Muχe

A Search for Familons in Muon decay using HPGe detectors

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Potential Fermilab Muon Campus & Storage Ring Experiments
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Introduction to the Familon [1,2,3,4]

Major puzzle: why do quark and lepton families replicate?

Postulate some family symmetry:

(1) discrete symmetries

(2) continuous and local

(3) continuous and global

Any number of symmetry groups or any combination of (1),(2),(3).

Family symmetries must be spontaneously broken, options are:

(1) Domain walls: Can't be studied in particle physics labs

(2) Continuous symmetries are highly constrained. From k^0- $\overline{k^0}$ mixing

(3) Global symmetry implies massless Nambu-Goldstone bosons, called "Familons".

(a)Familons are from the spontaneously broken family symmetry.

(b)This family symmetry may be either Abelian or non-Abelian.

Introduction to the Familon [1,2,3,4]

The couplings of familons at low energies are determined by the non-linear realization of the family symmetry. The couplings are:

$$\frac{1}{F}\,\partial_\mu f^a \bar{\varphi}_L^i \gamma^\mu T_{ij}^a \varphi_L^j$$

Where F is the family symmetry breaking scale, i.e., the familon decay constant, f^a are the familons, T^a are the generators of the broken symmetry, and the φ_L are fermion fields in terms of which the flavor symmetry is defined. The strength of the familon coupling is therefore inversely proportional to F and can be constrained for a given family symmetry group in a model-independent manner

Familon Search Experiment

$$\mu^+ \text{->} e^+ + \chi$$

Motivations

- 1. Coupling factor

---Derivative coupling, $\sigma \sim g$, not dependent on mass

- 2. Plot from review paper [9]

--- Muχe searches in magnetic spectrometers blind spots

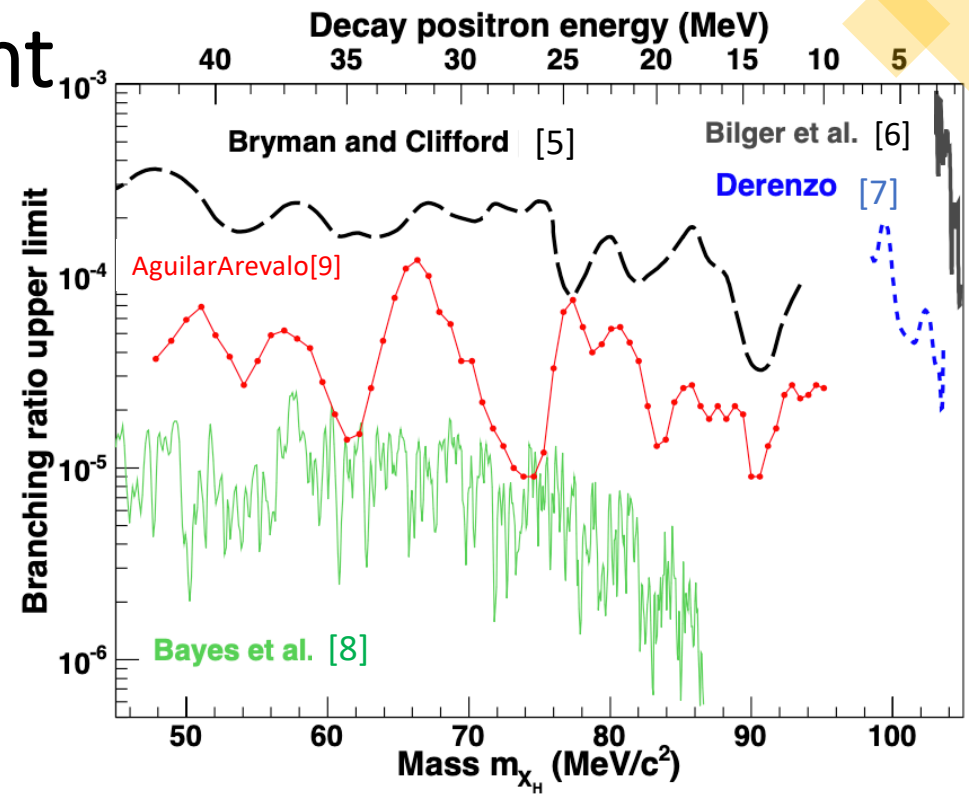
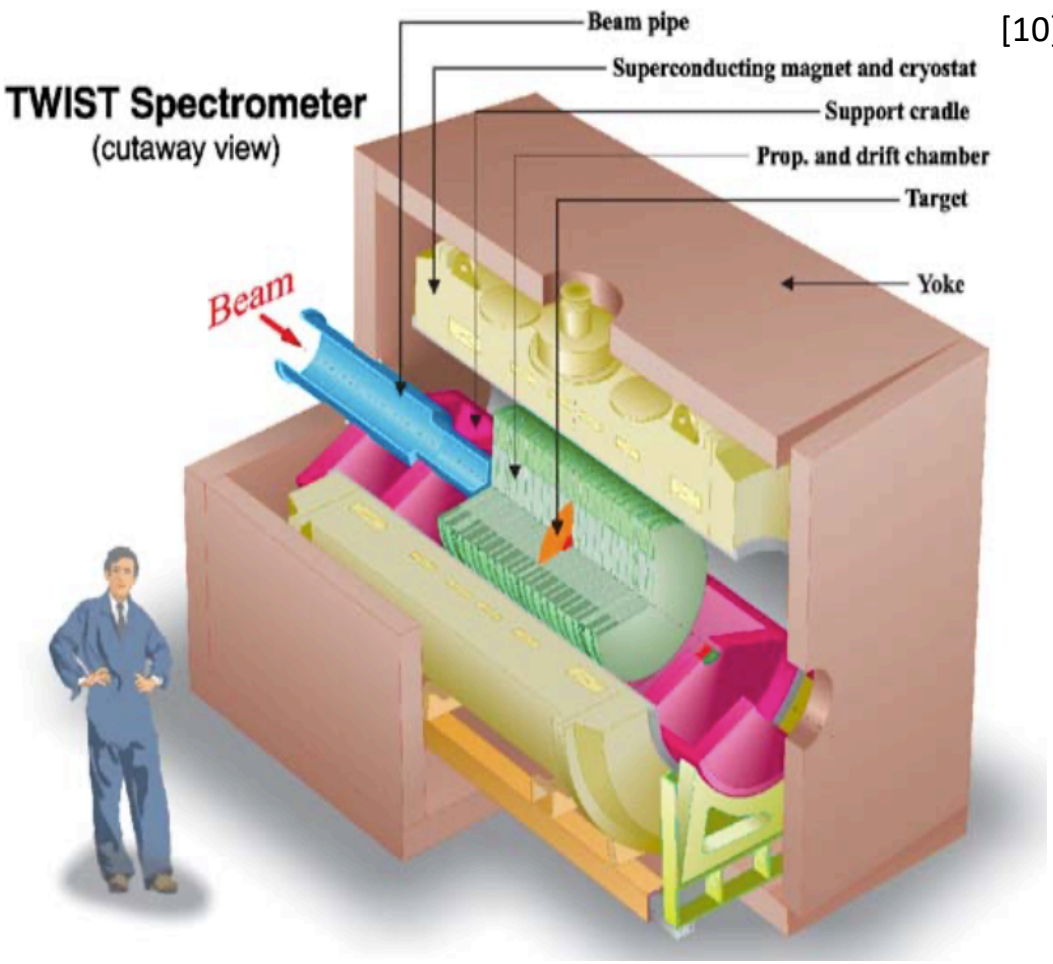


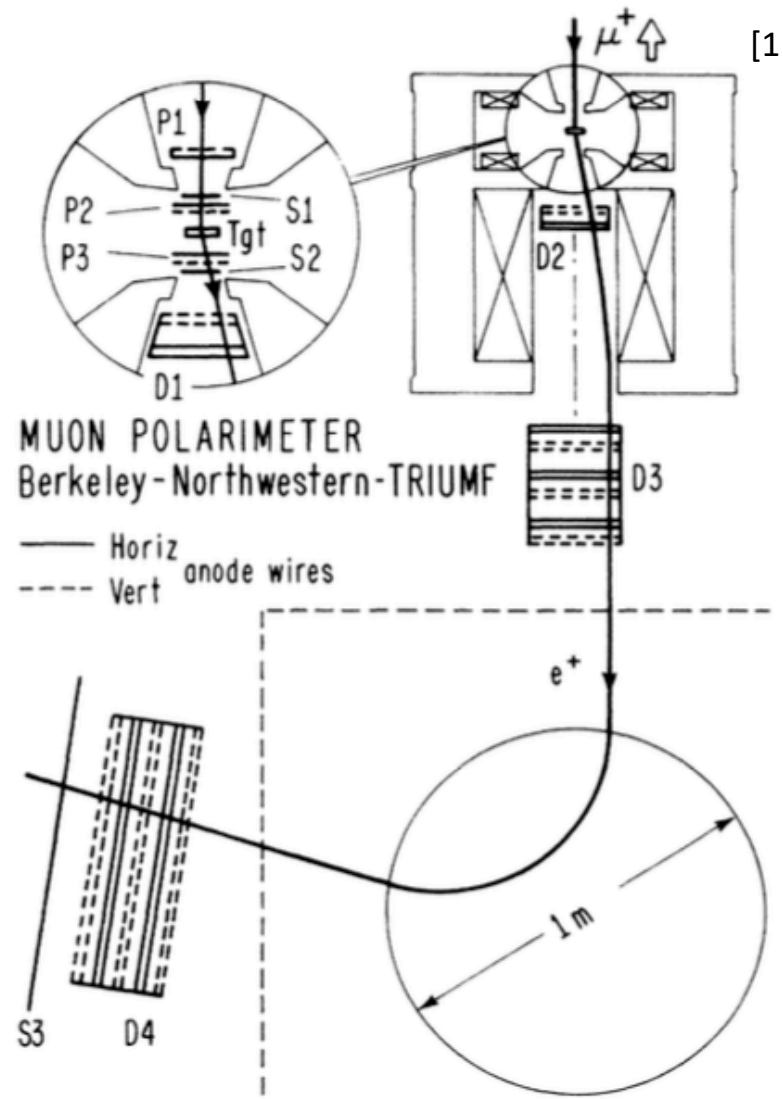
FIG.1. Summary of the experimental upper limits on the $\mu^+ \text{->} e^+ + \chi$ branching ratio.

