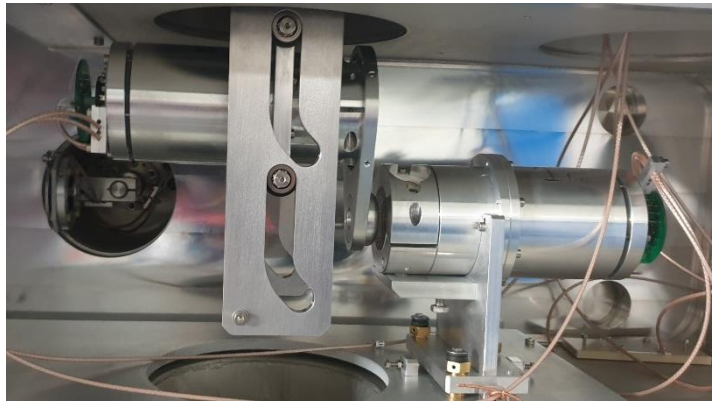

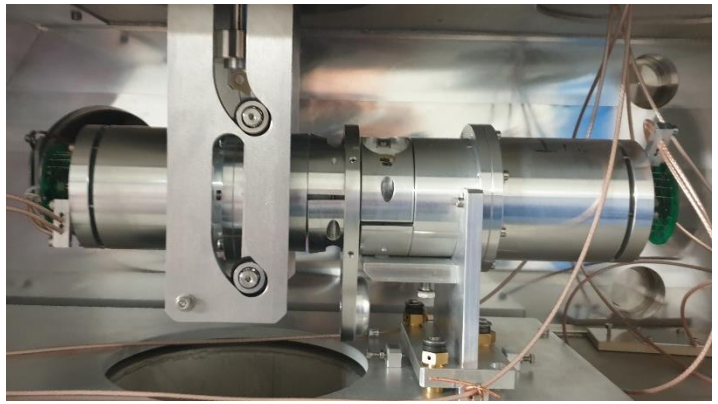

Precision measurement of the Fierz interference term b and of the Half-life of ^{6}He

Physics Workshop ISOL-France

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March 2022

GANIL, Caen

Outline

- Context and motivations
- Experimental setup
- Half life measurement
- Summary and outlook

Beyond the Standard Model

So far, the SM is our best description to what happens in the subatomic world, **BUT** it doesn't tell the whole story. There are plenty of questions that are not answered by the SM, which motivates us to search for proofs of new physics.

Two main Frontiers

High energy frontier

Direct observation of new particles

High precision frontier

Look for traces and prints

Precision measurements in the nuclear β decay

Beta decay Hamiltonian: Respect Lorentz invariance

$$H_\beta = \frac{G_F}{\sqrt{2}} V_{ud} \Big[(\bar{\psi}_p \psi_n)(\bar{\psi}_e (C_S + C'_S \gamma_5) \psi_\nu) + (\bar{\psi}_p \gamma_\mu \psi_n)(\bar{\psi}_e \gamma^\mu (C_V + C'_V \gamma_5) \psi_\nu) + \frac{1}{2} (\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(\bar{\psi}_e \sigma^{\lambda\mu} (C_T + C'_T \gamma_5) \psi_\nu) - (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(\bar{\psi}_e \gamma^\mu \gamma_5 (C_A + C'_A \gamma_5) \psi_\nu) + (\bar{\psi}_p \gamma_5 \psi_n)(\bar{\psi}_e \gamma_5 (C_P + C'_P \gamma_5) \psi_\nu) \Big] + h.c.$$

There are thus 10 coupling constants!!

Standard Model:

- $C_V = C'_V = 1$
- $C_A = C'_A = -1.25$
- $C_S = C'_S = C_T = C'_T = 0$

Severijns N. (2004). Weak Interaction Studies by Precision Experiments in Nuclear Beta Decay. In J. Al-Khalili & E. Roeckl (Reds), The Euroschool Lectures on Physics with Exotic Beams, Vol. I (bll 339-381).

Fierz interference term

The Fierz interference term b is one of the observables that could be used to probe physics beyond the Standard Model.

Pure Gamow-teller transition

$$b_{GT} \propto \gamma Re\left(\frac{C_T + C_T'}{C_A}\right)$$

Pure Fermi transition

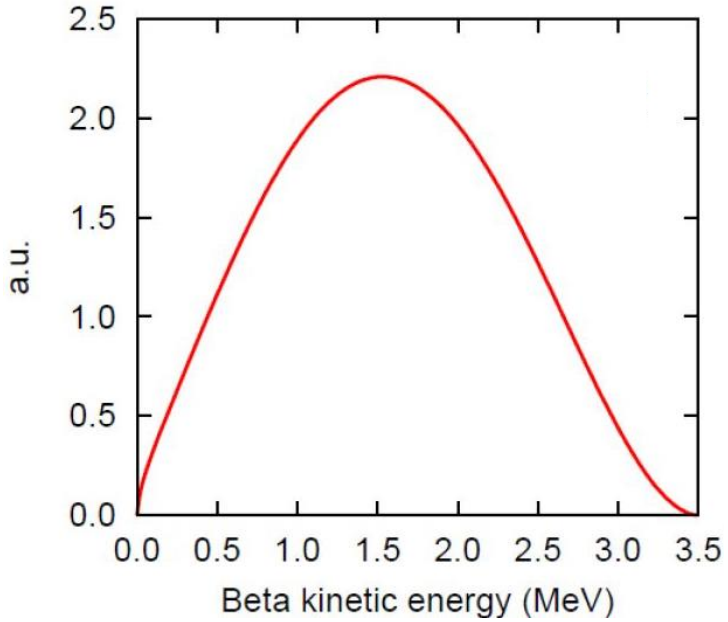
$$b_F \propto \gamma Re\left(\frac{C_S + C_S'}{C_V}\right)$$

- depends linearly on the tensor and scalar coupling constants
- Predicted to be zero in the standard model

It can be measured precisely by studying the shape of the beta energy spectrum:

$$N(E) \propto \underbrace{(1+\eta)}_{\text{Corrections term}}\underbrace{pE(E-E_0)^2}_{\text{Phase space}}\left(1+\frac{m}{E}b\right)$$

Low energies



b-STILED

b-STILED : **b-S**earch for **T**ensor **I**nteractions in nuc**L**ear b**E**ta **D**ecay

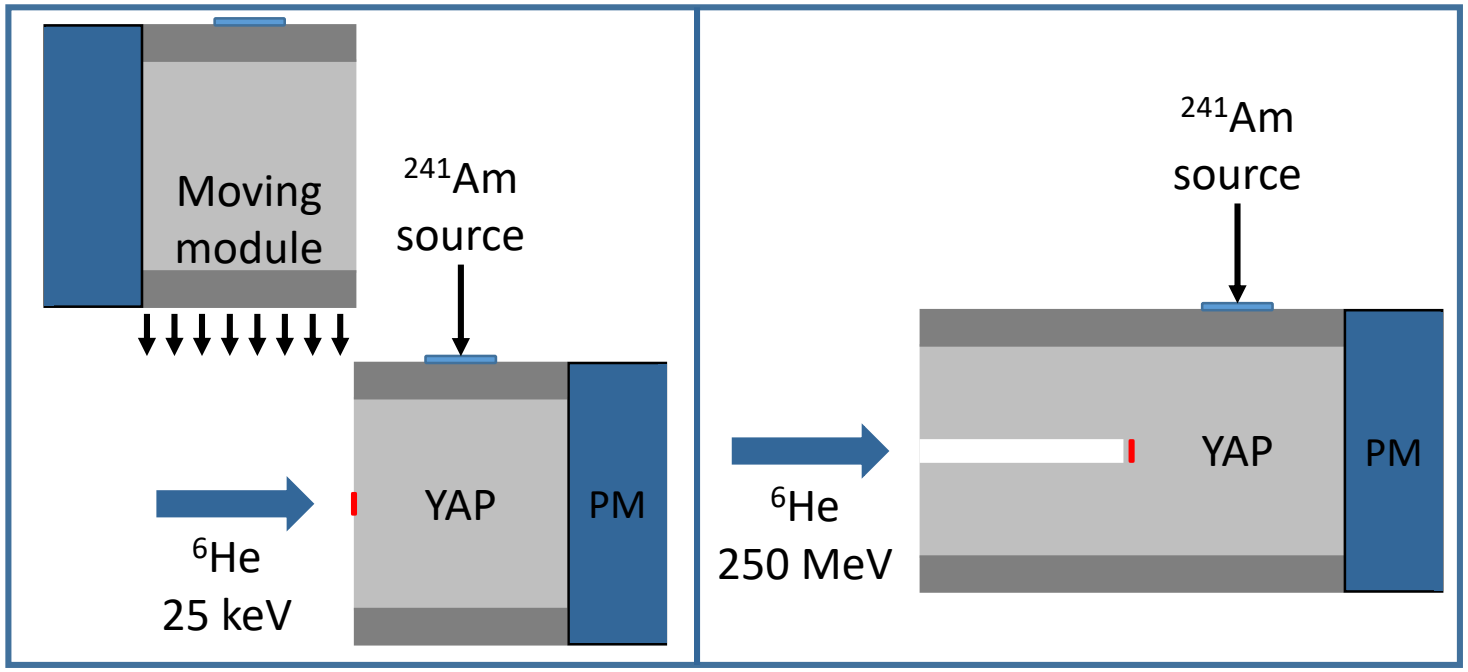
b_{GT} for ^{6}He decay with $\Delta b_{GT} = 10^{-3}$

- Convenient half-life ~0.8sec
- Relatively large endpoint ~3.5MeV
- Pure GT transition and thus exclusively sensitive to tensor currents
- Can be produced with a high production rate @GANIL
- Corrections are known with high precision

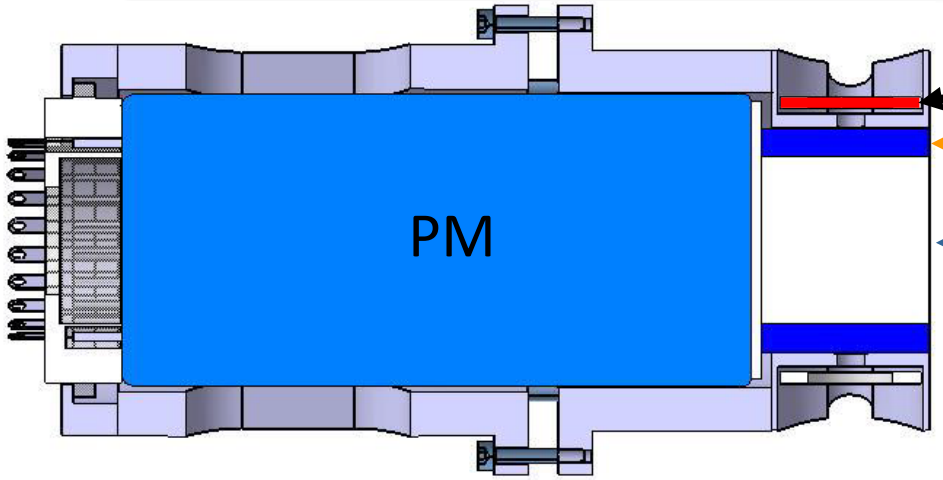
Phase I: 2 experiments with a goal of $\Delta b_{GT} = 4 \times 10^{-3}$:

- Low energy experiment
- High energy experiment

The ultimate setup will be used for the second phase.



