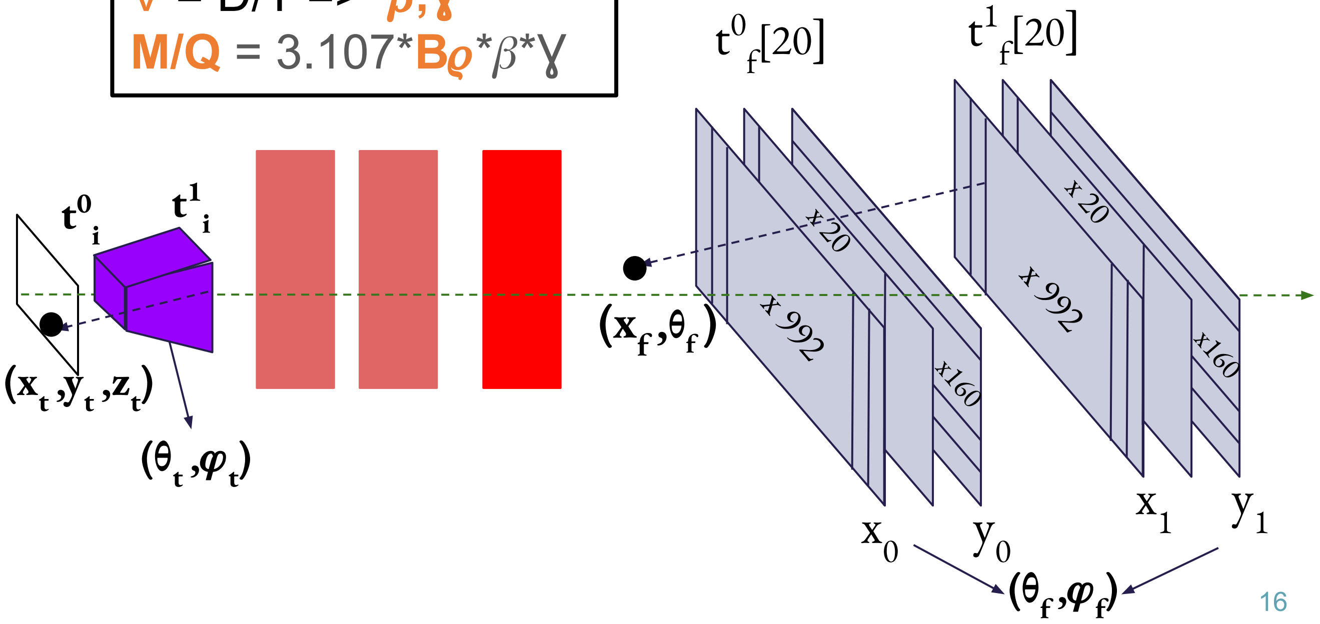
Simulation distance: 7.6 m

Experimentally

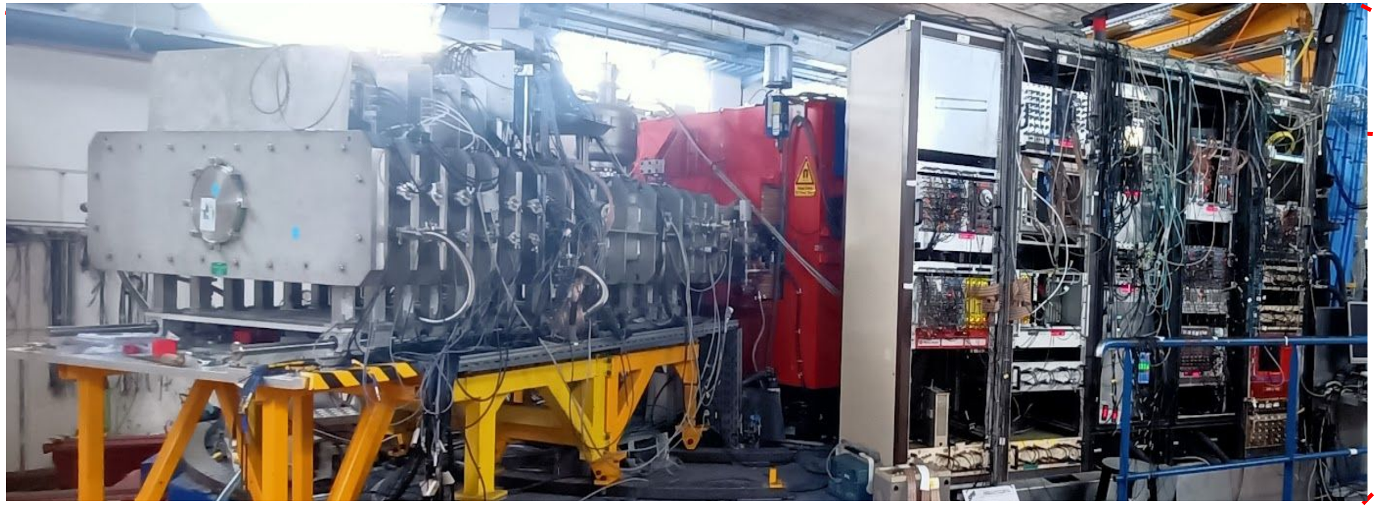
A pair of Multi-Wire Proportional counters (MWPC) at the target determine the **entrance coordinates** and **start time** (t_i)
A pair of MWPCs at the exit determine the **focal plane coordinates** and **20 stop times** (t_f)

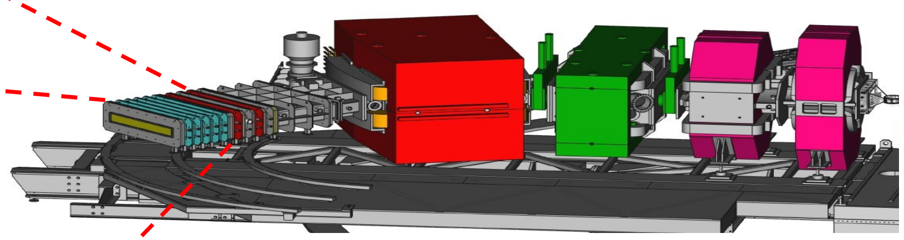
From measured positions, we extract the **Bϱ and l** of a fragment
Combining it with the **ToF (t_f - t_i)**, we get the **velocity and M/Q**:

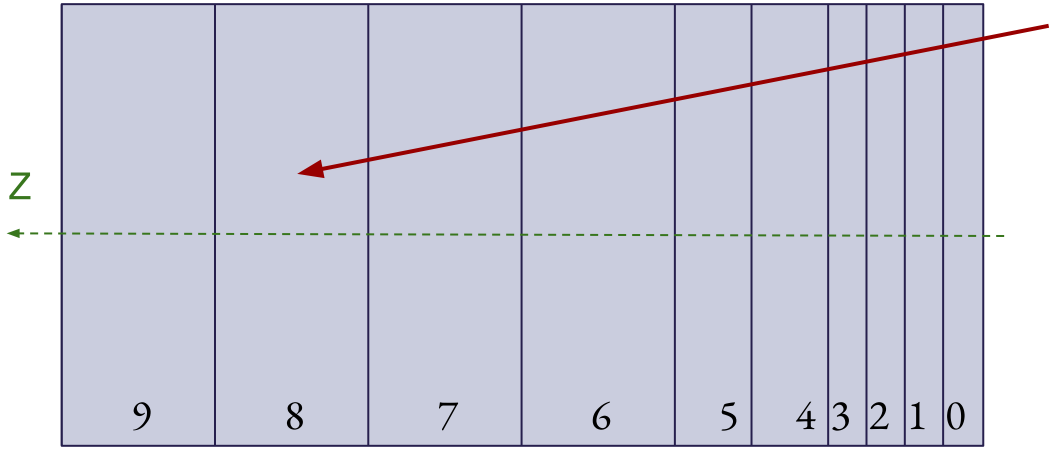
V = D/T => β,γ
M/Q = 3.107***Bϱ***β*γ



Experimental setup: Ionization Chamber (Q)







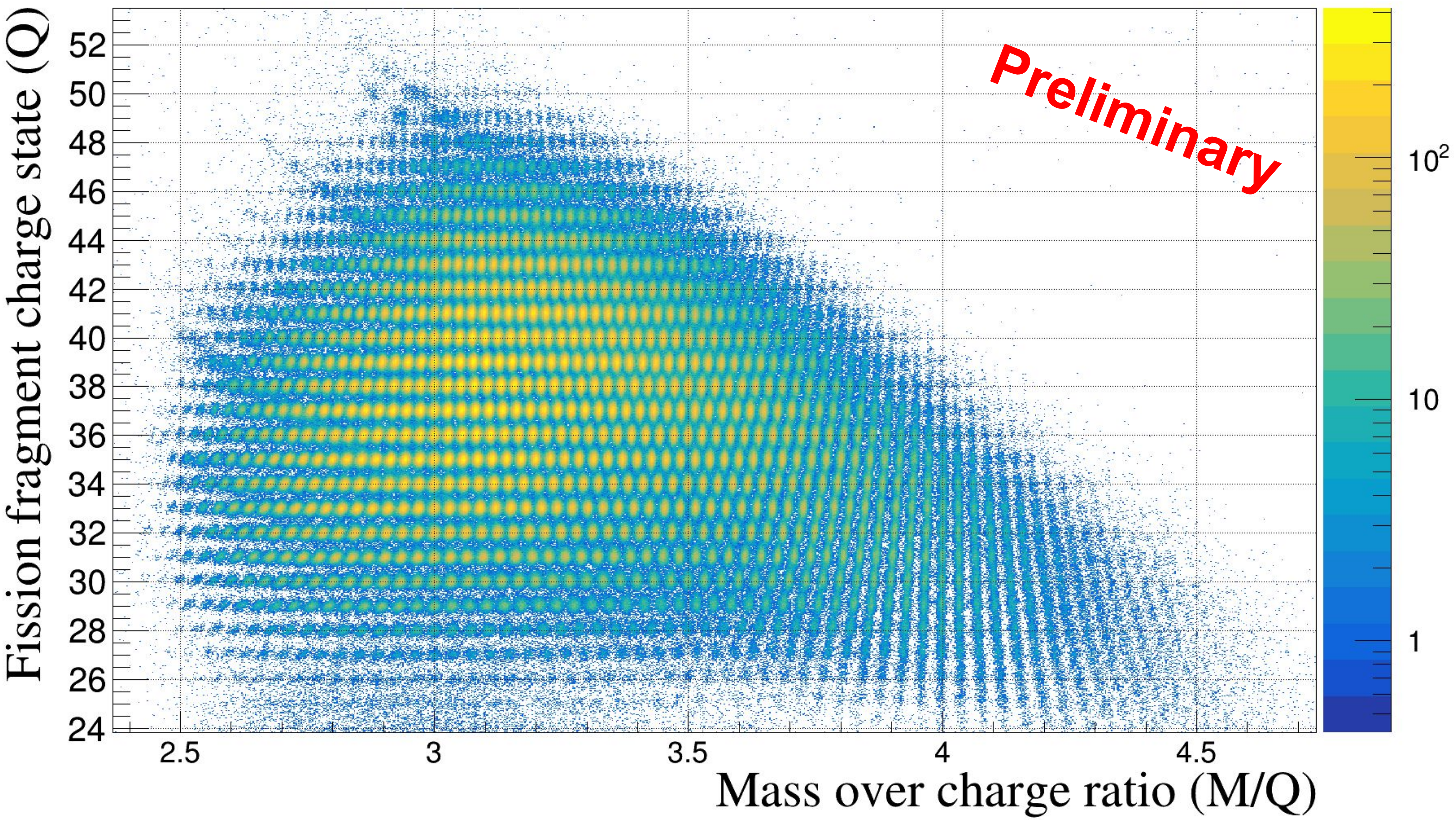
The **kinetic energy (E_{Kin})** of the fragment is proportional to the **mass** and the **velocity (ɣ)**

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

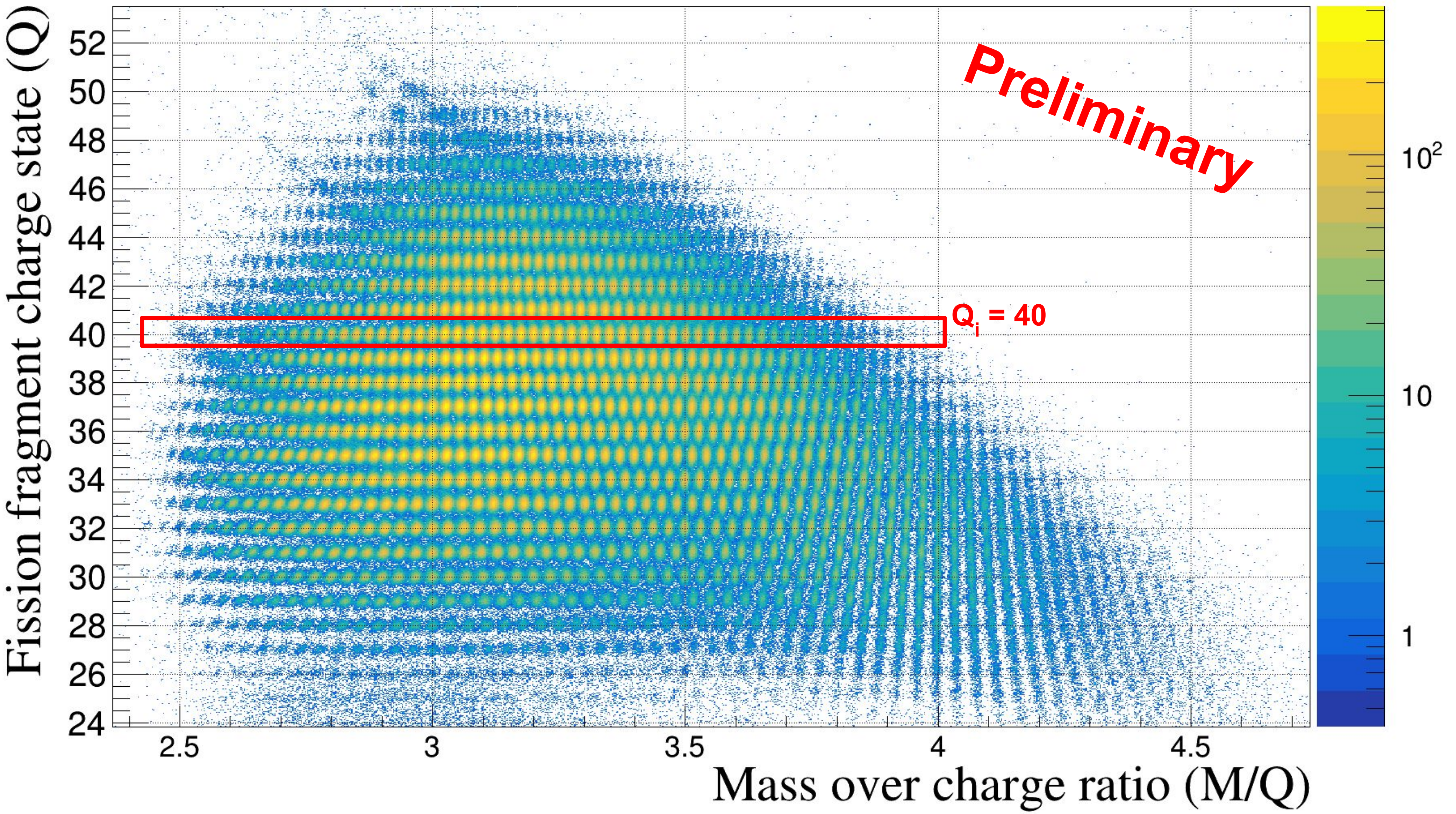
$E_{Kin} = \Sigma a_i * IC_i + b_0$
$M_{IC} = E_{Kin} / (\gamma_{VAMOS} - 1)$

