Exploring position reconstruction of HPGe detector events in LEGEND with a deep neural network

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Introduction

The LEGEND experiment:

- Goal: Measure $0\nu\beta\beta$ decay in ^{76}Ge
- LEGEND-1000: Sensitivity on half-lives of up to 10^{28}y

To reach this sensitivity, background reduction is very important

Motivation for position reconstruction:

The position of an event inside a Ge-detector can indicate signal or background origin:

- Surface events and events near the contact
- Spot local detector impurities

Position reconstruction has purpose beyond background reduction:

- Exploring possibilities of pulse shape simulation and machine learning

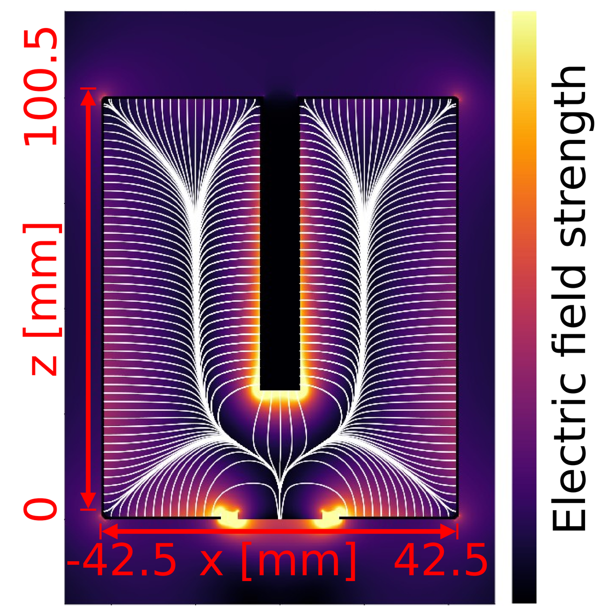
Germanium detectors and pulse shape simulation

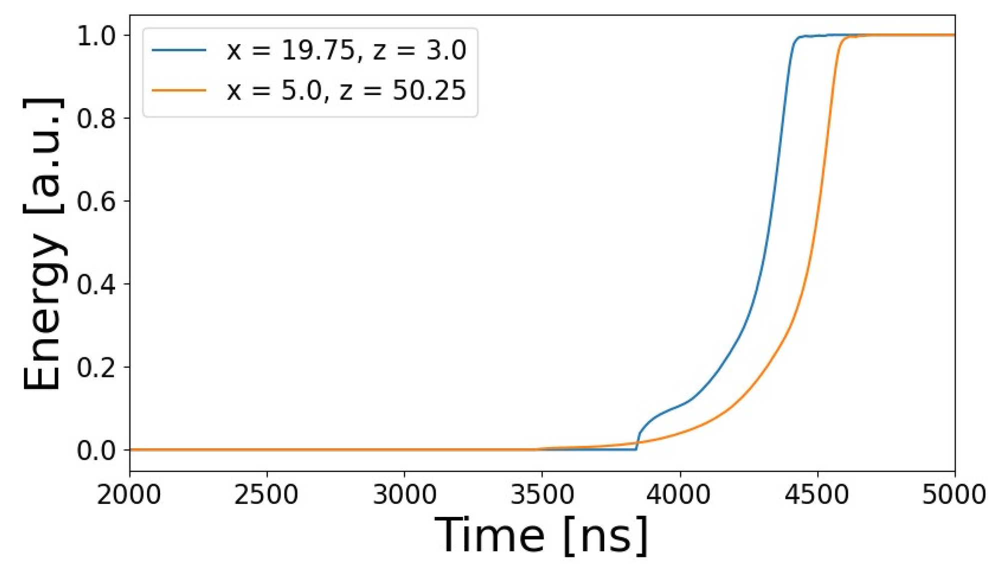
LEGEND-1000 mainly uses inverted coaxial point contact (ICPC) detectors (left)

- Can be produced with comparatively high masses (~3 kg), pulse shape discrimination works well

Pulse shape simulation:

Simulate detector geometry and electric field → Energy deposition creates charge cloud → Charge cloud measured at point contact as waveform, which depends on event position

