Neutrons from the s455 / $^{238}U(\gamma, f)$ experiment

Deša Jelavić Malenica
Ruđer Bošković Institute
Division of Experimental Physics, Laboratory for Nuclear Physics

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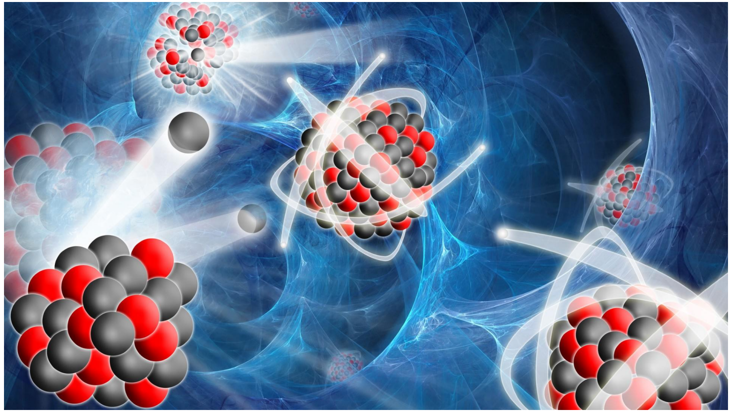
S455 experiment: Nuclear Fission Studies

- the fission process is one of the most dramatic scenarios a nucleus can endure: it leads to extreme deformations and provokes a complete re-arrangement of the nucleons

- R3B FAIR phase 0 fission program: fission of unstable nuclei in inverse kinematics - access to the complete characterization of the fissioning system and the fission fragments

- S455 experiment (conducted in April 2021.): 3 different proposals joined to measure (p, 2pf) and Coulomb induced fission, in order to map the fission modes of neutron-deficient nuclei in the mass range A = 180 - 210 (from Pt up to Th isotopes) and explore the transition from symmetric to asymmetric fission

- fission of primary ^{238}U → 20h measurement for calibration and proof of principle



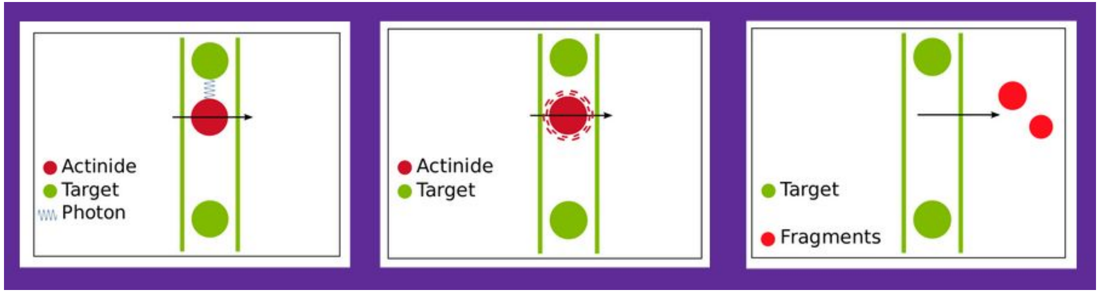
SOFIA - Studies On FIssion with GLAD (ALADIN)

Coulex induced fission $^{238}U(\gamma, f)$

- the Coulex process induces smaller excitation energies, better preserving structure effects in the fission, such as enhancement of asymmetric fission and closed-shell fragments, and even-odd staggering

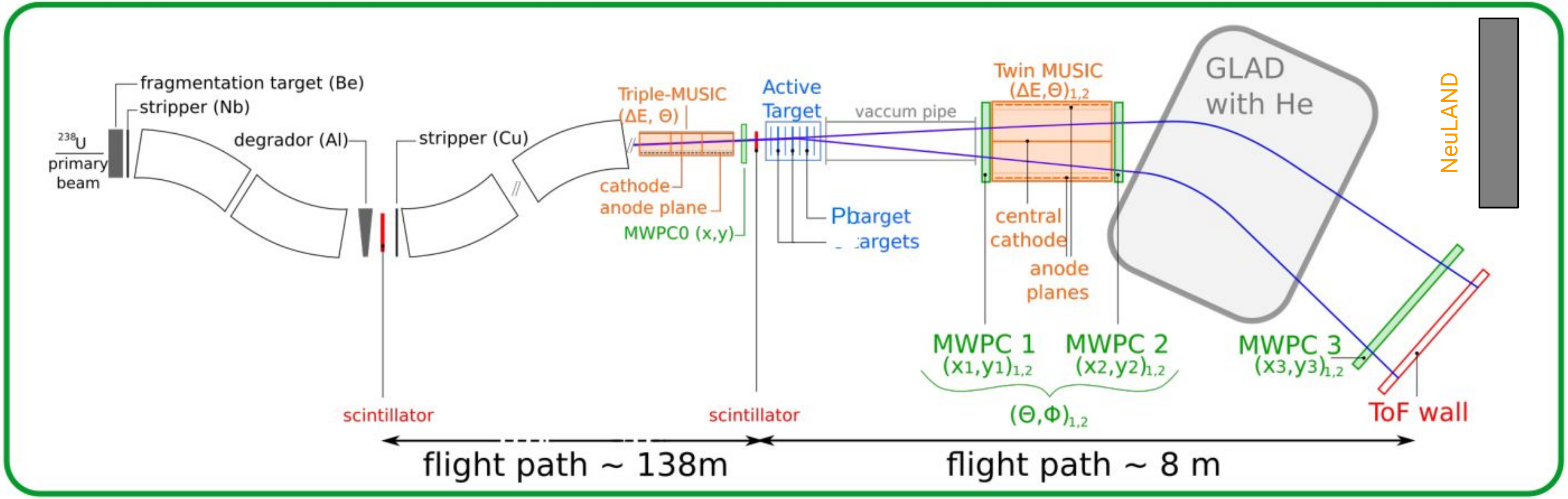
- in ideal case, no neutrons are ripped off before the fission

- active target: Pb - C - Pb



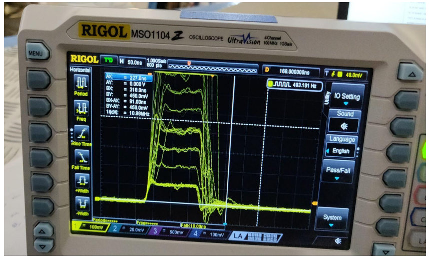
Coulex induced fission $^{238}U(\gamma, f)$

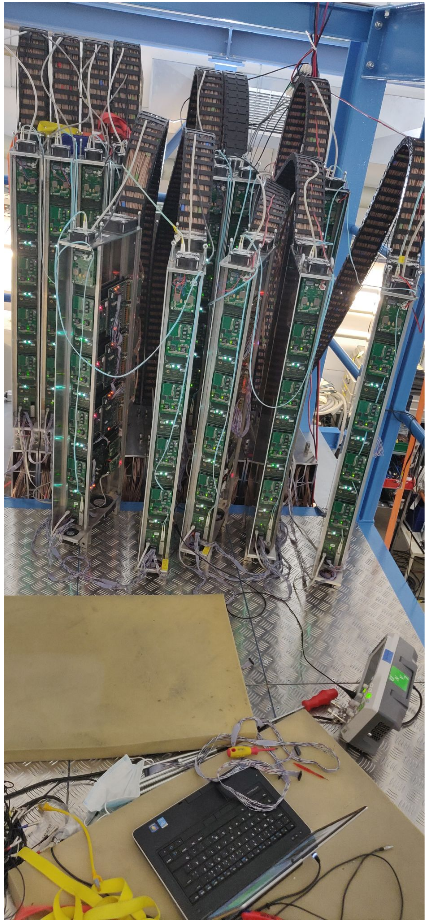
- experimental set-up: identification in nuclear charge and mass
- based on the well-known triptych Bϱ - Tof - ΔE from position, Tof, energy loss measurement
- MWPC for (x,y) measurement of the beam and the fission fragments
- Twin-MUSIC for charge identification of the fission fragments
- Tof Wall for time of flight of the fission fragments



