Development of the online DAQ system for the Mu2e STM detector and a Monte Carlo study determining the uncertainty in the number of stopped muons.

INTENSE Meeting

May-2023

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H2020 MSCA ITN
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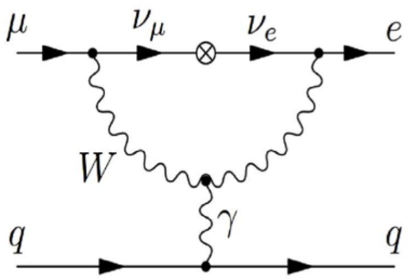
Mu2e - Overview.



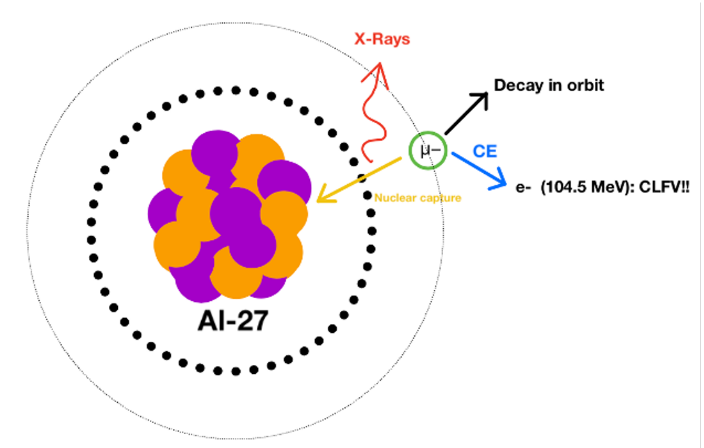
cLFV SM prediction.

$$\mathrm{BR_{SM}}(\mu^- + \mathrm{N} \rightarrow e^- + \mathrm{N}) = \mathrm{O}(10^{-50})$$

ANY observation of cLFV would be evidence of New Physics.

cLFV at Mu2e.

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



Stopped muons can:

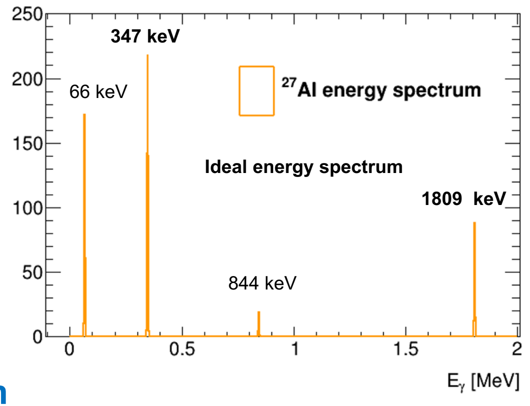
- Decay in orbit (DIO) emitting e^- and neutrinos.
- **Signal: Undergo CLFV and emit conversion e- (CE).**
- Be captured by nucleus (potentially emit X-Rays).

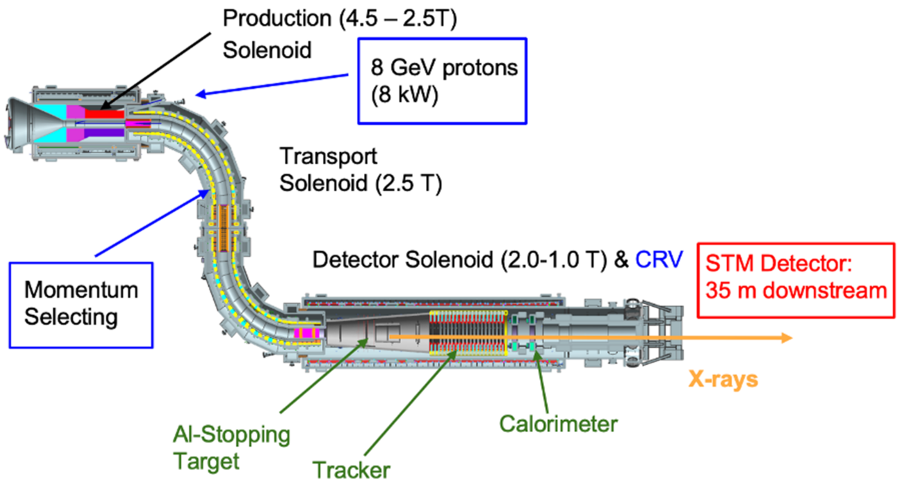
Mu2e - Overview.

- Captured muons normalize the cLFV measurement.
- Captured muons can emit characteristic Al X-rays.
- Captured muons are measured by reconstructing the ^{27}Al X-ray energy spectrum.
- Captured muons = 60.9% of Stopped muons

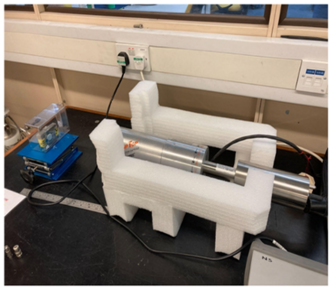
STM: Reconstructs ^{27}Al energy spectrum.

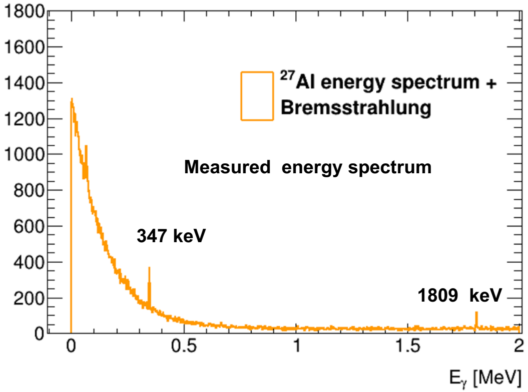
Corrected by STM acceptance





High Purity Germanium (HPGe) Detector.





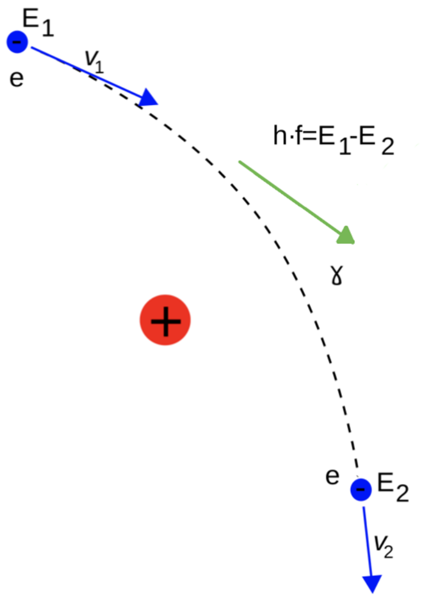
STM: origin of main backgrounds.

STM is required to measure the stopped muon rate with an accuracy of 10% every hour.

The ability to do this depends on:
- the rate and shape of the background : bremsstrahlung from electrons
- the HPGe detector resolution : approx. 1-2 keV.