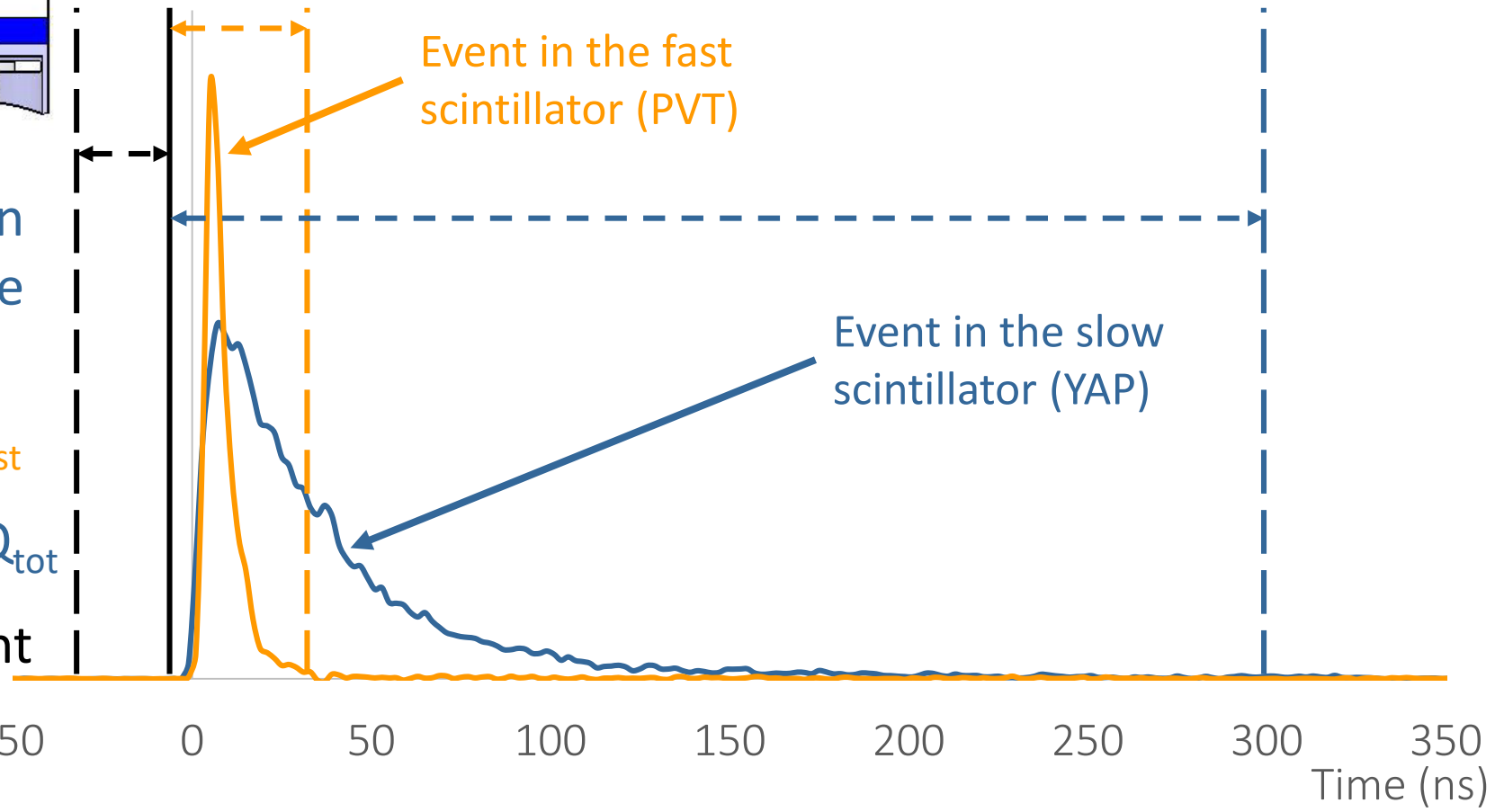
Phoswich detector



^{241}Am calibration source

PVT: Plastic scintillator with τ = 1.8 ns

YAP: Crystal scintillator with τ = 25 ns



For pulse shape discrimination we integrate the signal within the following windows:

