Development of the online data acquisition system for the Mu2e STM detector & a Monte Carlo study determining the uncertainty in the number of stopped muons for the Mu2e search for cLFV at Fermilab.

INTENSE Interim Review Meeting - 2nd December, 2022.

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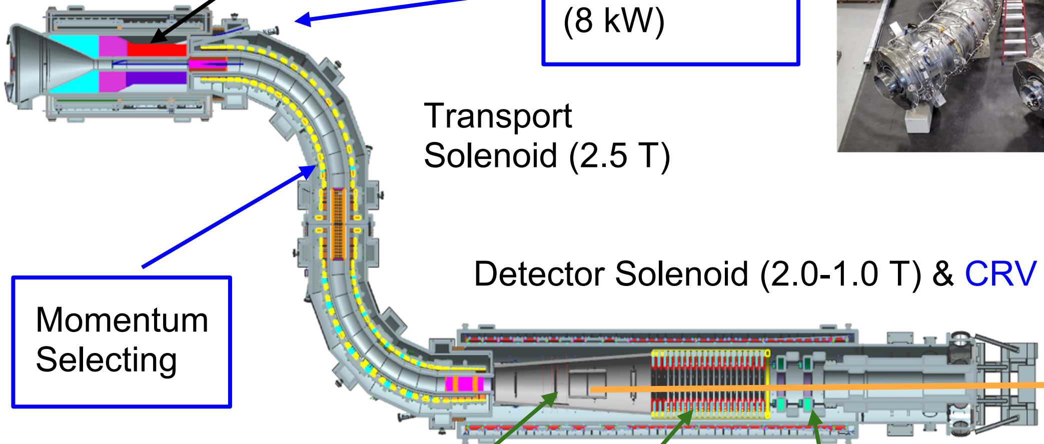
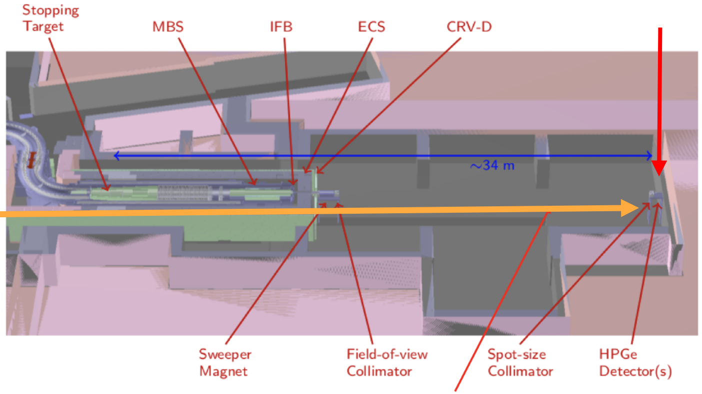
Mu2e.

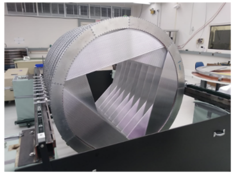


STM Detector:
HPGe and LaBr



Polyethylene Absorber

35 m



Sensitivity of 8x10^{-17} requires 10^{10} muons/s to interact with the aluminium (stopping) target.

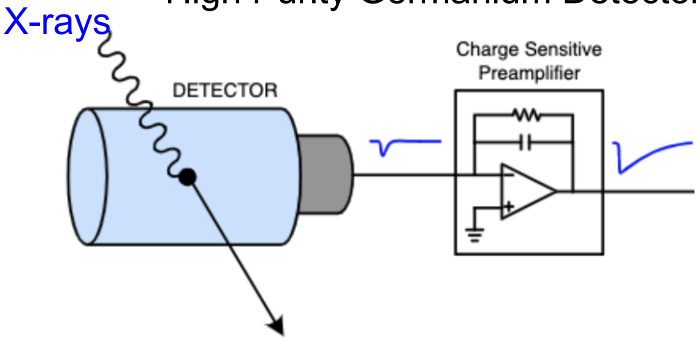
$$\mathrm{BR} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow e^- + \mathrm{N}\right)}{\Gamma\left(\text{nuclear } \mu^- \text{ captures}\right)}$$

Muons (< 75 MeV/c) are captured by the aluminium and in that process characteristic X-rays are emitted.

We detect these X-rays 35m away from the target to “count the muons”.

Measuring the energy deposited.

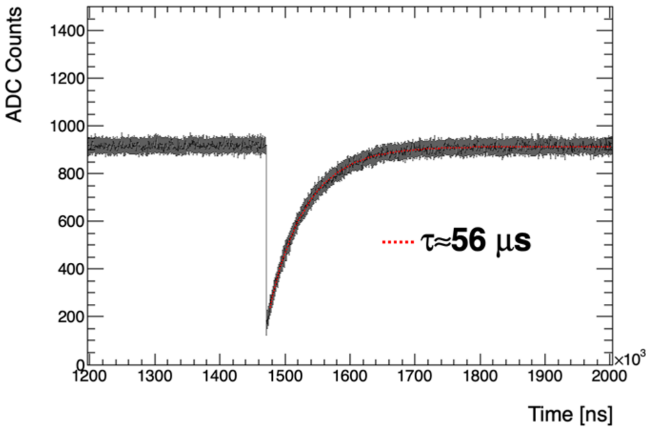
High Purity Germanium Detector: HPGe



+

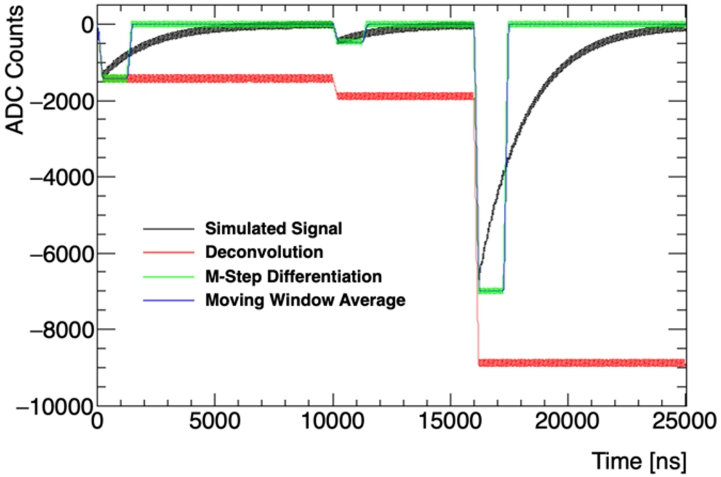
FPGA+ADC.

- The Mu2e measurement is reported relative to the rate of muons captured by the nucleus.
- Capture rate for Al is well-known from literature and it is related to the number of X-rays emitted at 347 keV, 844 keV and 1809 keV. Pulses are generated in the Stopping Target Monitor (STM).
- X-rays reach the detector, the electrons ionise the material creating e-h pairs that drift in the detector creating the pulses that are then shaped.
- The signal is sent to the readout board and an ADC samples these values in 16-bit words.
- Energy of pulses is related to pulse heights.

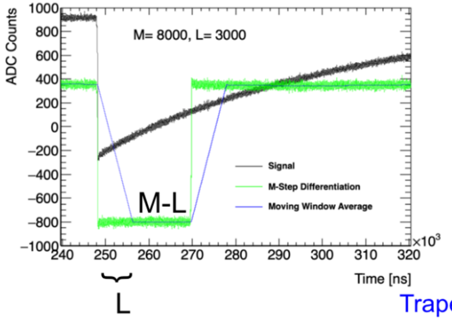


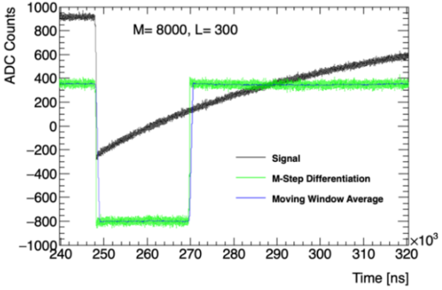
Moving Window Deconvolution Algorithm.

- Signal.
- Deconvolution.
- Differentiation (M window).
- Averaging (L values).

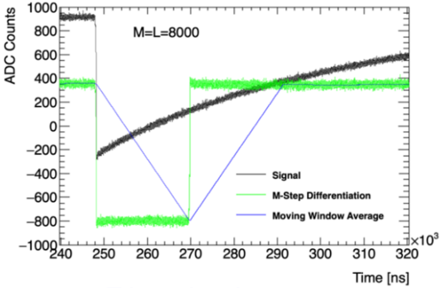


Shape of the signal: Trapezoid or triangle output.





