A Familon Search Using the Mu2e Calibration Run

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Introduction to the familon

Major puzzle: why do quark and lepton families replicate?

Postulate some family symmetry[1,2]:

(1) discrete symmetries

(2) continuous and local

(3) continuous and global

Family symmetries must be spontaneously broken. The spontaneous breaking of **continuous global symmetry** implies massless Nambu-Goldstone bosons, called "familons".

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

(b)This symmetry can also be explicitly broken, making familons massive.

Familon search experiments: μ^{+}-> e^{+} + χ

Past experiments have searched for muon two body decay to a familon through a charged lepton flavor violation(CLFV) decay:

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

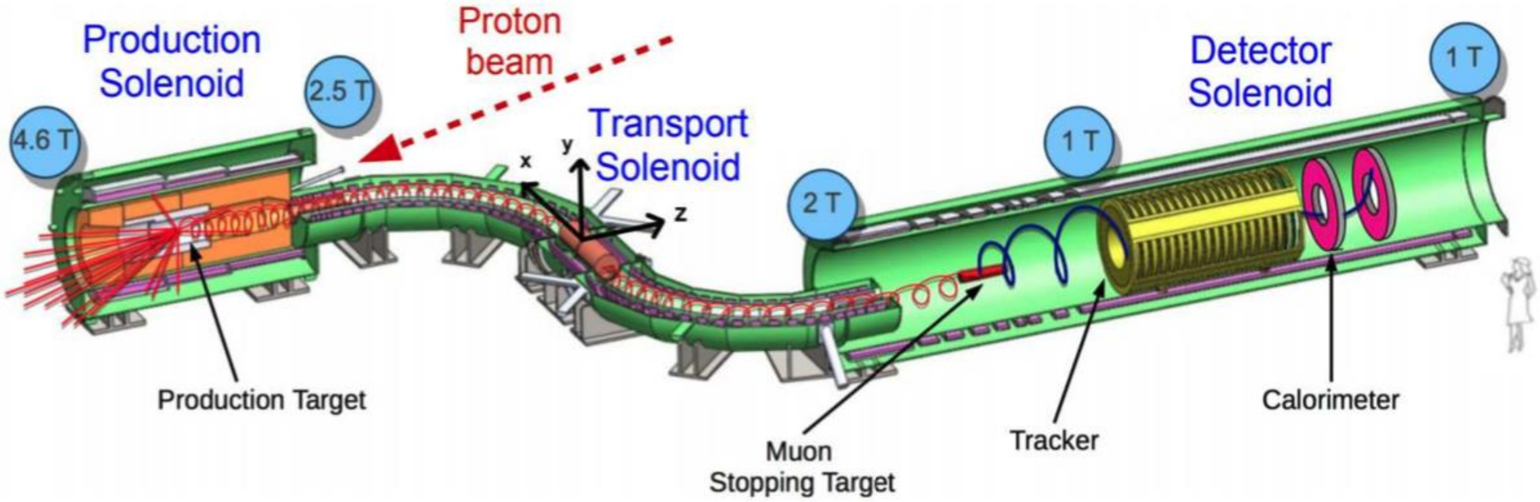
The available familon mass range is $0<m_x<m_\mu=105$ MeV.

searched familon mass	90% C.L. limit	dataset size	experiment
$M_x=0$	2.6×10^{-6} , [3]	1.8×10^{7} μ^{+} decays	TRIUMF (1986)
$3.2<M_x<86.6$ MeV/c^2	9×10^{-6} (avg) [4]	5.8×10^{8} μ^{+} decays	TWIST (2015)
$47.8<M_x<95.1$ MeV/c^2	~5×10^{-5} (avg) [5]	1.9×10^{8} μ^{+} decays	PIENU collaboration (2020)
$98.1<M_x<103.5$ MeV/c^2	$<2\times10^{-4}$ [6]	2.1×10^{6} μ^{+} decays	Chicago bubble chamber (1969)
$103<M_x<105$ MeV/c^2	$<5.7\times10^{-4}$ [7]	1.3×10^{6} μ^{+} decays	PSI (1999)

The Mu2e experiment at FNAL will search for CLFV μ^{-} decay with unprecedented $O(10^{18})$ μ^{-} stops. Nonetheless, this experiment is not sensitive to a familon search. (detector acceptance optimized for momenta around 100 MeV/c. Familon signal: e^{+} with P <53 MeV/c.)

However, a momentum calibration run for Mu2e using μ^{+} decays may improve the familon decay branching sensitivity by 10 to 100 times.

Mu2e calibration run: $\mu^+ \to e^+\nu\nu$



	Mu2e normal run	Mu2e calibration run
Particle type	$\mu^-; \mu^- Al \to e^- Al$	$\mu^+; \mu^+ \to e^+\nu\nu$
Muon decay time	864 ns	2197 ns
B-field	100%	50%
Tracker acceptance	[70-110]MeV/c	[35-55]MeV/c
Proton intensity	1.6×10^7 / pulse	Reduce by ~10-1000
Data taking time	~ years	~1 to 10 days