Magnetic spectrometer blind spots

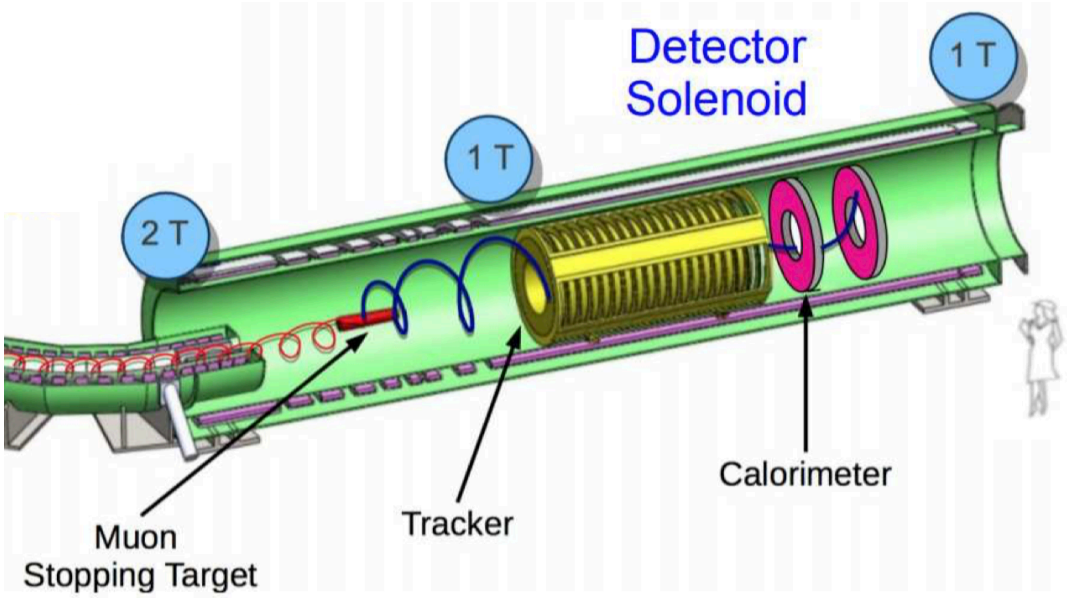
[10]

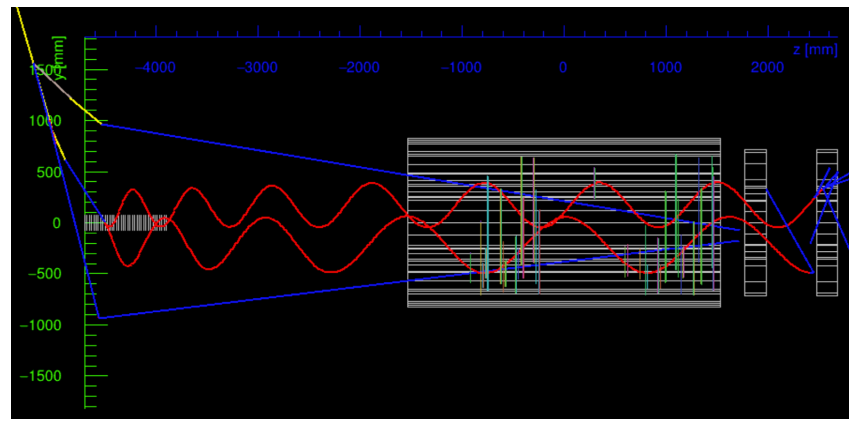


[11]



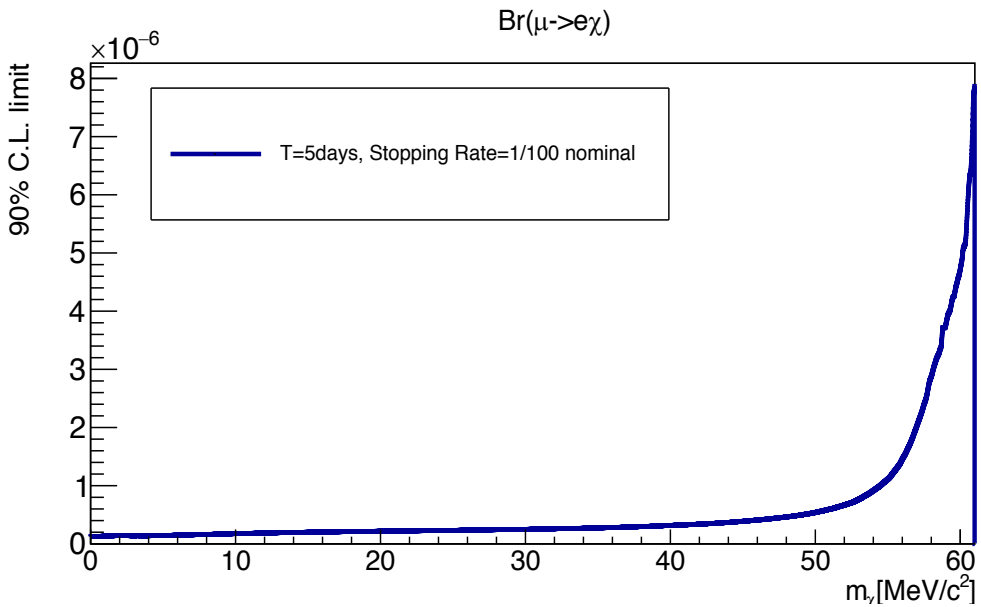
Mu2e Tracker

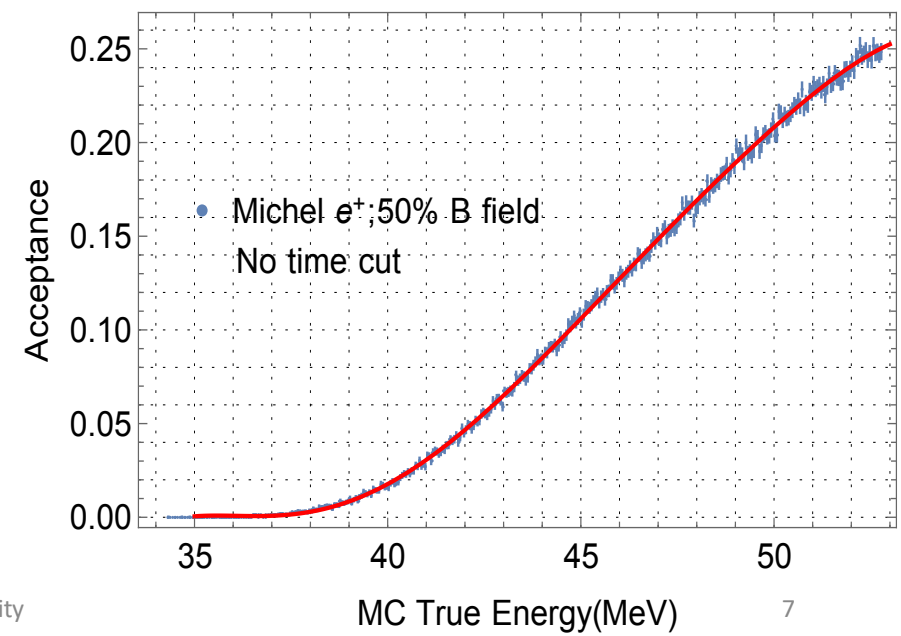




Search for Familon in Mu2e Experiment

- Using data from a Mu2e $\mu^+ \rightarrow e^+ \nu\nu$ calibration run at 50% B-field
- Thesis Project of Shihua Huang
- Sensitive to mass range <~60 MeV/c^2, complementary to this search.





Muχe

A Familon Search Experiment Using HPGe Detectors

D. Koltick, S. Huang, J. Chen, F. Bergin, H. Cao

Positive Muon Decay $\mu^+ \longrightarrow \chi_{Familon} + e^+$

Search for Familon's in the Magnetic Spectrometers Blind Spot

Familon's Mass Range from 90 to 105 MeV

Derenzo-Chicago Bubble Chamber[7]

Studied
2 million μ^+ decays

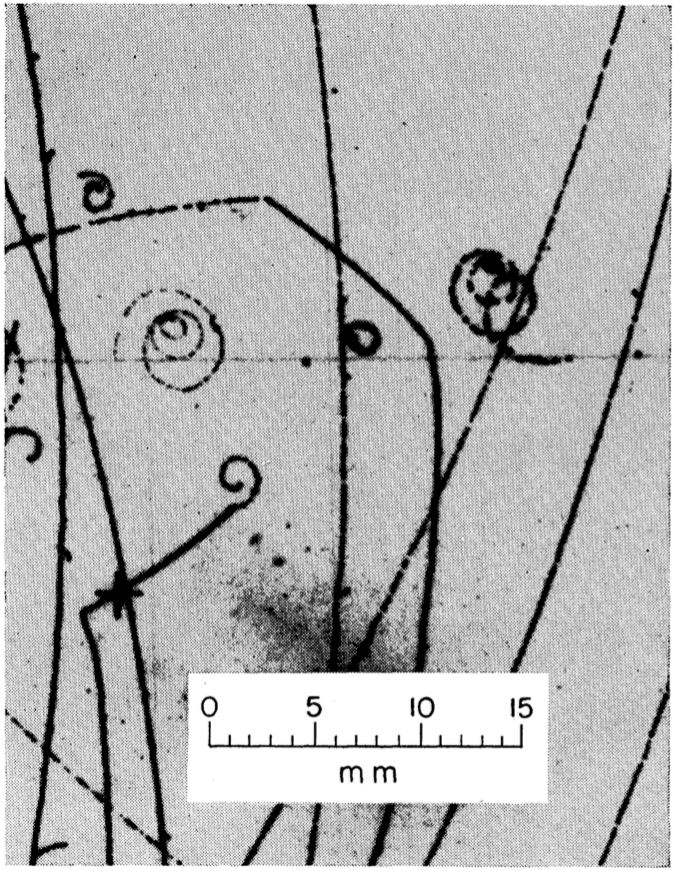
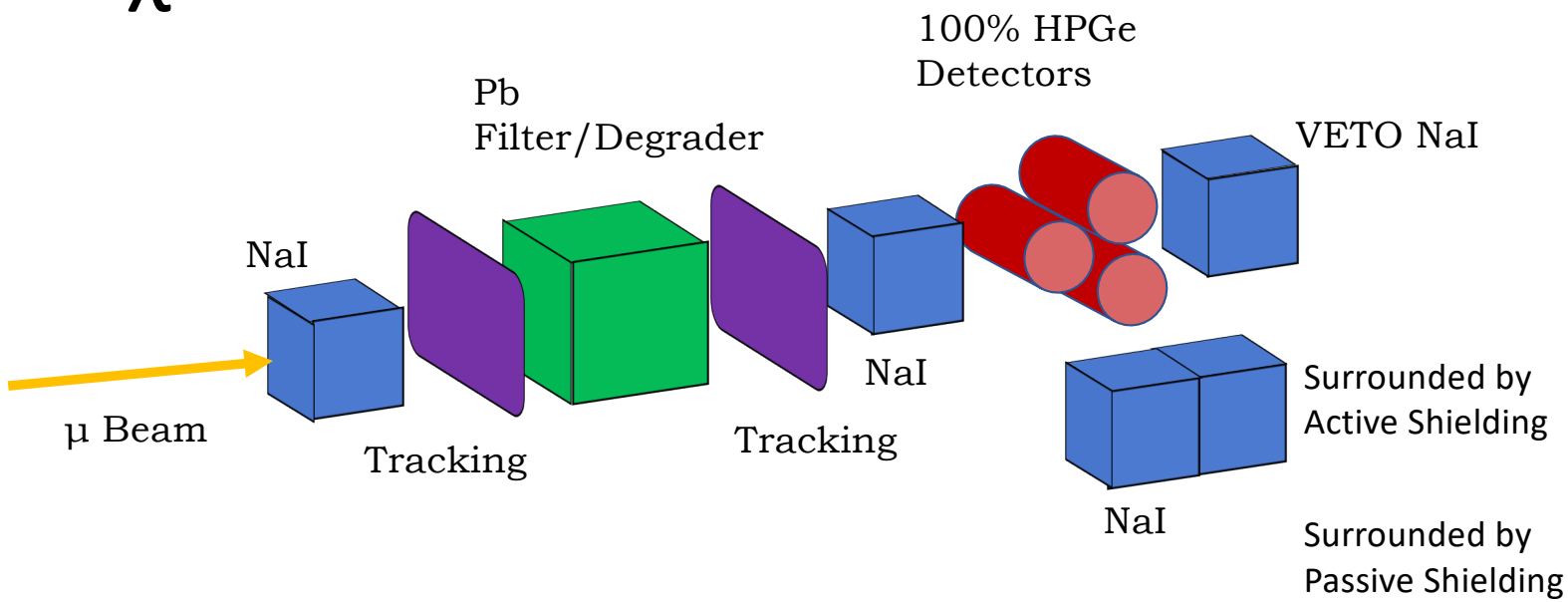


FIG. 3. Sample events. Picture shows two 1.4-MeV/c internal-conversion electrons emerging from the Mylar strip (faint horizontal line), and two $\pi^+-\mu^+-e^+$ decay chains. One of the positrons has a momentum of 0.7 MeV/c.

