MANCHESTER
1824
The University of Manchester

NeΨ 23 | NePSi 23

Development of the data acquisition system for the Mu2e STM detector.

Mu2e

15-17 Feb-2023,
Claudia Alvarez Garcia
The University of Manchester, United Kingdom

European Commission
Intense
H2020 MSCA ITN
G.A. 858199

A search for cLVF at Mu2e.

g-2 anomaly imply that muons may not be behaving as we expect in the SM.

NEWS

Home | Coronavirus | Brexit | UK | World | Business | Politics | Tech | Science | Health | Family & Education

Science & Environment

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

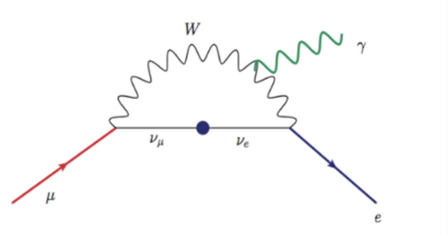
By Pallab Ghosh
Science correspondent

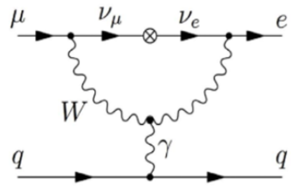
7 April

REIDAR HAHN / FERMILAB

The findings come from the US Muon g-2 experiment

- Lepton flavour is violated in the neutral sector through neutrino oscillations.
- Charged lepton flavour violation (cLFV) can be predicted as a consequence of neutrino mixing.
- cLFV processes are strongly suppressed in the SM including neutrino masses.

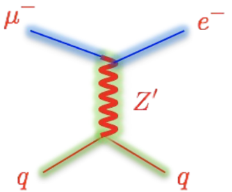


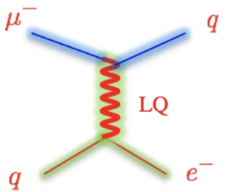


$$BR_{SM+neutrino\,masses}(\mu^- \to e^-\gamma) < 10^{-54} \approx O(\mathrm{BR_{SM}}(\mu^- N \to e^- N))$$

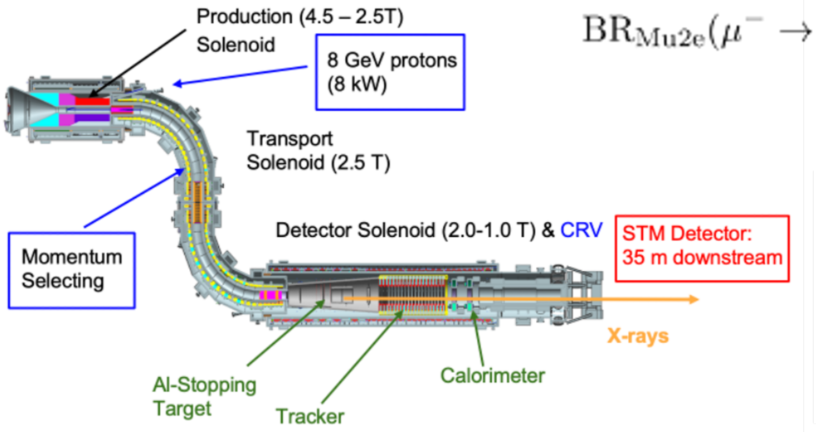
Several channels of cLFV can be explored.
ANY observation of cLFV would be evidence of New Physics.

Mu2e channel: $\mu^-\mathrm{N} \to e^-\mathrm{N}$, $O(\mathrm{BR_{BSM}}(\mu^- N \to e^- N)) > 10^{-54}$



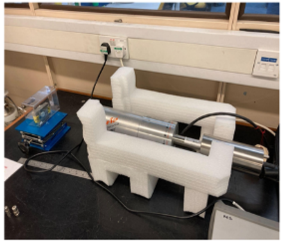


Mu2e sensitivity and measurement normalization.



$$\mathrm{BR}_{\mathrm{Mu2e}}(\mu^- \to e^-) = \frac{\Gamma(\mu^- + \mathrm{N} \to e^- + \mathrm{N})}{\Gamma(\text{nuclear } \mu^- \text{ captures})} < 8\cdot 10^{-17}(90\%\mathrm{C.L})$$

^{27}Al



Normalization of cLFV measurement.

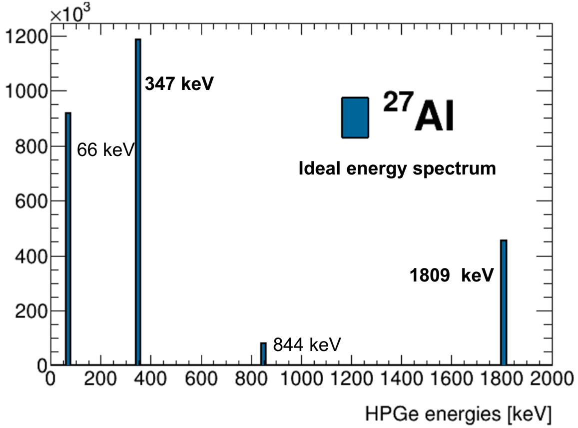
- Measured by the Stopping Target Monitor (STM).
- STM: Two detectors (HPGe and LaBr$_3$).
  HPGe: Better resolution.
  LaBr$_3$: Can run at higher rates.

