Analysis status of $^{94}Nb(n,\gamma)$ cross section measurement

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AGENCIA ESTATAL DE INVESTIGACIÓN

nTOF

VNIVERSITAT DE VALÈNCIA

CSIC Consejo Superior de Investigaciones Científicas

Outline

- Brief summary of prev. analysis status
- Monte Carlo simulations & dead time model
- Results of Maximum Likelihood estimation for exp. yield
- Self-shielding corrections
- Take home messages

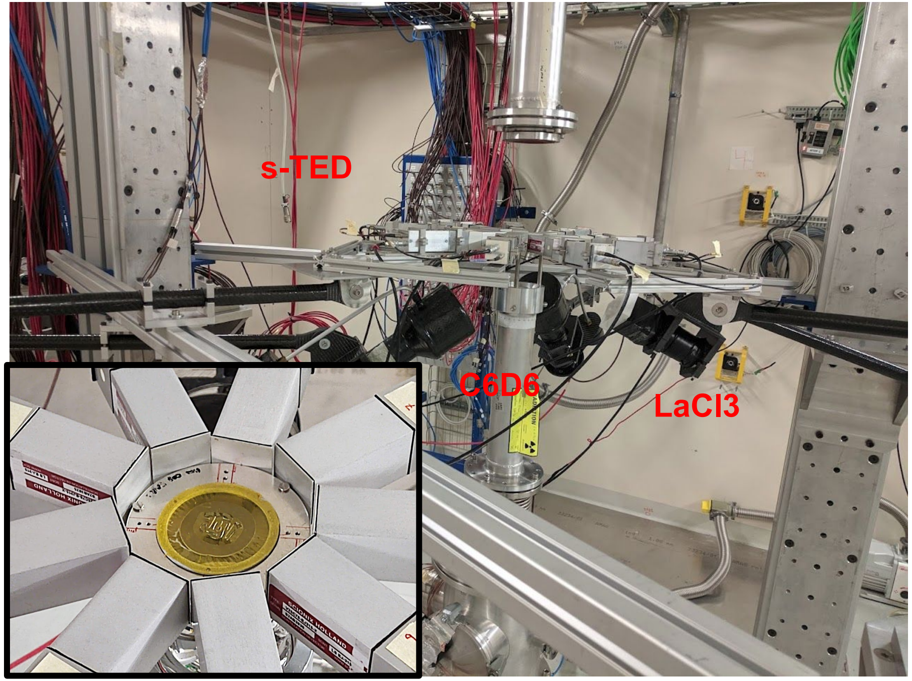
Brief summary

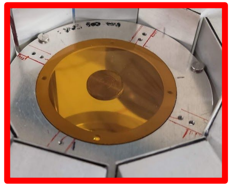
First (n,ɣ) measurement in **EAR2** for **2022** campaign:

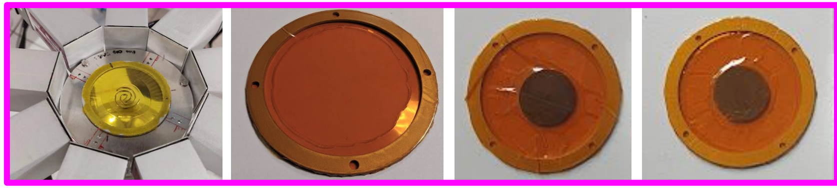
- Experiment performed between end of **March** and **April** of this year.

- Experimental setup:
  - **9 s-TEDs** in a ring configuration @ **4.5 cm**. →Main detectors for (n,ɣ) (~1 L of C6D6).
  - **2 C6D6** @ **17.5 cm** with the **new PMT+VD** →Validation.
  - **1 LaCl3** @ **9 cm** →Spectroscopic inf. & angular distribution.

- A total of **3.2**x10^{18} protons / **3.0**x 10^{18} INTC distributed in **several configurations** devoted to:
  - **Isotope** of interest
  - **Bkg** estimation
  - **Normalization** with a controlled geometry



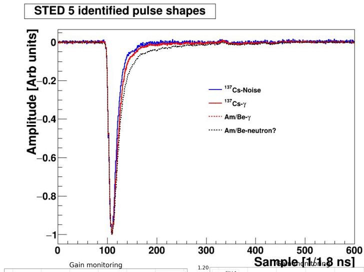




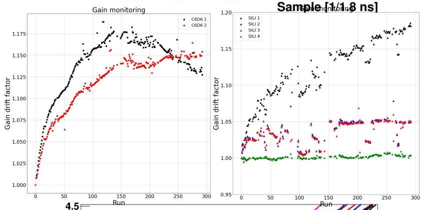
Brief summary

In the last meeting:

- Pulse shapes identification for all detectors ✔

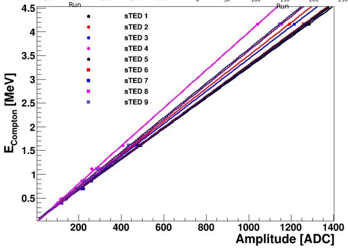


- Gain drift for all detectors along the measurement ✔

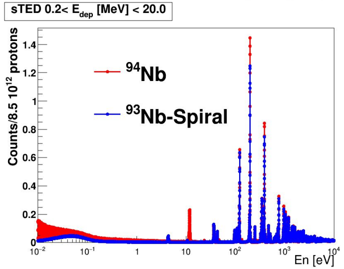


So, what is new since May?

- Detector individual energy calibration and t-flash ✔

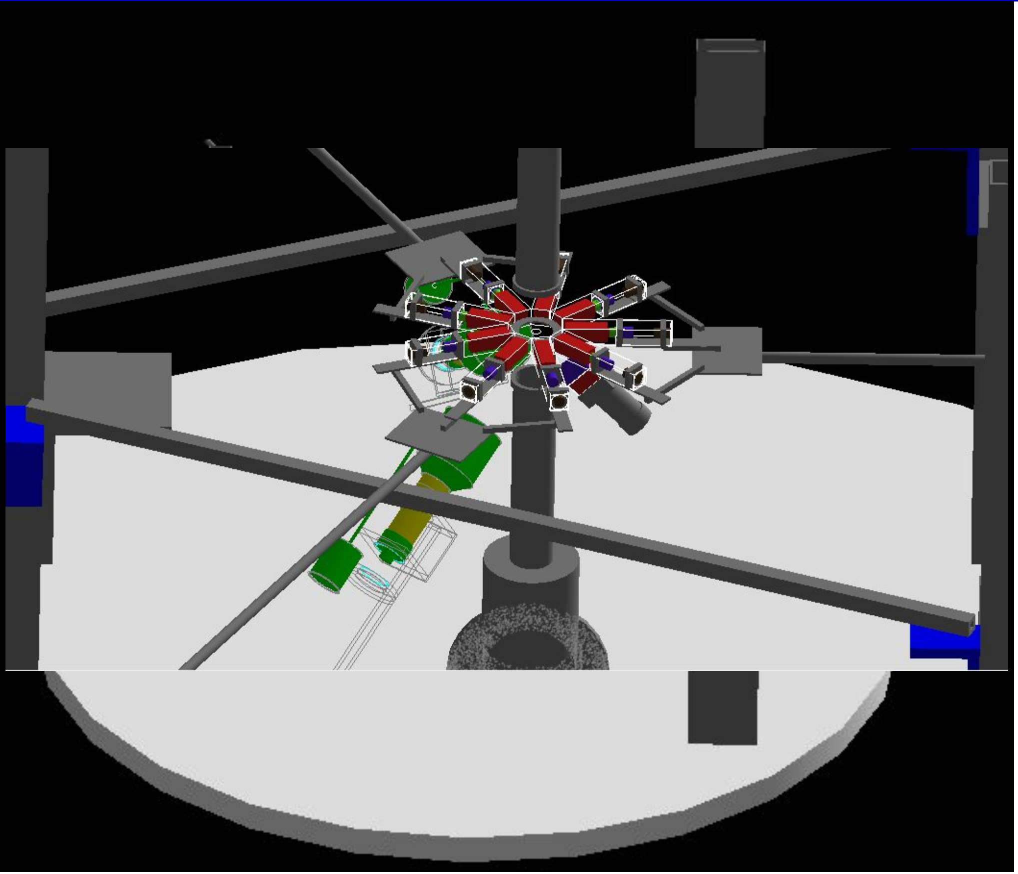


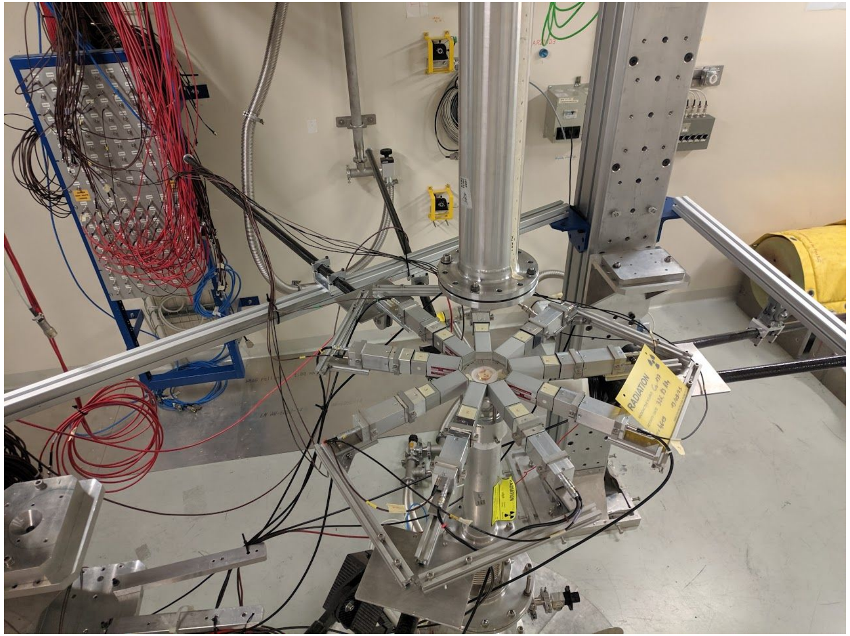
- Preliminary yield for all configurations ✔