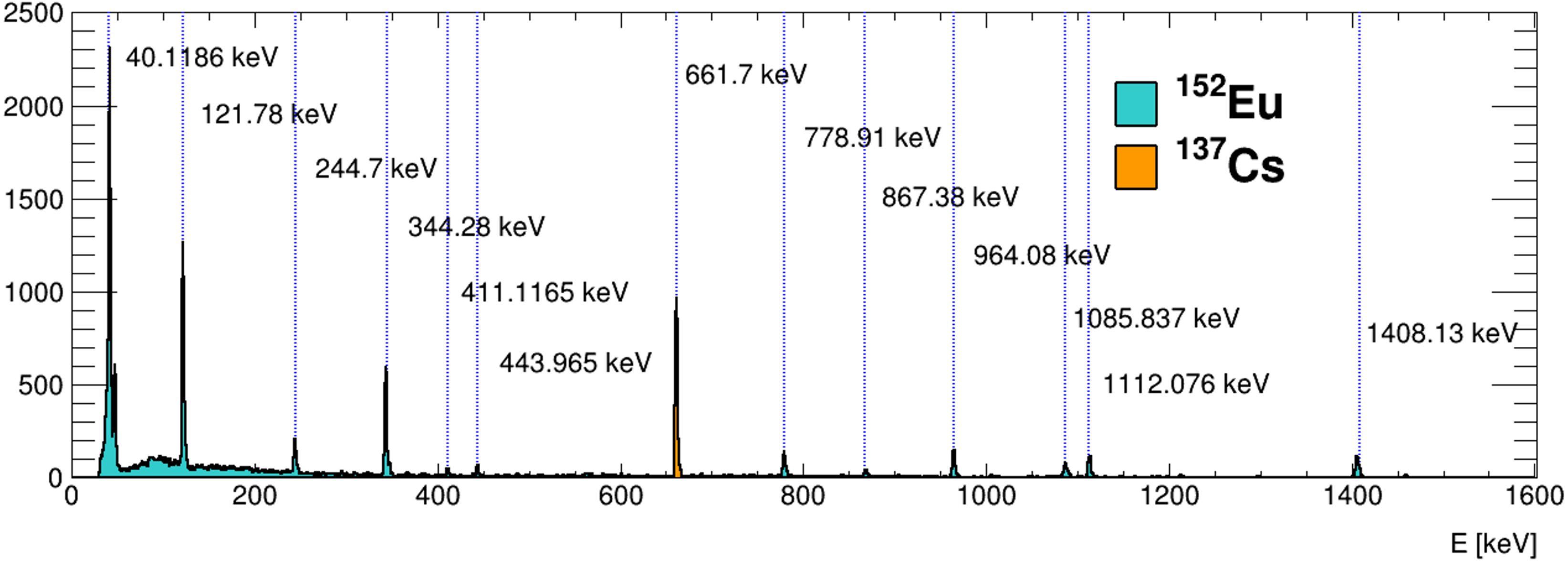
Trapezoidal shape



Triangular shape

Energy Spectrum.

Calibrated energy spectrum obtained from the ^{137}Cs and ^{152}Eu source data, using an optimized M and L combination that provides the best energy resolution for the STM detector based in real data.



Need to achieve the best resolution so that we can resolve the aluminium X-rays at the Mu2e experiment.

Main contributions.

Past Results

- I have implemented the **Moving Window Deconvolution** (MWD) algorithm to determine the pulse heights in ADC Counts. The input parameters of this algorithm have been tested on real X-ray data from 137-Cs and 152-Eu radioactive sources which has allowed to calibrate the detector and optimised to achieve the best resolution using simulated data.

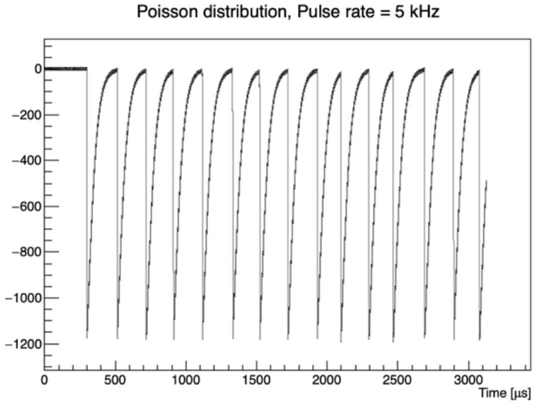
- This algorithm has also been tested with data from a **Test-beam** at gELBE in April 2022.

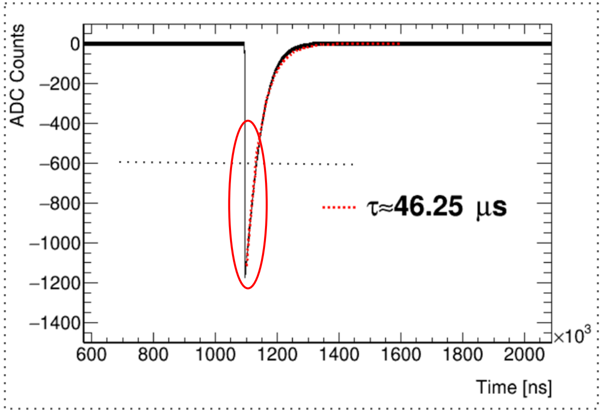
2nd Year Contributions

- Development of a **New HPGe Simulation** has allowed to have an accurate description of the HPGe data and define the theoretical MWD efficiency and resolution at different rates.

- Development of a **Zero Suppression** algorithm in C++ to reduce the amount of raw data needing to be stored and analysed. This algorithm has also been tested on real data and simulation.

HPGe Simulation.





- Developing a simulation allows to define the MWD efficiency and resolution based on the rate.
- Initially pulses where generated with the function:

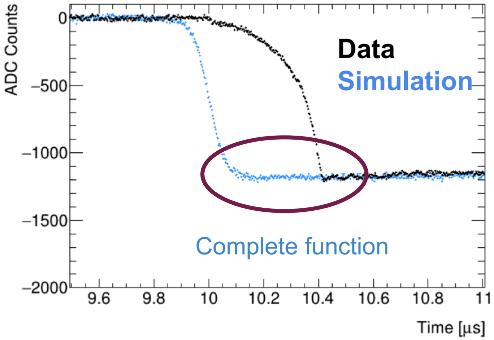
$$pulse[\mathrm{ADC}] = -\frac{2A}{\left(1+e^{-\frac{(t-tshift)}{\tau_{fall}}}\right)} \cdot \left(1 - \frac{1}{\left(1+e^{-\frac{(t-tshift)}{\tau_{decay}}}\right)}\right)$$

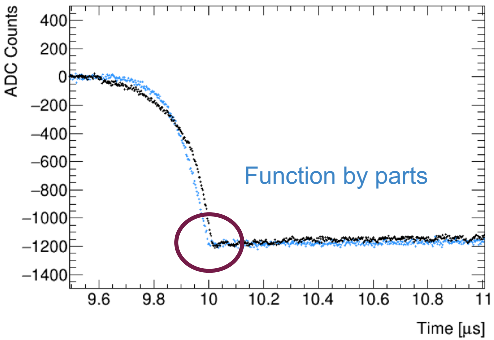
All pulses looked the same, a new simulation is required in order to better describe the HPGe pulses.

At our nominal rate of 20 kHz the HPGe pulses overlap

New Simulation: reproduce data kinks.

Defining the function by parts.



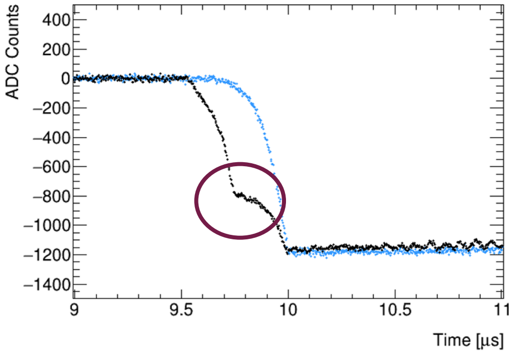


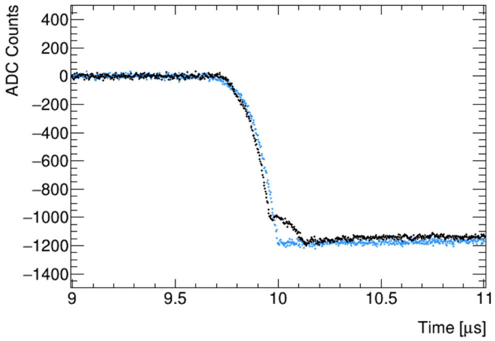
$$x >= xshift: \quad pulse[\mathrm{ADC}] = -2A \cdot \left(1 - \frac{1}{\left(1 + e^{-\frac{(t - tshift)}{\tau_{decay}}}\right)}\right)$$

Falling edge

$$x < xshift: \quad pulse[\mathrm{ADC}] = -\frac{2A}{\left(1 + e^{-\frac{(t - tshift)}{\tau_{fall}}}\right)}$$

This change can account for the final kink at the end of the falling edge but it cannot account for the rest of the kinks observed in the falling edge of data pulses.

