Updated analysis of the Mu2e STM detector: Acceptance and testing DAQ with new data taken at FNAL.

INTENSE Meeting

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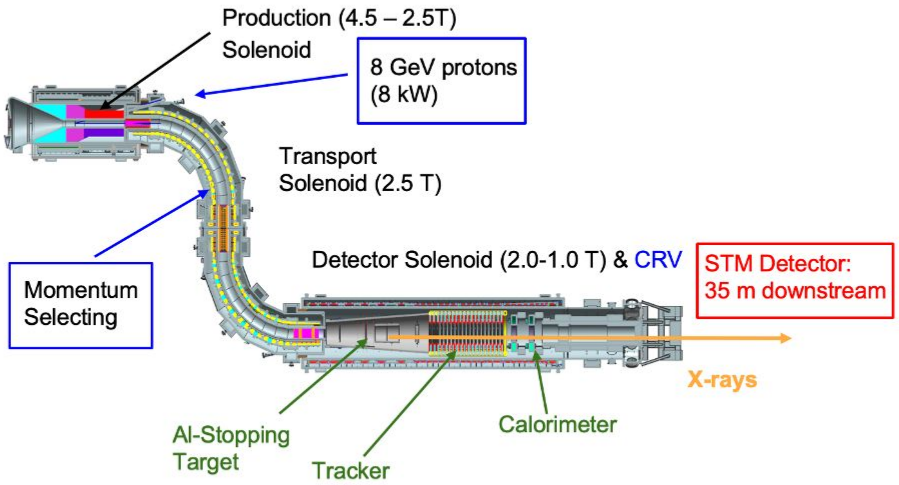
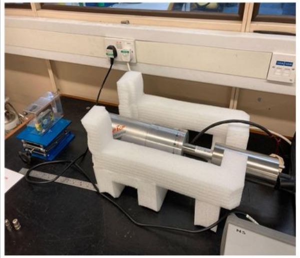
Mu2e - Overview

- 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

STM: Reconstructs ^{27}Al energy spectrum.



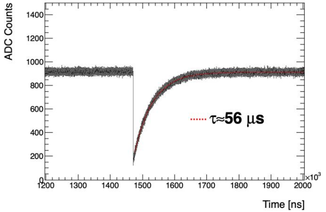
High Purity Germanium (HPGe) Detector.



Summary.

- Optimise analysis algorithm parameters.
- Characterise bremsstrahlung spectrum at HPGe detector using MDC2020 dataset.
- Study STM X-ray acceptance. Comparing pure solid angle propagation and ART-Geometric effects.
- Develop a simulation including bremsstrahlung effects and STM acceptance attenuation.
- Data taking at FNAL with radioactive source and comparison with a GEANT-4 simulation.

Decay time study: MWD Input



- M,L values previously optimised using simulation developed.
- Study decay time constant.

- Signal.
- Deconvolution:

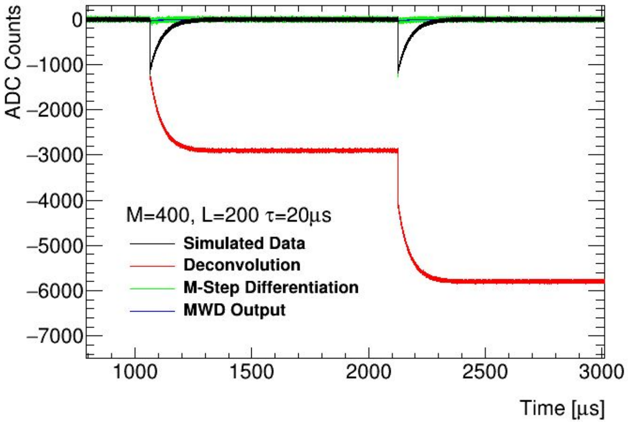
$$A[i] = V[i] - \left(1 - \frac{T_0}{\tau_{decay}}\right) V[i-1] + A[i-1]$$

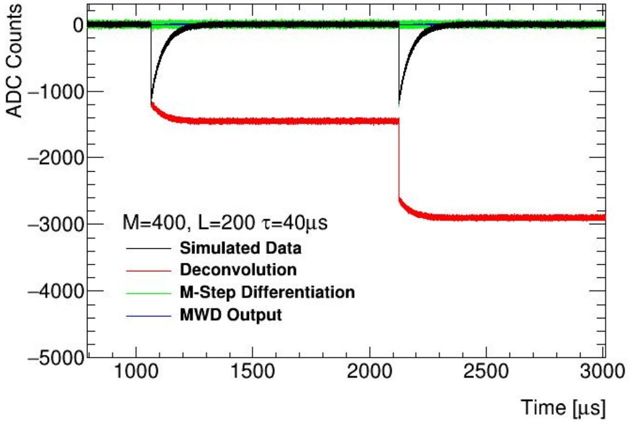
- Differentiation:

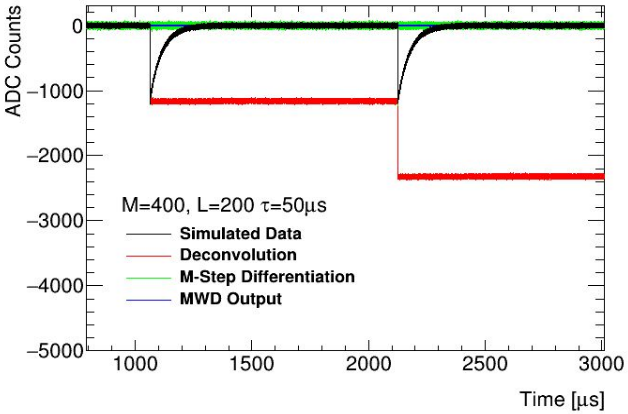
$$D[i] = A[i] - A[i-M]$$

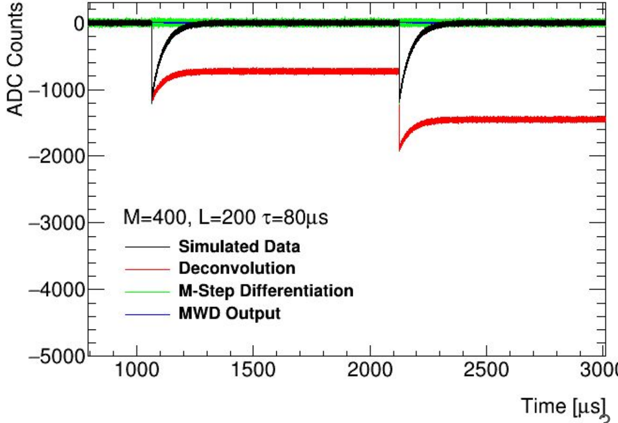
- Averaging:

$$l[i] = \frac{1}{L} \sum_{k=i-L+1}^{i} D[k]$$

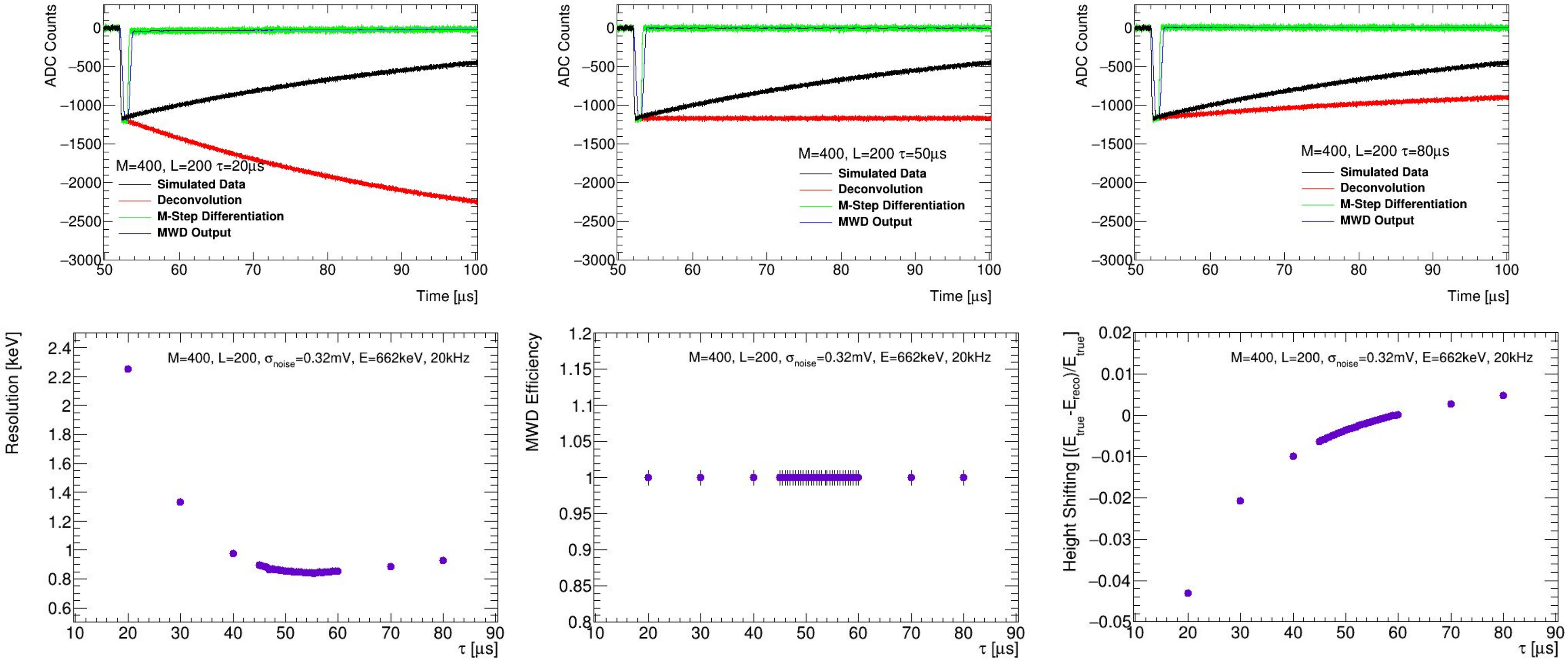






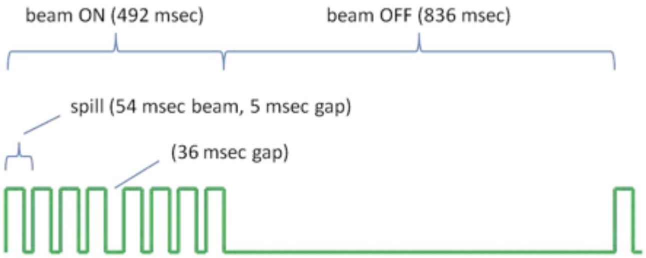


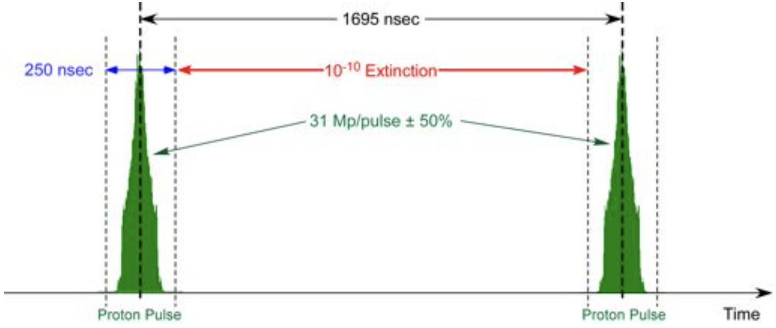
Decay time study at 20kHz: MWD Input



Flat in time decay fitted value.

Mu2e Beam Structure





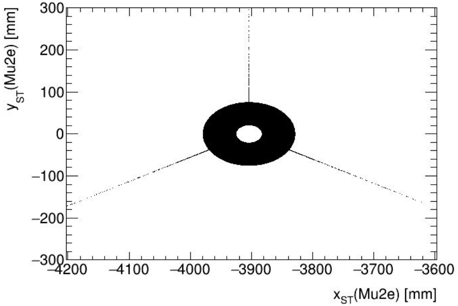
microbunch

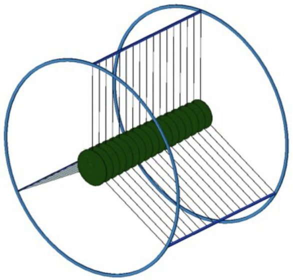
Each main injector cycle (1.4 s), pulses are delivered continuously for about 0.4 s and the beam is off for the rest of the cycle.
Each pulse/microbunch is 250 ns-wide separated by 1695 ns.

Mu2e simulations estimate 1.6×10^{-3} stopped muon per proton on target (POT).

MDC2020 simulated dataset

- Simulation contains 2×10^{8} POT.
- ^{27}Al Stopping Target (ST) geometry.

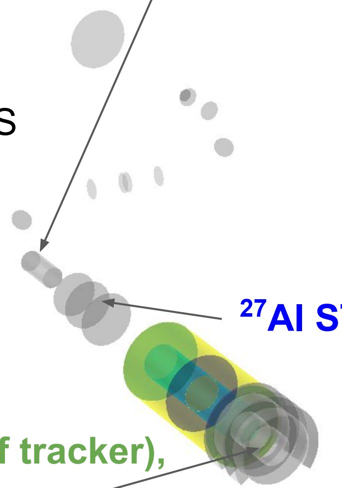




MDC2020: Muon Beam.

VD8 (start DS),
z=3929.98 mm:

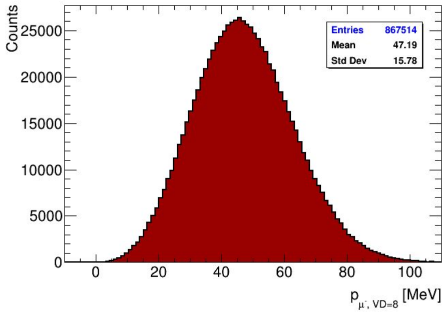
TS



^{27}Al ST

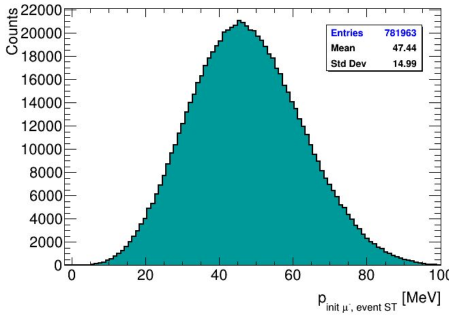
VD15 (end of tracker),
z=11810.1 mm:

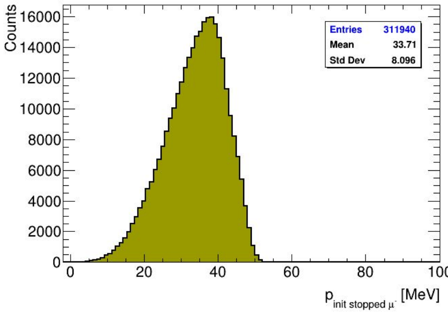
Configuration Virtual Detector (VD8) :



Input muon momentum configuration at VD8

Propagation to Stopping Target (ST) :

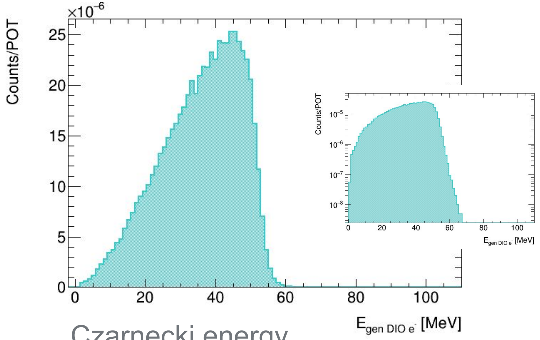




Stopped Muon to DIO/X-Rays at ST

DIO and Al X-ray spectrum at ST.

