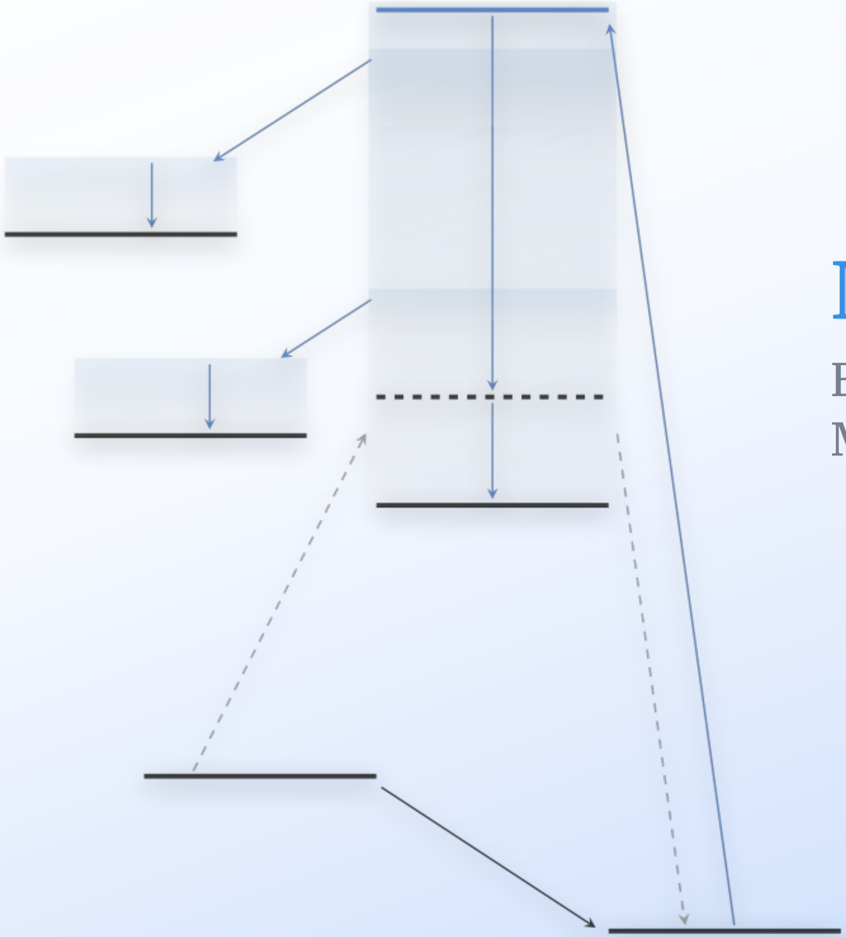
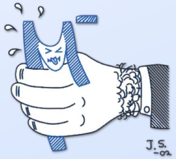
MAYORANA
Workshop II edition



Muon lifetime of ^{76}Se

Benchmarking NMEs with the MONUMENT experiment



Elizabeth Mondragón on behalf of the MONUMENT Collaboration

June 18th 2025

Max-Planck-Institut für Kernphysik Heidelberg
Technical University of Munich

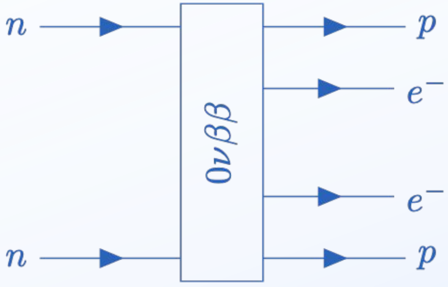
Motivation

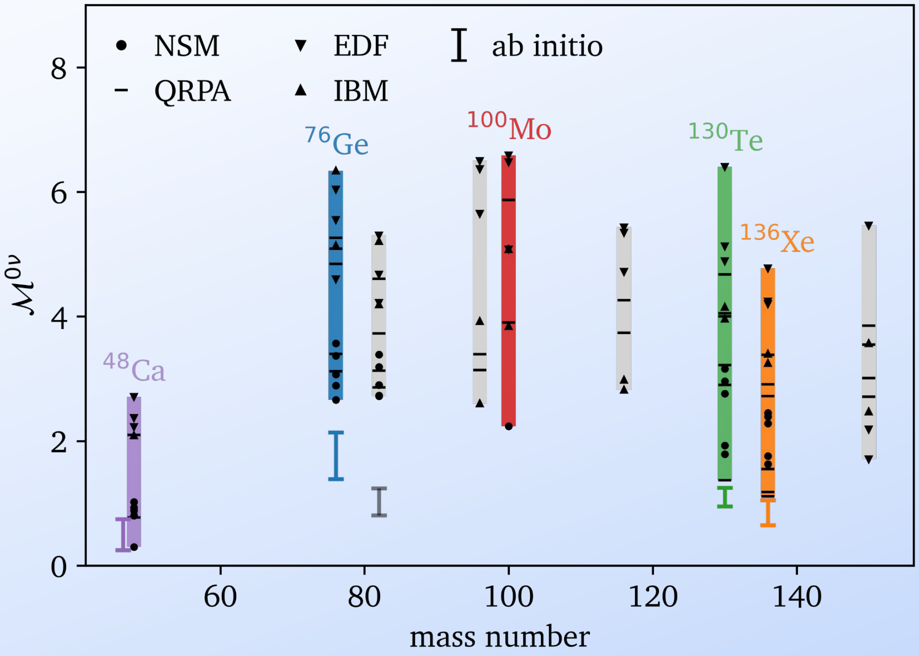
[1] J. Schechter and J. W. F. Valle, Neutrinoless double-β decay in SU(2)×U(1) theories, Phys. Rev. D, vol. 25, pp. 2951–2954, 11 (1982)

$0\nu\beta\beta$ decay

observable kinematics nuclear physics particle physics

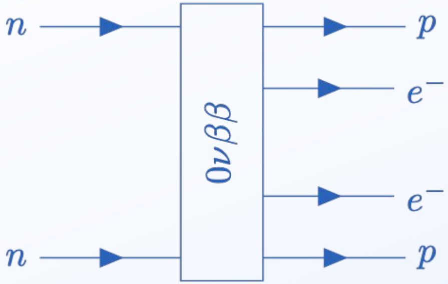
$$\frac{\Gamma^{0\nu}}{\ln 2} = \frac{1}{T^{0\nu}_{1/2}} = \sum_i \mathcal{G}^{0\nu}_i(\mathcal{Q}_{\beta\beta}, Z) \cdot \left|\widetilde{\mathcal{M}}^{0\nu}_i\right|^2 \cdot \eta_i^2$$

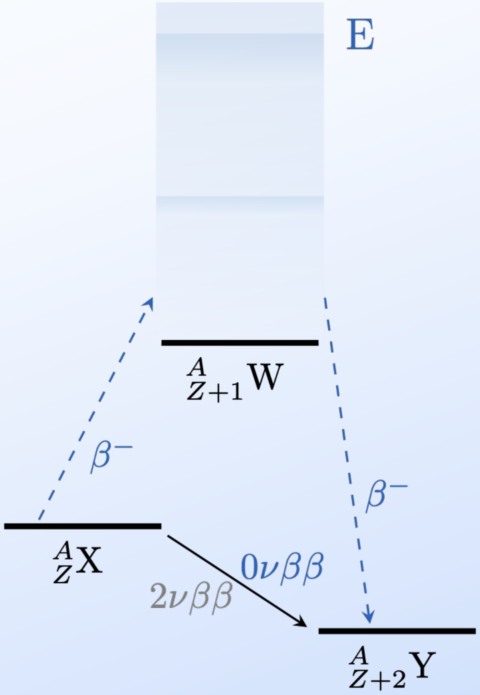




- Beyond the SM physics
- Majorana nature of neutrinos[1]

$0\nu\beta\beta$ decay

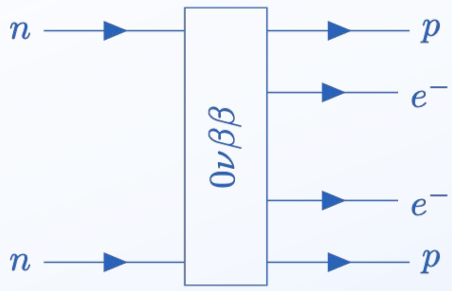




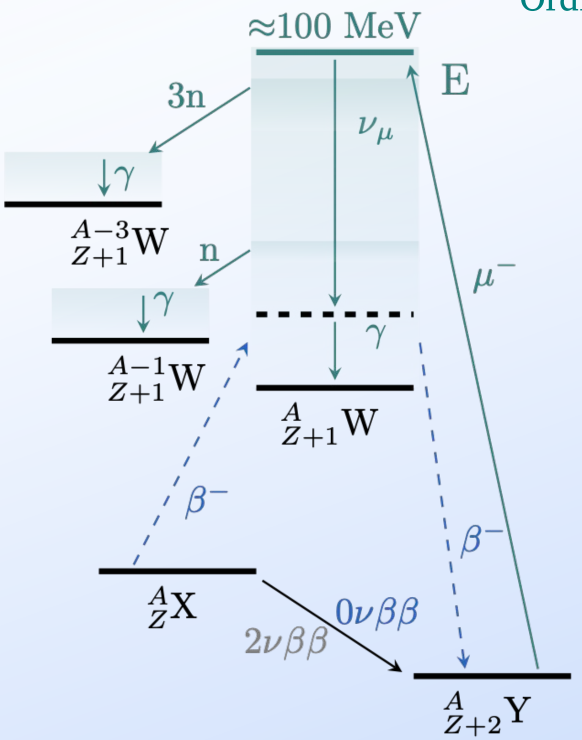
- Beyond the SM physics
- Majorana nature of neutrinos[1]

[2] M. Kortelainen and J. Suhonen, Ordinary muon capture as a probe of virtual transitions of double-beta decay, EPL, vol. 58, pp. 666–672, (2002).
[3] M. Kortelainen and J. Suhonen, Nuclear muon capture as a powerful probe of double-beta decays in light nuclei, J. Phys. G, vol. 30, no. 12, p. 2003, (2004).

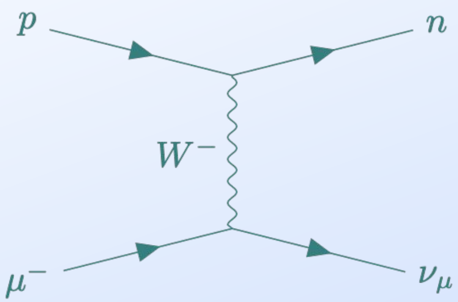
$0\nu\beta\beta$ decay



- Beyond the SM physics
- Majorana nature of neutrinos[1]



Ordinary Muon Capture [2,3]



- Similar momentum transfer
- Probe intermediate states
- Benchmark nuclear matrix element calculations

Measurement

Collaboration

ETH Zurich, Switzerland

IEAP, CTU, Prague, Czech Republic

CIFRA, Romania

JINR, Dubna, Russia

KU Leuven, Belgium

Osaka University, Japan

PSI, Switzerland

TU Munich, Germany

The University of Alabama, USA

Universiti Teknologi Malaysia, Malaysia

University of Jyväskylä, Finland

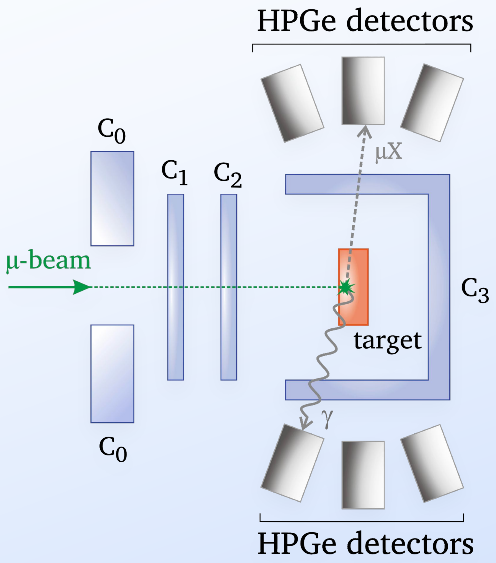
University of Zurich, Switzerland

[4] M. Schwarz, Tracing impurities and illuminating their impact, Ph.D. Thesis, Technical University of Munich, (2024)

Measurement

PAUL SCHERRER INSTITUT PSI

- Beam momentum $\sim$40 MeV/c



- **Tag muon trajectory** from beam to target

$$\mu_{stop} = \hat{C}_0 \wedge C_1 \wedge C_2 \wedge \hat{C}_3$$

rate of stopped muons $\mathcal{O}(10^4)$ Hz

- ***γ*-spectroscopy** with HPGe detectors, typical rates of $\mathcal{O}(10^3)$ Hz

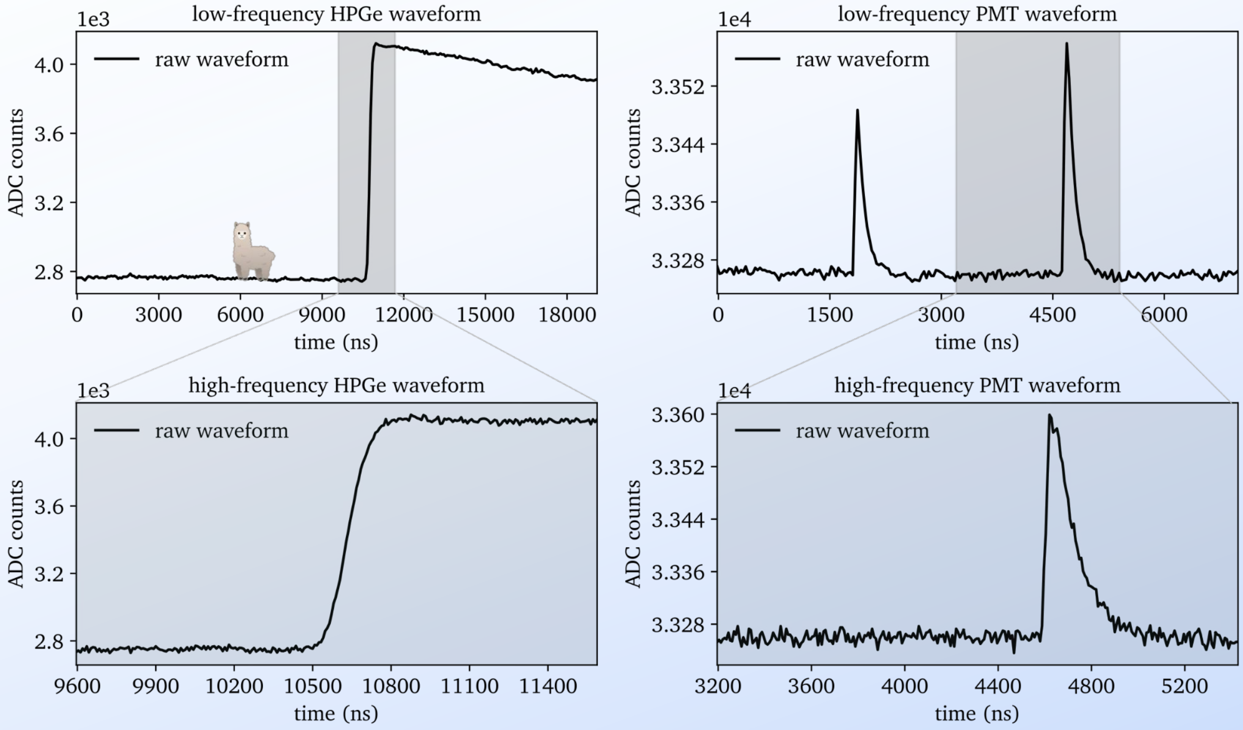
- **Coincident measurement,**

$$\Delta t = t_{HPGe} - t_{\mu stop}$$

- Two parallel DAQ systems, **ALPACA** developed at Technical University of Munich[4]

[4] M. Schwarz, Tracing impurities and illuminating their impact, Ph.D. Thesis, Technical University of Munich, (2024)
[5] Agostini, M. and Pandola, L. and Zavarise, P. and Volynets, O., GELATIO: A General framework for modular digital analysis of high-purity Ge detector signals, JINST, vol. 6, P08013, (2011)

ALPACA [4]



- **Full waveform** digitisation, low and high frequency windows
- **Offline analysis**
- >150 TB data
- Analysis routines **based on GERDA**[5]

[6] E. Mondragon for the MONUMENT collaboration, The MONUMENT experiment: Ordinary Muon Capture as a benchmark for neutrinoless double beta decay nuclear structure calculations, AIP conf. Proc., Conference ID:C22-06-13.1, (2022).
[7] MONUMENT Collaboration, The Monument Experiment: Ordinary Muon Capture for $0\nu\beta\beta$-decay studies, Eur. Phys. J. C., vol. 84, p. 1188, (2024).

