The Mu2e experiment: STM detector.

INTENSE Meeting - September 2022.

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Motivation.

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Science & Environment

Muons: 'Strong' evidence found for a new force of nature

By Pallab Ghosh
Science correspondent

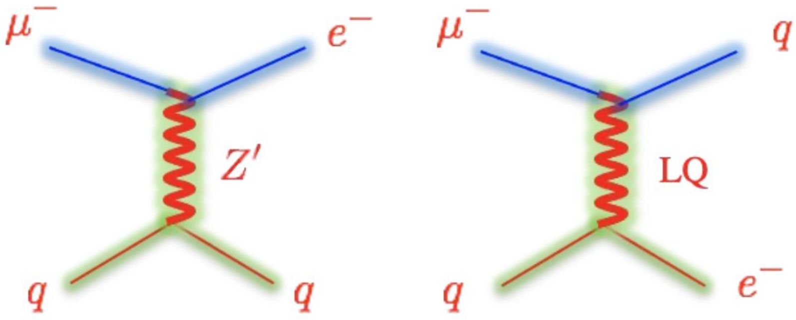
7 April

REIDAR HAHN / FERMILAB

The findings come from the US Muon g-2 experiment

Hints from FNAL Muon g-2 and LHCb that muons may not be behaving as we expect in the Standard Model.

New physics explaining these anomalies could also imply lepton flavour violating (CLFV) transition in muons.



CLFV only occurs in SM via neutrino oscillations over tiny distance : it is thus heavily suppressed to 10^{-50} level.

Thus **ANY** observation of CLFV would be evidence of new physics.

The Mu2e Experiment.

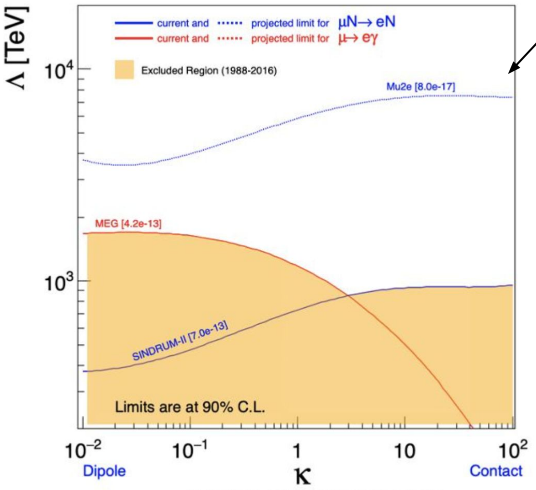
Mu2e experiment can probe both dipole and contact BSM interactions to mass scales in the multi-TeV region

Muon is captured by aluminium and forms a muonic atom and in doing so it emits characteristic X-rays

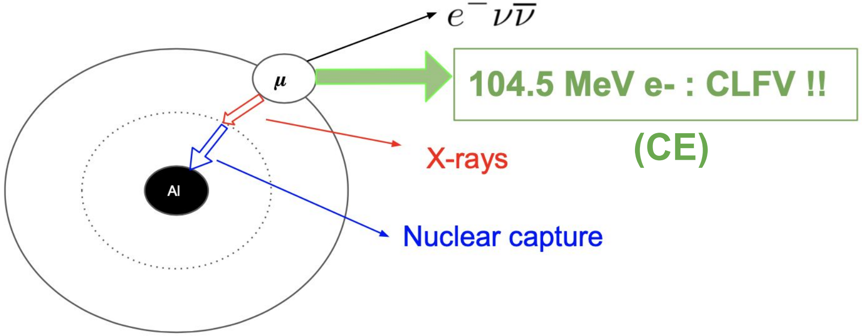
As a muonic atom:

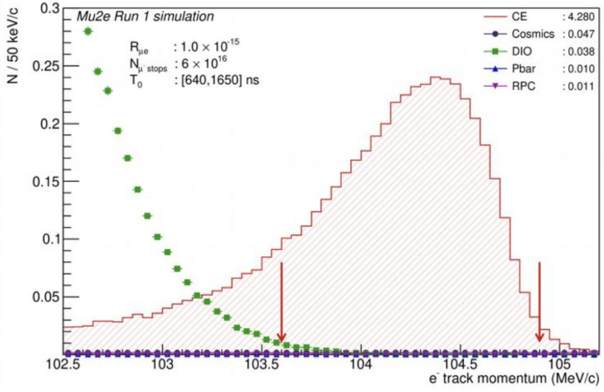
- Muon can decay as usual emitting e- and neutrinos
- Be captured by nucleus
- Signal: **Undergo CLFV and emit e- (conversion electron: CE) and NO neutrinos**

Main Background: Muon Decay in Orbit (DIO)

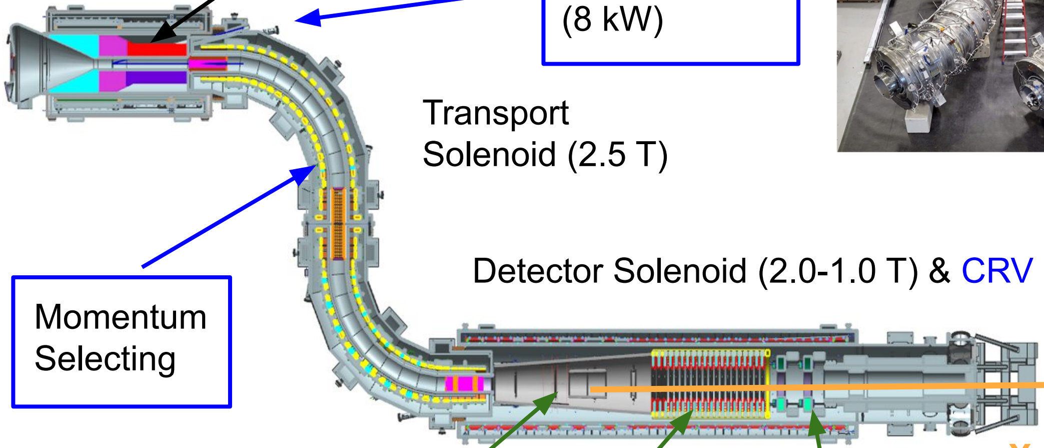


Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097





Mu2e.



