Search for new fission modes in light systems using PPAC detectors.

XVII CPAN Days

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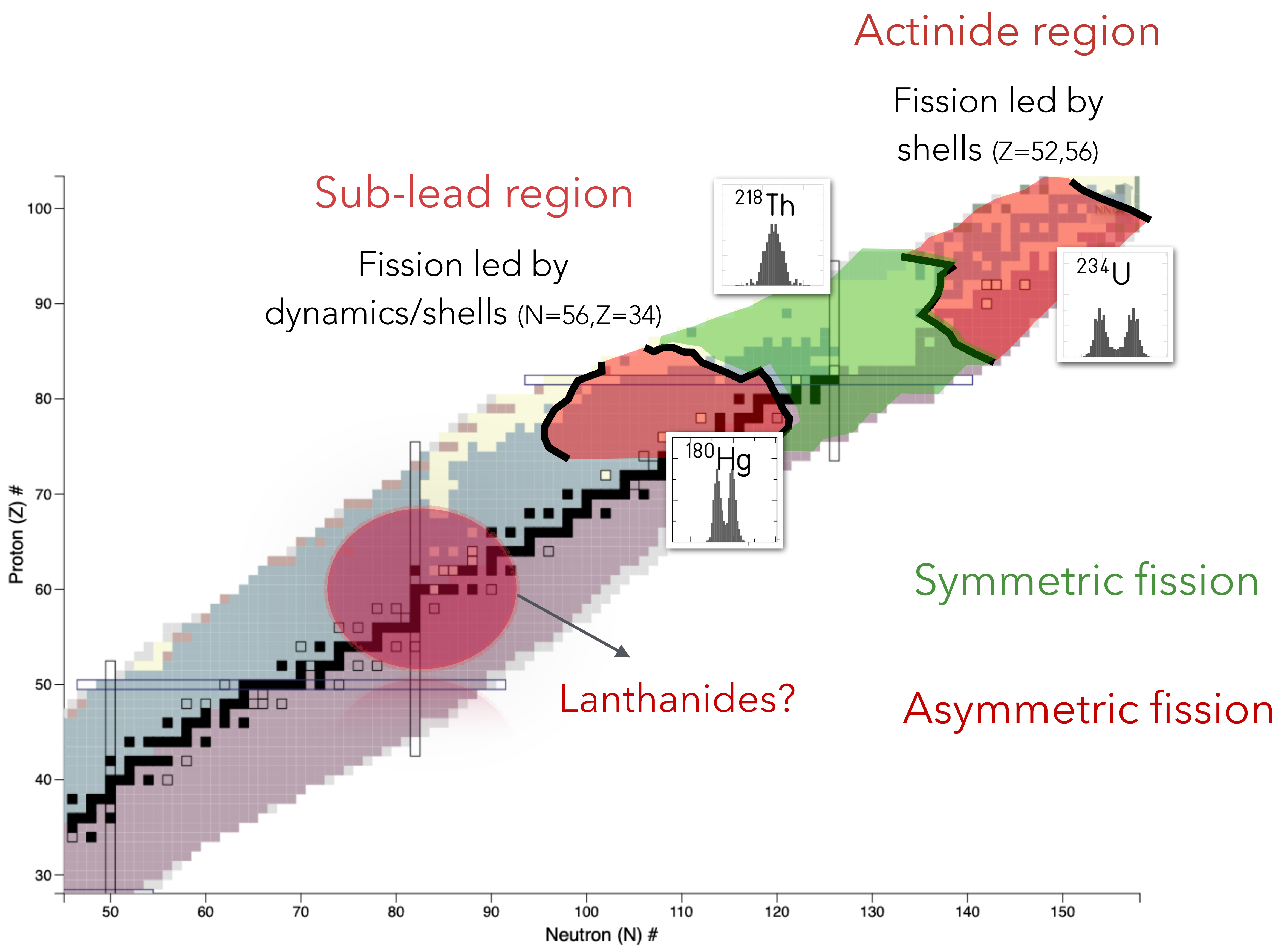
19th November 2025

Introduction

- Fission in actinides is known to present an asymmetric mass-distribution at low energies (near the fission barrier). The liquid drop model cannot explain these results.

- Recent studies, both theoretical and experimental, have established the effect of certain shells as main drivers of mass asymmetry in fission in neutron-deficient sub-lead systems.

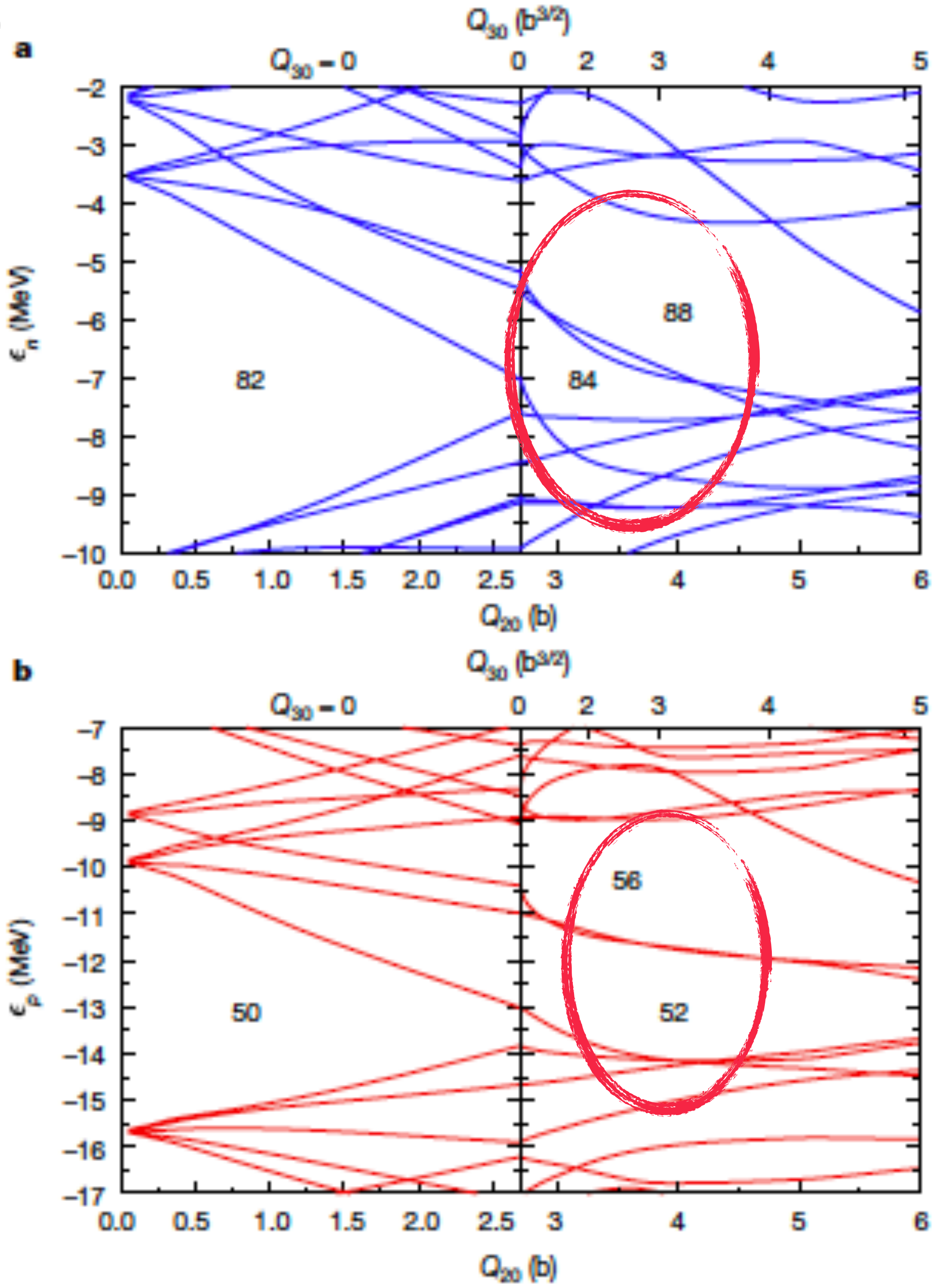
- These results leave us with an open question: how far can we move across the nuclide chart and still observe shell effects?



Octupolar deformations

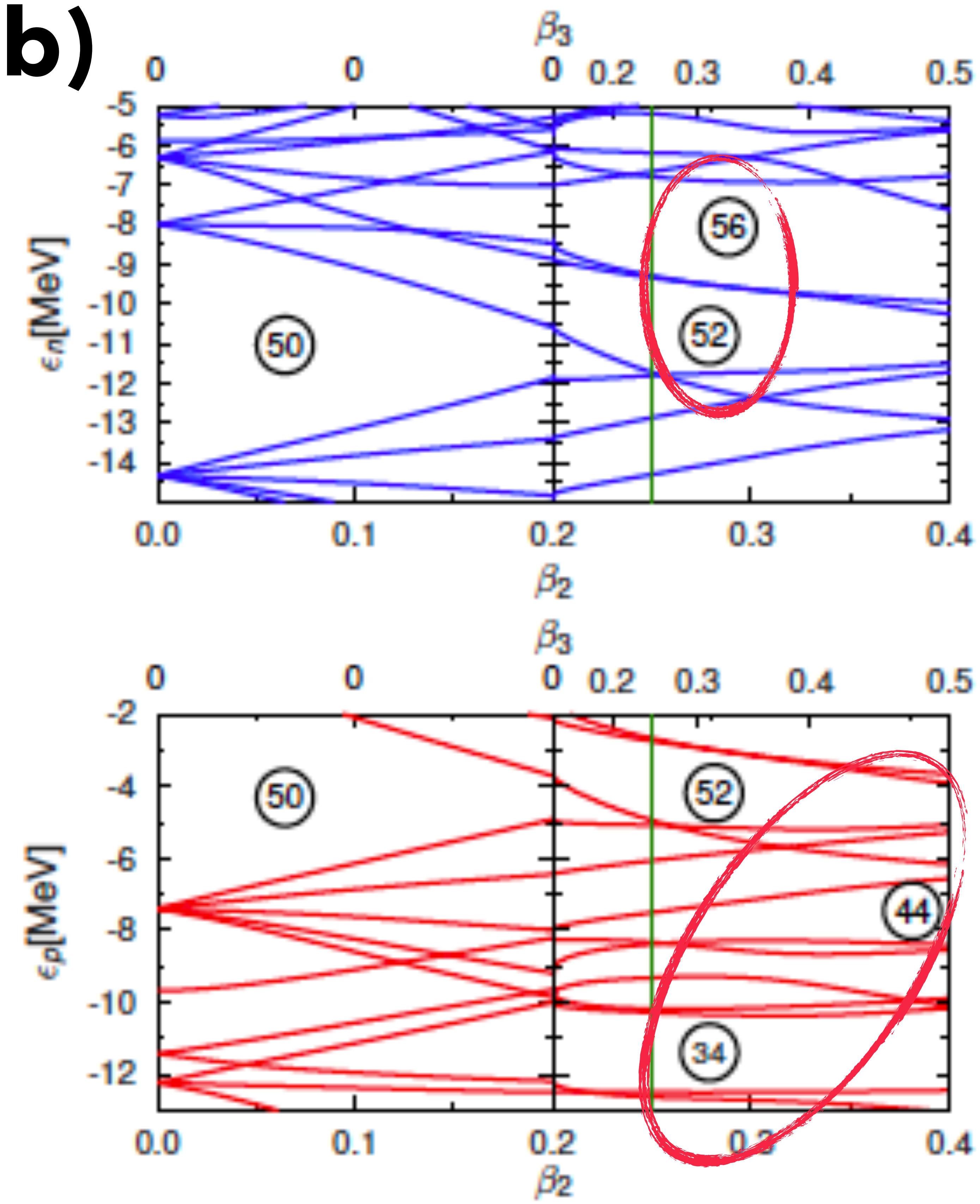
Single-particle energy levels in ^{144}Ba in **^{240}Pu (a)** and ^{100}Ru in **^{180}Hg (b)**

a)

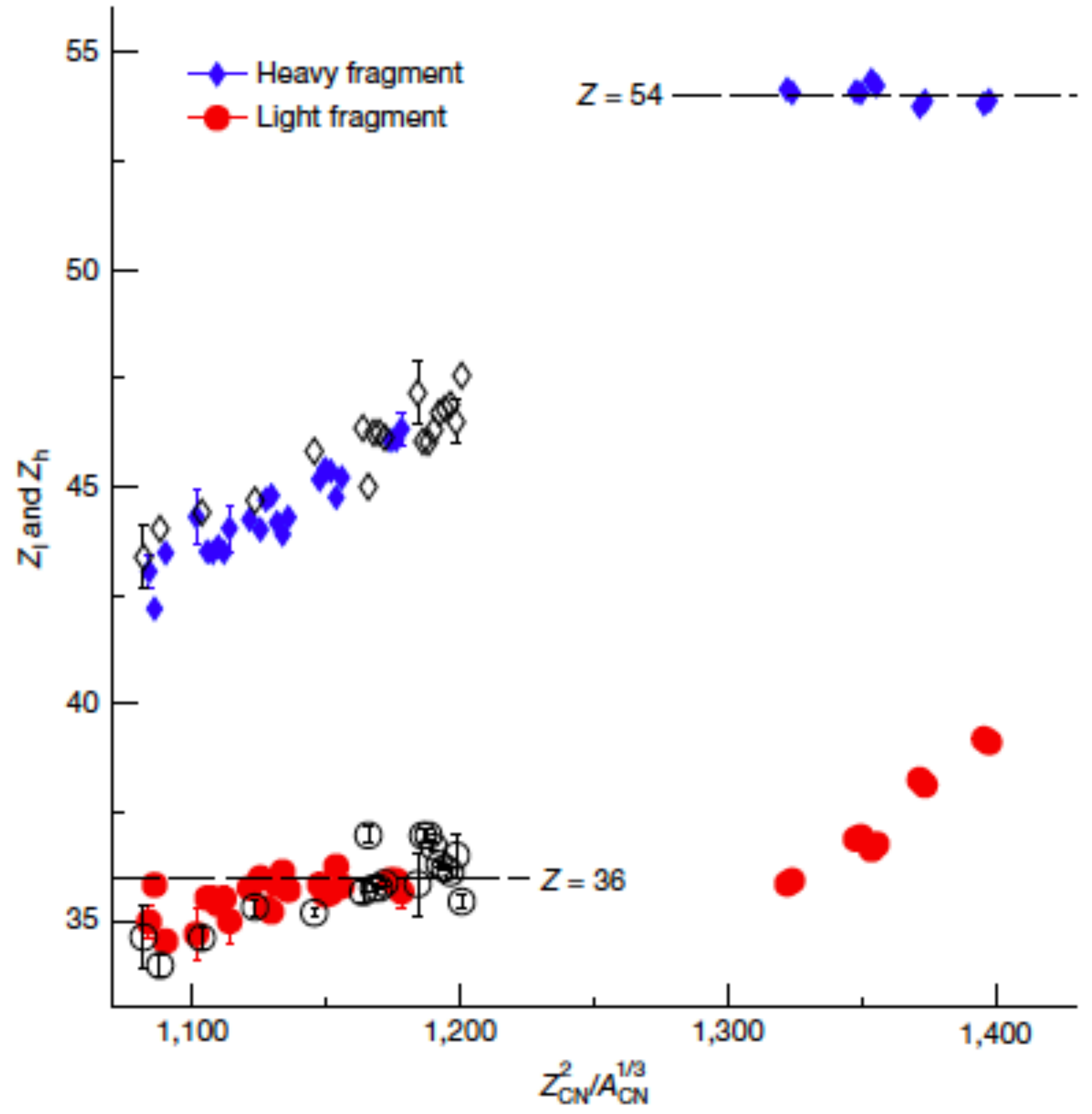


G. Scamps, C. Simenel, Nature 564, 382 (2018).

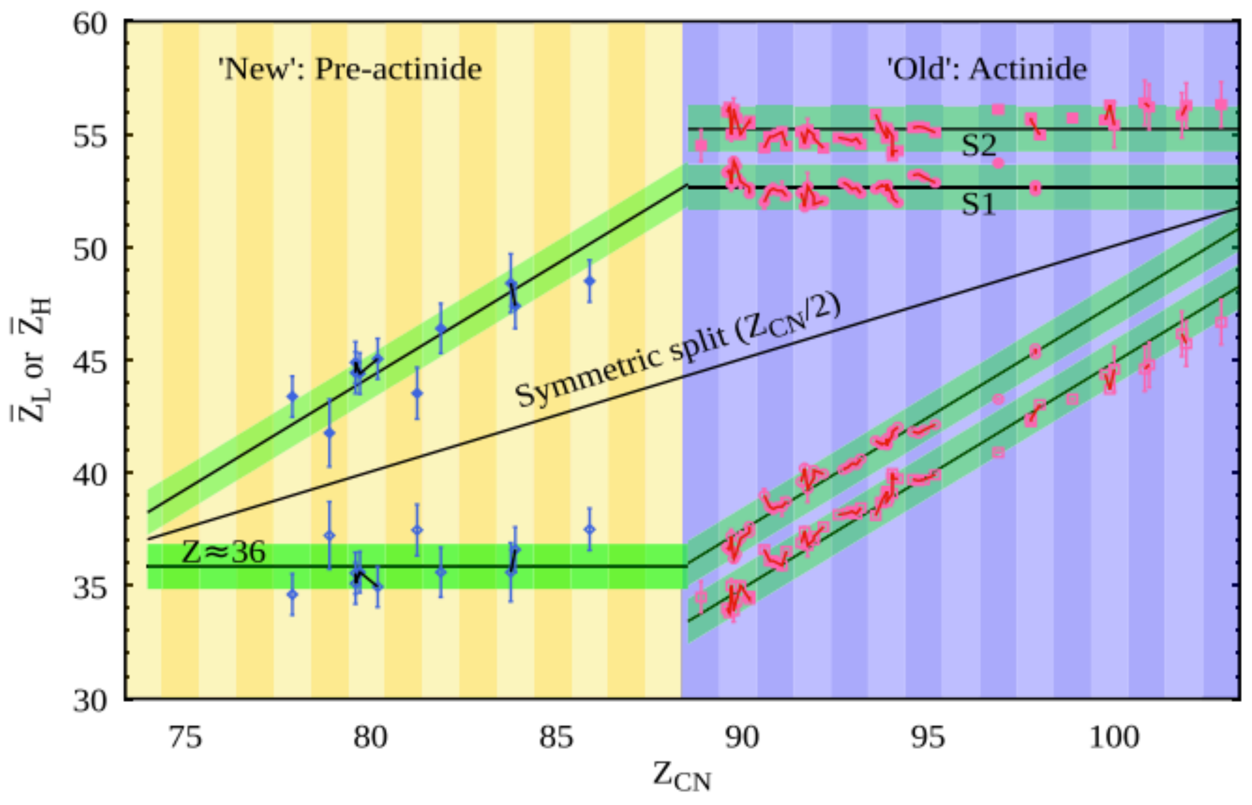
b)



Physical Review C 100, 041602(R) (2019)



Morfouace, P., Taieb, J., Chatillon, A. et al. An asymmetric fission island driven by shell effects in light fragments. Nature (2025).



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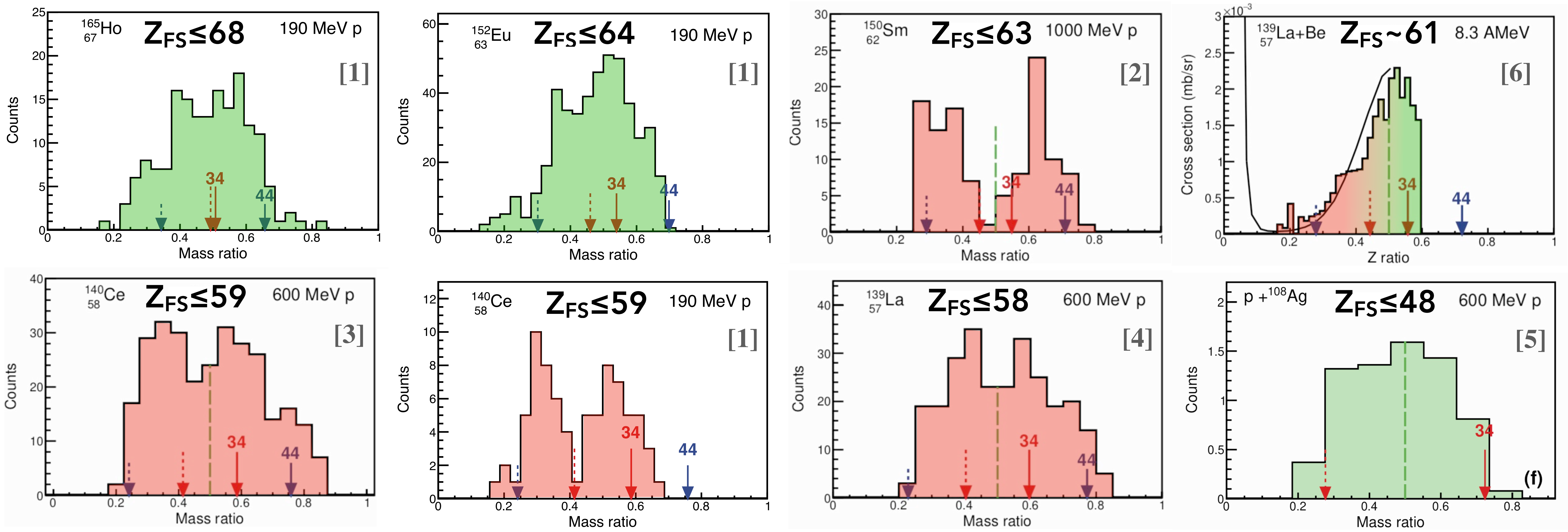
Volume 825, 10 February 2022, 136859

➡ Theoretical calculations explained the asymmetric split with the appearance of favoured octupolar configurations (Z=56), and also predicted new, lighter shells (Z=34).

➡ Experimental studies agree in affirming the role of shell dynamics in the asymmetric split of both actinides and sub-lead elements.

High-energy fission of $Z_{FS} \approx 60$ systems



[1] Phys. Rev. C **28**, 276 (1983)
[2] JETP Lett. **40**, 1327 (1984)
[3] Phys. Rev. C **24**, 769 (1981)
[4] "Physics and Chemistry of Fission", IAEA, Jülich (1979)
[5] Z. Phys. A **293**, 241 (1979)
[6] Phys. Rev. Lett. **53**, 2004 (1984)

➡ Previous studies suggest the influence of shell dynamics in fission of lanthanides.

➡ High fission barriers (>30 MeV) and competition with evaporation channels result in low statistics, which does not allow us to firmly assess the asymmetric character.

➡ Thus, the goal of this work is to establish the fission fragment mass-distribution of ^{140}Ce using the n-TOF EAR-1 facility.

Our goal

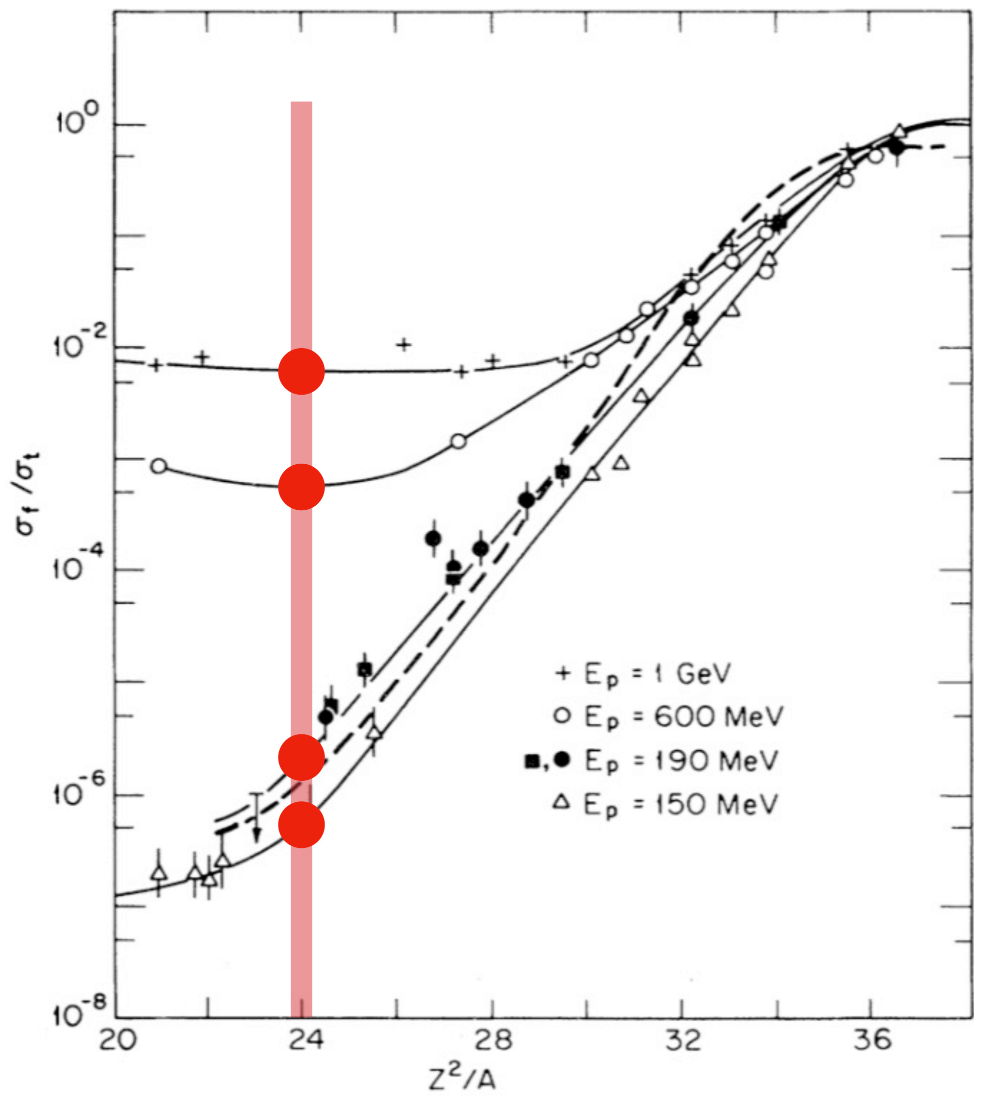
Measurement of fragments of neutron-induced fission in ^{140}Ce

- Assessing the symmetric or asymmetric mass distribution of the fragments.
- Measuring the angular distribution of the fragments.
- Determining the cross section of the process.

