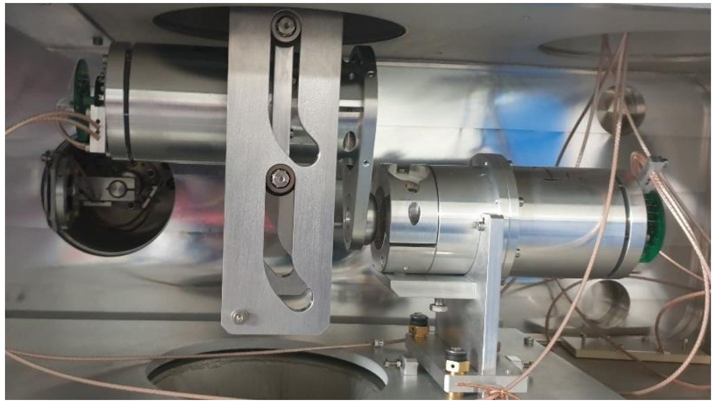
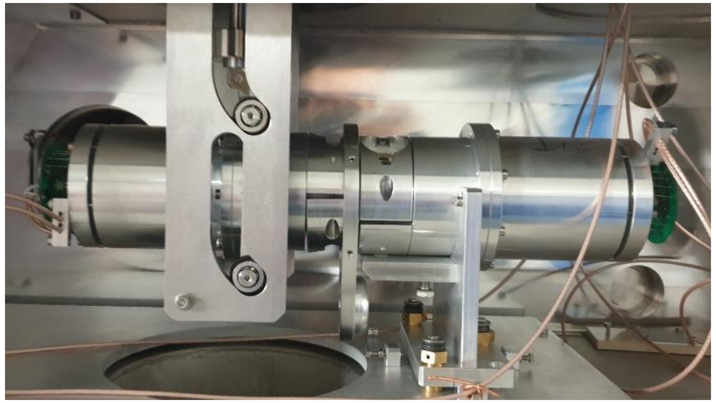




Search for Tensor Interactions in bEta Decay: b-STILED project status

ISOL-France Workshop VI

Mohamad Kanafani

May 28, 2024

Strasbourg, France

Outline

- Context and motivations
- Experimental setups
- Overview of the b-STILED experiments
- Data analysis and preliminary results
- Summary and outlook

Hamiltonian of the β-decay:

$$H_\beta = g_F \sum_i (\bar{\psi}_p \mathcal{O}_i \psi_n)(\bar{\psi}_e \mathcal{O}_i (C_i + C_i' \gamma_5)\psi_\nu) + h.c.$$

- g_F → Fermi coupling constant
- $(\bar{\psi}_p \mathcal{O}_i \psi_n)$ → Hadron current
- $(\bar{\psi}_e \mathcal{O}_i (C_i + C_i' \gamma_5)\psi_\nu)$ → Lepton current

C_i & C_i' → 10 coupling constants → 5 forms of currents: Scalar, Vector, Tensor, Axial-vector, Pseudo-scalar

C_i: Even; C_i': Odd

$C_V, C_V', C_A, C_A', C_T, C_T', C_S, C_S', C_P, C_P'$ → Determined experimentally

Standard Model:

- $C_V = C_V' = 1$
- $C_A = C_A' = -1.25$
- $C_S = C_S' = C_T = C_T' = 0$ → (Current Constraints) → Possibility for search of new physics

Fierz interference term b_{GT}

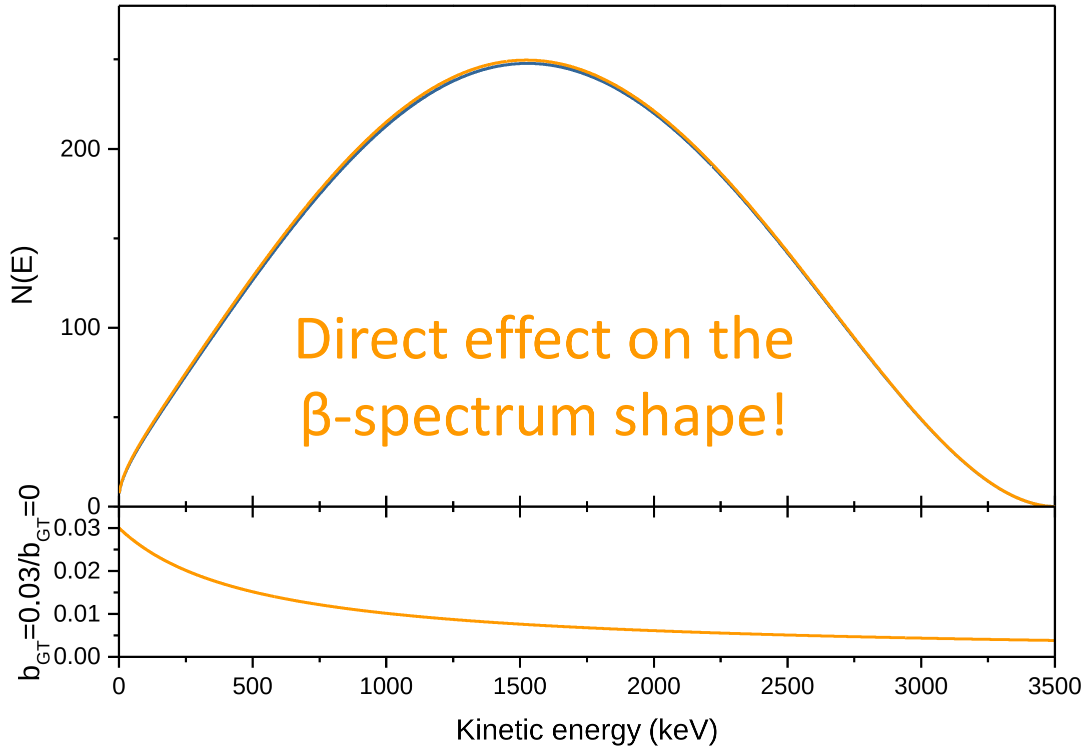
For pure Gamow-Teller transitions:

$$N(E) \propto F(Z,E)(1+\eta)pE(E-E_0)^2\left(1+\frac{m_e}{E}b_{GT}\right)$$

Fermi function — $F(Z,E)$

Theoretical corrections — $(1+\eta)$

Phase space — $pE(E-E_0)^2$



$$b_{GT} \propto \gamma Re\left(\frac{C_T + C'_T}{C_A}\right) = 0$$ } Standard Model

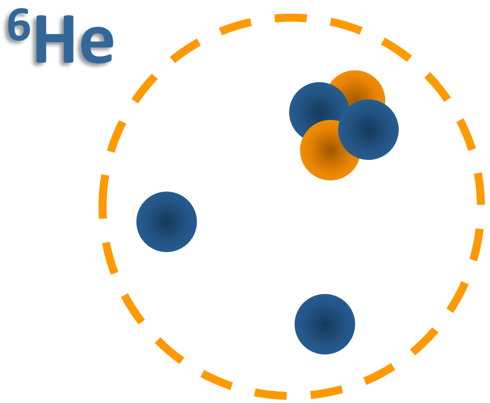
b-STILED: extract b_{GT} for ^6He decay from a super precise measurement of the β-spectrum

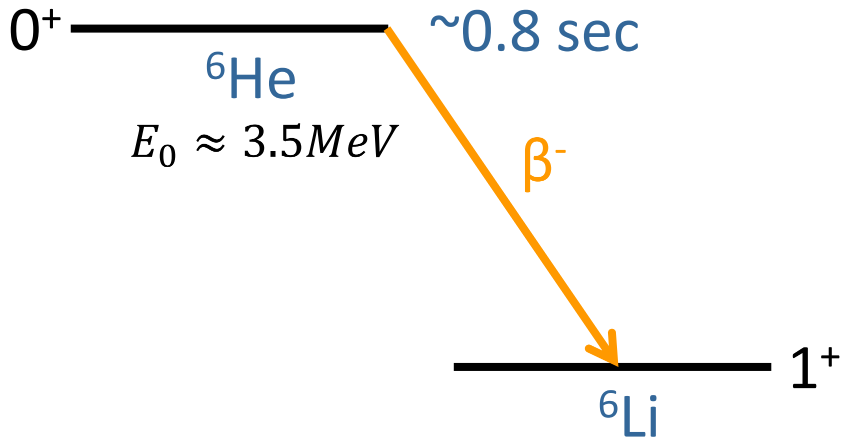
Precision goal:

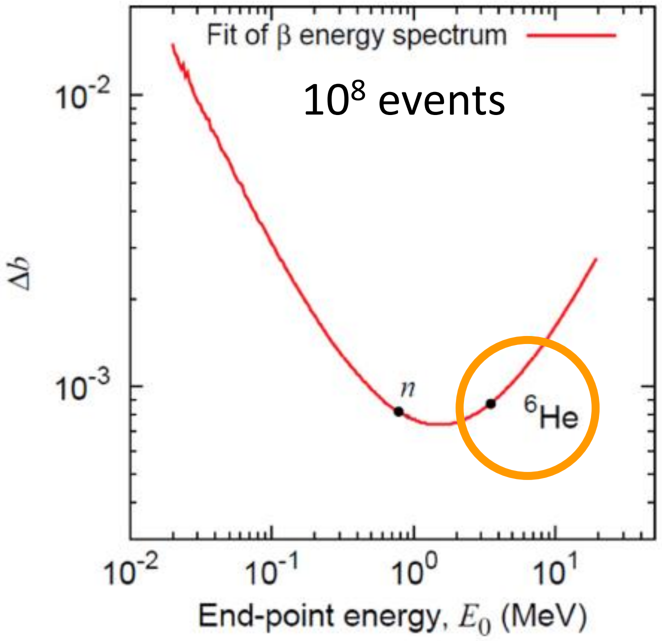
- Phase I: $\Delta b_{GT} = 4 \times 10^{-3}$ ⟶ Current limits from β decay experiments
- Phase II: $\Delta b_{GT} = 1 \times 10^{-3}$ ⟶ Better than LHC @14 TeV

The perfect candidate ^{6}He

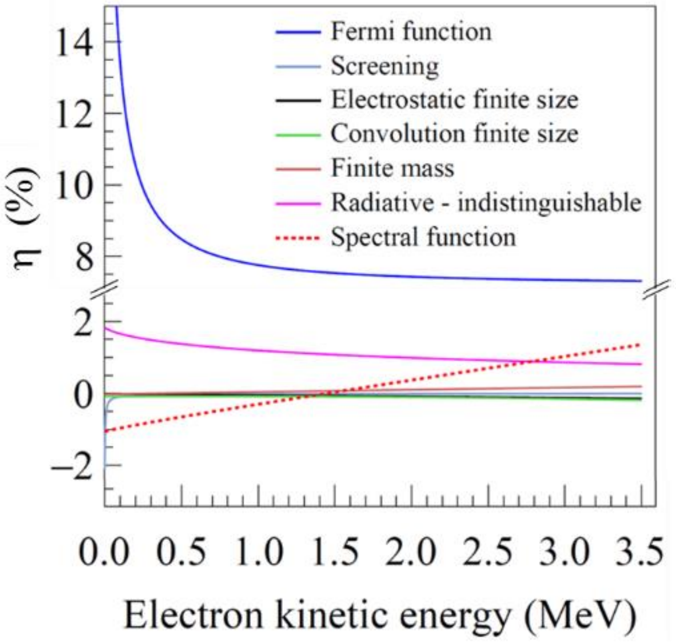
- Pure GT transition and thus exclusively sensitive to tensor currents
- Endpoint energy providing high sensitivity
- Theoretical corrections known with high precision
- Convenient half-life for implantation-decay cycles







