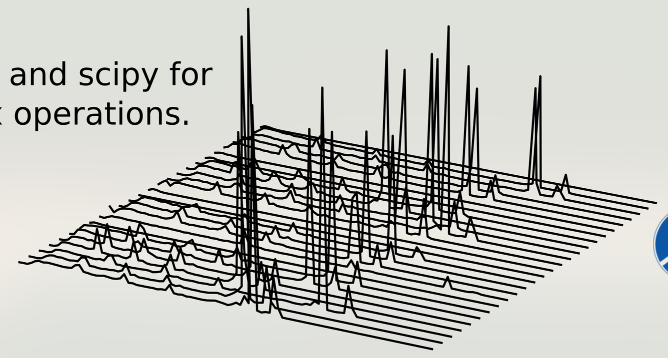
M. Borghesi, D. Becker, D. Bennet, M. De Gerone, R. Dressler, M. Faverzani, M. Fedkevych, E. Ferri, J. Fowler, G. Gallucci, J. Gard, F. Gatti, A. Giachero, G. Hilton, J. Mates, A. Nucciotti, L. Origo, G. Pessina, C. Reintsema, D. Schmidt, D. Swetz, J. Ullom, L. Vale

Signal processing and data analysis for the HOLMES experiments

19th International Workshop on Low Temperature Detectors (LTD)
July 19 - 29, 2021
Virtual Only Event

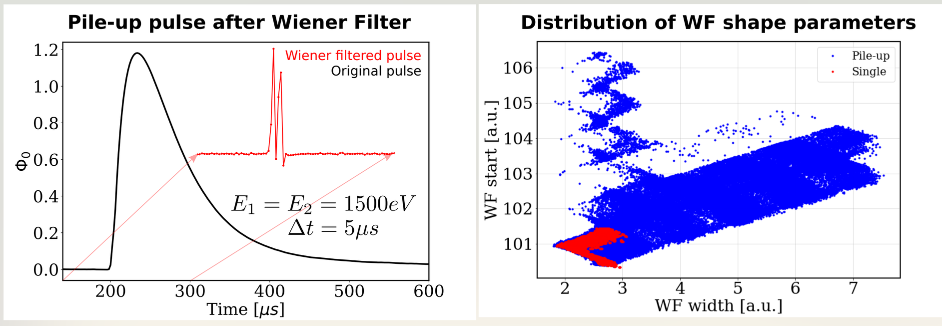
The Watson software

- Software for LTD data analysis.
- Object oriented programming. Written in python, numpy and scipy for fast (yes, even with python) and robust array and matrix operations.
- Easy to read, easy to fix code.
- GUI with QT5 for handy day to day operations.
- Data are saved in hdf5. → Hierarchial, filesystem-like data format



Pile-up discrimination

- The expected main source of background for HOLMES will be unrecognized pile-up events.
  Two techniques were studied with simulated data: **Wiener Filter** and **DSVP** (*)
- A FIR **Wiener Filter** of order *N* is used to deconvolve the response funtion of the detector from the signal.

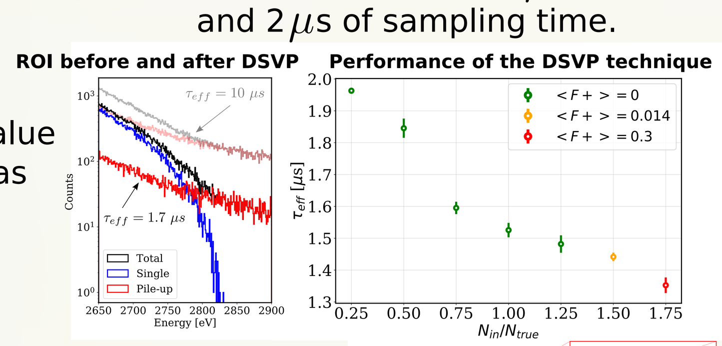


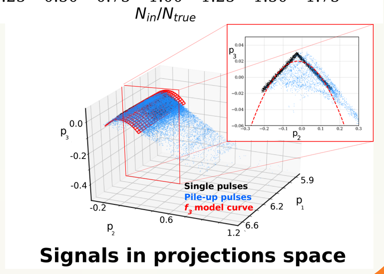
$$x[n] = \sum_{i=0}^{N} a_i w[n-i]$$

(filtered signal; WF coefficients; original signal) → Only the average pulse is needed to evaluate the a_i coefficient. → Expected time resolution τ_R: $2.2 < \tau_R < 3\ \mu s$ for signals with $O(10\mu s)$ of RT and $2\mu s$ of sampling time.