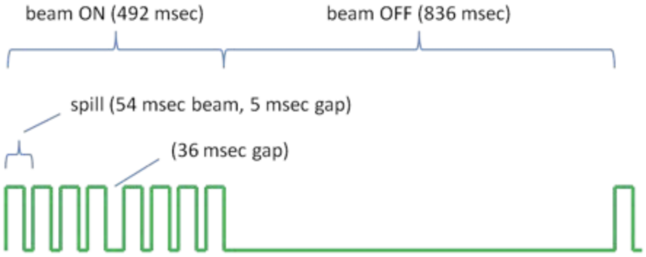
There are 3 sources of electrons that can bremsstrahlung in the stopping target and material beyond the stopping target before the STM
- beam electrons from the production target and muon decays before the stopping target
- DIO electrons from stopped muons
- electrons (and positrons) from X-rays converting in stopping target

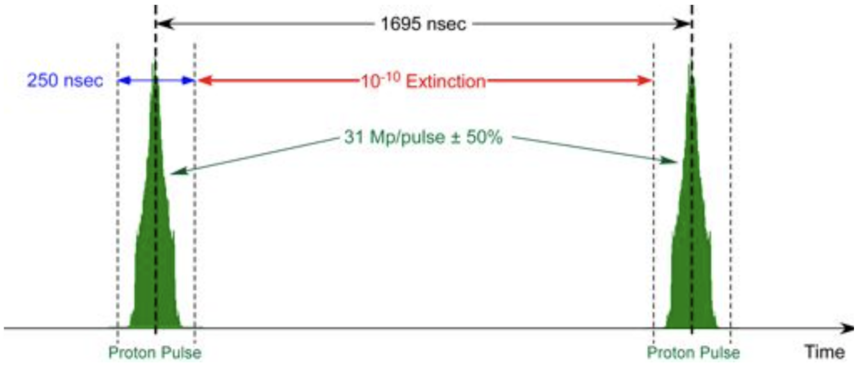
The STM however has a small acceptance (35m from stopping target) of ~ 10^{-7}



I have analysed the MDC2020 dataset to determine the **bremsstrahlung** spectrum, its rate and the relative contributions of the above 3 sources.

Mu2e Beam Structure.





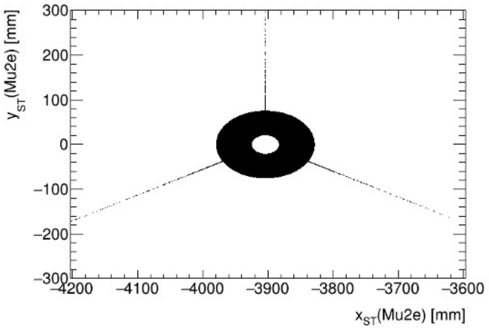
microbunch

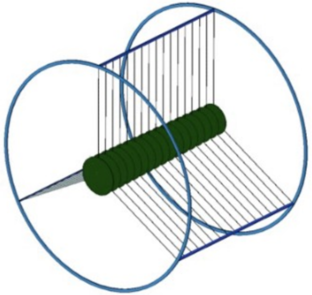
8 spills per main injector cycle (1.4 s)
32,000 microbunches separated by 1695 ns per spill
Each microbunch has ~ 3×10^7 protons over 250 ns

1.6×10^{-3} stopped muon per proton on target (POT)

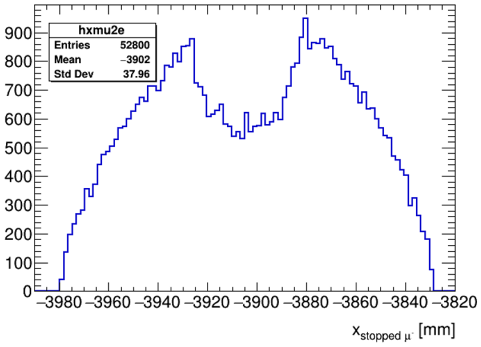
MDC2020 simulated dataset

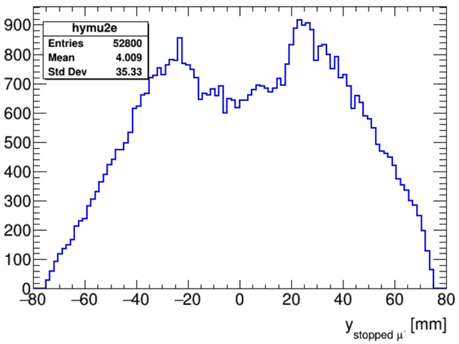
- ~ 1 microbunch: 3.3×10^7 POT
- ~ 52800 stopped muons in ST.
- ^{27}Al Stopping Target (ST) geometry.

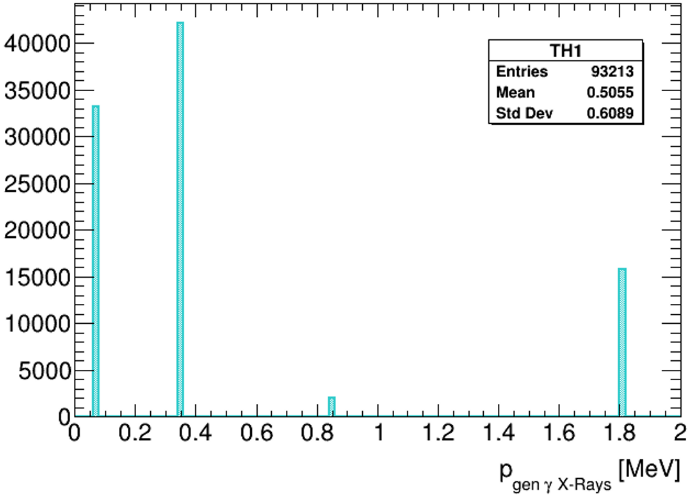




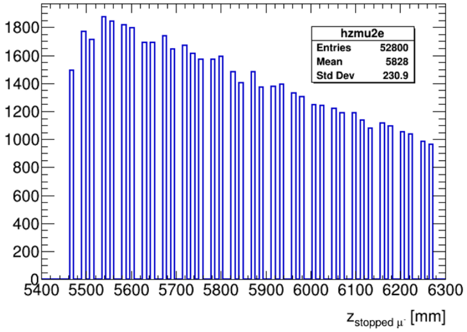
Coordinates of Stopped Muons: X-rays generated.