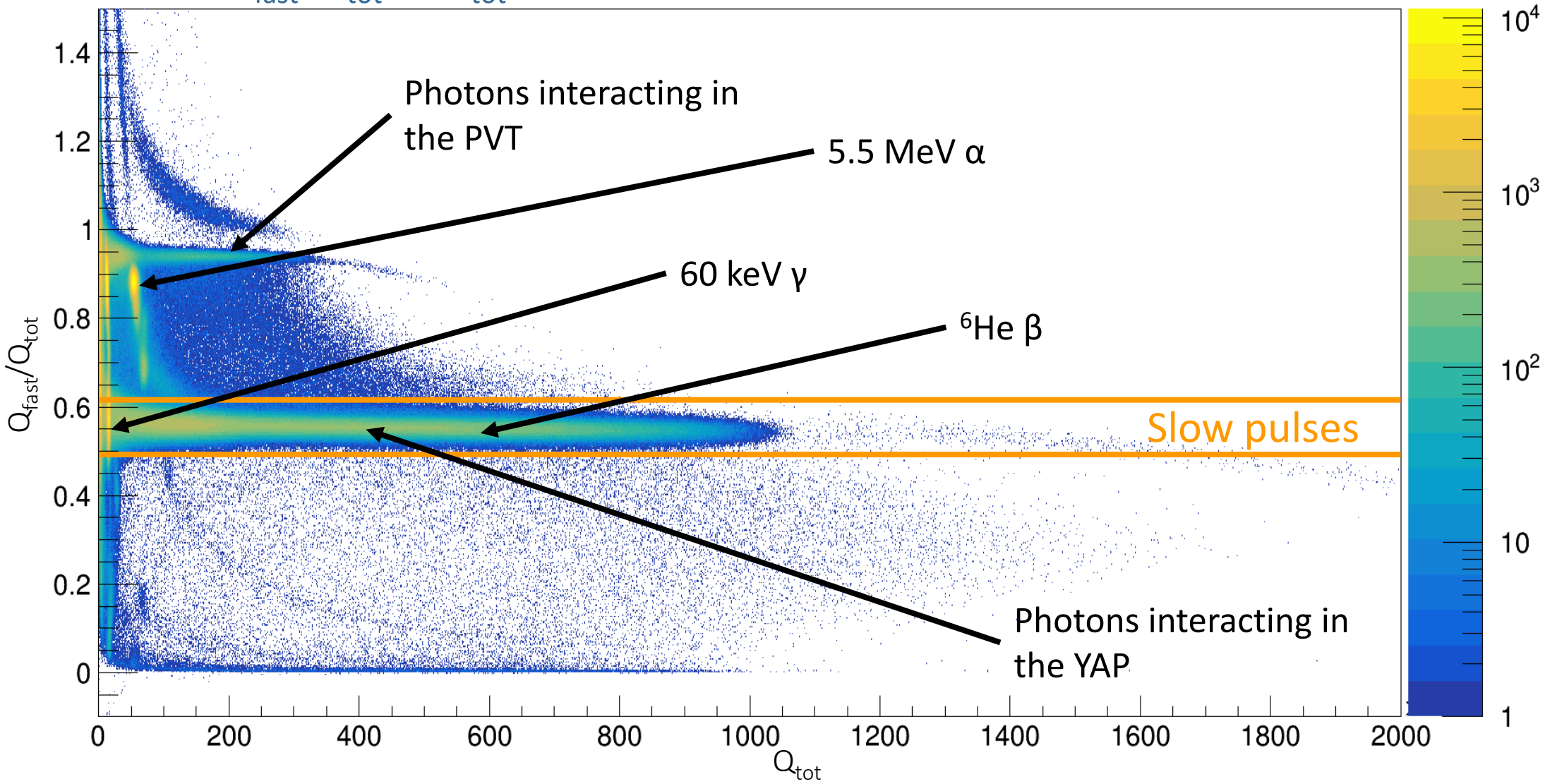
[-6;30] ns => Fast component Q_{fast}

[-6;300] ns => Total component Q_{tot}

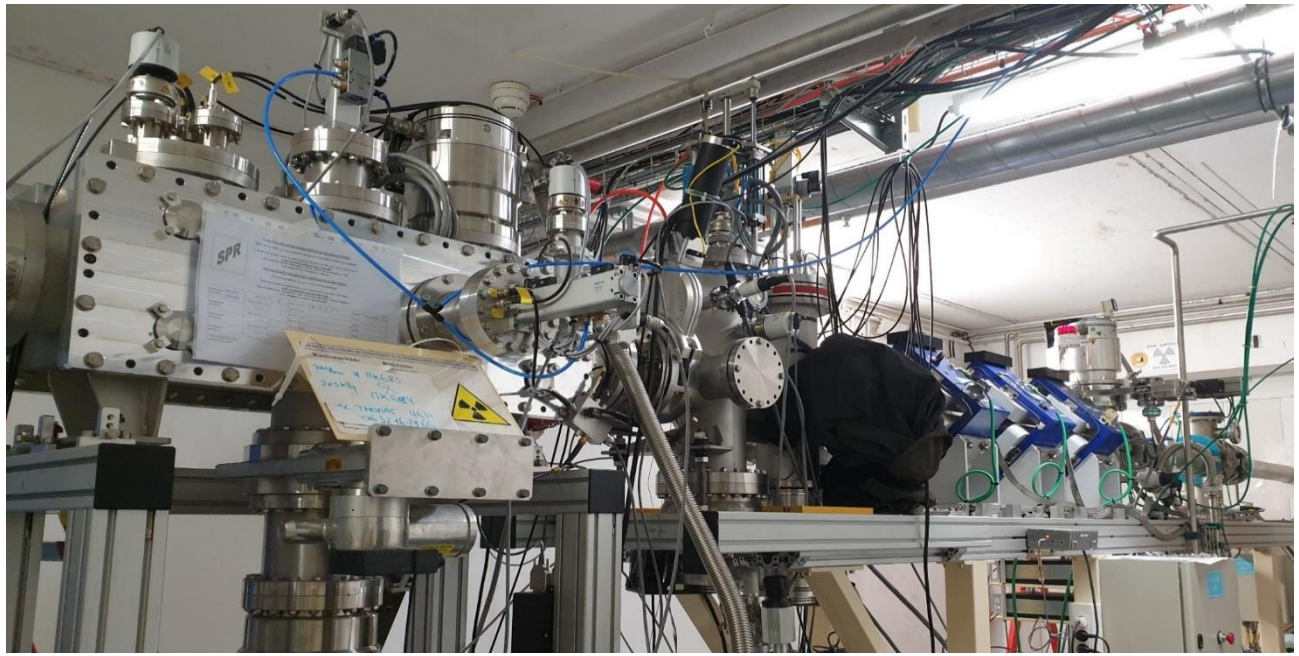
[-30;-6] ns => Baseline component

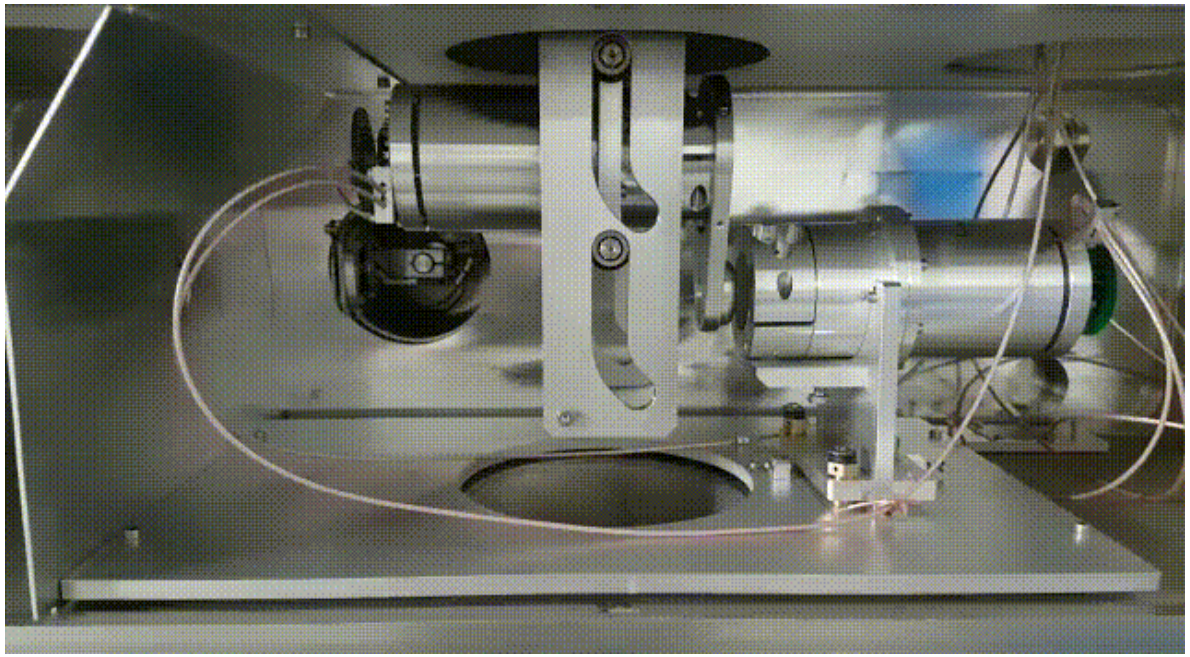
Pulses discrimination

Q_{fast}/Q_{tot} vs Q_{tot} for one run of the low energy experiment



Low energy experiment





May 2021 @GANIL

3 sets of measurements:

1) Cycles length
2) PMs polarization voltages
3) Beam intensity

All the following analysis was done offline.

Typical cycle:

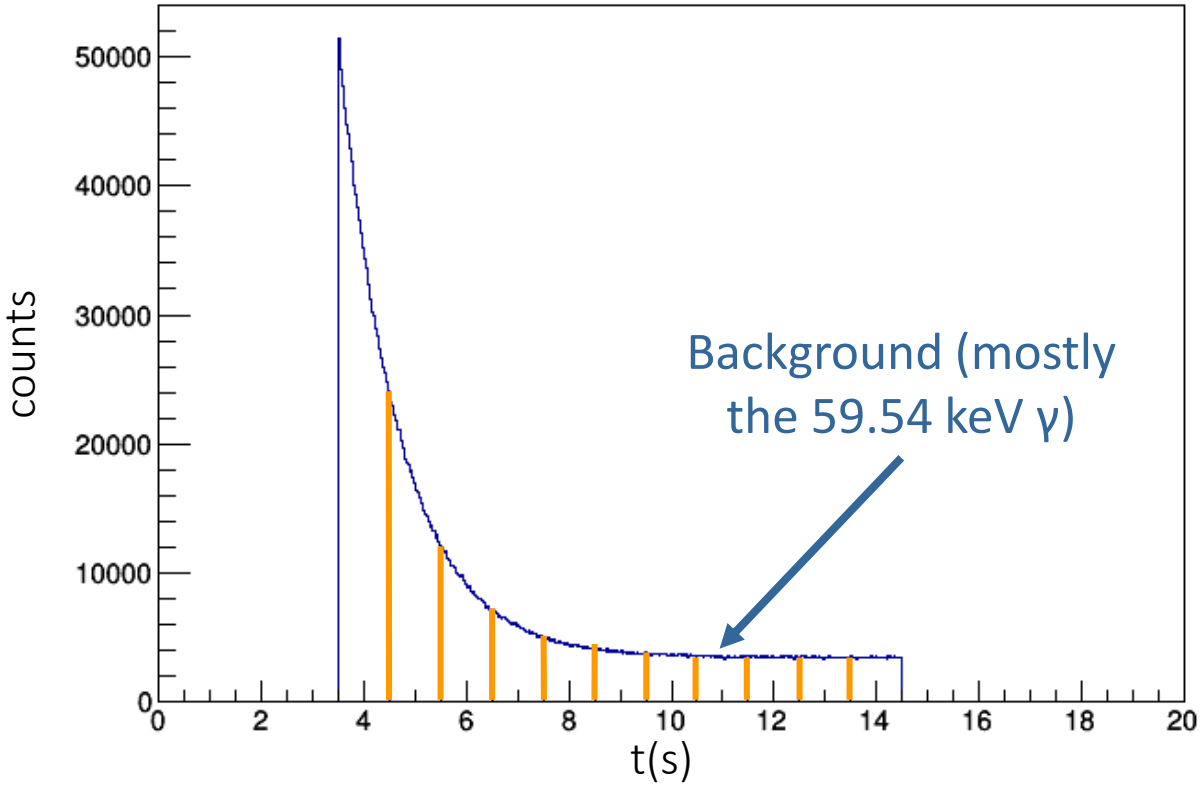
- 2.5 sec of implantation
- 12 sec of acquisition

Each event was recorded with a time stamp and an energy signal => High precision measurement of the half-life of ^{6}He.

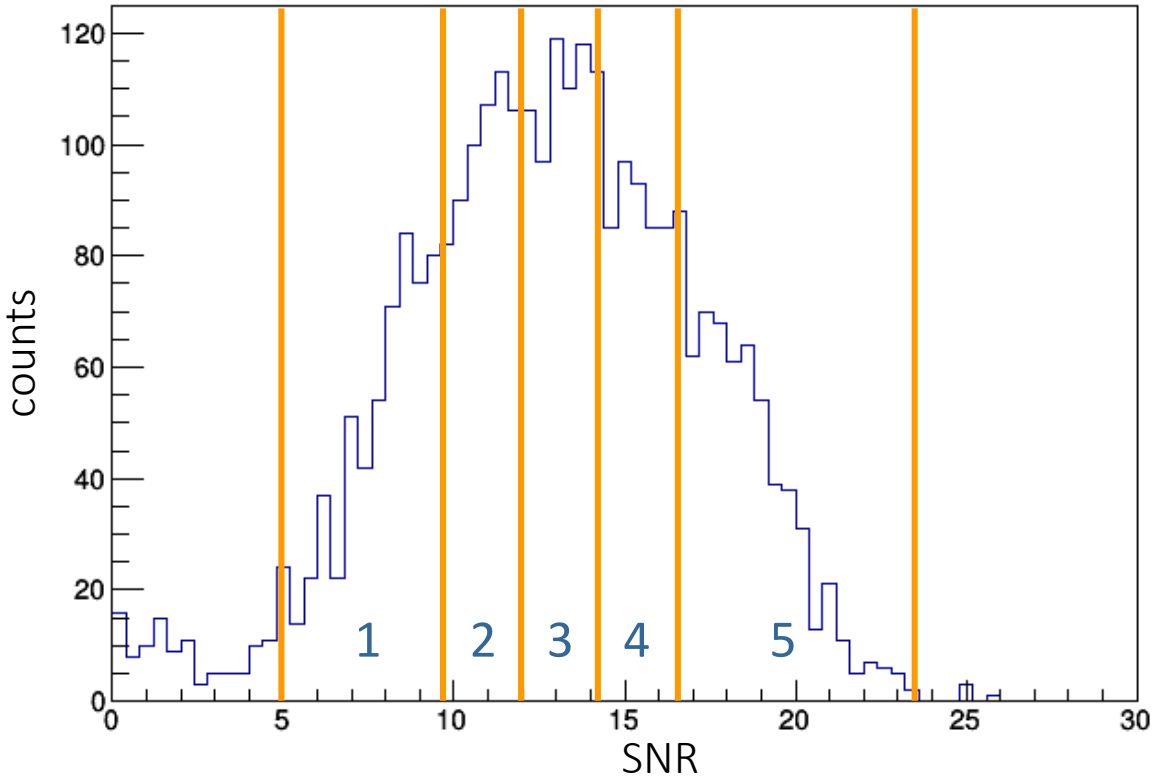
Energy calibration

A very accurate energy calibration is required to control any baseline or gain variation.