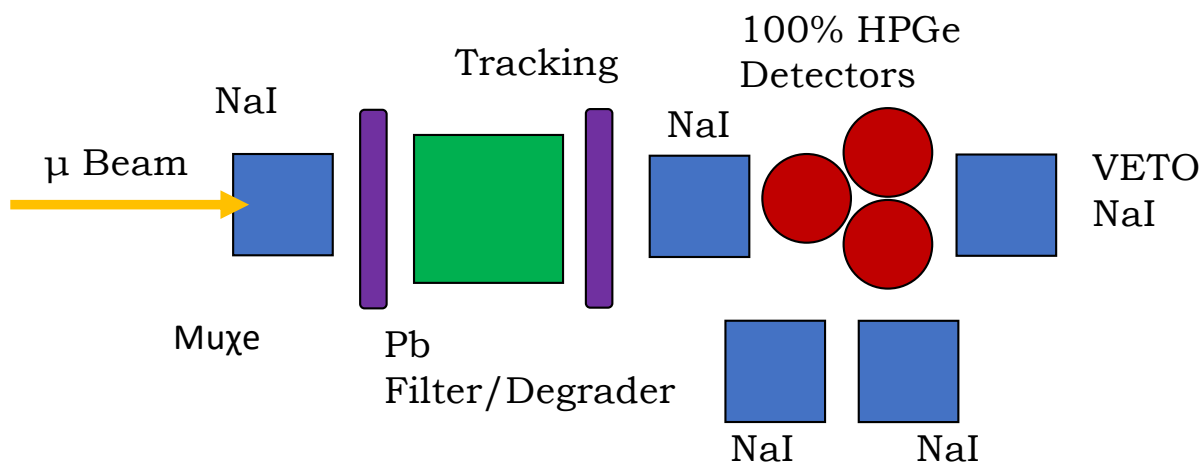
Muχe


100% HPGe
Detectors
Pb
Filter/Degrader
VETO NaI
NaI
μ Beam
Tracking
Tracking
NaI
Surrounded by
Active Shielding
NaI
Surrounded by
Passive Shielding

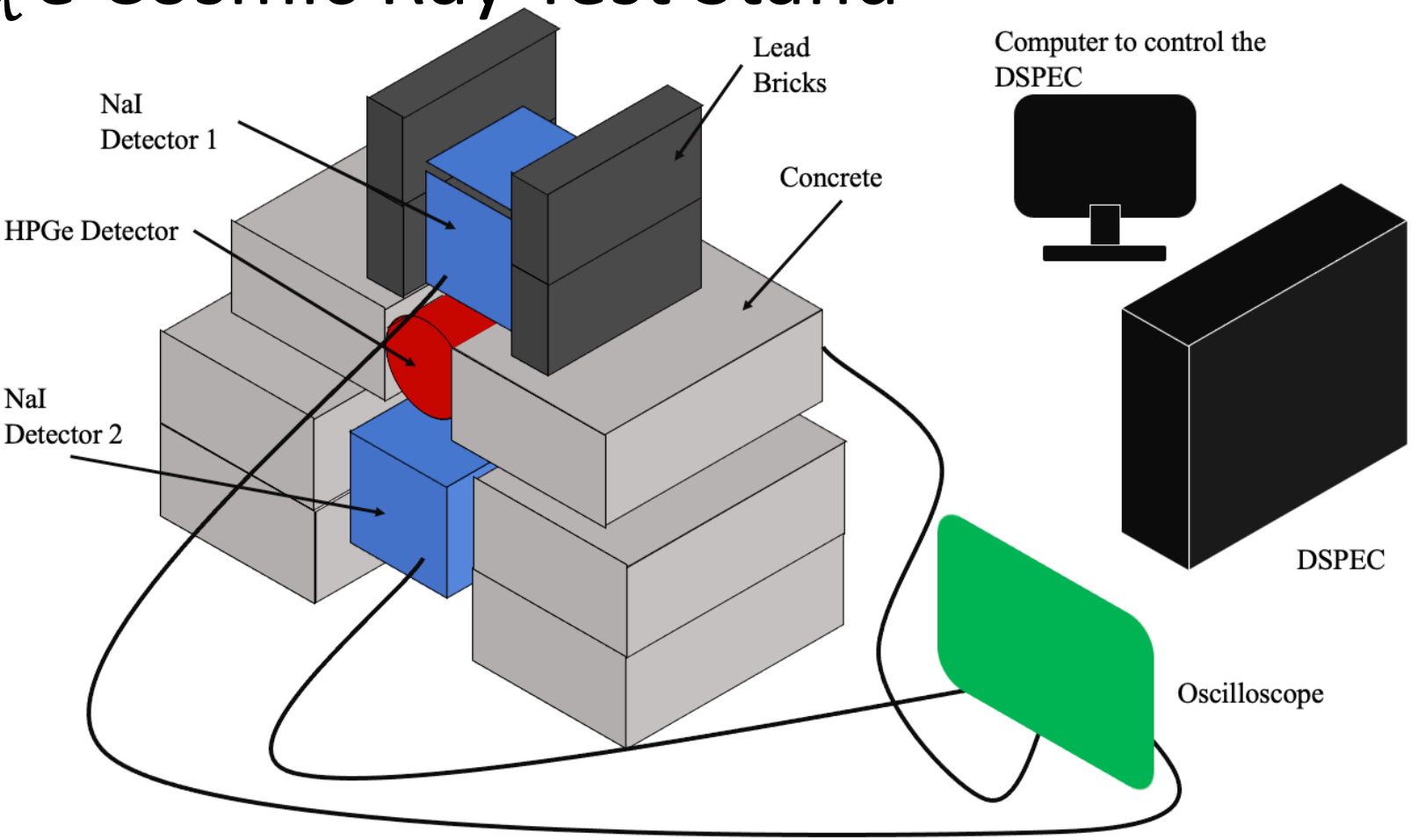
Muχe

Fermilab Fast μ+ Beam

- Trigger detectors have ~100 MeV Signals, Large and Distinguishable from Background Signals
- Thick Degrader ⟶Filters Background
- Large Pulses ⟶ Excellent Timing
- Active Shielding ⟶ Complete Energy Measurement
- Passive Pb Shielding ⟶ Reduced Background
- Charged Particle Tracking ⟶ Points to Estimated Stopping Location.