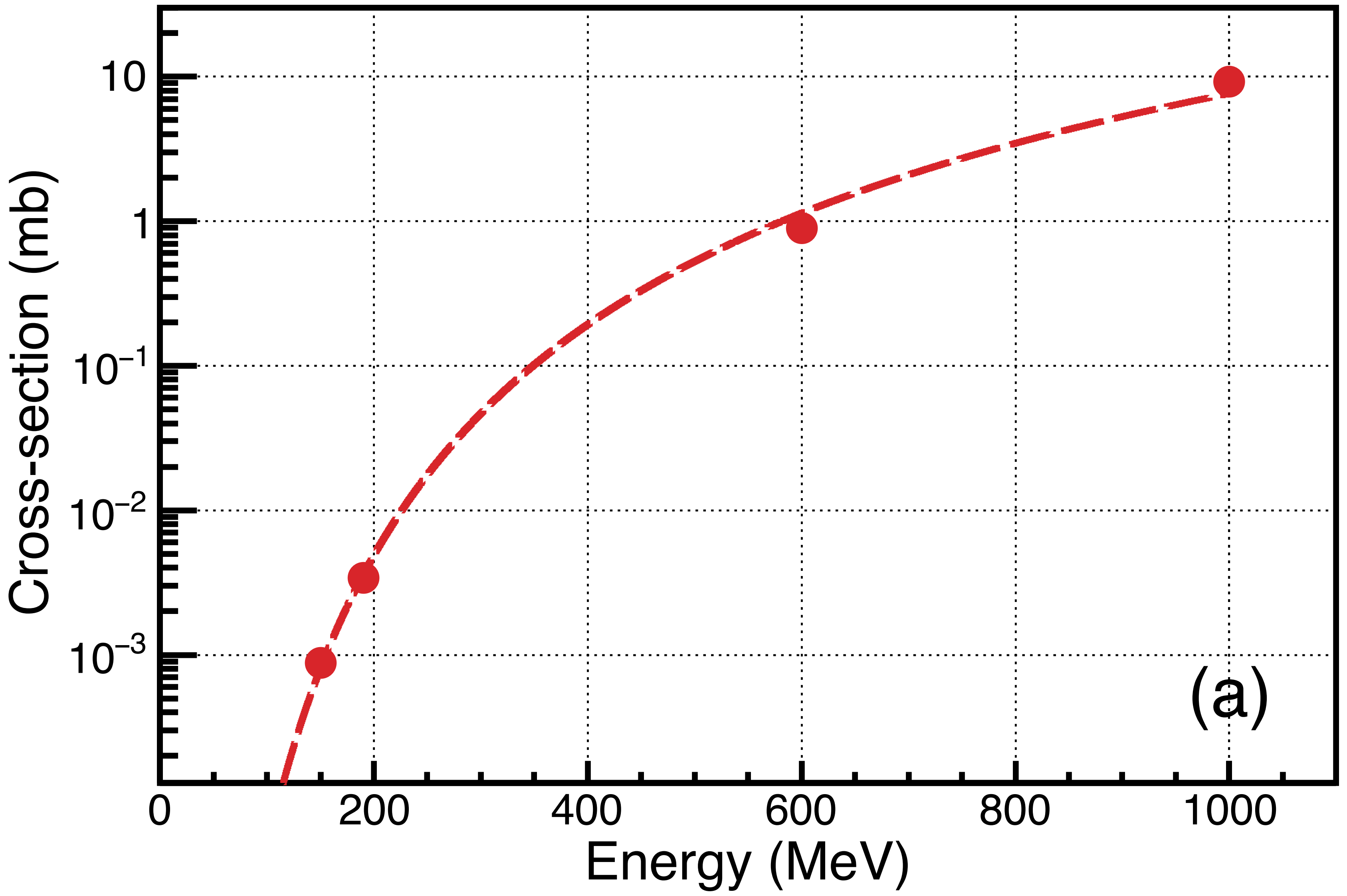
What we expect from previous data

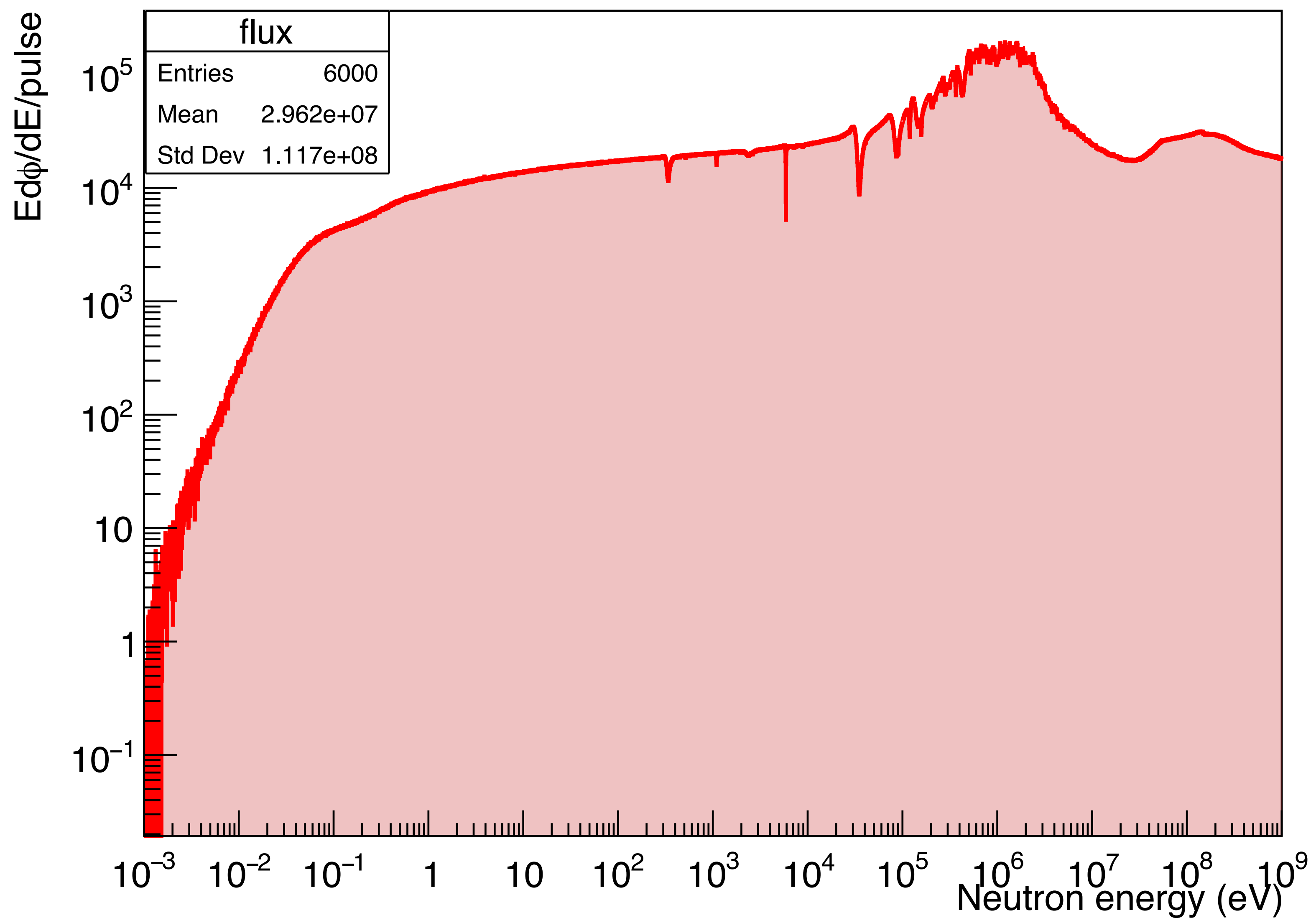
The high energy needed for the reaction makes n-TOF a perfect candidate to test it!

Phys. Rev. C **28**, 276 (1983)



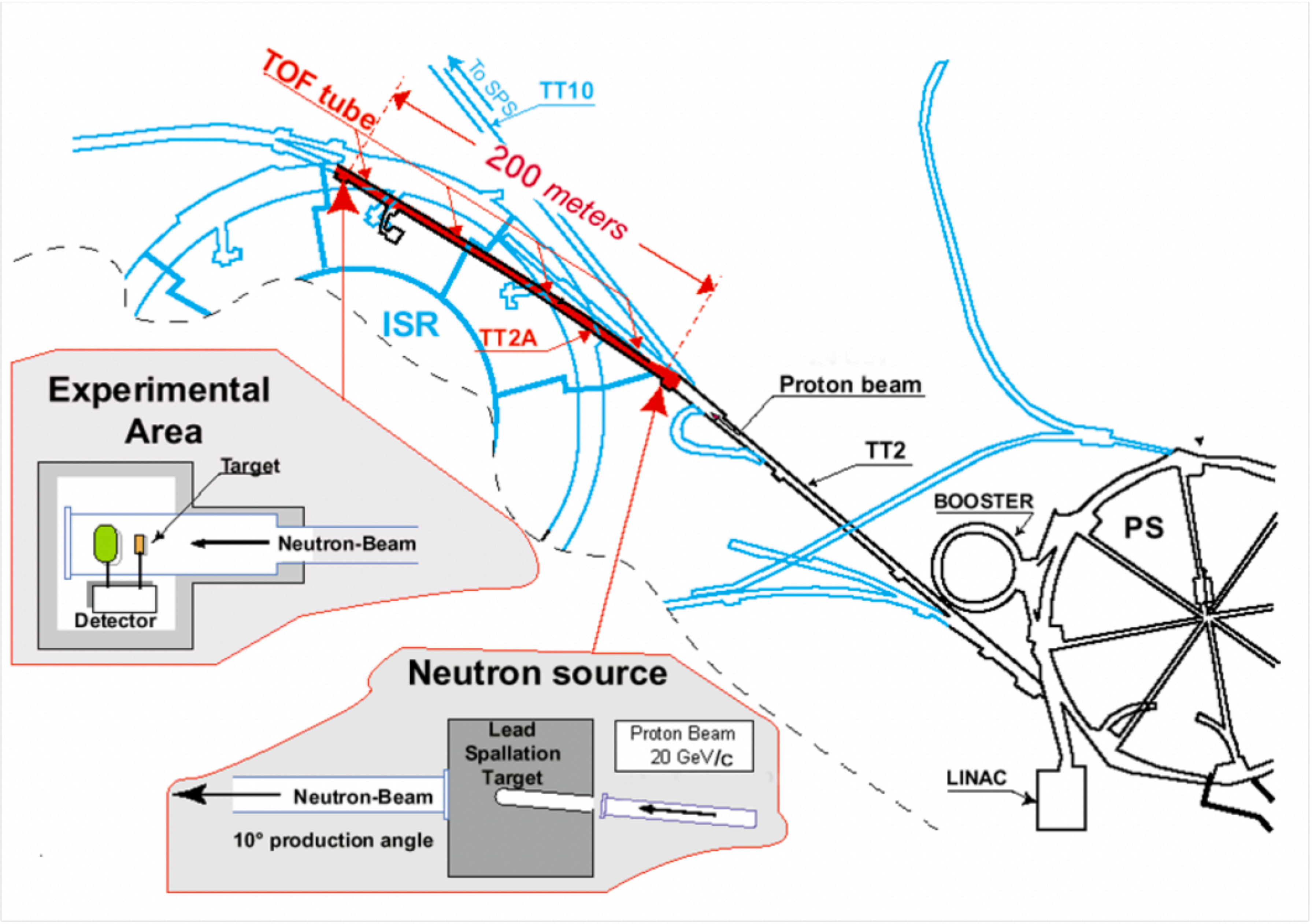
parameterization after
Phys. Rev. C **70**, 054603 (2004)

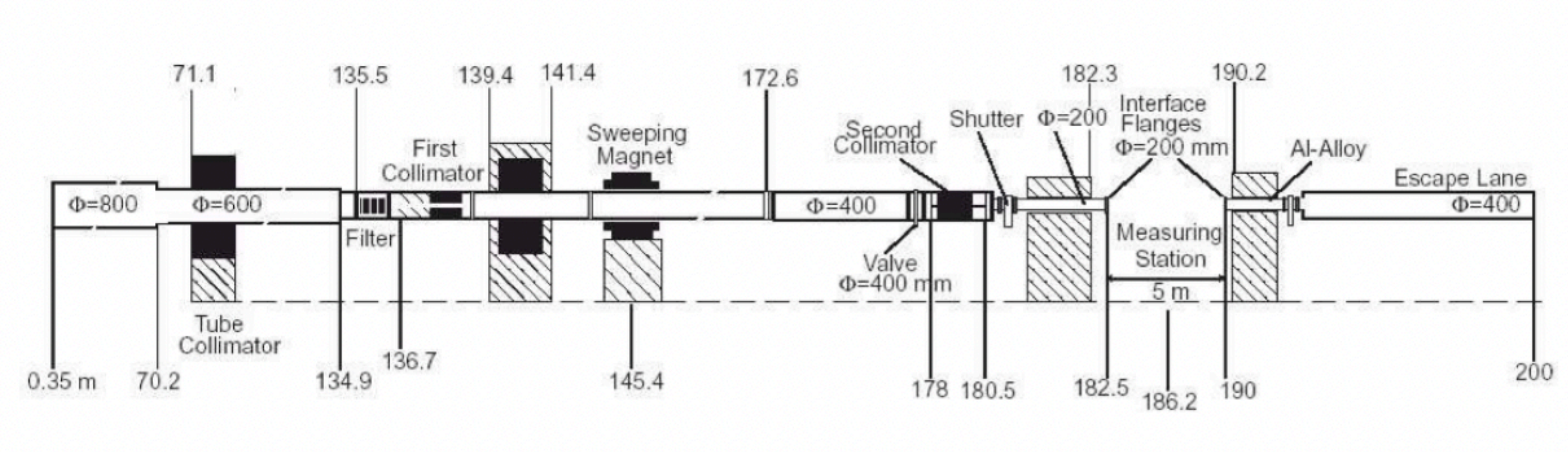




n_TOF facility

- Protons are accelerated up to 20 GeV/c before reaching the lead spallation target.
- Charged particles and background radiation are swept away using magnets and an iron shielding embedded in lead.
- After the collision, neutrons travel 182.5 meters until they reach the experimental area.

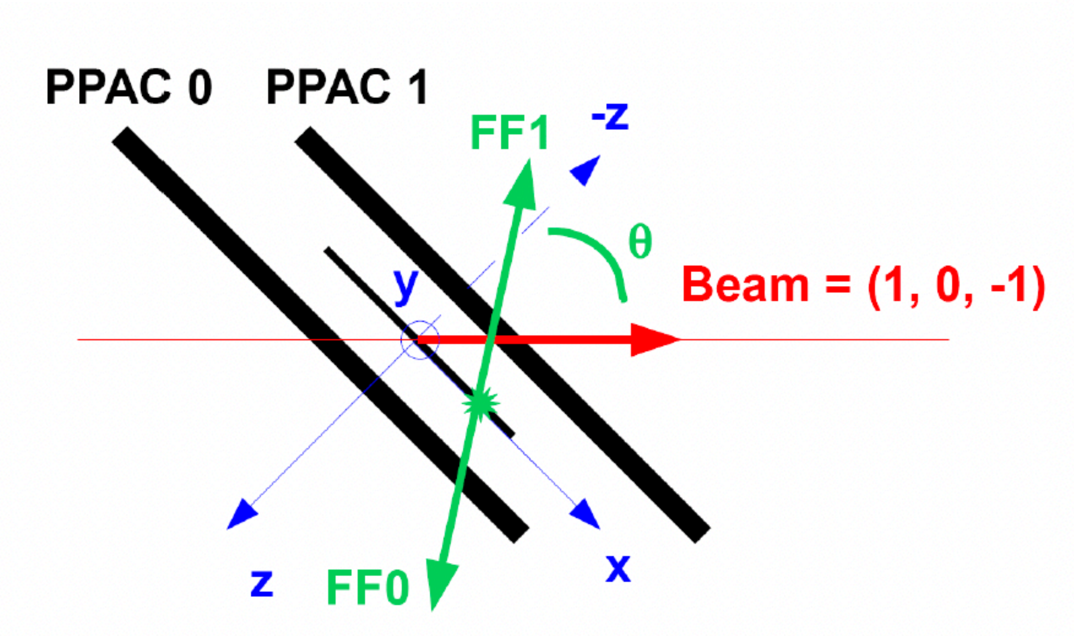


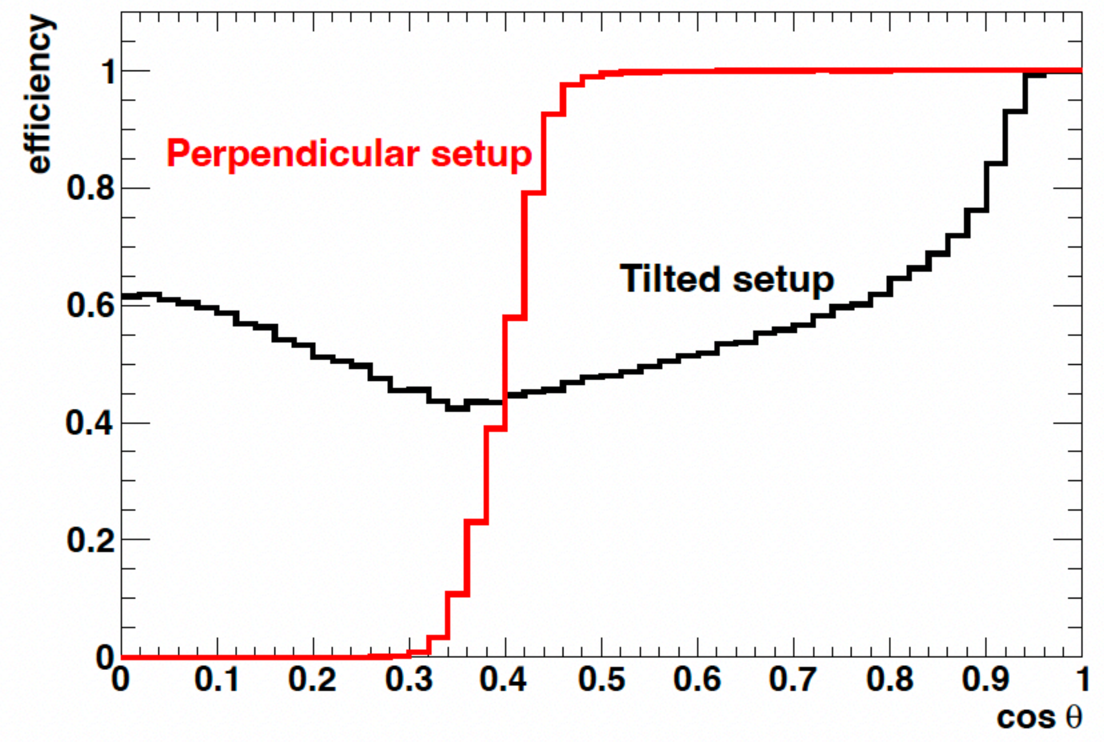


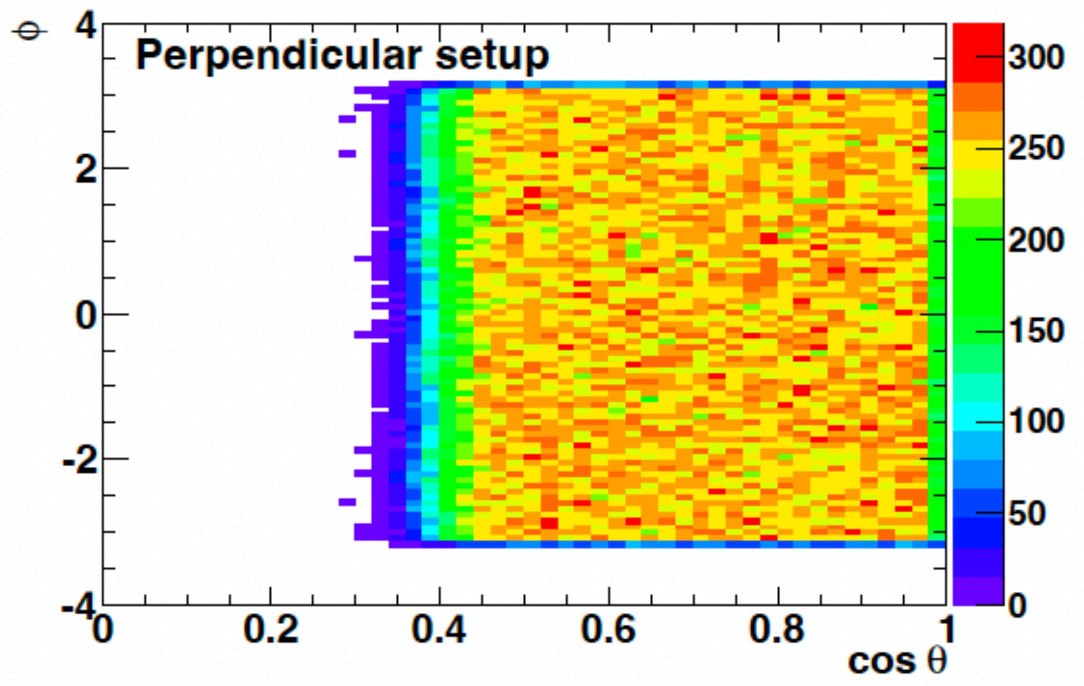
Experimental setup

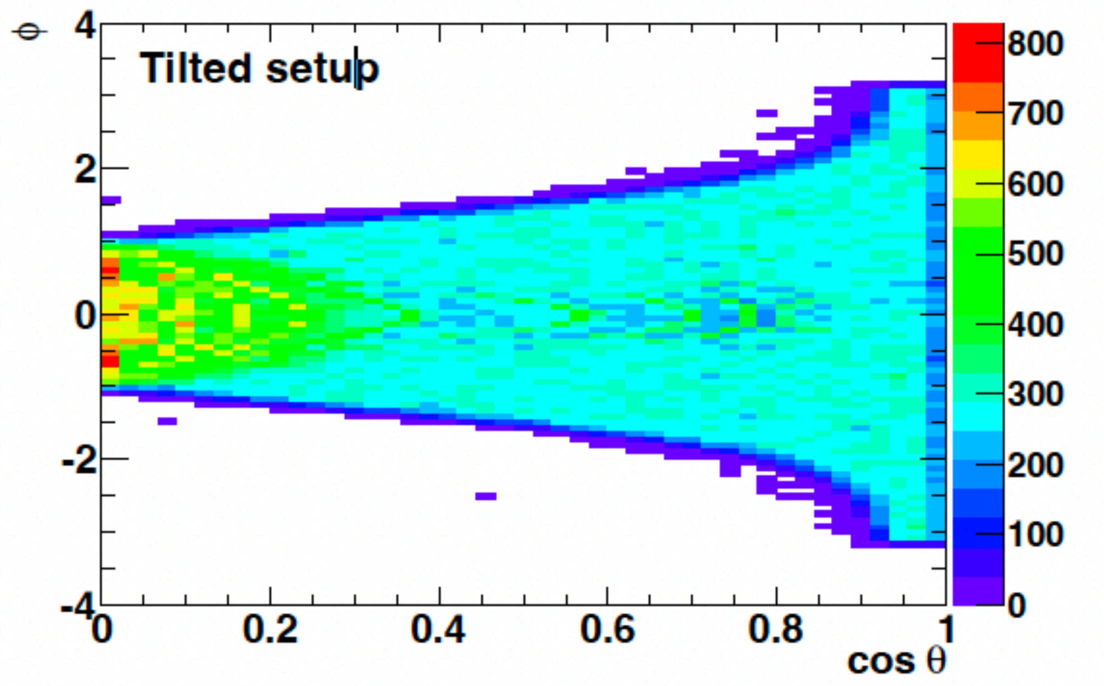
D.Tarrio thesis, U. Santiago de Compostela (2012)

- We used an ensemble of 10 PPACs, tilted 45° with respect to the neutron beam to measure the ToF, energy loss and position of the fission fragments.
- PPACs are made of 2 cathodes to obtain the X and Y position of the impact of the fragments and 1 anode that gives information about their time-of-flight and energy loss.
- 7 targets are made of ^{140}Ce, accompanied of ^{197}Au and ^{238}U reference foils for normalisation purposes.

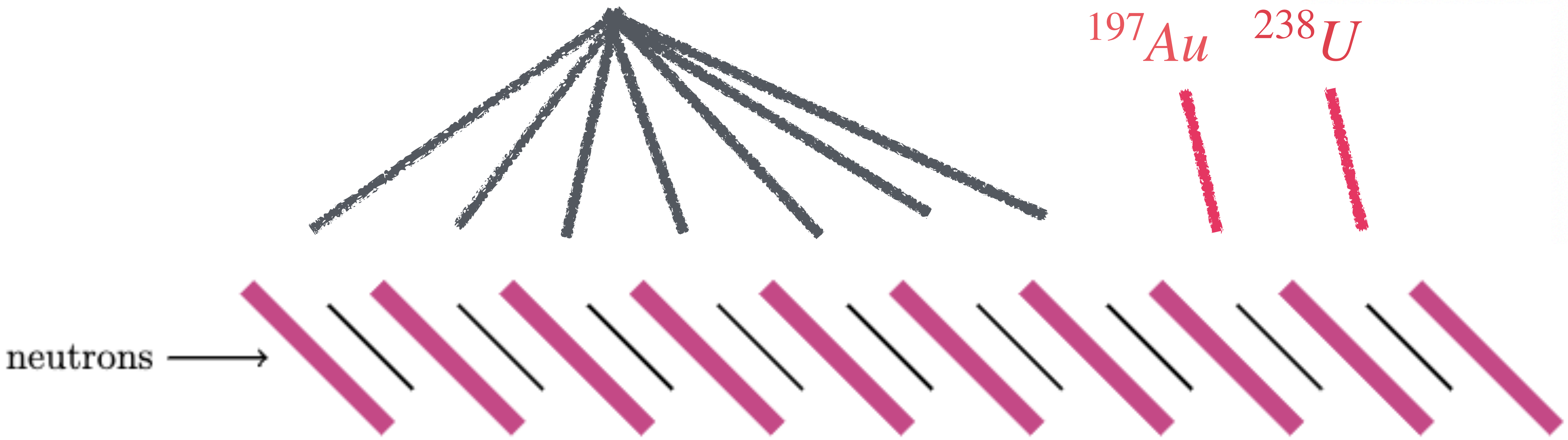


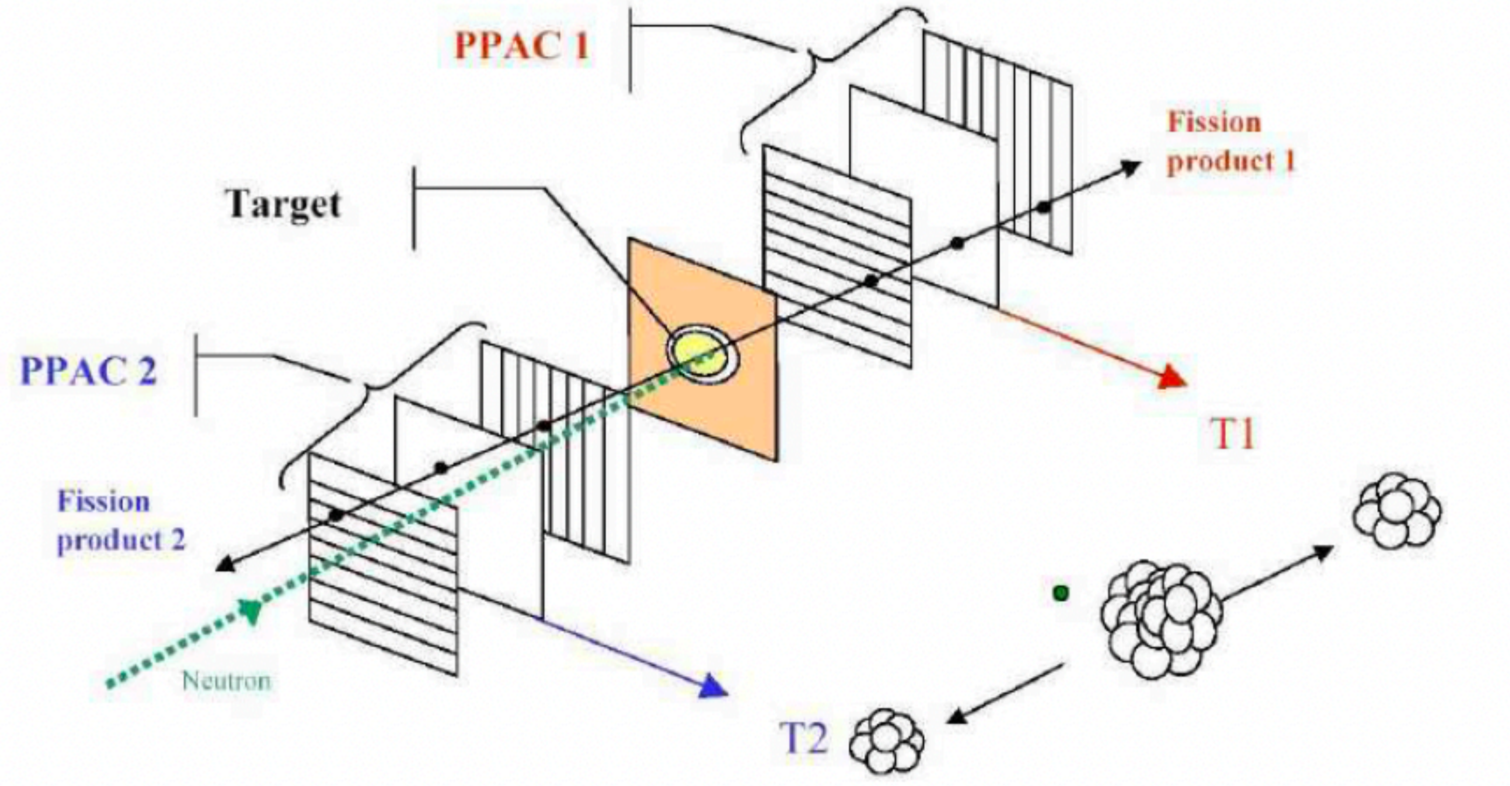






$^{140}Ce\ (\sim 1.2\ mg/cm^2)$





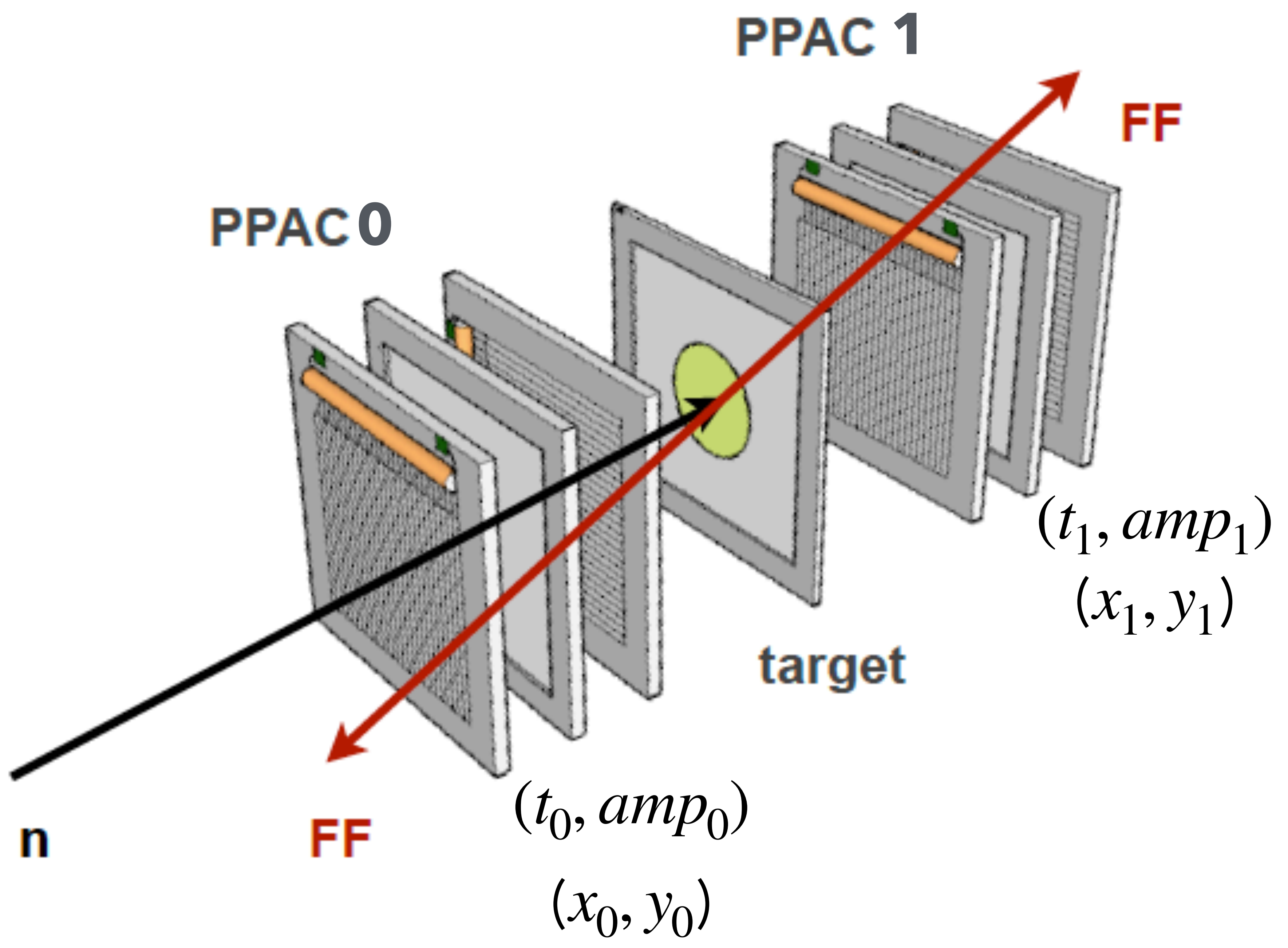
Selection of fission events

- A fission event will, in general, involve 2 (or more) adjacent PPACs, so we can detect them using a time coincidence condition between adjacent anodes ($t_1 - t_0 \approx 0$ ns).