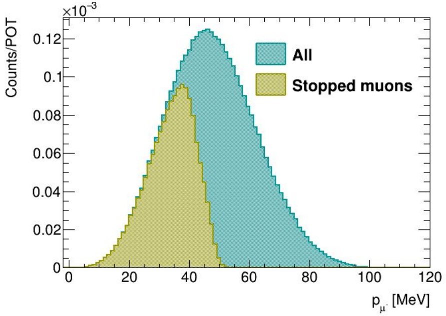
Determine bremsstrahlung spectrum from a virtual detector at the end of the tracker (VD15).



Czarnecki energy spectrum

- 40% of stopped muons produce a DIO electron.

- 40% of muons are stopped.



- 62% of stops emit 66 keV X-rays.
- 80% of stops emit 347 keV X-rays 2p-1s (1s = 864 ns).
- 31% of stops emit 1809 keV gammas.

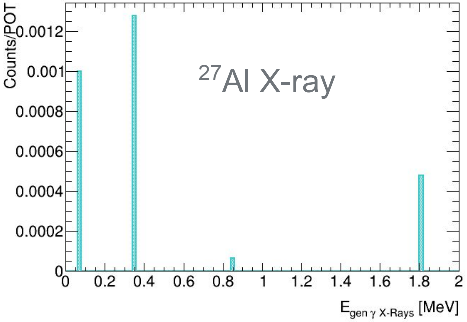
$$\mu^- + ^{27}_{13}Al \rightarrow \nu_\mu + ^{26}_{12}Mg^* + n$$

$$\rightarrow\ ^{26}_{12}Mg + \gamma$$

- 5.7% of stops emit 844 keV gammas.

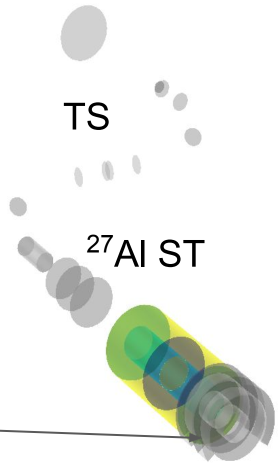
$$\mu^- + ^{27}_{13}Al \rightarrow \nu_\mu + ^{27}_{12}Mg$$ β⁻ (9 min)

$$\rightarrow\ ^{27}_{13}Al + e^- + \bar{\nu}_e + \gamma$$



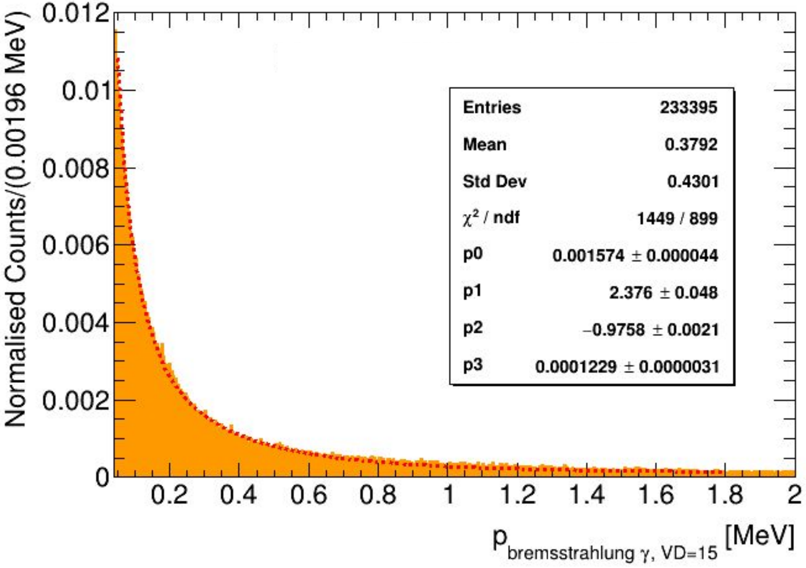
Bremsstrahlung Energy Spectrum at VD15

MDC2020: Electron Beam.