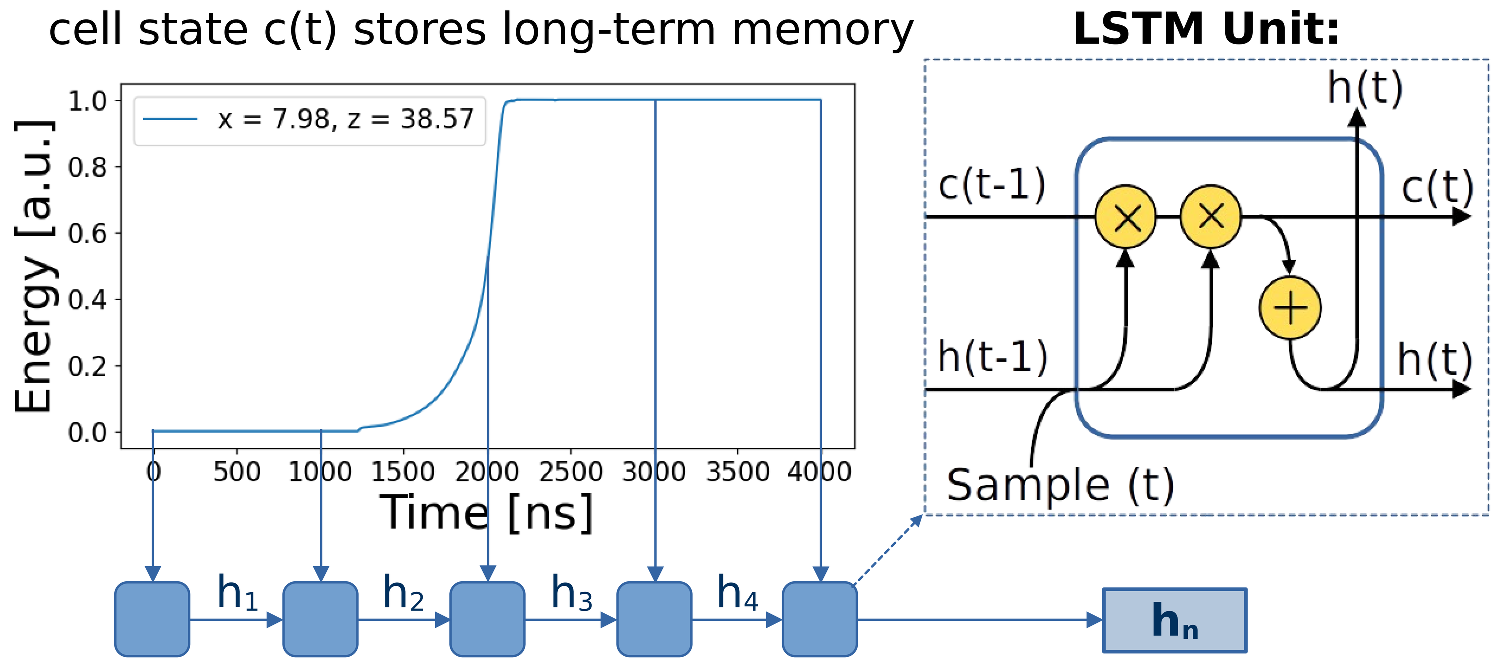




LSTM with attention mechanism

Long-Short-Term-Memory (LSTM):

- Iterates an LSTM unit over each waveform sample
- Hidden state h(t) stores short-term memory, cell state c(t) stores long-term memory