Issues

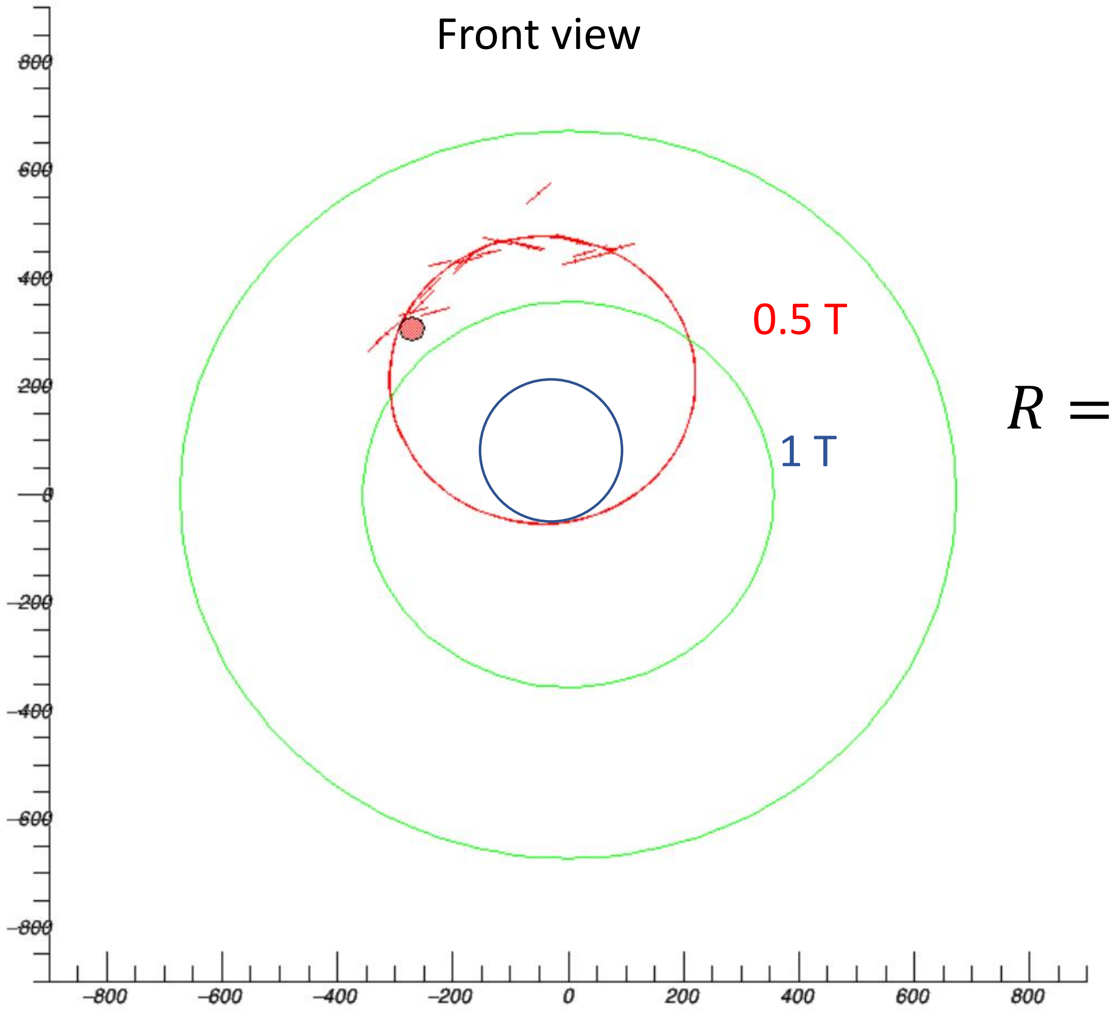
List below are three main categories of issues that must be addressed for this familon search to happen.

- Reduce B-field at the detector solenoid to 50% of nominal.
  - Measure and map the B-field at 50% of nominal.
- Select positive muons in the transportation solenoid.
  - Rotate central collimator by 180 degrees to select positive muons.
- **Reduce the beam intensity to avoid saturating the tracker(details later).**

Reduce B-field to 50%

- In order to have acceptance to the familon signal P<53 MeV/c.
- Needs to measure and map the B-field at 50% of nominal.

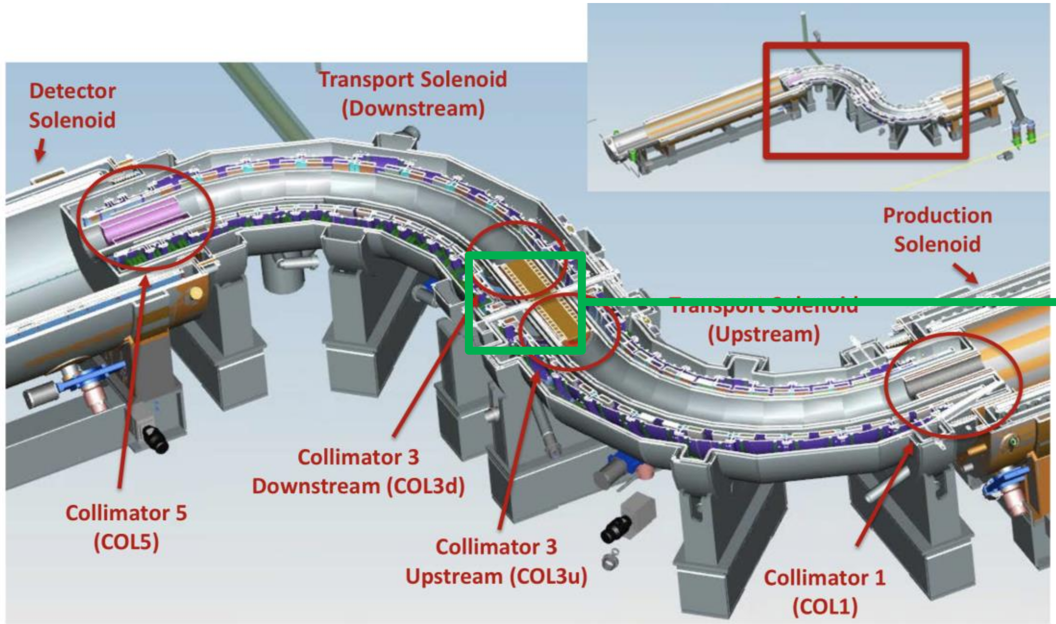
A reconstructed e+ event at 50% B field, corresponding to a familon signal with mass m_x=7 MeV/c^2. (Left) View from the plane perpendicular to the tracker; (Right) View from the side of the tracker.

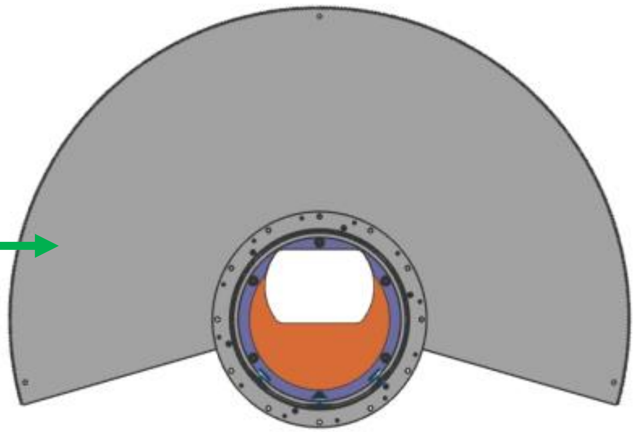


$$R = \frac{P_\perp}{|q|B}$$

Select positive muons

- Curved B-field separates positive and negative particles.
- Rotate central collimator by 180 degrees to select positive muons.





Inner bore radius = 15.0/10.0 cm
Outer radius = 24.3 cm
Length = 91 cm
Mass = 1,012 kg

Rotate this collimator by 180 degrees to let positive particle through.

Designed to be rotated.

