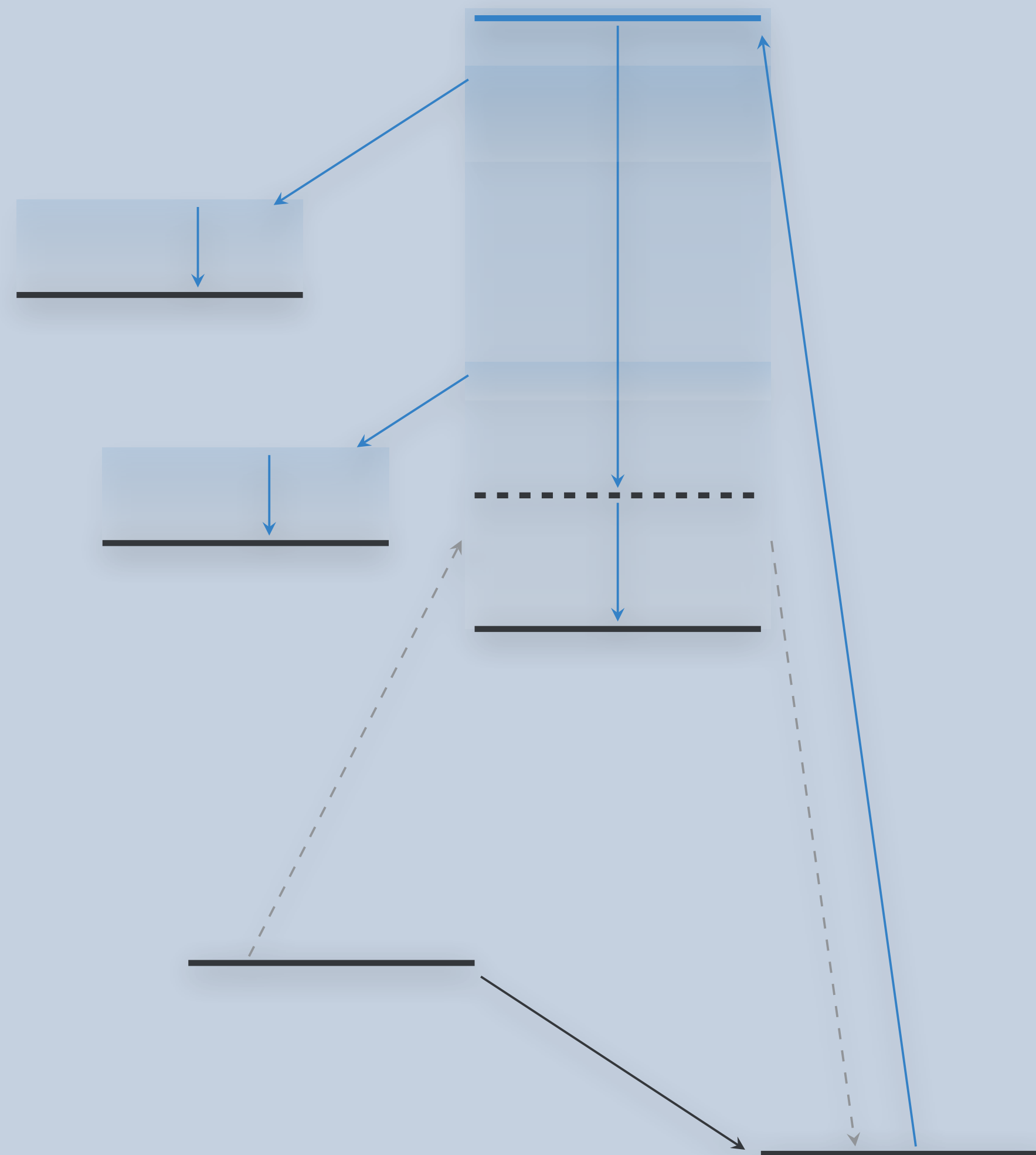
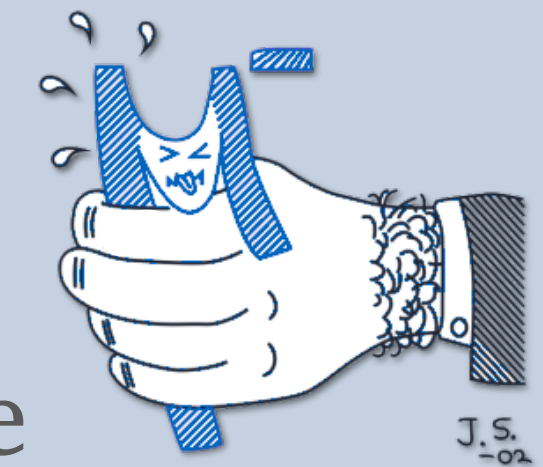




The MONUMENT Experiment

Probing ^{76}Ge Neutrinoless Double Beta Decay through **Ordinary Muon Capture** on ^{76}Se



Elizabeth Mondragón

August 24th 2025

Collaboration



Collaboration meeting in Munich, 2022

Formed in 2021
30 members
12 institutions

ETH Zurich,
Switzerland

IEAP, CTU, Prague,
Czech Republic

CIFRA, Romania

JINR, Dubna, Russia

KU Leuven, Belgium

**Osaka University,
Japan**

PSI, Switzerland

**Technical University
of Munich, Germany**

The University of
Alabama, USA

Universiti Teknologi
Malaysia, Malaysia

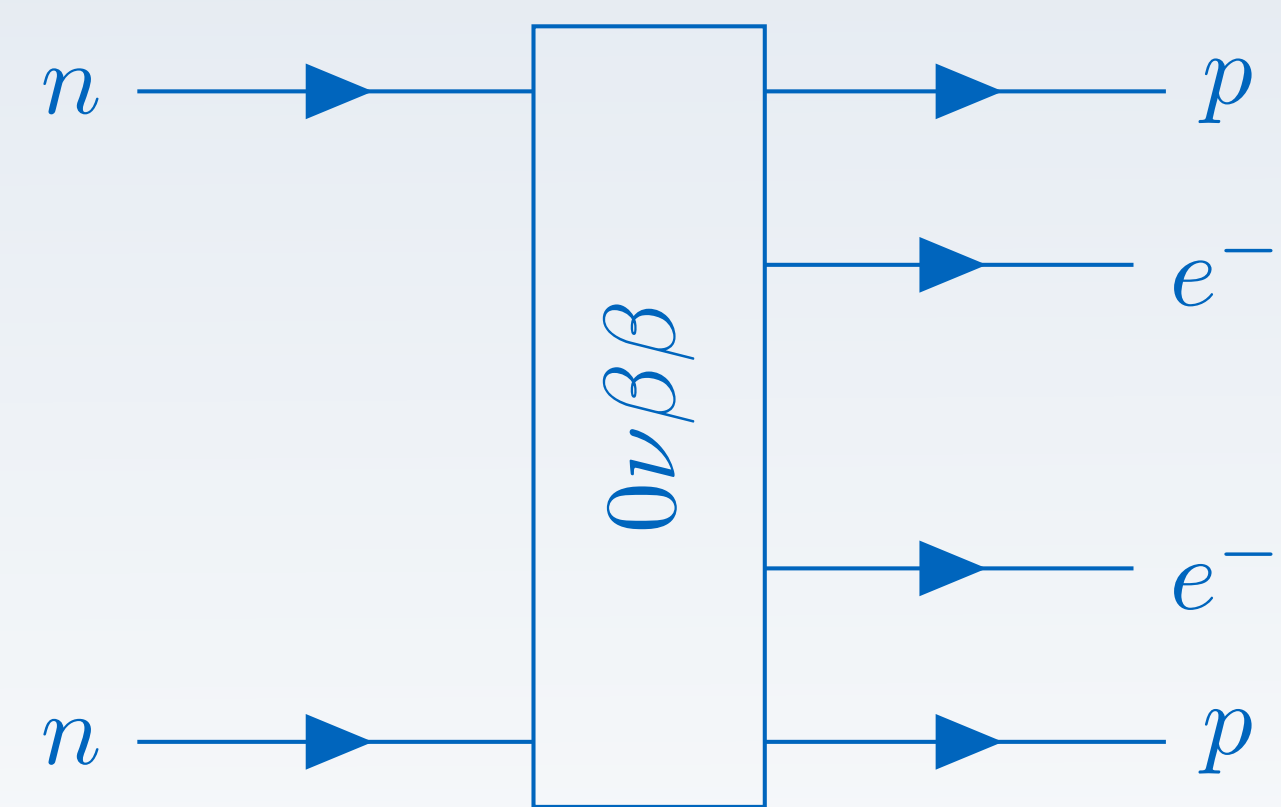
University of Jyväskylä,
Finland

University of Zurich,
Switzerland

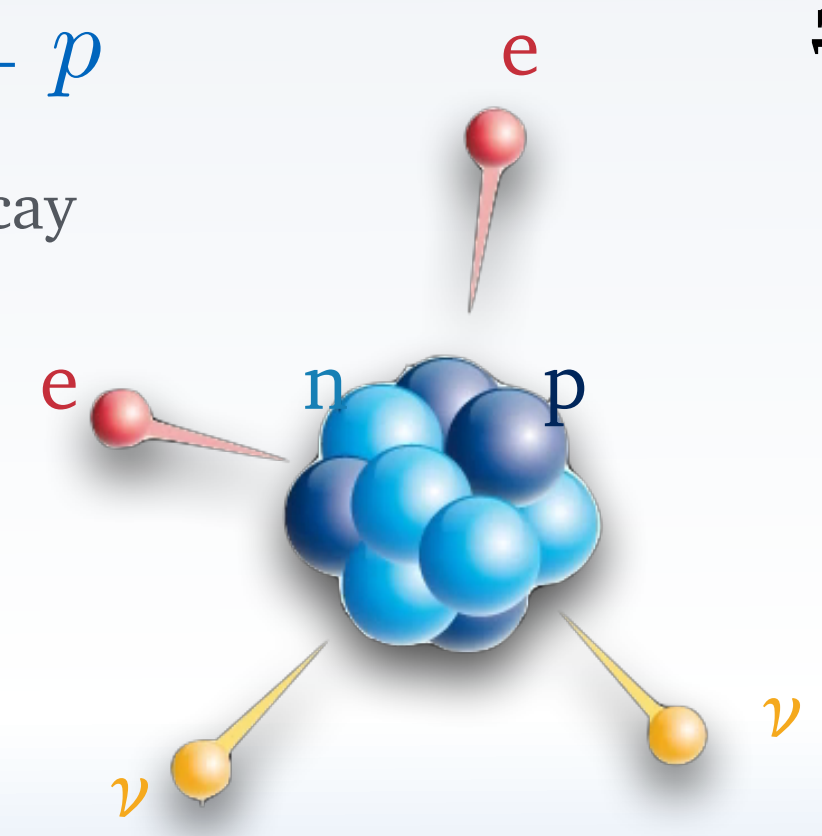
[3] MONUMENT Collaboration, Determination of the muon lifetime in ^{76}Se with the MONUMENT experiment, Phys. Rev. C, vol. 113, 064613 (2026)

Motivation

$0\nu\beta\beta$ decay



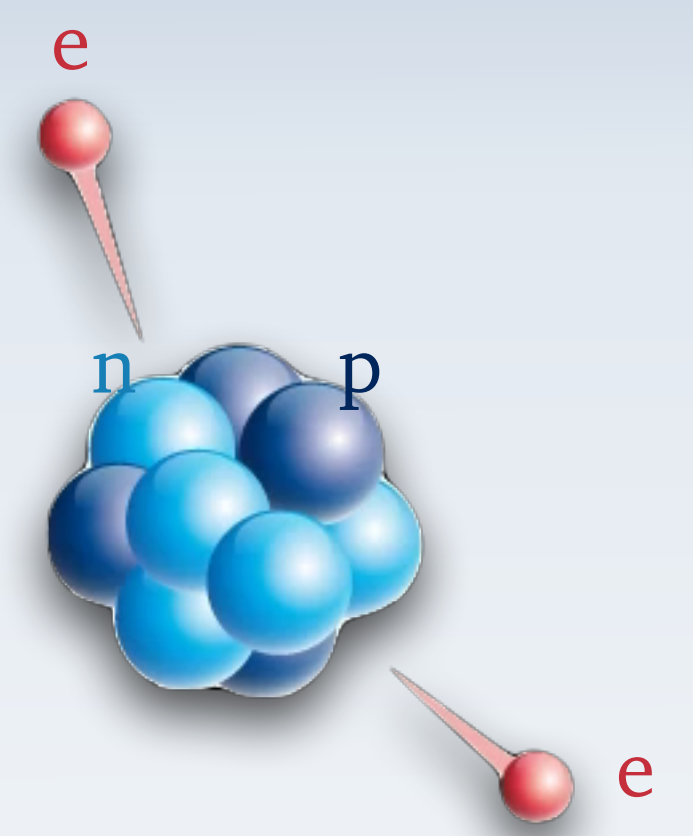
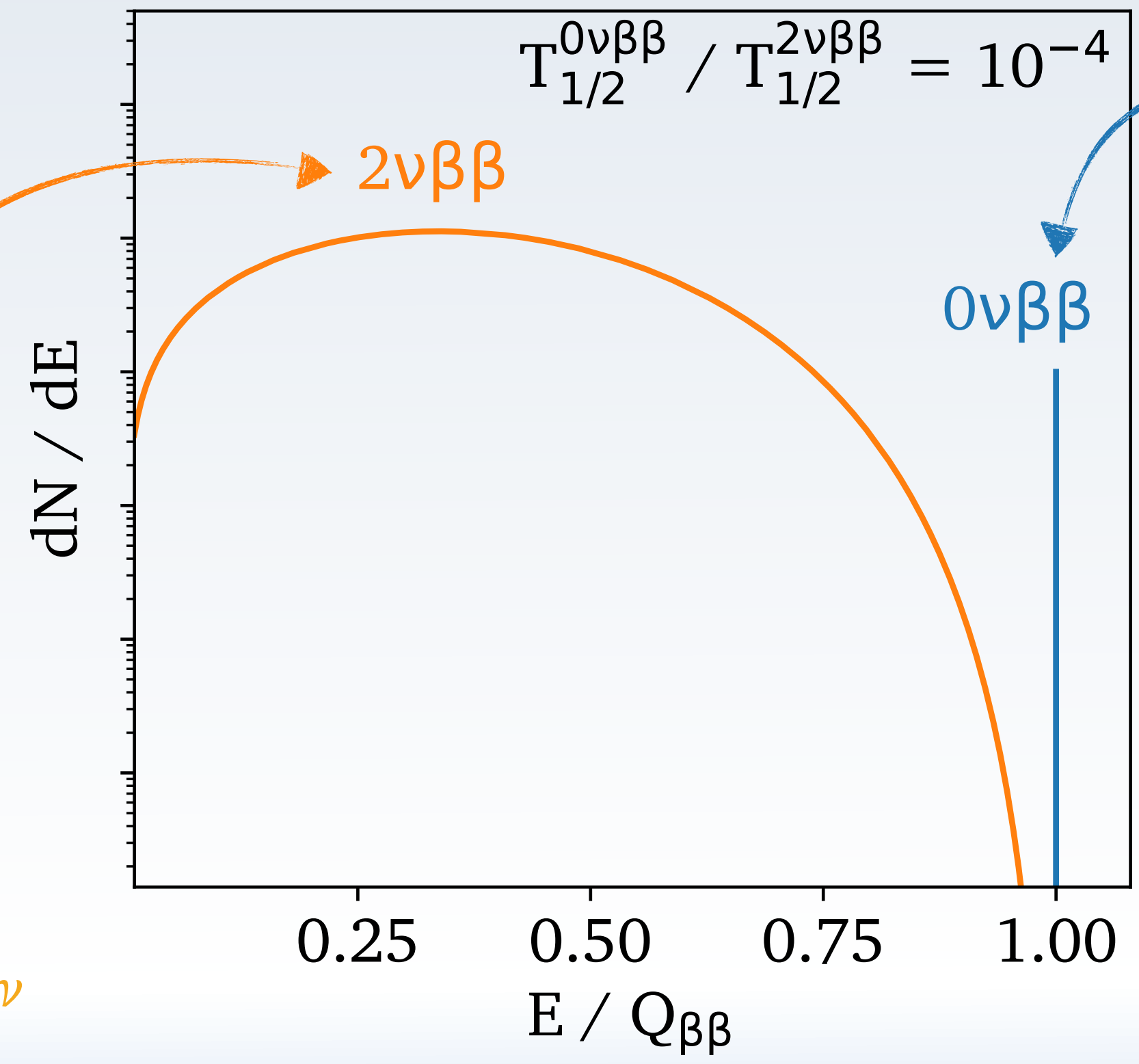
Neutrinoless double beta ($0\nu\beta\beta$) decay



$2\nu\beta\beta$ decay [4]

SM allowed
2nd order process
 $T_{1/2} > 10^{18}$ yr

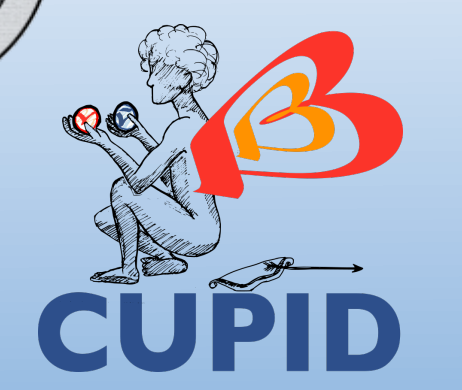
Experimental Signature



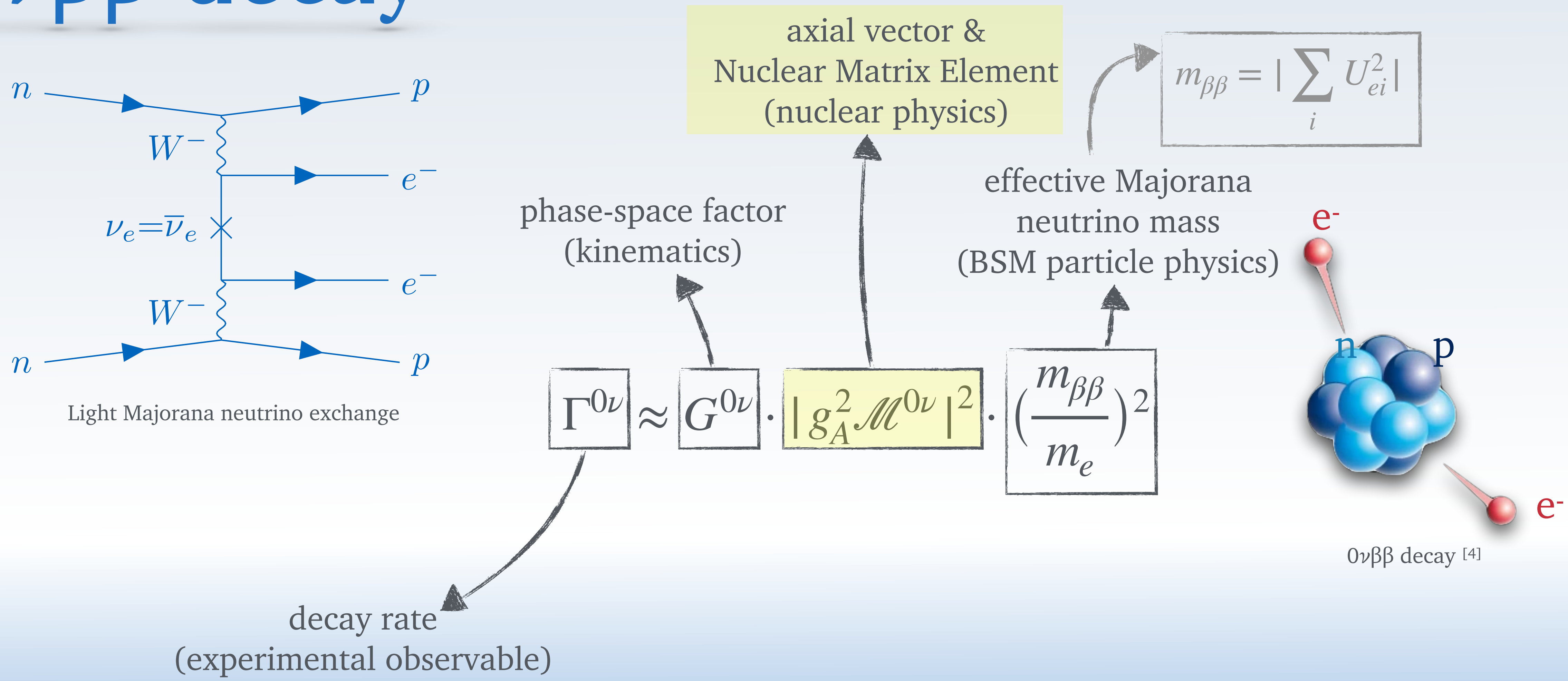
$0\nu\beta\beta$ decay [4]

Beyond the SM physics
Majorana nature of
neutrinos
 $T_{1/2} > 10^{26}$ yr
Limits on $m_{\beta\beta}$

LEGEND

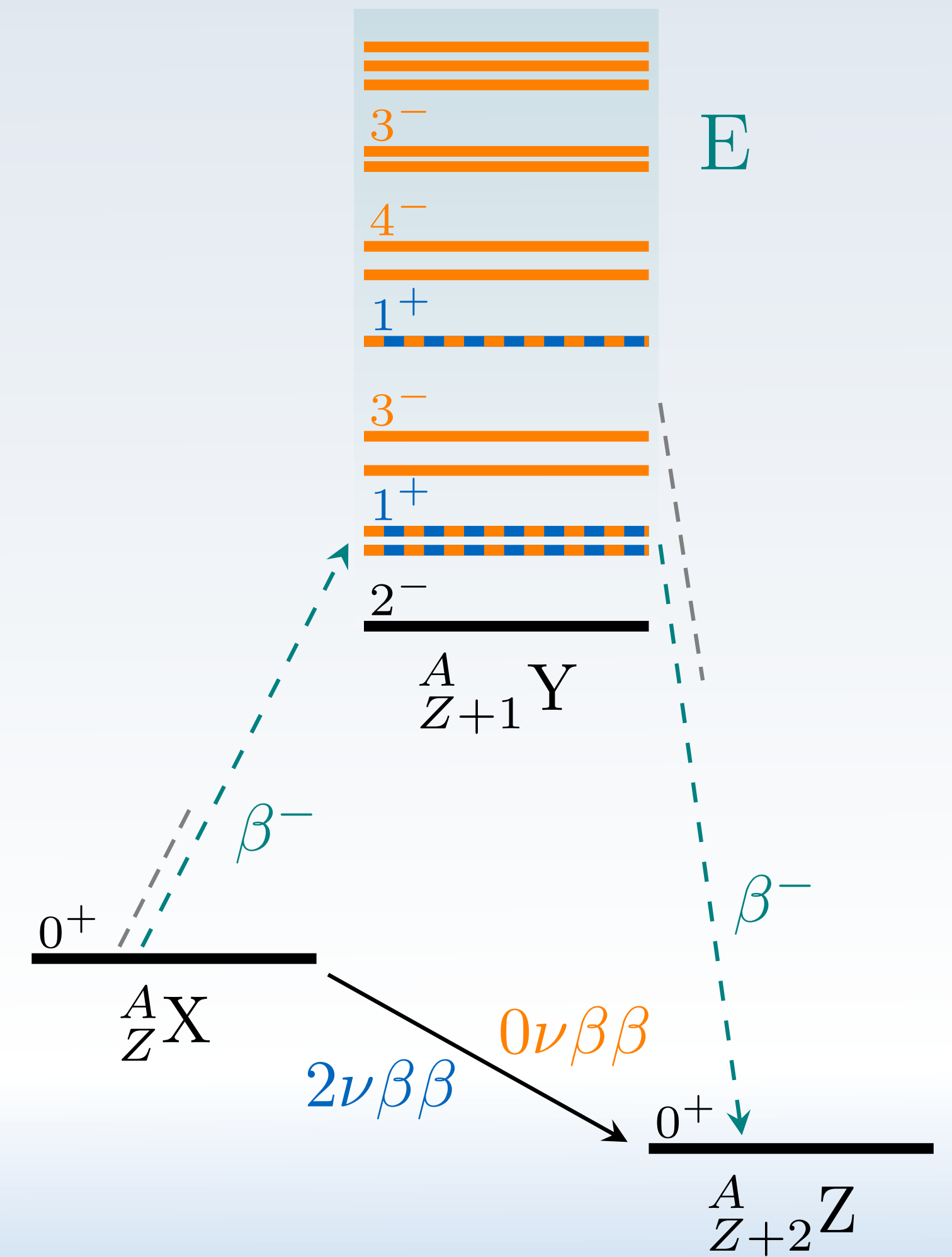
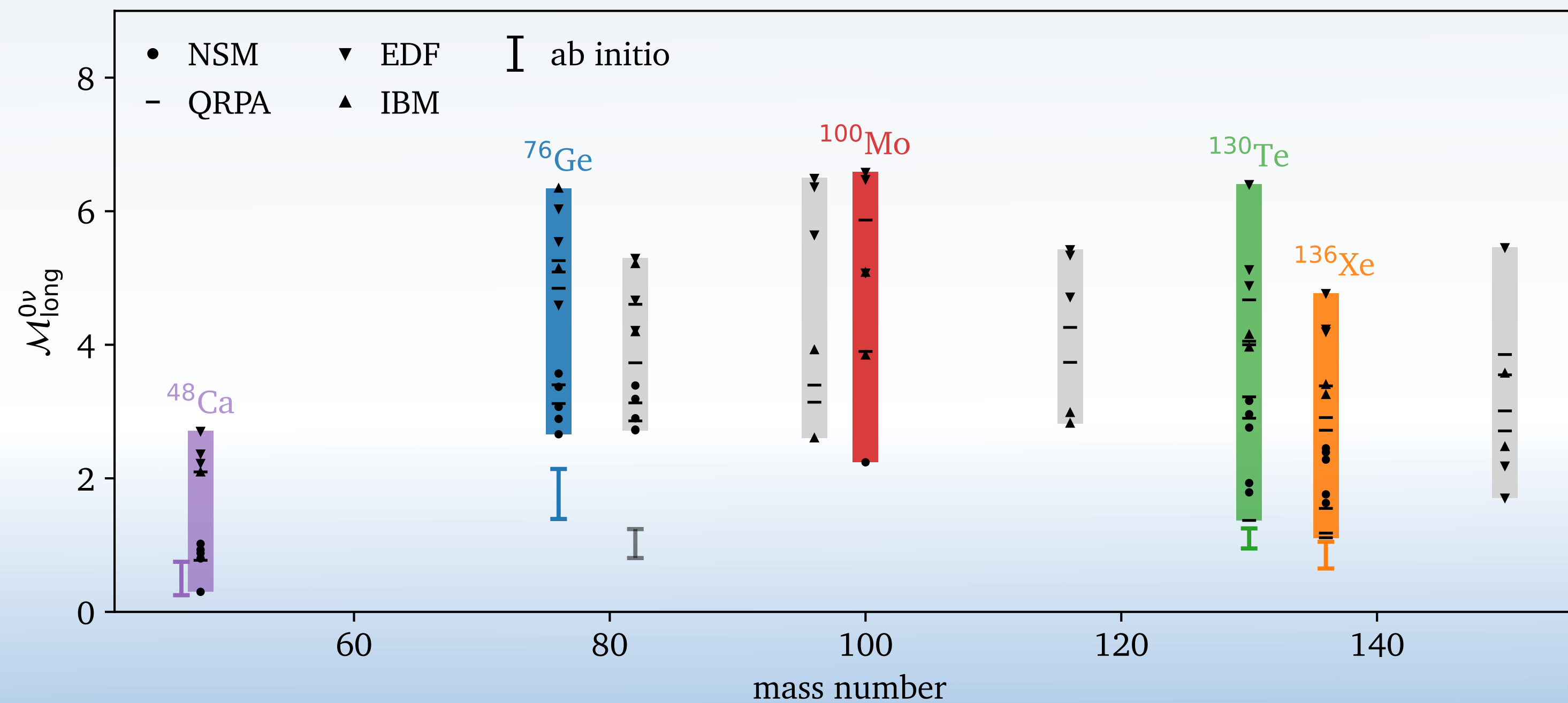