Monte Carlo & Dead time model

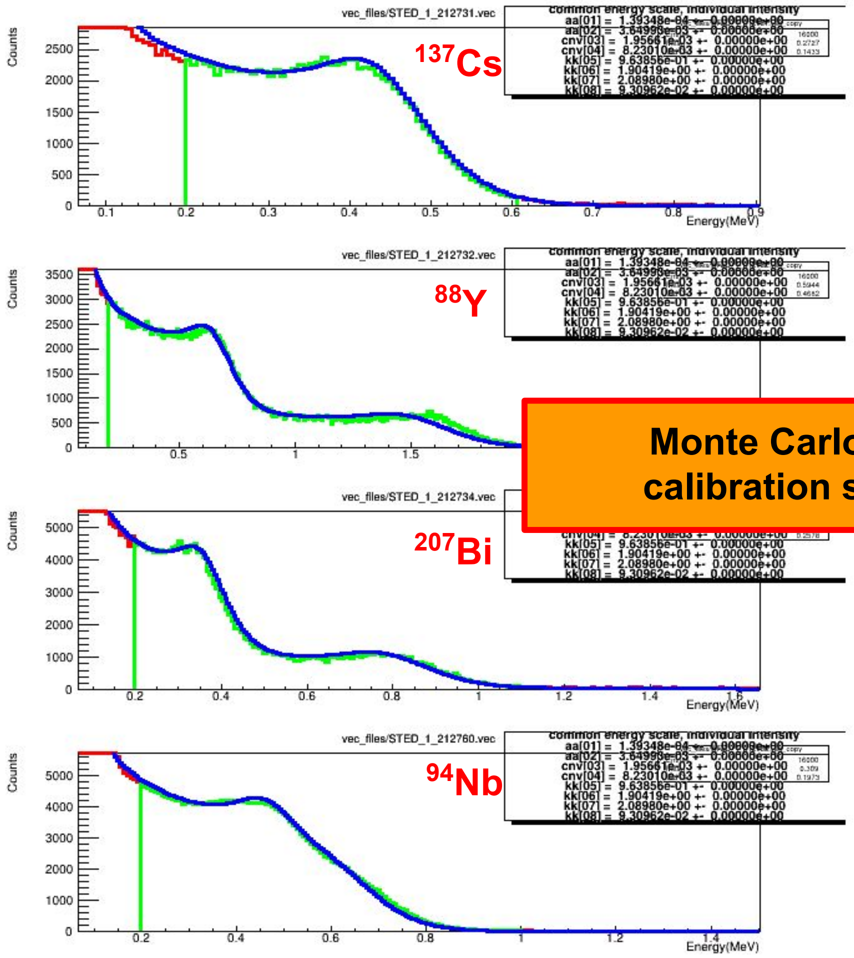
Monte Carlo geometry

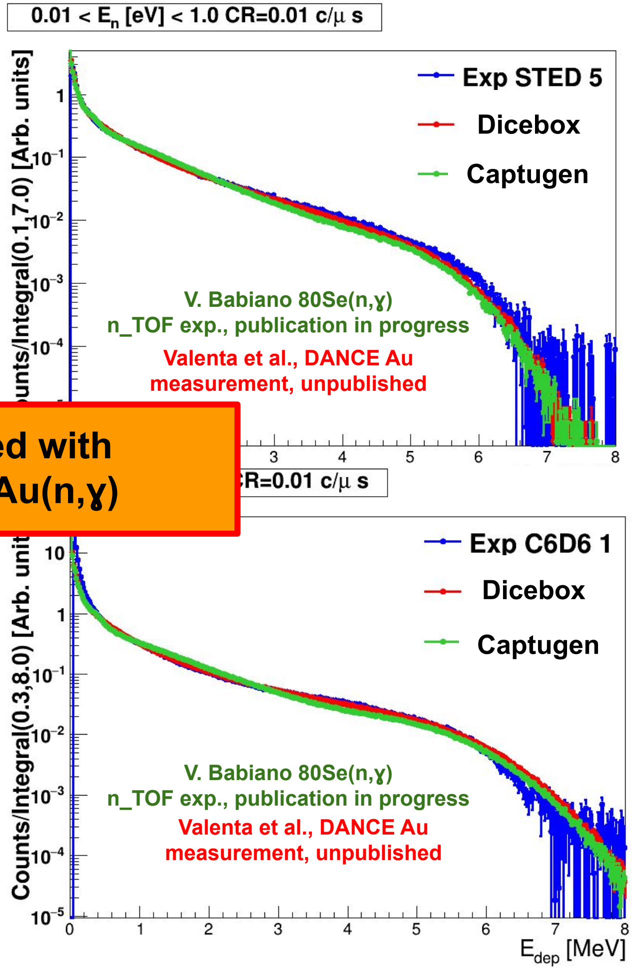




Detailed geometry of the setup implemented in GEANT4

Monte Carlo validation

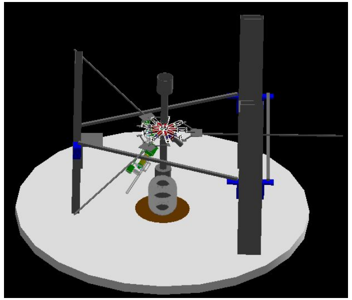


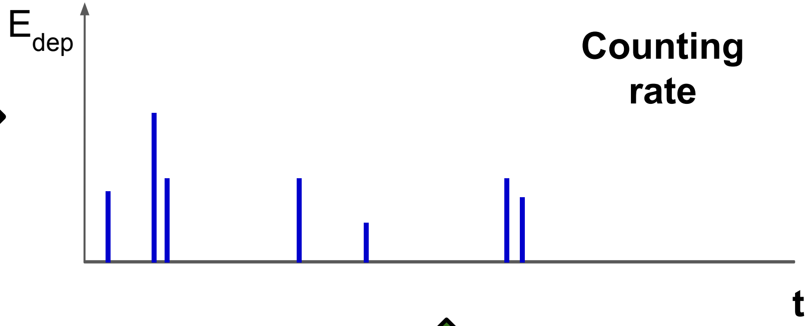


Monte Carlo model validated with calibration samples and ^{197}Au(n,ɣ)

(n,ɣ) MC simulations for EAR2

(n,ɣ) cascade model





Physics model

Response of the detector

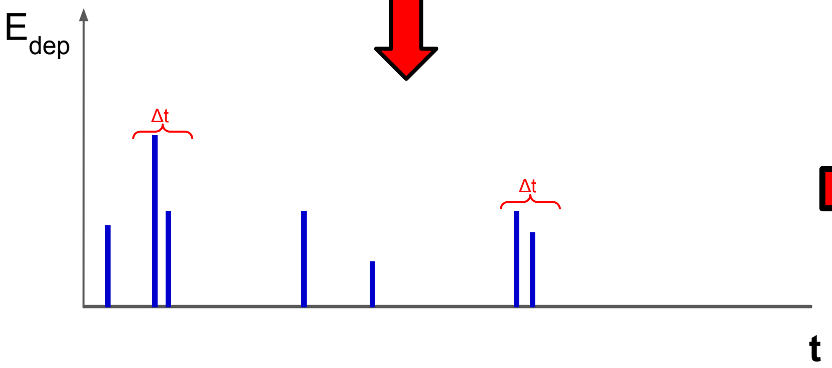
Experimental conditions

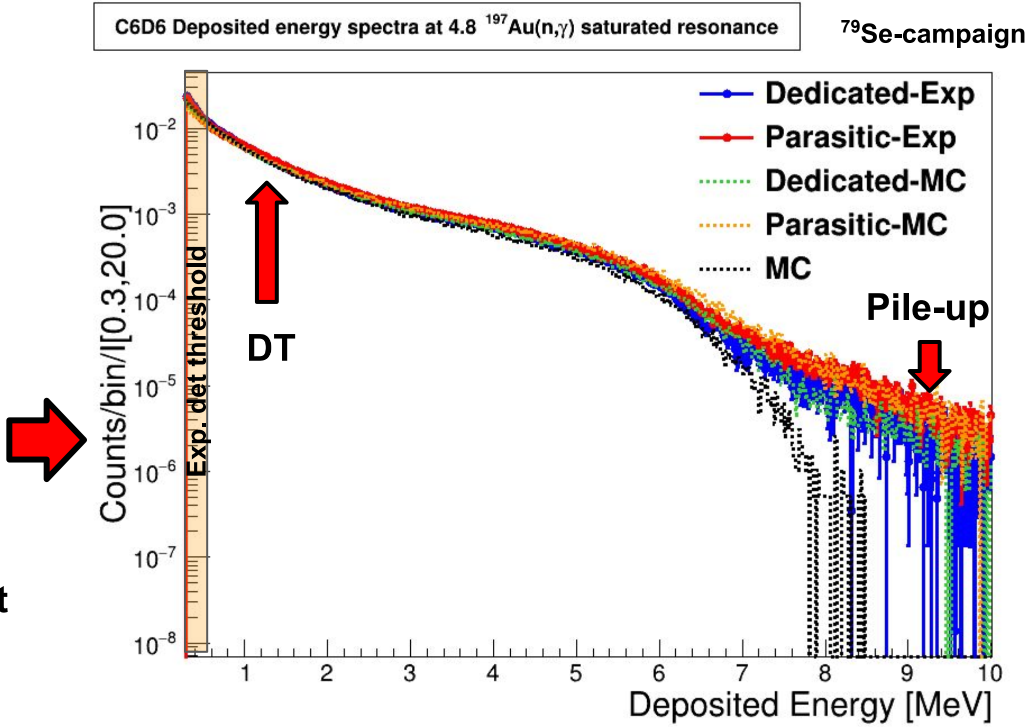
(n,ɣ) Monte Carlo simulation process

E. Mendoza NIM-A 768 (2014) 55
C. Guerrero NIM-A 777 (2015) 63

Dead time & pile-up modelization

Apply dead time model





Comparing **dead time & pile-up model** spectra with ideal case we can get:

- **Dead time corrected counting rates** applying **exp. detection threshold**.
- **Correction for pile-up+DT** using a weighting function $\mathbf{Q=W(E_{dep,DT})/W(E_{dep})}$

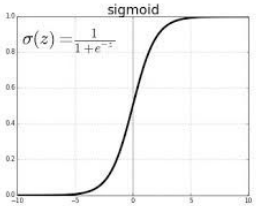
Dead time & pile-up modelization

Small modification of [C. Guerrero et al.] dead time model:

- Dead time **depends** on **amplitude** of **consecutive** detected **signals**

- Dead-time is **characterized** by a **soft** detection probability **function**:

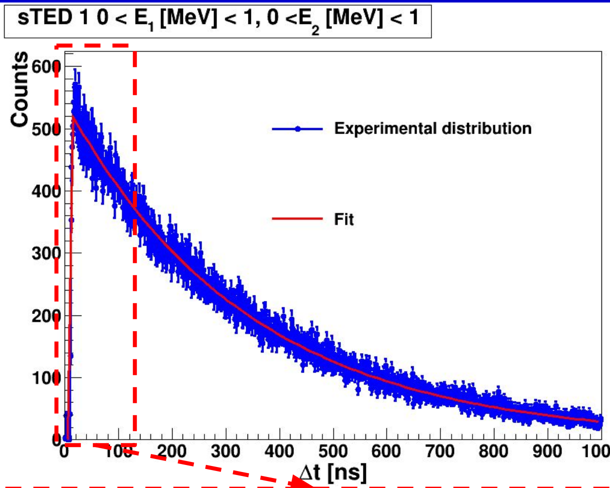
$$f(\Delta t) = \frac{1}{\left(1 + e^{-a(\Delta t - \Delta t_0)}\right)} A e^{-CR\Delta t}$$

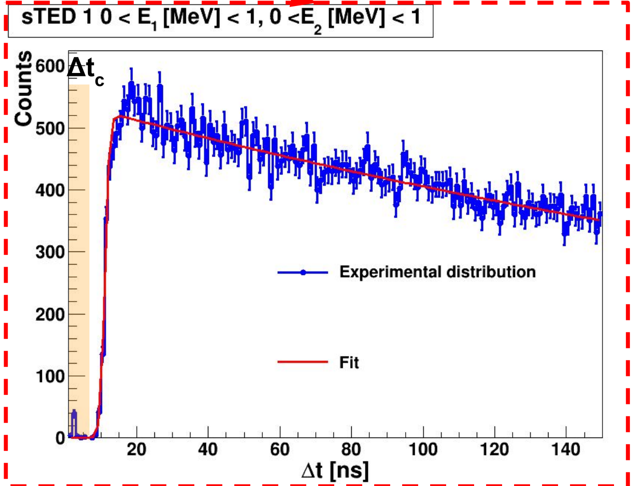


← Detection probability

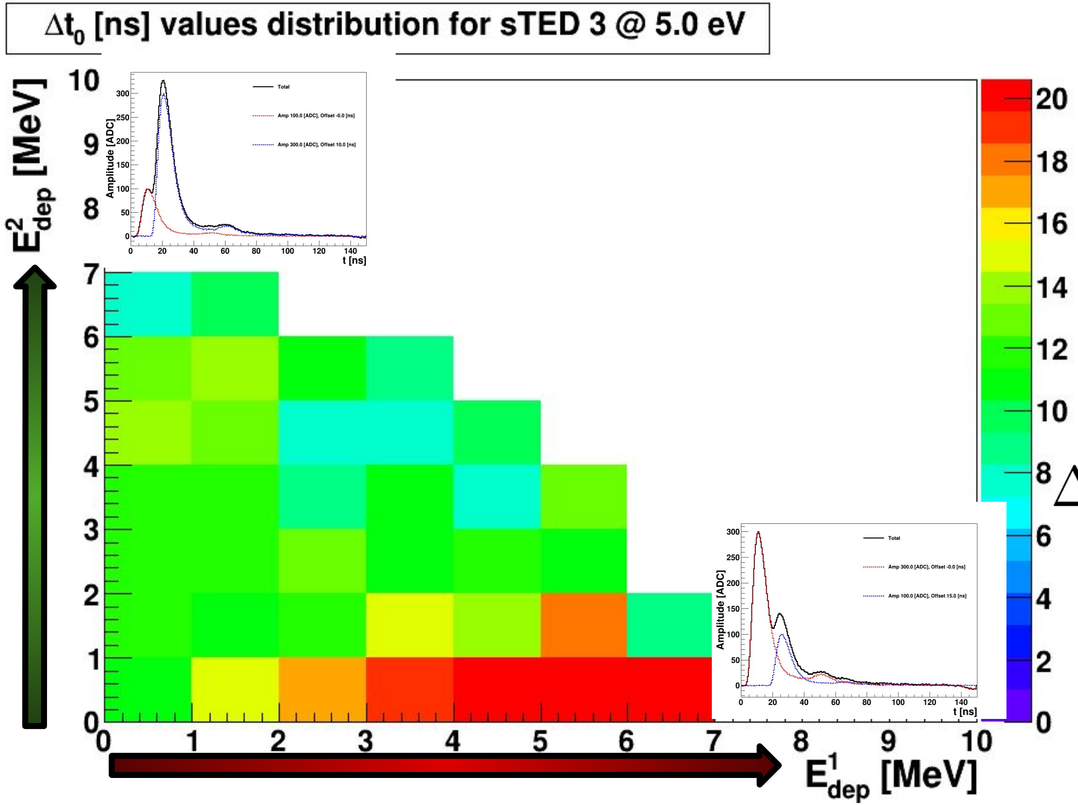
Underlying distribution

- Pile-up parameter Δt_c in the model is **not accessible** experimentally → **Estimated** matching experimental data in ^{197}**Au saturated resonance**.





