bSTILED
b:Search for Tensor Interactions in nucLear bEta Decay

Journée EAP

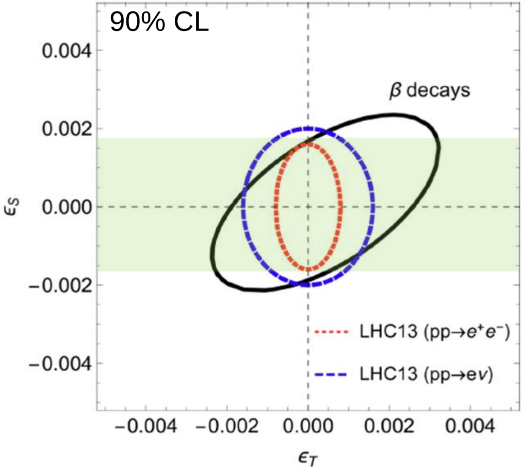
09 octobre 2025

Campus Gérard Mégie, Paris

Search for BSM Physics at TeV scale in beta decay

- b-STILED: b – Search for Tensor Interaction in nucLear bEta Decay
  - Measurement of the Fierz interference term ***b_{GT}*** in a **pure GT** transition (b_{GT} α ϵ_T)
  - Phase I (now): ***Δb_{GT}* = 4.10^{-3}** → present constraints from beta decay on ϵ_T
  - Phase II (future): ***Δb_{GT}* = 1.10^{-3}** → competitive with LHC

For left-handed neutrinos



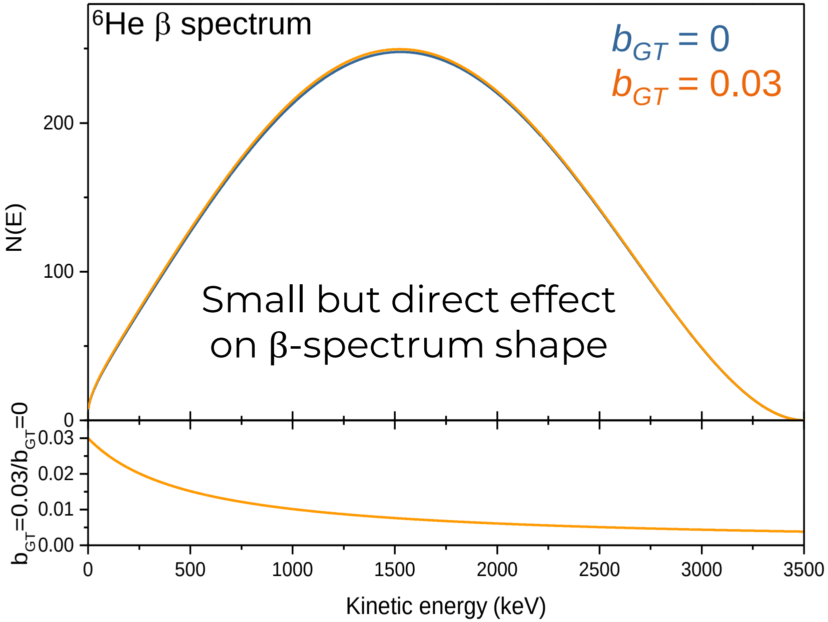
- Best constraints on ϵ_S
  Ft values in 0+→0+ transitions
  LHC (*pp* → *e$^+$e$^-$ + MET*)
- Best constraints on ϵ_T
  dominated by
  LHC (*pp* → *e$^+$e$^-$ + MET*)

A. Falkowski, M. Gonzáles-Alonso,
O. Naviliat-Cuncic, JHEP04 (2021)

Principle of the measurement

- Extract the Fierz term b_{GT} from the β-spectrum shape in the decay of ^{6}He

$$N(E) \propto \overbrace{\underbrace{F(Z,E)}_{\text{Fermi function}}\underbrace{(1+\eta)}_{\text{Theoretical corrections}}\underbrace{pE(E-E_0)^2}_{\text{Phase space}}}^{\text{SM}}\left(1+\overbrace{\frac{m_e}{E}b_{GT}}^{\text{BSM}}\right)$$



Small but direct effect on β-spectrum shape

- Why ^{6}He:
  - Pure GT transition
  - Precise theoretical corrections
  - $E_{\beta max}$=3.5MeV → high sensitivity
  - Convenient T1/2 of 0.8s
  - Copiously produced at GANIL

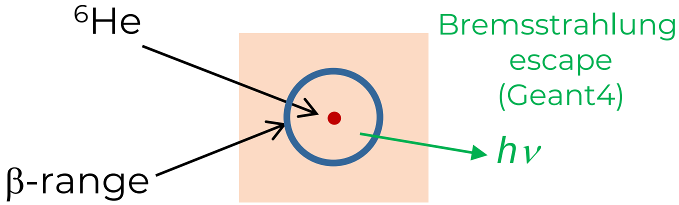
Project genesis and resources

- Collaborative effort between three French institutions (2020):
  - Main actor: detector design & characterization, DAQ, data analysis and systematic effects… (X. Fléchard, L. Hayen, E. Liénard, O. Naviliat-Cuncic & technical staff)
  - Production of ^{6}He beams at low- and high-energy with sufficient intensity and purity (J-Ch. Thomas & technical staff)
  - Production of calibration sources for the detectors calibration (X. Mougeot & S. Leblond)

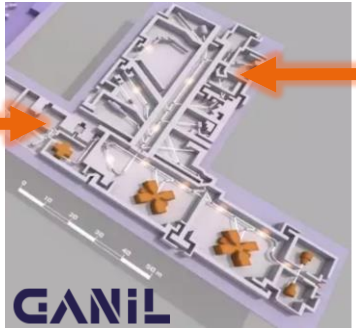
- Project submitted to ANR and GANIL PAC in 2020
  - Approved for funding by ANR (**290k€** for 4 years, extended to march 2026)
  - PhD of Mohamad Kanafani (2020-2023) funded by Region Normandie
  - PhD of Romain Garreau (2023-2026) funded by IN2P3
  - Postdoc of Anjli Rani (2024-2026) funded by ANR

Experimental Program at GANIL

- Phase I:
  - YAP with 4π detection solid angle (backscat.)
  - test two techniques (different systematic effects)



Low-energy implantation
on **LIRAT**/GANIL
25 keV ^{6}He

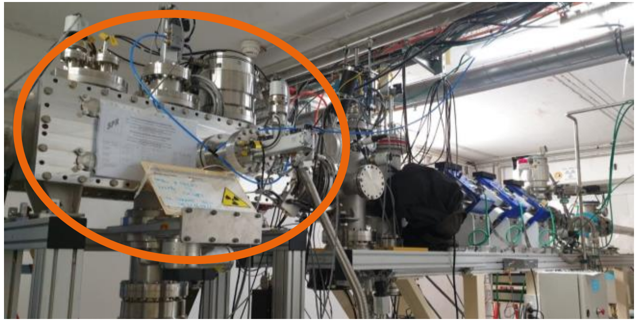


High-energy implantation
on **LISE**/GANIL
312 MeV ^{6}He

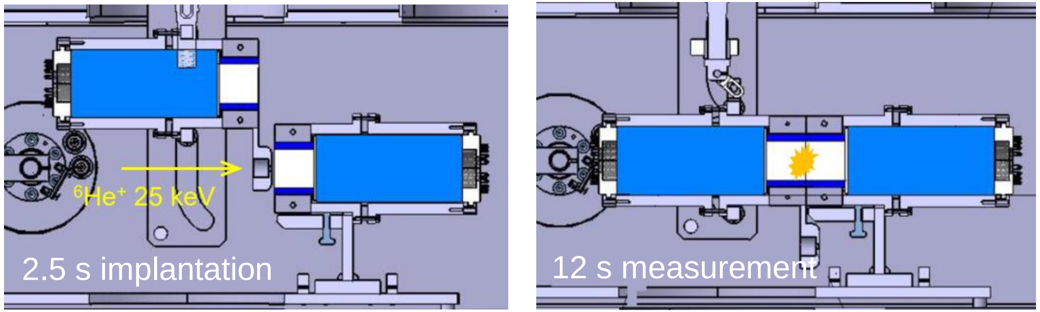
- Phase II: select most promising technique, improve it → $\Delta b_{GT} = 1.10^{-3}$

Low-energy experiment (2021)

LIRAT-GANIL line, 25 keV $^{6}He^{+}$

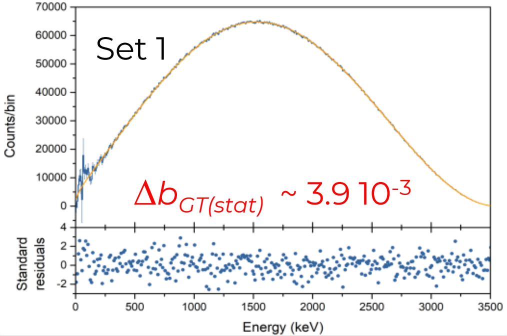


Detection setup



- 5 sets of measurements (for systematics) stat = 4.5×10^{7} → $\Delta b_{GT(stat)}$ ~ **2.8 10^{-3}**
  - 3 sets (1,2,3) with different cycle duration, intensity, PMT voltages
  - 2 sets (4,5) for beam-on background (collimator obturated)

Fit after calibration, background & light cross-talk correction



Discrepancies between Sets 1,2,3 …
(Δb_{GT} ~2.10^{-2} > 3 $\Delta b_{GT(stat)}$)

→ Suspect unstable on-line BKDG (Brem. Photons from collimator, difficult to deal with)

M. Kanafani, PhD Thesis, UniCaen (2023)

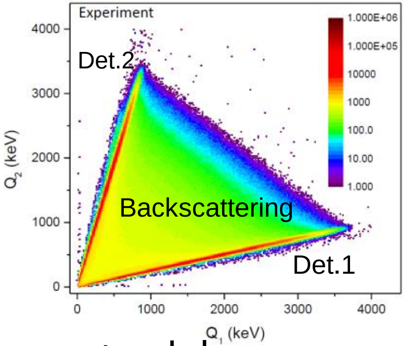
Complementary results

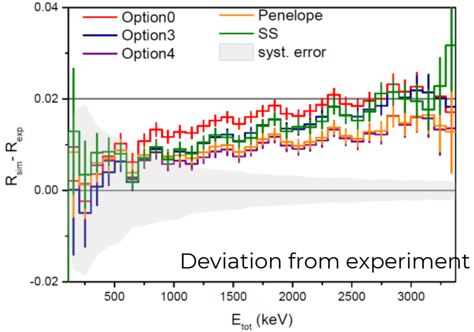
- Most precise half life measurement for ^{6}He