Production (4.5 – 2.5T) Solenoid

8 GeV protons (8 kW)

Transport Solenoid (2.5 T)

Momentum Selecting

Detector Solenoid (2.0-1.0 T) & CRV

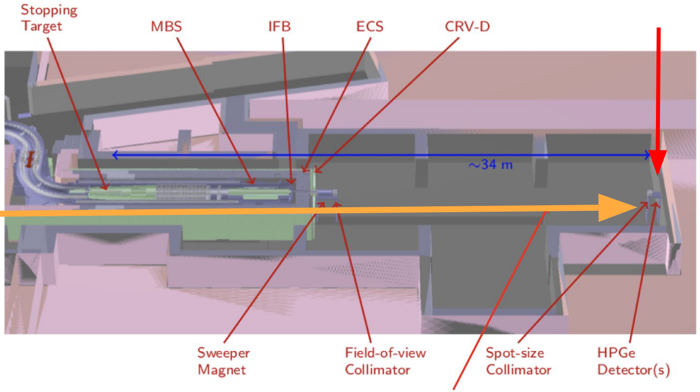
Al-Stopping Target

Tracker

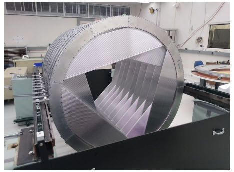
Calorimeter

X-rays

STM Detector: HPGe and LaBr



Polyethylene Absorber



35 m

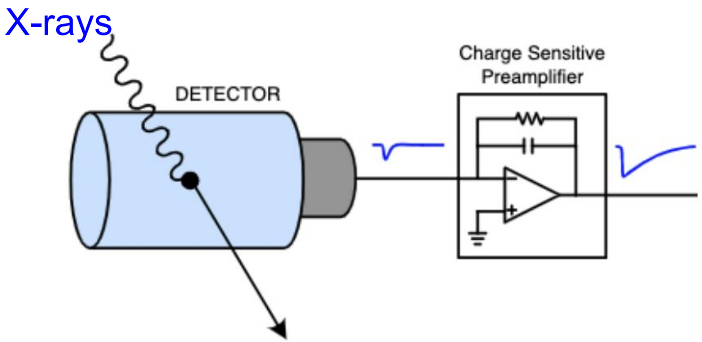
Sensitivity of 8x10^{-17} requires 10^{10} muons/s to interact with the aluminium (stopping) target.

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".

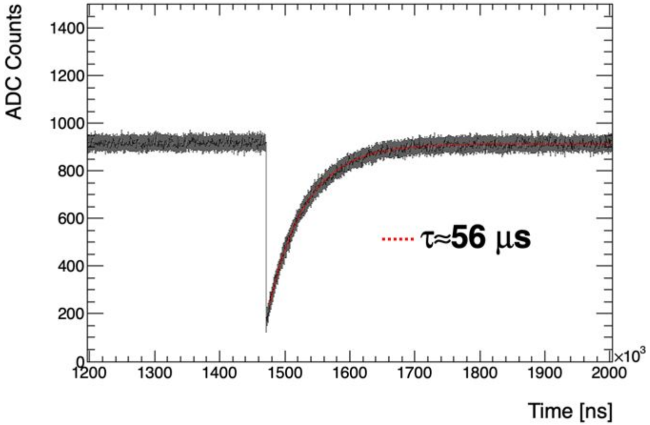
$$\mathrm{BR} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow e^- + \mathrm{N}\right)}{\boxed{\Gamma\left(\text{nuclear } \mu^- \text{ captures}\right)}}$$

Measuring the energy deposited.



+

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.

Main contributions.

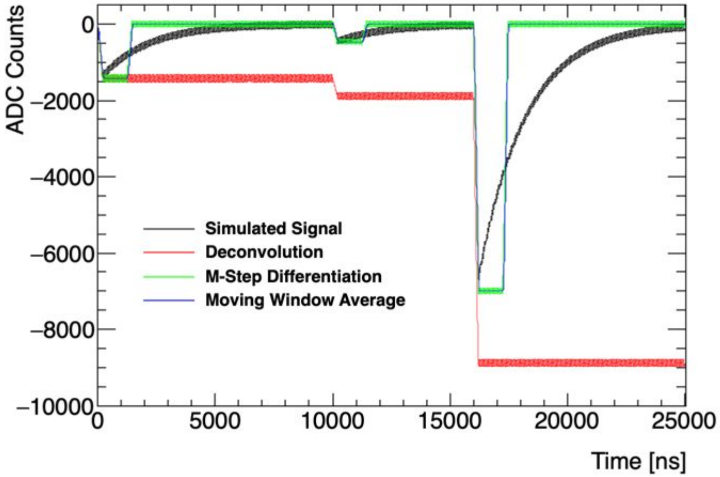
- I have implemented the **Moving Window Deconvolution** (MWD) algorithm to determine the pulse heights. The input parameters of this algorithm has been tested on real X-ray data from 137-Cs and 152-Eu radioactive sources and optimised using simulated data. Testing this algorithm on simulation has allowed to determine the MWD resolution and efficiency dependence with rate, noise and energy of the signal.

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

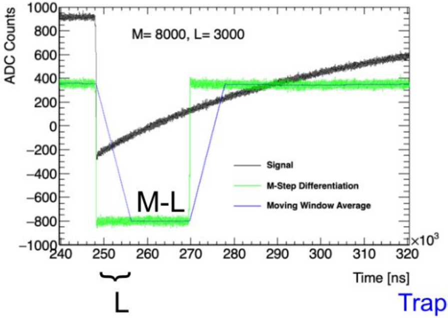
- Development of a **Zero Suppression** algorithm in C++ to reduce the amount of raw data needing to be stored and analysed. This algorithm has also been tested on real data and simulation.