M. González-Alonso et al, PRC, 2016.



$\Delta b_{GT} < 10^{-3}$

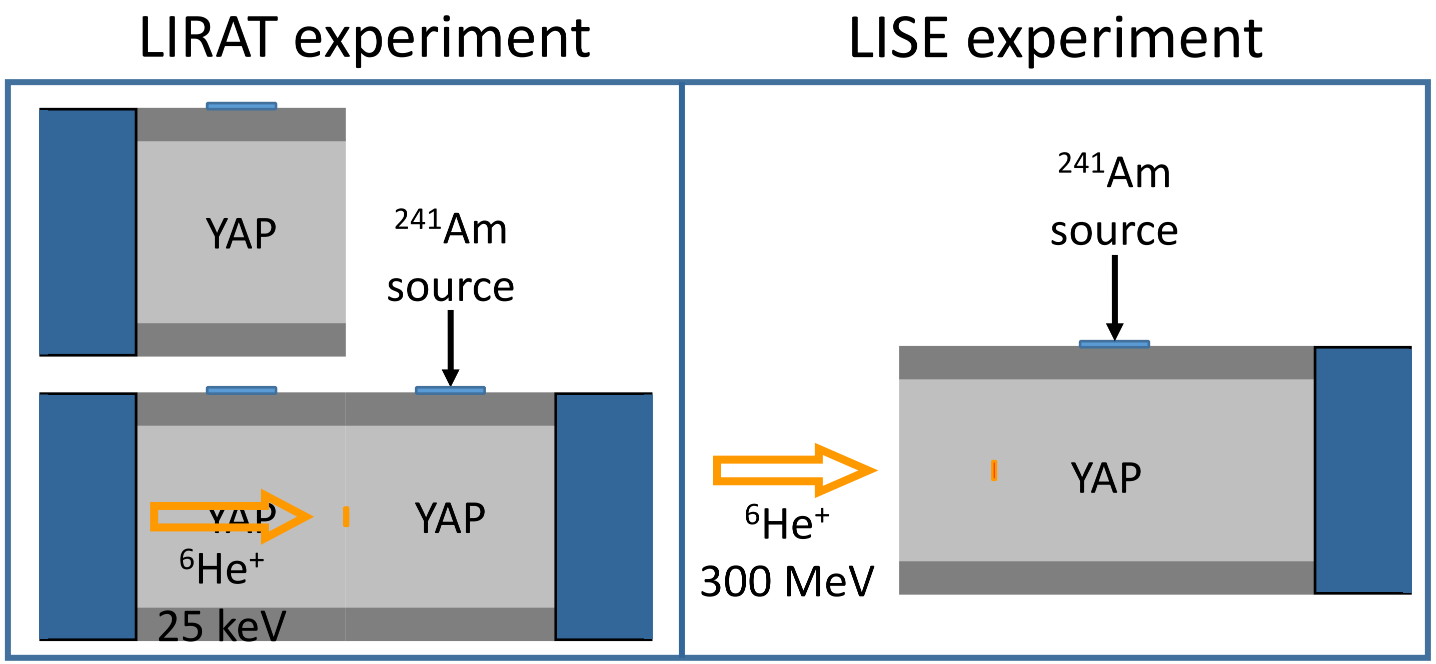
The two experiments

Principal systematic effect: electrons backscattering

Solution: 4π detection geometry

Phase I: 2 experiments $(\Delta b_{GT} = 4 \times 10^{-3})$

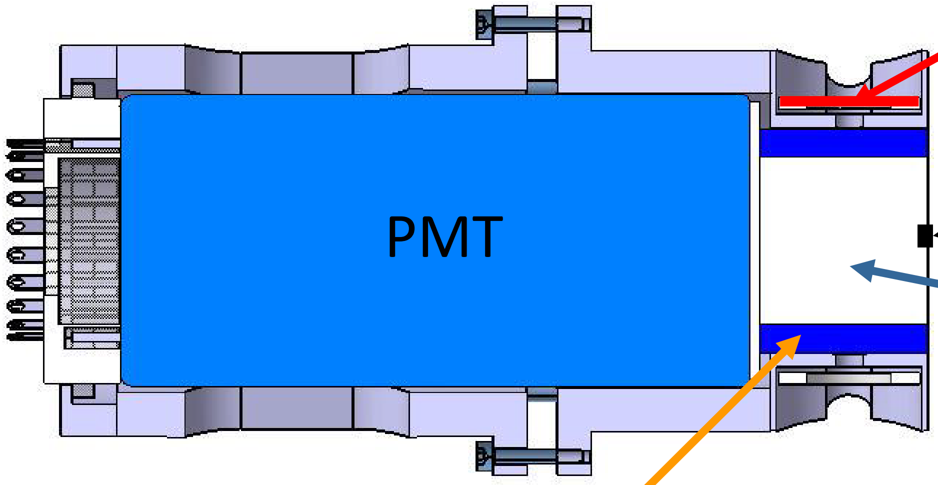
- LIRAT experiment
- LISE experiment



The phoswich detector

Phoswich detector:
2 scintillators read out by one PMT

Reference point for gain variations:
^{241}Am source



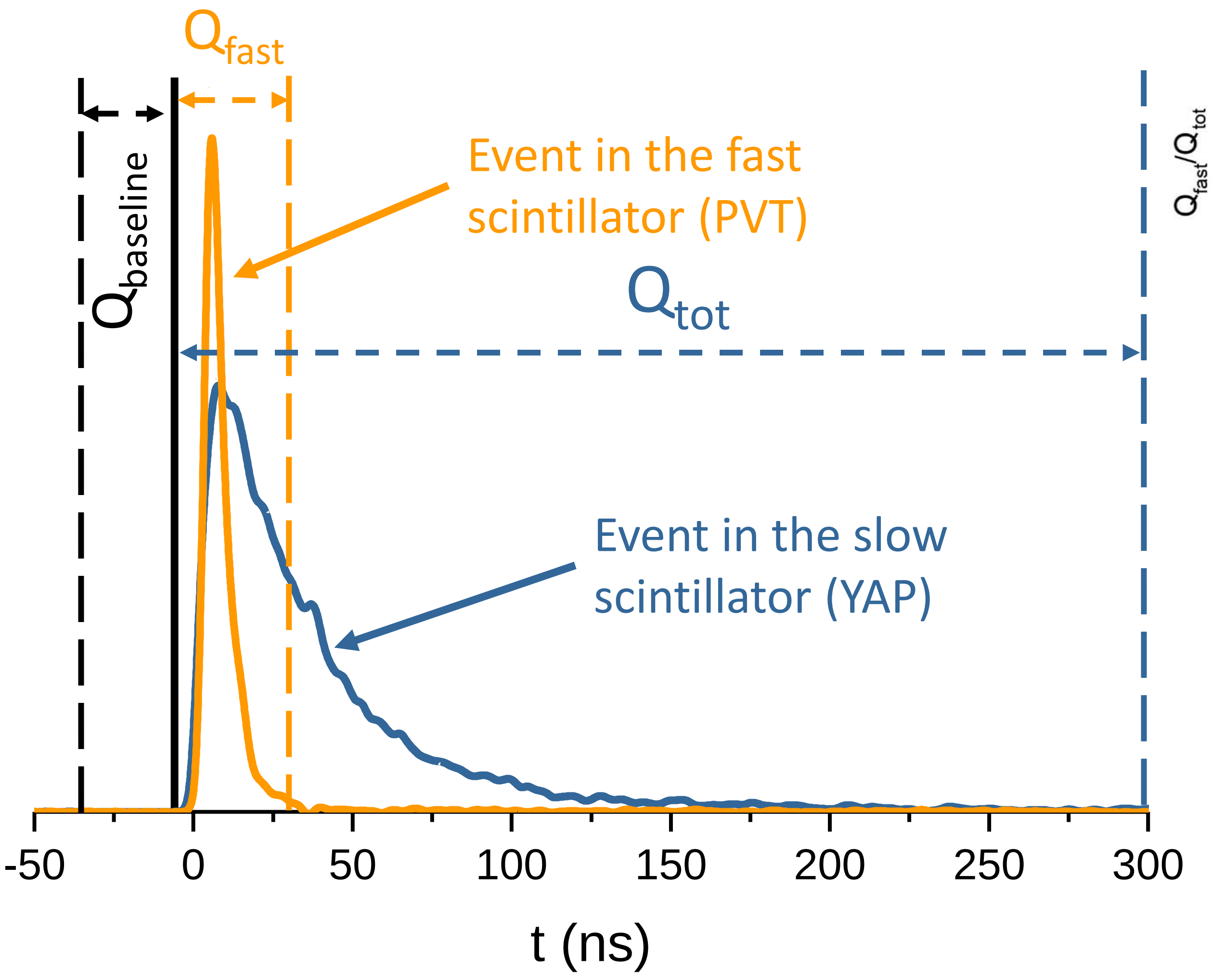
^{6}He implantation (For LIRAT experiment)

The main scintillator:
YAP: Crystal scintillator with τ = 25 ns

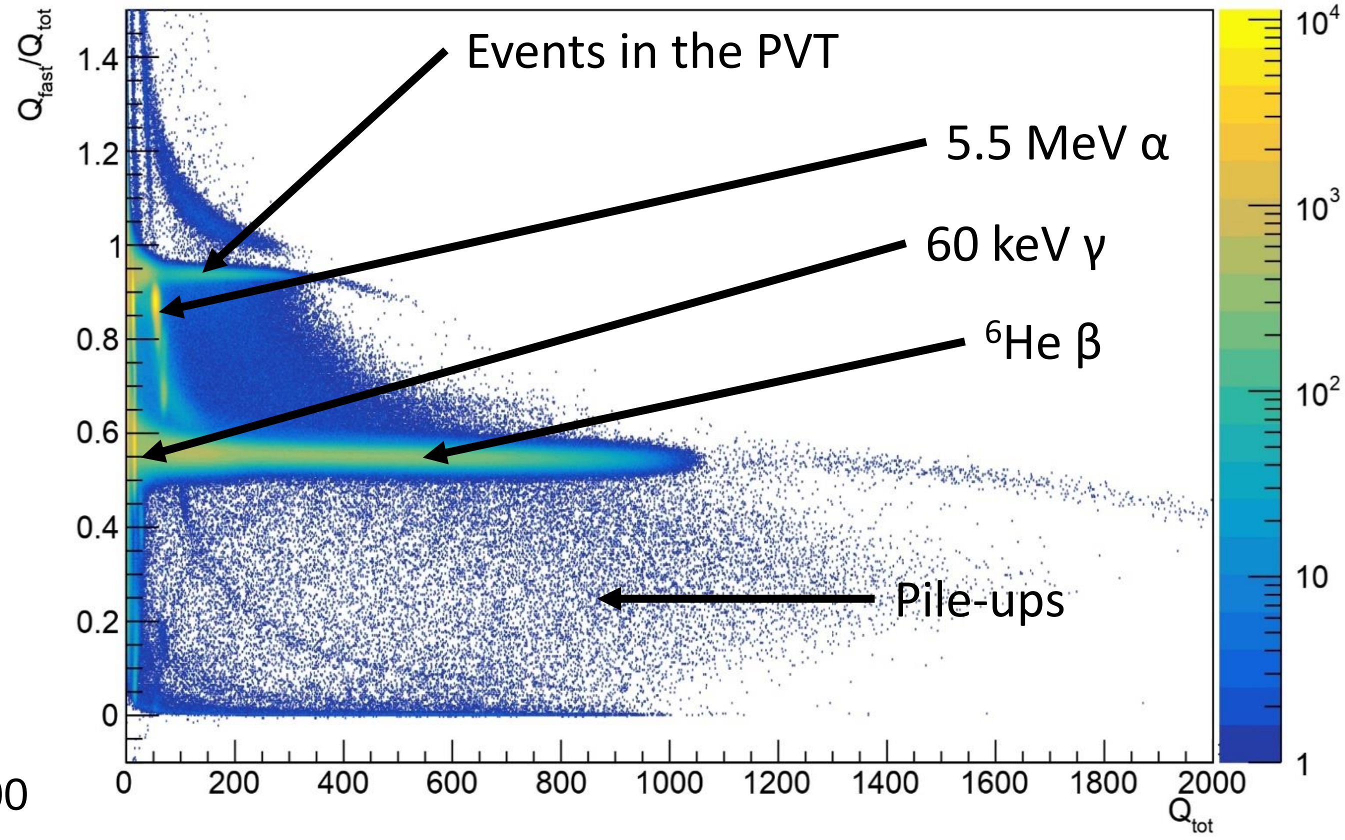
Properties:
- Linear energy response
- Good resolution ~5% @ 1 MeV
- Low Bremsstrahlung energy escape