Dead time function parametrization



Dead time parameters for individual detectors fitted as a function of signals energy @ 4.9 ^{197}Au(n,ɣ) resonance:

$$f(\Delta t) = \frac{1}{(1 + e^{-a(\Delta t - \Delta t_0)})} A e^{-CR\Delta t}$$

$$\Delta t_0 = \Delta' t_0 + \Delta' t_1 E^1_{dep} + \Delta' t_2 E^2_{dep}$$

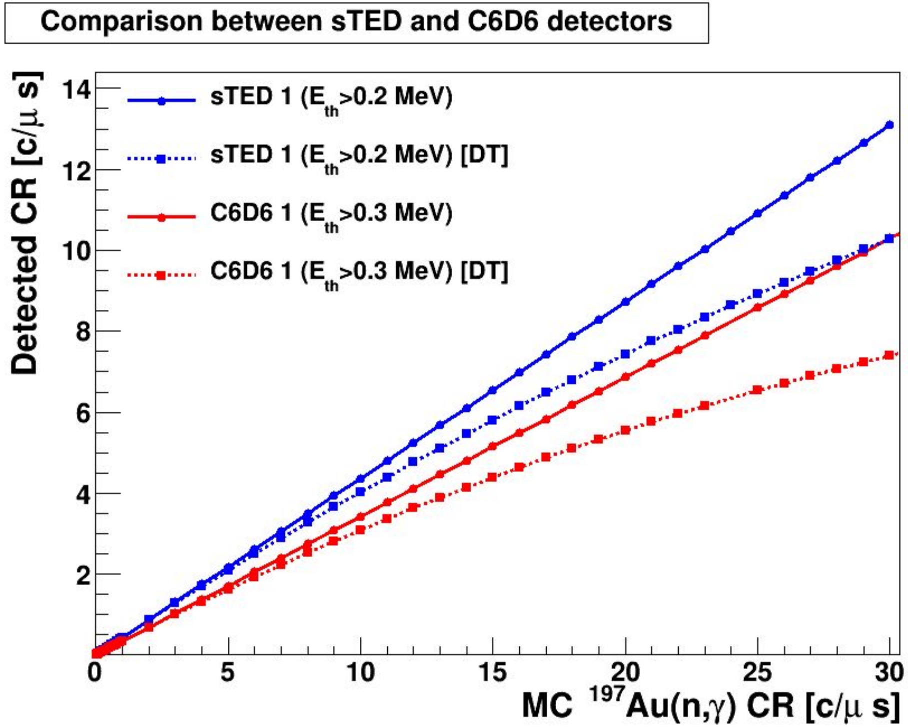
50% detection chance

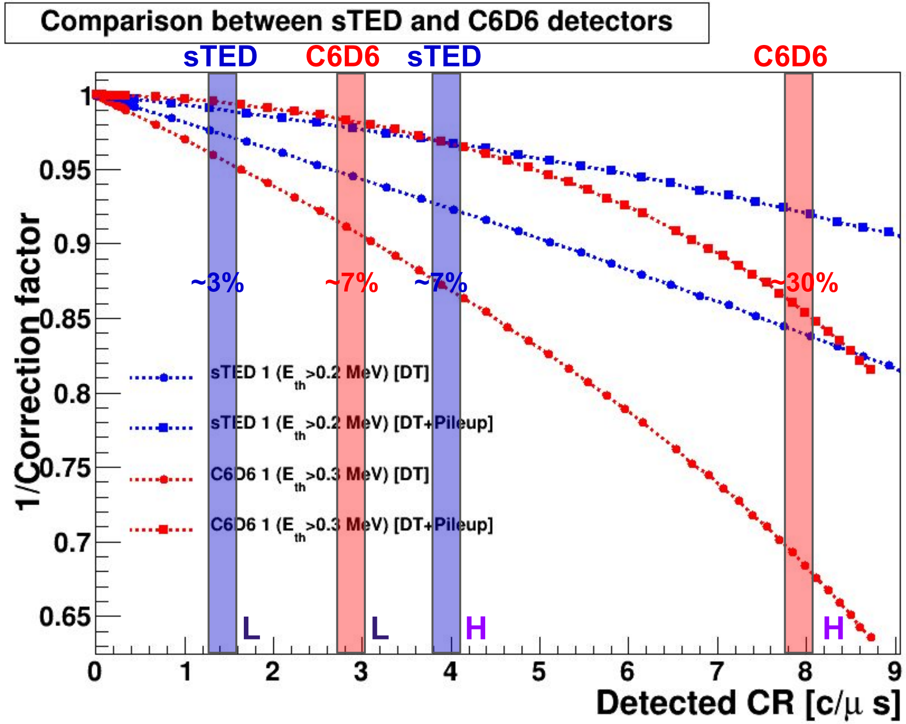
$$a = a_0 + a_1 E^1_{dep} + a_2 E^2_{dep}$$

Probability change rate

General rule: $E^2_{dep} > E^1_{dep}$ → Easier to detect the second signal

Dead time & pile-up modelization



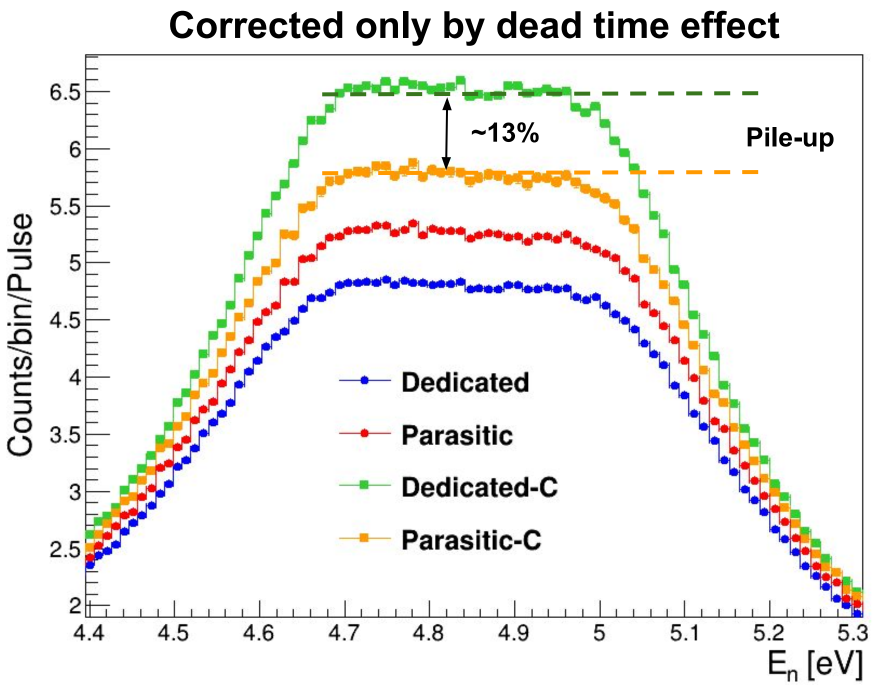


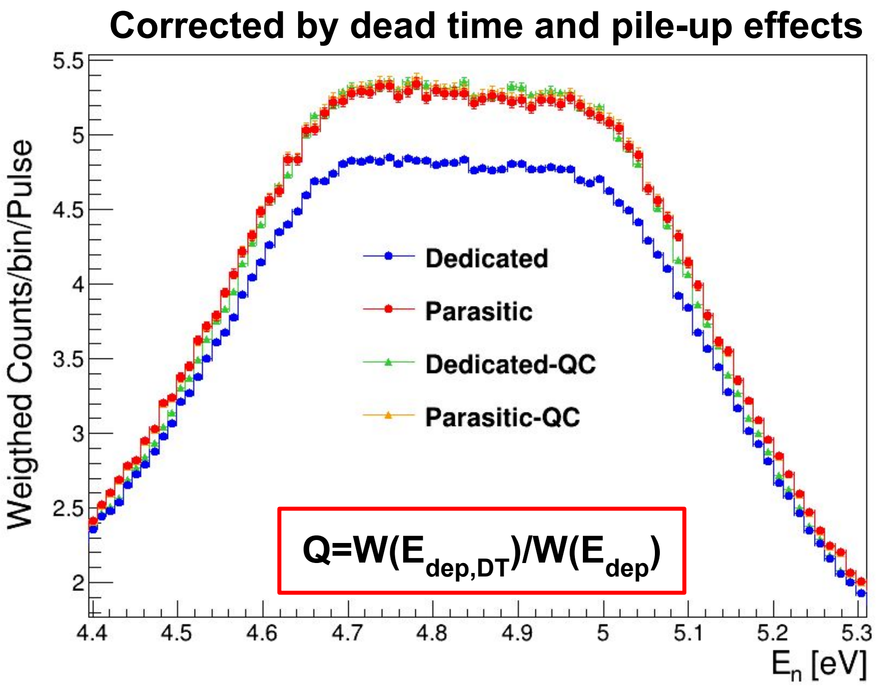
Saturated ^{197}Au resonance during ^{79}Se campaign

Dead time corrections can be large even for s-TEDs!

H: High intensity pulses
L: Low intensity pulses

^{197}Au Saturated resonance C6D6 1





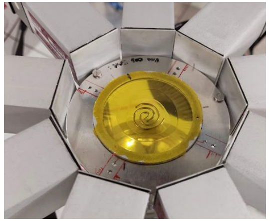
Correcting only by dead time is not enough: in addition on has a large pile-up effect which requires further corrections!