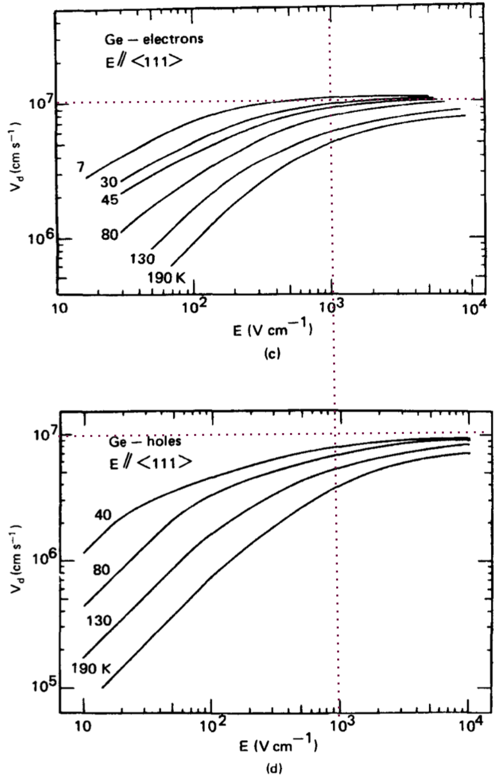




Need a simulation / model that accounts for these additional kinks

Electrons and holes arrivals (charge collection times).

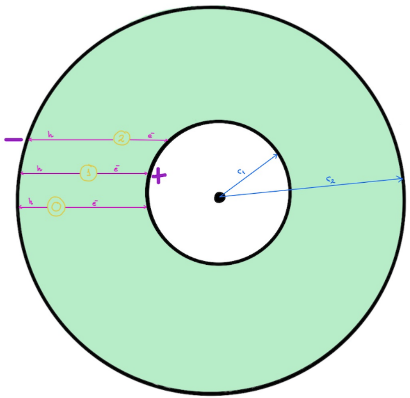
Drift velocity for e and h

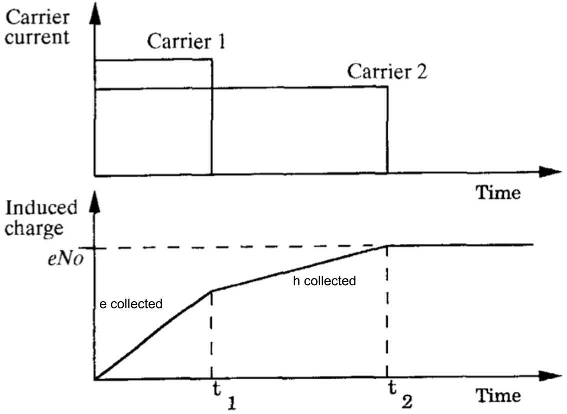


- **Charge collection times of e and h are different** because of differences in drift distances (opposite directions towards the electrodes).
- In Ge semiconductor detectors, t**he mobilities of e and h are somewhat similar.**
- The **mobility of charge carriers depends on the electric field.**

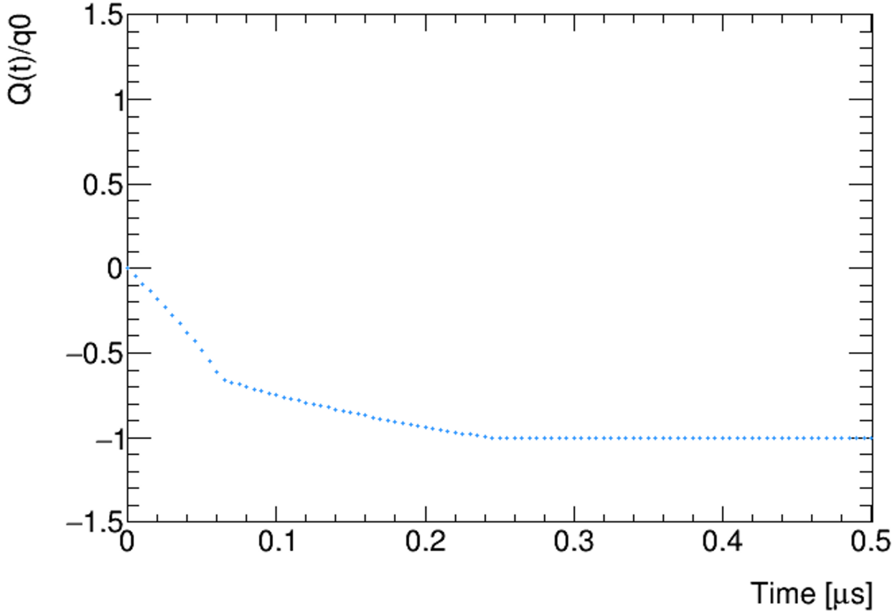
- **Simulation assumptions:** All charge carriers are assumed to be generated entirely within the active volume of the detector where the electric field has its full expectation value. The electric field is sufficiently high to cause saturation of the drift velocity of both electron and holes:

v_{drift}(77K, 10^3 V/cm)=10 cm/μs.





Induced charge in Ge detector.



For a single e-h pair from a single Compton scatter the induced charges in a n-type HPGe detector is given by:

Both e- and h+ are drifting.

$$t < t_h \text{ and } t < t_e \qquad Q(t) = \frac{q_0}{ln\left(\frac{R_2}{R_1}\right)}\left[ln\left(1 + \frac{v_h t}{r_0}\right) - ln\left(1 - \frac{v_e t}{r_0}\right)\right]$$

e- have been collected but h+ are still drifting.

$$t_e < t < t_h \qquad Q(t) = \frac{q_0}{ln\left(\frac{R_2}{R_1}\right)}\left[ln\left(1 + \frac{v_h t}{r_0}\right) - ln\left(\frac{R_1}{r_0}\right)\right]$$

h+ have been collected but e- are still drifting.

$$t_h < t < t_e \qquad Q(t) = \frac{q_0}{ln\left(\frac{R_2}{R_1}\right)}\left[ln\left(\frac{R_2}{r_0}\right) - ln\left(1 - \frac{v_e t}{r_0}\right)\right]$$

Both e- and h+ have been collected.

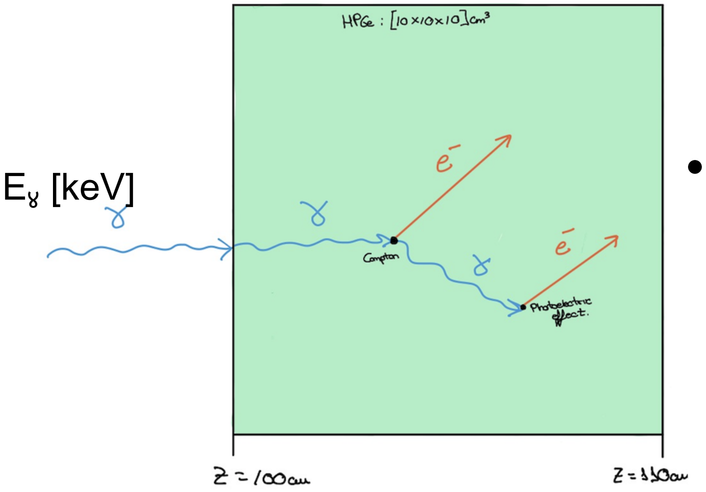
$$t > t_h \text{ and } t > t_e \qquad Q(t) = q_0$$

But in reality

- there are several Compton/PE processes per X-ray. They occur at almost the same time but at different locations in the detector and hence pulse produced at different times (GEANT4)
- The number of e-h pairs generated per Compton/PE process (is not one) and depends on the energy deposited in each process.

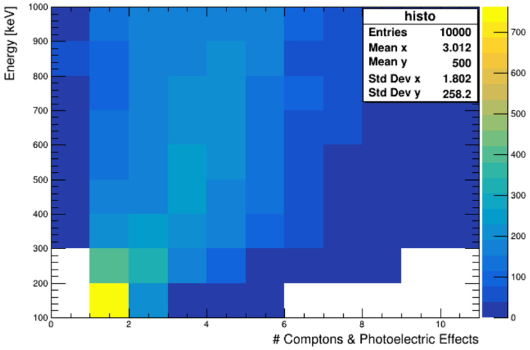
Geant4 HPGe Simulation.

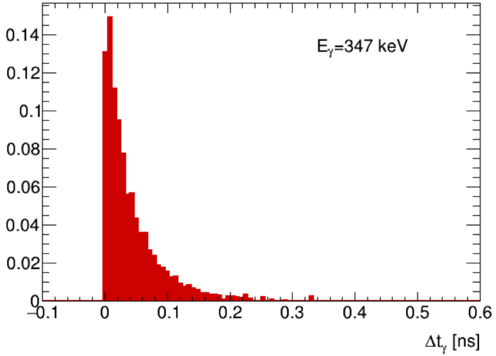
Example of event taking place in HPGe detector:

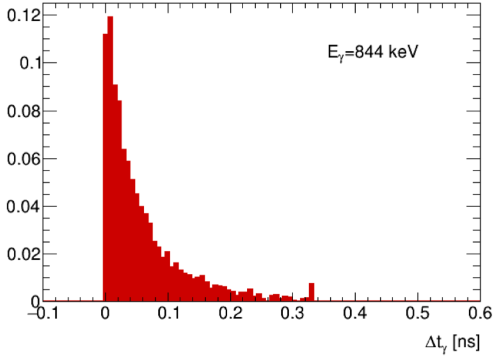


- **Number of comptons and photoelectric effects** as a function of the energy. Need to account for the number of processes taking place in one event.