Neutrons from the fission

- the idea is to combine the SOFIA set-up with the NeuLAND detector, in order to make direct neutron multiplicity measurement and be able to assign the emitted neutron to either of the fragments, which is a good probe for the configuration of the fragments at scission
- once NeuLAND reaches its full size, an experiment dedicated to the neutron multiplicity can be performed



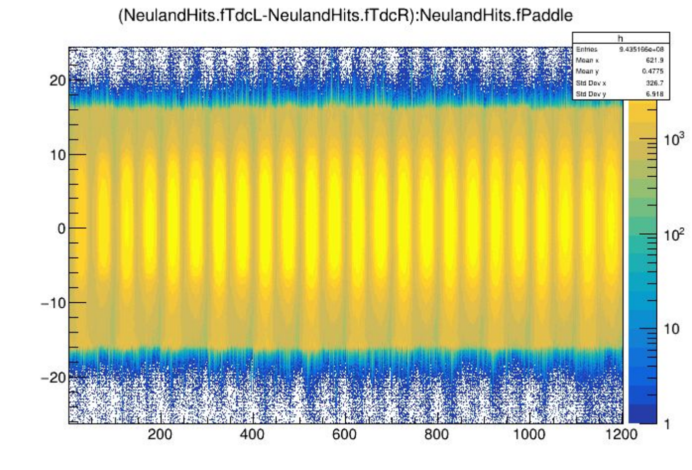


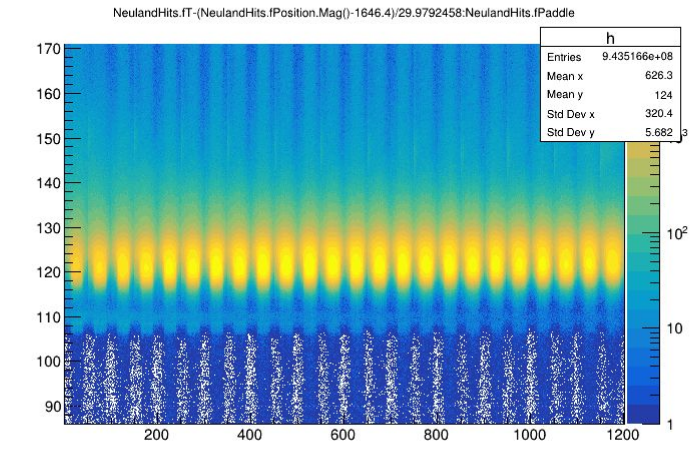
S455 experiment:
- NeuLAND with 12dp
- electronics fine tuned just before the experiment
- good statistics for ^{238}U fission

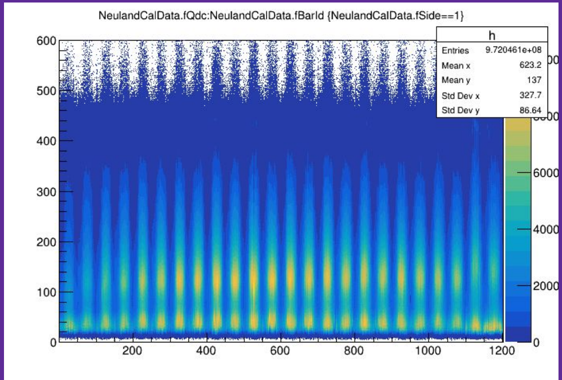
The goal of the present analysis:
- to construct the framework for the analysis of neutrons from fission
- to investigate gammas, GTO, background subtraction, simulations, multiplicity reconstruction….
- to look for physics

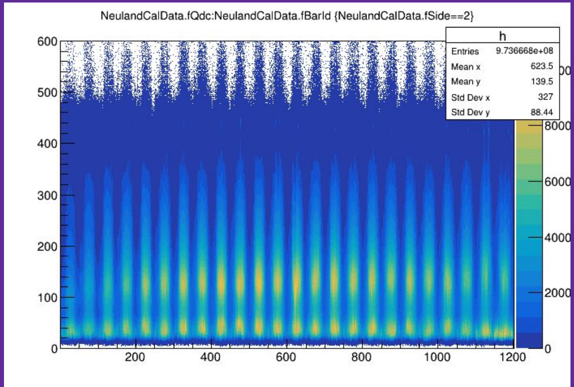
NeuLAND calibration

- runs : 348 - 363
- beam energy: 740 AMeV (^{238}U)
- neuland planes: 24 (12 dp)
- all 2400 channels operational (and all look ok!)
- **raw→ mapped** – raw data assigned to respective submodule (paddle and PMTs)
- **mapped → cal** – time calibrated in ns for individual PMT
- **cal → hit** – time, energy and position into physical units, time synchronization between individual submodules