Reduce beam intensity

- If not, occupancy of the tracker will be ~30 times higher than during Mu2e normal running, overwhelming the detector.
- Options to reduce the proton beam intensity are
  - 1) Reducing the booster load;
  - 2) Defocusing protons on production target;
  - 3) Steering the beam away from the target and
  - **4) Use only protons scattered from the up-stream foil plane.**
- The combined options of 1), 2) and 3) will reduce the beam intensity by a factor ~10, while 4) will reduce the intensity by a factor of 1000, as shown above.

Reduce beam intensity; issues

1) Reduce the booster load;
   Concern: Stability of the accelerator control systems at low beam intensity.
2) Defocusing protons on target;
   The proton target simulation needs to be updated to reflect the current target design.
3) Steering beam away from the target;
   Concern: The deformation of the target due to asymmetric heating. This needs to be studied.
4) Use protons scattered from ESS foil plane.
   Concerns: Extra heat load could cause out-gassing in the proton target beam absorber. Analyze temperature as a function of deposited power; Update the deliverer ring extraction efficiency model.

Summary of tasks to be performed

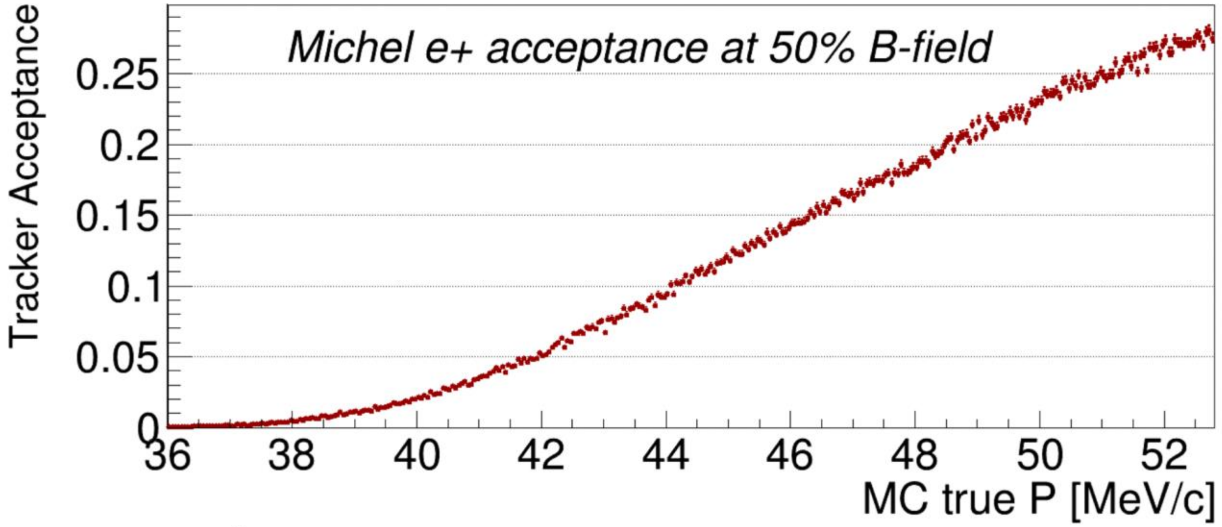
	Issues breakdown	Problem(s) need to be studied
Reduce B-field to 50%		Need to map the 50% field
Select positive particles	Rotate the central collimator	engineering plan required
Reduce the proton beam intensity	Reduce the booster load	Accelerator control systems functionality
	Defocus protons on target	Update target simulation
	Steer the beam off target	Asymmetric target heating
	Use scattered proton 'tail'	Extra heat load on the absorber; Study delivery ring extraction efficiency
Charge particle tracker	Occupancy to be acceptable	Need to understand tracking efficiency

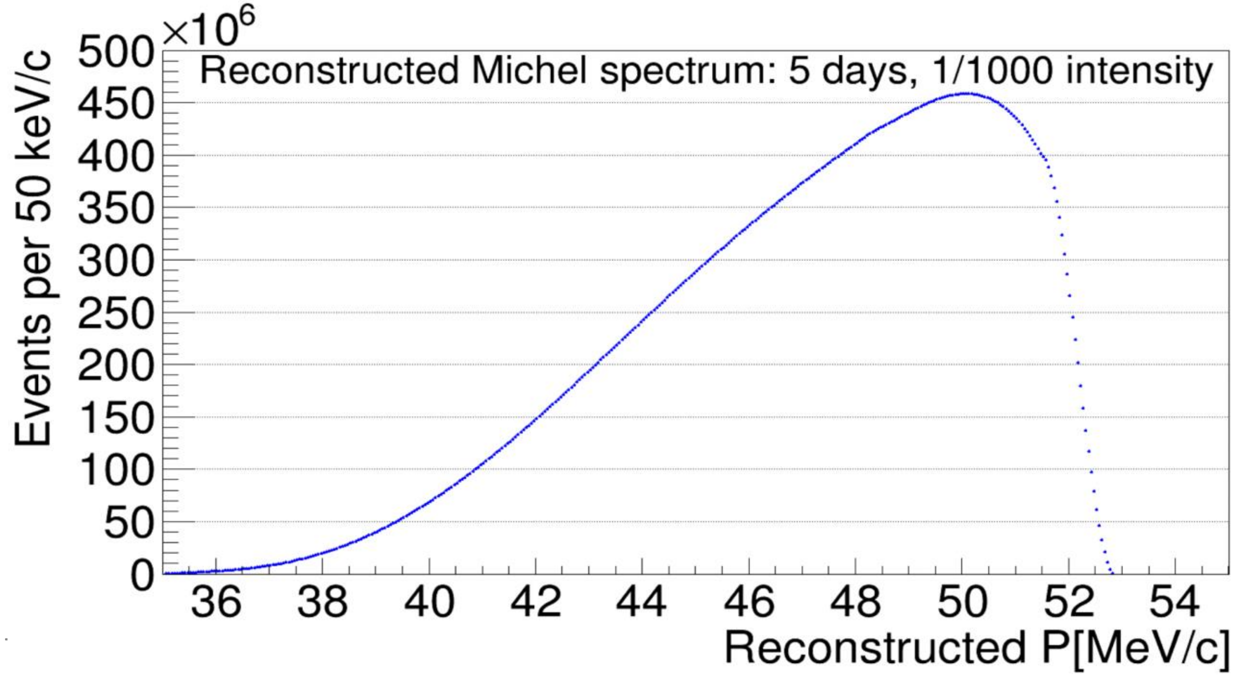
Estimated 90% CL sensitivity limit

Total number of stopped μ^+ events (N_{tot})		
Intensity	Runtime = 1 day	Runtime = 5 days
1/10th nominal	2.2×10^{13}	1.1×10^{14}
1/1000 th nominal	2.2×10^{11}	1.1×10^{12}