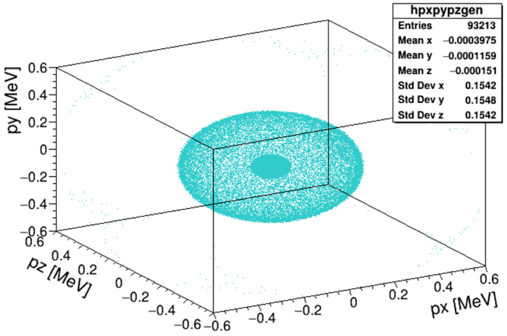




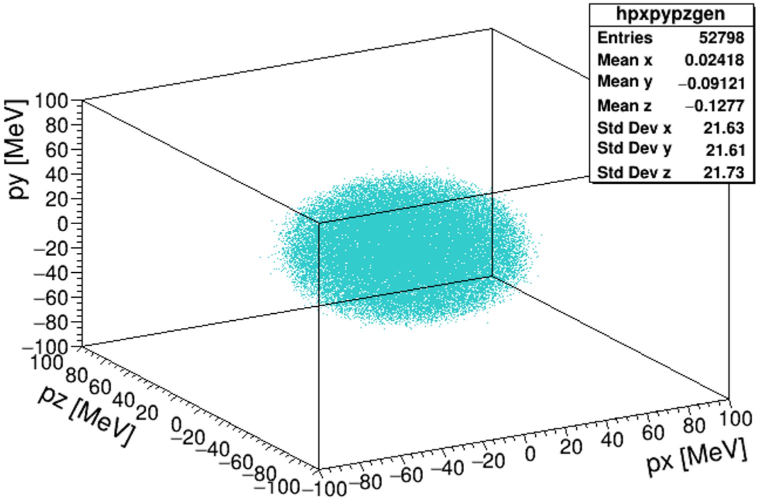


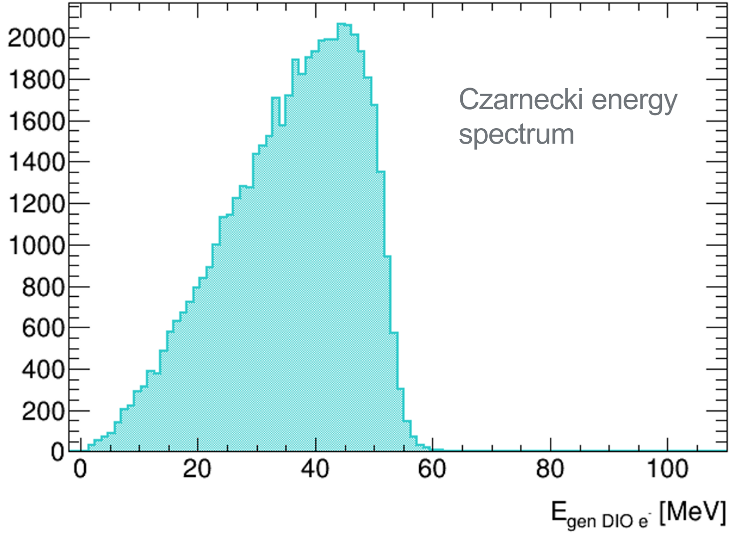
Generated ^{27}Al X-ray energy spectrum at ST.





DIO electrons generated.

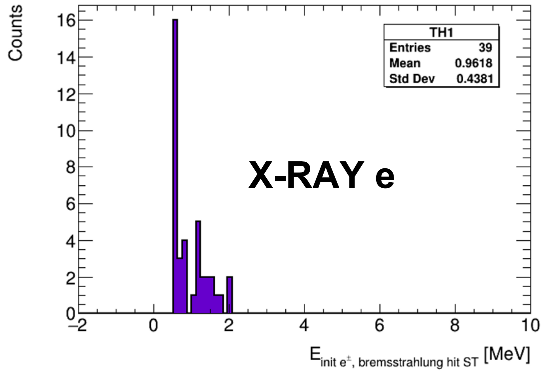


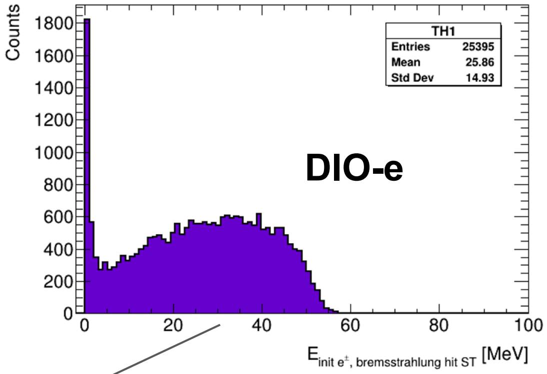


DIO electrons from 40% of stopped muons.

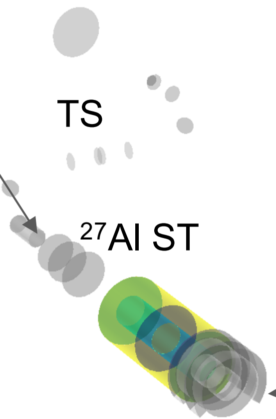
Determine bremsstrahlung spectrum from a virtual detector at the end of the tracker.

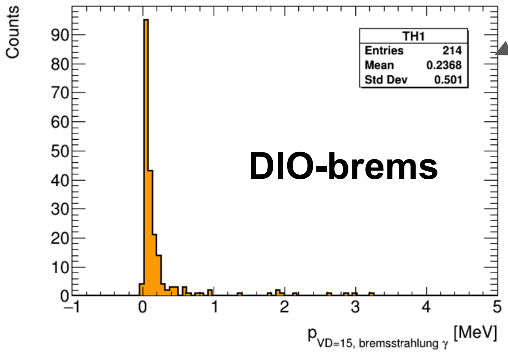
Electrons and Bremsstrahlung in Mu2e Virtual detectors





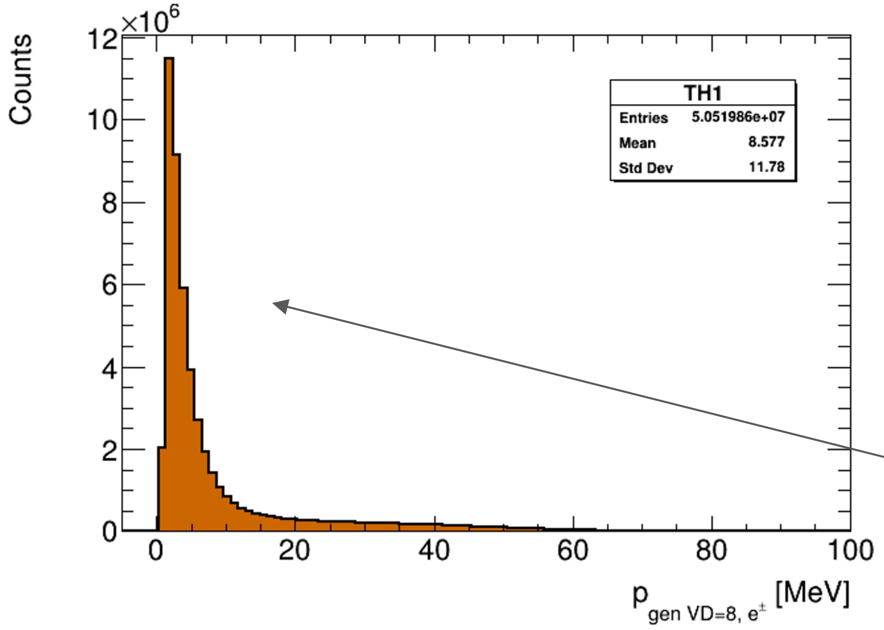
VD8 **(end DS2), z=3929.98 mm:**





VD15 **(end of tracker), z=11810.1 mm:**

MDC2020: Electron beam bremsstrahlung component.