Results of ML estimation

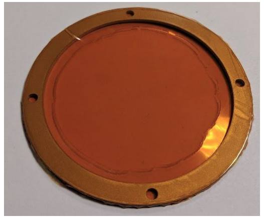
Maximum likelihood yield estimation

We have implemented a pulse by pulse maximum likelihood estimation for ^{93}Nb, ^{94}Nb and Empty contributions simultaneously using the three configurations:

^{94}Nb, ^{93}Nb & Empty

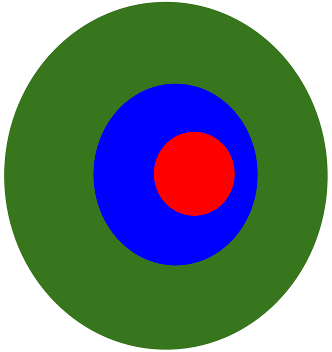


^{93}Nb & Empty



Empty

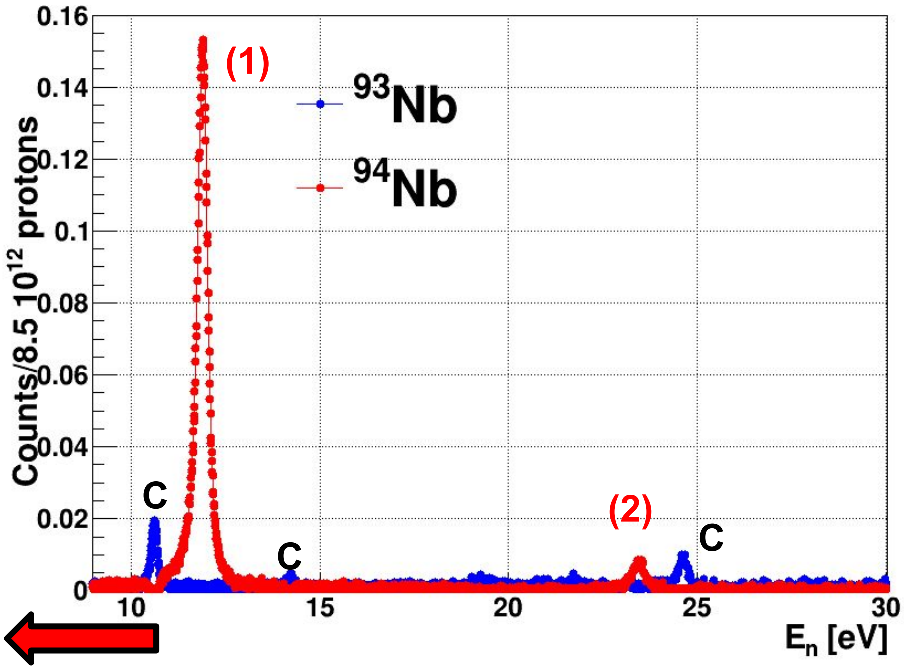
Parameter Likelihood space

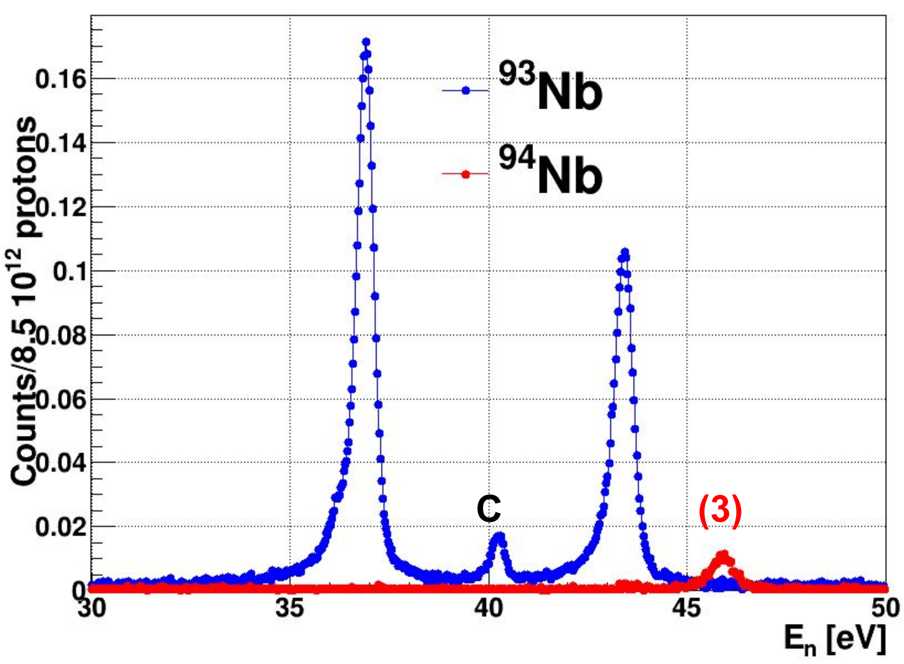


- Maximum Likelihood estimation has **smallest variance** →**Larger sensitivity** for small “signal”
- Allow **easily hypothesis contrast** via likelihood-ratio →Well behaved for **nested model** (**^{94}Nb=0**)
- **Registered counts** by detection systems in any ToF period **easily model**→ $x \sim \frac{\lambda^x e^{-\lambda}}{x!}$
- **Systematics** (Norm. between configurations, Unc in no-beam components) included via **Monte-Carlo**

Next slides: Only s-TEDs included & confidence level >0.95

Maximum likelihood results

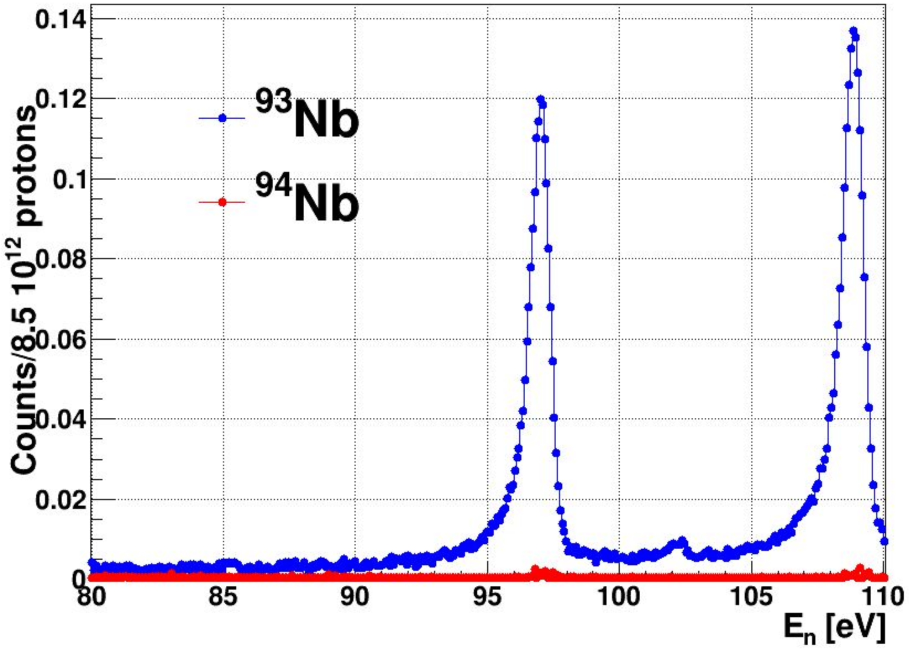


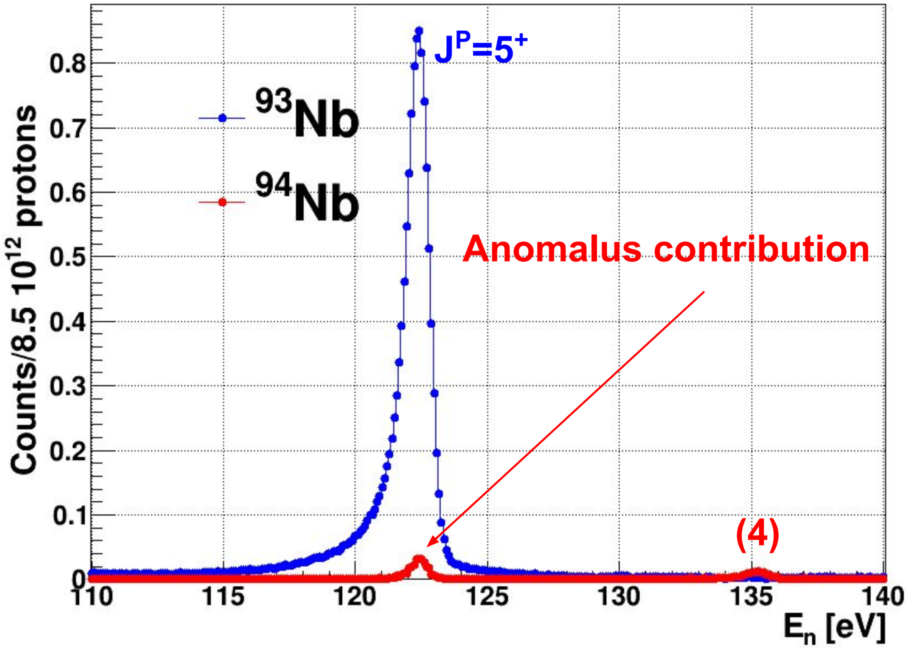


No enough sensitivity for ^{94}Nb thermal region because of large contribution from target decay

The contaminant resonances are only for 93Nb spiral target and they do not overlap with “good resonances”

Maximum likelihood results



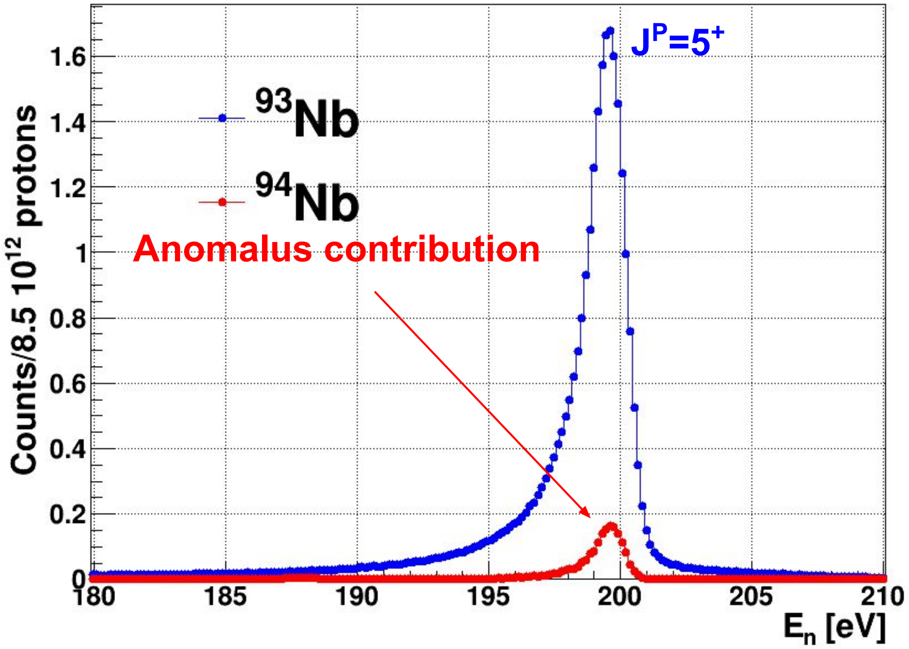


The calculated yields are not calibrated in ToF

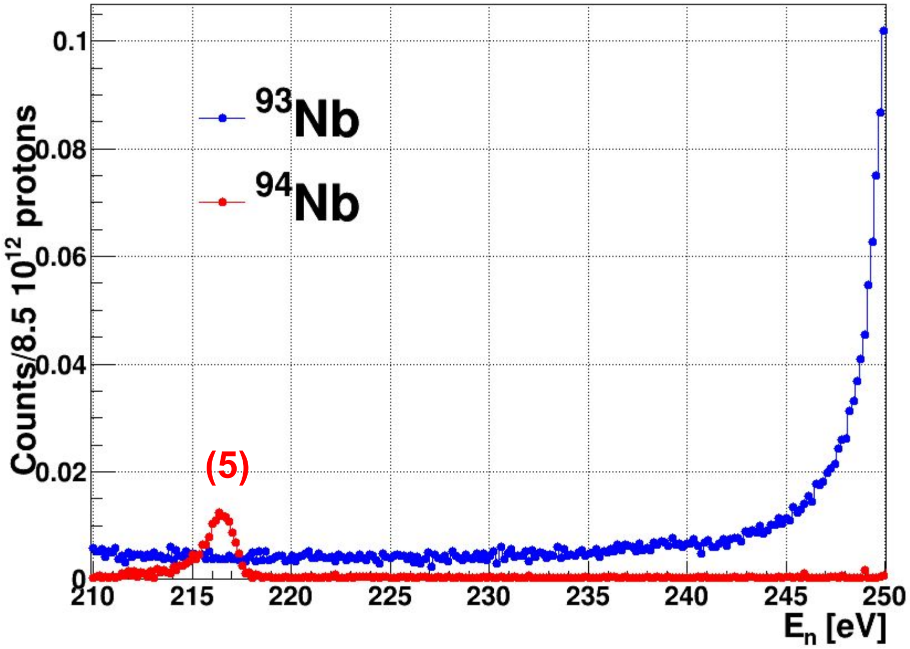
Anomalous contribution from "^{94}Nb" to ^{93}Nb resonance