$0\nu\beta\beta$ decay



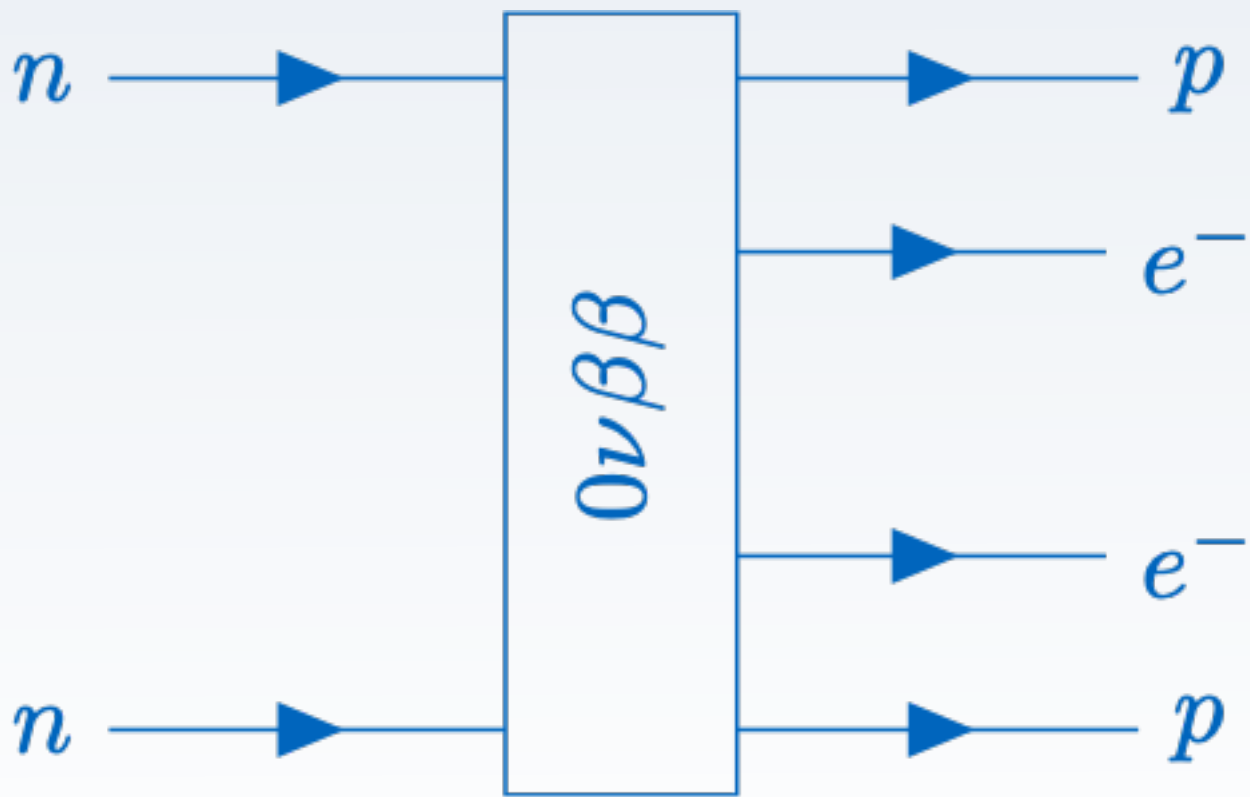
$0\nu\beta\beta$ decay

$$\Gamma^{0\nu} \approx G^{0\nu} \cdot |g_A^2 \cdot \mathcal{M}^{0\nu}|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

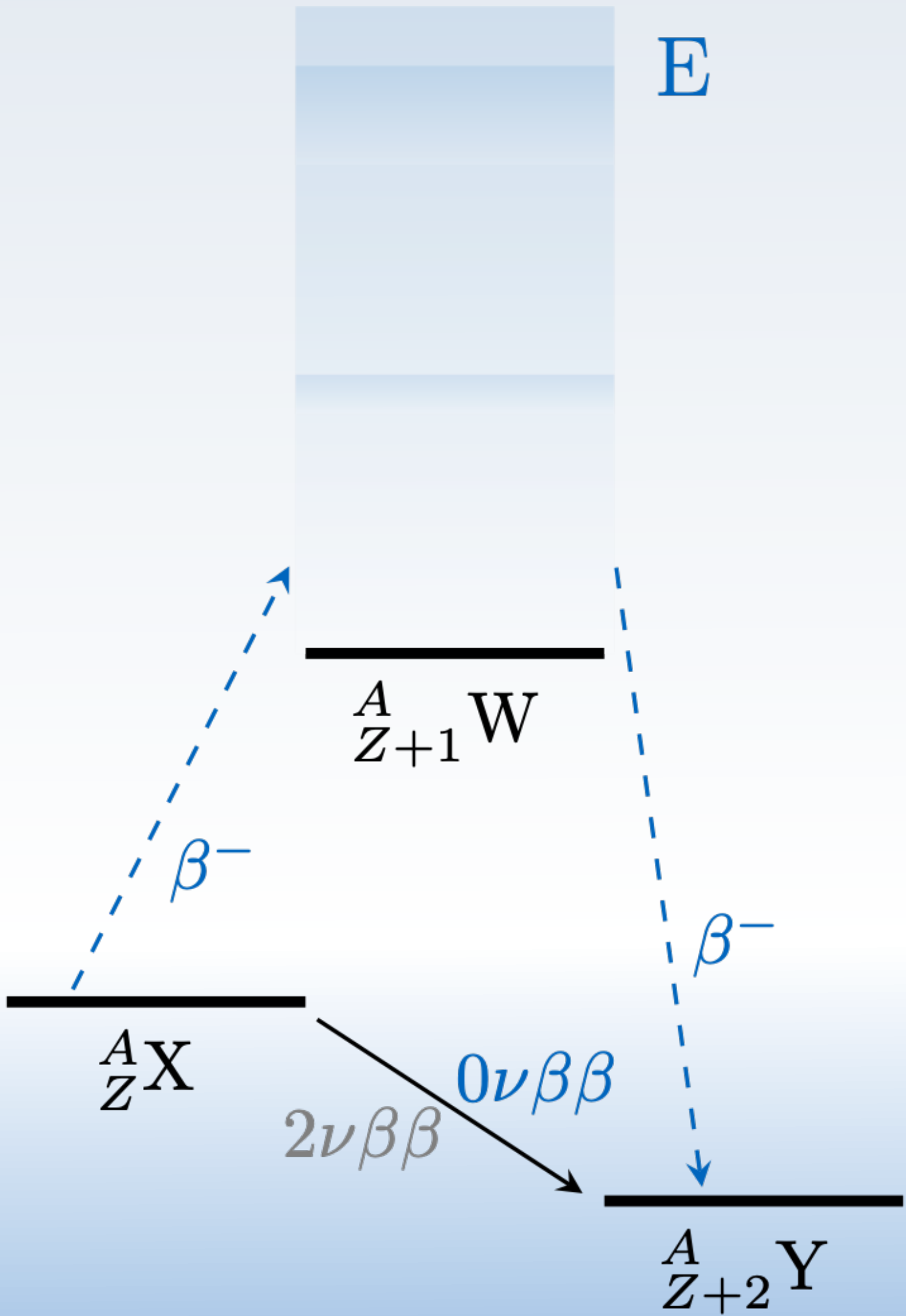


$0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay



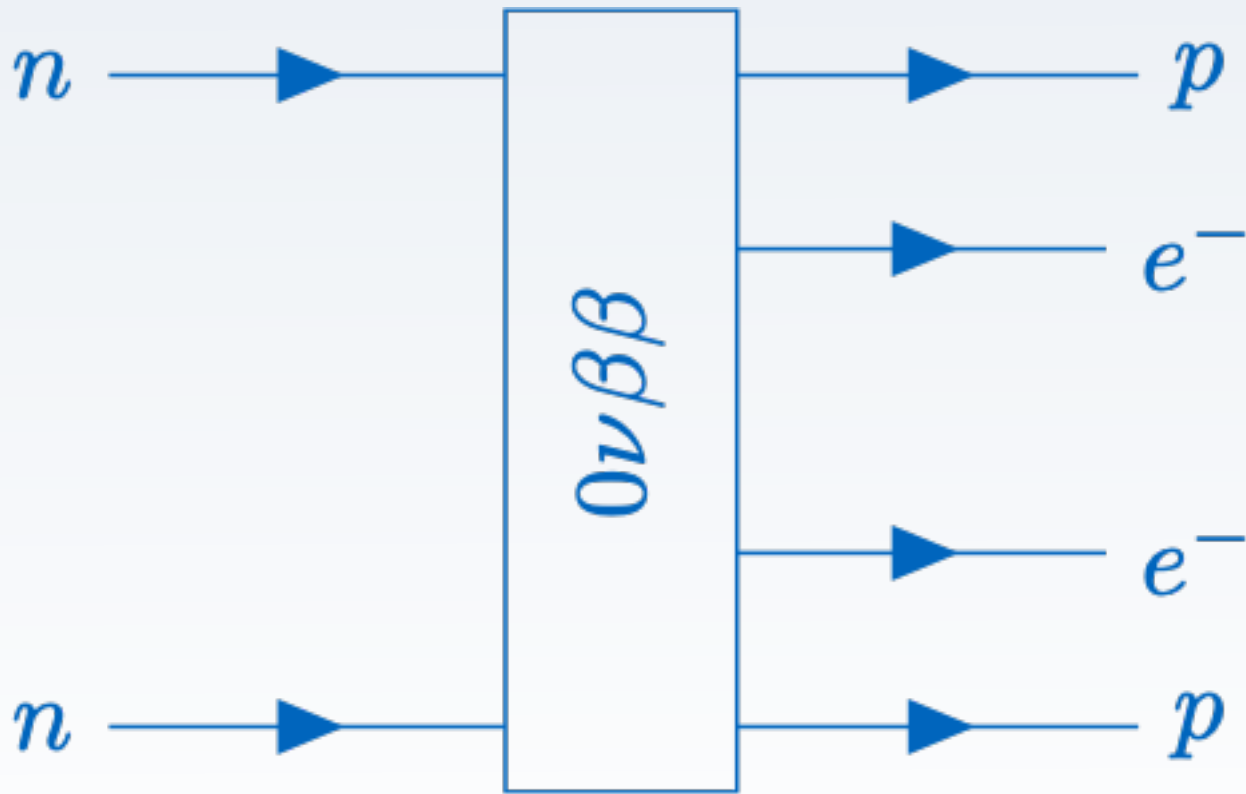
- Beyond the SM physics
- High-momentum transfer process
- Majorana nature of neutrinos [5]



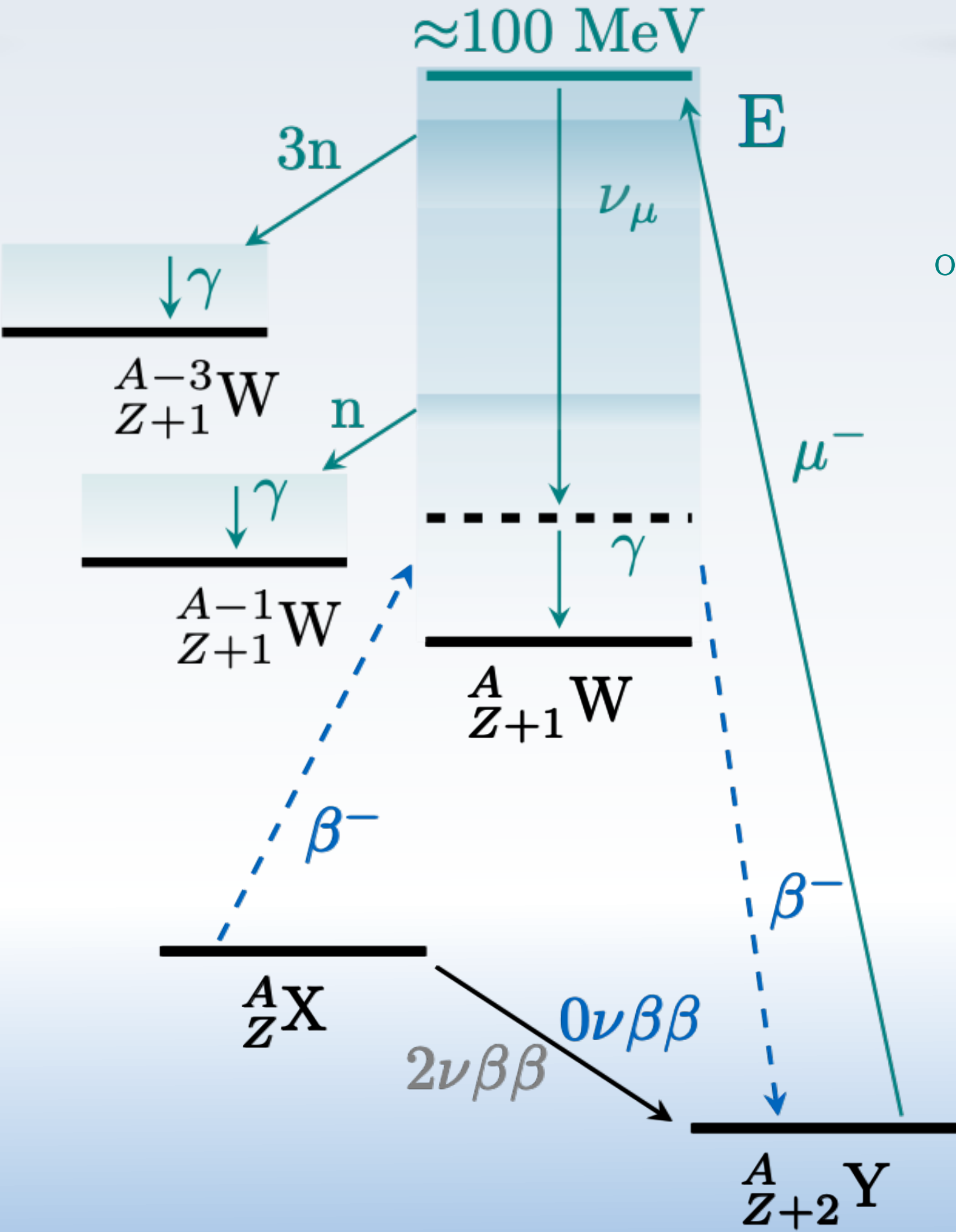
0νββ decay

OMC

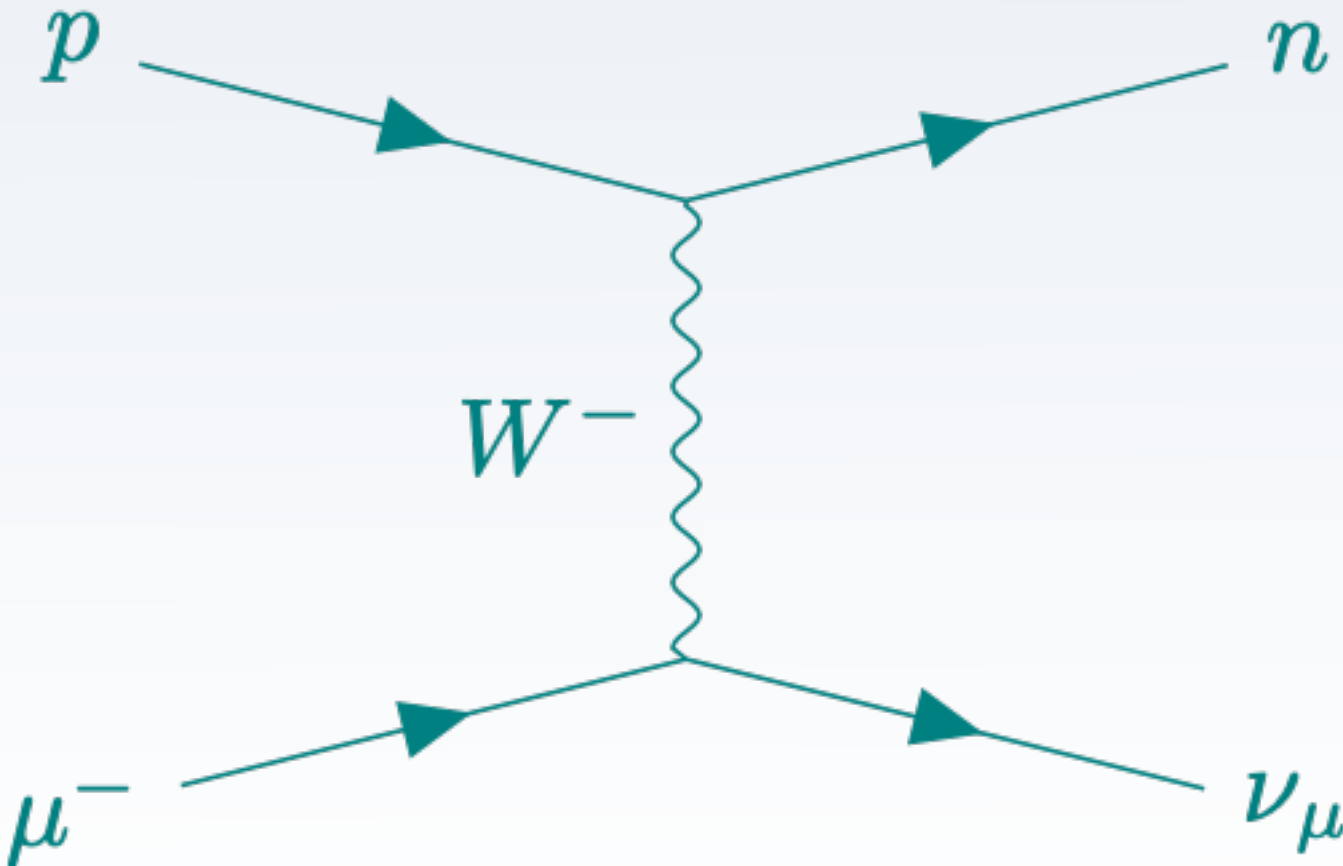
0νββ decay



- Beyond the SM physics
- High-momentum transfer process
- Majorana nature of neutrinos [5]



Ordinary Muon Capture [6, 7]

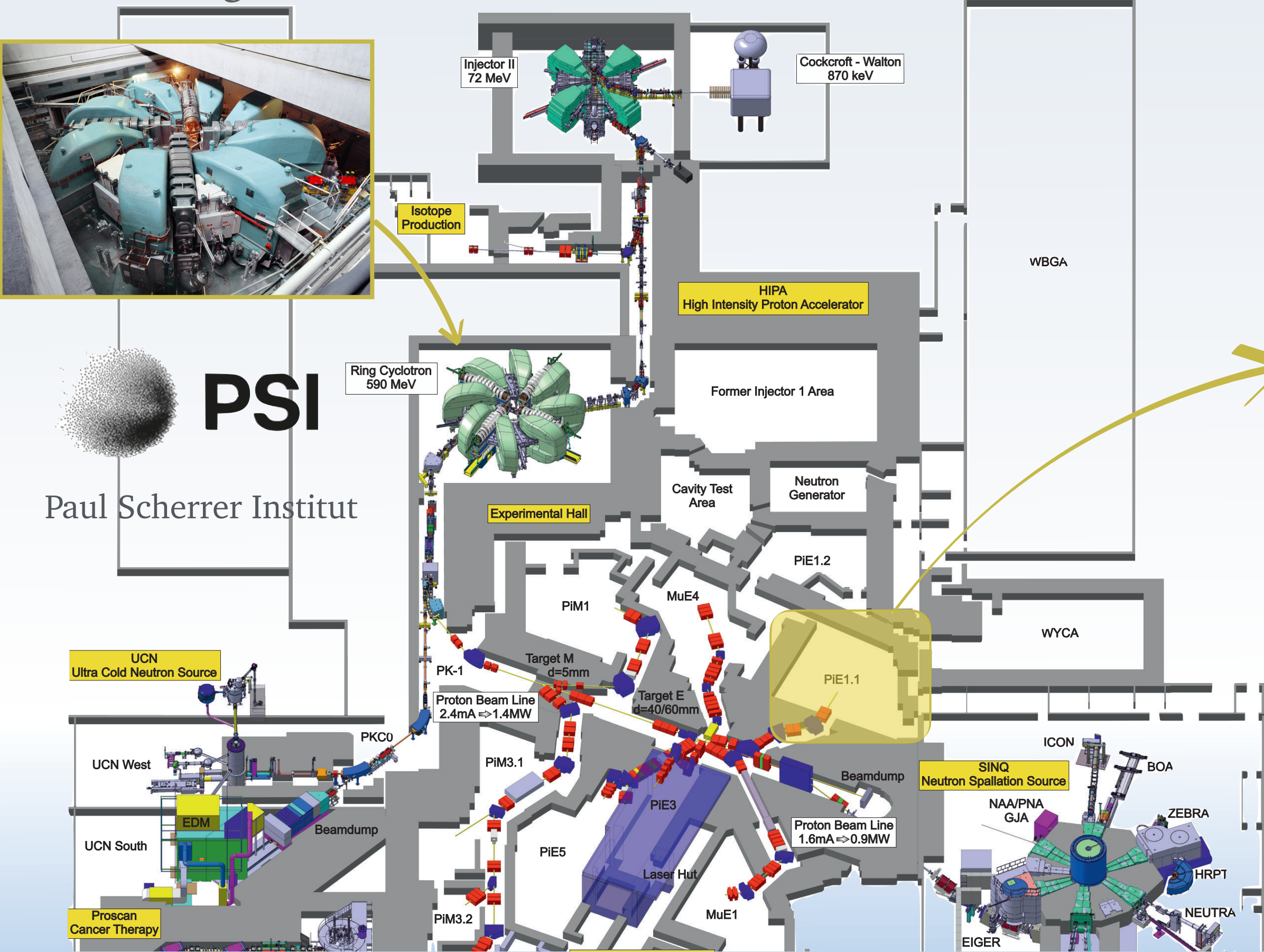


- Similar momentum transfer
- Probe intermediate states
- Benchmark nuclear matrix element calculations

Measurement

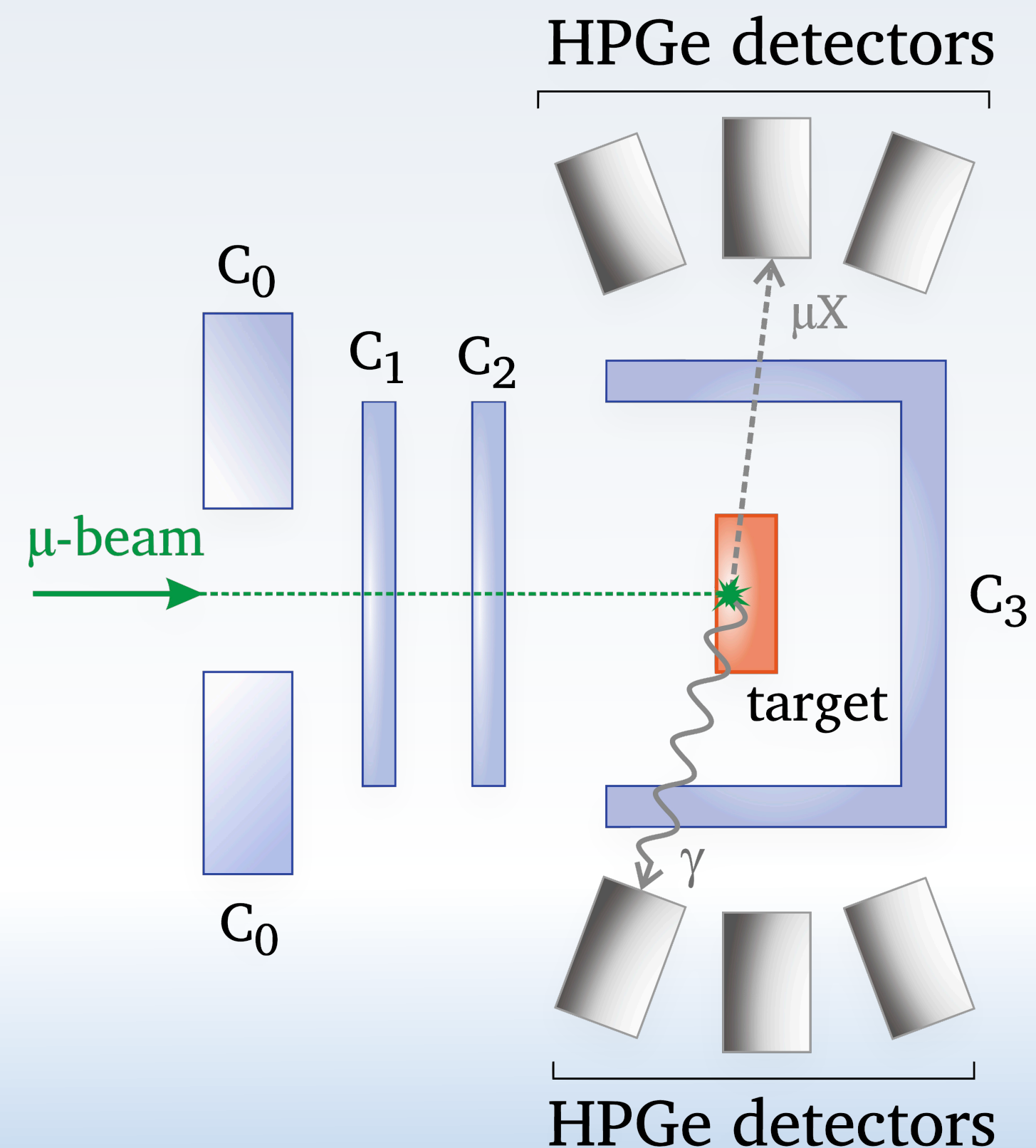
Experimental concept

High Proton Accelerator (HIPA)