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

M. Kanafani et al, Phys.Rev. C 106 (2022) 045502

- Precise quantification of backscattering (0.2-3.2 MeV range)



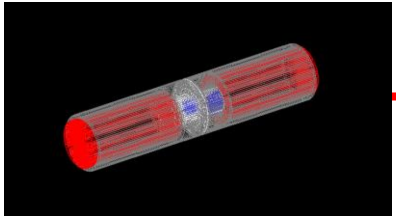


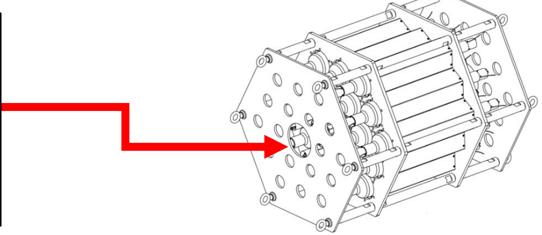
M. Kanafani et al, arXiv:2505.18406
Submitted to PRC (published soon)

- Bremsstrahlung escape characterization using MTAS detector @ FRIB

YAP + ^{90}Sr source

MTAS NaI ~100% efficiency

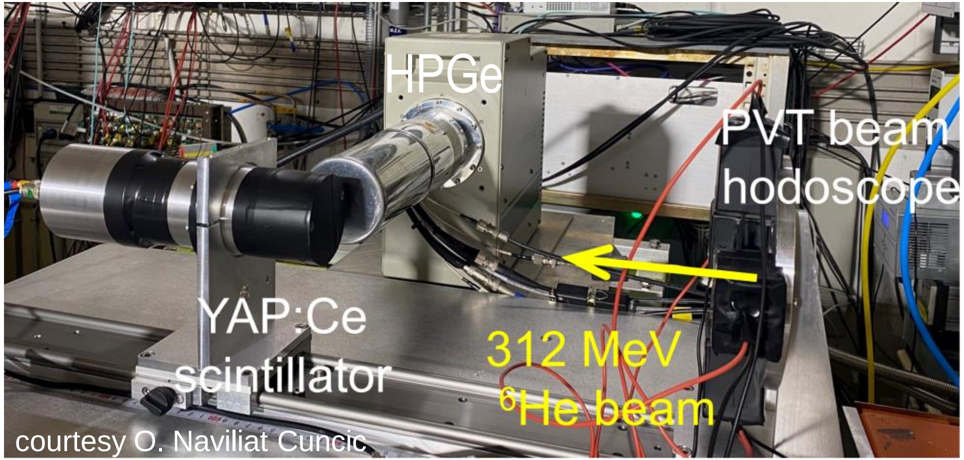




R. Garreau et al.,
Article in preparation

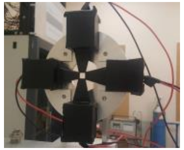
High-energy experiment (2023)

- Experiment at LISE - GANIL
  → 312 MeV ^{6}He nuclei implanted 9.5 mm deep into the YAP (max β-range 4mm)



courtesy O. Naviliat Cuncic

- Single YAP as main detector
  (PMT Voltage lowered during implantation
  → implantation energy)
- Thin PVT hodoscope
  (control implantation profile)
- HPGe
  (Beam induced contaminants)



- 4 sets of measurements (2 crystal sizes, 2 distances, 2 beam intensities)
  1.1×10^{8} good events → expected stat. uncertainty $\Delta b_{GT(stat)}$ < $1.\mathrm{x}10^{-3}$

High-energy experiment analysis

Stat

- High statistics (even enough for Phase II)

Sources of systematic error studies

- High beam purity → OK ($<10^{-5}$, PhD Romain Garreau)
- Excellent implantation profile → OK (<1% beyond 6mm from center)
- Induced contaminants → OK (5 beta emitters, $\Delta b_{syst} \sim 1.0\ 10^{-3}$, PhD Romain Garreau)
  Proceeding INPC2025
- Cerenkov radiation → OK (Postdoc Simon Vanlangendonck, IKS,)
  S. Vanlangendonck et al., in preparation

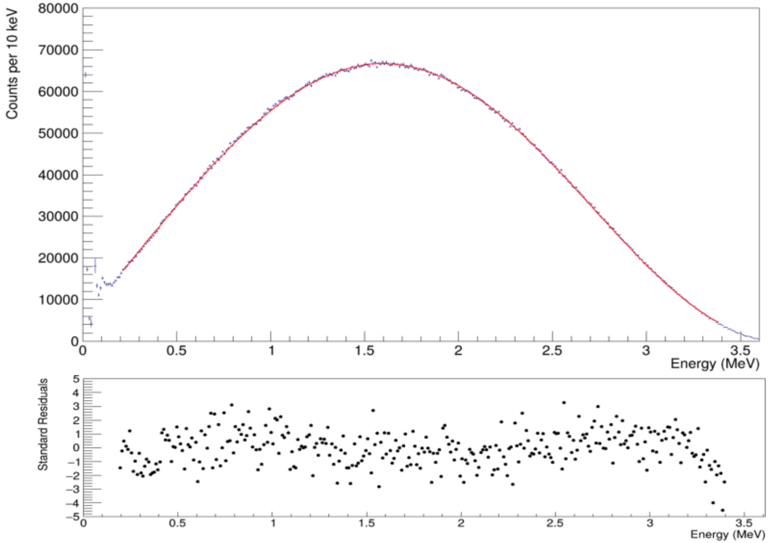
- Uncertainty from Bremsstrahlung escape not negligible ($\Delta b_{syst} \sim 5.0\ 10^{-3}$, MTAS experiment)
  R. Garreau et al., in preparation

- Uncertainty due to YAP non linearity dominant ($\Delta b_{syst} \sim 1.0\ 10^{-2}$, data from literature)
  → To be improved with dedicated offline measurement

High-energy experiment analysis

Ongoing work

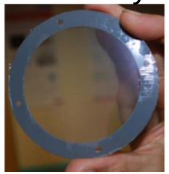
- PhD Romain Garreau : fit templates with G4 simulations, implement background subtraction and detector response function…



- Postdoc Anjali Rani : study detector response function with gamma sources + G4
  → slow progress, unclear results

- Prepare production of beta and conversion electron sources at LNHB (Bi-207, Cs-137, Cd-109, Ru-106/Rh-106, Sr-90/Y-90, In-114)

500 nm mylar



Prospects

Short term (2026)

- PhD Romain. G: progress on preliminary analysis including most of the systematic effects, result with $\Delta b_{GT} \sim 10^{-2}$ (eq. to $\Delta\tilde{a}_{\beta\nu} \sim 10^{-3}$ for sensitivity to NP)
- M2 student (+ Anjali R.) : study of the detector response function with LNHB sources
  - Measurements in January-February 2026
  - At least 6 months for analysis (need for G4 simulations)

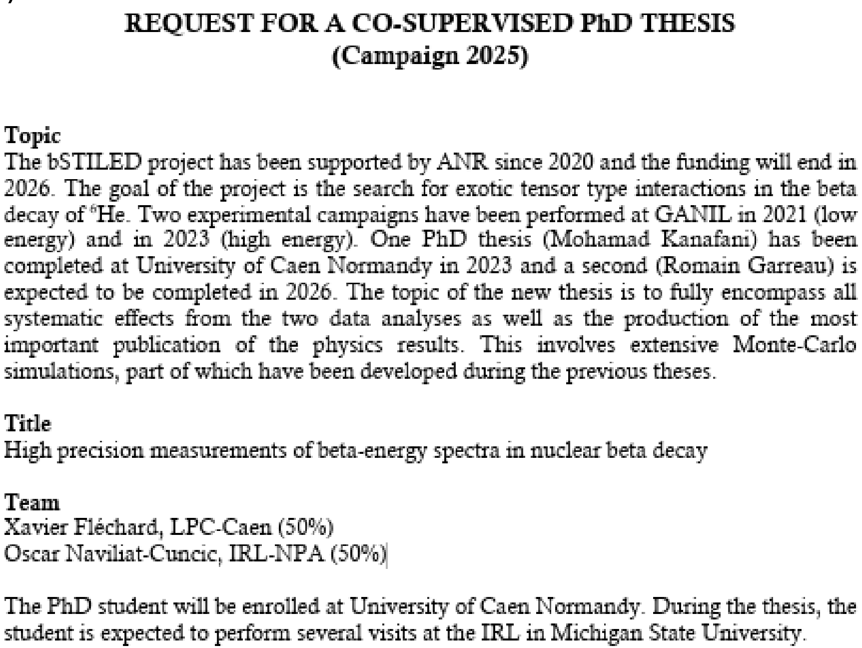
Longer term (2026-2029)

- New PhD starting in fall 2026 to finalize the analysis of both experiments
  - Include all systematics in high-energy experiment to publish a final result
  - Prospective for phase II (switch to semiconductor detectors? 1st measurement?)

Request for 2026

- Request project prolongation to ANR (6-9 months)
  → no need for equipment, travel in 2026
  (~35 k€ left on ANR budget)

- Request for a co-supervised PhD Thesis through IRL-NPA



REQUEST FOR A CO-SUPERVISED PhD THESIS
(Campaign 2025)

Topic
The bSTILED project has been supported by ANR since 2020 and the funding will end in 2026. The goal of the project is the search for exotic tensor type interactions in the beta decay of ^{6}He. Two experimental campaigns have been performed at GANIL in 2021 (low energy) and in 2023 (high energy). One PhD thesis (Mohamad Kanafani) has been completed at University of Caen Normandy in 2023 and a second (Romain Garreau) is expected to be completed in 2026. The topic of the new thesis is to fully encompass all systematic effects from the two data analyses as well as the production of the most important publication of the physics results. This involves extensive Monte-Carlo simulations, part of which have been developed during the previous theses.