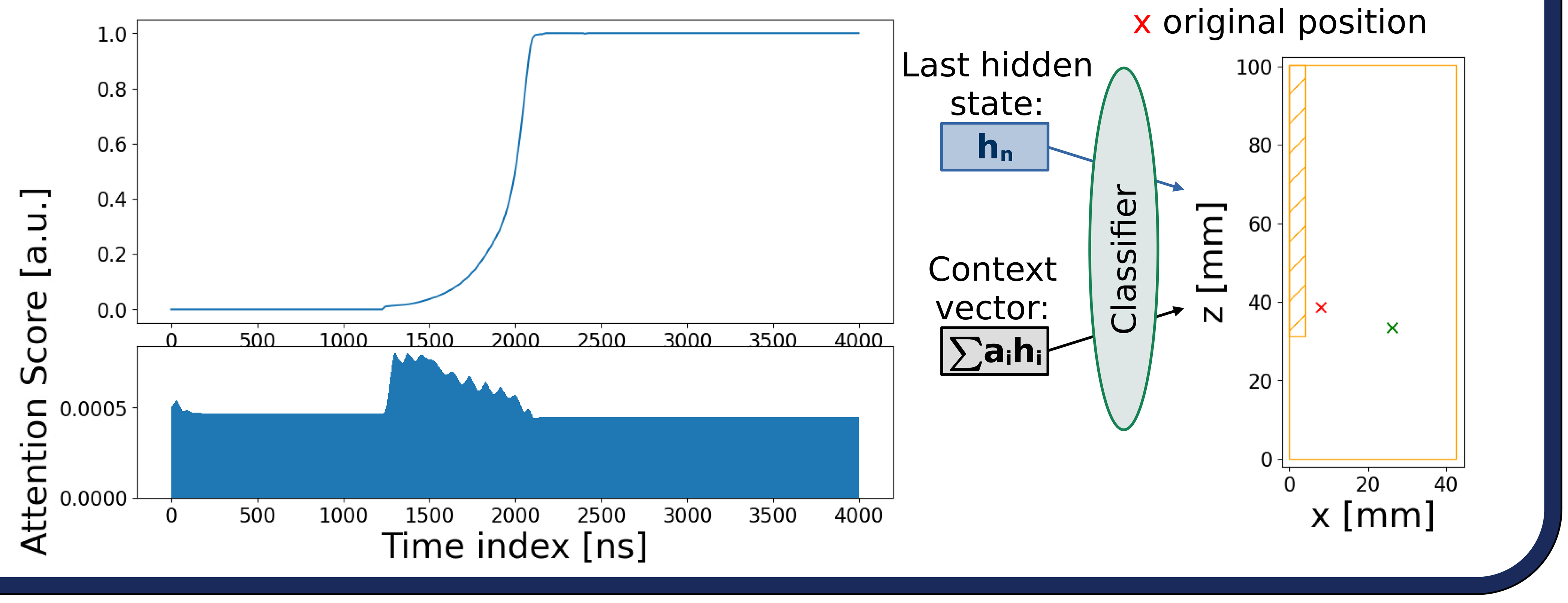


Attention mechanism:

- Highlight important hidden states to optimize reconstruction

Result:

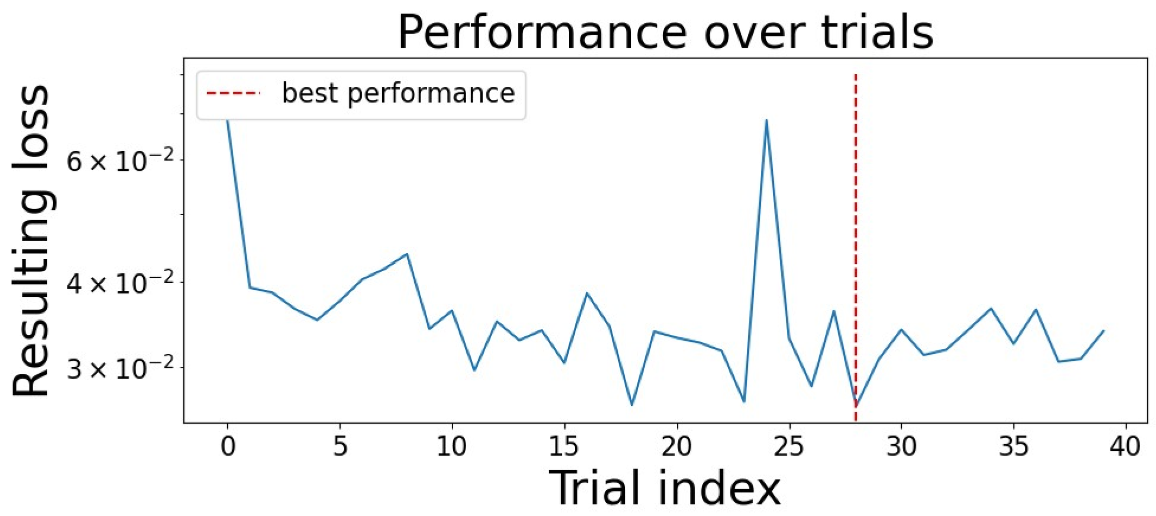
x reconstructed position
x original position