- The amplitude recorded in each anode should be similar.

- With the position of impact (x,y) of each PPAC, we can reconstruct the fission fragments trajectories, as well as the point of impact inside the target.

- With the time-of-flight of the anodes, we can obtain an estimate of the neutron energy.



Simplified version of a fission event for a perpendicular setup. E.Leal thesis, U. Santiago de Compostela (2017)

$$E_n = m_n \left(\frac{1}{\sqrt{1 - \left(\frac{l}{c} \frac{1}{(t_0 - \gamma_{flash} + l_{path}/c)} \right)^2}} - 1 \right).$$

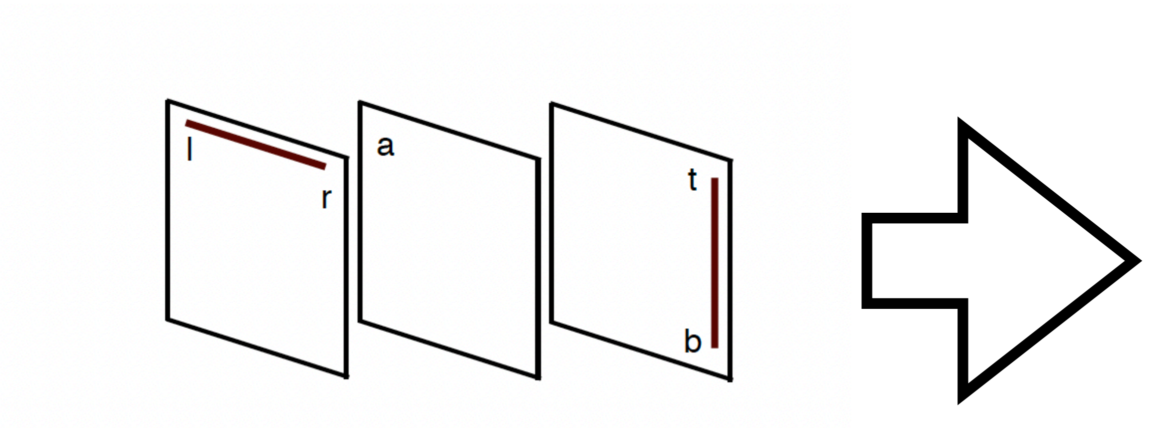
γ-flash signals come from relativistic particles formed after the spallation target (from γ radiation)! They can be used as a timing reference.

Selection of fission events

- We consider a fission event as the one that satisfies the following conditions:

1. The time difference between adjacent anodes must be smaller than 8 ns.

2. The sum of times of every valid pair of cathode signals (top-bottom and left-right) for a certain anode must follow



$$t_l + t_r - 2t_a = t_p$$

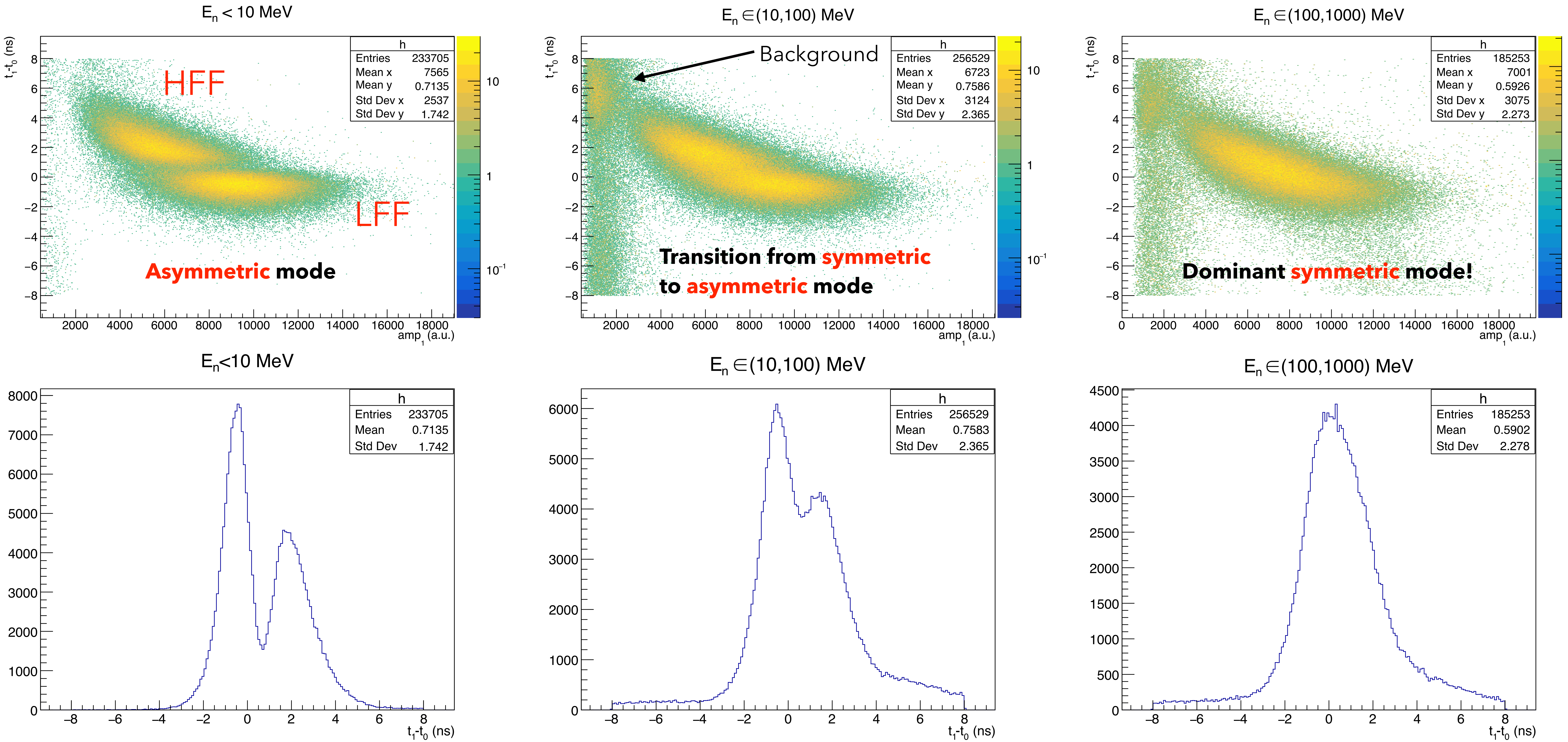
$$t_t + t_b - 2t_a = t_p$$

3. The ratio of the sum of the amplitudes of each pair of cathode signals and the anode signal, $\frac{amp_t + amp_b}{amp_a}$ and $\frac{amp_l + amp_r}{amp_a}$, must be similar to that of the anode (between 0.2 and 1.6).

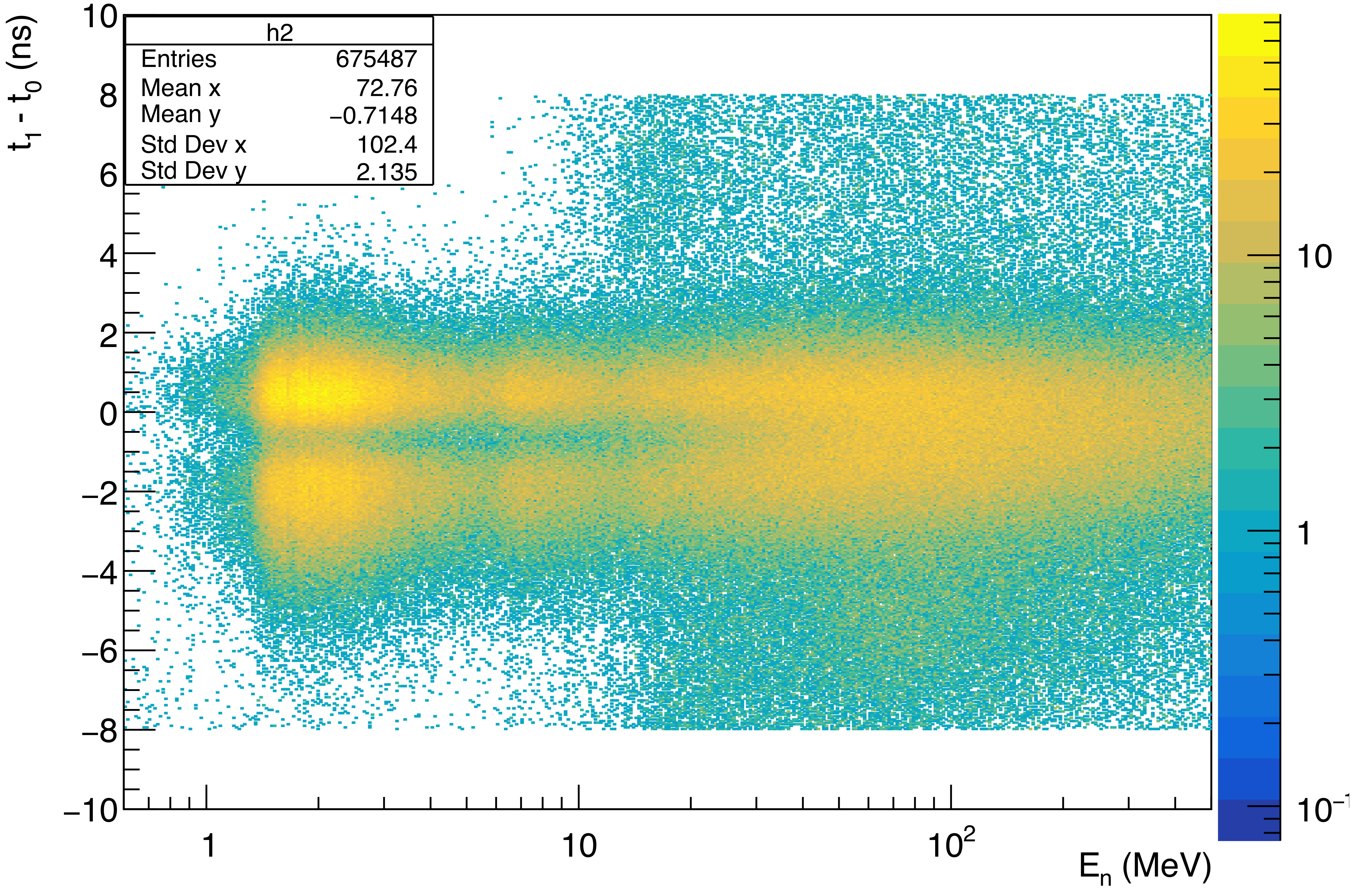
4. The ratio of the amplitudes $\frac{amp_t}{amp_b}$ and $\frac{amp_l}{amp_r}$ must behave linearly with respect to the time difference of the pair of cathodes (attenuation of the delay line).

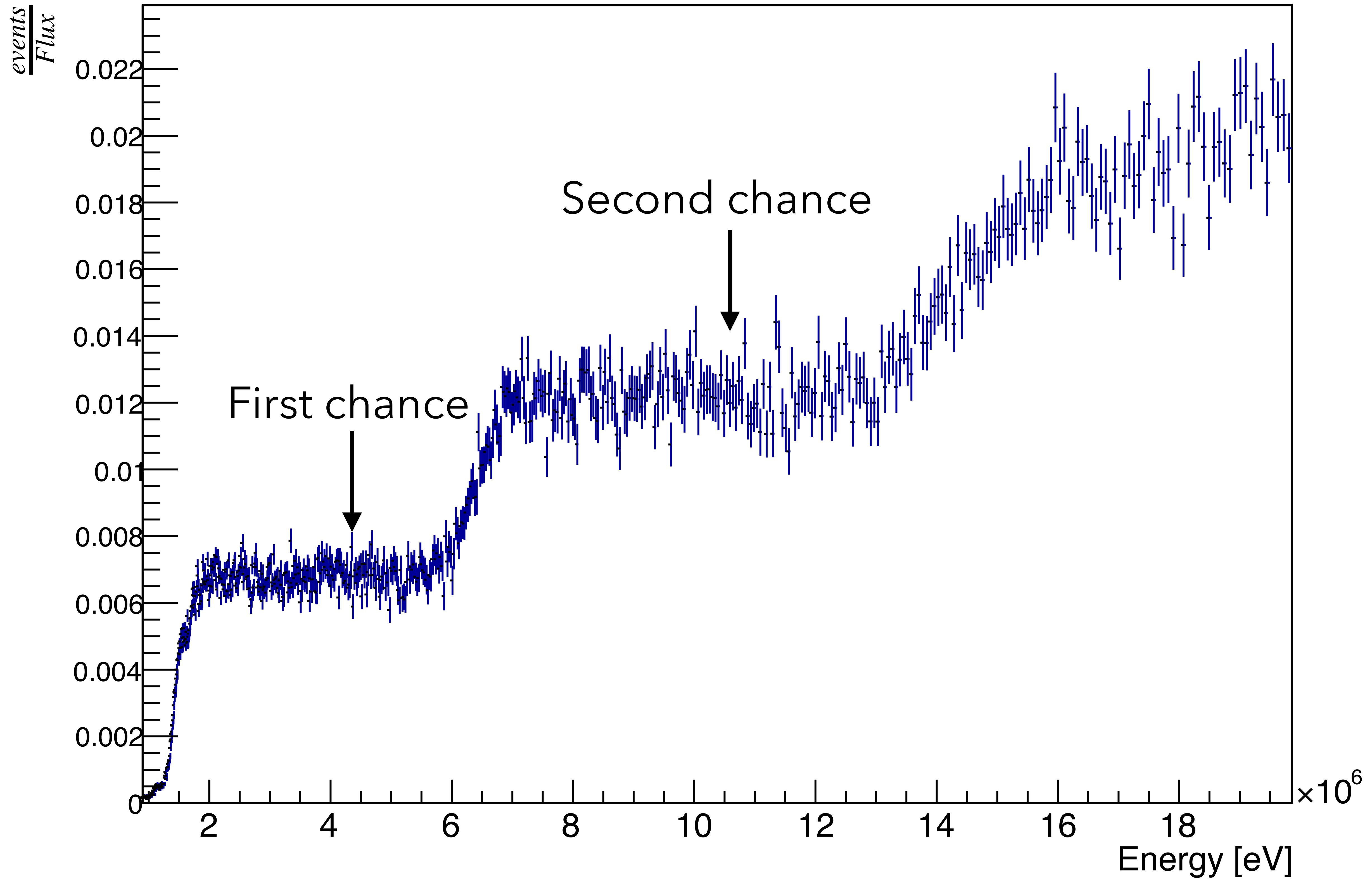
5. The differences $t_l - t_r$ and $t_t - t_b$ must be within the limits of the delay line (given by its length and speed).

Preliminary results U-238



Preliminary results U-238



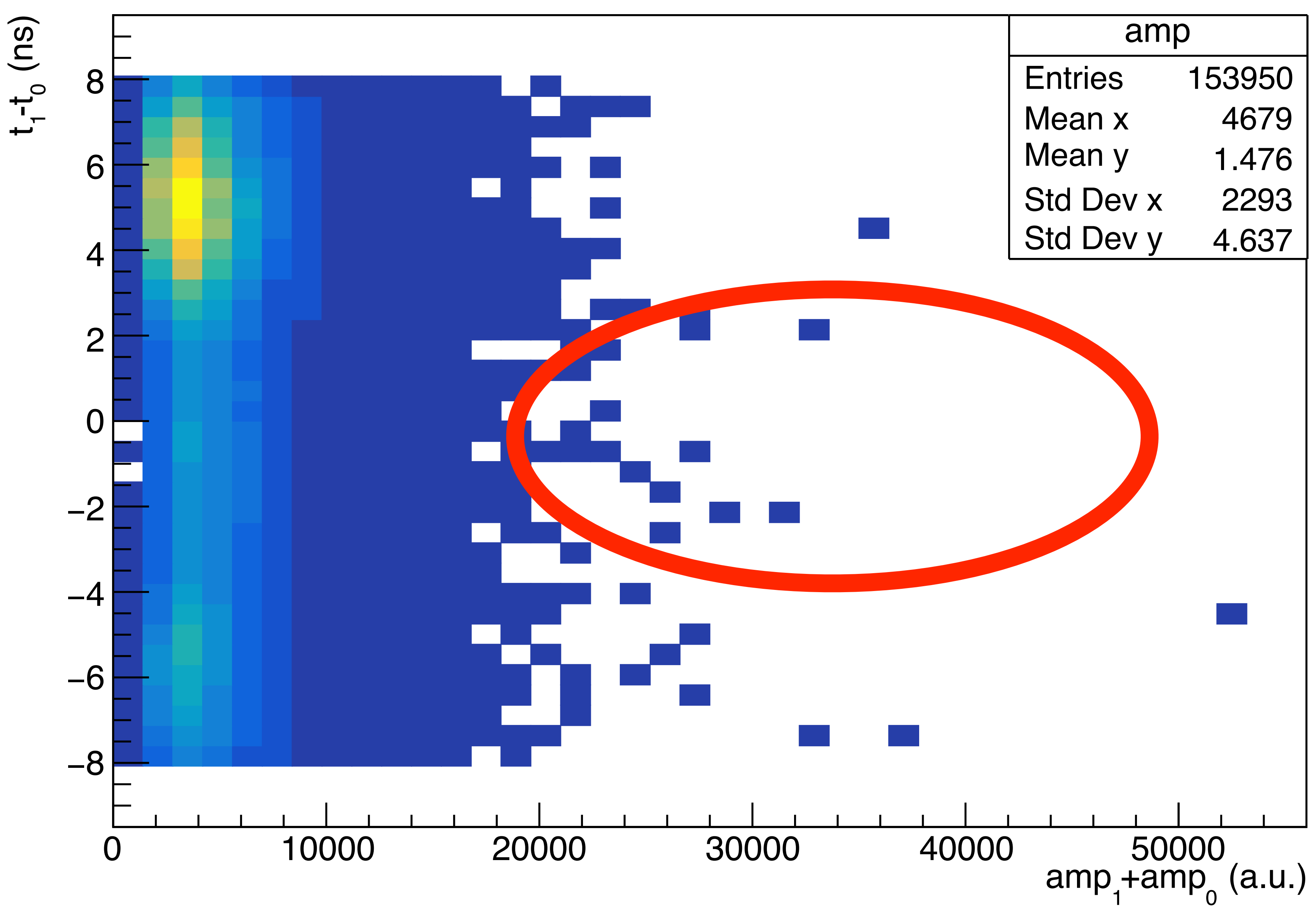


- We can observe the transition from asymmetric to symmetric fission modes.
- Background reactions become significant above 10 MeV.

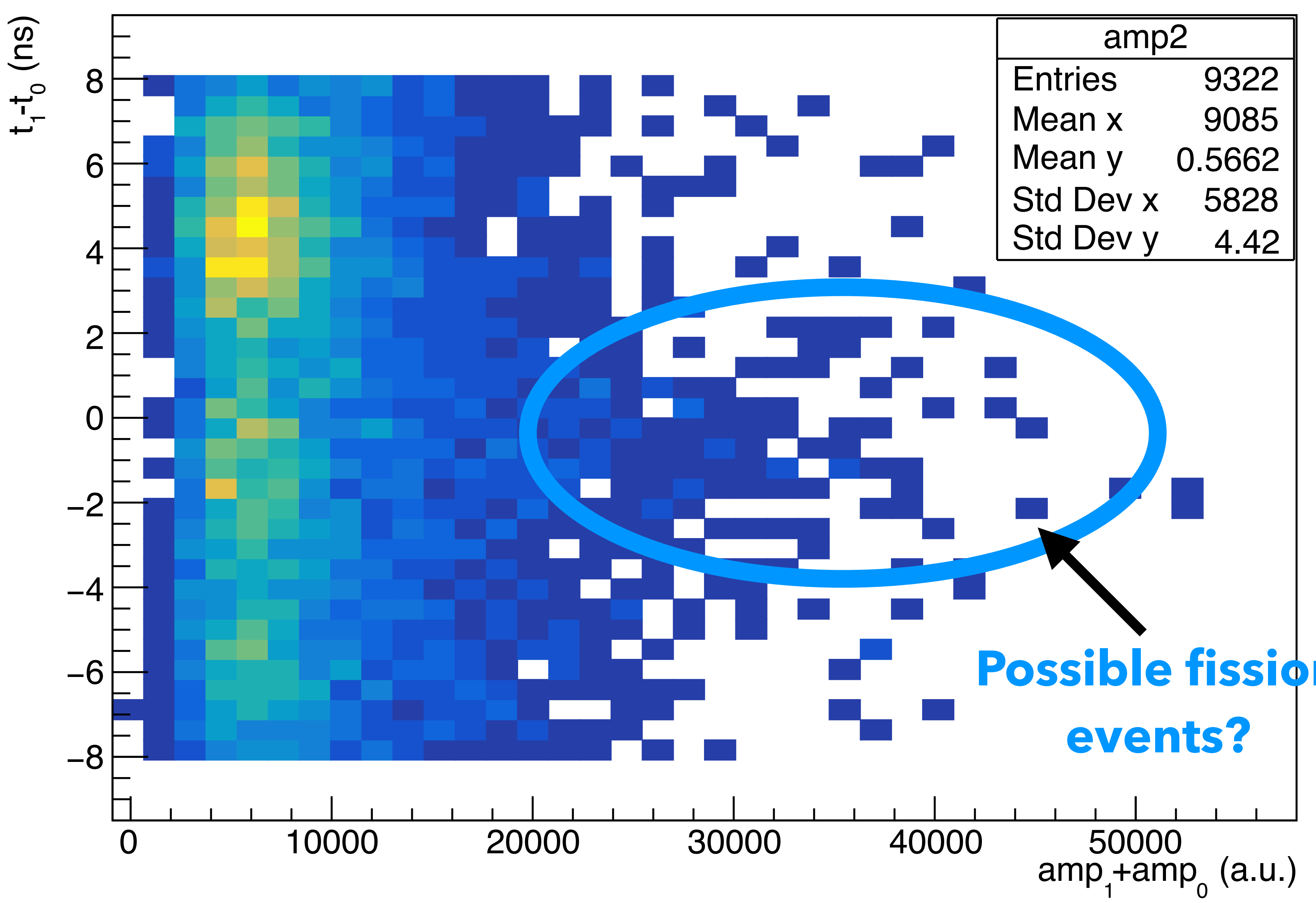
- Very preliminary fission cross section.
- Unnormalized with other measures.
- No corrections for efficiency or anisotropy.