Veto and PMT gain fluctuations:
PVT: Plastic scintillator with τ = 1.8 ns

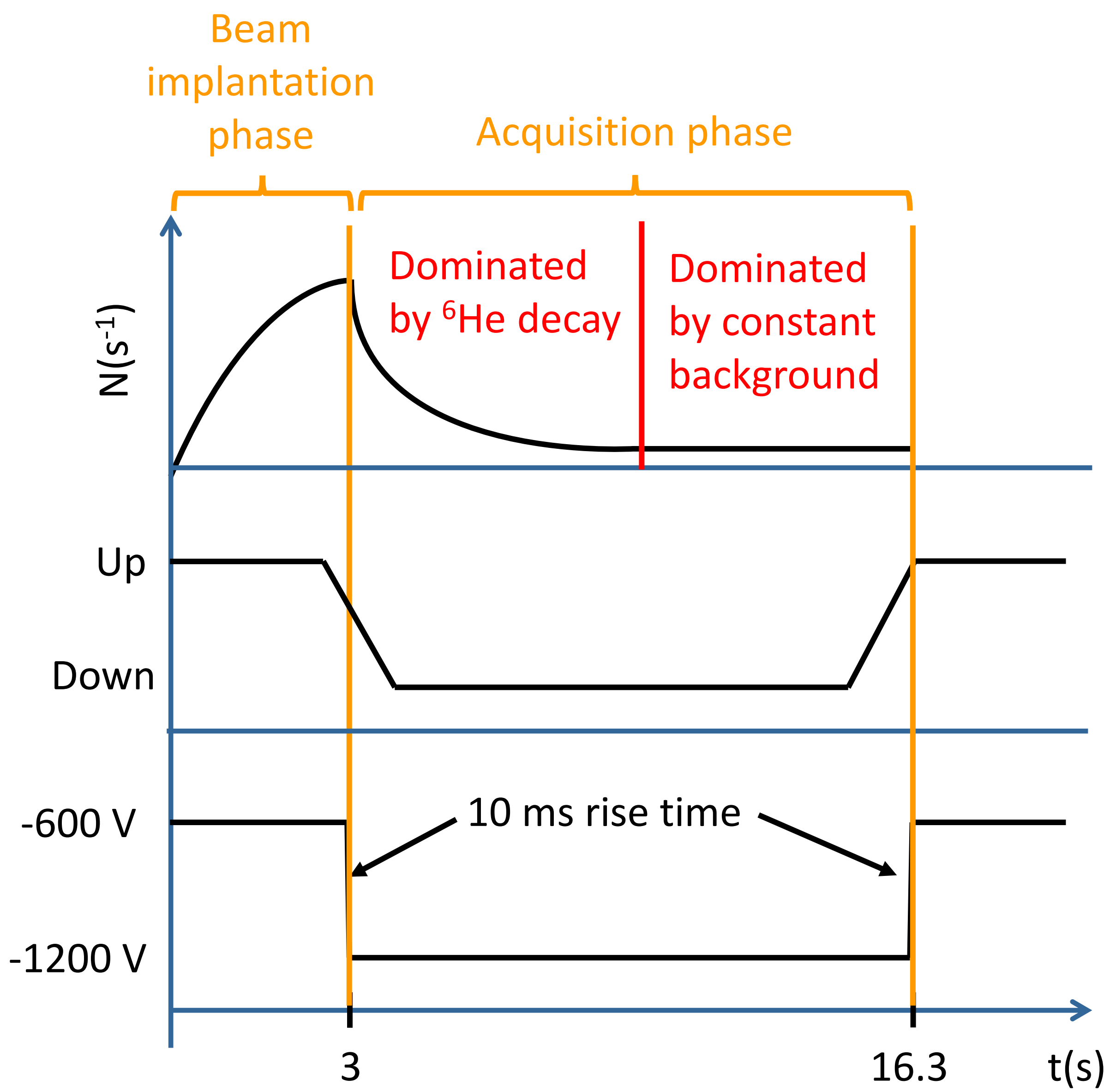
The phoswich detector



One hour run of LIRAT experiment



The measurement cycles



LIRAT experiment => Det2 alternating between two positions

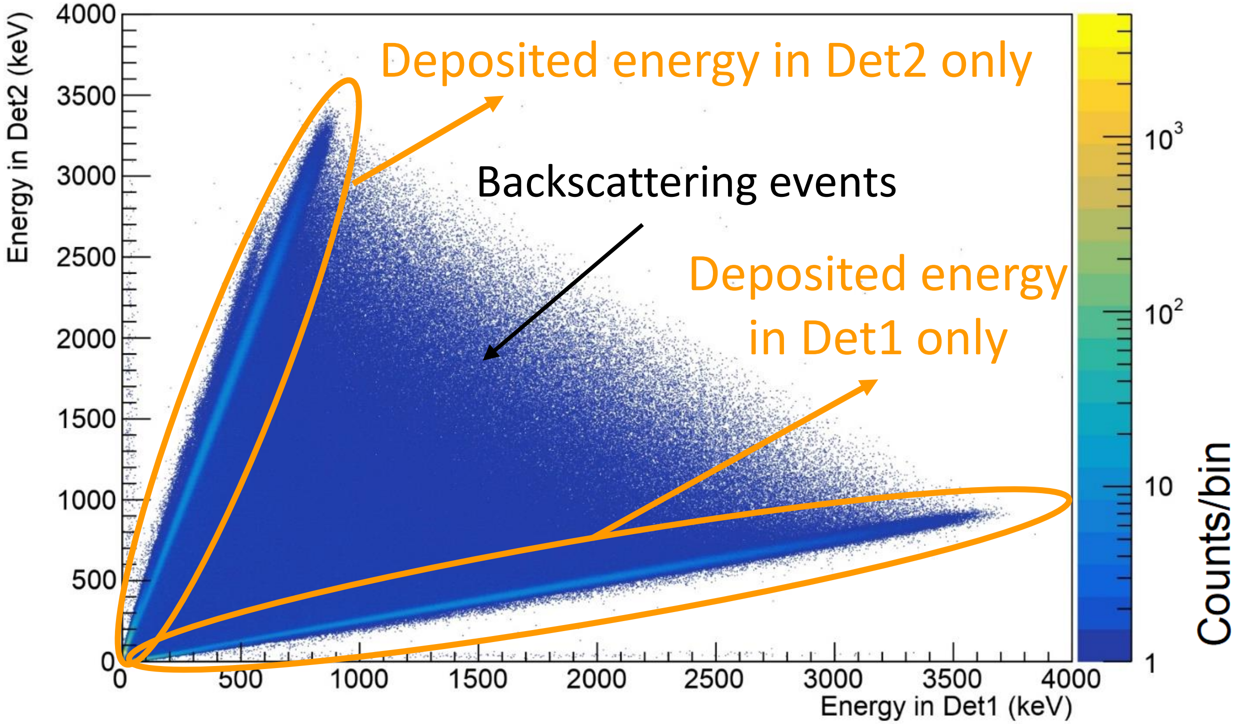
Measured ^{6}He decays : ~4.5 x 10^7

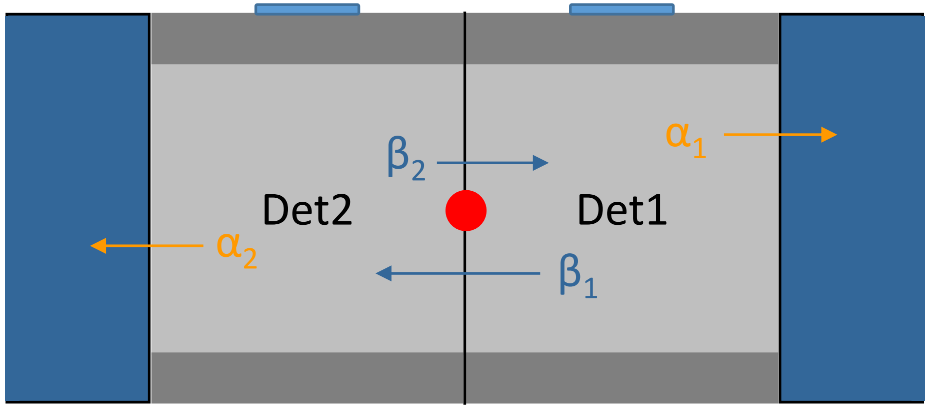
LISE experiment => PMT polarization voltage alternating between two values