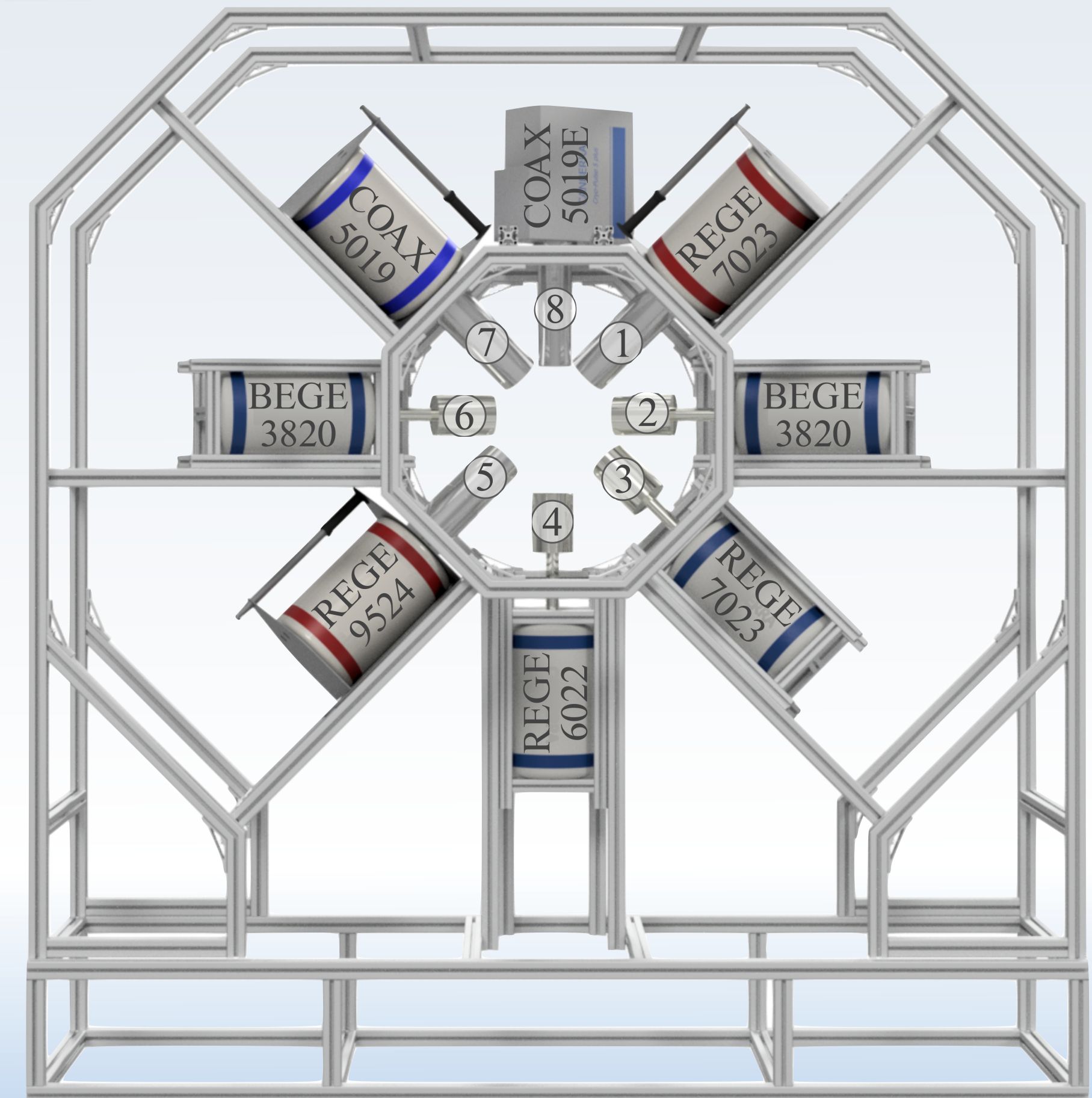
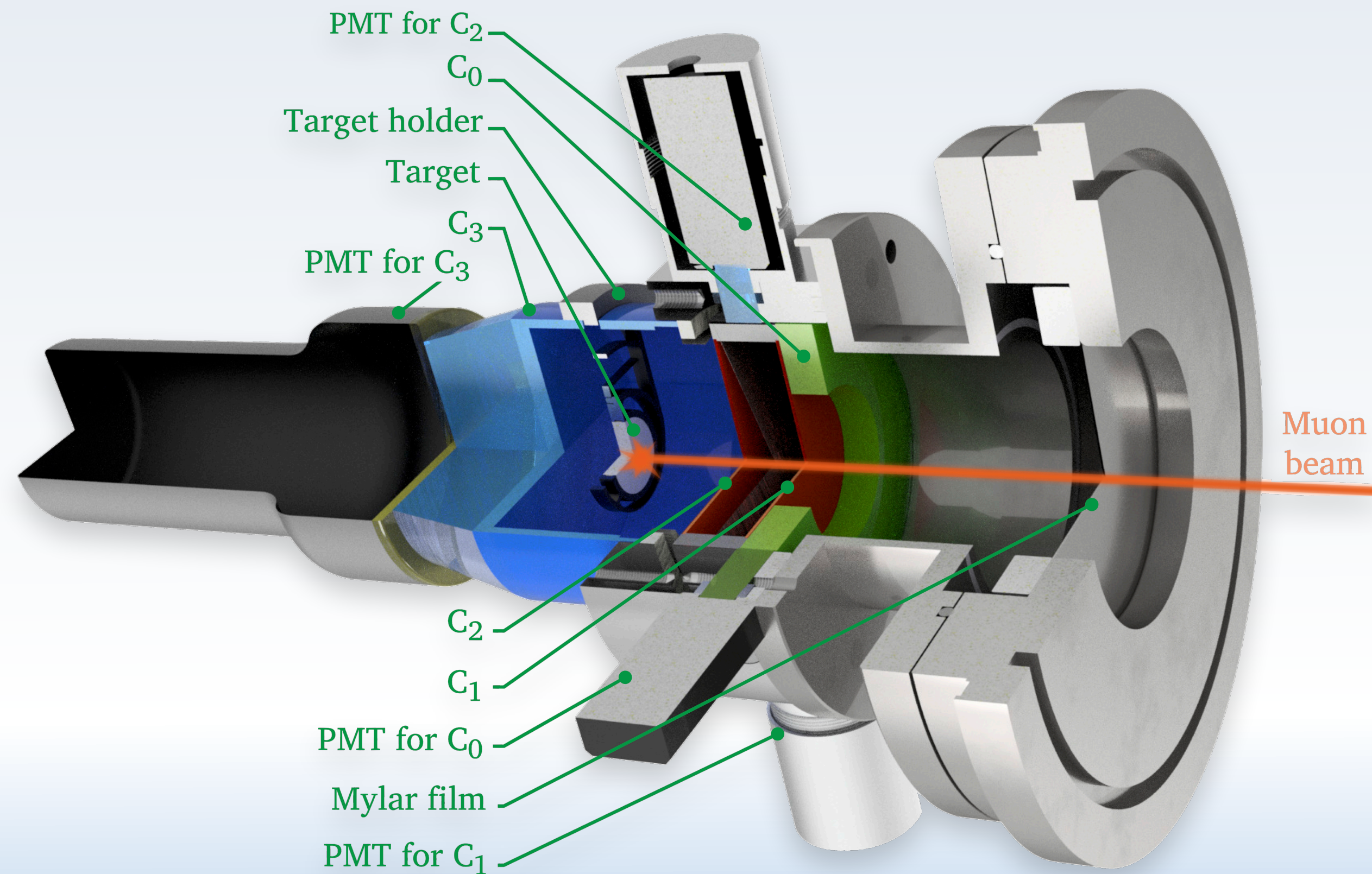
Proton beam $\rightarrow$ Graphite target $\rightarrow \pi, \mu$
Beam momentum ~ 40 MeV/c

Experimental concept

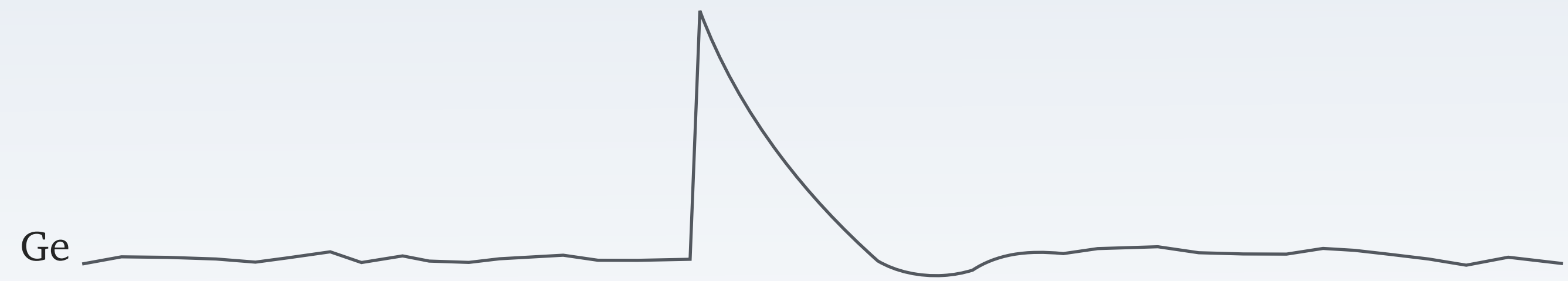


- Tag muon trajectory from beam to target
- Rate of stopped muons $\mathcal{O}(10^4)$ Hz
- γ -spectroscopy with HPGe detectors, typical rates of $\mathcal{O}(10^3)$ Hz
- Coincident measurement, $\Delta t = t_{\text{HPGe}} - t_{\mu\text{-stop}}$

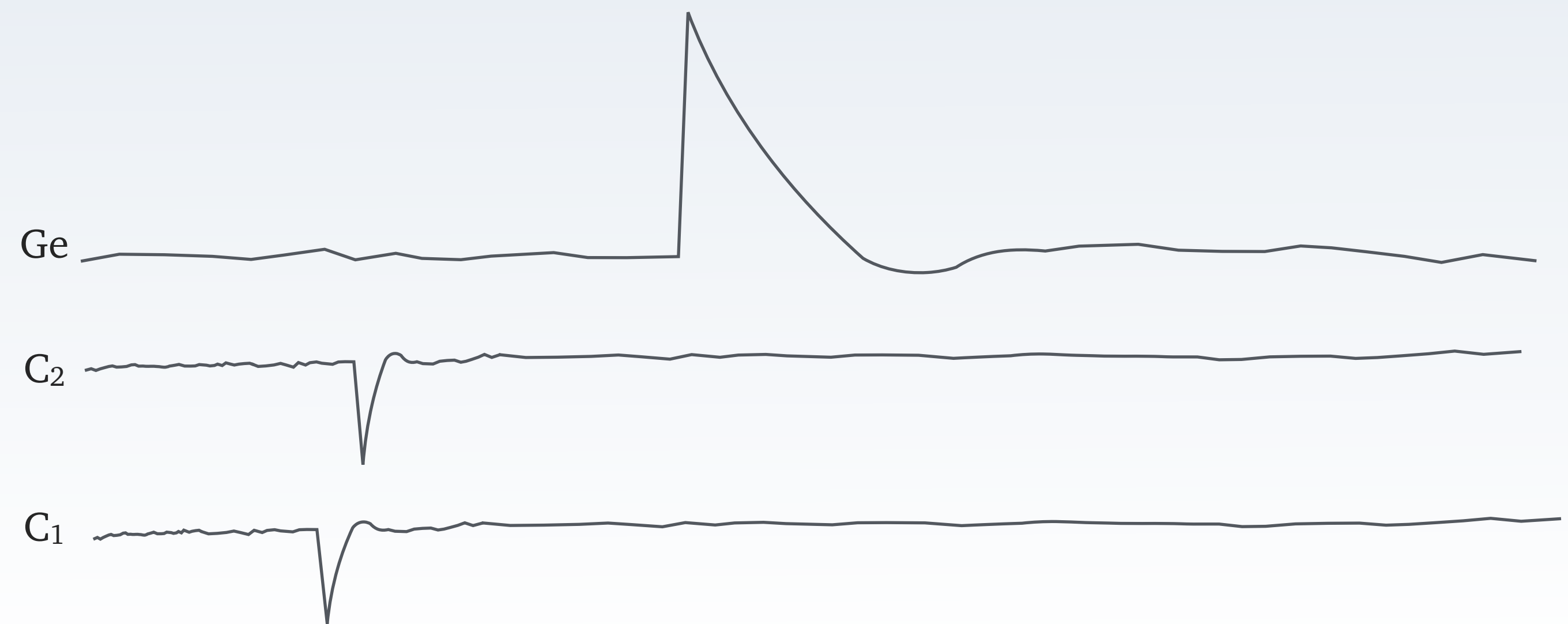
Experimental concept



Correlated events

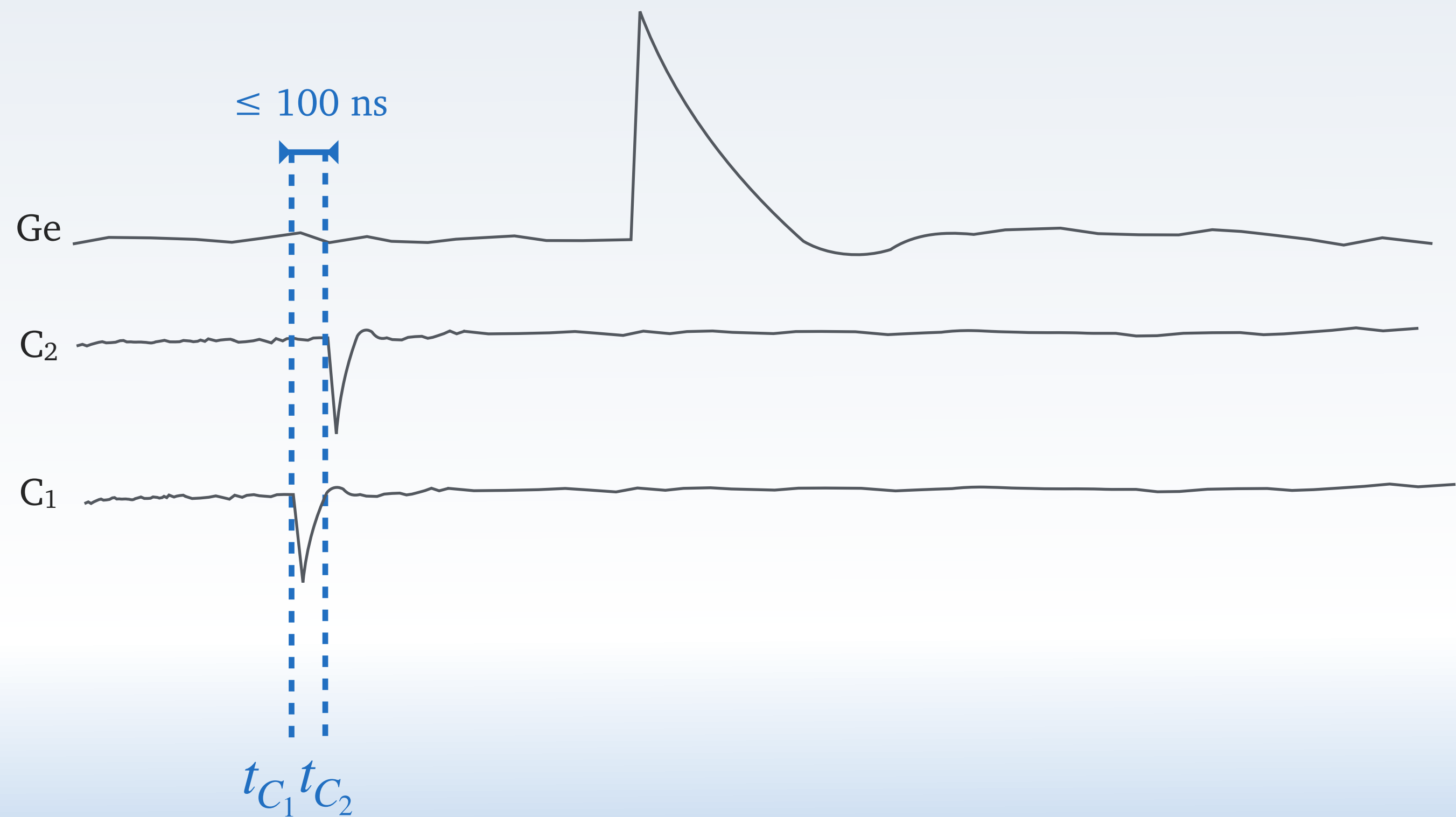


Correlated events



Correlated events

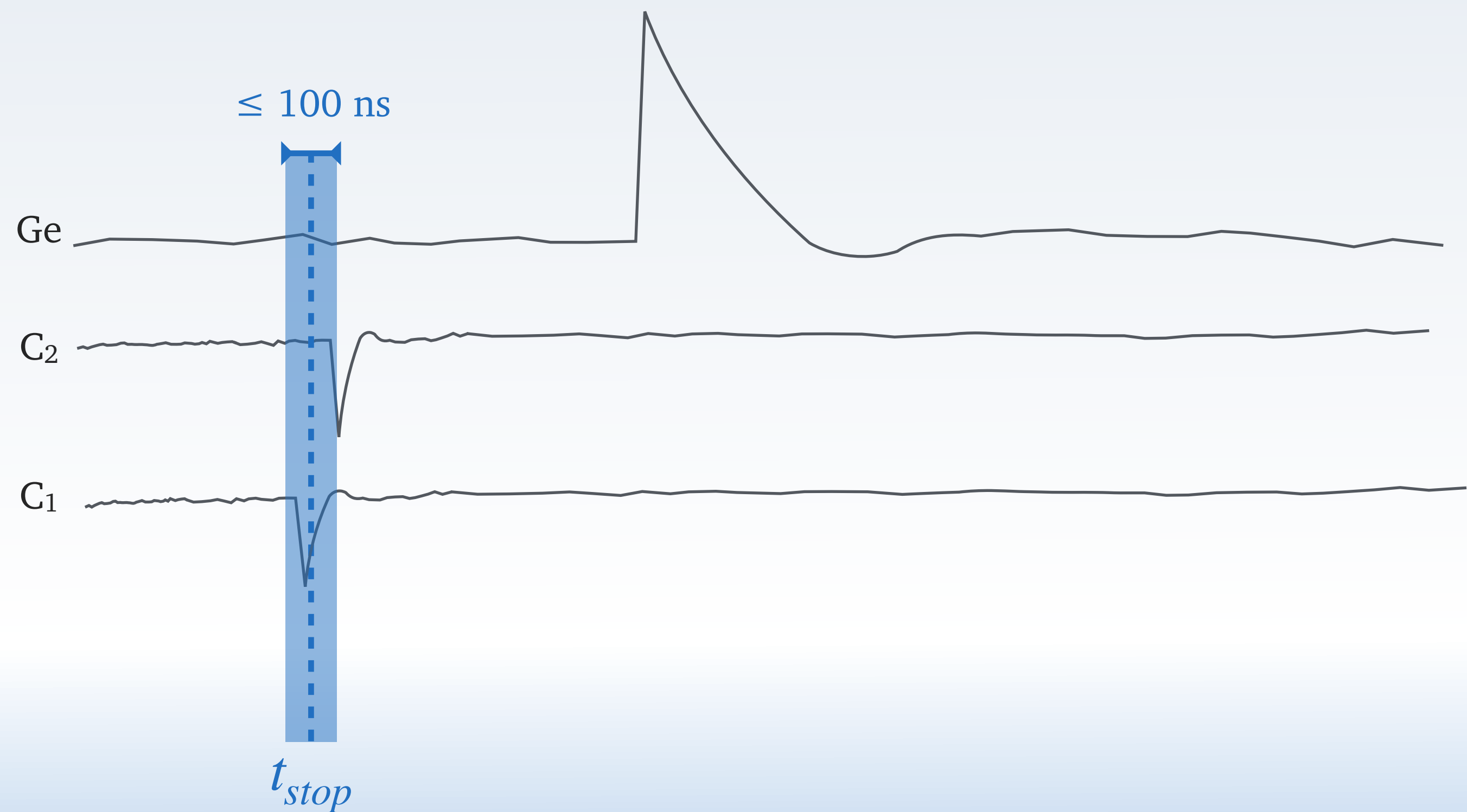
- $\Delta t_{C_1 C_2} \leq 100 \text{ ns}$



Correlated events

- $\Delta t_{C_1 C_2} \leq 100 \text{ ns}$

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

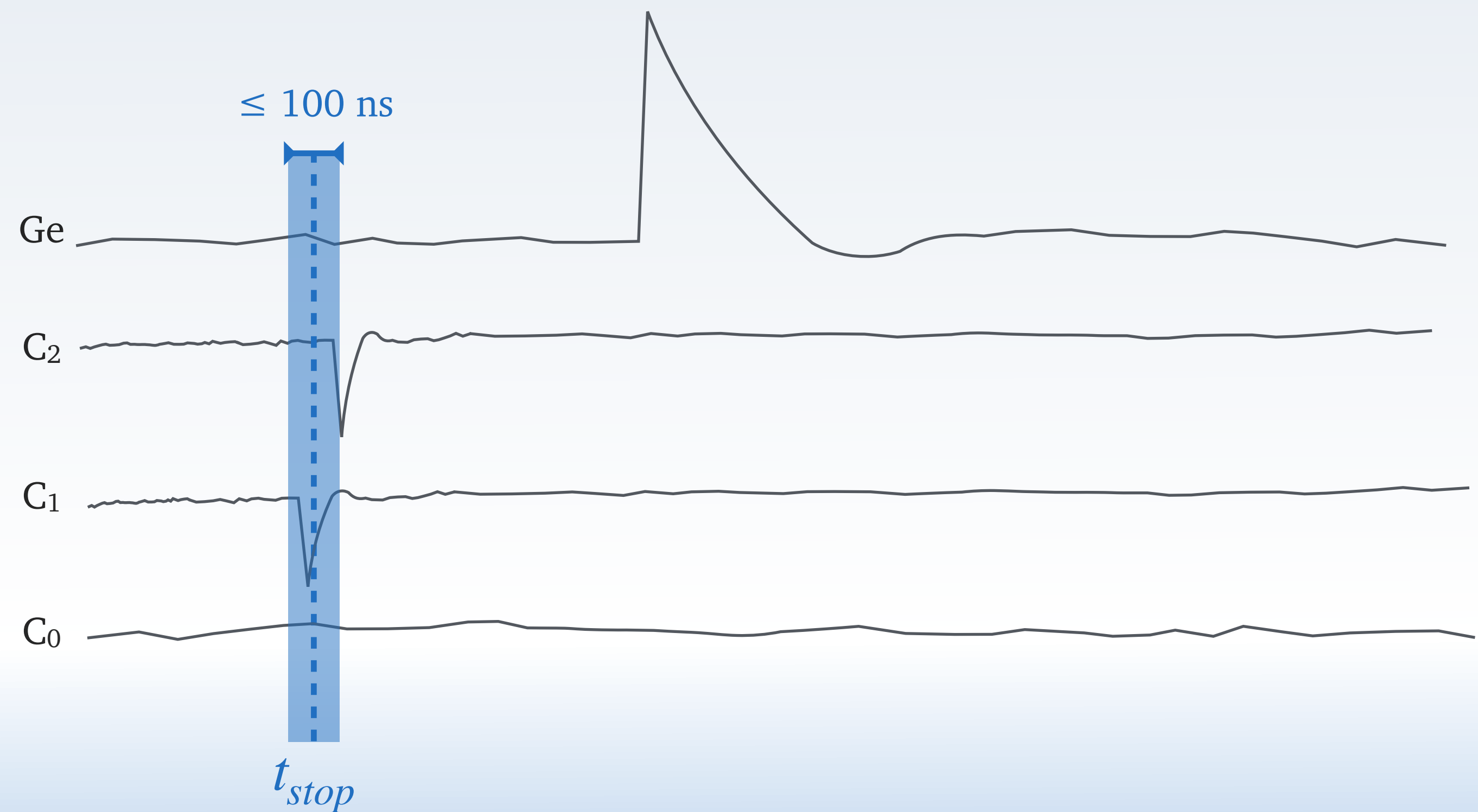


Correlated events

- $\Delta t_{C_1 C_2} \leq 100 \text{ ns}$

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

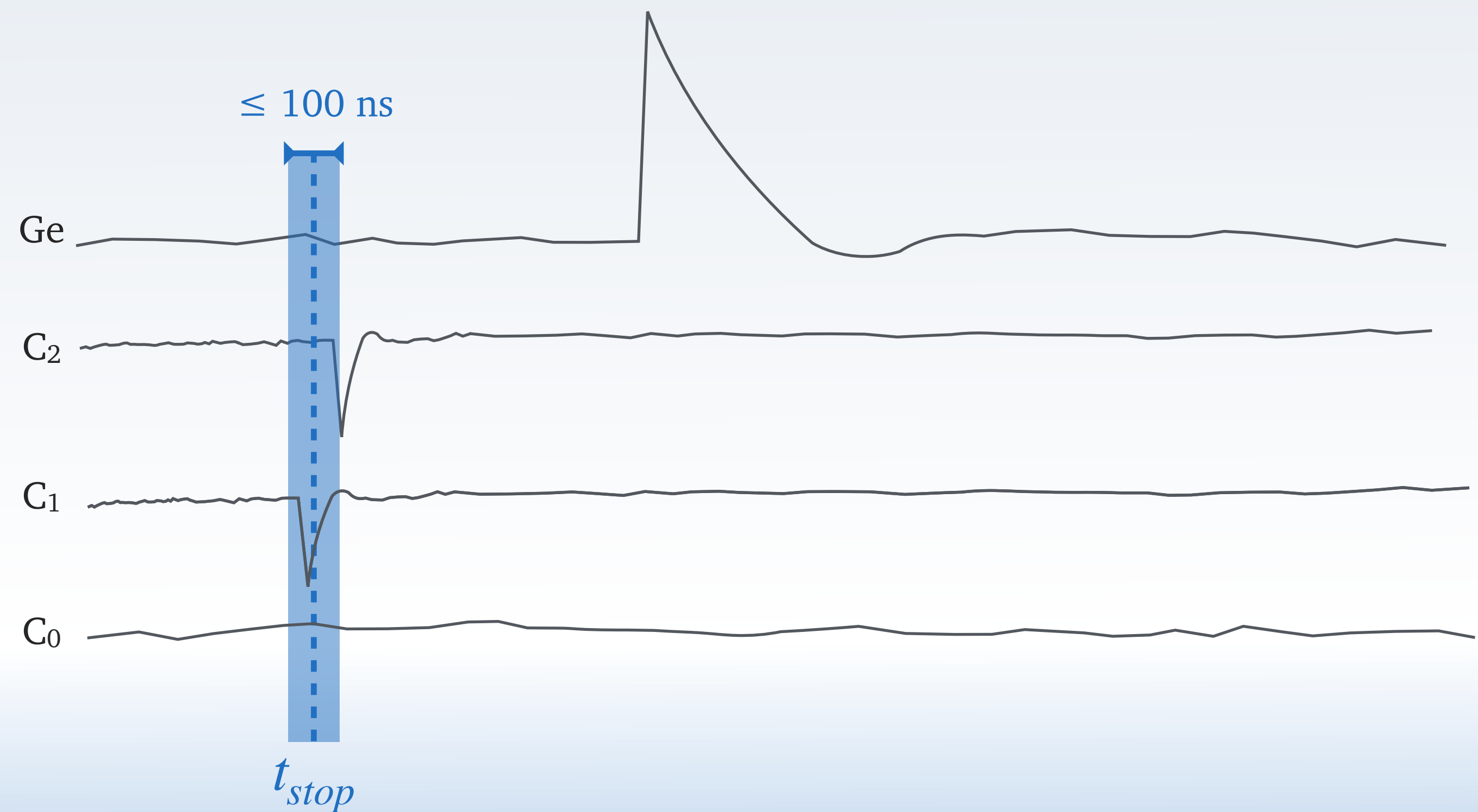
- $\Delta t_{stop C_0} \leq 100 \text{ ns}$



