Acceptance and Signal/Background Rates from MDC2020 Dataset

May - 2024

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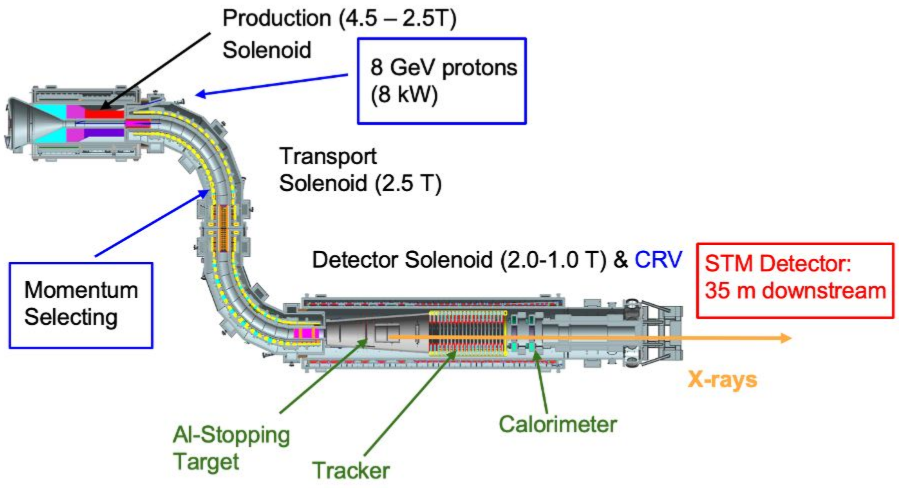
Mu2e - Overview

- 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

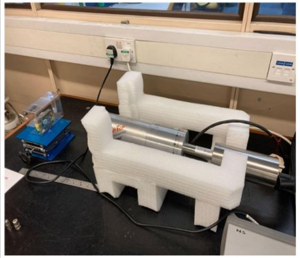
- **SINDRUM-II limit: 7×10^{-13} (90% C.L)**.
- Mu2e requires a high intensity, pulsed proton beam.
- Total of 3.6×10^{20} protons on target (POT) over 3 years of data taking.

STM: Reconstructs ^{27}Al energy spectrum.

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

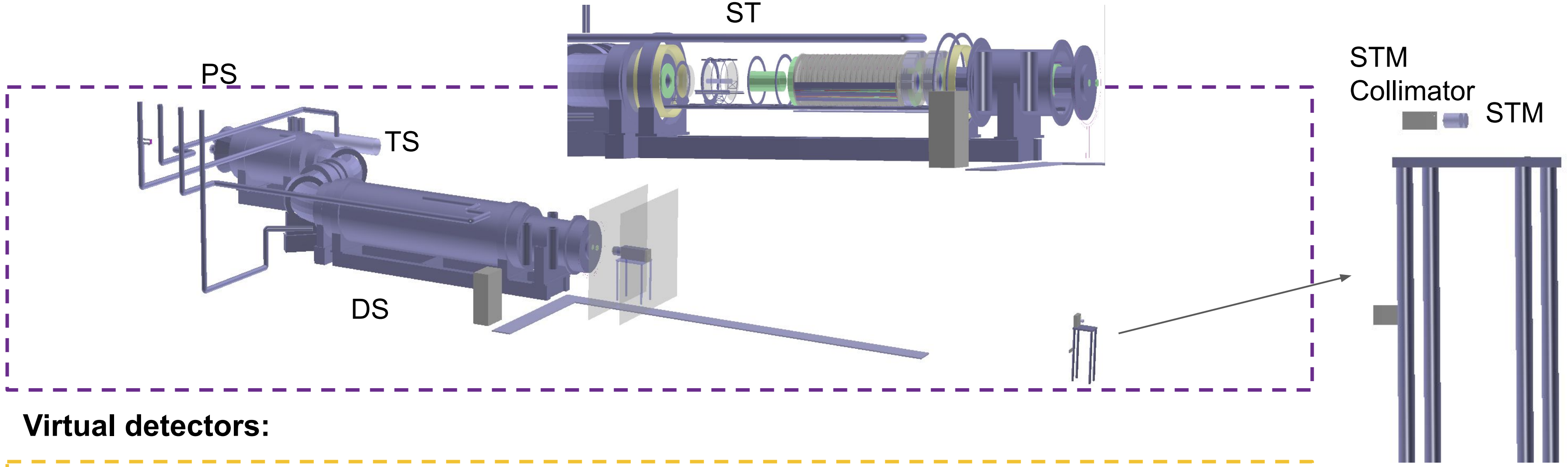


High Purity Germanium (HPGe) Detector.

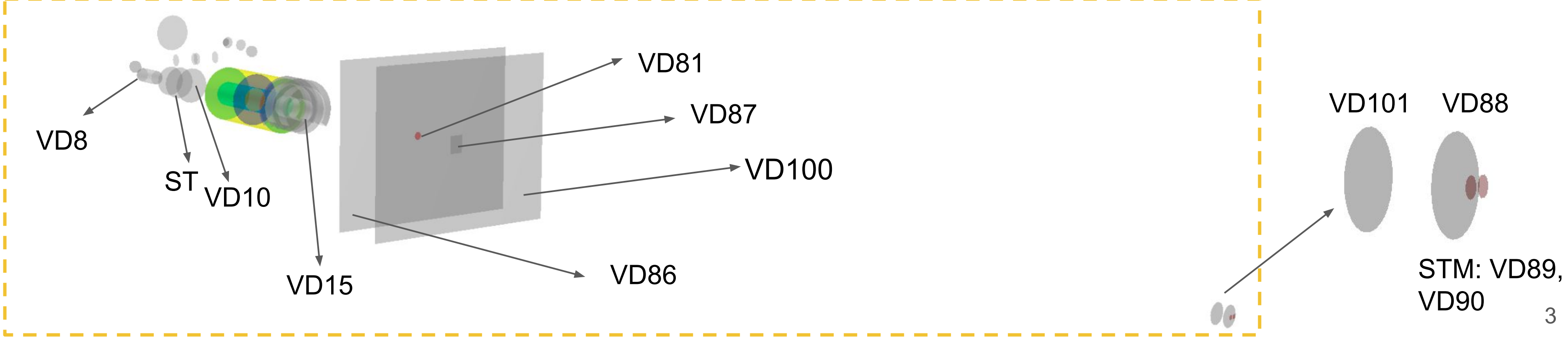


- Study ST-STM acceptance for X-rays and photons from the flash.

Mu2e Geometry



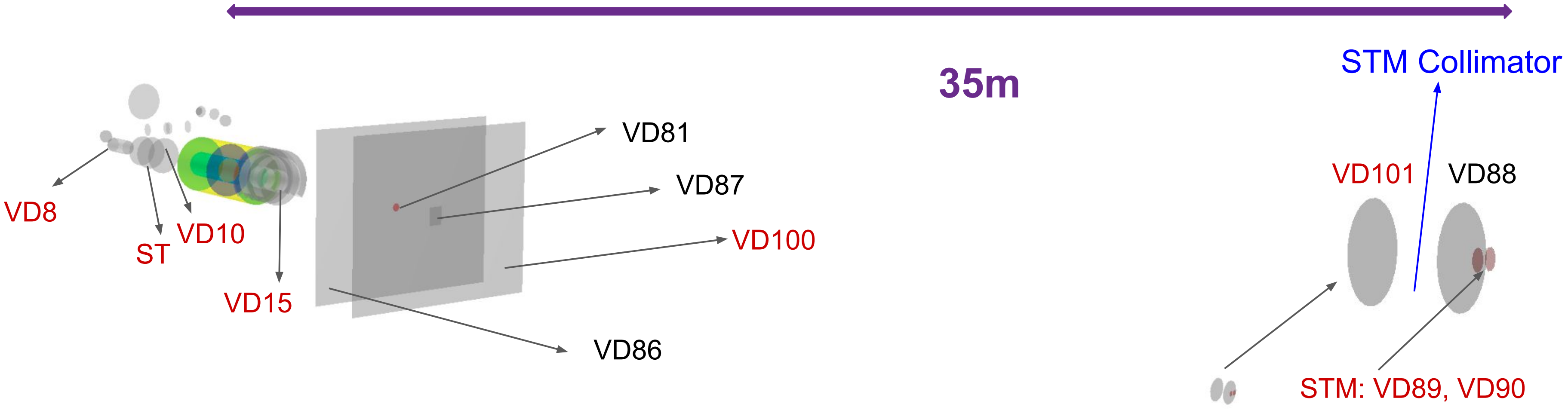
Virtual detectors:



MDC2020 Dataset

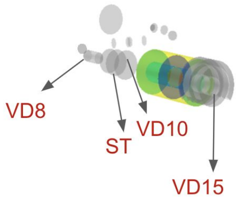
See DocDB-44084 : this simulates 2×10^8 POT but simulation stops at end of TS (VD8) before ST.

Average Run-1 intensity is ~ 2×10^7 protons per microbunch so MDC2020 simulates ~ 10 microbunches i.e 17 μs of data.

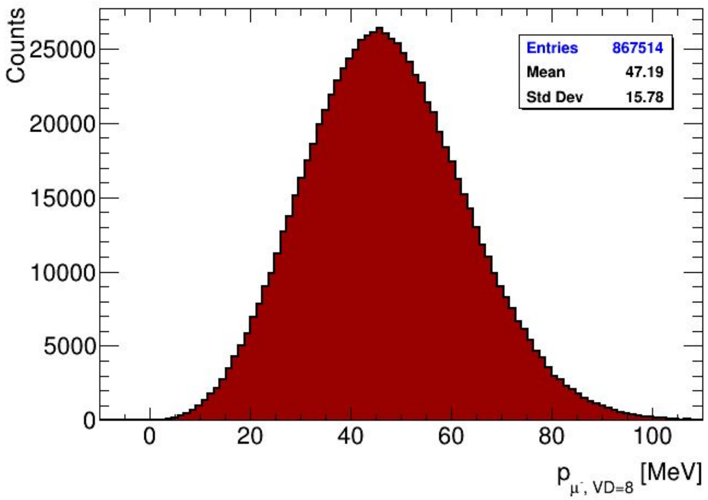


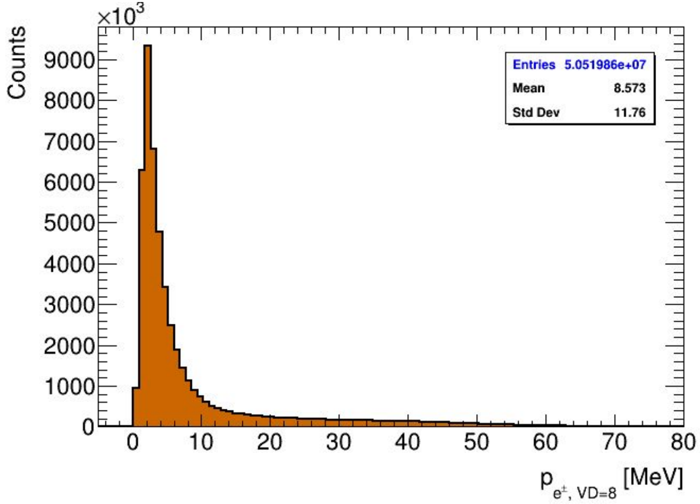
Extrapolating this sample from VD8 with Art-geometry yields zero hits in the STM. But we can re-sample it to estimate acceptances and hence rates in STM using distributions in the virtual detectors.