- We developed a novel technique, called **DSVP** (Discrimination through Singular Vectors Projections). It exploits the Singular Value Decomposition, PCA and Multiple Linear Regression to identify as many undesireble events as possible in a dataset.

  Expected time resolution τ_R: $1.5 < \tau_R < 2\ \mu s$ for signals with $O(10\mu s)$ of RT and $2\mu s$ of sampling time. → Sub-sample time resolution!





- Both the algorithms match the specification of the HOLMES experiment ($\tau_R < 3\ \mu s$)

(*) https://doi.org/10.1140/epjc/s10052-021-09157-x

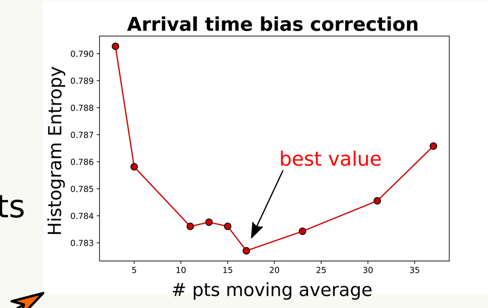
Amplitude evaluation

- The energy of the pulse is estimated through optimal filtering for amplitude evaluation.

$$E = C \times \int H(\omega) S(\omega) d\omega \qquad H(\omega) = K \frac{S^*_{avg}(\omega)}{N(\omega)}$$

(Optimal filter function; Pulse in frequency domain; Average pulse; Noise power spectral density)

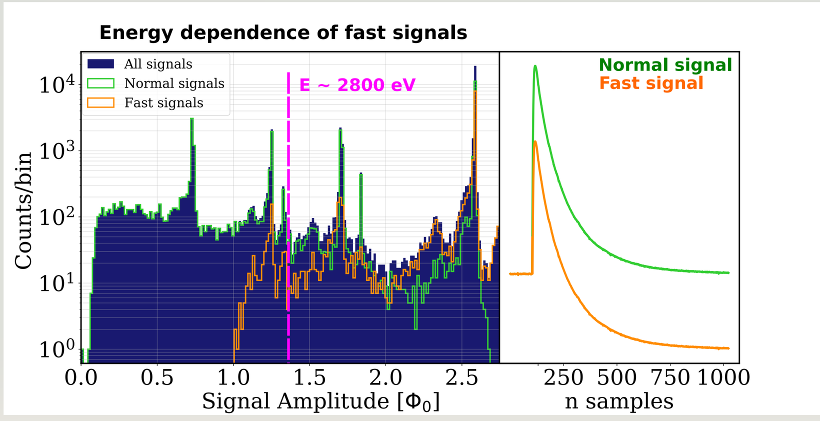
The average pulse is evaluated with an iterative procedure, selecting only a subset of events and correcting the time-jitter between pulses.



- The pulse heights produced by optimal filtering are sometimes subject to an unwelcome dependence on the exact arrival time of the energy deposition in the detector, relative to the sampling clock.
  This bias is reduced by smoothing the signals with a moving average of *k* points
  k is choose as the value which minimize the "entropy" *I* of the histogram $I = -\sum_i^{nbin} c_i \times \log_2(c_i)$ (normalized bin entries)
- We are also testing a procedure to evaluate the energies of two overlapping signals (pile-up on the tail of the pulse) using a modified version of the optimum filter.
  Dead time reduction!

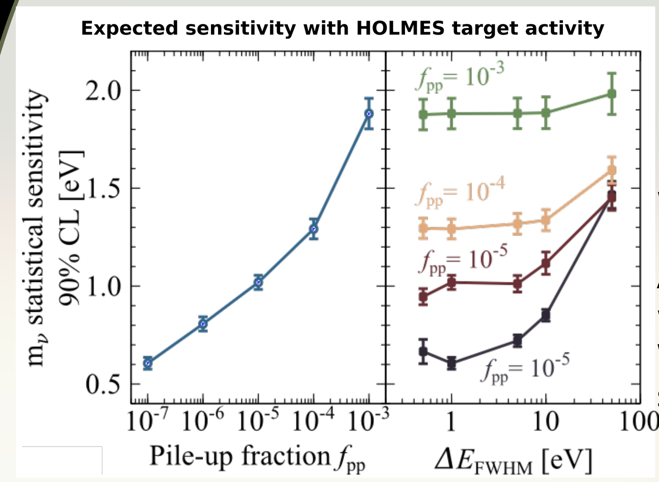
Event tagging and correction

- The pulses are classified before their parameters are extracted.
  Coincidence signals, cross-talk, noise events, fast signals (*)...
- (*) Fast signals are pulses which have a large slew rate → the demodulation algorithm can not record them correctly.
  Probability of a fast signals ∝ Rise Time of the pulse, Time Jitter, Energy of the pulse (!)
- This signals are identified and corrected by our algorithm. If they were simply discarded, the energy spectrum would be distorted → systematic error.



