Is there a dark decay of neutrons in ^{6}He ?
E819S analysis

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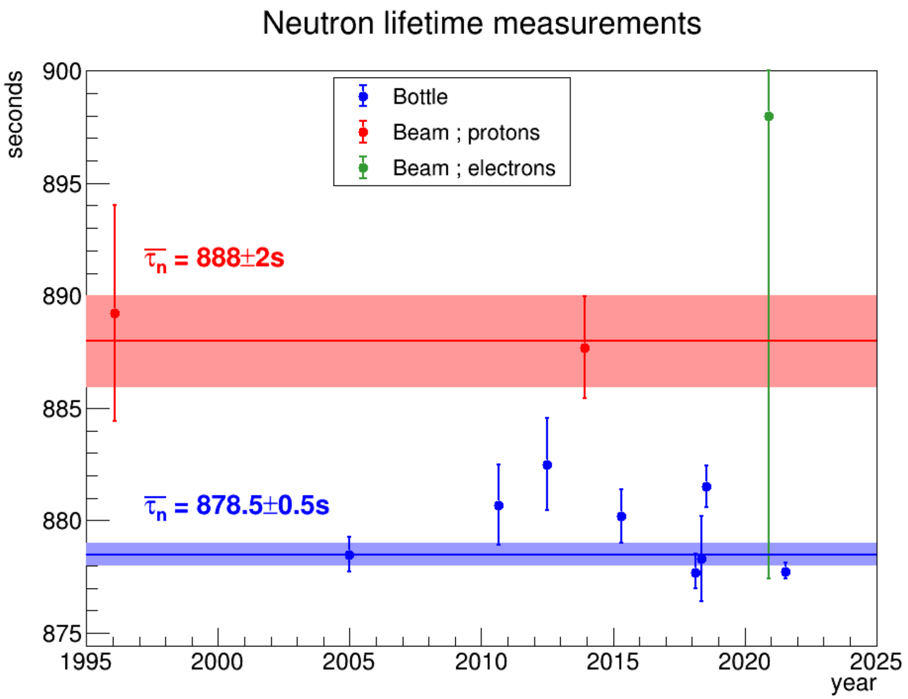
The neutron lifetime anomaly

There are two types of experiment that measure the neutron lifetime :



- The beam experiment which counts both the number of neutrons in a cold neutron beam and the number of protons or electrons emerging from it
  τ_n = 888±2 seconds
- The bottle experiment which counts the number of remaining ultra cold neutrons stored in a magneto-gravitational trap over time
  τ_n = 878.5±0.5 seconds

There is a ~1 % discrepancy between the two methods

The neutron lifetime anomaly

What could be the reason for such discrepancy ?

The **bottle** experiment directly monitors the number of neutrons over time whereas the **beam** experiment looks at the β-decay channel and $\tau_n \propto N_n/N_p$ where N_n and N_p are the number of neutrons and protons measured respectively.

Therefore we have 3 different options :

- Experimental bias with the presence of systematic effect(s) not taken into account in the final result
- The neutron can decay into other SM particles : excluded
- The neutron can decay into either SM particles and dark matter or into dark matter only [1]

If it exists, how can we observe this dark matter decay channel ?

[1] Fornal and Grinstein Phys. Rev. Lett. 120, 191801, 2018

Dark matter decay inside nuclei

Can neutrons inside nuclei decay into dark matter ?

Energy condition [2]

Mass range for the dark matter particle χ :

$$937.993 \text{ MeV} < m_\chi < m_n - S_n$$

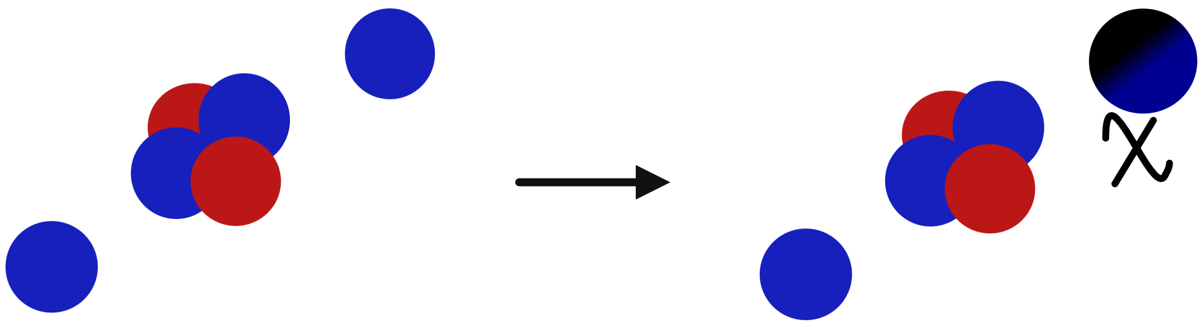
Where 937.993 MeV corresponds to the mass difference between ^{9}Be and 2α and $S_n < 1.572$ MeV

List of nuclei satisfying this condition : **^{6}He, ^{11}Li, ^{11}Be, ^{15}C and ^{17}C**

Heavier nuclei are also possible but are less practical candidates for a nuclear physics experiment. In our case we are interested in **^{6}He** with **$S_n = 1.7$ MeV** which does not meet the energy condition but **$S_{2n} = 975.45(5)$ keV** does

[2] Pfützner and Riisager Phys. Rev. C 97, 042501(R), 2018

^{6}He quasi-free neutron dark decay



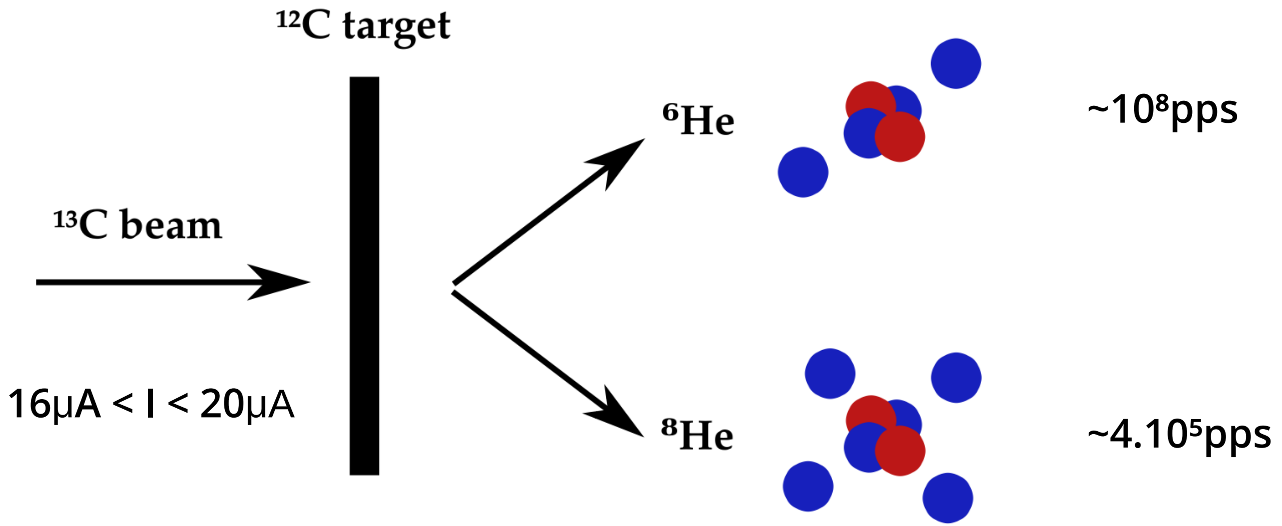
^{6}He $\qquad\qquad$ $^{4}He + \chi + n$

- ^{6}He can only decay with an emitted neutron if we consider a dark decay channel : unique signature !
- Estimated branching ratio upper limit : $B_{\chi} = 1.2 \times 10^{-5}$ [2]