GEANT4 simulates all interactions beginning with 8 GeV protons hitting target to when the particles exit the TS.

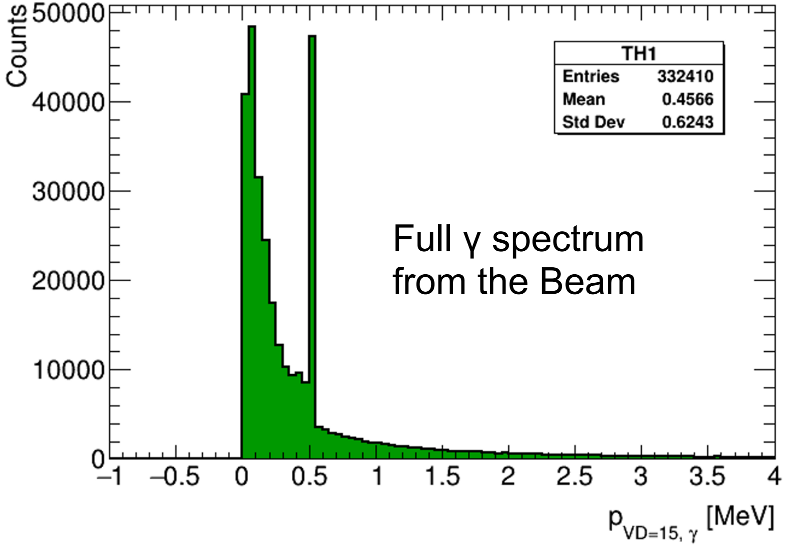
Electrons at the end of DS2 (VD8).

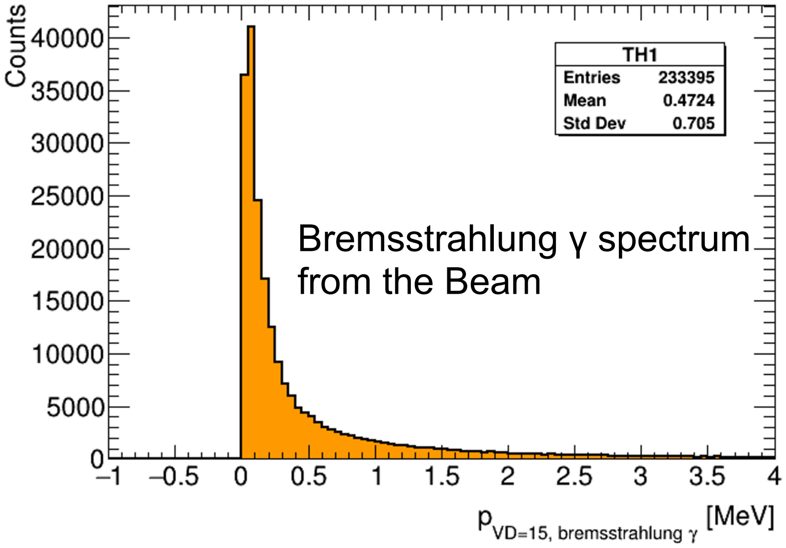
Main photon sources contributing at VD15.

Most photons at VD15 come from bremsstrahlung (70%) with an additional 511 keV annihilation peak (29%) and a small contribution from photoelectric process (1%).

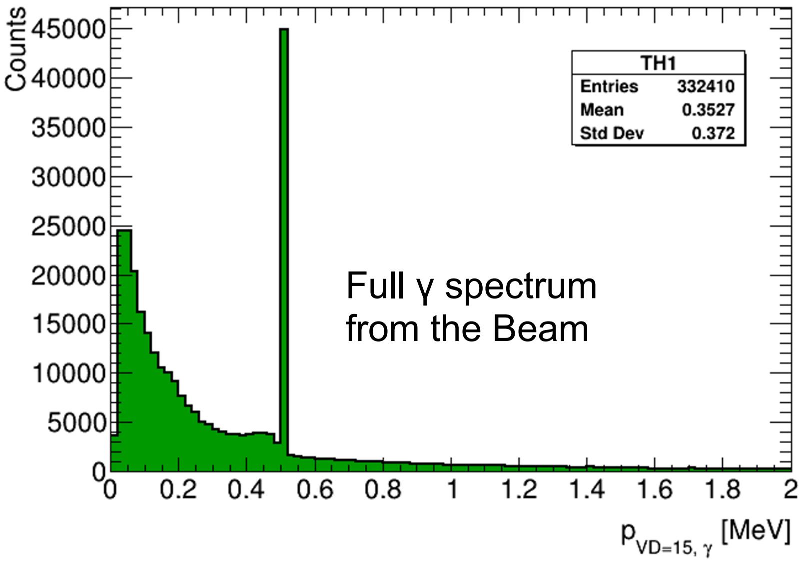
Bremsstrahlung photon contribution from different sources at VD15 per stopped muon:

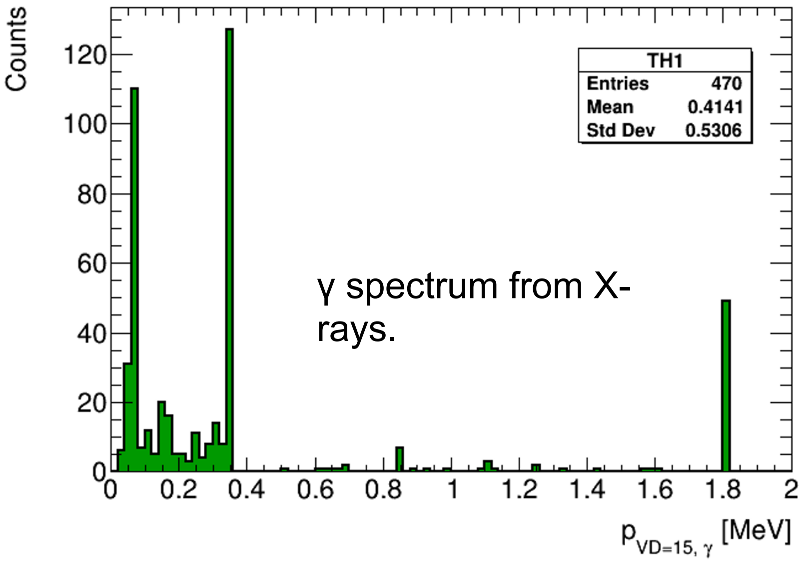
Beam	DIO	X-rays
4.42	1.62×10^{-3}	3.7×10^{-5}





VD15 : signal and background from $3.3x10^7$ POT.