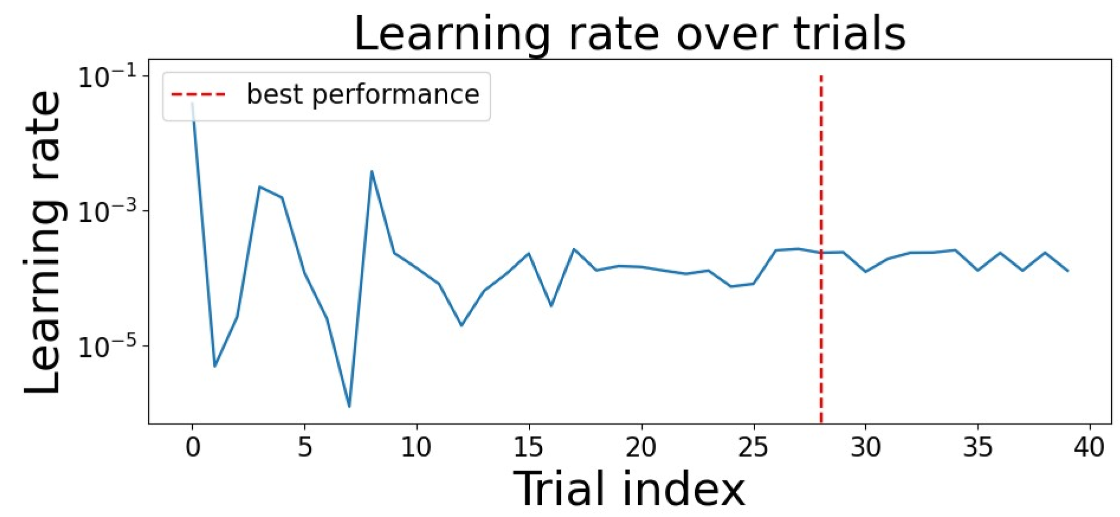


Results: Training the LSTM on simulated pulses

Optimization of the neural network:

- Precision of a neural network depends on various fixed parameters
- Bayesian optimization: Choose parameters of the next training based on previous trainings → Efficient optimization
- Optimization with 120000 simulated events and 50 iterations over the dataset (epochs)



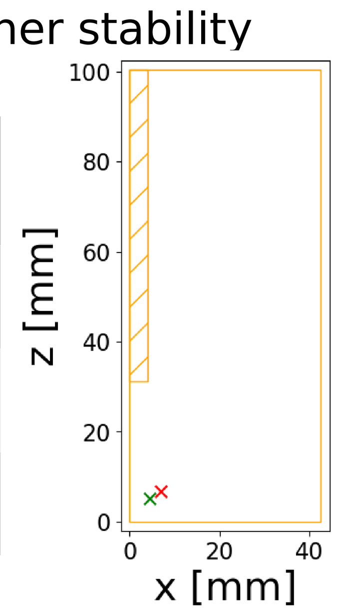


Extended training with optimized parameters

- 240000 events, 100 epochs → Higher stability

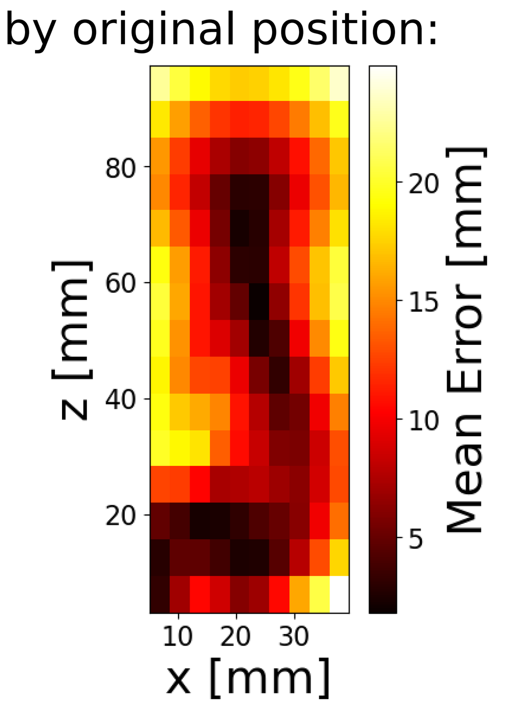
Average errors:

	Absolute error [mm]	Relative to detector size [%]
dx	7.44 ± 0.02	17.5 ± 0.1
dz	7.05 ± 0.02	7.01 ± 0.02
dr	11.00 ± 0.02	19.68 ± 0.05