- Comptons and photoelectric effects happen within O(0.01ns) they can be considered **simultaneous**.

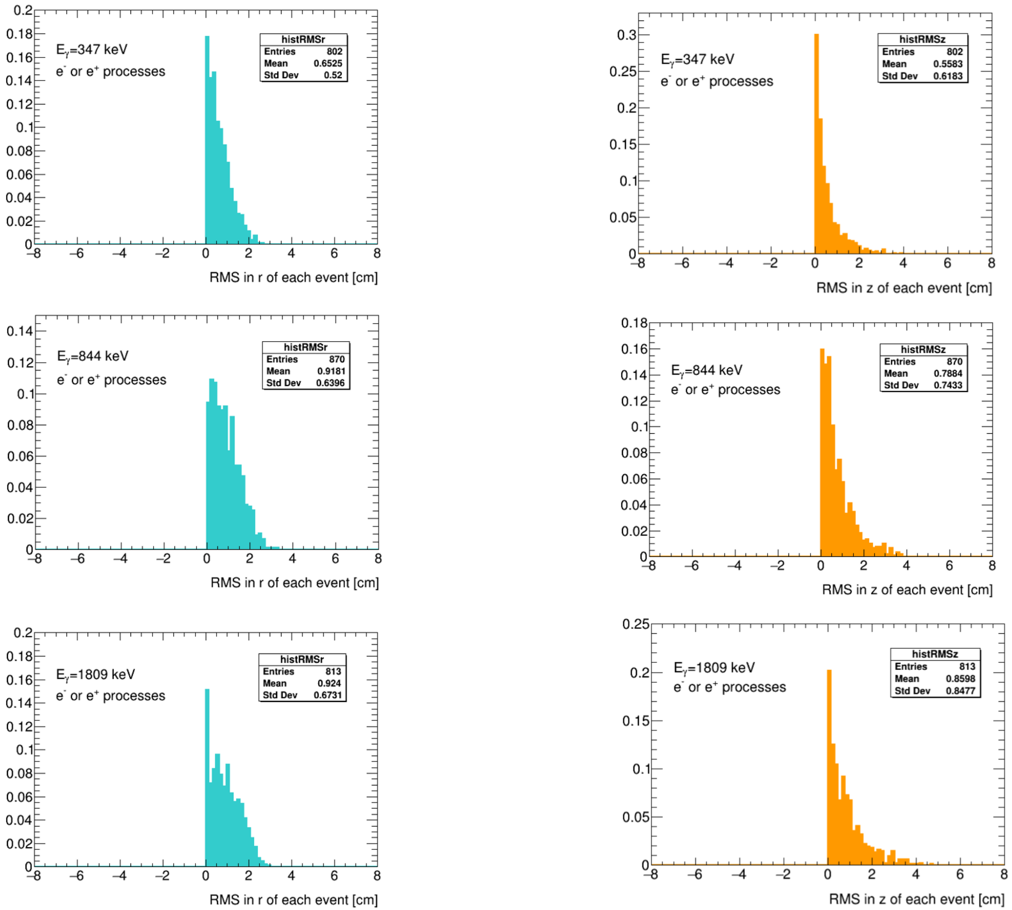






- Some models for the pulse shape in HPGe assumes that **all processes in one event take place in a fixed point within the detector active volume** : this is however not a very good approximation.

Geant4 HPGe Simulation.



- 347, 844 and 1809 keV: X-Rays at Mu2e.
- Spreads in positions up to **2 cm: they cannot be considered a point in the detector**.
- The simulation needs to account for the #comptons+phot scatters

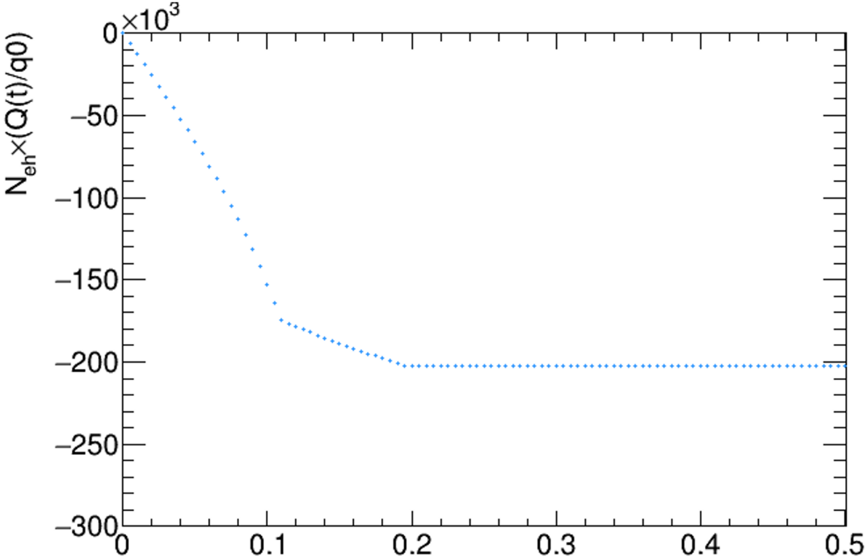
Induced charge in the detector.

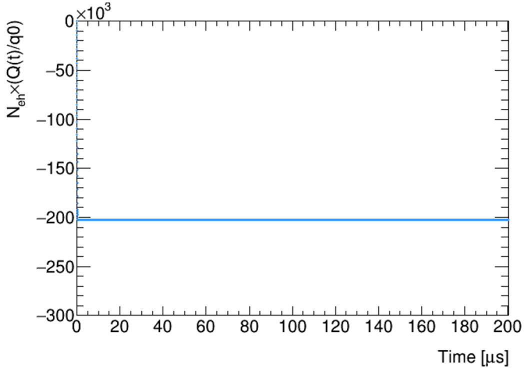
E = 600 keV

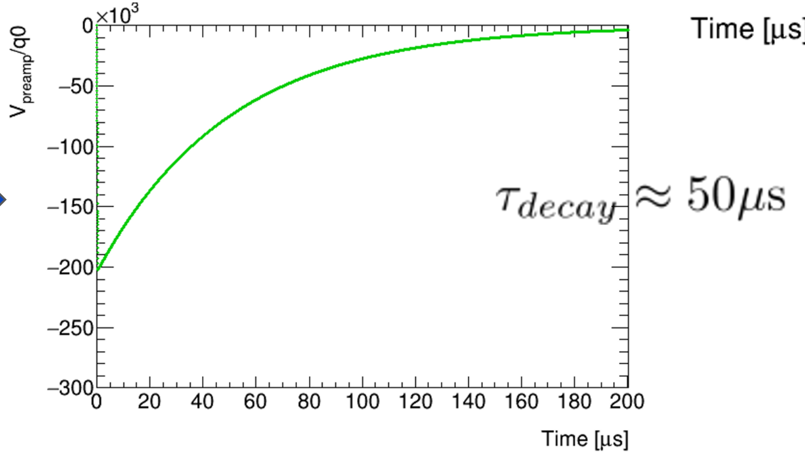
N_{eh}= E/ϵ_{eh}(Ge,77K) = 202702

Also need to accounts for:

- Preamp shaping after charge collection process.
- Conversion to ADC counts



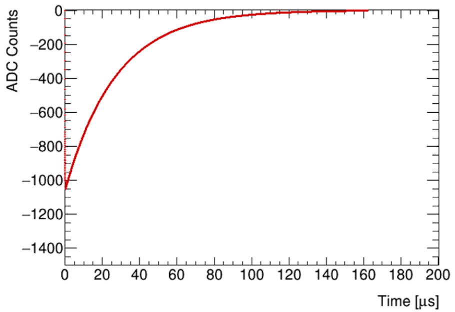




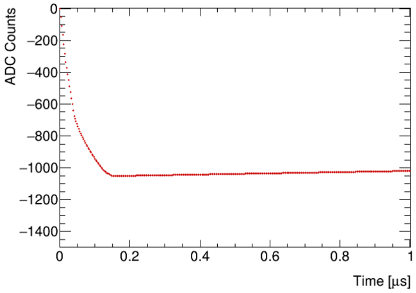
Plus ADC calibration and electronic noise

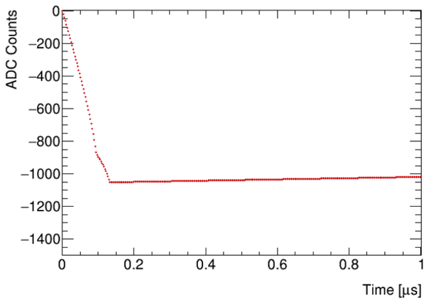
ADC Calibration and detector electronic noise.