The evolution of the count rate within a cycle



Distribution of the signal to BKG ratio for all the cycles of 1 set of measurements



The gain and baseline variations depends on the count rate variations

Energy calibration

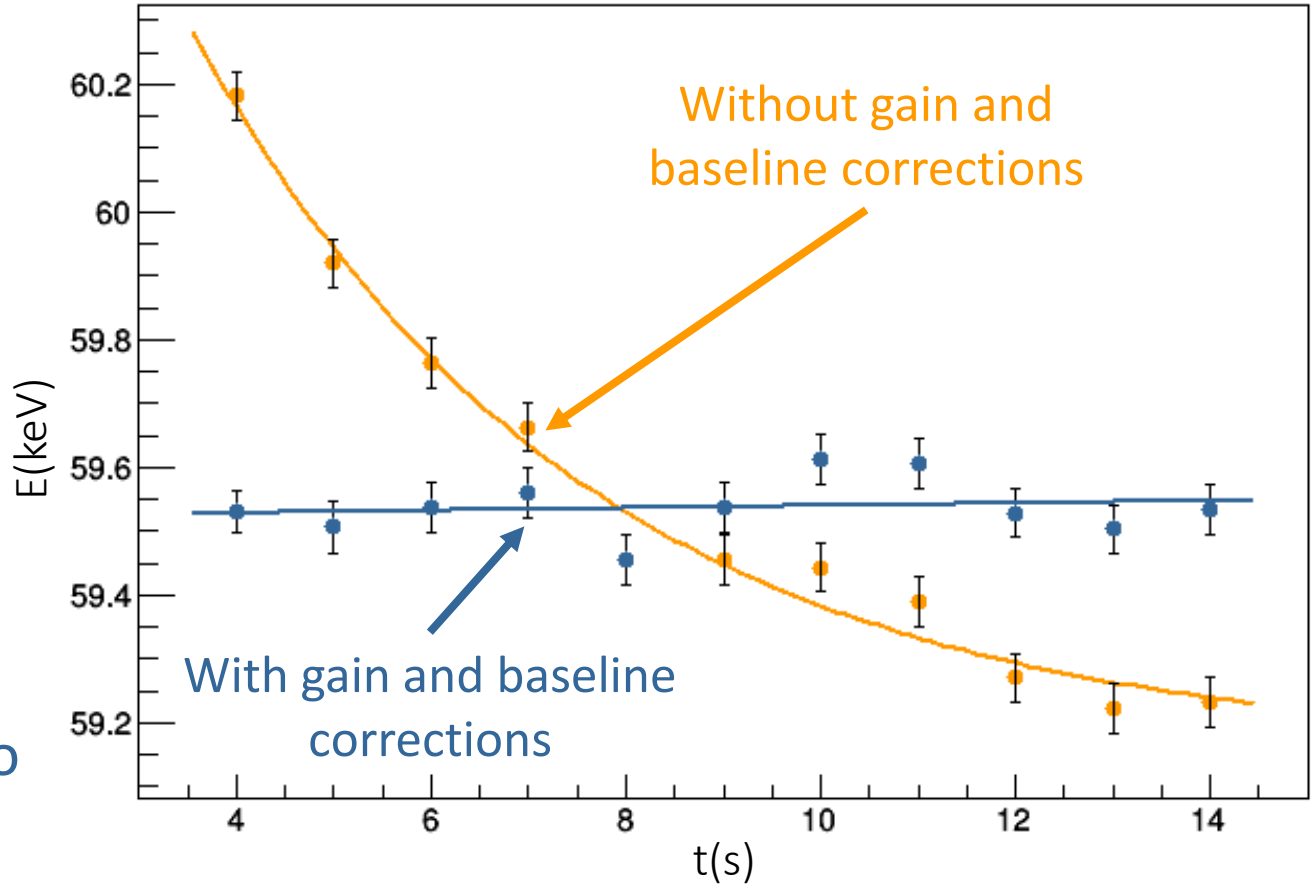
We used the position of the 59.54 keV gammas of the ^{241}Am to form a correction model that compensate for the gain and baseline variations.

Difference of ~1.5% between the beginning and the end of the cycle.

Study the potential systematic effects:

- Dead time
- Pile-ups
- Gain shifts
- Baseline shifts

This offline study is possible due to the time and charge stamped data.



Dead time correction

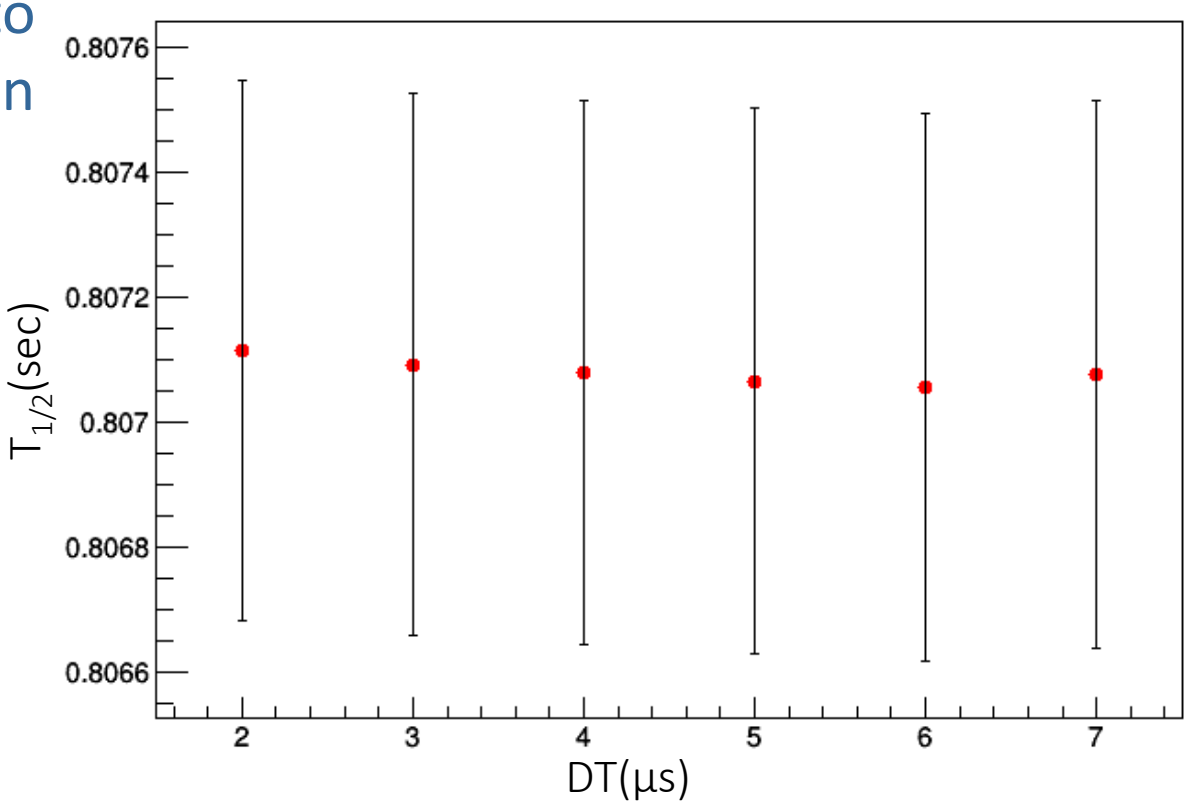
Instead of applying corrections to the data to compensate the loss of events due to dead time, we used the following function to fit each cycle :

Constant background

$$N_{th}(t) = \frac{N_{0_{th}} e^{-t/\tau_{th}} + BKG_{th}}{1 + neDT \times N_{tot}(t)}$$

non extensible dead time

The fit function for a selected energy threshold



The measured half life values for a 600 keV threshold and for several neDT

Pile-ups correction

For a selected energy threshold, the detected decay function is the following:

$$N_{det}(t) = N_0 e^{-t/\tau}\left[P_{th}^{sing} + P_{Pup}(t) \times (P_{th}^{Pup} - P_{th}^{sing})\right]$$