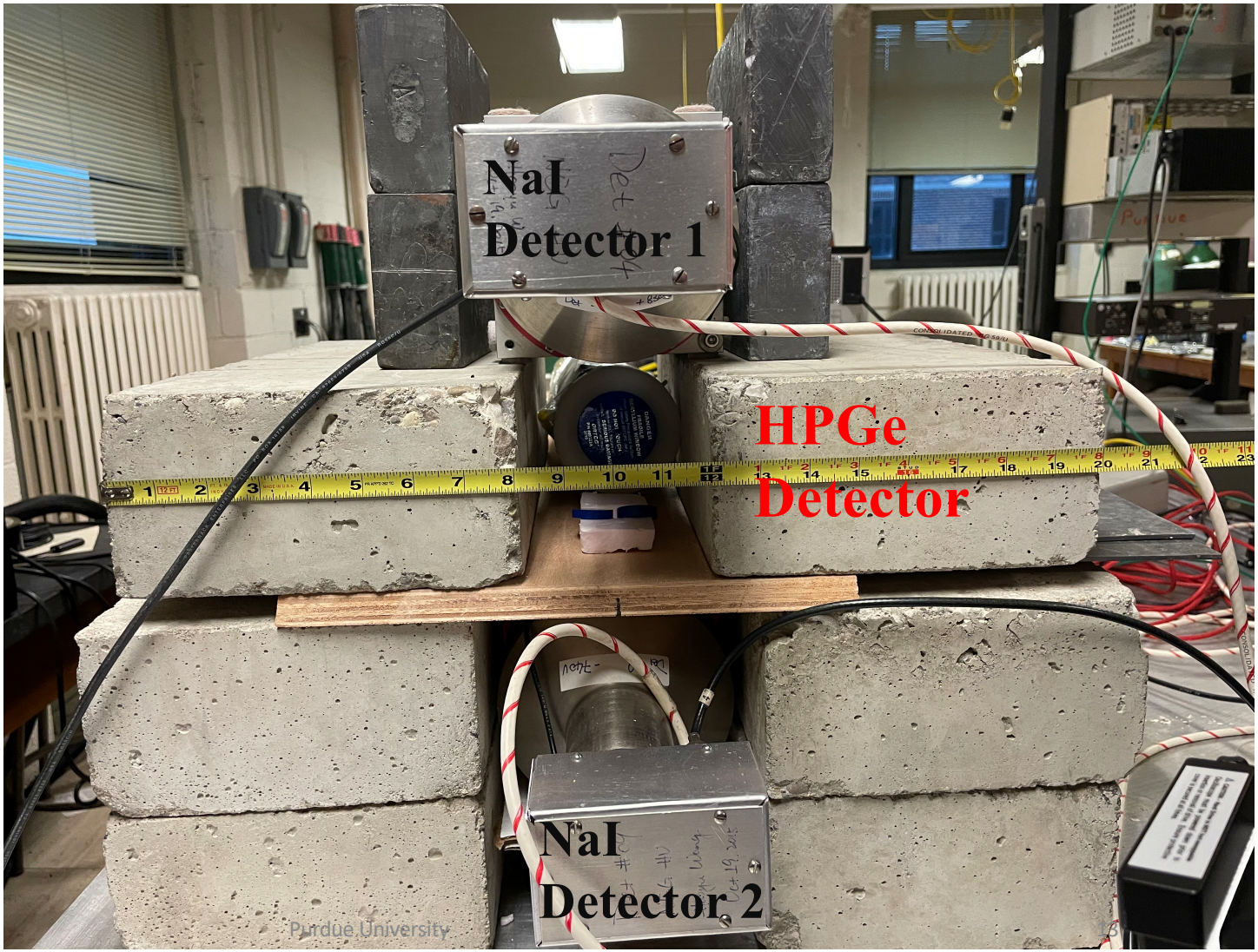


Muχe Cosmic Ray Test Stand

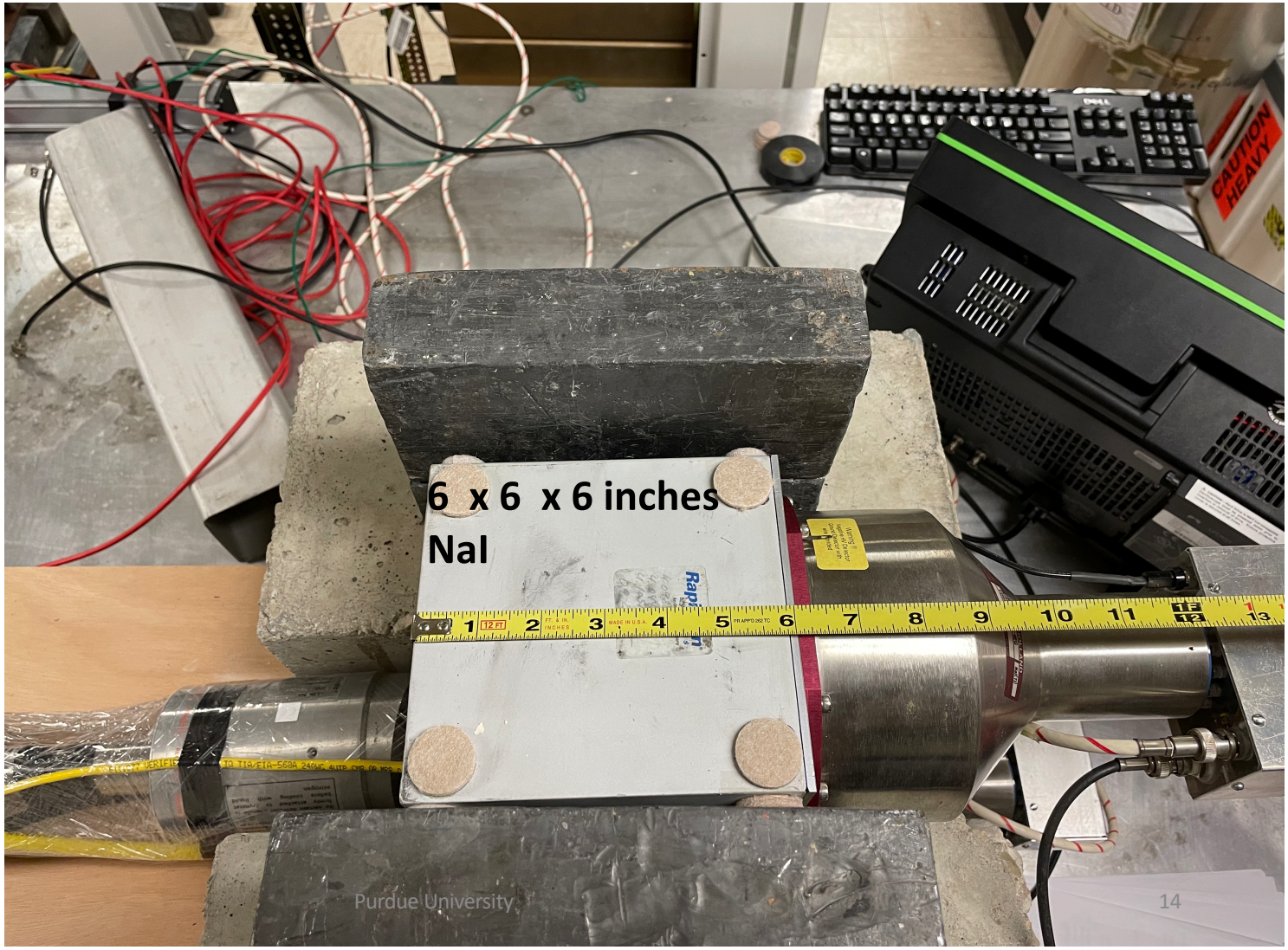


Muχe Cosmic Ray Test Stand at Purdue University

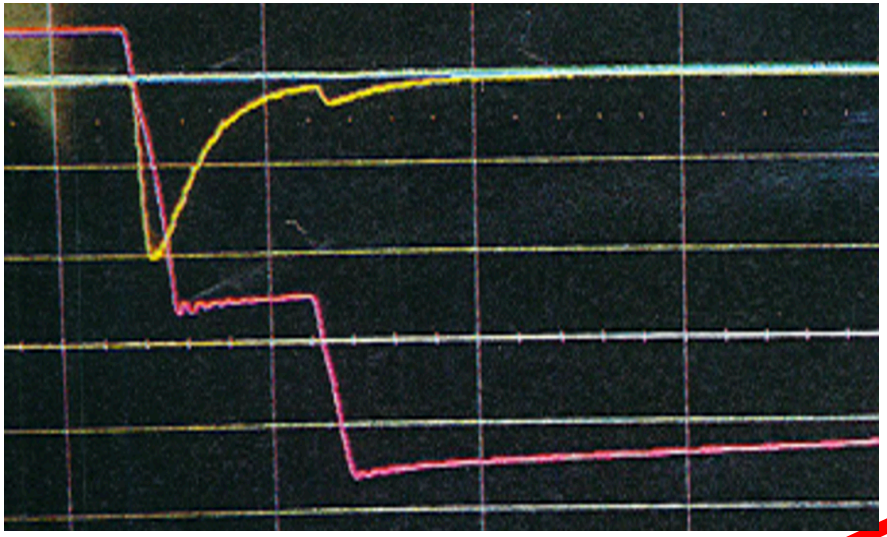
50% HPGe



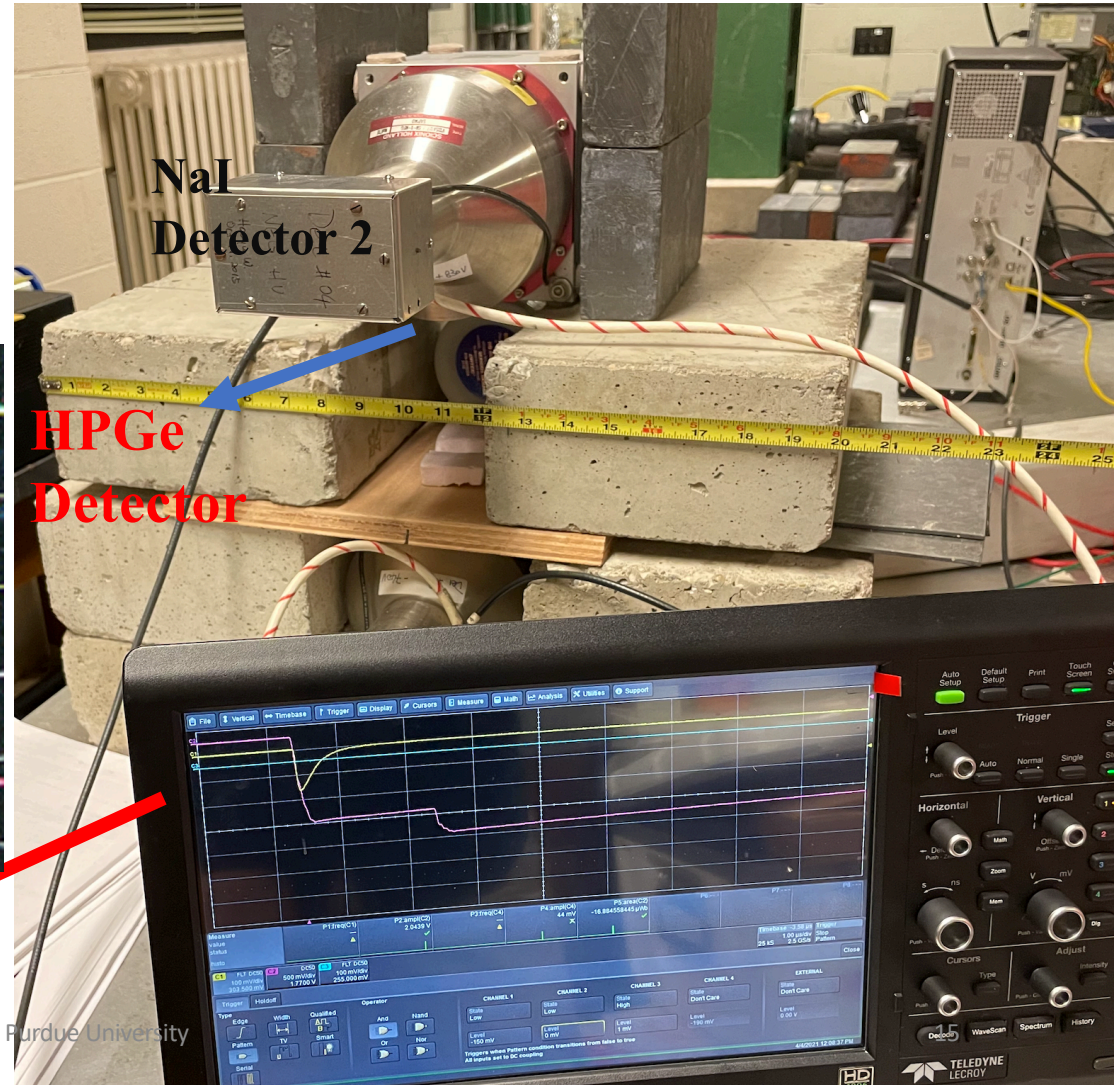
Large NaI Trigger/Veto Detectors



Muχe Cosmic Ray Test Stand at Purdue



Stopped muon with decay event



Cosmic Ray Stopping Muon Trigger

NaI detector 1 + HPGe **not** NaI detector 2

NaI detector 1, 10~20MeV trigger

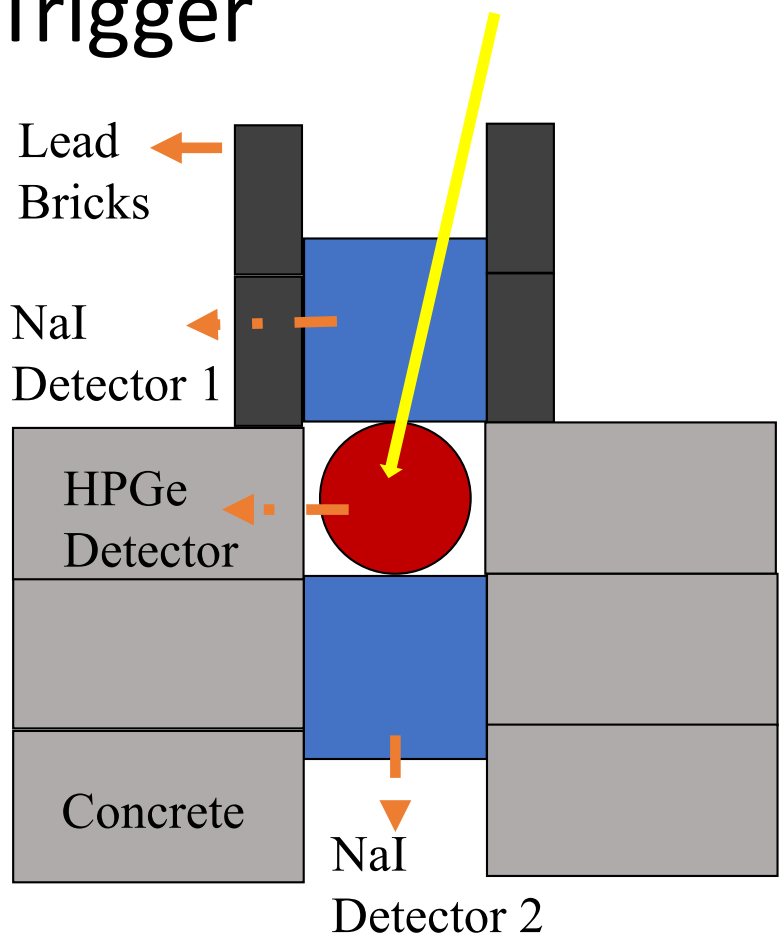
HPGe Trigger ~10 mV

NaI detector 2 is a trigger veto set at 0 MeV

Collected File numbers: 161802
Number of stops found: 1837

$$\frac{\text{stops}}{\text{triggers}} = \frac{1837}{161802} = 0.0114$$

Want to improve the stops/triggers ratio to 0.1



Front view