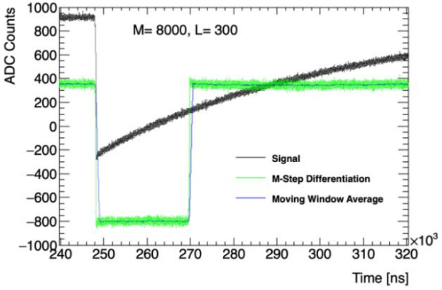
Moving Window Deconvolution Algorithm.

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

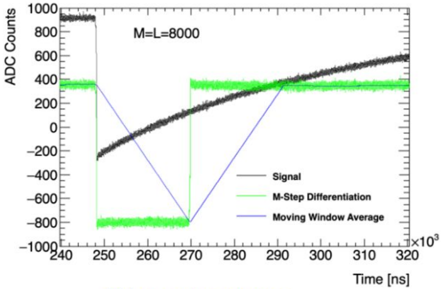


Shape of the signal: Trapezoid or triangle output.





Trapezoidal shape

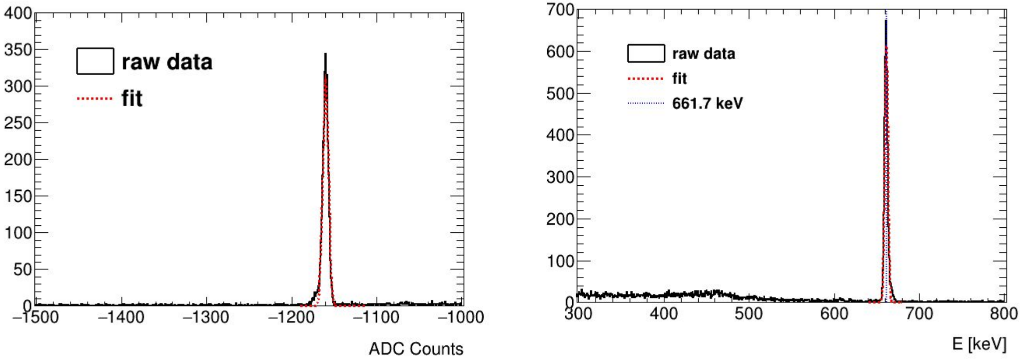


Triangular shape

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

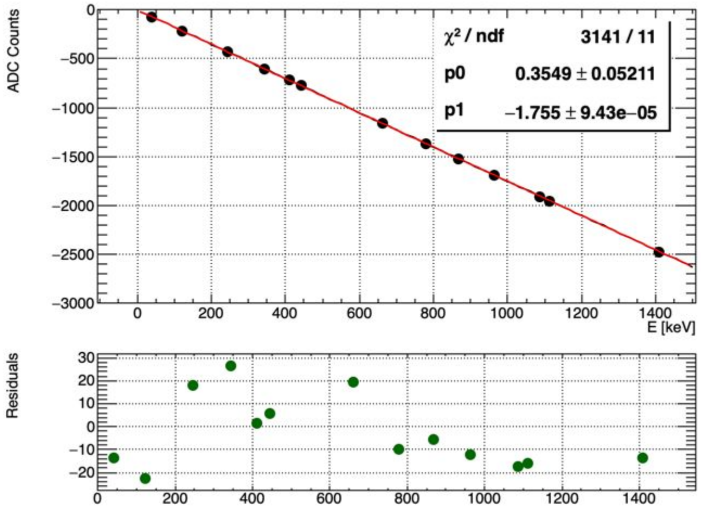
MWD + Pulse Finding

- ^{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.