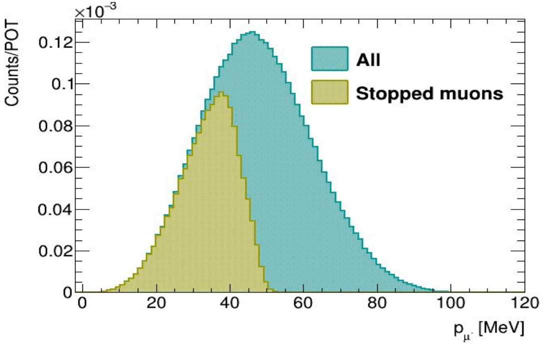
Input particles



VD8 : end of TS / beginning of DS : 50M e$^-$

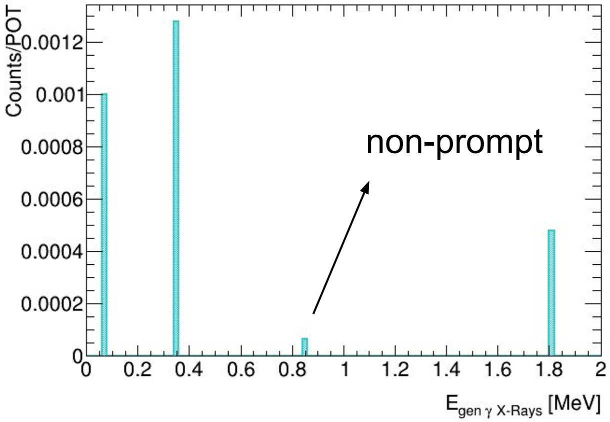


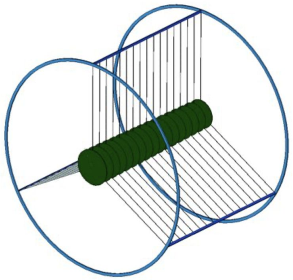


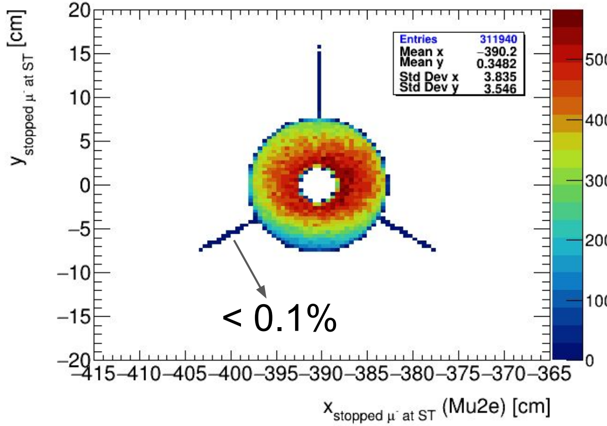


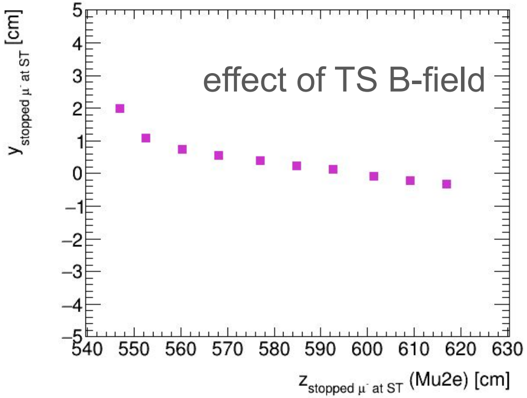
40% stopped
0.0016 per POT

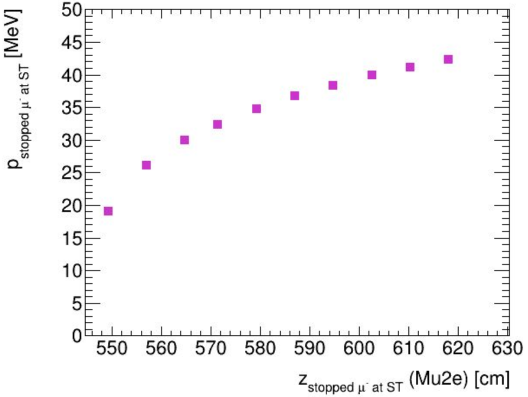
Stopped Muon X-rays









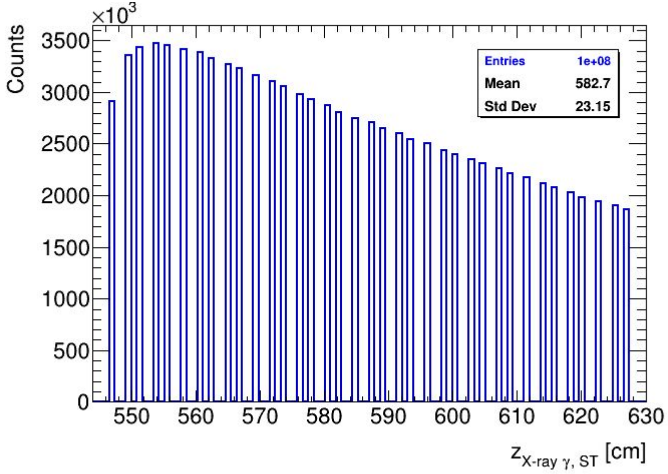


Acceptance of 347 keV muon X rays

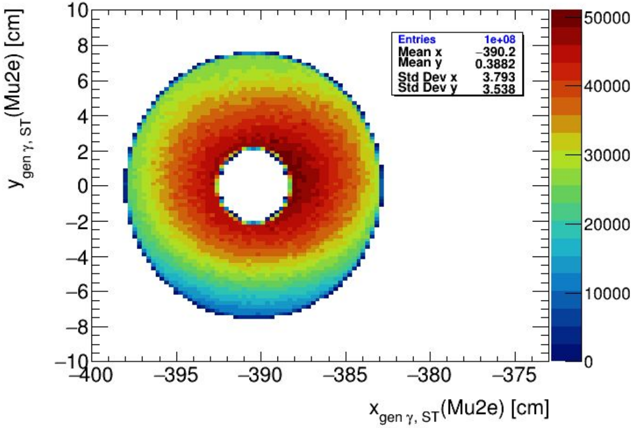
1. Purely geometric acceptance : solid angle + collimator
2. Attenuation in poly absorbers

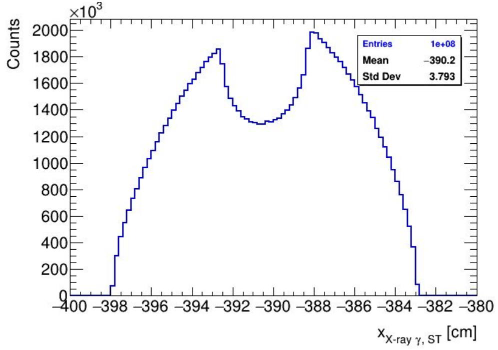
End-end ART simulation : $(8.03 \pm 0.05) \times 10^{-10}$

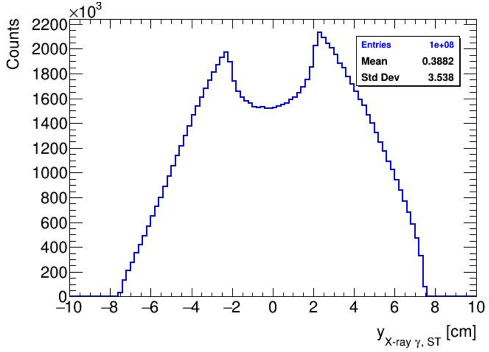
Generated 10^9 347 keV X-Ray in a limited solid angle range in ART.



Generated positions of 347 keV X rays in ST (Art)

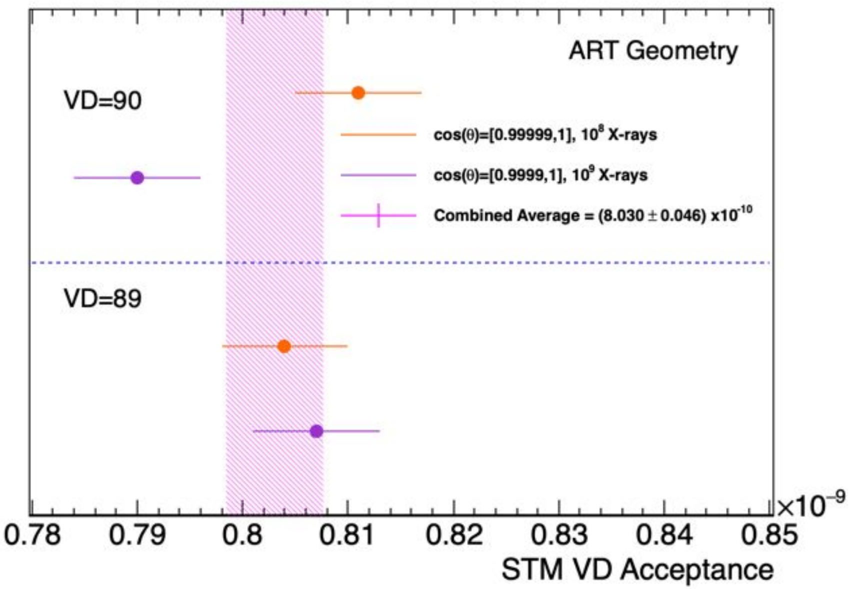




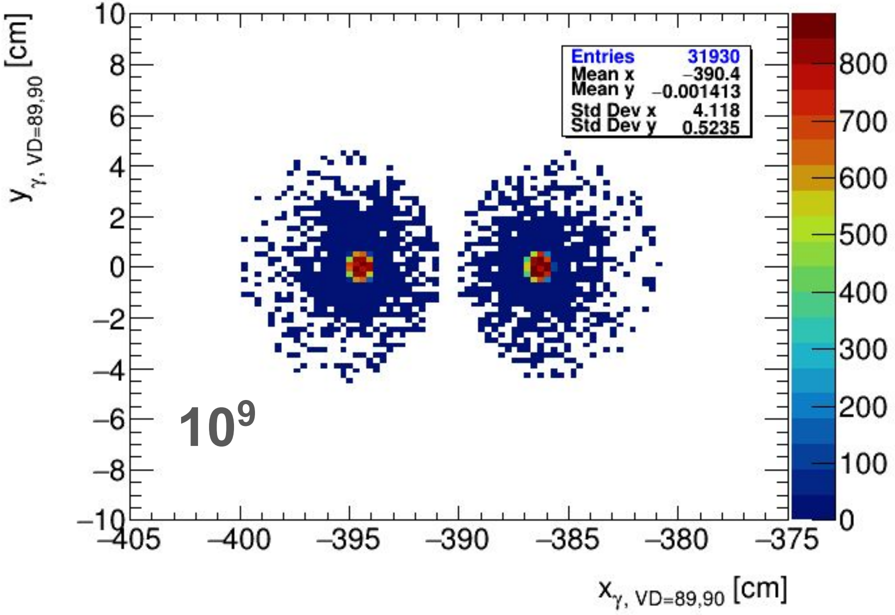


Not generated the < 0.1% from the ST support structure which in any case have a much lower acceptance.