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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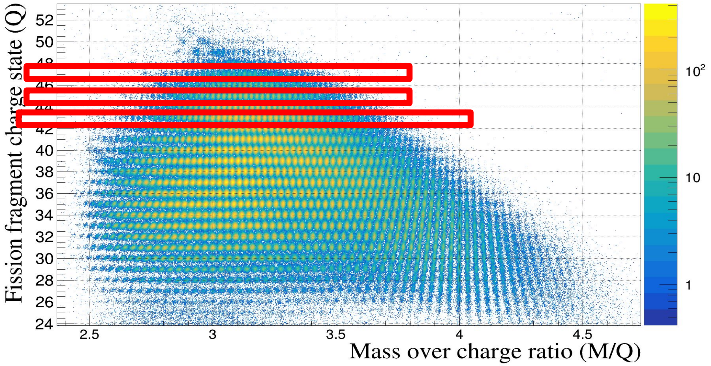
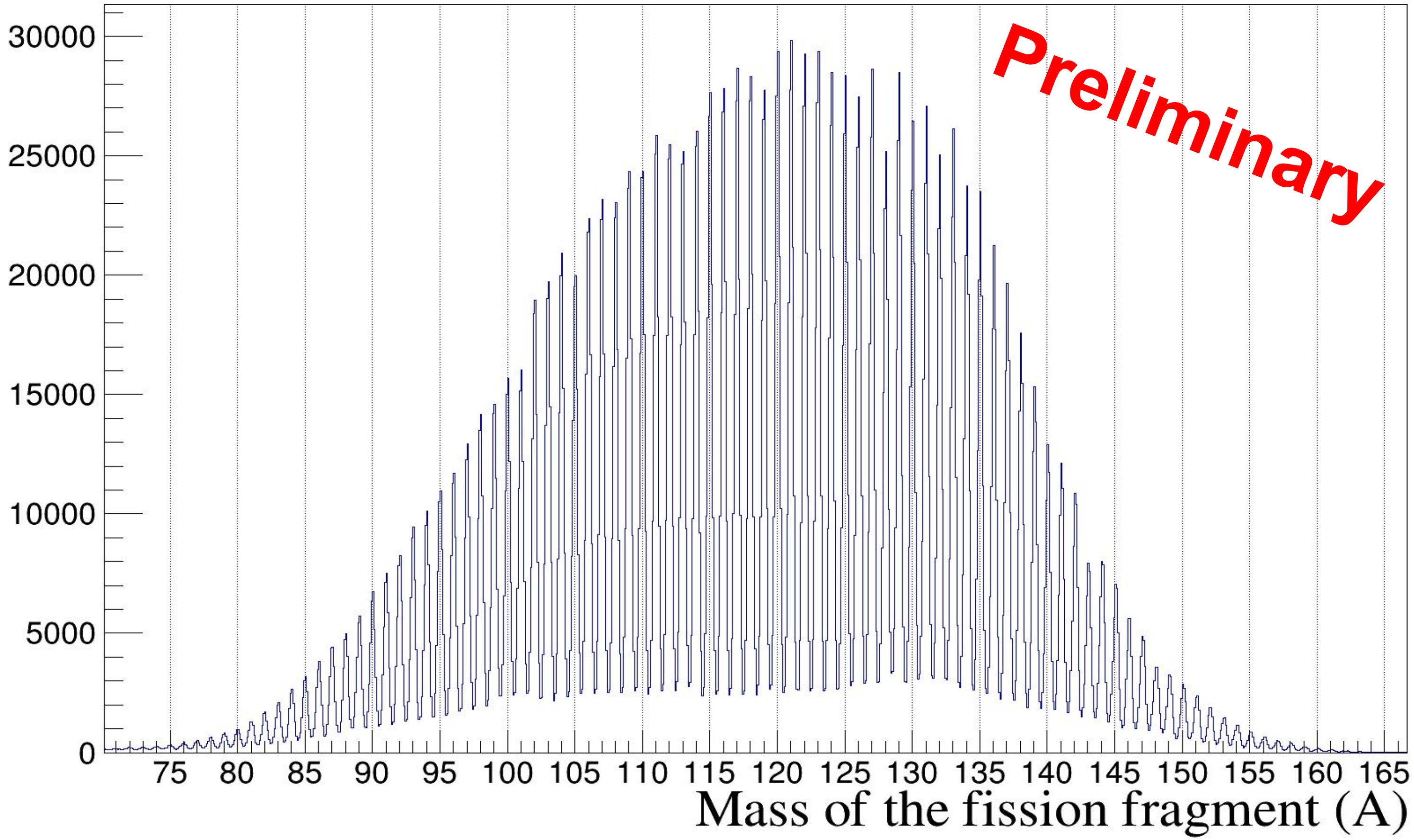


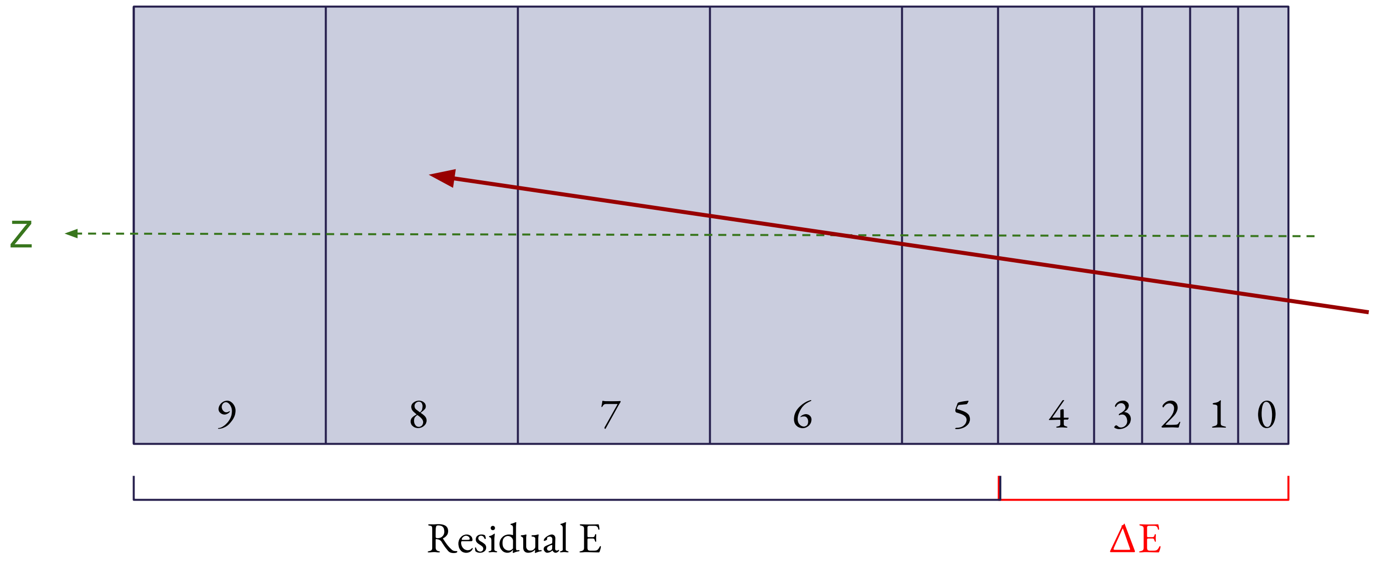
$$M = Q_i * M/Q$$

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



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

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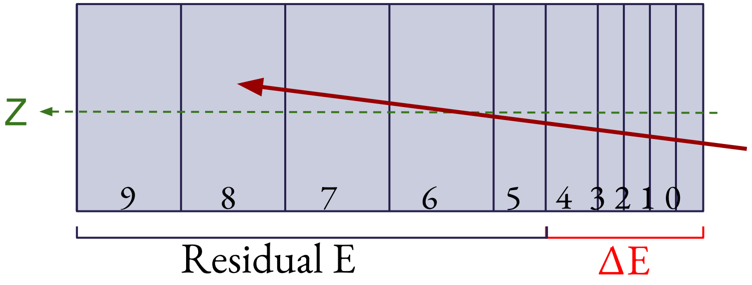