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

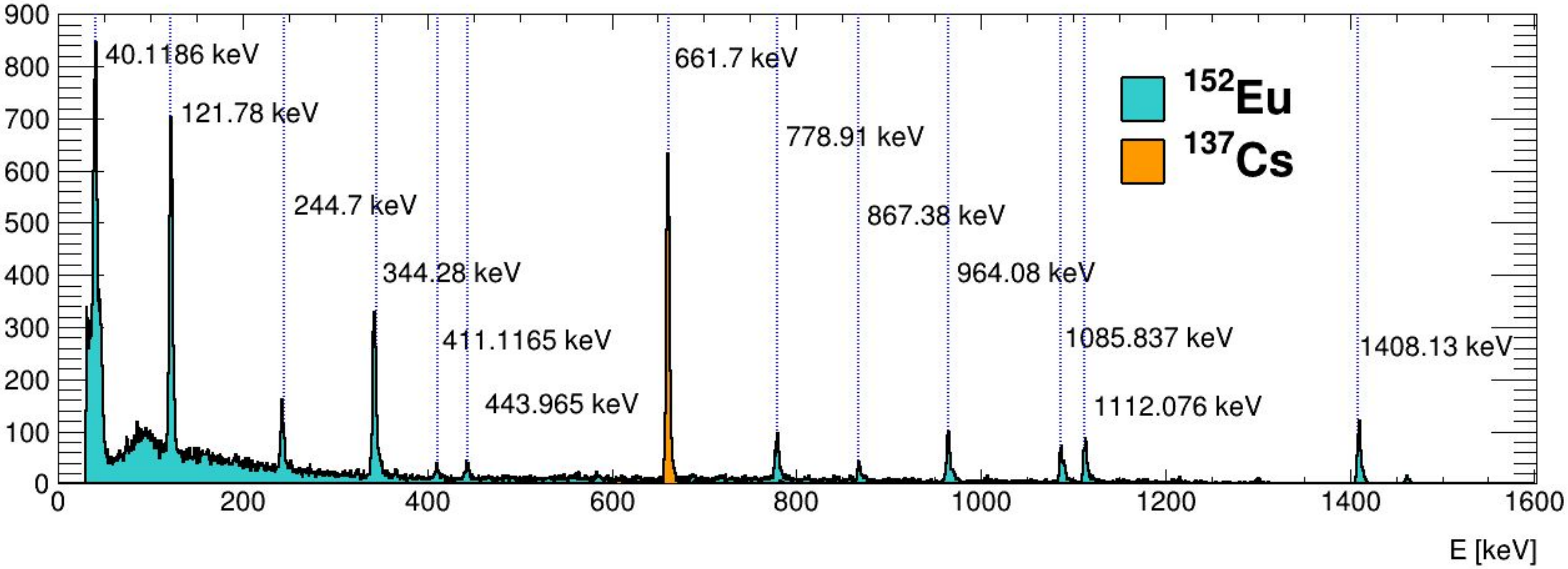
^{137}Cs + ^{152}Eu Calibration



$$\boxed{\sigma_{\rm ADC} = 0.57\,{\rm keV}}$$

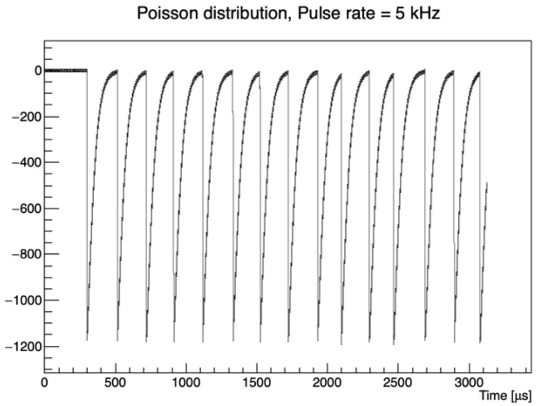
Energy Spectrum.

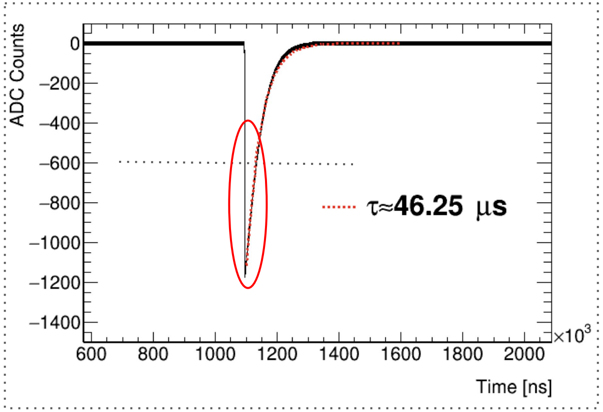
Calibrated energy spectrum obtained from the ^{137}Cs and ^{152}Eu source data.



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

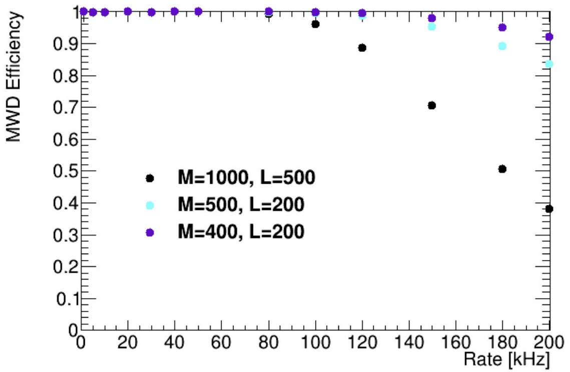
MWD Efficiency and Resolution at different rates based on Simulation.

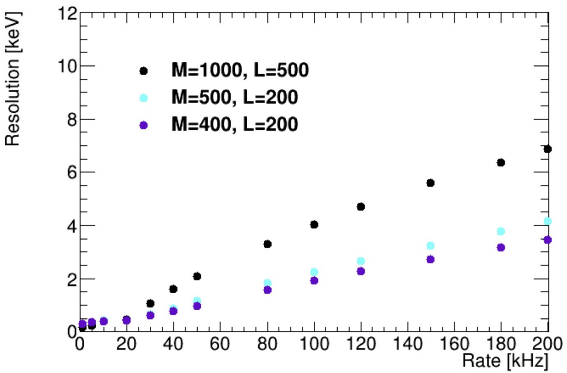




- For real data, we are not able to know the MWD efficiency, because we don't know the number of pulses generated or the rate.
- Developing a simulation allows to define the MWD efficiency based on the rate.

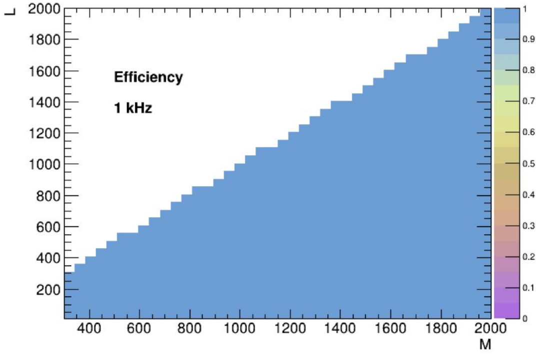
At our nominal rate of 20 kHz the HPGe pulses overlap

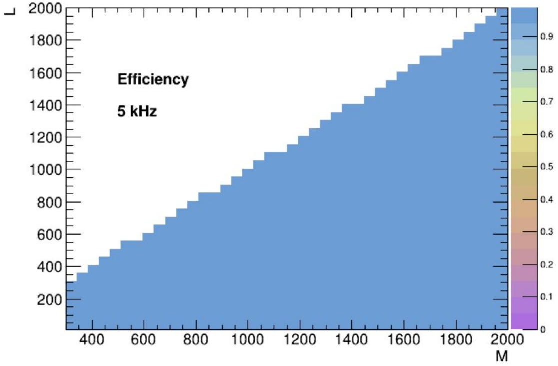


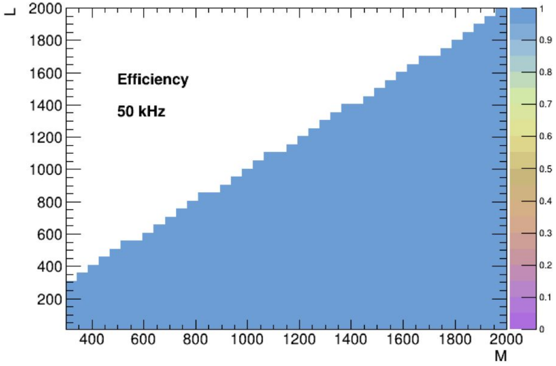


- At high beam rates the MWD efficiency strongly depends on the M and L parameters so an in-depth study of this dependence is required.