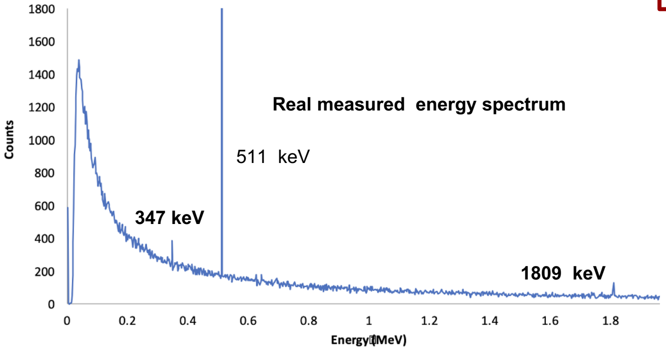
The best experimental limit for this process is from the **SINDRUM-II** experiment at PSI using a gold nucleus: **7×10^{-13} (90% C.L)**. The aim of the Mu2e experiment is to extend the sensitivity to cLFV by four orders of magnitudes beyond the SINDRUM-II limit.

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.**

^{27}Al Stopping Target.

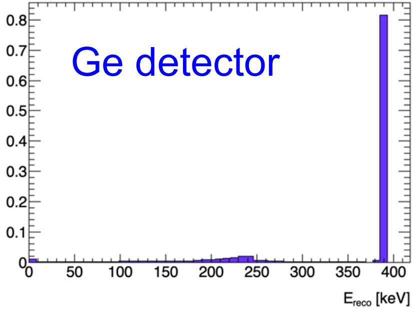


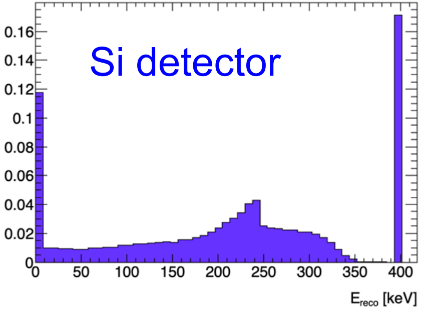


- Reconstruct ^{27}Al energy spectrum.
- Captured muons = 60.9% of Stopped muons.
- Stop rate can be determined by measuring the X-rays:
  - 80% of stops emit 347 keV X-rays 2p-1s (1s orbit lifetime = 864 ns).
  - 31% of stops emit 1809 keV gammas.
  - 5.7% of stops emit 844 keV gammas.

Reconstructed energy from Ge and Si detector:

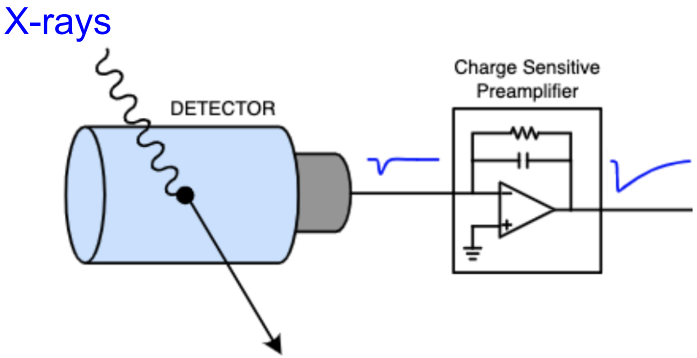
Better resolution for Ge detector (higher photon interaction cross section).

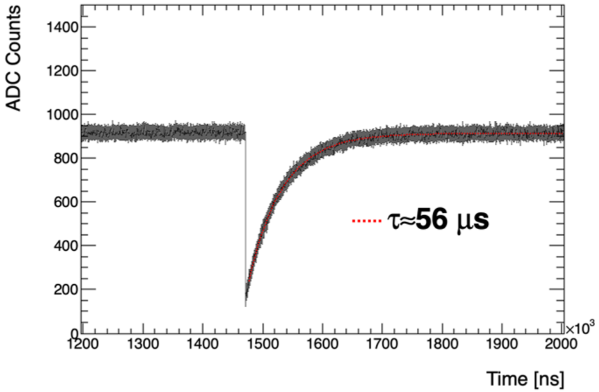




Measuring X-Rays: Stopping Target Monitor (STM).

High Purity Germanium Detector: HPGe and LaBr$_3$



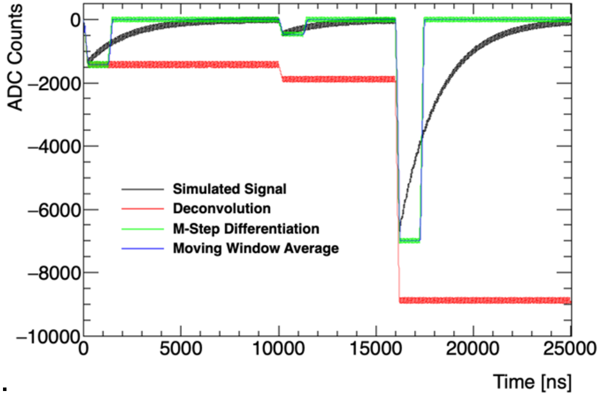


- X-rays reach the detector, the electrons ionise the material creating e-h pairs that drift in the detector creating the pulses that are then shaped.
- The signal is sent to the readout board and an ADC samples these values in 16-bit words.
- Energy of pulses is related to pulse heights.
- Calibration: 1 ADC = 0.57 keV.

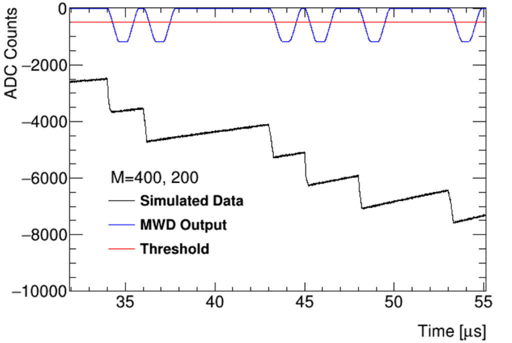
Moving Window Deconvolution (MWD) Algorithm.