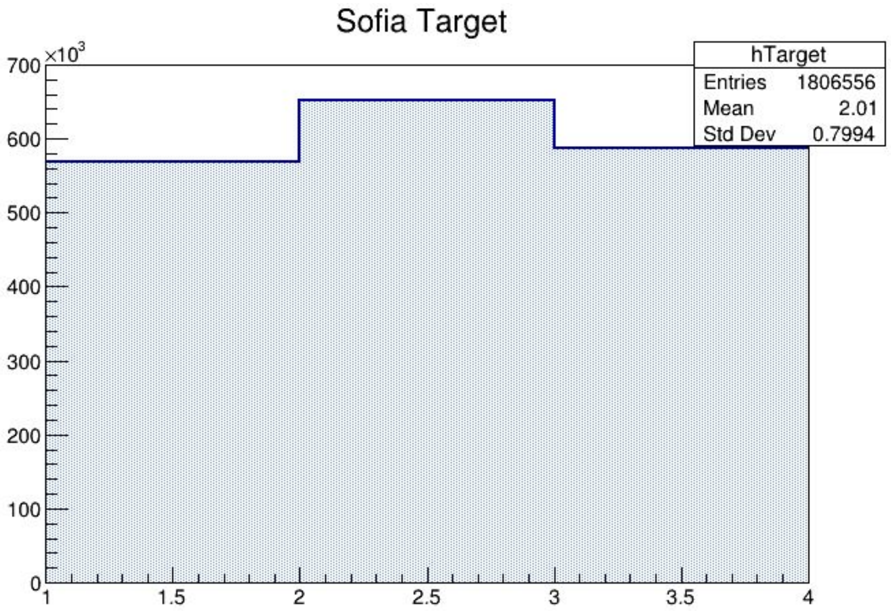




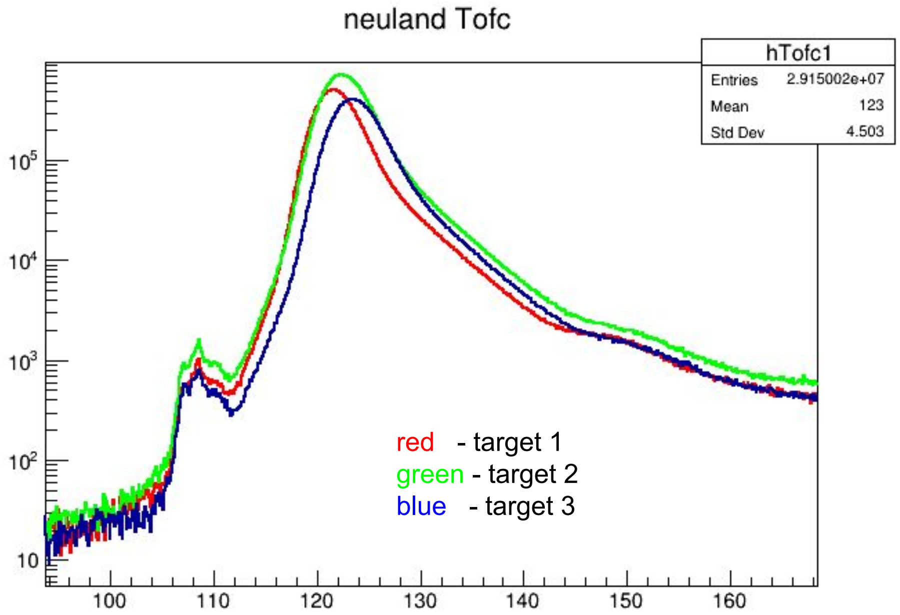


NeuLAND hits → merged with SOFIA data

- merging is done based on event number matching



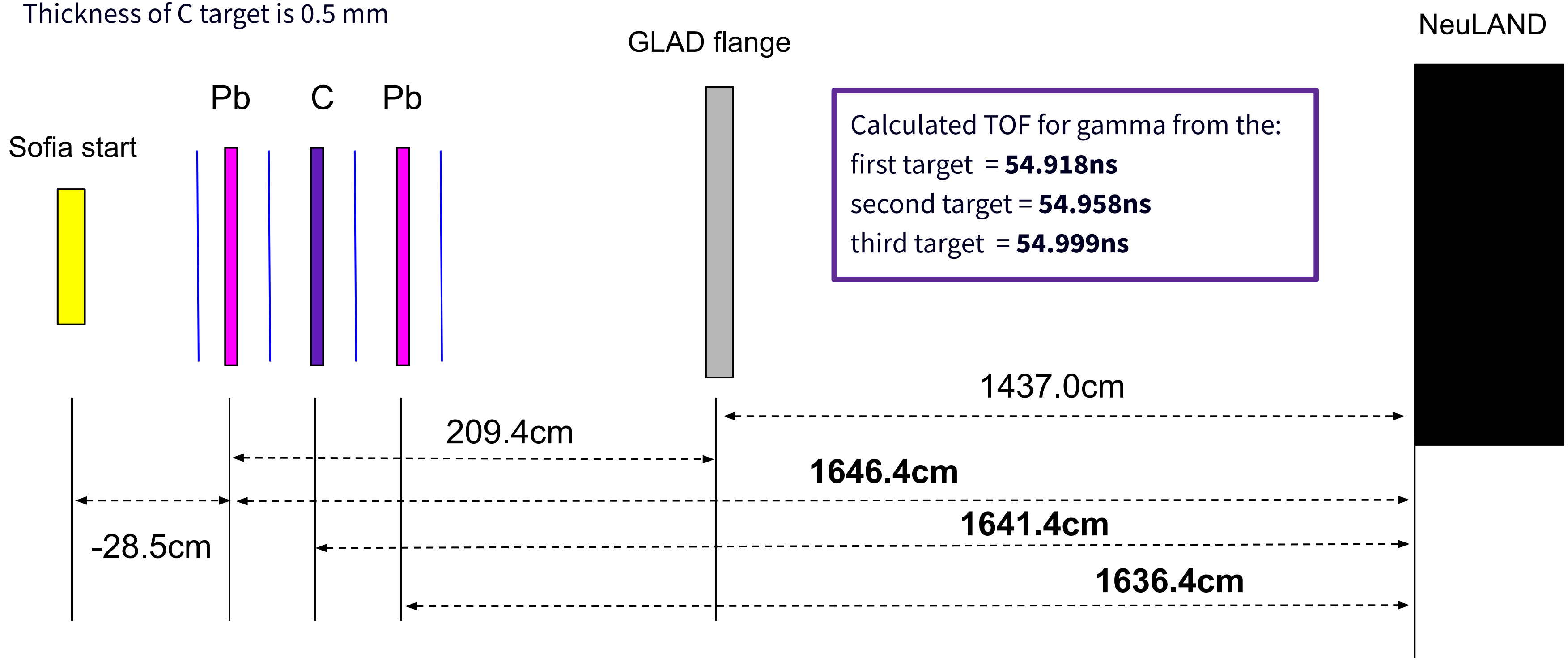
- multiplicity of neutrons expected after the cut on Z=92 -> 5 n per event
- after nuclear reaction subtraction -> 3.8 n per event