Acceptance of 347 keV muon X rays



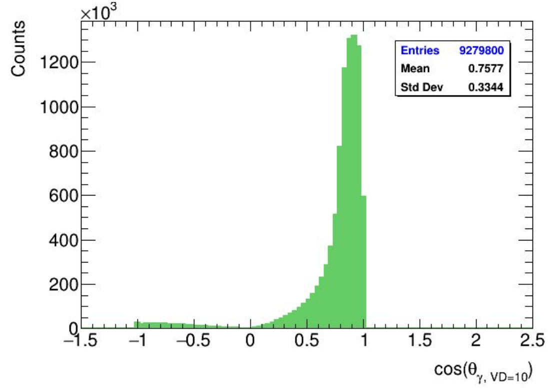
(8.03 ± 0.05) x10^{-10}

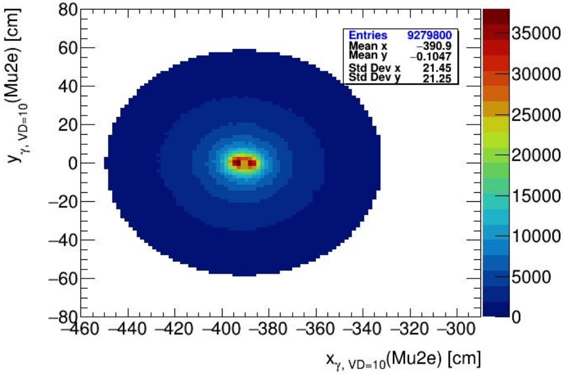


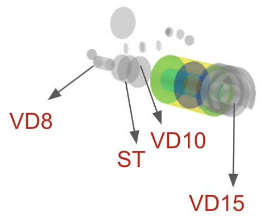
VDs at the STM front face

Flash Photon Acceptance

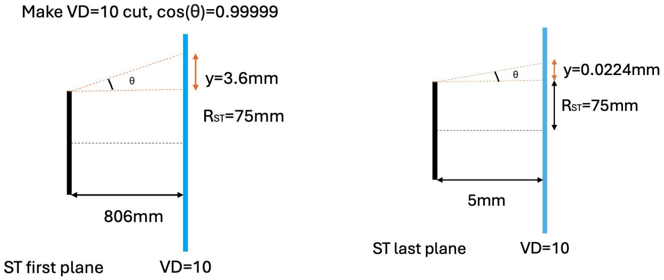
Flash photon acceptance will be higher since mostly forward compared to 347 keV X-rays

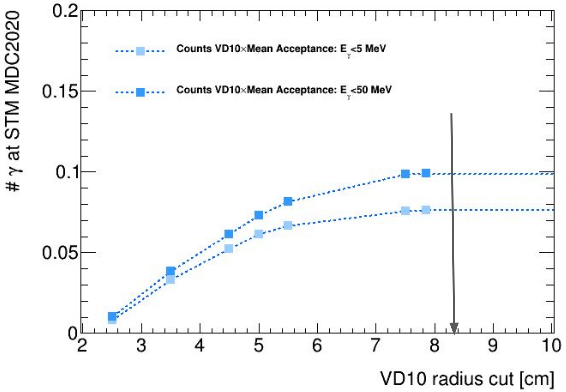




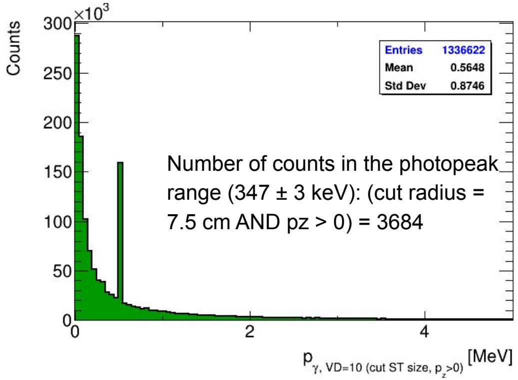


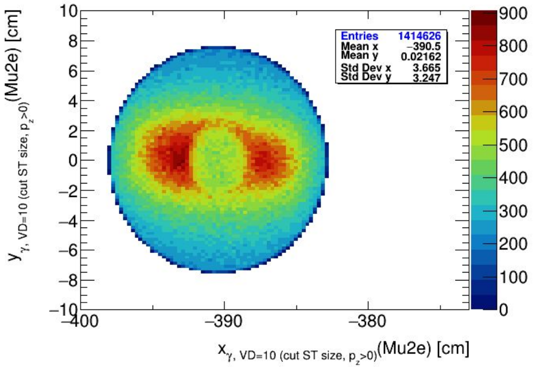
Use the VD10 distributions for |r| < 75 mm

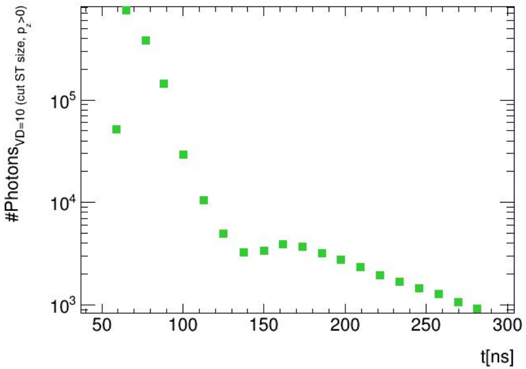




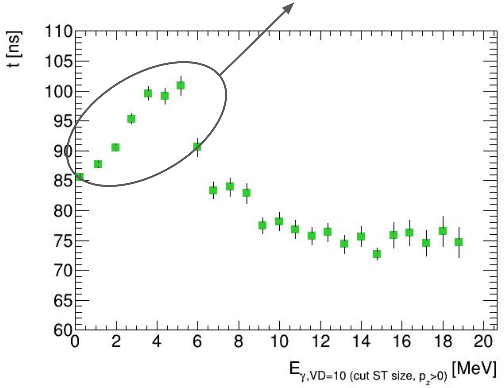
Forward going Flash Photons at VD10







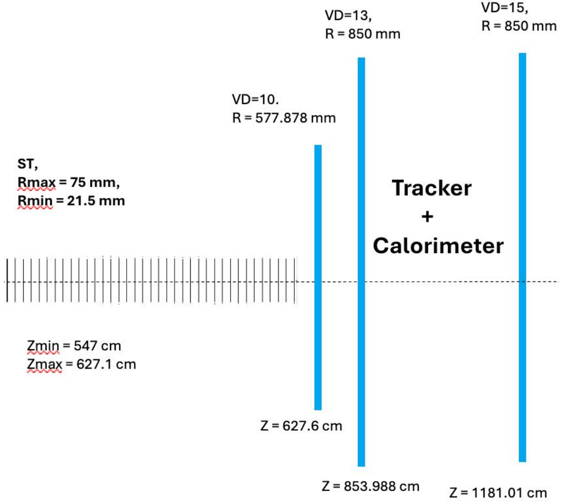
0-5 MeV t ~ 800 ns nuclear captures



Only 1.86 x 10^{-4} of the MDC2020 flash photons are in the solid angle range that can reach the STM. So the MDC2020 sample produces zero in the STM.

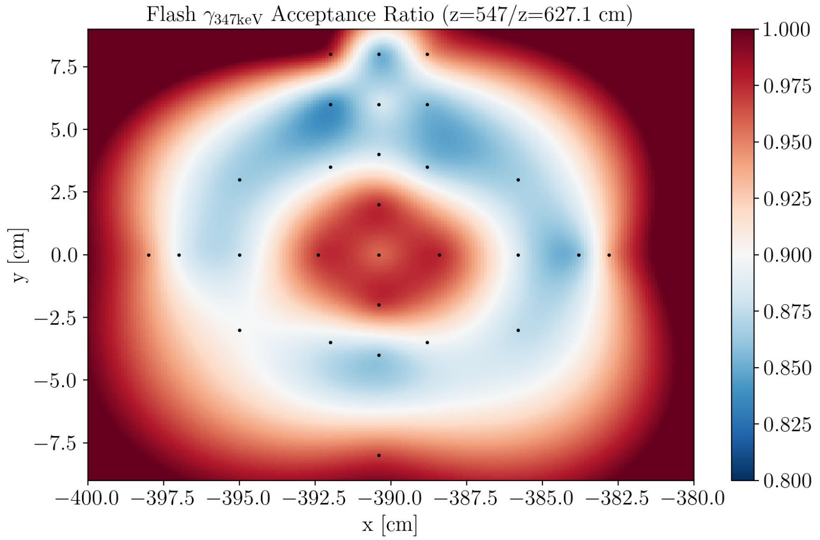
Thus we generate 10^7 at VD10 but only in a restricted solid-angle ($d\Omega = 10^{-5}$) to have equivalent of 7.6 x10^{12} POT (~ 15 spills) vs 2x10^8 (4 x 10^{-4} spill)

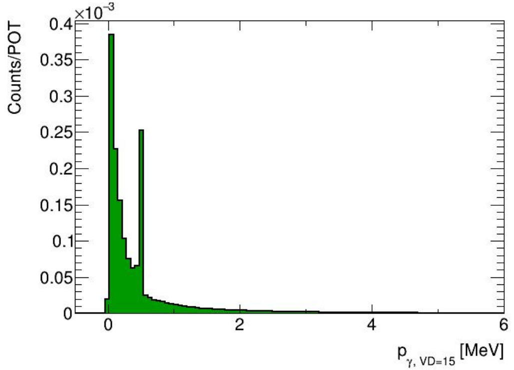
Acceptance of stopped muon X rays



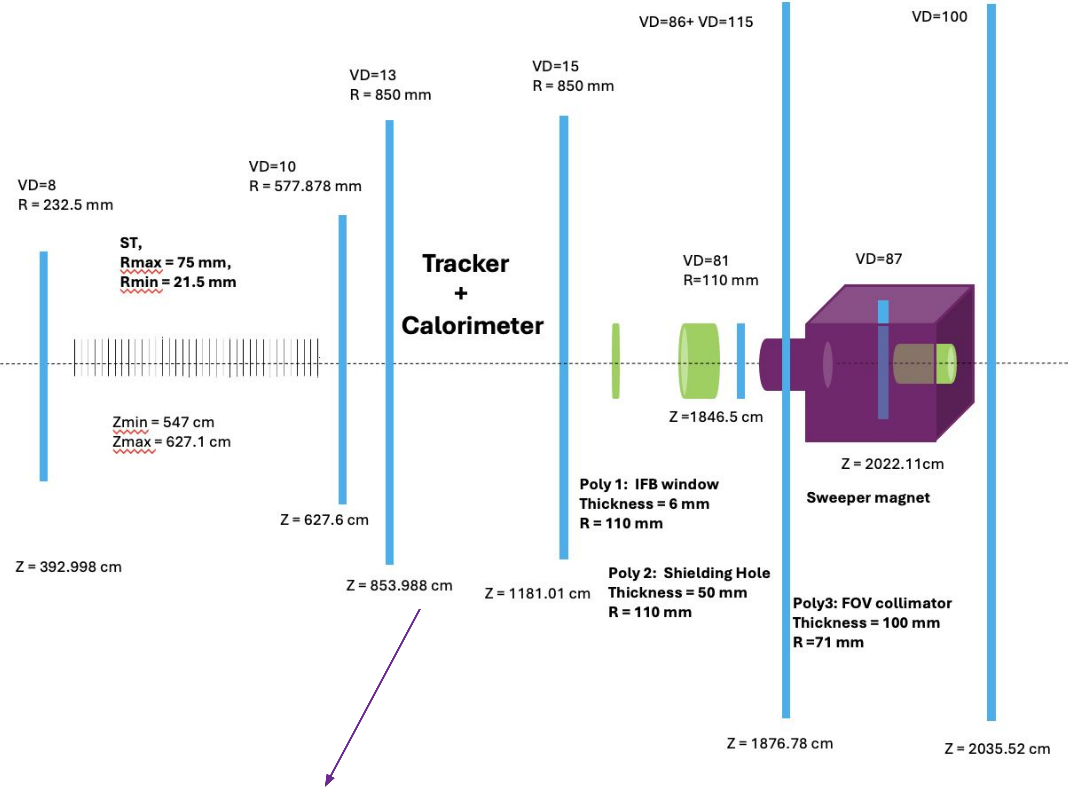
We generate at VD10 : acceptance of last ST plane.

Acceptance from 1st ST plane is lower by ~ 10% due to attenuation in ST-foils (and is energy dependent).