P_{th}^{sing}: Probability for a single event to be above the energy threshold

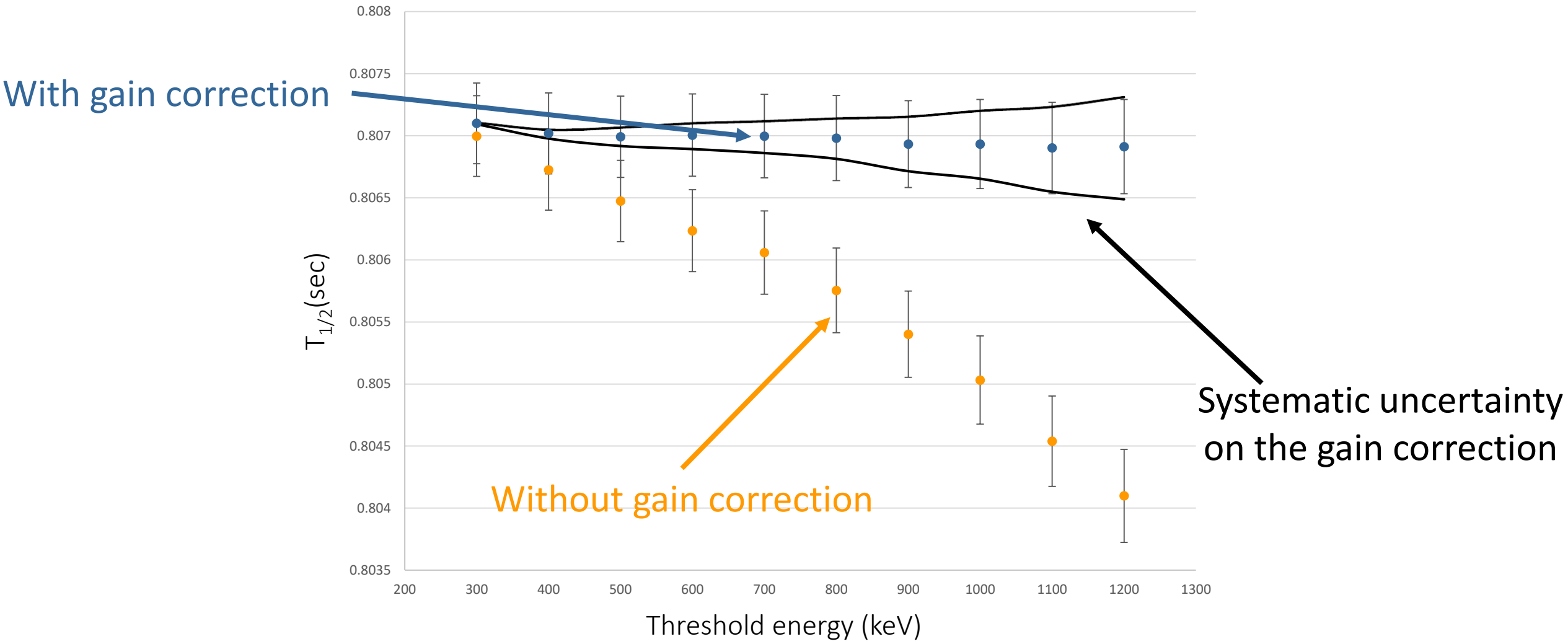
P_{th}^{Pup}: Probability for a pile-up event to be above the energy threshold

$P_{Pup}(t)$: Probability of having a pile-up event

$P_{Pup}(t) = N_0 e^{-t/\tau} \times 306ns$ ← Depends on the count rate

$$P_{th}^{sing} < P_{th}^{Pup}$$

Gain correction effect



For 600 keV we have about 1 ms difference for the gain correction

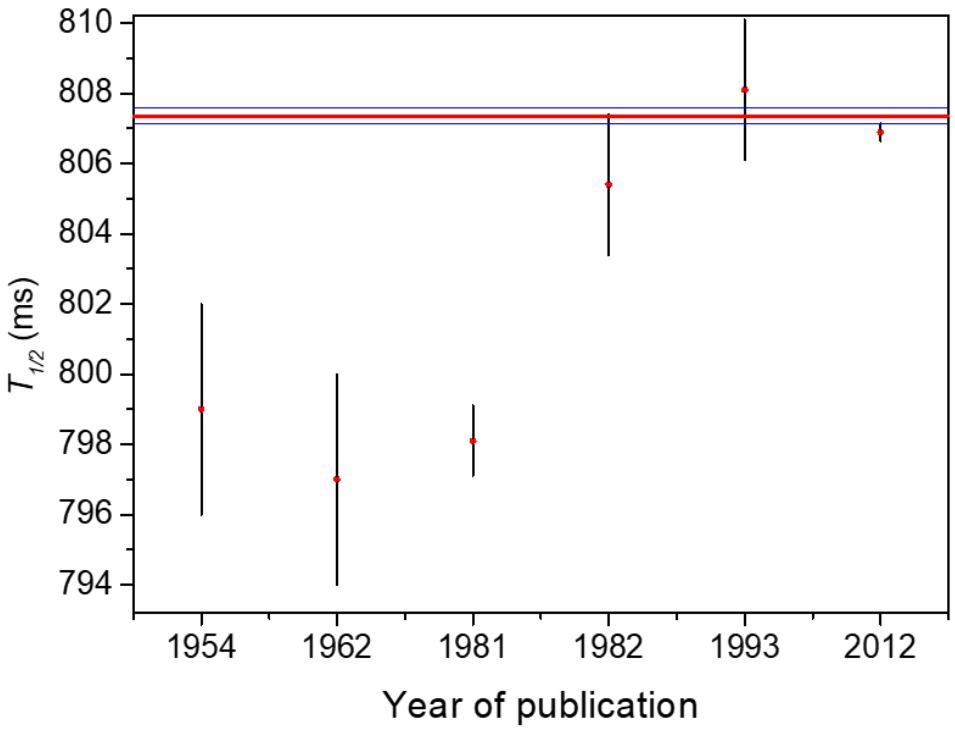
Results

	Set (1)	Set (2)	Set (3)
$T_{1/2}$	807.50	807.25	807.23
Stat. error	0.31	0.33	0.43
Gain shift	0.75	0.77	0.78
Baseline shift	0.09	0.04	0.05
Pile-up shift	0.12	0.25	0.14
total shift	0.96	1.06	0.97
Gain error	0.06	0.10	0.06
Baseline error	0.03	0.02	0.09
Pile-up error	<0.01	<0.01	<0.01
Total syst. error	0.07	0.11	0.11

$$T_{1/2} = 807.35 \pm 0.20_{stat} \pm 0.11_{syst}\ ms$$

Our result is in agreement with the last and most accurate value, but is larger by 1.5 σ

PRELIMINARY



A. Knecht, Phys. Rev. Lett. 108, 122502 (2012).

Summary and outlook

Summary:

- The gain and baseline corrections are crucial for measuring the half life with a precision higher of 10^{-3} sec.
- Our preliminary results are in agreement with the latest values and have a similar total uncertainty with the latest one.

Outlook:

- Finish the analysis for the half life measurement and publish the results.
- Start the analysis for the extraction of the Fierz term.

Thank you for your attention !

Nuclear beta decay

Analogy with Electromagnetism : $H = G_F \, J_H \, J_L = G_F \, (\bar{\psi}_p \mathcal{O} \psi_n)(\bar{\psi}_e \mathcal{O} \psi_\nu)$

G_F → Fermi coupling constant

$(\bar{\psi}_p \mathcal{O} \psi_n)$ → Hadron current

$(\bar{\psi}_e \mathcal{O} \psi_\nu)$ → Lepton current

Where: ψ_p, ψ_n, ψ_e and ψ_ν → Wave functions

$\mathcal{O}$ → Quantum operator (Dirac γ-matrix)

Respect Lorentz invariance:

H must be a scalar or a pseudoscalar → The operators in hadron and lepton currents should be the same

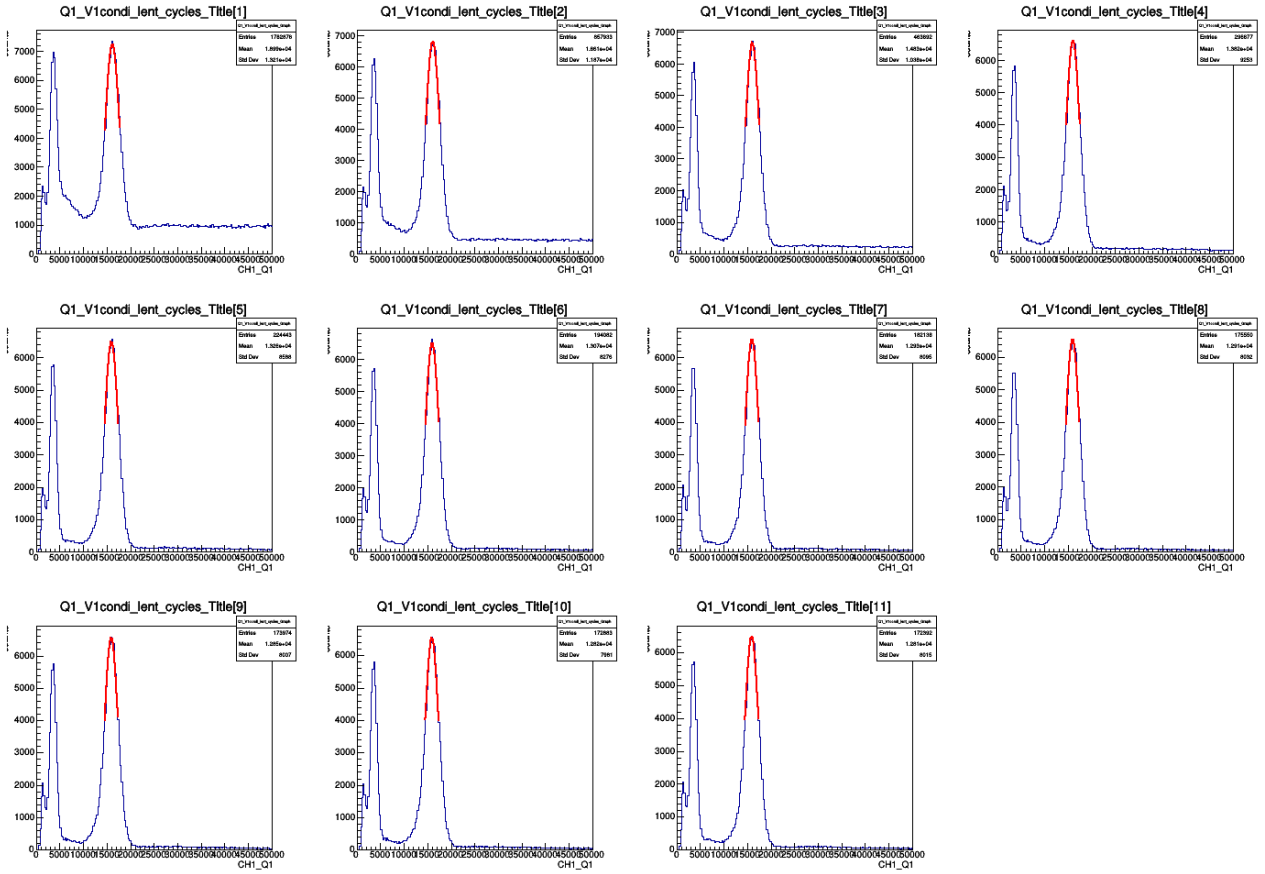
$$H_i^{even} = g_i (\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \, \psi_\nu) + h.c. \qquad \text{(Scalar)}$$

$$H_i^{odd} = g_i' (\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \gamma_5 \, \psi_\nu) + h.c. \qquad \text{(Pseudoscalar)}$$