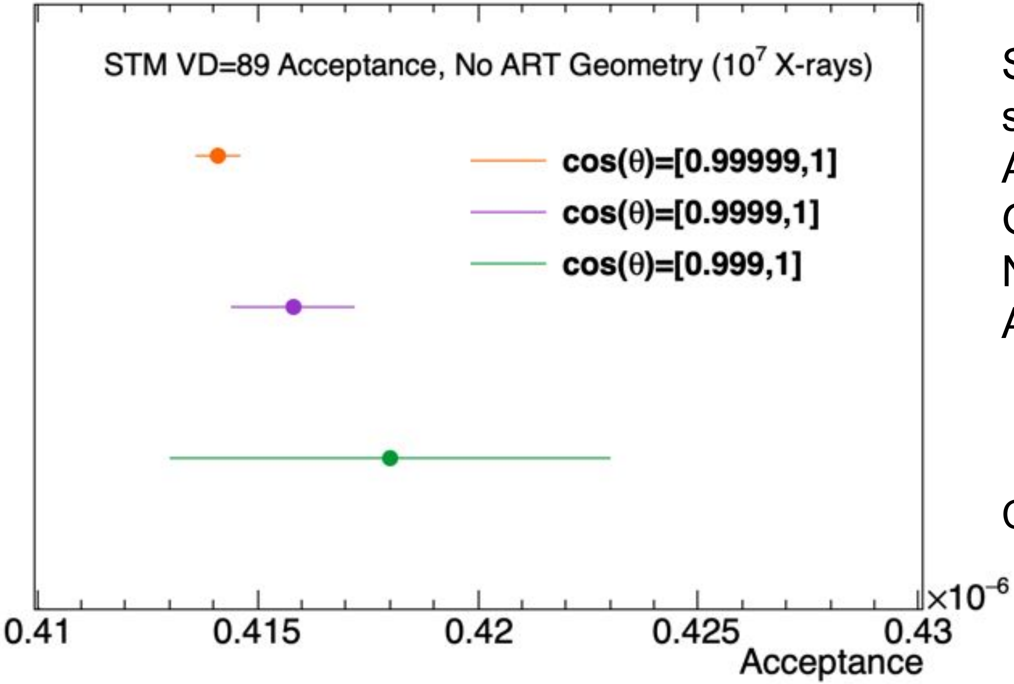


VD15 **(end of tracker), z=11810.1 mm:**

$$f(p) = \frac{p_0}{e^{p_1 p} + p_2} + p_3$$



X-ray Acceptance - solid angle

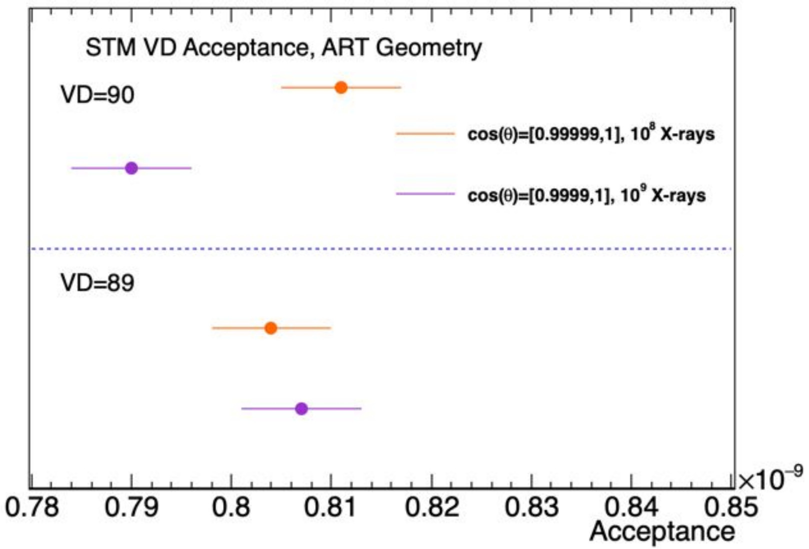


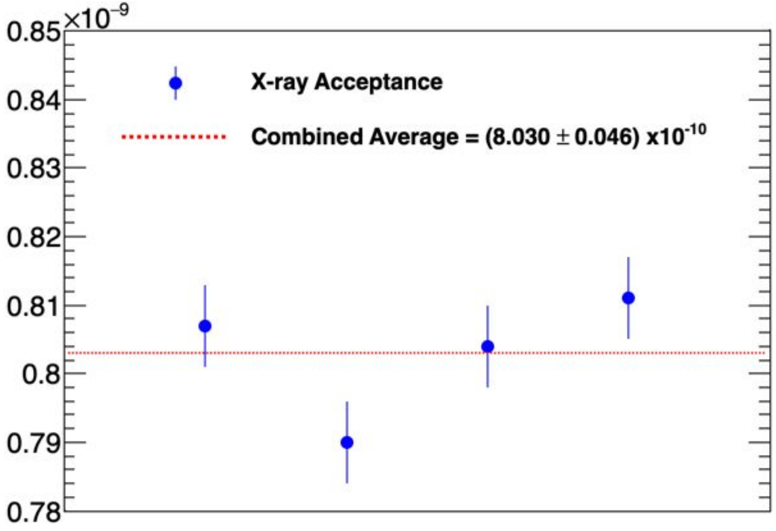
STM X-ray acceptance using pure solid angle approach with input Al-stopping positions (No ART Geometry).
Need to account for Mu2e ART-Geometry.

Combined Average = (4.160±0.011)e-7

Combined X-ray Acceptance - ART Geometry

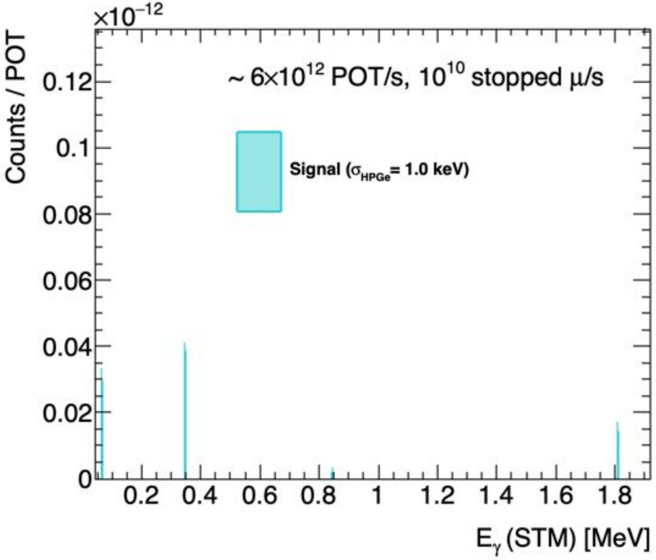
Studied STM X-ray acceptance using Offline Mu2e Code including ART Geometry effects at STM virtual detectors: VD89 and VD90.

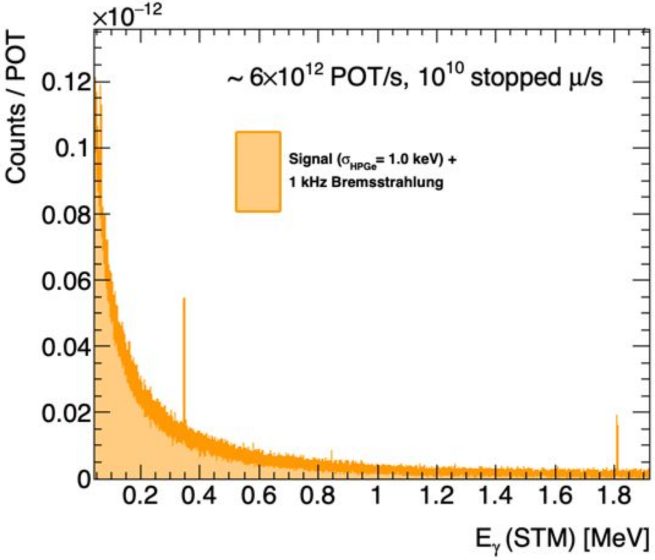




Signal over background study at STM

- Adding STM acceptance and resolution.
- Developing a simulation to get the time that we have to run for to get a significant signal/background.





Data taking at FNAL

Sent data simultaneously into the two ADC channels

- Data from signal generator: sine wave data from 500 Hz to 50 MHz
- HPGe data both with and without the ^{40}K salt source that was ~ 30cm from detector

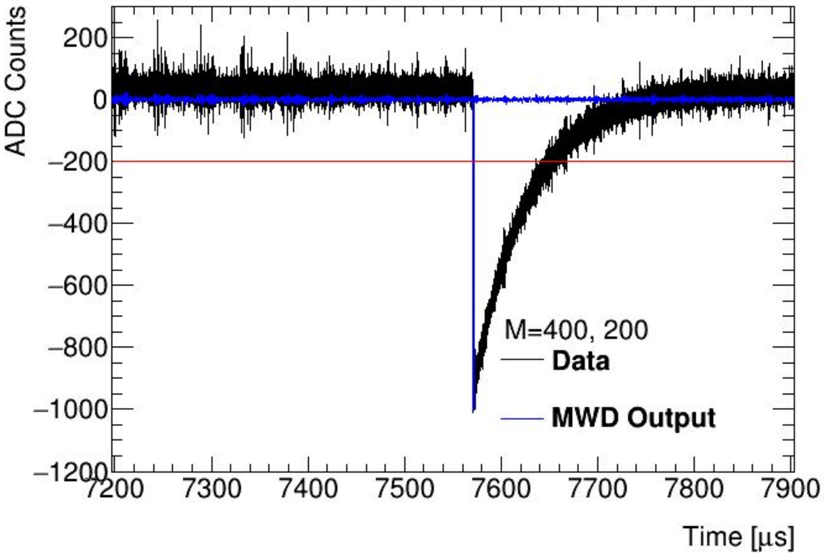
Recorded only raw data

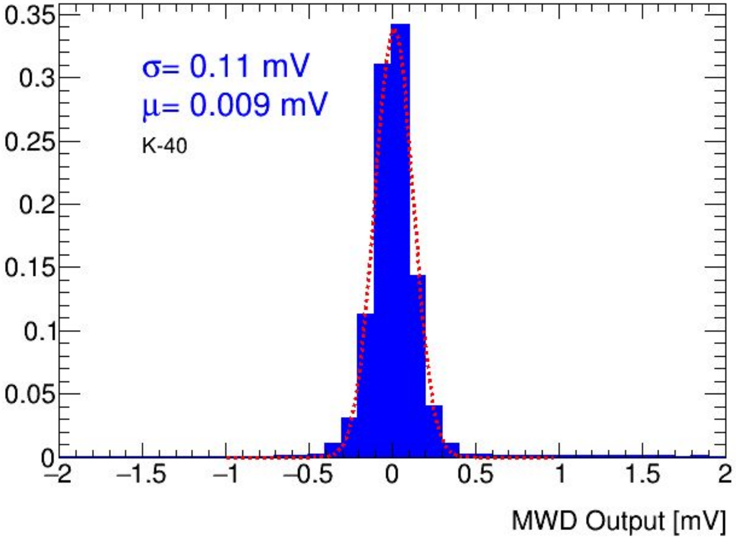
- With prescale = 1 for short periods
- With prescale = 20 for longer period