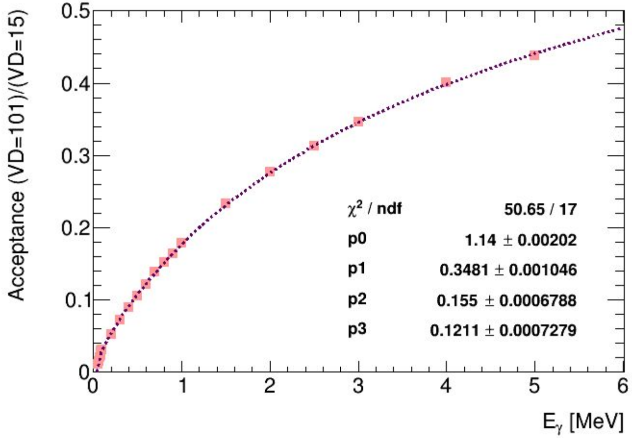


VD10-VD101 acceptance



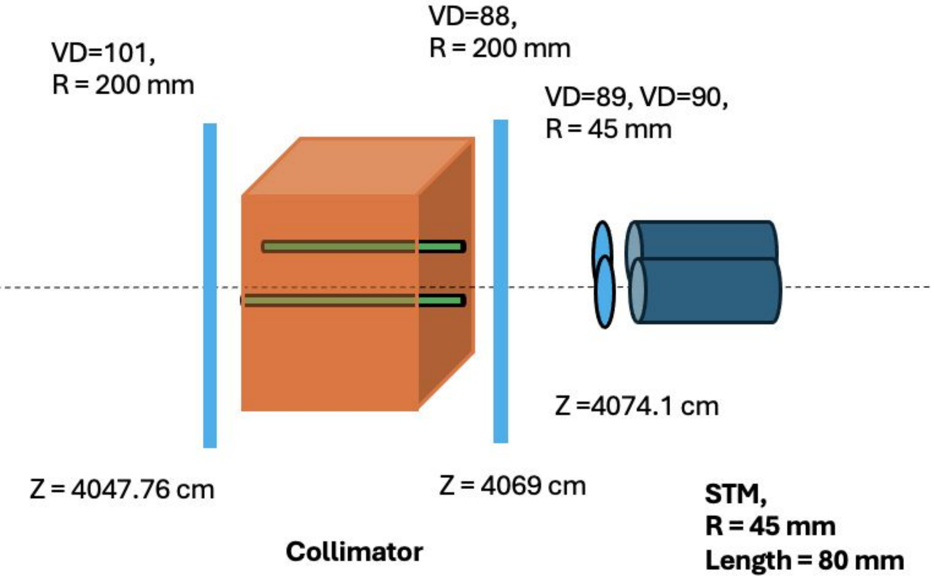
VD10-VD15 acceptance ~ 1

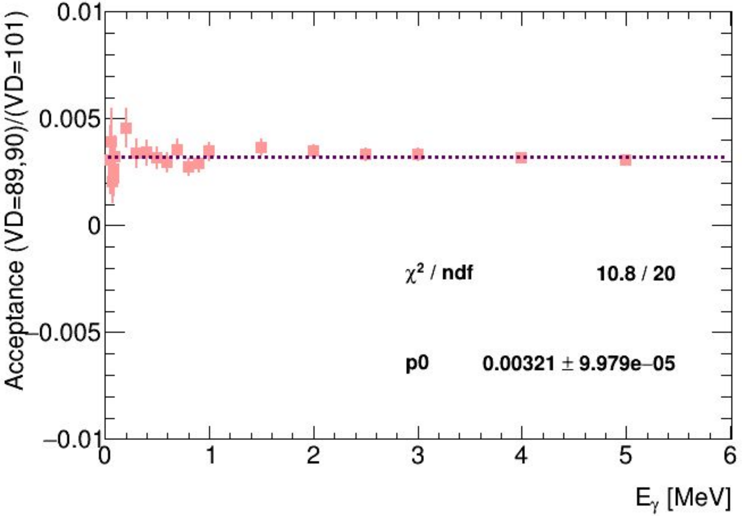
VD10-VD101 acceptance
is defined by energy-dependent attenuation in poly.



$$\text{Acceptance}(E) = p0 + \frac{1}{p1 * E} - \sqrt{\frac{1}{p2 * E} + \frac{1}{p3 * E^2}}$$

Effect of collimator



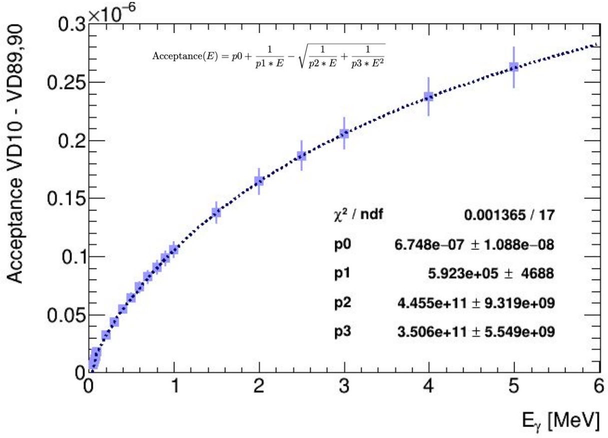


Purely geometry : energy independent

Acceptance of flash photons

In restricted solid angle : which is $(1.86 \pm 0.11) \times 10^{-4}$ of total sample

VD10-VD89/90 Acceptance = Acc(VD10-15) x Acc(VD15-101) x Acc (VD101-89/90)
= 0.9999 x Acc(E) x 0.0032



= 0.082 @ 347 keV

At 347: Acceptance = $1.86 \times 10^{-4} \times 0.999 \times 0.082 \times 0.0032 = (4.9 \pm 0.3) \times 10^{-8}$

cf 347 X-ray acceptance is = $(8.03 \pm 0.05) \times 10^{-10}$

347 keV X-rays at STM / POT = (1 POT) x (0.0016 stopped muons/POT) x (0.8 X-rays(347)/stopped muon) x (8.03×10^{-10} X-ray at STM/X-ray generated at ST) = $(10.2 \pm 0.1) \times 10^{-13}$ → for 2×10^7 protons/μbunch → 12 Hz (on-spill)

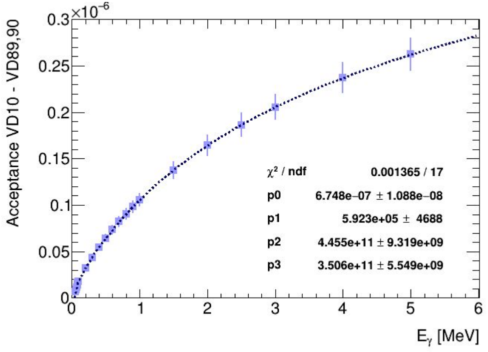
347 ± 3 keV Flash photons at STM / POT = (1 POT) x ($3684/2 \times 10^8$ counts at VD10/POT) x (4.9×10^{-8} acceptance) = $(9.0 \pm 0.6) \times 10^{-13}$

Ratio of 347 X-ray to 347 flash (per POT) = 1.13 ± 0.08

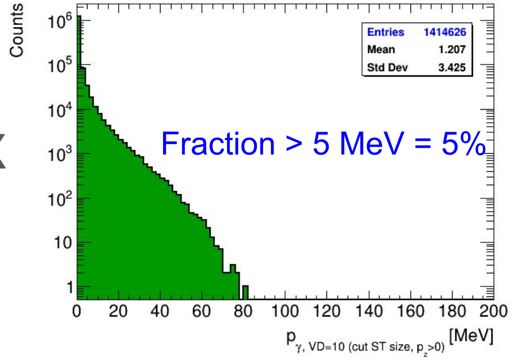
Integrated Flash Rate

At 347 keV - on-spill rate: 12 Hz for X-rays & 10 Hz for Flash

Acceptance for 1.8 MeV X-ray higher but production rate lower → 8 Hz.



X



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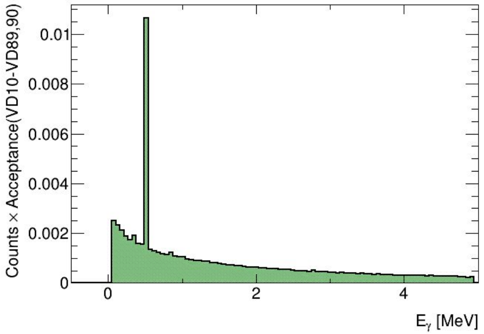
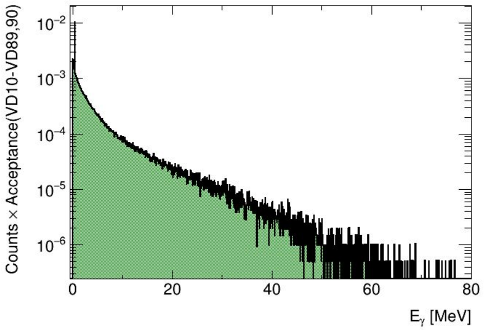




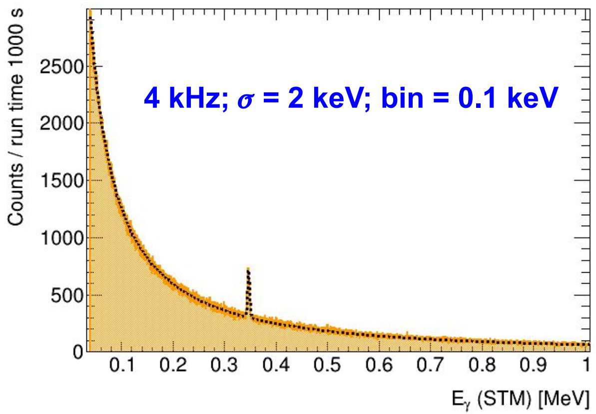
Average acceptance (E < 80 MeV) = (6.9 ± 0.1) $\times 10^{-8}$

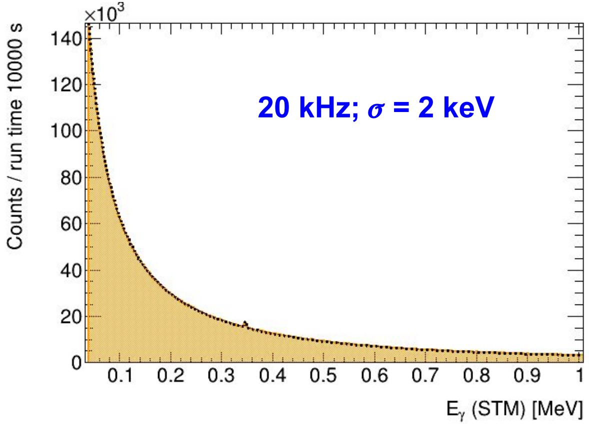
Integrated rate = (5.8 ± 0.1) kHz

Rate below 5 MeV ~ 4 kHz

Signal / Background

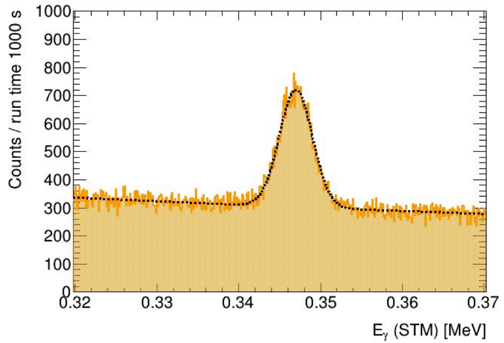
Using S/B = 1.13





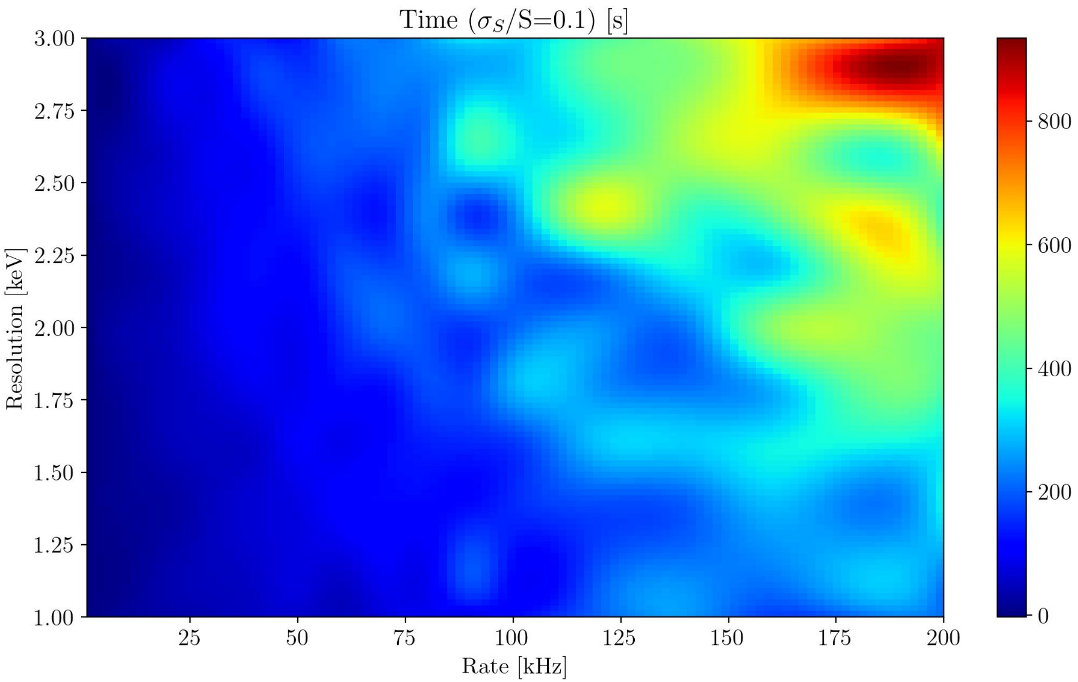
Binned likelihood fits to flash background shape (- 511 keV) to determine σ (S=347)/S and thus the running (clock) time for this to be < 10% at different rates.