[2] Pfützner and Riisager Phys. Rev. C 97, 042501(R), 2018

E819S experiment at GANIL

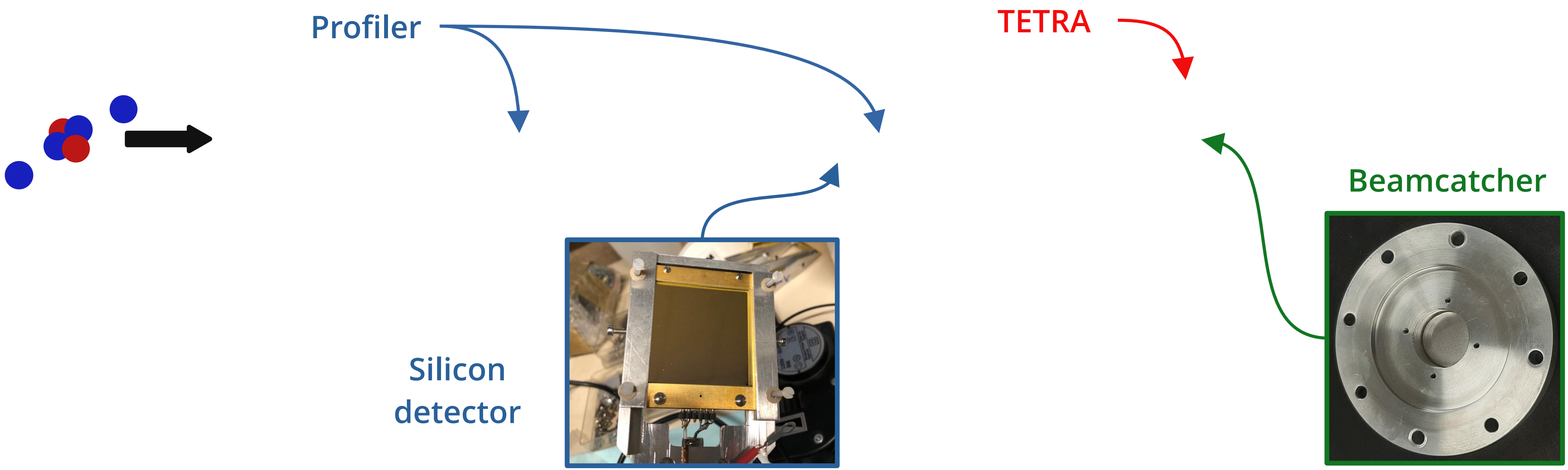
CSS1 and CSS2 were used in order to produce a primary ^{13}C beam (95MeV/A) directed toward a thick ^{12}C target to produce both $^{6}He^{1+}$ and $^{8}He^{1+}$ **(25keV)**



The particles are then selected to form a pure ^{6}He or ^{8}He beam at **low energy (25keV)** going through the LIRAT line to the detection setup

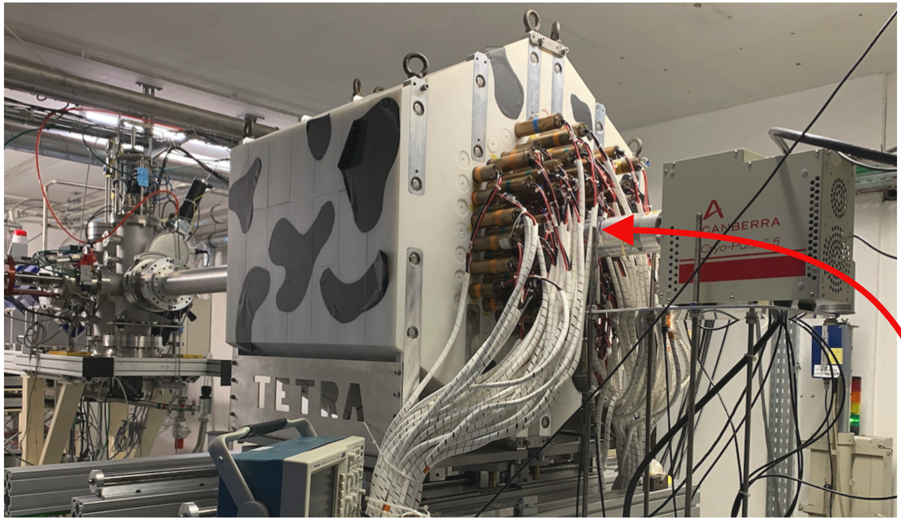
E819S experiment at GANIL

The LIRAT line and the detection setup



The beamcatcher simply consists of a thin 150µm aluminum foil placed in the center of the neutron detector TETRA

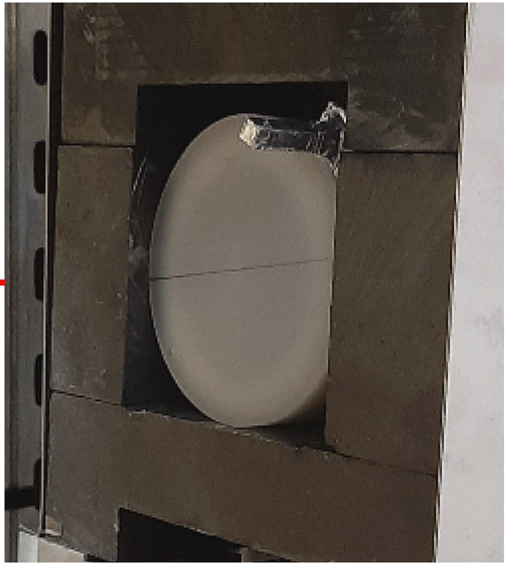
E819S experiment at GANIL



4π neutron dectector using ^{3}He gas counters called **TETRA** calibrated with a ^{252}Cf neutron source

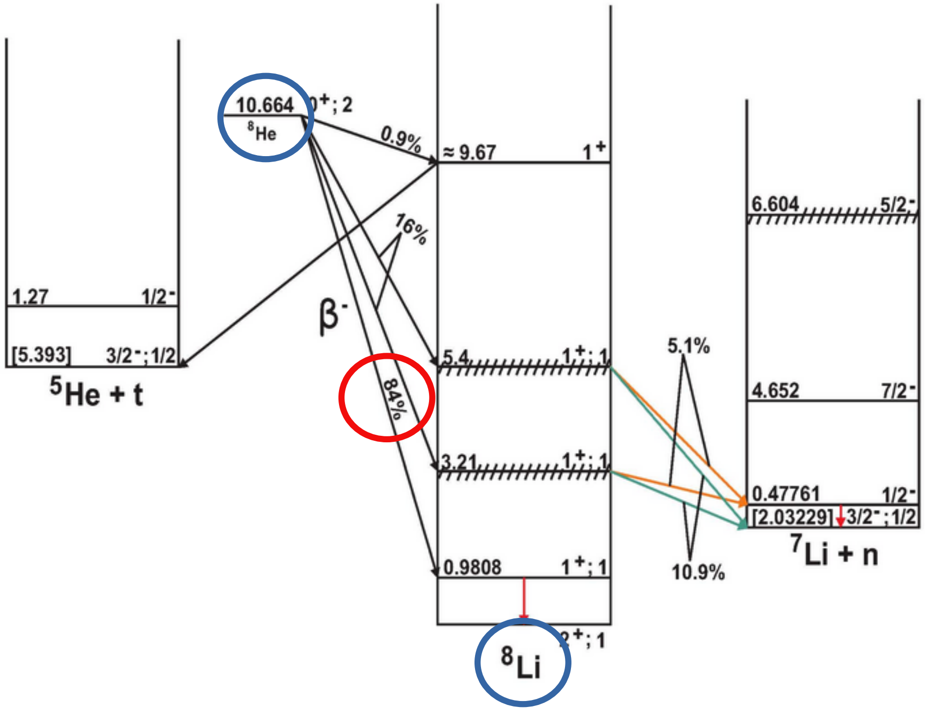
Germanium semiconductor (HPGe) for γ-rays detection calibrated with a ^{152}Eu source

Small solid angle **plastic scintillator** for β-particles detection placed on top of the HPGe



Plastic scintillator efficiency

We used ^8He runs data to assess the plastic scintillator efficiency at ~20cm and ~40cm from the beamcatcher



There is a β filiation between ^8He and ^8Li so for each decay there is 1.84 β emitted

We computed the implanted rate of ^8He thanks to 980.8keV γ-ray with the HPGe

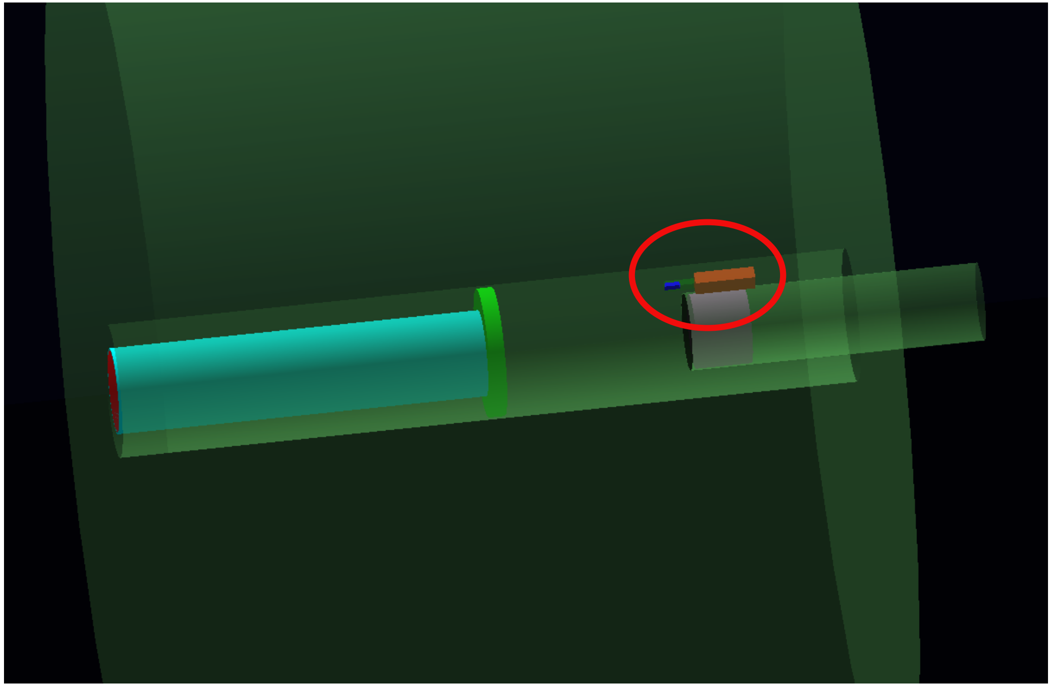
We then compared the values with the statistics from the plastic and we have :