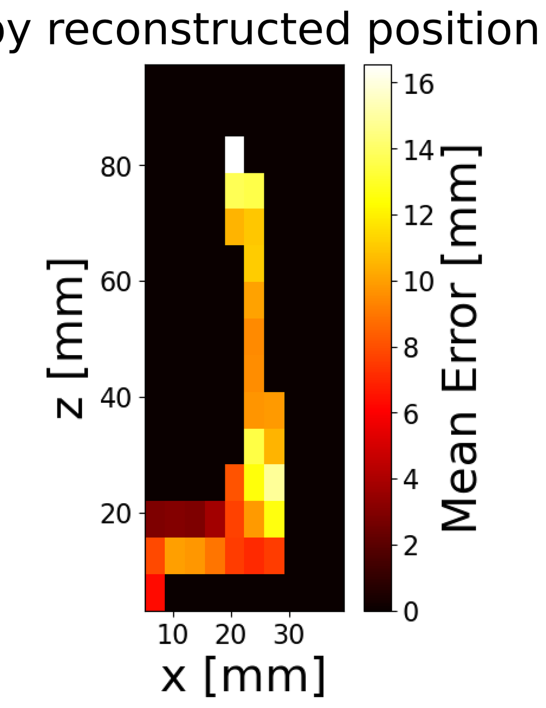


Error heatmaps:

by original position:



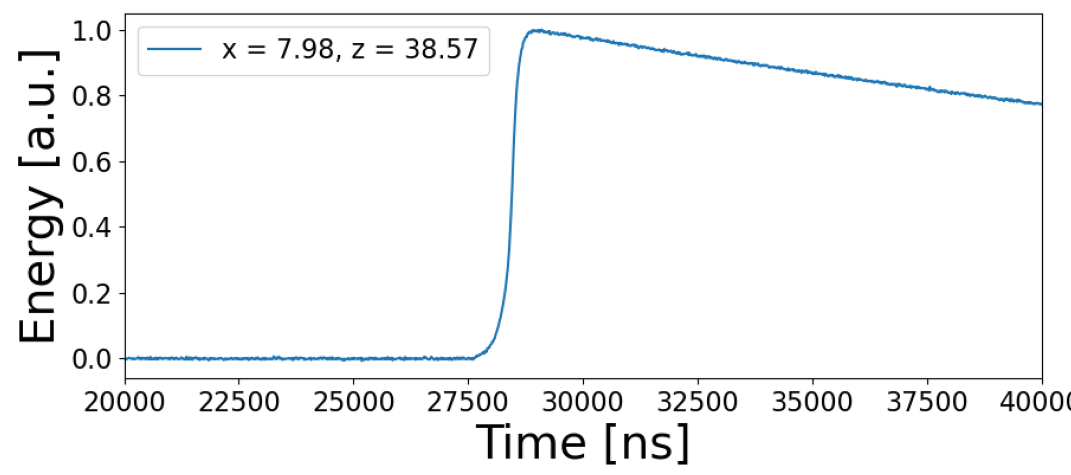
by reconstructed position



- x-reconstruction only possible close to contact
  - (Wanted) property of ICPC detectors
- z-reconstruction works better (7 % average error)

Position reconstruction of realistic waveforms

- Adding features of the data acquisition (electronic noise, preamplifier) to mimic real data waveforms



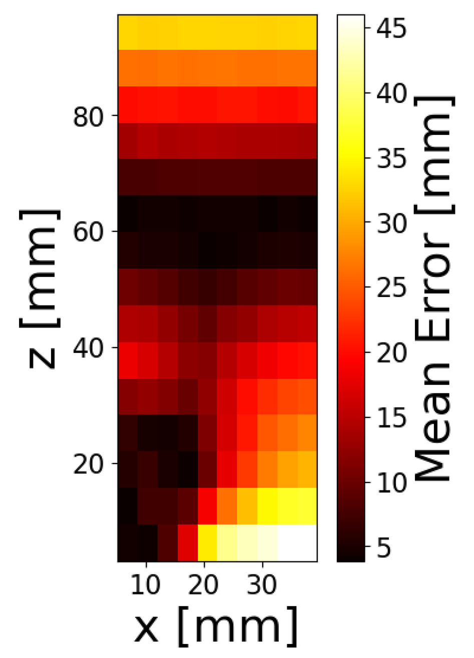
Train network to reconstruct z-coordinate of events:

Results:

- **Average Error** [mm]: **15.95 ± 0.05**
- z-reconstruction good for near-point-contact events
- z-reconstruction difficult for events far from contact
- Such events have waveforms with a long rising edge
- The start of the rising edge is "hidden" by noise
- **Reconstruction limit** of approximately **70 mm**

Error heatmap:

by original position:



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