The experiment

HOLMES is an ERC project started in 2014 which is being currently set uo in the cryogenic laboratory of the University of MIlano Bicocca. It will perform a direct measurement of the neutrino mass with a sensitivity of the order of 1 eV. In addition, it will prove the scalability of this technique to a next generation experiment that might go beyond the spectrometers sensitivity. The neutrino mass will be studied through the calorimetric measurement of the decay products of the decay of Ho163.



In order to reach the goal sensitivy, HOLMES will use 1024 Transition Edge Sensors, each implanted with an activity of 300 Hz, that will record about 10e13 events in three years. Although ~ 110 MBq of purified Ho163 is avaliable, we haven't yet implanted the Ho in the TES abosrbers. We are currently testing the detectors fabrication steps and the analysy routines.

The TES microcalorimeters for HOLMES must fulfill stringent requirements in terms of time resolution (<3μs), energy resolution (O(5 eV)) and stability.

The analysis of the pulses from microcalorimeters requires great care, because their excellent intrinsic energy resolution can hardly be achieved whitout an accurate analysis. This contribution is an overview of the essential part of our analysis techniques.

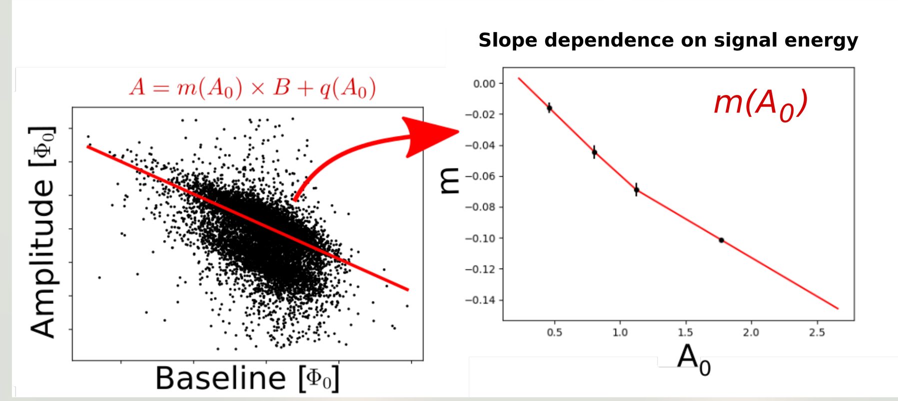
Thermal drift corrections

- The detector gain is not stable during the measurament time. This trend is due to the oscillation of the bath temperature/voltage bias.
- The drift be corrected by removing the dependence of the signal amplitude on the pretrigger mean (Baseline)...

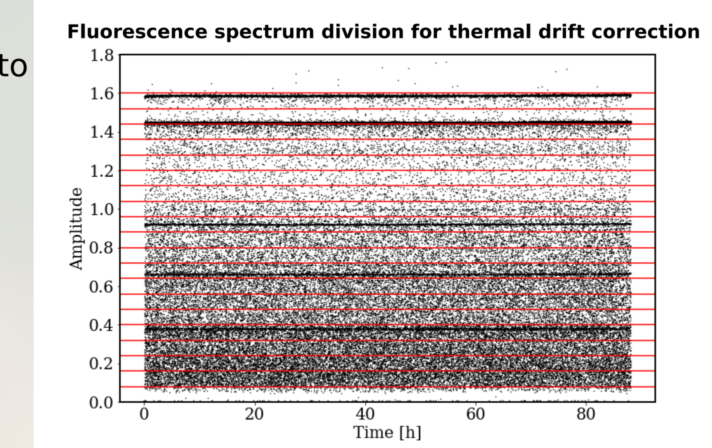
  ... however, the slope of this function depends also on the signal energy.

  $m = m(A_0)$ (pulse amplitude at time 0)

- First, the function $m(A_0)$ is approximated to a spline of degree 1, using the peaks of known energies as reference.