Title
High precision measurements of beta-energy spectra in nuclear beta decay

Team
Xavier Fléchard, LPC-Caen (50%)
Oscar Naviliat-Cuncic, IRL-NPA (50%)

The PhD student will be enrolled at University of Caen Normandy. During the thesis, the student is expected to perform several visits at the IRL in Michigan State University.

Scientific production

- Publications
  - High precision measurement of the ^{6}He Half-life, M.Kanafani et al., PRC (2022)
  - Precision measurements in the beta decay of ^{6}He, M.Kanafani et al., EPJ Web of Conf (2023)
  - Backscattering Study of Electrons from 0,1 to 3,4 MeV, M.Kanafani et al., submitted to PRC
  - Study of Bremsstrahlung Radiation Escape for beta shape measurements, R. Garreau et al., in preparation
  - Nonlinearities in the response of scintillation detectors and their impact on the Fierz interference term extraction in beta spectrum shape measurements, S. Vanlangendonck et al., in preparation

- Conferences and workshops
  - Posters: SSP 2022, PSI 2022, ARIS 2023, EJC 2025, EUNPC2025
  - Talks: Colloque GANIL 2021, JRJC 2021, LISE Workshop 2022, ISOL-France 2022, INPC 2022, PhyNuBE 2023, Colloque GANIL 2023, Workshop LISE 2024, JRJC 2024, ISOL-France 2025, INPC 2025, ESNT Workshop 2025, EUNPC 2025, GDR INF 2025

Collaboration

lpc Caen

D. Etasse
X. Fléchard
R. Garreau
L. Hayen
M. Kanafani
F. Lebourgeois
E. Liénard
J. Lory
O. Naviliat-Cuncic
J. Perronnel
A. Rani
Ch. Vandamme

Laboratoire National LNHB Henri Becquerel

X. Mougeot
S. Leblond
G. Craveiro

GANIL

J.C. Thomas
V. Morel
F. Marie-Saillenfest

MICHIGAN STATE UNIVERSITY

T.E. Haugen
O. Naviliat-Cuncic

IRL NPA CNRS - MSU

O. Naviliat-Cuncic

KU LEUVEN

S. Vanlangendonck

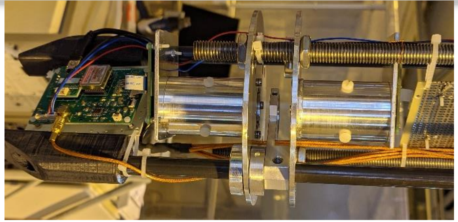
Backup slides

Techniques to avoid or limit backscattering effect

- INESS @ WISArD (see next talk by M. Versteegen)

  - Confine beta particles between two detectors with high B-field

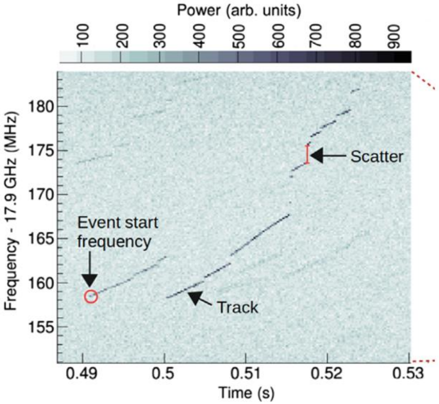
  S. Vanlangendonck, PhD, KU Leuven (2023)
  (unpublished)



- CRES @ UW

  - Measure the cyclotron frequency of radiating β particles in a B-field

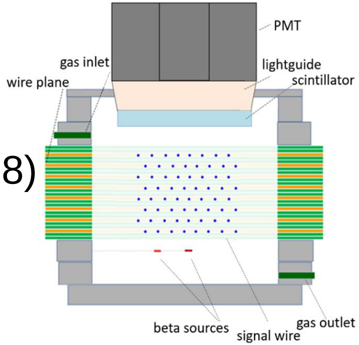
  Byron W. et al. PRL 131 (2023)



- miniBETA

  - Use a scintillator combined to a multi-wire drift chamber for tracking ($\Delta b = 0.068$)

  L. De Keukeleere et al.
  ArXiv:2404.03140



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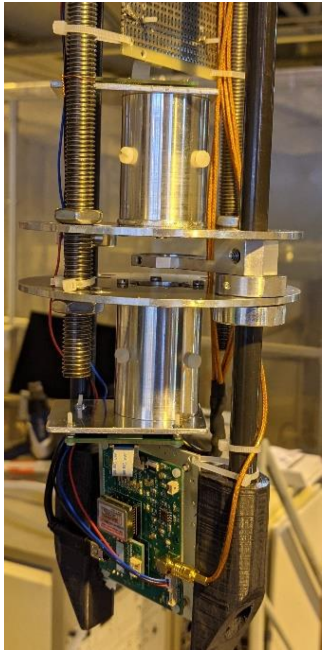

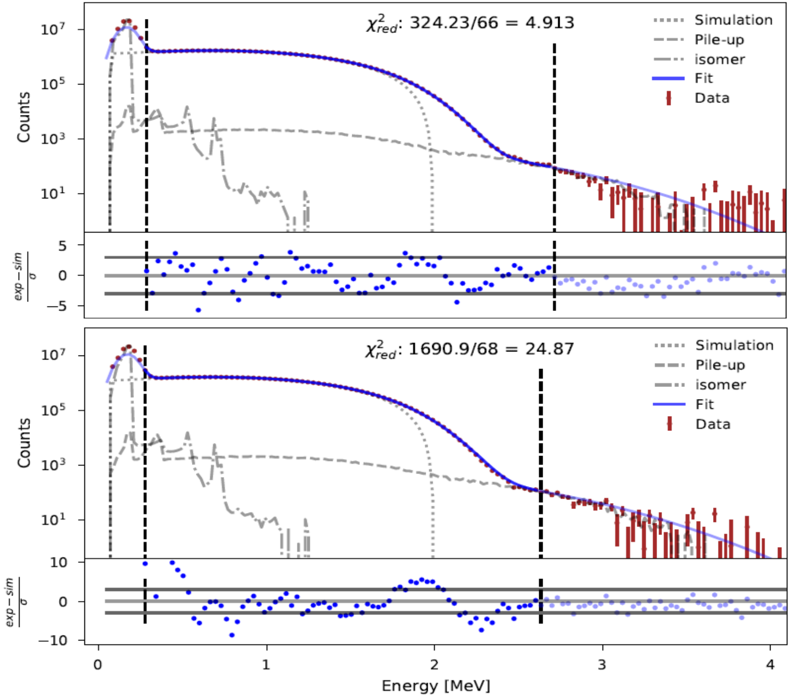

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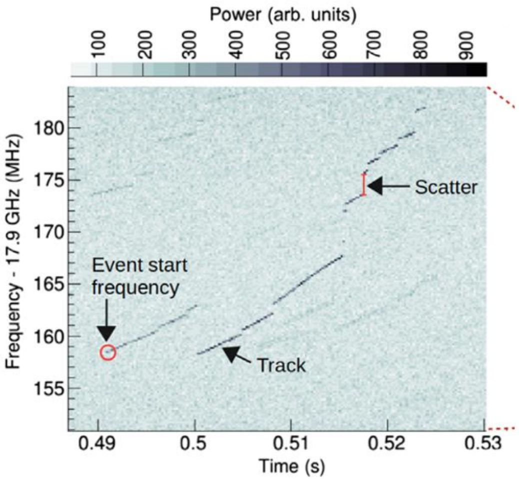