Calibration: 1ADC Count = 0.57 keV.

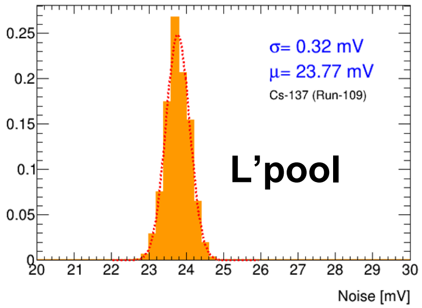


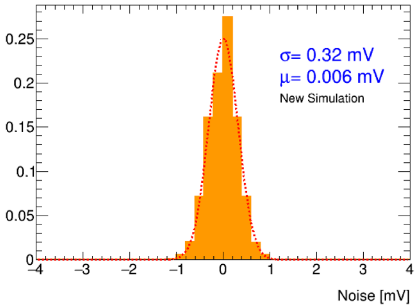
zoom falling edge.

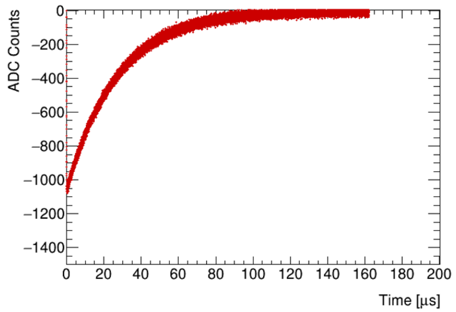


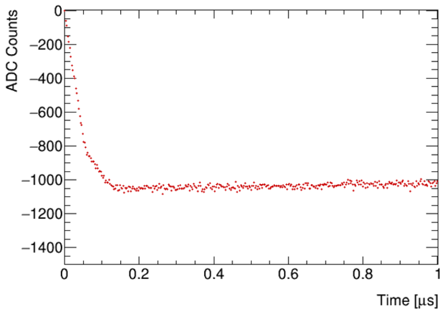


Sampling with fADC=370MHz and 0.32 mV electronic noise.

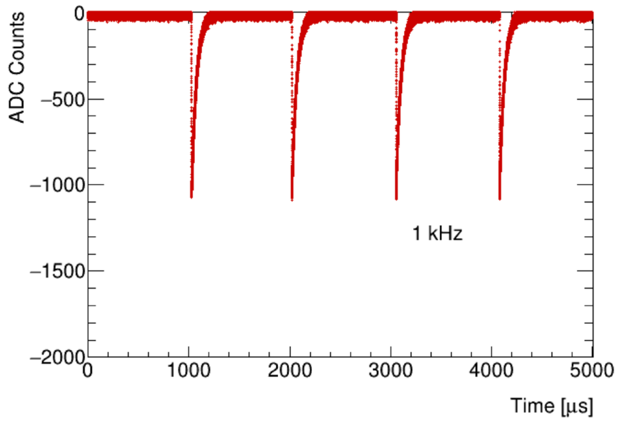


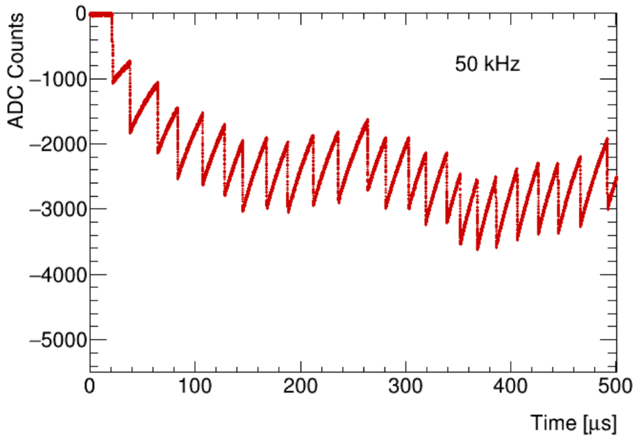


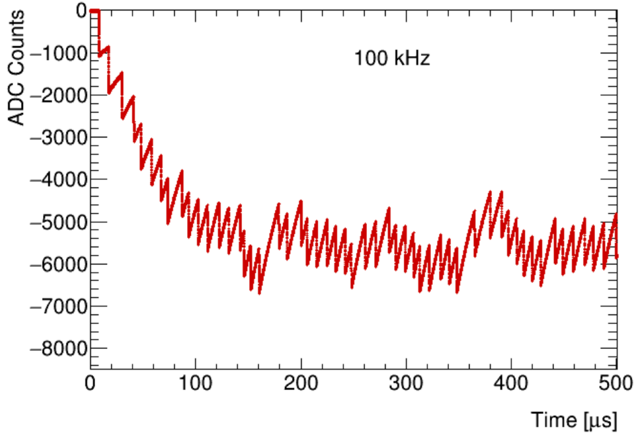


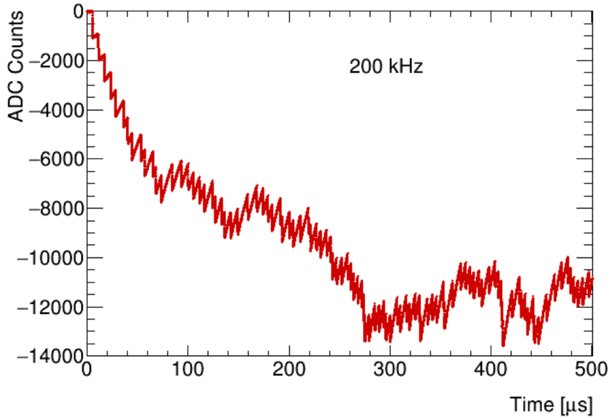


Final Pulse Simulation at different rates.

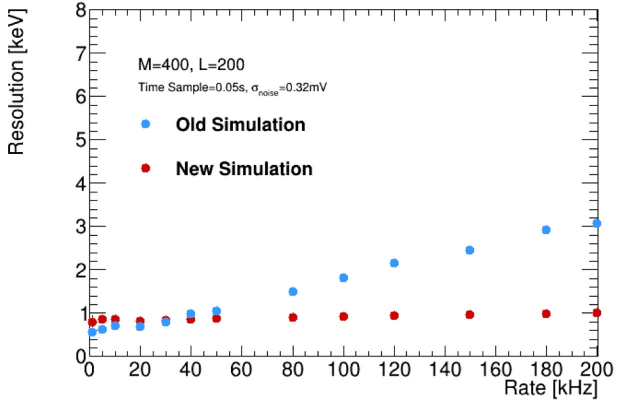


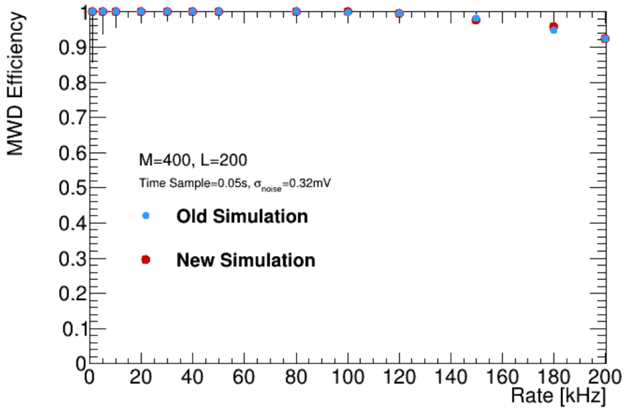






Resolution and efficiency: Old and New Simulations.





M=400: resolve peaks separated more than 1.08μs.

Better efficiency with low M at high rates: we are able to resolve more peaks.

The tendency of efficiency remains the same with old and new simulation.

The MWD resolution with old simulation was strongly affected by the MWD output shape.

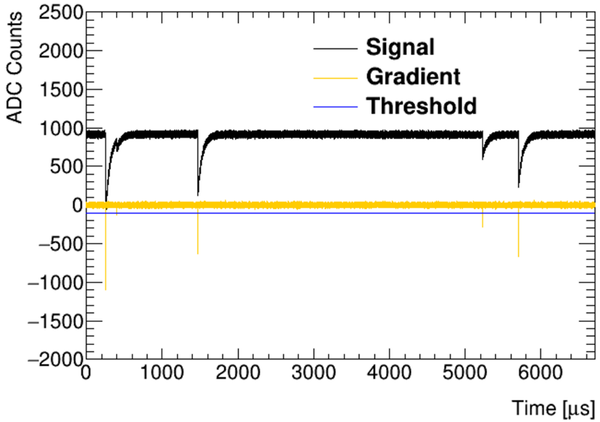
The MWD resolution is ∼1 keV.