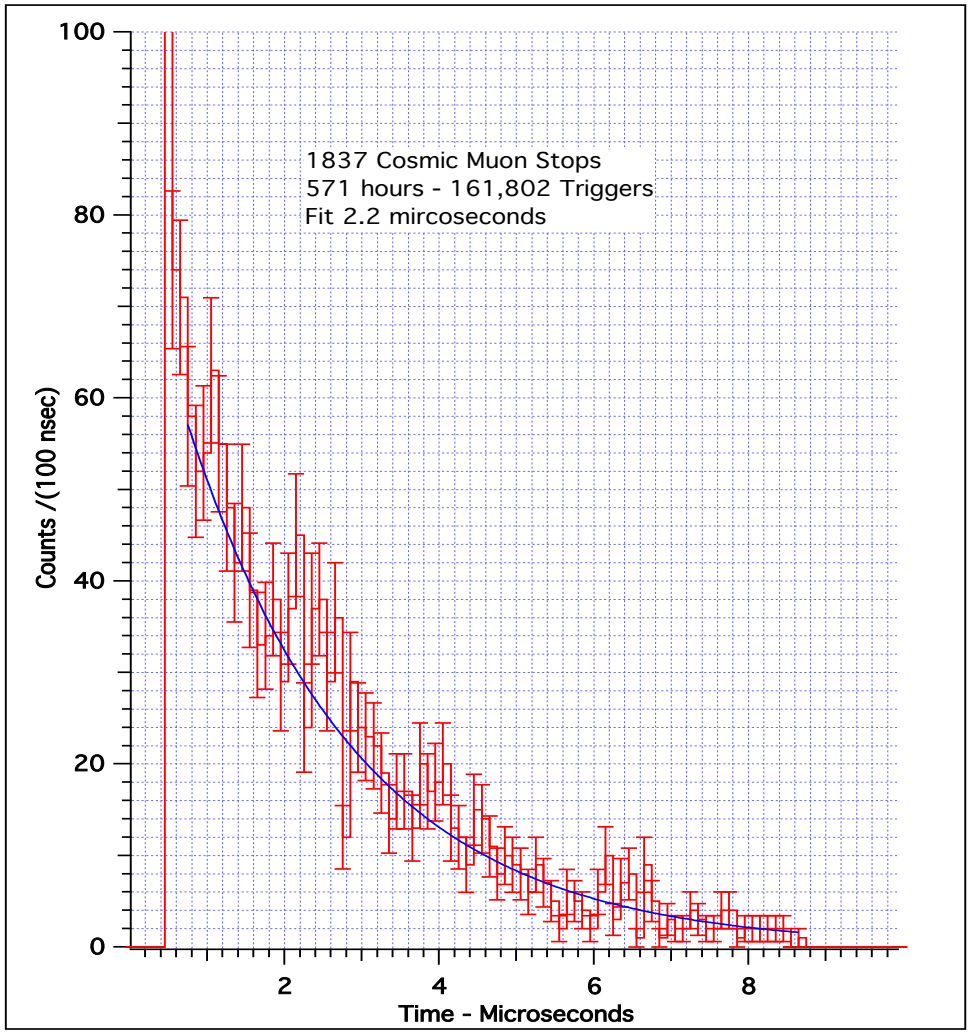
Mu Lifetime in Cosmic data

- Fit background per bin: 0.1 ± 0.4
- Estimated the background per bin:

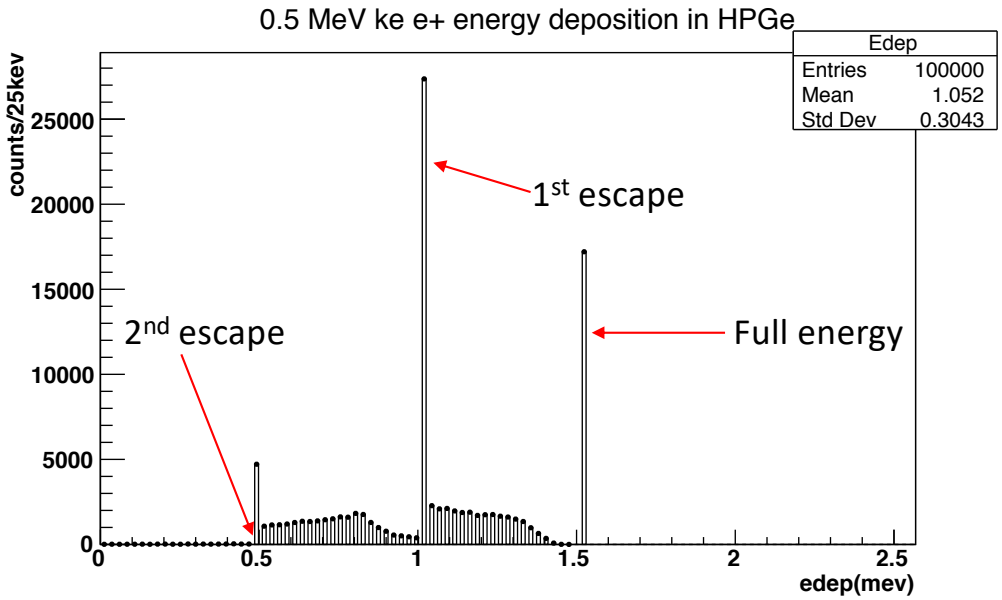
Events x DAQ window x HPGe background rate

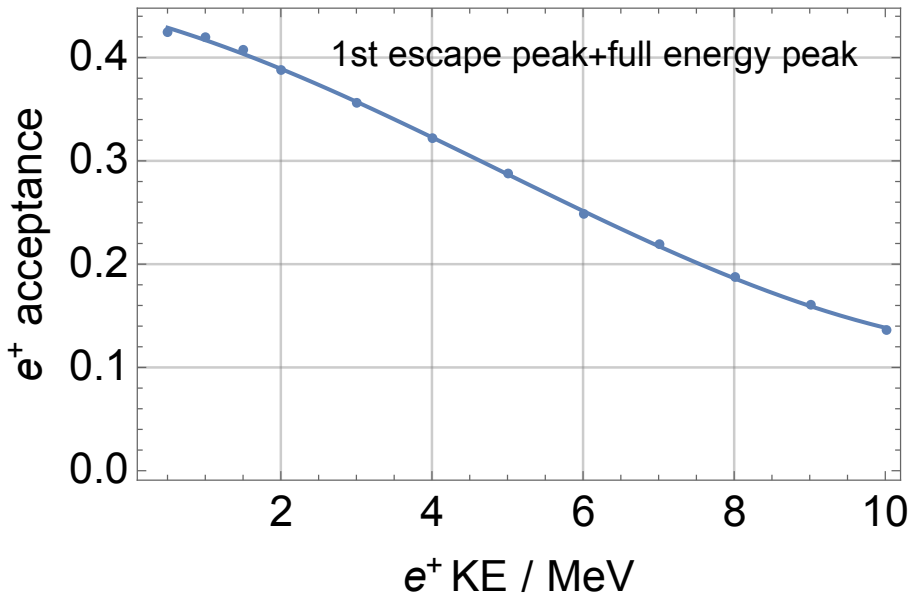
1.61×10^5 x 8 us x 17cps

= 0.27 counts/bins



The e^+ Signal and Energy Acceptance





GEANT simulated energy deposition of mono-energetic positrons and acceptance in a 100% HPGe detector. (Left) Spectrum of 10^6 e^+ having KE = 0.5 MeV and (Right) Estimated acceptance combining the 1st escape peak(KE+511keV) and the full energy peak(KE+2x511keV) over the e^+ energy range from 0-10MeV.

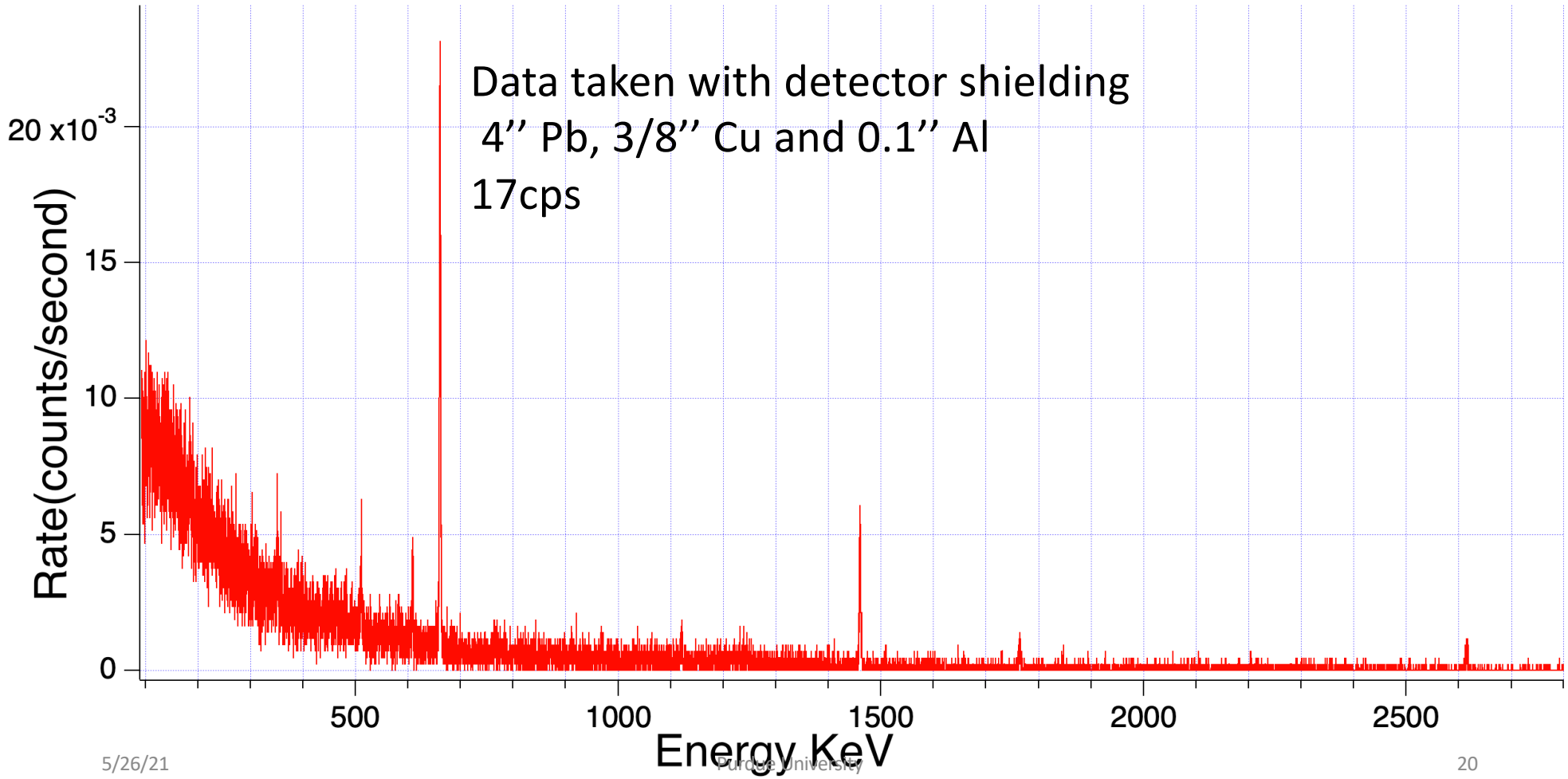
Define Search Limits

- The 'search window' is the combination, positron's 1st escape peak plus the full energy peak,