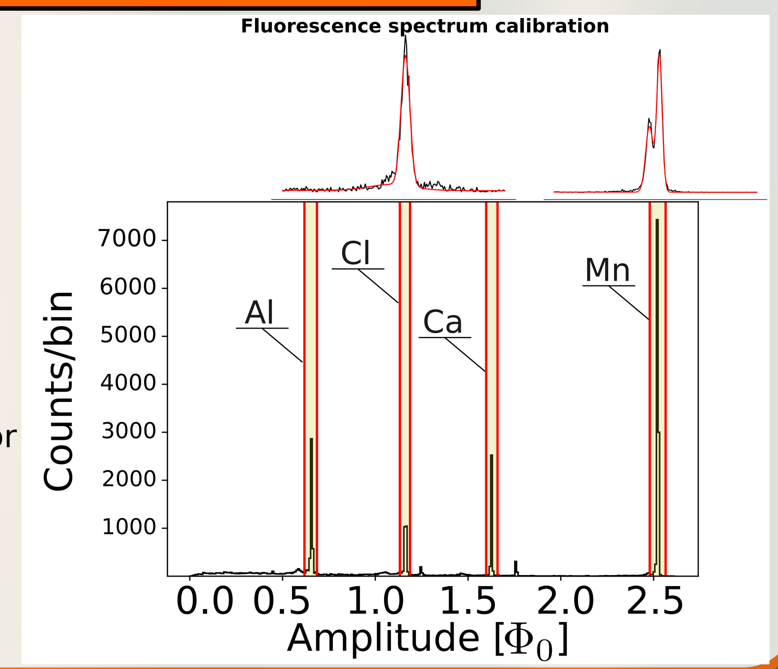


- Then, the amplitude spectrum is divided into an arbitrary number of intervals.
  In order to correct the gain drift for all the signals, a different value of *m* will be used for each interval.



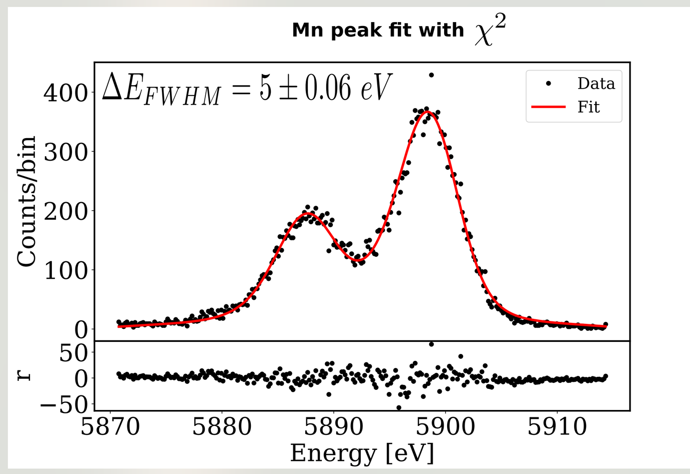
Calibration

- Automatic multi-peak calibration.
- The position of each peak is evaluated with a gaussian fit + non-uniform background.
- Second grade or one grade polinomial for calibration function is enough.

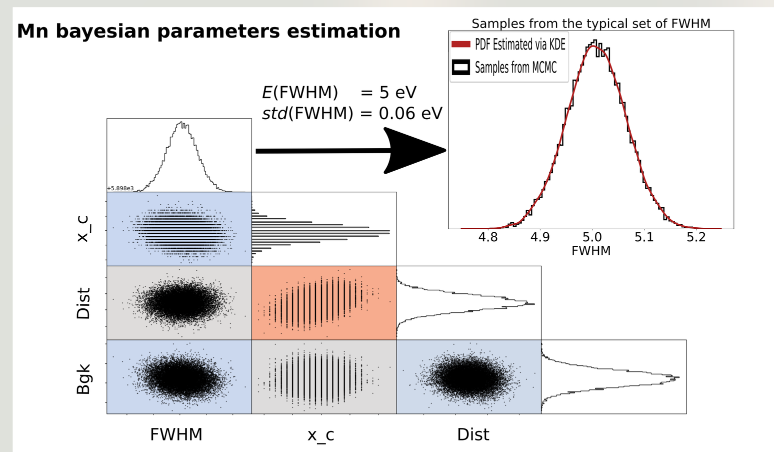


Parameters estimation

- Frequentist and bayesian parameter estimation.
  - Maximum-likelihood or minimum chi-square with MINUIT as minimizer.



- Hamiltonian MCMC with STAN.
- Powerful for multi-dimensional parameters space.



- Detector energy resolution is very close to the one expected from the NEP (4.8 eV).