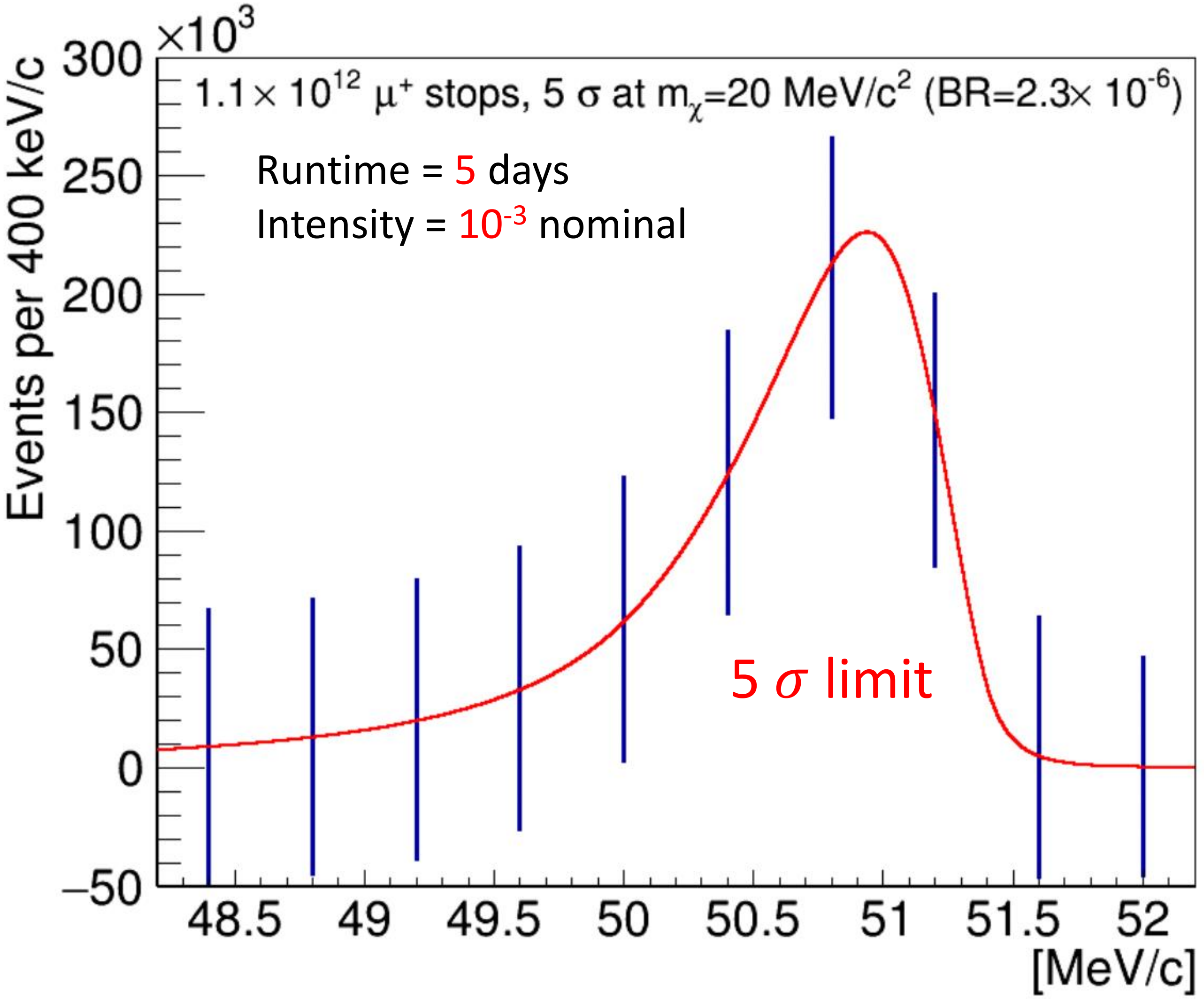
The 'Runtime' refer to the data-taking time of the expected calibration run. This is a example of time scale.

Averaged 90% CL limit over m_x=[0-40] MeV/c^2		
Intensity	Runtime = 1 day	Runtime = 5 days
1/10th nominal	1.3×10^{-7}	6.0×10^{-8}
1/1000 th nominal	1.3×10^{-6}	6.0×10^{-7}
Current best limit in this m_x region : BR ~1×10^{-5} [4]		





A visual example; 5 σ discovery limit



Summary

- A number of changes to the standard Mu2e running conditions need to be implemented to accomplish the familon search.
- Critical problems needs to be answered before having a reasonable plan to run the beam at reduced intensity.
- Running at a beam intensity of 1/10 of nominal at 50% magnetic field requires the tracker to operate outside its Mu2e parameter-set, which is now under-study.
- Nonetheless, the existing sensitivity limits will be surpassed by one to two orders of magnitude in a few days of running, depending on the proton beam intensity.

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Shihua Huang

Thank you.

Reference

- [1]. J. Feng et. al., *Phys. Rev. D* **57**, 5875 (1998).
- [2]. T. Maehara and T. Yanagida, *Prog. Theor. Phys.* **60**, 822 (1978); **61**, 1434 (1979).
- [3]. A. Jodidio et al., *Phys. Rev. D* **34**, 1967 (1986).
- [4]. R. Bayes et al., *Phys Rev. D* **91**, 052020 (2015).
- [5]. A. Aguilar Arevalo, et. al., *Phys. Rev. D* **101**, 052014 (2020)
- [6]. S. Derenzo, *Phys. Rev.* **181**, 1854(1969)
- [7]. R. Bilger et. al., *Phys. Lett. B* **446**, 363 (1999).

Back ups

Introduction to the familon [1]

Major puzzle: why do quark and lepton families replicate?

Postulate some family symmetry:

(1) discrete symmetries

(2) continuous and local

(3) continuous and global

Family symmetries must be spontaneously broken, options are:

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

(2) Local gauge symmetries are highly constrained from k^0- $\overline{k^0}$ mixing [2].

(3) Spontaneous breaking of **continuous global symmetry** implies massless Nambu-Goldstone bosons, called "familons".

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

(b)This symmetry can also be explicitly broken, making familons massive.