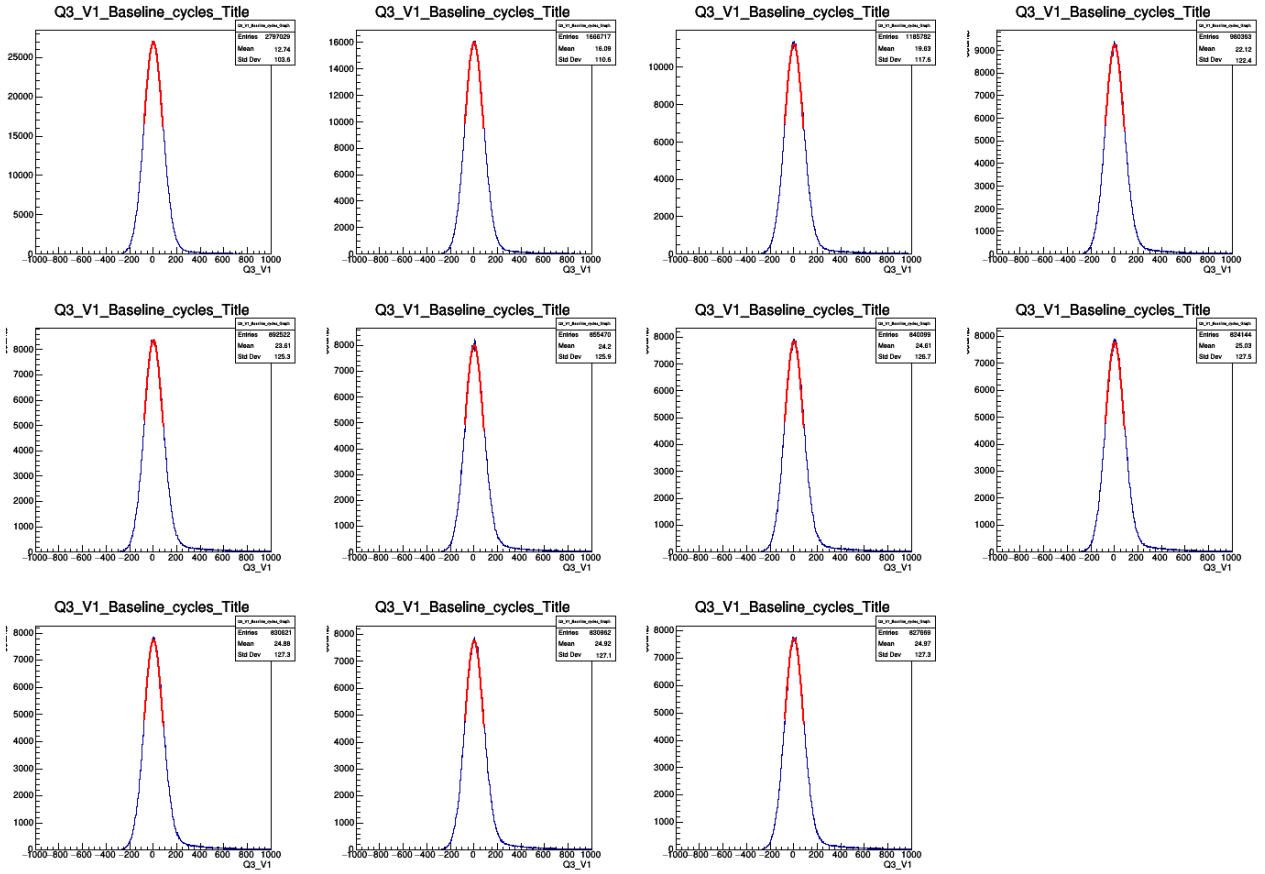
with $g_i = g_F C_i \qquad g_i' = g_F C_i' \qquad i = S, V, T, A, P$

Corrections model

The 60 KeV peak position

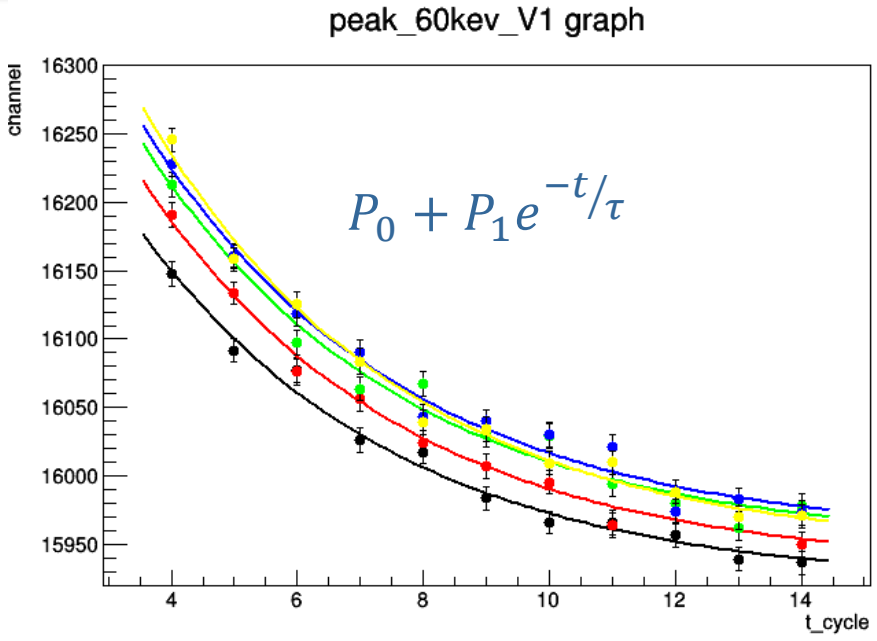


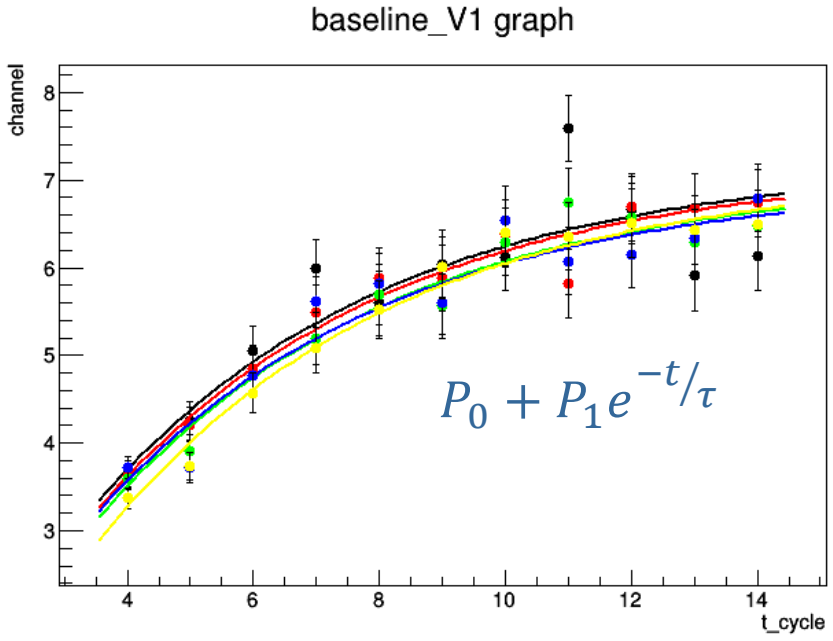
Baseline position



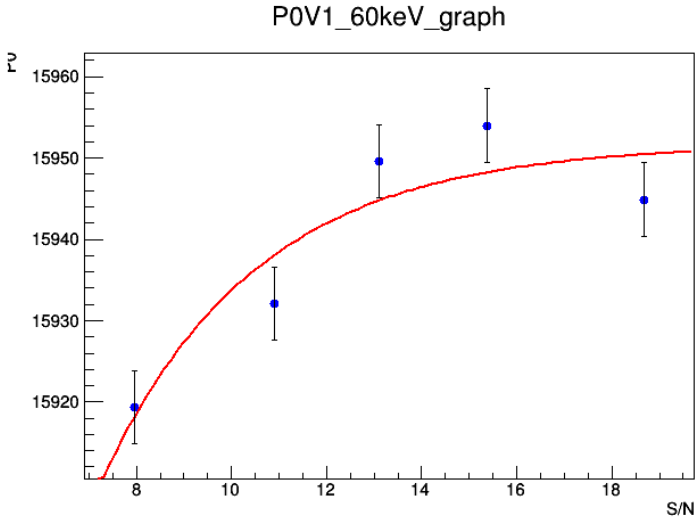
Corrections model

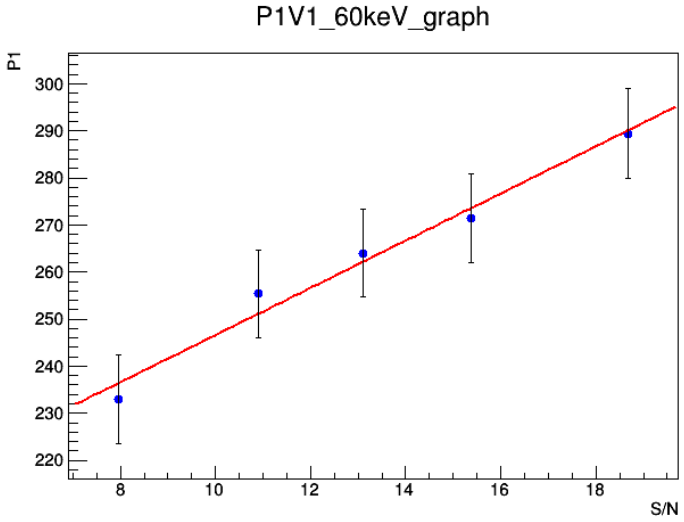
For both the gain and baseline correction model, P_0 and P_1 is a function of SNR.