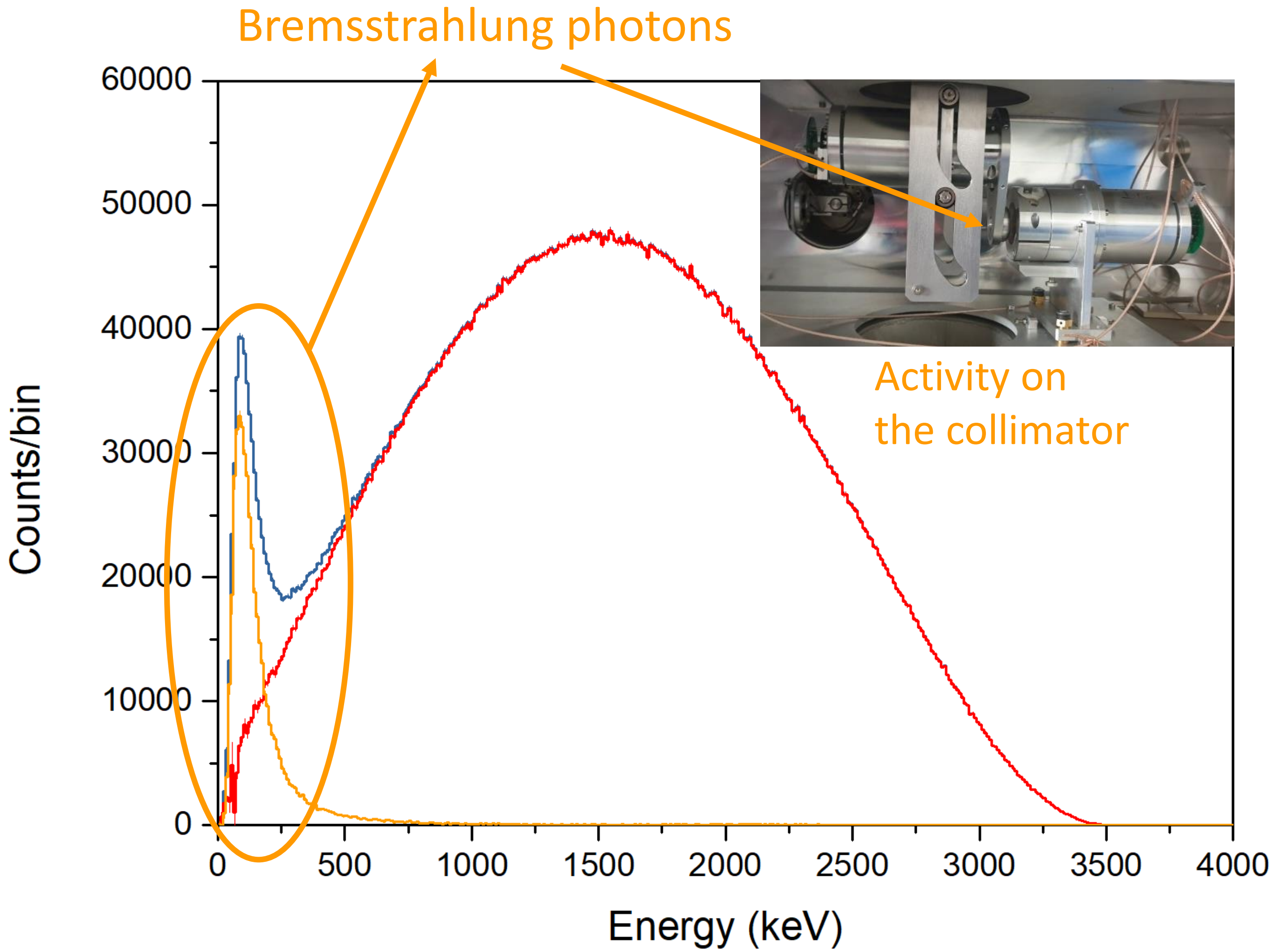
Measured ^{6}He decays : ~1 x 10^8

LIRAT experiment

Light cross-talk

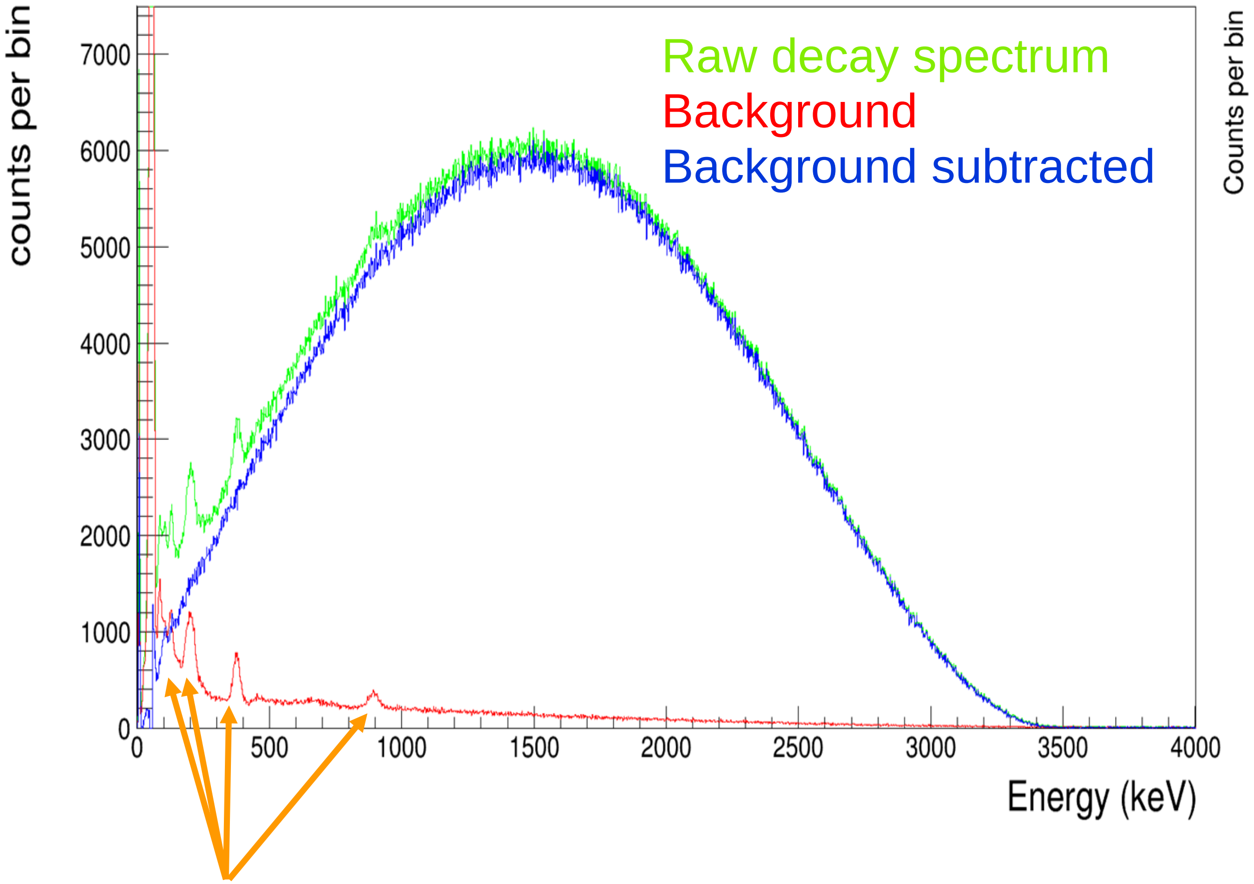


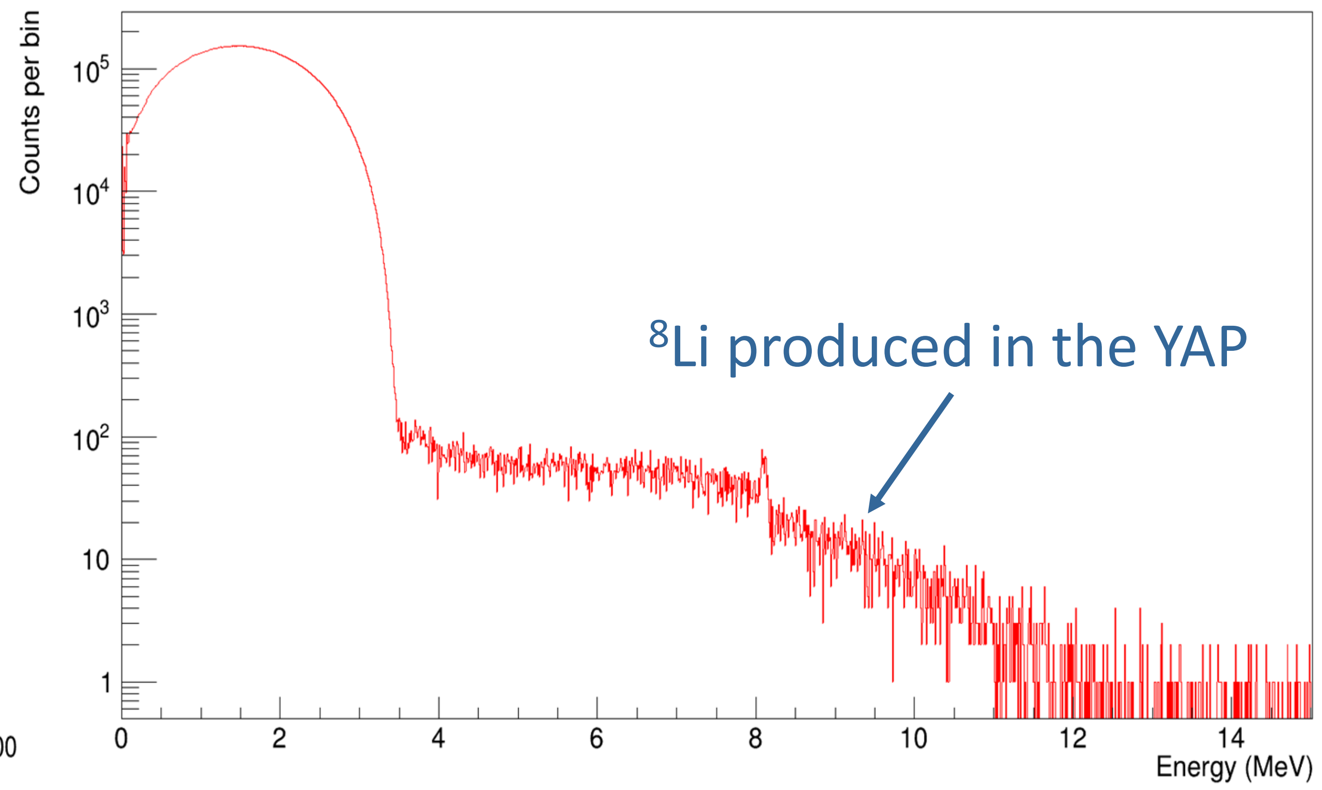




LISE experiment

Nuclear reactions inside the YAP volume





Plots by Romain Garreau

Unidentified but are completely subtracted with ambient background subtraction

Fit function

$$N(E) \propto F(Z,E)pE(E-E_0)^2\underline{(1+\eta)}\left(1+\frac{m_e}{E}b_{GT}\right) \longrightarrow$$ Energy distribution of electrons

Theoretical corrections

$$N(E) = F(Z,E)pE(E-E_0)^2\left[\varepsilon_0 + (\varepsilon_{-1}+b_{GT}m_e)\frac{1}{E} + \varepsilon_2 E + \varepsilon_3 E^2\right]$$

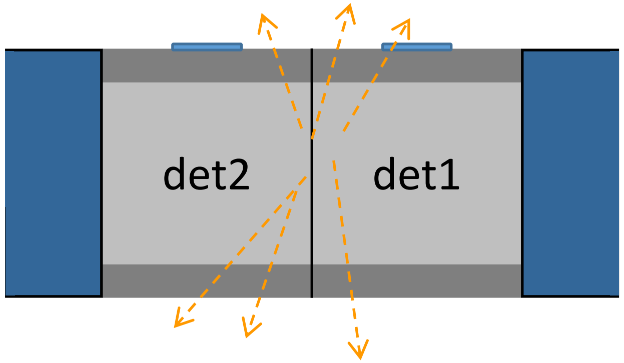
Radiative corrections, Weak magnetism, …

Not enough to fit the deposited energy spectrum!

Remaining components of the deposited energy distribution:

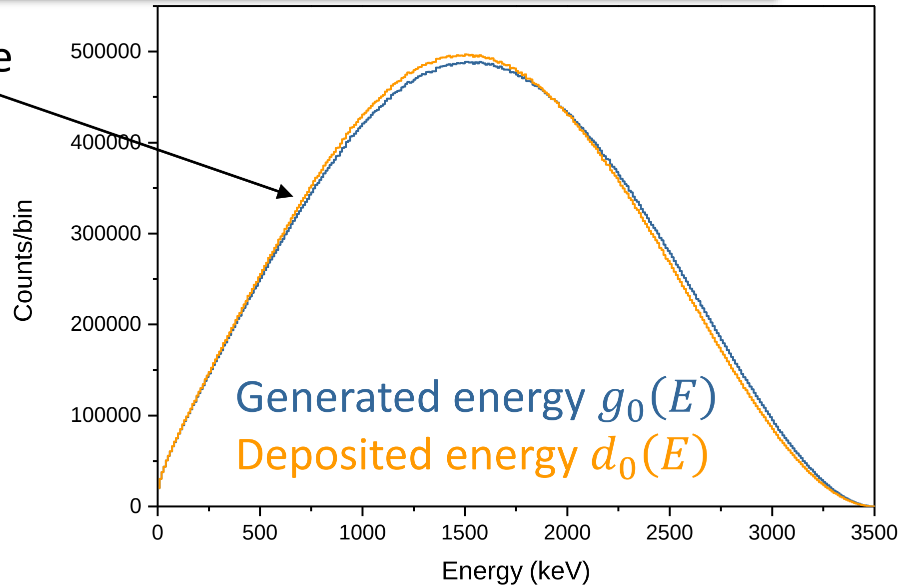
- Calibration parameter
- Detector’s resolution
- Bremsstrahlung escape (Geant4)

Bremsstrahlung energy escape



Distortion due to Bremsstrahlung escape

$$N(E_{dep}) = ?$$



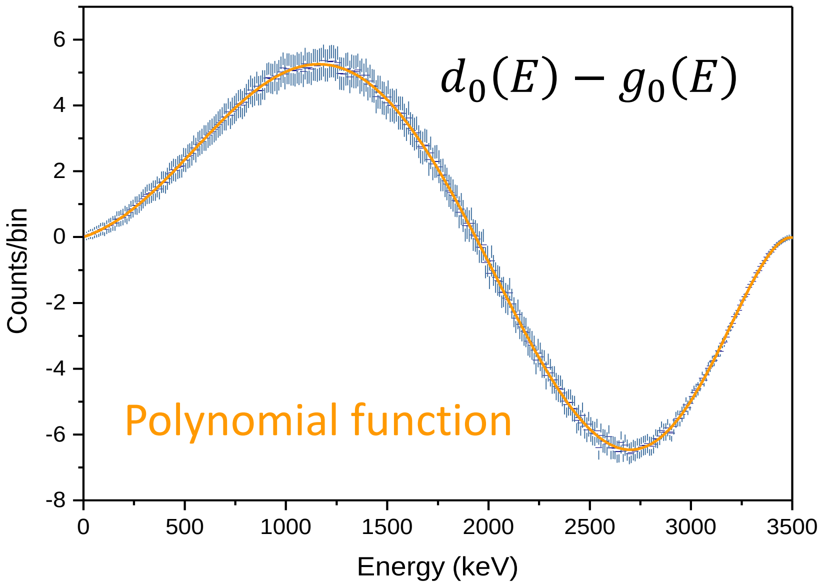
$$N(E) = F(Z,E)pE(E-E_0)^2\left[\varepsilon_0 + \varepsilon_{-1}\frac{1}{E} + \varepsilon_2 E + \varepsilon_3 E^2\right]$$