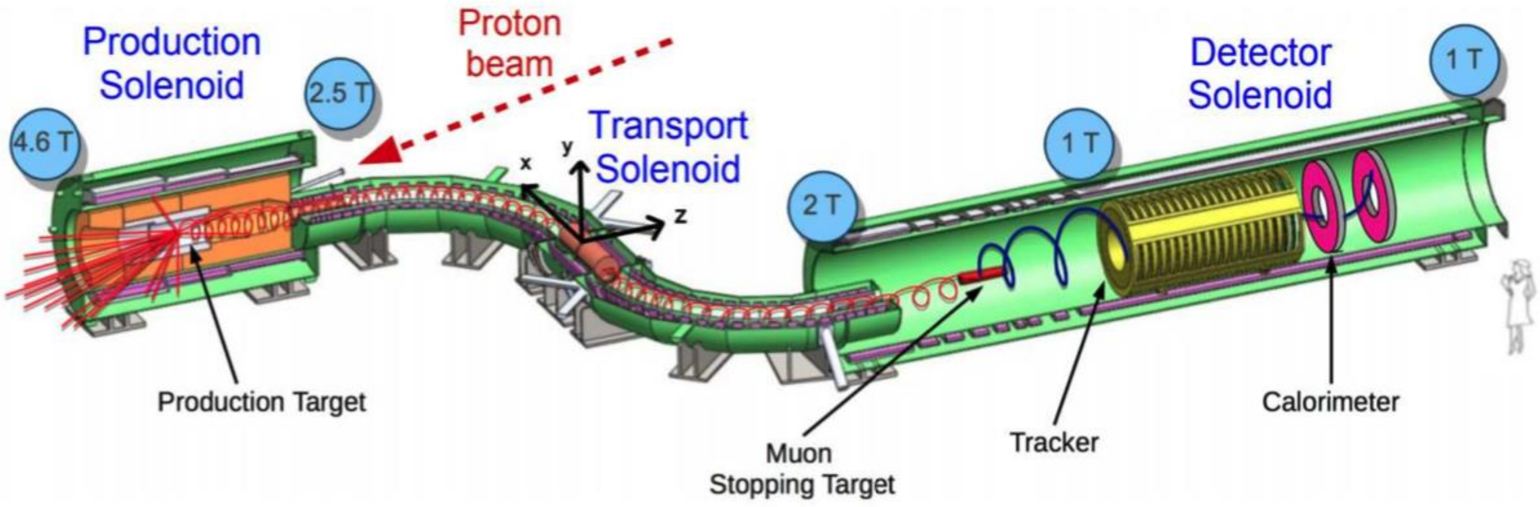
Introduction to the familon [1]

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

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

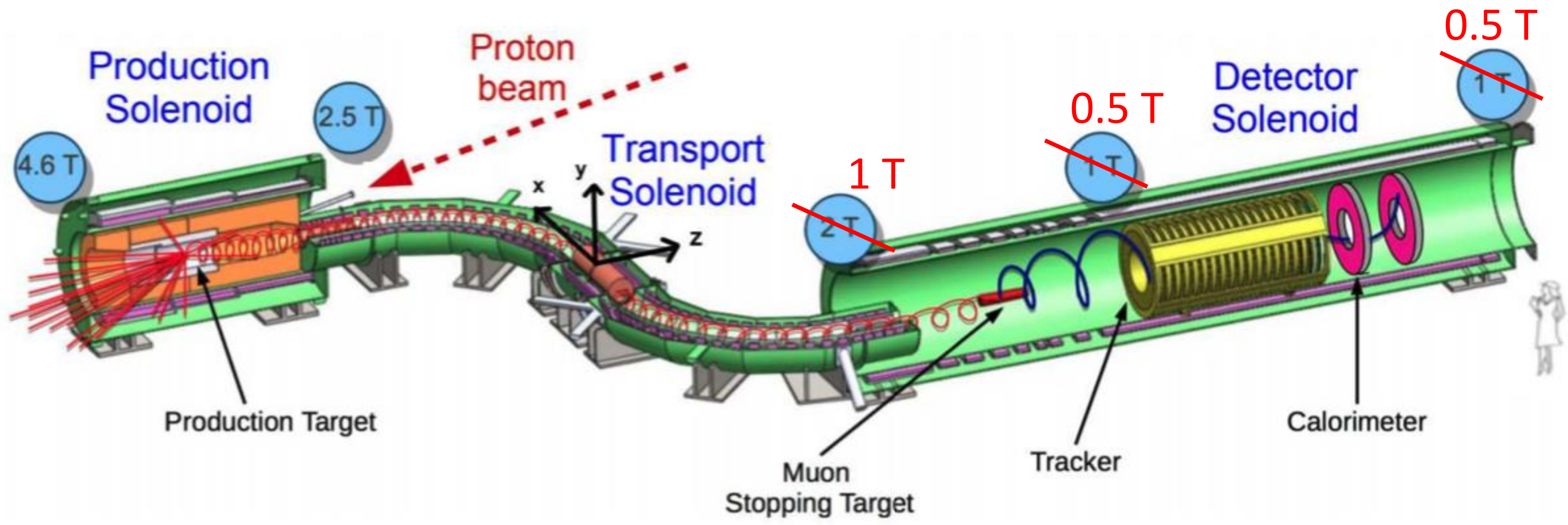
Where F is the family symmetry breaking scale, i.e., the familon decay constant, f^a are the familons, T^a are the generators of the broken symmetry, and the φ_L are fermion fields in terms of which the flavor symmetry is defined. The strength of the familon coupling is therefore inversely proportional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