→<u>Related to sample geometry (Next slides)</u>

Maximum likelihood results

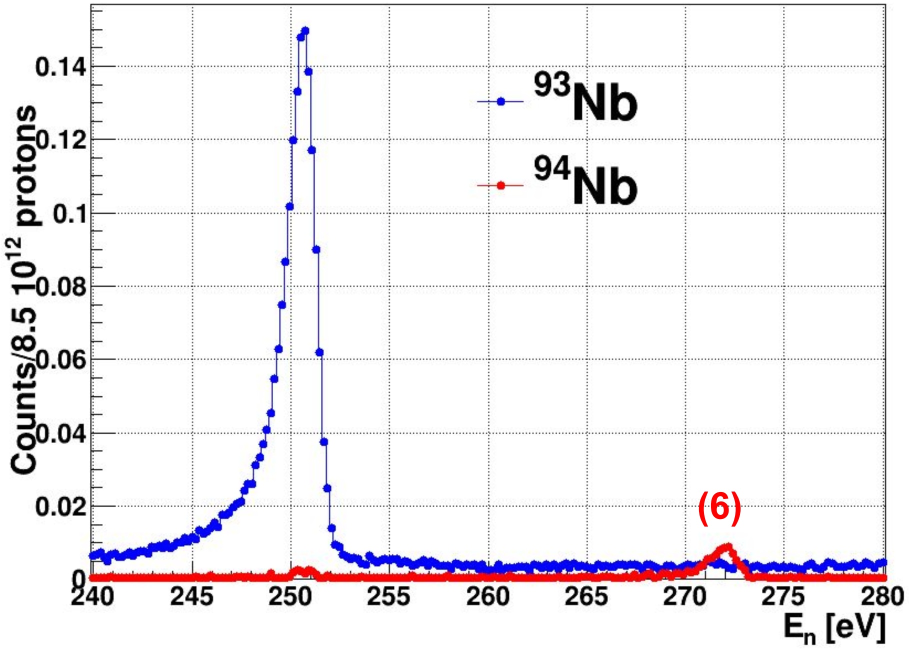


Another contribution from “^{94}Nb” to same spin-parity ^{93}Nb

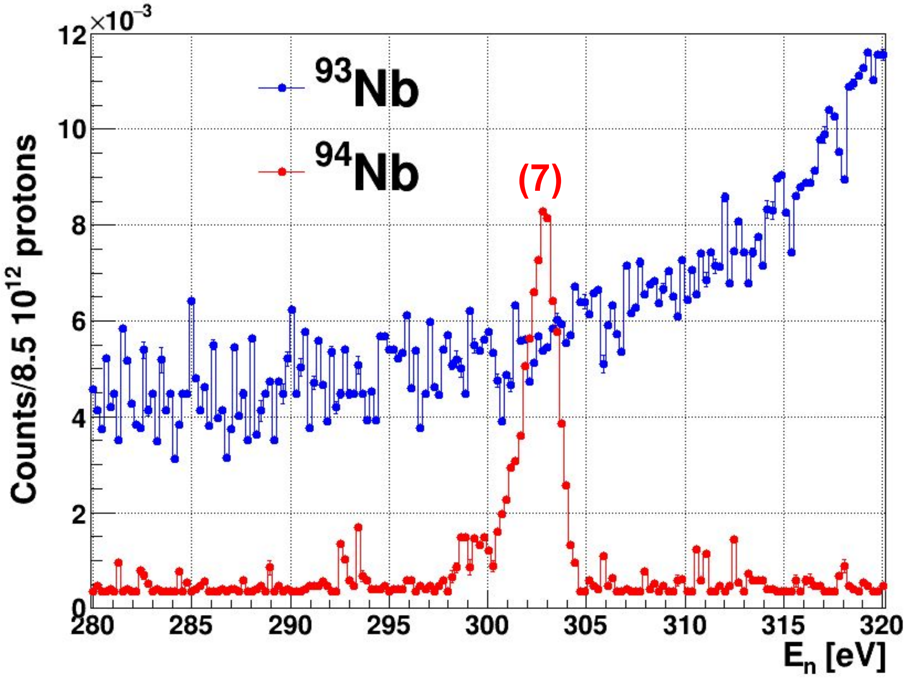


Good ^{94}Nb resonance definition

Maximum likelihood results

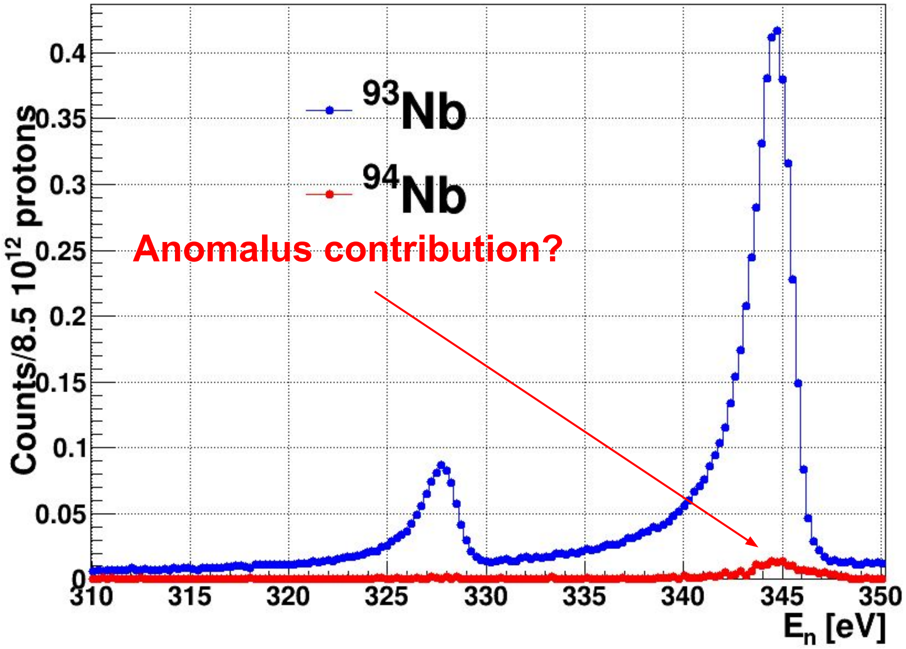


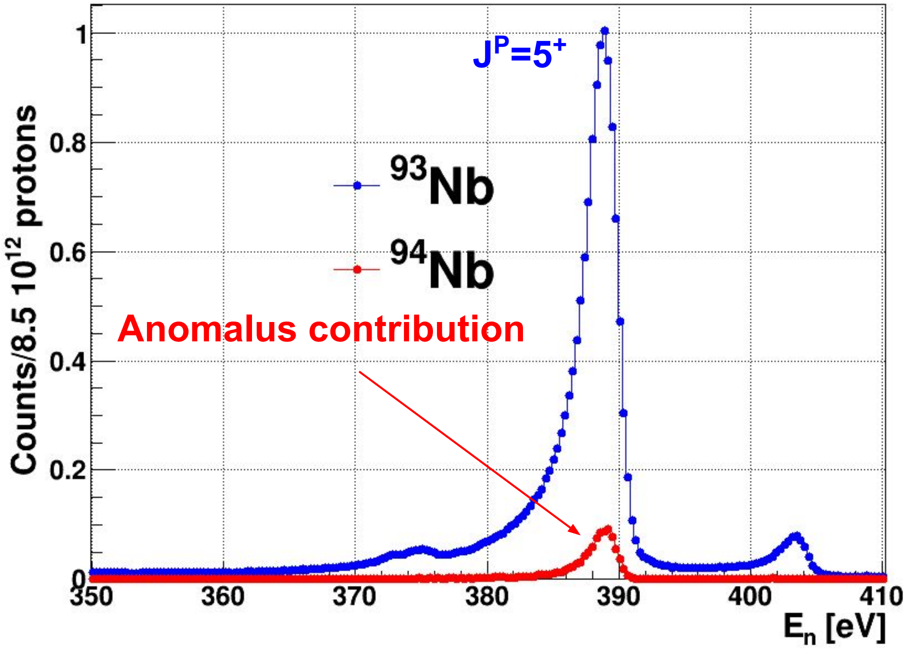
Resonances of ^{94}Nb appears to be so “small” because of the ^{94}Nb/^{93}Nb ratio ~3%.



^{94}Nb resonance in a tail of a “big” ^{93}Nb resonance

Maximum likelihood results

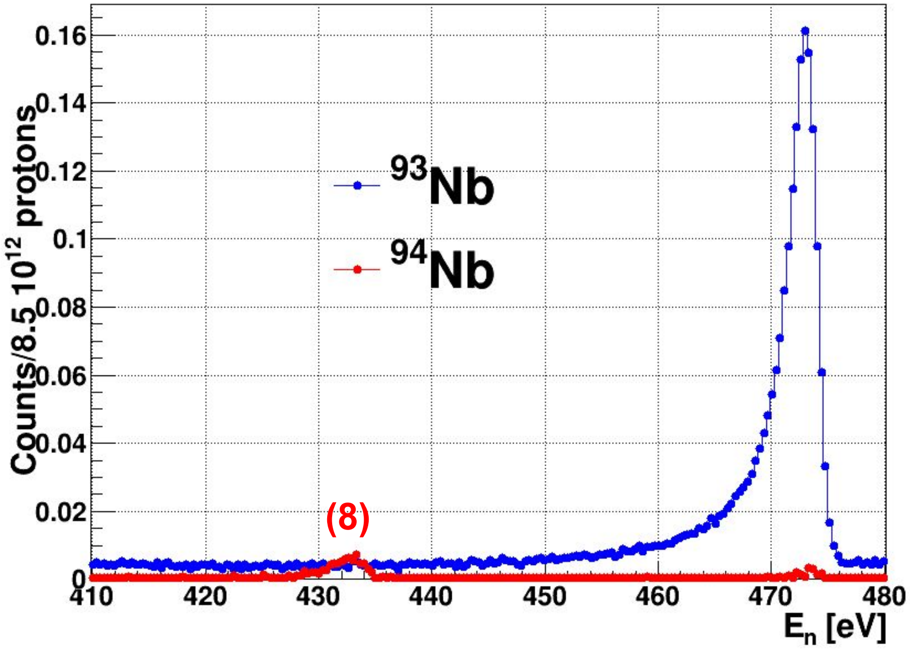




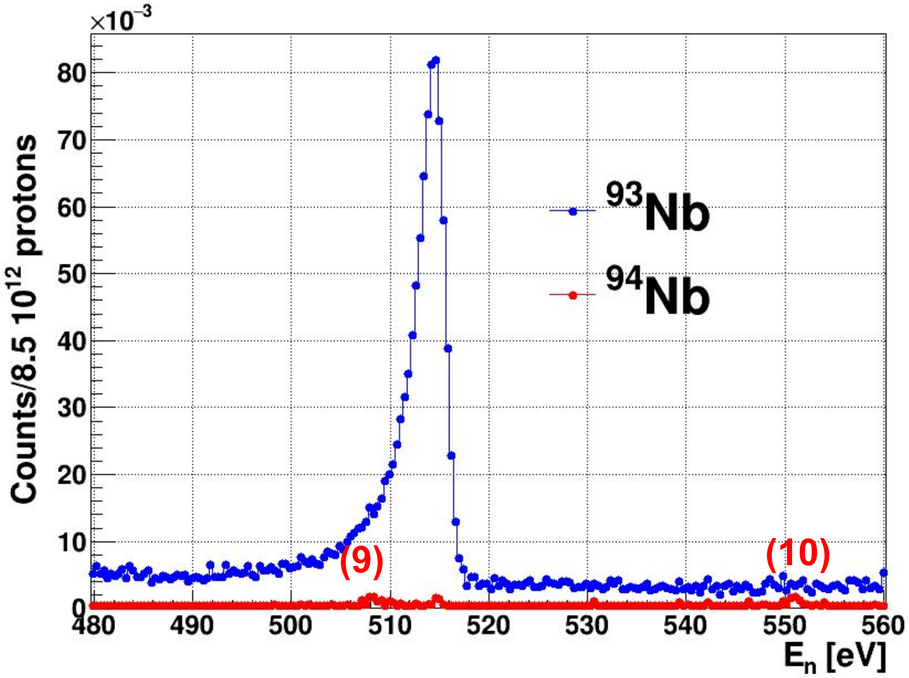
In this case, the anomalous contribution has a weird shape compared to other well-defined shapes