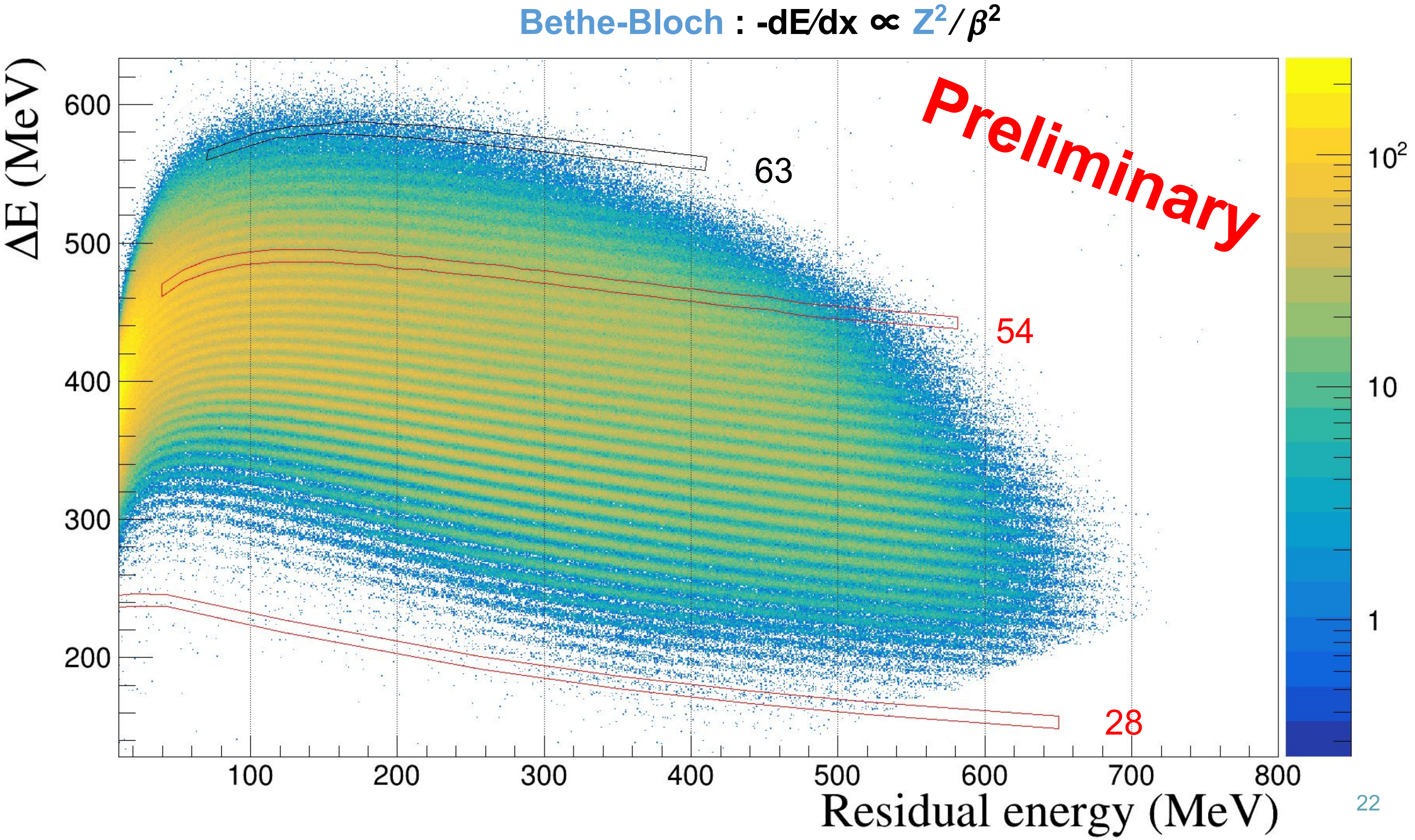

Each **line** corresponds to **one Z**
A resolution of **ΔZ/Z ~ 1/70**

Experimental result: Z

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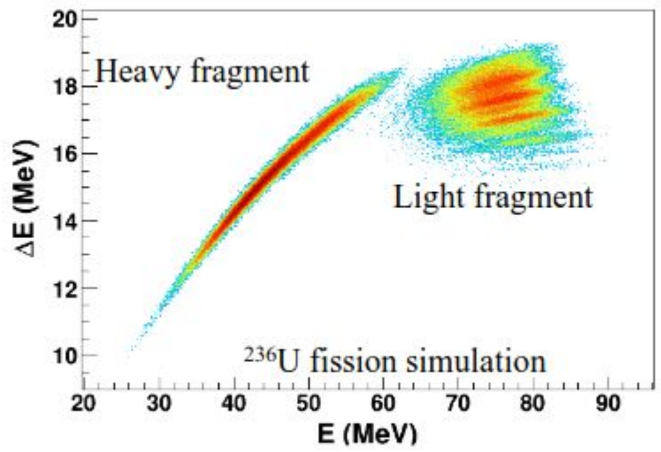
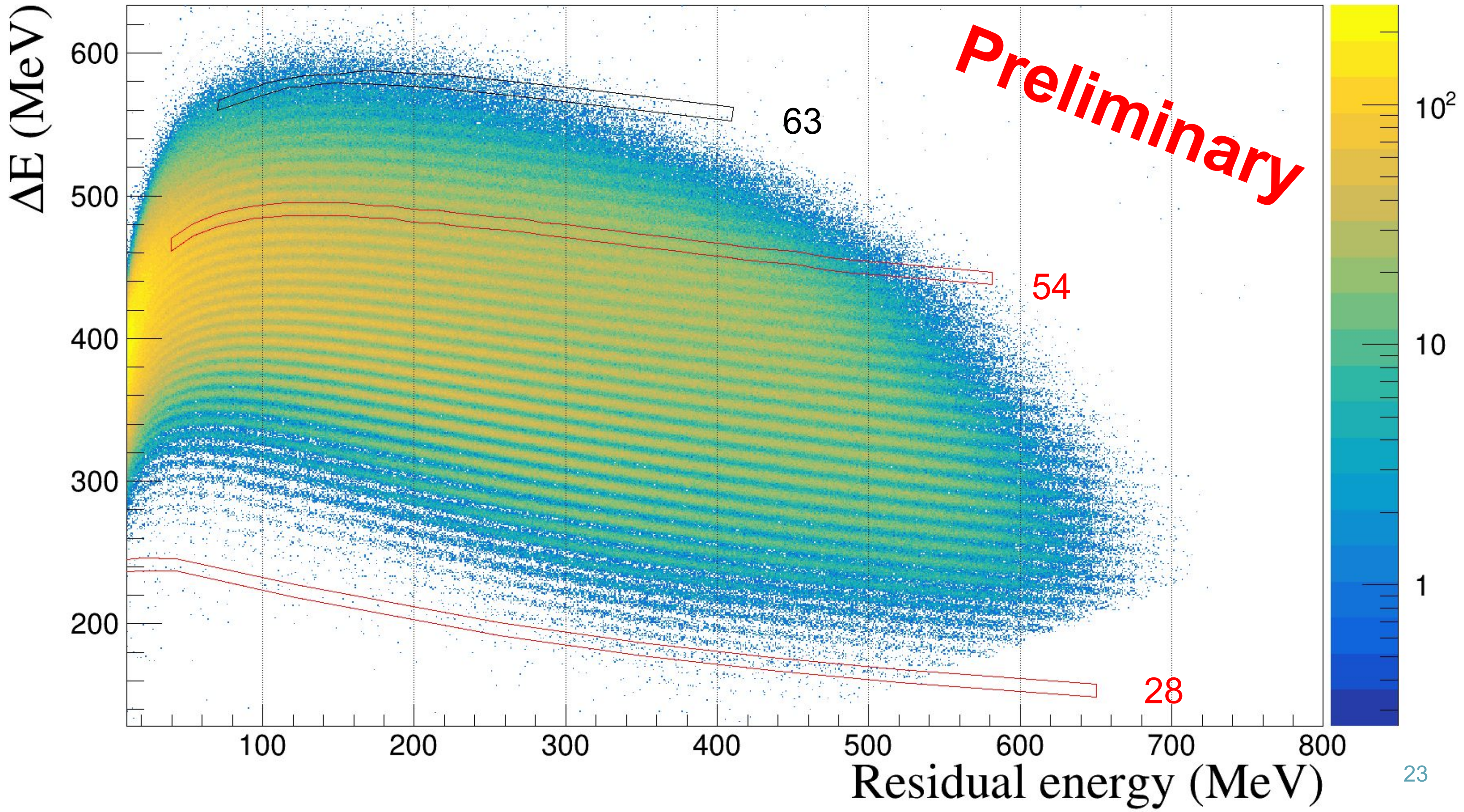
Direct-kinematics

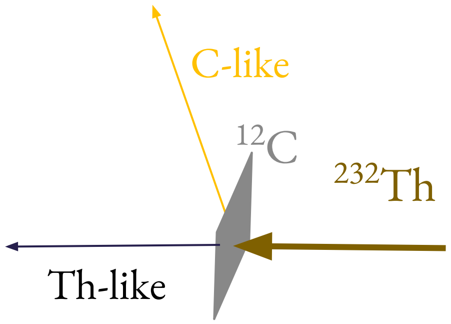


Identify Z from ~26 to ~65
Thanks to inverse-kinematics

Bethe-Bloch : **-dE/dx ∝** Z^2/β^2



Experimental setup



Experimental setup: PISTA

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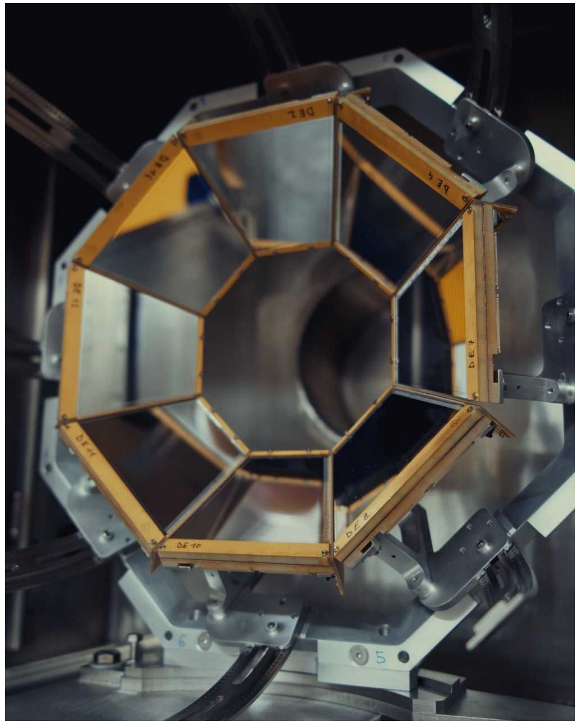
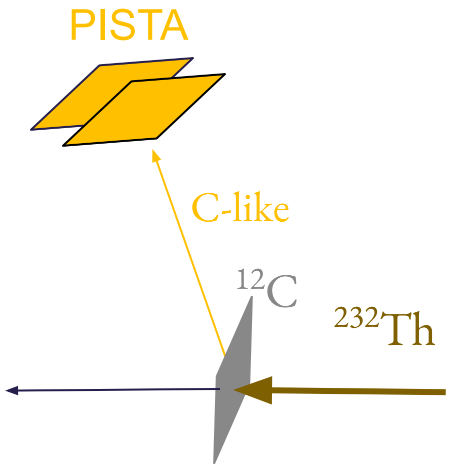
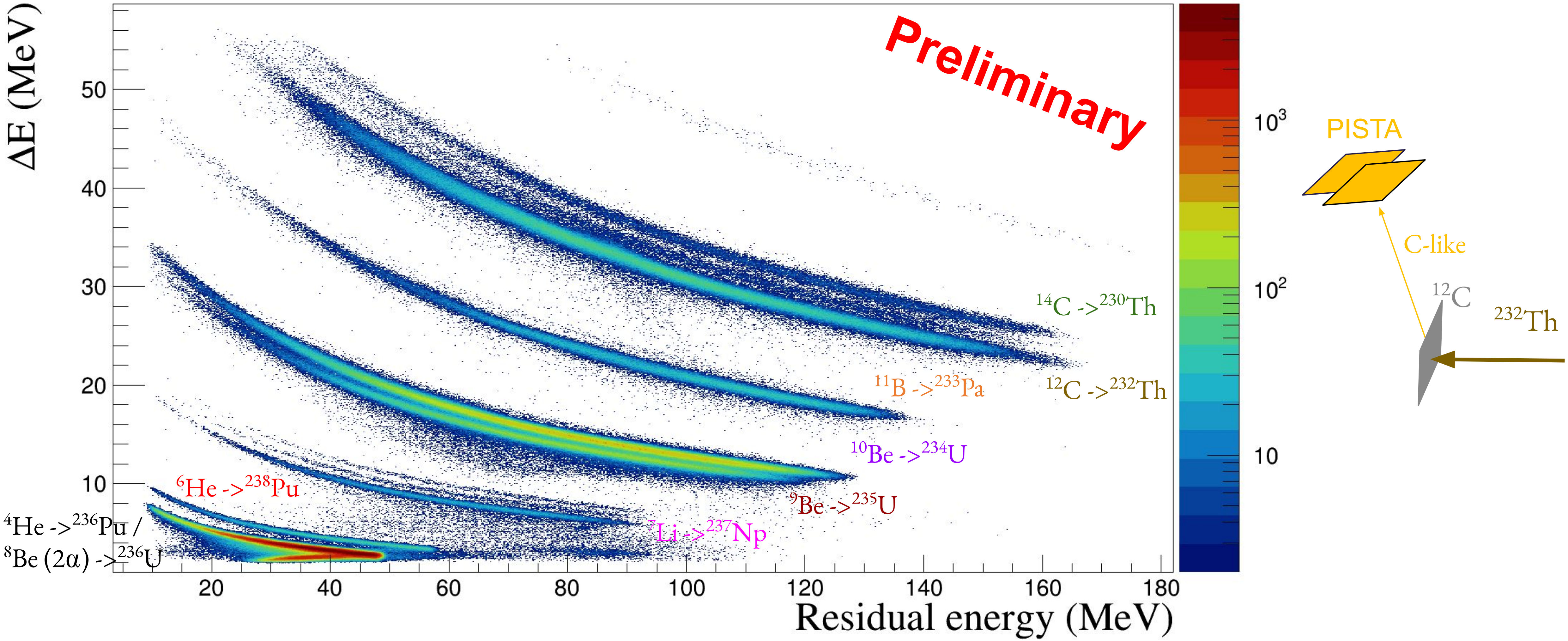




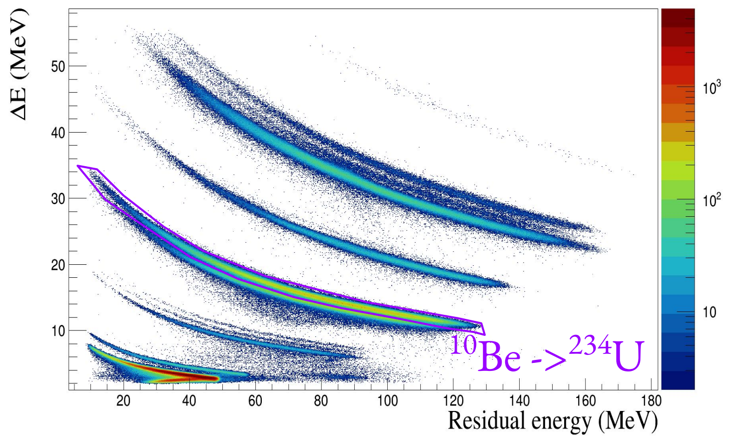
Striped silicon ΔE-E detector
Measure the energy of the target-like nucleus
The ΔE strips (horizontal) allow to get the emission angle:

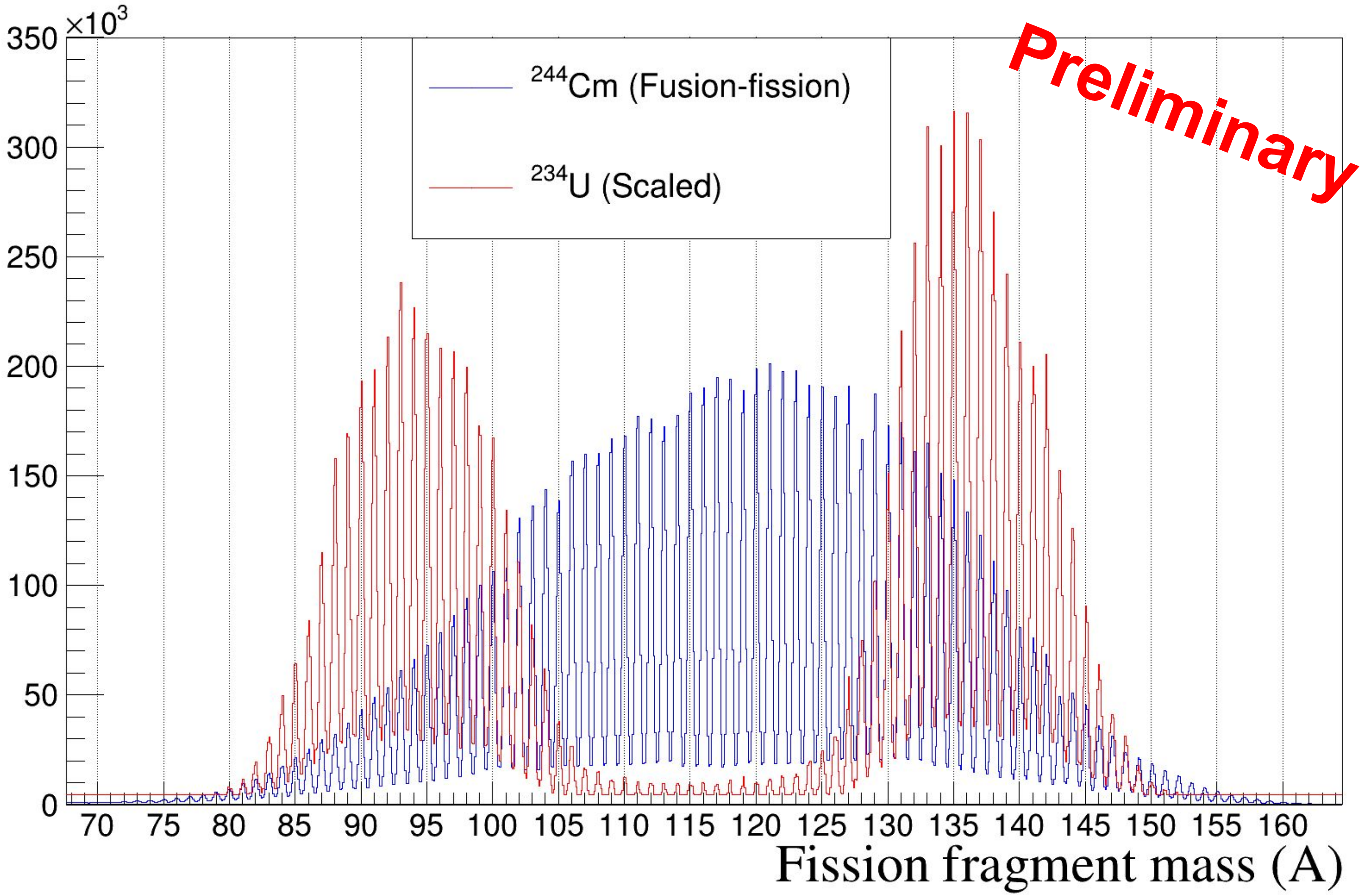
- **Identify** the **fissioning system(Z,A)** and its **excitation energy** for each event