675 Gb data stored in bespoke binary files.

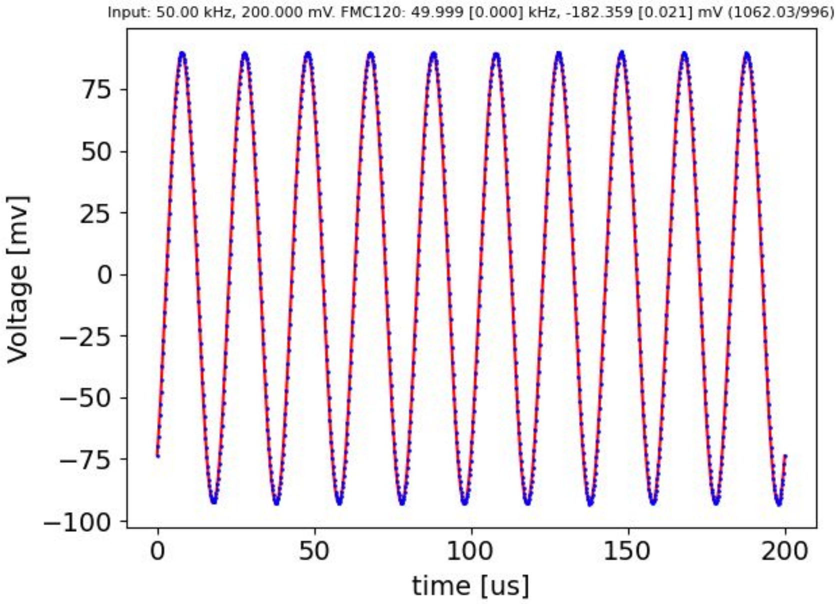
MWD to reconstruct energy spectrum

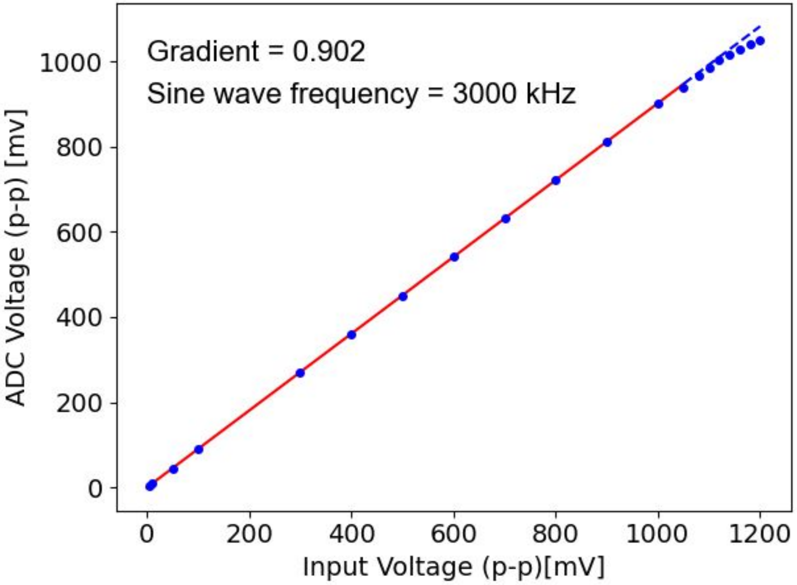
Baseline noise is reduced after applying MWD, 0.11mV (~ 1.8 keV)
Optimised MWD parameters : M=400, L=200 with ADC frequency = 300MHz.





Sine wave data





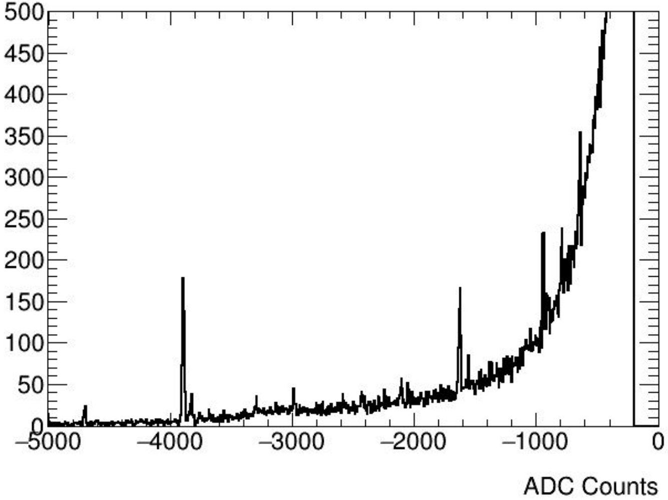
Modest dependence of gradient on signal frequency.
Dynamic range of FMC120 ADC is 1000 mV (p-p) so effectively an energy range of ~ 13 MeV (~ 0.4 keV per ADC).

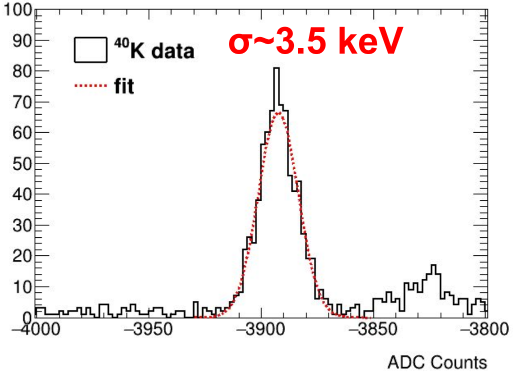
ADC spectrum

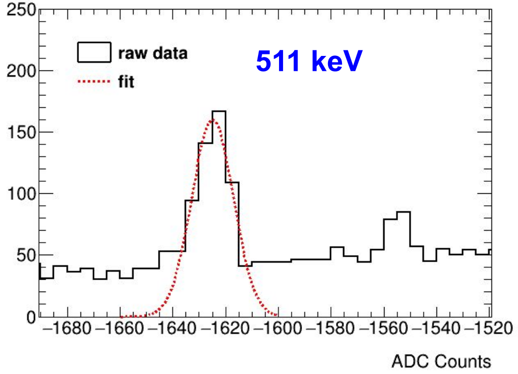
After accounting for prescales:
- Salt source data ~ 430 secs.
- Cosmic data ~220 secs.

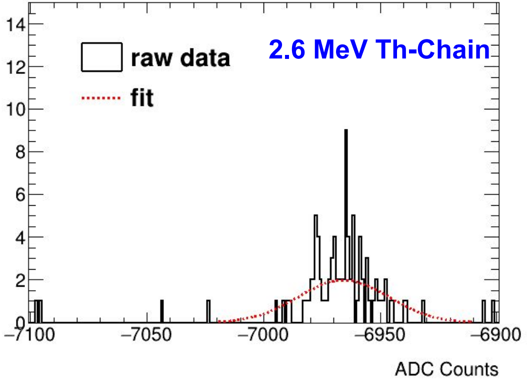
Calibrated data with:
- ^{40}K peak.
- 511 keV Annihilation peak.
- Last Thorium chain peak (^{208}Pb decay).

Accounting for Ge binding energy (11.103 keV).