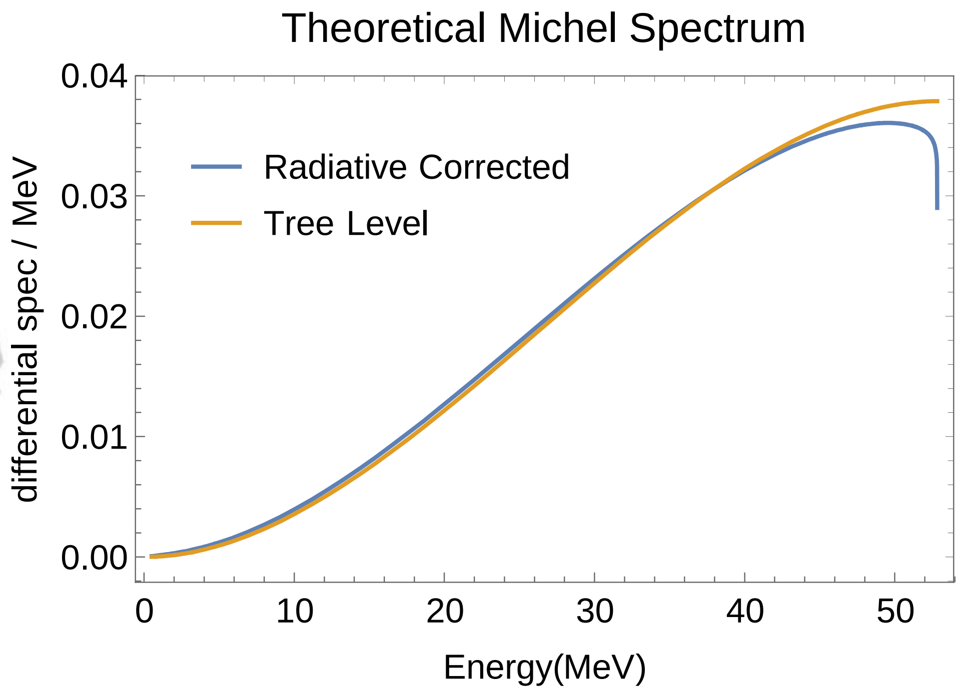
Mu2e experiment at FNAL



- 8 GeV proton beam hit the production target, produce pions and decay into muons.
- Negative muons were selected when transported to the muon stopping target.
- Searching for 105 MeV electron signal in neutrinoless muon decay $\mu^- N \rightarrow e^- N$.
- Electron less than ~70 MeV have no acceptance to the tracker. Very difficult for a familon search.

Mu2e calibration run: $\mu^+ \rightarrow e^+\nu\nu$

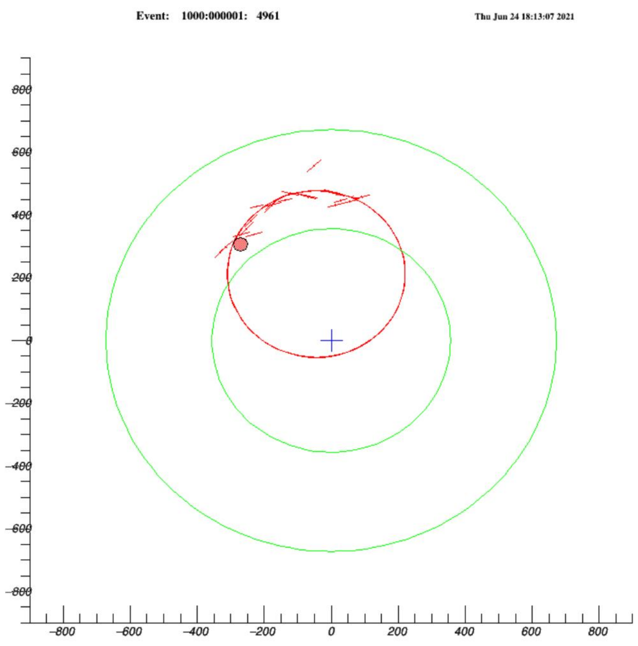


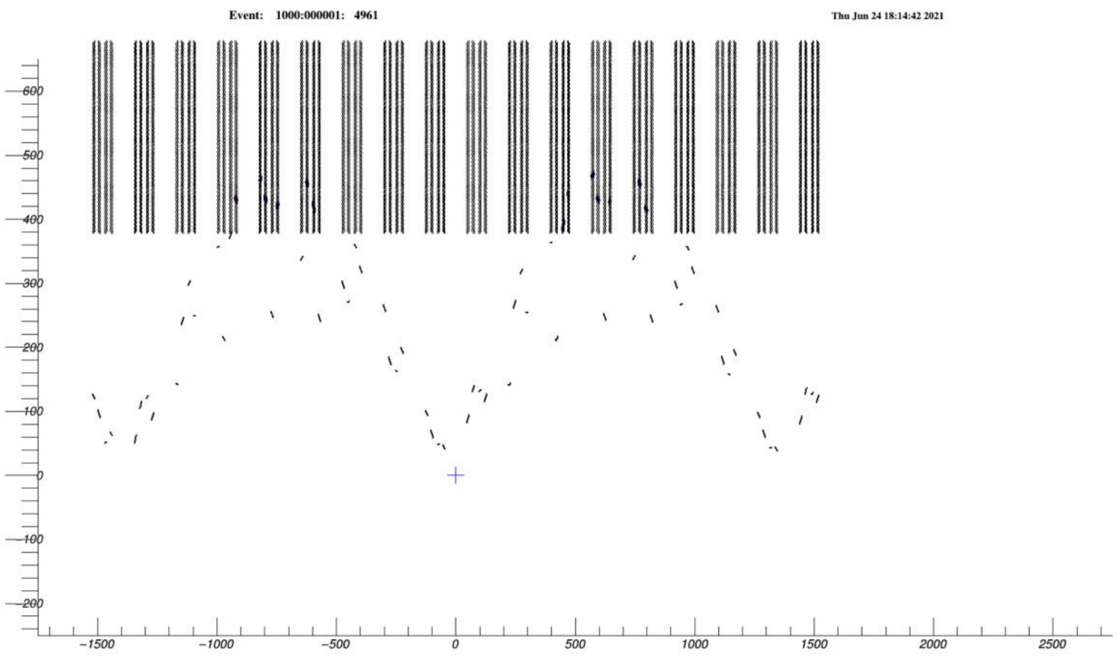


- A special run: calibrating Mu2e momentum scale by measuring μ^+ Michel spectrum.
- Have momentum acceptance for μ^+ from [35,53]MeV/c, ideal for a familon search!

Technical requirements

- Require some changes to the normal Mu2e running condition;
  - **Reduce B-field at detector solenoid to 50% to have acceptance for Michel e^+.**
  - Rotate TS3 collimator by 180 degrees to select positive particles during transport.
  - Reduce the muon beam intensity to avoid saturating the straw-tube tracker.





A 52.6 MeV/c e+ event at half-B field. (Left) View from the x-y plane; (Right) View from the R-z plane.