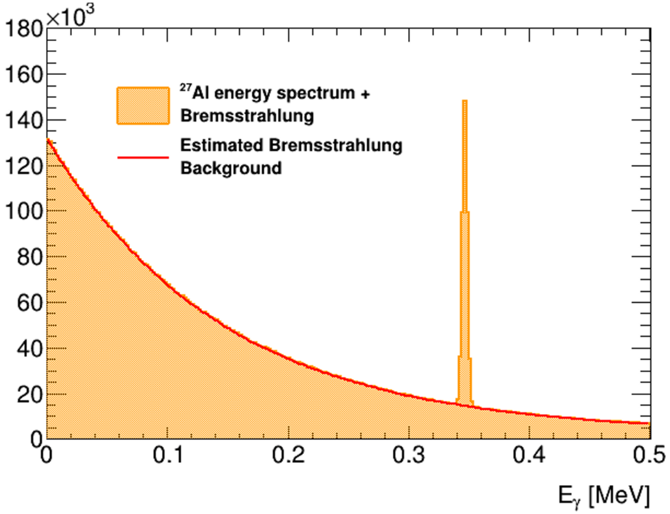


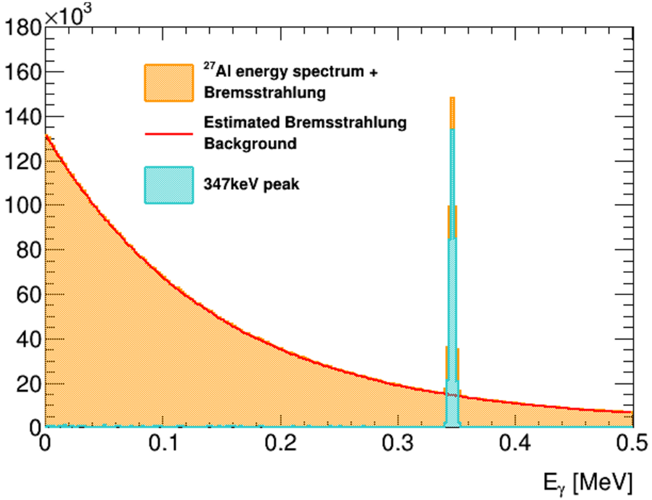


$3.3x10^7$ POT ~ 1 microbunch = 250 ns.

The above bremsstrahlung and X-ray distributions are what we use to estimate signal/background in the STM.

X-Ray/Background.

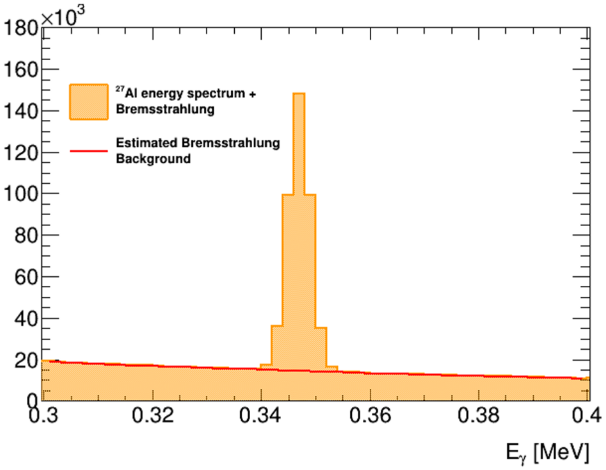




Bremsstrahung rate: 200 kHz
Bin width: 2 keV
Peak resolution: 2 keV

Simulation time 1 min ~ 43 main injector cycles (60x8x32000/1.4 microbunches) with a constant protons/s rate.
3.3×10^{14} protons simulated.

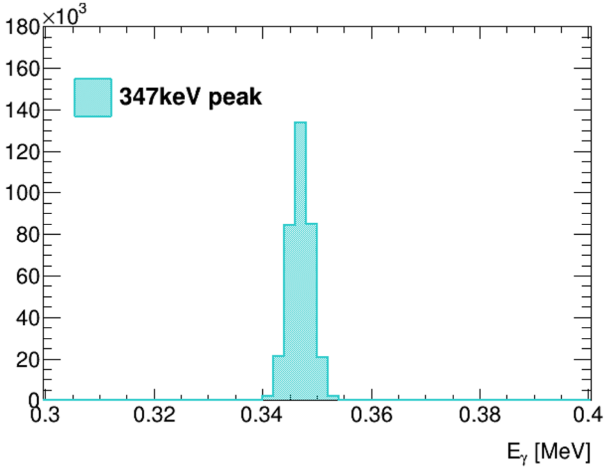
X-Ray/Background.



Signal+Background

1 min simulation
200 kHz bremsstrahlung background
Cut: mean±2.5σ

signal / background = 78%



Signal: Subtracted Background

8.8×10^9 stopped muons/s should generate 349216 347keV peaks in 1 min.

Next step:
Study how the signal to background uncertainty changes as a function of simulation time (POT), bremsstrahlung rate and STM resolution to get the muon rate with an accuracy of 10%.

Conclusions.

- Defined main background source in the STM.
- Studied ~1 microbunch of data with 3.3×10^7 POT - using Offline-art simulation.
  - Al X-ray and DIO contribution is negligible in the bremsstrahlung spectrum.
  - Beam electron component dominates in the bremsstrahlung energy spectrum.
- Model bremsstrahlung shape using beam electron data.
- Developed a simulation to study the X-ray to background ratio as a function of the bremsstrahlung rate, STM resolution and bin width to determine the number of stopped muons in the STM.
- Next: Define the time required assuming a constant protons/s rate to get 10% accuracy on the determination of stopped muons as a function of the bremsstrahlung rate and STM resolution.

Conferences.

- **I've attended the following Workshops:**

1. "Fermilab – C++ / Standard Template Library Course", held online (Fermilab, August 17th – September 14th, 2021).

2. Intense Training Program: Cosmic Ray Muography (Ghent, Belgium, November 2021).

3. "Advanced Graduate Lectures on practical Tools, Applications and Techniques in HEP", (Harwell Science and Innovation Campus, Oxfordshire, June 13 – 17th, 2022, https://indico.stfc.ac.uk/event/461/timetable/20220614).

- **I have given talks or presented posters at the following events:**

1. "High Energy Physics Forum", Talk title: "Search for Charged Lepton Flavour Violation at Mu2e" (Cosener's House, Abingdon, Oxford, November 23 – 24th, 2021).