Correlated events

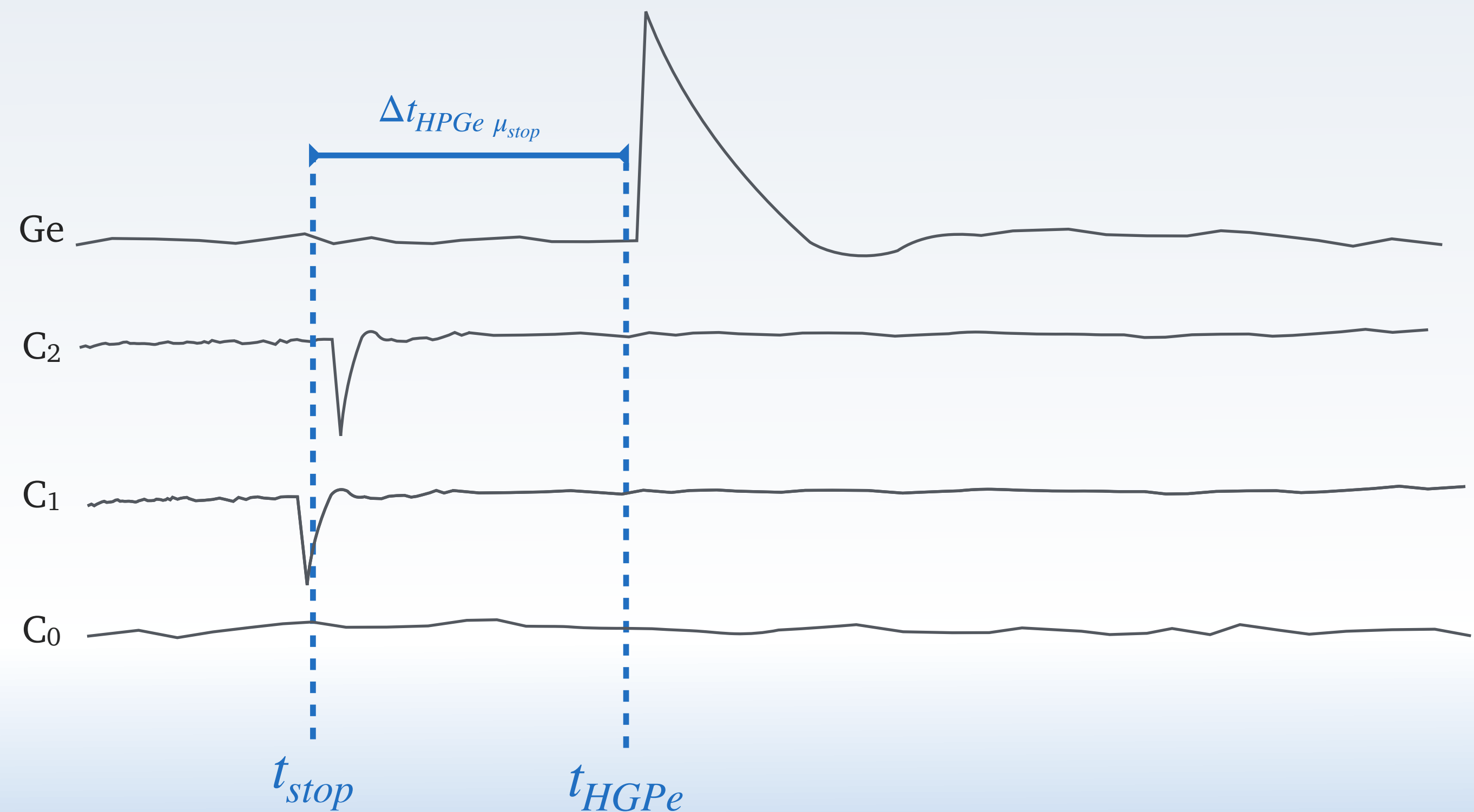
$$\mu_{\text{stop}} = \bar{C}_0 \wedge C_1 \wedge C_2$$

- $\Delta t_{C_1 C_2} \leq 100 \text{ ns}$
- $t_{\text{stop}} = \frac{t_{C_1} + t_{C_2}}{2}$
- $\Delta t_{\text{stop } C_0} \leq 100 \text{ ns}$



Correlated events

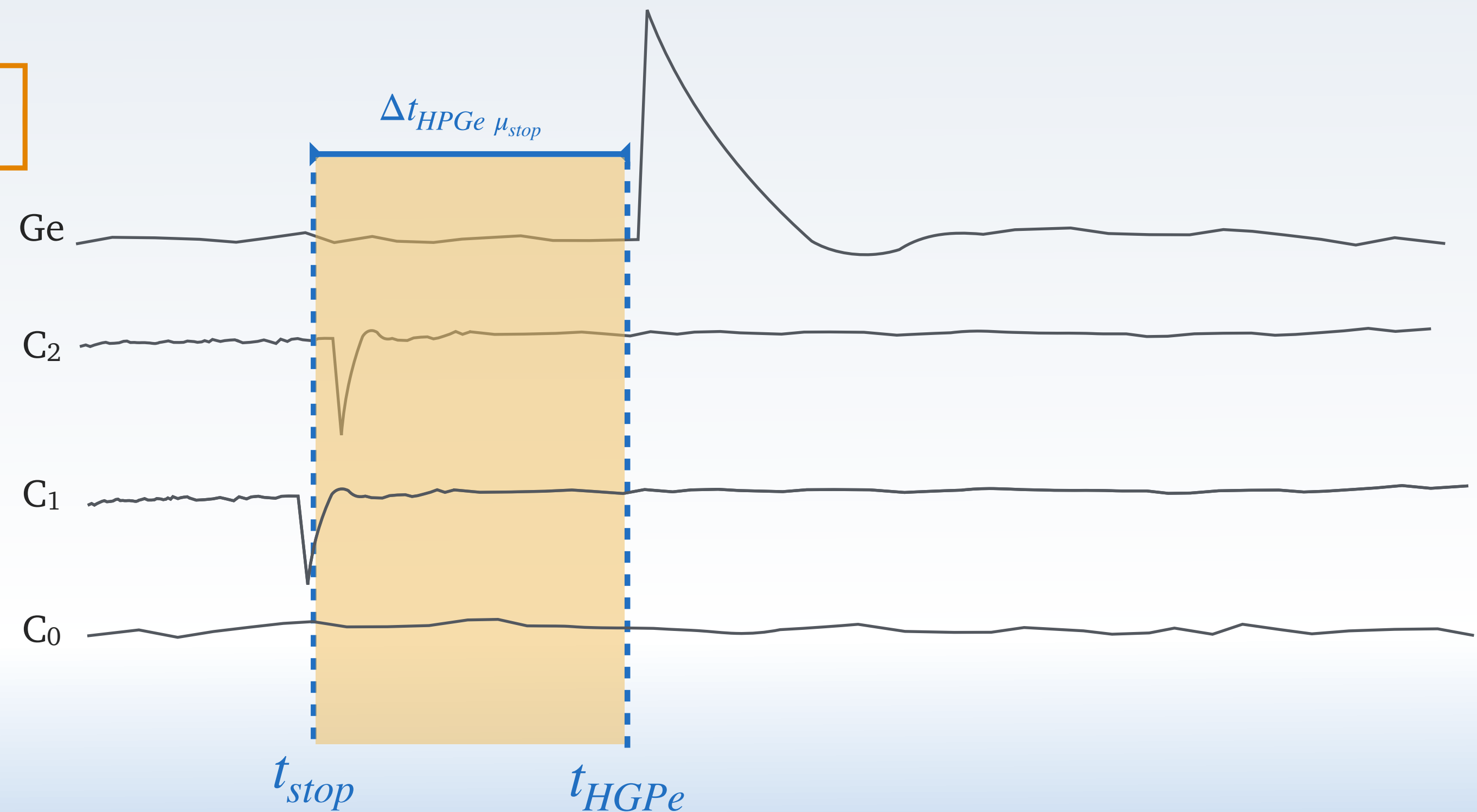
$$\mu_{\text{stop}} = \bar{\mathbf{C}}_0 \wedge \mathbf{C}_1 \wedge \mathbf{C}_2$$



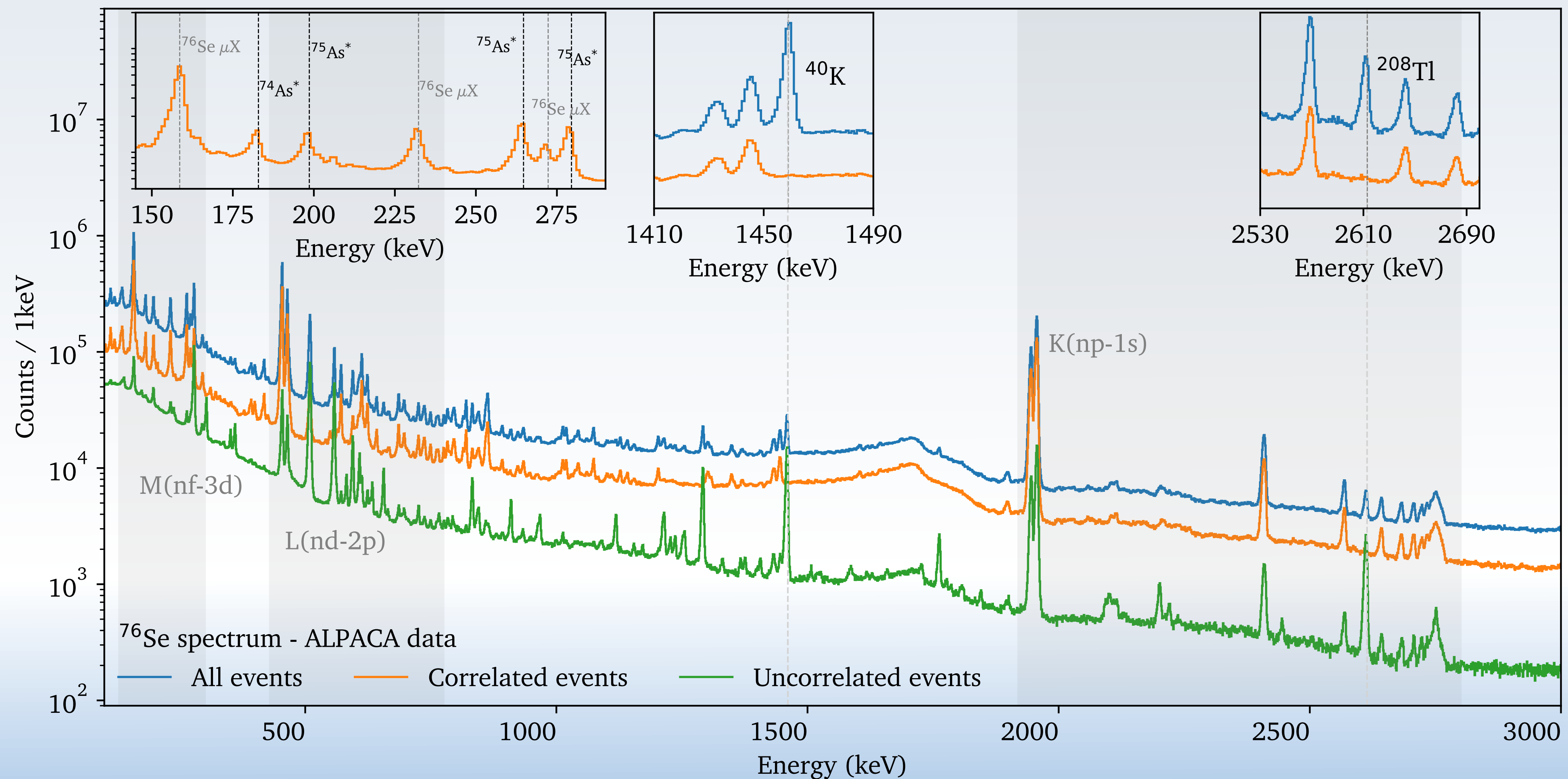
Correlated events

$$\mu_{\text{stop}} = \bar{C}_0 \wedge C_1 \wedge C_2$$

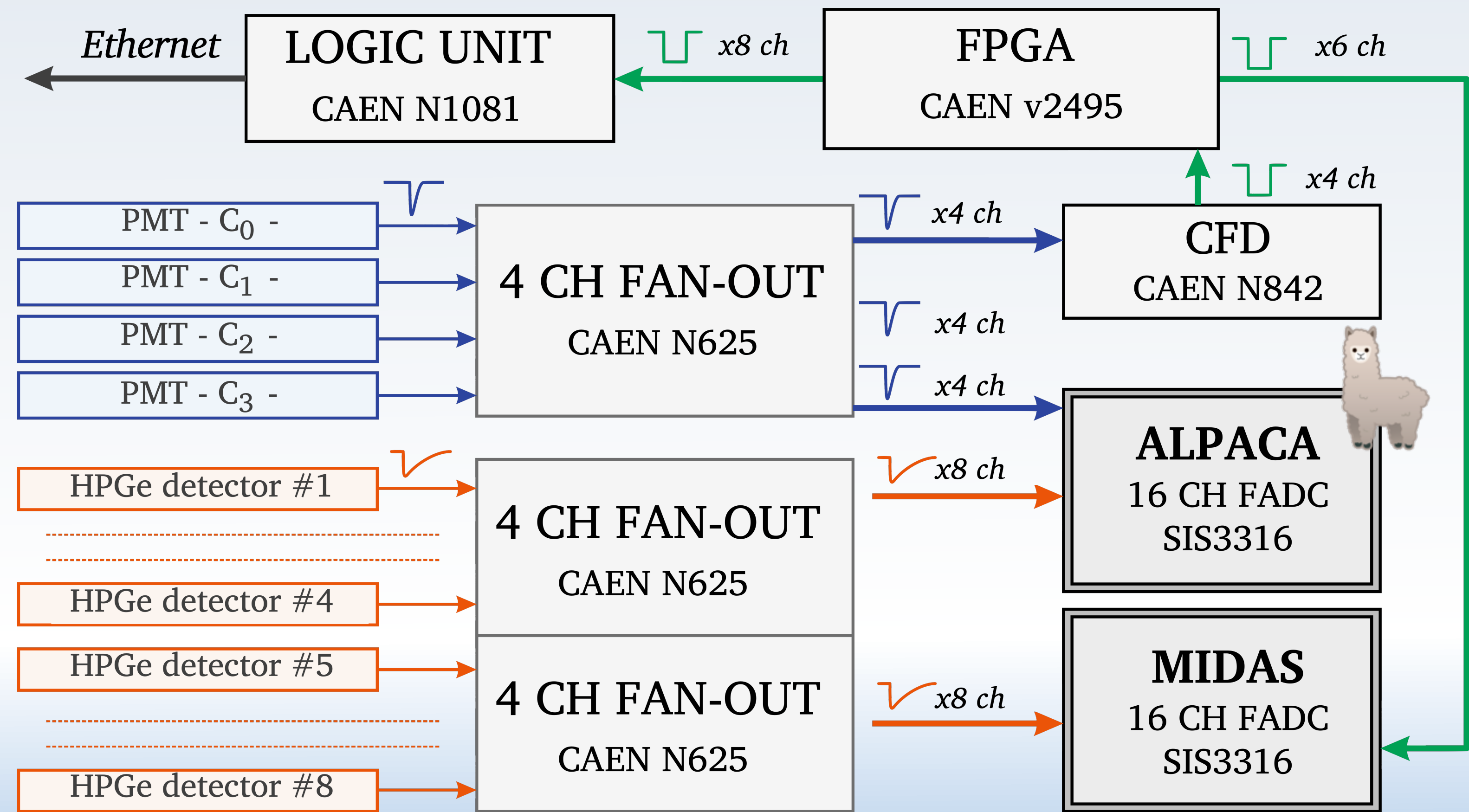
$$\mu_{\text{correlated}} : \Delta t_{HPGe \mu_{\text{stop}}} \leq \pm 800 \text{ ns}$$



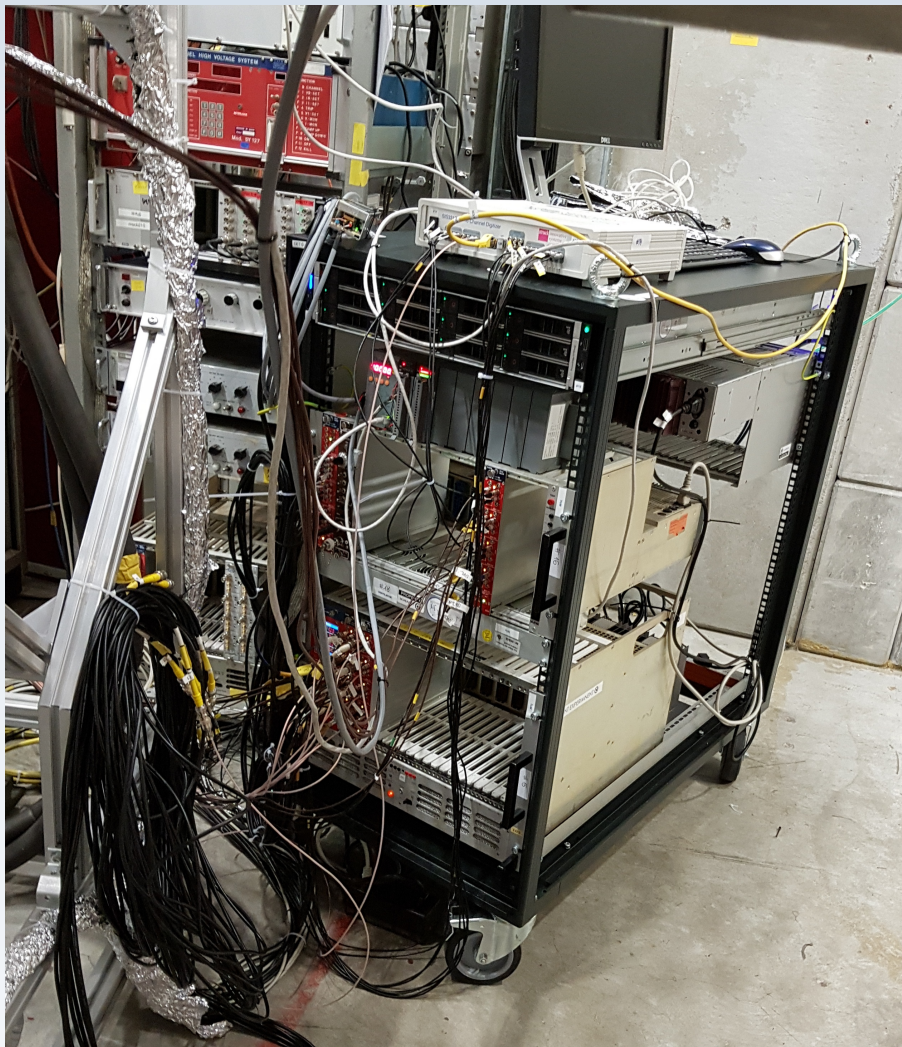
Experimental concept



Experimental concept

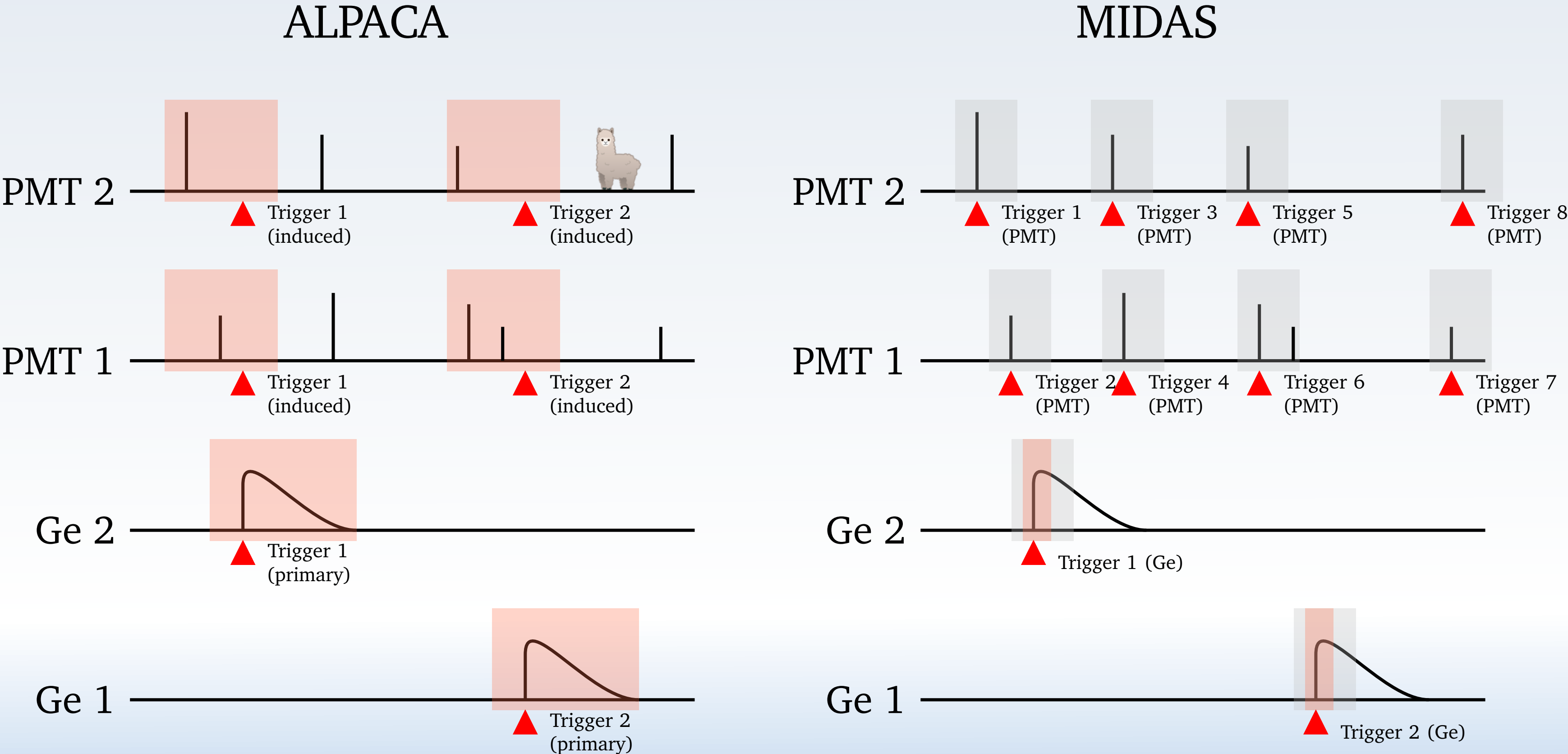


Electronic system [4]