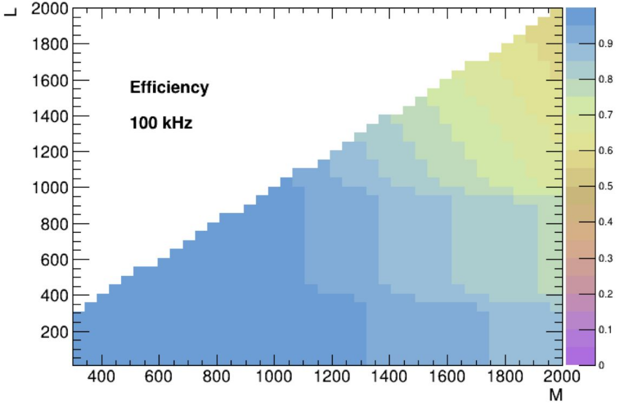
MWD Efficiency dependence on M and L vs rate.

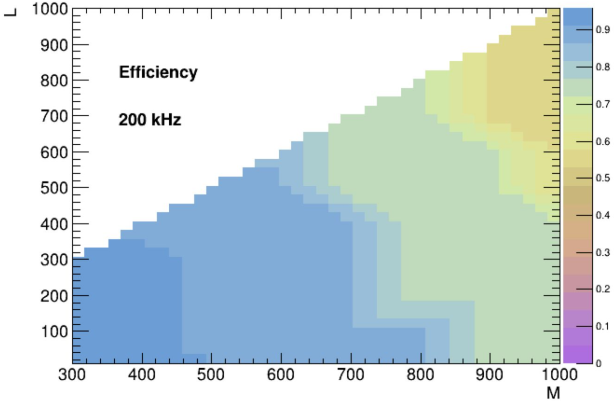






At nominal rate MWD efficiency is essentially unity for all L,M.
At highest rates can be as low as ~ 50% at large M but ~ 100% at M ~ 400.

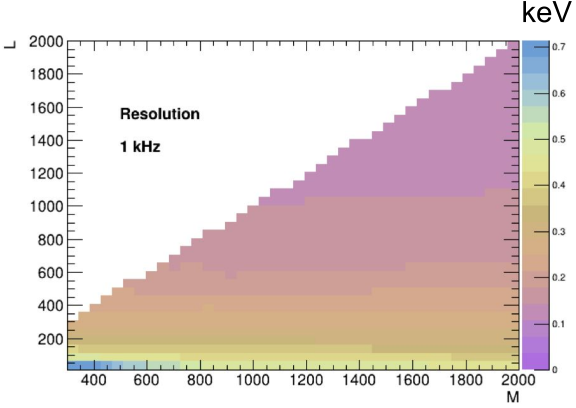


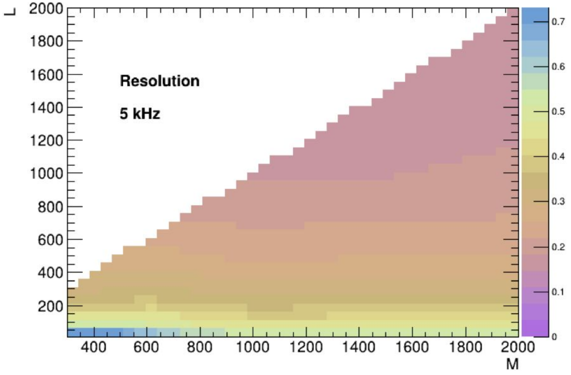


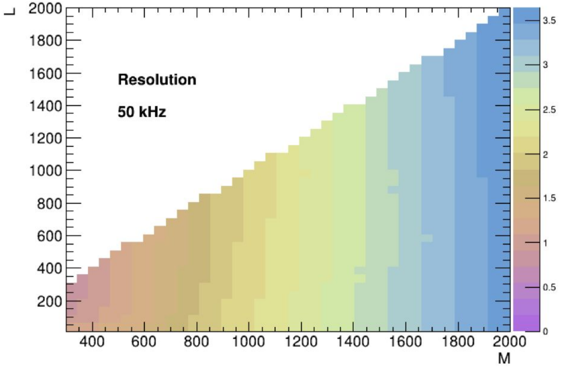
- Better efficiencies are reached for low M values.

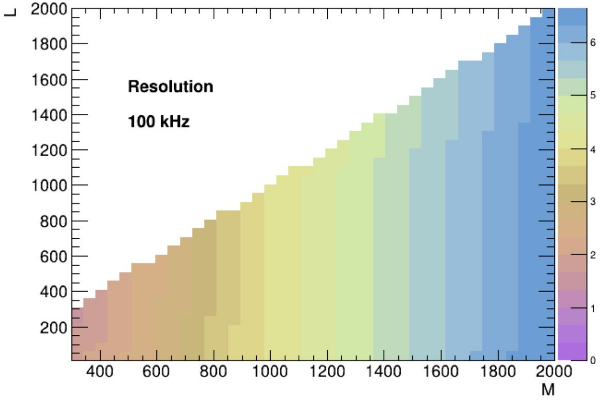
- The larger the M value, the larger the size of the step after deconvolving the signal.