Technical requirements

- Require some changes to the normal Mu2e running condition;
  - Reduce B-field at detector solenoid to 50% to have acceptance for Michel e^+.
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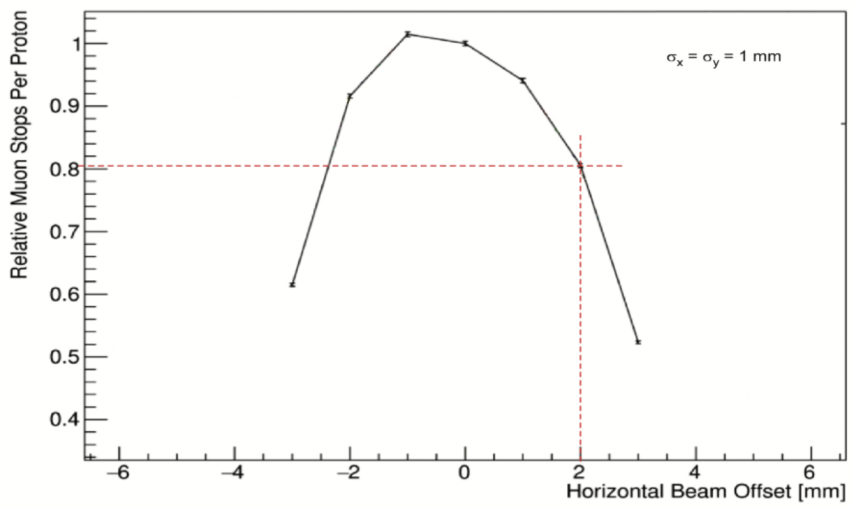
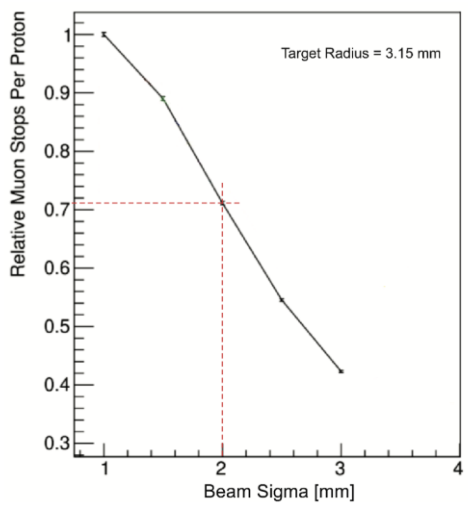
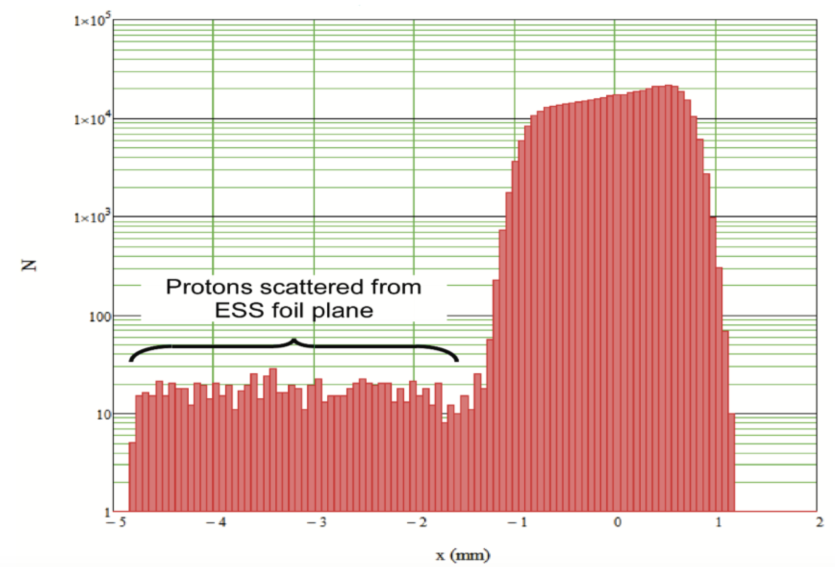






Reduce beam intensity by a factor of ~**10**, requiring reducing booster loading forMu2e and defocusing protons on target;

Reduce intensity by a factor of ~**1000**, by turning the beam off the target and measure a horizontal tail from scattered of protons.

Define the branching ratio

In Mu2e, the muon decays while they are **stopped** in the aluminum target. Because μ^+ is not bounded in aluminum, the expression should be analogous to the free muon decay;

$$Br(\mu^+ \to e^+\chi) = \frac{\mu^+ \to e^+\chi}{\mu^+ \to e^+\nu_e\overline{\nu}_\mu}.$$

The number of reconstructed e$^+$ is related to the number of emitted μ^+ from the stopping target as the following;

$$\begin{aligned}\frac{N^{Rec}_{\mu\to e\chi}}{N^{Rec}_{\mu\to e\nu\nu}} &= \frac{\epsilon_{\Omega B}(p_e) \times \epsilon_{Trig} \times \epsilon_{Trk_Q}(p_e) \times \epsilon_{purity}(p_e) \times N_{\mu\to e\chi}(p_e)}{\sum_p \epsilon_{\Omega B}(p) \times \epsilon_{Trig} \times \epsilon_{Trk_Q}(p) \times \epsilon_{purity}(p) \times N_{\mu\to e\nu\nu}(p)} \\ &= \frac{Acceptance(p_e) \times N_{\mu\to e\chi}(p_e)}{\sum_p Acceptance(p) \times N_{\mu\to e\nu\nu}(p)},\end{aligned}$$

Where $\epsilon_{\Omega B}$ is the geometric efficiency, ϵ_{Trig} is the trigger efficiency, ϵ_{TrkQ} is the efficiency lose determined by the track quality cuts, and ϵ_{purity} is the possibility of a reconstruct event being a real track. Their combined effect, $Acceptance(p)$ is defined as the tracker acceptance for positron momentum p.