At 4 kHz : time to get to 10% for σ(S=347)/S is 12 sec



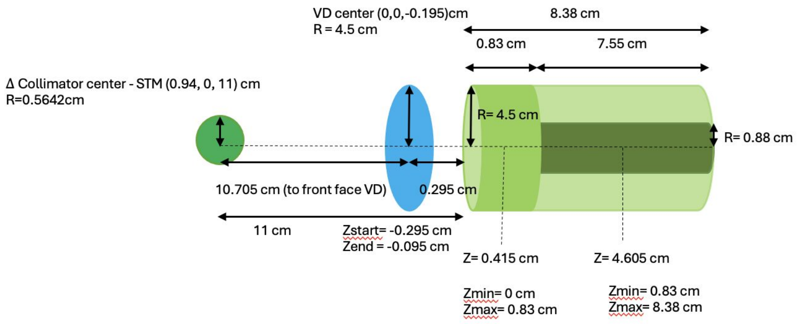
Signal / Background

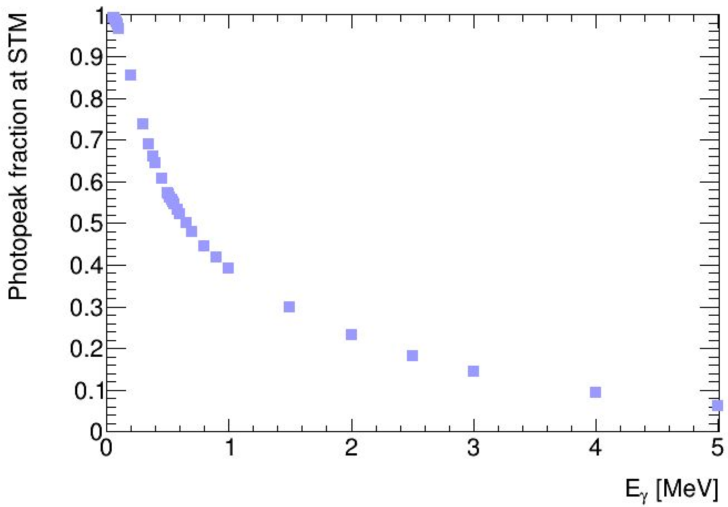
Time to achieve 10% precision clearly also depends on resolution (as well as rate)

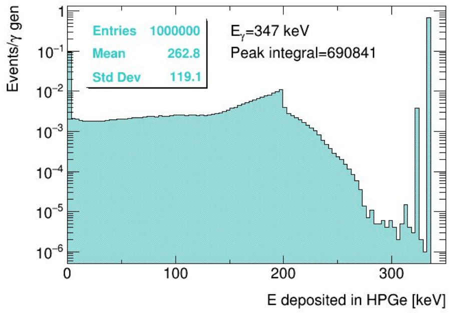


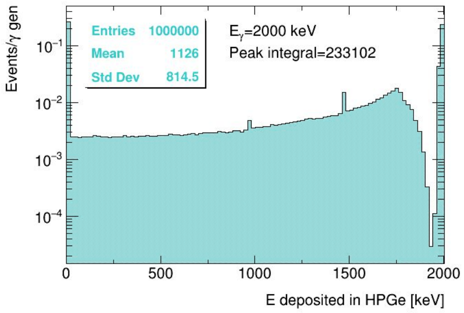
Photopeak Efficiency

Measured (ADC) energy determined by energy-loss processes in detector
We've developed standalone GEANT4 simulation firing particles from collimator



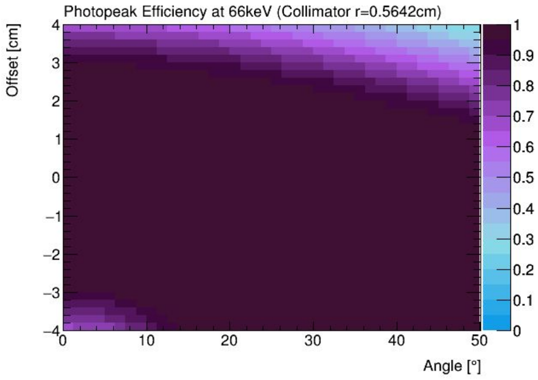


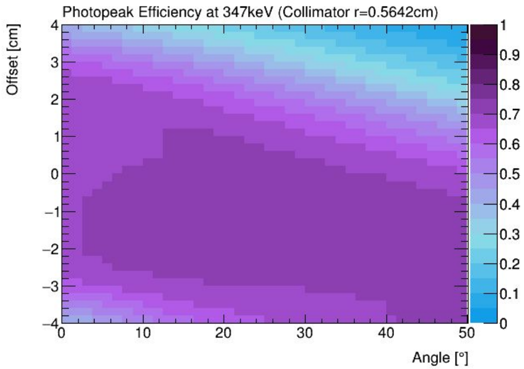


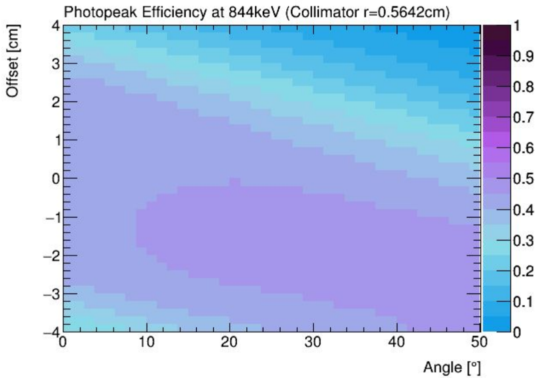


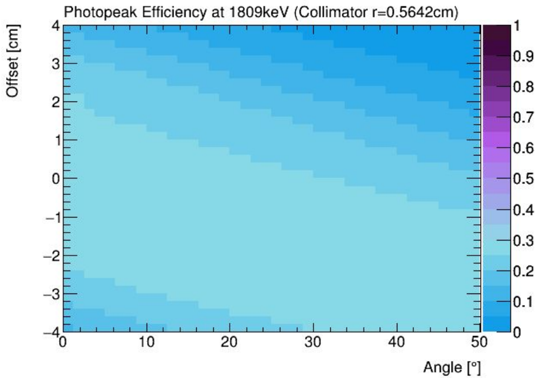
Detector Angle Orientation

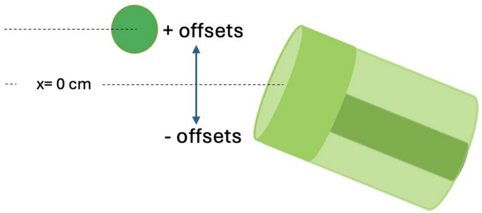
The photopeak efficiency depends on orientation (& offset) with respect to collimator











Next Steps and Conclusions

Have used the MDC2020 data to determine

- Ratio of the 347 X-rays to the flash background at 347 keV: 1.13 ± 0.08
- Absolute rate in detector : 5.8 kHz : ~ x10 lower compared to 2016 estimate
- Time to get 10% statistical uncertainty on 347 line versus flash rate & resolution

Having determined times to get 10% statistical uncertainty, will move onto evaluate some systematic uncertainties.

- Effect of varying fitting region to determine signal
- Effect of different fit shapes for background
- Uncertainty / non-linearities in ADC to energy scale calibration
- Uncertainties / non-linearities in energy resolution
- Uncertainty in rate-dependent correction factor (inefficiency) due to overlapping pulses
- Uncertainty in correction to get from measured signal to true signal number
- Uncertainty in X-ray geometric acceptance
- Uncertainty in fraction of stopped muons giving 347 line

Conferences and Workshops

- **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).
4. CLFV2023: The 4th International Conference on Charged Lepton Flavor Violation (Heidelberg University, Physics Institute, June 20 – 22nd 2023, https://indico.desy.de/event/37920).
5. IOP Joint APP and HEPP Annual Conference (Liverpool).

- **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).

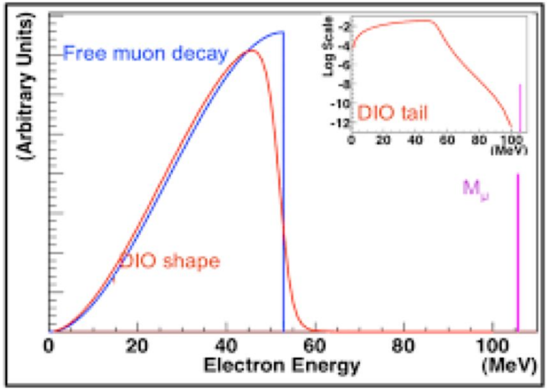
6. New Physics Signals (NePSi) Workshop, Talk Title: "Development of the data acquisition system for the Mu2e STM detector" (University of Pisa, Italy, February 15 – 17th, 2023, https://agenda.infn.it/event/32931/).

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).

8. Mu2e STM Collaboration meeting, Talk title: "Acceptance and Signal/Background Rates from MDC2020 Dataset" (10th May, 2024).

Backup

Backgrounds and momentum selection



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

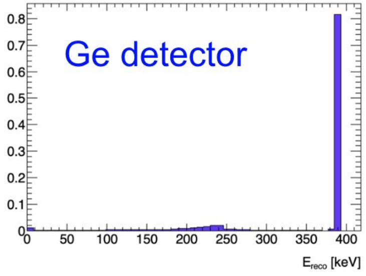
- “S shape”: removes neutral particles to enter the detector solenoid (unaffected by B and do not travel the S-shape)
- Particles with large momentum hit the wall of the solenoid and are not transmitted:

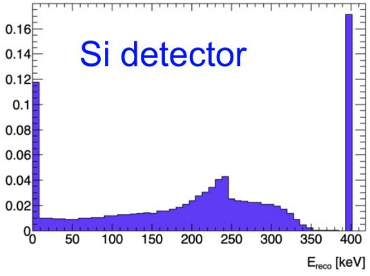
  $r = p_\perp/(0.3B)$

- 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).