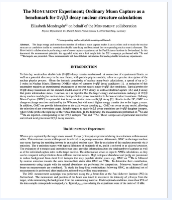
Timeline

Collaboration formed

Beam-time

^{76}Se & ^{136}Ba

- ALPACA data production, DSP & low-level analysis
- Production of 2nd target chamber
- Dissemination work [6]



Beam-time

^{48}Ti

- ALPACA high-level analysis (total capture rates)
- Conceptual Paper [7]

2021 | 2022 | 2023 | 2024 | 2025

- Detector characterisation
- Testing & configuring ALPACA-DAQ
- Assembly experimental setup & electronics

^{100}Mo

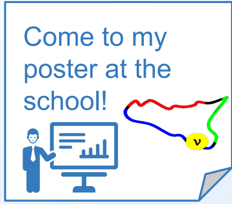
Beam-time

- ALPACA high-level analysis (partial capture rates)

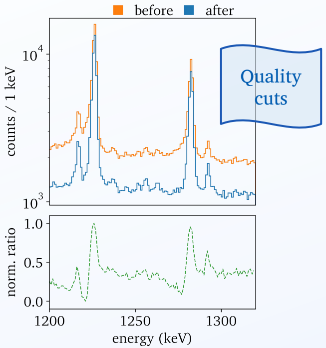
- Release of first results

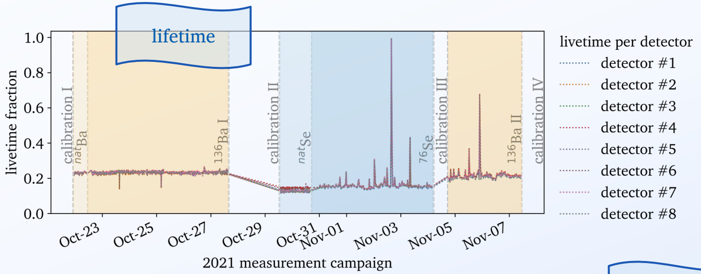
me

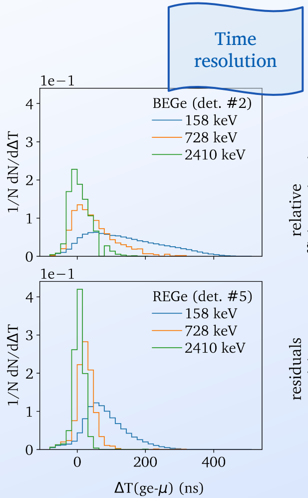
[7] MONUMENT Collaboration, The Monument Experiment: Ordinary Muon Capture for $0\nu\beta\beta$-decay studies, Eur. Phys. J. C., vol. 84, p. 1188, (2024).

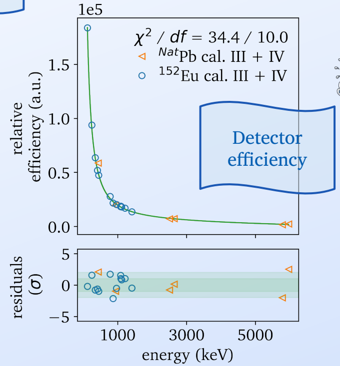


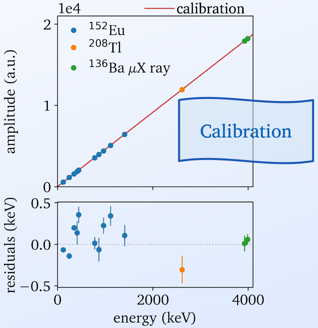
Low-level analysis

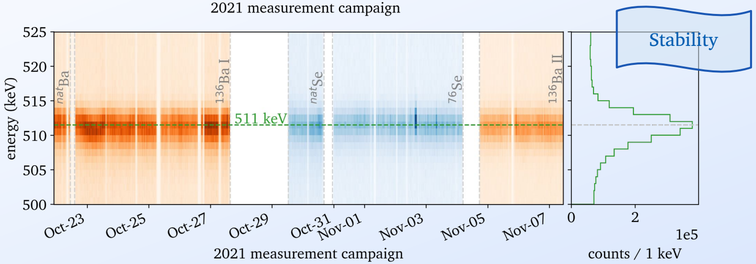


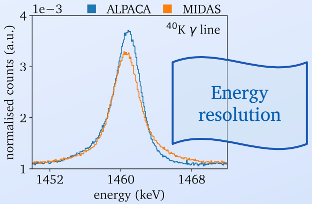


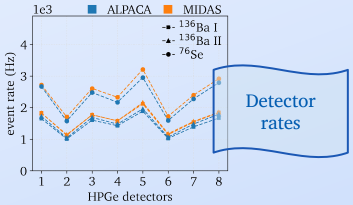


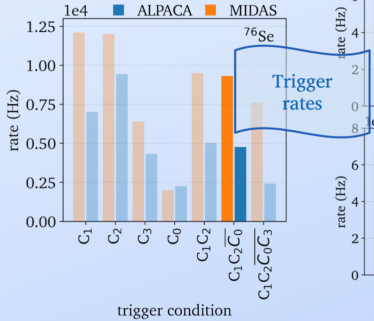


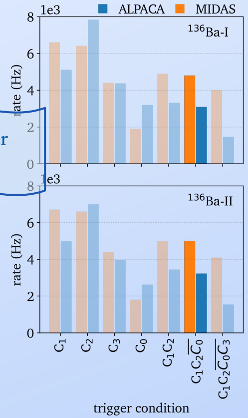








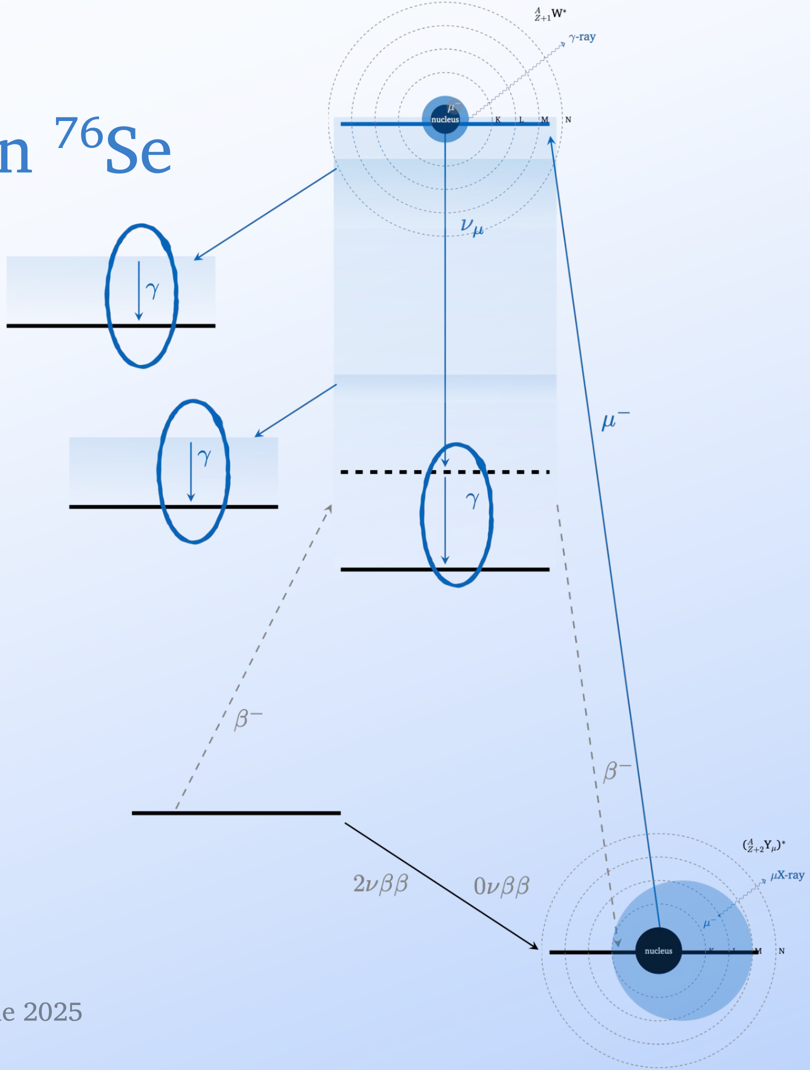




Results

High-level analysis: μ lifetime in ^{76}Se

- Muon stopped at target atom → µX-rays
- After OMC, de-excitation via γ-ray emission
- $\Delta t = t_{\gamma\text{-rays}} - t_{\mu\text{stop}}$ tell about the muon lifetime
- Related to **total capture strength which can be calculated by nuclear structure theorists**



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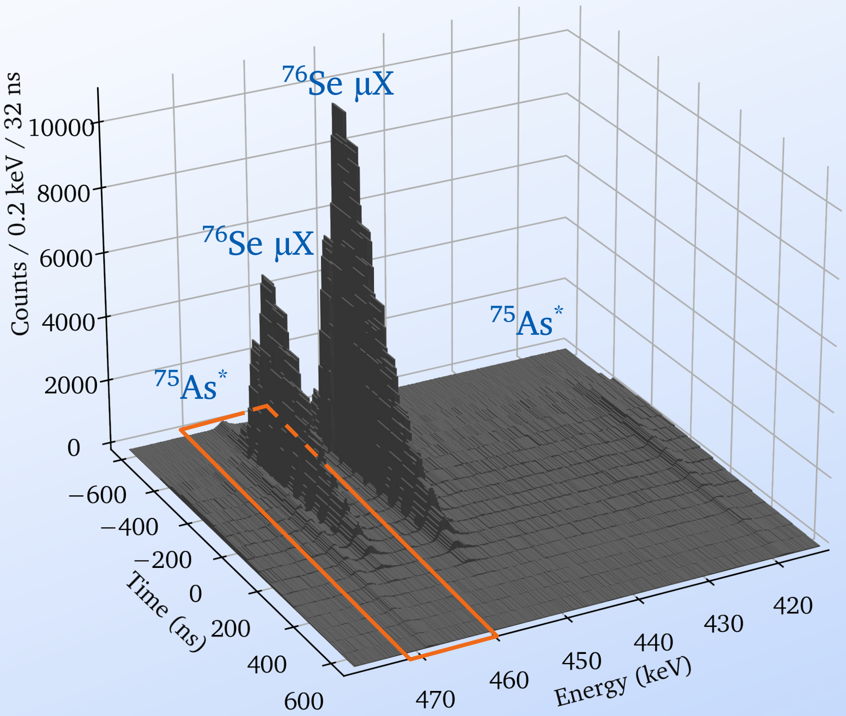
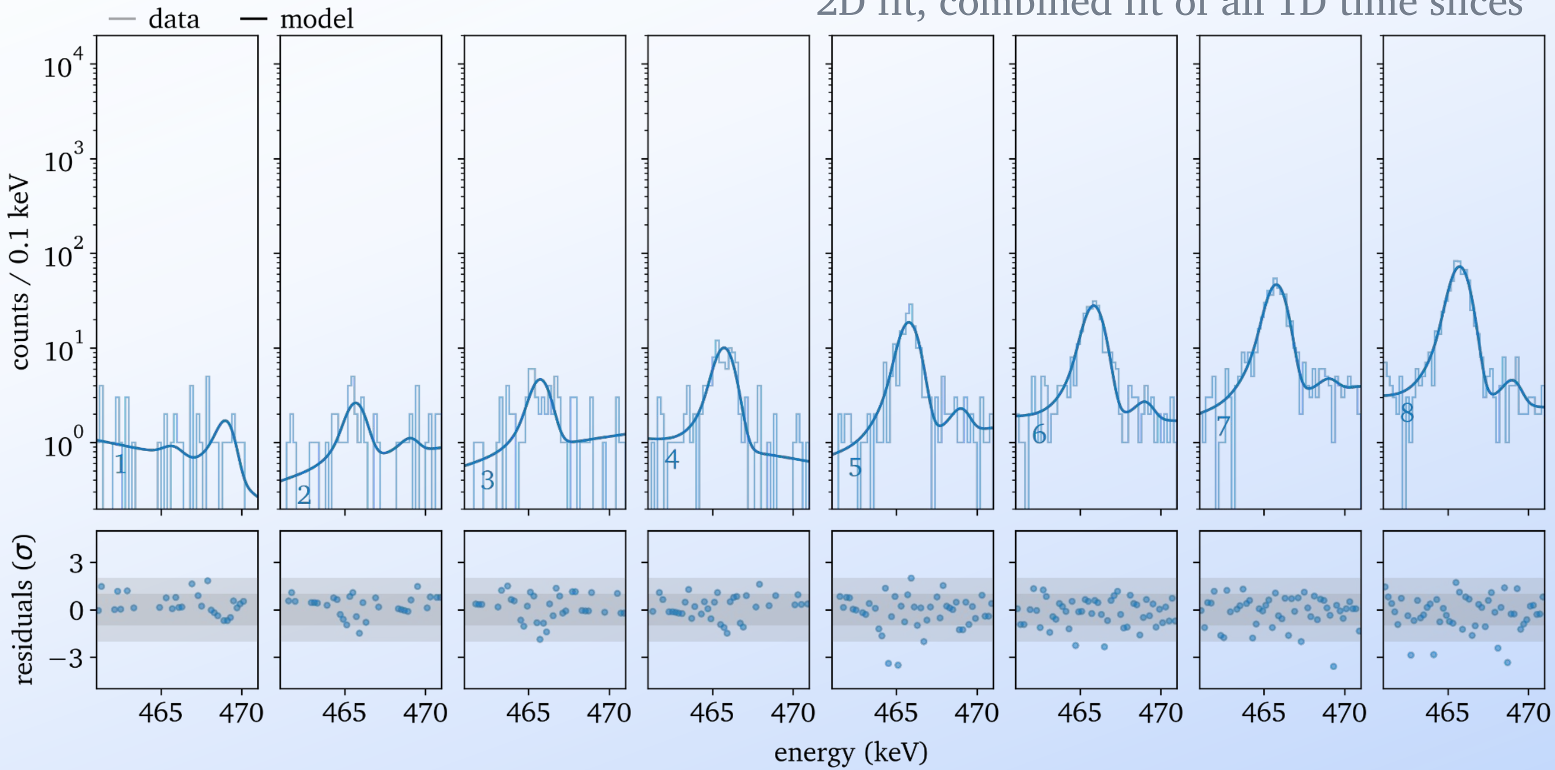