Preliminary results Ce-140

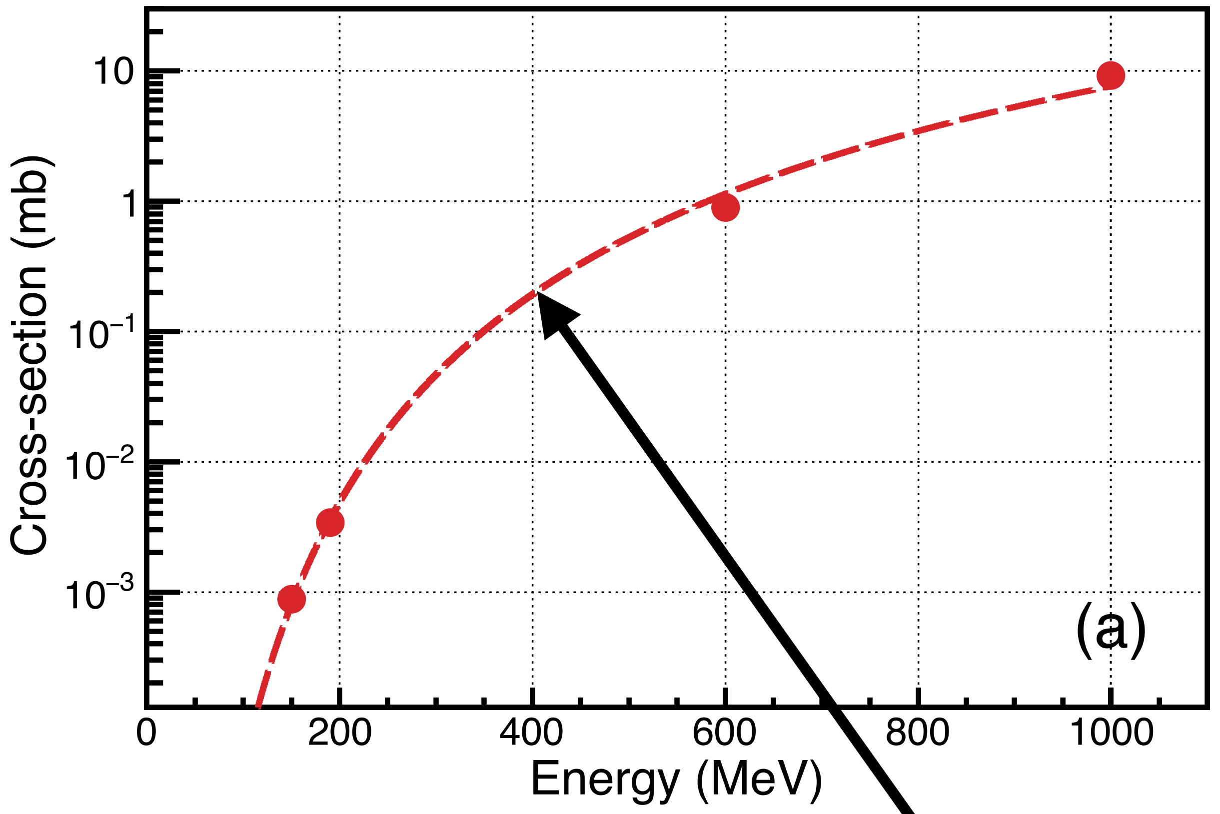
$E_n < 400$ MeV

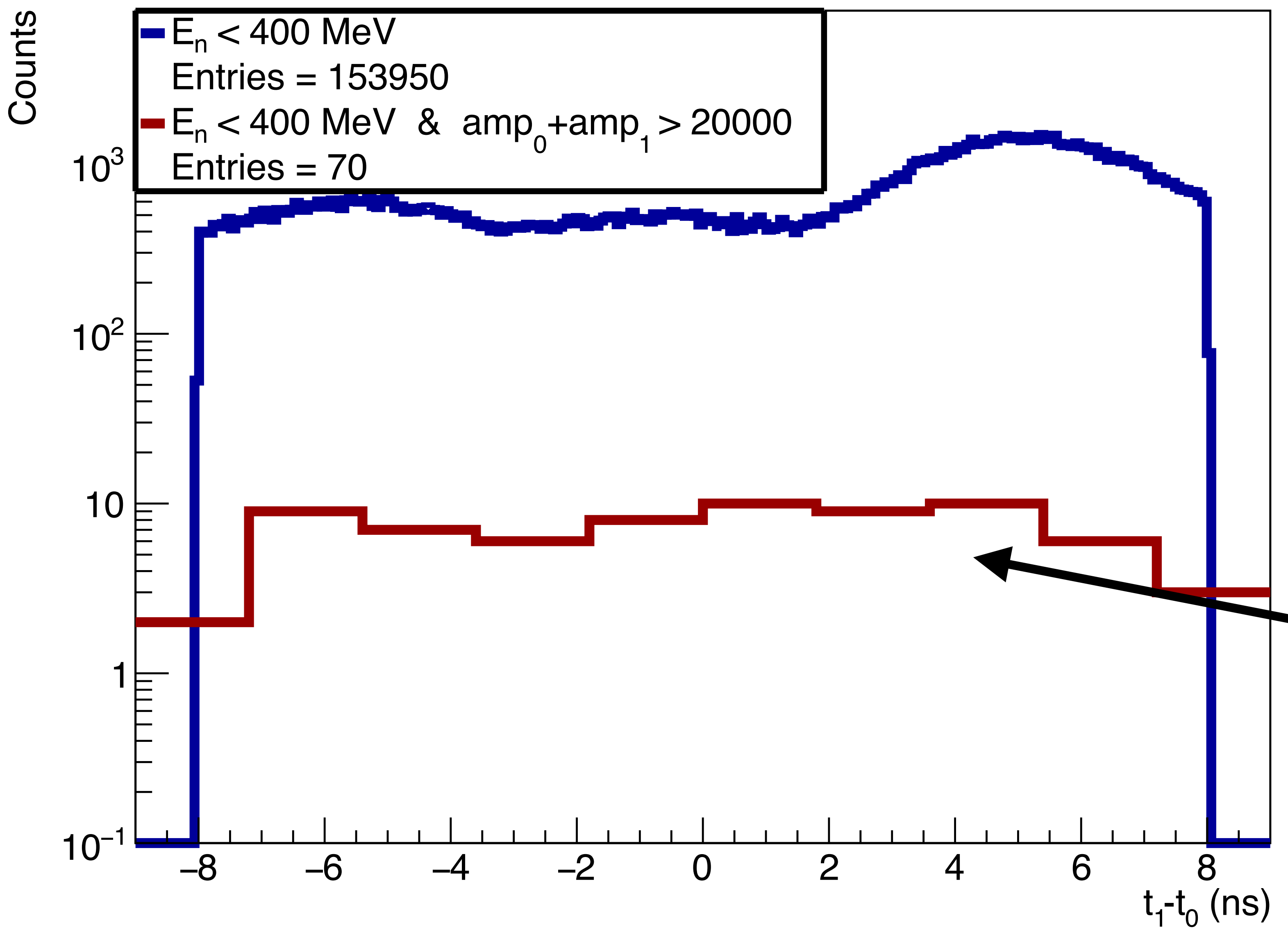


$E_n > 400$ MeV



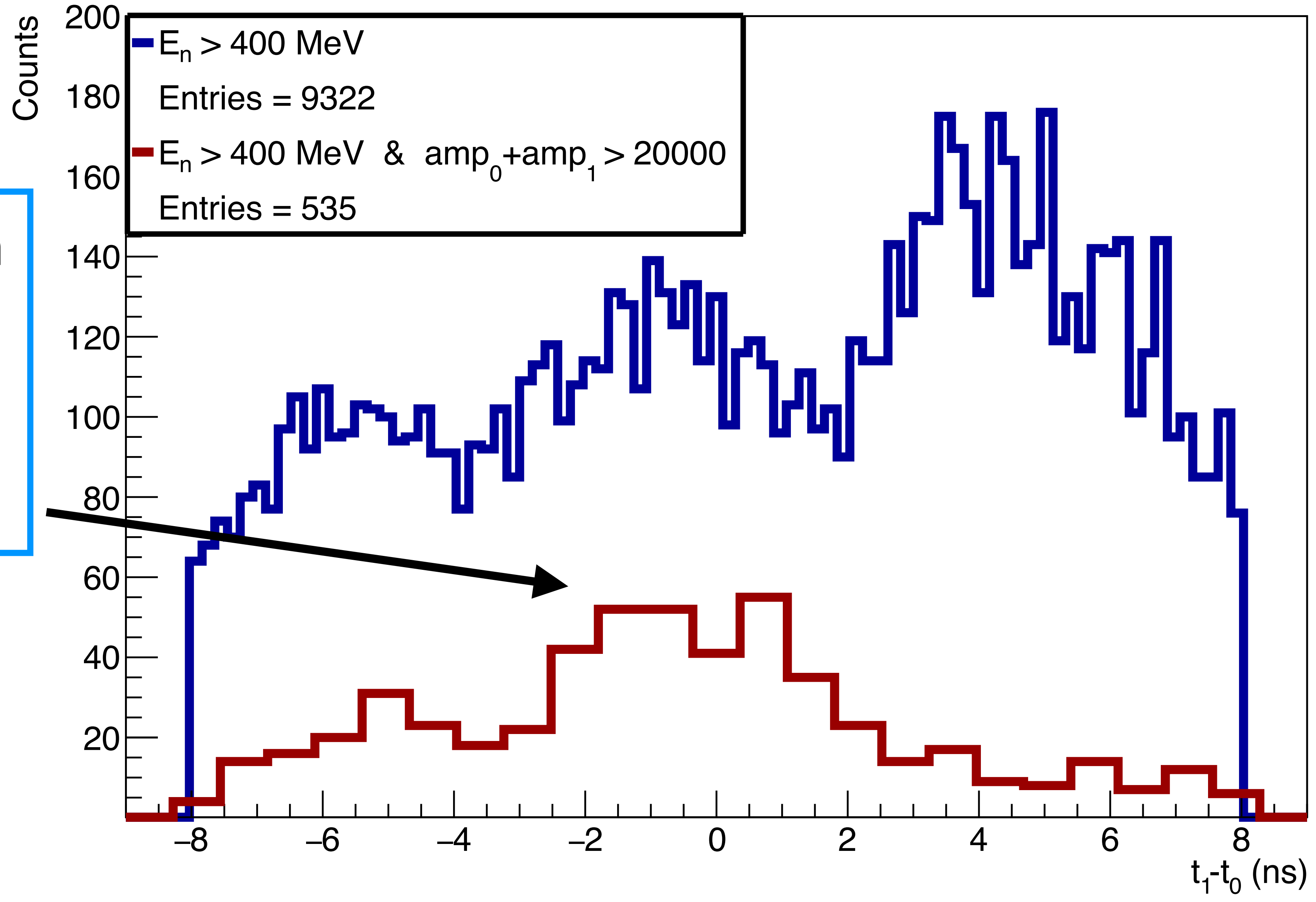
Possible fission events?





Nothing here...

A peak appears at high energies, as expected for cerium fission events



Summary and outlook

- For uranium, the preliminary results are satisfactory, as we were able to observe the transition from asymmetric to symmetric fission modes, and the preliminary cross section matches the expected shape correctly at low energies.

- Corrections for efficiency and anisotropy are needed in order to obtain a precise result.

- For cerium, stronger selection criteria is required to separate background from fission signals.

- The angle of emission could be a good observable since spallation and other high-energy reactions are expected to be forward-emitted.

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Acknowledgements

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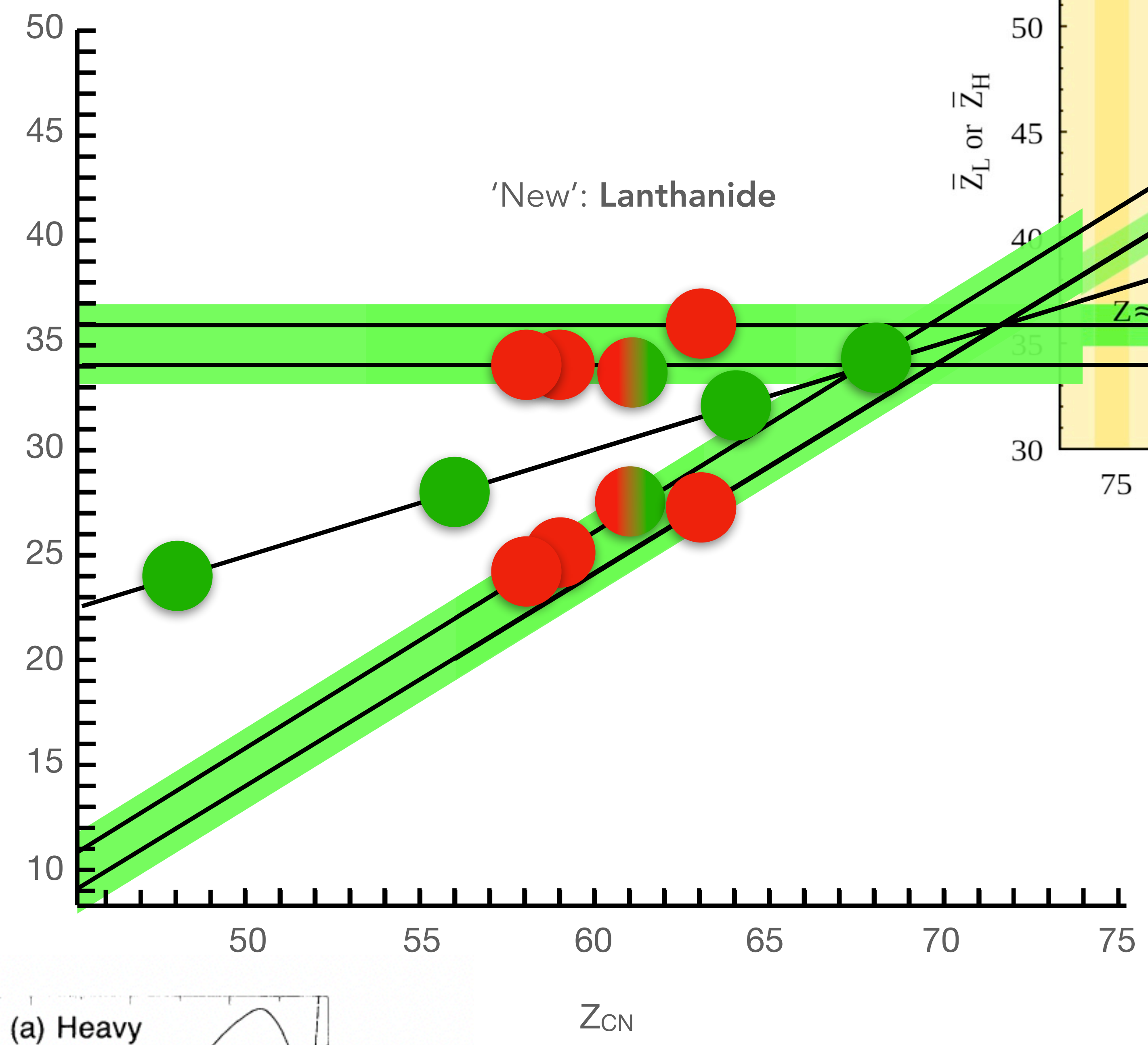
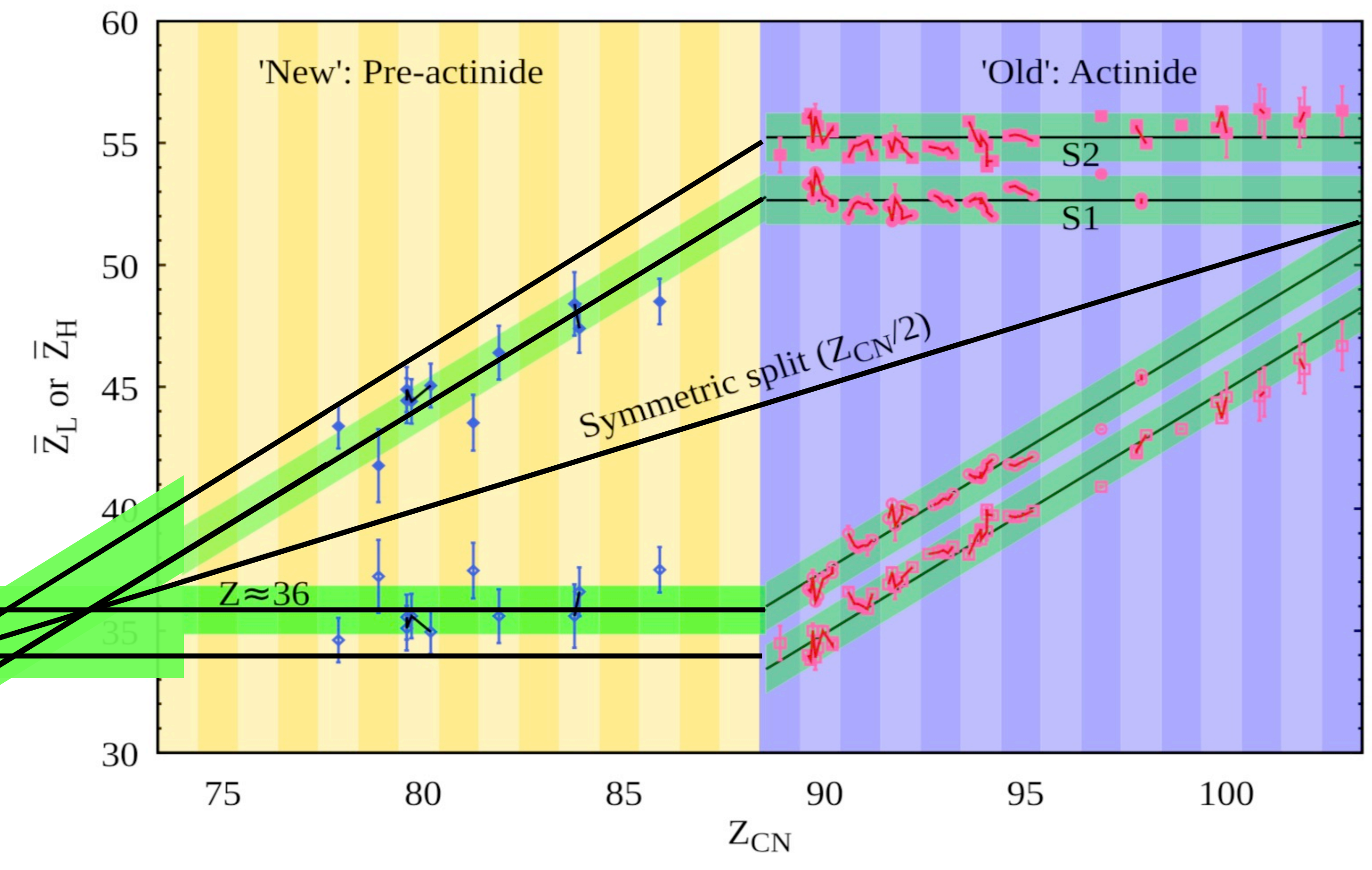
Cofinanciado pola Unión Europea
Fondos Europeos

What we expect

We expect that the octupolar Z=34 shell will take part in the fission dynamics of lanthanides favouring the heavy fragment charge to be nearly constant through the lanthanide region.

Below this area, we enter in the Businaro-Gallone region ($x = 0.4$*). The asymmetric fission of the elements below the B-G region is explained by the Liquid Drop model by instability against reflection asymmetric distortions of equilibrium shapes… and is characterized by a strongly asymmetric splitting (division in clusters).





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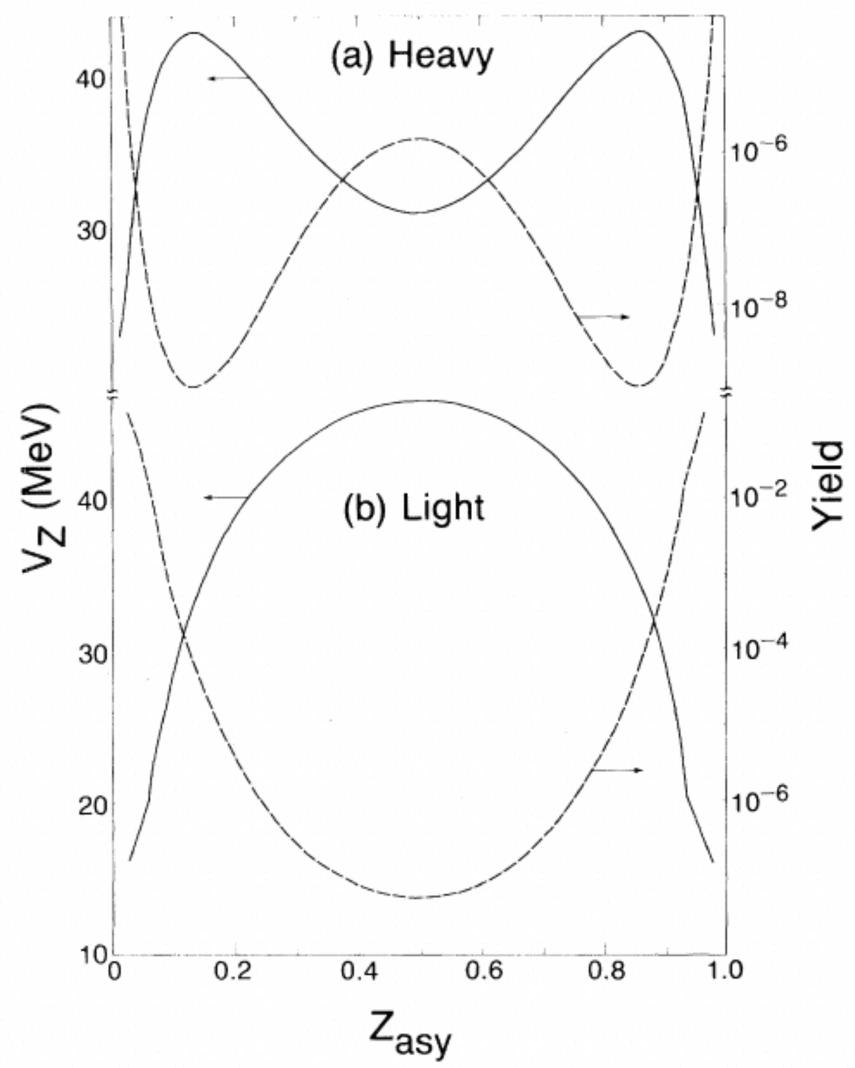
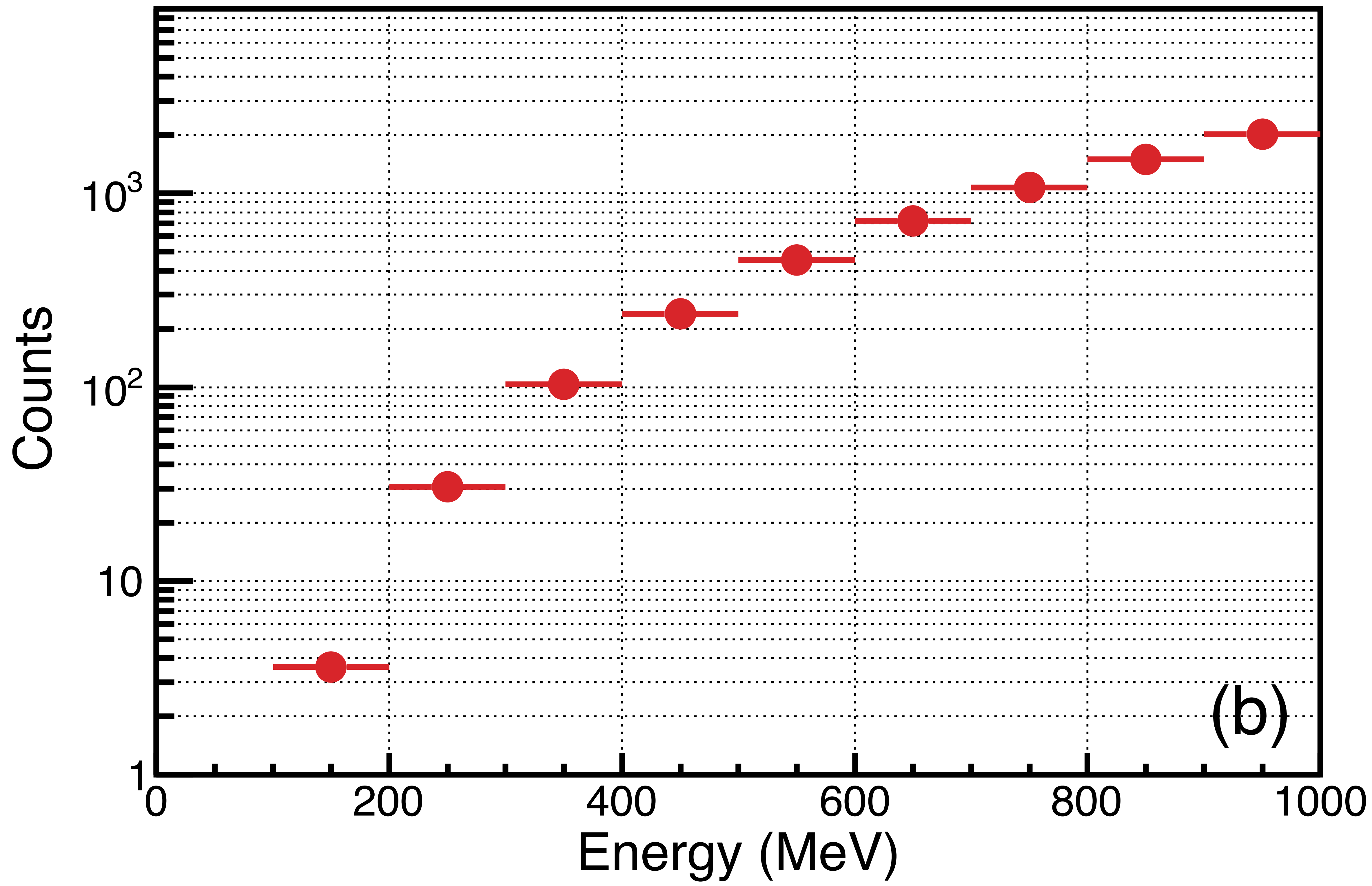


FIG. 1. Comparison of the potential energy surfaces (solid curve) and expected yields (dashed curve) for (a) a heavy CN (Au at $l=0$ and $E^*=97$ MeV) and (b) a light CN (Ge at $l=0$ and $E^*=72$ MeV).

*x= *Fissility parameter* $\approx \dfrac{1}{50} Z^2 A$

For cerium, $x = 0.48\ldots$

What we expect (in counts)

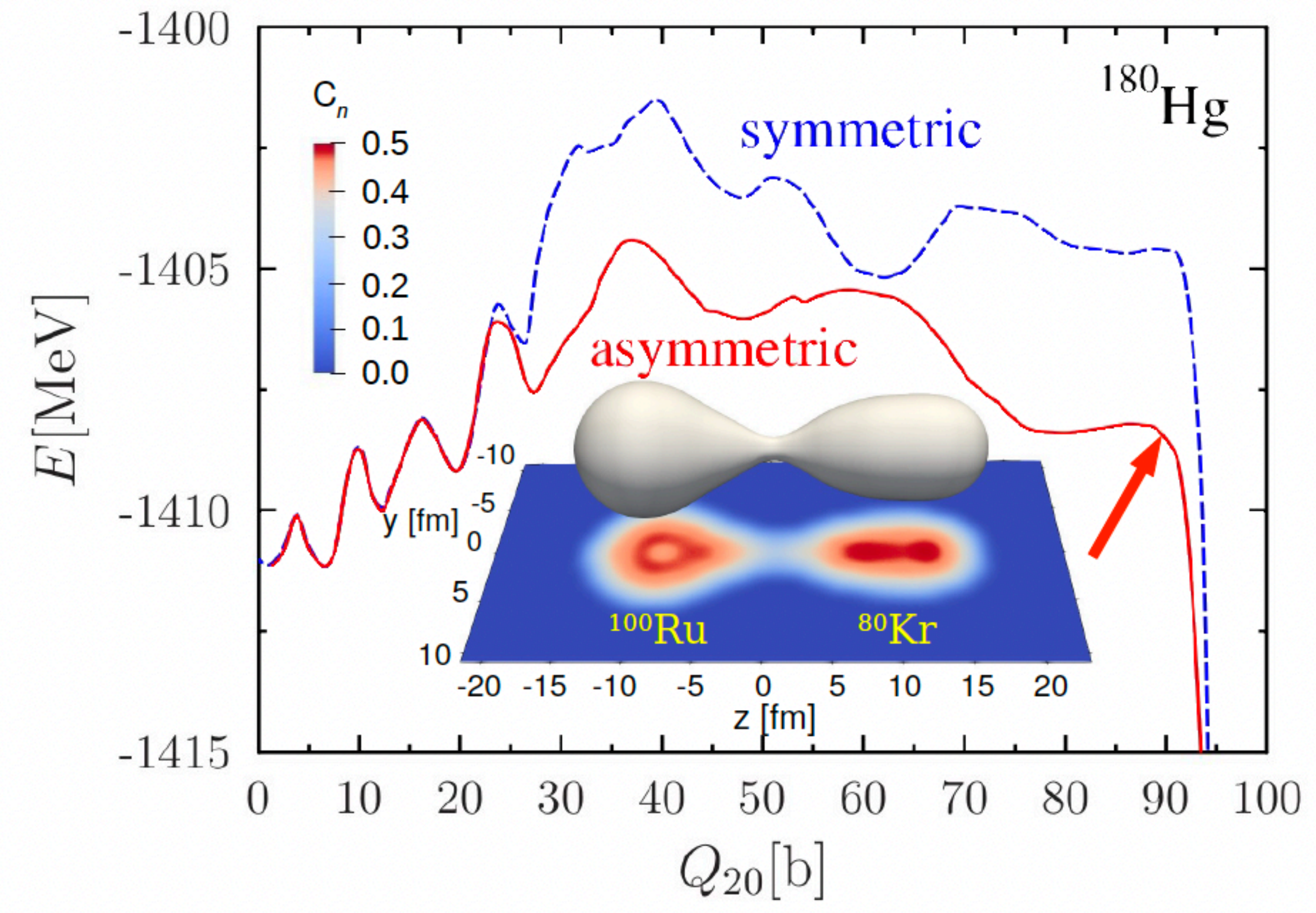


With 7 samples of ~**1 mg/cm²** and **3x10¹⁸ protons**, the statistics are enough to cover a wide energy range.