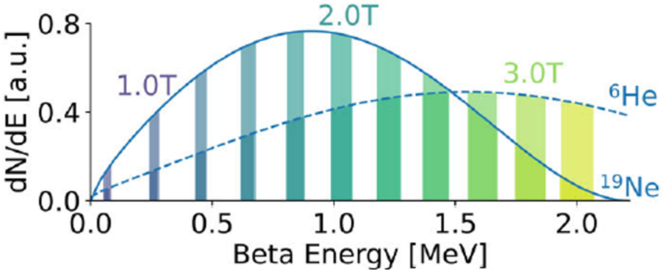

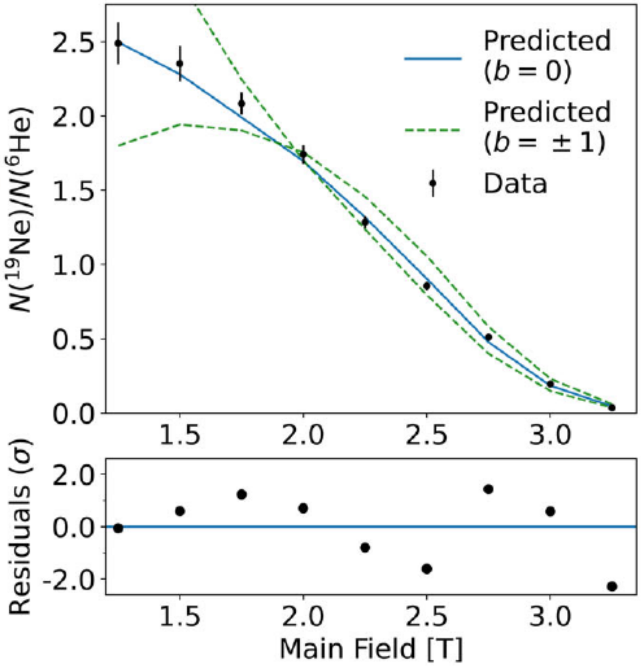

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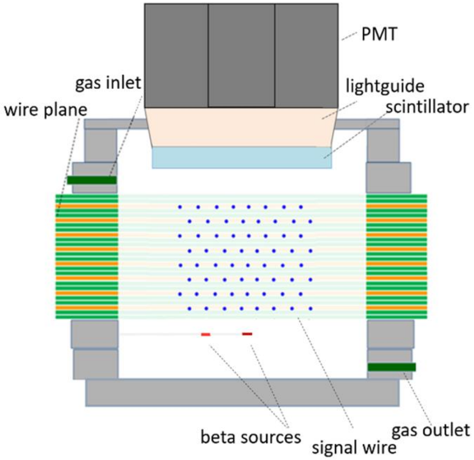
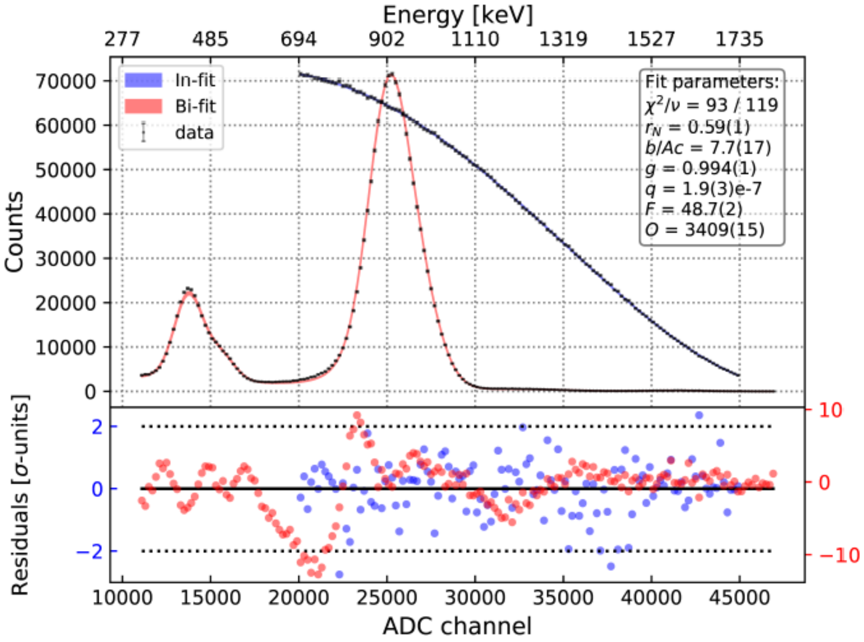


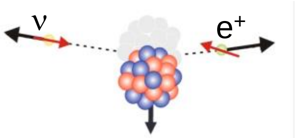


Search for BSM Physics in beta decay

- Dominant *Vector - Axial vector (V – A)* form of weak interaction well established in SM
  But no fundamental reason to exclude small *Scalar* (ϵ_S) and *Tensor* (ϵ_T) contributions
- ϵ_S (Fermi), ϵ_T (Gamow-Teller) → part of BSM theories (leptoquarks, susy…)

- Precision measurements in β-decay *(talks by A. Garcia and E. Liénard this morning)*
  S & T → involve leptons with **opposite helicity**

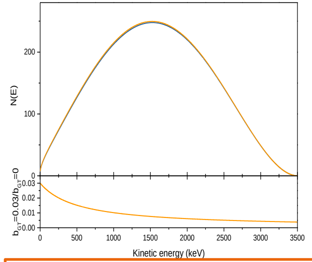
S & T → Affects angular correlation $a_{\beta\nu}$



- Recoil energy spectrum
  (BPT, WISArD, ASGARD…)
- Quadratic dependence of $a_{\beta\nu}$ on $\epsilon_{S,T}$
  Difficult to compete with constraints from LHC…

S & T → Fierz interference term ***b* ≠ 0**

Affects *β spectrum shape* and $T_{1/2}$



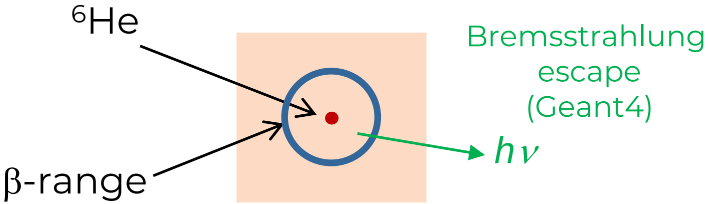
- Correlations (WISArD…)
- Ft values (0+ →0+)
- EC/β+ (ASGARD)
- β spectrum shape
  (^{6}He-CRES, b-STILED…)

- Linear dependence on $\epsilon_{S,T}$
  Competitive with LHC

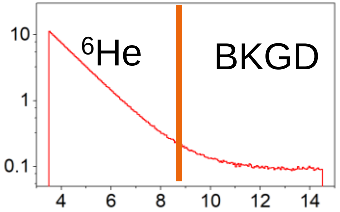
Phase I program at GANIL

- Use simple setups based on YAP scintillators (fast and linear response)

- Achieve a 4π detection geometry
  → suppress E_{loss} from β backscattering
  (main systematic effect)



- Use implantation-decay cycles (3 s – 12 s)
  → cst BKGD subtraction
  → $T_{1/2}$ measurement for free



- Test two techniques (different systematic effects)

Low-energy implantation
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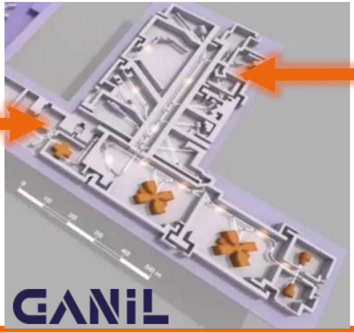


High-energy implantation
on **LISE**/GANIL
312 MeV ^{6}He

Exotic currents beyond *V-A* theory: latest review

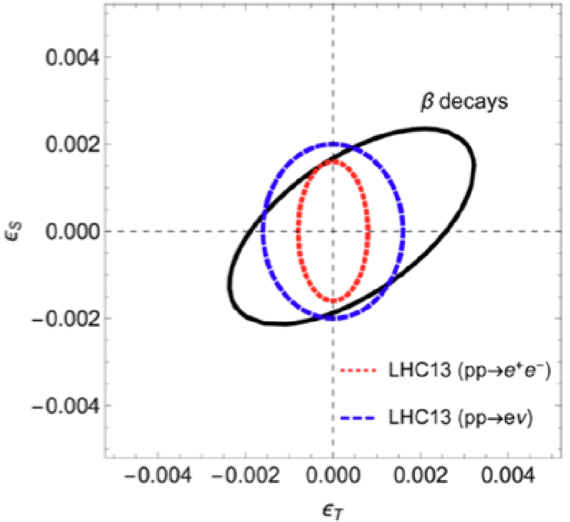
A. Falkowski, M. Gonzáles-Alonso, O. Naviliat-Cuncic, JHEP04 (2021)

- global constraints for *LH* ν
- in EFT framework
- ϵ_S , ϵ_T: Wilson coefficients @ quark level, related to C_S , C_T @ nucleon level thanks to corresponding "charges" computed in L-QCD:

R. Gupta et al PRD90 (2018)

$$\epsilon_i \sim \left(\frac{M_W}{\Lambda_{BSM}}\right)^2 \sim 10^{-3}$$
$$\rightarrow \Lambda_{BSM} \sim \text{TeV}$$

$$C_S = \left(\frac{G_F^0 V_{ud}}{\sqrt{2}}\right) g_S \epsilon_S \quad C_T = 4\left(\frac{G_F^0 V_{ud}}{\sqrt{2}}\right) g_T \epsilon_T$$



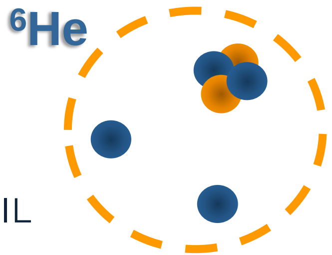
⇒ *to stay competitive, precision levels < 5×10^{-3} for b and < 1×10^{-3} for â are required*

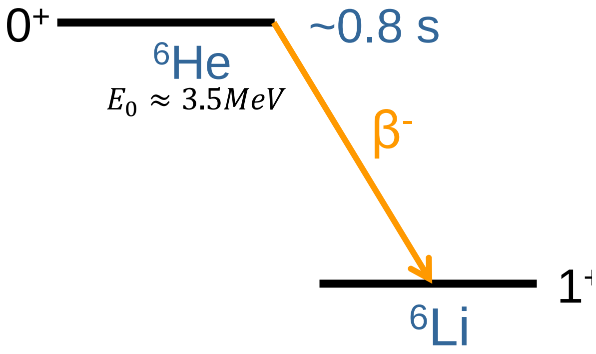
... and effects of nuclear medium (strong & EM) = "recoil & radiative corrections"

to be calculated @ 10^{-4} level *L. Hayen et al, RMP90 (2018)*

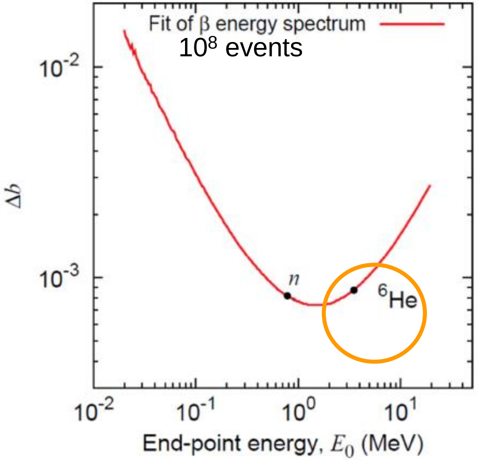
The choice of ^{6}He

- Pure GT transition (GS to GS) only sensitive to tensor currents
- Endpoint energy providing high sensitivity to b_{GT}
- Theoretical corrections known with high precision
- Convenient half-life for implantation-decay cycles, copiously produced at GANIL

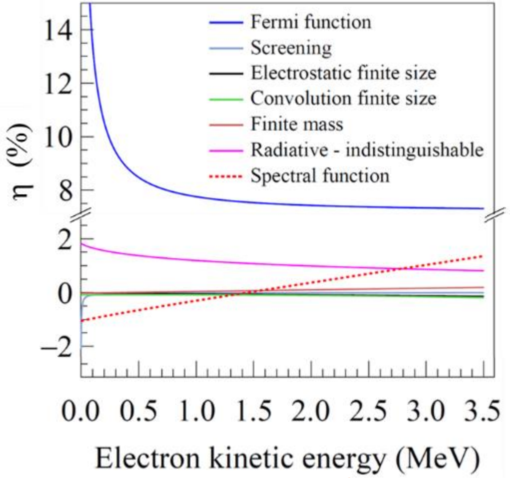




M. González-Alonso et al, PRC, 2016.



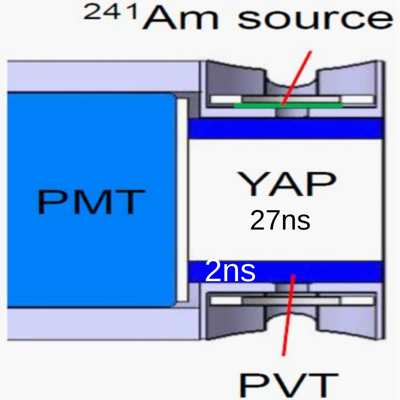
O. Naviliat-Cuncic et al,
prop. AAPG 2020, CE31.