Experimental setup: PISTA



Experimental result: Entrance channel identification

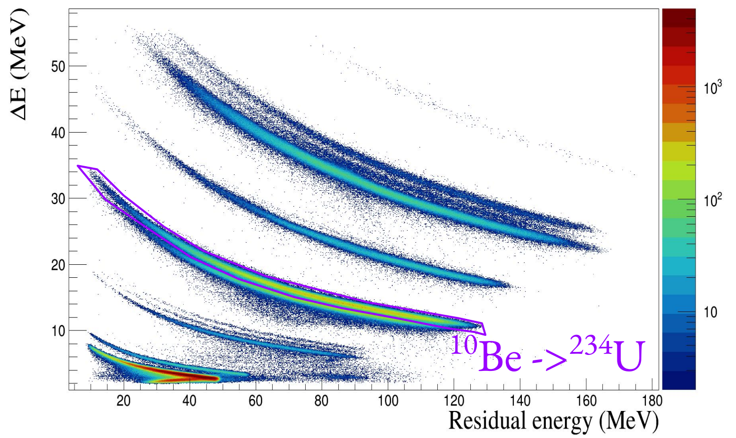


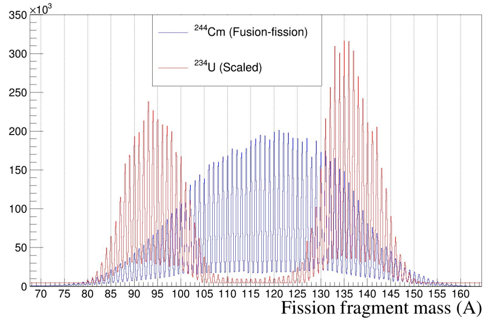


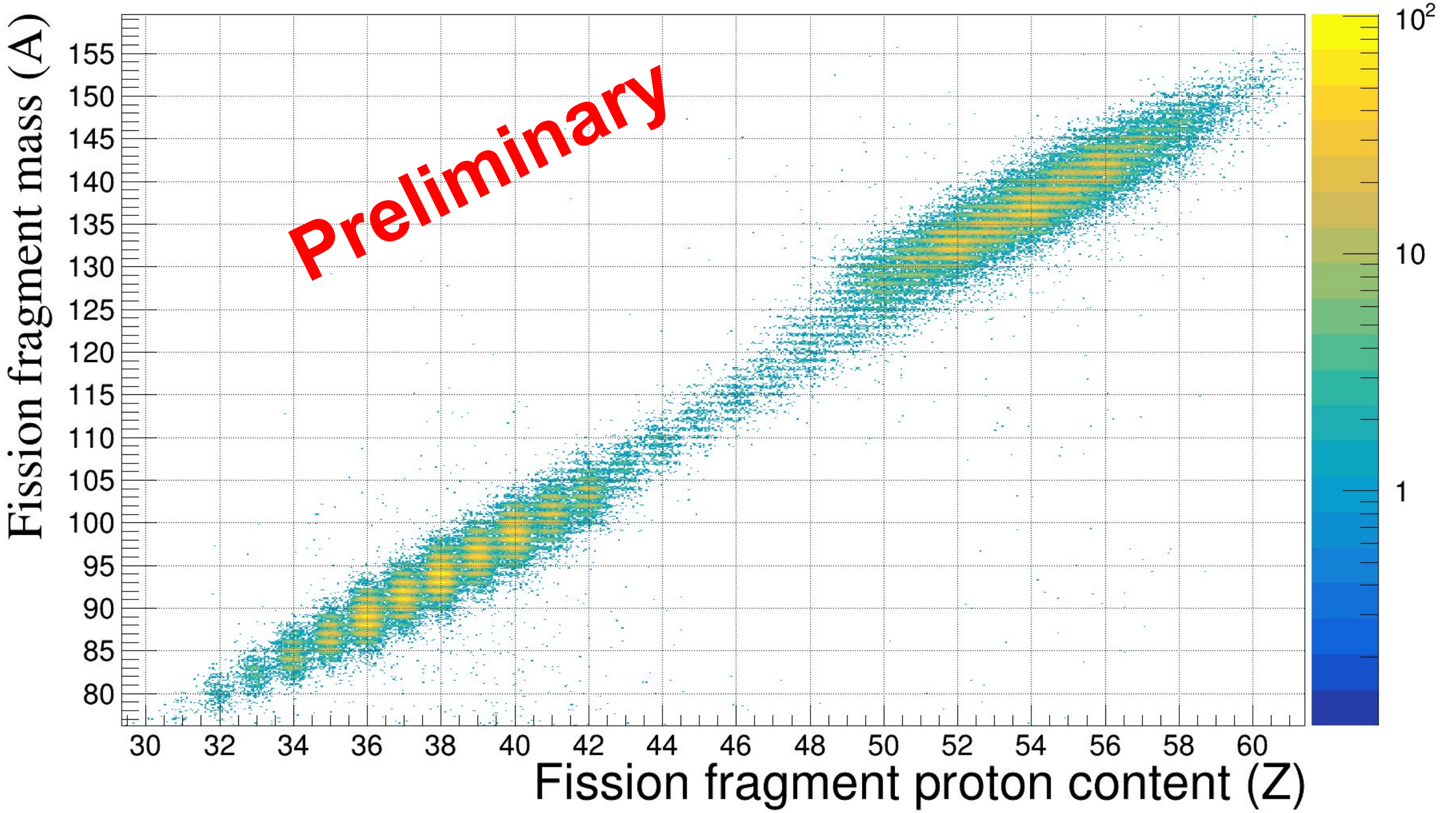
The **highest number** of event come from **fusion-fission** reactions

PISTA allows to select **the fissioning system** of interest

Experimental result: Exit channel identification







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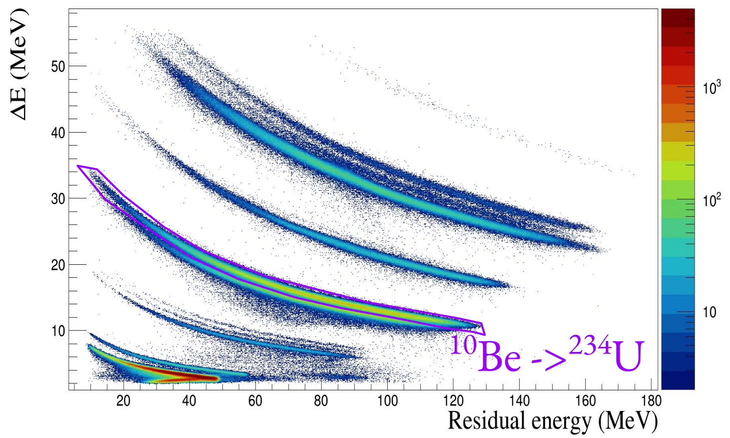
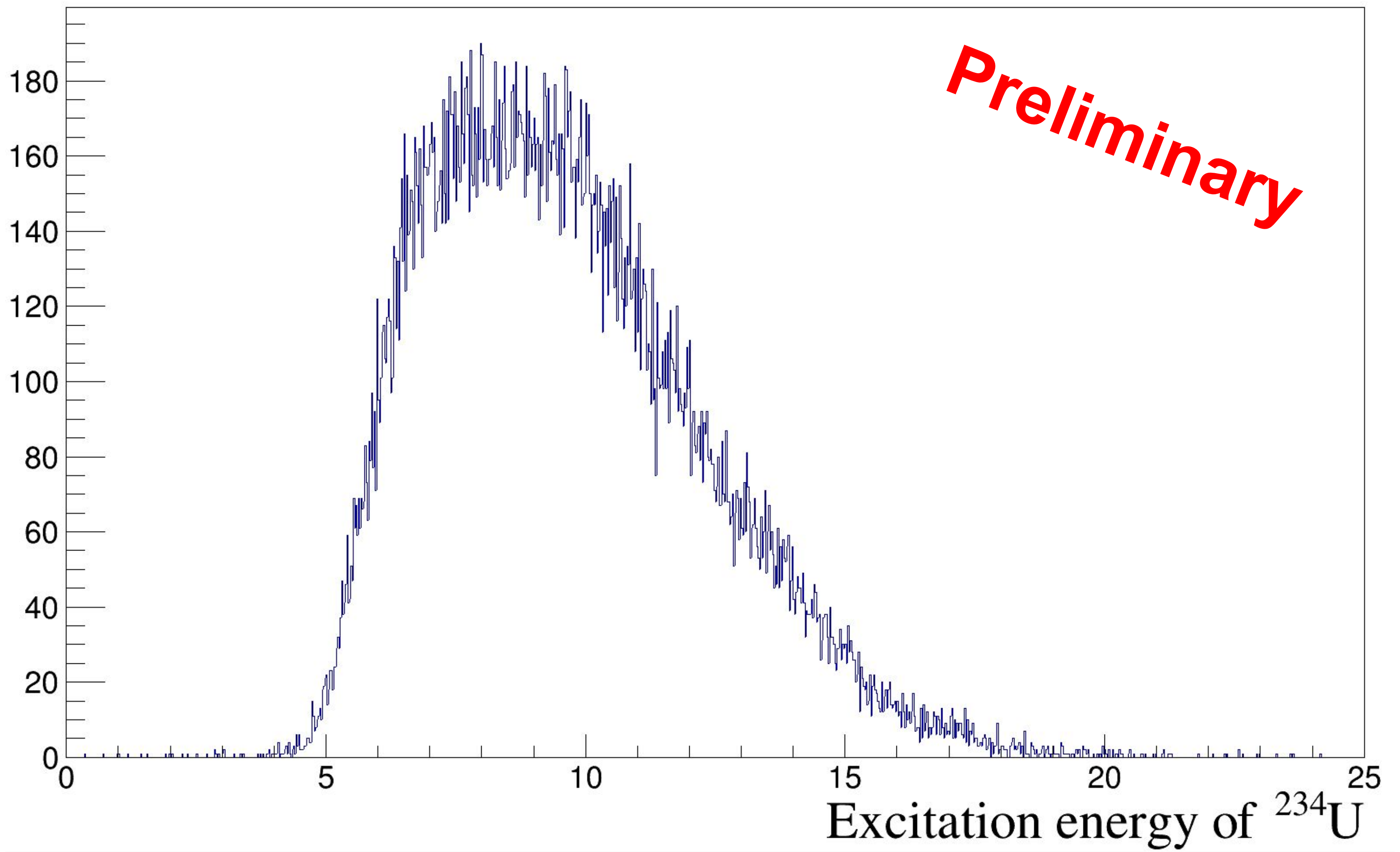
Experimental result: Fissioning system E*





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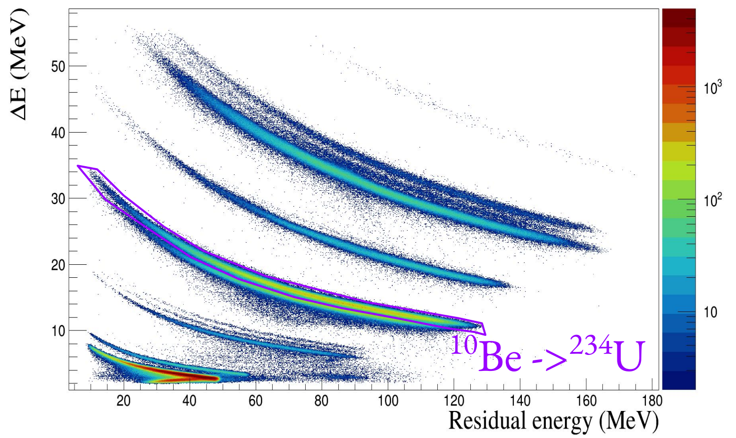
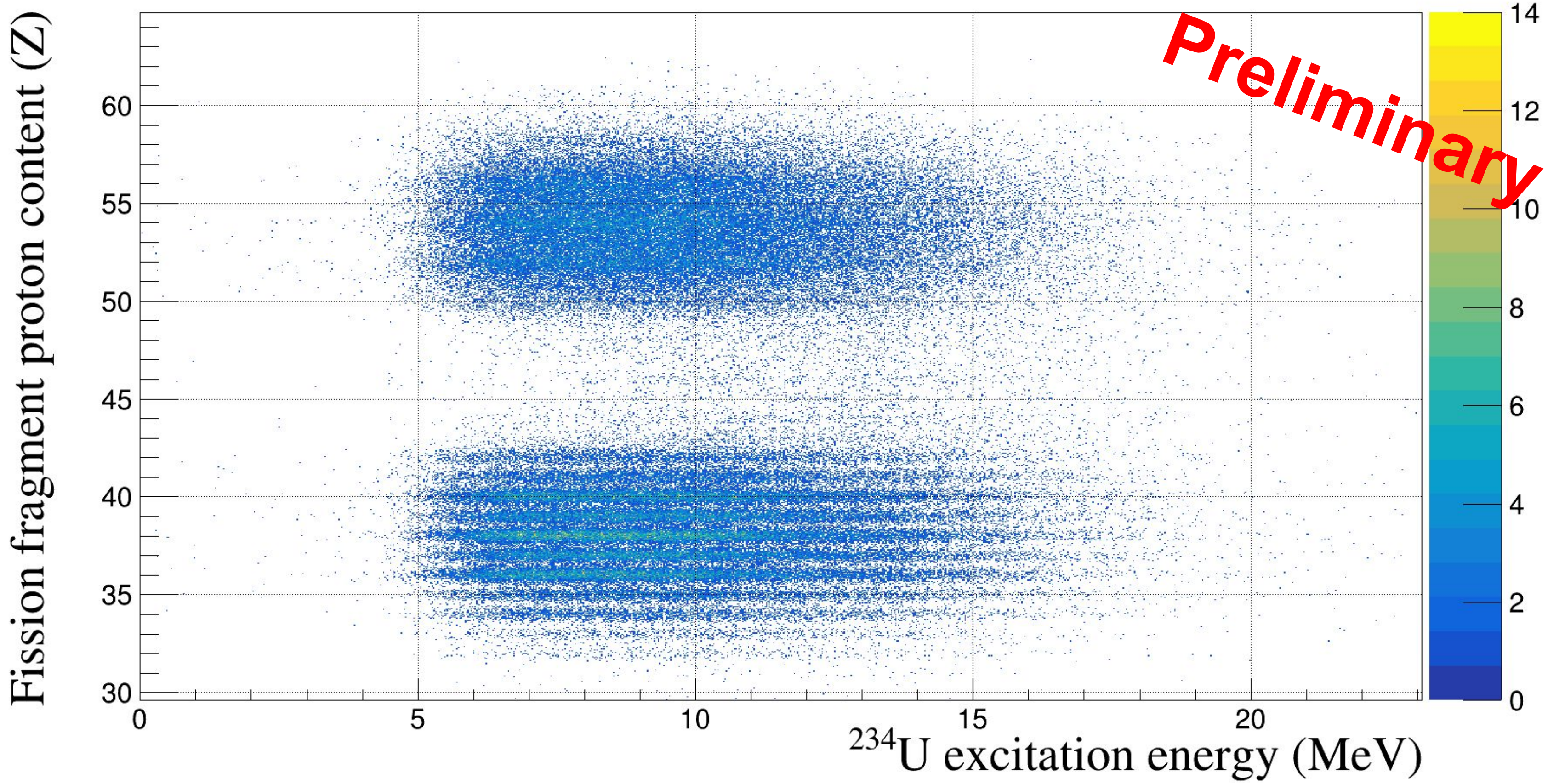
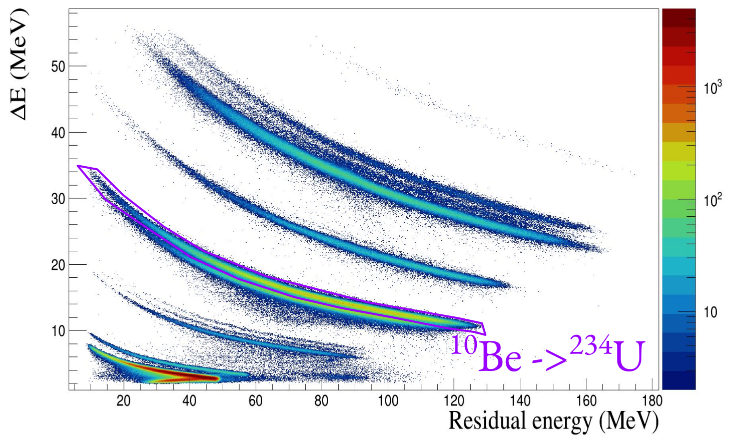