2. Mu2e STM Collaboration meeting, Talk title: "MWD and gELBE data analysis" (17th June, 2022).

3. Mu2e STM Collaboration meeting, Talk title: "Zero Suppression Algorithm for STM" (25th August, 2022).

4. Mu2e STM Collaboration meeting, Talk title: "New HPGe Pulse Simulation" (27th October, 2022).

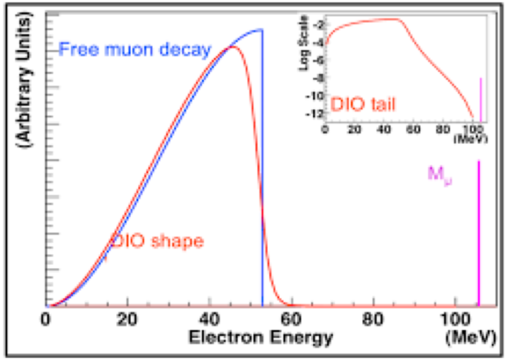
5. "STFC High Energy Physics Summer School", Lectures covering Quantum Field Theory, Quantum Electrodynamics and Quantum Chromodynamics, the Standard Model and non-collider phenomenological topics (neutrino, dark matter, cosmology), Poster title: "Mu2e experiment: STM detector data analysis" (Oxford Lady Margaret Hall, September 4 – 16th, 2022).

6. New Physics Signals (NePSi) Workshop, Talk Title: "Development of the data acquisition system for the Mu2e STM detector" (University of Pisa, Italy, February 15 – 17th, 2023, https://agenda.infn.it/event/32931/).

7. IOP Joint APP and HEPP Annual Conference, presented a poster (King's College London, London, UK, 3 – 5th April 2023, https://iop.eventsair.com/hepp2023).

Backup…

Backgrounds and momentum selection.



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

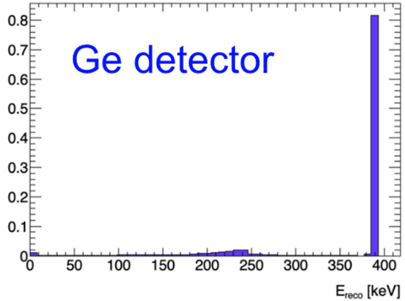
- "S shape": removes neutral particles to enter the detector solenoid (unaffected by B and do not travel the S-shape)
- Particles with large momentum hit the wall of the solenoid and are not transmitted:

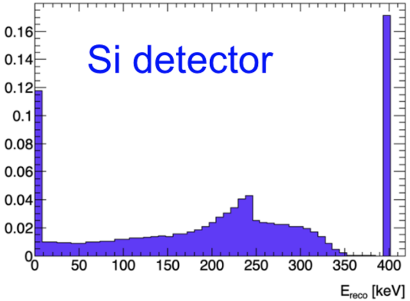
  $r = p_{\perp}/(0.3B)$

- 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

Stopping Target Monitor - STM.

- X-rays are detected 35 m away from the target at the STM detector (reduces background).
- Need a detector with a good resolution:
- Better resolution for Ge detector (higher photon interaction cross section).



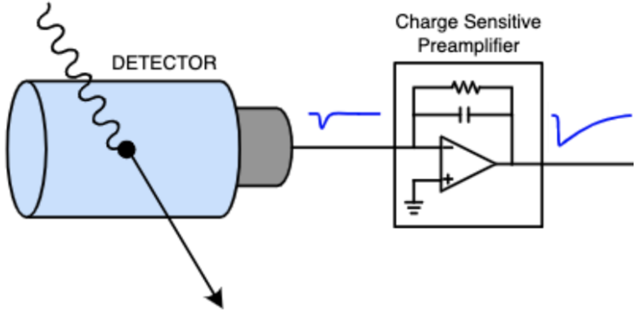


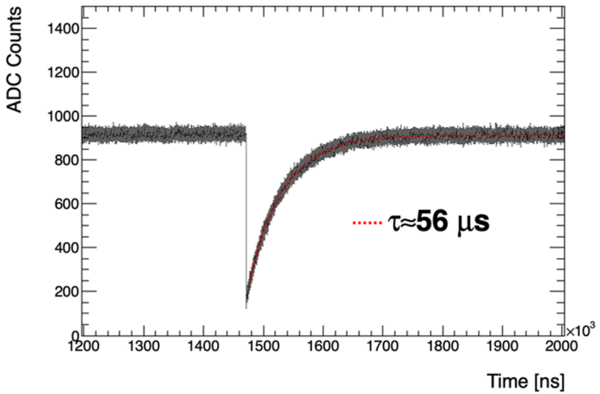
Pure **GEANT4** Simulation

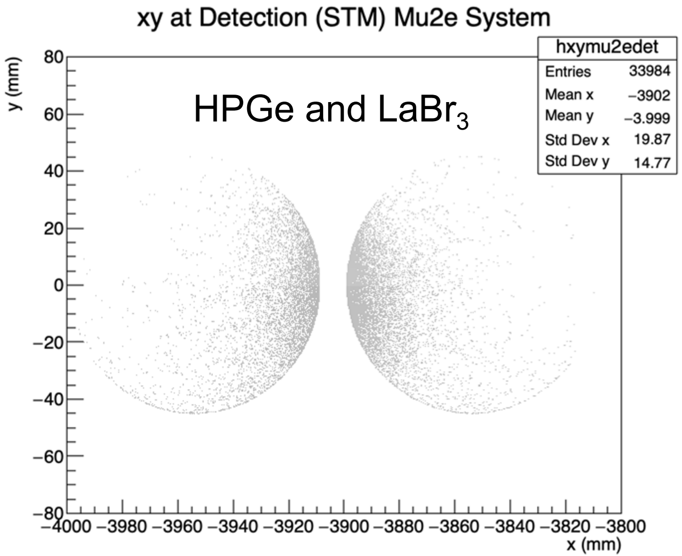
- Captured muons = 60.9% of Stopped muons.
- Stop rate can be determined by measuring the X-rays:
  - 80% of stops emit 347 keV X-rays 2p-1s (1s orbit lifetime= 864 ns).
  - 31% of stops emit 1809 keV gammas.
  - 5.7% of stops emit 844 keV gammas.
- Need an estimation of STM background.

STM Geometry and pulse analysis.