Thickness of the SofSci is 1.5 mm

Thickness of Pb target is 1 mm

Thickness of C target is 0.5 mm



E_beam after START = 703.8 AMeV

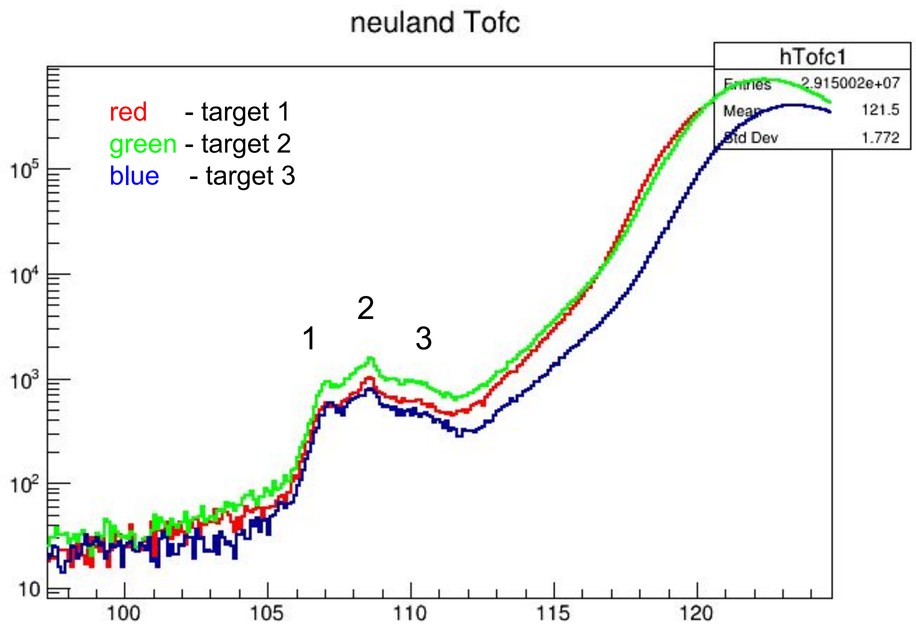
E_beam after K1 (Pb) = 641.0 AMeV

E_beam after K2 (C) = 630.722 AMeV

E_beam after K3 (Pb) = 569.145 AMeV

Difference in TOF between different targets is ≈ 40ps

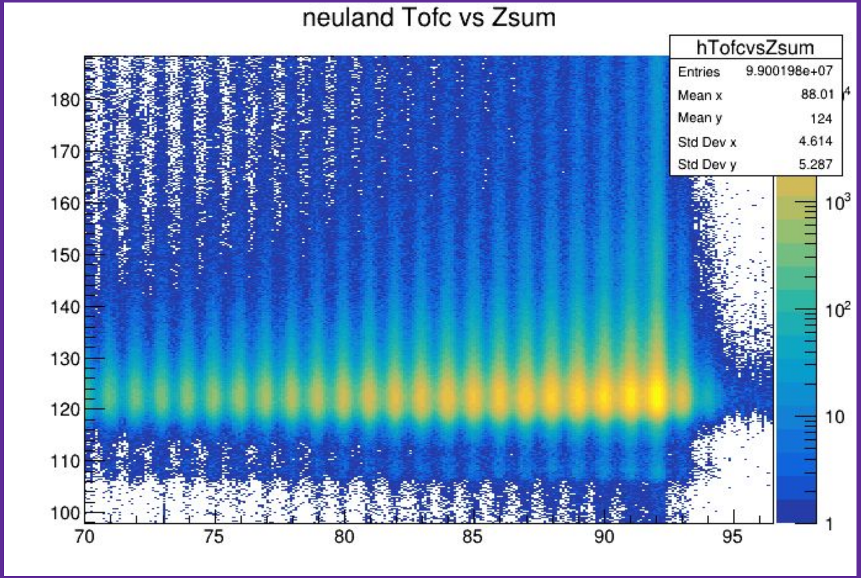
Global TOF adjustment

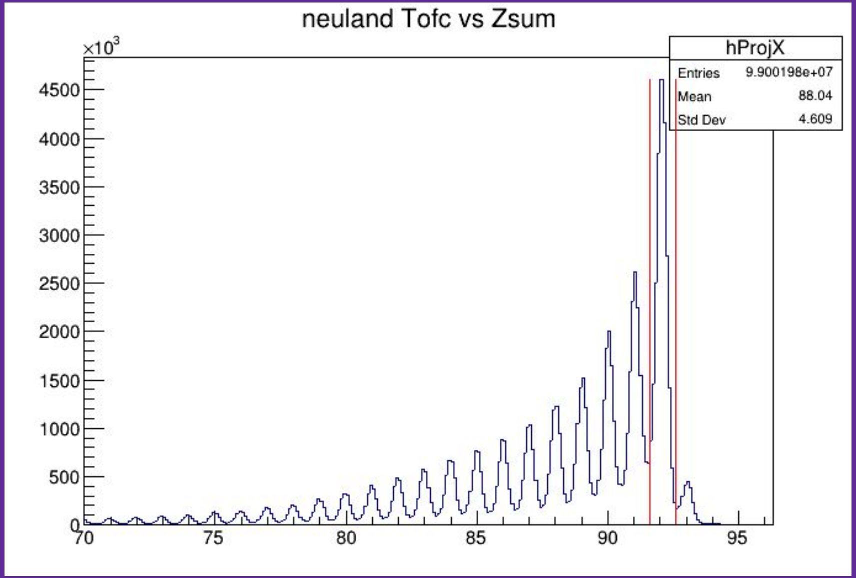


- width of the peaks ≈ 500-600ps
- TOF difference between peak 1 and 2 ≈ 1.2ns
- TOF difference between gammas from SOFIA start and the first Pb target ≈ 200ps

- **first peak** → gammas from the material before the active target: Triple-Music, MWCP0, SOFIA start
- **second peak** → gammas from all three TARGETS (always the strongest and sharpest peak); the TOF difference in gammas coming from different targets is smaller than the neuland time resolution (which is 130ps)
- **third peak** → gammas from the material after the active target

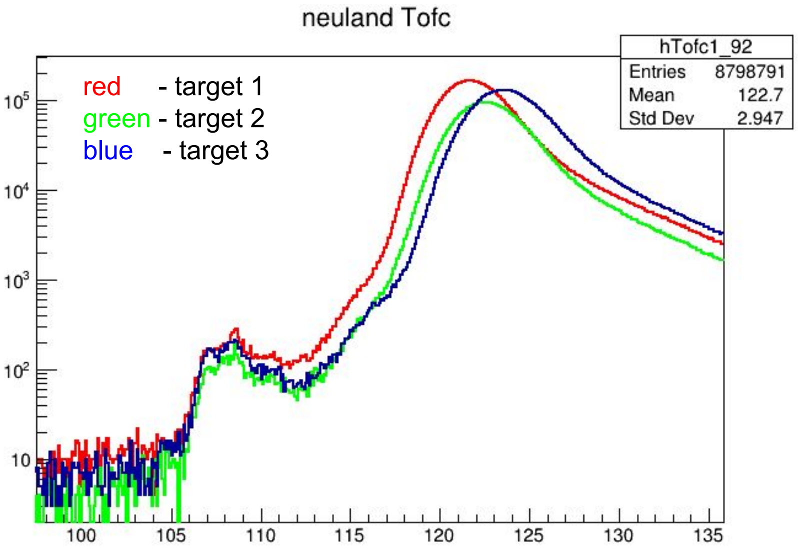
Z = 92 selection

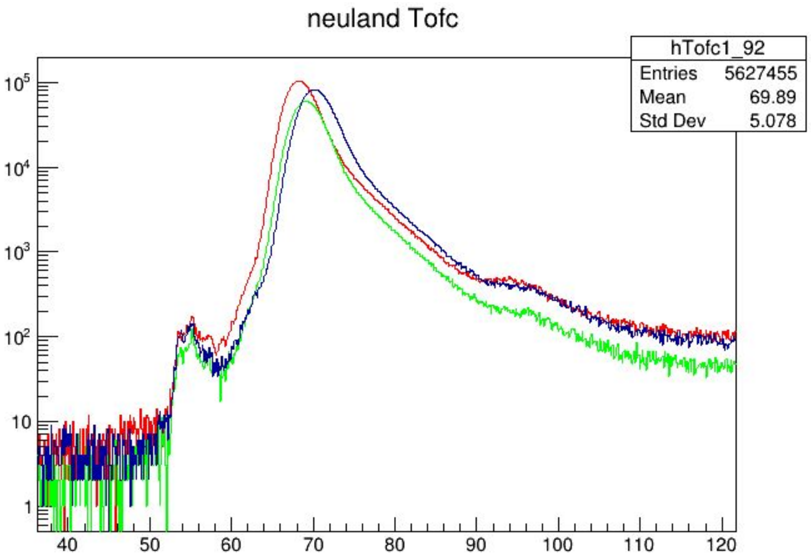




- to make the global TOF and continue with analysis from this moment on we select only Z=92 (coulomb - induced fission)

Global TOF adjustment





GLOBAL TOF CHECK (VERY ROUGH) - prompt neutron peak compared to the neutrons from the target, having the velocity of the beam:

E_beam in the middle of target 1 (Pb): 673.499 AMeV, β = 0.814351, **TOF1=67.438ns**

E_beam at the middle of target 2 (C): 638.27 AMeV, β = 0.80491, **TOF2=68.436ns**

E_beam at the middle of target 3 (Pb): 602.571 AMeV, β= 0.794544, **TOF3=69.534ns**