Another contribution to the same spin-parity resonance

Maximum likelihood results

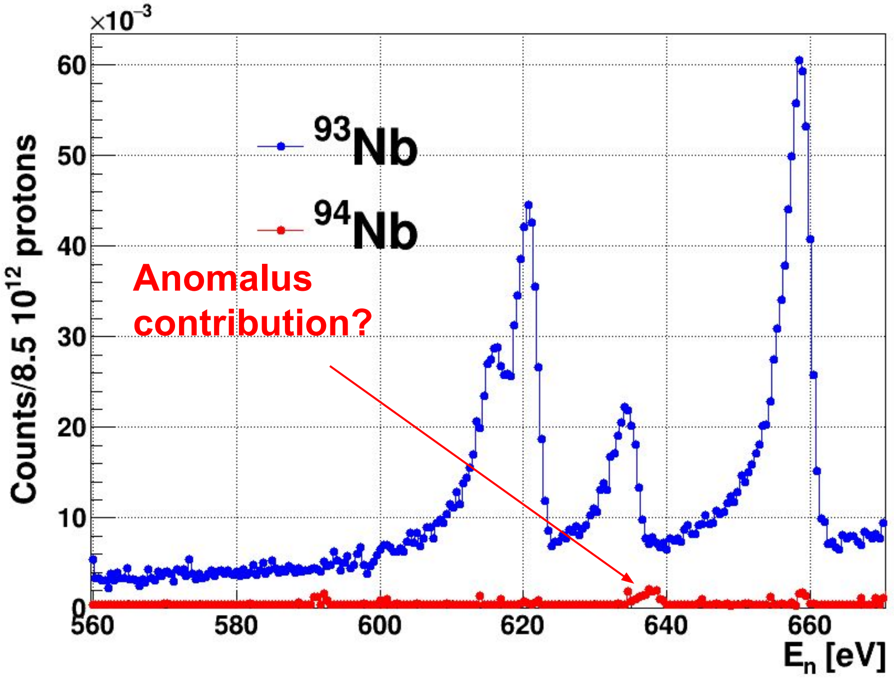


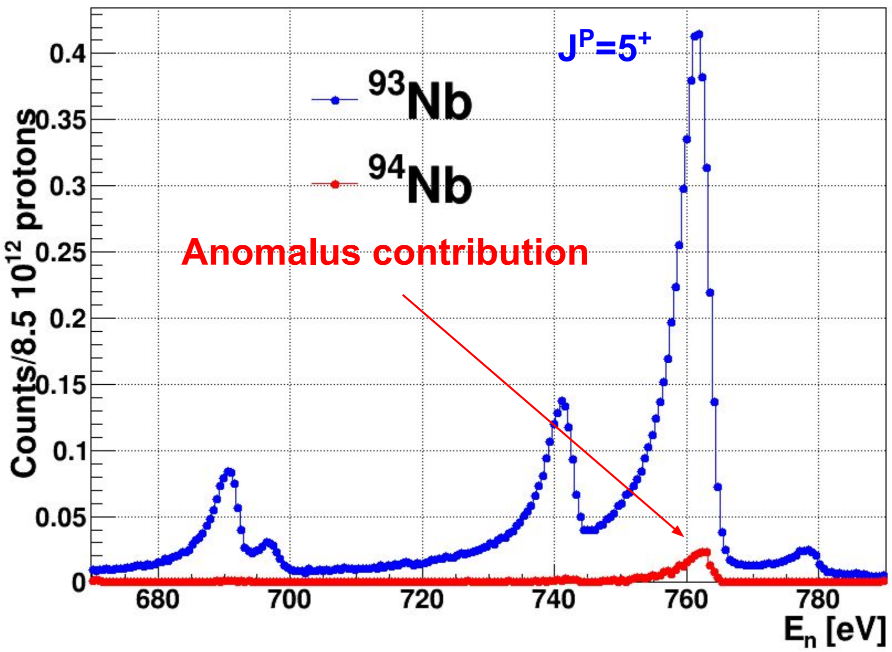
Small, but well located resonance



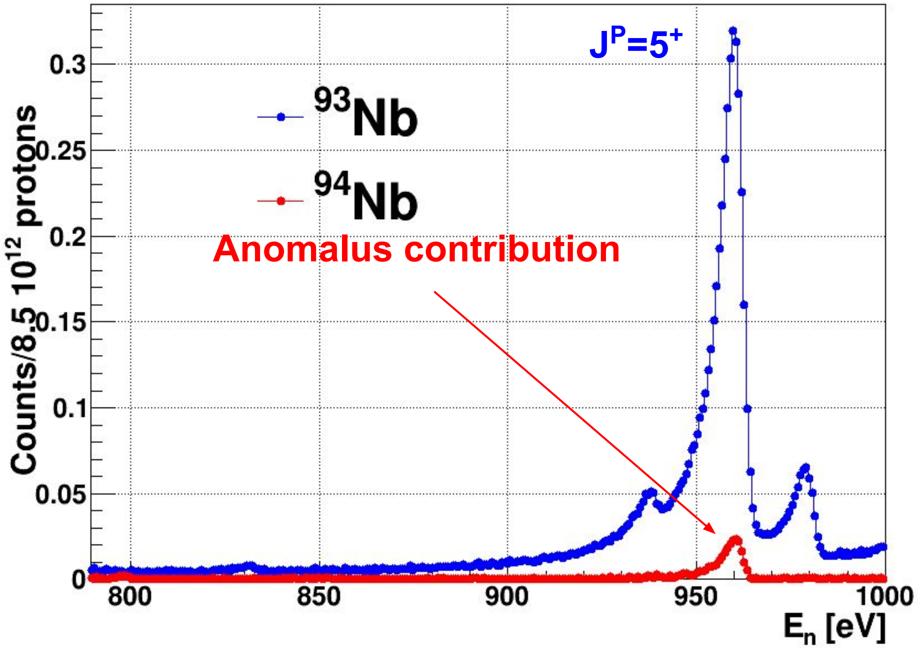
(9) and (10) are not a fluctuation to a confidence level > 95%