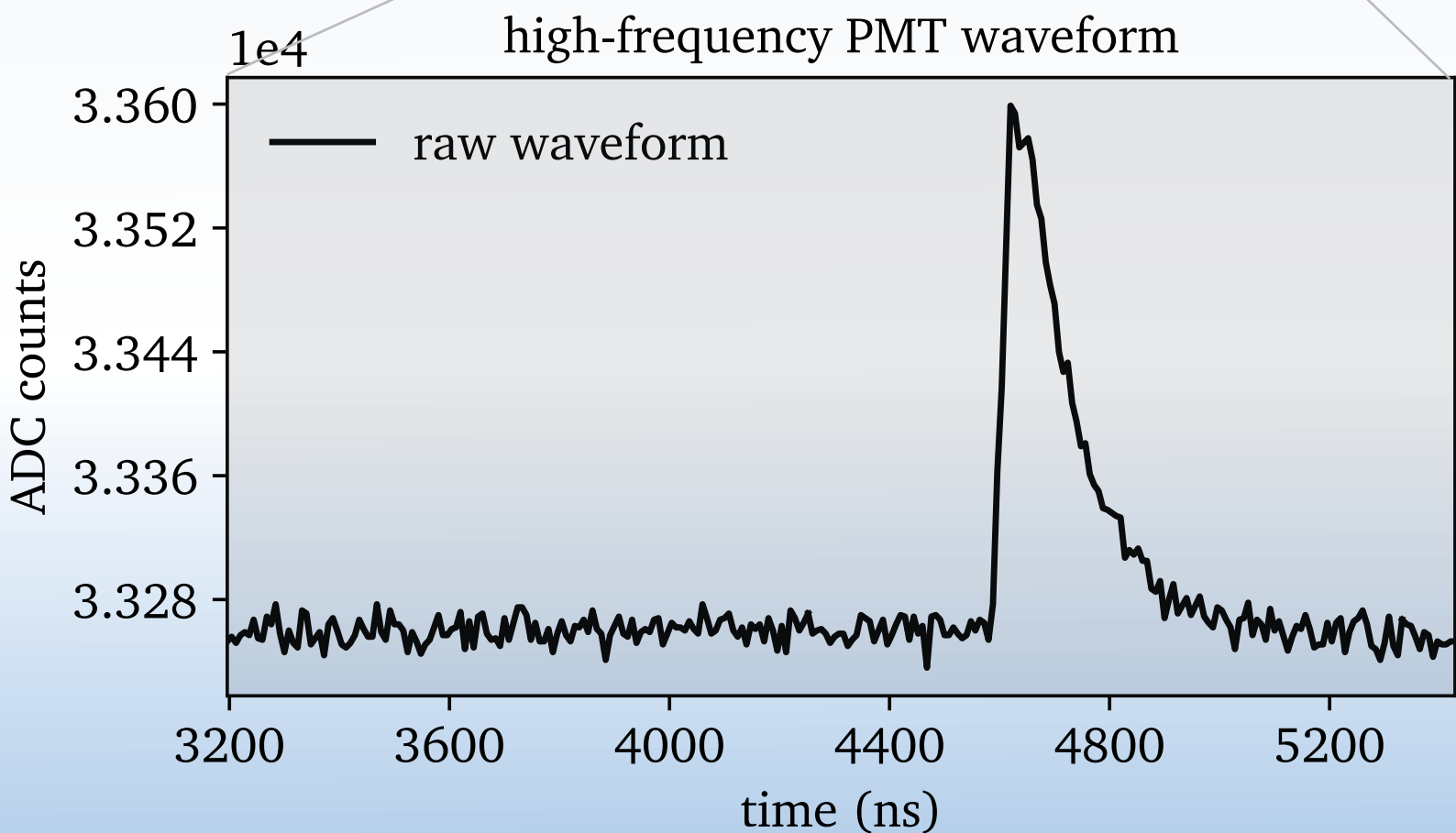
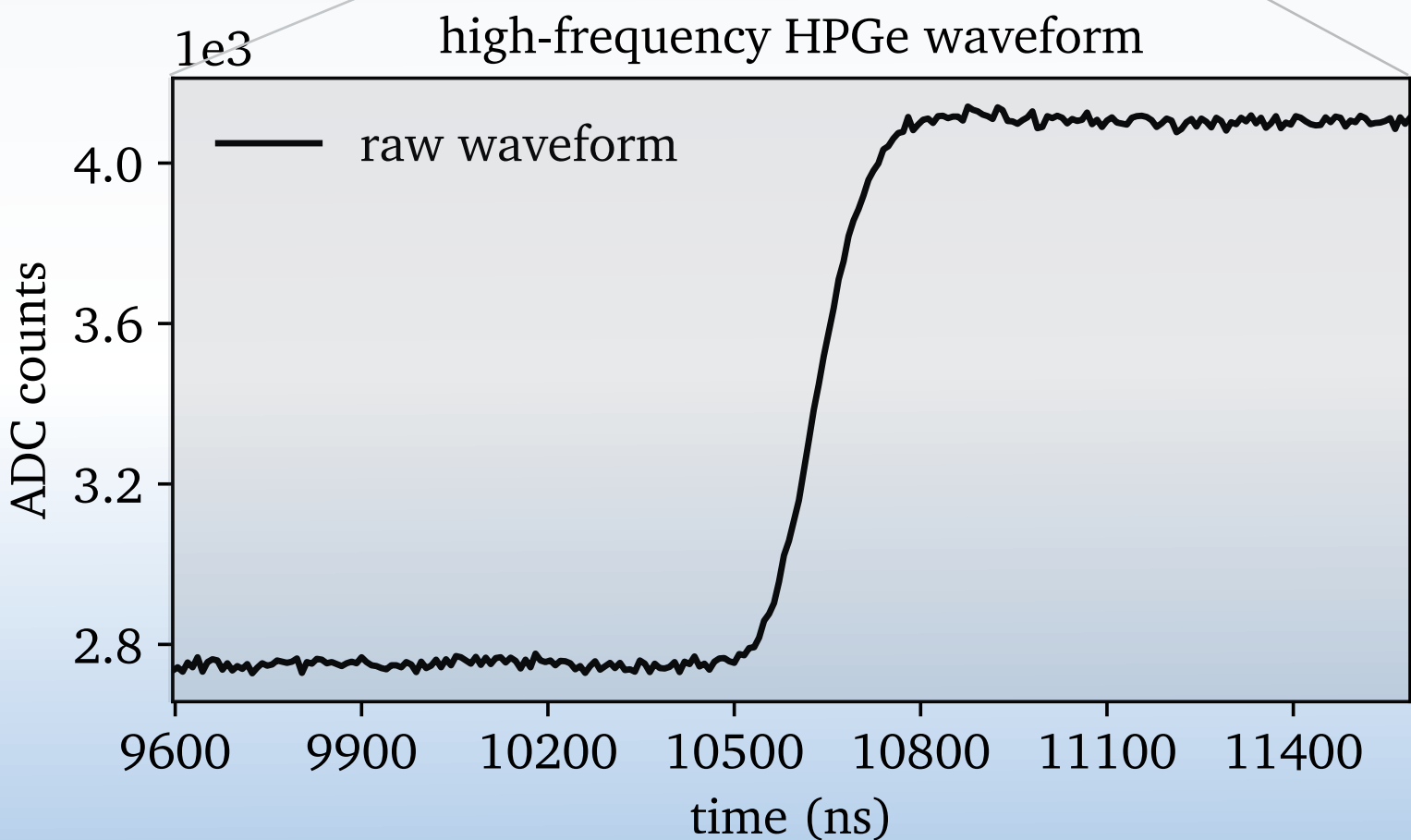
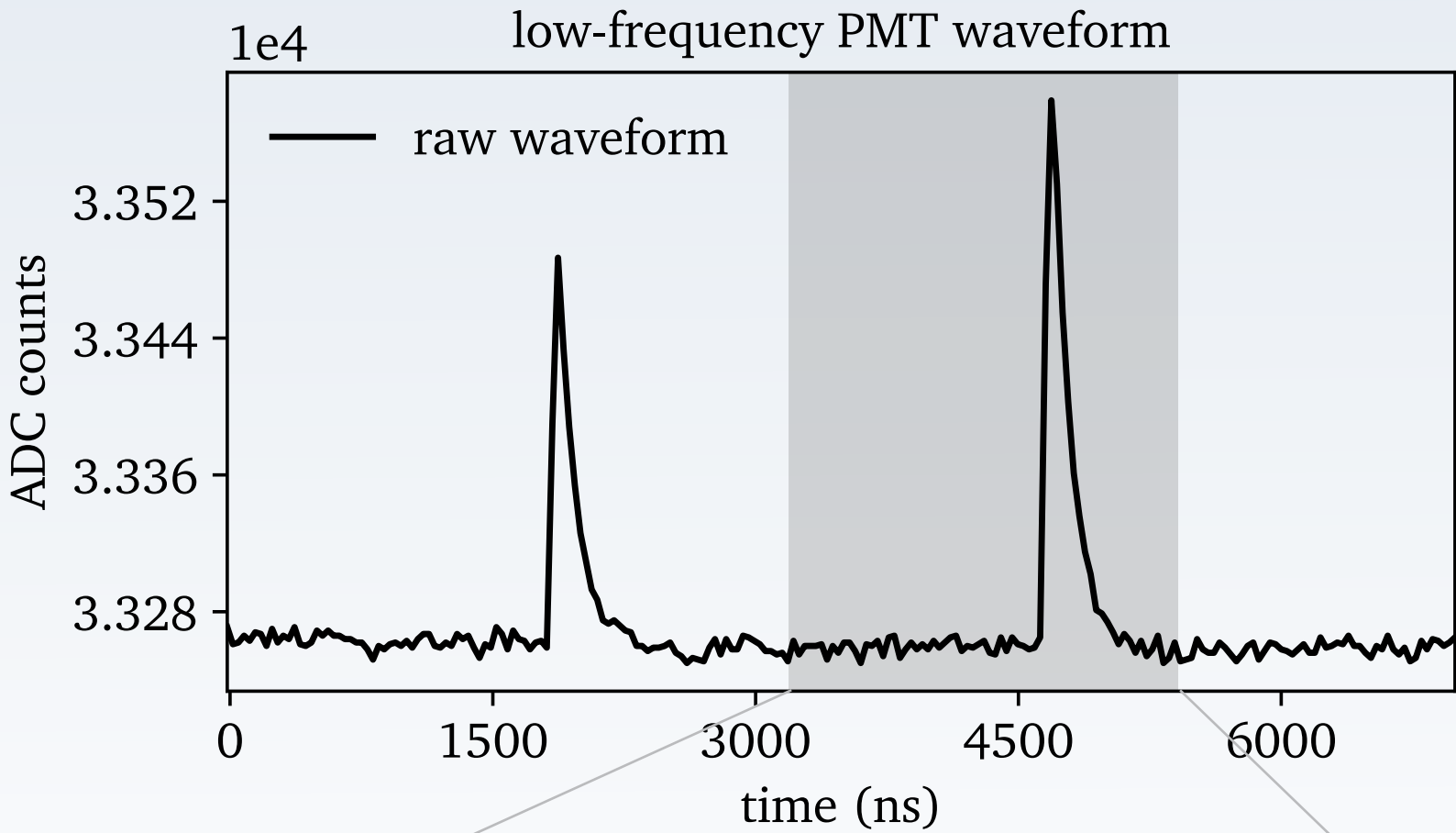
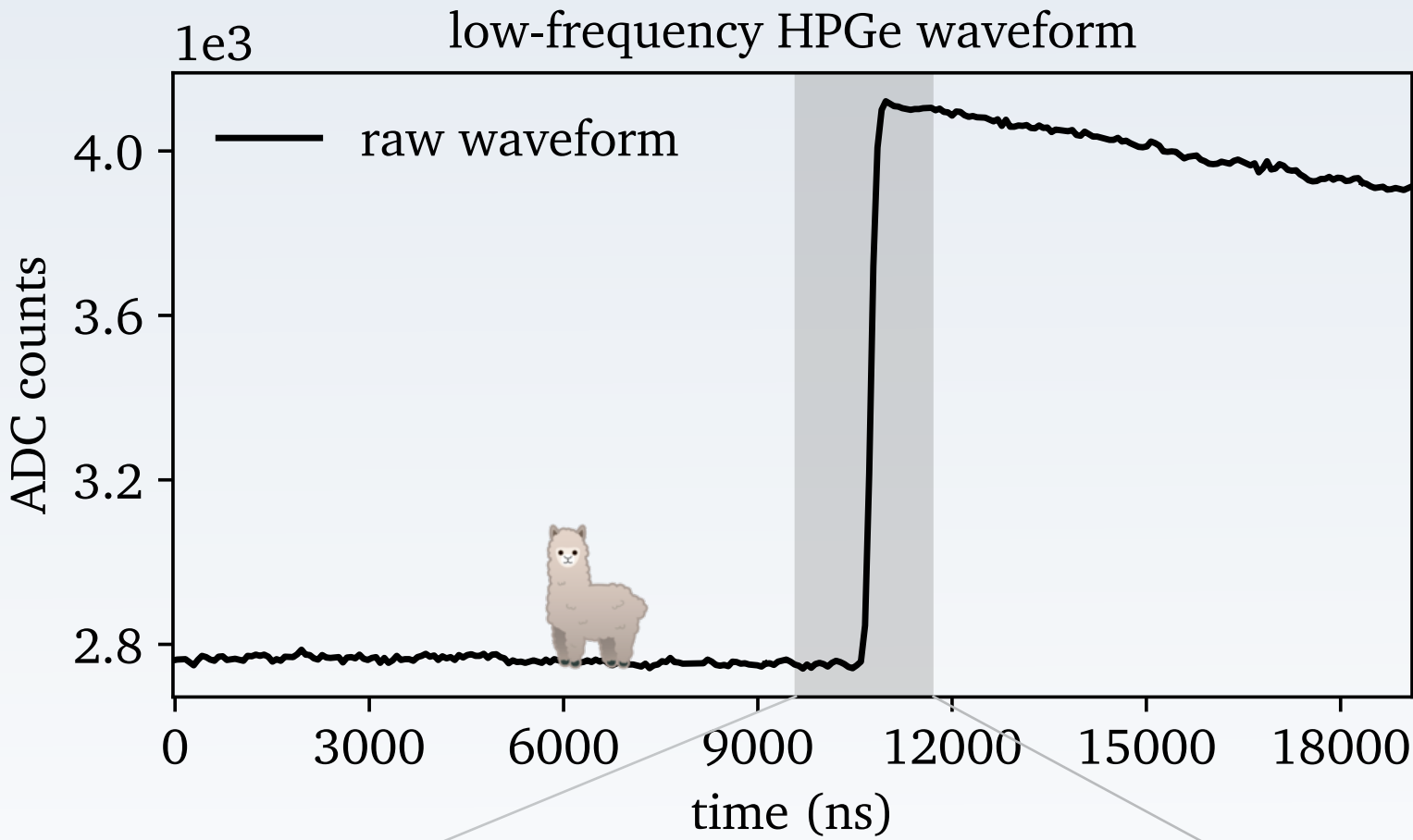


- Two parallel DAQ systems; ALPACA developed at Technical University of Munich [9]

Experimental concept



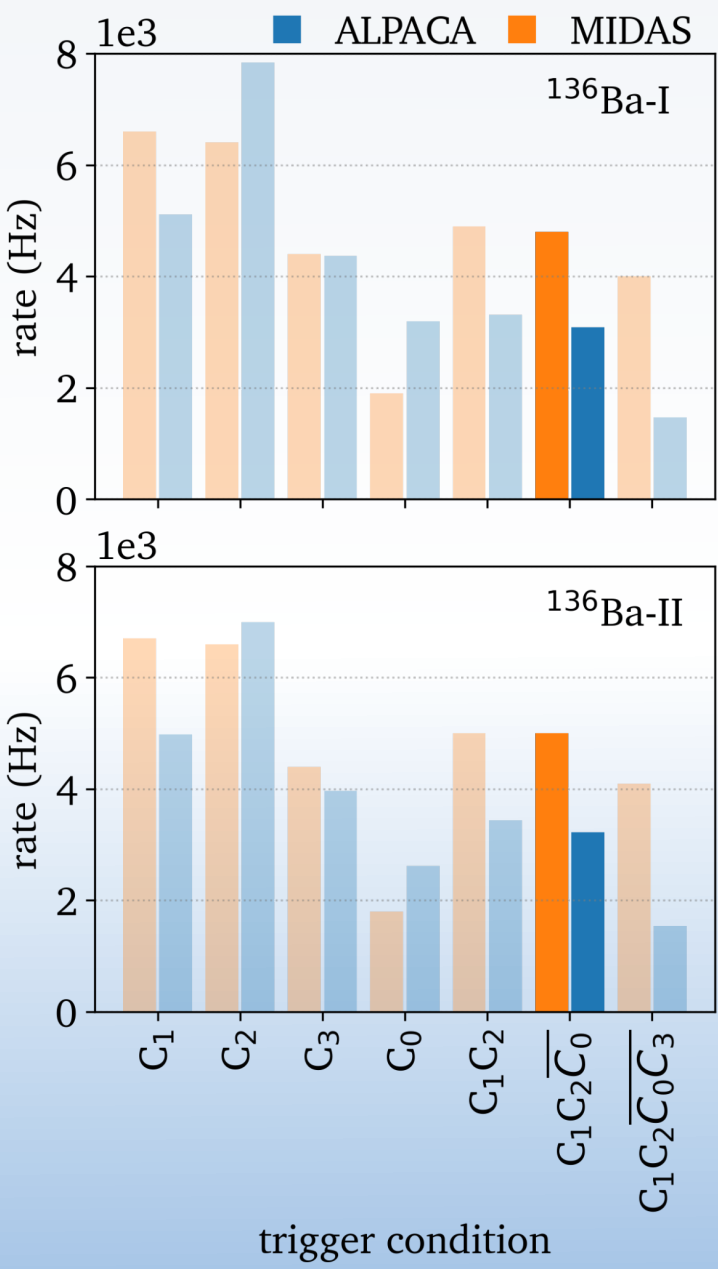
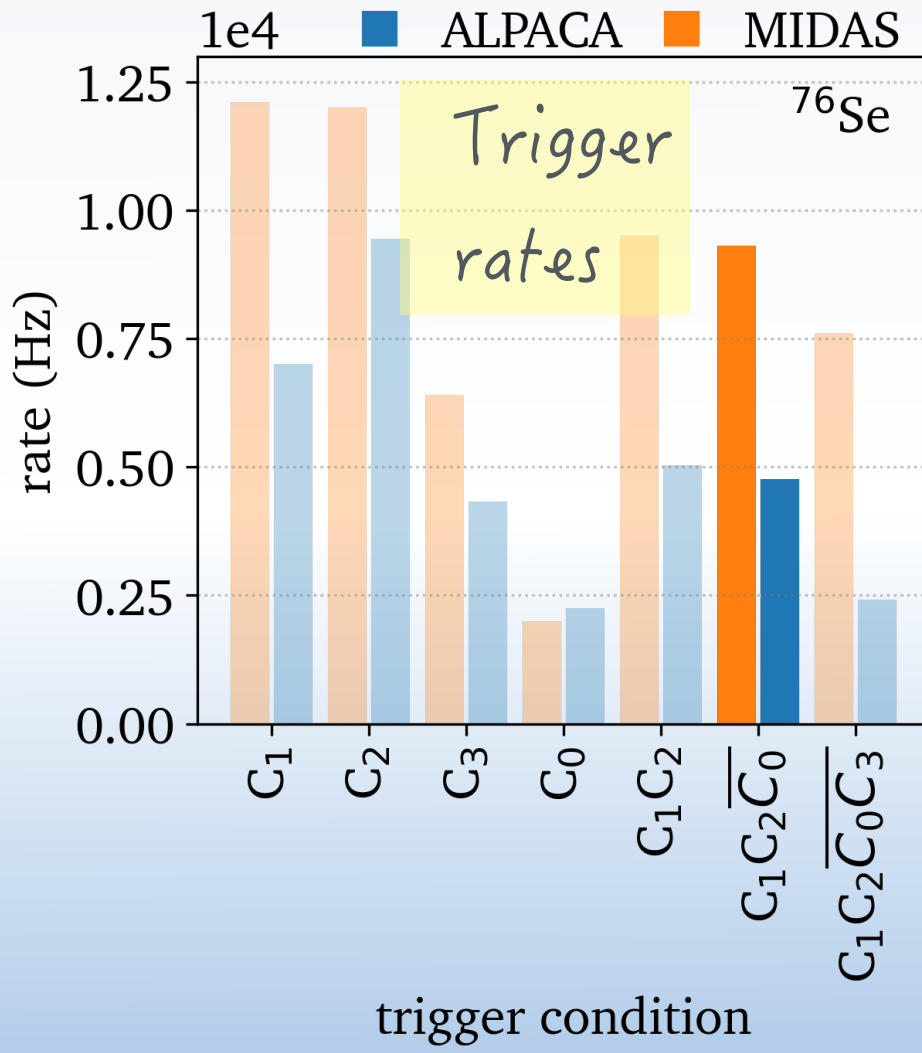
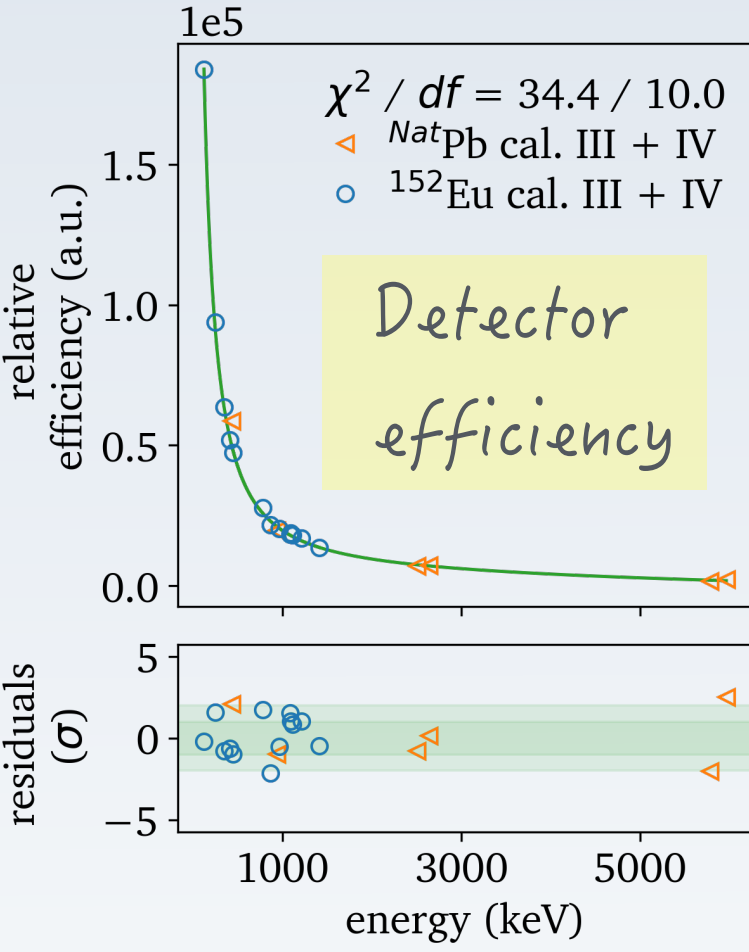
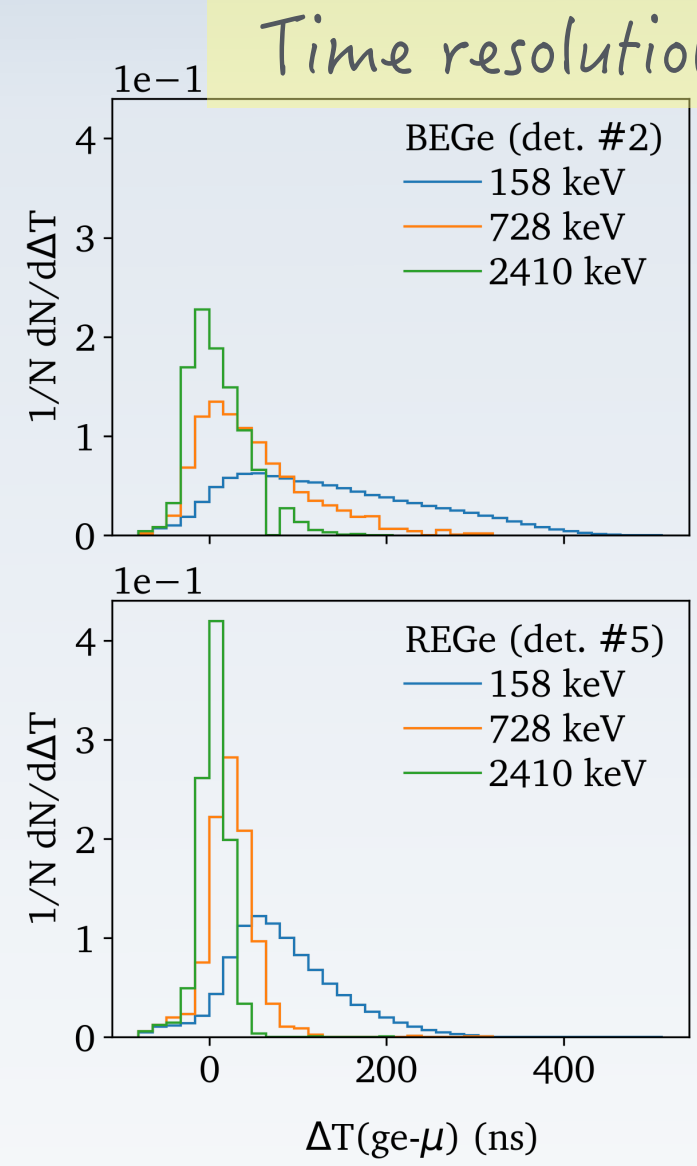
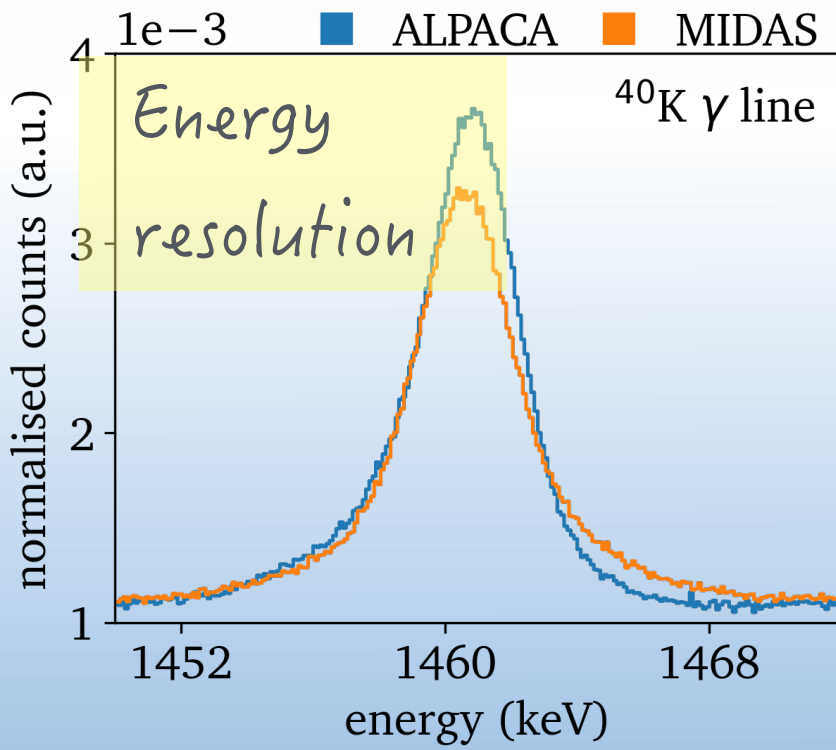
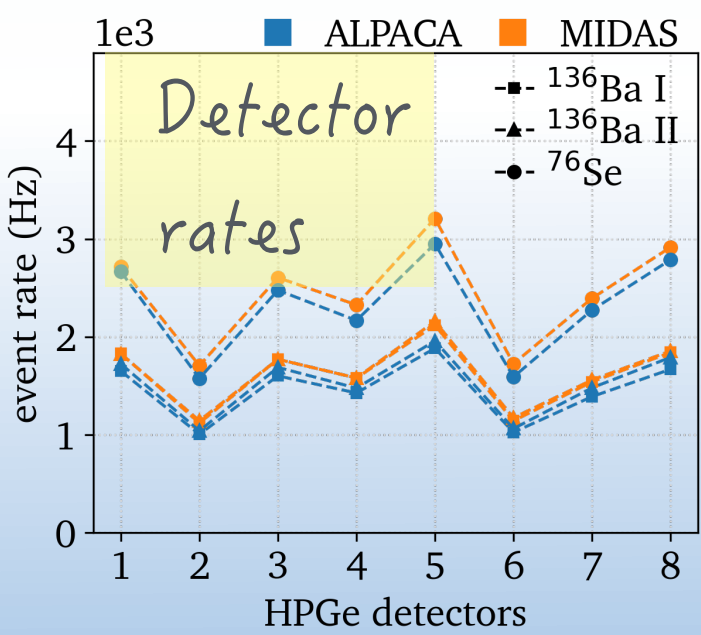
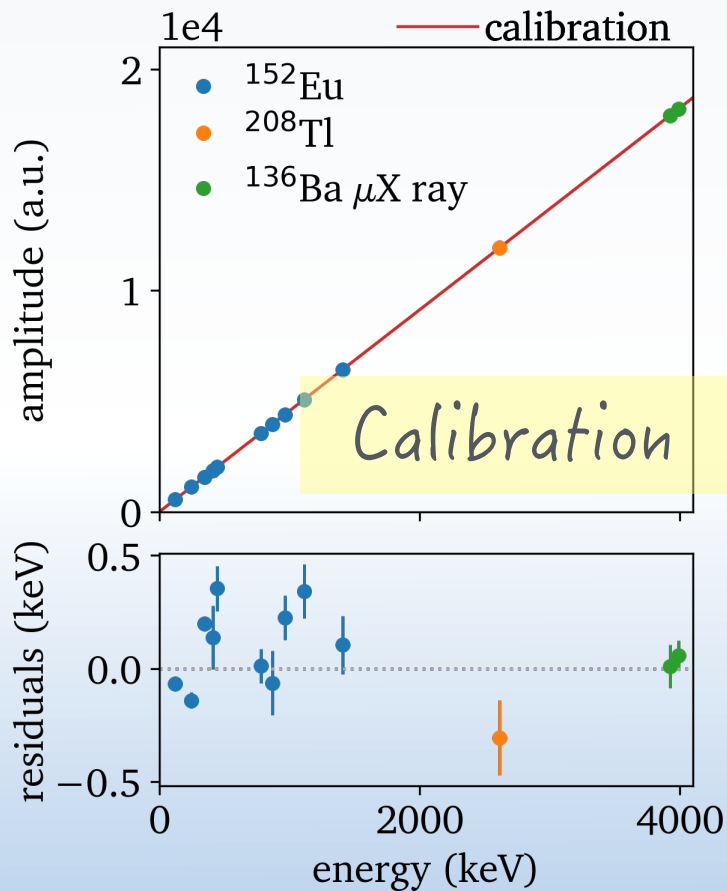
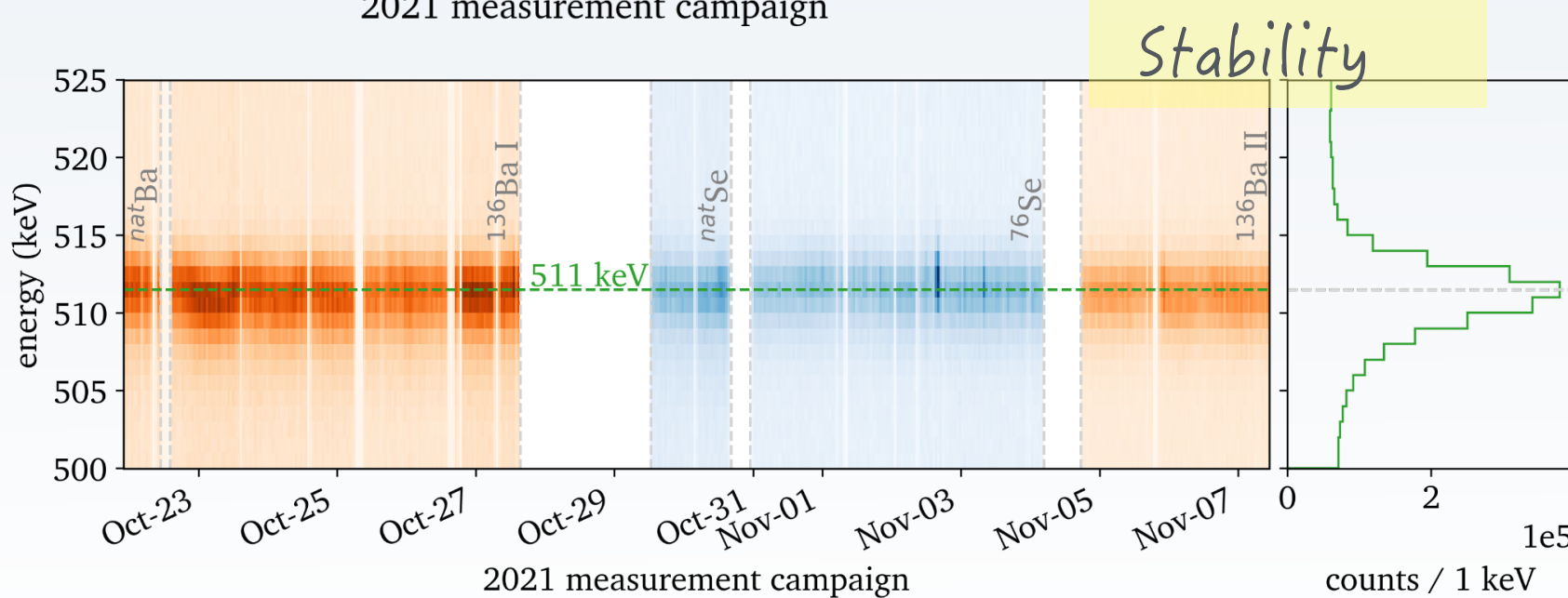
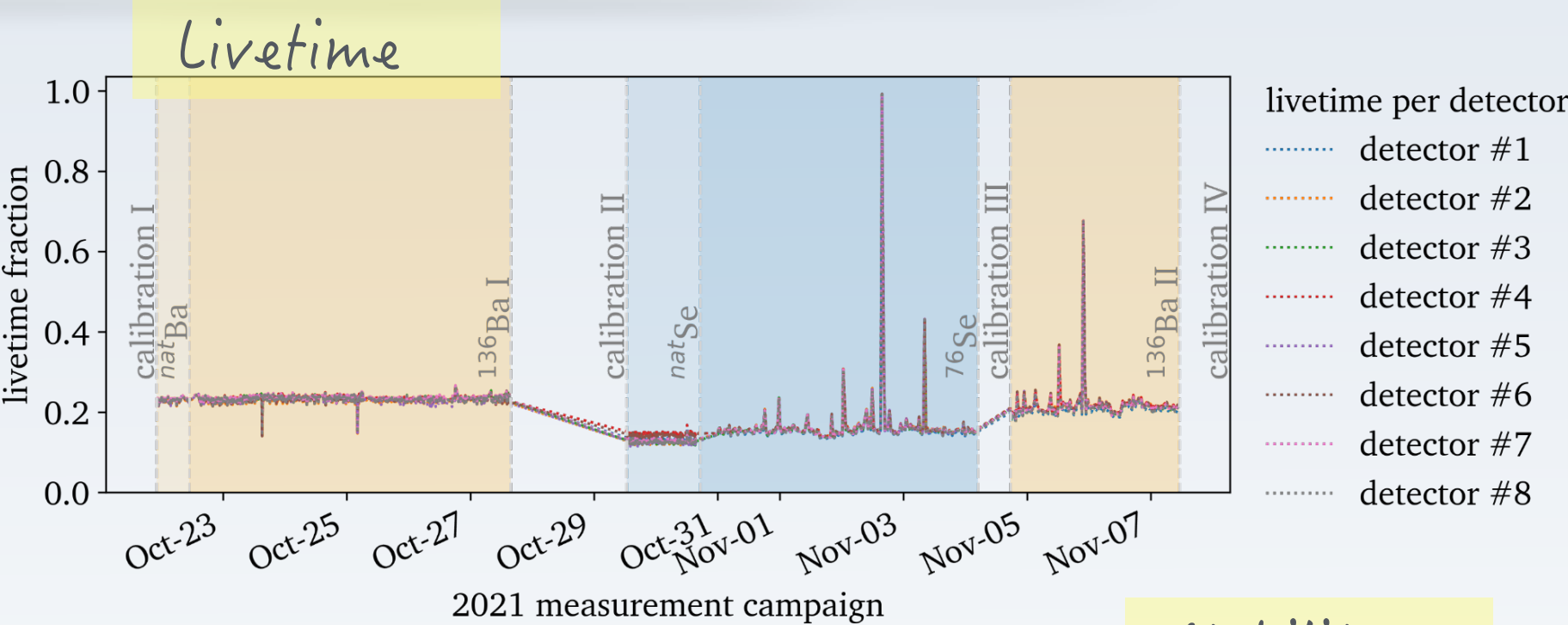
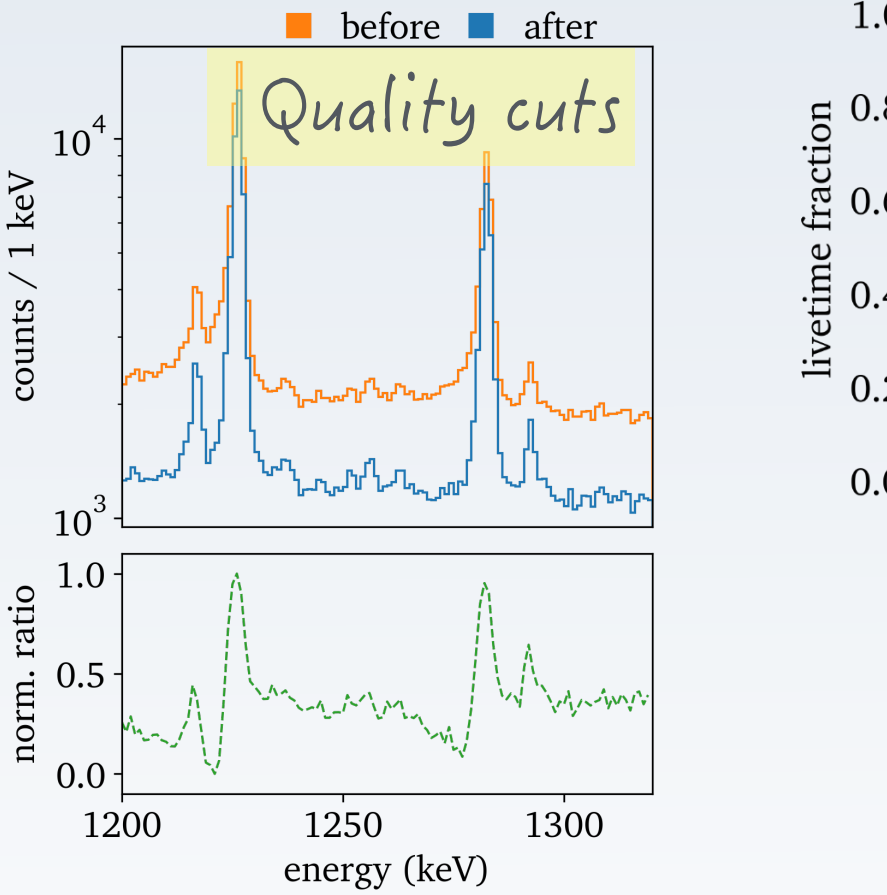
ALPACA [9]