Fit of the prompt neutron peak:

target1 **68.376ns**

target2 **69.230ns**

target3 **70.266ns**

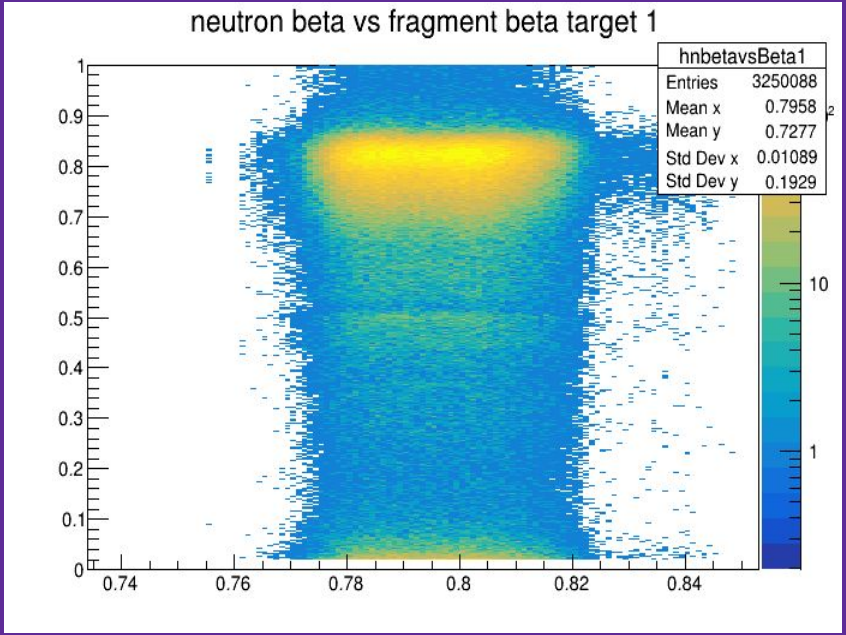
NeuLAND Hit → Cluster → First Hit

- clustering – sorting hits that are close in time and space into clusters → cluster multiplicity still higher than the number of incoming neutrons and depends on the neutron energy

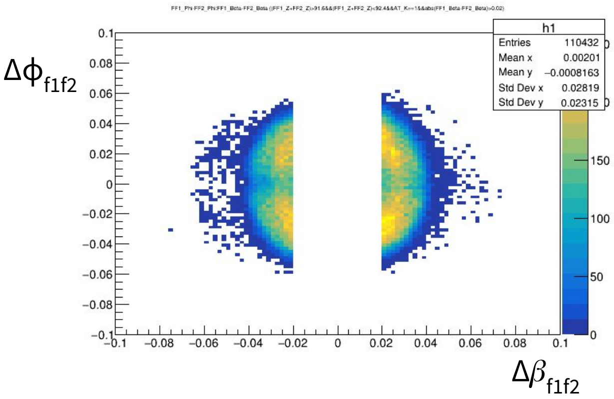
- cluster size: Δx, Δy, Δz < 15cm, Δtof < 5ns, 1ns

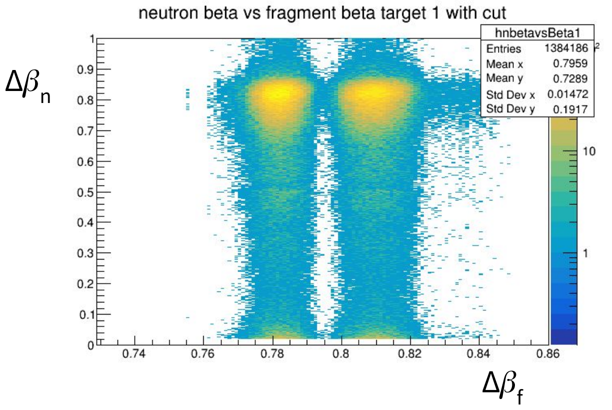
- first hits of neuland clusters should be closer to the real neutron behavior

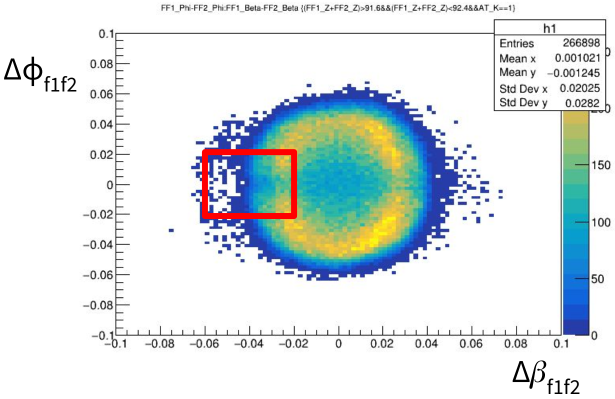
- we try to find correlations with fragments that can be seen on this level

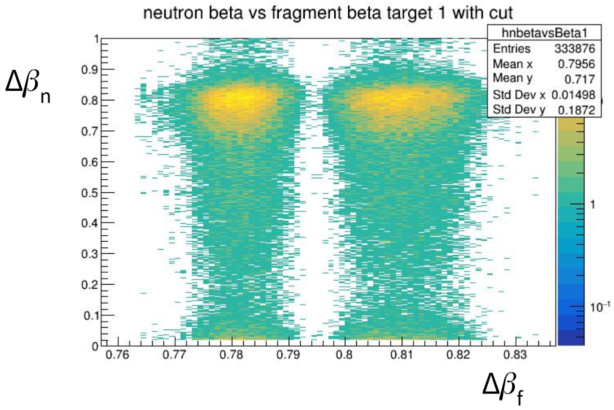


Neutron - fragment correlations









- the idea was to quickly check correlations between neutrons (first hits of the clusters) and fragments, both in terms of time and space
- different cuts on fragments in β and ϕ
- neutrons from two fragments cannot be distinguished in NeuLAND at this level
- we need real neutrons → simulations to find the multiplicity cuts