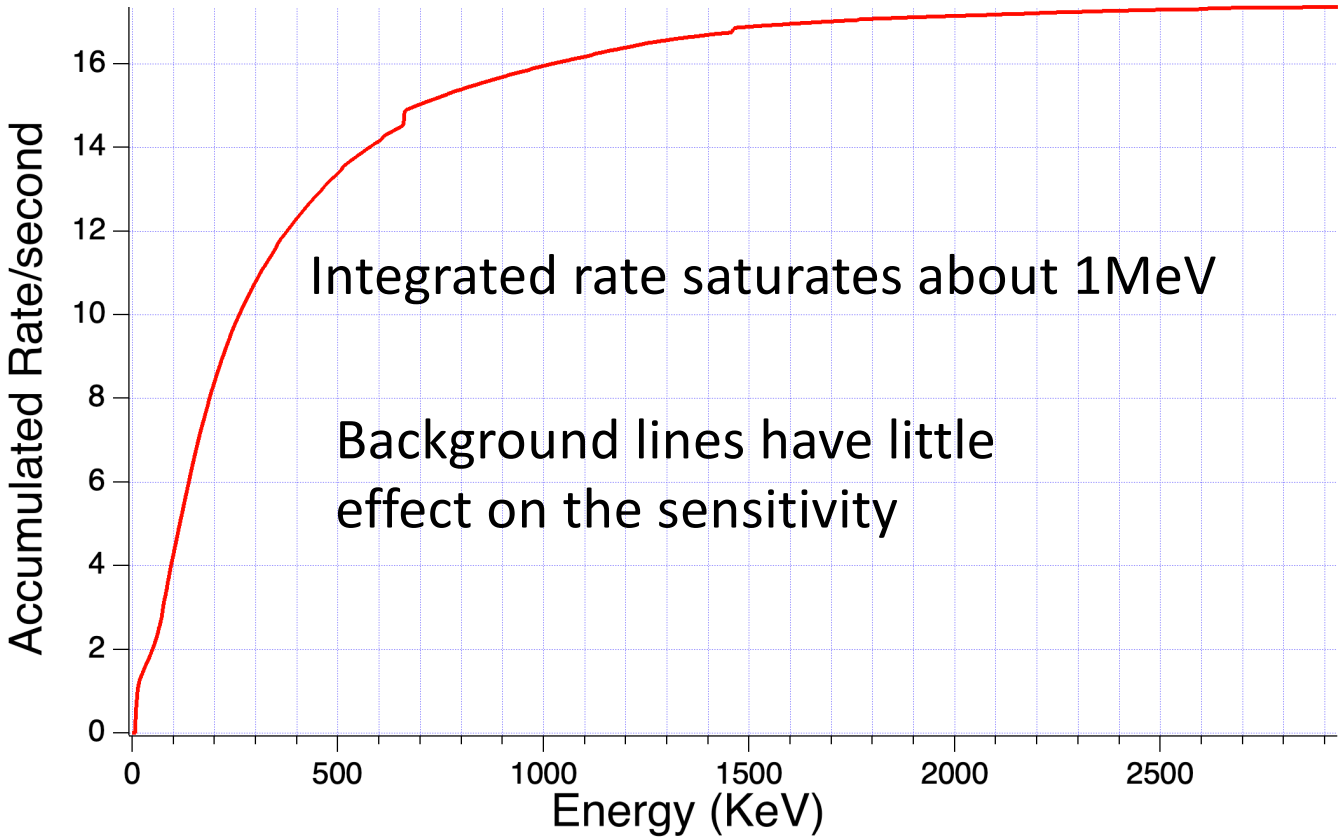
$$window = \left[E_{1st-escape} \pm 2\sigma\right] + \left[E_{full-energy} \pm 2\sigma\right]$$

- The **90% confidence level** is estimated assuming a signal with an amplitude equivalent to a 1.28 σ effect in this search window.
- The **'discovery' limit** is set to 5σ in the combined 1st escape peak and full energy peak window.

Background from room



Integrated HPGe Rate as a Function of Energy



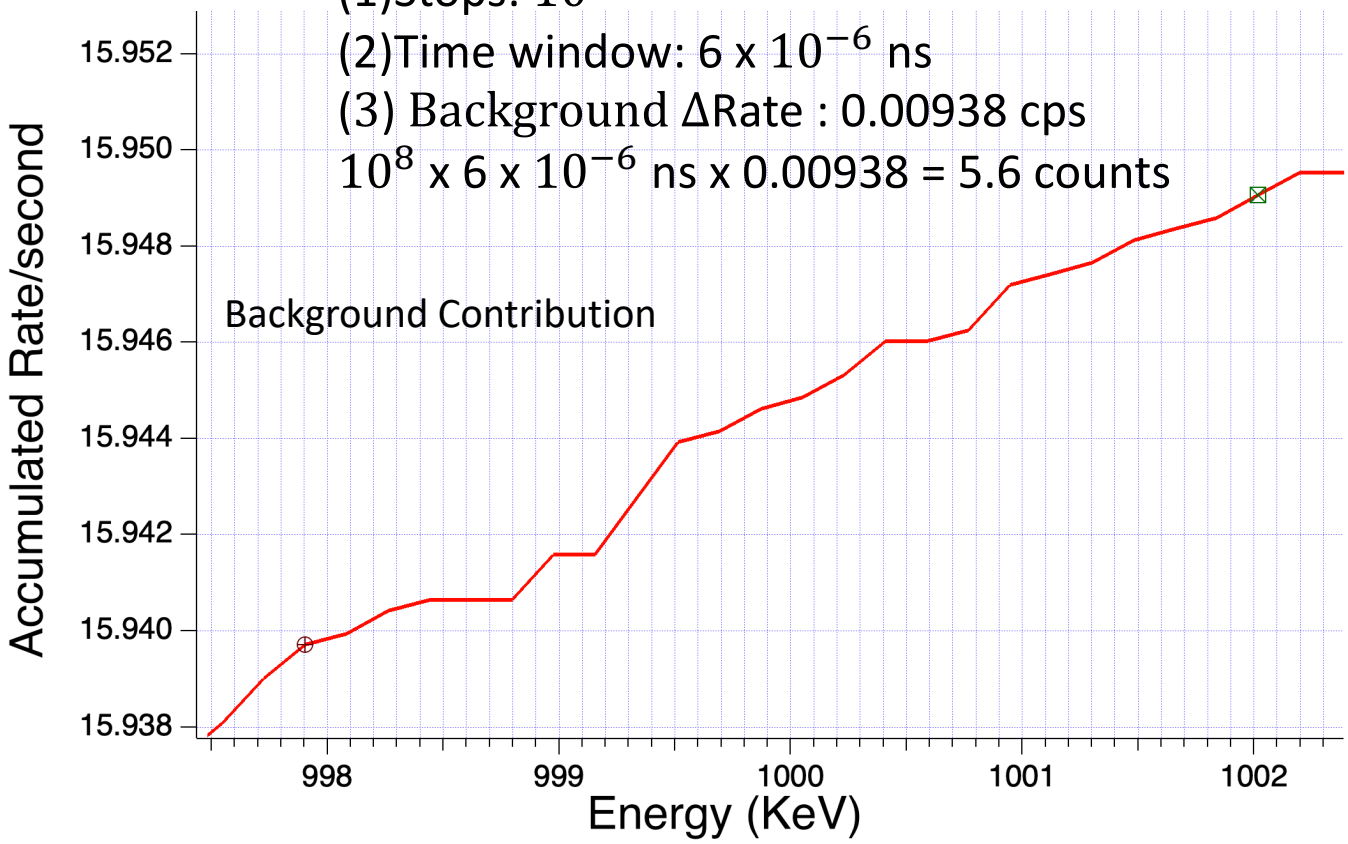
Example Case: Signal at 1 MeV and Search Window $\pm$ 4

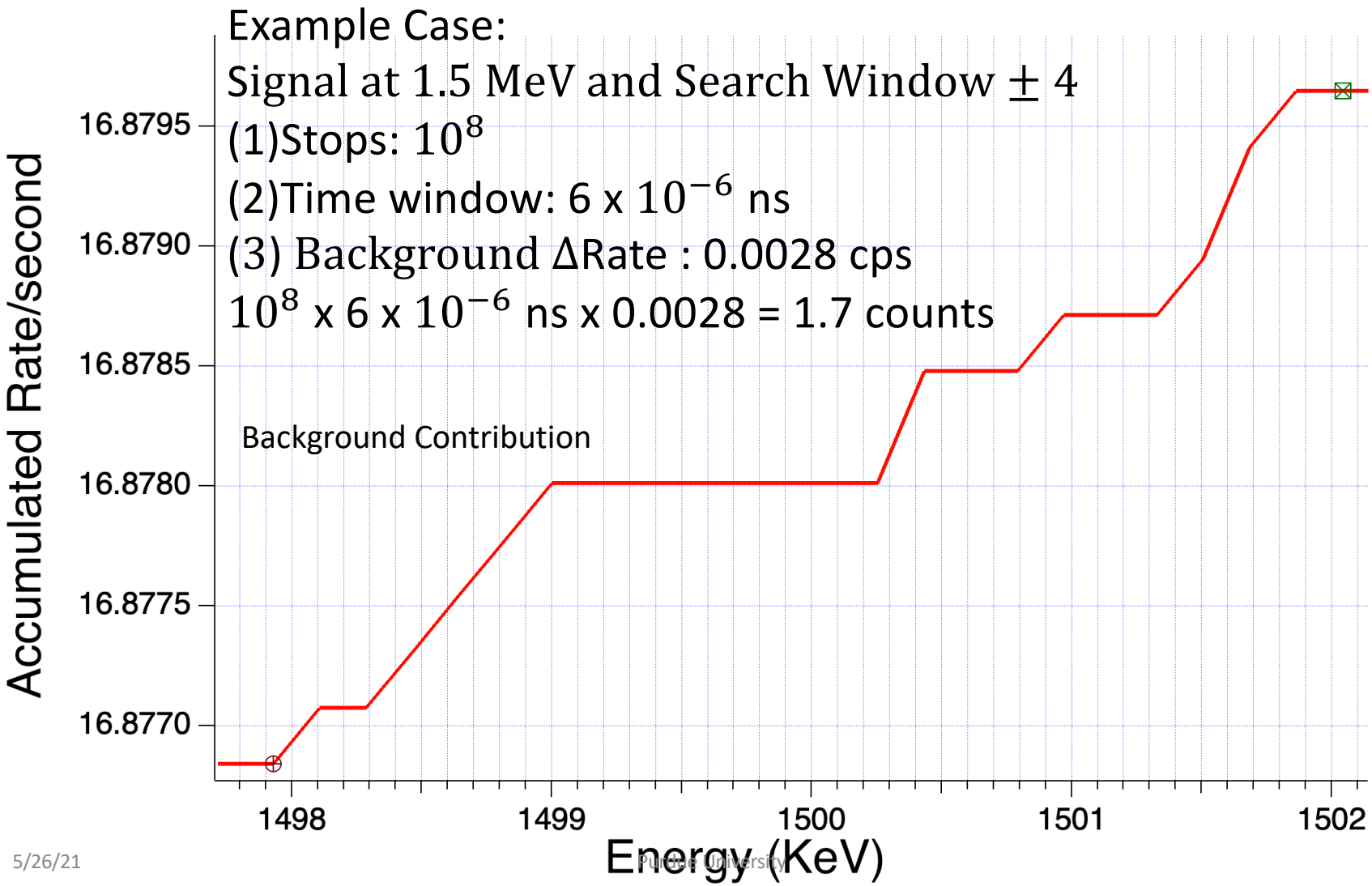
(1)Stops: 10^8

(2)Time window: 6 x 10^{-6} ns

(3) Background ΔRate : 0.00938 cps

10^8 x 6 x 10^{-6} ns x 0.00938 = 5.6 counts




Example Case:
Signal at 1.5 MeV and Search Window $\pm$ 4
(1)Stops: 10^8
(2)Time window: 6 x 10^{-6} ns
(3) Background ΔRate : 0.0028 cps
10^8 x 6 x 10^{-6} ns x 0.0028 = 1.7 counts
Background Contribution
Accumulated Rate/second
16.8795
16.8790
16.8785
16.8780
16.8775
16.8770
1498
1499
1500
1501
1502
Energy (KeV)

Background counts

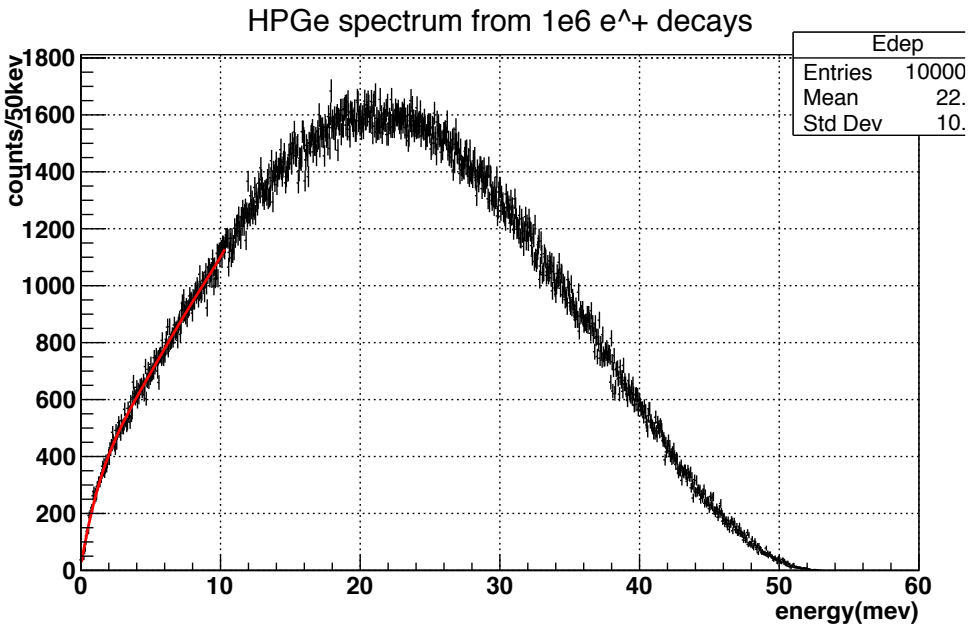
- **Trigger at $\frac{100}{1}$ (for Cosmic Ray)**