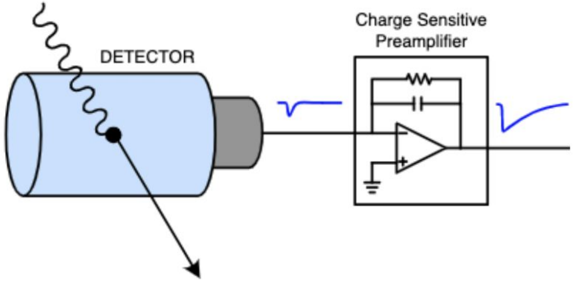


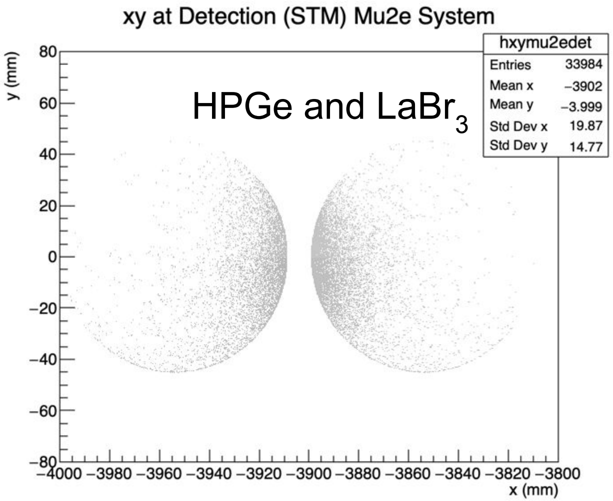
Pure **GEANT4** Simulation

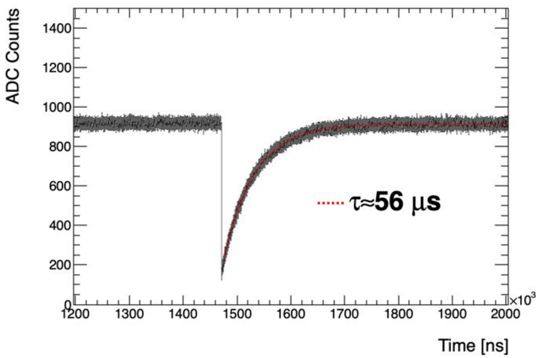
- Captured muons = 60.9% of Stopped muons.
- Stop rate can be determined by measuring the X-rays:
  - 80% of stops emit 347 keV X-rays 2p-1s (1s orbit lifetime= 864 ns).
  - 31% of stops emit 1809 keV gammas.
  - 5.7% of stops emit 844 keV gammas.

STM Geometry and pulse analysis

X-rays





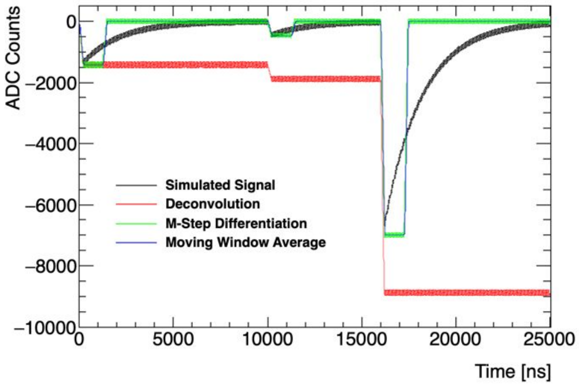


- X-rays reach the detector, the electrons ionise the material creating e-h pairs that drift in the detector creating the pulses that are then shaped.
- The signal is sent to the readout board and an ADC samples these values in 16-bit words.
- Energy of pulses is related to pulse heights.
- Calibration: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

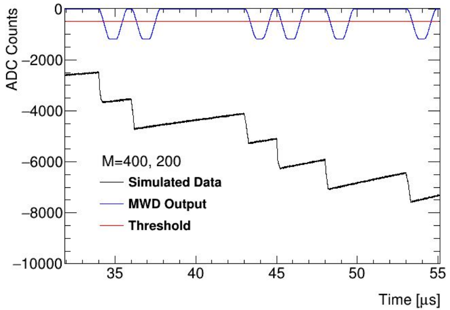
Moving Window Deconvolution (MWD) algorithm

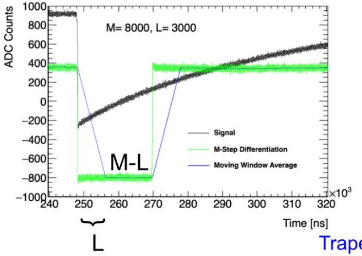
Finding pulse heights : MWD algorithm .

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

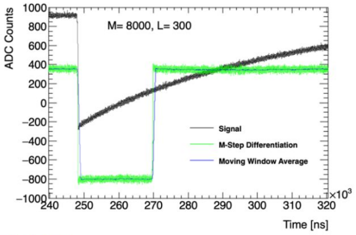


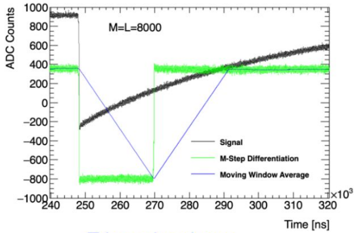
Efficiency strongly affected by MWD parameters at high rates (~200 kHz)



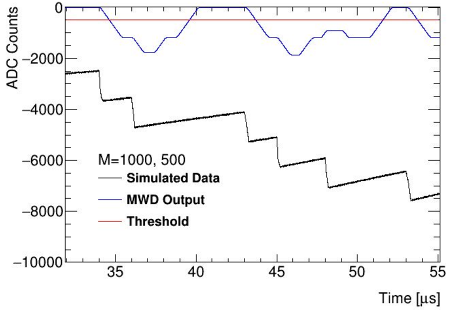


Trapezoidal shape



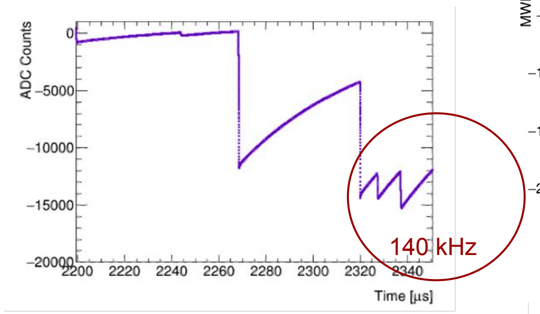


Triangular shape



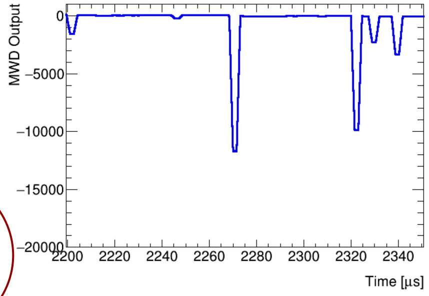
MWD reconstructed energy spectrum: ELBE Test-Beam and radioactive sources

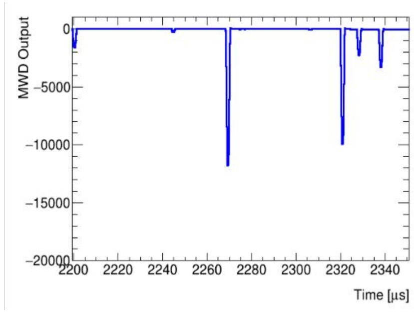
Data:



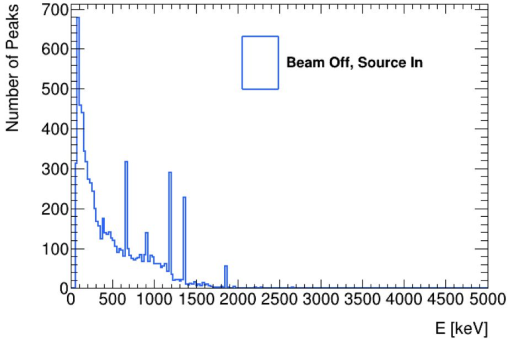
Low M values can resolve overlapping pulses at high pulse rates.

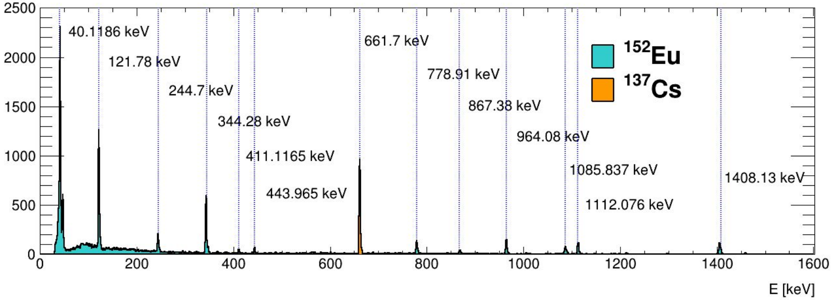
MWD parameters:





Reconstructed energy spectrums:



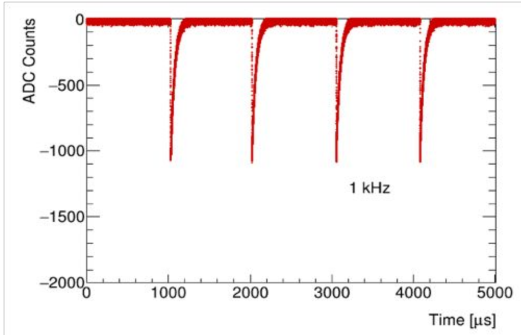


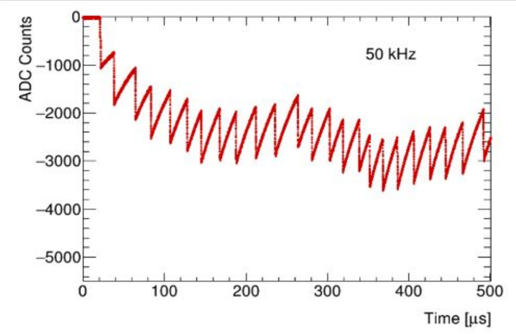
MWD + STM simulation developed: Resolution and efficiency

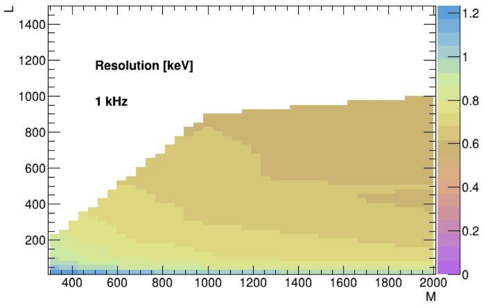
High M values give a better algorithm resolution but worse efficiency at high rates.

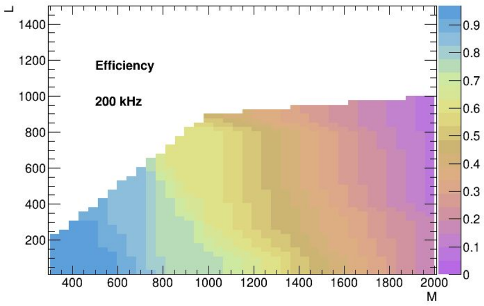
However difference in efficiency is more significant.

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.



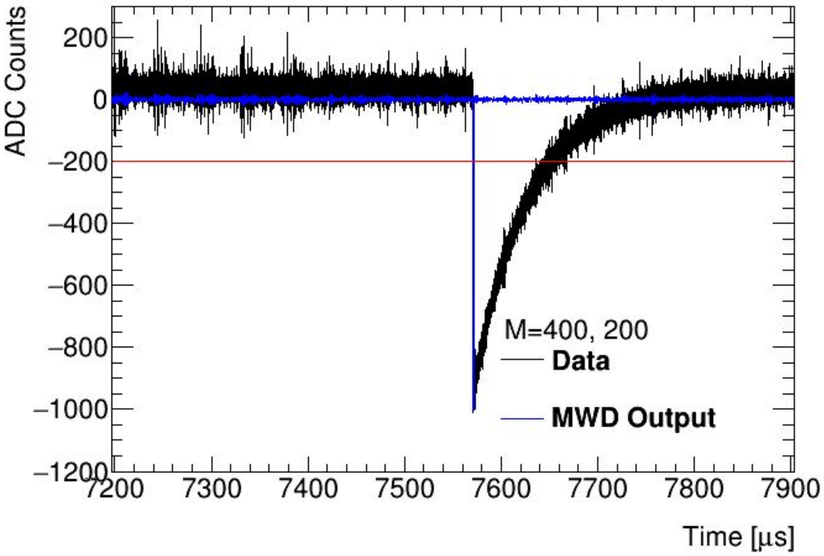


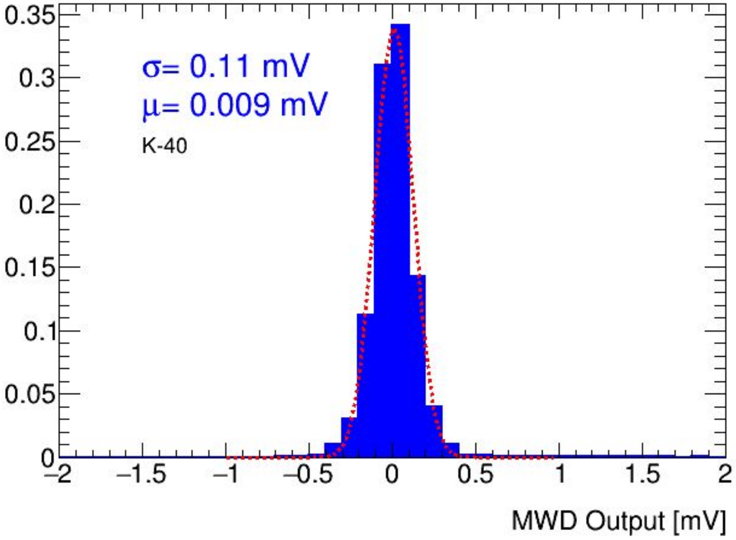




MWD to reconstruct energy spectrum

Baseline noise is reduced after applying MWD, 0.11mV (~ 1.8 keV)
Optimised MWD parameters : M=400, L=200 with ADC frequency = 300MHz.