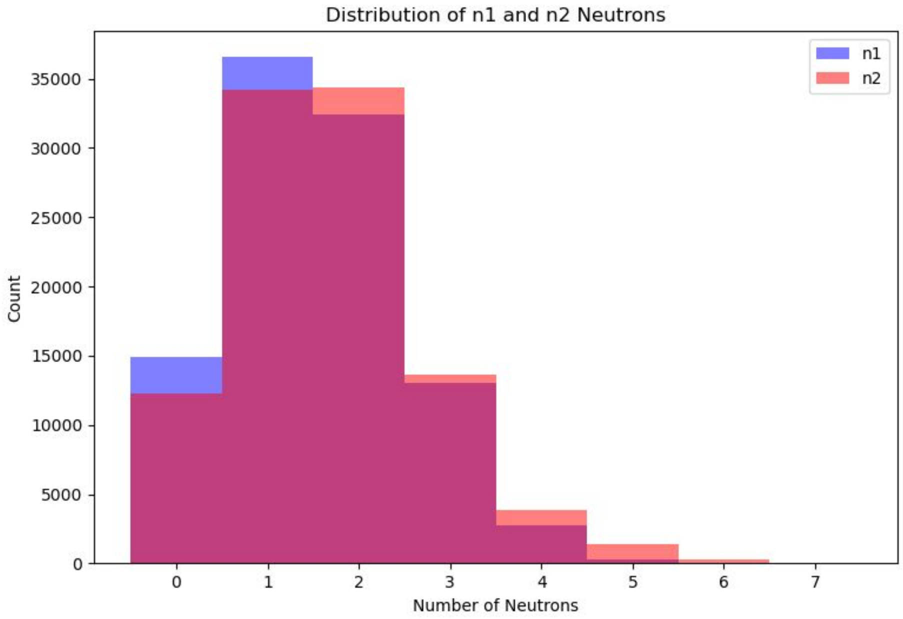
Simulations

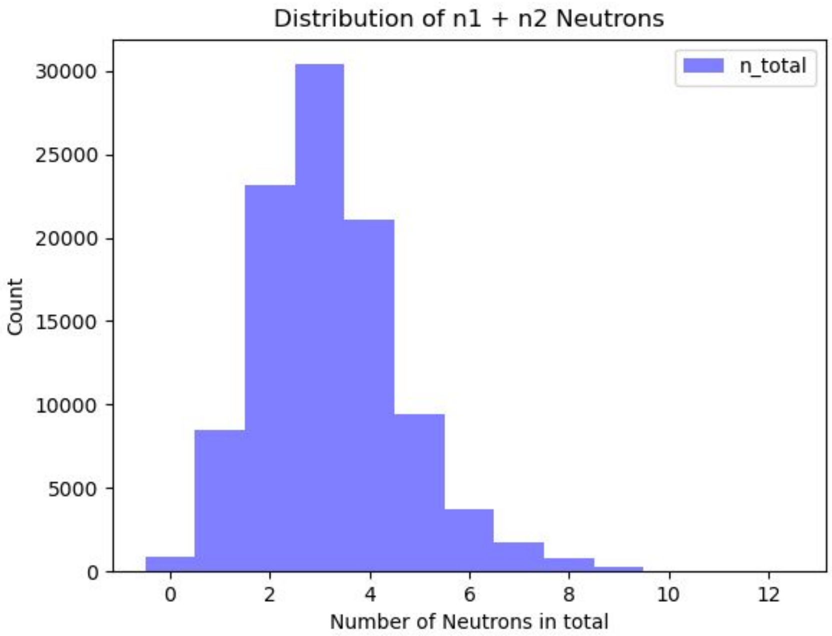
- we use neutrons from the GEF calculation (performed by Audrey Chatillon)
- *"GEF is a computer code for the simulation of the nuclear fission process. The GEF code calculates pre-neutron and post-neutron fission-fragment nuclide yields, angular-momentum distributions, isomeric yields, prompt-neutron yields and prompt-neutron spectra, prompt-gamma spectra, and several other quantities for a wide range of fissioning nuclei from mercury to seaborgium in spontaneous fission and neutron-induced fission"*
- input to GEF simulation is the distribution of the total electromagnetic excitation function of the ^{238}U

```
-----------------------------------------------
(gammaE1,tot) : SumSigGDR = 5.14249 barns
(gammaE2,tot) : SumSigGQR = 0.675787 barns
(gamma,tot)   : SumSigGR = 5.81828 barns
-----------------------------------------------
(gammaE1,tot) : <E*> = 11.8664 MeV
(gammaE2,tot) : <E*> = 14.0072 MeV
(gamma,tot)   : <E*> = 12.1151 MeV
-----------------------------------------------
```

- the total electromagnetic cross section is around 5.8 barns with a mean energy of 12.1 MeV
- when the fission cross section is taken into account, the (gamma, fission) will drop to ~2 barns and the mean excitation energy of the ^{238}U compound nucleus will increase ~14 MeV

Neutrons from the GEF calculations

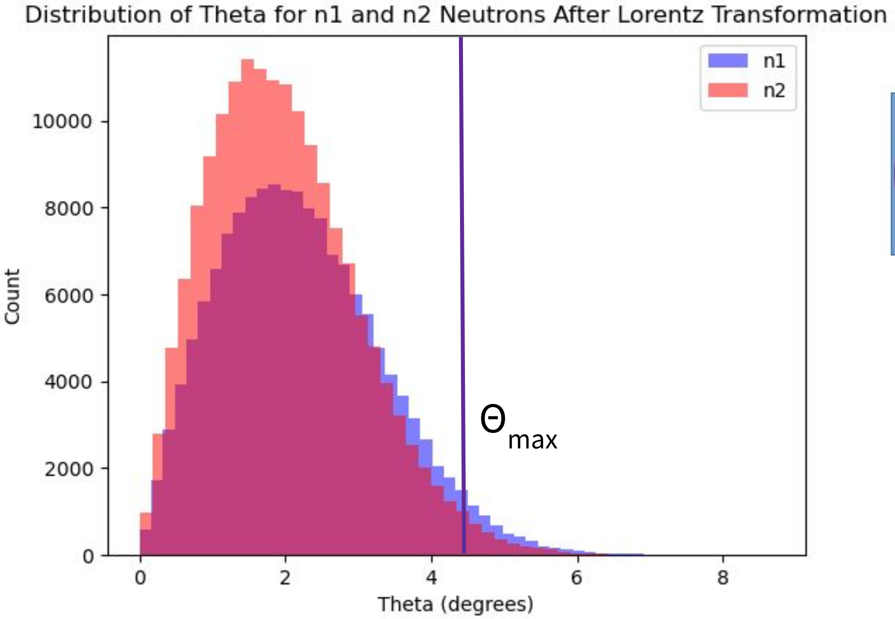


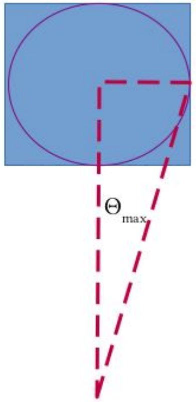


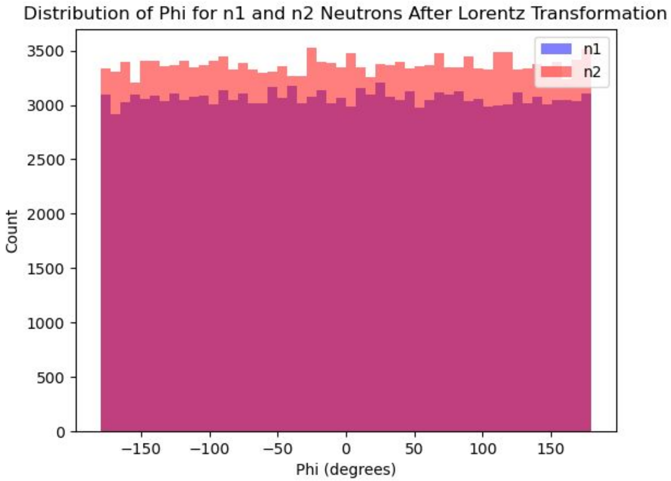
- different modes of fission - different multiplicity of neutrons
- how to handle this for the multiplicity cuts?