① Time profile extraction (intensities over time)

2D fit, combined fit of all 1D time slices



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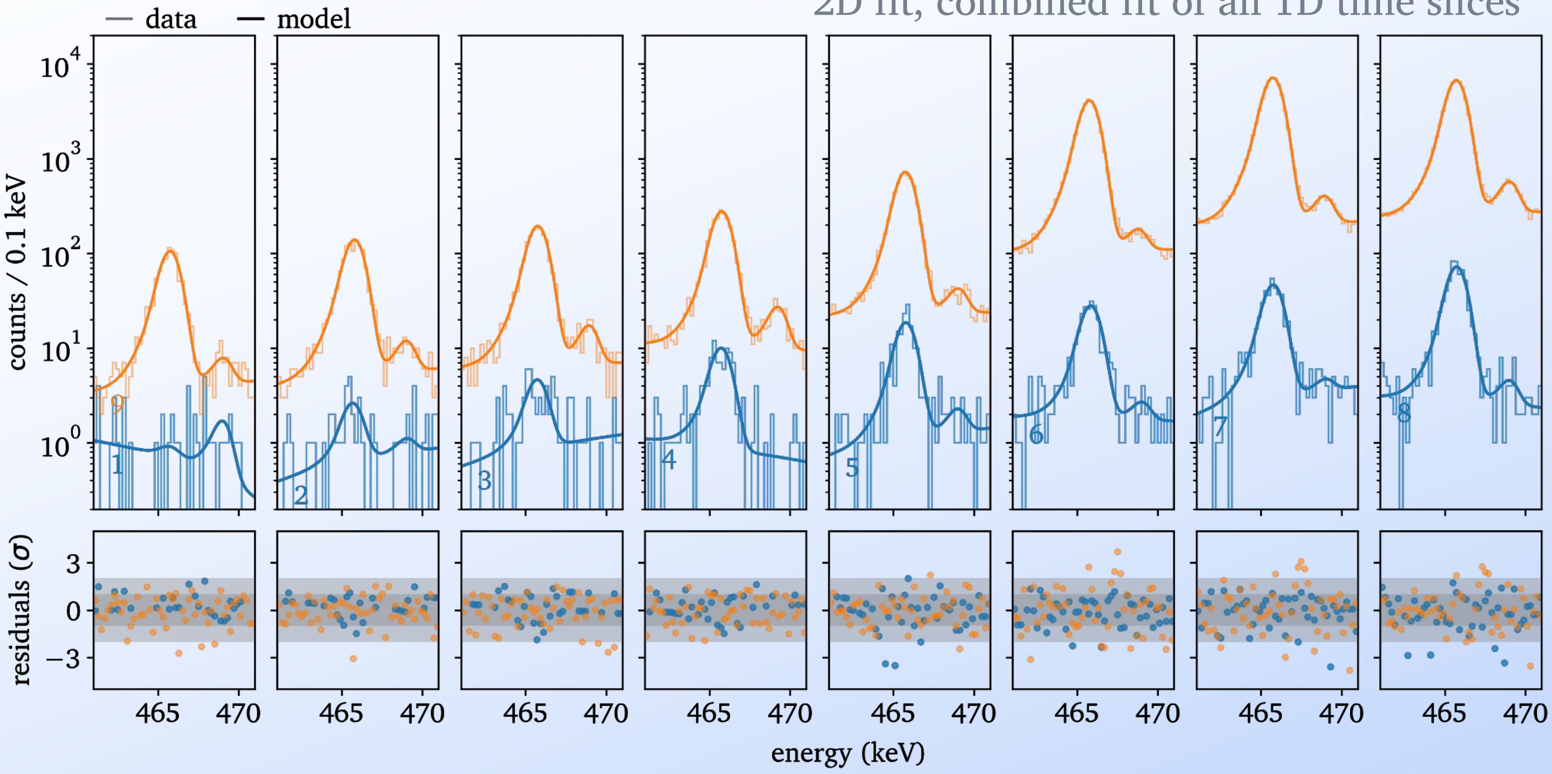

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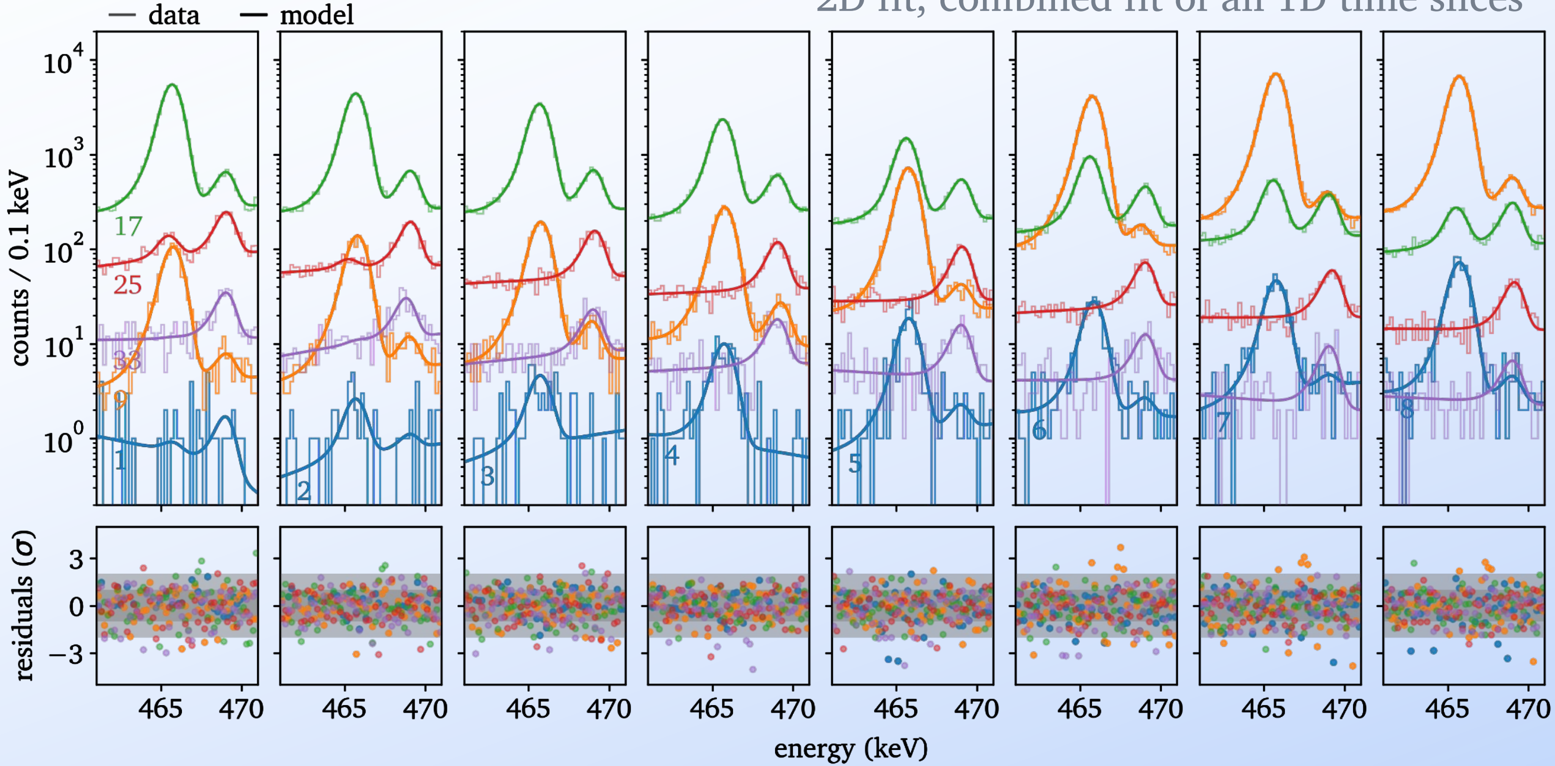


② Lifetime fit (muon lifetime τ)

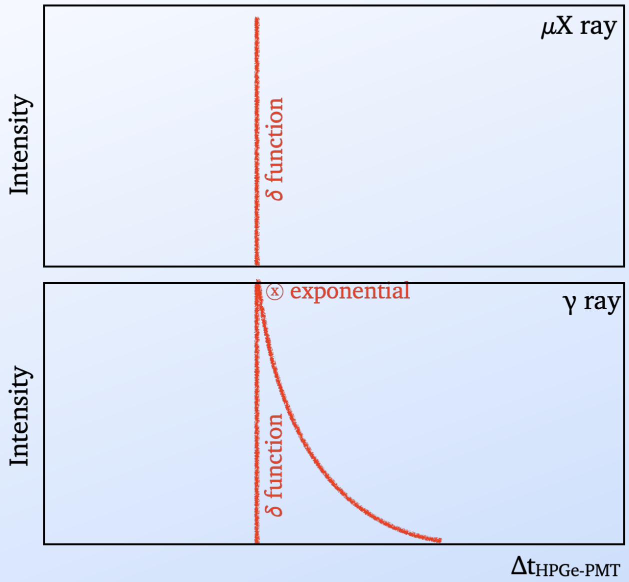
- μX ray provides prompt response of the detector system, γ is convolution with exponential decay due to muon lifetime

- Prompt profile not trivial, use monotonic cubic spline
- Combined shape-only χ^2 fit using covariance matrix from ①

$$(138.9 \pm 1.3_{\text{stat}} \pm 3.5_{\text{syst}})\ \text{ns}$$

- Tail fit for comparison

Combined μX- and γ-ray fit



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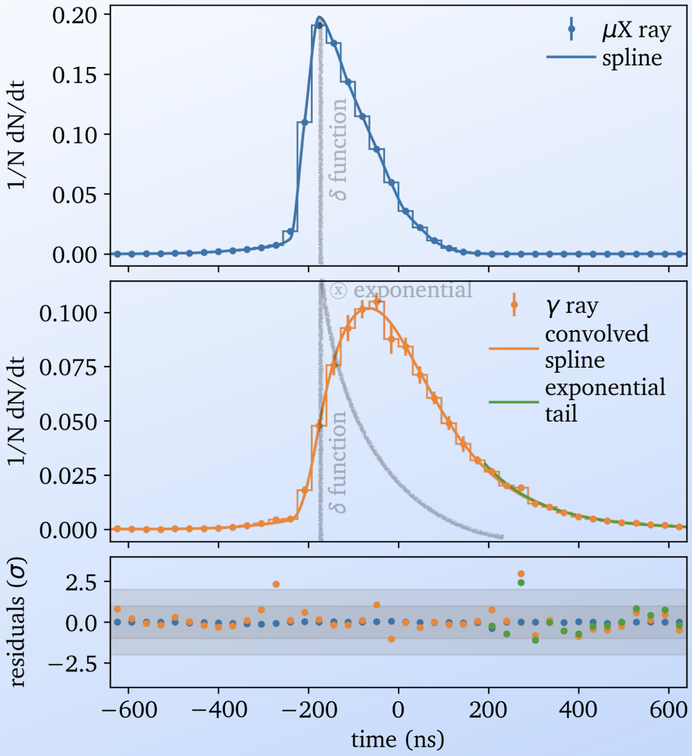
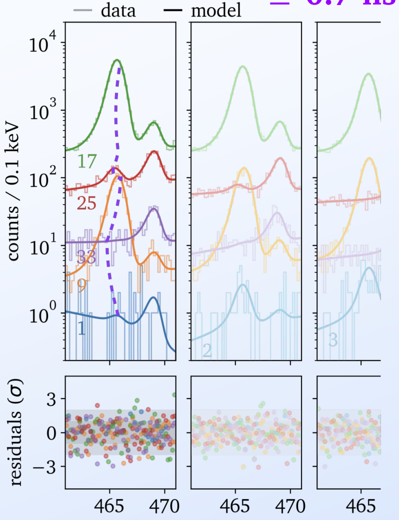


Systematics

A. Line position drift

Charge collection effect due to drift time selection

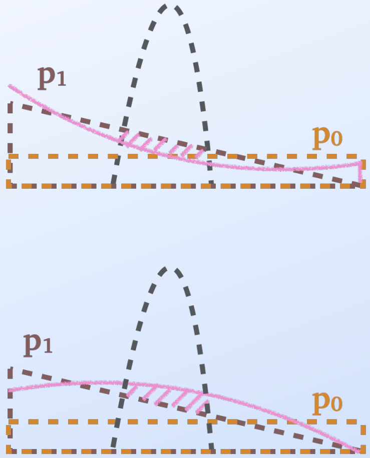
± 0.7 ns



B. Background shape

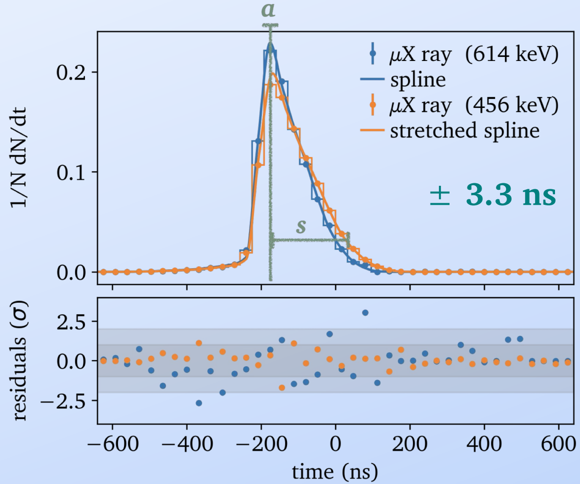
Over/under estimation of intensity due to background model insufficiencies

± 0.9 ns



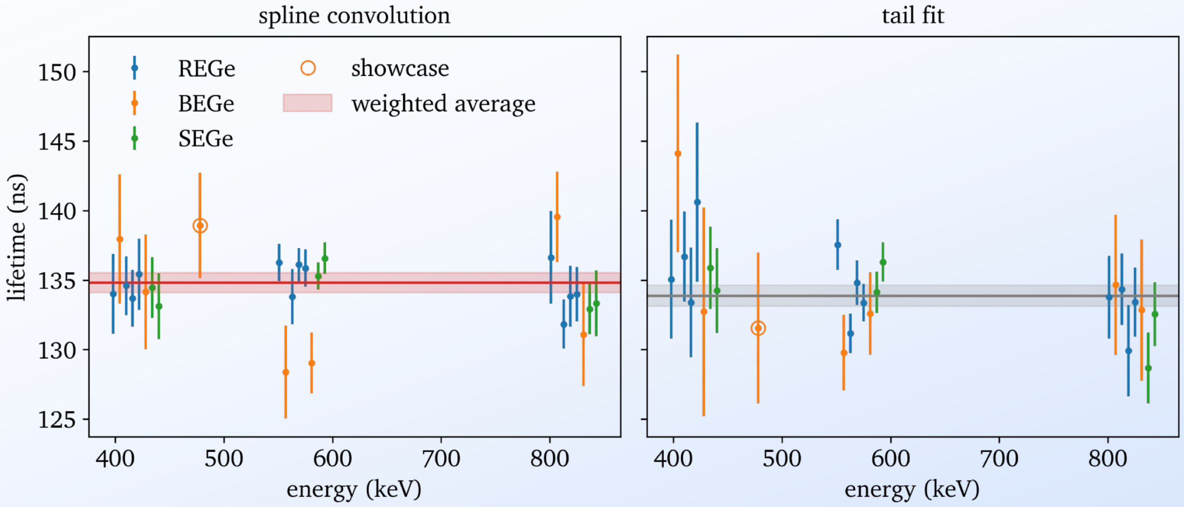
C. Prompt timing energy-dependence

Stretched time response due to energy dependence



[8] E. Mondragón, The MONUMENT Experiment: Ordinary Muon Capture for 0νββ-decay Nuclear Matrix Elements, PhD Thesis, Technical University of Munich (2025)

Muon lifetime in ^{76}Se: new result!