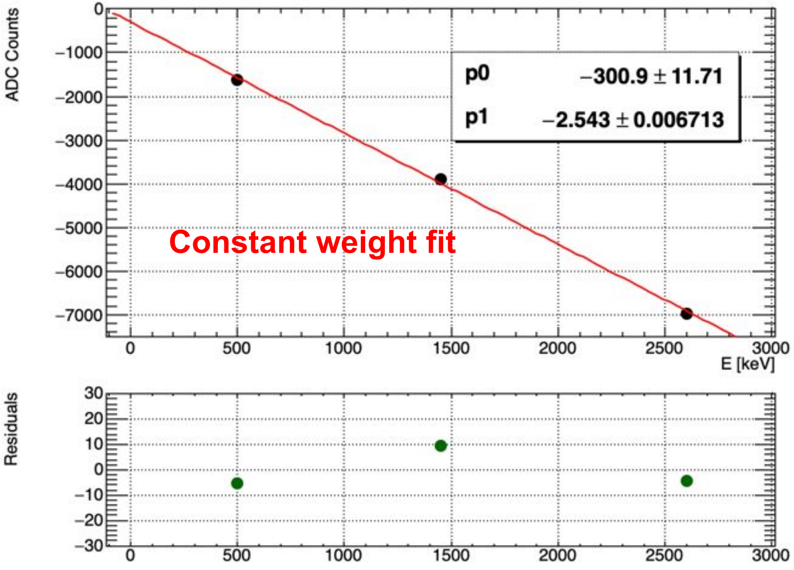


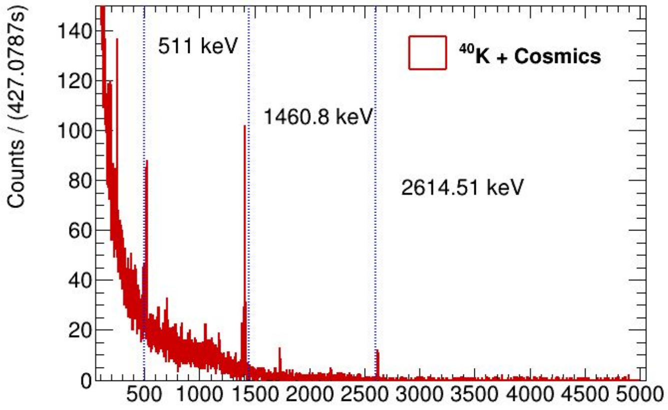


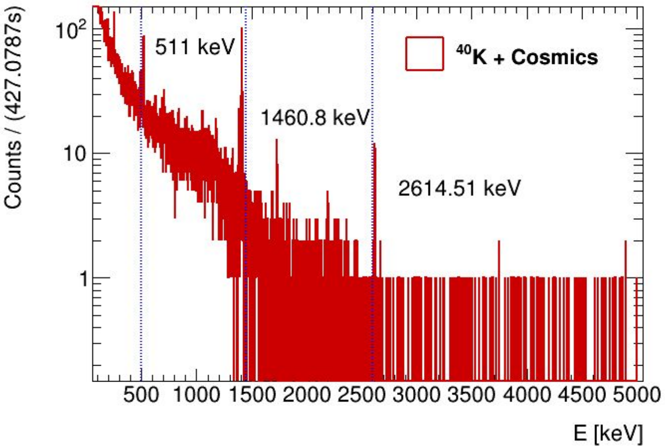




Calibration

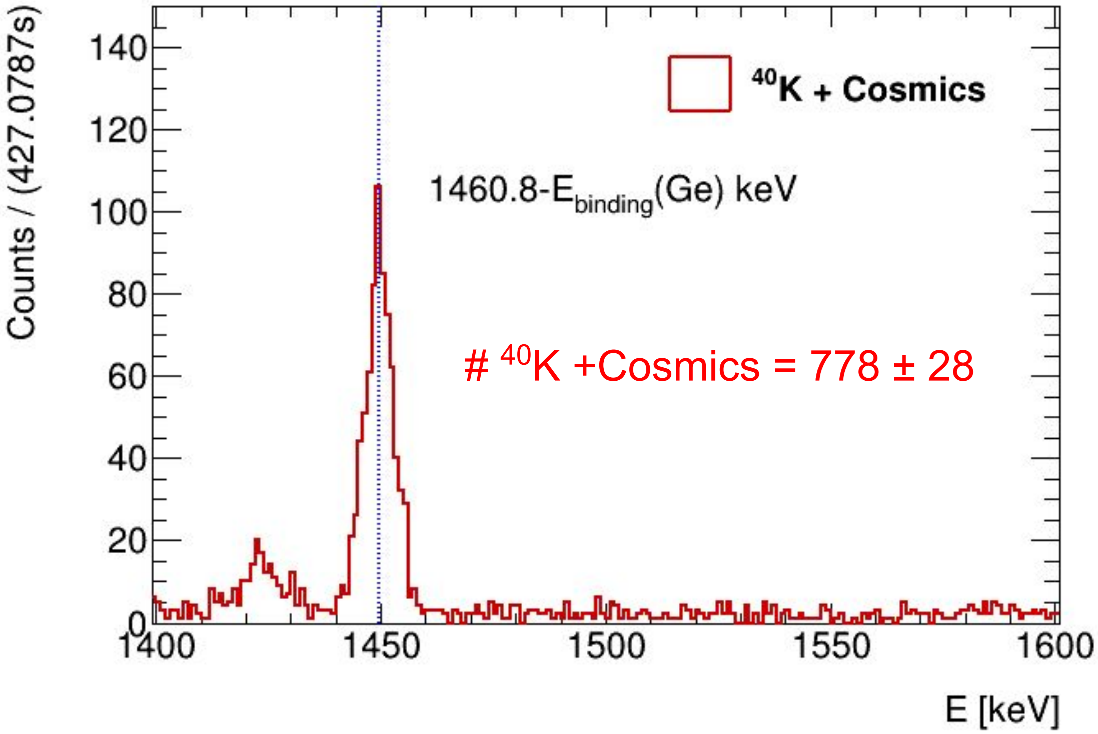






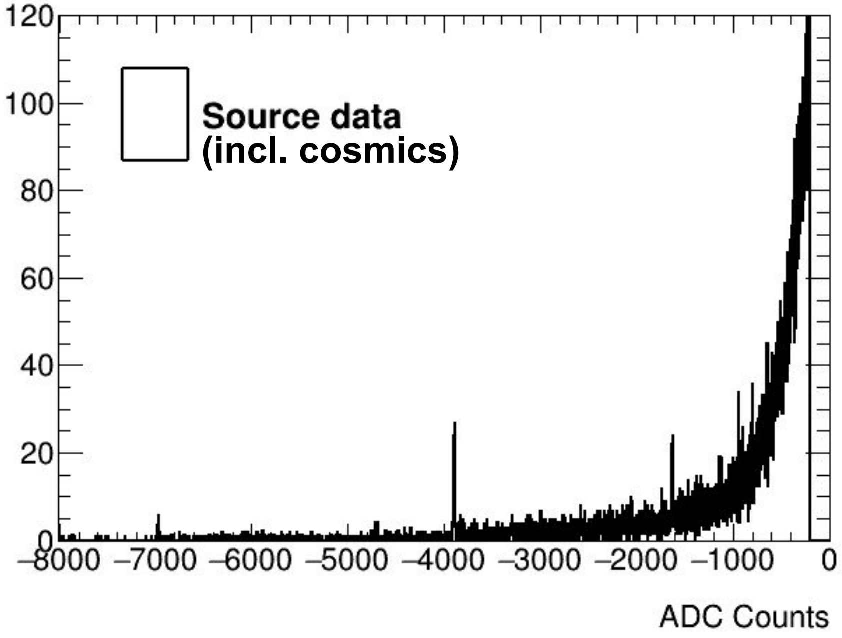
Calibration fit is sensitive to weighting of the 3 peaks. If increase ^{40}K weight so it has no residual then get 15 keV offsets in the other 2 lines.