NeuLAND acceptance for neutrons from GEF

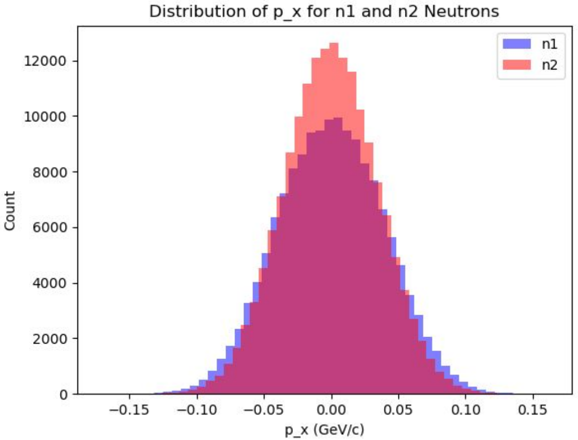
- after the Lorentz transformation (in the lab system)

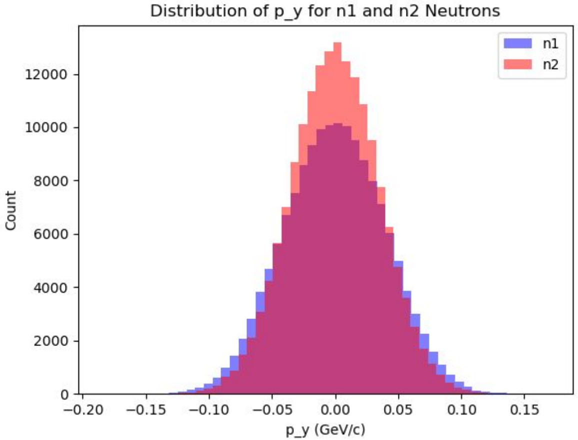


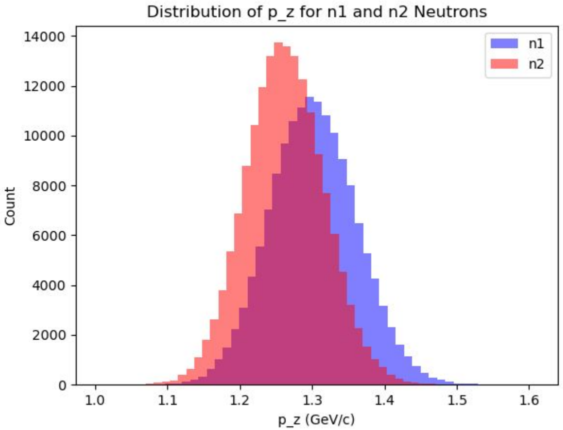




Input file for NeuLAND simulation







- number of events ~ 100 000

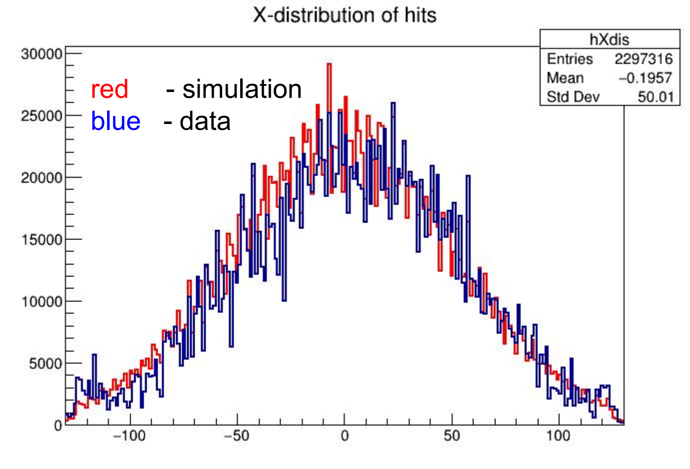
Data - simulation comparison

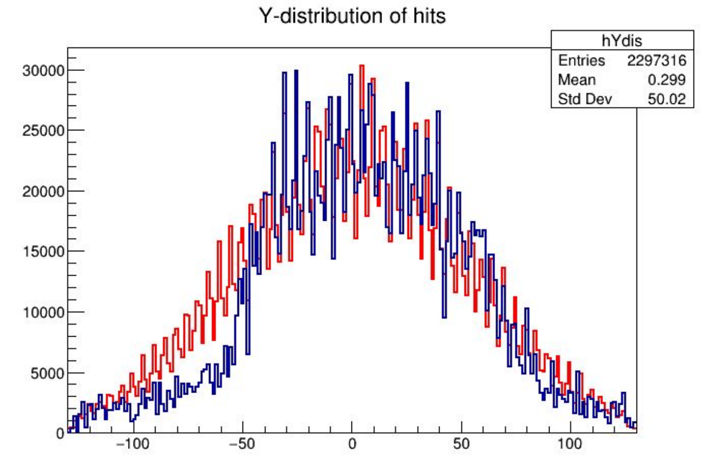
Cuts applied to the data:

- Z1 + Z2 = 92 cut
- Target 1 cut

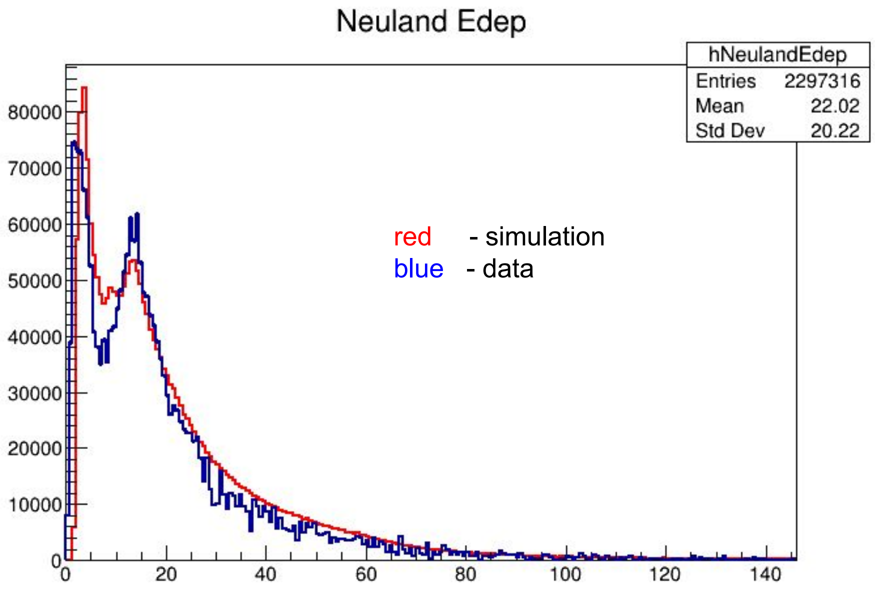
Parameters used for the simulation (other than standard Tamex parameters):

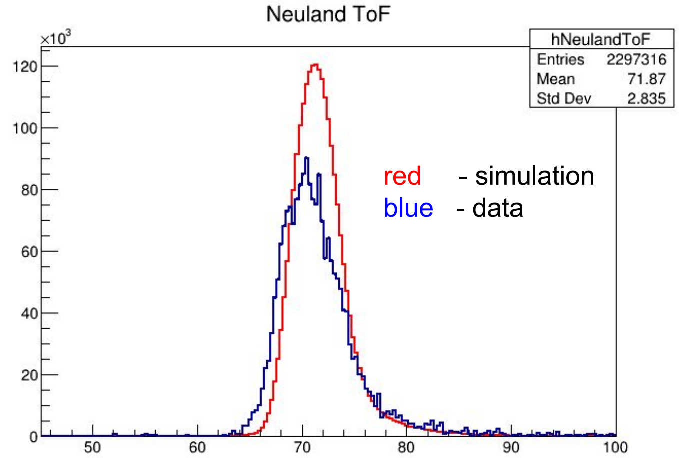
- double fPMTThresh = 0.6 MeV (probably too small)
- double fTimeRes = 0.23 ns