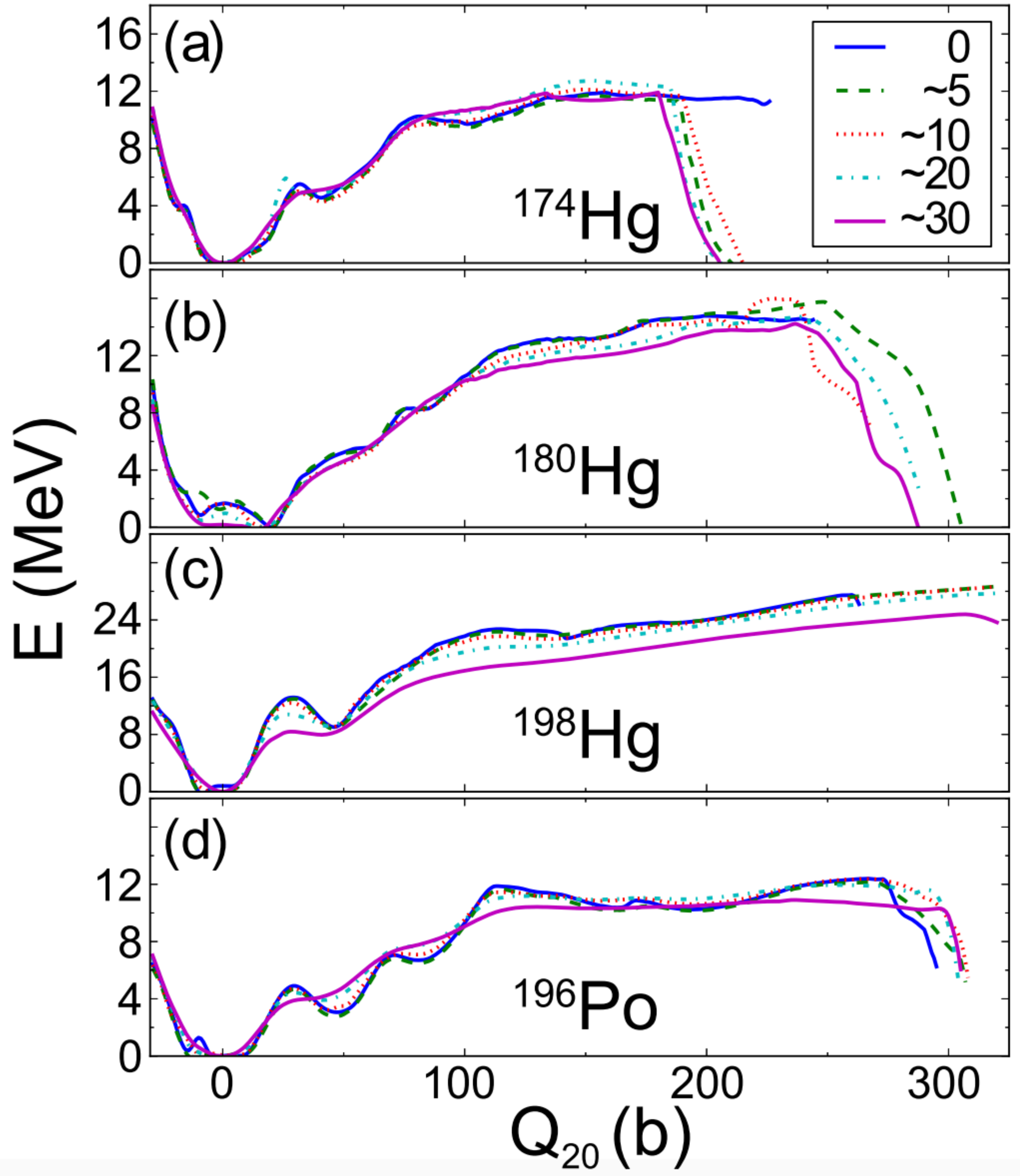
From 400 MeV to 1 GeV, more than 100 cts per 100-MeV can be collected.

Why is no change in fission mode expected for Cerium?

- Theoretical studies on the fission potential for sub-lead systems with respect to the excitation energy show a more gentle relation compared to actinides.
- This suggests that asymmetric valleys are still favoured at high excitation energies



Physical Review C 100, 041602(R) (2019)



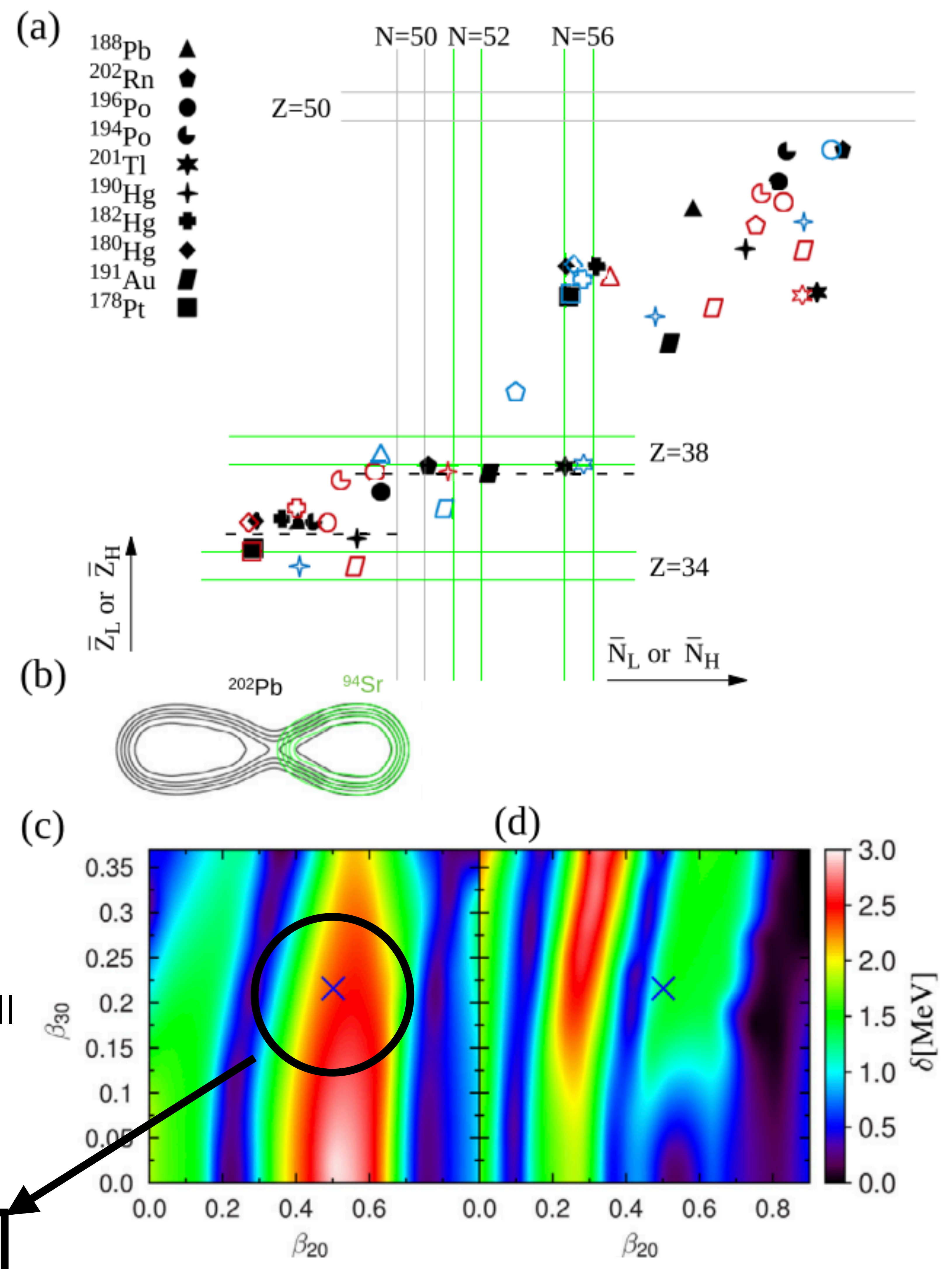
J. D. McDonnell, W. Nazarewicz, J. A. Sheikh, A. Staszczak, and M. Warda, Phys. Rev. C 90, 021302(R) (2014).

Why the shell appears at Z=36?

- According to Mahata, Schmitt, Gupta et al, this fluctuation between Z_L=34 and Z_L=38 appears due to 2 different dynamics.

1. For N_L<50 , a shell gap appears at Z_L=34 due to an elongated $\beta_2 > 0.5$ quadrupole-octupole deformation.

2. On the other hand, for N_L>50, a shell gap appears at Z_L=38 due to a more compact deformation ($\beta_2 < 0.5$).



Proton shell
Z=38

Neutron
N=56

Scission is determined by proton shell!

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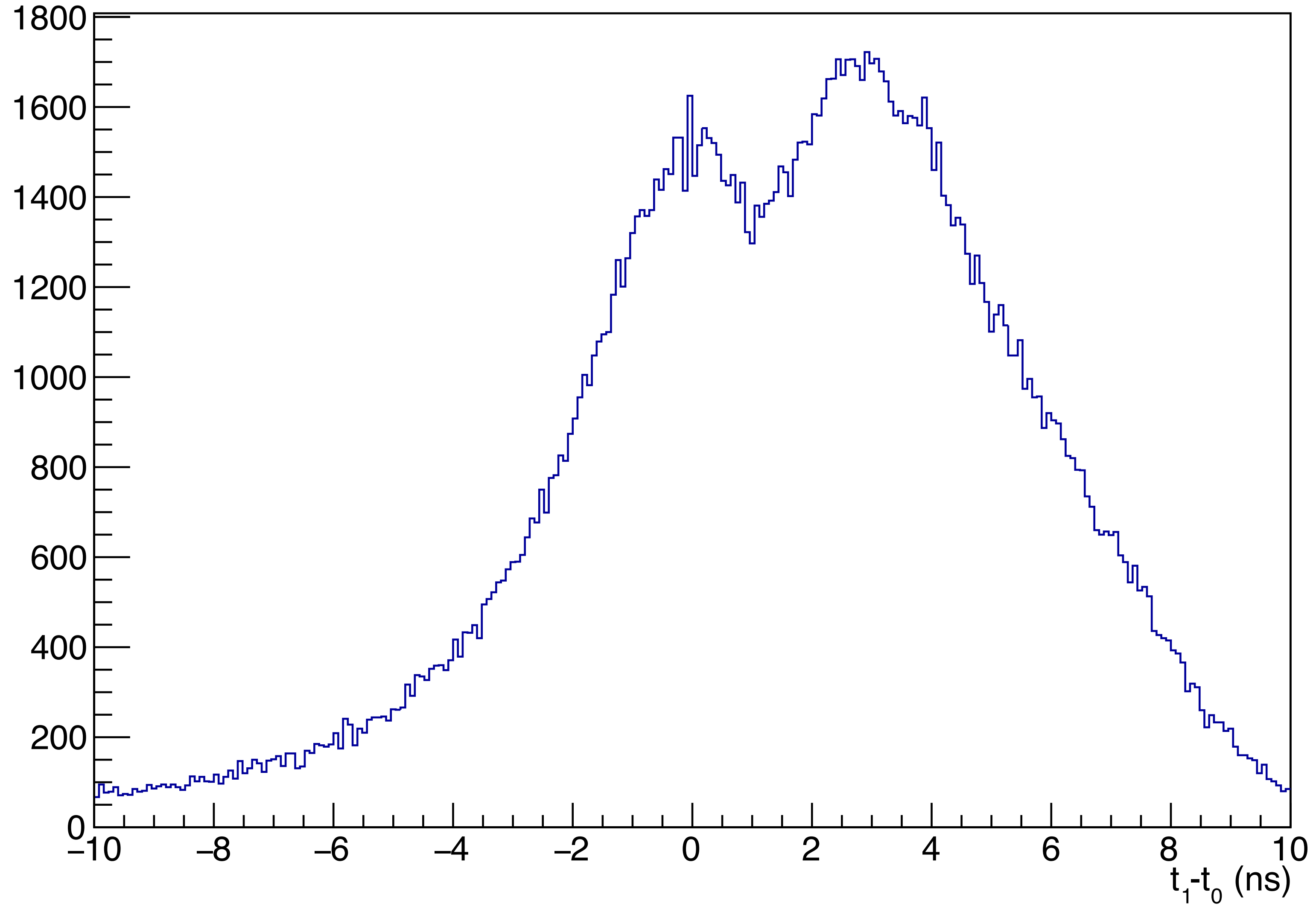
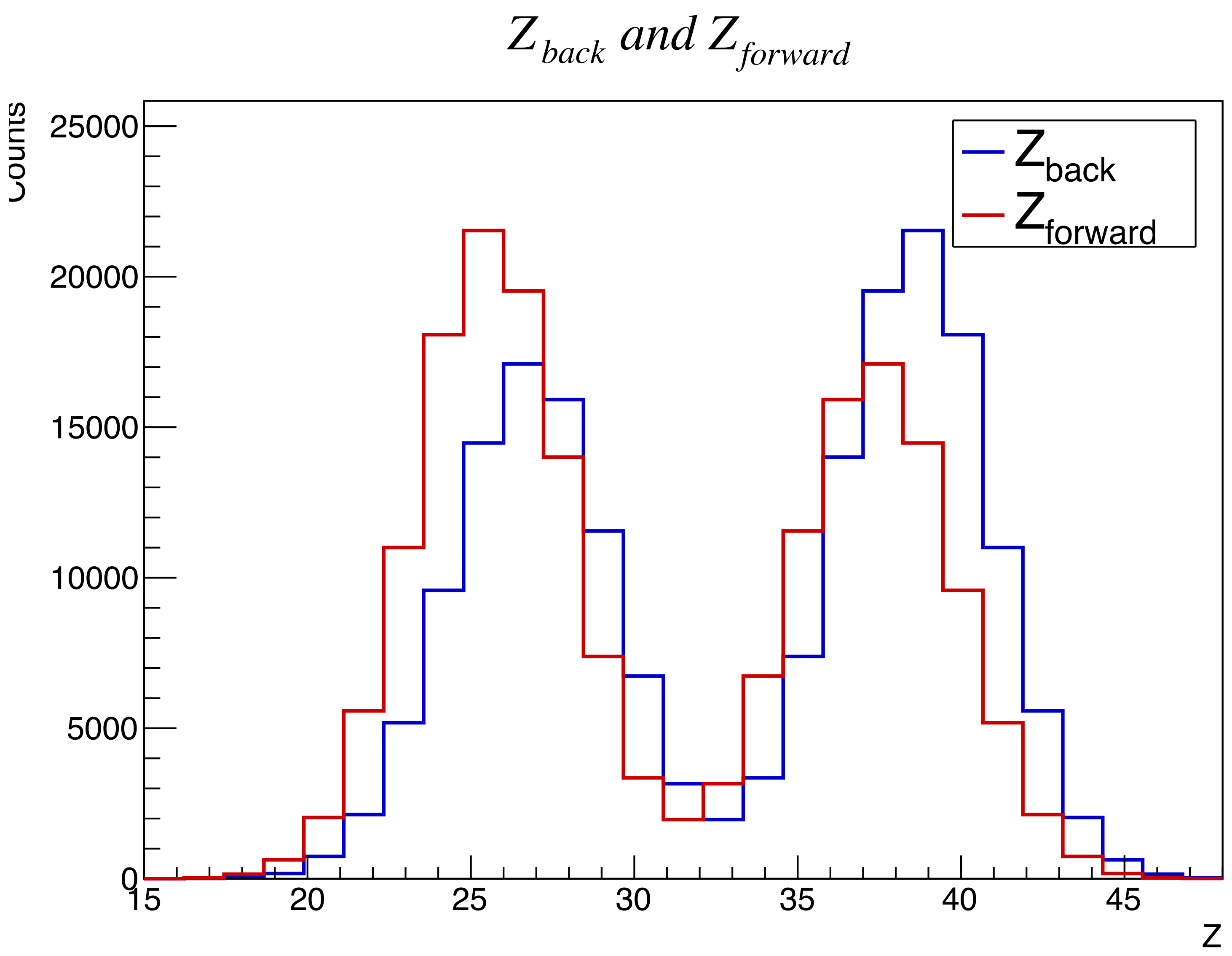
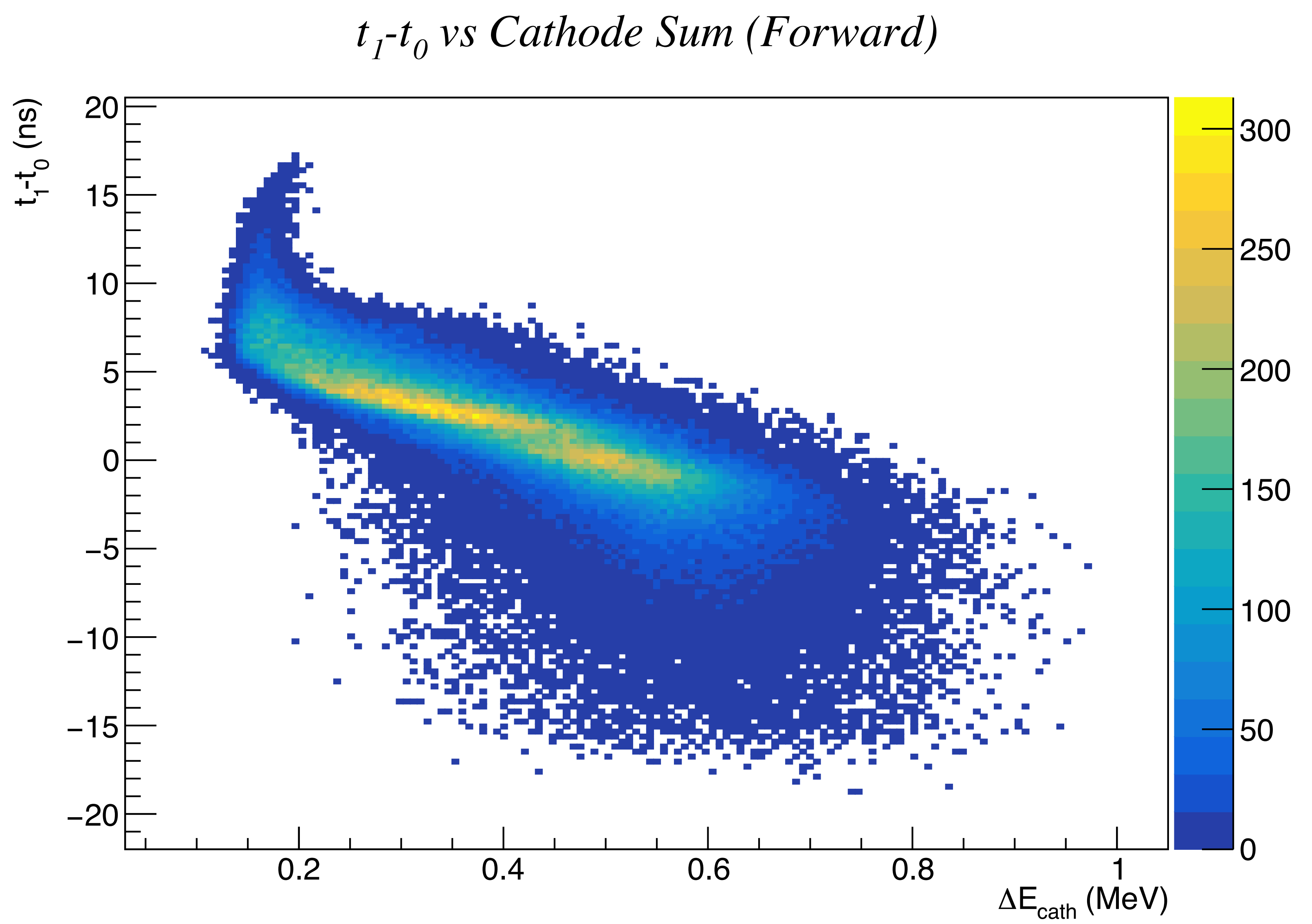
What we expect from Cerium fragments



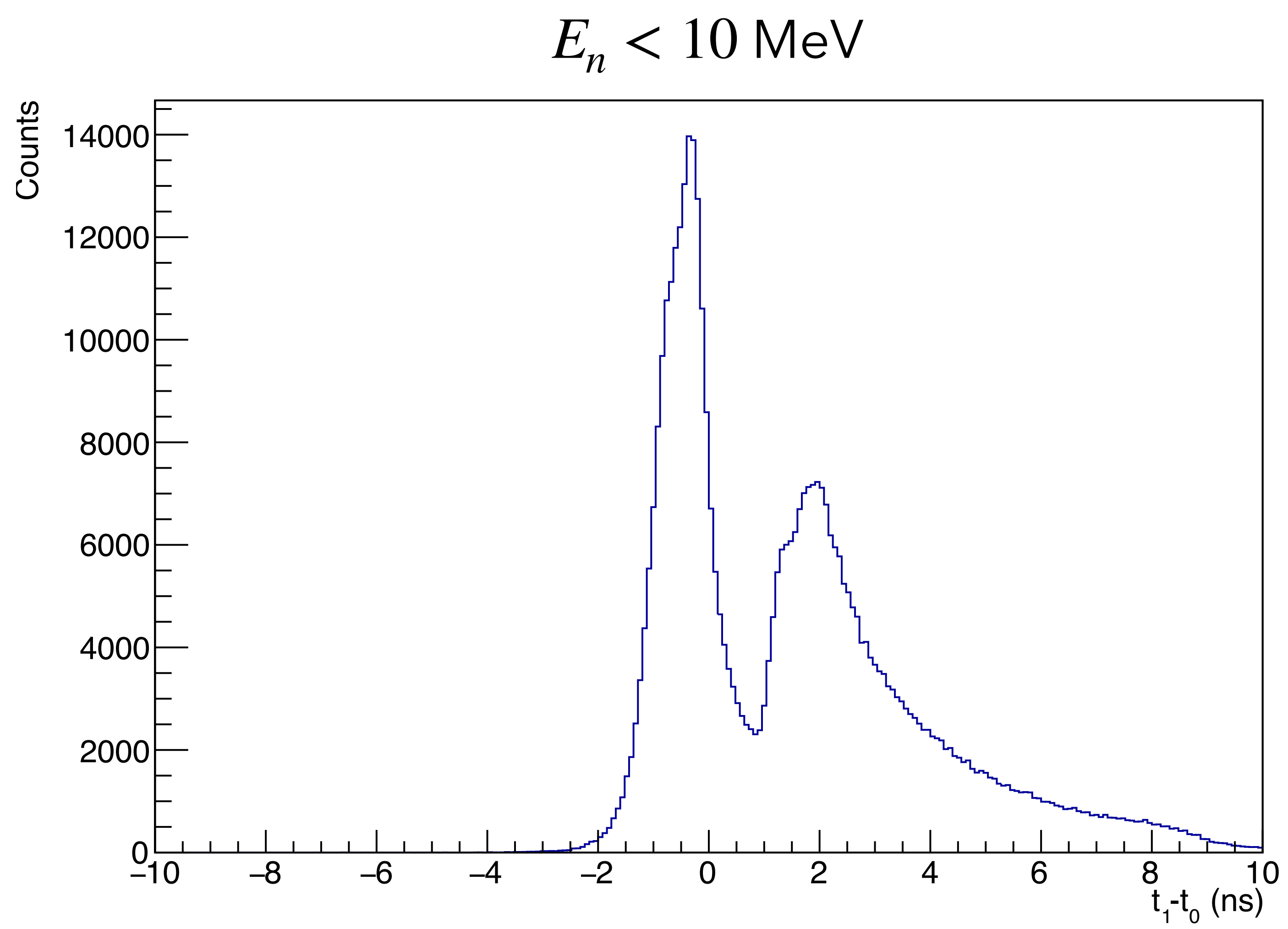




*The simulation was performed using ATIMA for energy losses and the fragments were formed by using Viola systematics to match the TKE, and one of the fragment follows a gaussian distribution with mean Z=34 and $\sigma = 2$ (where the mass is computed under the UCD assumption). We assume that the mass and charge of the parent nucleus is the sum equal of the fragments masses and charges (no neutron evaporation).

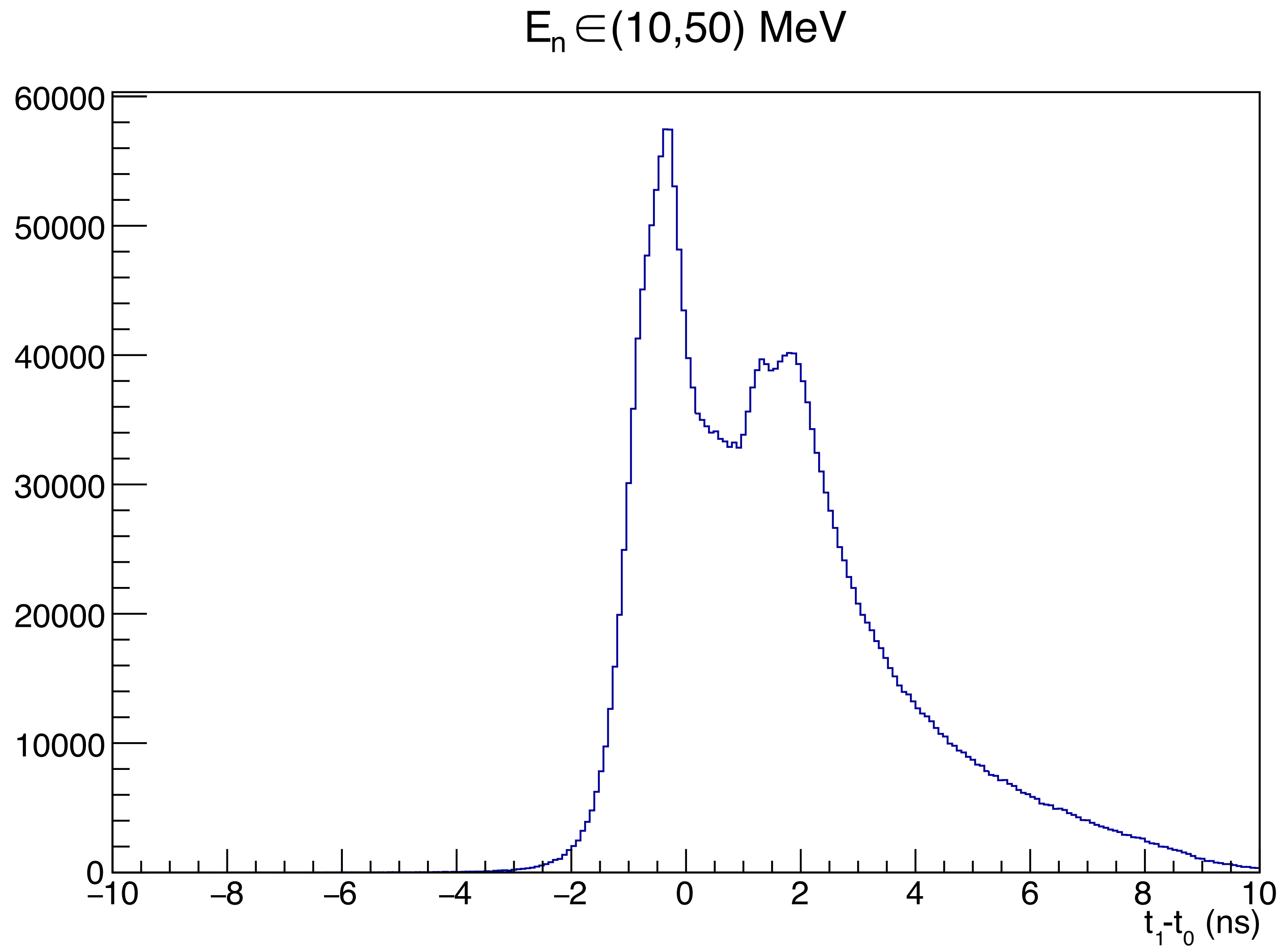
If fission of cerium were asymmetric, we would see 2 peaks. The backing effect is not pronounced as the heavy fragments have a low detection efficiency when they go through the backing. Thus, most of the detected heavy fragments must traverse less matter hence smaller time differences between the peaks.