Need for analytical function accounting for the distortion for each term

$$g_i(E) = F(Z,E)p(E-E_0)^2 E^i \quad \xrightarrow{\text{GEANT4}} \quad d_i(E)$$

$$i = -1, 0,1,2$$

$$f_i(E) = norm \times \left(d_i(E) - g_i(E)\right)$$



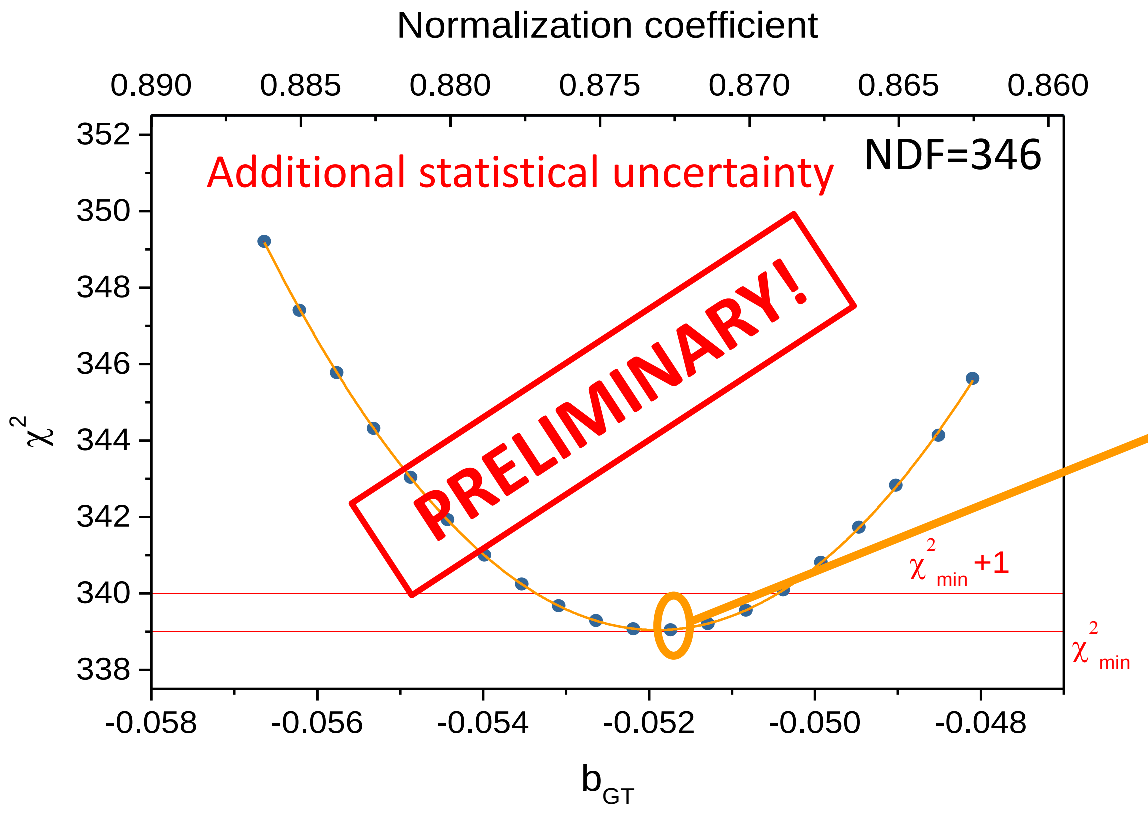
M. Kanafani et al, EPJ Web of Conferences, 2023

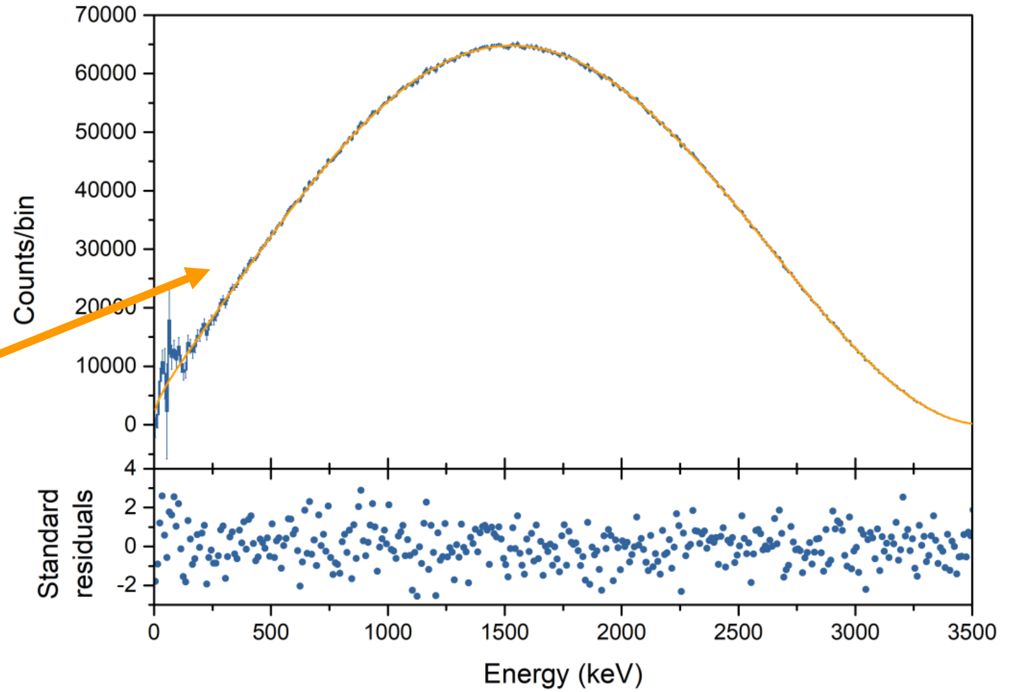
Analytical function accounting for the bremsstrahlung escape

Preliminary results with LIRAT experiment data

$$F(E) = N\left\{\sum_{i=-1}^{2} \varepsilon_i[g_i(cE) + f_i(cE)] + b_{GT} m_e[g_{-1}(cE) + f_{-1}(cE)]\right\} * Gaus\left(0, \alpha\sqrt{cE}\right)$$

Several normalization values for the subtraction of Bremsstrahlung peak





$$\Delta b_{GT\,stat} < 4 \times 10^{-4}$$

Summary and outlook

- Statistical goal achieved for the two experiments of phase I
- Bremsstrahlung BKG (LIRAT) and beam induced BKG (LISE, preliminary) seems handable
- Precise study of the detector linearity still ongoing (electron sources, gamma sources + light collection simulations)
- Several by products can be obtained from the data of the two experiments
  - most precise 6He half-life measurement (published in PRC 2022)
  - Benchmarking of G4 physics library (Bremsstrahlung and backscattering)
  - More precise characterization of the YAP response function

Thank you for your attention!

b-STILED: the precision goal

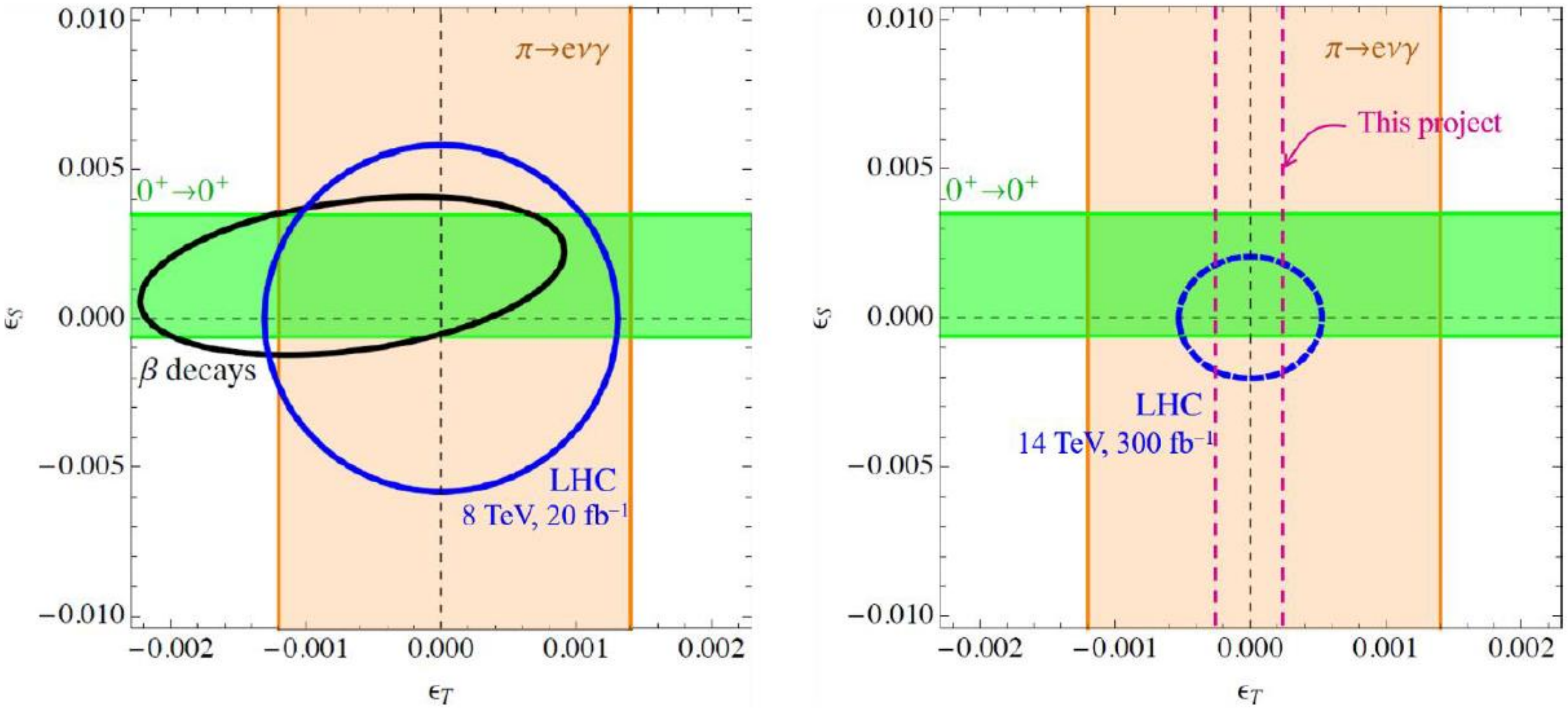
b-STILED : **b-S**earch for **T**ensor **I**nteractions in nuc**L**ear b**E**ta **D**ecay

b_{GT} for ^{6}He decay from a measurement of the β-spectrum

Precision goal:

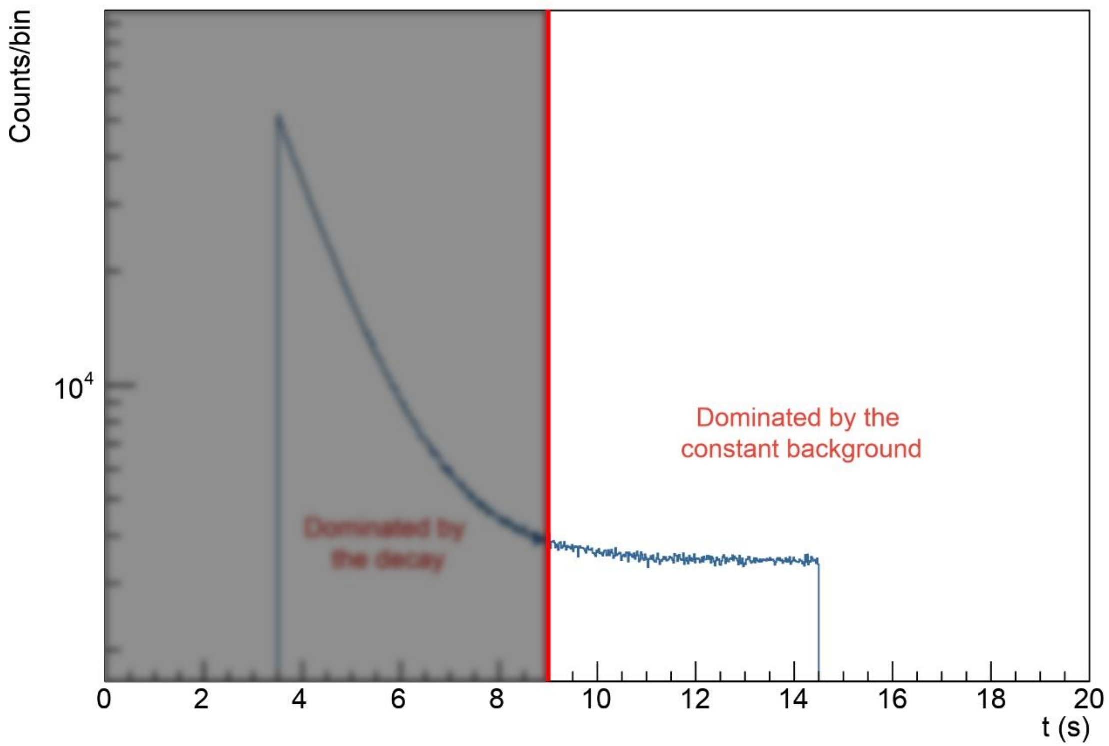
- Phase 1: $\Delta b_{GT} = 4 \times 10^{-3}$
- Phase 2: $\Delta b_{GT} = 1 \times 10^{-3}$