$\varepsilon(20cm) = (1{,}017 \pm 0{,}002).10^{-3}$

$\varepsilon(40cm) = (2{,}146 \pm 0.020).10^{-4}$

Plastic scintillator efficiency

Quick Geant4 BeamLine (G4BL) simulations to take into account the different Q_β values between ^{8}He/ ^{8}Li (Q~10MeV) and ^{6}He (Q~3.5MeV) decays



MonteCarlo simulations with rejection method were used to model the β decay

10^8 (^{6}He) and 1,84.10^8 (^{8}He and ^{8}Li) events for each simulation at both positions for the plastic scintillator

By comparing the statistics we can correct the efficiency values and we have :

ε(20cm) = (8.64±0,10).10^{-4}

ε(40cm) = (1,64±0.04).10^{-4}

(~10/15% difference)

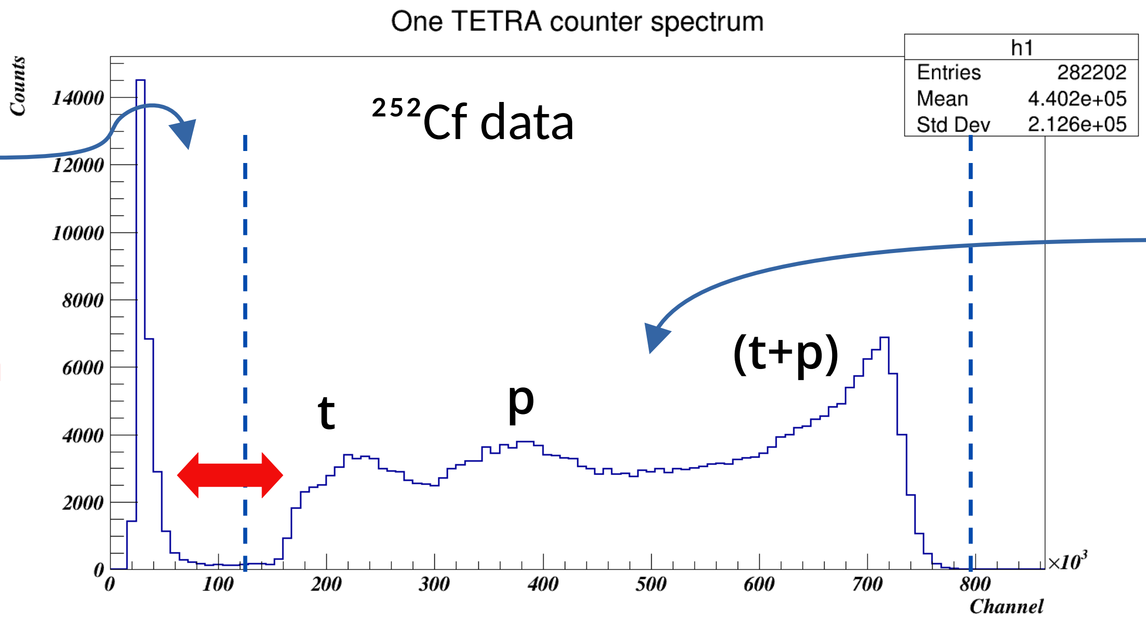
TETRA detection efficiency

Neutron detection is based on secondary charged particles detection :

$^{3}He + n \rightarrow t + p + 765keV$

Piedestal and γ-ray/bremsstrahlung

Good discrimination between the low energy peak and neutron events



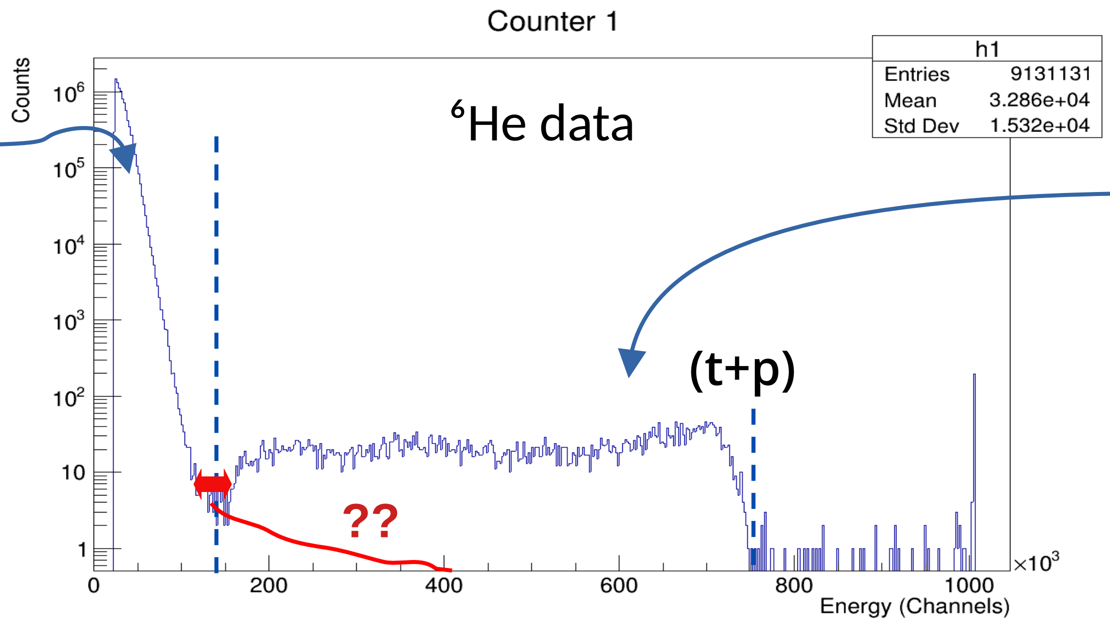
Neutron events from the ^{252}Cf source

The **(t+p)** peak amplitude is related to the gas pressure inside the counter ; here the pressure is lower than what it used to be

TETRA detection efficiency

Discrimination between the low energy peak and the neutron events is not as good ;
where does the bremmstrahlung tail stops ?

Bremsstrahlung events from the ^{6}He β decay



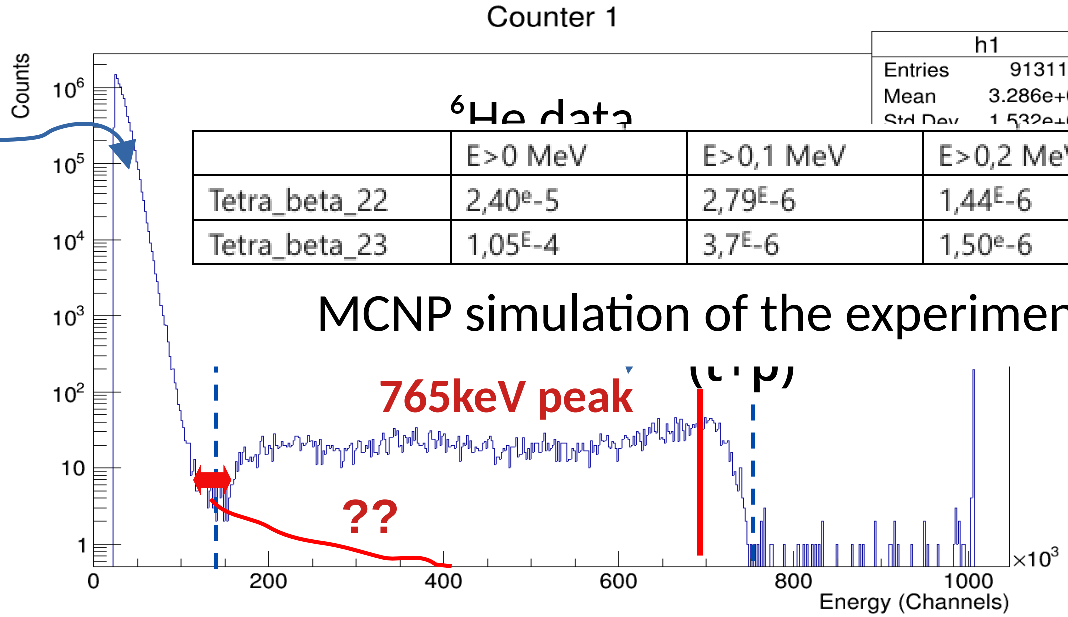
^{6}He neutrons ?