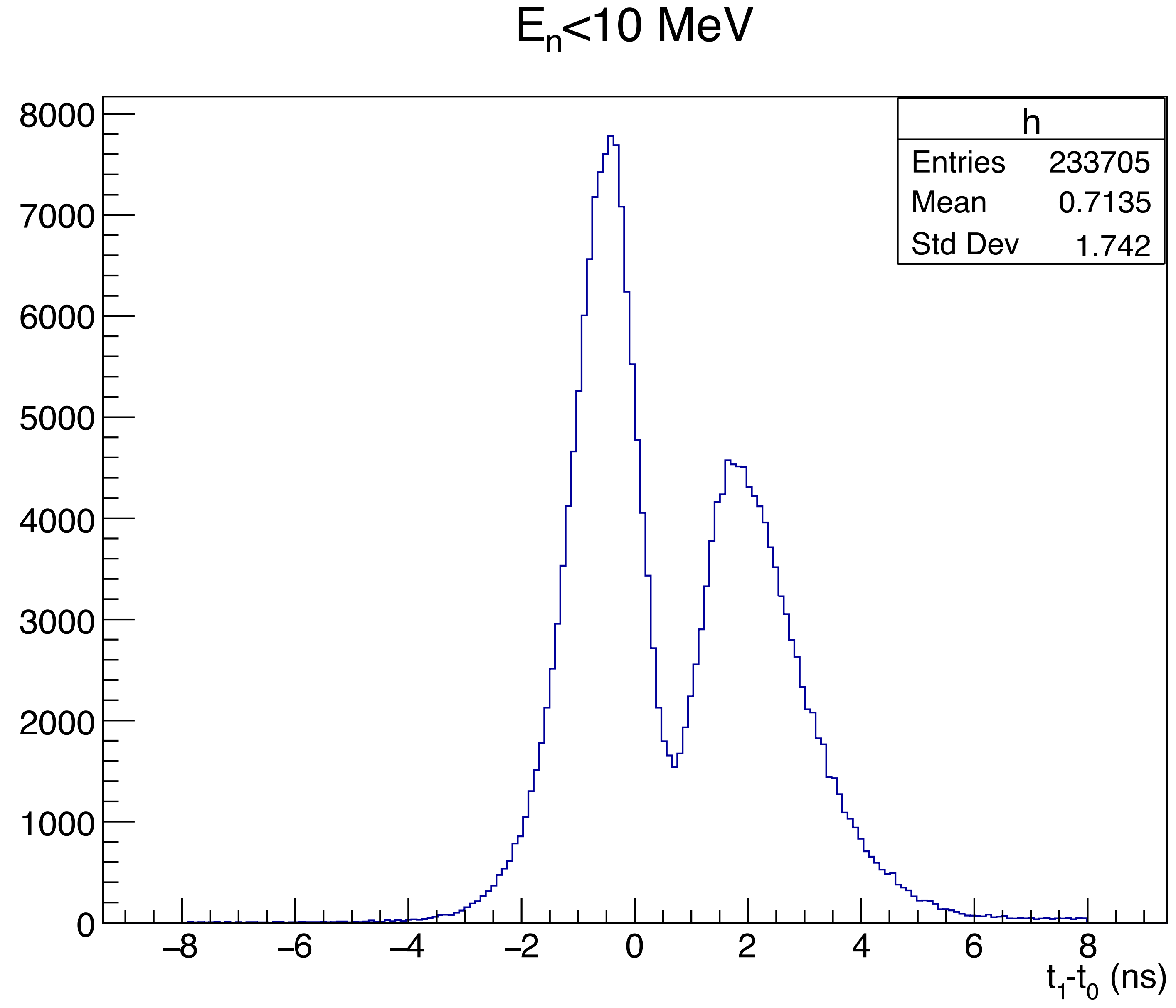
Simulation vs Data Uranium



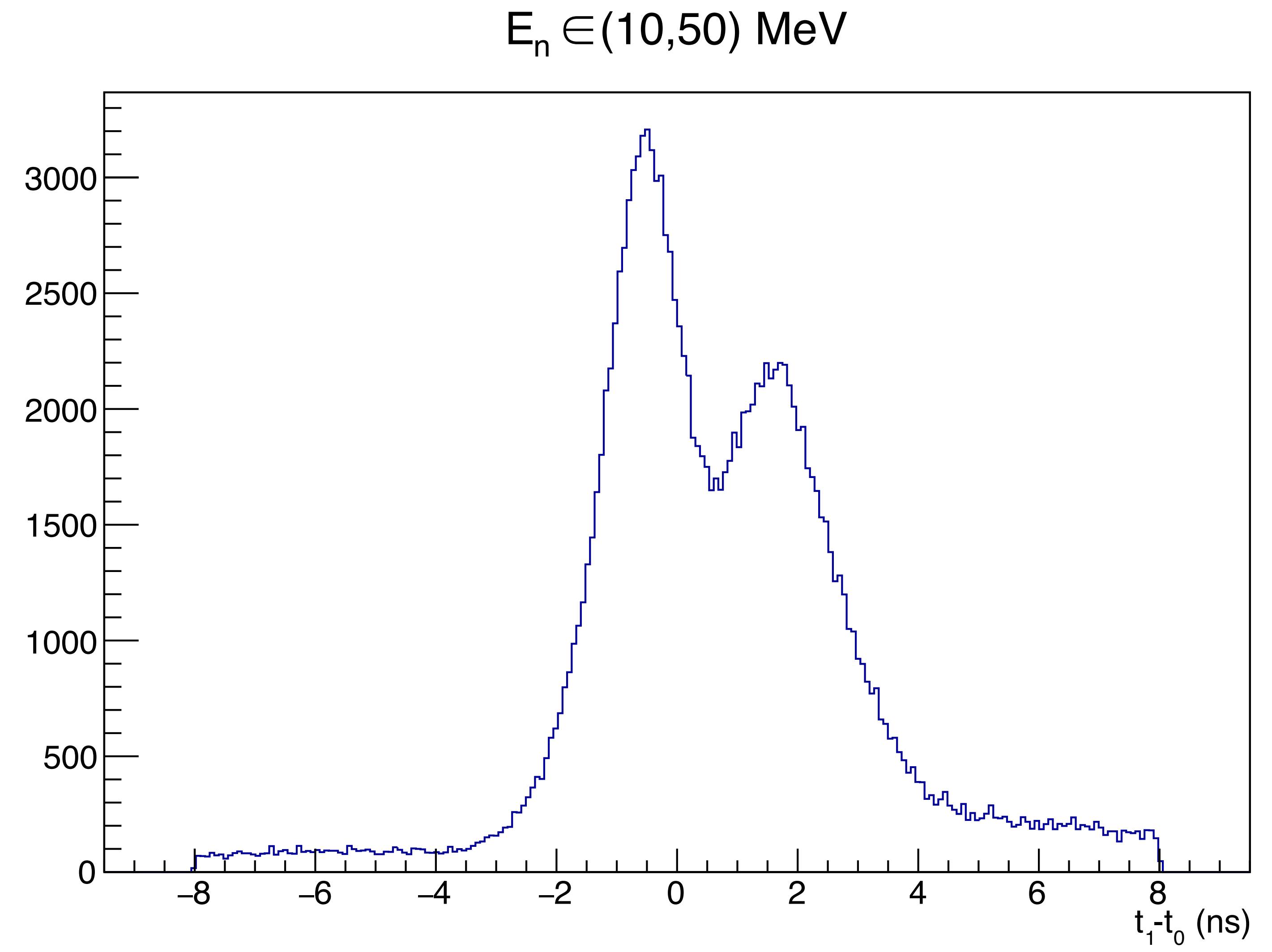
Simulation

(Fission events obtained with GEF and energy losses with ATIMA)

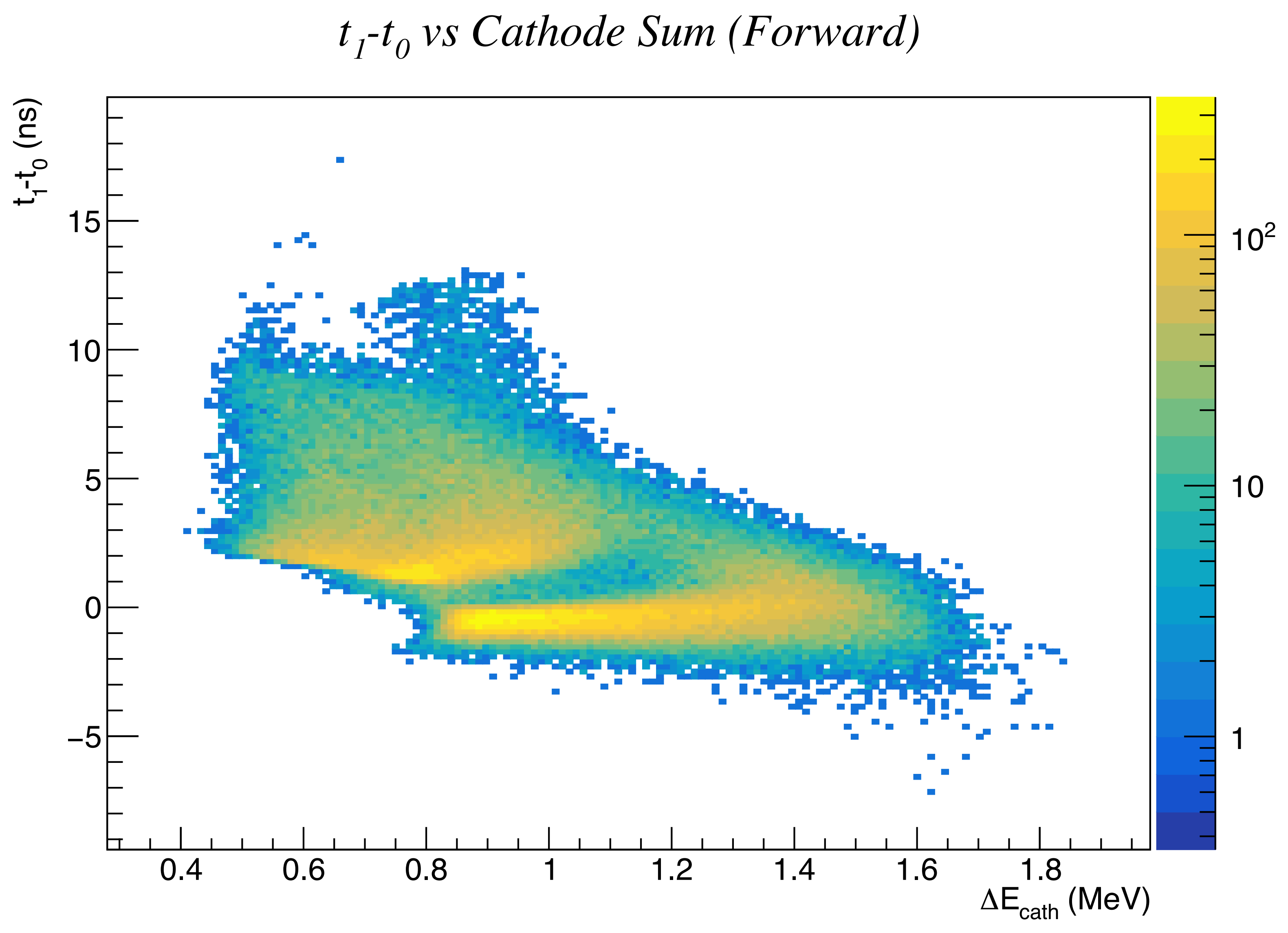




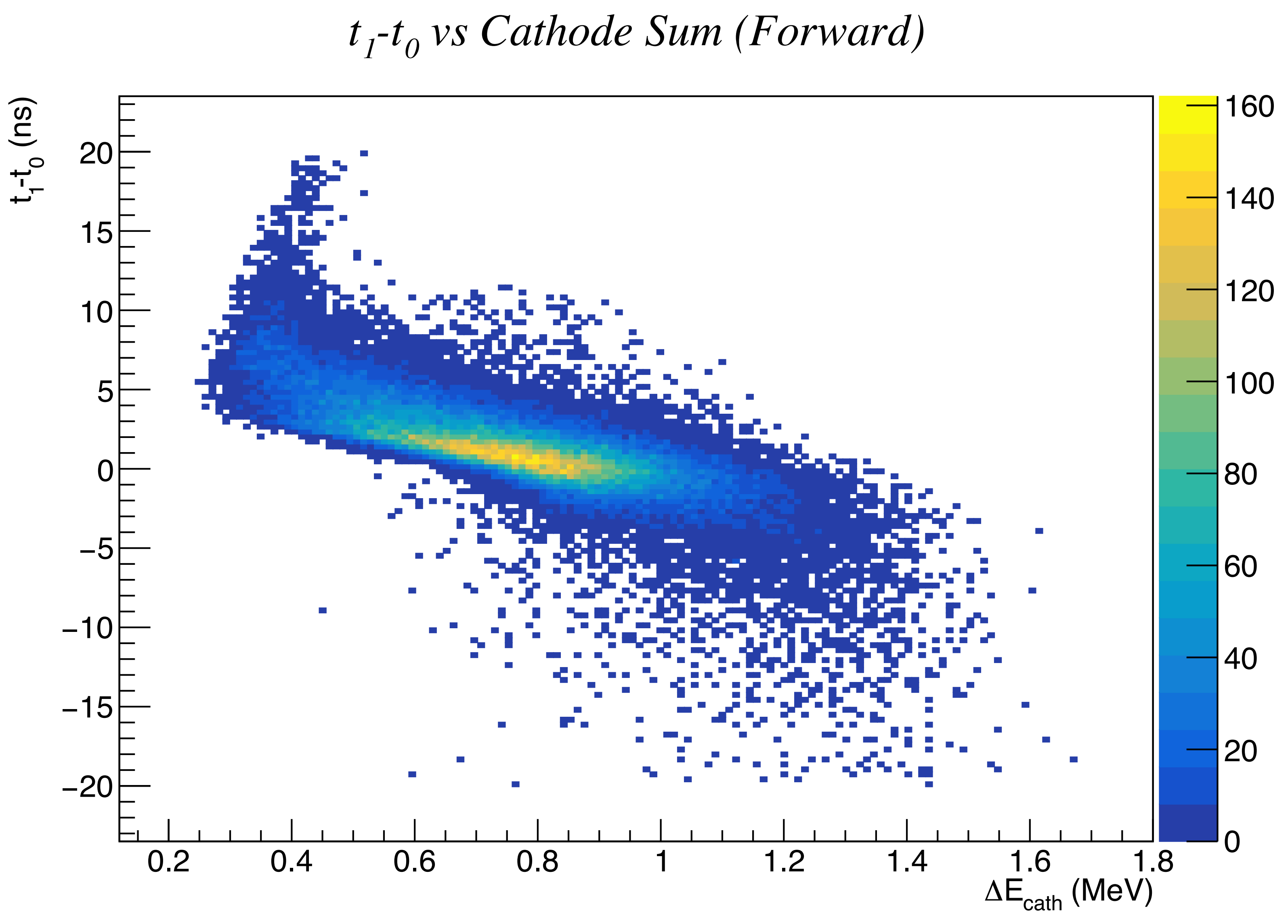
Data



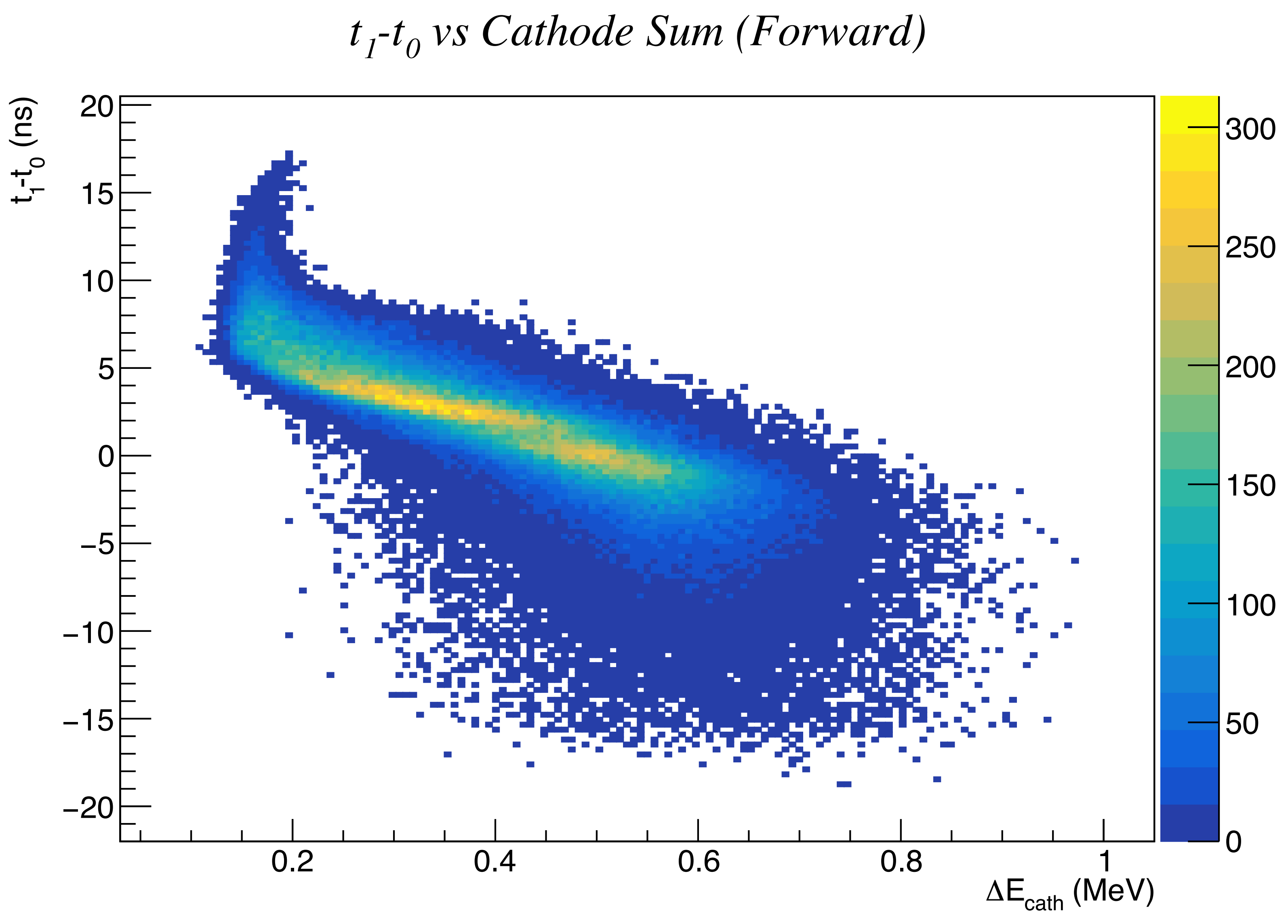
Amplitude differences between U and Ce



U-238, 5 MeV



U-238, 100 MeV

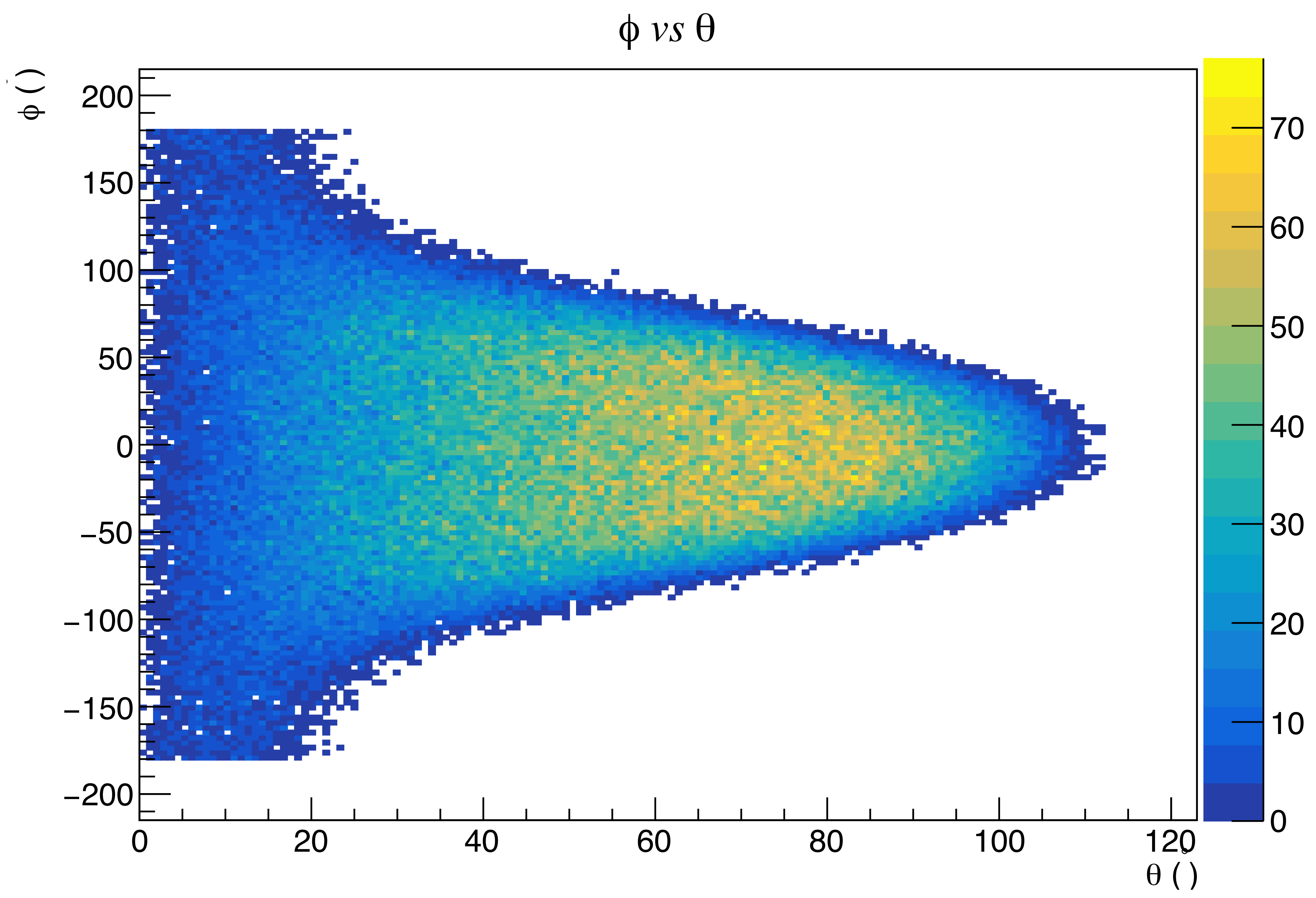


Ce-140

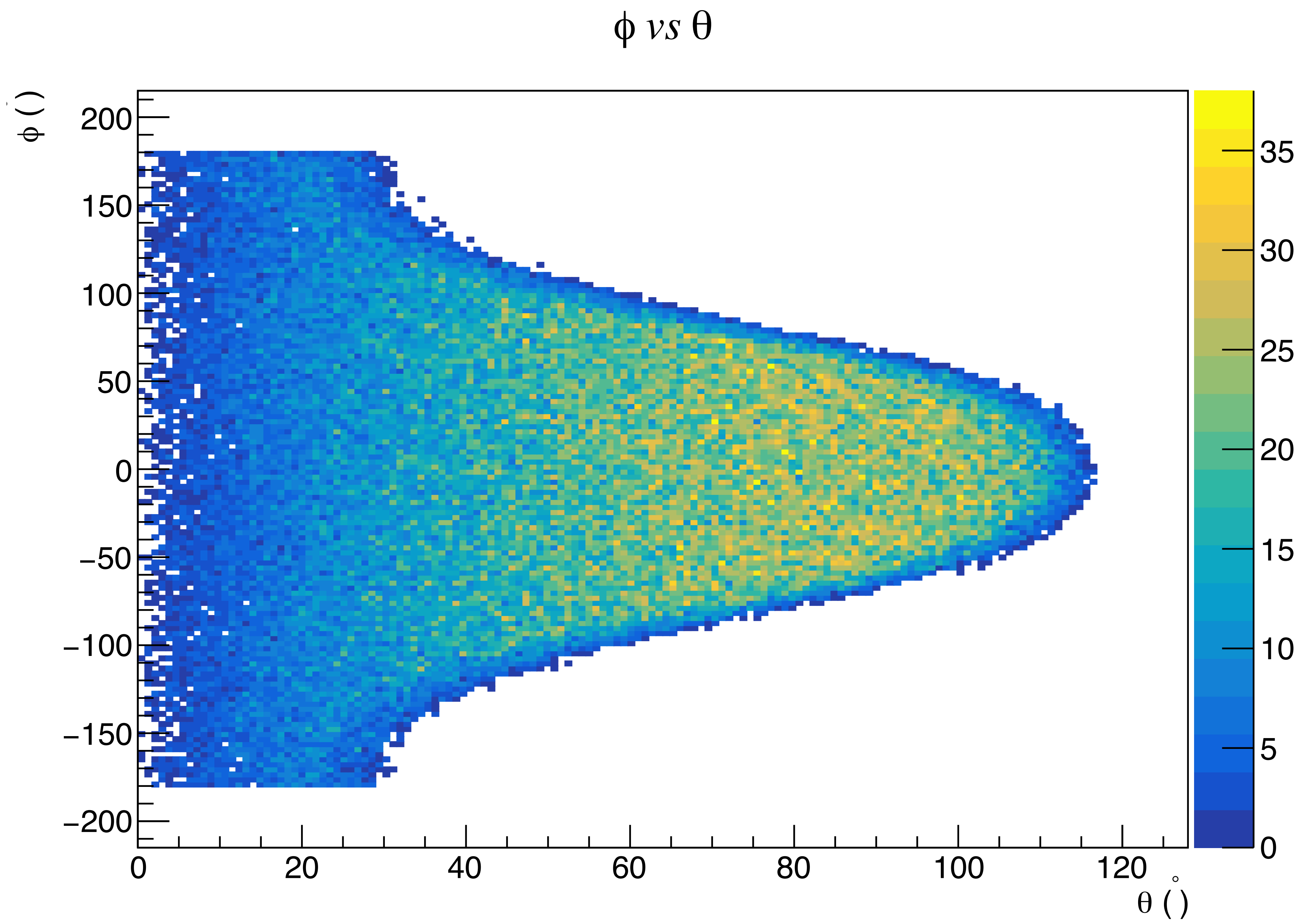
In general, the ratio of energy loss in the gas for Cerium fragments is around half of that of Uranium fragments. These energies range from 200 to 400 keV for the HFF and from 400 to 800 keV for the LFF.

Expected efficiency of detection

Efficiency cerium



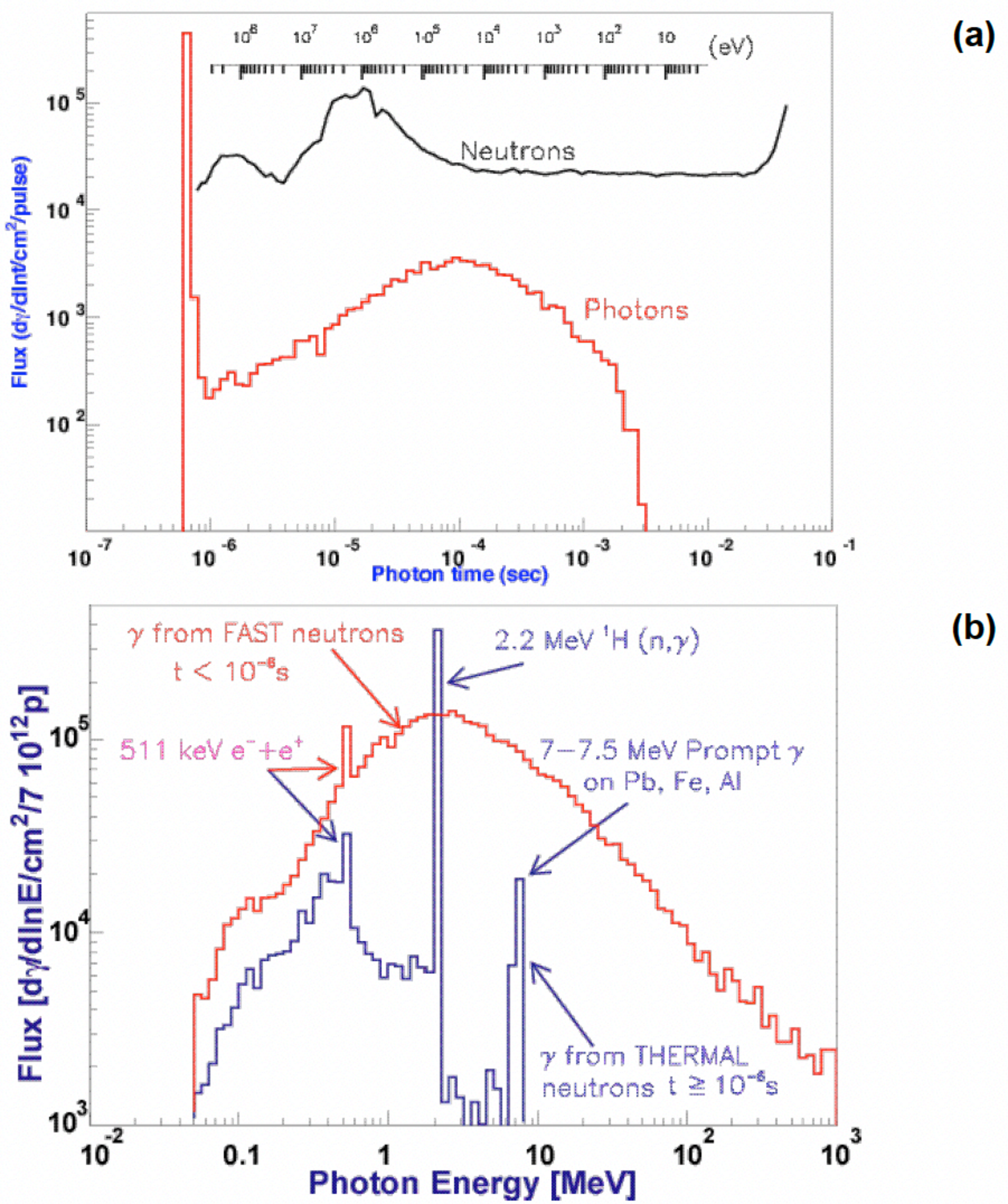
Efficiency of Uranium 5 MeV



Lower detection efficiency due to the lower TKE of the fragments.