Finding pulse heights : MWD algorithm .

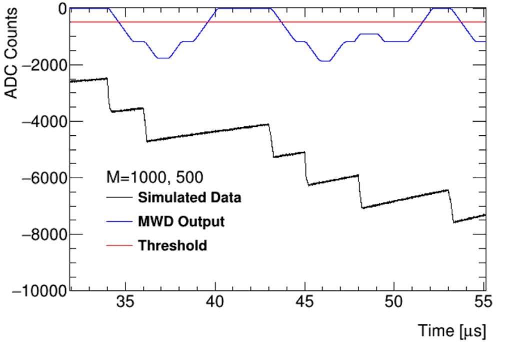
- Signal.
- Deconvolution.
- Differentiation (M window).
- Averaging (L values).

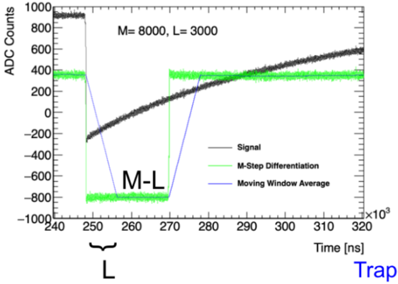


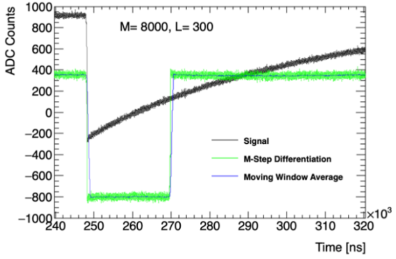
Efficiency strongly affected by MWD parameters at high rates (~200 kHz)



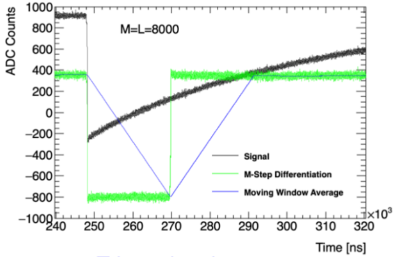
Shape of the signal: Trapezoid or triangle output.







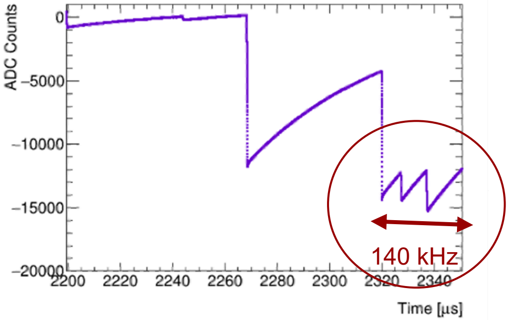
Trapezoidal shape

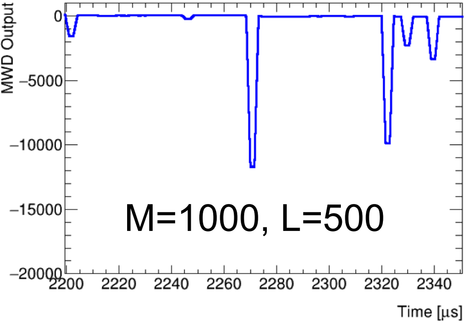


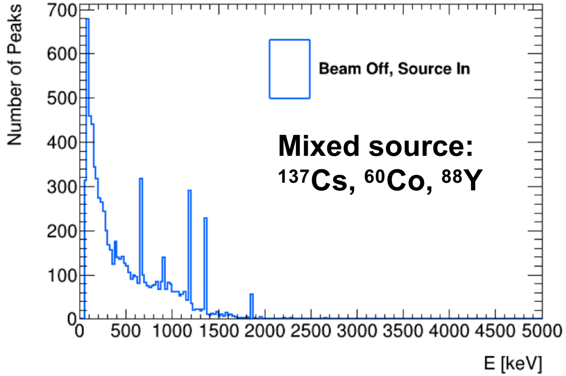
Triangular shape

MWD reconstructed energy spectrum: Test-Beam and radioactive sources.

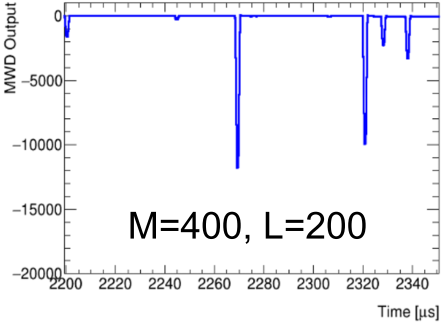
MWD parameters:

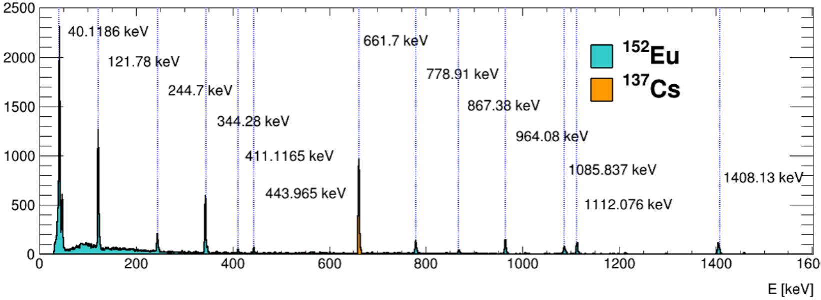






Mixed source: ^{137}**Cs**, ^{60}**Co**, ^{88}**Y**



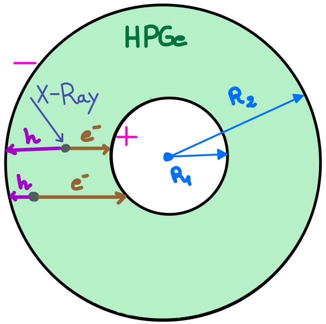


Low M values can resolve overlapping pulses at high pulse rates.