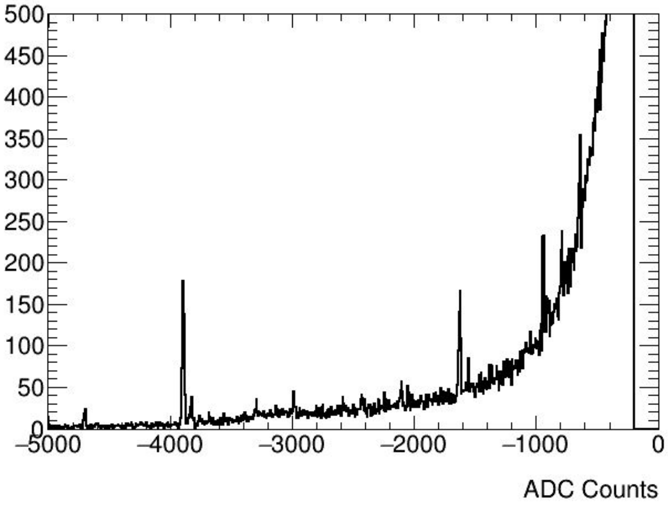


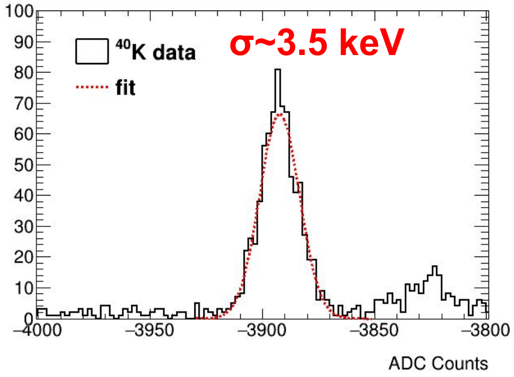
ADC spectrum

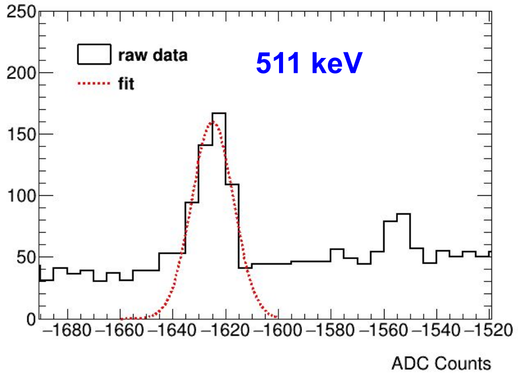
After accounting for prescales:
Salt source data ~ 430 secs.
Cosmic data ~220 secs.

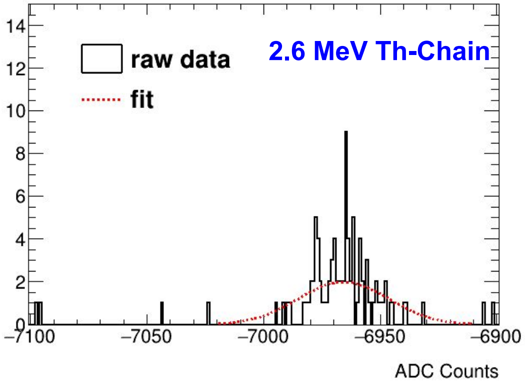
Calibrated data with:
- ^{40}K peak.
- 511 keV Annihilation peak.
- Last Thorium chain peak (^{208}Pb decay).

Accounting for Ge binding energy (11.103 keV).

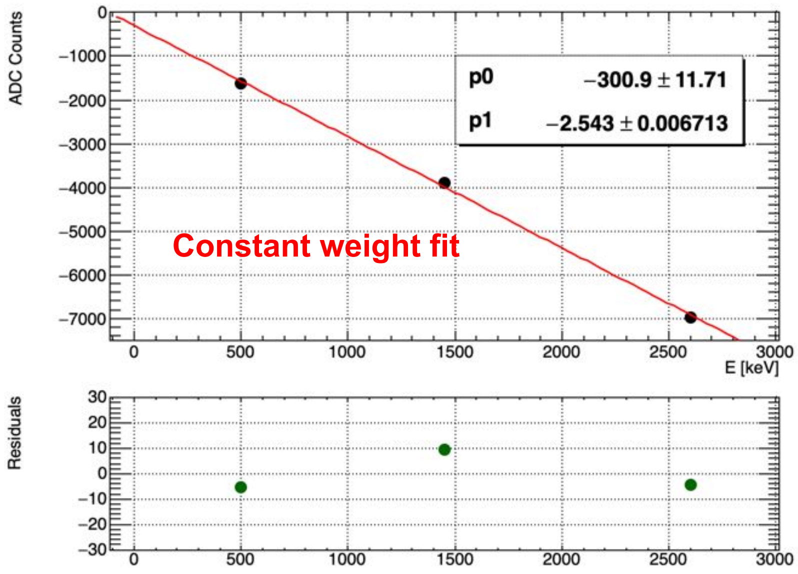


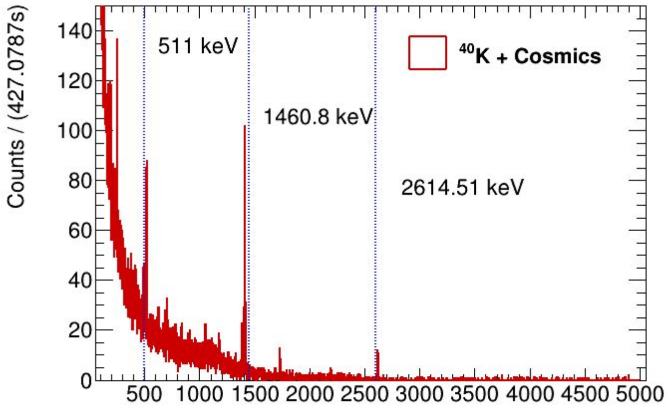


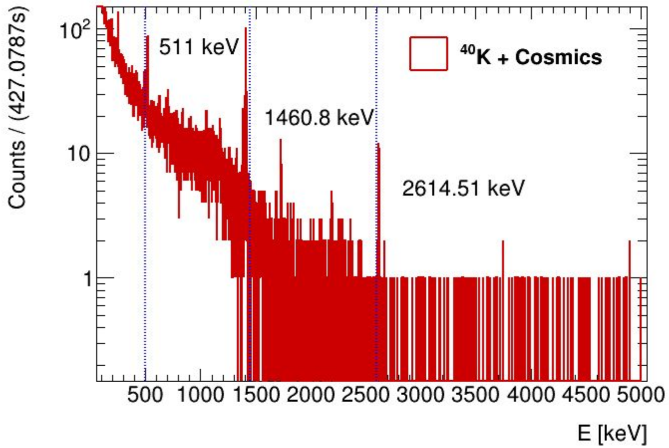




Calibration

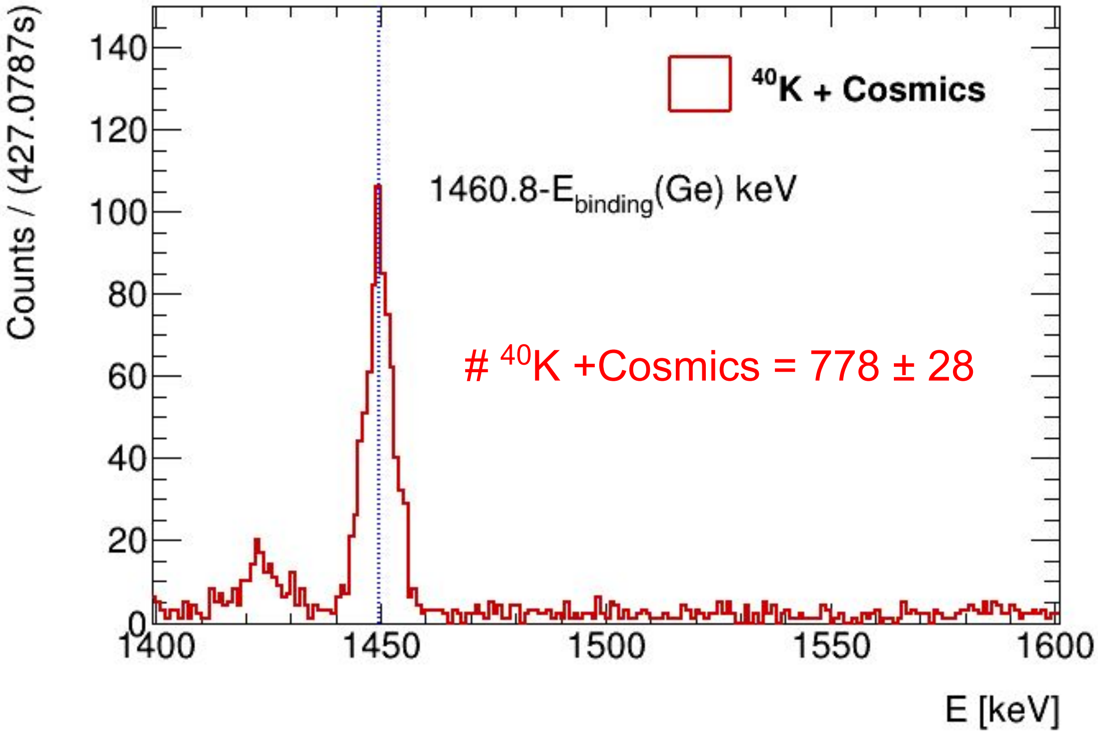






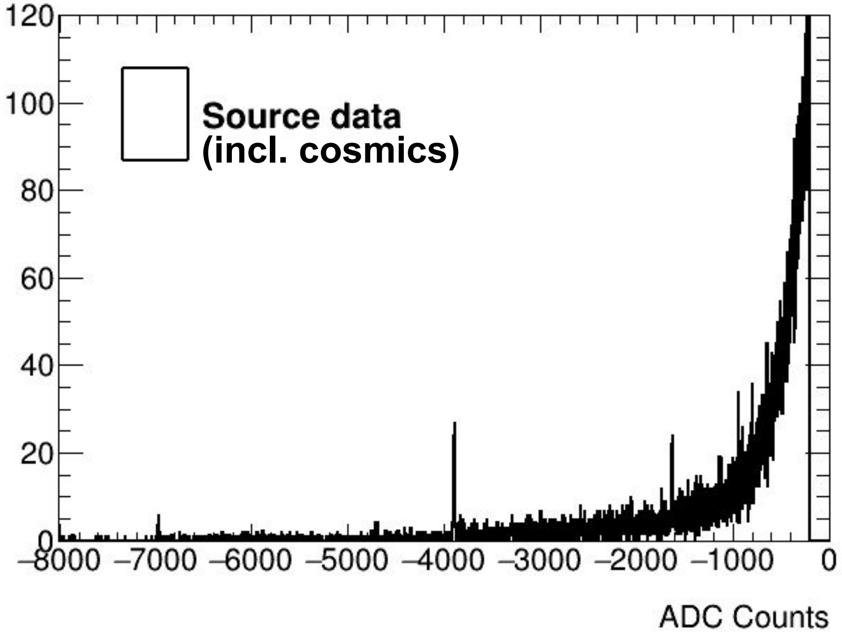
Calibration fit is sensitive to weighting of the 3 peaks. If increase ^{40}K weight so it has no residual then get 15 keV offsets in the other 2 lines.