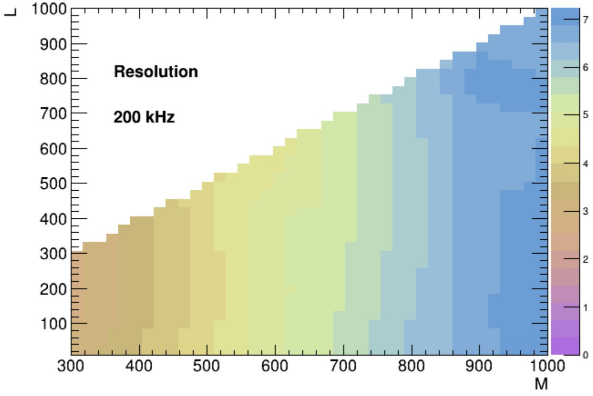
MWD Resolution dependence on M and L vs rate.







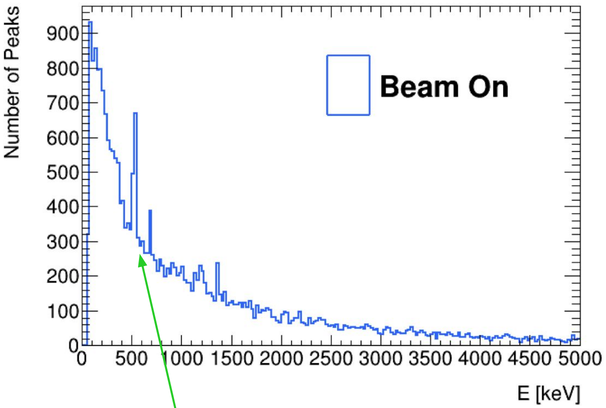




Test-Beam: gELBE Energy Spectrum.

M=400, L=200

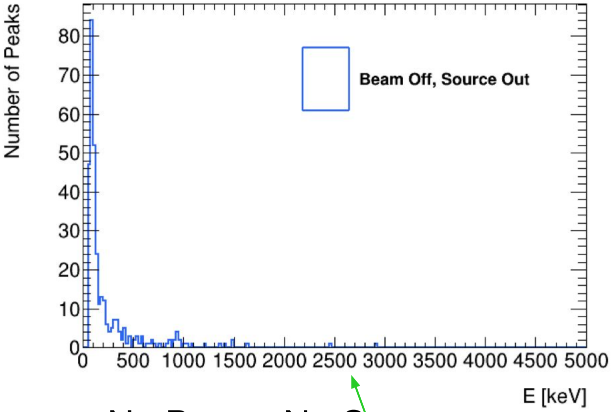
Run 26



Beam Data

Annihilation peak at E=511 keV

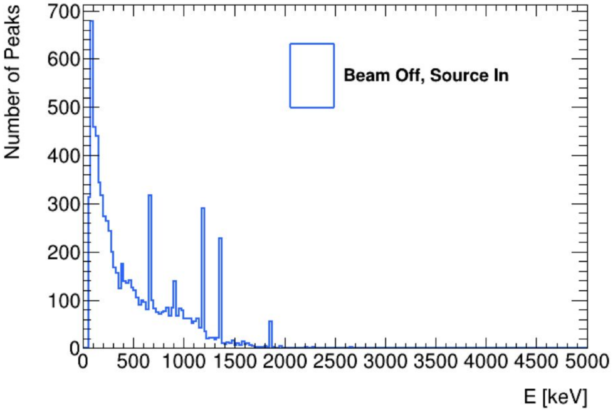
Run 27



No Beam, No Source

Cosmic Rays

Run 28



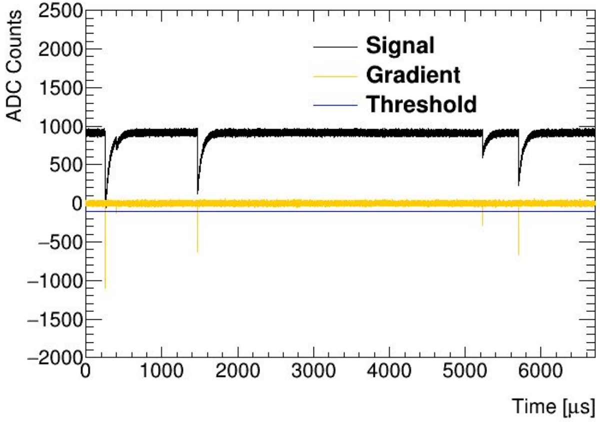
Source Data

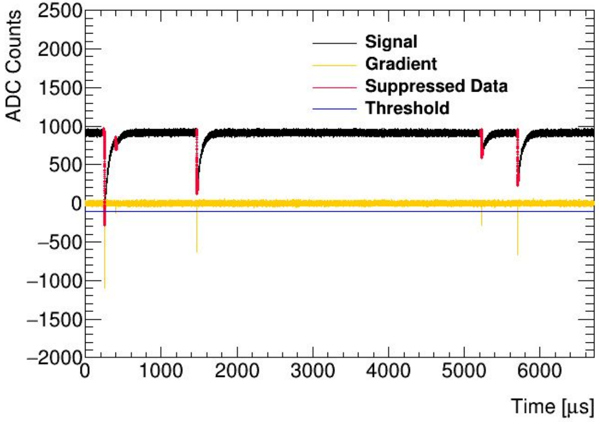
Zero Suppression (ZS) Algorithm.

- 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.