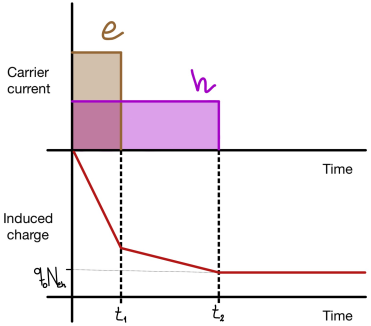
Full STM simulation developed.

Developing a simulation allows to define the MWD efficiency and resolution based on the rate.

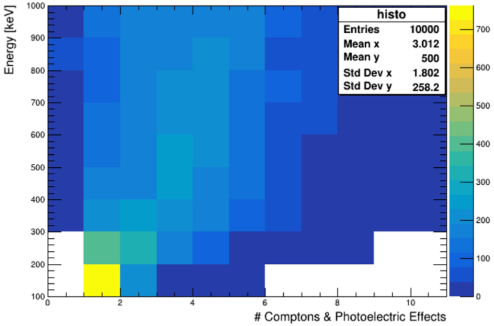
HPGe
coaxial
detector

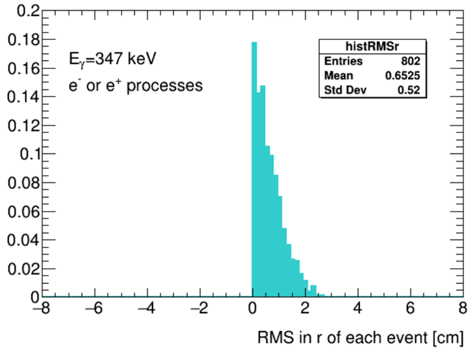


v_{drift}(77K, 10^3 V/cm)=10 cm/μs.



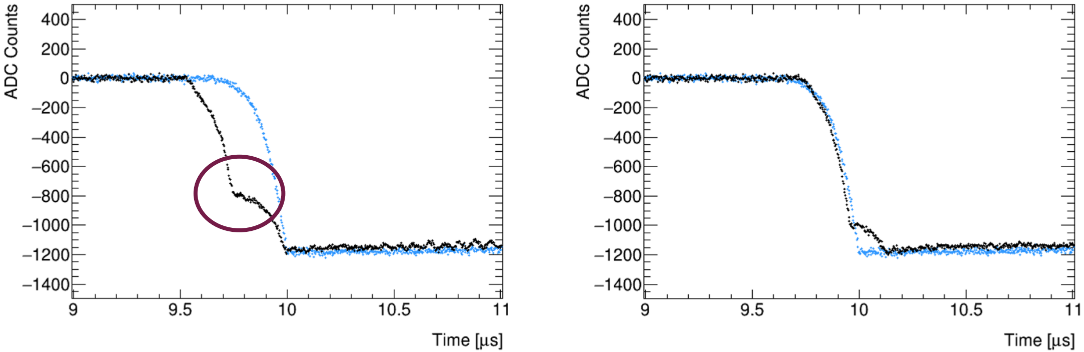
- **Charge collection times of e and h are different** because of differences in drift distances.
- The **mobility of charge carriers depends on the electric field and temperature.**
- **Simulation assumptions:** All charge carriers generated entirely within the active volume of the detector where the electric field has its full expectation value: saturation of the drift velocity.
- Spreads in positions up to **2 cm: events cannot be considered a point in the detector**.





Full STM simulation developed.

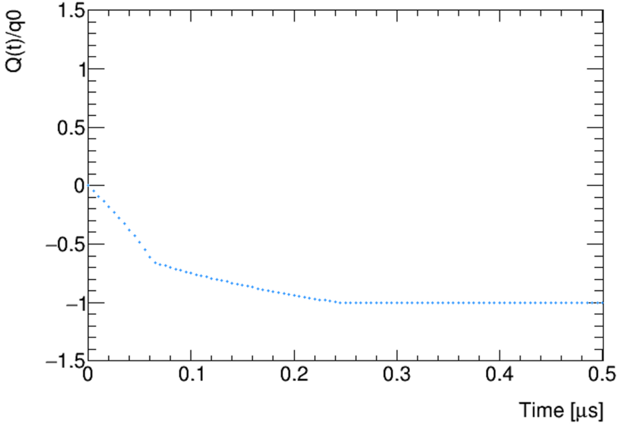
Data
Function-based Simulation



Need a simulation / model that accounts for these **kinks in HPGe data**

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

- The number of e-h pairs generated per Compton/PE process (is not one) and depends on the energy deposited in each process. Need to sum over all the processes in one event.