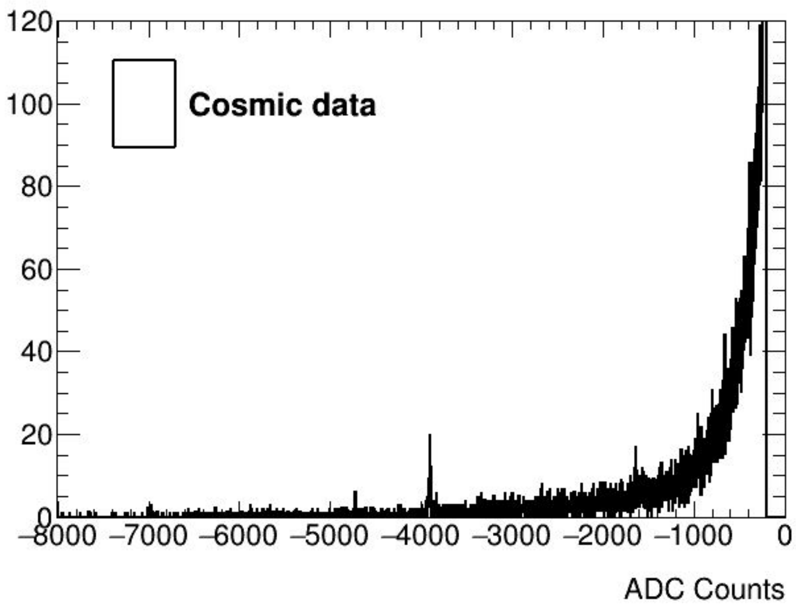
Calibration weighted to ^{40}K



To get a source-only event size need to subtract ^{40}K arising from cosmics

Cosmics + ^{40}K and Cosmics





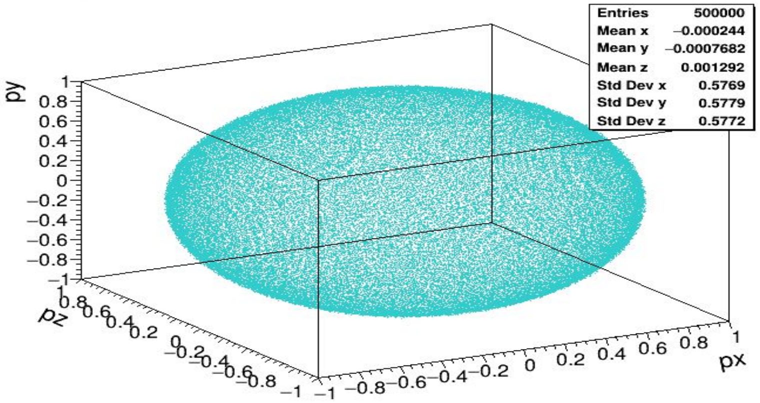
Get # ^{40}K (source) after cosmic subtraction.

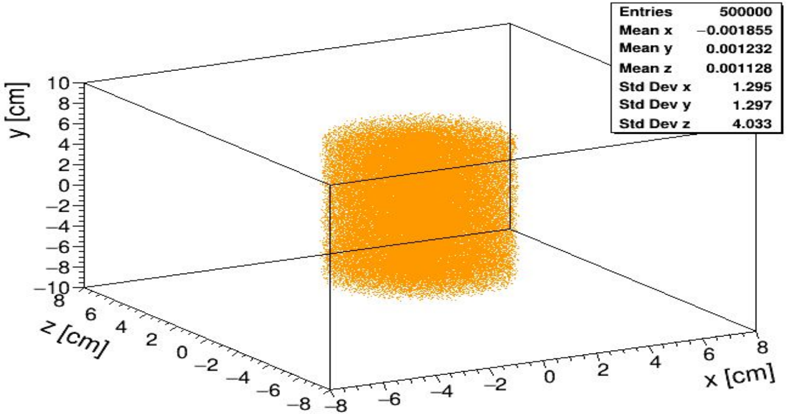
GEANT4 Prediction

~ 150g of K with 0.012% of ^{40}K producing 503 (1.461 MeV) X-rays/sec.

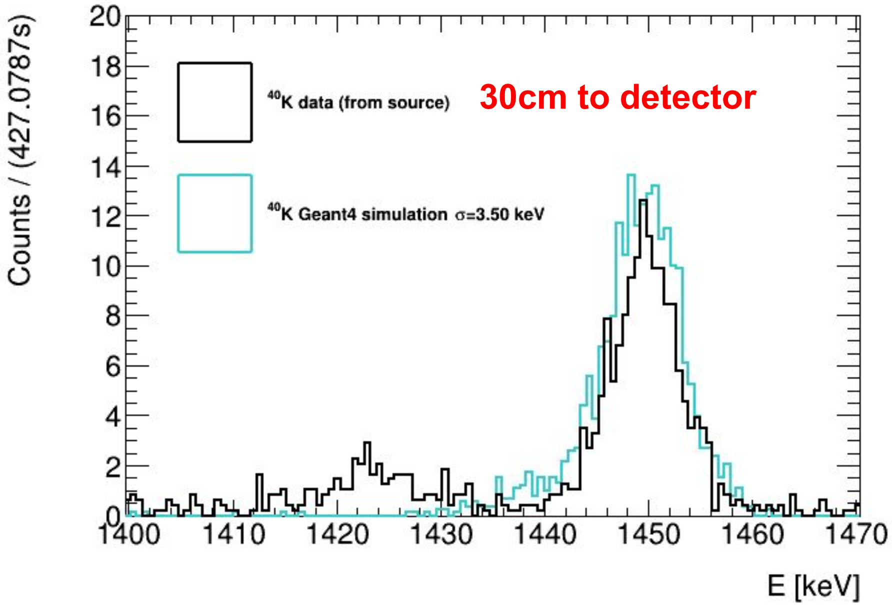
Developed a GEANT4 simulation to account for attenuation in salt and HPGe and the acceptance of the detector.

Simulation based on 4 x 0.5M generated X-rays.





GEANT4 prediction for ^{40}K line



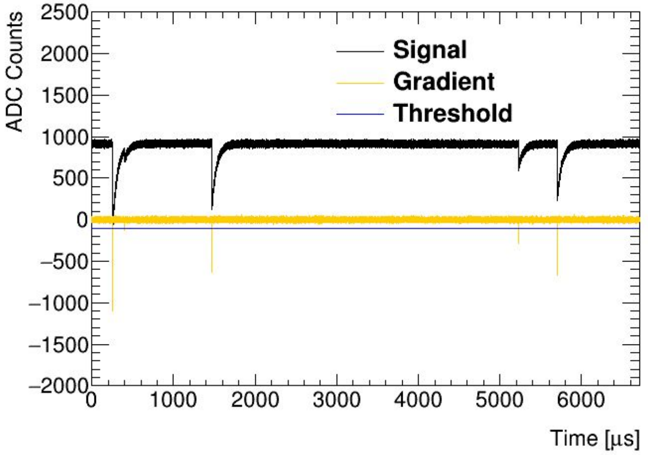
GEANT4 prediction (30 cm displacement).

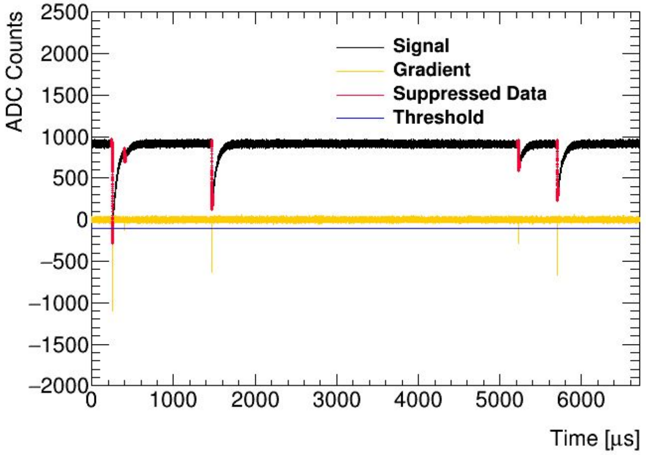
STM data acquisition system: Zero Suppression (ZS) algorithm

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

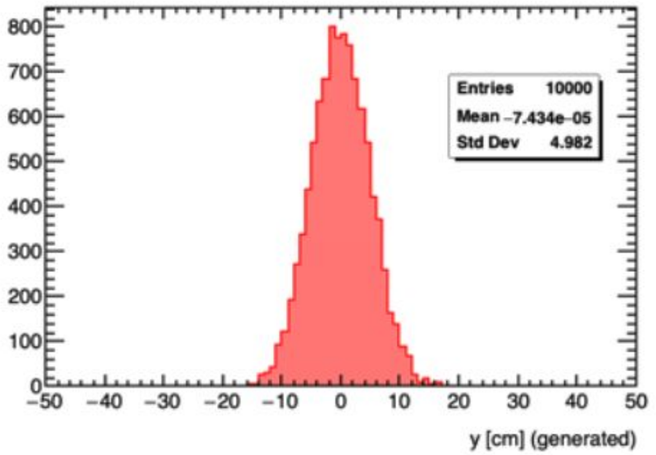
```
gradient[i]=ADC[i+window]-ADC[i];
```

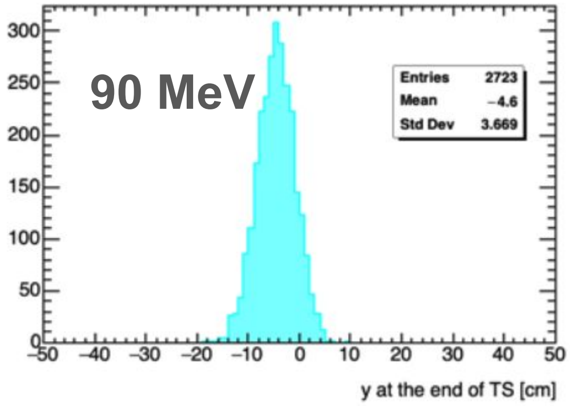
- Window = 100 ADC (~ 0.3 μs) : so in principle can distinguish peaks to rates well above the rates required (5 μs = 200 kHz)
- Gradient threshold = –100 ADC Counts.
- The trigger is then established in the first point where the gradient is below the threshold chosen and store t_{before} [μs] of data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

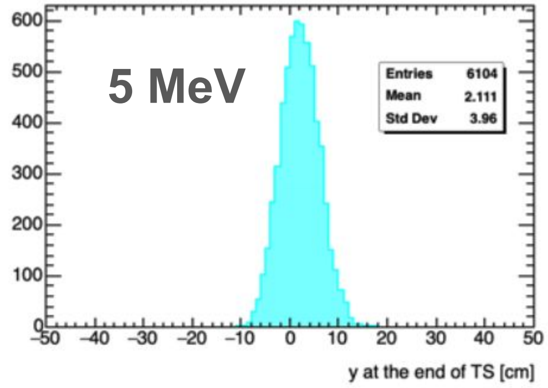




Backup : TS B field







Mu2e Weighted average for run I

Running mode	Mean proton pulse intensity	Running time (s)	N(POT)	N(stopped muons)
Low intensity	1.6×10^7	9.5×10^6	2.9×10^{19}	4.6×10^{16}
High intensity	3.9×10^7	1.6×10^6	9.0×10^{18}	1.4×10^{16}
Total		11.1×10^6	3.8×10^{19}	6.0×10^{16}