How to deal with these events ?

TETRA detection efficiency

Discrimination between the low energy peak and the neutron events is not as good ;
where does the bremmstrahlung tail stops ?

Bremsstrahlung events from the ^{6}He β decay



	E>0 MeV	E>0,1 MeV	E>0,2 MeV	E>1 MeV
Tetra_beta_22	2,40e-5	2,79E-6	1,44E-6	9,025E-8
Tetra_beta_23	1,05E-4	3,7E-6	1,50e-6	7,49e-8

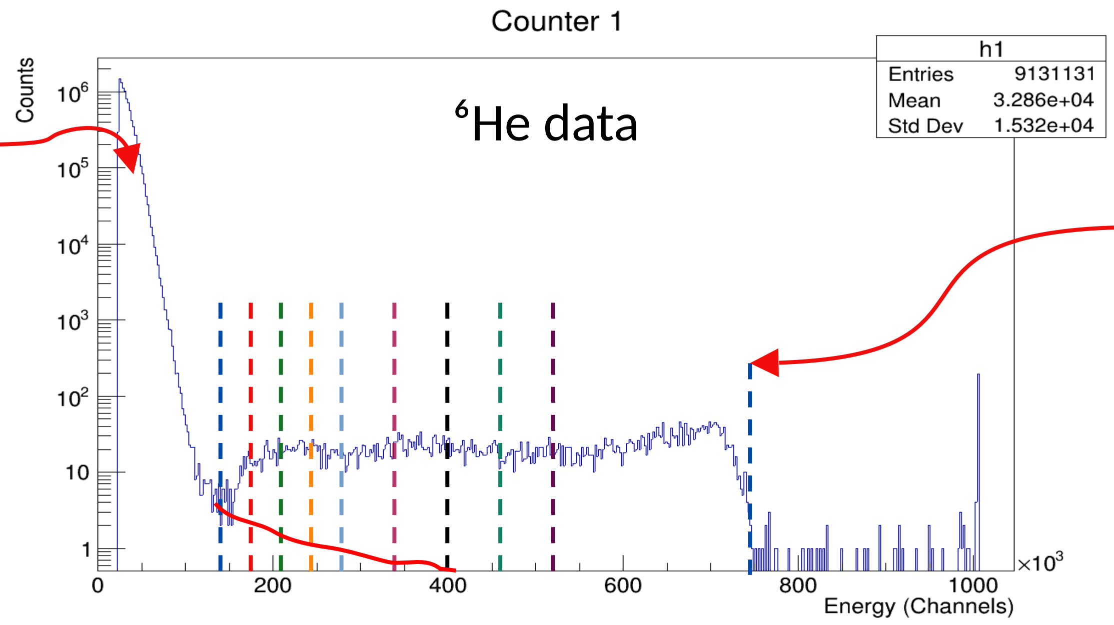
MCNP simulation of the experimental setup

How to deal with these events ?

TETRA detection efficiency

We set different lower threshold values that increase the distance from the low energy peak but also reduce the total neutron statistics

Bremsstrahlung events from the ^{6}He β decay



Common upper threshold placed after the **(t+p)** peak

Efficiency values go from ε(THR1) = 45.29±4.91% to ε(THR1_S300) = 19.05±2.07%

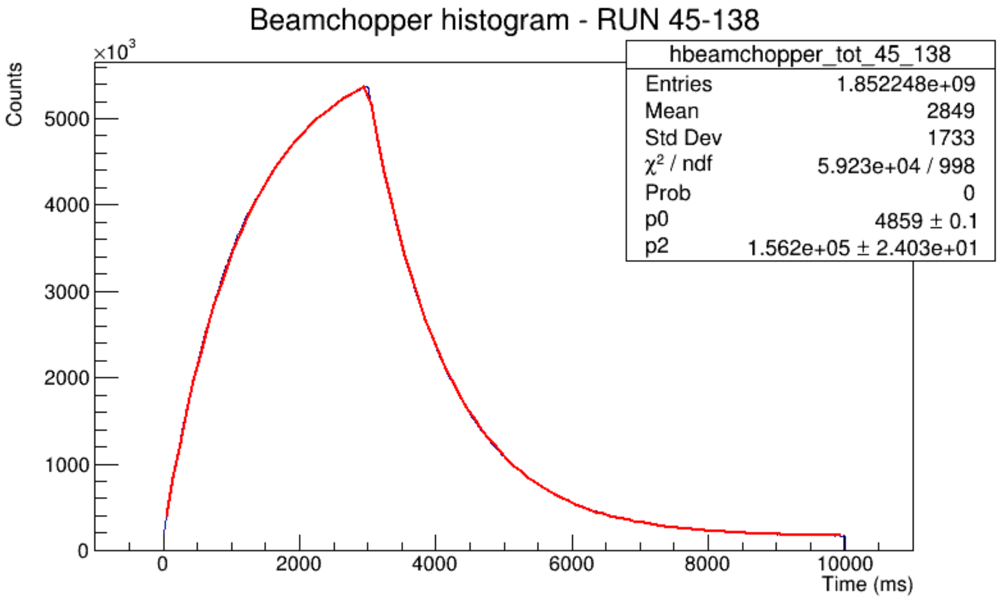
Number of implanted ^{6}He

Beam On/Off cycles with t_{ON} = 3s and t_{OFF} = 7s

Data is stacked into one histogram and fitted with the following function :

$$y_1(t) = bck + \phi\tau(1 - exp(-t/\tau)) \quad \text{for} \quad 0s \le t < 3s$$

$$y_2(t) = bck + y_1(t = 3s)exp(-(t - 3s)/\tau) \quad \text{for} \quad 3s \le t \le 10s$$



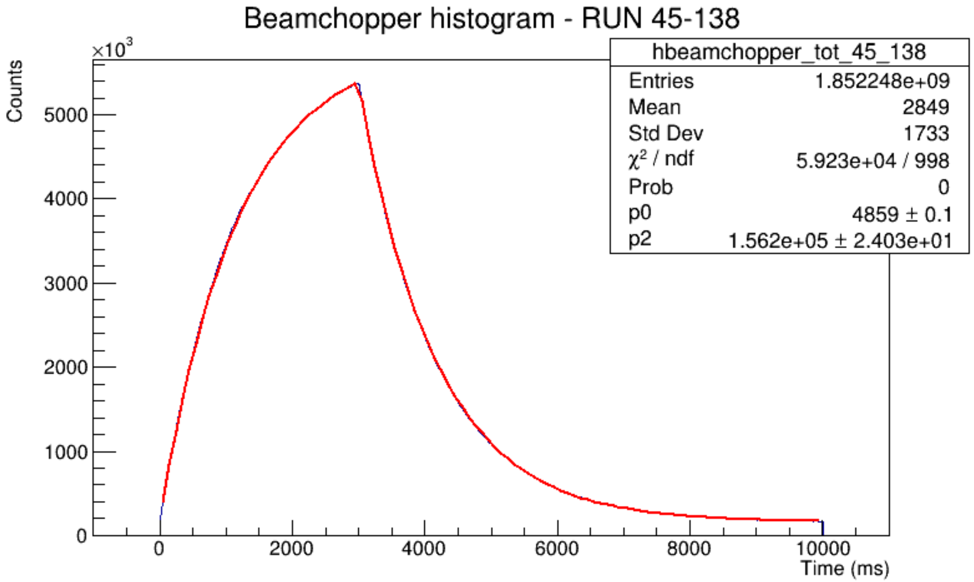
- *bck* is a constant parameter
- *Φ* is linked to the number of implanted ^{6}He/detected events
- *τ* is the ^{6}He lifetime value fixed at 1164ms **[3]**

[3] M. Kanafani, PhysRevC.106.045502

Number of implanted ^{6}He

Beam On/Off cycles with t_{ON} = 3s and t_{OFF} = 7s

Just need to remove the *bck* component from the fit to get the ^{6}He decay events