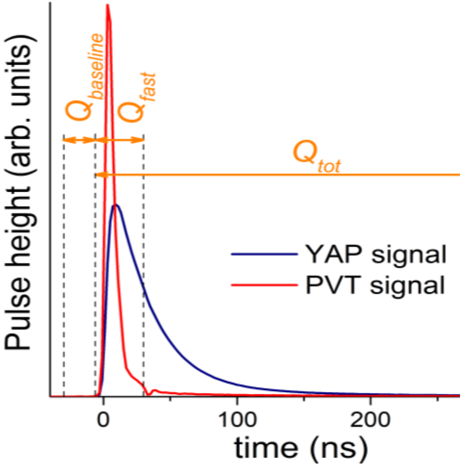
$\Delta b_{GT} < 10^{-3}$

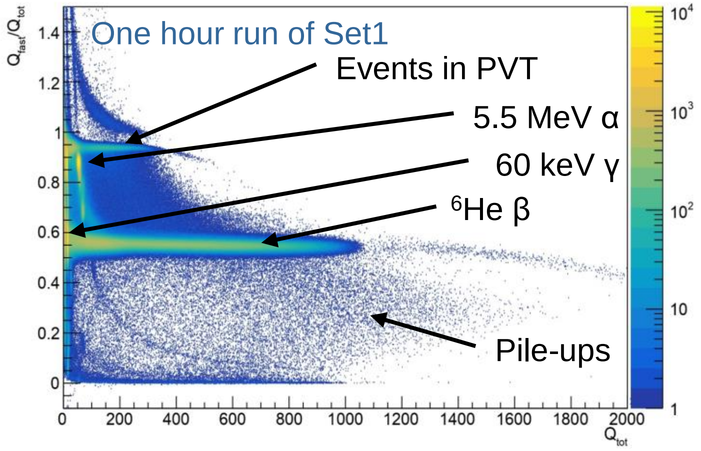
Choice of the detectors

- Use YAP:Ce as main scintillator → fast, linear, less Bremsstrahlung escape
  + plastic scintillator (veto) and ^{241}Am source (gain monitoring)



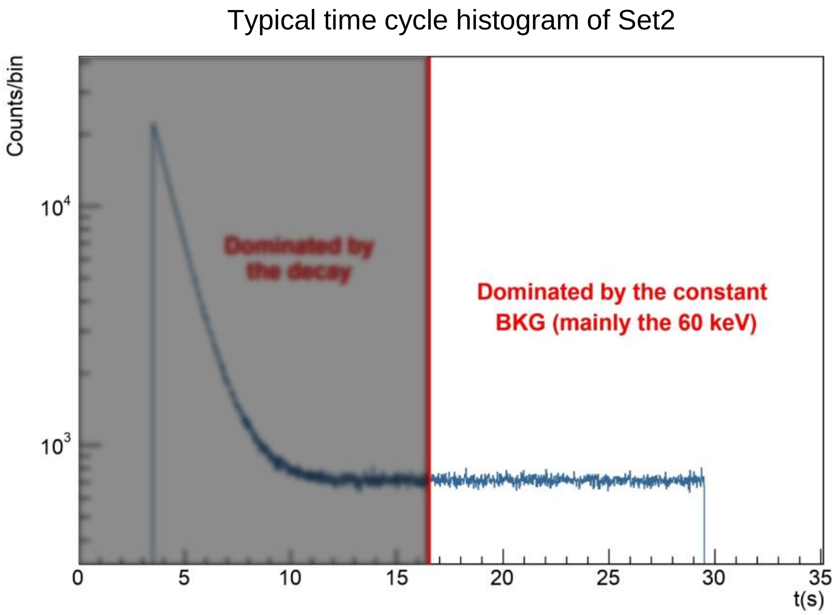
FASTER DAQ
(high rates, minimal dead time)



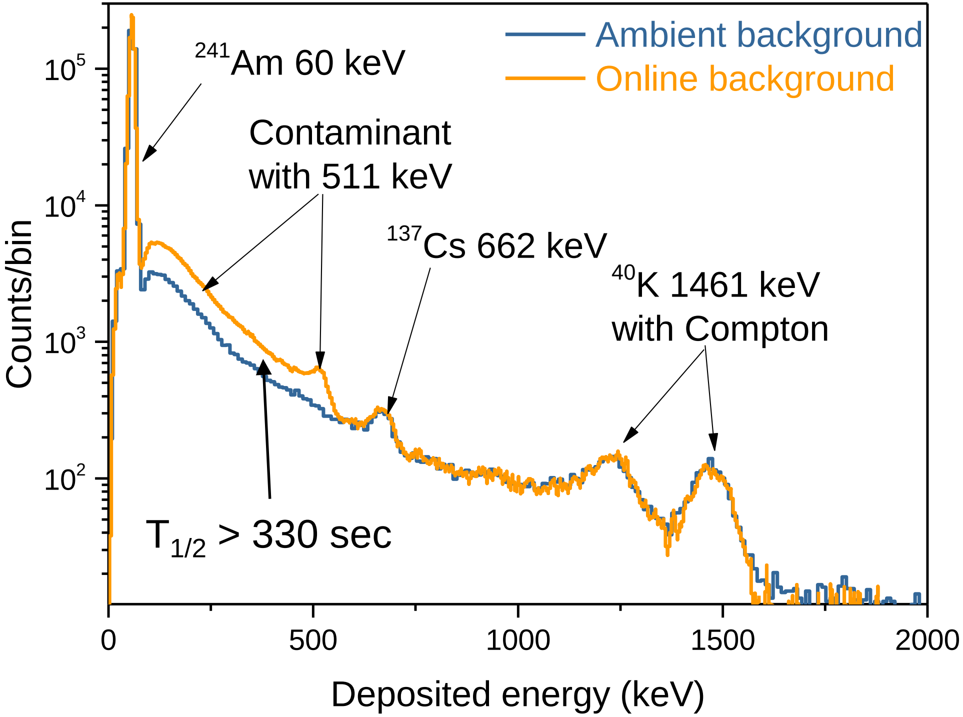


- 3 integration windows for PMT
  → baseline monitoring, pulse shape analysis and pile-up
- timestamp (2ns)
  → event time within implantation/decay cycle