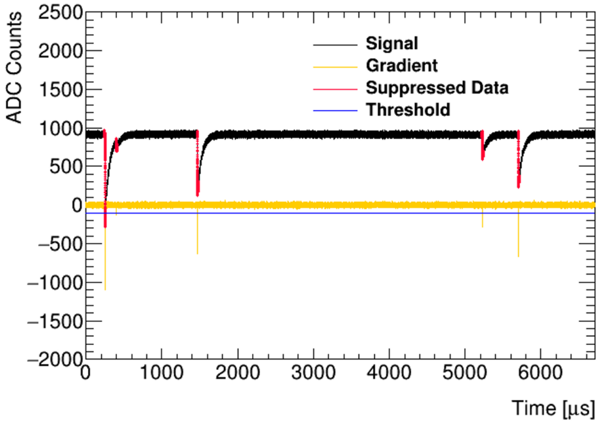
New ZS code: Introduction.

- This algorithm is based on the calculation of the gradient of the signal over a window of ADC values:

```
gradient[i]=ADC[i+window]-ADC[i];
```

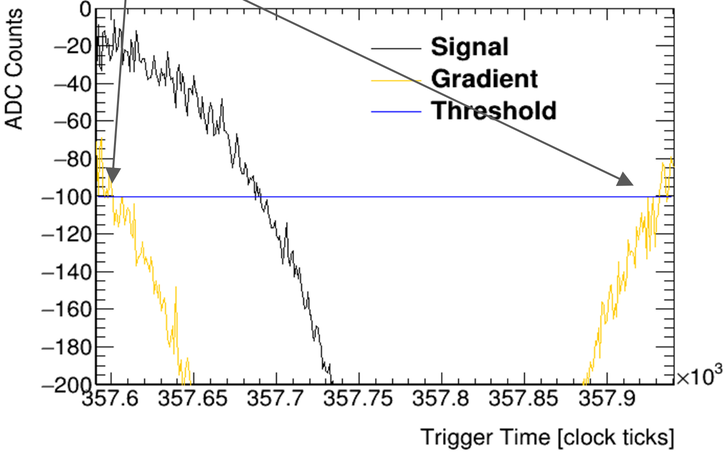
- Window = 100 ADC (~ 0.3 μs) : so in principle can distinguish peaks to rates well above the rates required (5 μs = 200 kHz)
- Gradient threshold = –100 ADC Counts.
- The trigger is then established in the first point where the gradient is below the threshold chosen and we will store t_{before}μs of data before the trigger and t_{after} μs of data after the trigger.
- Algorithm is much simpler - relies on 4 parameters that can be set in FPGA registers - likely can be implemented in VHDL and doesn't require complication of HLS (and sychornistation with VHDL).

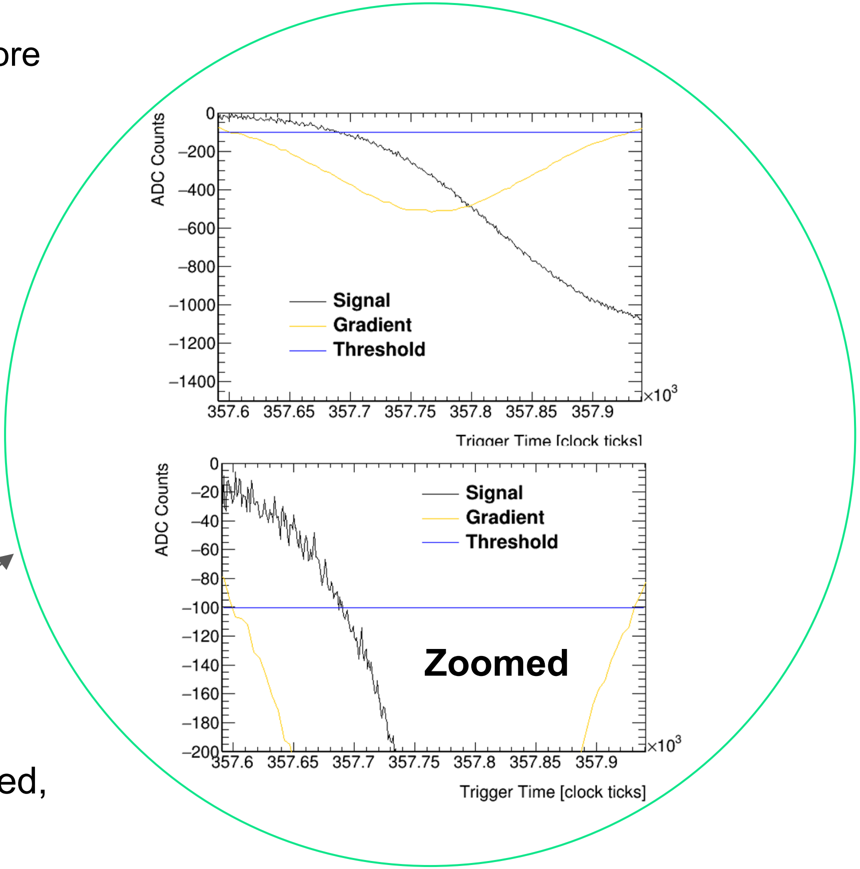




Testing new ZS code on simulation.

Gradient fluctuations (due to noise in signal) cause more than one trigger per peak.

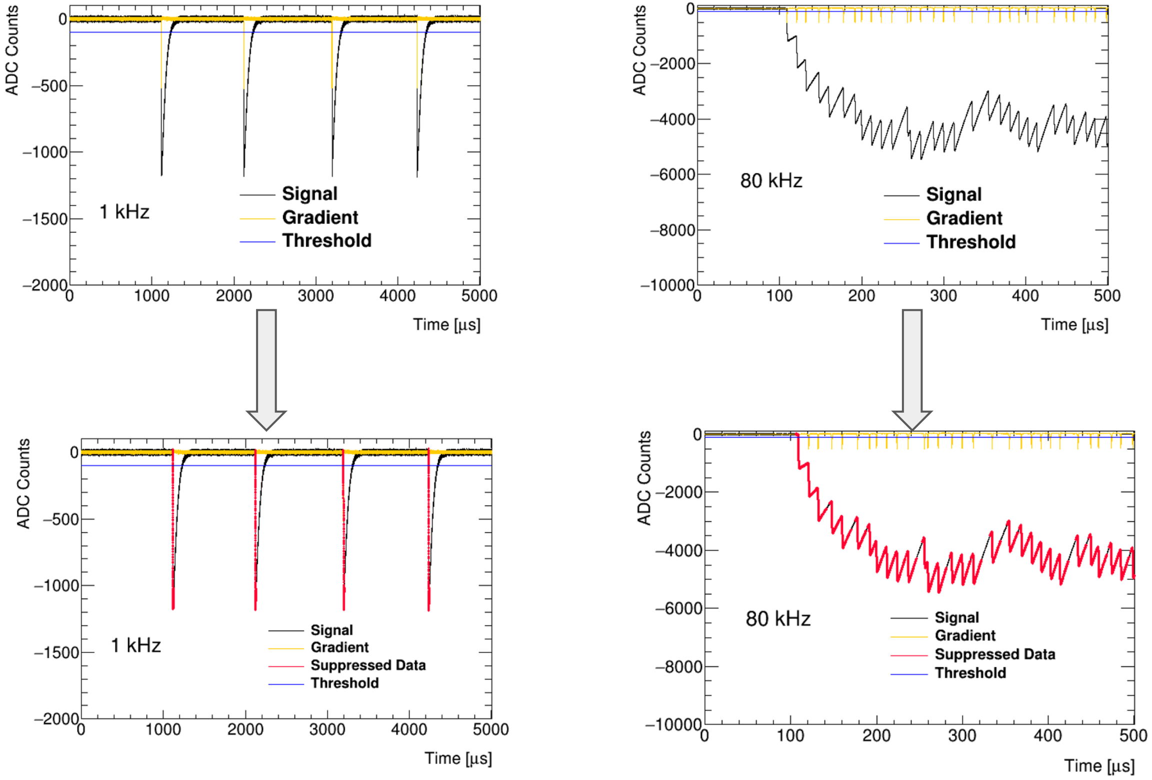




The average over **n** (=5) gradient values is calculated, so that the variation in gradient are softer.

Testing new ZS code on simulation.