We can see the **evolution** of the distribution as a **function of** the **excitation energy**



Experimental result: Fissioning system E*



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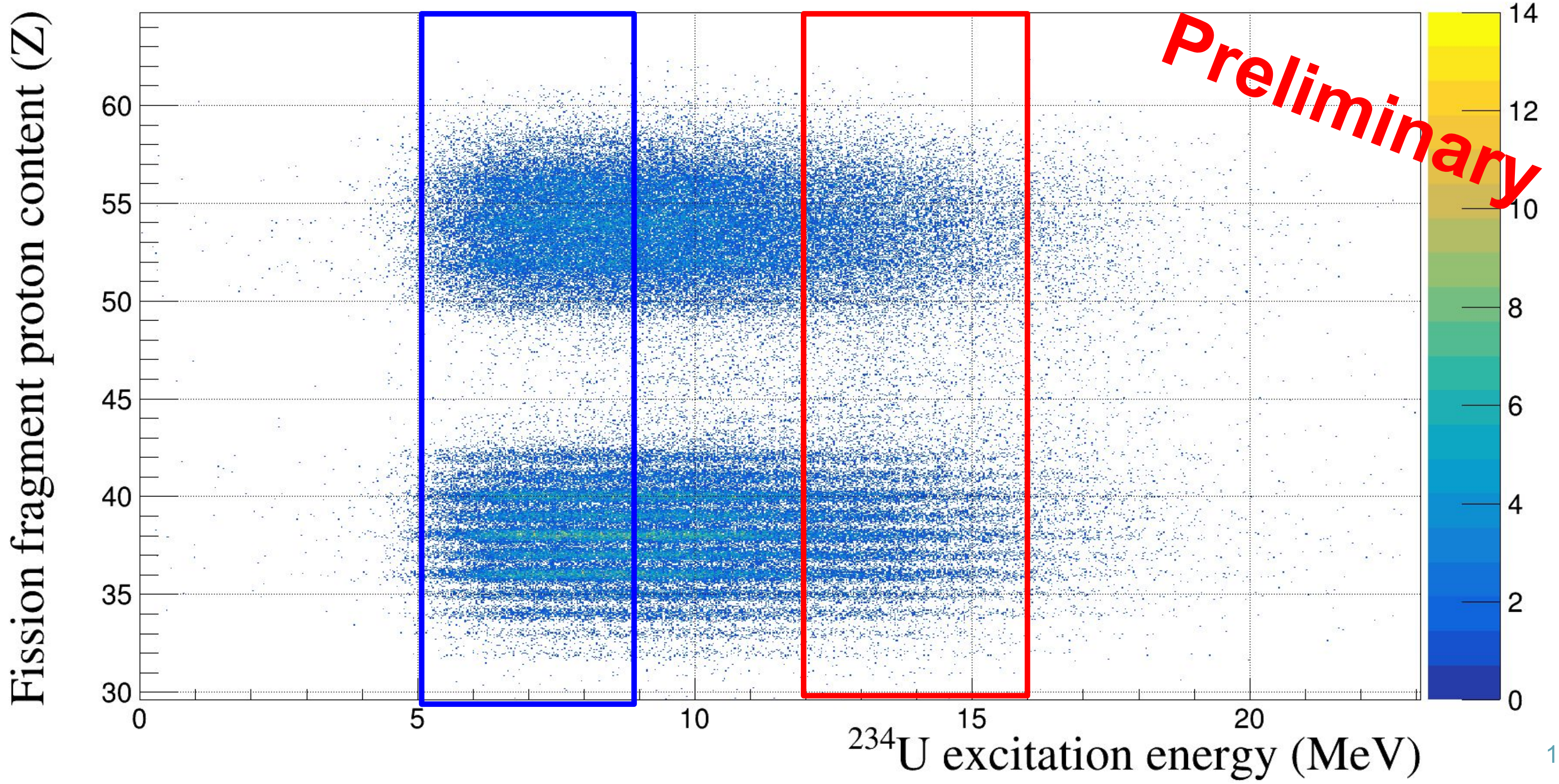

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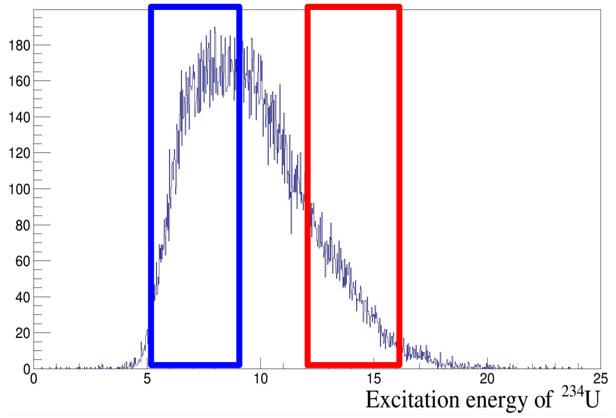
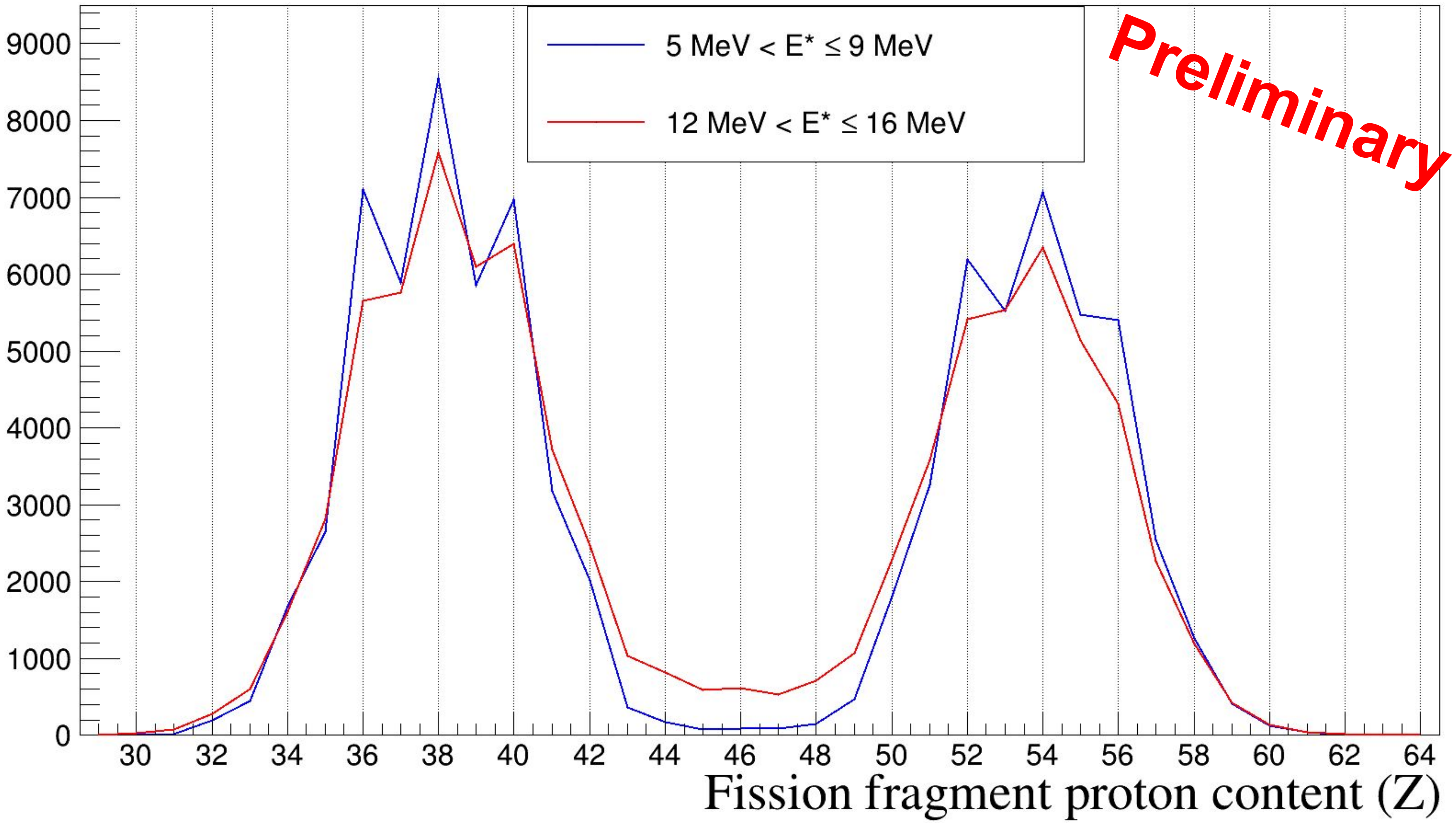


Odd-even staggering effect in the **light** and **heavy** fragment
Less notorious for **higher Ex**

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



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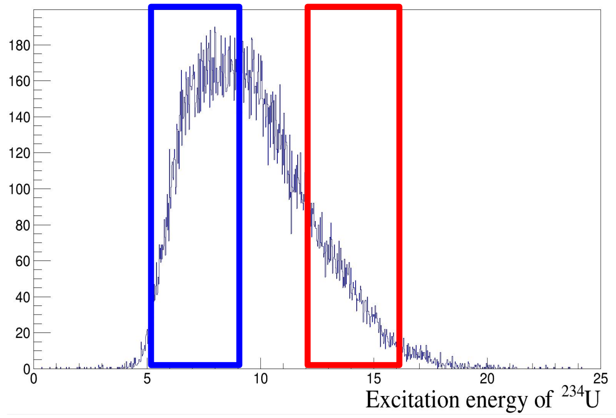
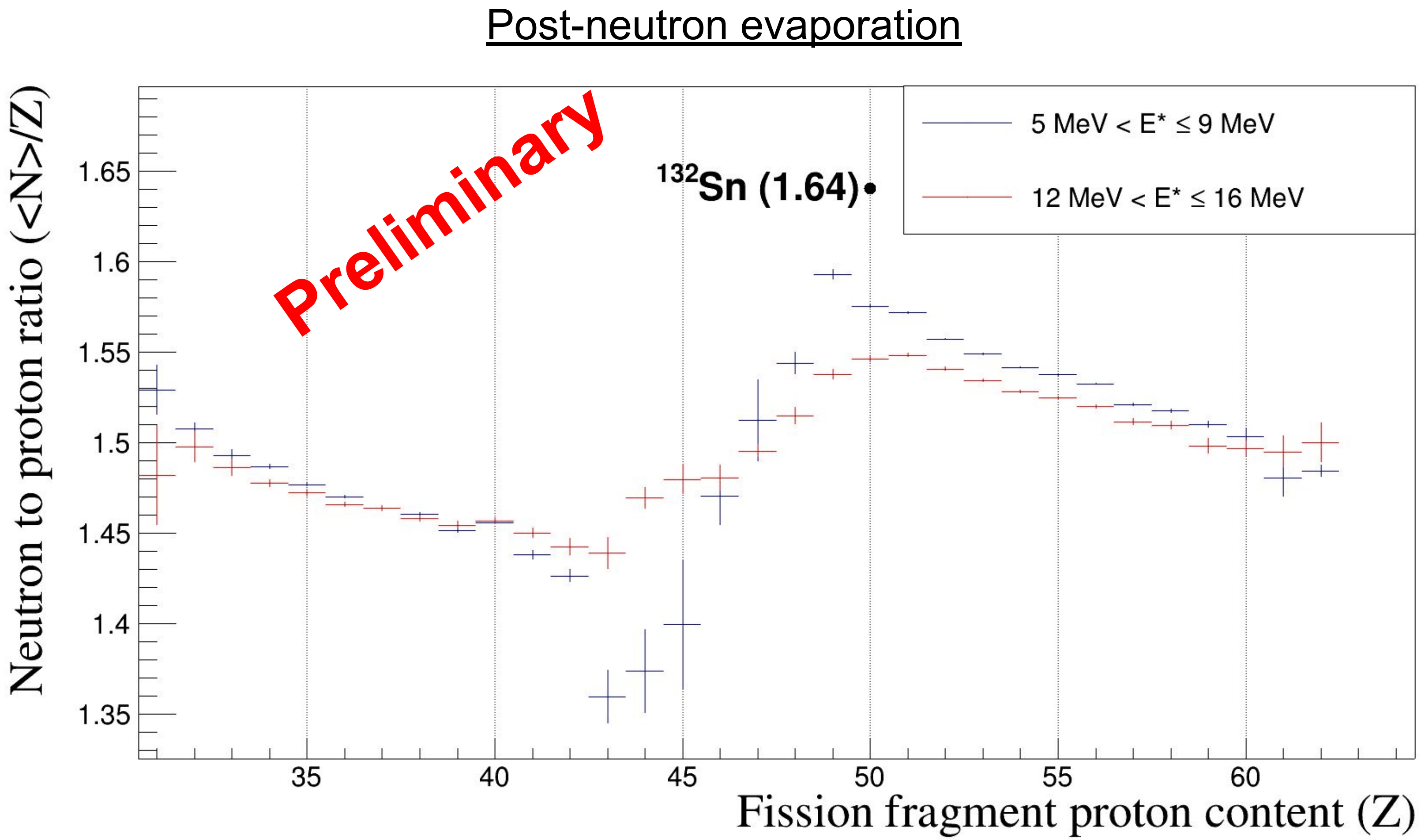


Highest N/Z ratio for Z around **50** (corresponding to ^{132}Sn)

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

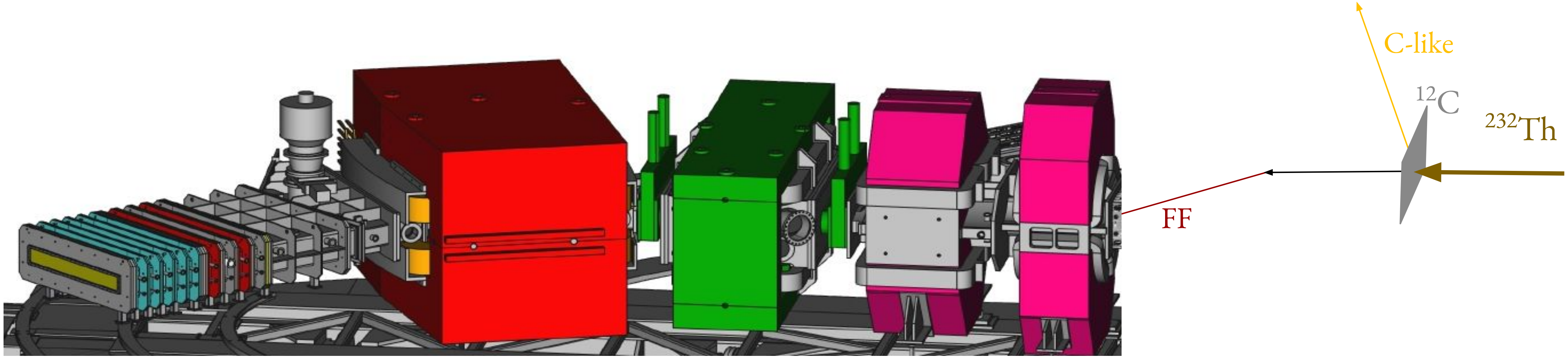


Back-up slides

THANK YOU

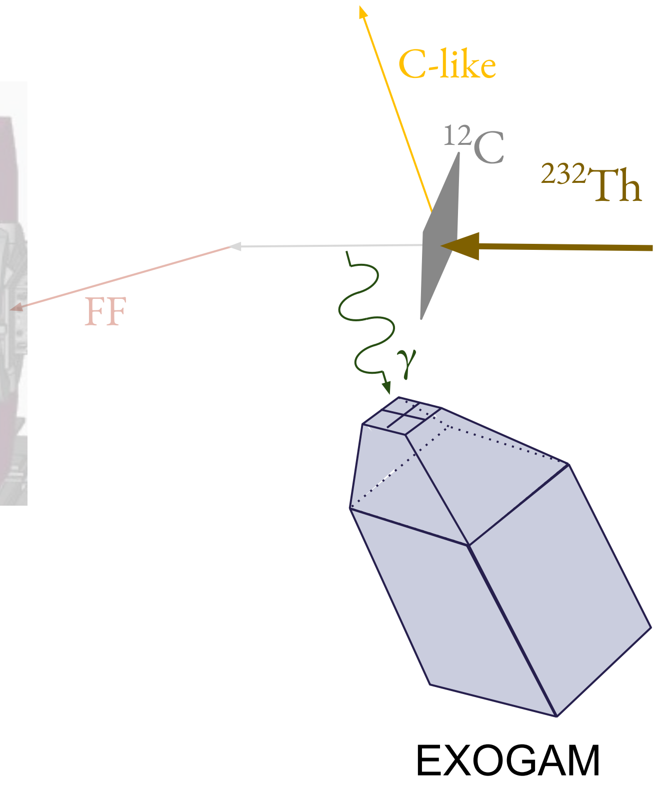
Experimental setup: EXOGAM

How do we know that the Q=40 is correct? And the Z?