Background investigation

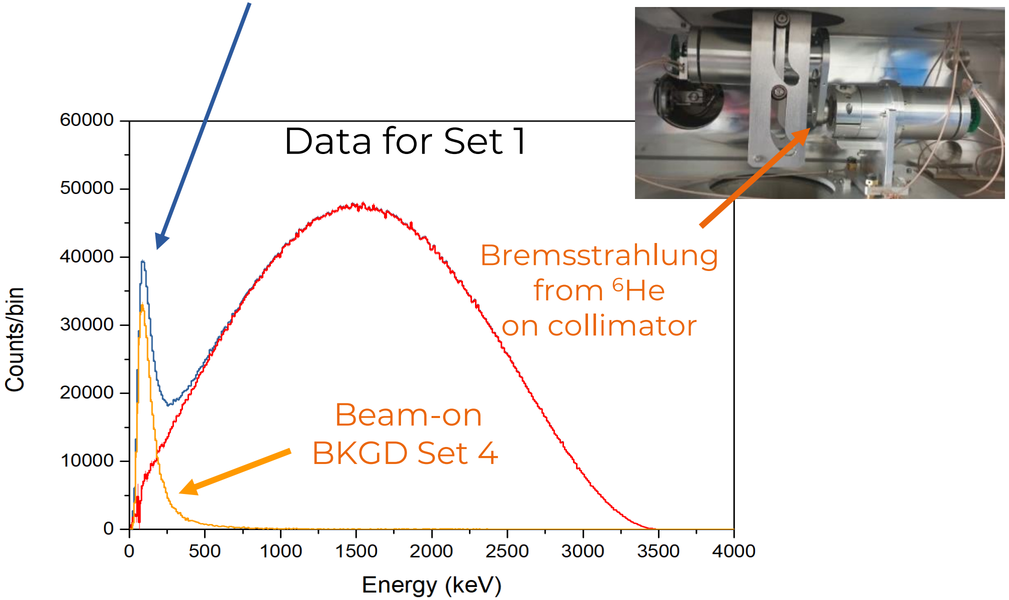


Constant background inside the YAP



Low-energy experiment analysis

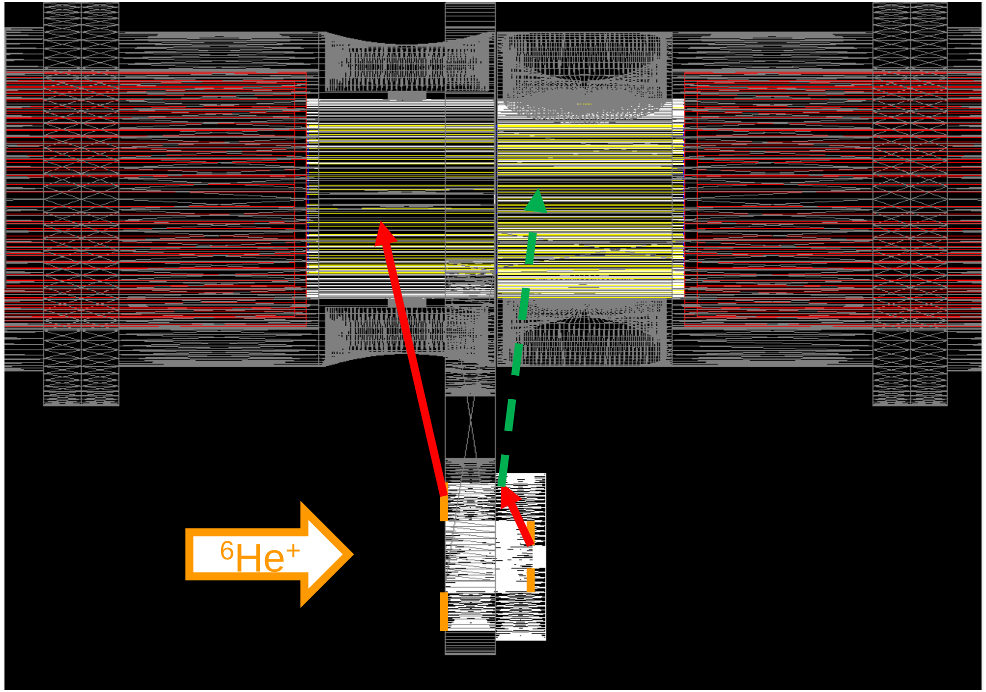
Unexpected peak at low energy…

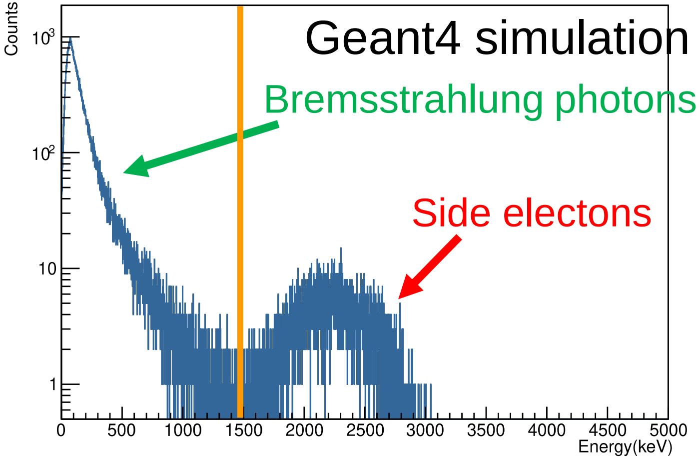


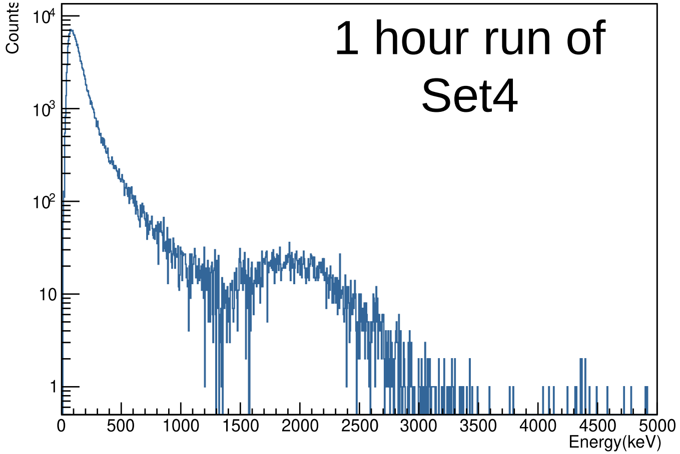
Bremsstrahlung from ^{6}He on collimator

Beam-on BKGD Set 4

Background investigation

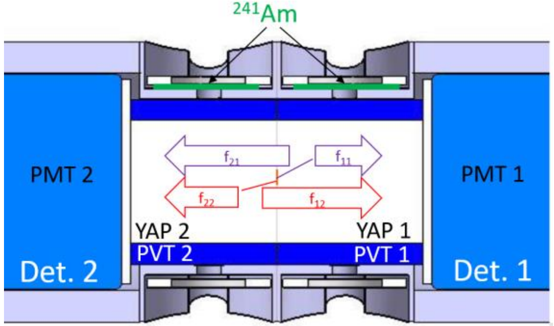




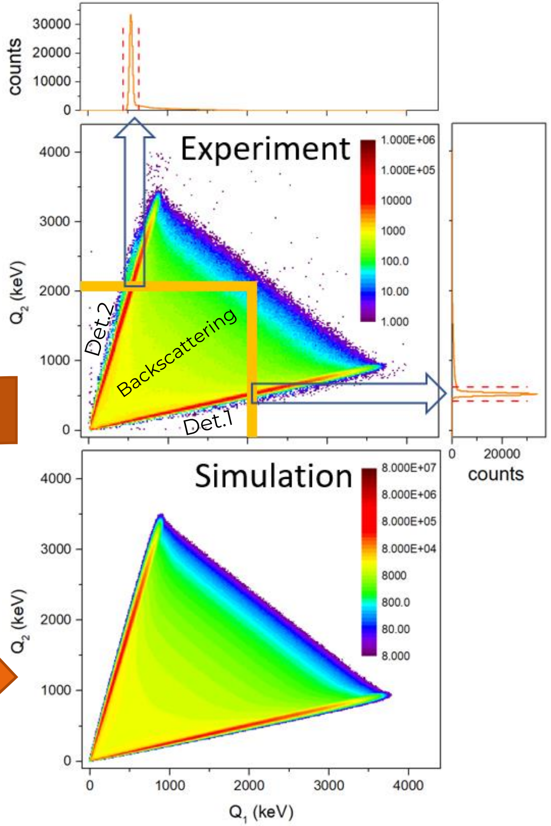


Analysis: calibration

- Problem of YAP cross talk

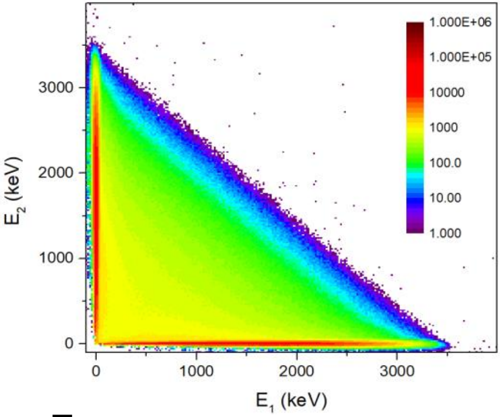


Use Geant4 simulation
Assume linear response



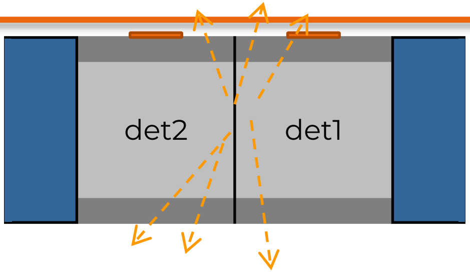
f_{11}, f_{12}
f_{21}, f_{22}

f_{11}, f_{12}
f_{21}, f_{22}



$E_{tot} = E_1 + E_2$
Considered as relative calibration
(free slope in final fit)

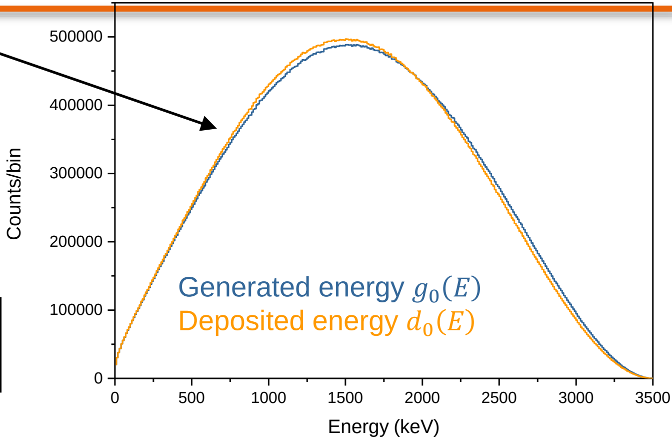
Bremsstrahlung escape correction



Energy escape

Distortion due to Bremsstrahlung escape

$$N\left(E_{dep}\right) = ?$$



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

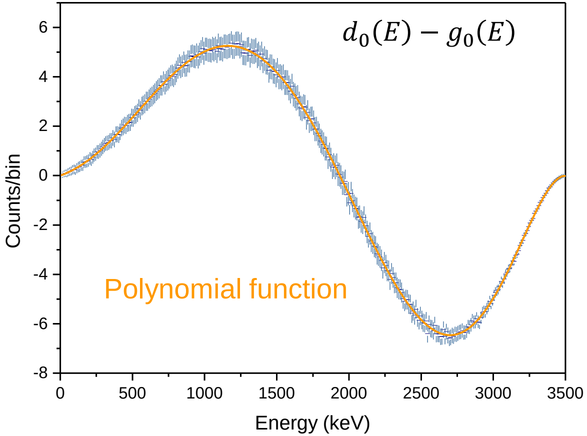
Need for analytical function accounting for the distortion for each term

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

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

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

Analytical function accounting for the bremsstrahlung escape



The fit function

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

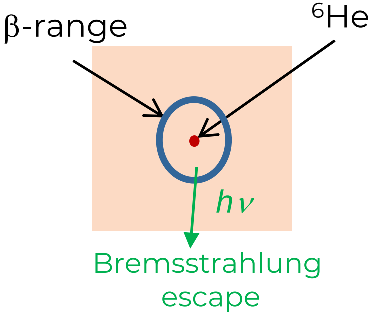
Remaining components of the deposited energy distribution:

- Calibration parameter
- Resolution
- Bremsstrahlung escape (Geant4)

Low-energy experiment analysis

- Systematic errors M. Kanafani, PhD Thesis, UniCaen (2023)

Systematic effect	Δb_{GT}
b_{WM}	2.6×10^{-4}
Radiative corrections	3.7×10^{-4}
Bremsstrahlung escape (5% error on G4)	2.5×10^{-3}
Cerenkov (10% error on G4)	5×10^{-4}
Detectors resolution	$< 2 \times 10^{-3}$
Pile-up (preliminary)	$< 1 \times 10^{-3}$
Calibration for BKGD run (preliminary)	$< 2 \times 10^{-3}$
Detector non-proportionality (literature)	~10^{-2} ☹



Need dedicated measurements

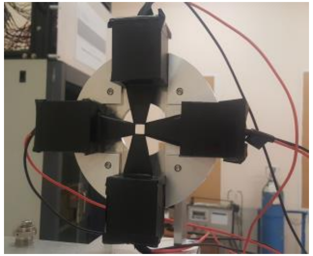
→ discrepancies due to on-line background (changes from one set to another)