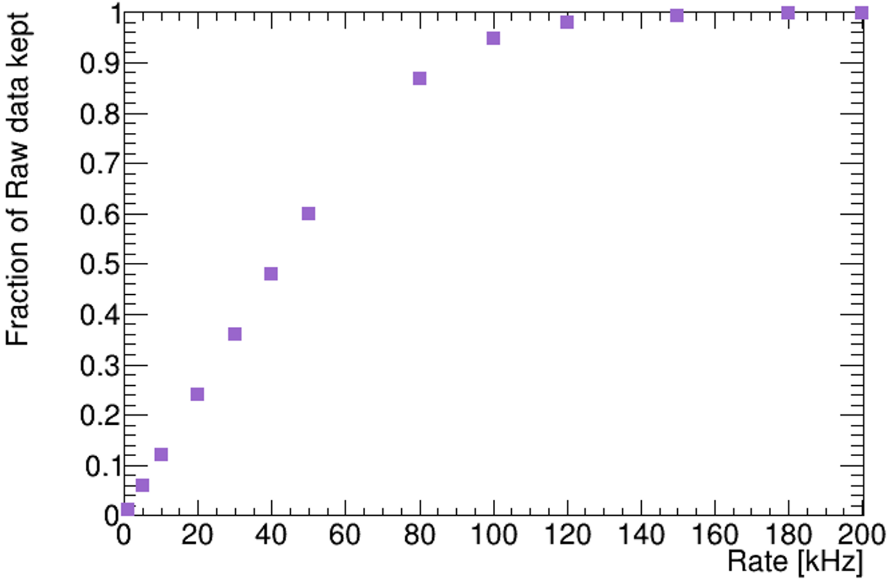
The timings chosen for storing data is t_{before}= 2 μs of data before the trigger and t_{after} = 10 μs of data after the trigger.



Red is stored (ZS) data.
Black is raw data

No triggers in noise.

Testing new ZS code on simulation.



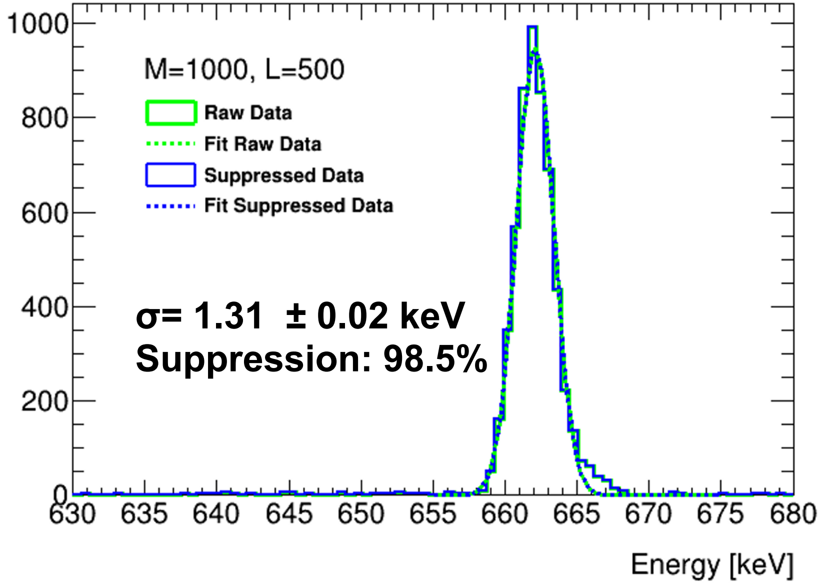
At low rates the the suppression is very efficient, we keep ~ 1% of the raw data at 1 kHz, 25% at 20 kHz (nominal Mu2e rate).

At higher rates > 80 kHz we keep 95% which means that we are only able to suppress 5% of the original data.

ZS: Testing on ^{137}Cs data.

As expected resolution is not affected by ZS. Suppression is 98.5% (1.5% data retained)

Amount data is suppressed can also be changed slightly by amending t_{before} & t_{after} eg reducing 1.5% → 1.2%



Conclusions.

- STM DAQ for HPGe: Acquiring data, developing algorithms (MWD + Pulse Finding) and analysing data. Algorithms optimised and tested on:
    - New Simulation: define MWD efficiency and resolution at different rates.
    - Radioactive sources: Calibrate the STM Germanium detector.
    - Data from a Test-beam (source data, beam data and noise data).

- Zero Suppression Algorithm: same MWD resolution and efficiency on ZS data and raw data and it is proven to be very efficient at low rates, can suppress data up to 100 kHz. Beyond this ZS doesn’t reduce the data volume for HPGe data due to overlapped pulses.

Conferences.

1. “Fermilab – C++ / Standard Template Library Course”, held online (Fermilab, August 17 – September 14, 2021)
2. Intense Training Program: Cosmic Ray Muography November 2021, Ghent, Belgium.
3. HEP Forum 23rd, 24th November 2021, Cosener's House, Abingdon, Oxford.
4. “Viva Exam”, including oral presentation and a report, 15th March 2022.
5. “Advanced Graduate Lectures on practical Tools, Applications and Techniques in HEP”, (Harwell Science and Innovation Campus, Oxfordshire, June 13-17, 2022).
6. “STFC High Energy Physics Summer School”, lectures covering Quantum Field Theory, Quantum Electrodynamics and Quantum Chromodynamics, the Standard Model and non-collider phenomenological topics (neutrino, dark matter, cosmology) (Oxford,, September 4-16, 2022).

Next Steps.

- Integrate the ZS algorithm in the full STM simulation.

- Prove the integrity of online (HLS/FPGA) ZS algorithms using known data cross-checked with offline simulation.

- Verify the implementation pre-scales for the spill and gap-triggers and demonstrate that the data to disk rate can be kept to the required level using these pre-scales.

- Establish a full end-to-end test of the STM DAQ at Manchester verifying required data throughput rates.

- Port software and firmware to FNAL and begin commissioning of the STM at FNAL (summer 2023).

- Integrate the STM DAQ with the Mu2e DAQ (end 2023).

- Improve the simulation of the STM based on data taken at beamtests and teststands.

- Perform Monte-Carlo Studies quantifying the STM performance, demonstrating that its design goals can be achieved with the algorithms and alignment methodologies developed.

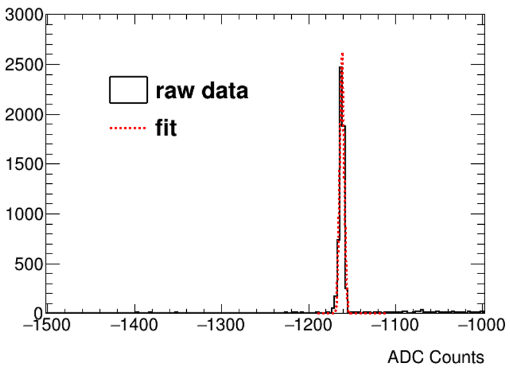
- Write thesis covering the STM DAQ, development of pulse finding and zero-suppression algorithms and the estimated performance that the STM can achieve based on simulation.

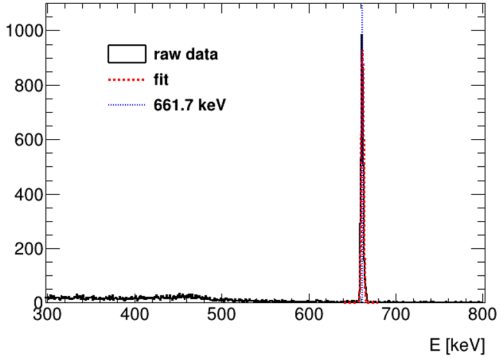
Back-up…

^{137}Cs and ^{152}Eu source: ADC-Energy Calibration.

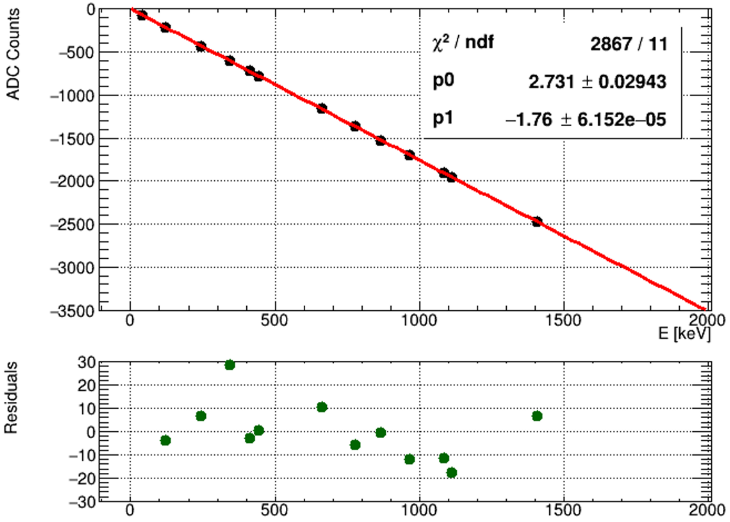
MWD + Pulse Finding

- ^{137}Cs peak (661.7 keV) after applying the MWD and the Pulse Finding algorithm, the output is in ADC counts so we need a calibration between ADC counts and energy.