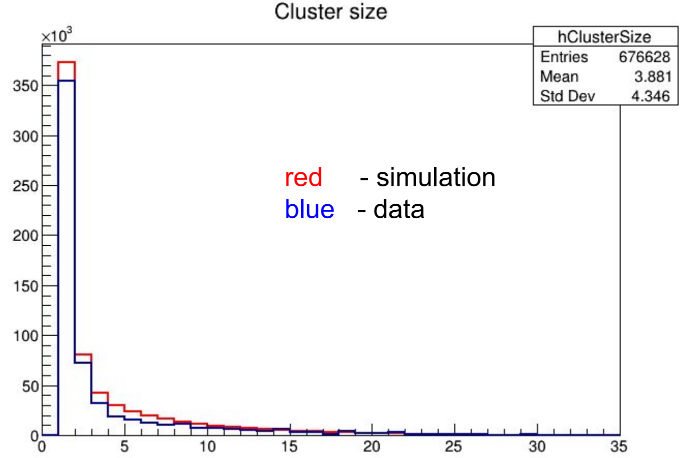




Data - simulation comparison

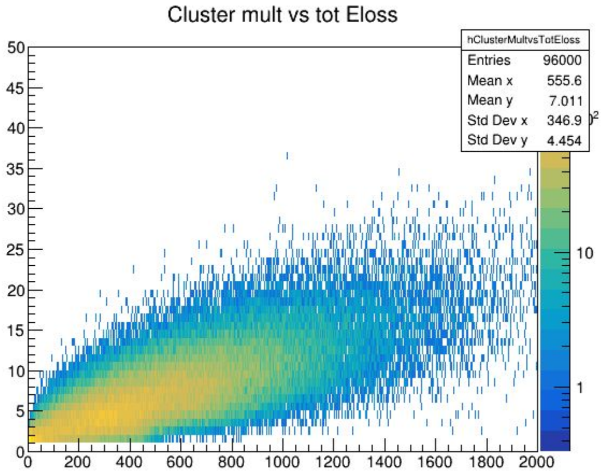




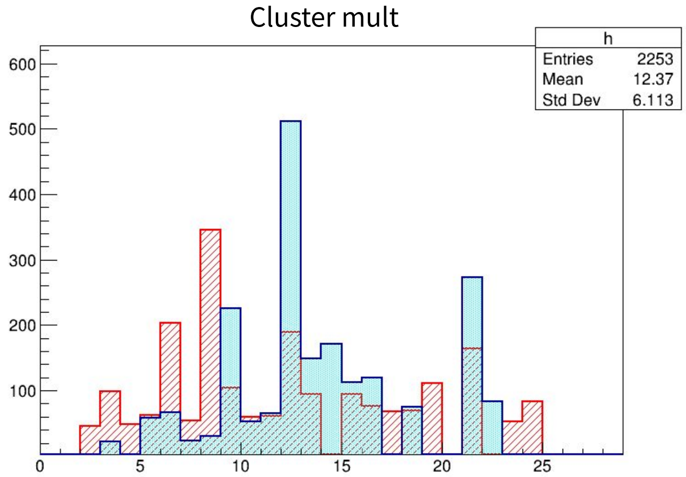


Data - simulation comparison

Red - bigger difference iz Z1, Z2
Blue - smaller difference in Z1, Z2

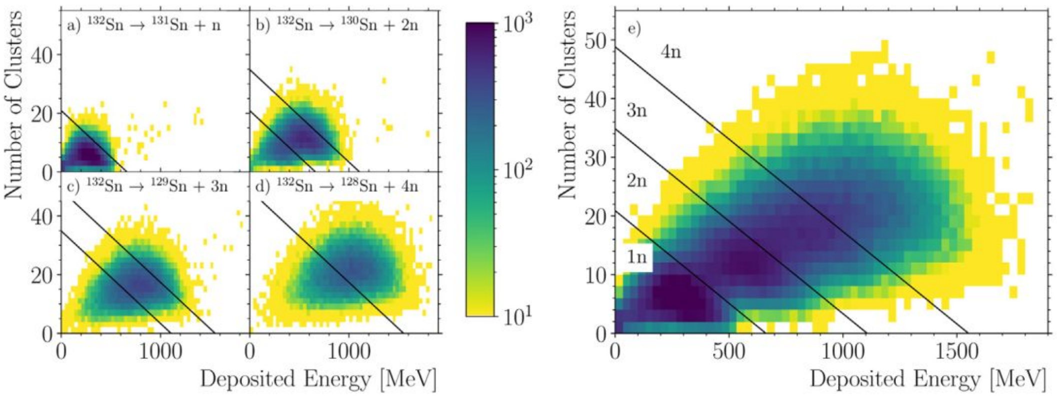


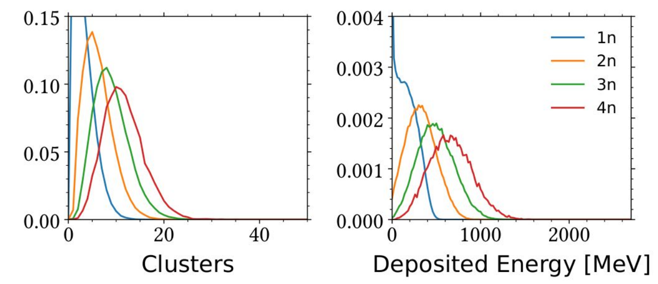
The idea is to look for different neutron multiplicities in symmetric and asymmetric fission (cuts on Z1 and Z2, preserving Z1+Z2 =92)



- data-simulation comparison are done for all the neutrons from both fragments together
- we need to separate different neutron multiplicities in data and in simulation
- once we match the simulation to the data perfectly, we can use cuts from simulation for the multiplicity determination

Calorimetric method





200 MeV		generated 1	2	3	4	5
detected	0	29	8	2	1	0
	1	**63**	45	24	11	5
	2	8	**28**	27	18	10
	3	0	15	**24**	23	16
	4	0	3	15	**20**	19
	5	0	0	8	27	**50**

600 MeV		generated 1	2	3	4	5
detected	0	24	5	1	0	0
	1	**63**	45	23	11	5
	2	13	**28**	25	16	9
	3	0	16	**24**	22	16
	4	0	5	16	**22**	19
	5	0	1	10	29	**51**

1000 MeV		generated 1	2	3	4	5
detected	0	21	4	1	0	0
	1	**58**	38	19	8	3
	2	19	**30**	24	15	8
	3	1	18	**25**	22	15
	4	0	7	17	**22**	20
	5	1	2	14	33	**53**

- the best method for higher neutron multiplicities available at the moment
- for the calorimetric method the matching in Edep and cluster multiplicity between the simulations and the data is crucial
- cuts on the fragment mass

Next steps

- check the input for NeuLAND simulation
- study the simulation on the level of MCTracks
- adjust the simulation (minimal energy deposition cut, time resolution etc.)
- investigate different cluster sizes

- modify the format of the event numbers - needed to match fragment - neutrons for the whole statics
- improve the mass resolution of fragments if possible (Audrey is doing fragment analysis from scratch)
- put cuts on the fragment mass spectra to distinguish between different neutron multiplicity
- look for the correlations between fragments and neutrons

Thank you for your attention!