X-rays





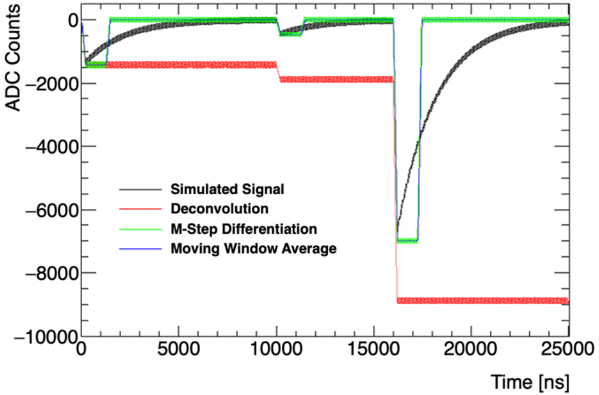


- X-rays reach the detector, the electrons ionise the material creating e-h pairs that drift in the detector creating the pulses that are then shaped.
- The signal is sent to the readout board and an ADC samples these values in 16-bit words.
- Energy of pulses is related to pulse heights.
- Calibration: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

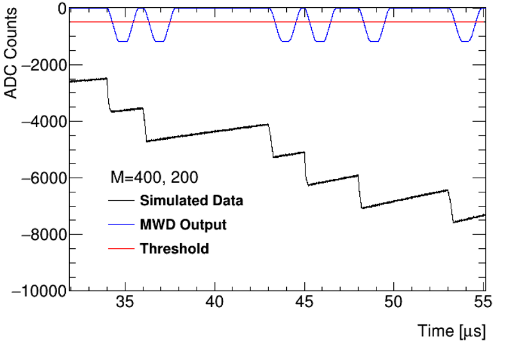
Moving Window Deconvolution (MWD) algorithm.

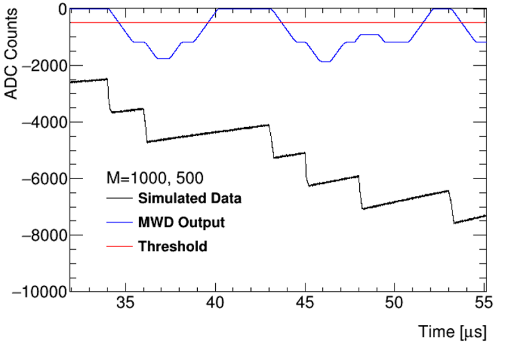
Finding pulse heights : MWD algorithm .

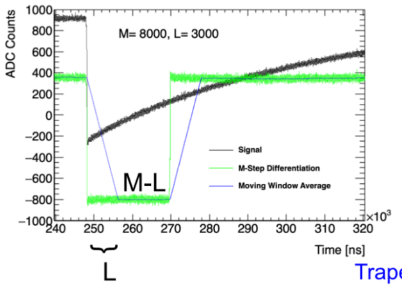
- Signal.
- Deconvolution.
- Differentiation (M window).
- Averaging (L values).

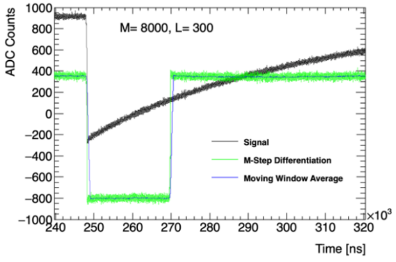


Efficiency strongly affected by MWD parameters at high rates (~200 kHz)

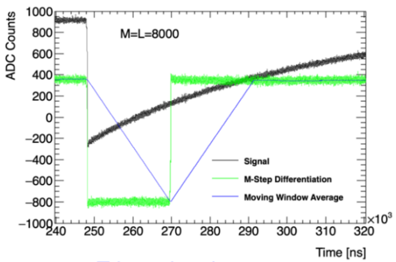








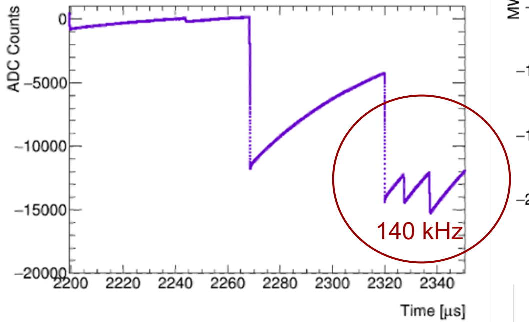
Trapezoidal shape

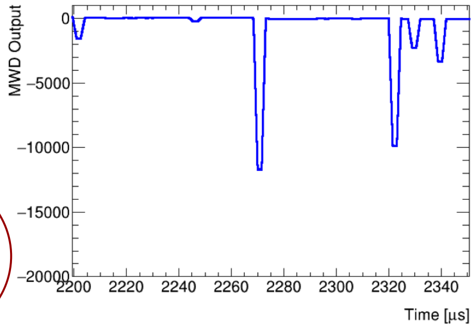


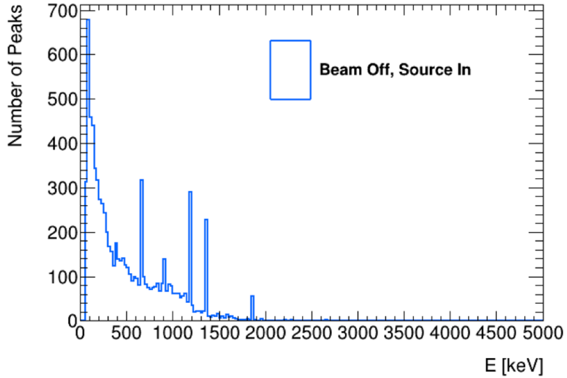
Triangular shape

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

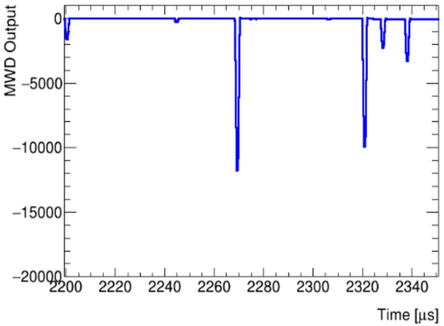
MWD parameters:

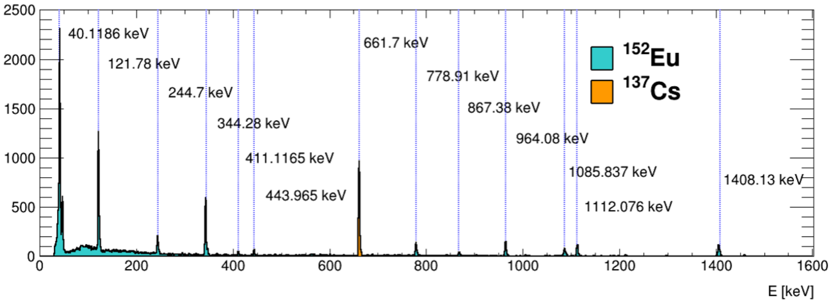






Low M values can resolve overlapping pulses at high pulse rates.