^{137}Cs + ^{152}Eu Calibration



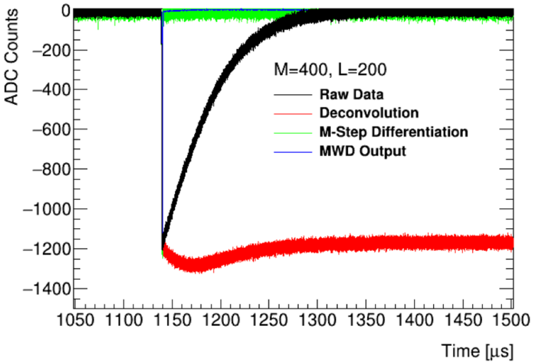
- Calibration: the ADC peaks have been identified with the well-known energy peaks of the Cs and Eu.

$$\sigma_{\mathrm{ADC}} = 0.57\,\mathrm{keV}$$

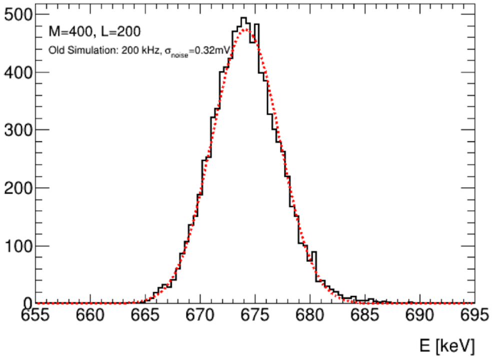
MWD output shape and reconstructed energy spectrum (resolution).

Input simulated energy: 675 keV at 200 kHz.

- **Old simulation**



Reconstructed energy spectrum:

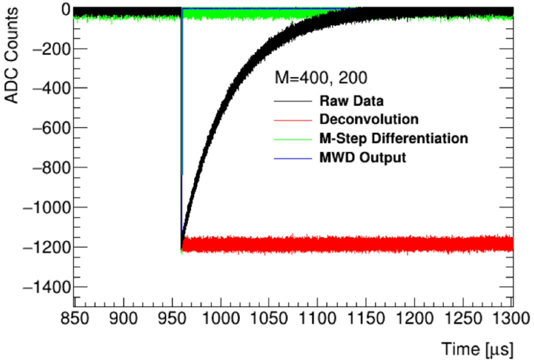


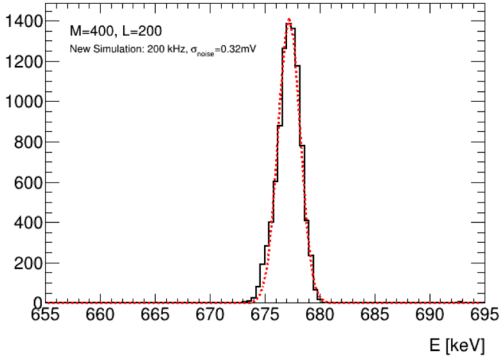
Old Simulation: E_{reco}: 678.045 keV

New Simulation: E_{reco}: 675.747 keV

New simulation brings better resolutions.

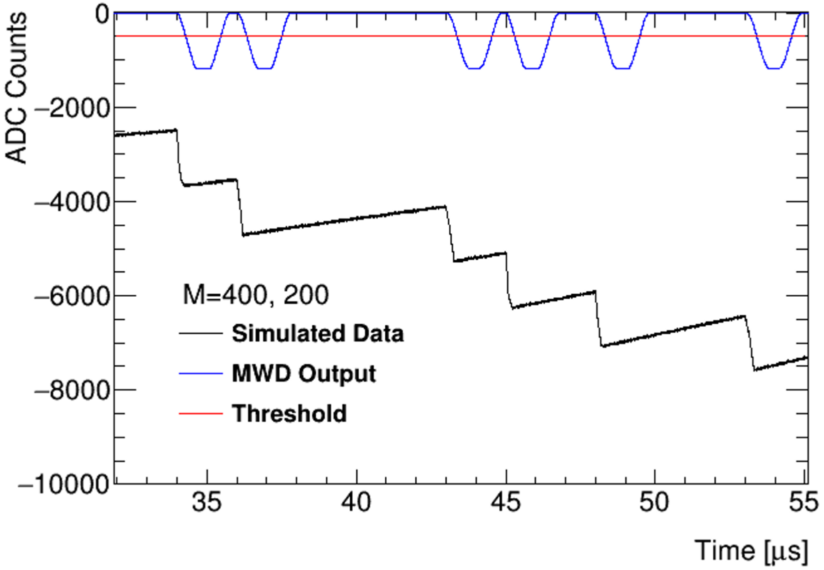
- **New simulation**



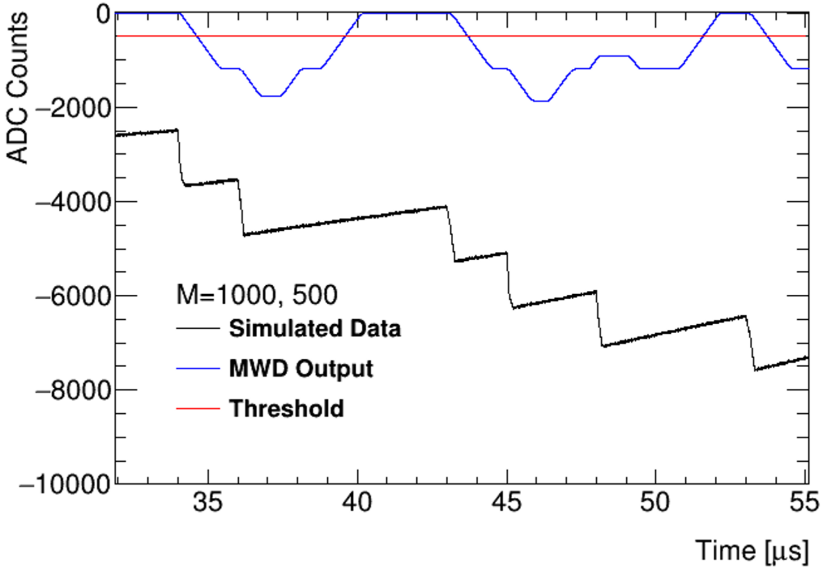


As coded right now MWD takes the minimum value of trapezoid reconstructing a higher height, that's why the energy spectrum slightly shifted to higher energies.

M value and efficiency.



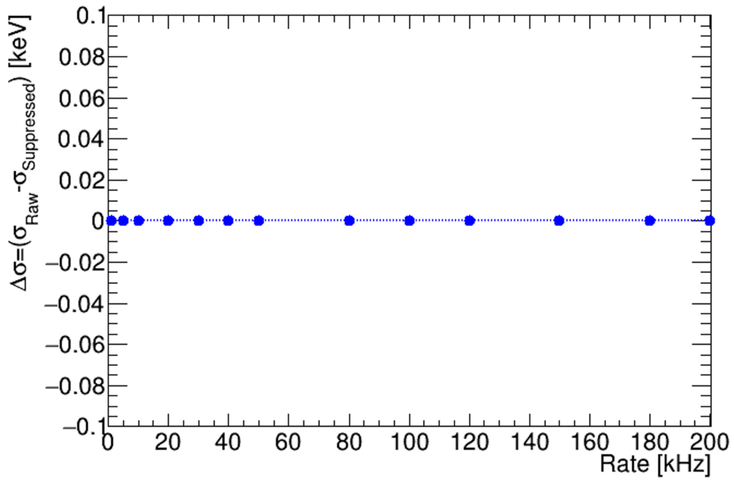
M=400 MWD finds the 6 simulated peaks below threshold.

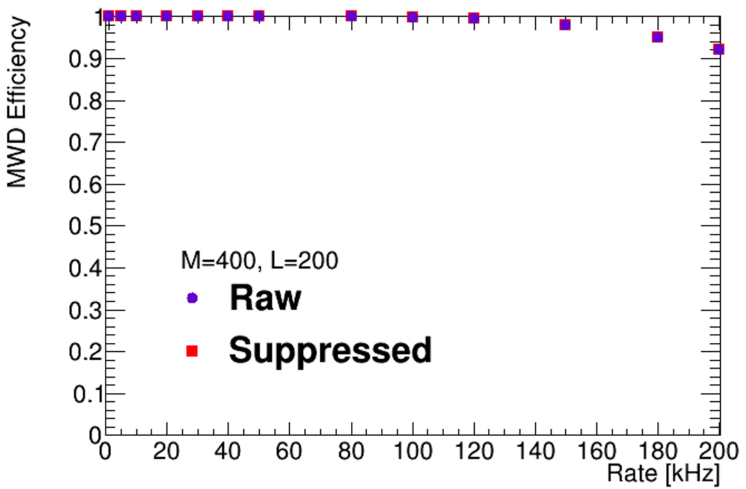


M=1000 MWD finds the 2 peaks below threshold with wrong energy.

With M=1000 we are not able to resolve all peaks at 200 kHz affecting the efficiency of the algorithm.

ZS: Testing on simulation.





The MWD resolution and efficiency is same with the raw and ZS data.