What is the gamma flash?

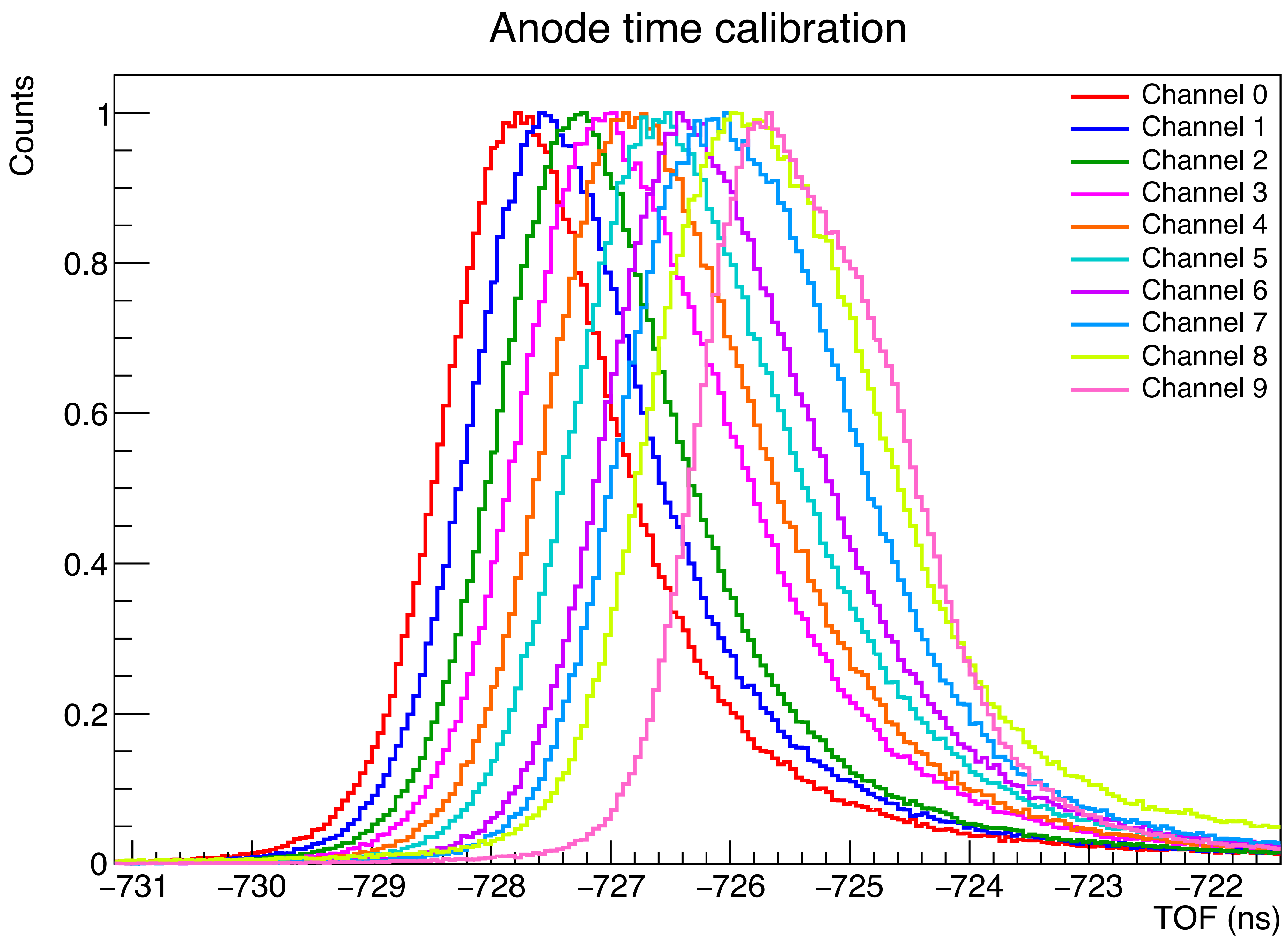
- Photons are produced after the spallation in the lead target.
- These photons may have sufficiently high energies in order to induce the creation of particle-antiparticle pairs.
- These particles, mainly electron-positron pairs, may reach the detector area and pass through every detector (since they are MIPs).
- These signals can be used as time references since they reach all detectors almost simultaneously.



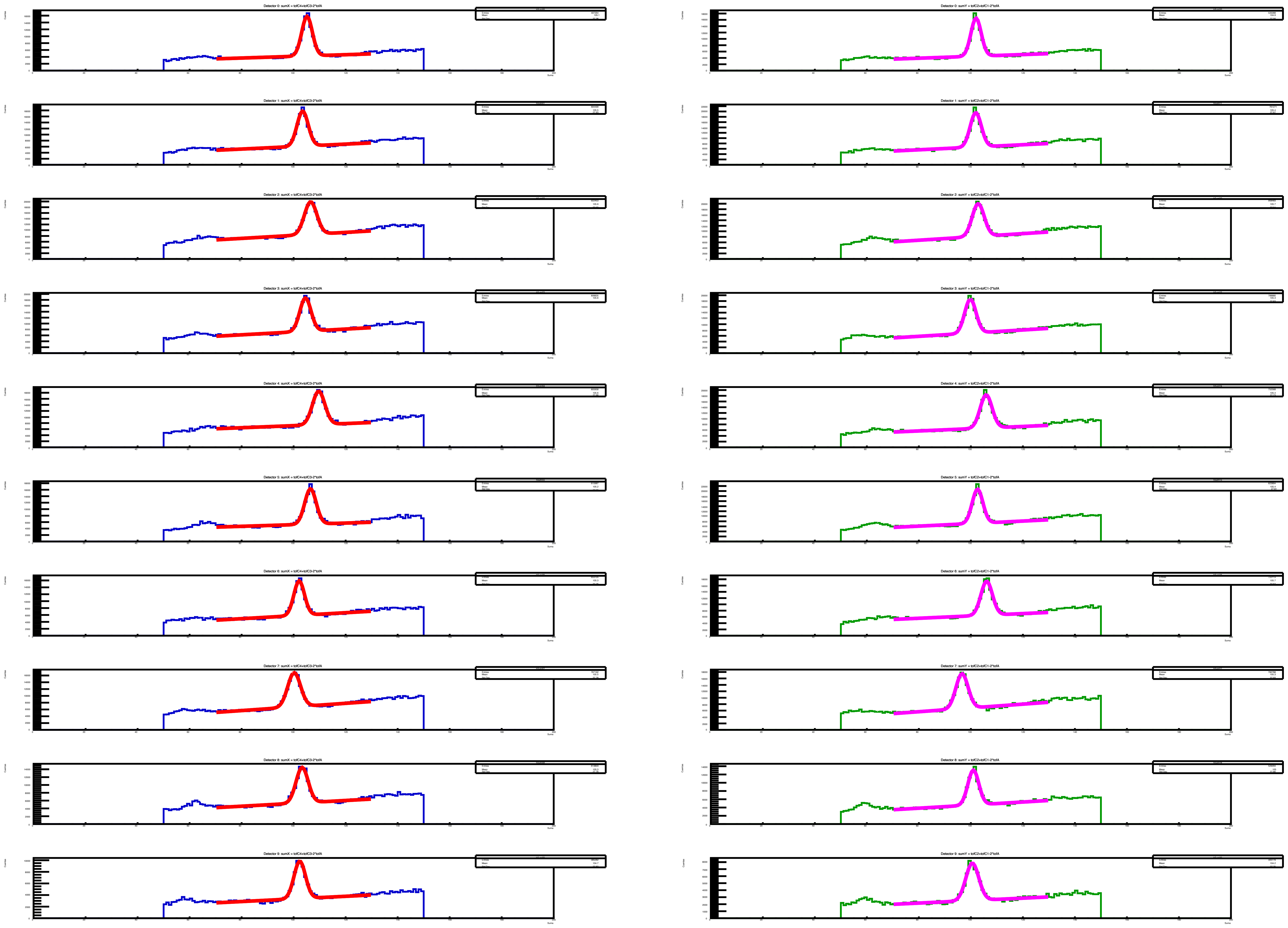
Guerrero, C., Tsinganis, A., Berthoumieux, E. *et al.* Performance of the neutron time-of-flight facility n_TOF at CERN. *Eur. Phys. J. A* **49**, 27 (2013). https://doi.org/10.1140/epja/i2013-13027-6

Time calibration anodes

- In order to calibrate anode signals, we use the γ-flash signals, as they pass through all detectors almost simultaneously.
- Since the separation between PPACs is not negligible (5 cm), we have to take into account the time spent by light to travel that distance.
- Gaussian fits provide timing offsets for calibration.



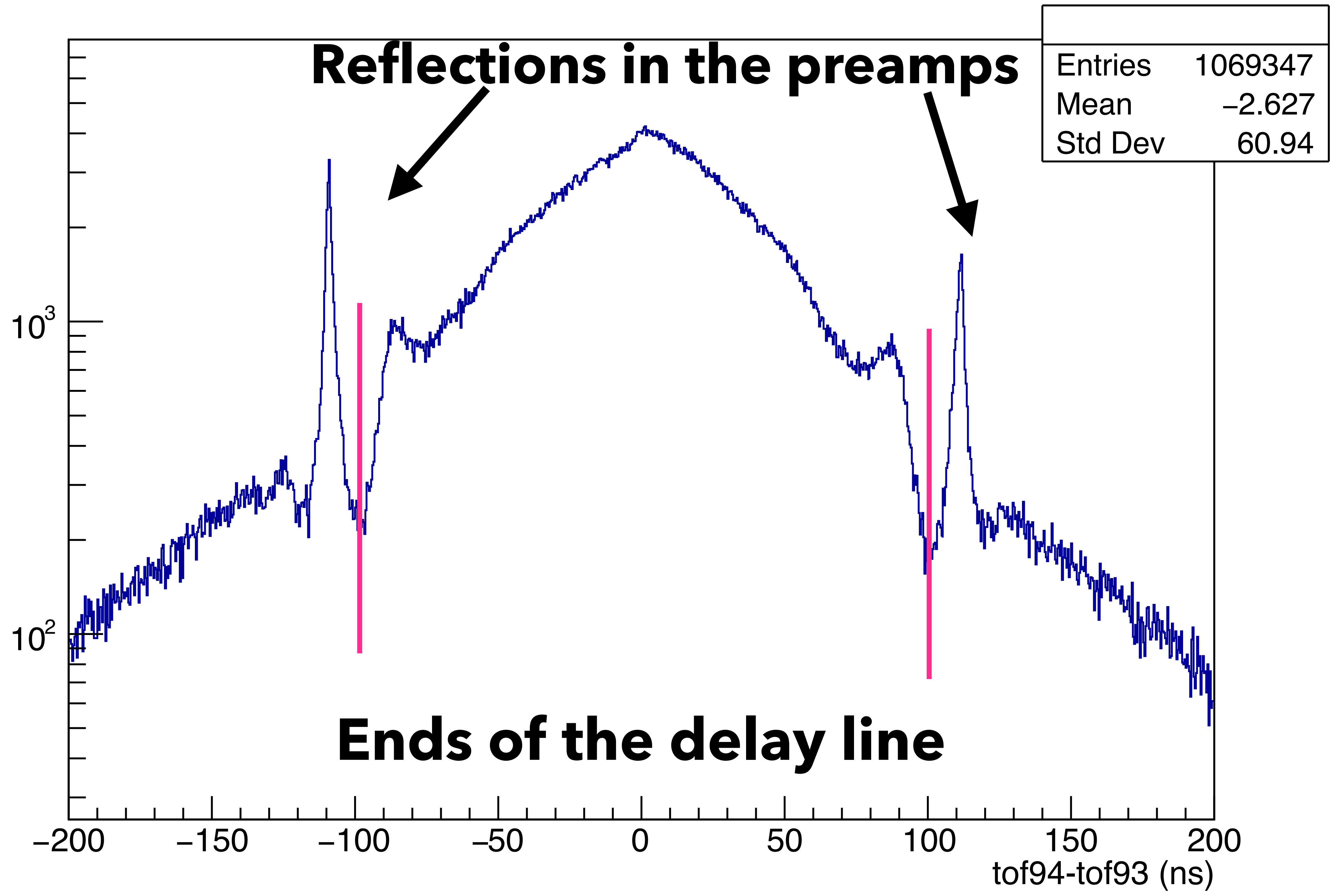
Sum of cathode signals



- Gaussian fit to the peak.
- Valid signals must be within 2 sigmas.

Speed of the delay lines

- With these reflections in the preamps, and knowing the length of the delay line (100 mm), we can compute the speed of the signal.
- In order to do it, we must compute the mean of the centroid of each of the peaks (in abs value).
- This can be used to enforce constraints on allowable cathode time differences.



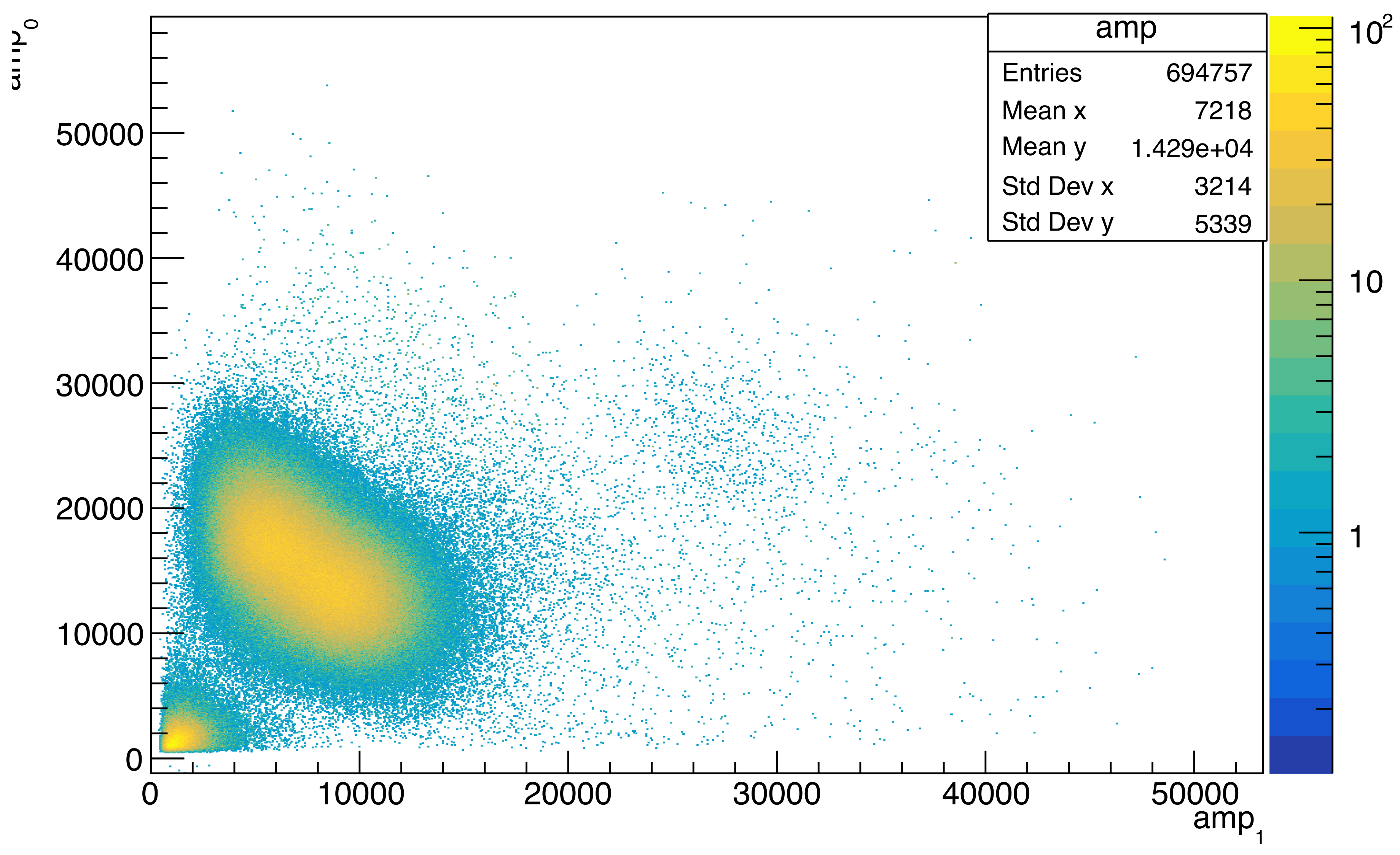
Amplitudes correlation

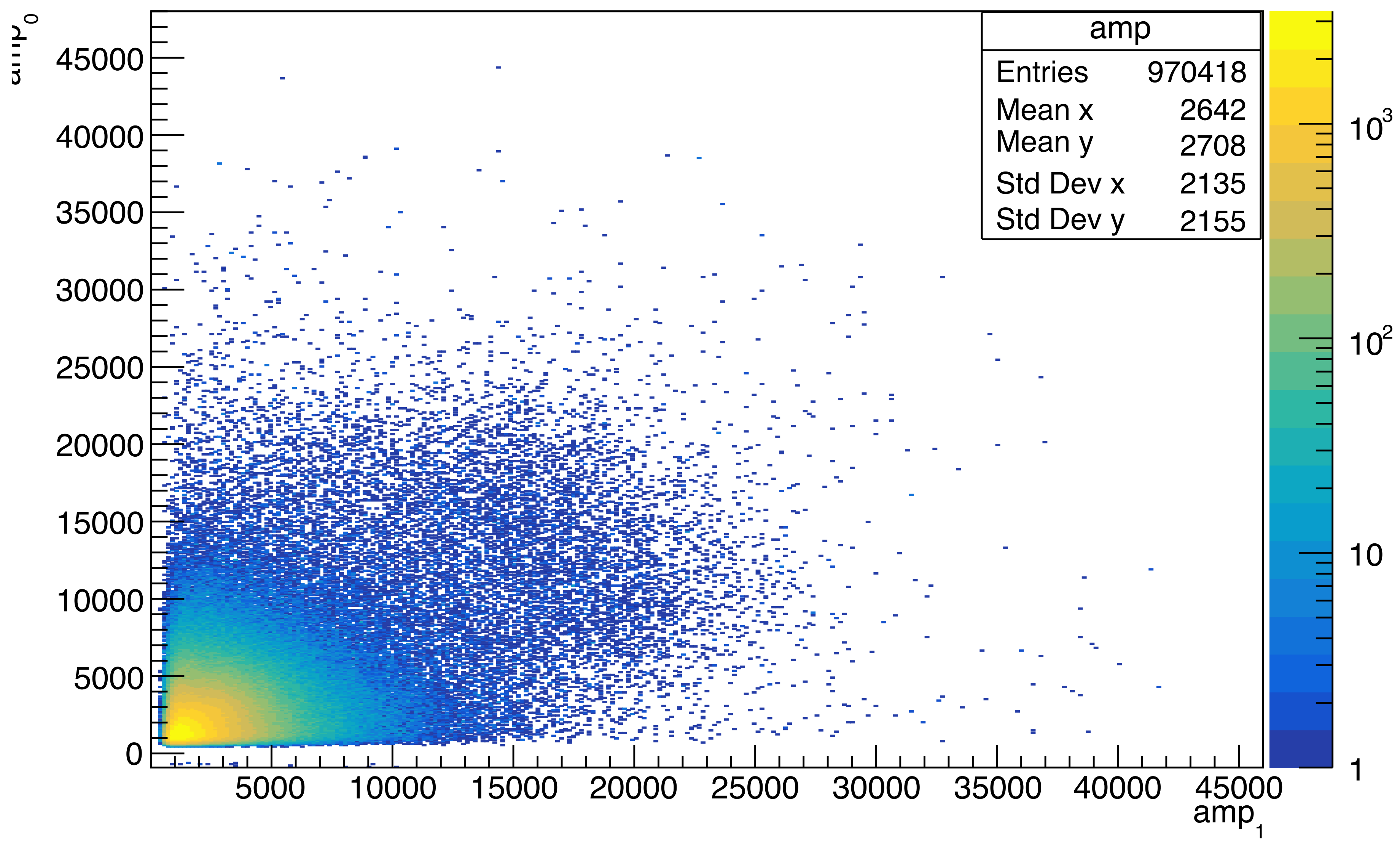
- For Uranium, the correlation between the amplitudes of the two anodes allow us to easily distinguish fission events and background reactions.

- For Cerium, on the other hand, things get messy…

- No clear threshold.

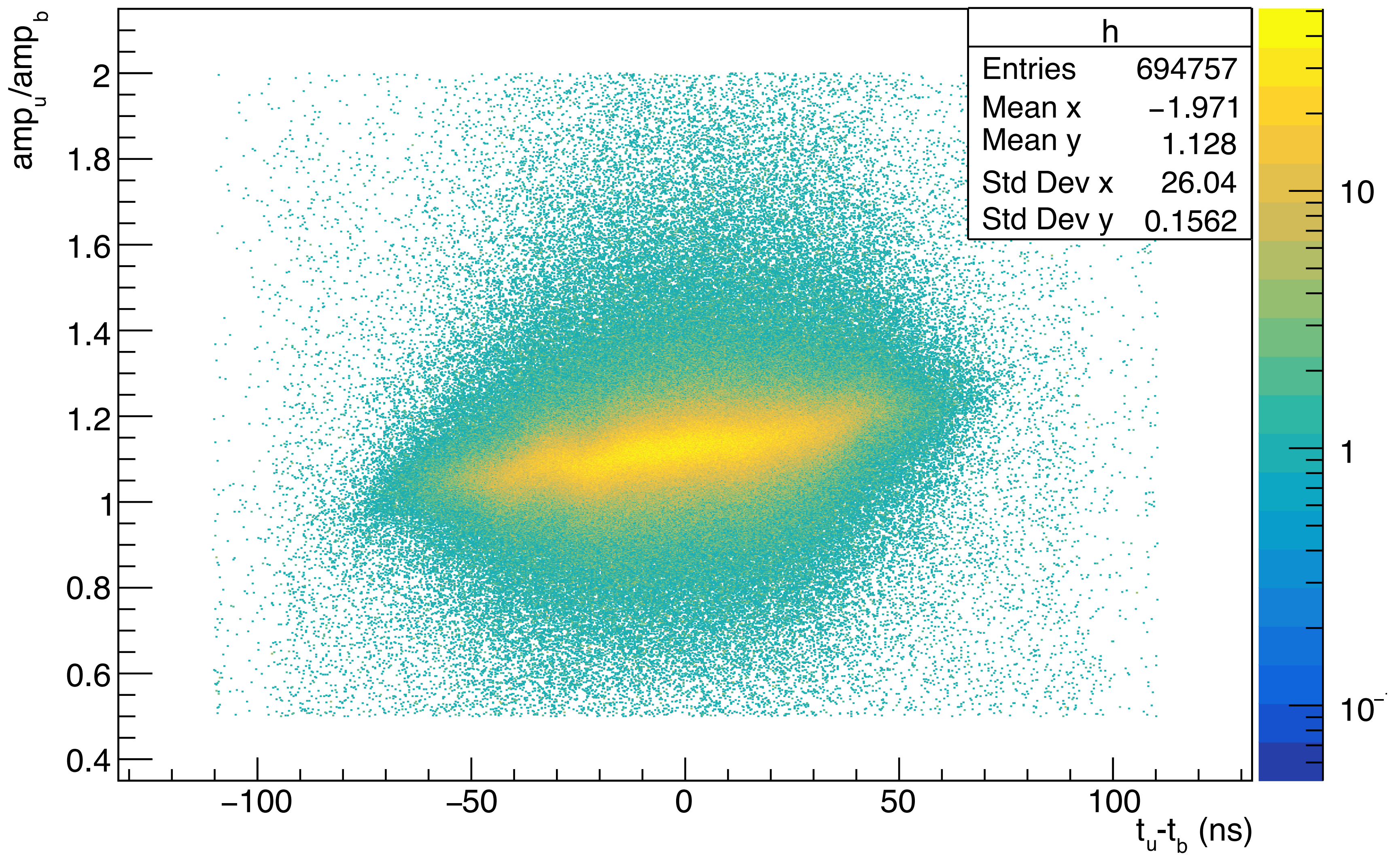
- Statistics are lower than that of the background radiation.