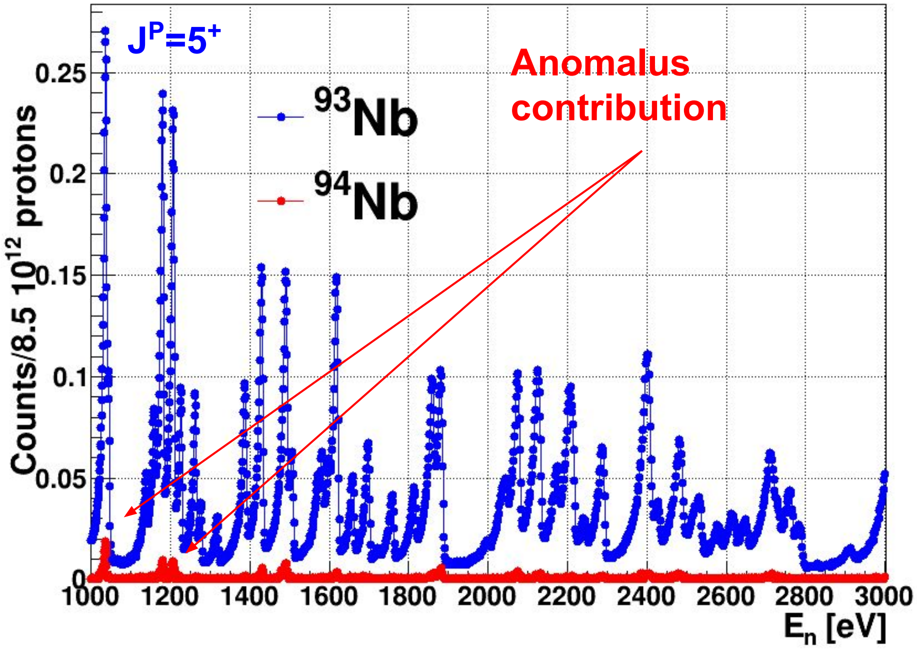
Maximum likelihood results



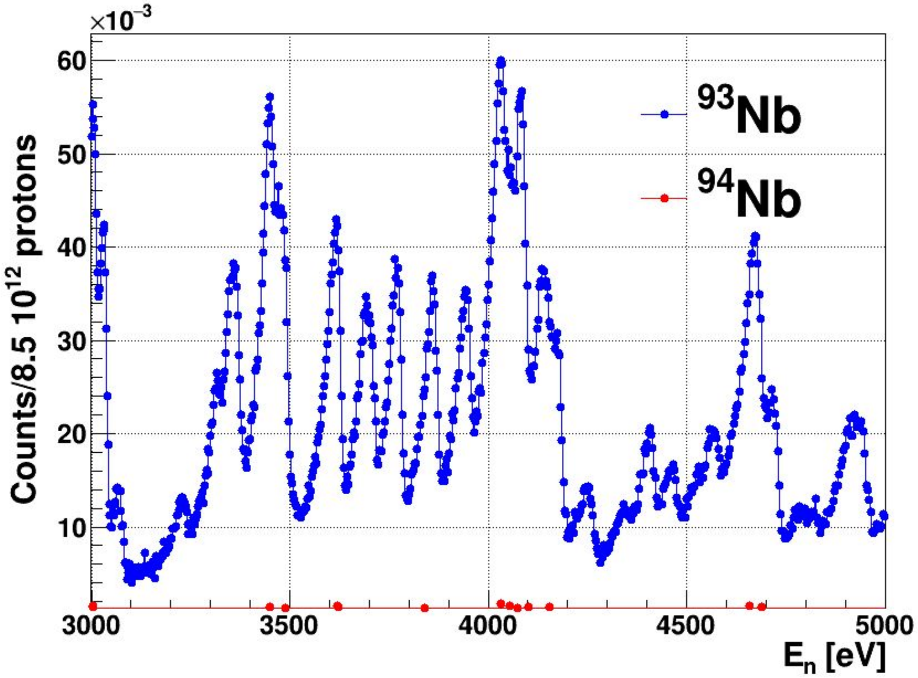


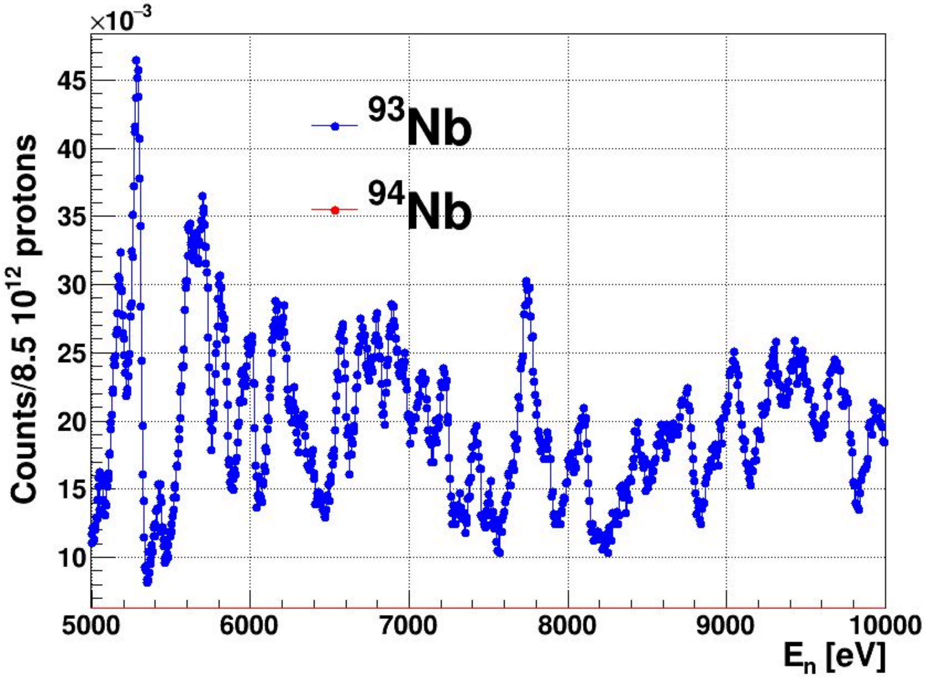
Maximum likelihood results





Maximum likelihood results

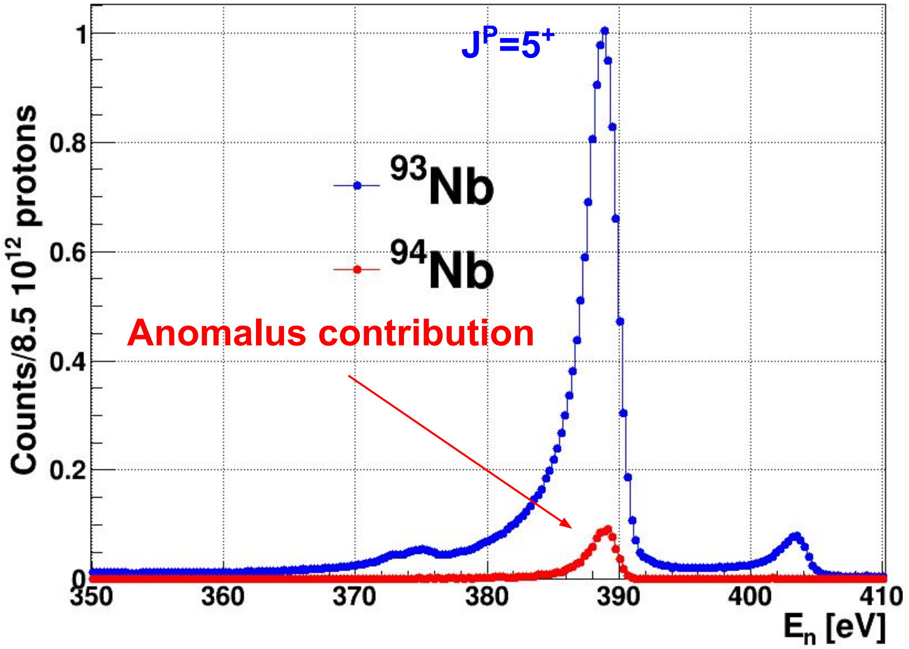




Beyond En = 3 keV: not enough sensitivity to extract any additional information from ^{94}Nb(n,ɣ)

Self-shielding corrections

Anomalous contribution to $^{93}Nb(n,\gamma)$



Anomalous contribution is clearly visible for a very well characteristic neutron resonances:

- $J^P=5^+$
- $\Gamma_n >> \Gamma_\gamma >>$
- $\Gamma_n/\Gamma_\gamma >>$

Hypothesis we worked on:

- ^{93}Nb isomer contribution
  ^{94}Nb target: $^{93}Nb \rightarrow {}^{94}Nb + {}^{93*}Nb \rightarrow {}^{94}Nb$
  ^{93}Nb target: $^{93}Nb \rightarrow {}^{94}Nb$

Not possible due to angular momentum

- Direct neutron sensitivity contribution
  $\Gamma_n/\Gamma_\gamma >>$

Not possible because of $\Gamma_n/\Gamma_\gamma \sim 3$

- Self-shielding →Wires' diameter wrong?

MC setup for self-shielding

Neutron flux **simulation**:

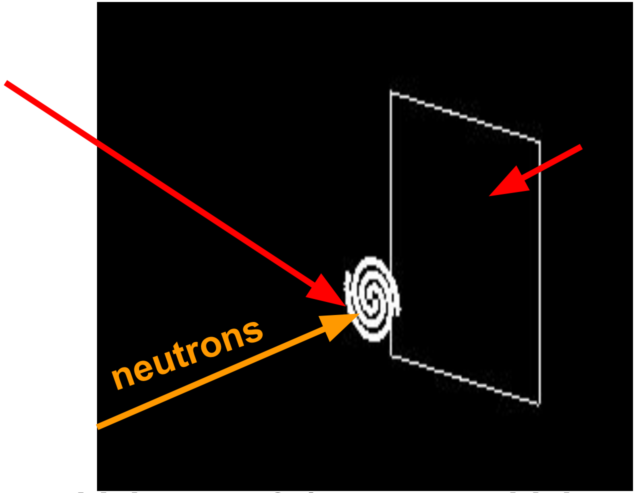
- 350 < En [eV] < 400 flat distribution
- $\sigma_x = 1.5$ mm, $\sigma_y = 1.5$ mm

Targets:

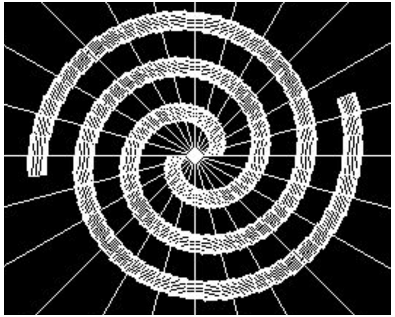
- **geometries** and **thickness according** to targets in the **experiment**

Two **sensitive detectors**:

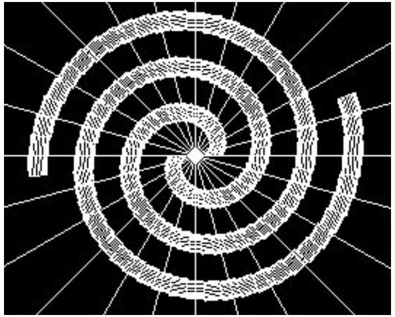
  - **Sample** itself for **(n,ɣ)**
  - neutron flux **monitor** for **transmission**



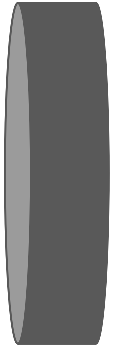
diameter= 1.0 mm



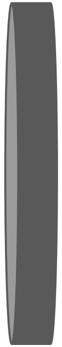
diameter= 0.8 mm



thickness= 2.1 mm

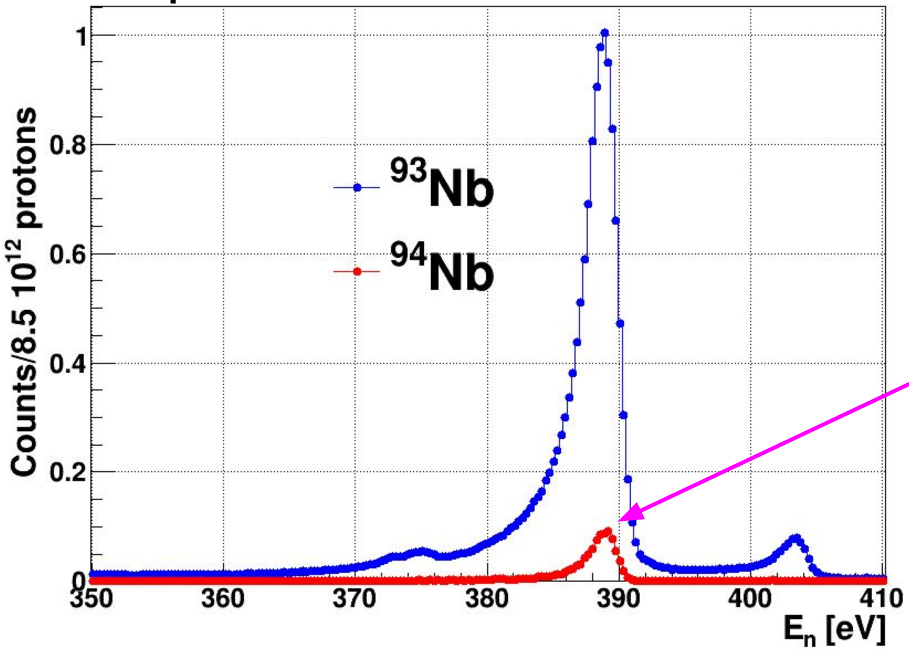


thickness= 0.02 mm

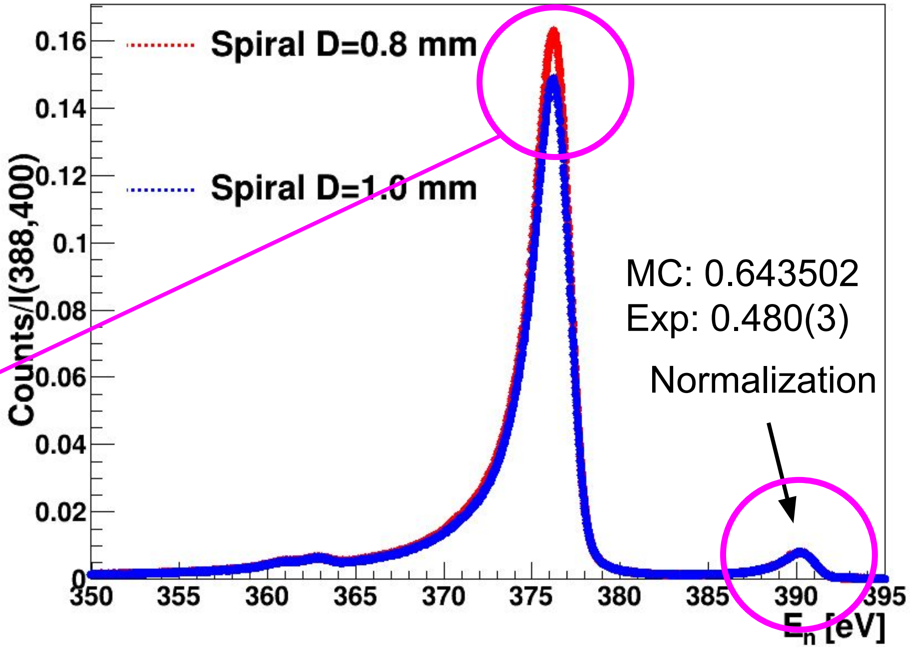


Exp. & MC results

Experimental data obtained from ML



Monte Carlo data from simulations*RF

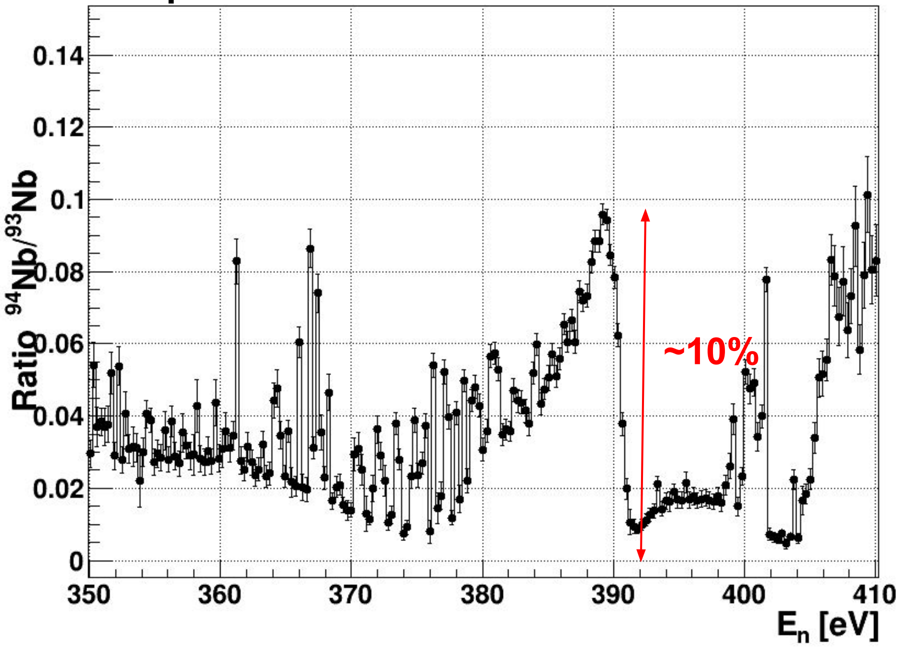


- The experimental data is not yet calibrated in distance of ToF
- **Monte Carlo** data shows the **same excess of counts** in the l**argest resonance**, once **normalized to ~400 eV** resonance