→ difficult to deal with, focus on high-energy experiment

Analysis: LISE beam characteristics

- Beam profile

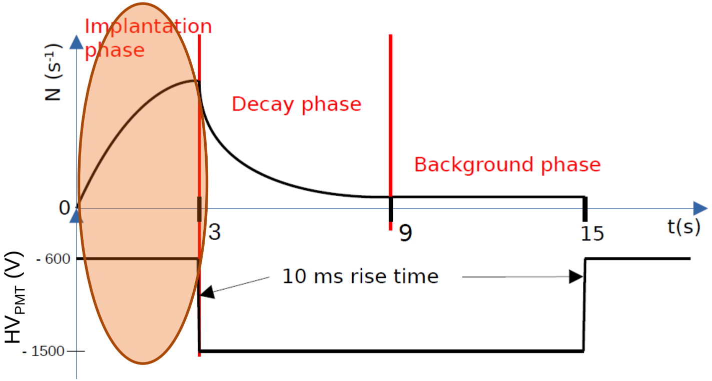
(rates from hodoscope)



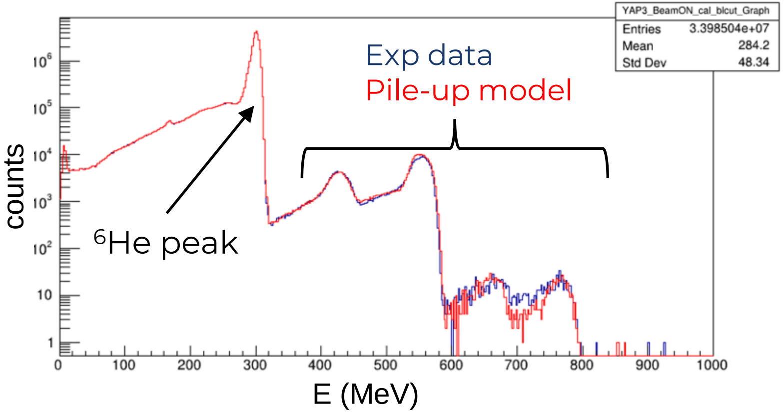
~ 0.4% implantation beyond 6mm from center

- Potential contaminants (LISE++): ^{8}Li & ^{9}Be

Should appear at higher energy



YAP energy spectrum (Implant. phase)



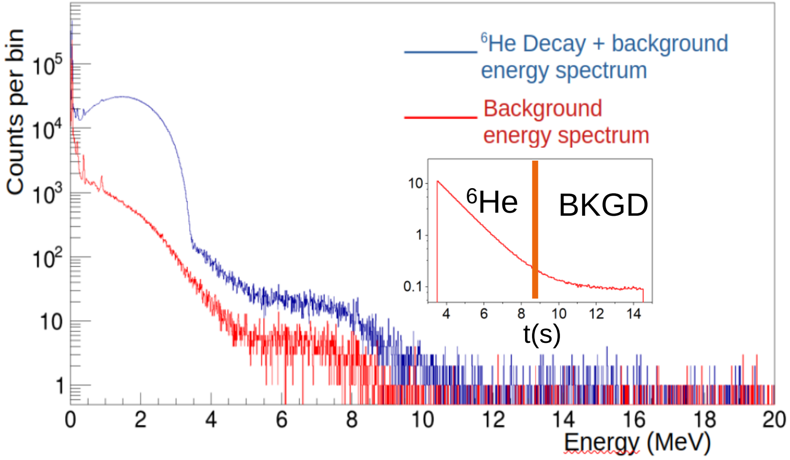
No visible contaminant (at the 10^{-5} level)

Analysis: beam induced contaminants

- Identification of beam induced contaminants created during implantation

R. Garreau, PhD Thesis, UniCaen

Raw calibrated spectra



Using both the YAP spectrum and HPGe

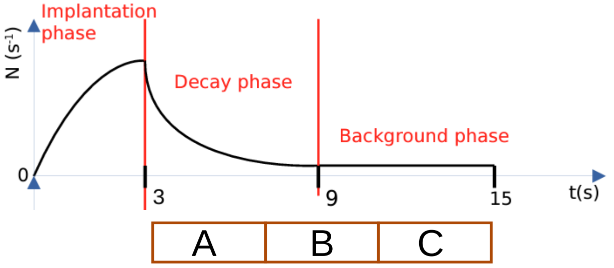
- 909 keV gamma from ^{89m}Y (15.66s) at the 10^{-3} level
- 5 beta emitters

  ^{16}N (7.13s), ^{16}C(0.747s), ^{8}Li(0.840s), ^{20}F(11.07), ^{10}C(19.29s)

Expected impact on extraction of *b* is Δb_{syst} ~ **1.0 10^{-3}**

Beam induced contaminants

- Extract contaminant contribution and impact on b_{GT}

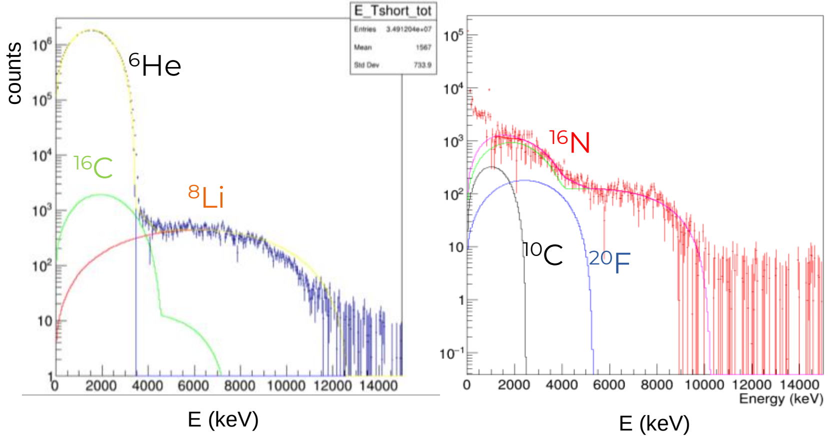


3 windows in cycle

Build linear combinations suppressing a specific half life and cst bkgd

Suppressing $T_{1/2}$ = 7s (no ^{16}N, negligible ^{20}F ^{10}C)

Suppressing $T_{1/2}$ = 807ms (no ^{6}He, ^{8}Li, ^{16}C)



- Expected fraction of decay (preliminary):
  - ^{8}Li→ ~7.0 10^{-4}
  - ^{16}C→ ~1.0 10^{-3}
  - ^{16}N→ ~2.0 10^{-3}
  - ^{20}F→ ~5.0 10^{-4}
  - ^{16}C→ ~3.0 10^{-4}

$\Delta b_{GT(syst)}$ ~ 10^{-3} (assuming 20% error on contaminant fraction)

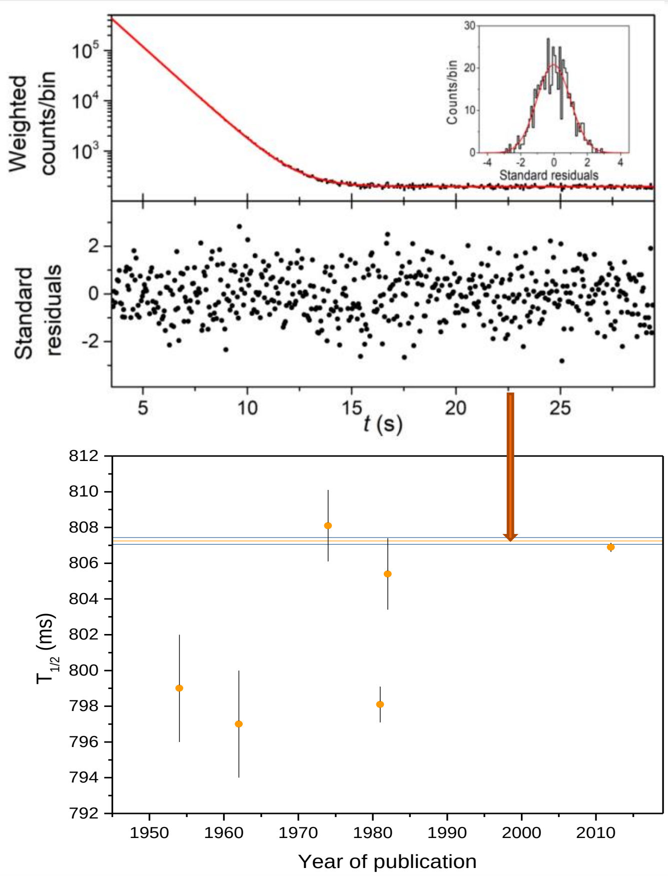
BP 1: Half life measurement of ^{6}He

- LIRAT experiment is an ideal setup:
  - Use adapted cycles
  - High rates, high purity beam
  - Gain and baseline corrections
  - Data Time stamp for offline analysis (not simple scalers)

Most precise half life measurement for ^{6}He

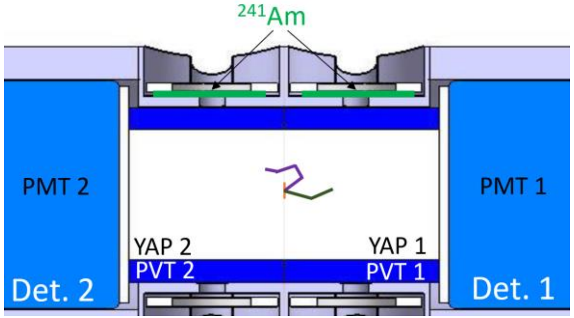
$$\boxed{T_{1/2} = 807.25 \pm 0.16_{stat} \pm 0.11_{syst}\ ms}$$

M. Kanafani et al, Phys.Rev. C 106 (2022) 045502



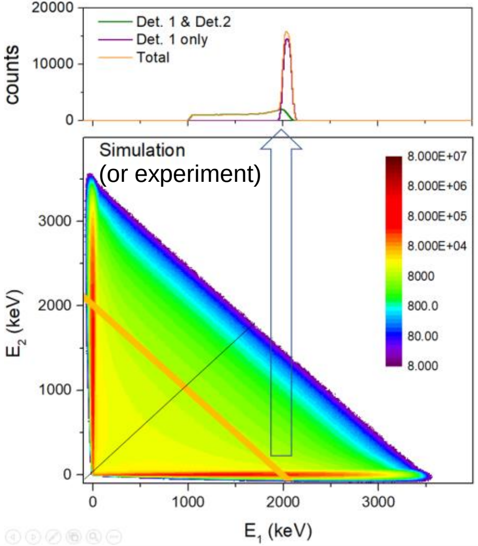
BP 2: Precise measurement of electron backscattering