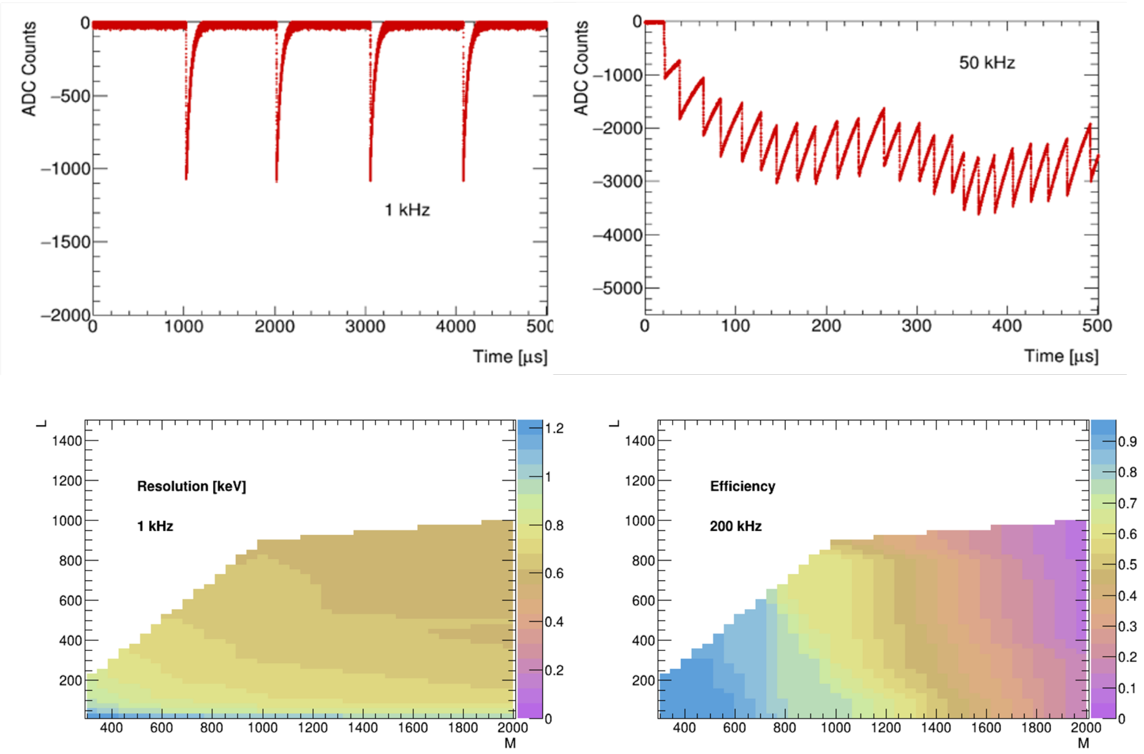


MWD + STM simulation developed: Resolution and efficiency.

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.

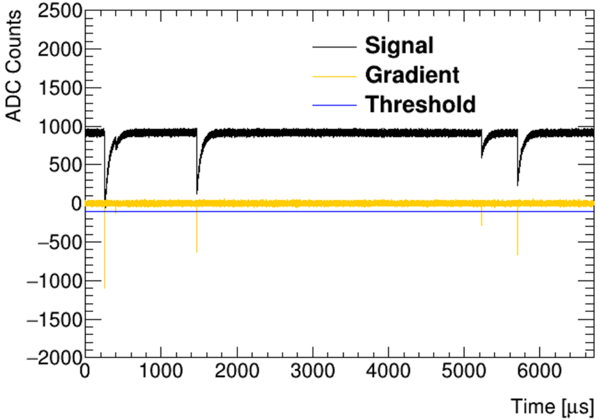


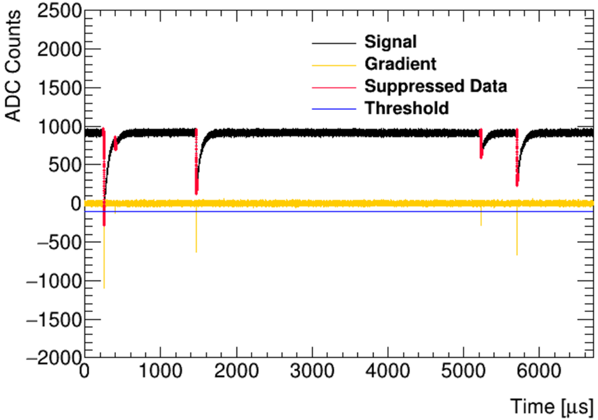
STM data acquisition system: Zero Suppression (ZS) algorithm.

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

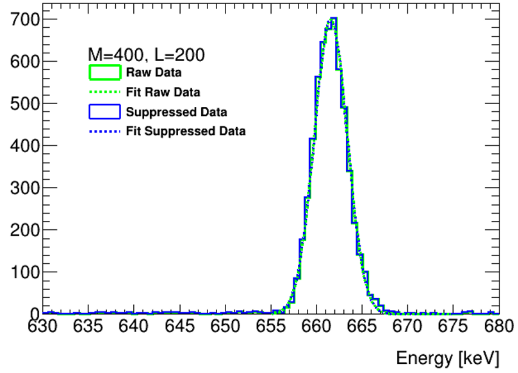
```
gradient[i]=ADC[i+window]-ADC[i];
```

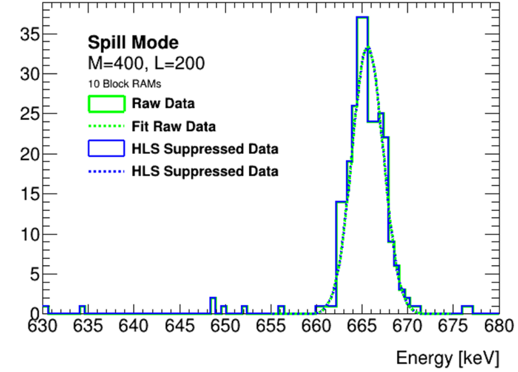
- Window = 100 ADC (~ 0.3 μs) : so in principle can distinguish peaks to rates well above the rates required (5 μs = 200 kHz)
- Gradient threshold = –100 ADC Counts.
- The trigger is then established in the first point where the gradient is below the threshold chosen and store t_{before} [μs] of data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

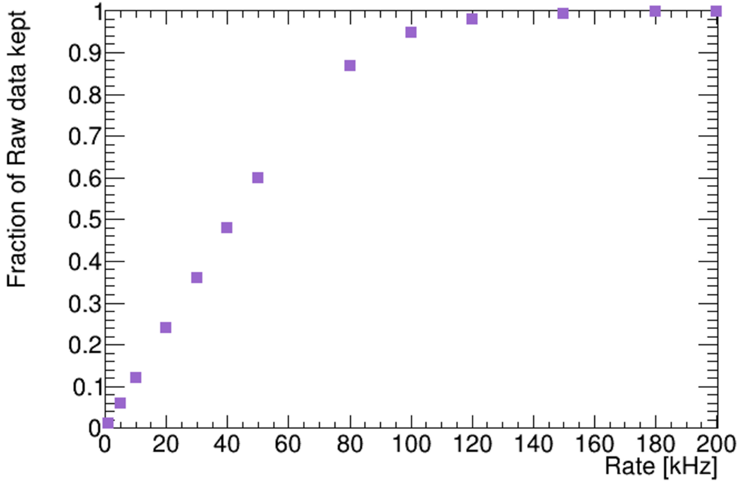




Implemented ZS in HLS (High-level synthesis).







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.