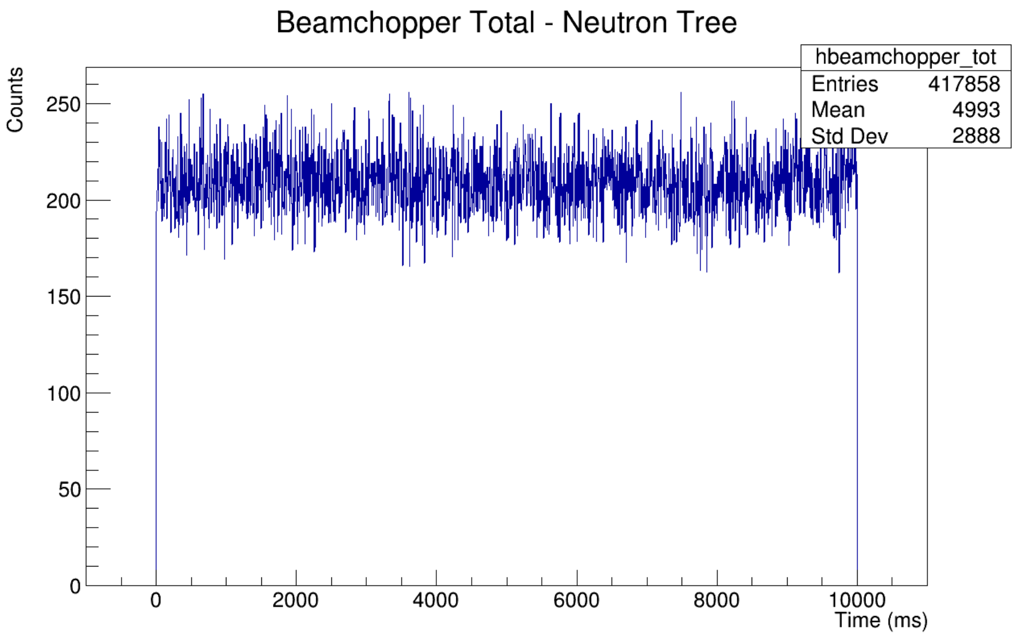


Total number of implanted ^{6}He over 37374 cycles : $(1,366\pm0,005).10^{13}$

Averaged implanted rate : $(1,040\pm0,023).10^{8}$ pps

TETRA analysis

Same beamOn/Off histogram as previously with a 5ms binning and with the largest TETRA thresholds

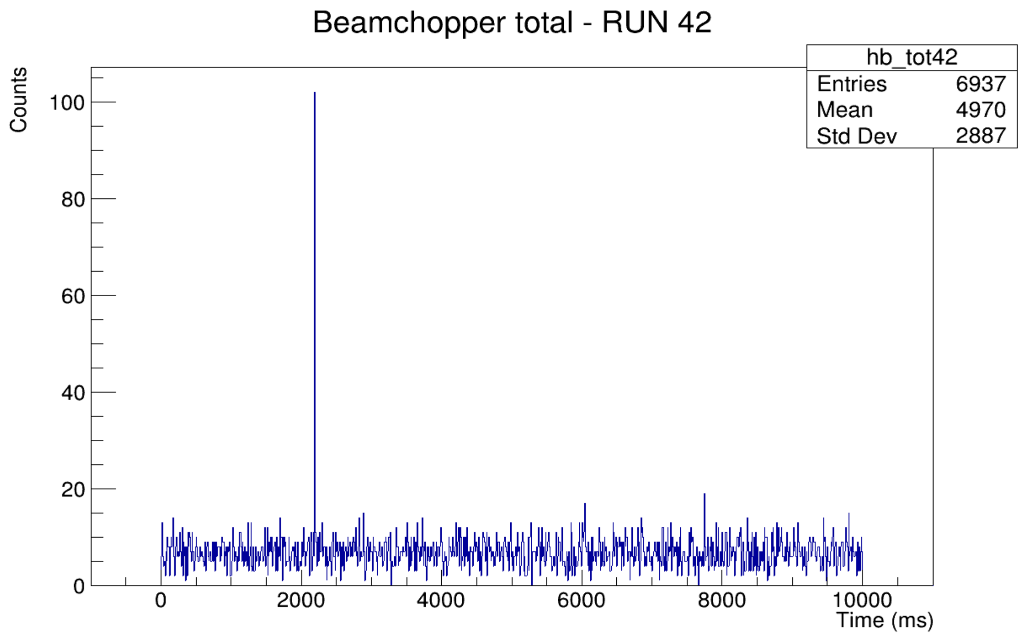


Mean value of 4.993 seconds hints to more statistics on the left i.e. the **beamOn** part

Is it due to the bremmstrahlung ? Or to another hidden problem ?

TETRA analysis

Some unexpected events came during the acquisition…



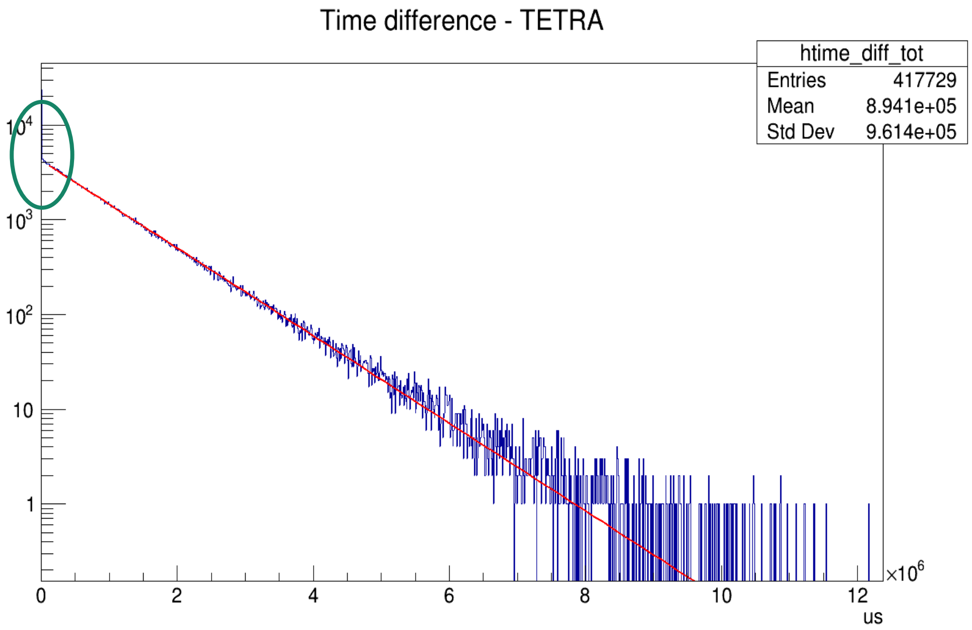
High burst of ~100events came during Run42 shared between all counters during the **beamOn** part

Might be from cosmic neutrons

Can we identify the background sources ?

TETRA analysis

The distribution of time difference between each event in TETRA should follow an exponential law (Poisson's statistics)…



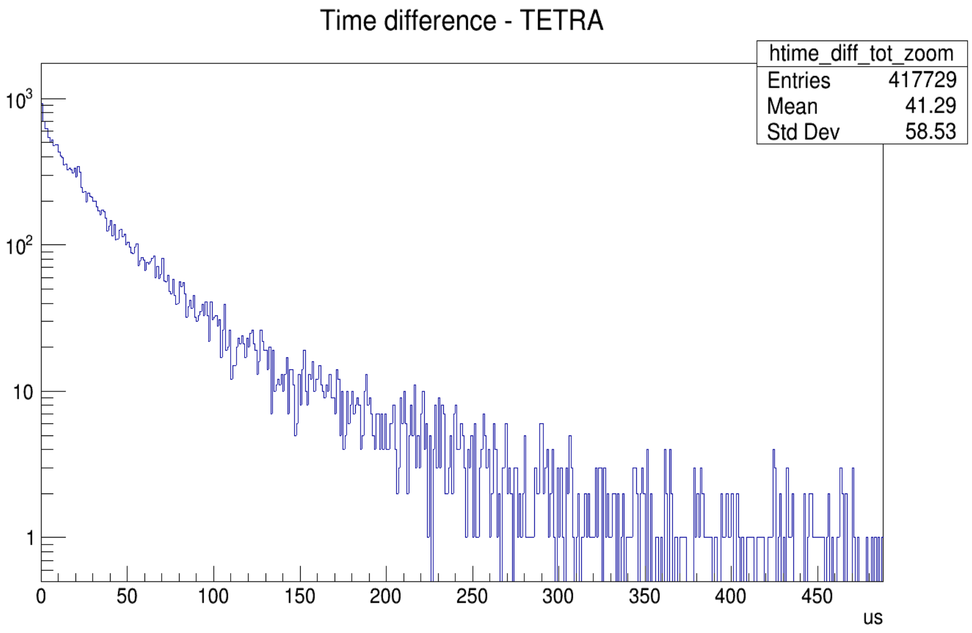
… and this is what we observe with the Poisson parameter from the fit giving the detection rate in TETRA during the experiment at ~1Hz for

$\Delta t > 500\mu s$

Let's zoom in the 0 to 500µs region

TETRA analysis

We see another distribution in this region : there is another source of events in TETRA which is **also observed in background run without the cyclotrons**



These events could come from :

- Cosmics that simulate a high detection rate (remember Run42)
- Sparks in some counters
- Radioactive nuclei in TETRA's component like Bi-Po