$\tau = (134.8 \pm 0.7)$ ns[8]

$\tau = (133.9 \pm 0.8)$ ns[8]

- **25 γ and μX ray pairs**
  8 x (**419**, 456) keV
  1 x (**469**, 466) keV
  (showcase data)
  8 x (**572**, 614) keV
  8 x (**822**, 752) keV
- Weighted average, χ^2 /d.f. = 25.2 / 24
- **Toy Monte Carlo** to evaluate the method uncertainty

Results from my PhD thesis

*This are models used to calculate $\beta\beta$-decay NMEs

Discussion

$$\frac{1}{\tau} = \mathscr{H}\Lambda_{dec} + \Lambda_{cap}$$

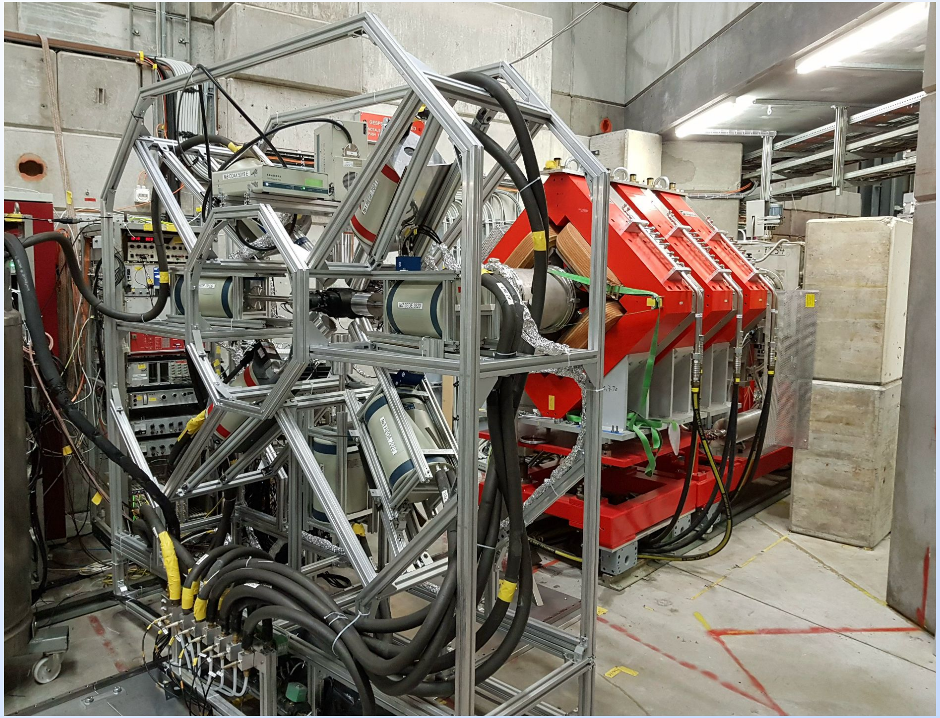
Experimental		Semi-empirical			Theoretical*	
This work	Other work[9]	Primakoff [10, 12]	Goulard-Primakoff [11, 12]	Fujii-Primakoff [12]	QRPA[12]	pnQRPA[13]
134.8 ± 0.7	148.5 ± 0.1	135.1	115.0–135.2	196.2	254.0	59.4

[9] D. Zinatulina et al., Ordinary muon capture studies for the matrix elements in $\beta\beta$ decay, Phys. Rev. C, vol. 99, no. 2, p. 024 327, (2019).
[10] H. Primakoff. Theory of muon capture. Rev. Mod. Phys., 31:802–822, (1959).
[11] B. Goulard and H. Primakoff, Nuclear muon-capture sum rules and mean nuclear excitation energies, Phys. Rev., C., v. 10, no. 5, pp. 2034-2044, (1974).
[12] F. Šimkovic, R. Dvornický, and P. Vogel, Muon capture rates: Evaluation within the quasiparticle random phase approximation, Phys. Rev. C, vol. 102, p. 034 301, 3 (2020).
[13] L. Jokiniemi and J. Suhonen, Muon-capture strength functions in intermediate nuclei of 0nbb decays, Phys. Rev. C, vol. 100, no. 1, p. 014 619, (2019).

[8] E. Mondragón, The MONUMENT Experiment: Ordinary Muon Capture for 0νββ-decay Nuclear Matrix Elements, PhD Thesis, Technical University of Munich (2025)

Conclusions

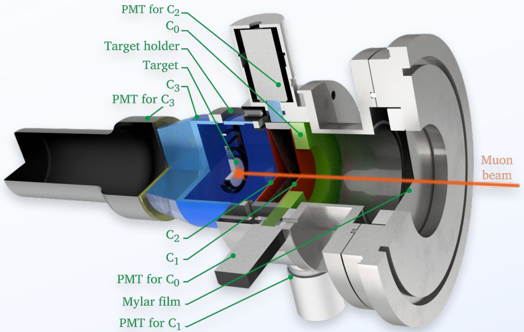
- MONUMENT measures OMC on $\beta\beta$-decay daughter isotopes to inform $0\nu\beta\beta$-decay NME calculations
- New experimental result for ^{76}Se muon lifetime based on novel analysis method
  (134.8 ± 0.7) ns [8]
- First comparison with with phenomenological calculations available

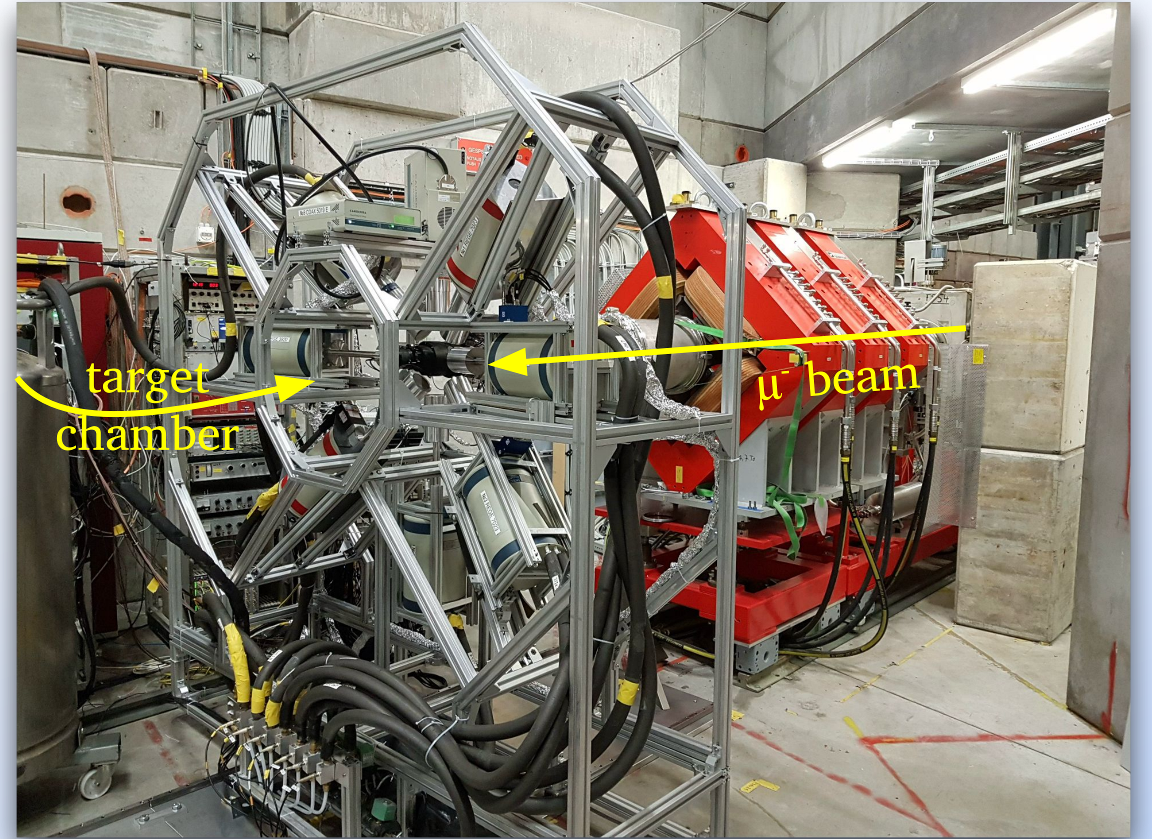


Thanks!