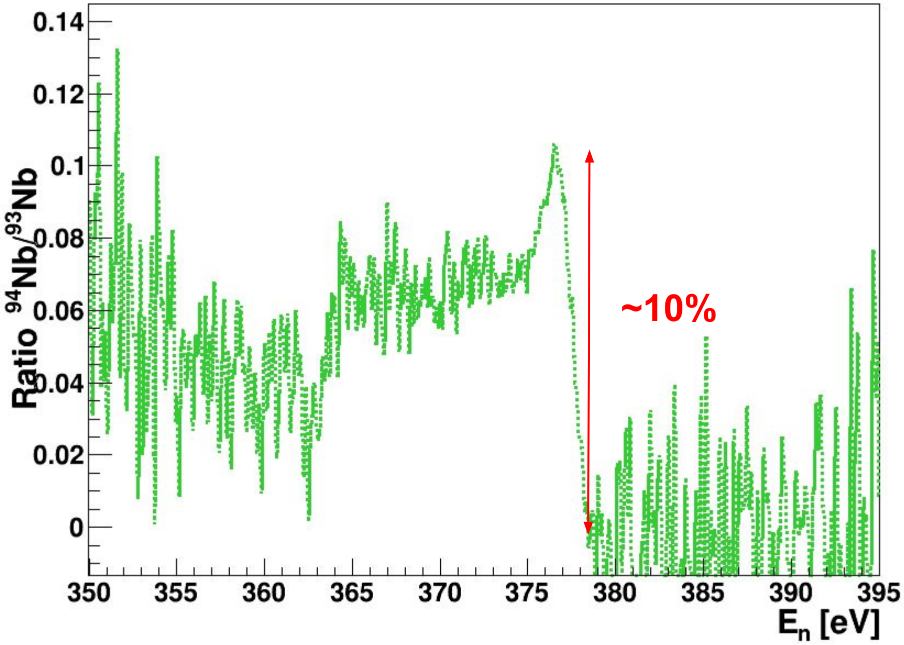
Excess of counts because of different wire diameter for ^{93}Nb and ^{94}Nb targets

Exp. & MC results

Experimental data obtained from ML



Monte Carlo data from simulations*RF



Reproduction of the effect is ok!

Work in progress for such complicated geometry!

Take home messages

EAR2 is not EAR1 !

DT and P-U corrections can be severe even for s-TEDs

The analysis of ^{94}Nb(n,ɣ) is in progress:

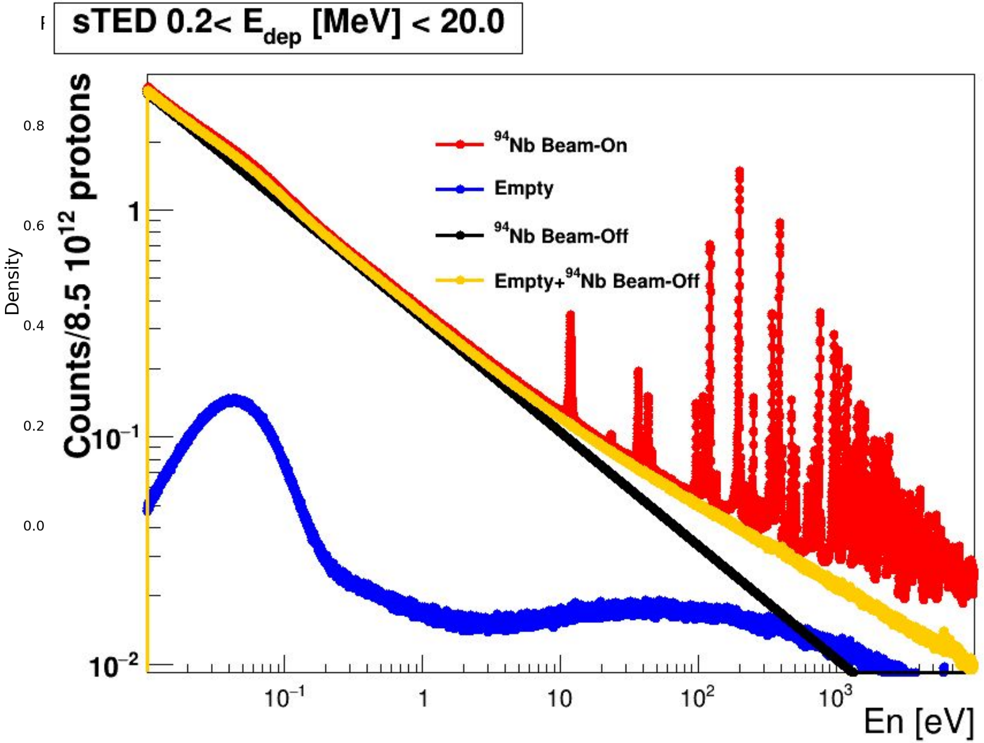
- Monte Carlo model implemented in GEANT4
- Dead time and pile model
- Maximum likelihood methodology applied to Exp. yield
- Self-shielding correction is ongoing

Thank you very much for your attention!

BACKUP

For each neutron bin energy (or ToF) we registered counts in the detector and proton intensity in a proton bunch:

Protons 10^{-12}	Counts
8.308993	3
8.3541387	1
8.3149104	2
8.251564	3



Usually we accumulate statistics and histograms and use Gaussian statistics

In an effective way we are averaging the results:

→Is there another way to do it?

Bayes’ theorem (Conditional prob)

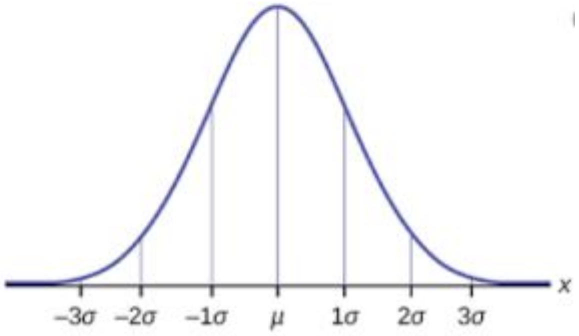
Bayes’ theorem states (or conditional probability of the model constrained to experimental data):

$$P(\textbf{theory}|\textbf{data}) \propto P(\textbf{data}|\textbf{theory}) \times P(\textbf{theory})$$

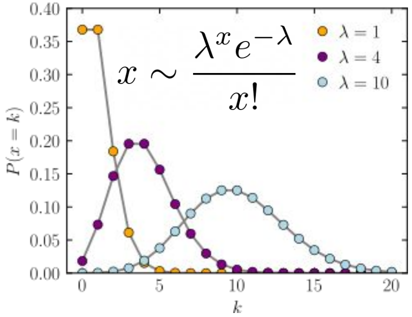
Posterior ↔Conditional probability

Likelihood ↔Conditional probability

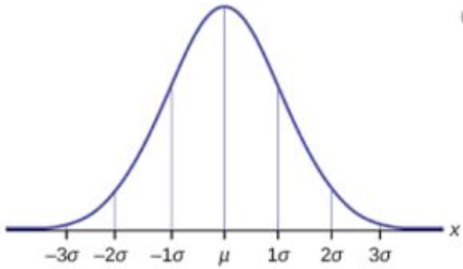
Prior ↔Probability



After experimental data



data modeling



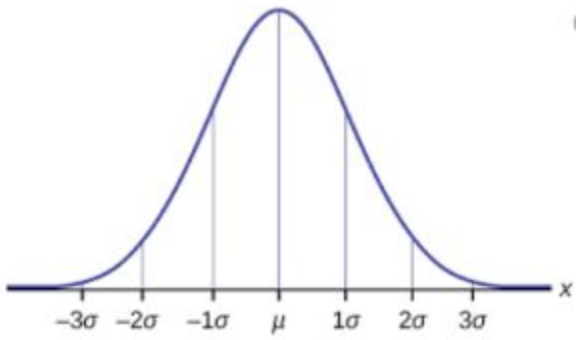
Prior experimental data

Bayes' theorem (Conditional prob)

Bayes' theorem states (or conditional probability of the model constrained to experimental data):

$$P(\textbf{theory}|\textbf{data}) \propto P(\textbf{data}|\textbf{theory}) \times P(\textbf{theory})$$

Posterior ↔Conditional probability



After experimental data

Asymptotic limit (n→∞):

- Prior does not matter ↔Maximum Likelihood Estimation

$$l^* = argmax_{\vec{\theta}} l(\vec{x}|\vec{\theta})$$

- Consistency: $\hat{\vec{\theta}} \to \vec{\theta}_*$
- Asymptotically Normal: $\frac{\hat{\vec{\theta}} - \vec{\theta}_*}{\hat{se}} \sim N(0,1)$
- Asymptotically optimal of efficient ! →Smallest variance
-
- Standard error can be computed using Fisher information

$$\hat{se} = \sqrt{1/I(\theta)} \qquad I(\theta) = E_\theta \left(\frac{\partial^2 l}{\partial \theta^2} \right)_{\theta=\hat{\theta}}$$

Hypothesis contrast

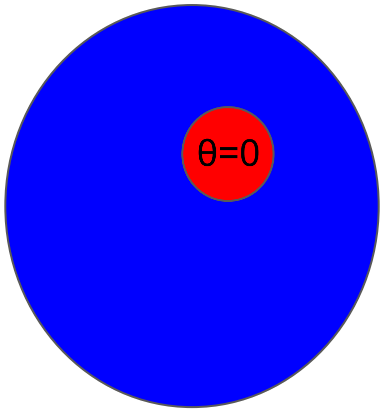
Together with the MLE it is a good good practice to include hypothesis contrast. The one we use in this work is the likelihood-ratio (Wilk-theorem):

$$\lambda_{\mathrm{LR}} = -2\ln\left[\frac{\sup_{\theta\in\Theta_0}\mathcal{L}(\theta)}{\sup_{\theta\in\Theta}\mathcal{L}(\theta)}\right]$$

The likelihood-ratio assesses the goodness of fit of two competing statistical models based on the ratio of their likelihoods:

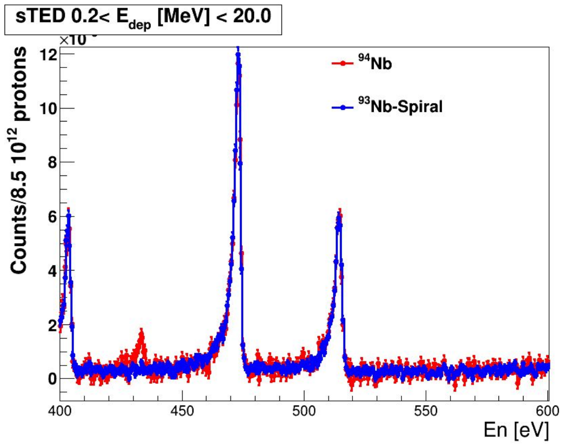
- It is especially well suited for nested hypothesis ($\theta=0$)
- It behaves as a χ_n where n is the number of parameters under test.
- It can be set a level of confidence α to contrast the hypothesis

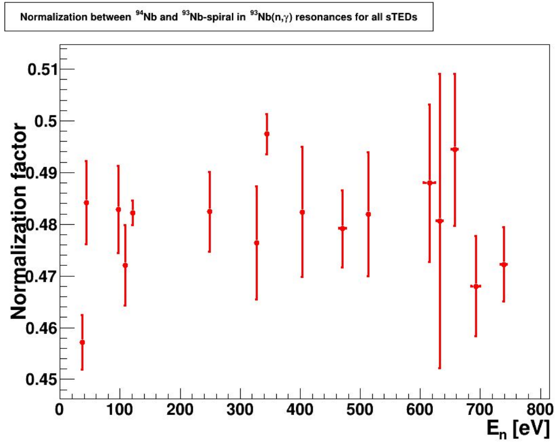
Parameter space



Systematics in ML

- Normalization of Empty (ɣ): Shared in ^{94}Nb-target and ^{93}N-spiral, 1.10(5).
- Normalization of ^{93}N in ^{94}Nb-target because of different beam-intersection factor η:
  - Calculated as the ratio of integrals for 3^- and 4^+ resonances 0.480(3).





- No beam background calculated from its configuration: 1.472(9) c/pulse
- No beam background with ^{94}Nb-target in place: 5785.5(2) c/pulse