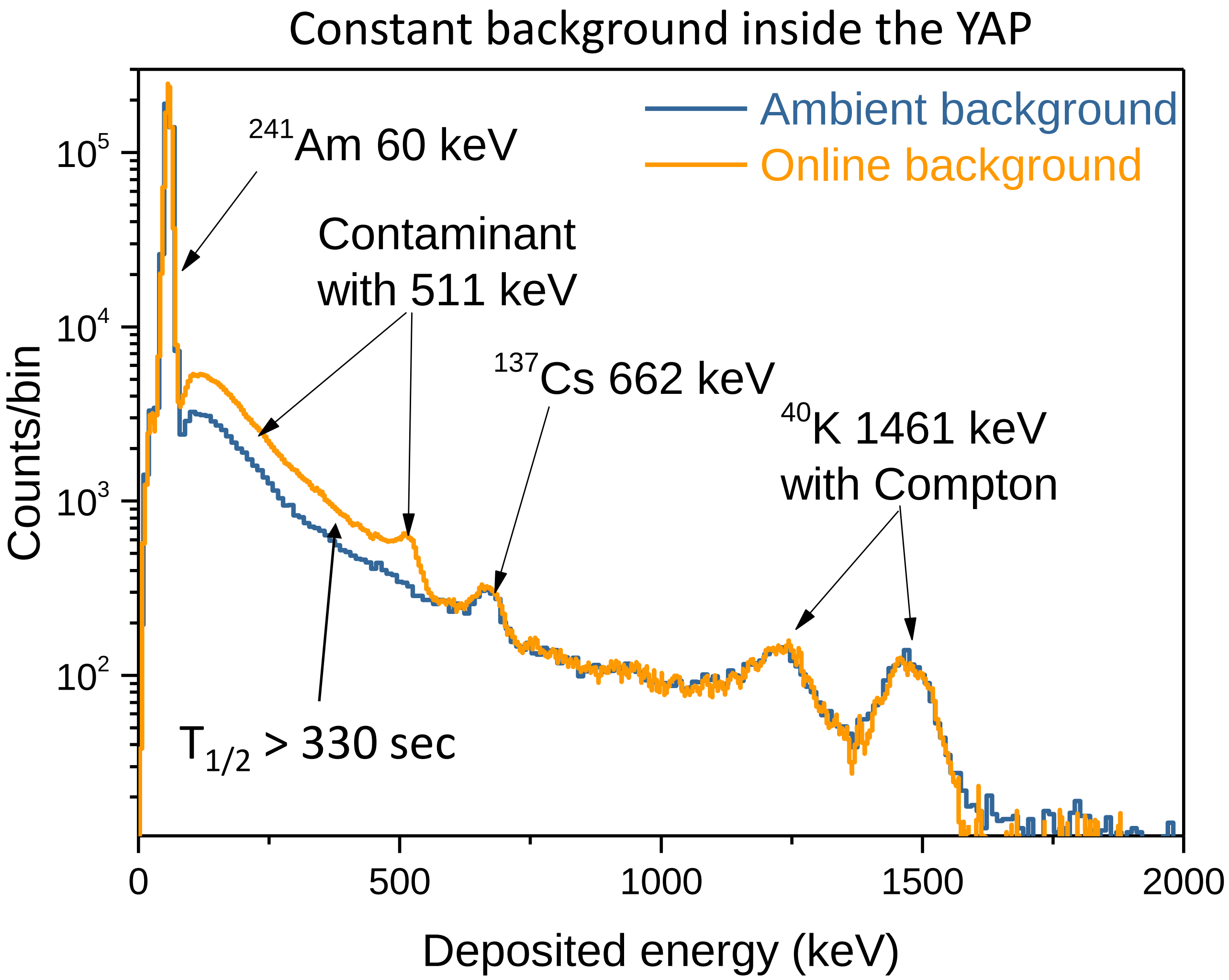
$$\varepsilon_T = \frac{b_{GT}}{6.2}$$



M. González-Alonso. et al, PRL, 2014.

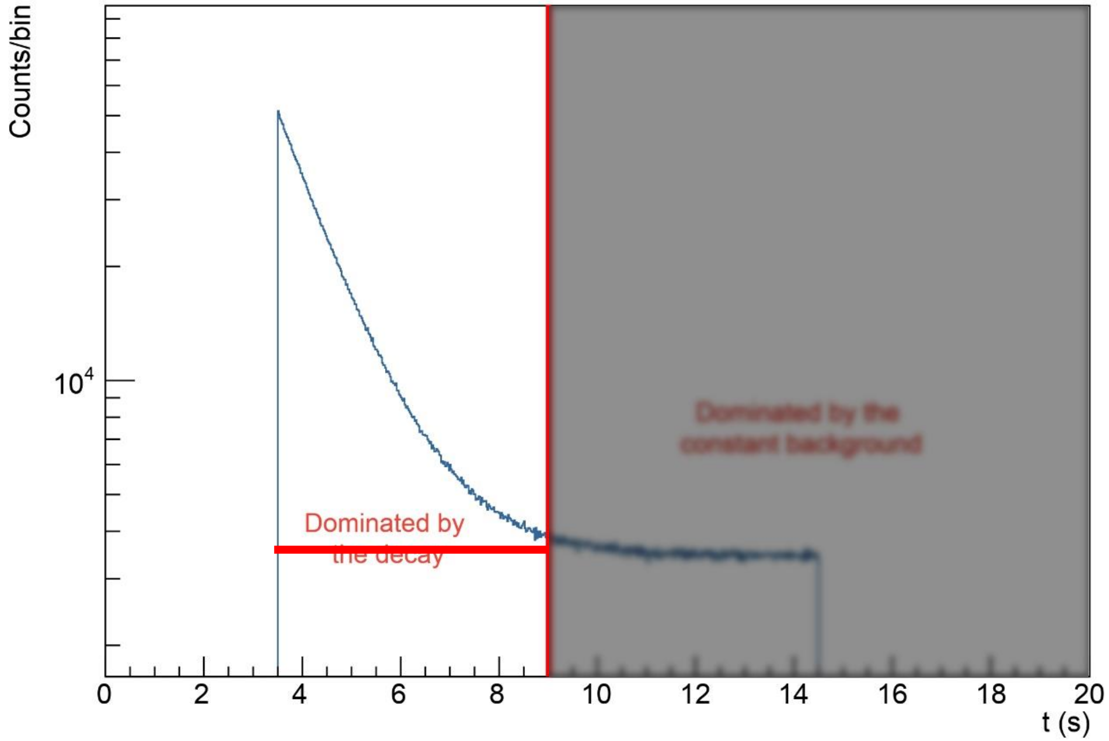
Background investigation



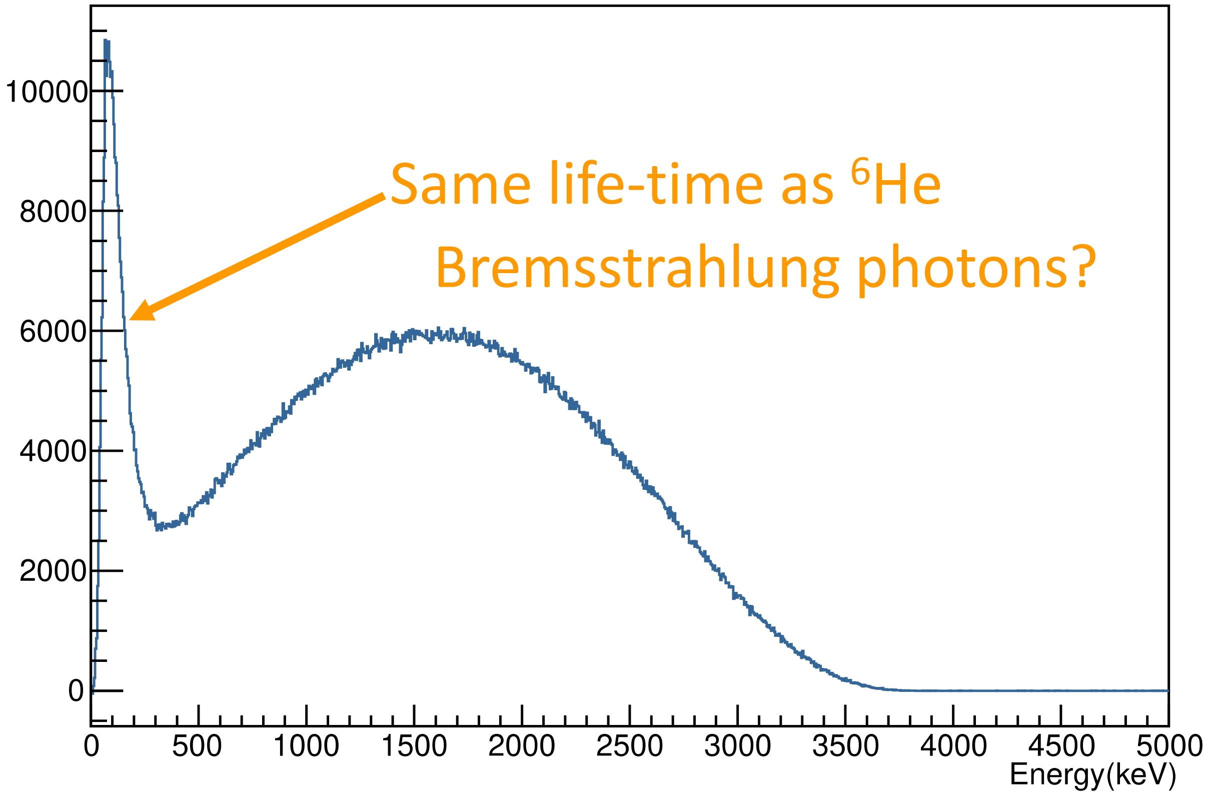


Background investigation

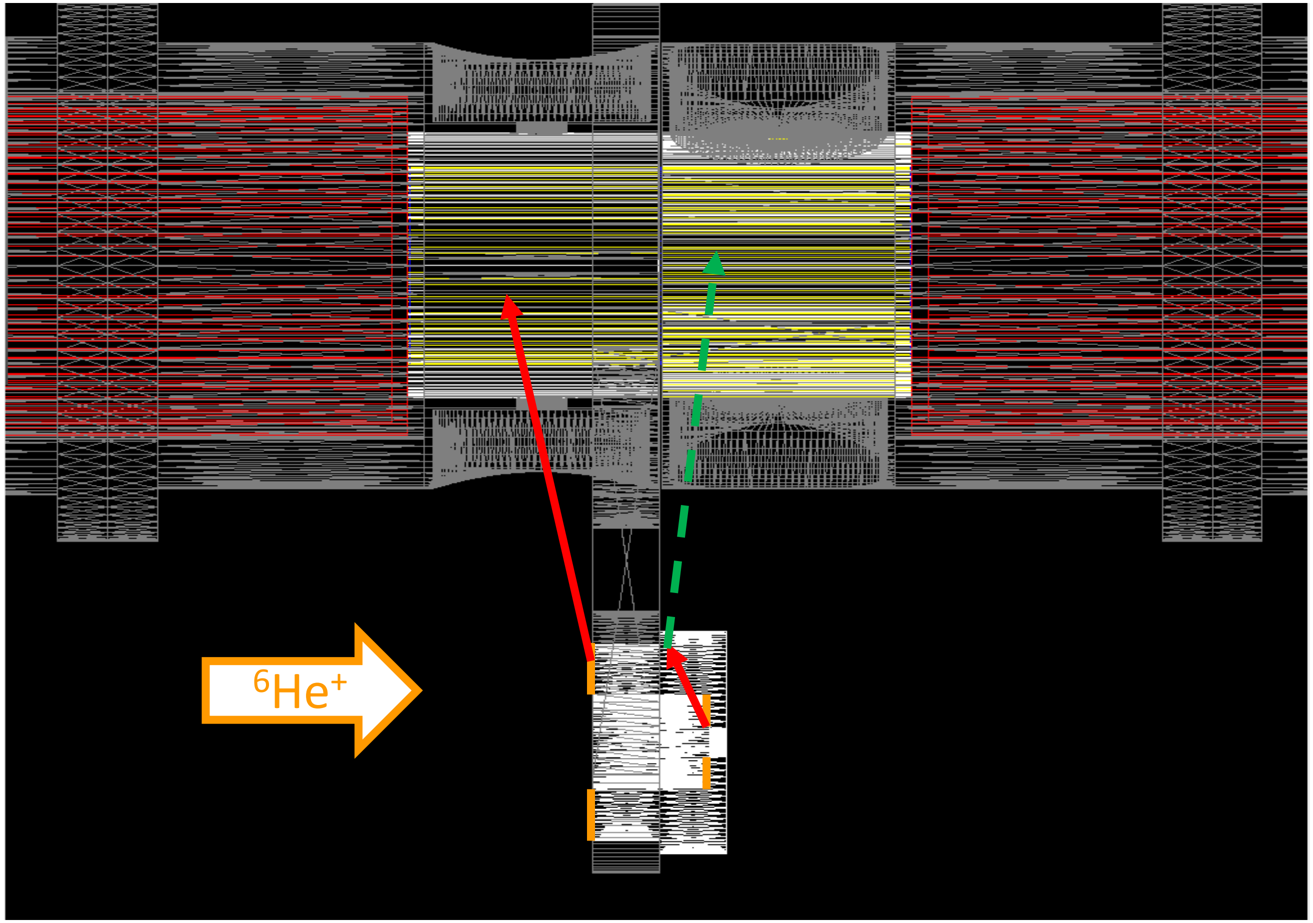
Following constant background subtraction