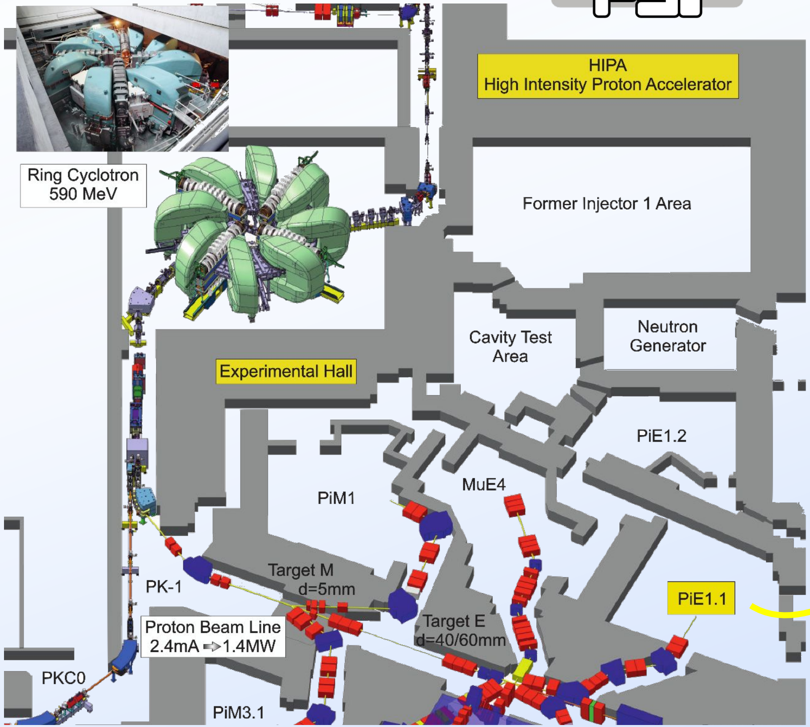
Backup

Measurement



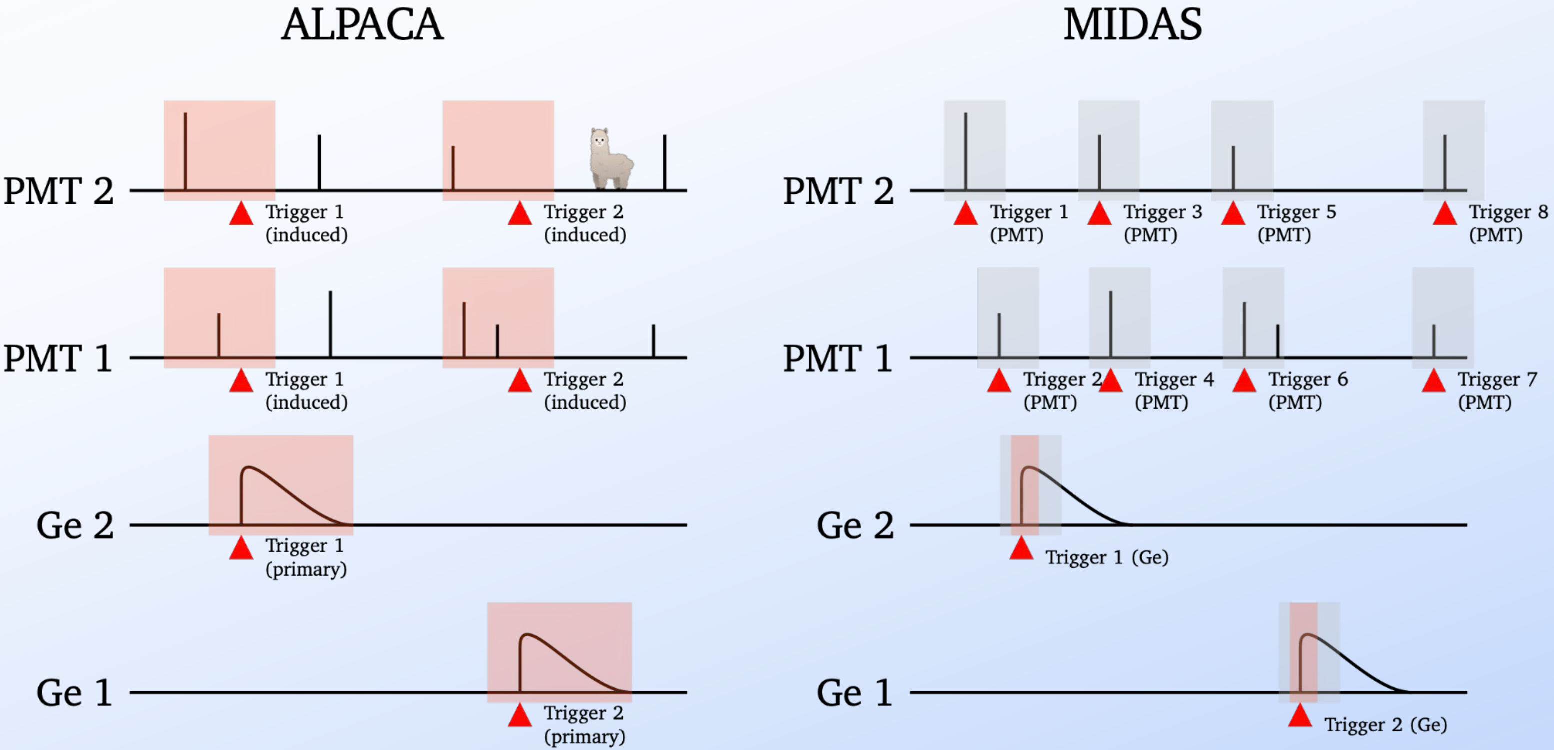


Measurement

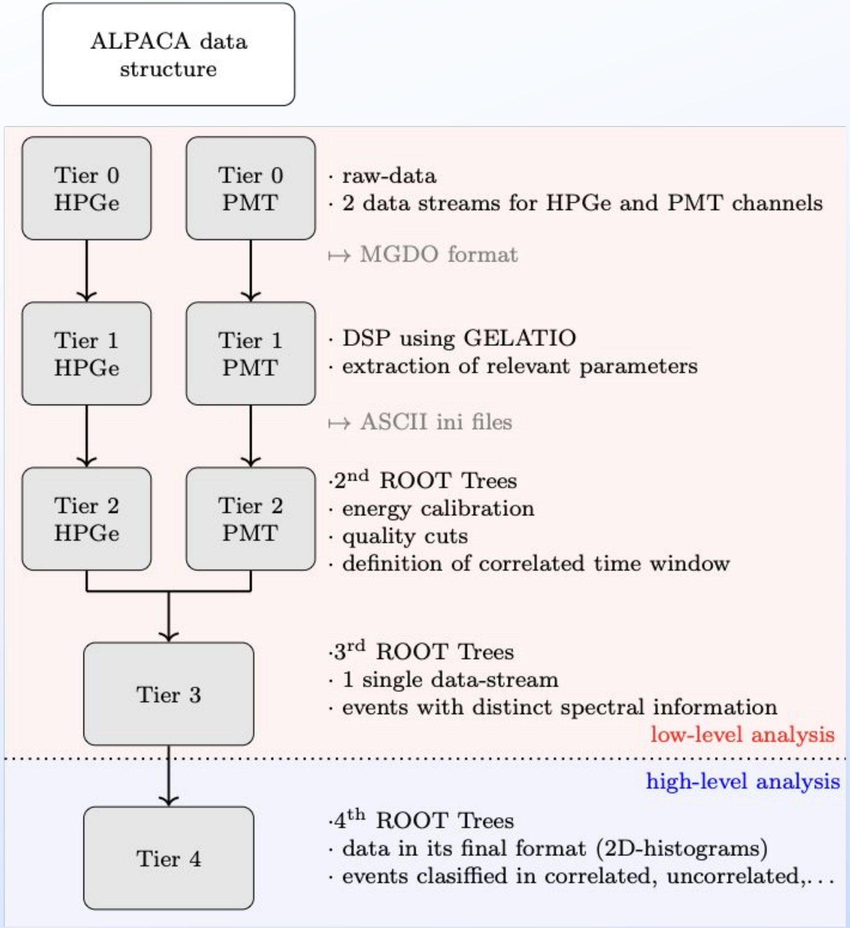


- Muon-beam momentum
  $\sim$40 MeV/c
- Rate of stopped muons
  $\mathcal{O}(10^4)$ Hz
- Rate in HPGe detectors
  $\mathcal{O}(10^3)$ Hz

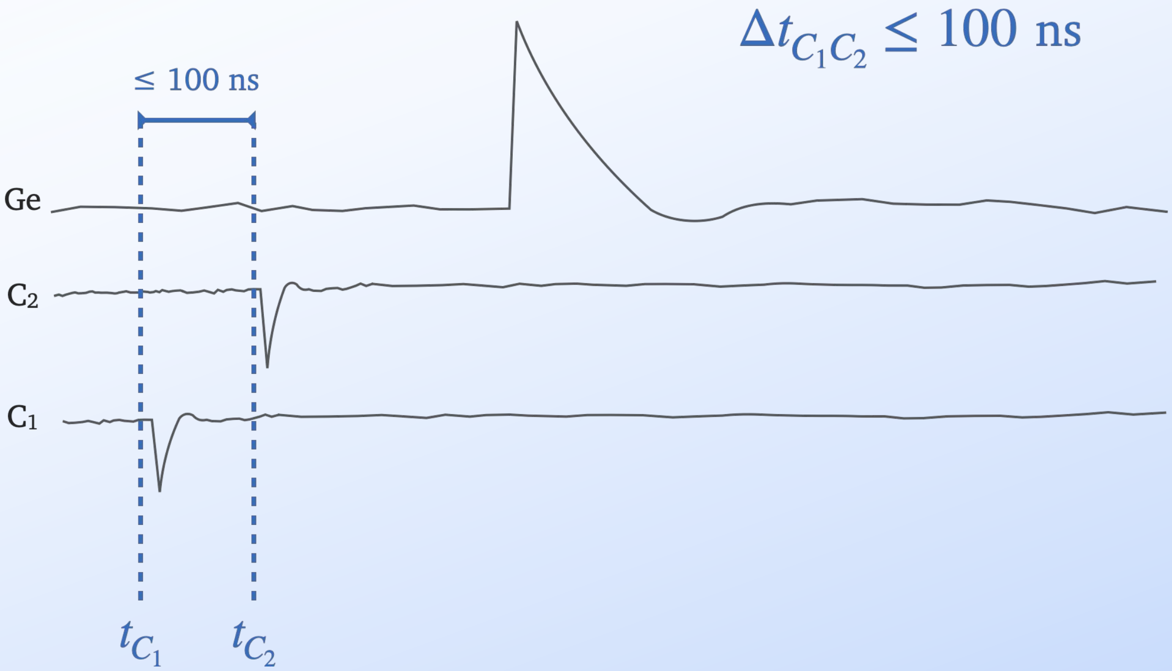
DAQ


ALPACA
MIDAS
PMT 2
Trigger 1 (induced)
Trigger 2 (induced)
PMT 1
Trigger 1 (induced)
Trigger 2 (induced)
Ge 2
Trigger 1 (primary)
Ge 1
Trigger 2 (primary)
PMT 2
Trigger 1 (PMT)
Trigger 3 (PMT)
Trigger 5 (PMT)
Trigger 8 (PMT)
PMT 1
Trigger 2 (PMT)
Trigger 4 (PMT)
Trigger 6 (PMT)
Trigger 7 (PMT)
Ge 2
Trigger 1 (Ge)
Ge 1
Trigger 2 (Ge)

ALPACA

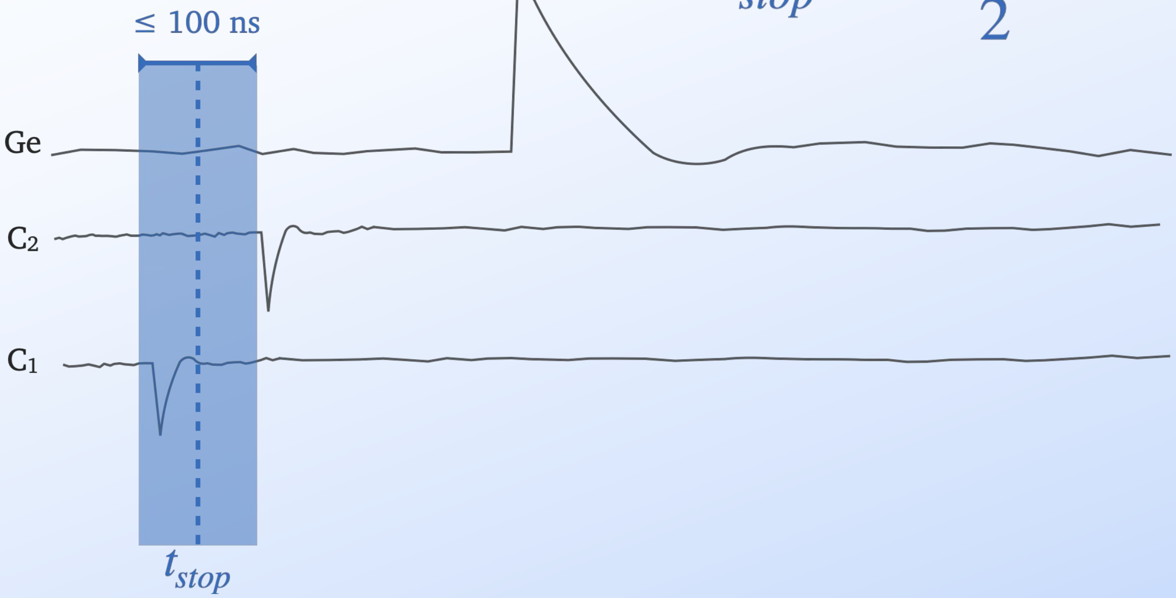

ALPACA data structure
Tier 0 HPGe
Tier 0 PMT
· raw-data
· 2 data streams for HPGe and PMT channels
↦ MGDO format
Tier 1 HPGe
Tier 1 PMT
· DSP using GELATIO
· extraction of relevant parameters
↦ ASCII ini files
Tier 2 HPGe
Tier 2 PMT
·2nd ROOT Trees
· energy calibration
· quality cuts
· definition of correlated time window
Tier 3
·3rd ROOT Trees
· 1 single data-stream
· events with distinct spectral information
low-level analysis
high-level analysis
Tier 4
·4th ROOT Trees
· data in its final format (2D-histograms)
· events clasiffied in correlated, uncorrelated,. . .

ALPACA



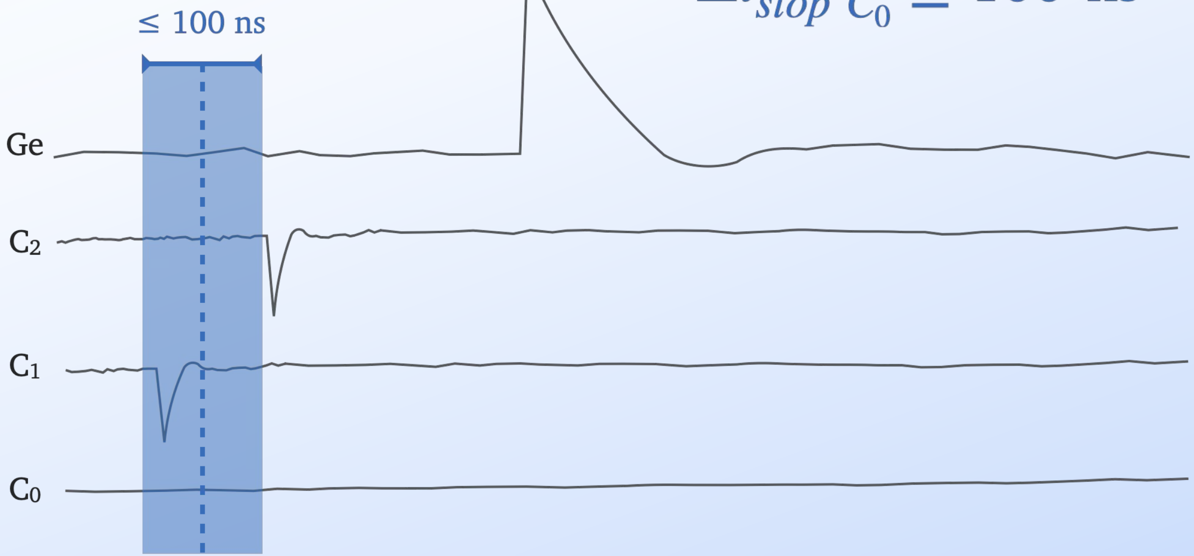
ALPACA

$$t_{stop} = \frac{t_{C_1} + t_{C_2}}{2}$$



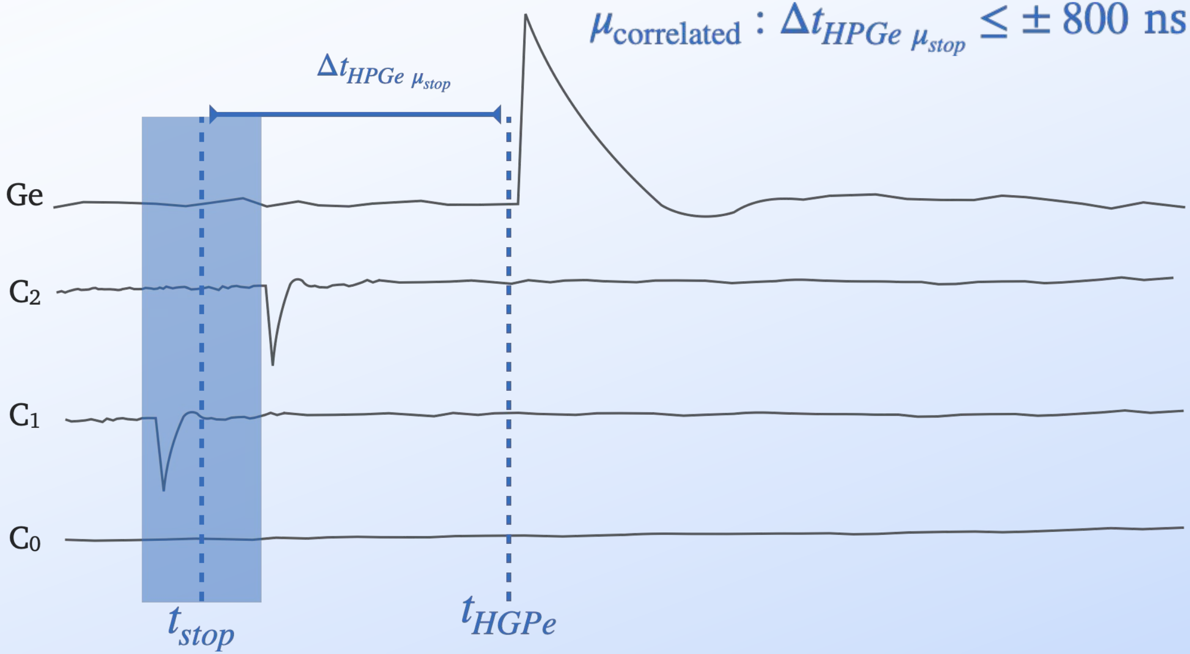
ALPACA

$$\Delta t_{stop\ C_0} \leq 100\ \text{ns}$$

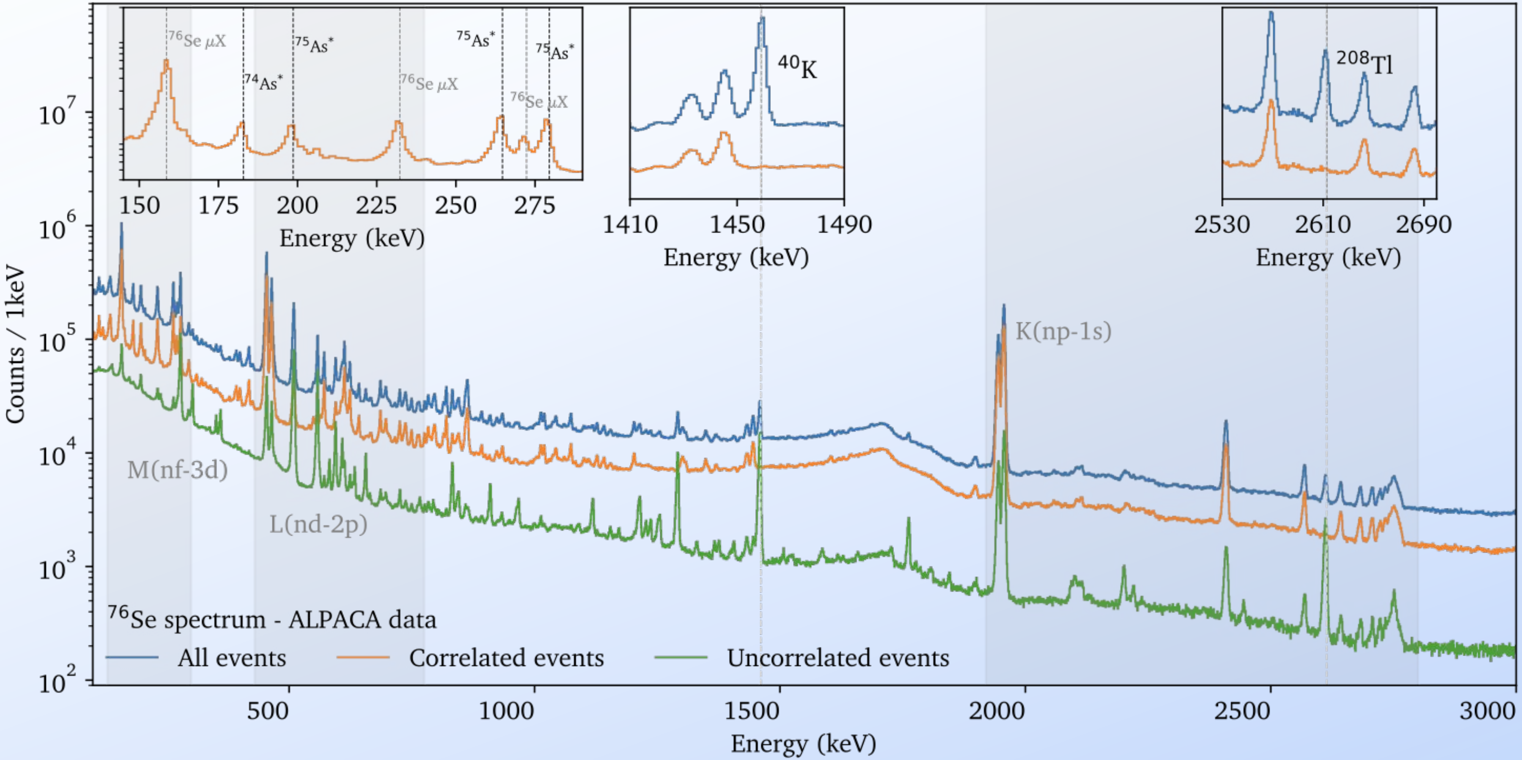


ALPACA

$$\mu_{\mathrm{correlated}} : \Delta t_{HPGe\ \mu_{stop}} \leq \pm 800\ \mathrm{ns}$$