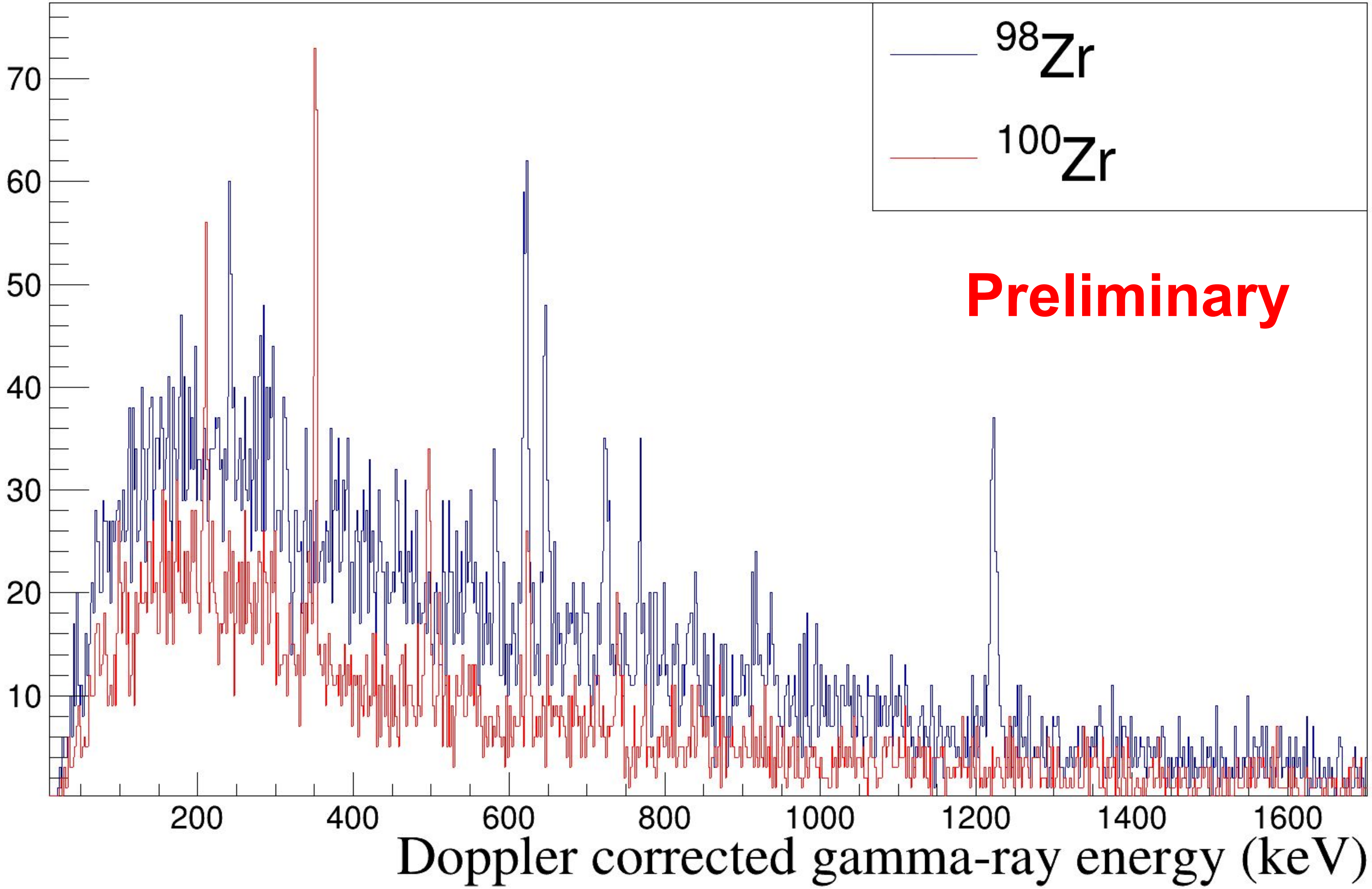


Experimental setup: EXOGAM

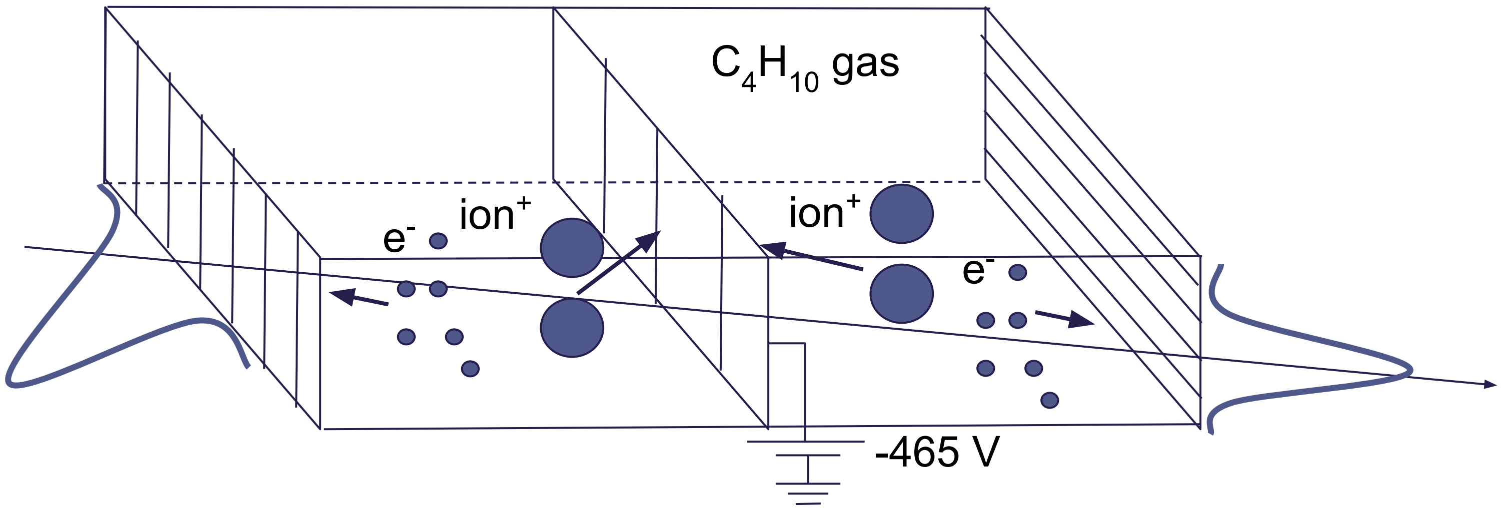
How do we **know** that the **Q=40 is correct?** And the **Z?**
=> **Check the gamma rays** with three HPGe detectors (EXOGAM)



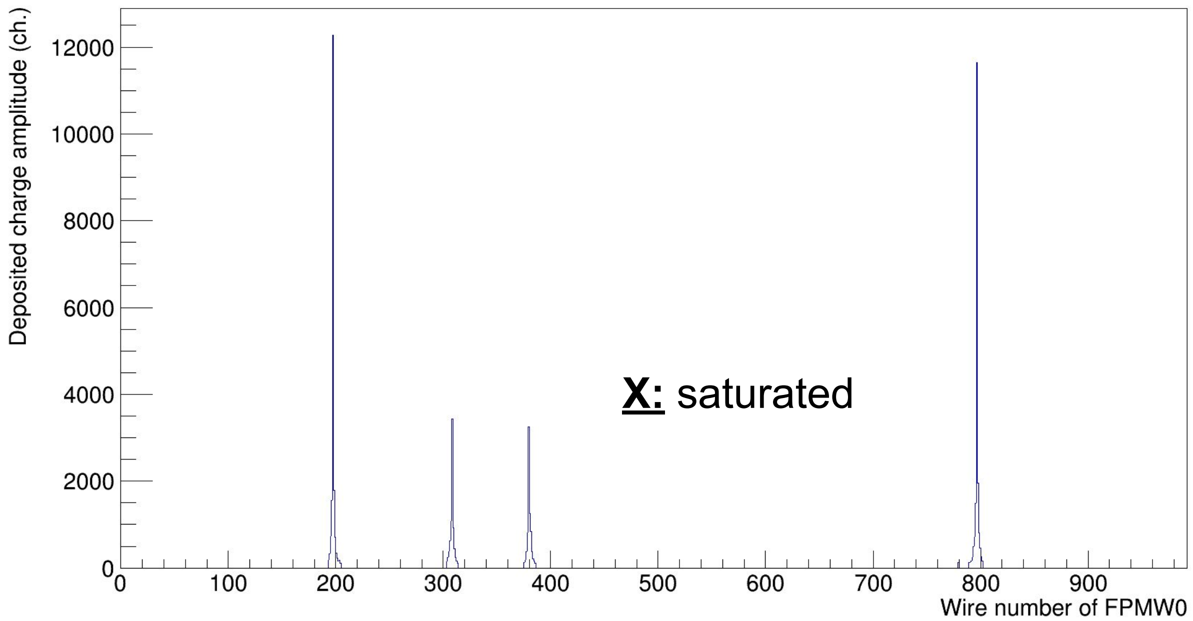
Experimental result: Gamma rays

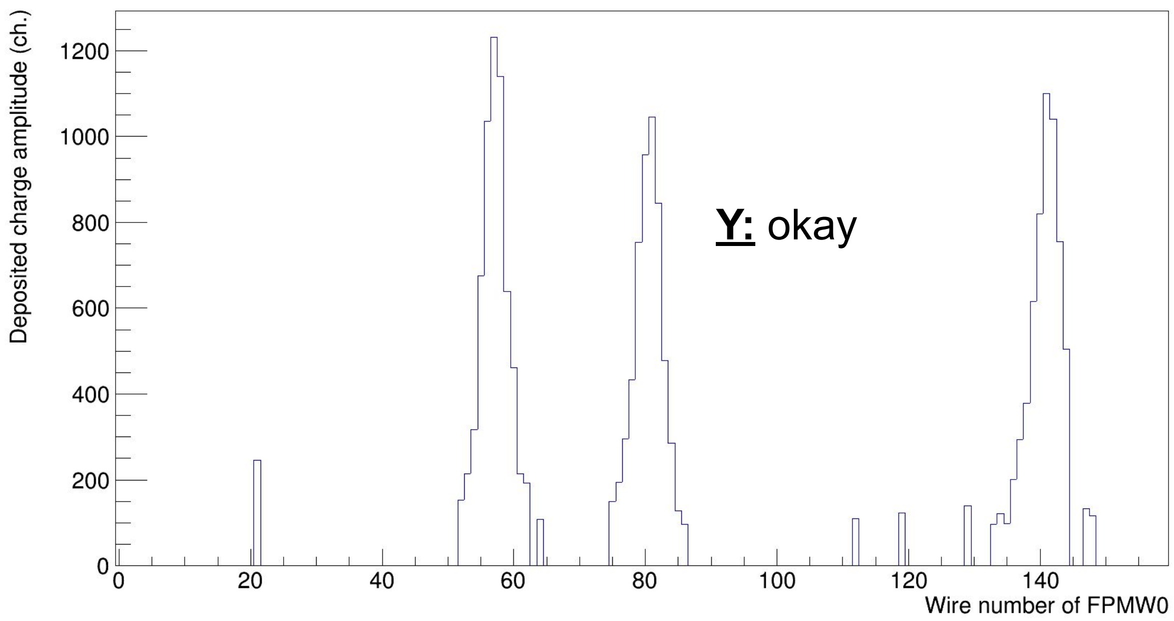


Methods to reconstruct positions

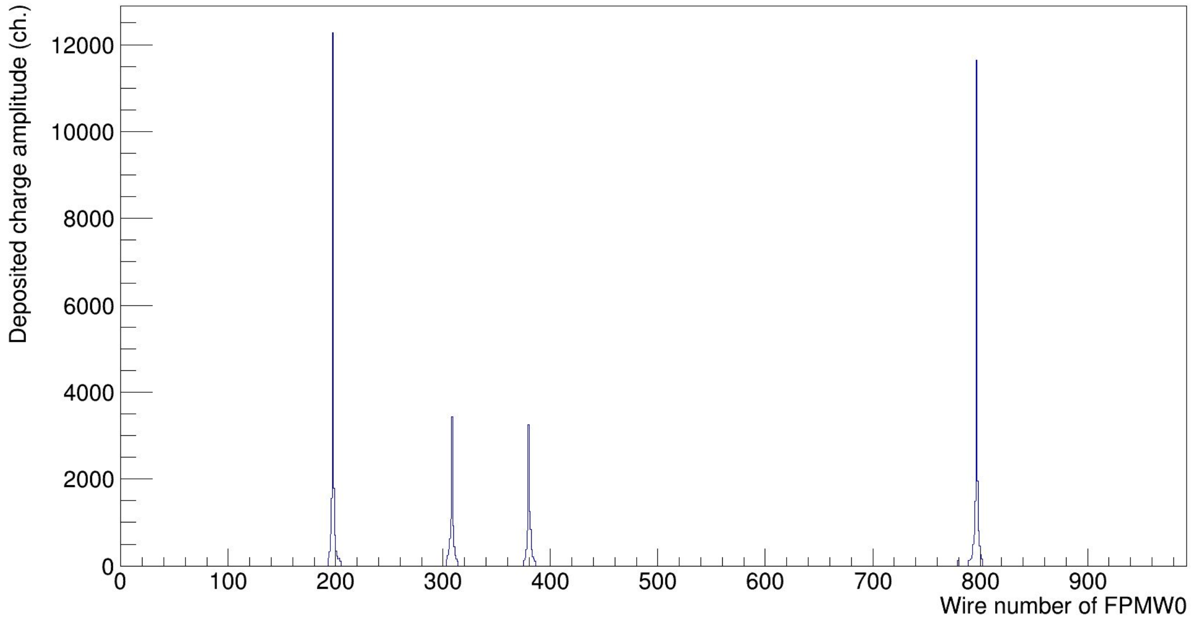


- **ions$^+$** drift to the central cathode and generate a **time signal**
- The faster **e$^-$** drift to the X,Y anodes, generating a **charge distribution**:
  - Position = centroid of the distribution
  - Need to have a “good shape”