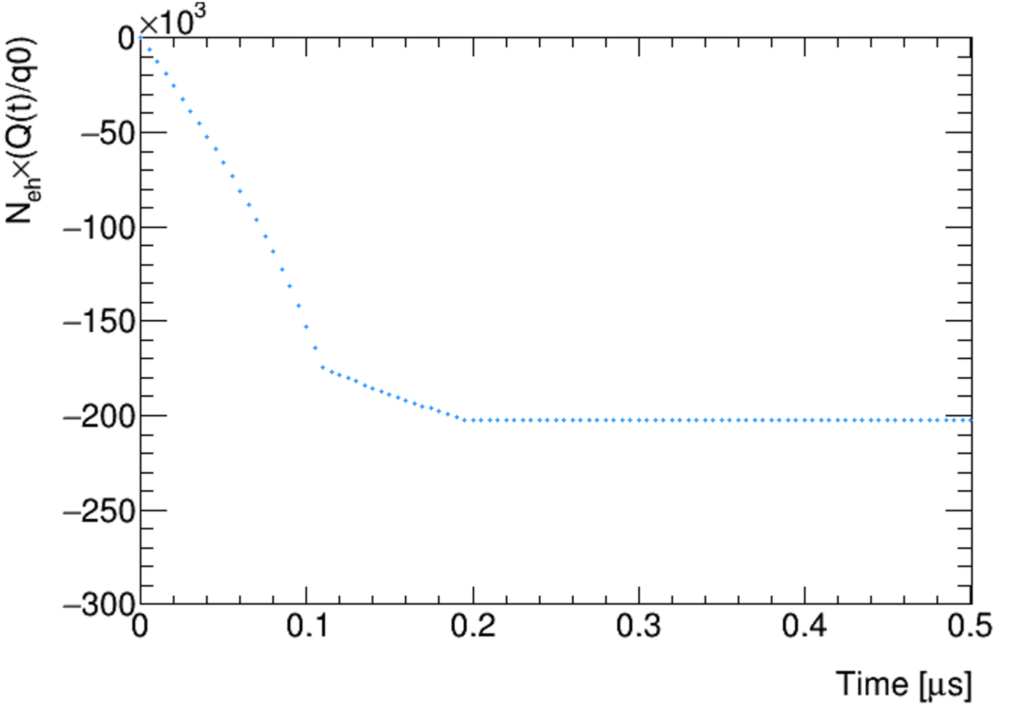


Full STM simulation developed.

Number of electron and hole pairs, amplitude of the signal

E = 600 keV

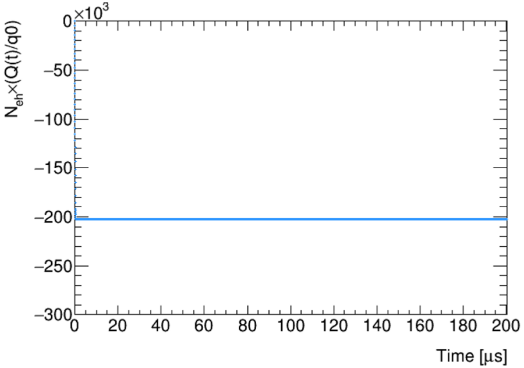
$N_{eh} = E/\epsilon_{eh}(Ge,77K) = 202702$

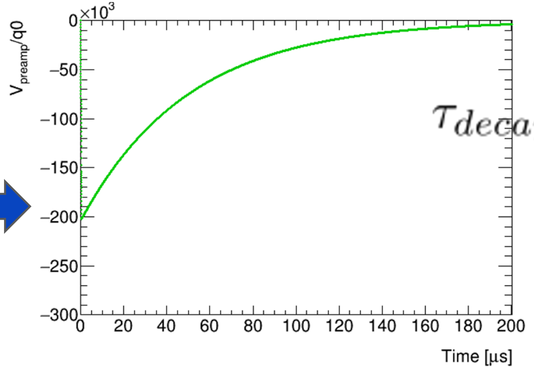


Additionally need to include:

- Effect of preamp shaping after charge collection process.
- Discrete digitisation (ADC) and electronic noise.

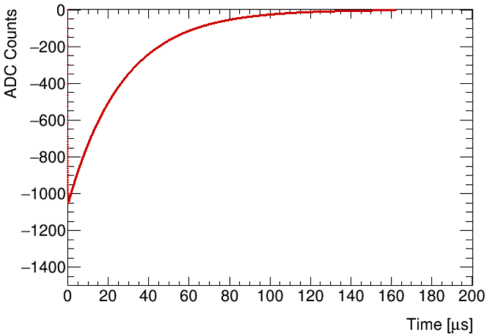
Full STM simulation developed.

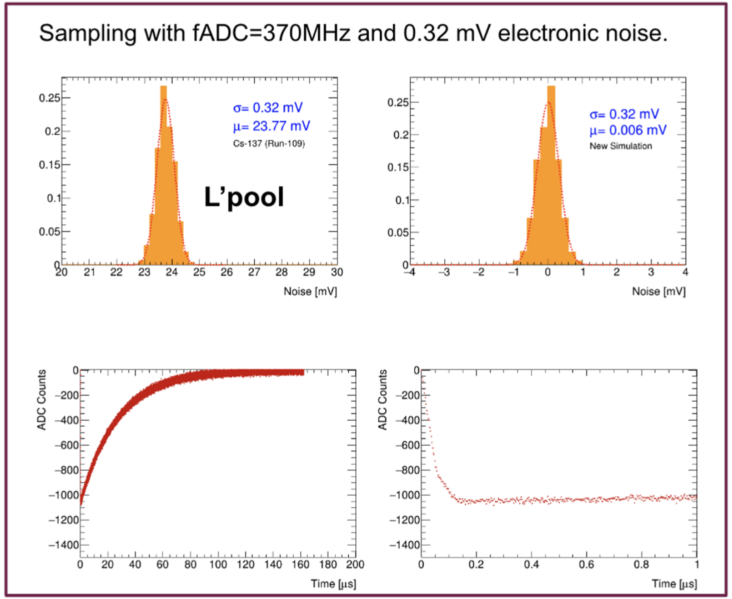




$$\tau_{decay} \approx 50\mu s$$

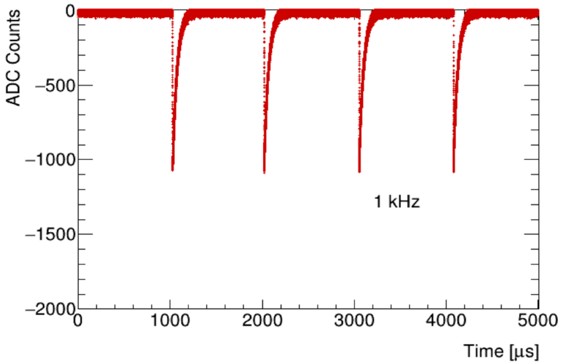
Plus ADC calibration and electronic noise