Energy spectrum

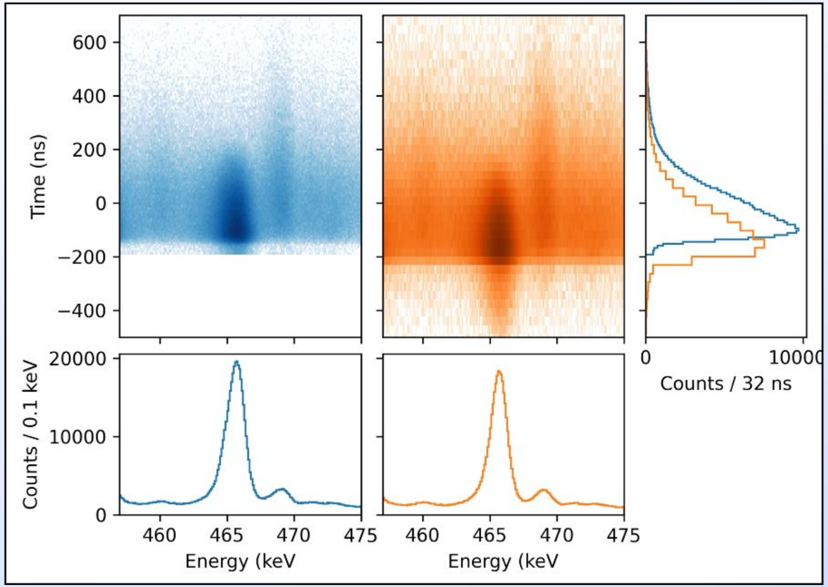


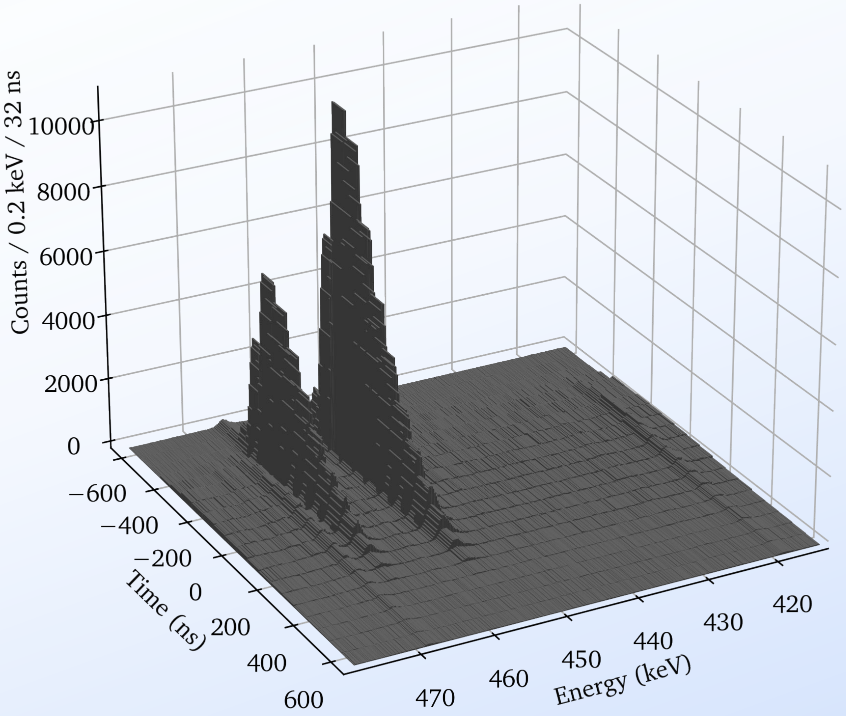
Dataset

126 out of 132 h of beam-on data,

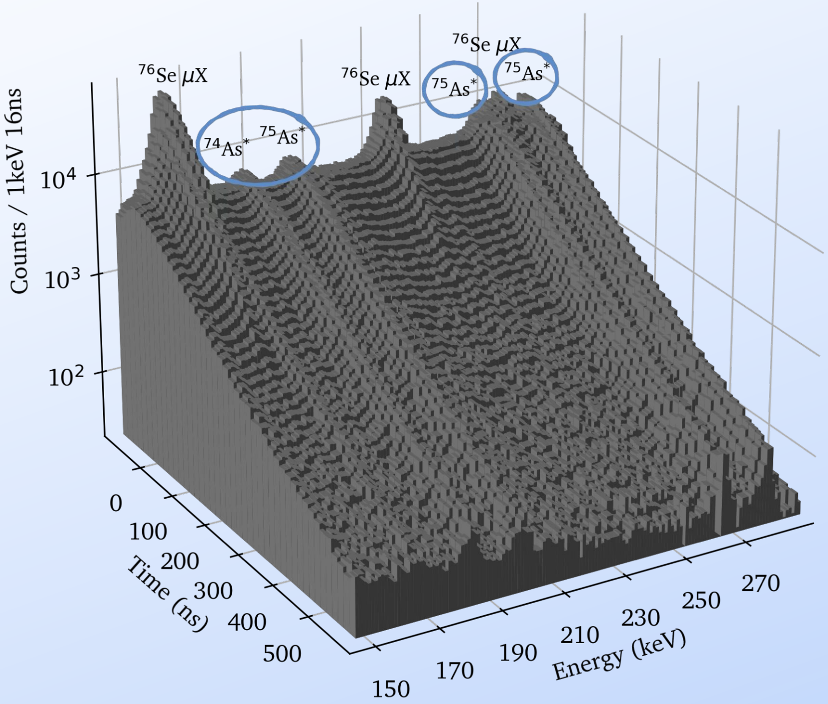
2D histograms mapping **HPGe energy over time** since last muon:

- Correlated events with $\Delta t = \pm$ 800 ns
- High-frequency HPGe waveforms (8ns sampling)
- **Low-frequency PMT** waveforms (32ns sampling)



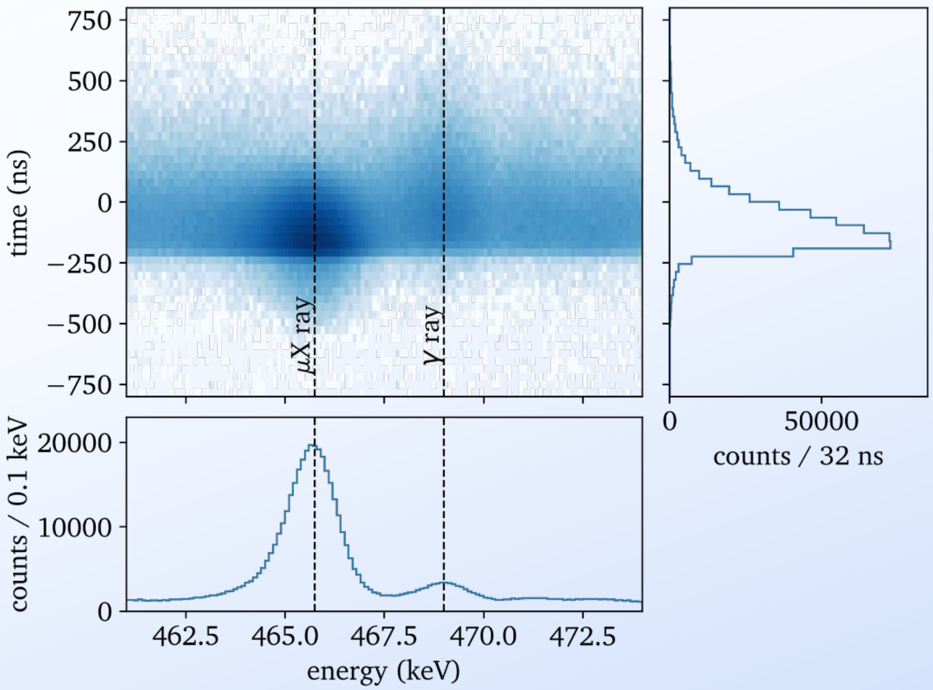


Counts / 0.2 keV / 32 ns
10000
8000
6000
4000
2000
0
−600
−400
−200
0
200
400
600
Time (ns)
470
460
450
440
430
420
Energy (keV)



^{76}Se μX
^{74}As*
^{75}As*
^{76}Se μX
^{75}As*
^{76}Se μX
^{75}As*
Counts / 1keV 16ns
10^4
10^3
10^2
0
100
200
300
400
500
Time (ns)
150
170
190
210
230
250
270
Energy (keV)

High-level analysis: muon lifetime



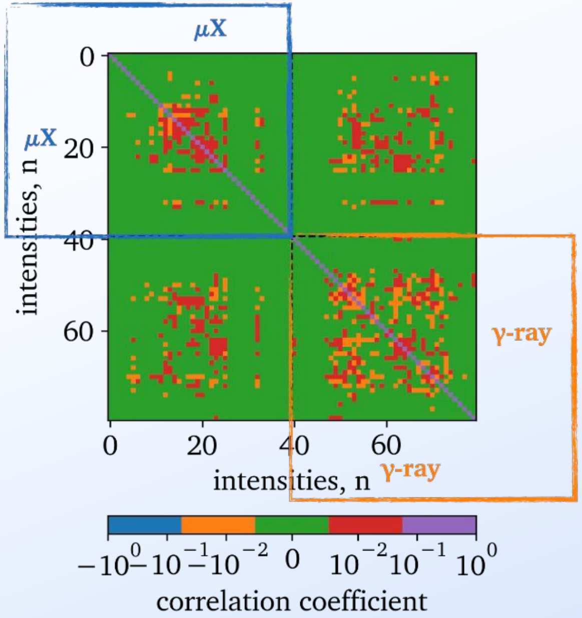
- **BEGe** detector #6
- Doublet of μX and γ ray at (466, 469) keV
- $\Delta t = \pm$ 640 ns → **40 bins in time dimension**
- 10 keV with 0.2 keV binning → **50 bins in energy dimension**
- **2000 data points**

① Time profile extraction

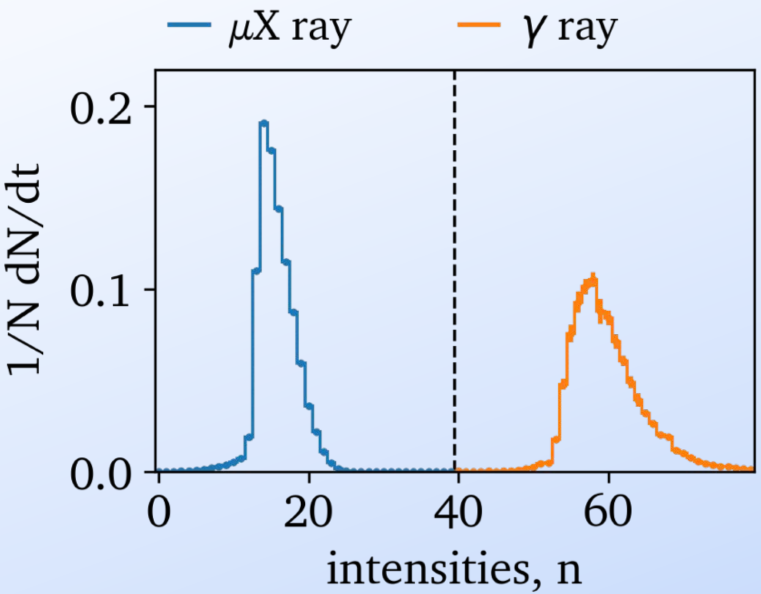
- Combined maximum likelihood fit using **Poisson likelihood**
- Shared shape (σ, α, β) and position (μ) parameters per line, individual intensity (n_j) and background (p_{0j}, p_{1j}) parameters per time slice j, **168 free parameters**
- Gaussian pull terms for systematics, **160 constrained parameters***

*Discussed in Systematics

① Time profile extraction



Marginalised covariance matrix Θ propagated to step ②, correlation not negiligible, up to $\mathcal{O}(10\%)$



1D histograms representing μX- and γ-ray intensities over time

Systematics

A. Line position drift (①, ①②)

B. Background shape (①②)

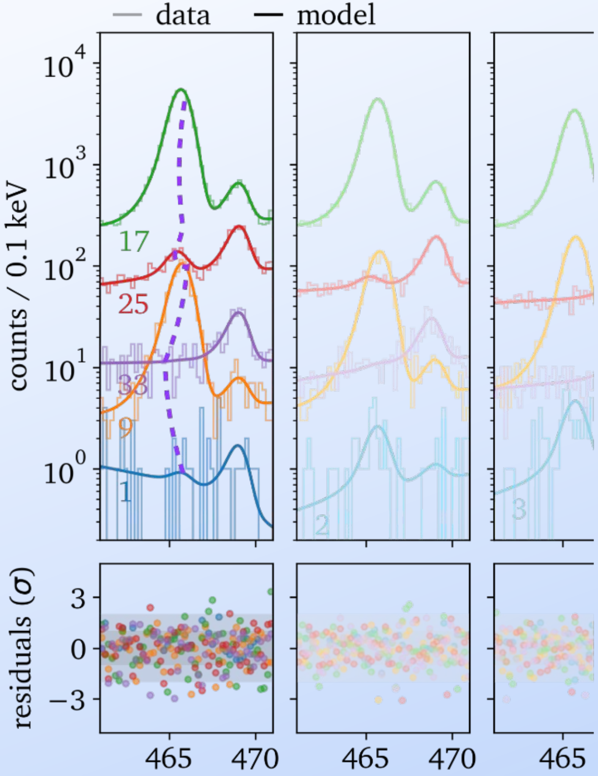
C. Prompt timing energy
-dependence (②)