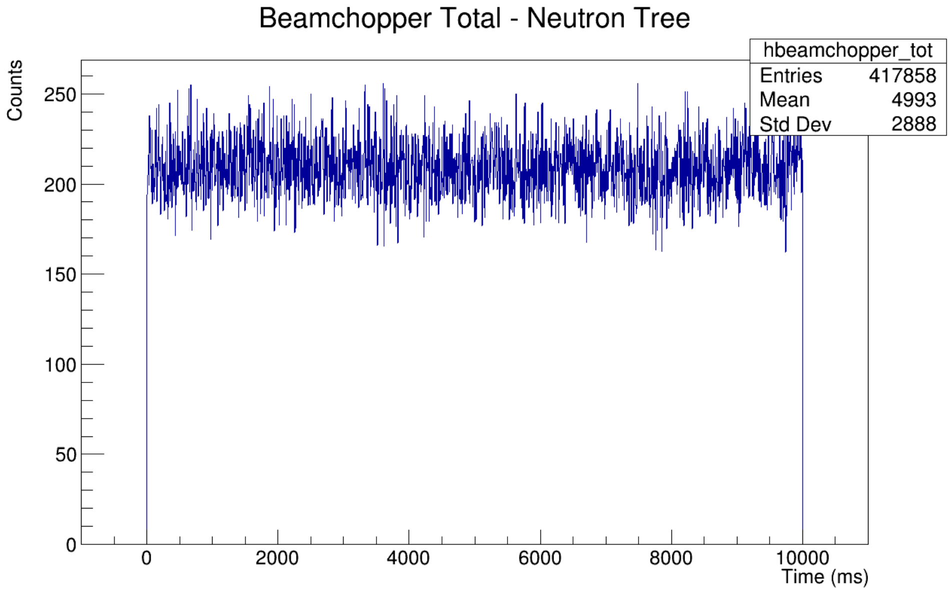
We flagged these events that were less than 0.3ms and 1ms away from each other to see their **distribution** in the beamOn/Off cycle : they are evenly distributed
But we are not done with them !

TETRA analysis

Fit analysis on the beamOn/Off histogram

$$y_1(t) = bck + \phi\tau(1 - exp(-t/\tau)) \quad \text{for} \quad 0s \leq t < 3s$$

$$y_2(t) = bck + y_1(t = 3s)exp(-(t - 3s)/\tau) \quad \text{for} \quad 3s \leq t \leq 10s$$

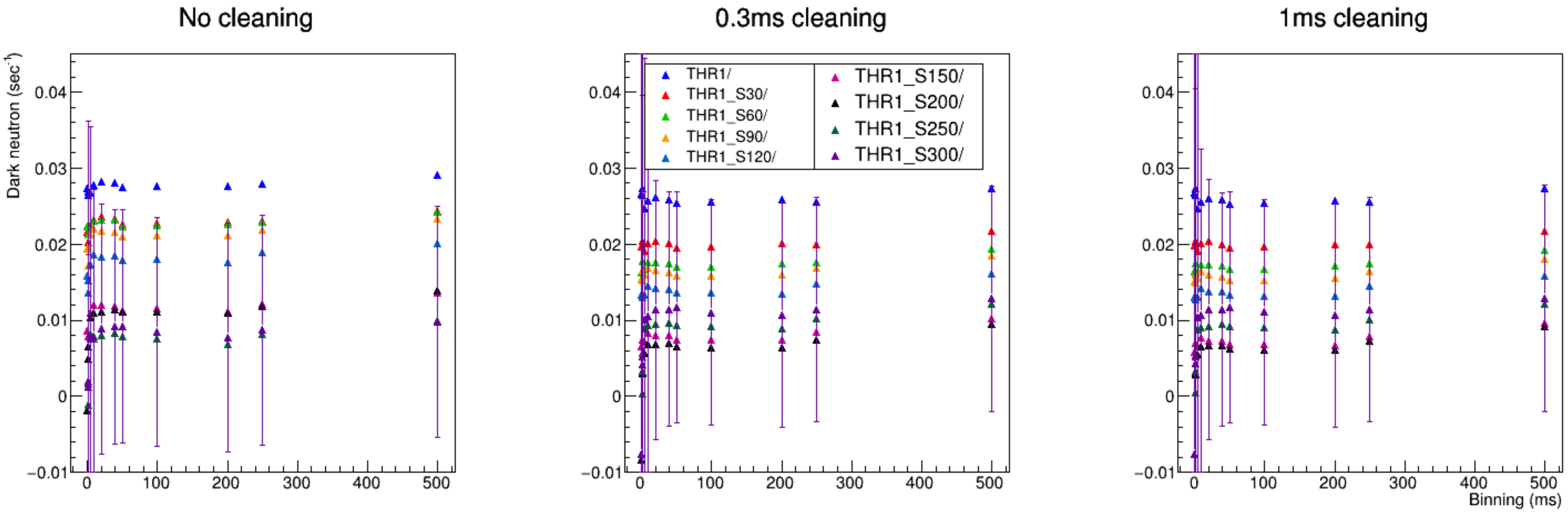


We made an analysis to see the impact of **three parameters** :

1. The binning of the histogram going from starting from 0.5ms with ~20 counts/bin to 500ms with ~20000 counts/bin
2. Removing or not the events that are less than 0.3ms or 1ms away from each other
3. Varying the neutron thresholds (detection efficiency)

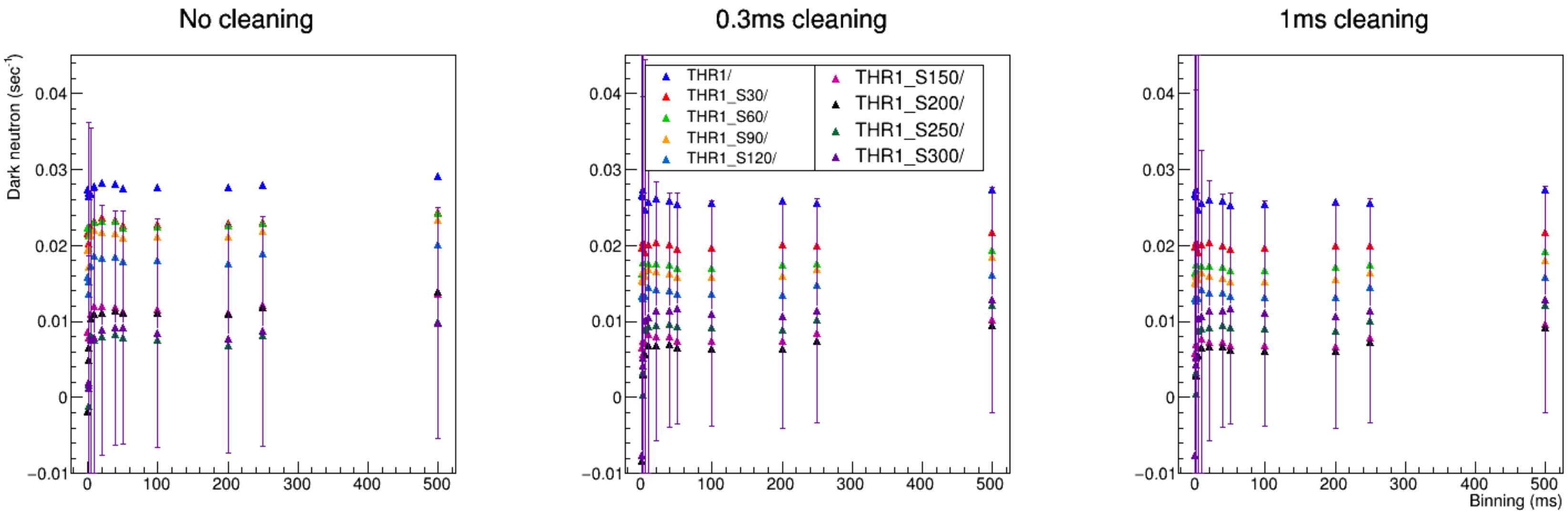
TETRA analysis

Event rate : the ϕ parameter returned by the fit (sec^{-1})
Dark neutron : event rate corrected by the detection efficiency (sec^{-1})
Br(χ) : dark neutron corrected by the implanted dose of ^{6}He (branching ratio)



TETRA analysis

What do we learn from this ?