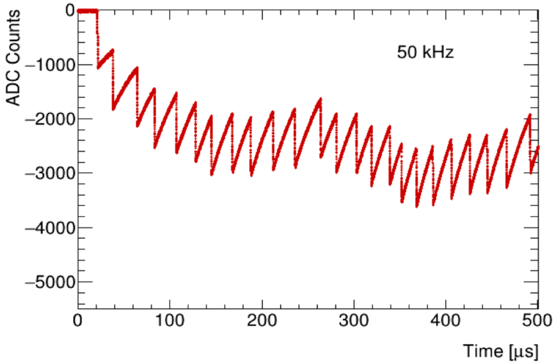


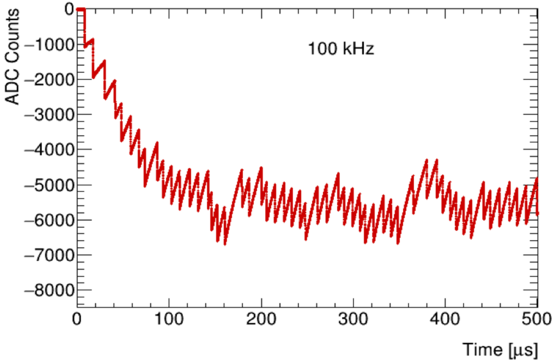


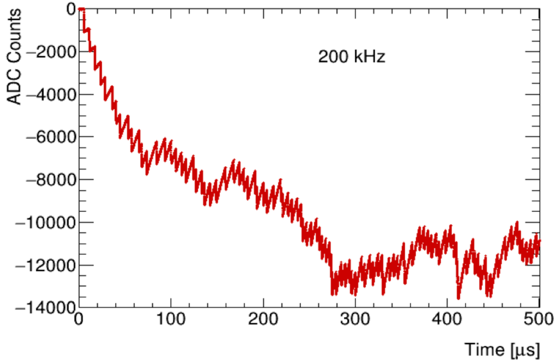
Sampling with fADC=370MHz and 0.32 mV electronic noise.

Full STM simulation developed: Pulse Rates.









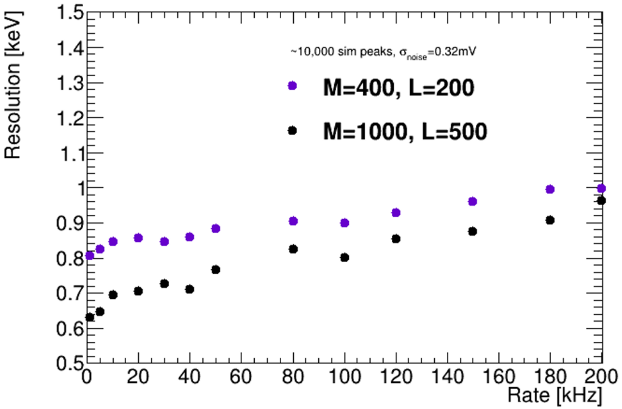
Resolution and efficiency of the MWD algorithm as a function of the rate using this new simulation.

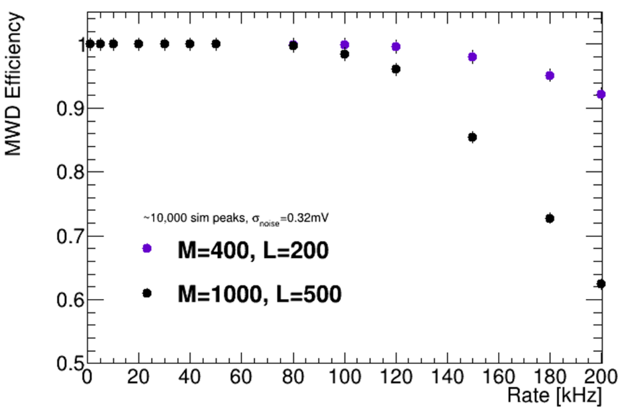
MWD + STM simulation: Resolution and efficiency.

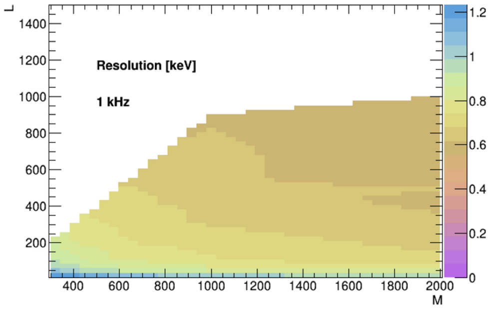
High M values give a better algorithm resolution but worse efficiency at high rates.

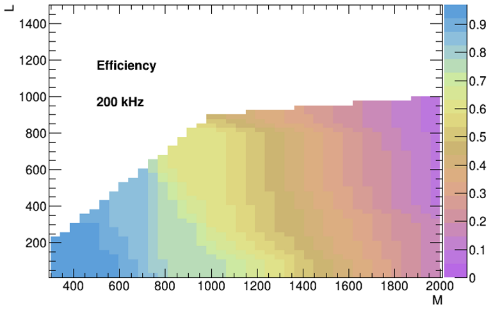
However difference in efficiency is more significant.