- **Full waveform** digitisation, low and high frequency windows
- **Offline analysis**
- **>150 TB data**
- Analysis routines **based on GERDA Experiment** [10]

Analysis

Performance [1]

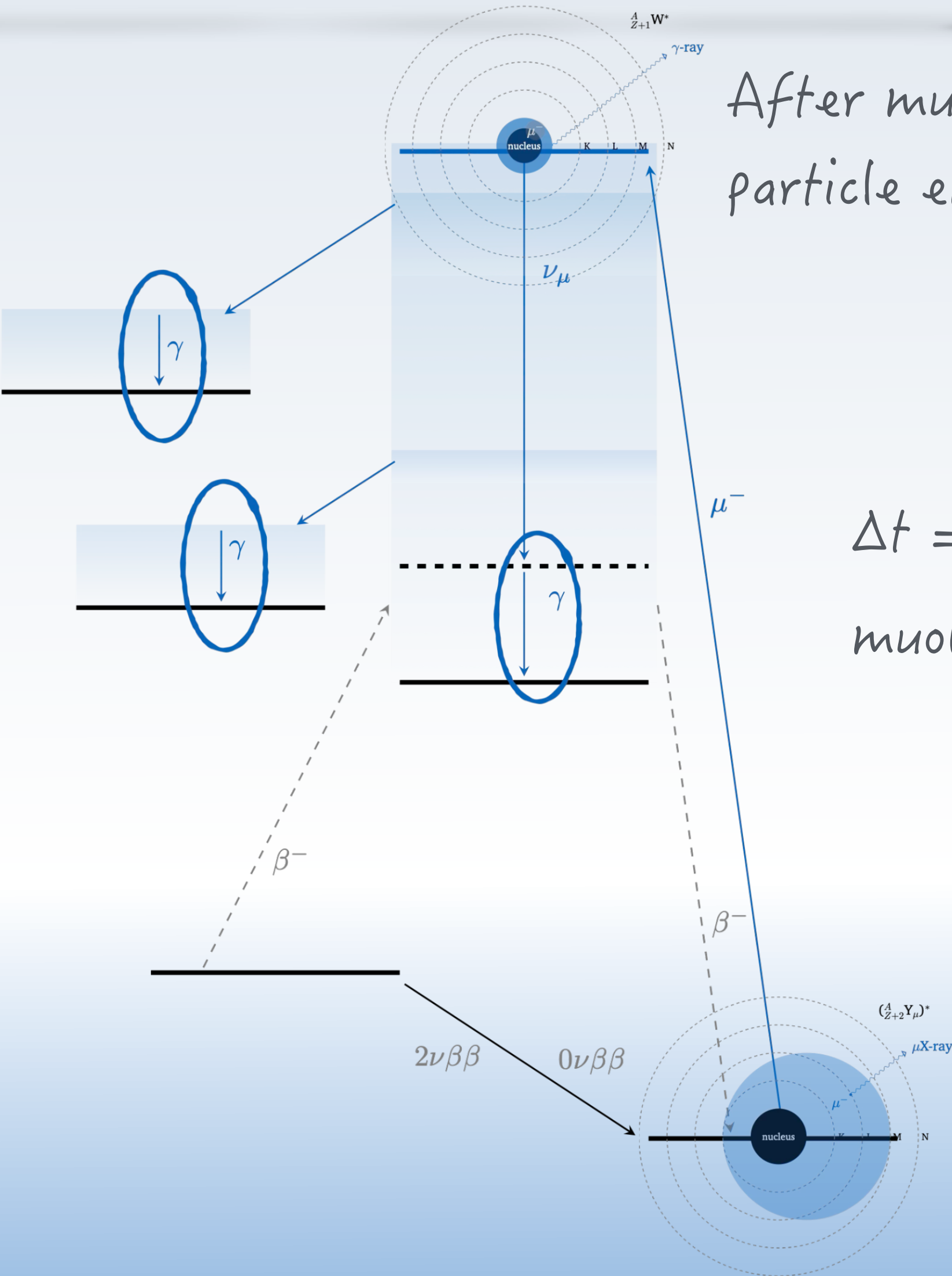


Total capture rate analysis

Muon lifetime, or total capture strength, can be calculated by theory and compared with experimental results

Calculated values for ^{76}Se predict:

$$115 \text{ ns} < \tau < 255 \text{ ns}$$

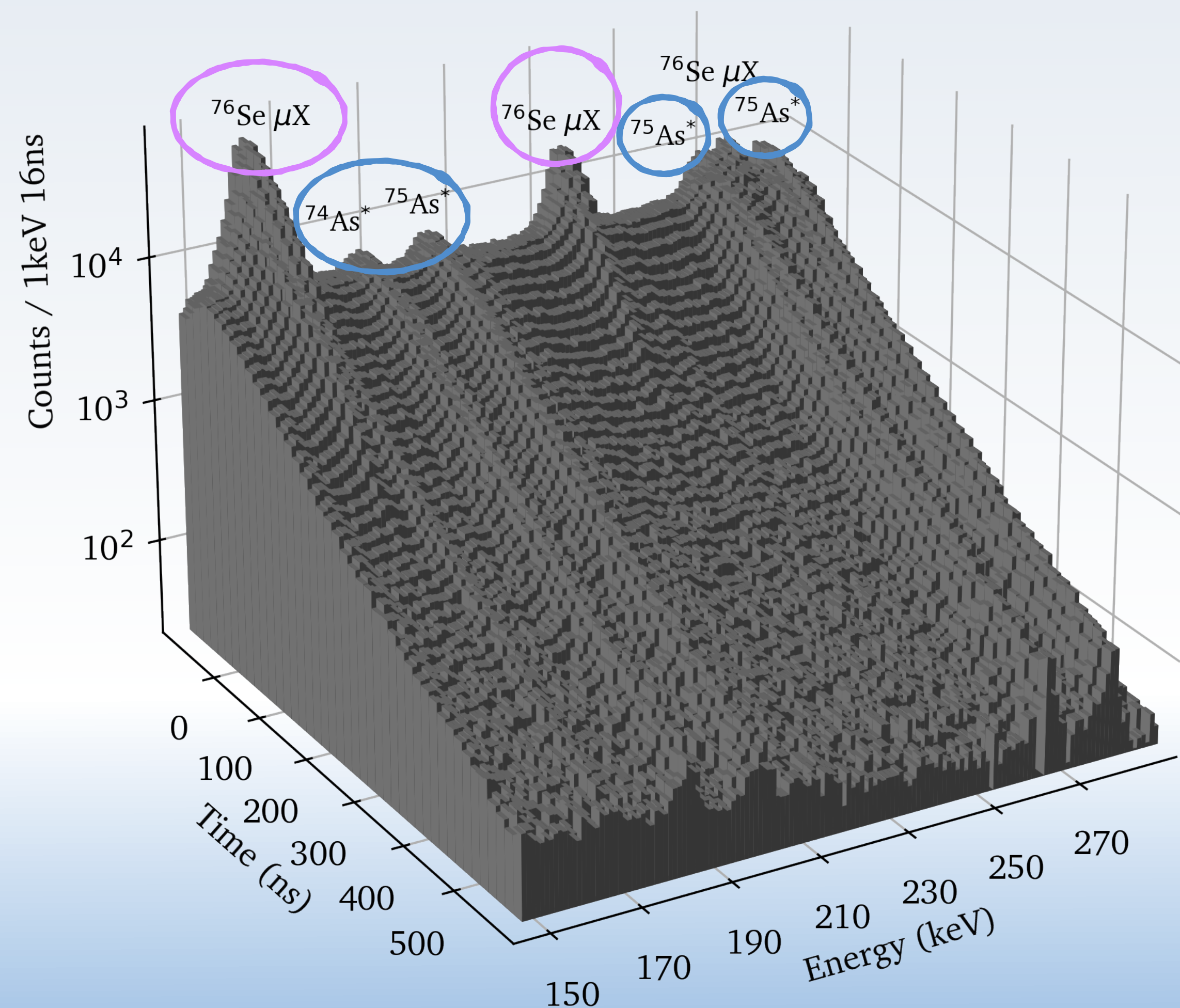


After muon capture $\rightarrow$ de-excitation via γ & particle emission

$$\Delta t = t_\gamma - t_{\mu\text{stop}} \rightarrow \text{informs about the muon lifetime}$$

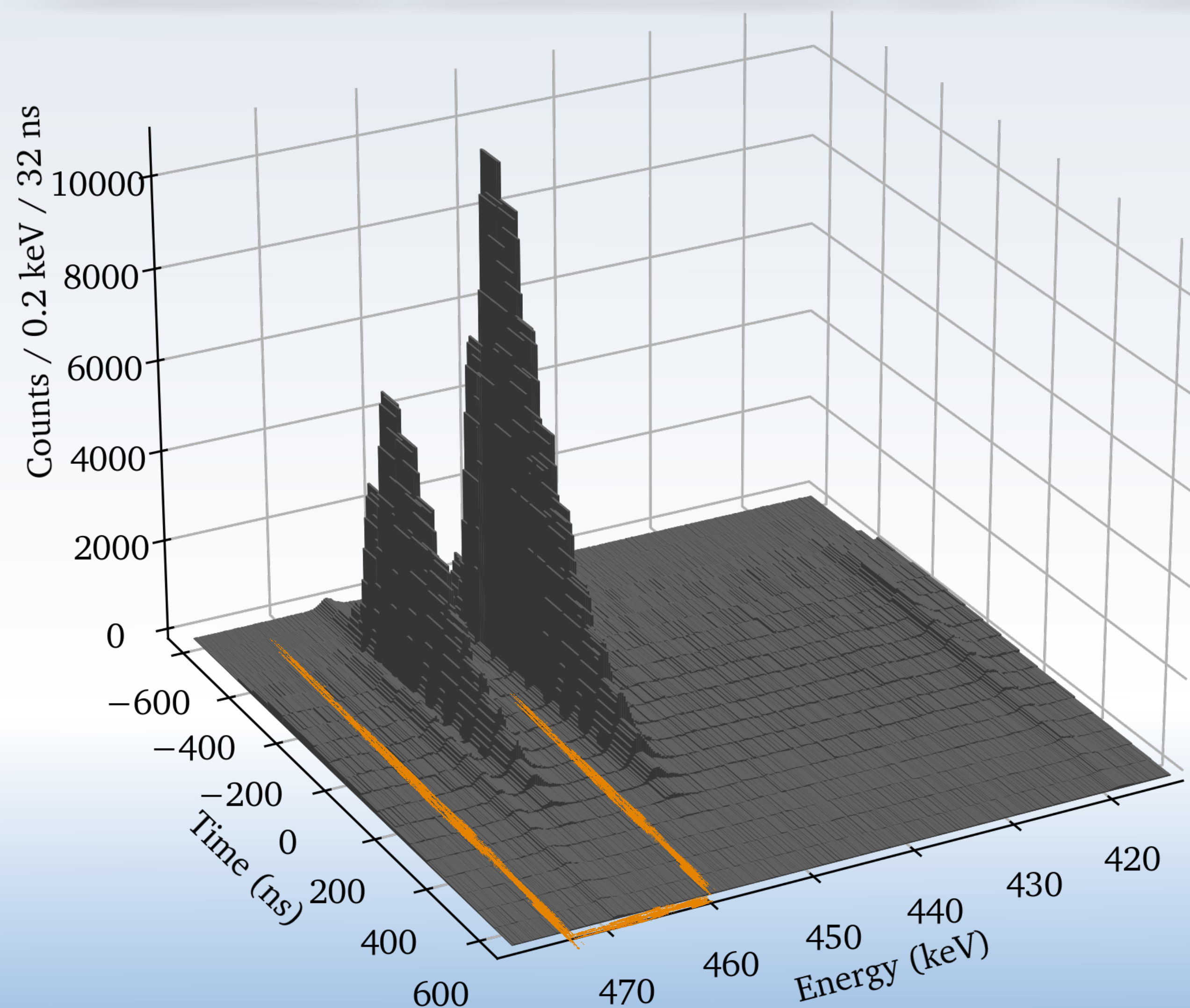
muon stopped at the target atom
 $\rightarrow \mu\text{X-rays}$

^{76}Se Dataset



- 2D histograms mapping HPGe energy over time (Δt) since the last muon
- γ -rays from daughter isotopes encode the muon lifetime
- μX -rays provide timing information ($\Delta t = 0$)
- $\sim 125\text{h}$ of beam-on data

Muon lifetime in ^{76}Se



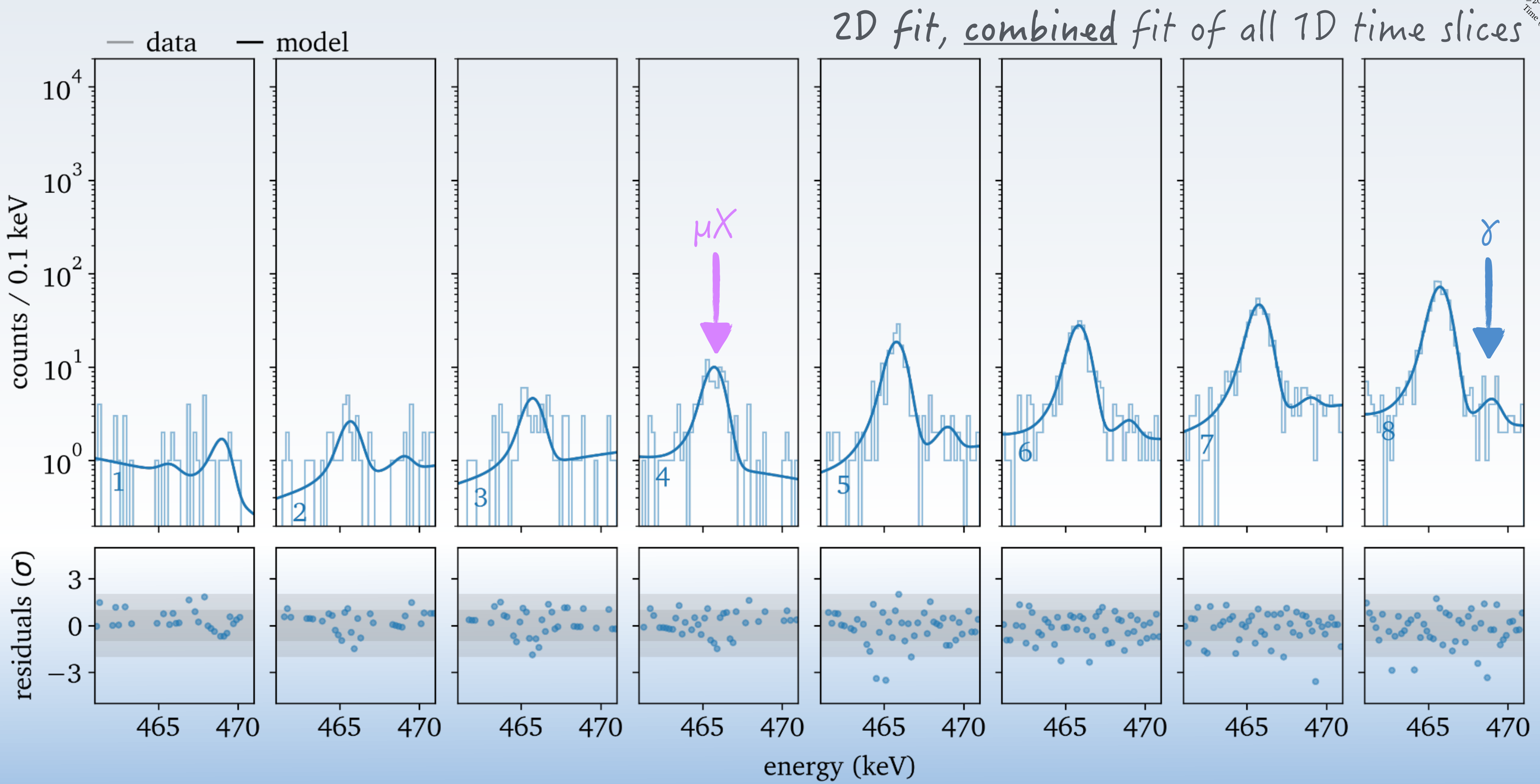
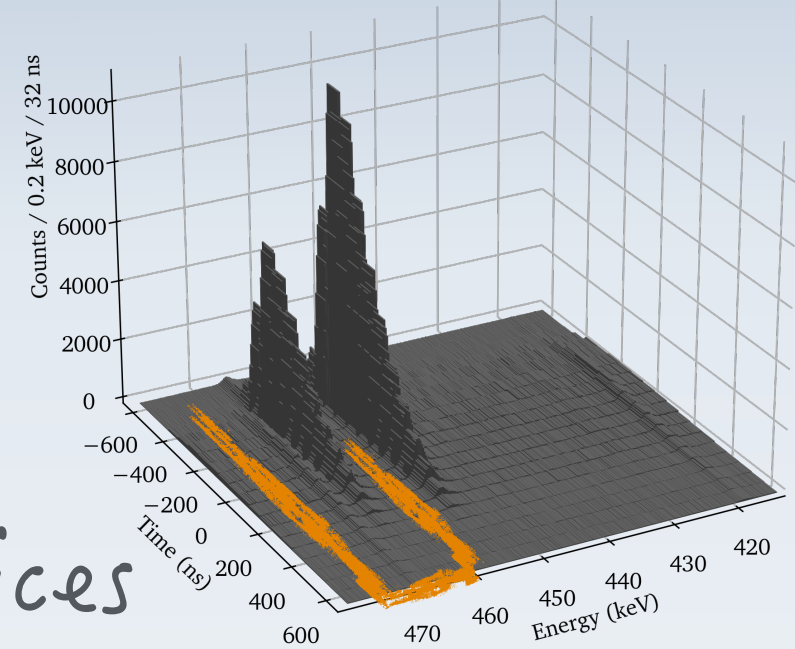
Analysis in 2 steps:

- ① Time profile extraction (intensities over time)
- ② Lifetime fit (muon lifetime τ)