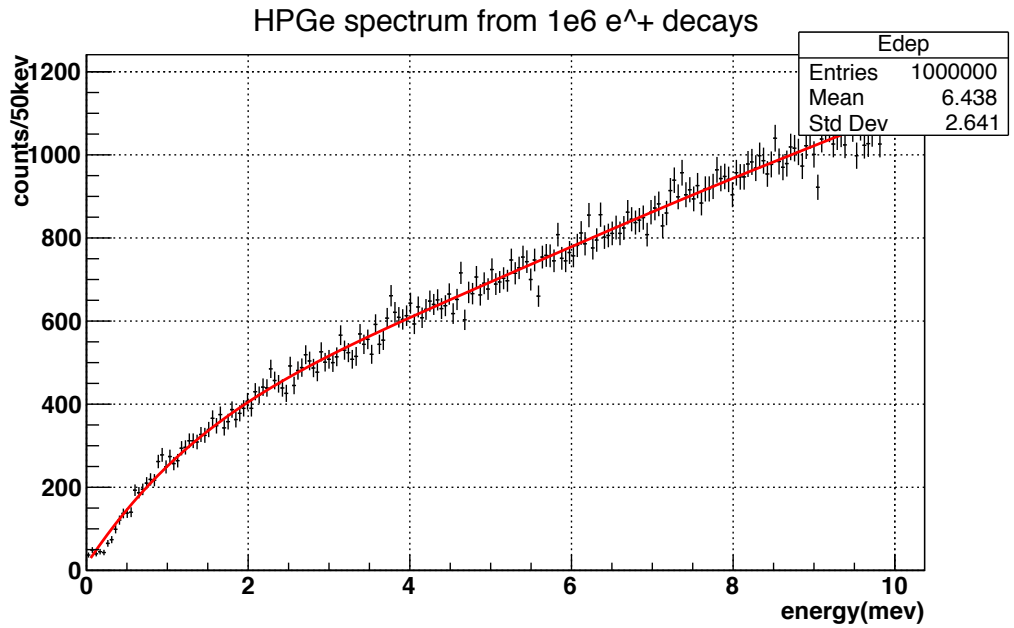
10^{10}x 6 μs x 0.01215 =729 counts background at the search region 1$\sim$ 1.5MeV

- **Trigger at $\frac{10}{1}$ (Goal at Fermilab)**
- 10^{9}x 6 μs x 0.01215 =73 counts background at the search region 1$\sim$ 1.5MeV

- Will be reduced by rejection of double ” decay signals”

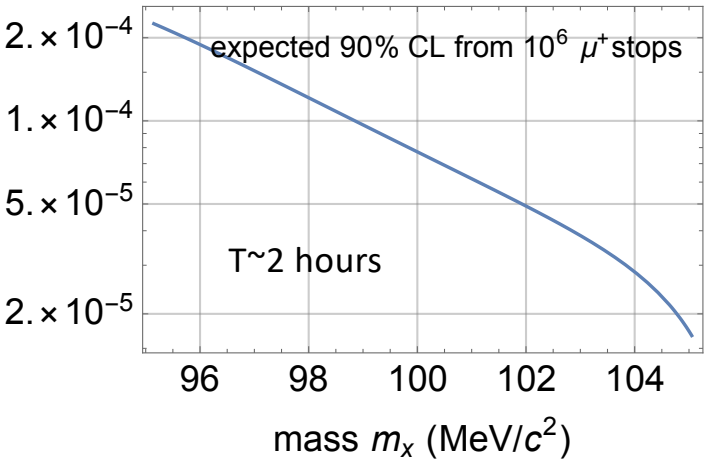
Shape of Michel Decay Backgrounds

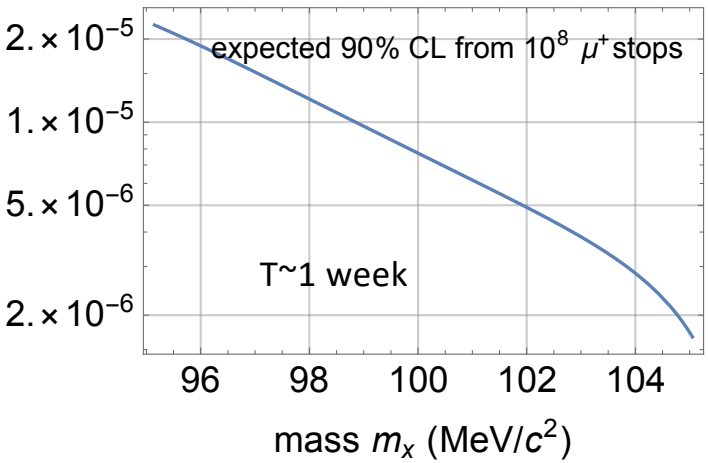


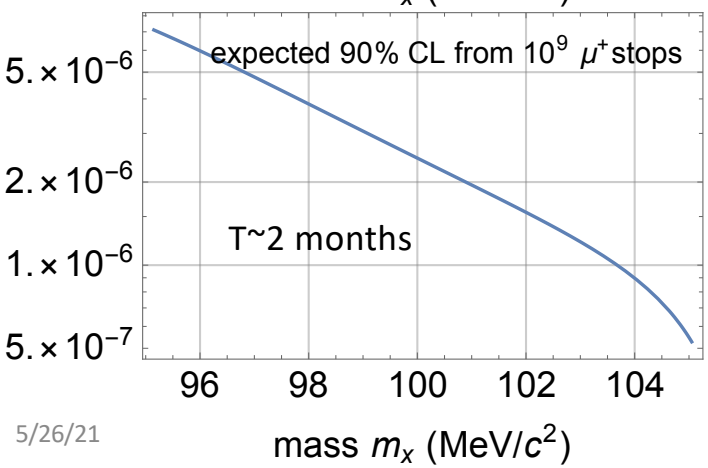


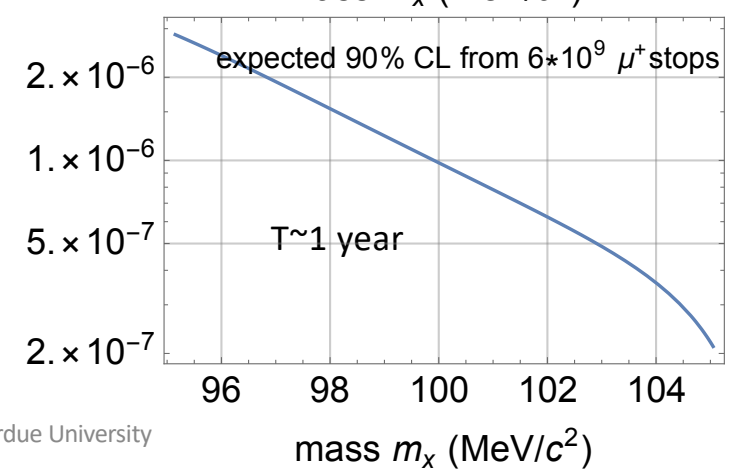
GEANT simulation of energy deposition of Michel decay positrons inside a 100% HPGe detector, showing (Left) the full decay energy range and (Right) the energy range of interest for this analysis.