Resolution differences from M-value are small: O(0.1 keV) from an overall resolution of 1-2 keV arising from noise, ADC resolution, charge collection and finite energy resolution (# of eh pairs): so prefer low-M value.







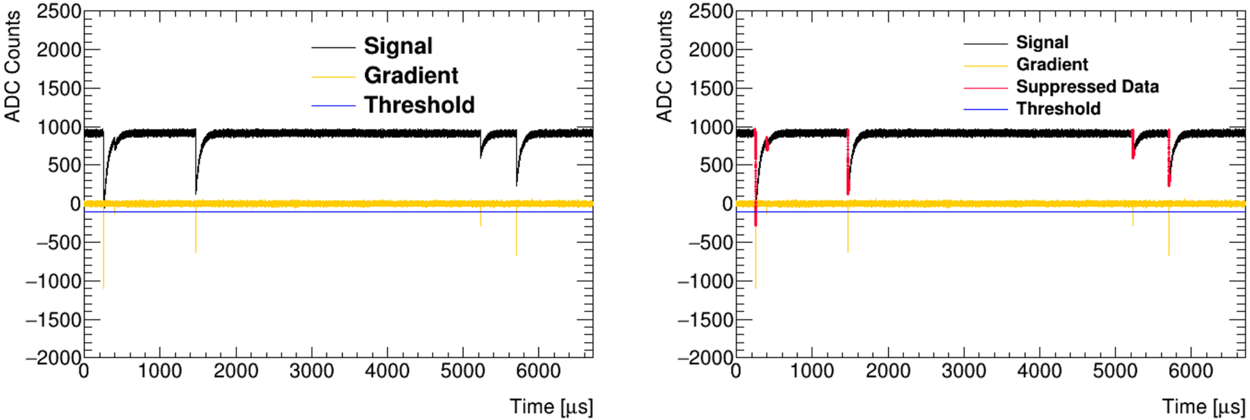


STM data acquisition system: Zero Suppression (ZS) algorithm.

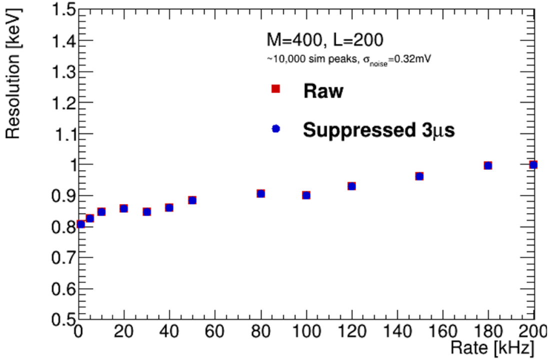
- This algorithm is based on the calculation of the gradient of the signal over a window of ADC values:

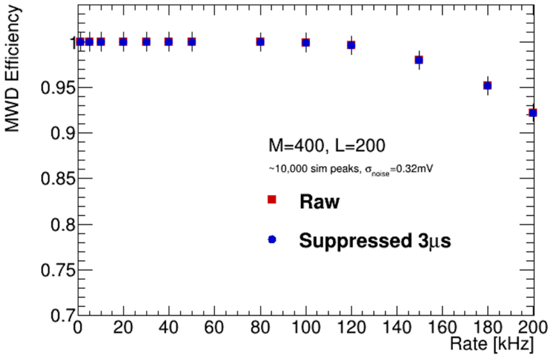
```
gradient[i]=ADC[i+window]-ADC[i];
```

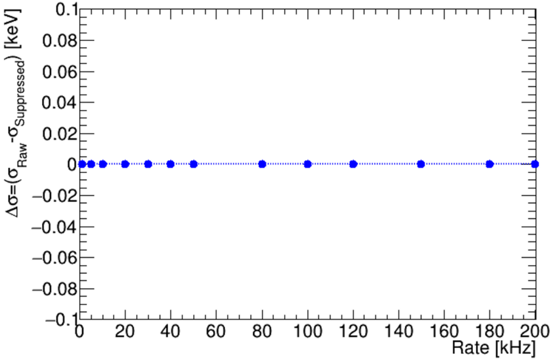
- Window = 100 ADC (~ 0.3 μs) : so in principle can distinguish peaks to rates well above the rates required (5 μs = 200 kHz)
- Gradient threshold = –100 ADC Counts.
- The trigger is then established in the first point where the gradient is below the threshold chosen and store t_{before} [μs] of data before the trigger and t_{after} [μs] of data after the trigger.



ZS using to New simulation: resolution and efficiency.