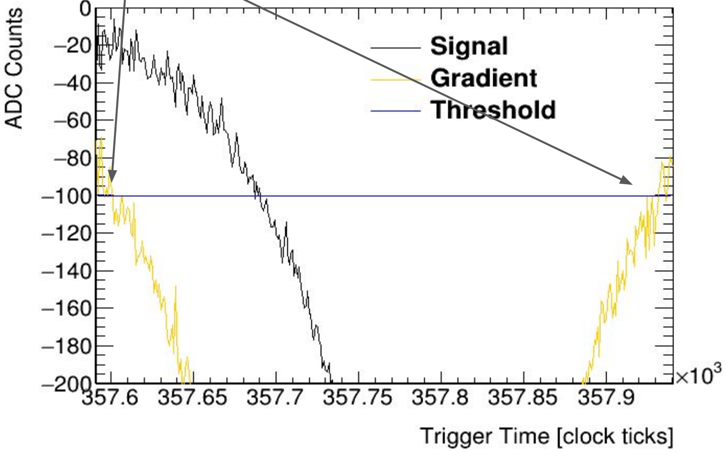


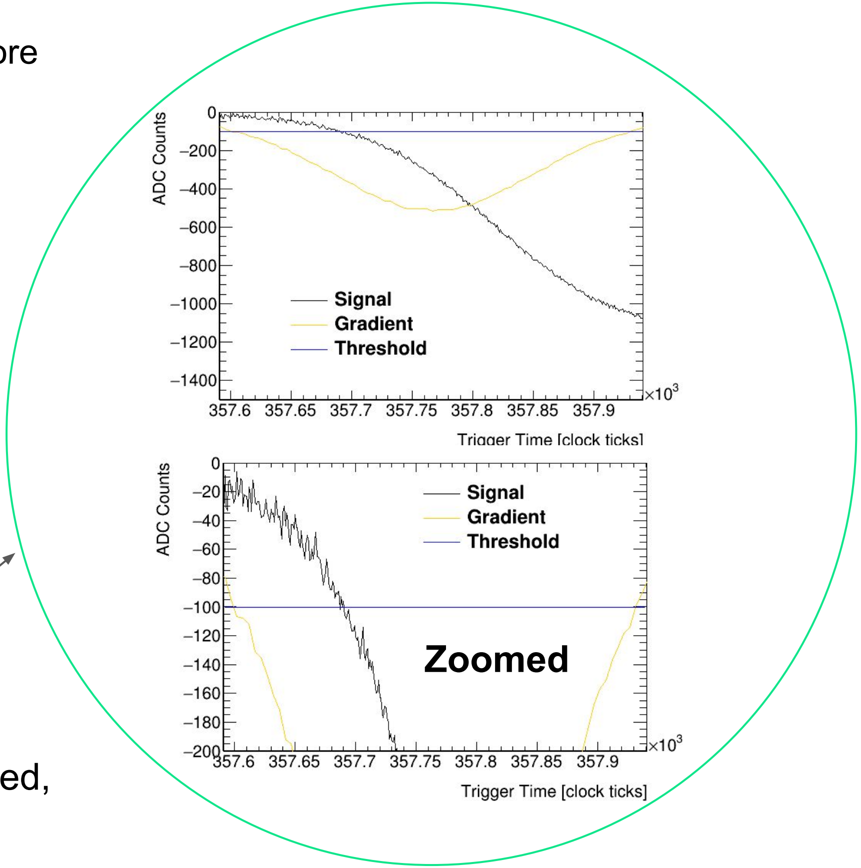


ZS algorithm applied to ^{137}Cs data.
Finds all the peaks.

ZS: Testing on simulation.

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

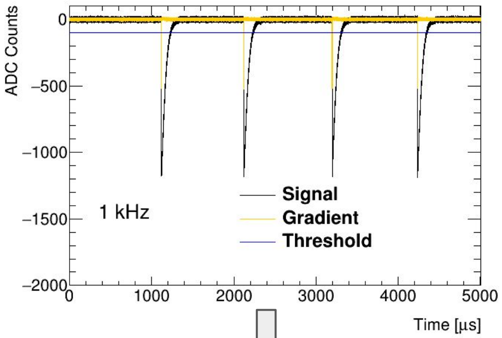


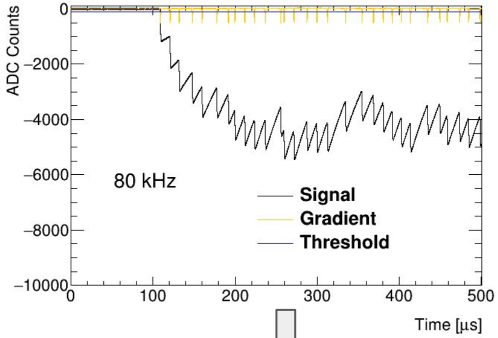


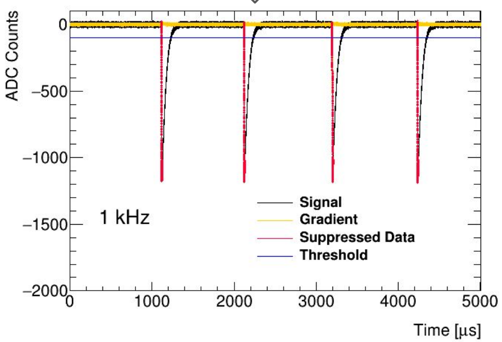
The average over **n** (=5) gradient values is calculated, so that the variation in gradient are softer.

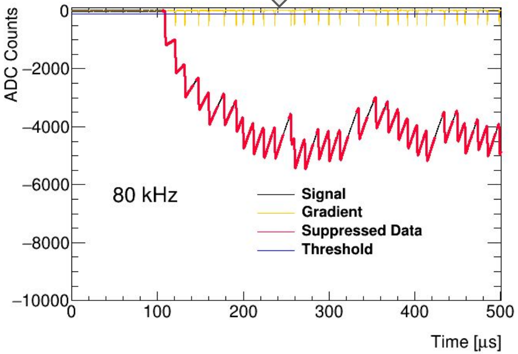
ZS: Testing on simulation.