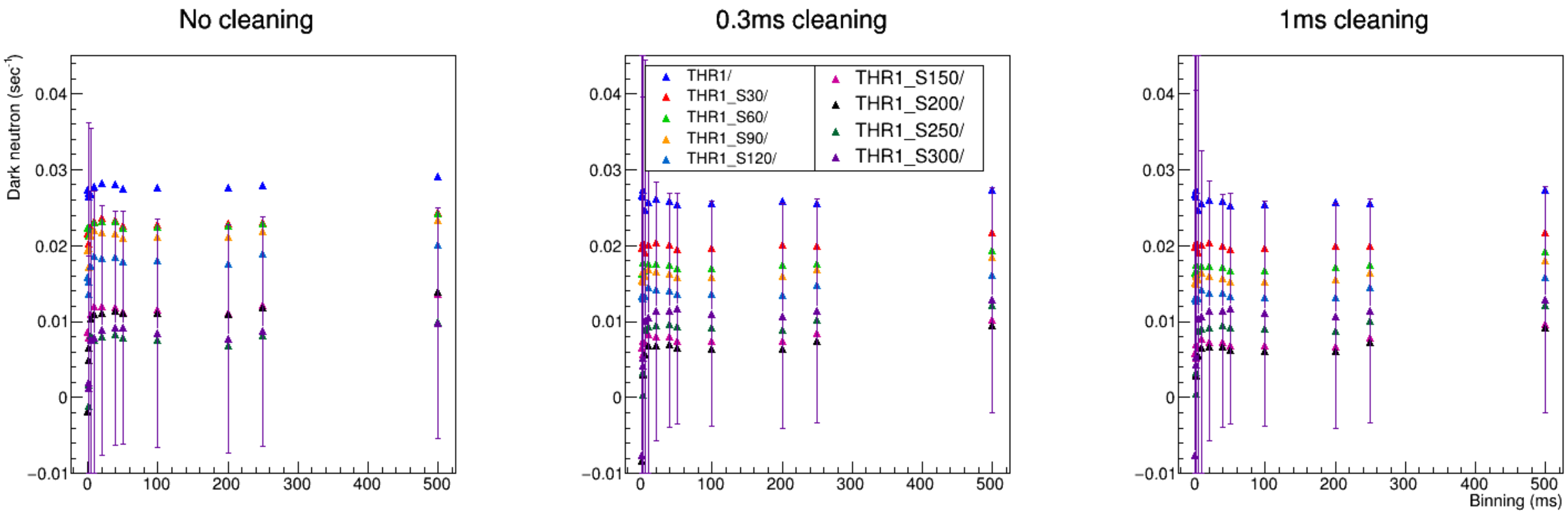
Binning :

- The fit gives back very consistant results for binning > 2ms
- Binning < 2ms give very different results (sometimes < 0) with higher error bars

For the rest of the analysis we therefore fix the binning at **100ms**

TETRA analysis

What do we learn from this ?



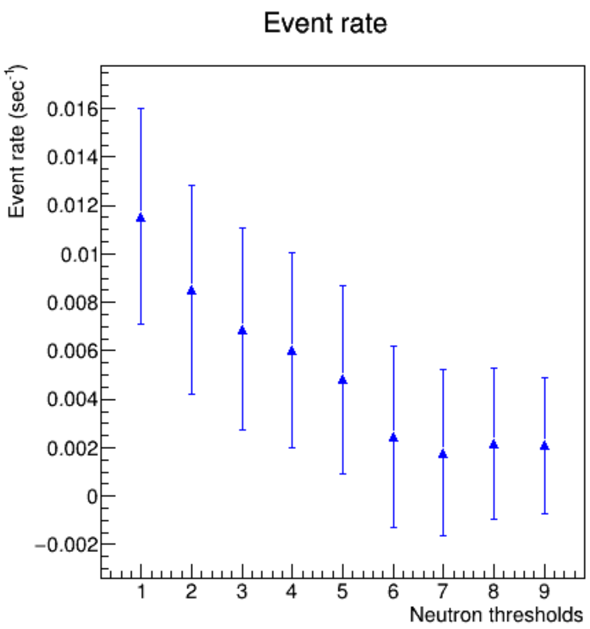
Cleaning events :

- No significant difference between *no cleaning* and *0.3ms cleaning* and even less between *0.3ms* and *1ms* in the fit parameter (the events were evenly distributed)
- *0.3ms* cleaning drastically improves the χ^2 value of each fit compared to *no cleaning*

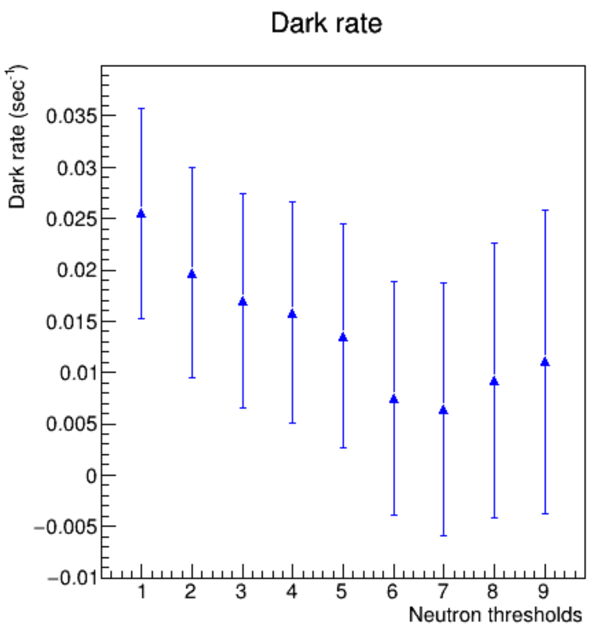
For the rest of the analysis we therefore use the 0.3ms cleaning

Results

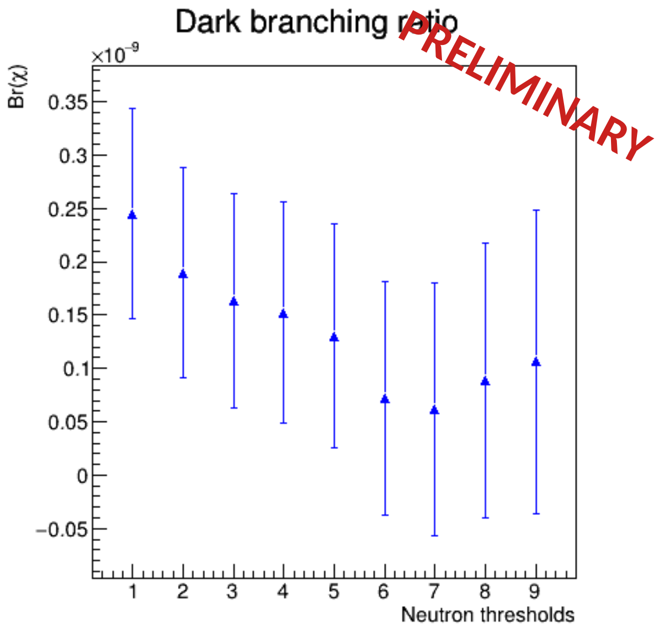
The only parameter left is the neutron detection threshold



Fit parameter…



…corrected by the detection efficiency…

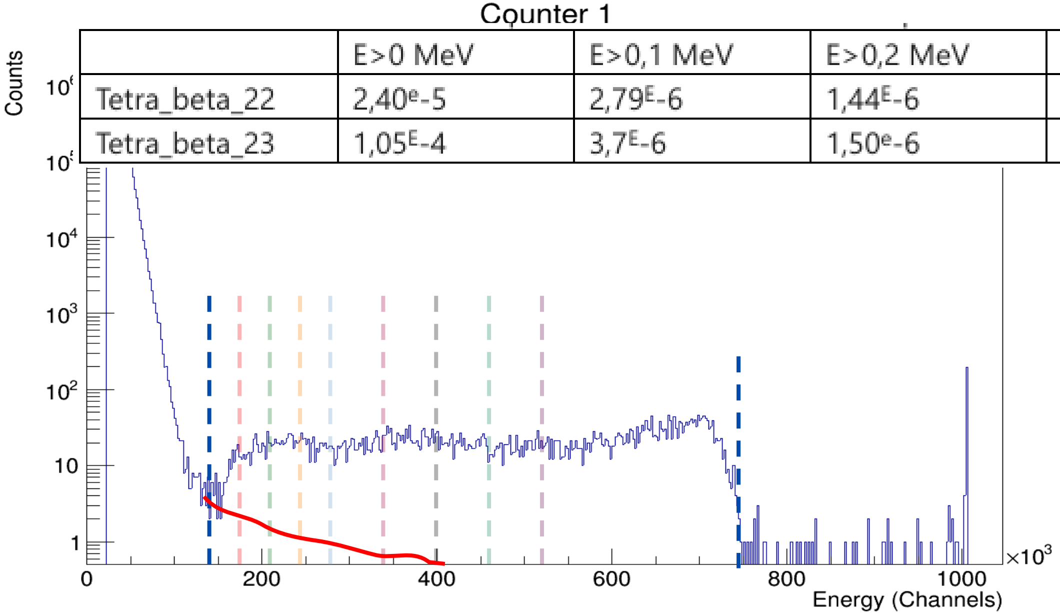


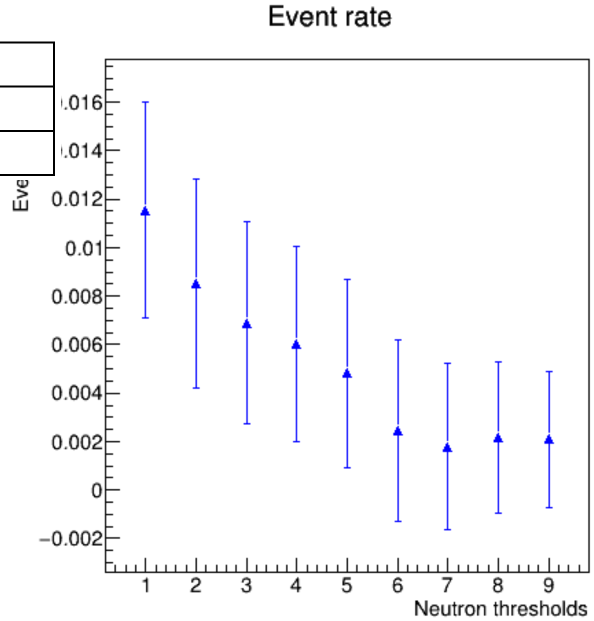
…corrected by the implanted rate of ^{6}He

Results

Is this a measure of the β energy deposition ?