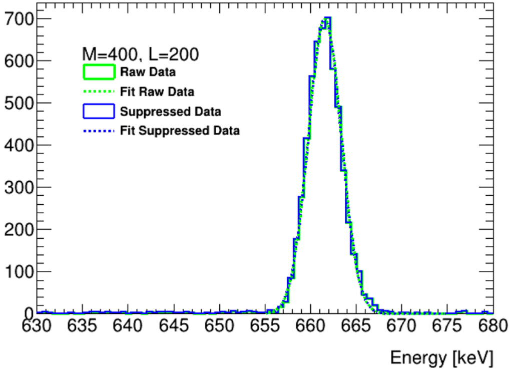




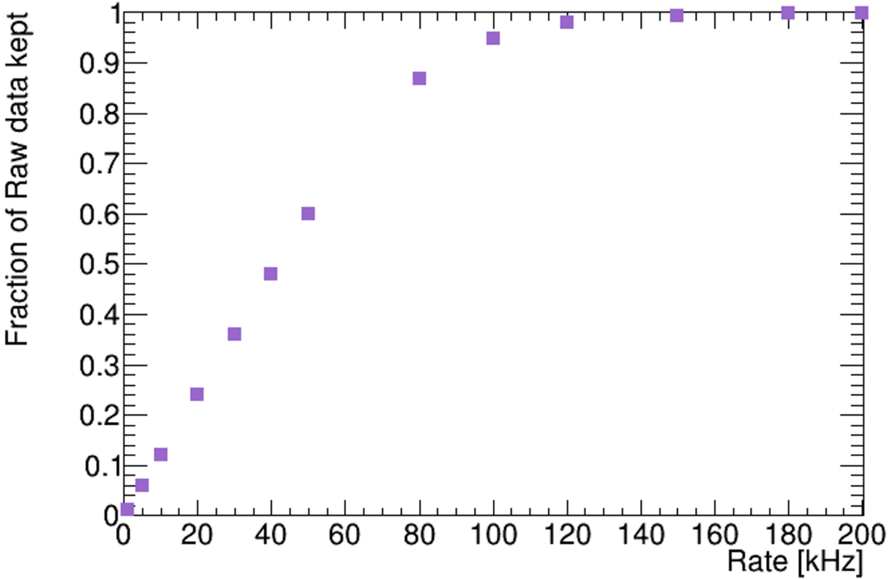


As expected resolution is not affected by ZS.

Suppression is 98.5% (1.5% data retained) but depends on the rate.



ZS rate suppression.



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.

Conclusions

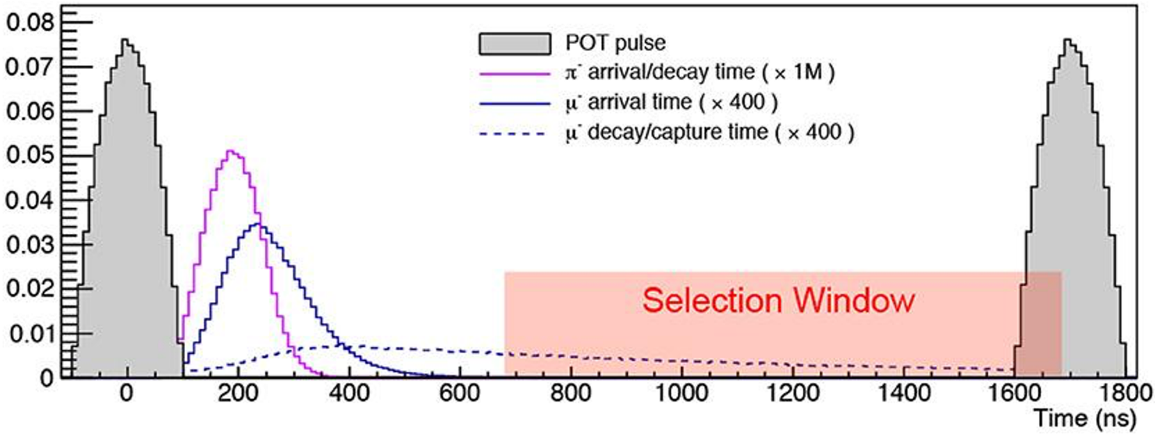
- STM DAQ for HPGe: Acquiring data, developing algorithms (MWD + Pulse Finding) and analysing data. Algorithms optimised and tested on:
  - Simulation: define MWD efficiency and resolution at different rates.
  - Radioactive sources: calibrate the HPGe STM detector.
  - Data from a Test-beam (source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

- A simulation based in physical processes taking place in the HPGe detector and the motion of e-h pairs under an E-field has been developed.

- 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.

Backup....

Backup: Why Aluminium?.



Al that stops muons will then produce bremsstrahlung photons at a rate: 51 MHz/cm^2 with a mean energy of 1.4 MeV. Many of these photons are above pair production threshold and can cause radiation damage in the STM.

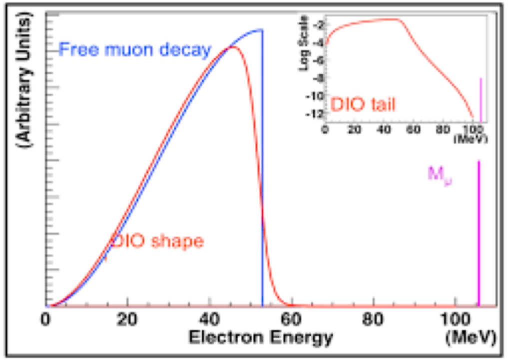
The detector needs to be far from the stopping target reducing the rate by ~ 1/r^2 (r distance stopping target-STM)

Life time of a muonic atom decreases with Z:

- $_{79}$Au (τ= 74 ns): The decays occur mostly during the time pions are still arriving (physics backgrounds are high)
- $_{13}$Al (τ= 864 ns): The decays in aluminium are well separated from the flash (after 100 ns)
- $_{22}$Ti (τ= 328 ns): Also a good choice

Since the beam pulse is 250 ns wide, too many of the muons would be captured and decay within the beam flash

Backgrounds and momentum selection.



- Muon decay in orbit (DIO)
- Radiative muon capture (RMC)
- Cosmic Rays
- Radiative pion capture (RPC)

- “S shape”: removes neutral particles to enter the detector solenoid (unaffected by B and do not travel the S-shape)
- Particles with large momentum hit the wall of the solenoid and are not transmitted:

  $r = p_{\perp}/(0.3B)$

- μ^- and μ^+ drift vertically in opposite directions. A central collimator covering half the aperture, blocks the μ^+ and transmits the μ^-
- The second half of the S-shaped transport solenoid brings the beam back to the nominal axis and provides additional length for pions to decay, suppressing the RPC background

Mu2e measurement.