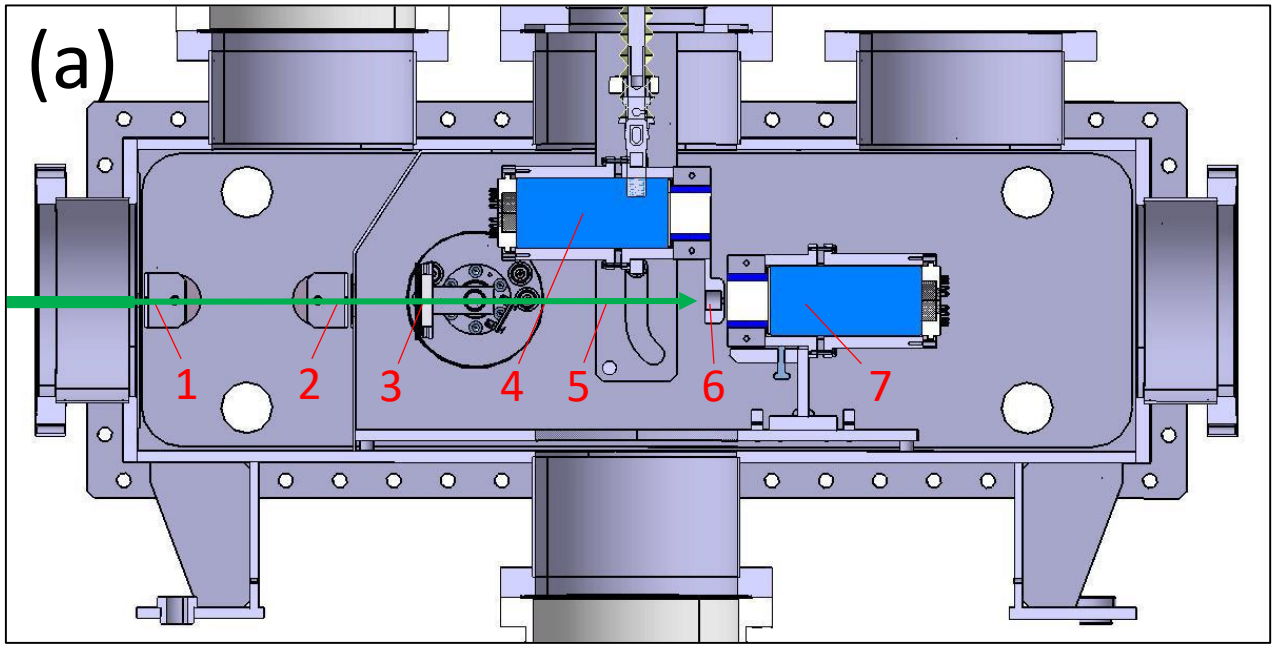


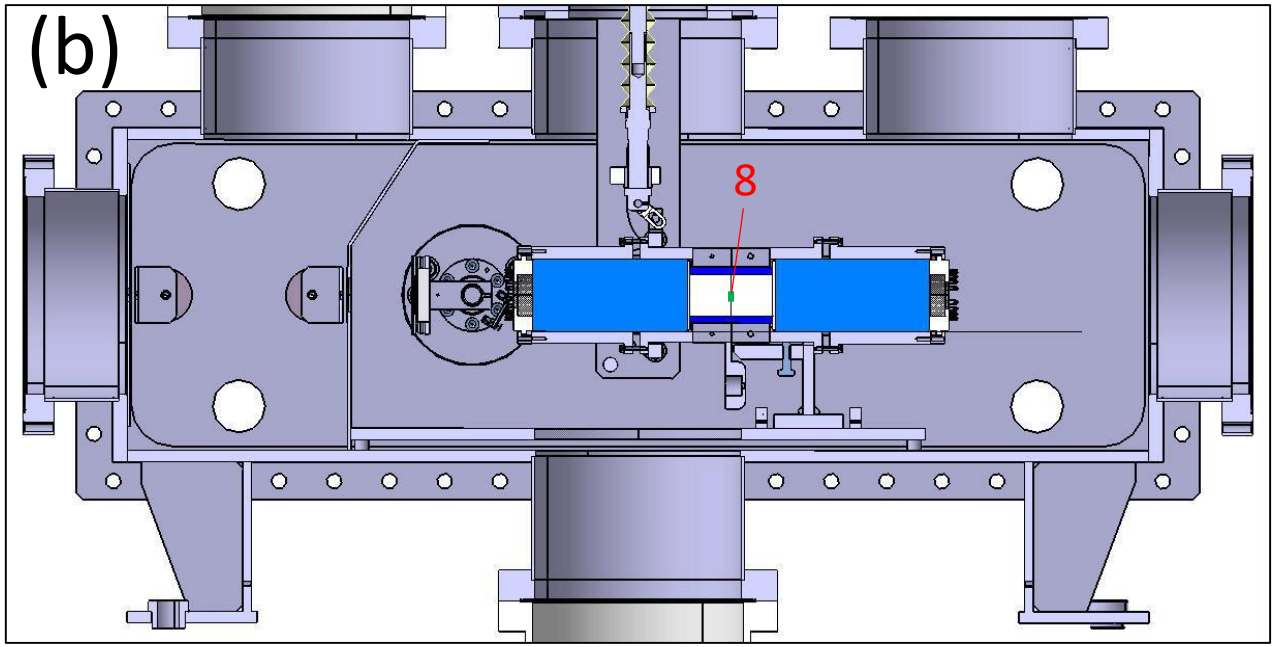
P_0 and P_1 variation against the SNR



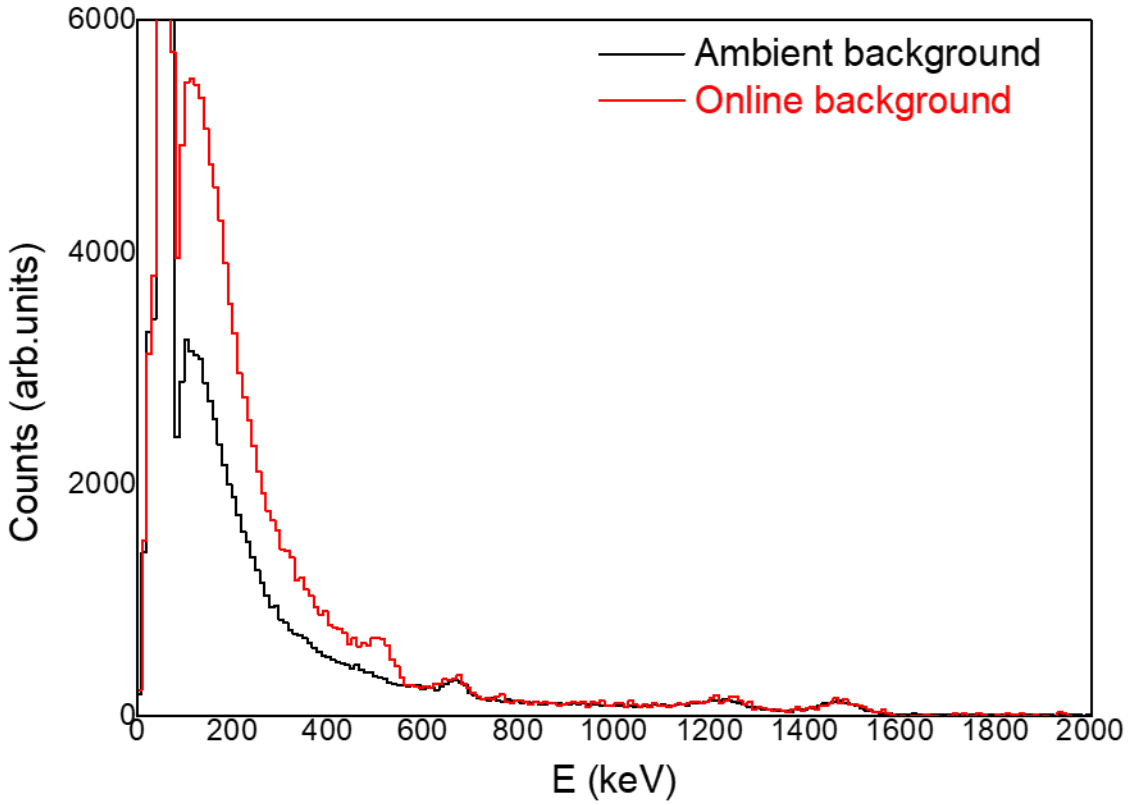


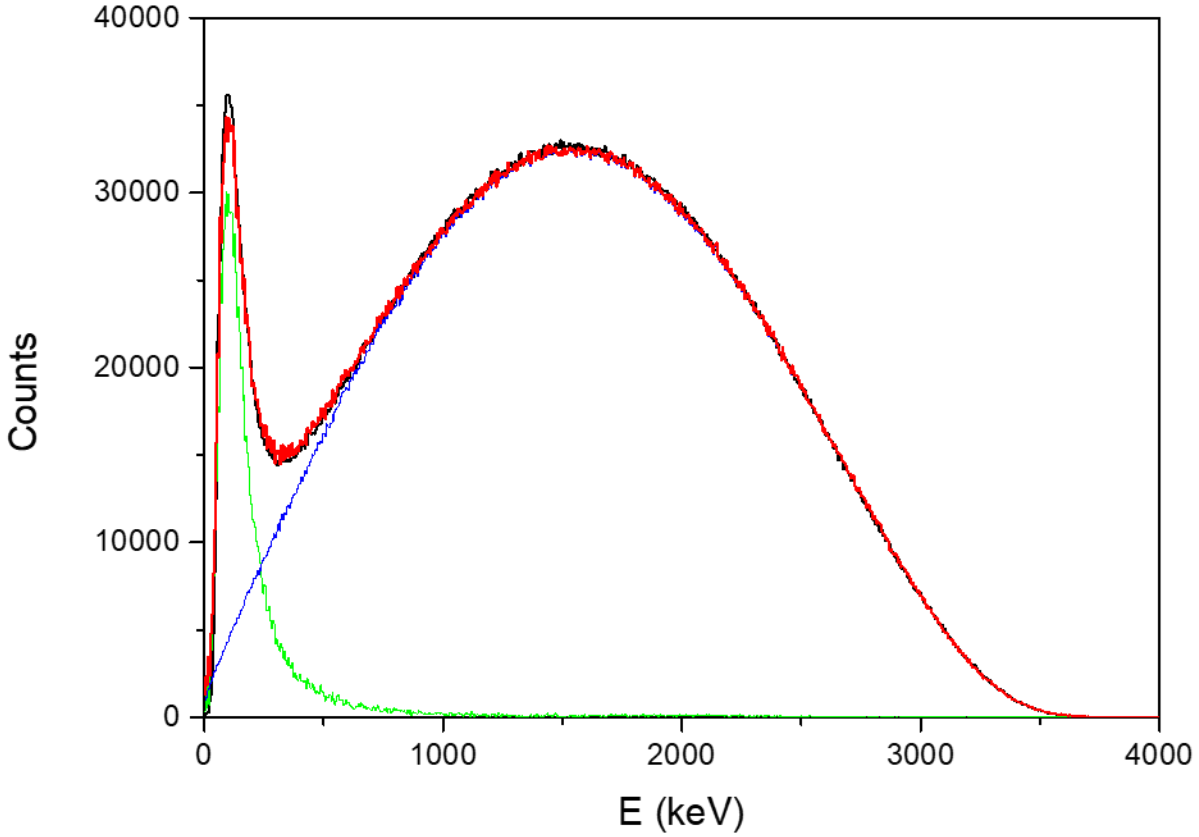
Experimental setup



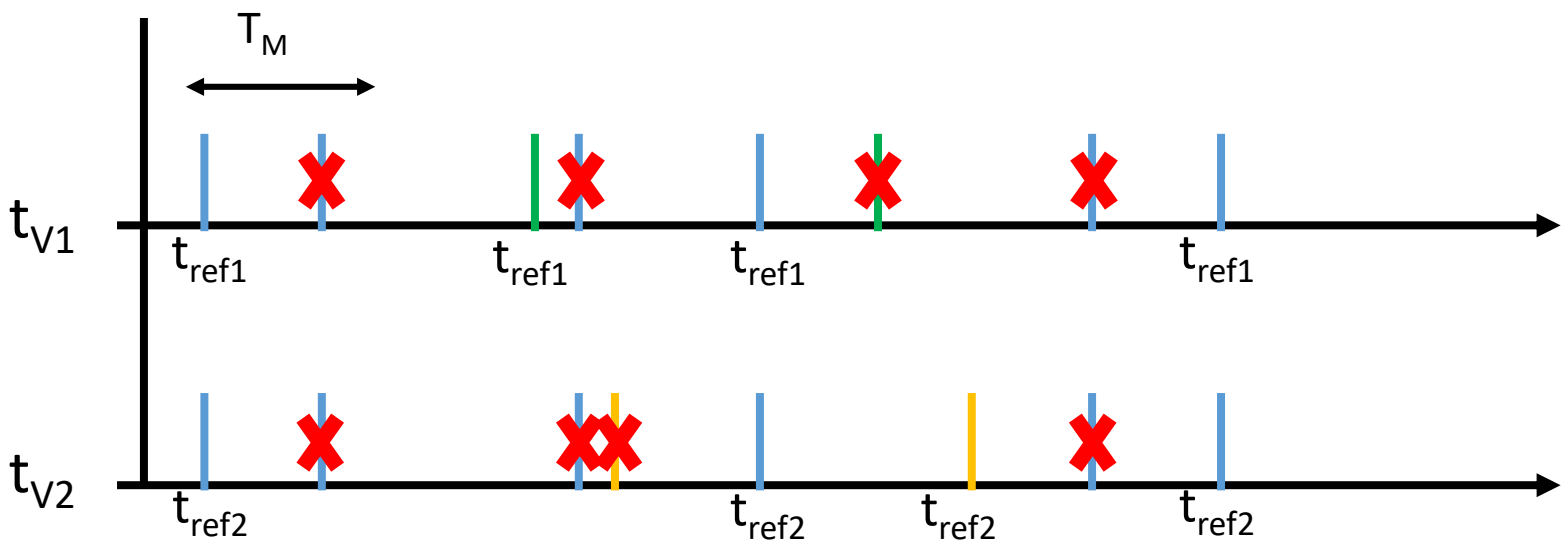


Backgrounds





Imposed dead-time



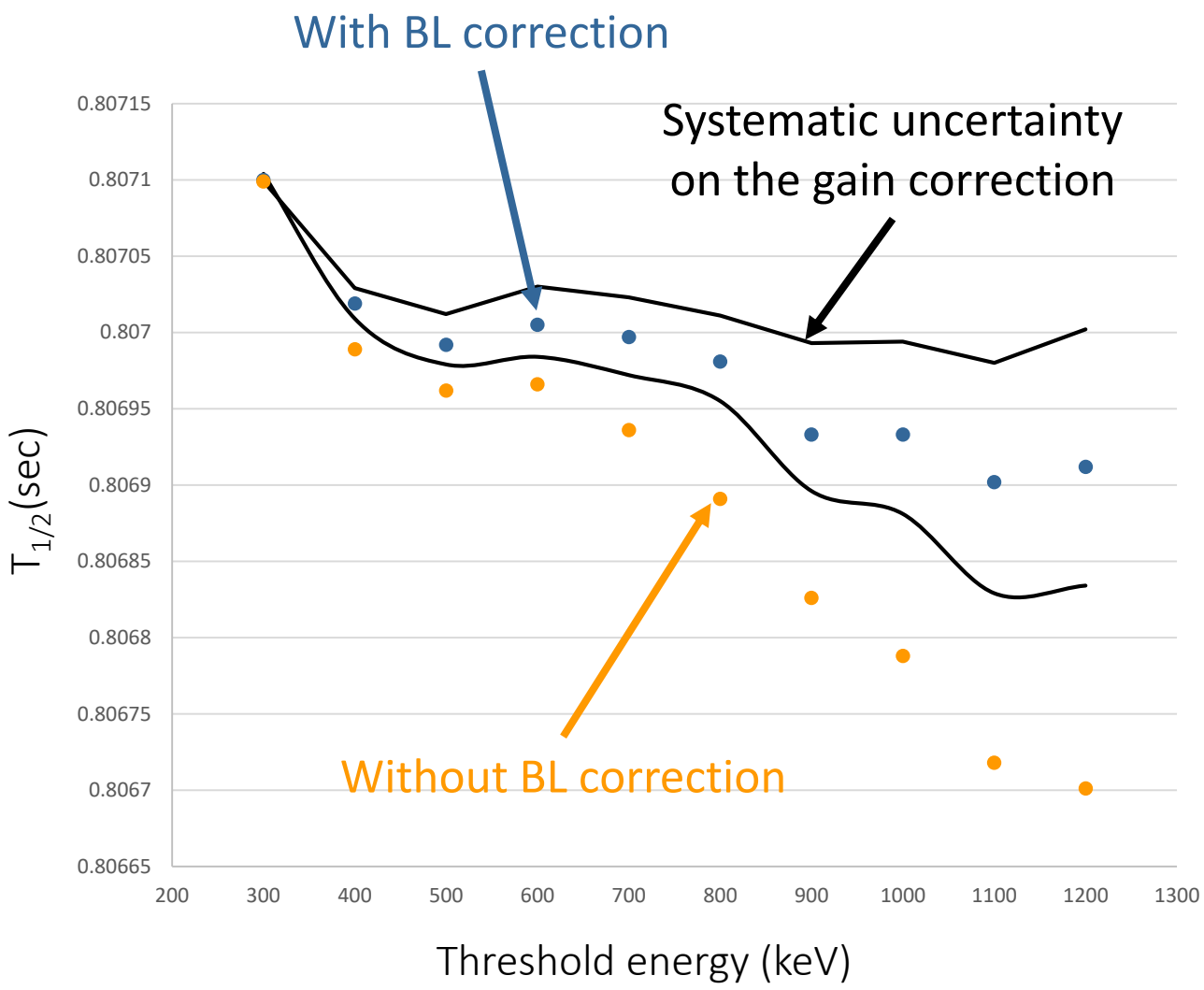
Coincidence events in both detectors

Single events in detector 1