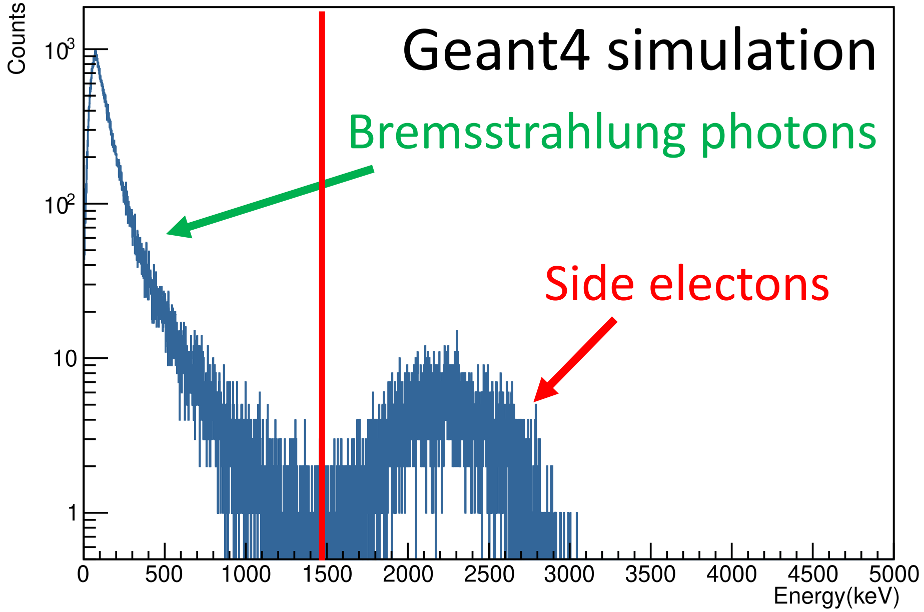


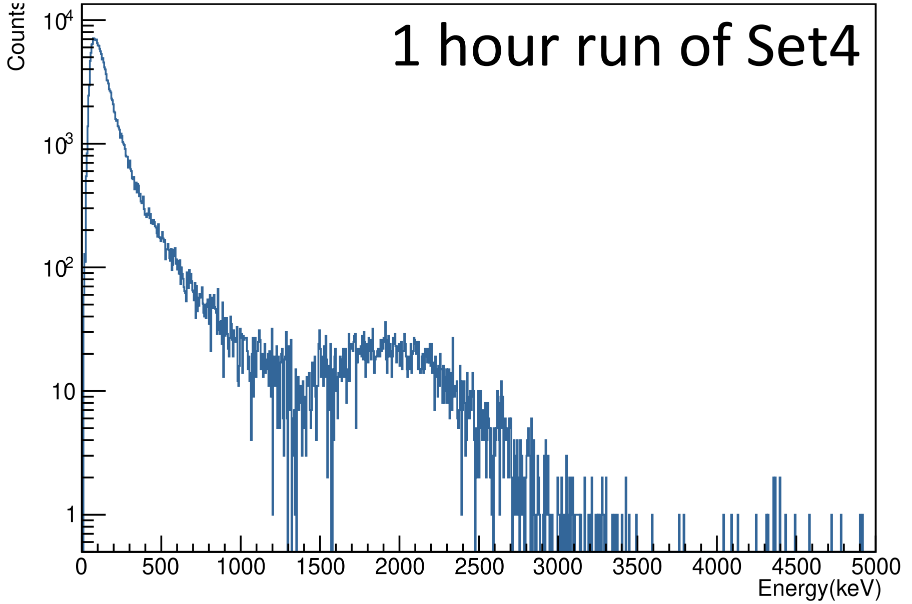
Experimental spectrum



Background investigation

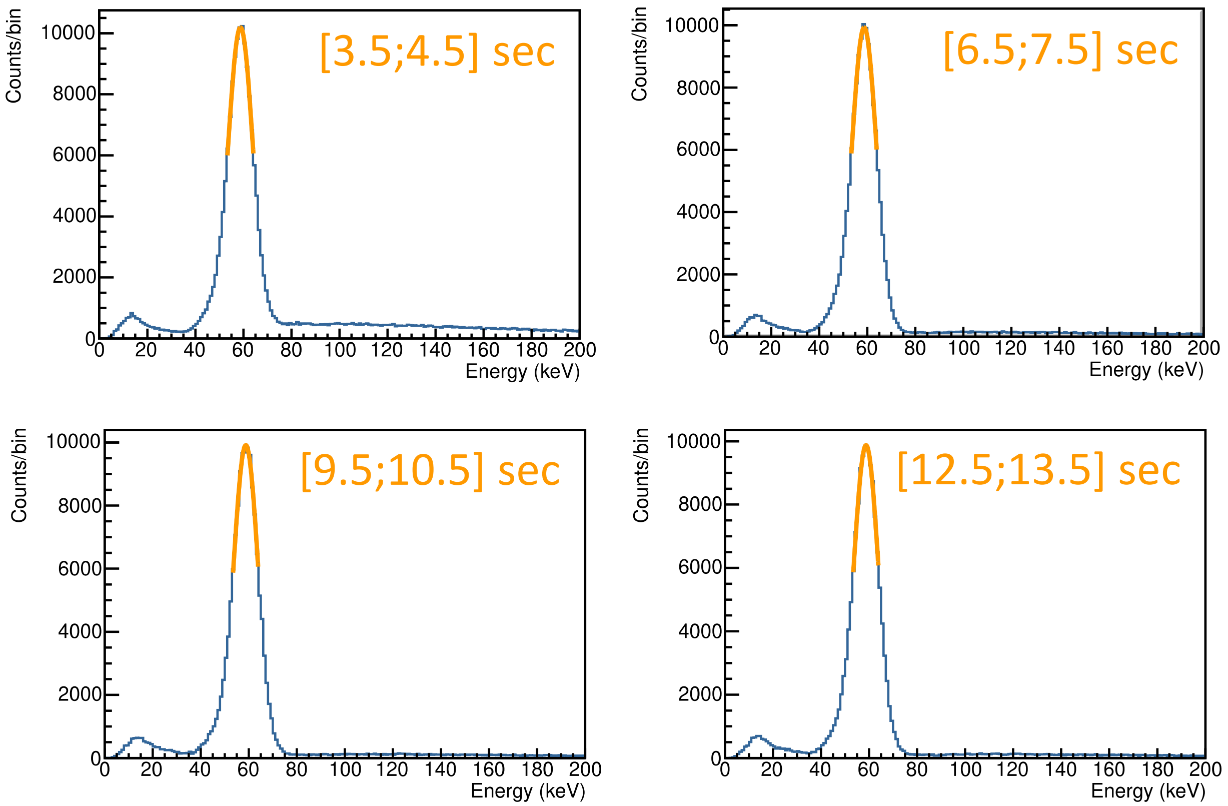


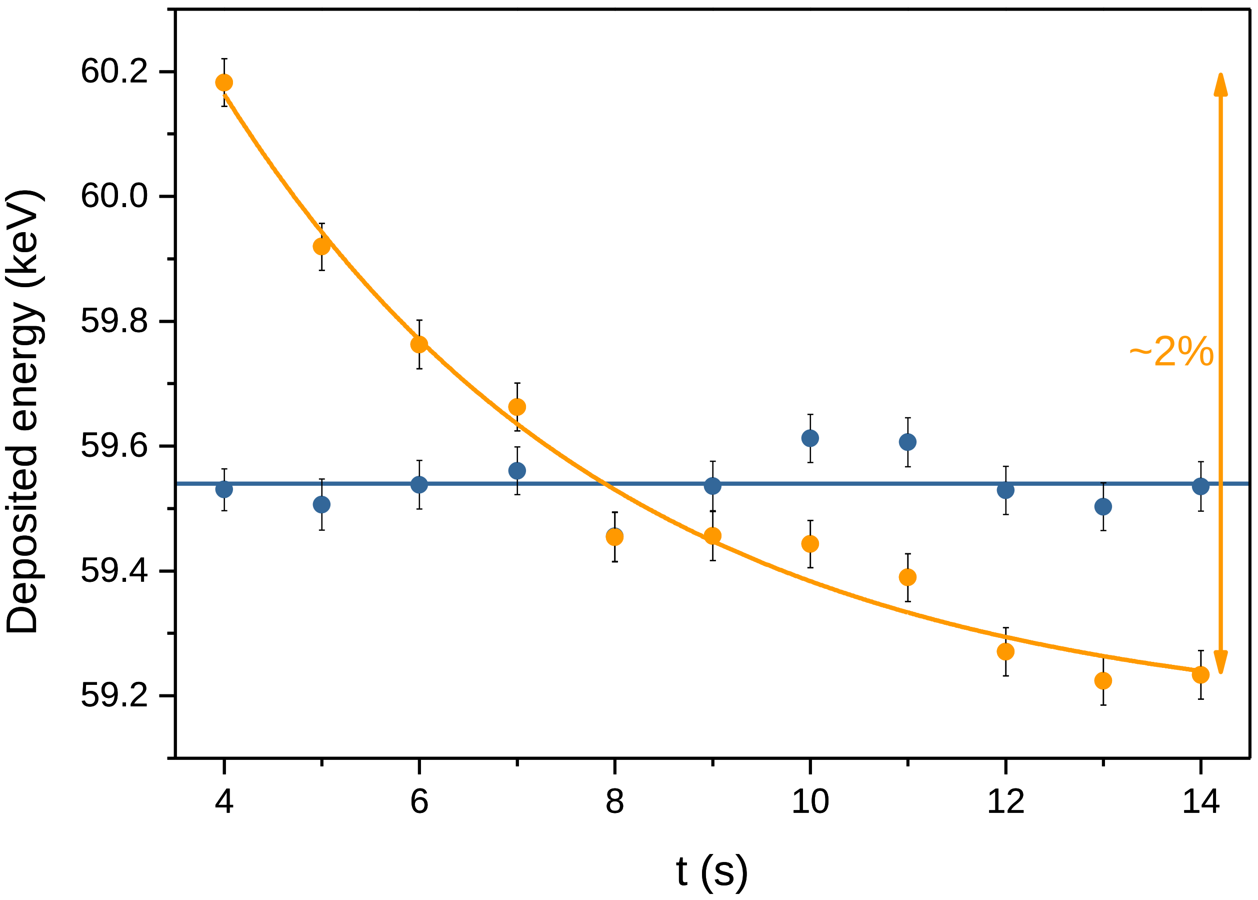




PMT gain and baseline corrections

Set by set energy calibration with the average 60 keV photopeak position





Correction model function of initial rate r_{0_i} and time in cycle t: $E_{60keV} = 59.54 \times \frac{Q_{tot} - C_{BL}(r_{0_i}, t)}{C_{Gain}(r_{0_i}, t) - C_{BL}(r_{0_i}, t)}$