Expected 90% C.L. Sensitivity

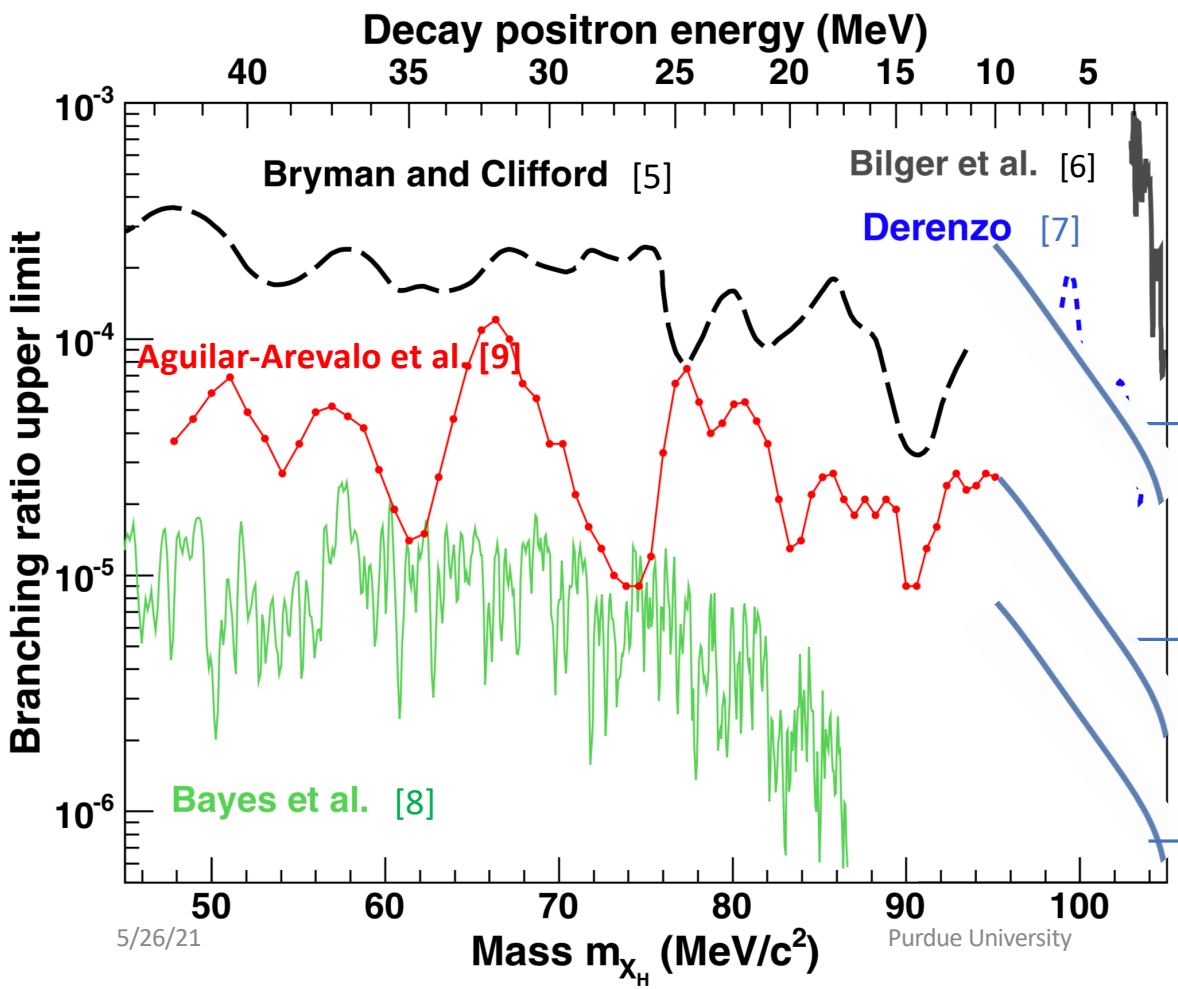


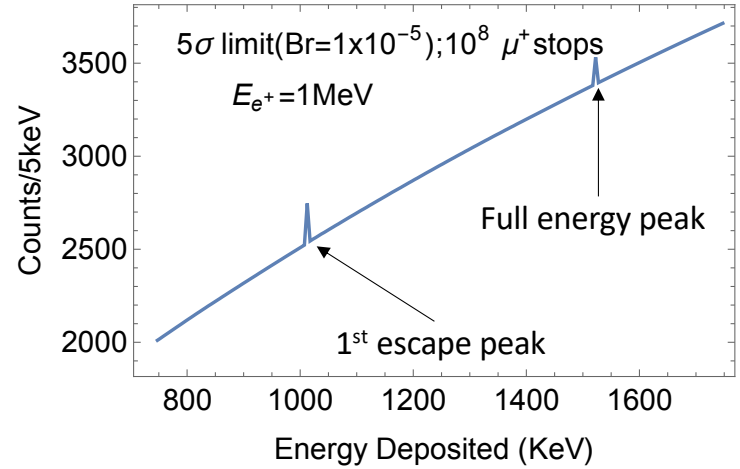






Compare with existing limits



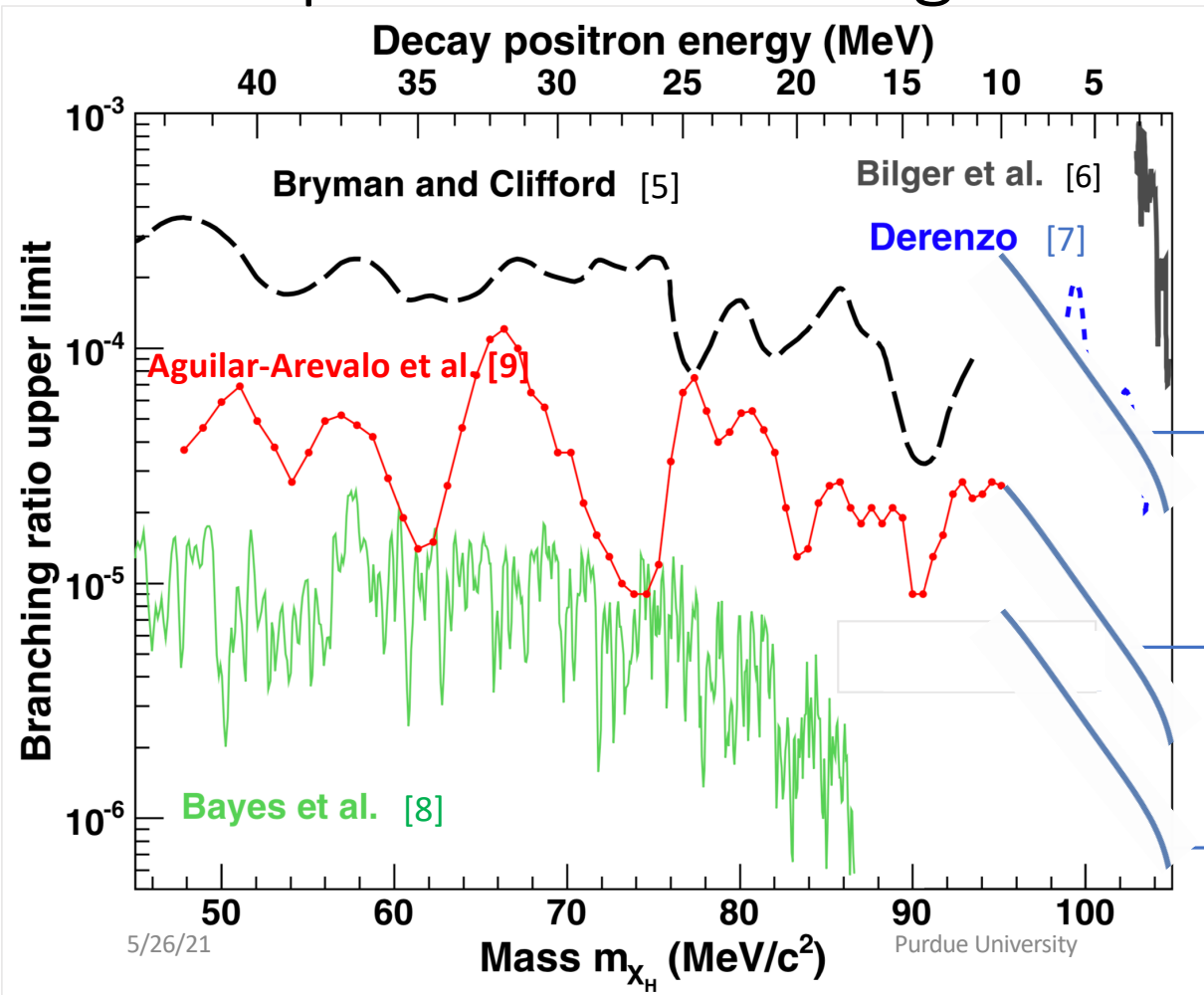


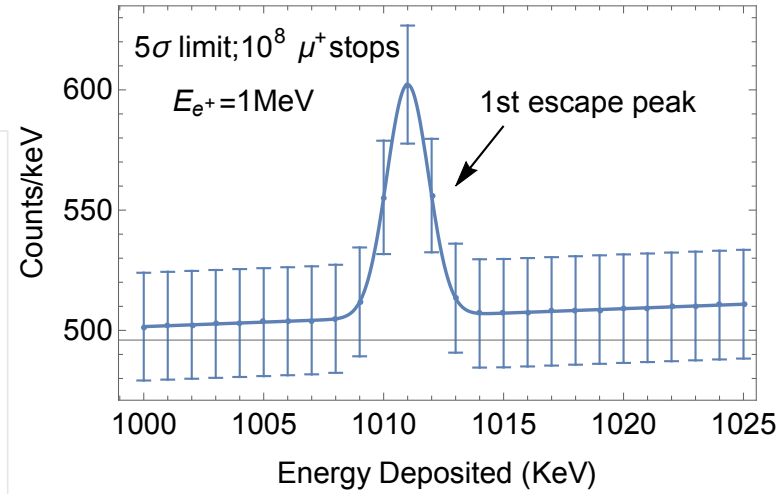
Expected 90% CL From 10^6 μ^+ stops — 2 hours

Expected 90% CL From 10^8 μ^+ stops — 1 week

Expected 90% CL From 10^9 μ^+ stops — 2 months

Compare with existing limits





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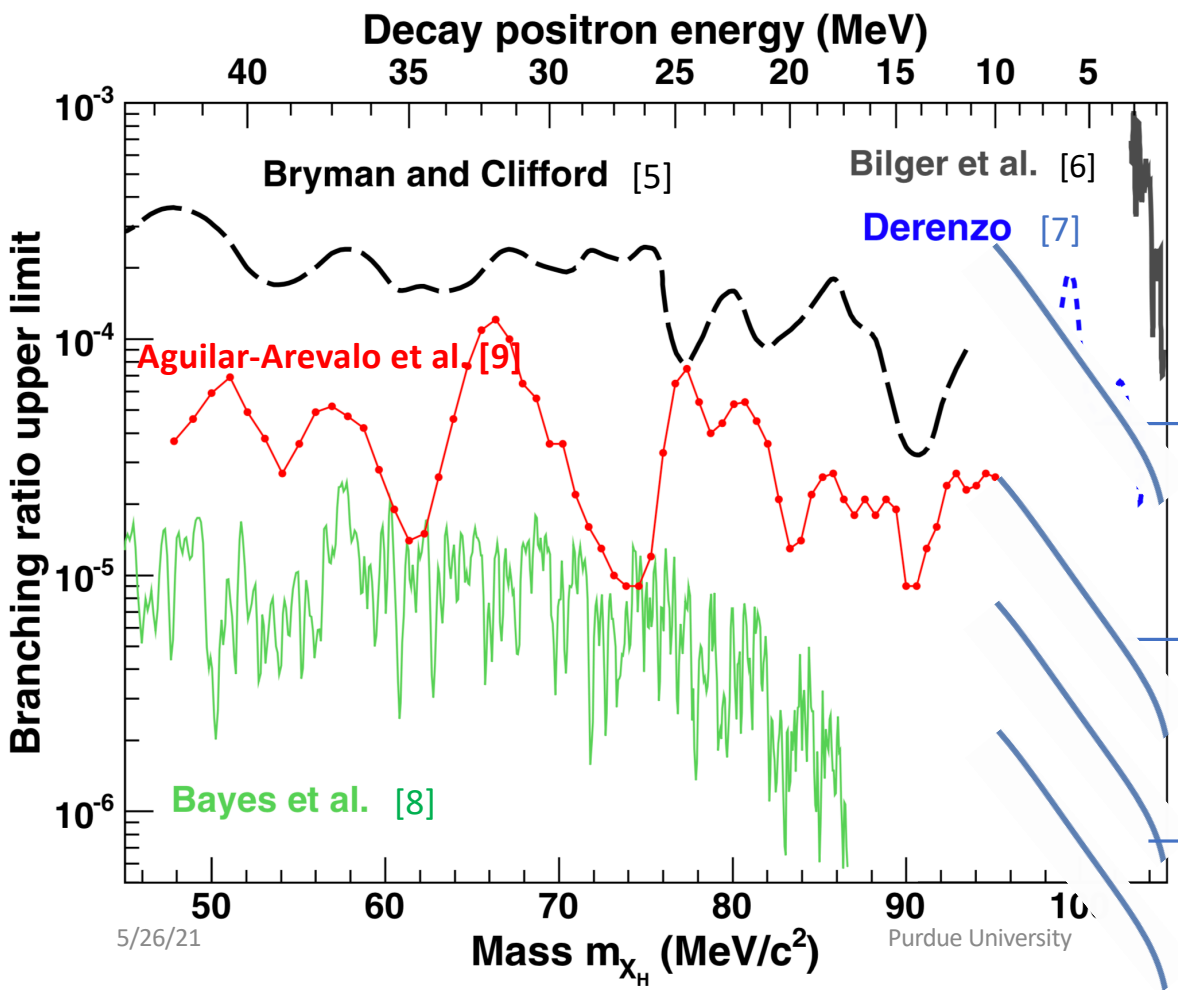

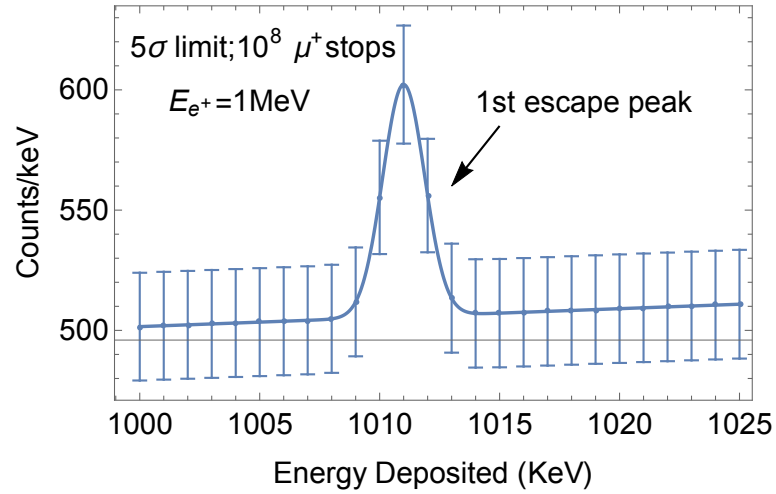

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Positive Muon Decay $\mu^+ \longrightarrow \chi_{Familon} + e^+$

Search for Familon's in the Magnetic Spectrometers Blind Spot

Familon's Mass Range from 90 to 105 MeV

Branching Ratio Sensitivity Limits for 1 year of data collection 10^{-6} to 10^{-7} .

Reference

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