- Lack of experimental data in the 100 keV- few MeV range
  → Poor benchmarking of Geant4
  → Conservative systematic error on BS (10%-20%) in data analysis



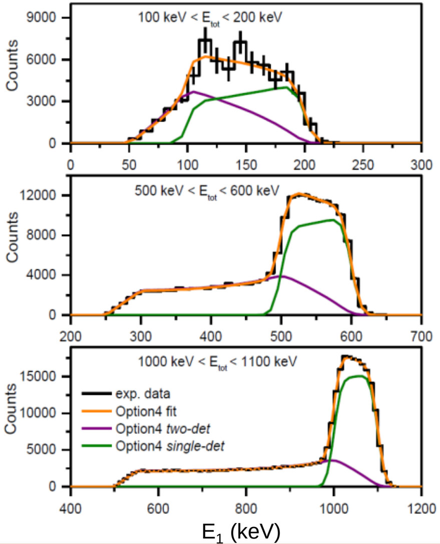
- ^{6}He decay electrons of LIRAT experiment
  → Backscattering probability up to 3.5 MeV

Det.1 vs Det.2 energy



Slices

E_1 energy profiles

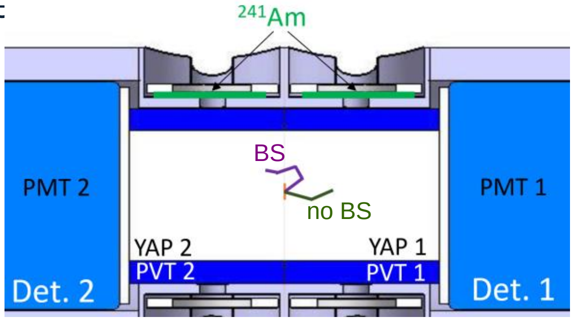


Fit exp w sim

Experimental vs Geant4 Backscattering probability

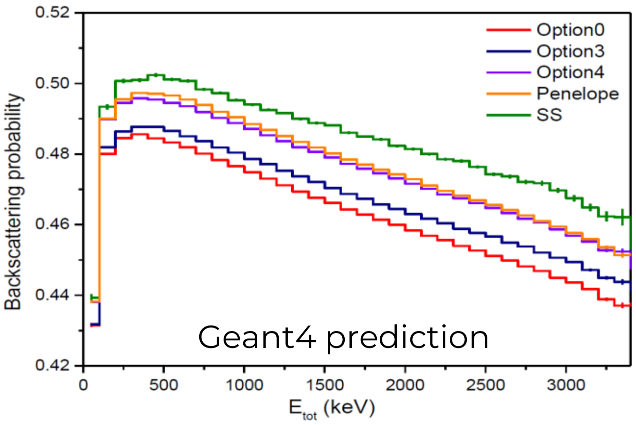
BP 2: Precise measurement of electron backscattering

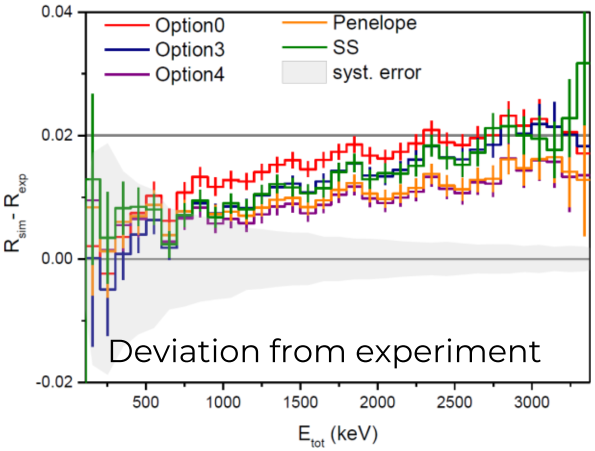
- Lack of experimental data in the 100 keV- few MeV range
  → Poor benchmarking of Geant4
  → Conservative systematic error on BS (10%-20%) in data analysis



- ^{6}He decay electrons of LIRAT experiment
  → Backscattering probability up to 3.5 MeV

- Comparison with Geant4, several EM low energy options





Best: Option4 & Penelope!
Relative deviations below 4%

Article in preparation…

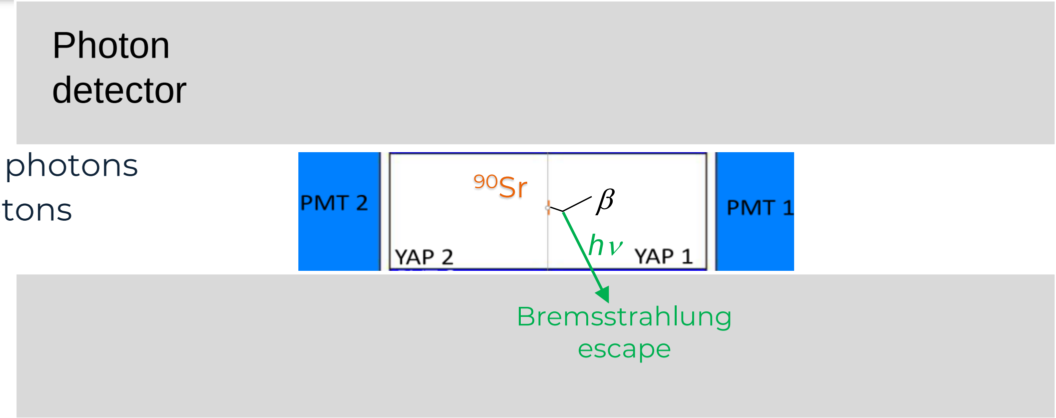
BP 3: Measurement of Bremsstrahlung escape

- Basic idea:

  LIRAT-like geometry with ^{90}Sr beta source

  Inserted in High efficiency γ detector for escaping photons

  Record single β events and coincidences with photons



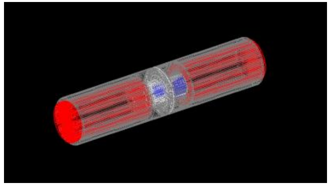
- Measurement at FRIB in April 2024

  Collaboration with ORNL and IRL

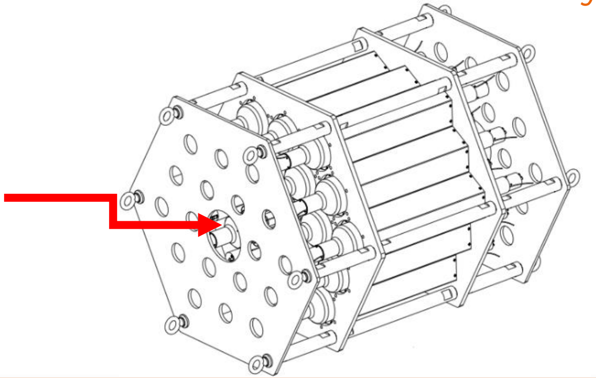
  Use of ORNL MTAS detector

  (talk by Charles Rasco Saturday)

YAP + ^{90}Sr source



MTAS NaI ~100% efficiency



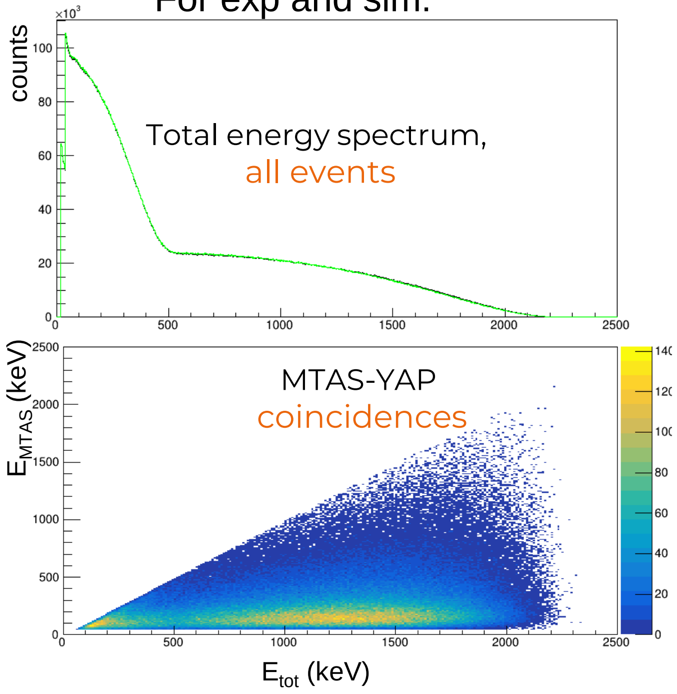
Oak Ridge National Laboratory

B.C. Rasco
Th. Ruland
K.P. Rykaczewski

BP 3: Measurement of Bremsstrahlung escape

- Comparison with Geant4 (EM option4):

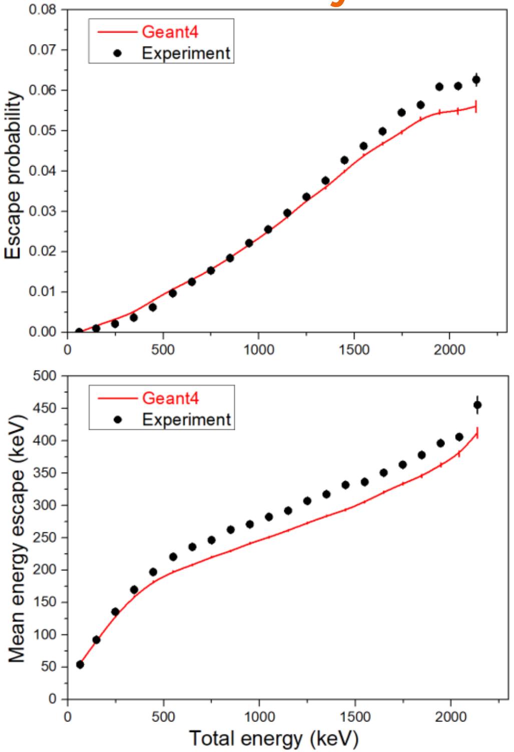
For exp and sim:



Total energy spectrum, all events

MTAS-YAP coincidences

Preliminary!



Deviations up to 10%