Methods to reconstruct positions



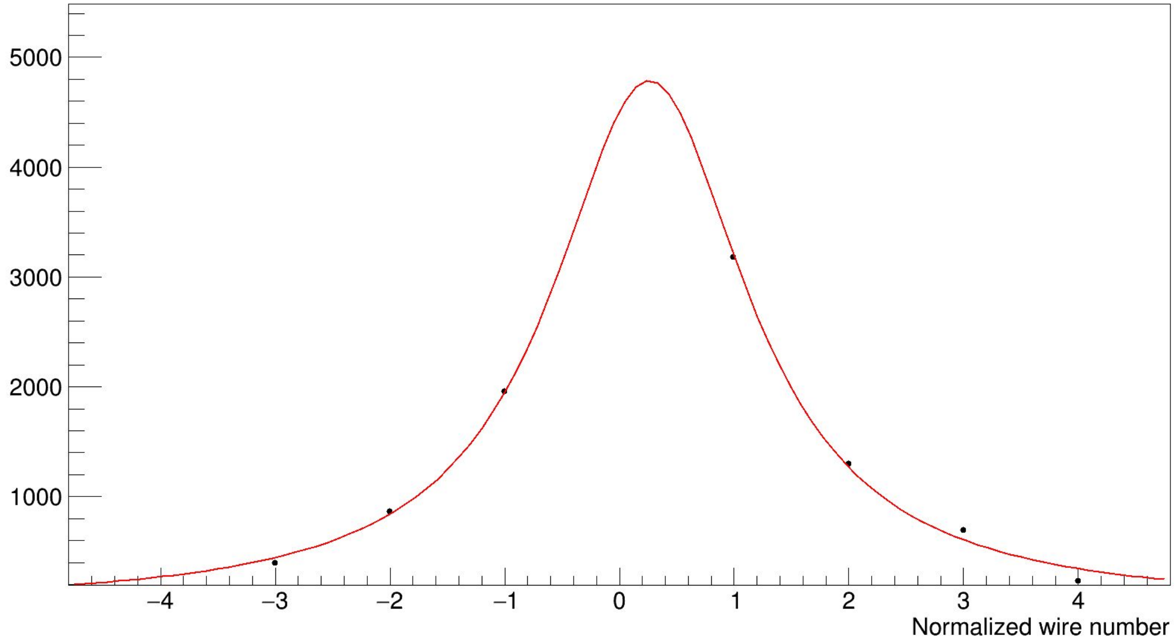
When a fission fragment passes through the MW, it ionizes the gas
The **e$^-$** drift to the X,Y anodes, generating a **charge distribution**:

- <u>Position = centroid</u> of the distribution
- Need to have a “good shape”

If there is pixelization, the fit is dominated by the maximum:

- Remove the maximum amplitude and do the fit
- The event by event fitting takes time:
    - Use the results to train a Neural Network (NN)
    - Faster and applicable to all the Multi-Wires (MW)

Charge distribution without maximum



The **lorentzian function represents better** the actual <u>charge distribution</u> generated in the X/Y wires

Methods to reconstruct positions

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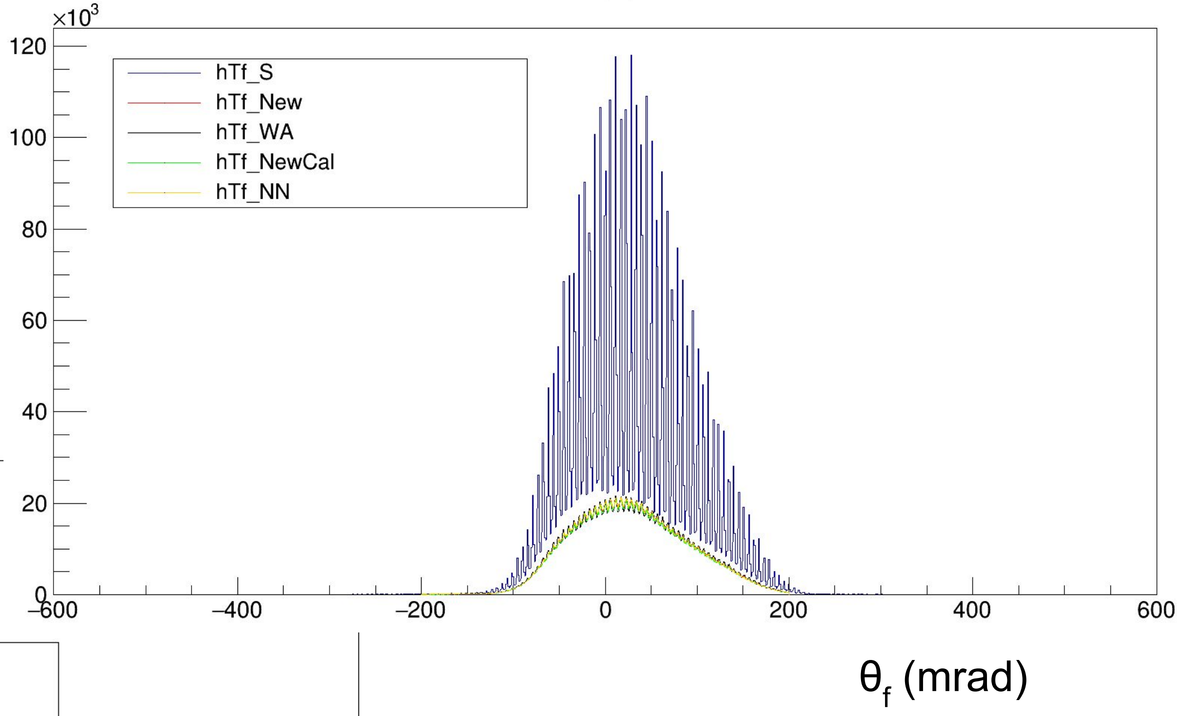
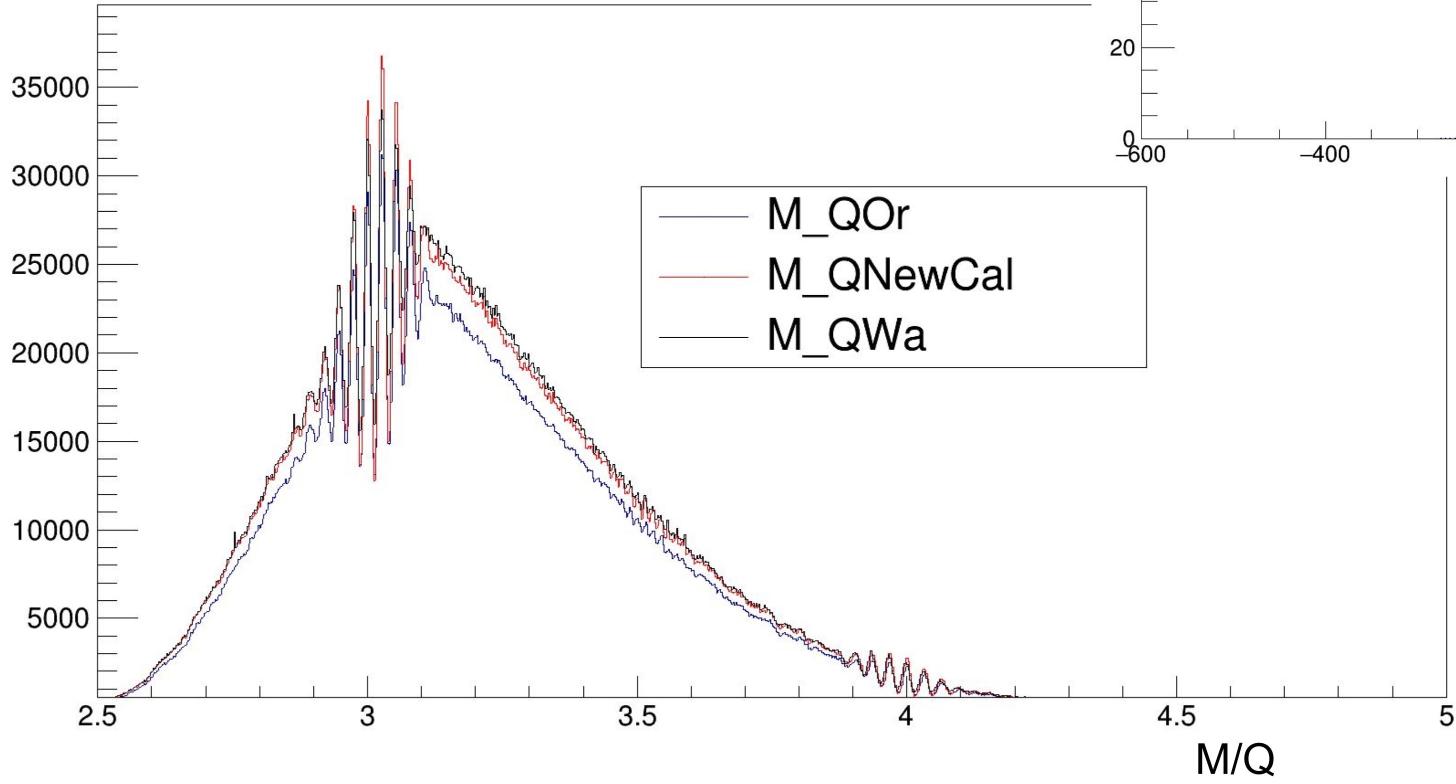
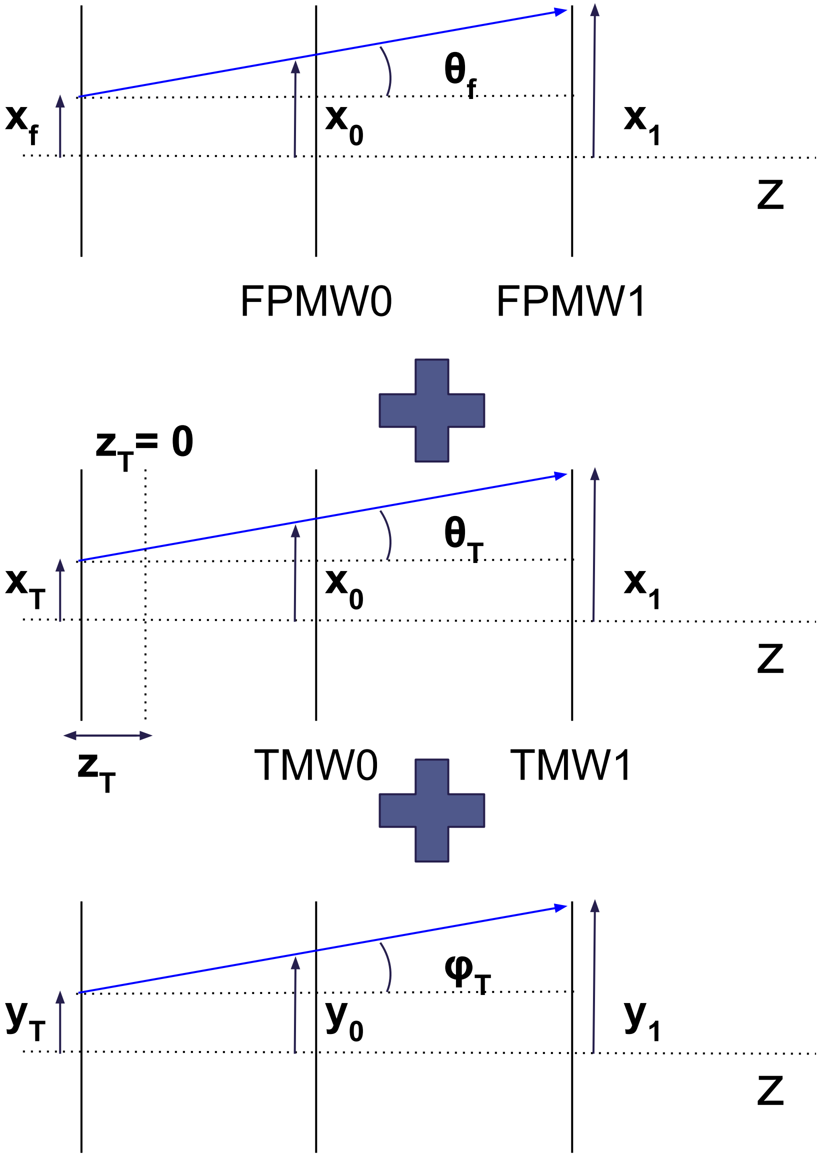
For this experiments (PISTA campaign), the separation between the FPMW was of ~177 mm (instead of ~1000 mm)
This feature makes **the pixelization in the angle (θ_f) even more significant**
Thanks to the NoMax Lorentzian fit, the **pixelization is reduced**





- The **NN improves** the **resolution** considerably with respect to the hyperbolic secant
- It **also allows to “recover”** some **events**, reaching a similar rejection level as for the WA (~98% of the WA events are accepted)

2D vs 7D(6D) reconstruction [5]



1) 2D: Assign **value from (x_f,θ_f)** measured at the Focal Plane => ΔA/A~6‰ at A=100