A. Line position drift

Hypothesis:

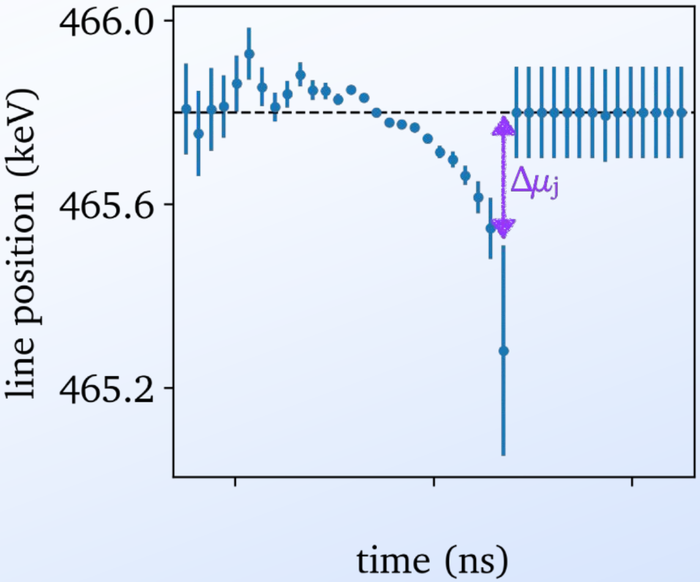
Time *slices correspond to HPGe detector* ***drift time selection****, later events are reconstructed with lower energies*

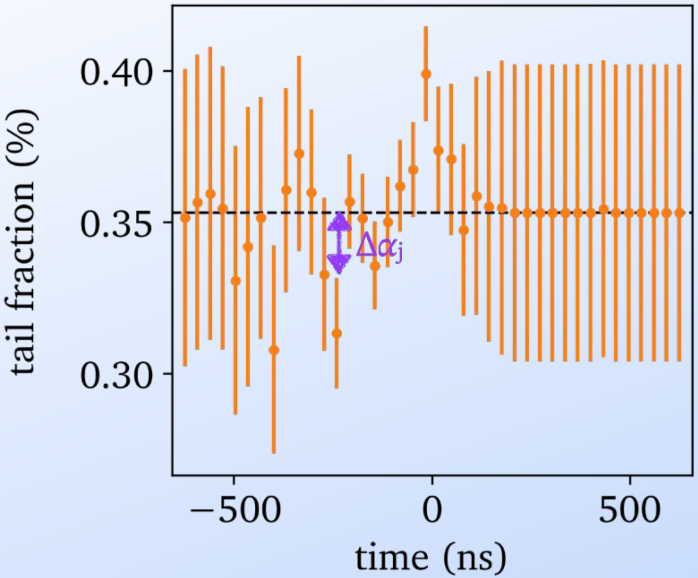
- Include **additional parameters** ($\Delta\mu_j$ and $\Delta\alpha_j$), bound by **pull terms** (1 keV and 5%) ↳①
- Additional uncertainty for slices where no line is present (statistical uncertainty of background counts under each peak, $\sqrt{p_0 \times FWTM}$) ↳ ①②



A. Line position drift

± 0.7 ns

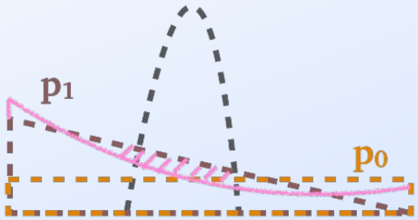


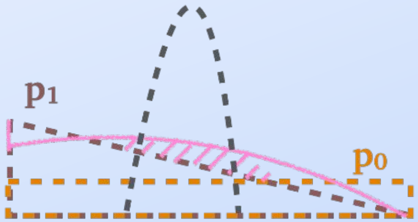


B. Background shape

- Simple **linear function might be insufficient** in some cases
- Convex/concave background shape can lead to **under/over-estimation of intensity**

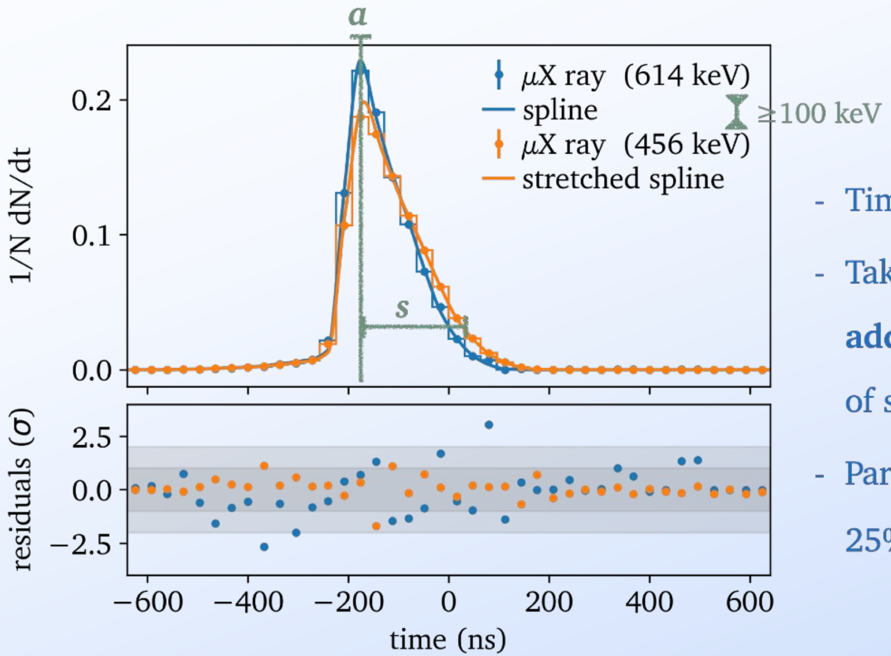
± 0.9 ns





- Assume number of **counts attributed to slope as uncertainty** that is missed without higher order of polynomial ↳ ① ②

C. Prompt timing energy-dependence



± 3.3 ns

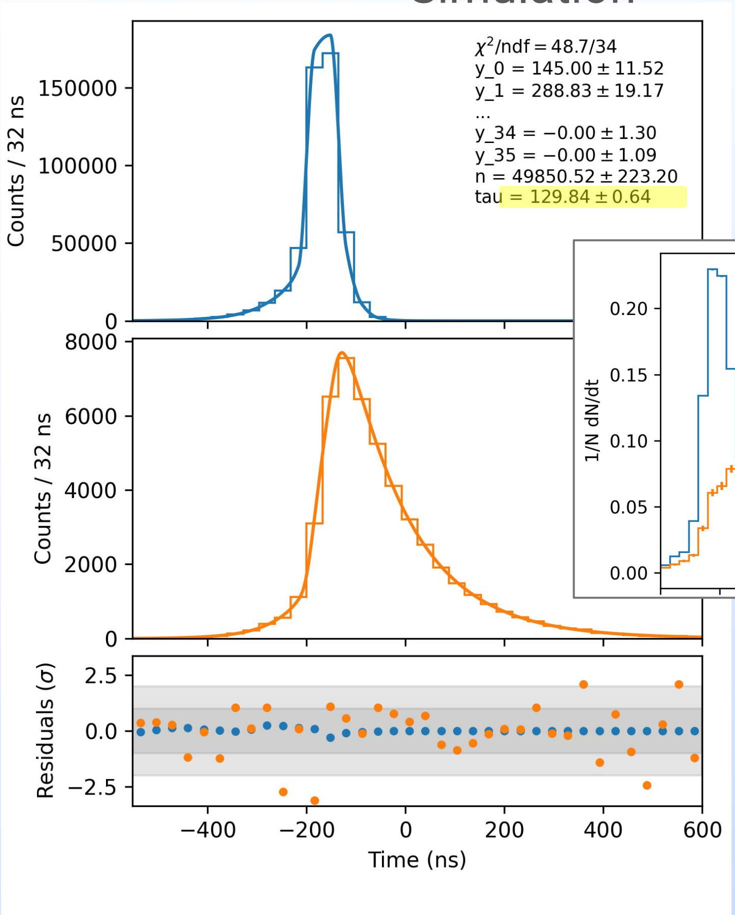
- Time response is energy and HPGe dependent
- Taken into account as **transformation adding 2 additional parameters**: stretch ***s*** from anchor ***a*** of spline before convolution
- Parameters constrained by **pull terms** (64 ns, 25%) based on μX rays ↳②

Features

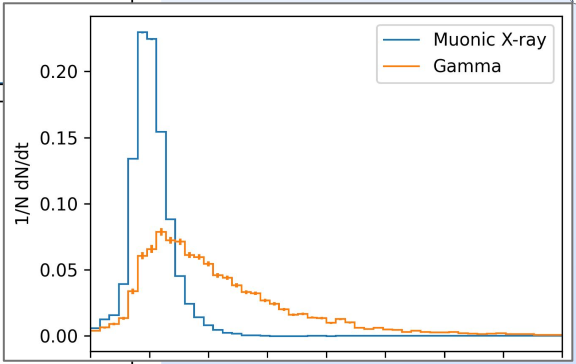
(Simulating detector 7 data…)

- **Asymmetric timing** modeled by two Gaussians with different central value and different left and right tail
- True Monte Carlo lifetime is 130 ns (feeding tau)

Simulation



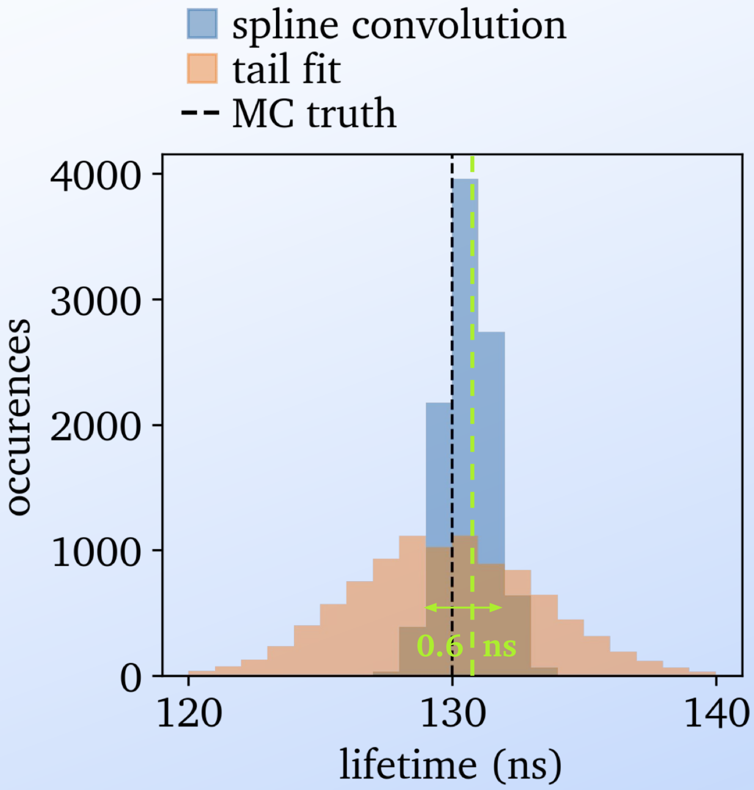
Real



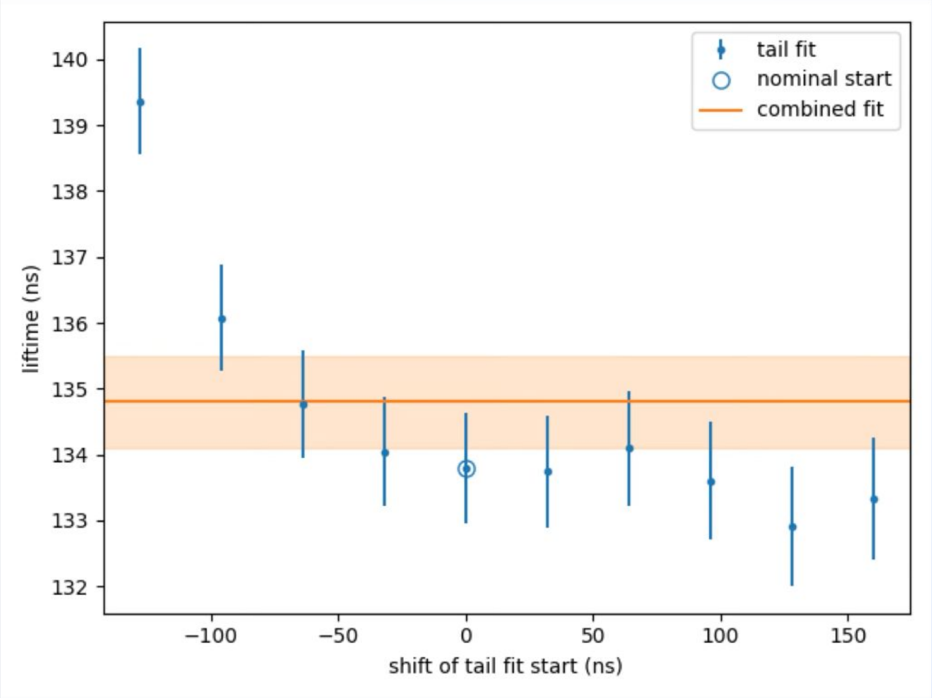
Toy study

- Monte Carlo study
  - Generate time profiles that resemble the real dataset using asymmetric prompt timing distribution
  - Apply combined lifetime fit (and tail fit) method

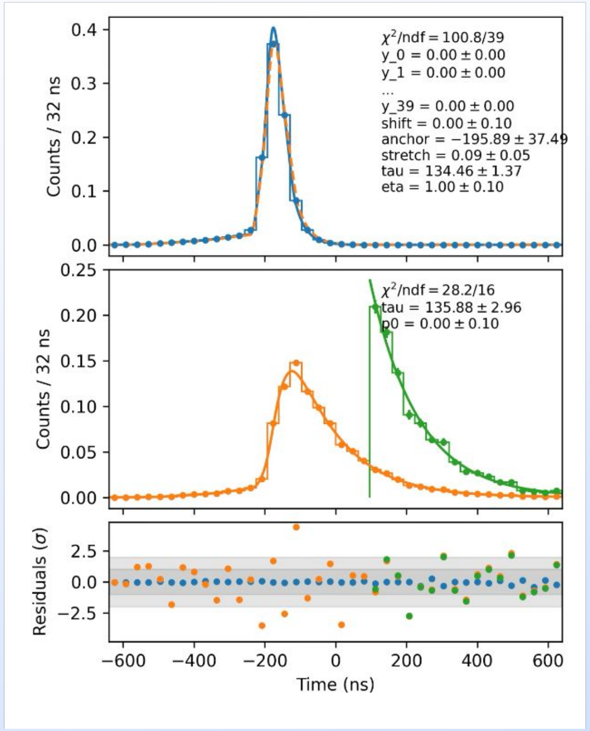
- Median result differs from Monte Carlo truth, added as method uncertainty to final result