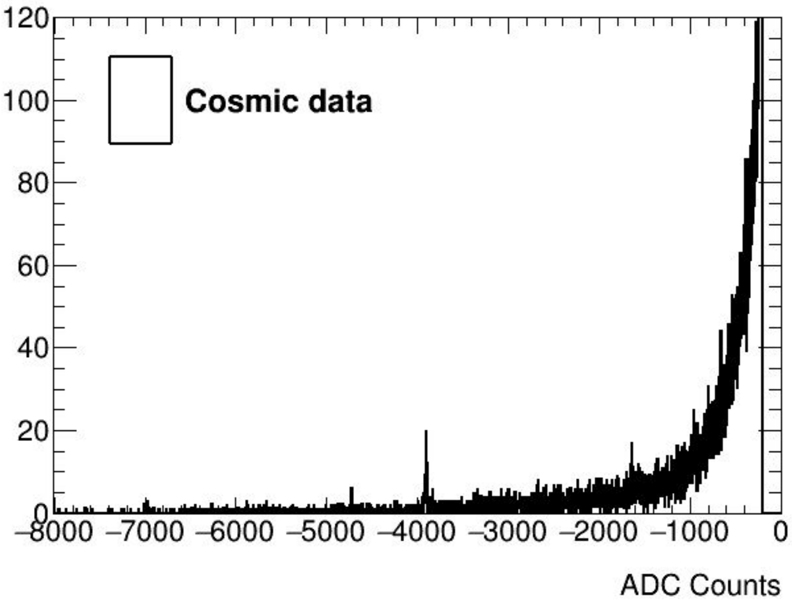
Calibration weighted to ^{40}K



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

Cosmics + ^{40}K and Cosmics





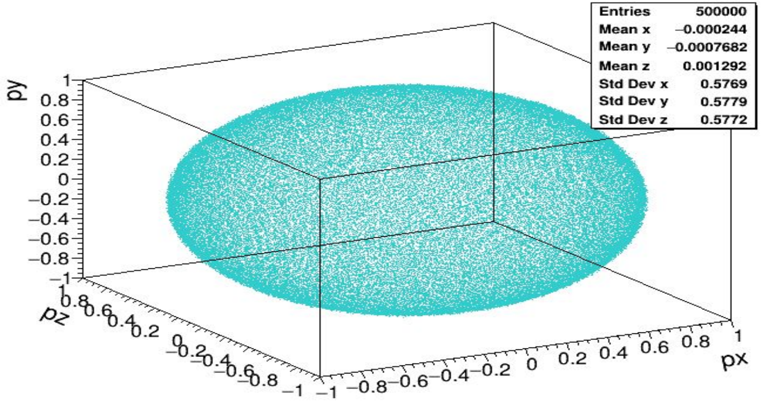
^{40}K (source) after cosmic subtraction = 161 ± 15 counts in 427s

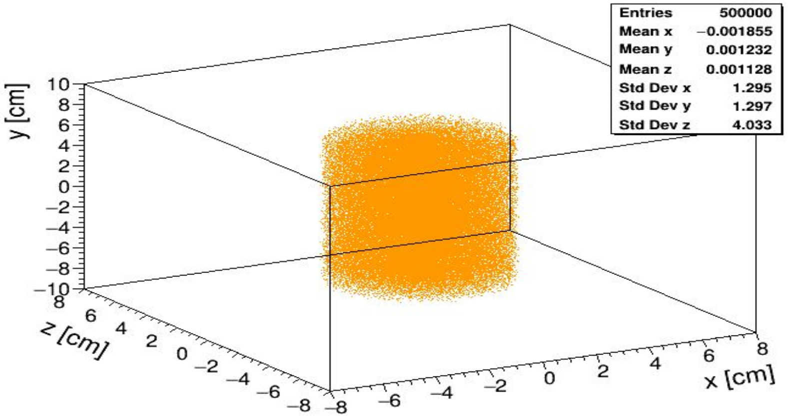
GEANT4 Prediction

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

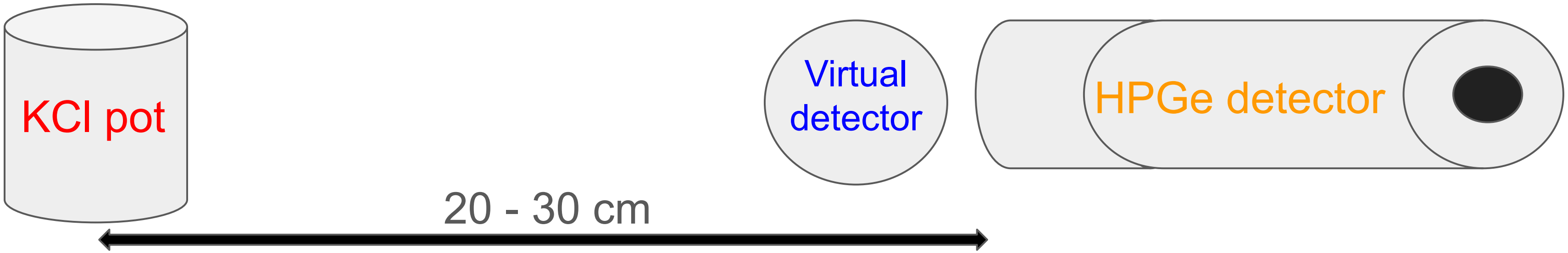
Developed a GEANT4 simulation to account for attenuation in salt and HPGe and the acceptance of the detector.

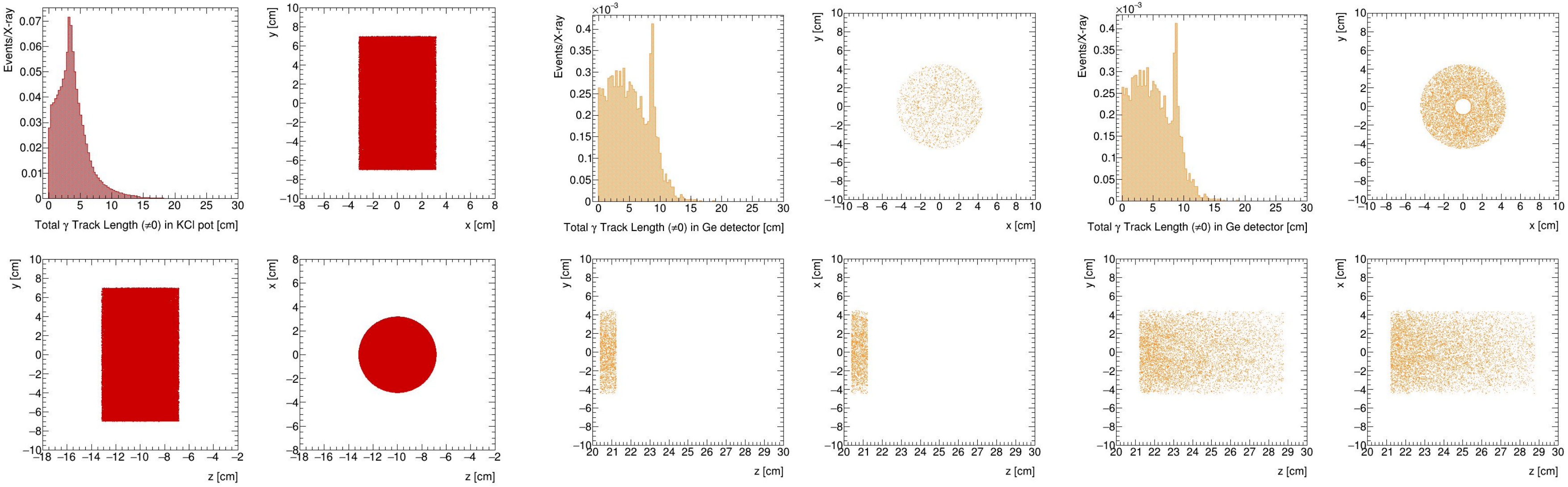
Simulation based on 4 x 0.5M generated X-rays.