	E>0 MeV	E>0,1 MeV	E>0,2 MeV	E>1 MeV
Tetra_beta_22	2,40e-5	2,79E-6	1,44E-6	9,025E-8
Tetra_beta_23	1,05E-4	3,7E-6	1,50e-6	7,49e-8

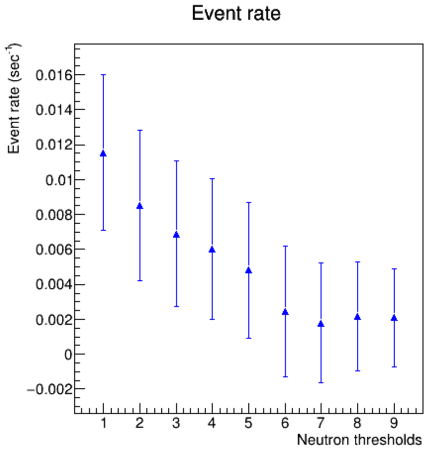


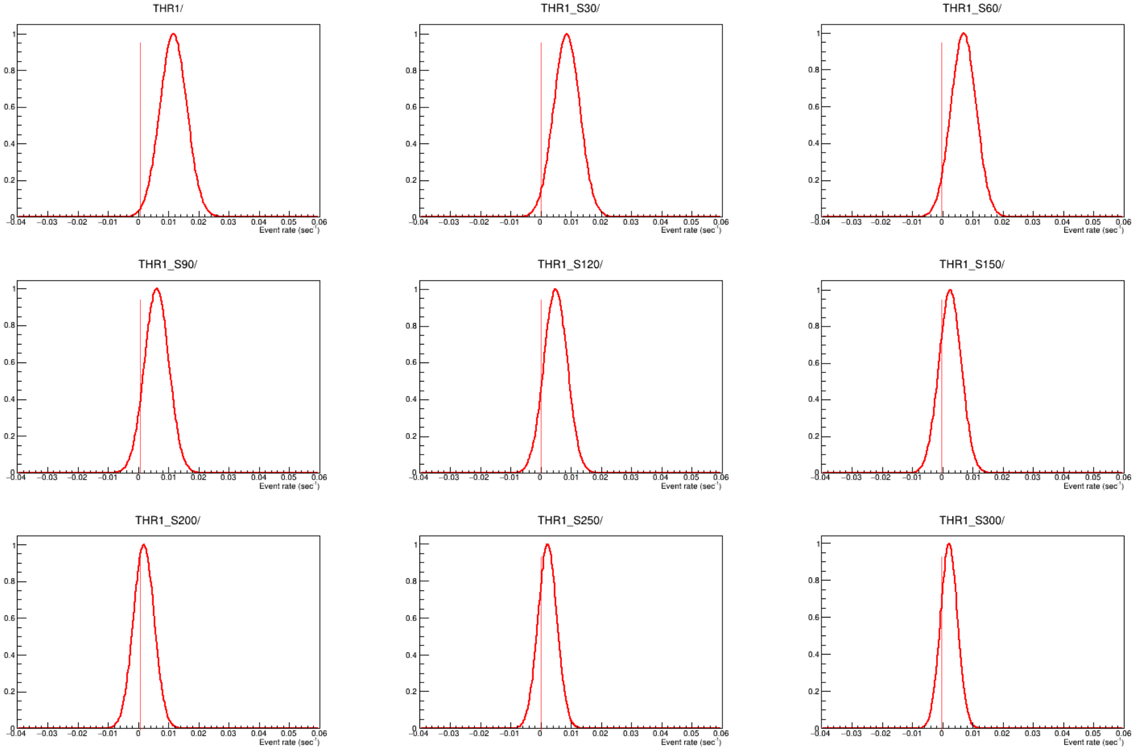


Future work to be done !

Results

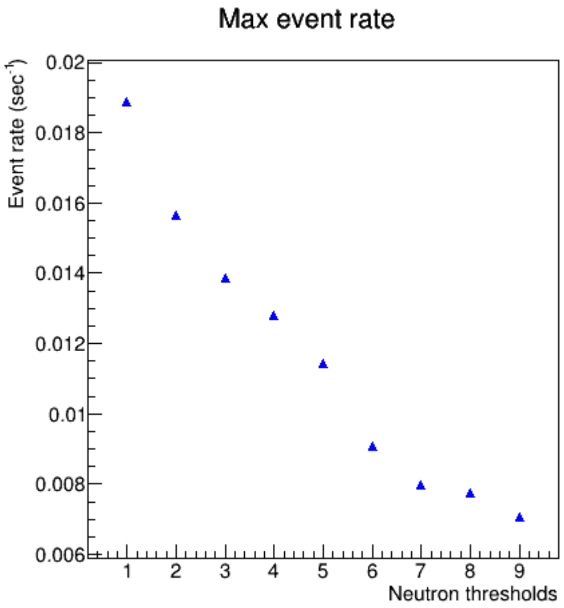
Exclusion zone : maximization of the fit parameter at 95% of the positive side of the normal distribution

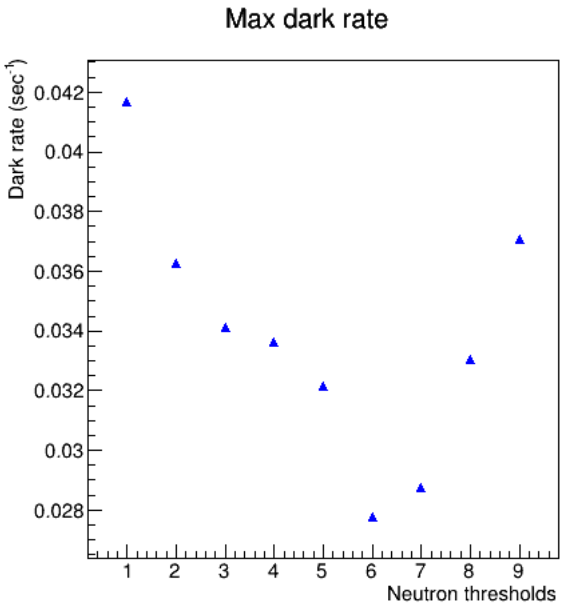


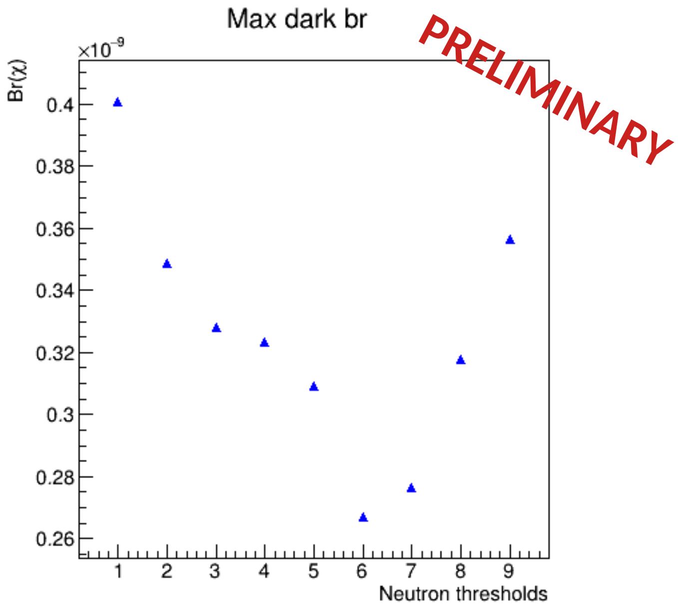


Results

Maximization of the fit parameter at 95% of the positive side of the normal distribution







The highest upper limit we have now for this dark decay is $4\times10^{-10} << 1.2\times10^{-5}$ (estimated upper limit) **[2]**

[2] Pfützner and Riisager Phys. Rev. C 97, 042501(R), 2018

Thank you for your attention !

PhyNuBE - March 2023

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