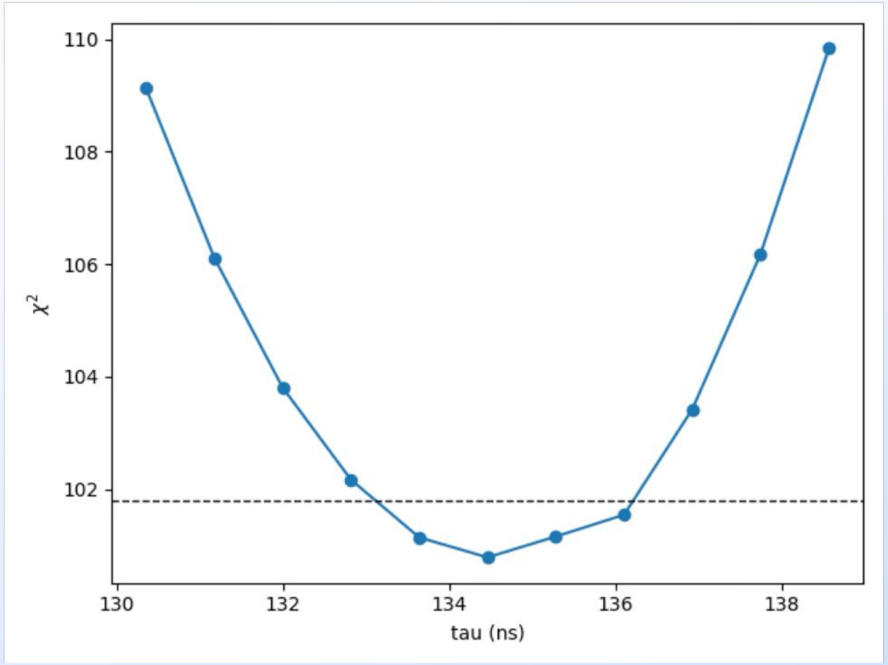
Tail fit start dependence



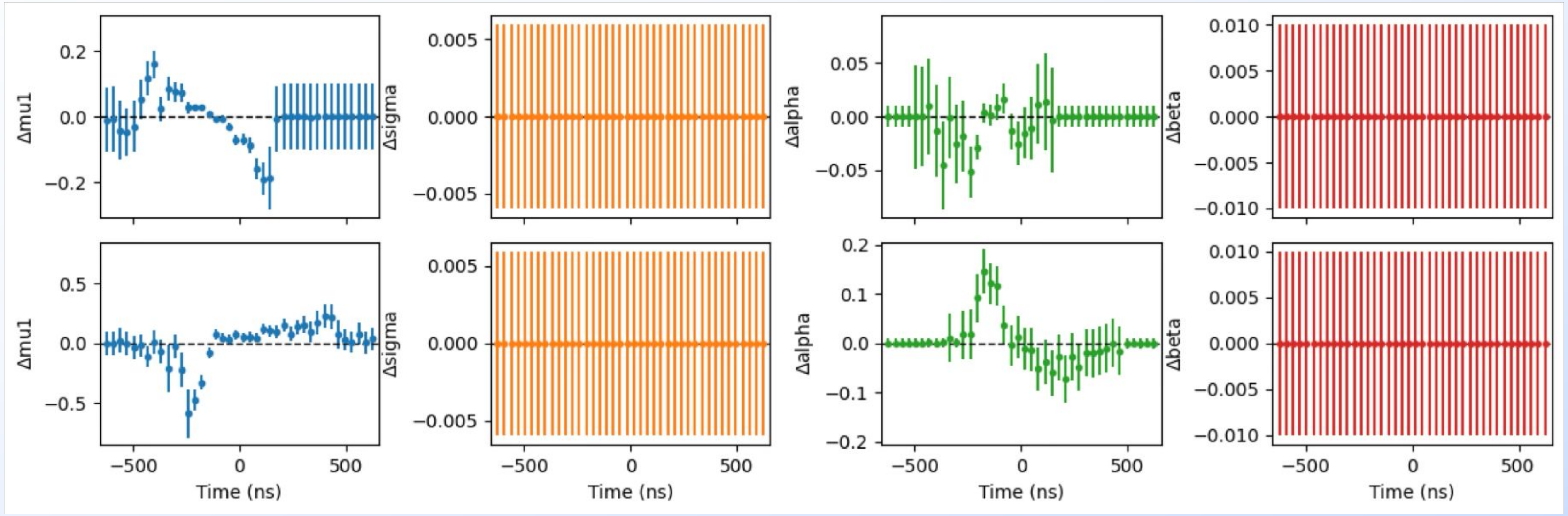
Example of “bad χ^2 -fit”



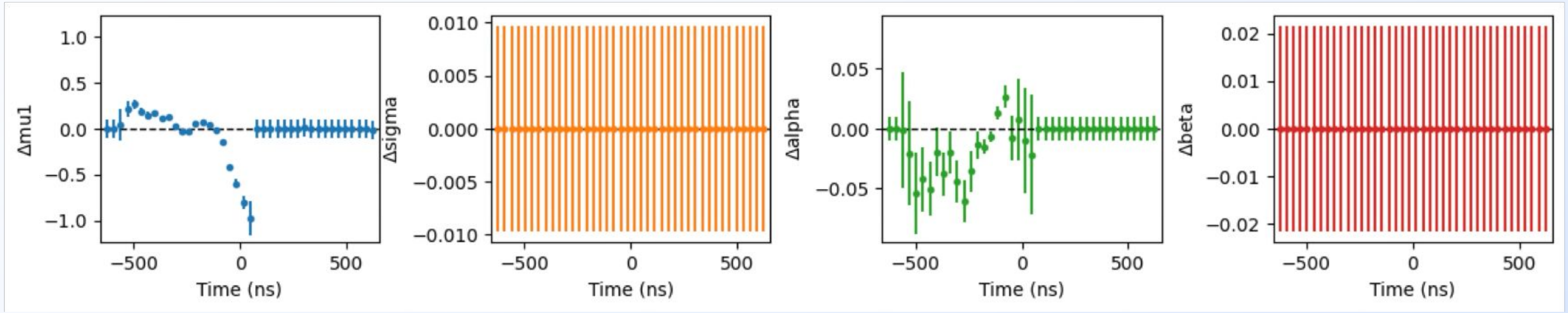
χ^2 profile



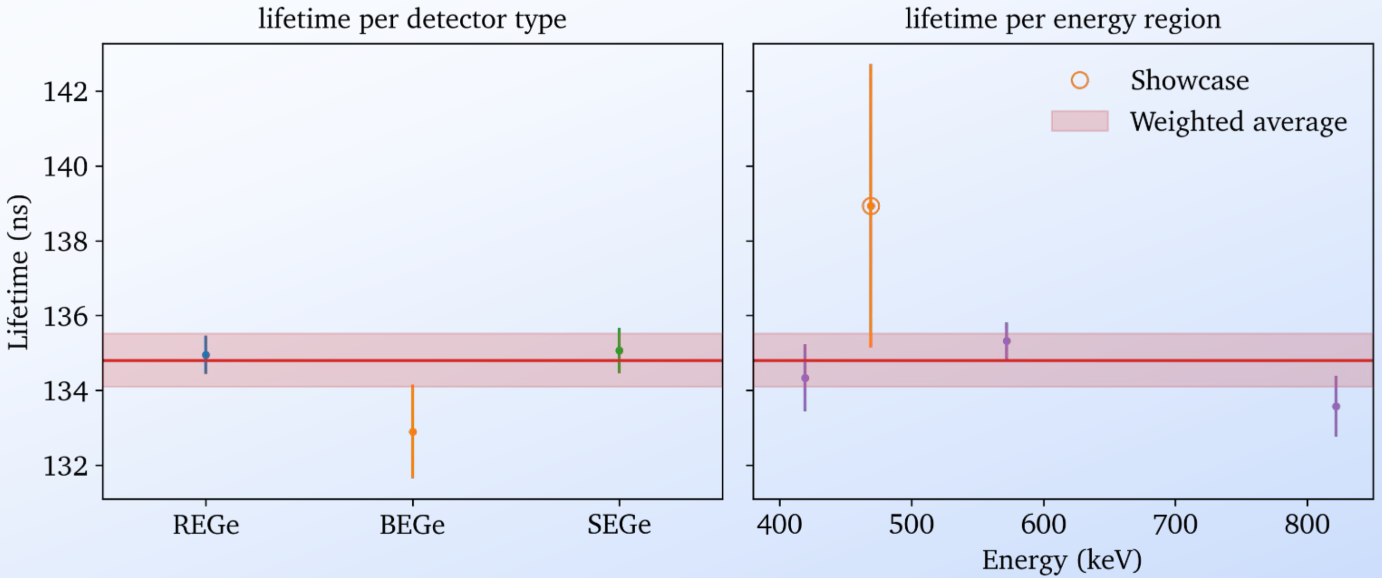
μ and α change over time



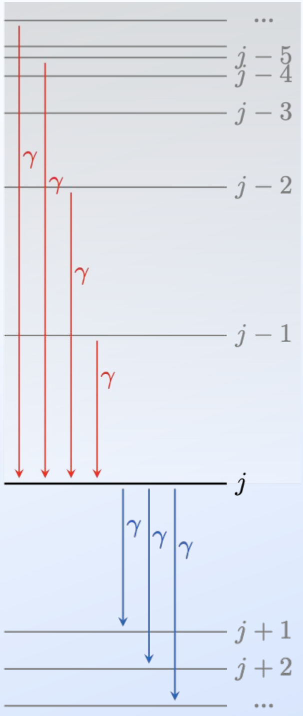
μ and α change over time



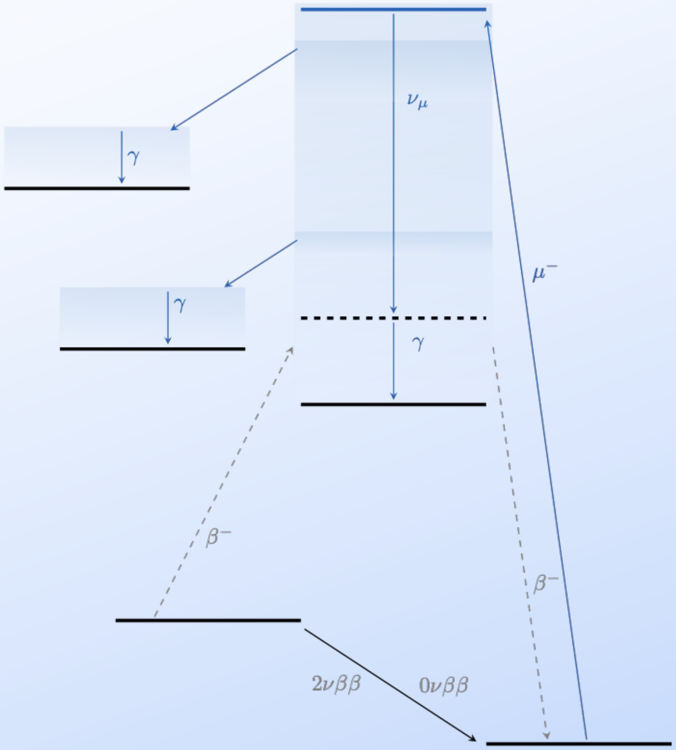
Results: per detector / energy



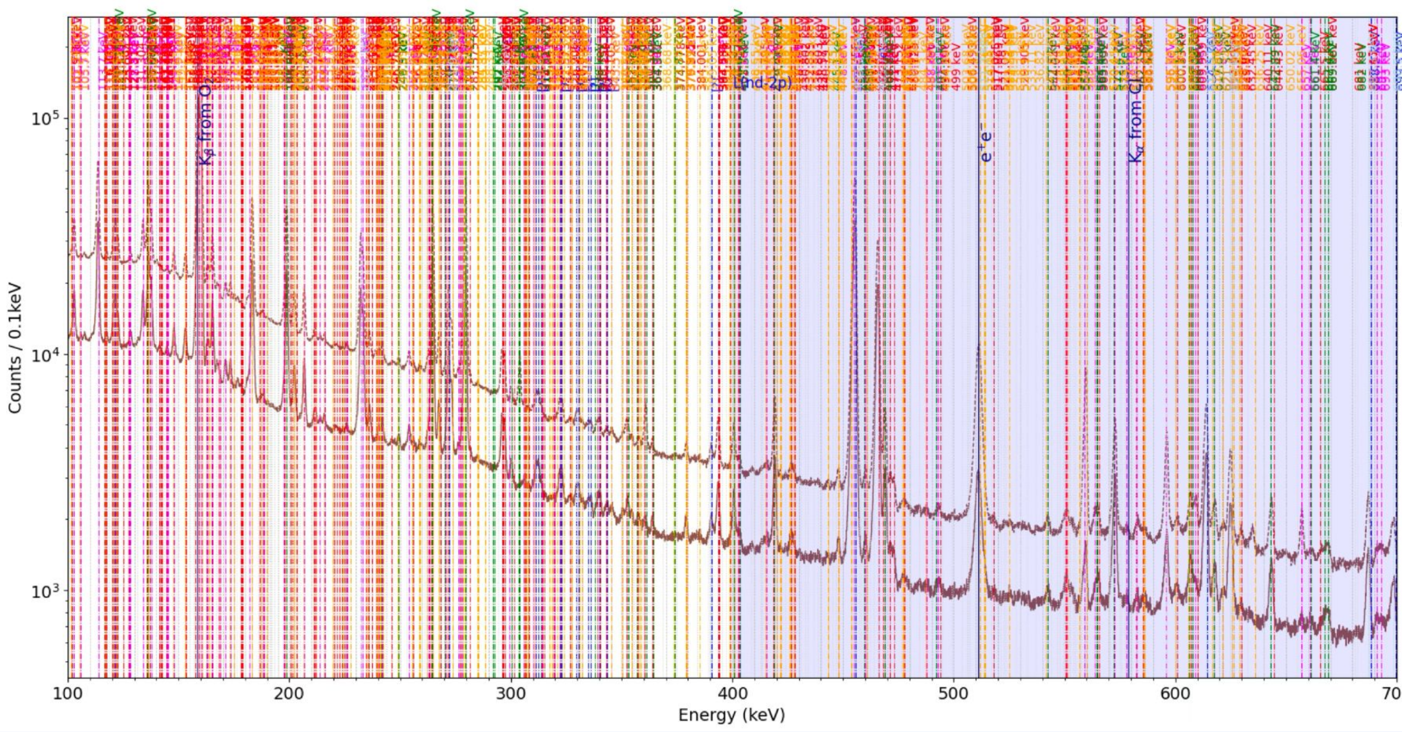
High-level analysis: strength functions



$$\mathcal{I}_j^{\mu} = \sum_j \gamma_{j\downarrow} - \sum_j \gamma_{j\uparrow}$$



High-level analysis: strength functions



$$Y_j^\mu = \frac{\sum I_{i\downarrow}^{\gamma} - \sum I_i^{\gamma\downarrow}}{\varepsilon \sum_n I(K_n)}$$

499.6 keV-level

Difficult to see due to
a) detector efficiency
and b) low statistics