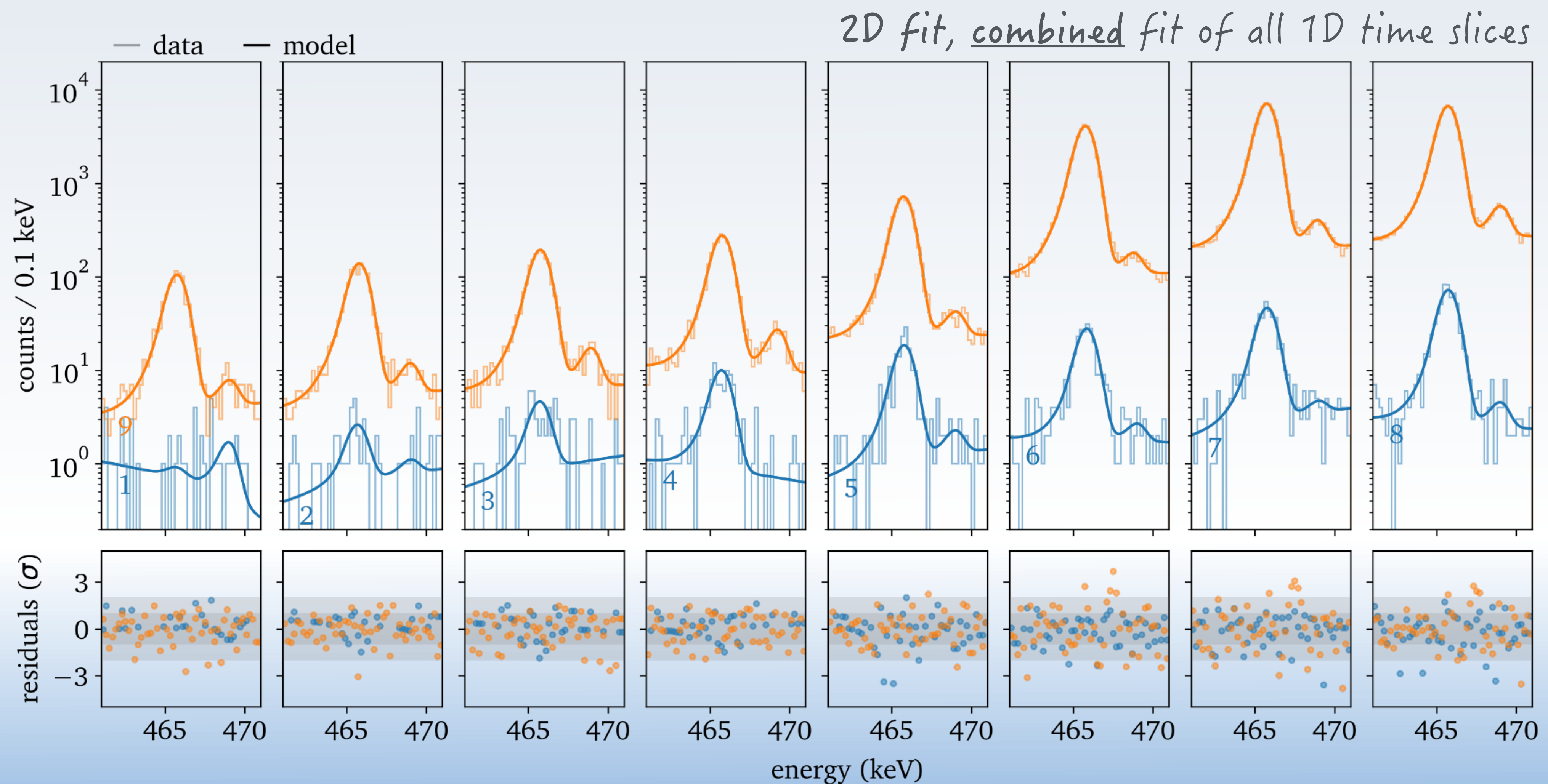
Showcase data:

^{76}Se , ALPACA, $\mu\text{X-ray}$ at 465 keV & $\gamma\text{-ray}$ at 469 keV

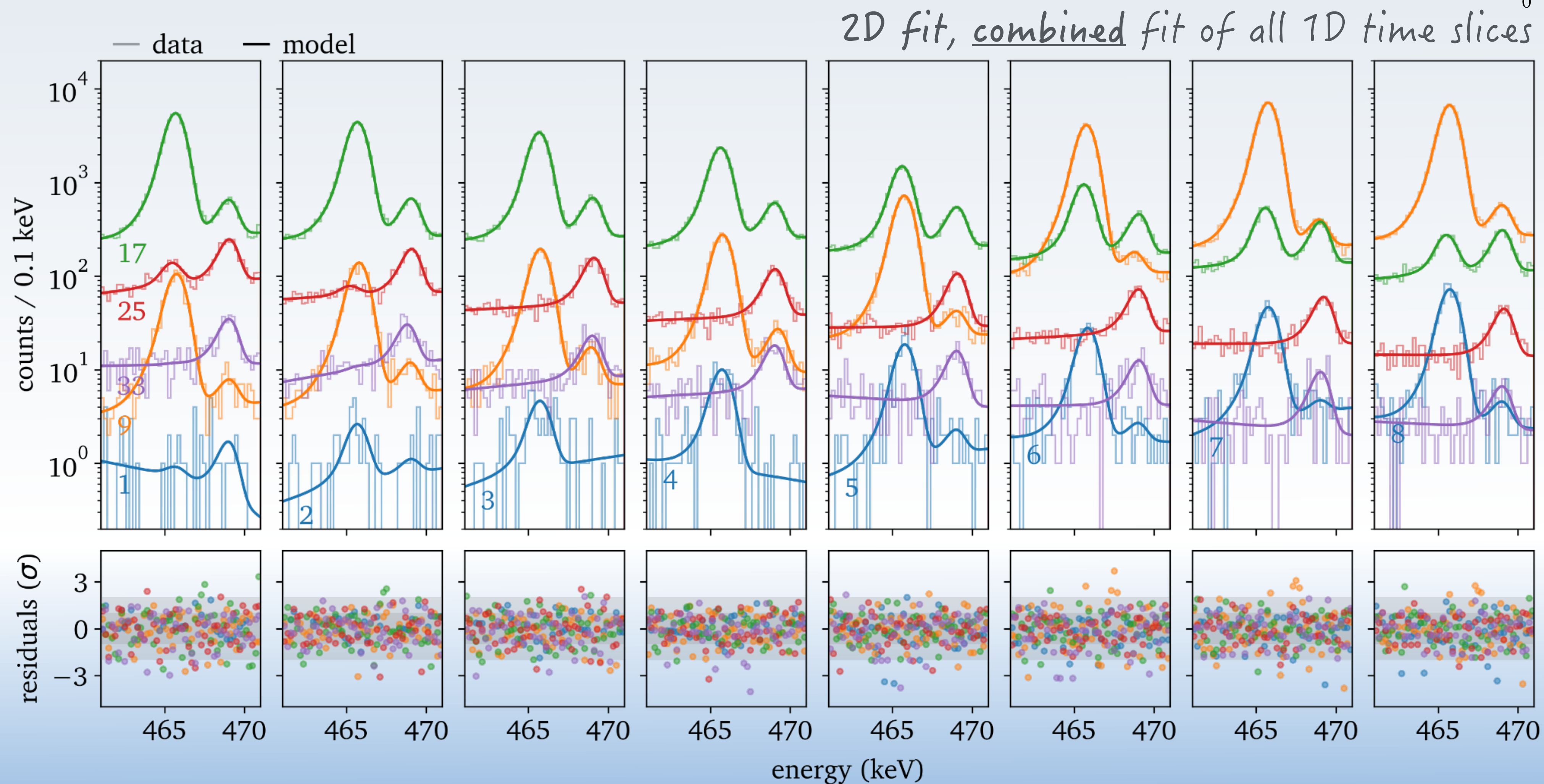
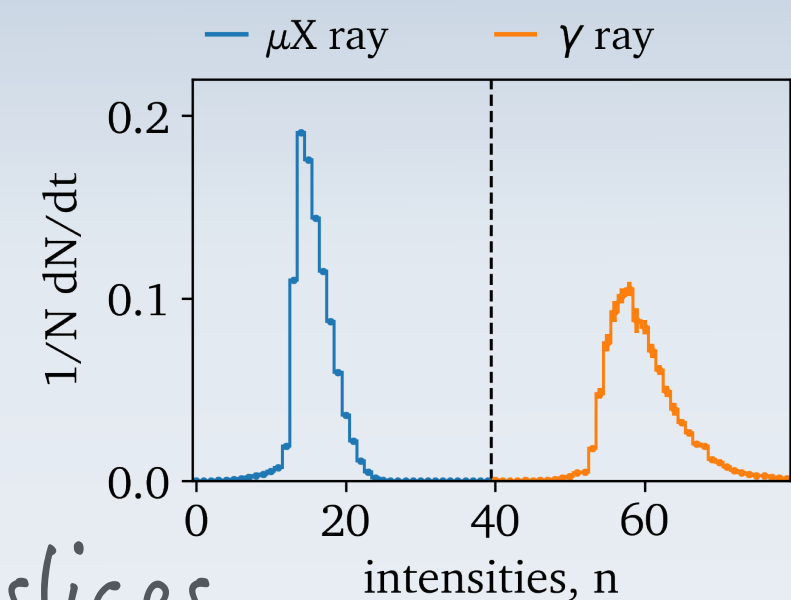
① Time profile extraction



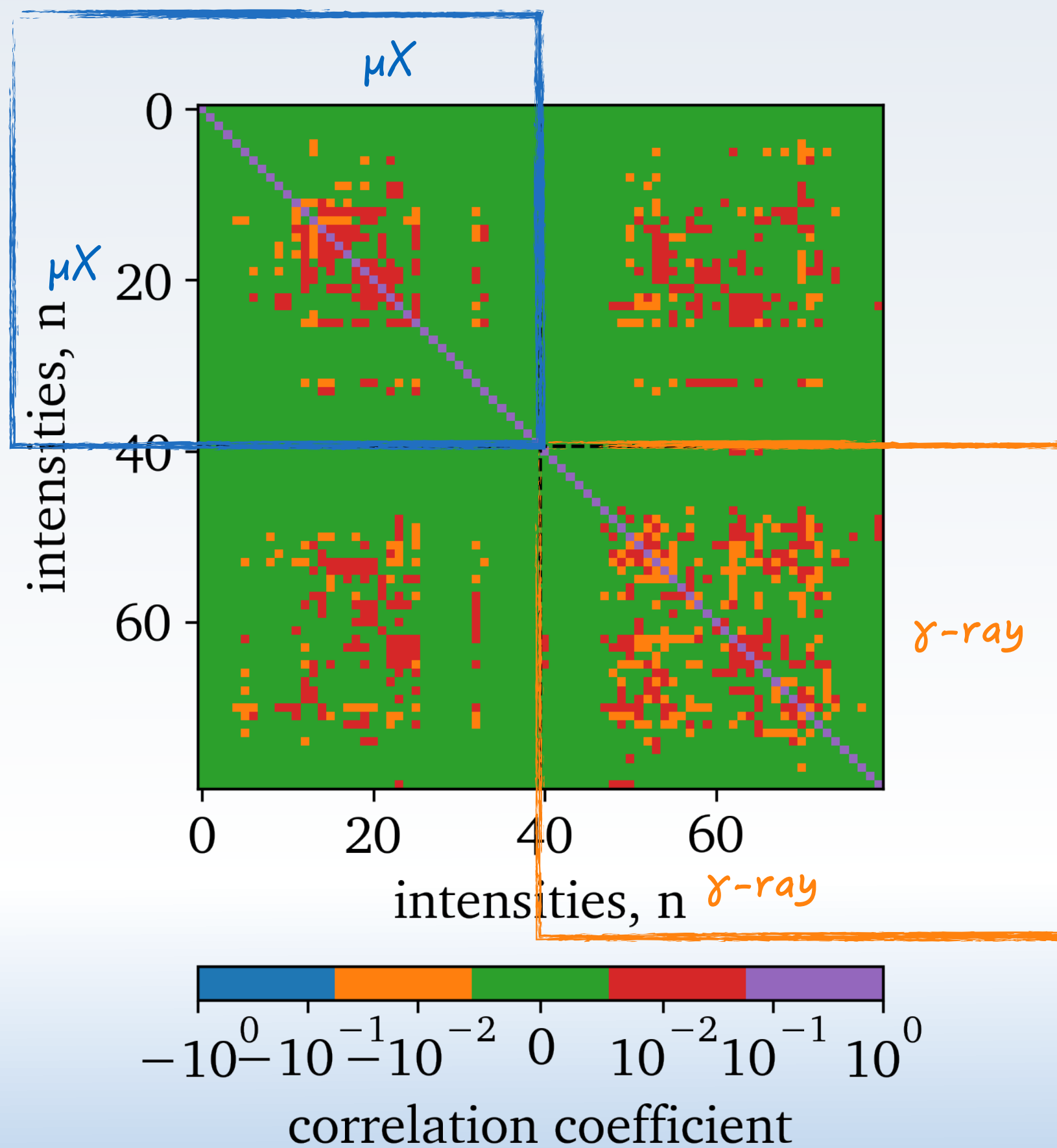
① Time profile extraction



① Time profile extraction



① Time profile extraction



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

- Combined fit on ALPACA data $\rightarrow$ covariance matrix
- Correlations are propagated to the next step
- Individual fits in MIDAS
 - From total energy projection $\rightarrow$ peak parameters
 - Fit each time slice with fixed peak parameters

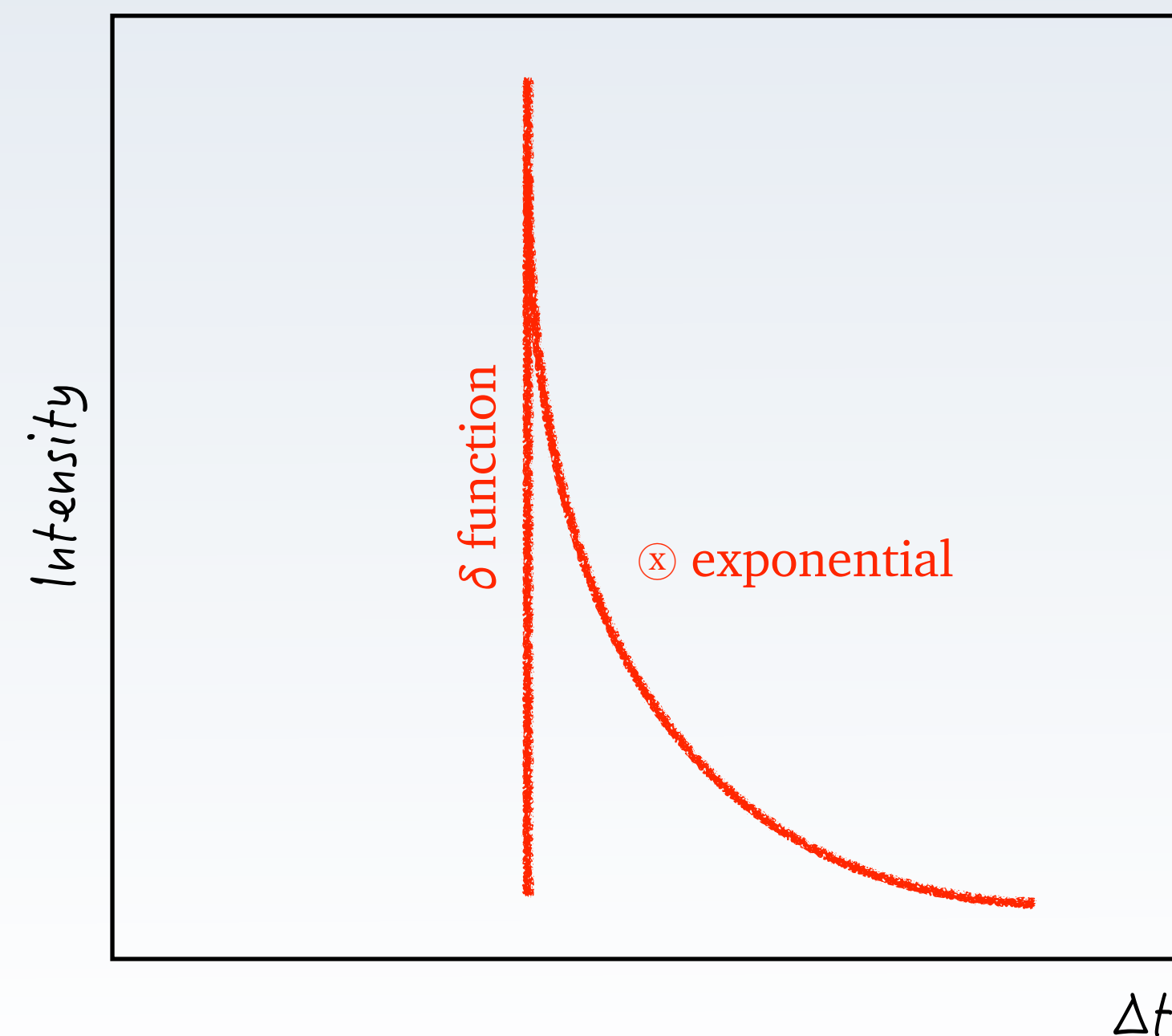
② Lifetime fit: conceptually



- The time profile is composed of a prompt response (system) and the decay time (muon lifetime)

$$f_{profile} = f_{prompt} \circledast \exp\left(-\frac{t}{\tau}\right)$$

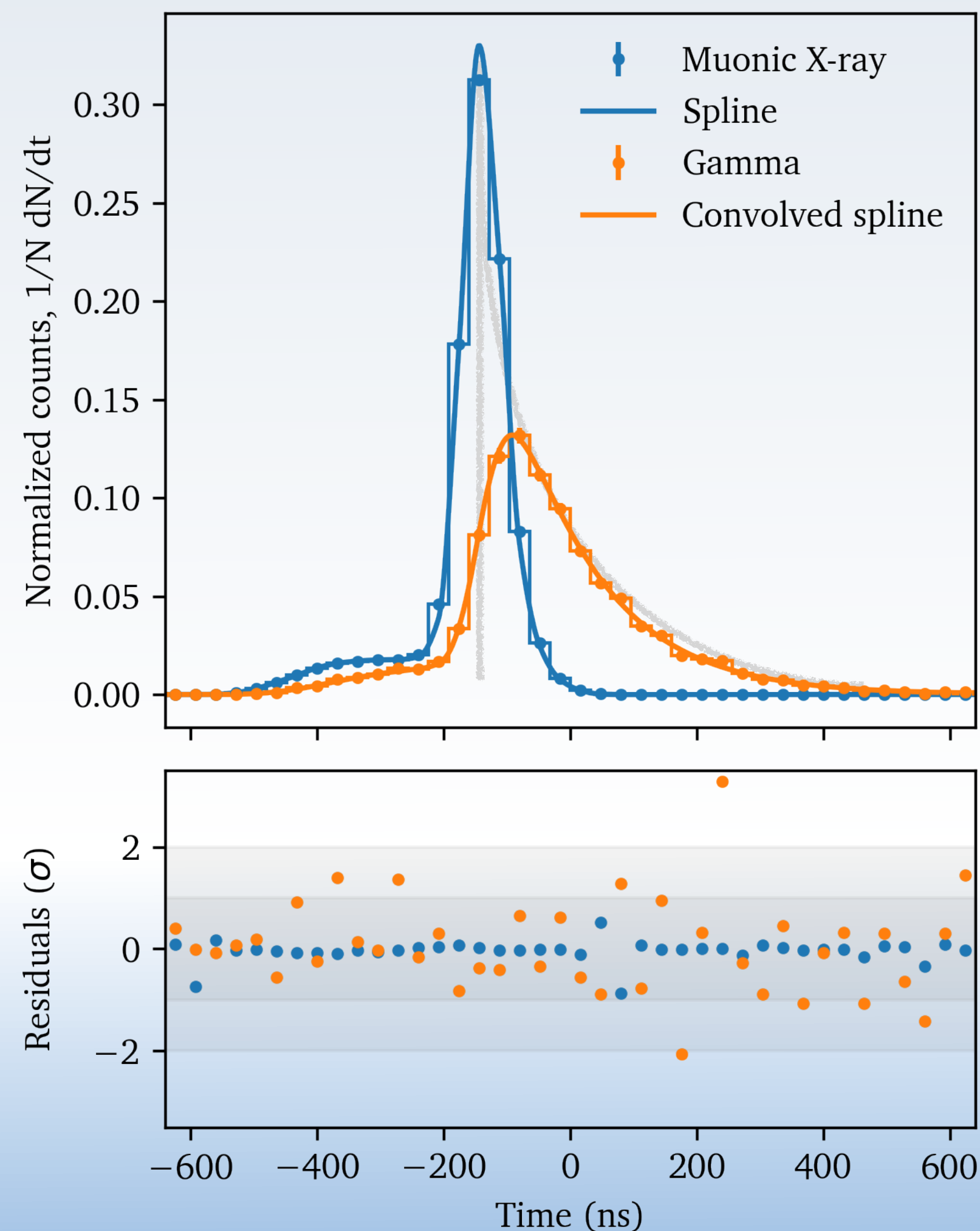
② Lifetime fit: conceptually



- The time profile is composed of a prompt response (system) and the decay time (muon lifetime)
- The prompt response is given by the μX -rays
- The decay time is encoded in the γ -rays
- With a perfect time resolution, the prompt response would be a δ -function

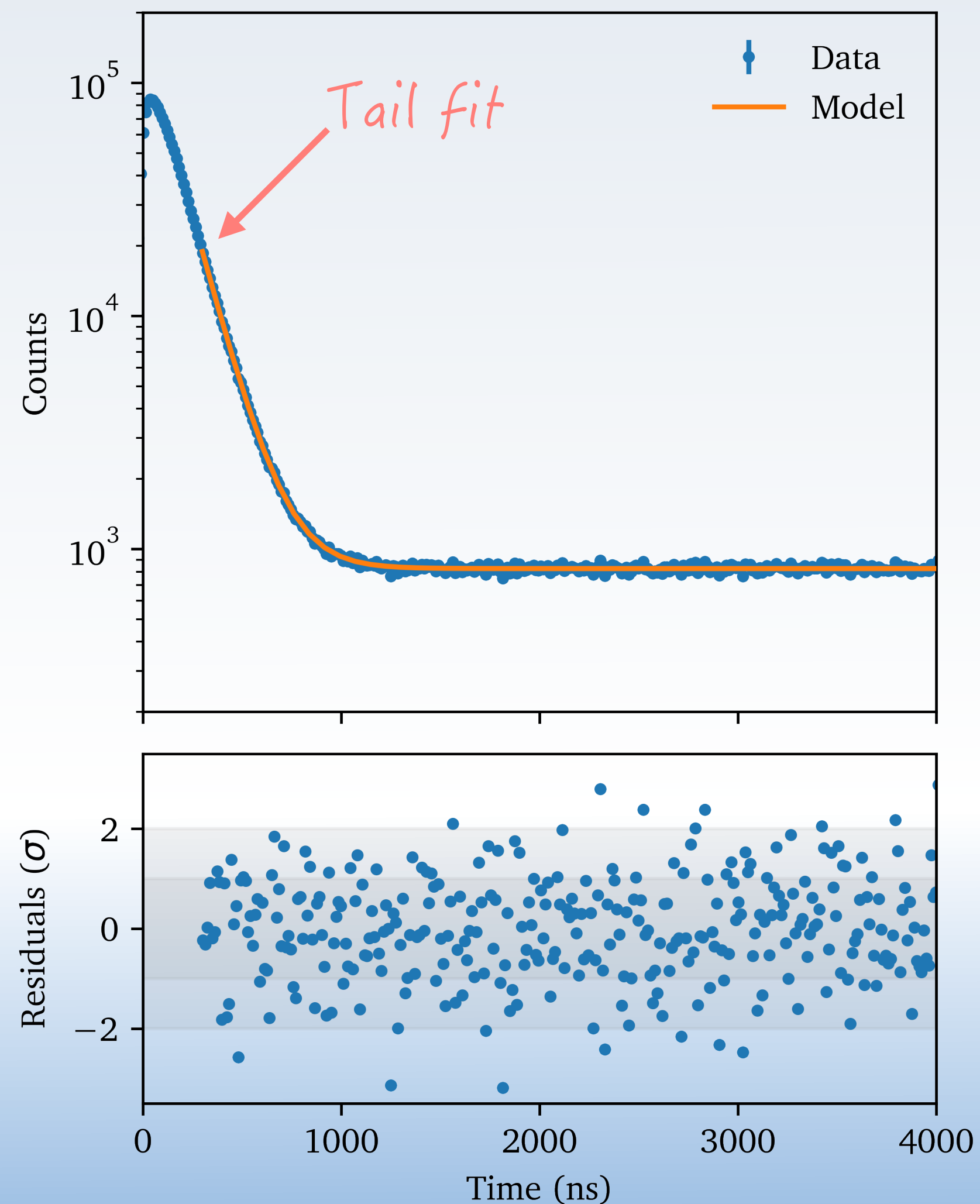
$$f_{\text{profile}} = f_{\text{prompt}} \otimes \exp\left(-\frac{t}{\tau}\right)$$

② Lifetime fit (ALPACA)



- 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

② Lifetime fit (MIDAS)



- Tail fit (no μX -ray close by)
- Restricted to the part of the profile where the prompt component has vanished
- MIDAS time profiles extend over larger Δt