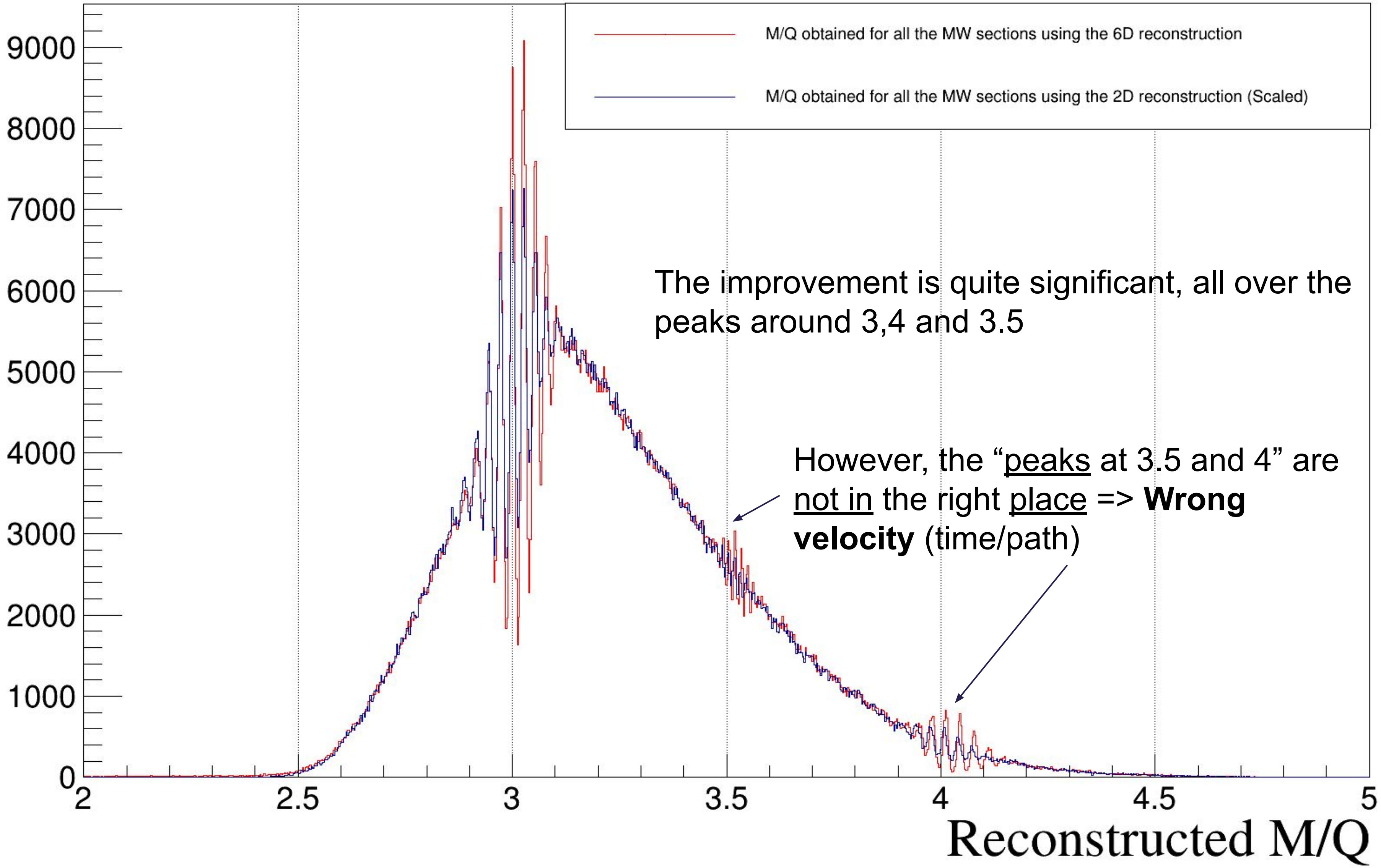
1) 4D: Using the telescope positions (TMW1-2), assign **entrance angles (θ_T,φ_T)** => ΔA/A~5‰

1) 7D*: Extrapolate the telescope positions to the target location (**x_T,y_T,z_T**) => ΔA/A~4‰

   *In reality, we *cannot precisely know the three* of them at the same time: assume one (**z_T= 0**, for example).

[5] 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

2D vs 7D(6D) reconstruction



The improvement is quite significant, all over the peaks around 3,4 and 3.5

However, the "peaks at 3.5 and 4" are not in the right place => **Wrong velocity** (time/path)

Both rotations mass

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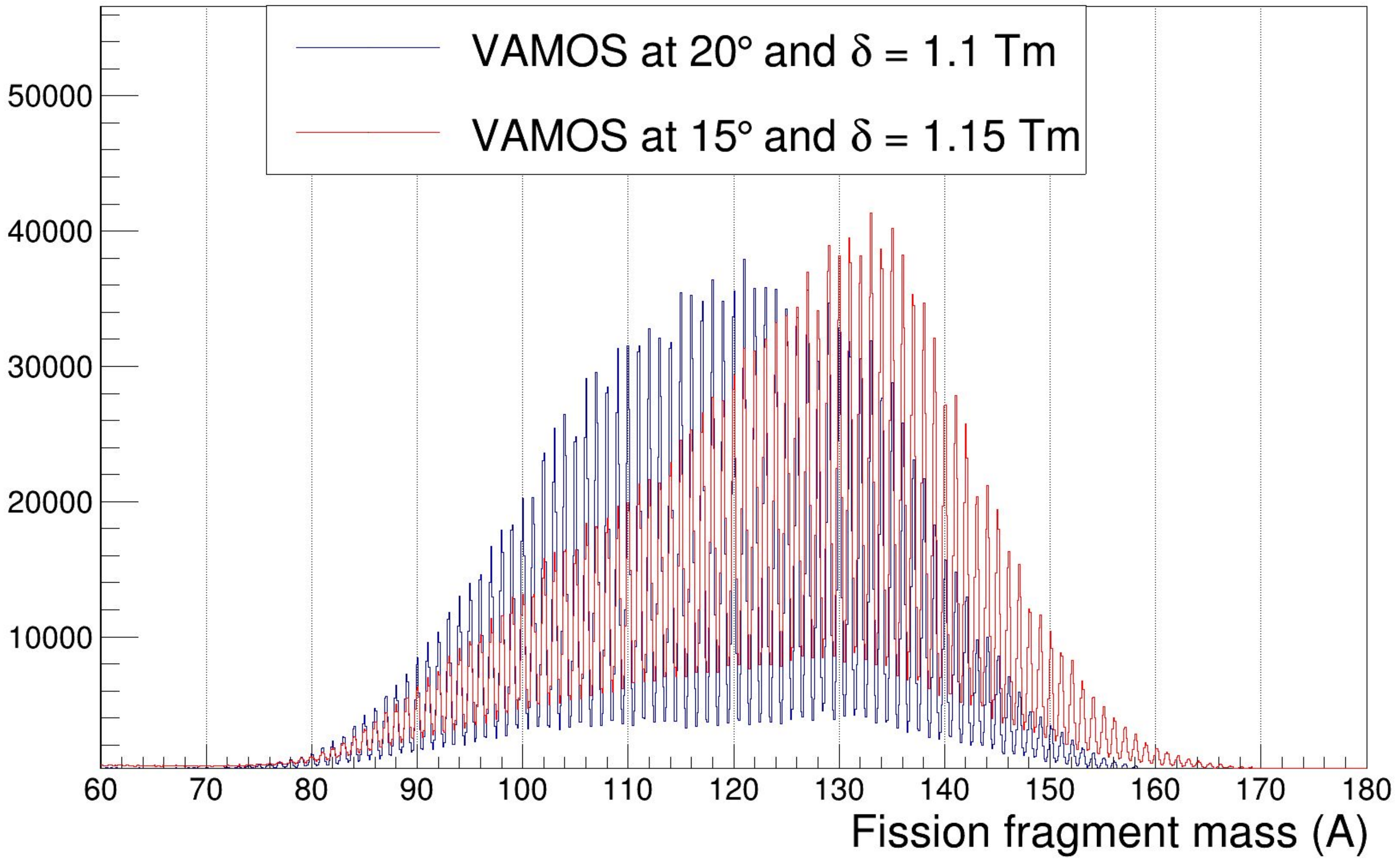
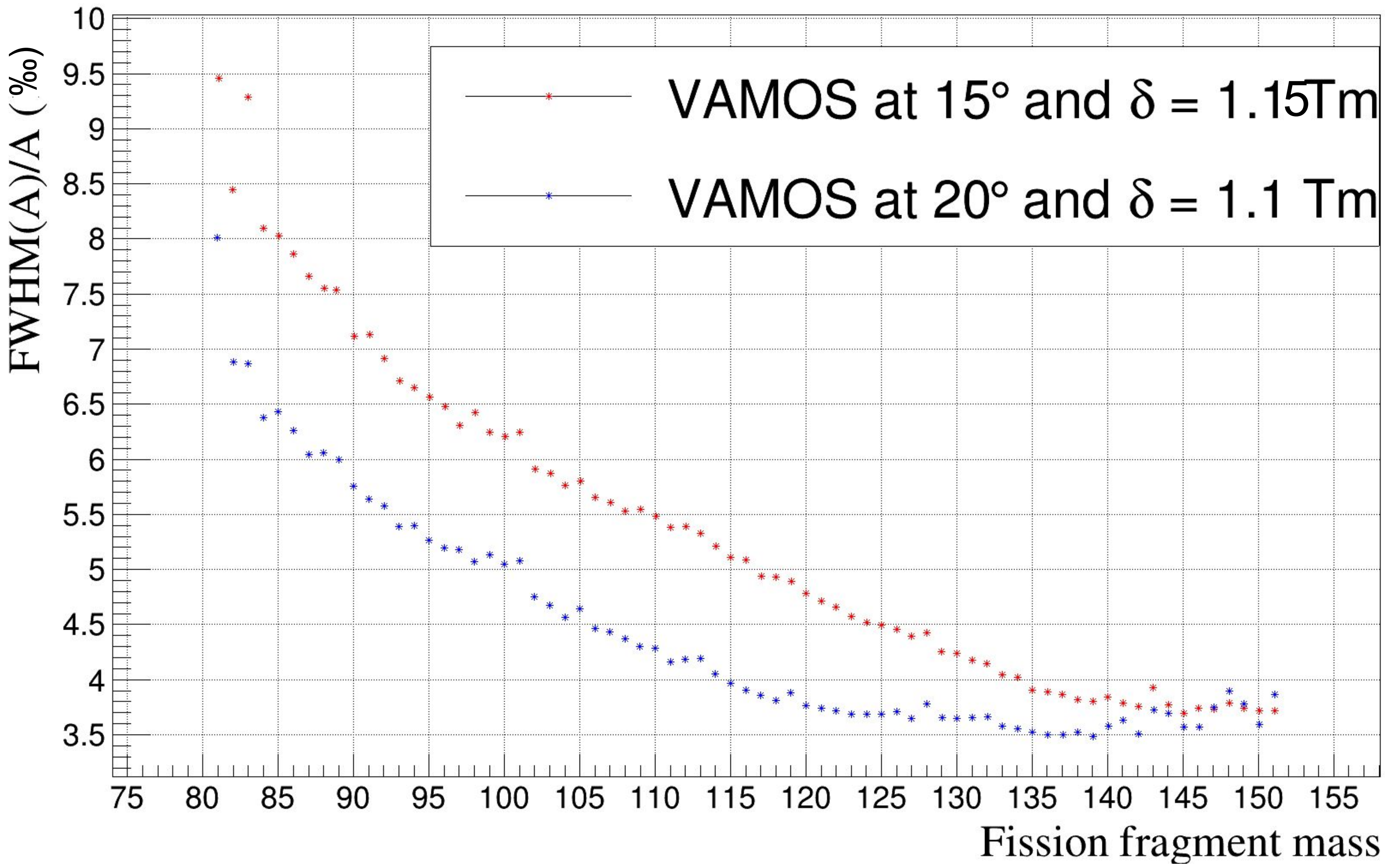
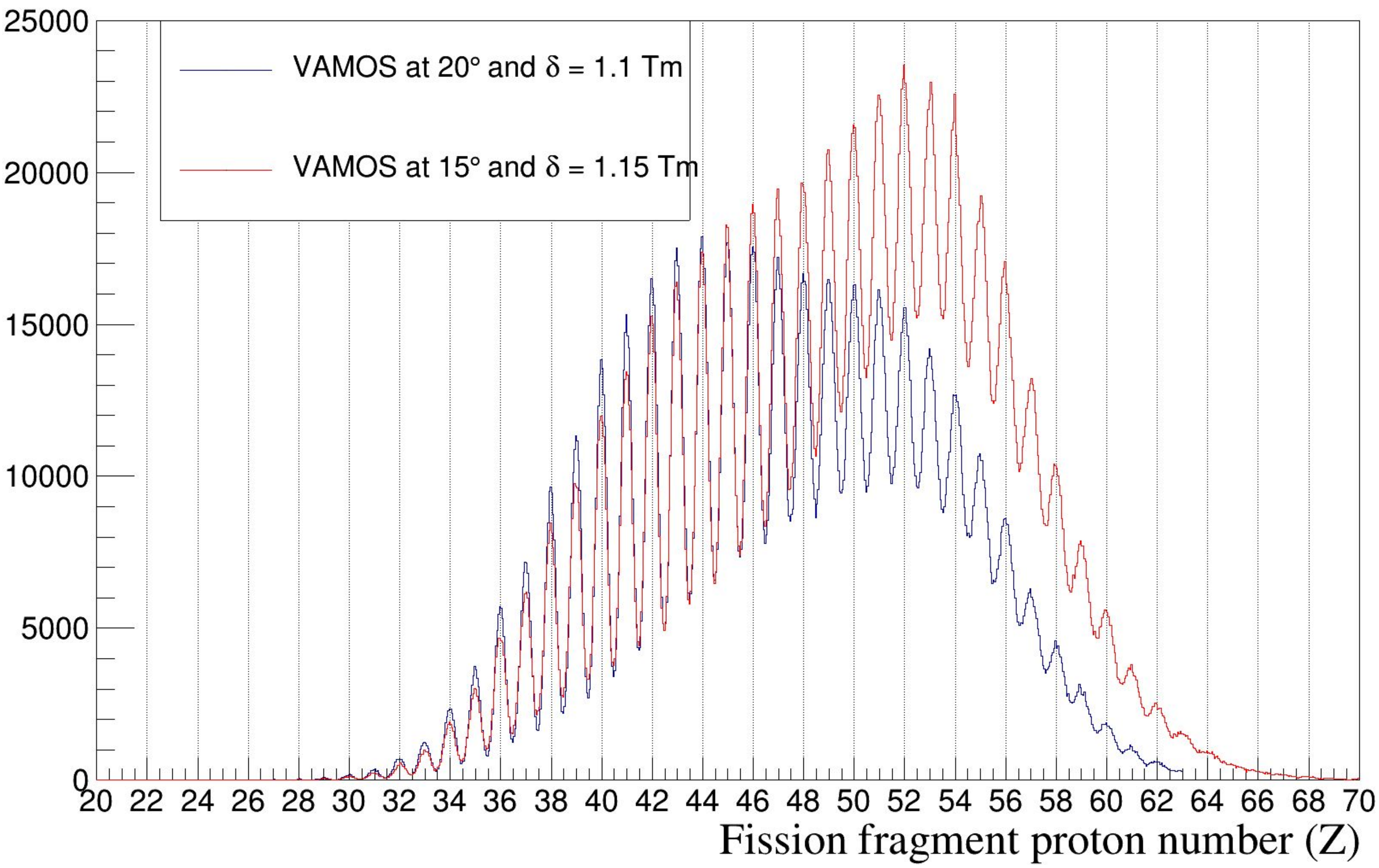


Both rotations mass



Both rotations Z



Both rotations Z

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