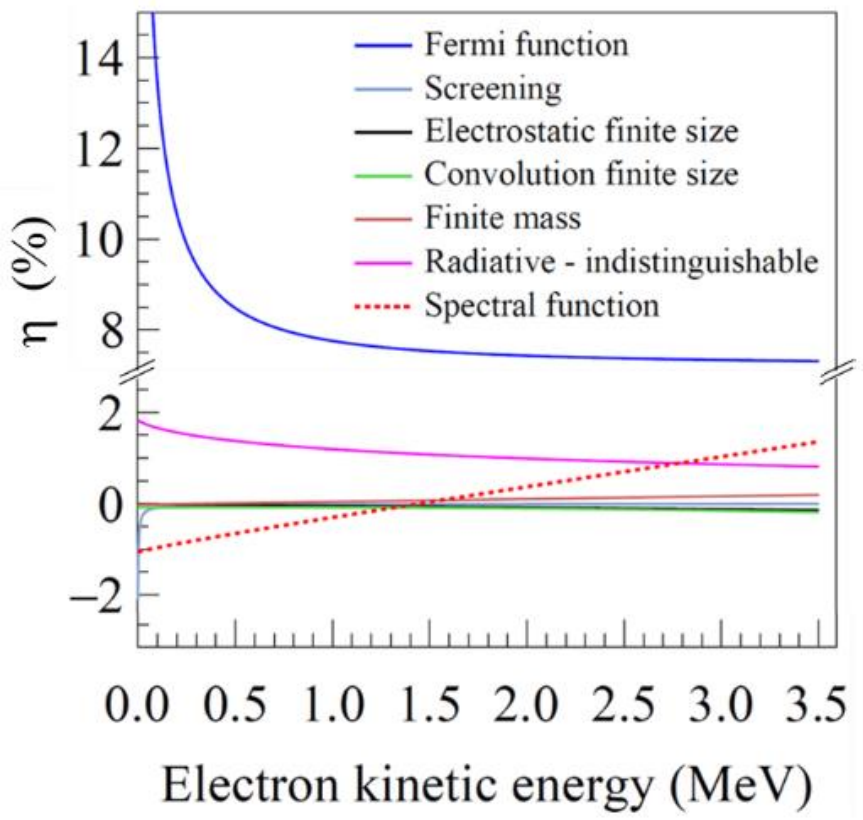
Single events in detector 2

2 detectors that work like one

Baseline correction effect



Corrections to the spectrum's shape



Source	Δb_{GT}
Nuclear charge radius of ^{6}Li	4.6×10^{-5}
End-point energy of the transition	1.8×10^{-4}
Weak magnetism form factor	5.7×10^{-4}
Induced tensor form factor	1.9×10^{-5}
Total theoretical uncertainty	$\mathbf{6.0\times10^{-4}}$