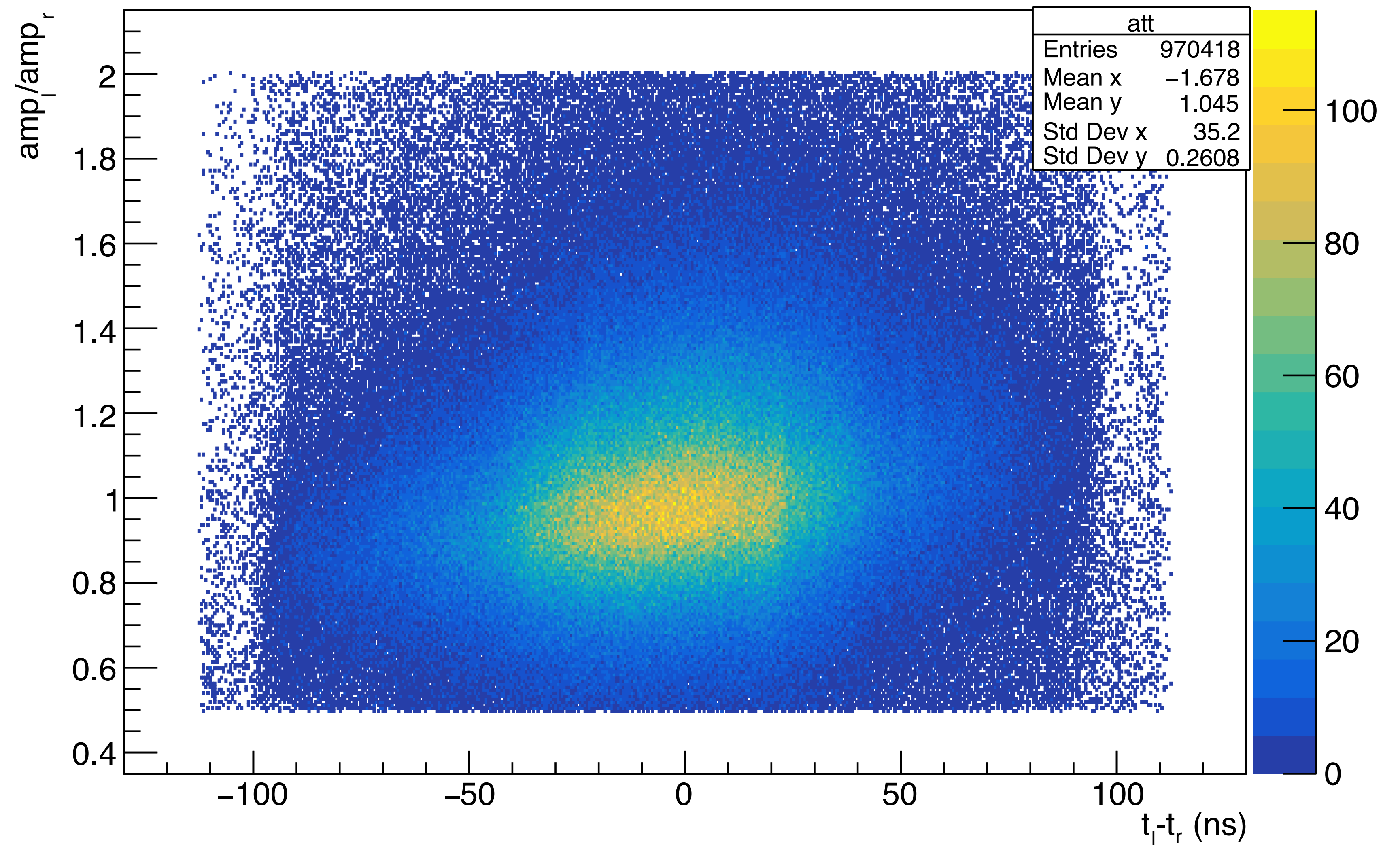




Attenuation of the delay line

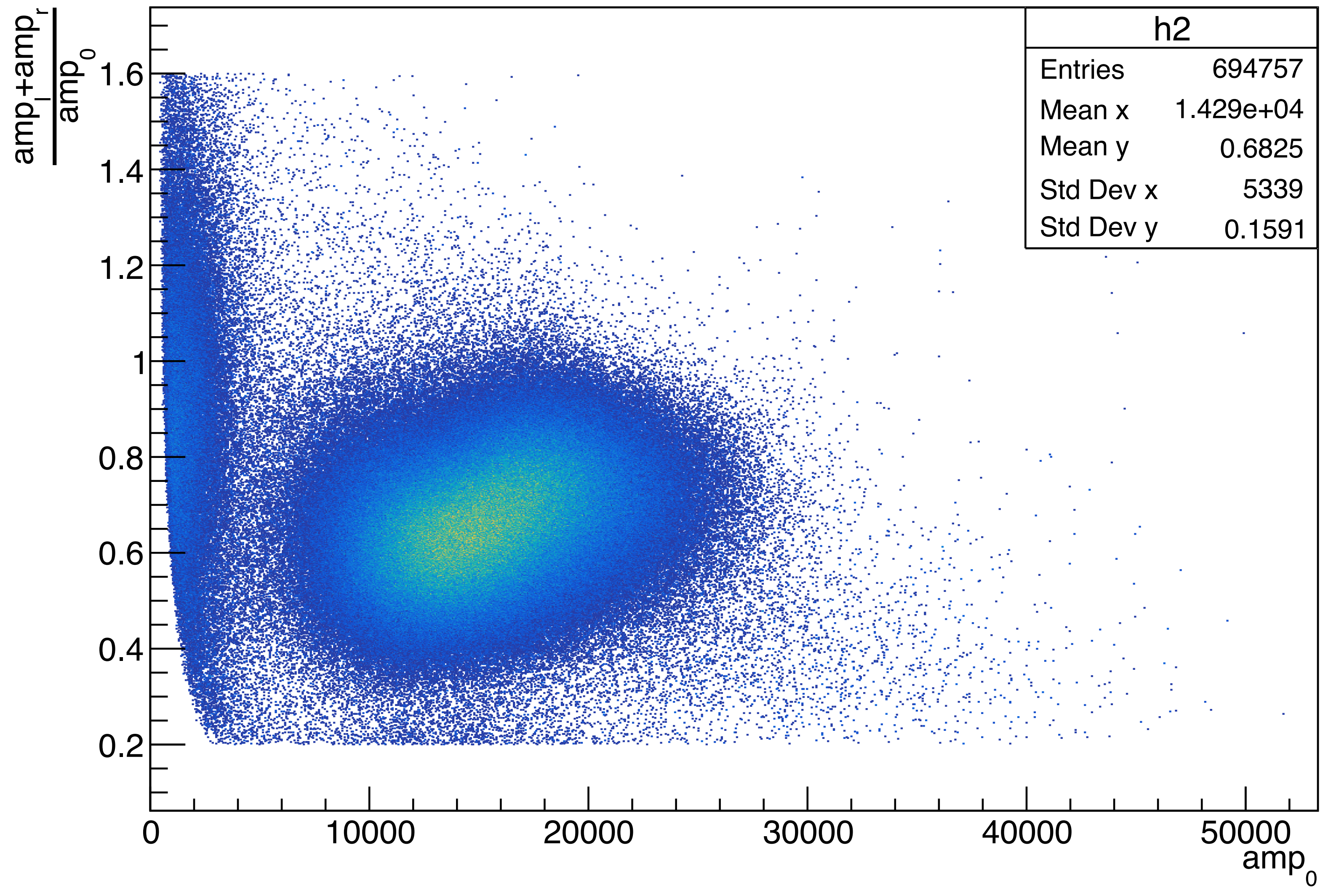
- We can clearly see a linear behaviour with the time difference.
- We can use this to select the fission events.
- We impose cuts between 2 and 0.5 for amp_u/amp_b.
- For Cerium, this linearity is not that clear.
- Background radiation dominates and the selection is not that clean.

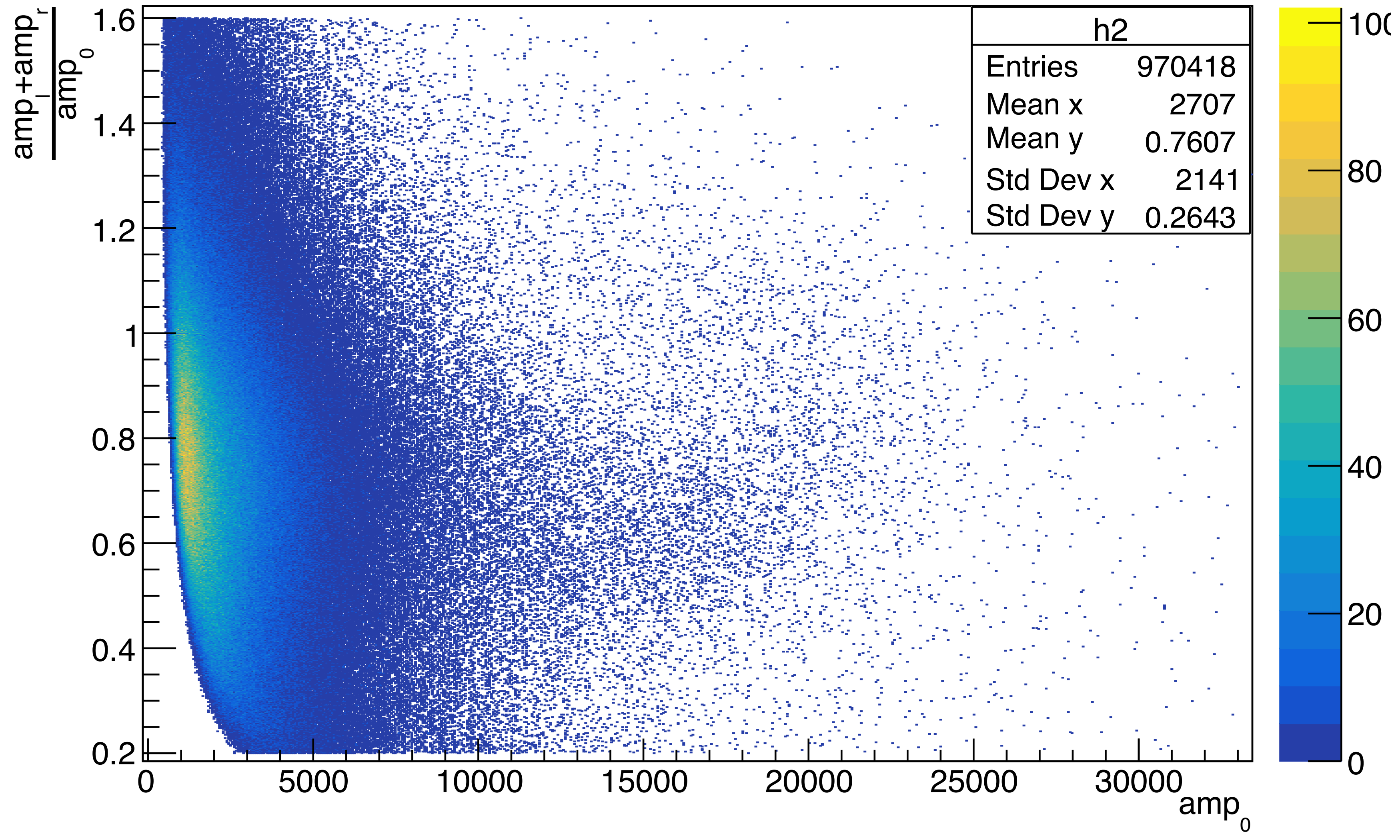




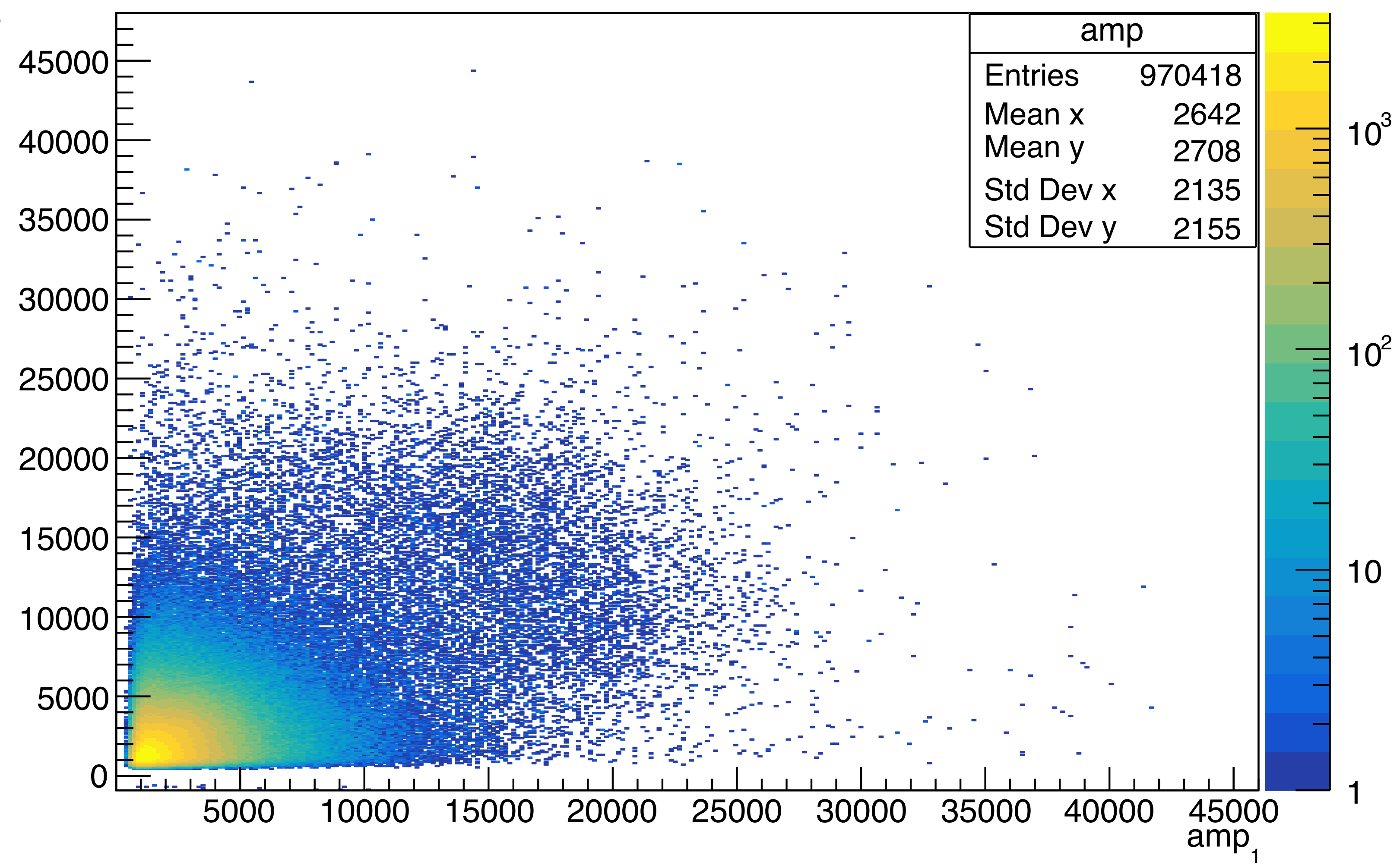
Correlation of cathode/anode amplitudes

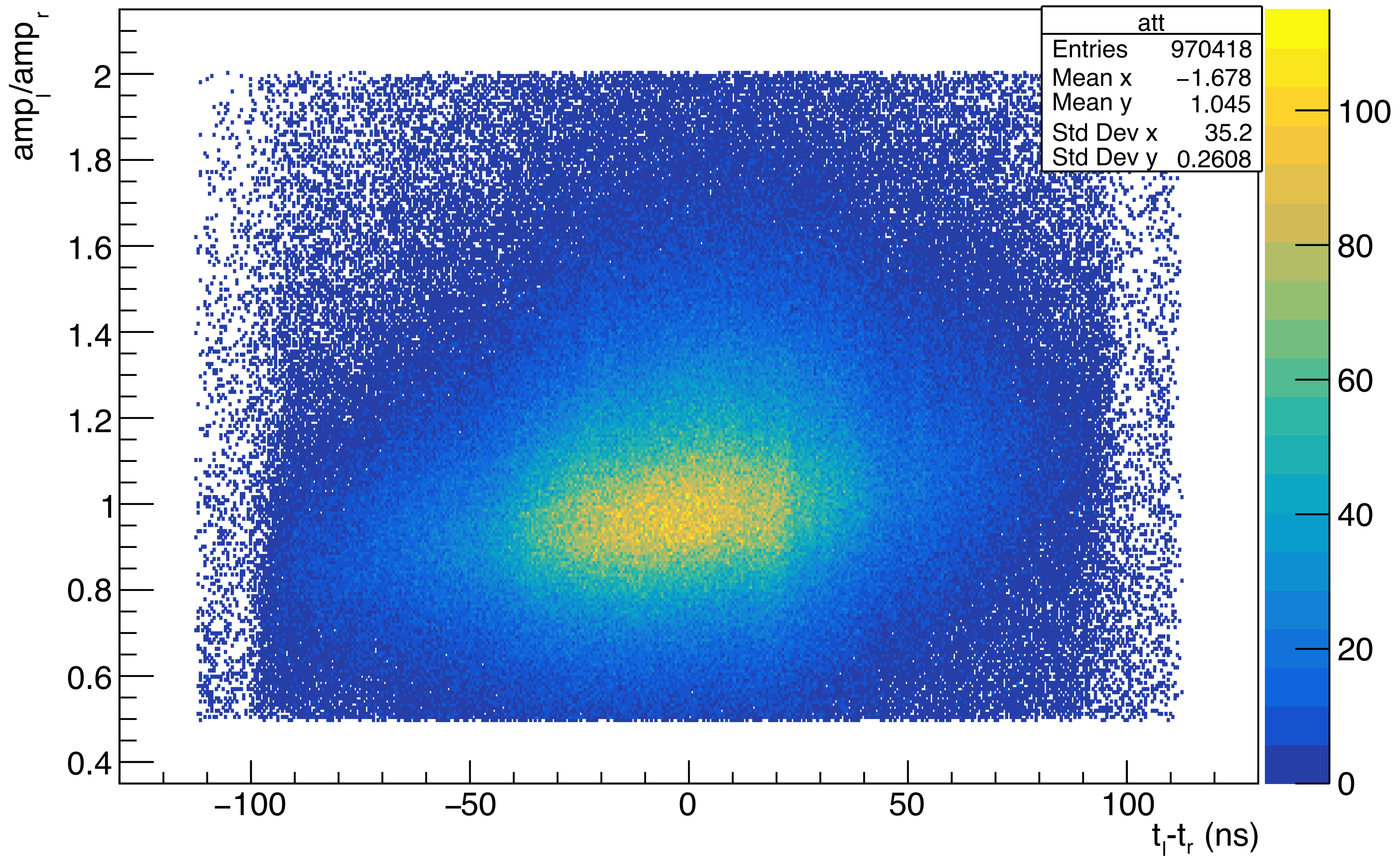
- We can see that cathode amplitudes correlate with the anode amplitude.
- This allows us to separate fission events from background or non correlated events.
- For Cerium results are mixed with background.

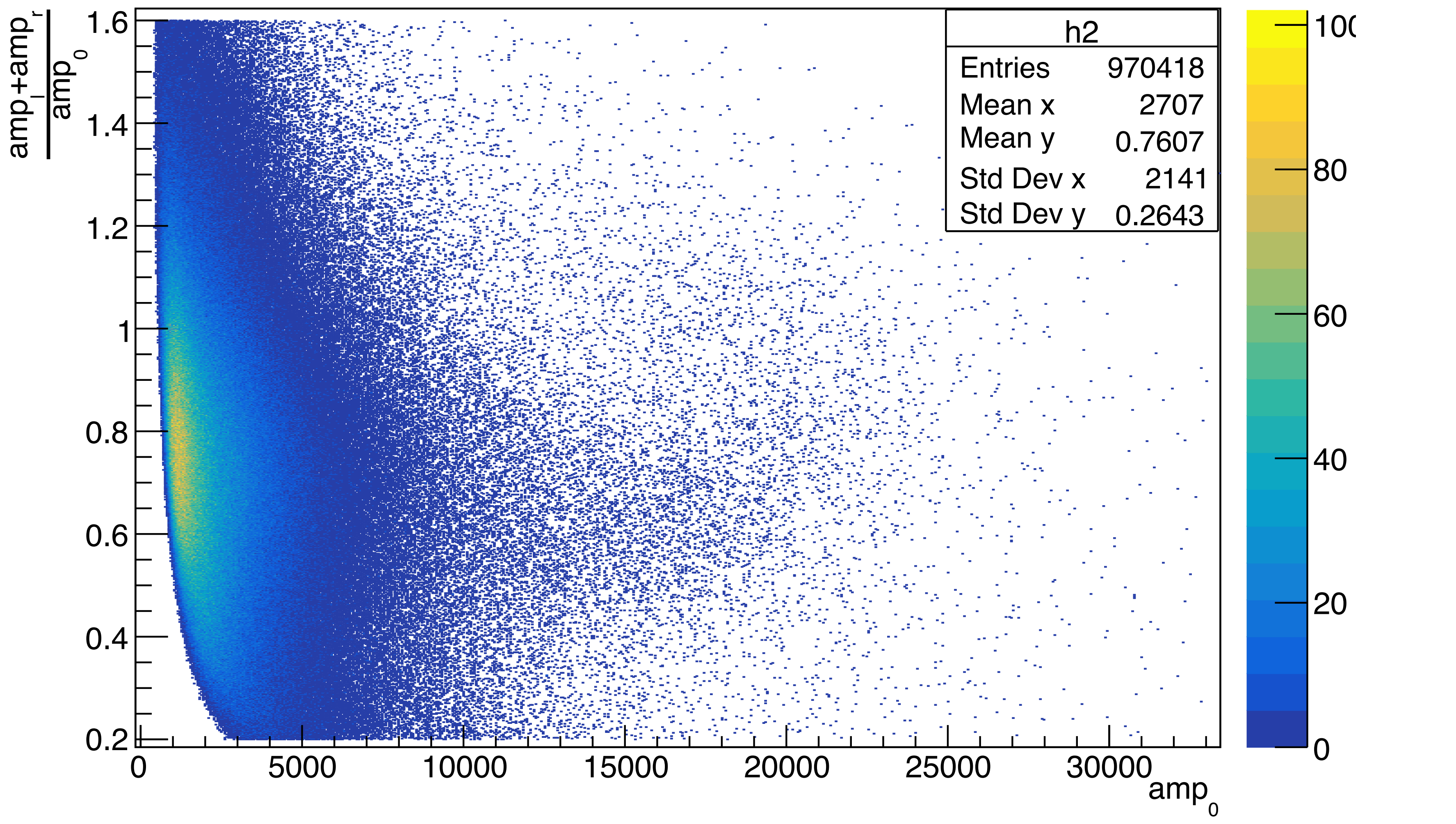




Why Cerium selection is harder?





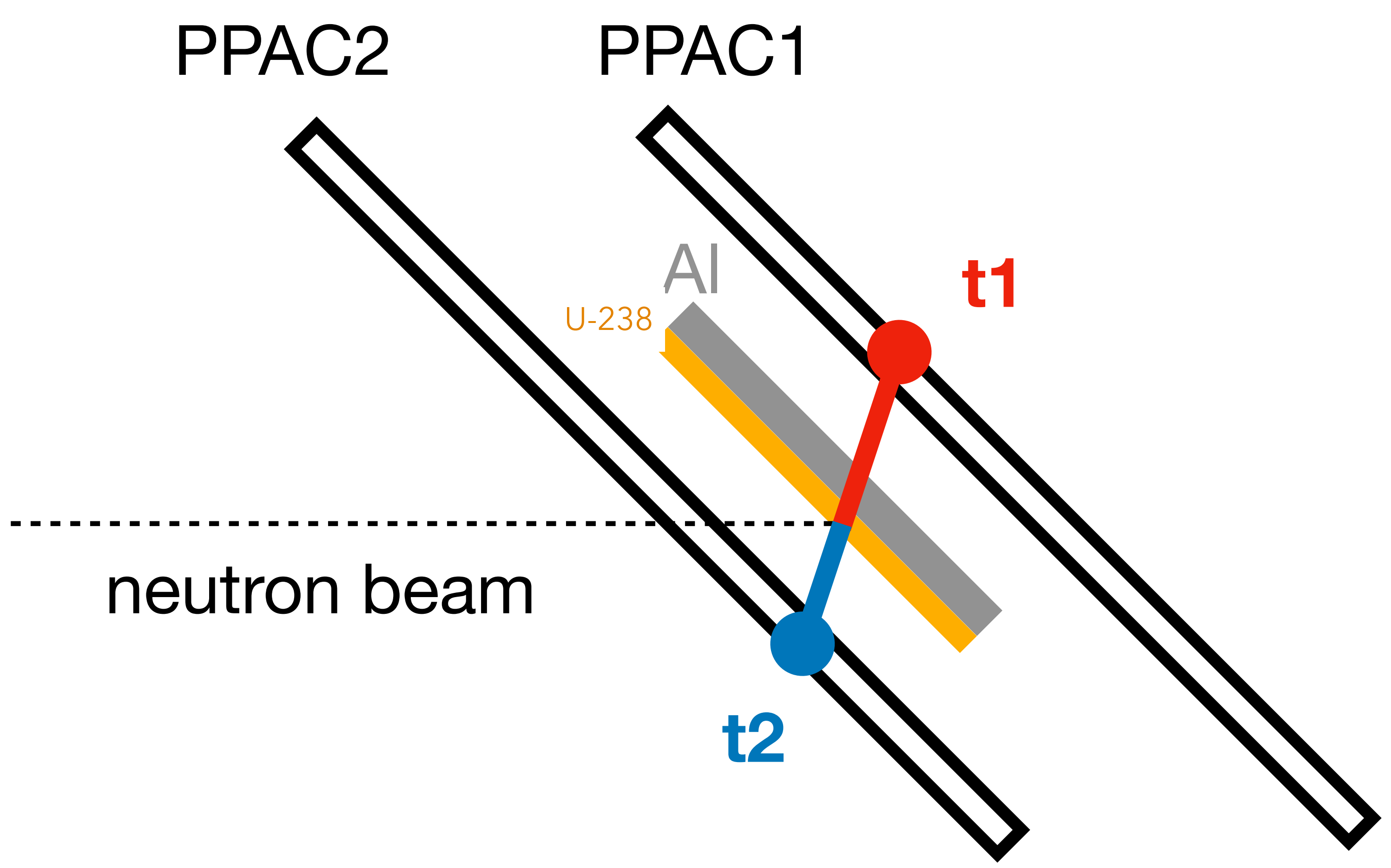


Correlations in amplitude are not effective

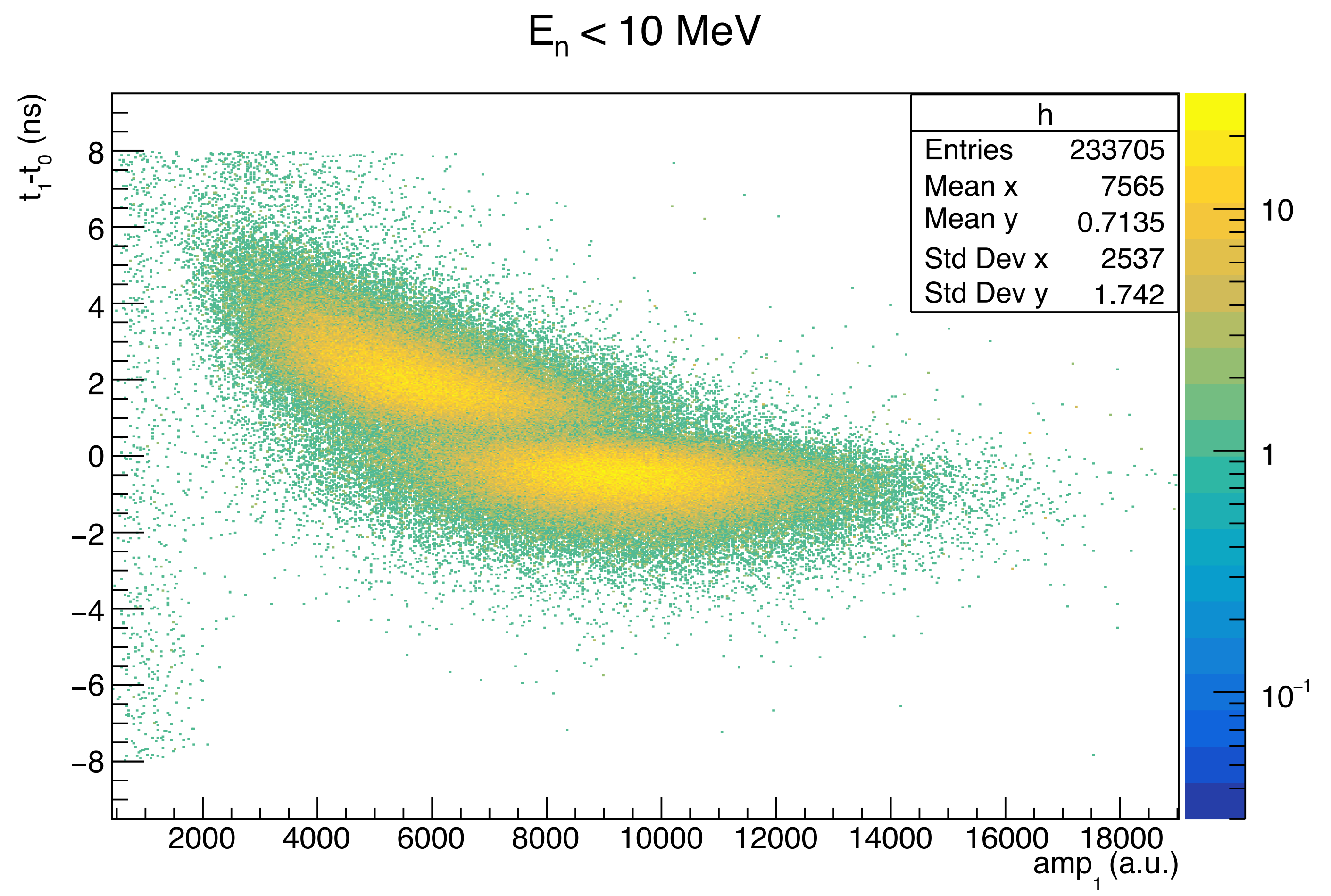
Cuts using attenuation of the lines are less clear

Events mixed with background

Backing effect



- When the heavy fission fragment is emitted towards the forward detector, since it has a lower TKE, it is slower and deposits more energy in each layer of matter.
- In addition, when it passes through the aluminium backing, as it has a higher Z, it will have greater ionization losses, meaning that it will take more time to reach the detector.
- Thus, it will induce higher time differences between the fragments and leave a lower amplitude in the detector.



Low energies

At higher energies, since there is no charge difference between the fragments, the backing effect is the same for the light and heavy fragments