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.





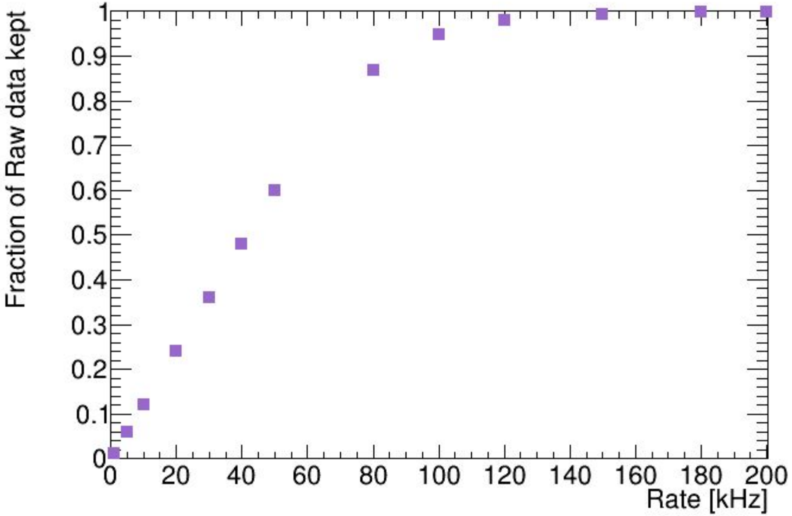




Red is stored (ZS) data.
Black is raw data

No triggers in noise.

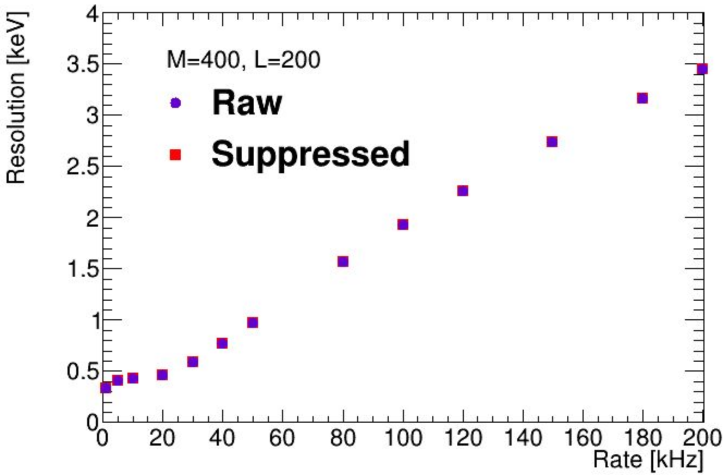
ZS: Testing on simulation.

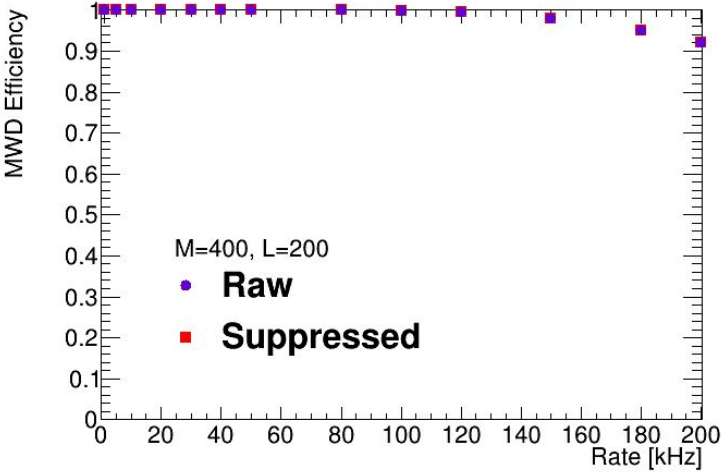


At low rates the the suppression is very efficient, we keep ~ 1% of the raw data at 1 kHz, 25% at 20 kHz (nominal Mu2e rate).

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 simulation.



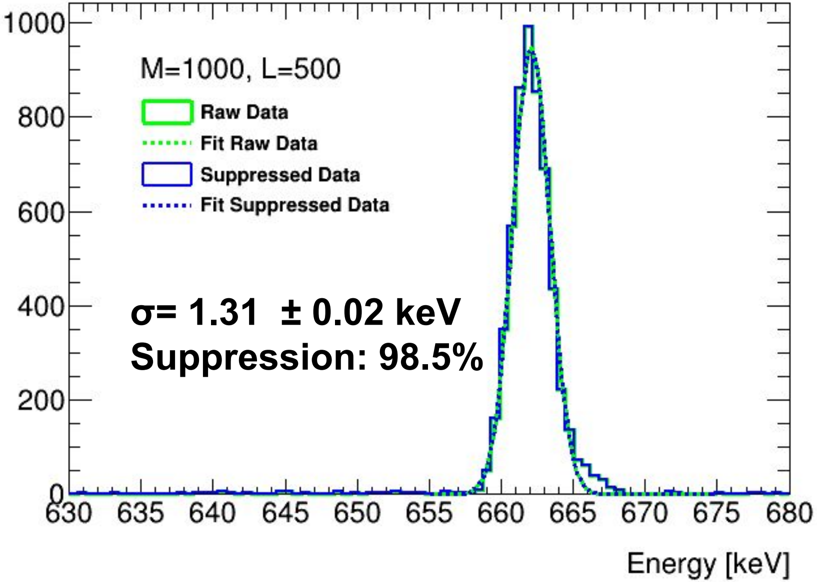


The MWD resolution and efficiency is same with the raw and ZS data.

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:
    - Simulation.
    - Radioactive sources.
    - Data from a Test-beam (source data, beam data and noise data).
- Zero Suppression Algorithm: same MWD resolution and efficiency on ZS data as raw data and is applicable up to 100 kHz. Beyond this ZS doesn’t reduce the data volume for HPGe data.

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).