Geant-4 simulation: Input geometry

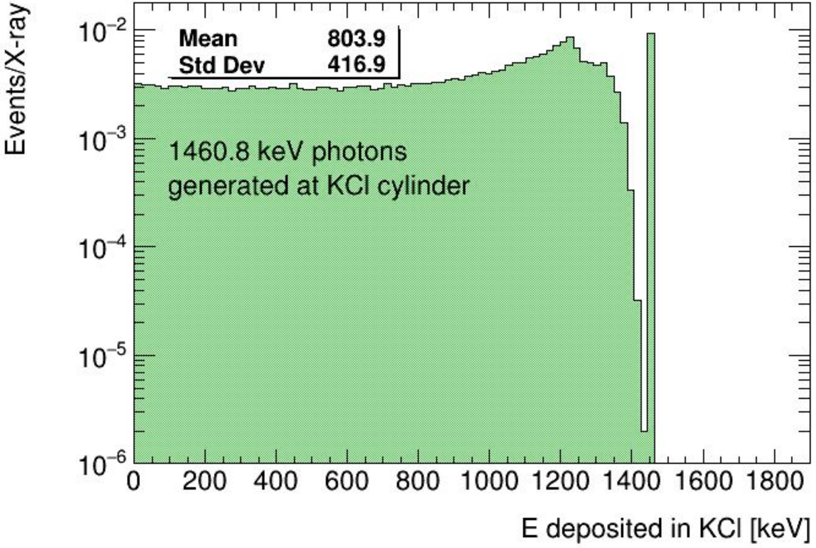


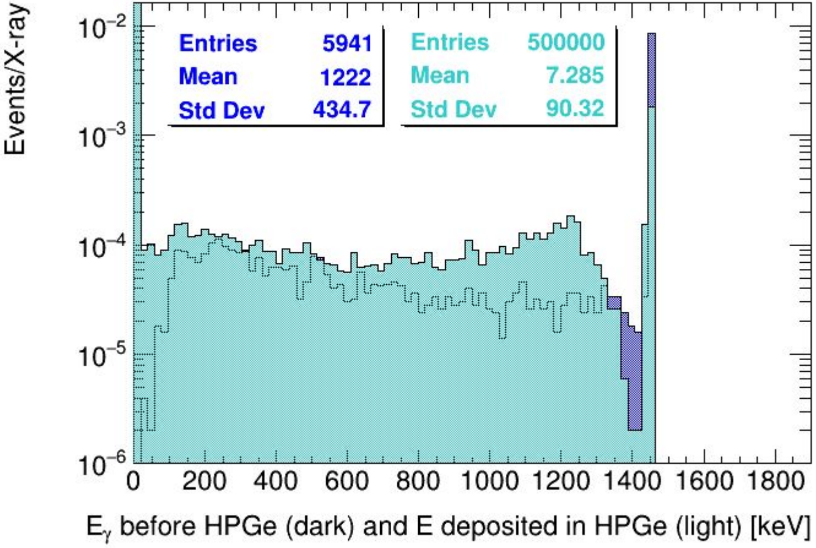


Energy deposited in salt and Ge

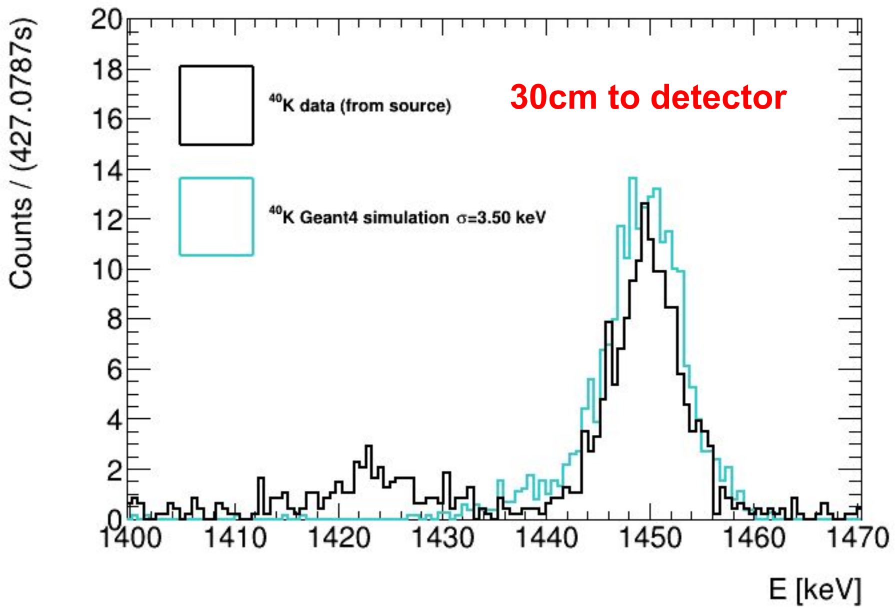
Average energy loss in salt is ~ 250 keV

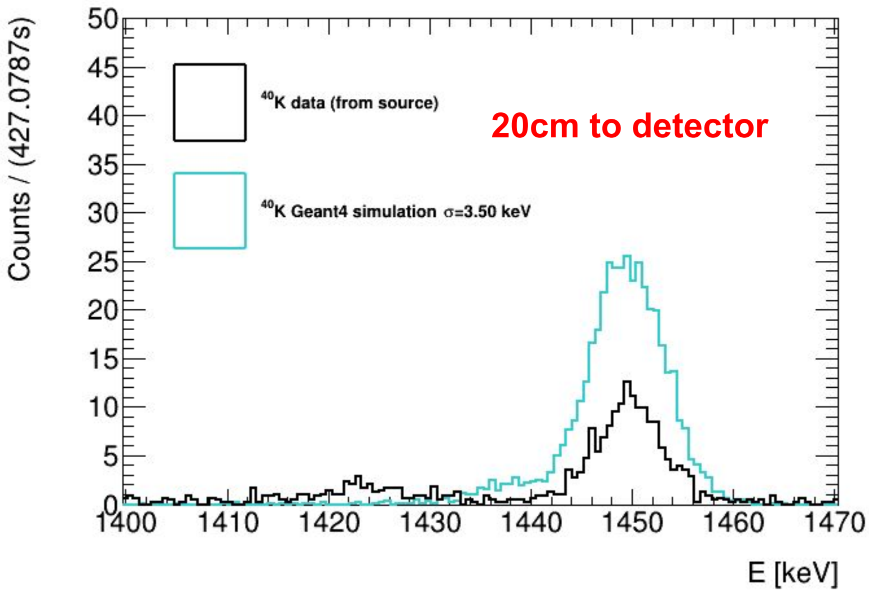
Acceptance ~ 1% and then attenuation in HPGe means only 20% of events remain in the photopeak





GEANT4 prediction for ^{40}K line





GEANT4 prediction (30 cm displacement) : 204 vs 161 ± 15 measured

but displacement and average height of salt and amount of salt are all estimated…

Summary

- Studied and optimised algorithm parameters (dependence with HPGe time decay constant).
- Characterised bremsstrahlung spectrum at HPGe detector using MDC2020 dataset.
- Studied STM X-ray acceptance. Comparing pure solid angle propagation and ART-Geometric effects.
- Develop an STM simulation including bremsstrahlung effects and STM acceptance attenuation.
- Analysed data from the first attempted STM VST:

- Noise is high and needs investigating / mitigating
- Statistics of data is limited and so calibration not optimal
- Rate seems as expected i.e. ~ reproduced by GEANT4 simulation

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).

- **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).