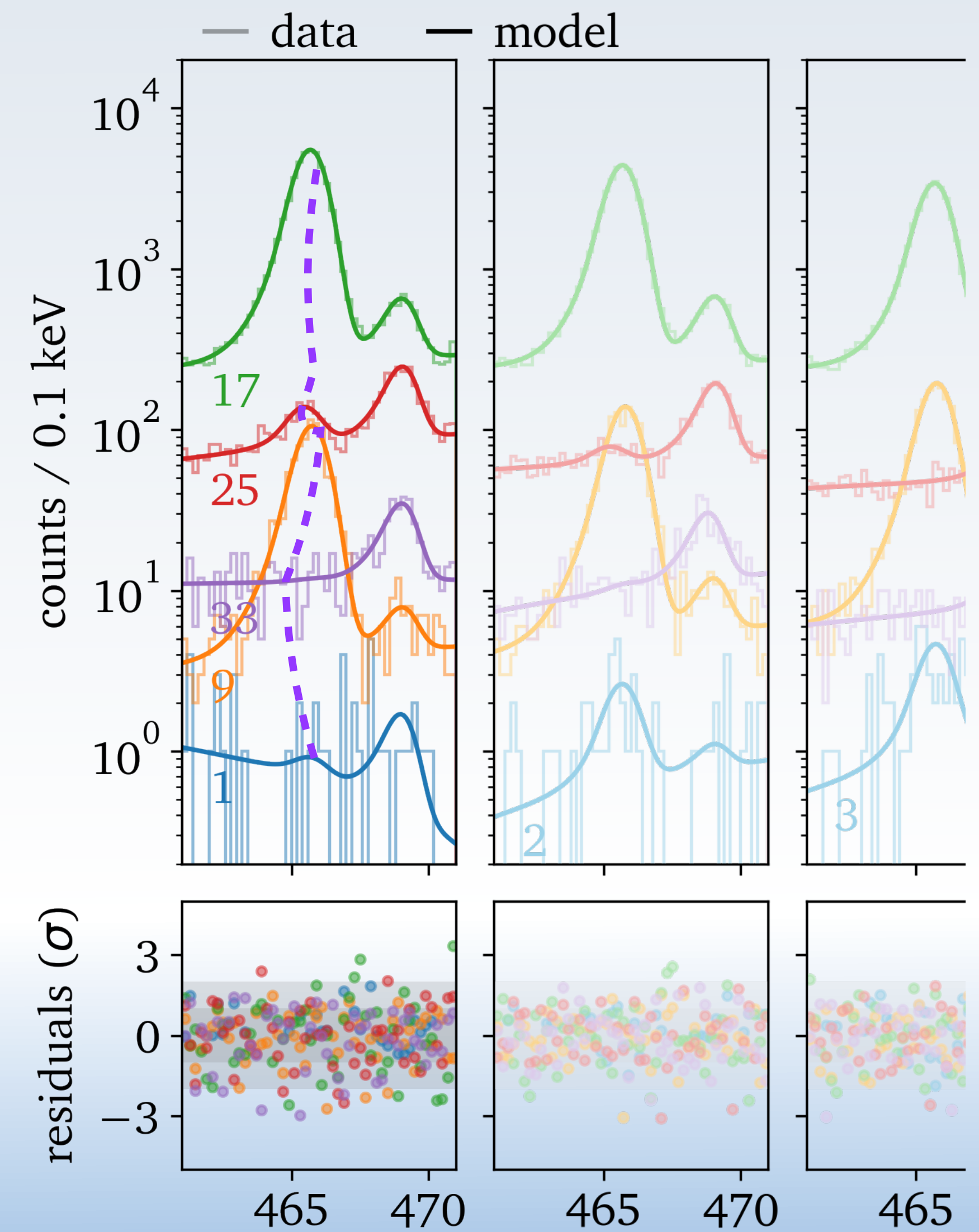
Systematics

- A. Line position drift (①, ①↔②)
- B. Background shape (①↔②)
- C. Prompt timing energy
-dependence (②)
- D. Method uncertainty: fully correlated

A. Line position drift

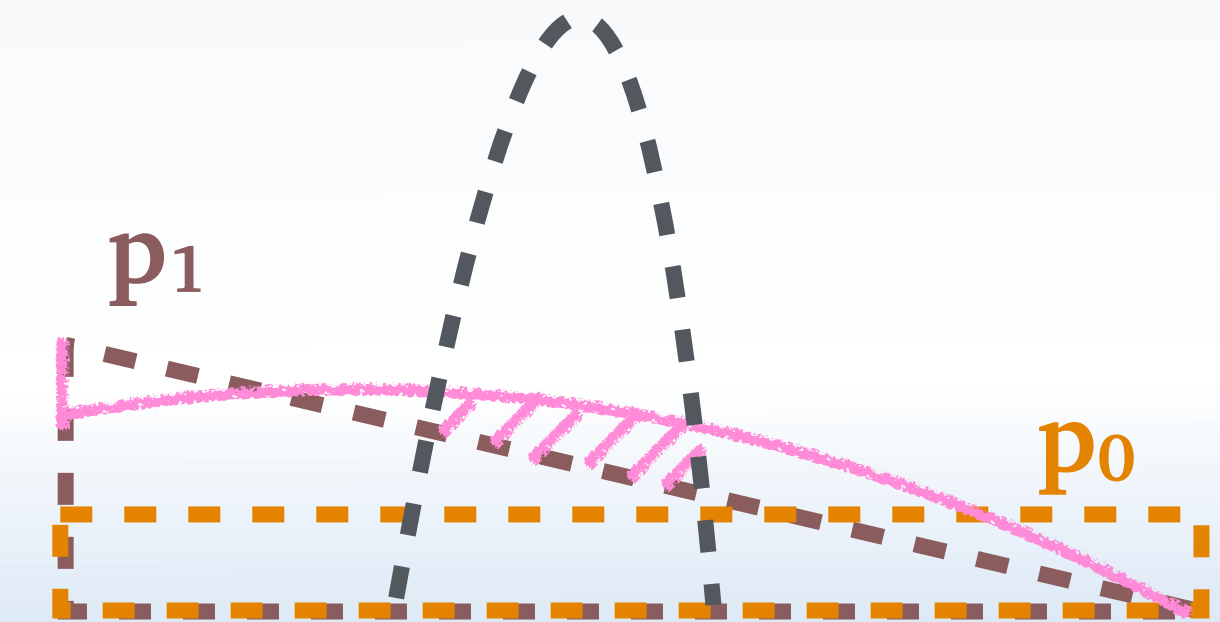
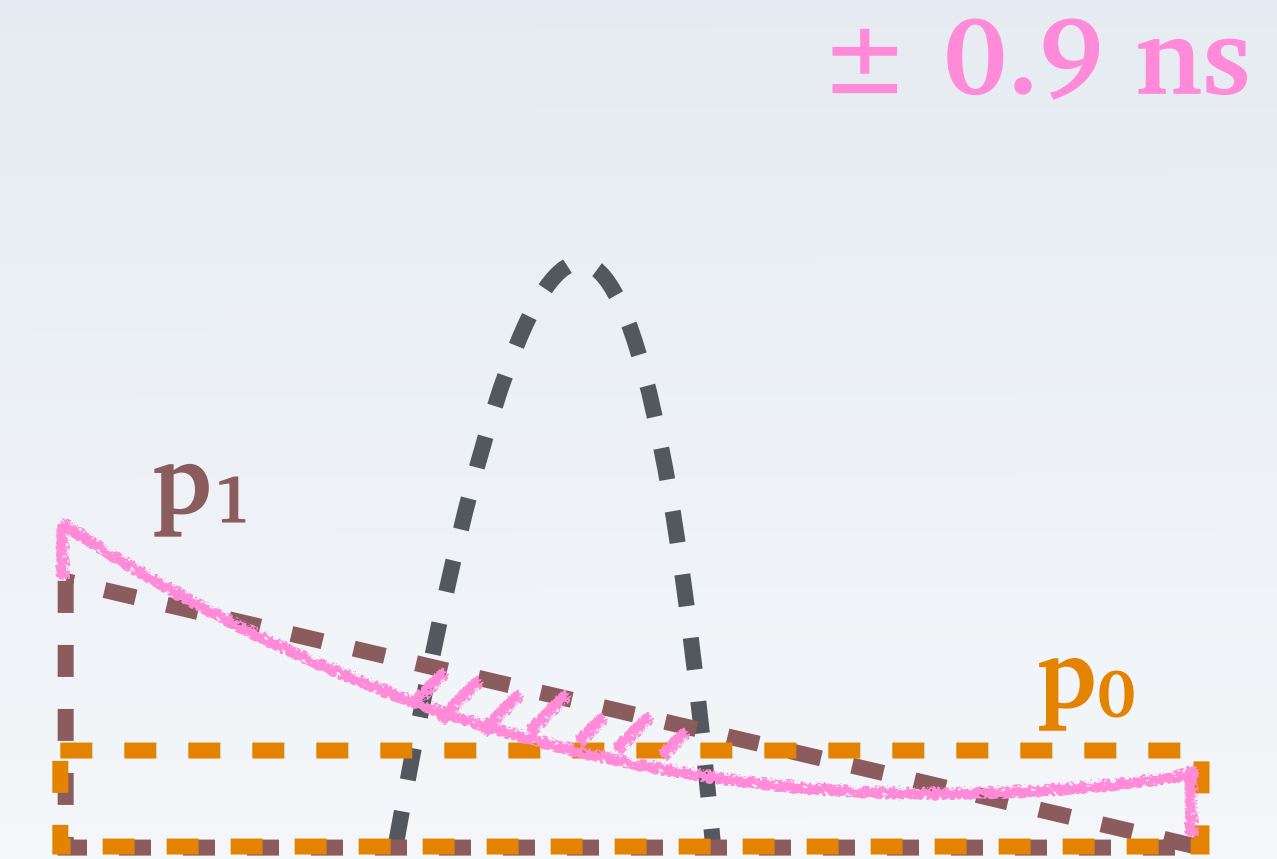
Time slices correspond to HPGe detector *drift-time selection*; later events are reconstructed at lower energies due to, e.g., charge trapping.

- Include additional parameters ($\Delta\mu_j$ and $\Delta\alpha_j$), bound by **pull terms** (1 keV and 5%) $\hookrightarrow$ ①

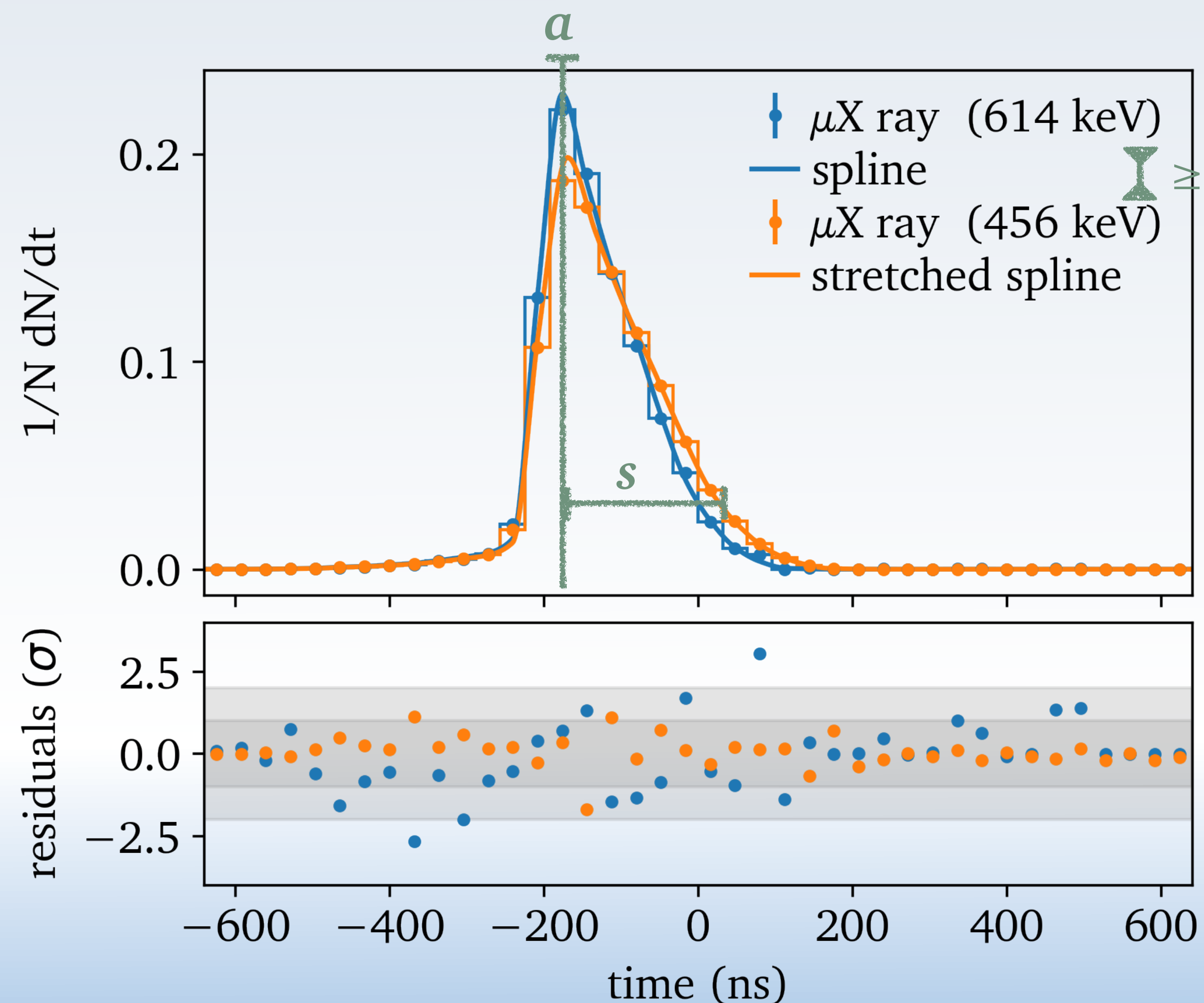


B. Background shape

- Simple linear function might be insufficient in some cases
- Convex/concave background shape can lead to **under/over-estimation of intensity**
- Assume number of **counts attributed to slope as uncertainty** that is missed without higher order of polynomial $\hookrightarrow$ ①↔②



C. Prompt timing energy-dependence



- 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 $\mu\text{X rays}$ $\hookrightarrow$ ②

Systematics: uncorrelated

A. Line position drift (①, ①↔②)

B. Background shape (①↔②)

C. Prompt timing energy
-dependence (②)

Uncertainty contributions for showcase data (ns)

Statistics 1.3

Line position 0.7

Background 0.9

Dominant contribution →

Prompt timing 3.3

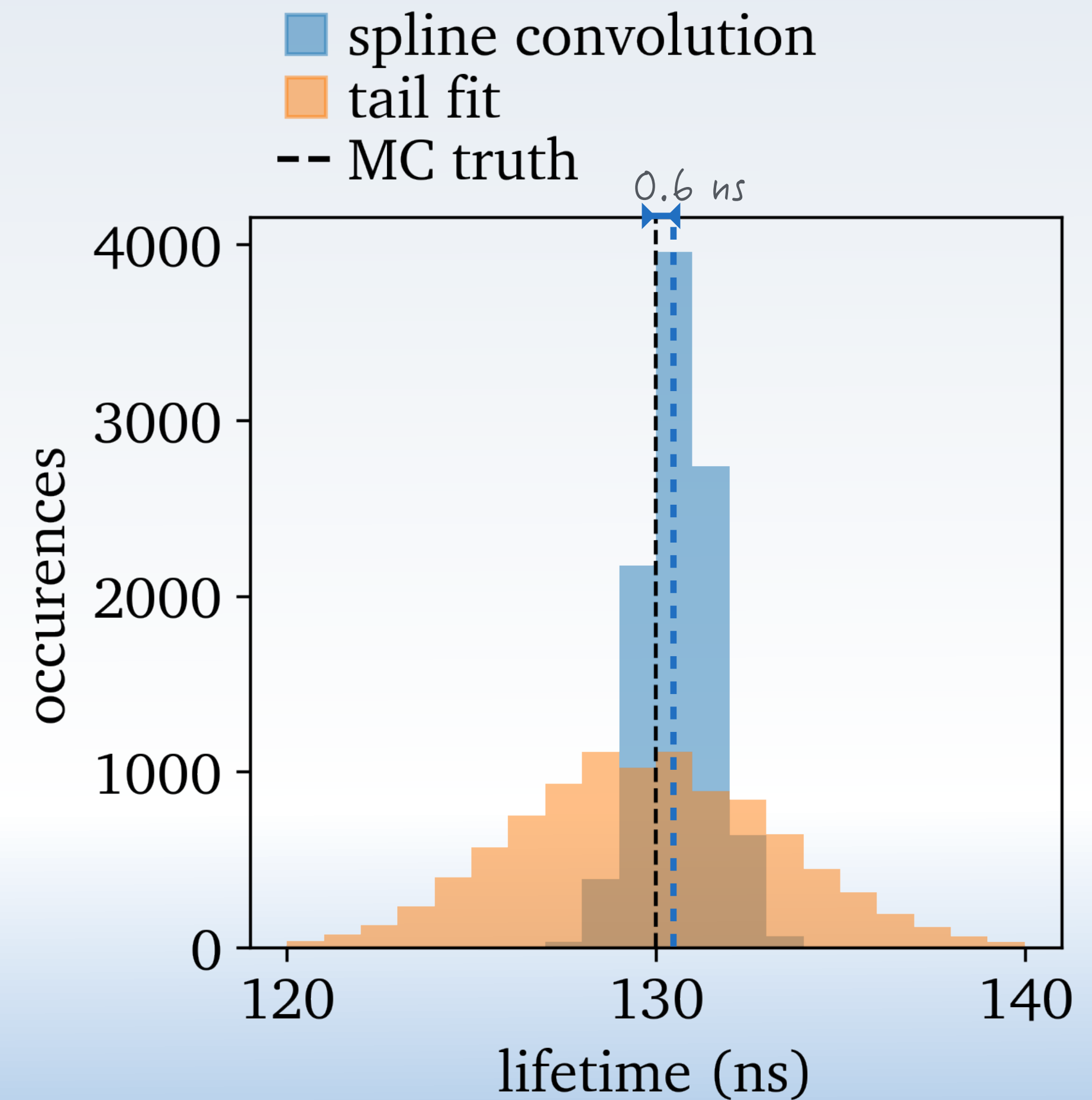
Treated uncorrelated across different lines

Total 3.7

D. 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 by 0.6 ns from Monte Carlo truth, added as uncertainty to final result

Treated correlated across different lines



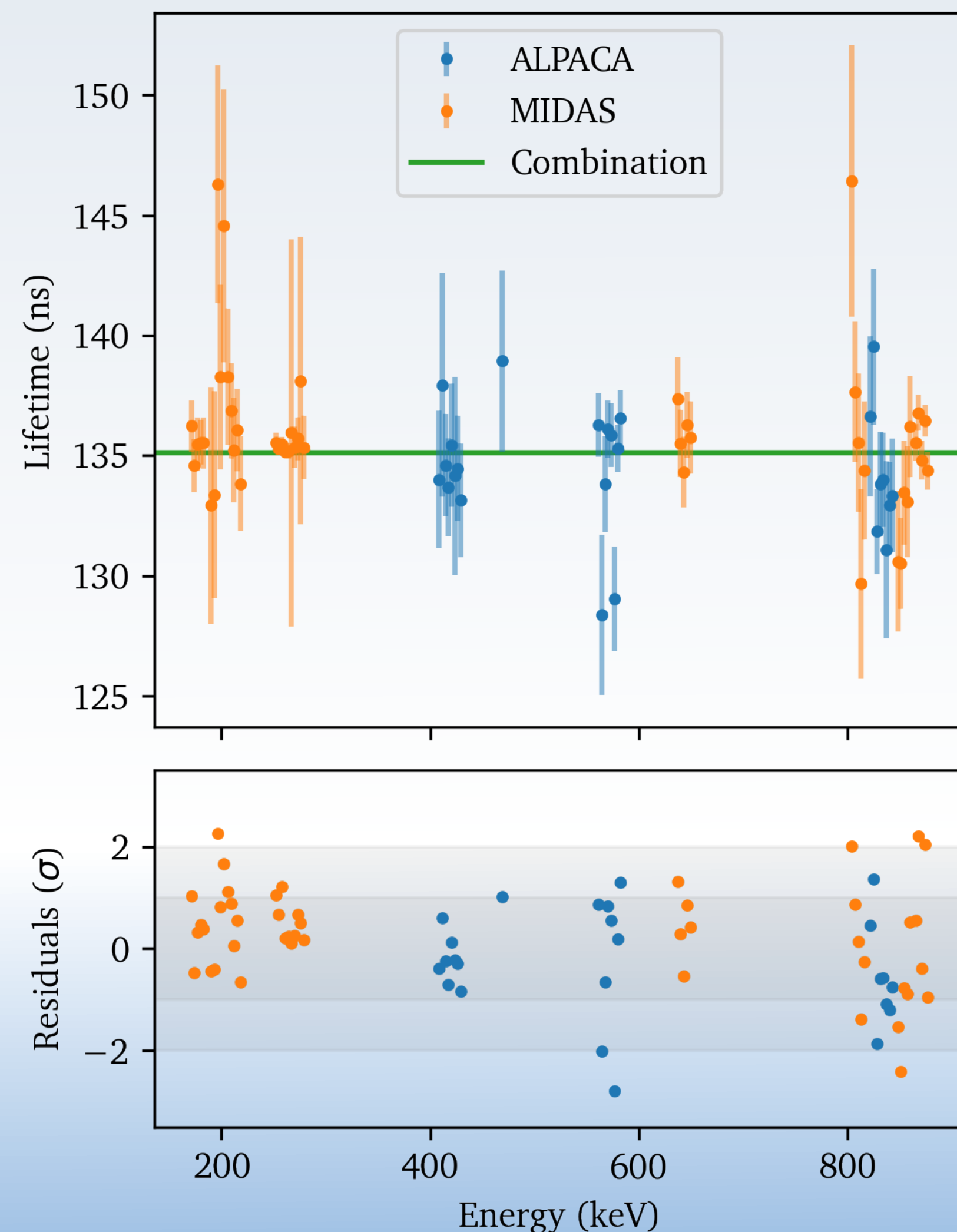
All systematics considered

Systematic effects

Effect	ALPACA	MIDAS
Line positions, HPGe detector charge collection	Additional nuisance parameters	0.5 ns
Background shape	0.2 ns	
Prompt timing response, energy dependence	Additional nuisance parameters	Not applicacable
Method	0.6 ns	0.4 ns

Results

MONUMENT result for ^{76}Se [1]



- 70 statistically independent values
- 25 from ALPACA
- 45 from MIDAS
- Systematic uncertainties as covariances

$$\tau = (135.1 \pm 0.5) \text{ ns}^{[3]}$$

$$\tau = (134.8 \pm 0.7) \text{ ns}$$

$$\tau = (135.4 \pm 0.7) \text{ ns}$$

[3] MONUMENT Collaboration, Determination of the muon lifetime in ^{76}Se with the MONUMENT experiment, Phys. Rev. C, vol. 113, 064613 (2026)

[12] 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)

[13] H. Primakoff, Theory of muon capture, Rev. Mod. Phys., 31:802–822, (1959)

[14] 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)

[15] 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)

[16] L. Jokiniemi and J. Suhonen, Muon-capture strength functions in intermediate nuclei of $0\nu\beta\beta$ decays, Phys. Rev. C, vol. 100, no. 1, p. 014 619, (2019)

[17] N. T. Zinner, K. Langanke, and P. Vogel, Muon capture on nuclei: Random phase approximation evaluation versus data for $6 \leq Z \leq 94$ nuclei, Phys. Rev. C 74, 024326 (2006)

[18] T. Marketin, N. Paar, T. Nikšić, and D. Vretenar, Relativistic QRPA calculation of muon capture rates, Phys. Rev. C 79, 054323 (2009)

Discussion

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

Lifetime values (ns)

Experimental		Semi-empirical			Theoretical*		
This work ^[1]	Other work ^[12]	Primakoff ^[13, 14]	Goulard-Primakoff ^[14, 15]	Fujii-Primakoff ^[14]	pnQRPA ^[14]	pnQRPA ^[16]	
135.1±0.5	148.5±0.1	135.2	115.1–135.3	196.3	254.1	59.4	$g_A = 0.8$
					134.5		$g_A = 1.27^{**}$

* These are models used to calculate $\beta\beta$ -decay NME

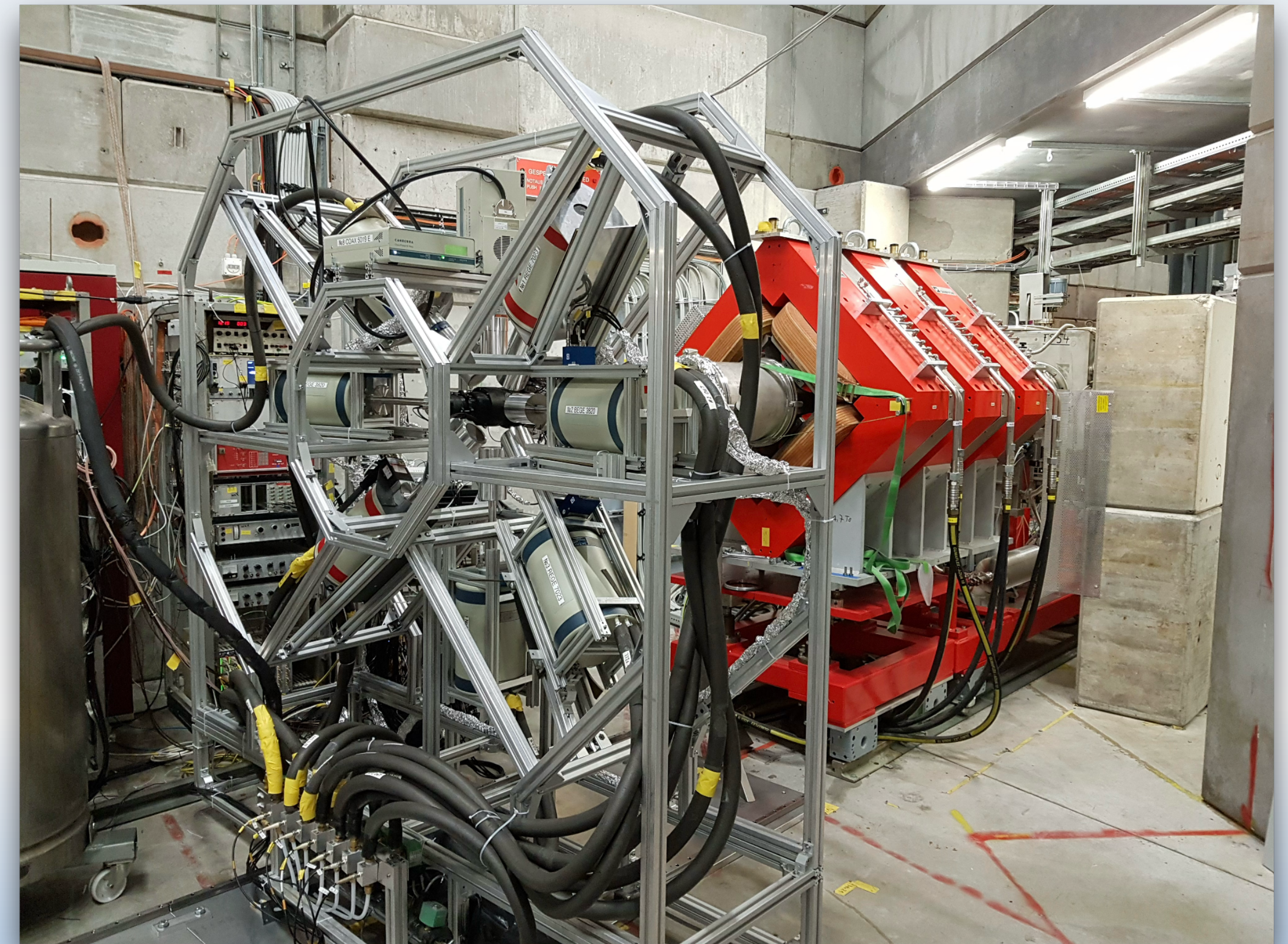
** Consistent with earlier capture-rate studies, where calculations match experiment without quenching ^[17, 18].

Outlook

- ^{136}Ba , ^{100}Mo & ^{48}Ti data -> ongoing analysis on muon lifetimes
- Request for further measurements with lighter targets, e.g., ^{12}C
- An adapted target chamber using Si to reduce contamination of C
- Simulation work to improve the experimental setup

Conclusions

- MONUMENT measures OMC on $\beta\beta$ -decay daughter isotopes to inform on $0\nu\beta\beta$ -decay NME calculations
- New experimental results for ^{76}Se muon lifetime: $\tau = (135.1 \pm 0.5) \text{ ns}$ [3]
- Comparison with QRPA calculations indicates no need for quenching



Thanks for your attention!