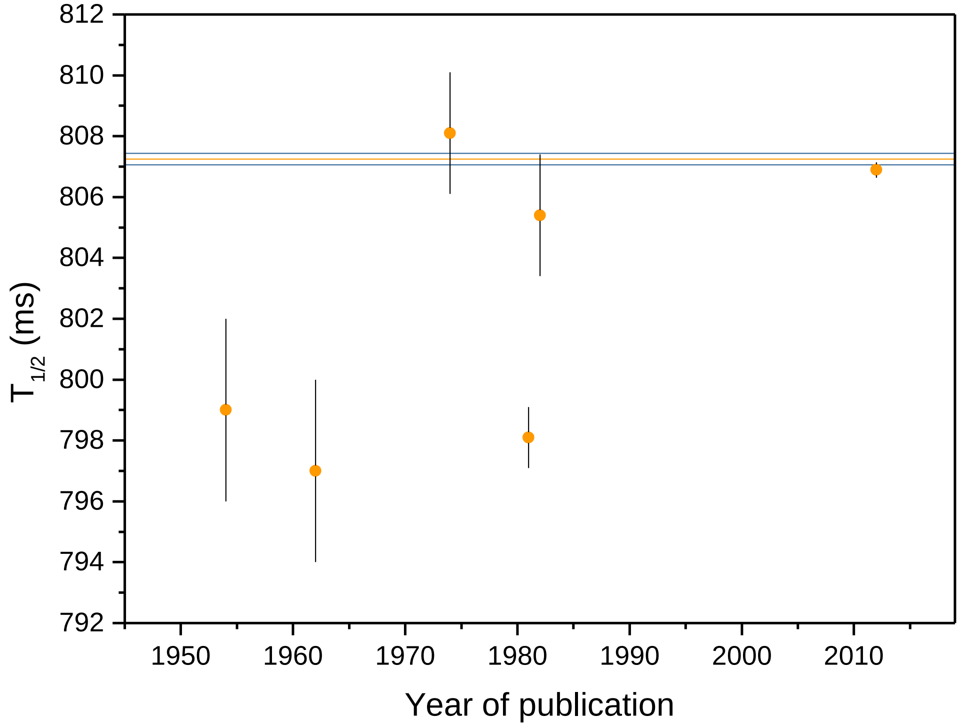
Half-life results

Corrections budget:

	Set1	Set2	Set3
$T_{1/2}$ [ms]	807.42(25)	807.16(26)	807.10(35)
Gain	0.75(7)	0.77(10)	0.78(6)
Baseline	0.09(3)	0.04(2)	0.05(9)
Pile-ups	0.10(1)	0.25(1)	0.11(1)
Binning	<0.01	<0.01	<0.01
Total correction	0.94(7)	1.06(11)	0.94(11)

$$T_{1/2} = 807.25 \pm 0.16_{stat} \pm 0.11_{syst}\ ms$$

Relative precision ~2×10^{-4}



A. Knecht et al, PRC, 2012.

M. Kanafani et al, PRC, 2022.

Our result is the most precise value, and is in agreement with the last and previously most accurate value.

Study of the systematic effects

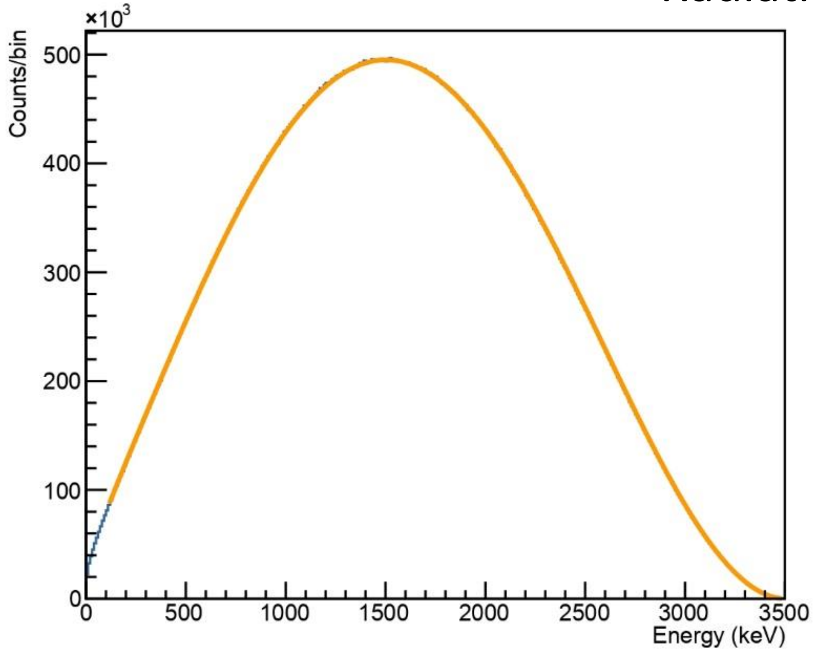
Bremsstrahlung escape model

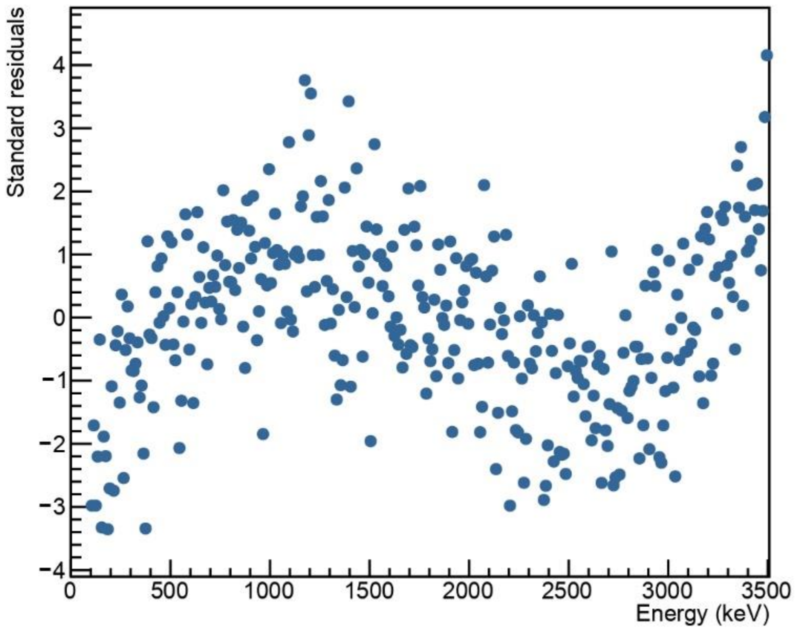
Physics constructor	b_{GT}	χ^2
G4EMStandardPhysics_option4	$(1.6 \pm 0.9) \times 10^{-3}$	348
G4EMLivermorePhysics	$(2.3 \pm 0.9) \times 10^{-3}$	332
G4EMPenelopePhysics	$(1.9 \pm 0.9) \times 10^{-3}$	342

NDF = 346

$\Delta b_{GT} = 7 \times 10^{-4}$

Radiative corrections



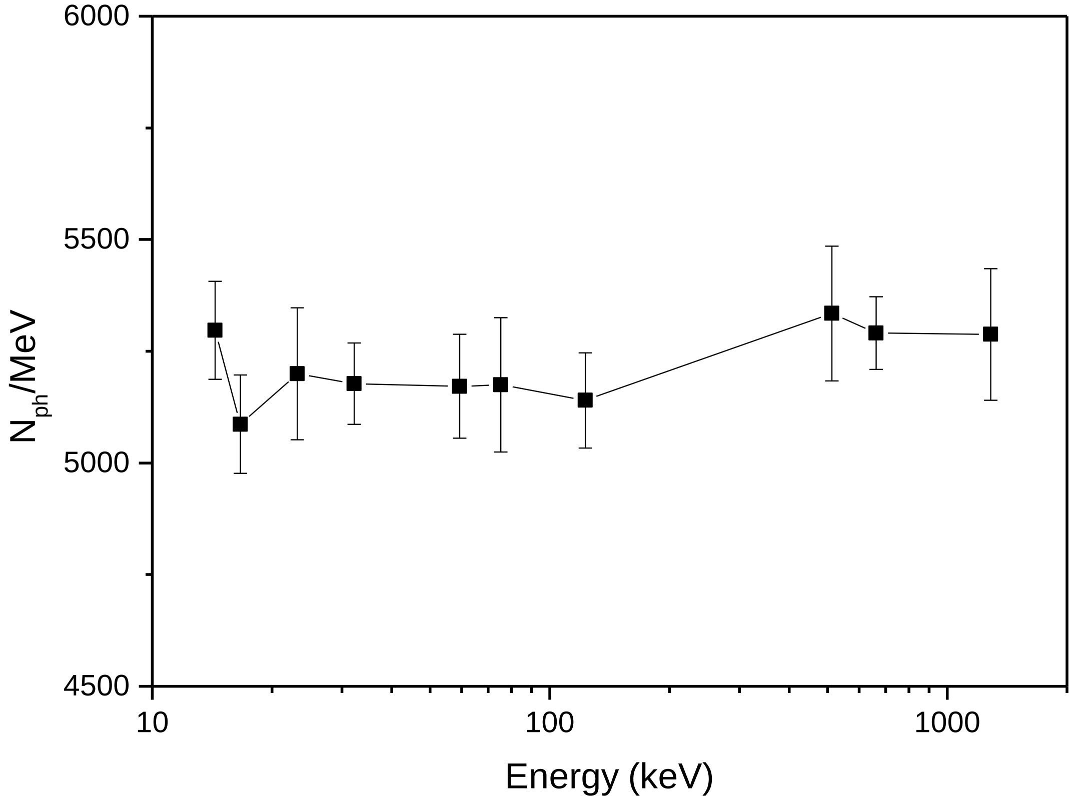


Deviated from the input value of b_{GT} by 3.7×10^{-2}

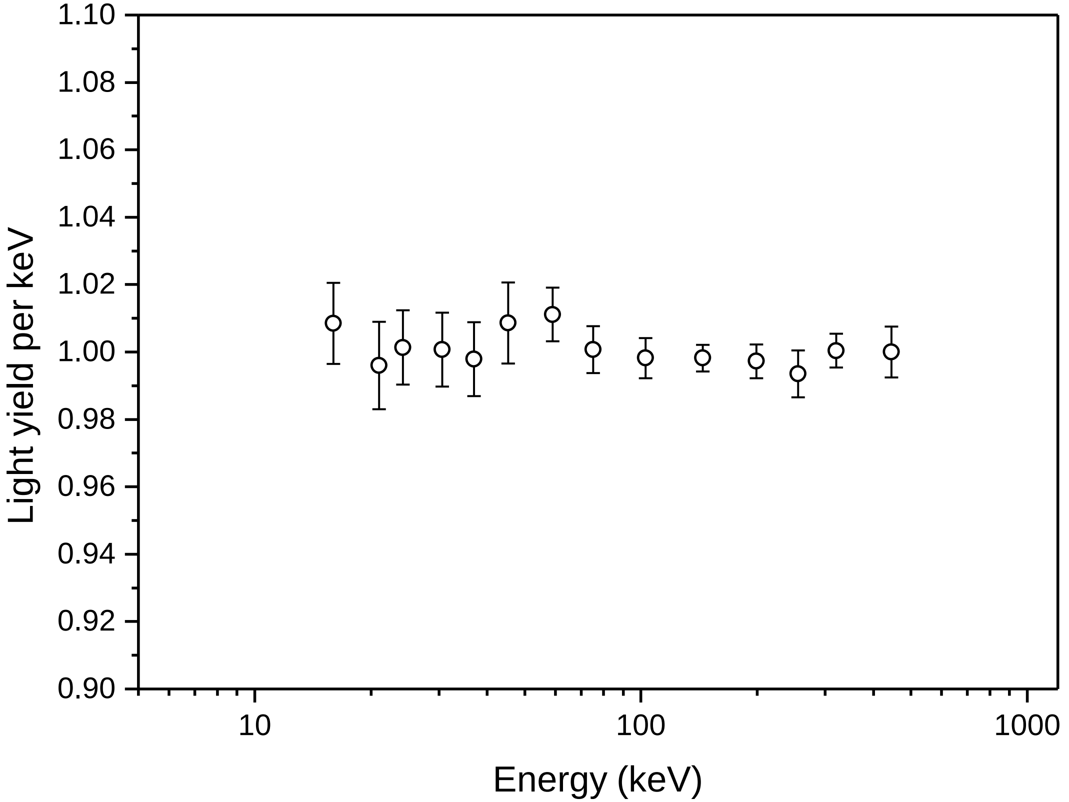
Radiative corrections are calculated with a precision in the order of 1%

$\Delta b_{GT} = 3.7 \times 10^{-4}$

YAP linearity



M. Kapusta et al, PRA, 1999



W. Mengesha et al, IEEE Transactions on Nuclear Science,1998

YAP linearity