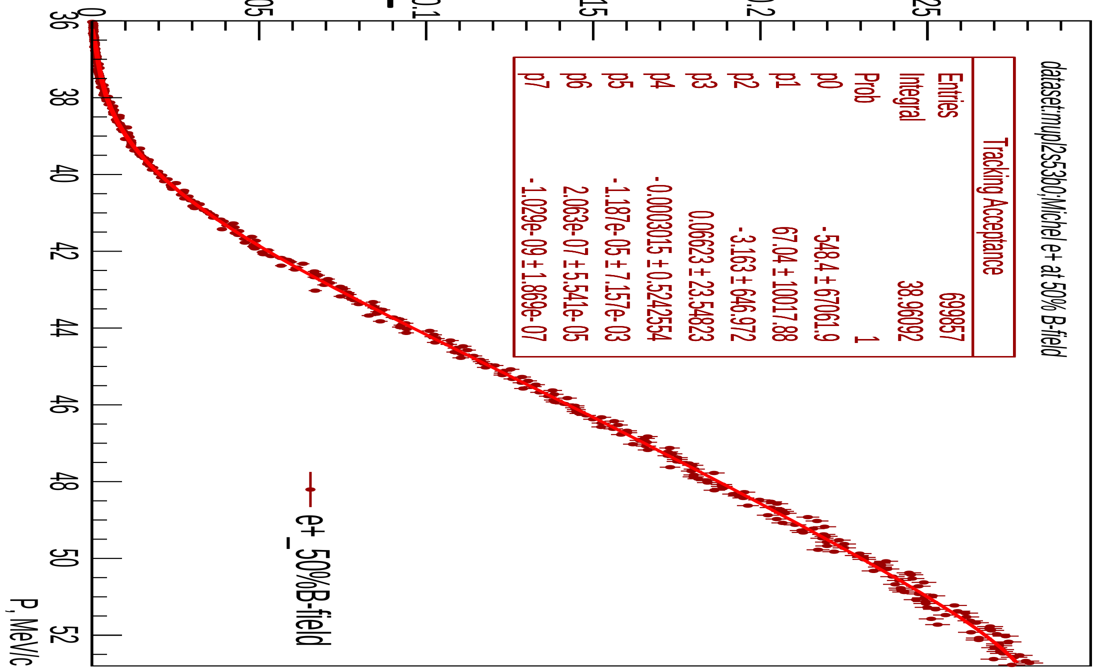
Search sensitivity estimate

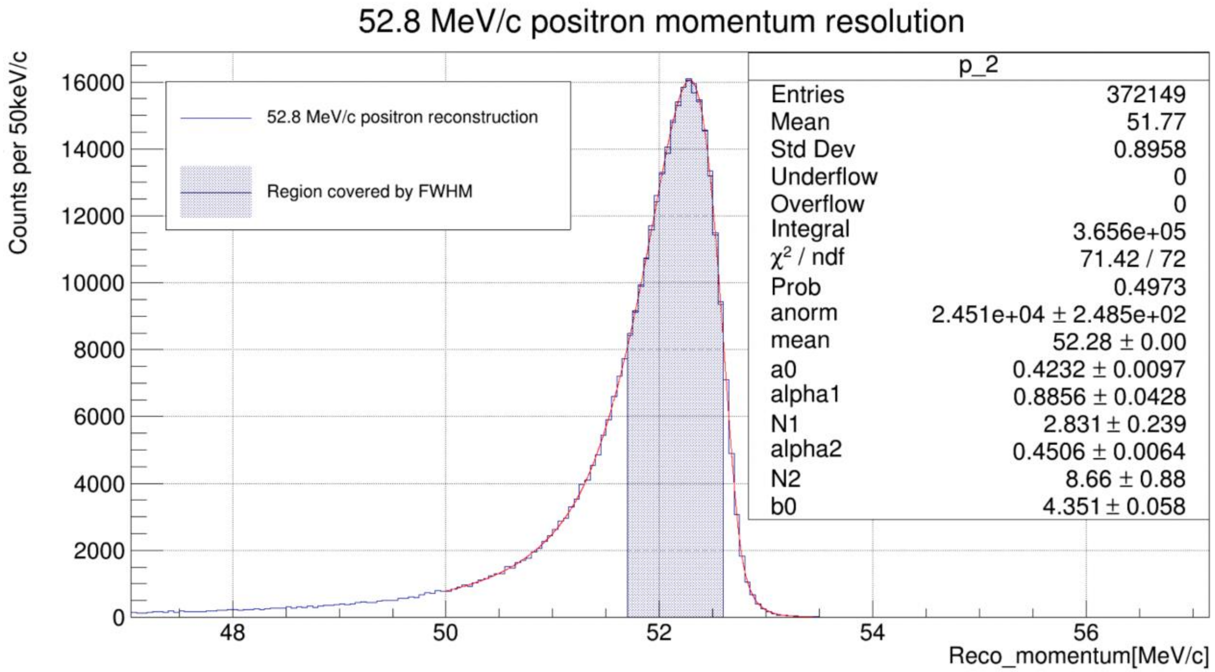
- Assuming very large data sample and perfect fit to the reconstructed Michel spectrum.
- In this limit, the sensitivity limit is set by fitting a smooth signal + background p.d.f to a binned histogram filled by the **expectation** of the same signal + background p.d.f, with bins error equal to the square-root of the bin count.
- The fit have only one free parameter, the size of the 'signal'. The fit will return its value and its error estimate σ_S.
- The 90% confidence level (CL) limit is defined as having a signal strength equivalent to a 1.282 sigma (σ_S) effect.
- For a given familon mass m_x , the decay positron will have momentum P_e. The 90% CL limit is expressed as:

$$Br(\mu \rightarrow eX) = (\frac{1.282\sigma_s}{Acceptance(P_e)})/N_{MC} \times \sqrt{\frac{N_{MC}}{N_{total}}}$$

Tracking performance

- Using Mu2e offline Geant4 software toolkits to study the Mu2e detector performance of reconstructing e$^+$ at 50% B-field.

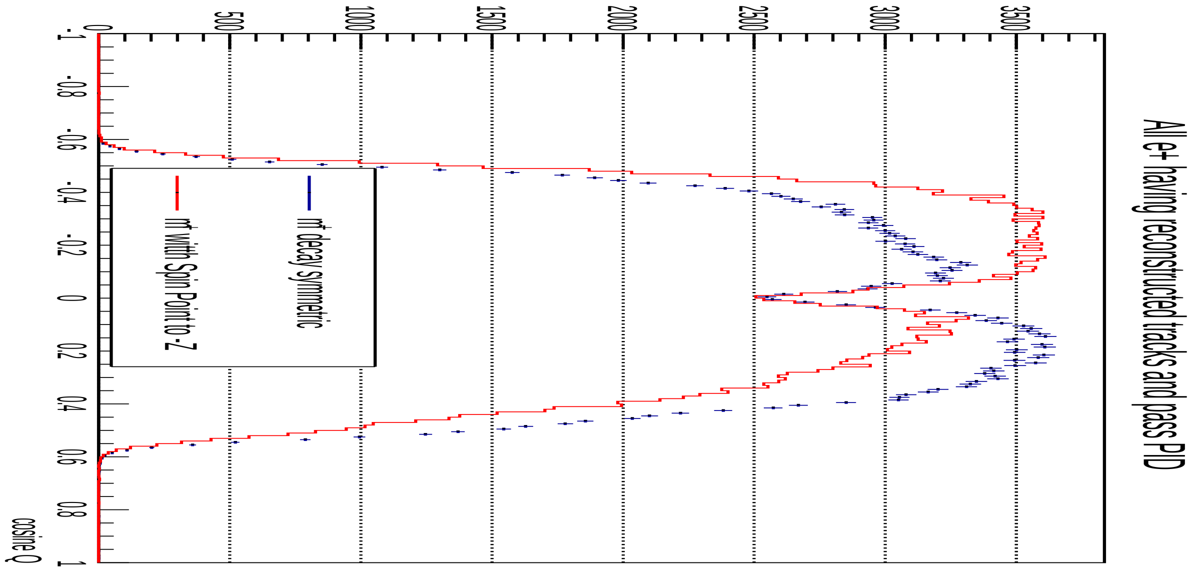


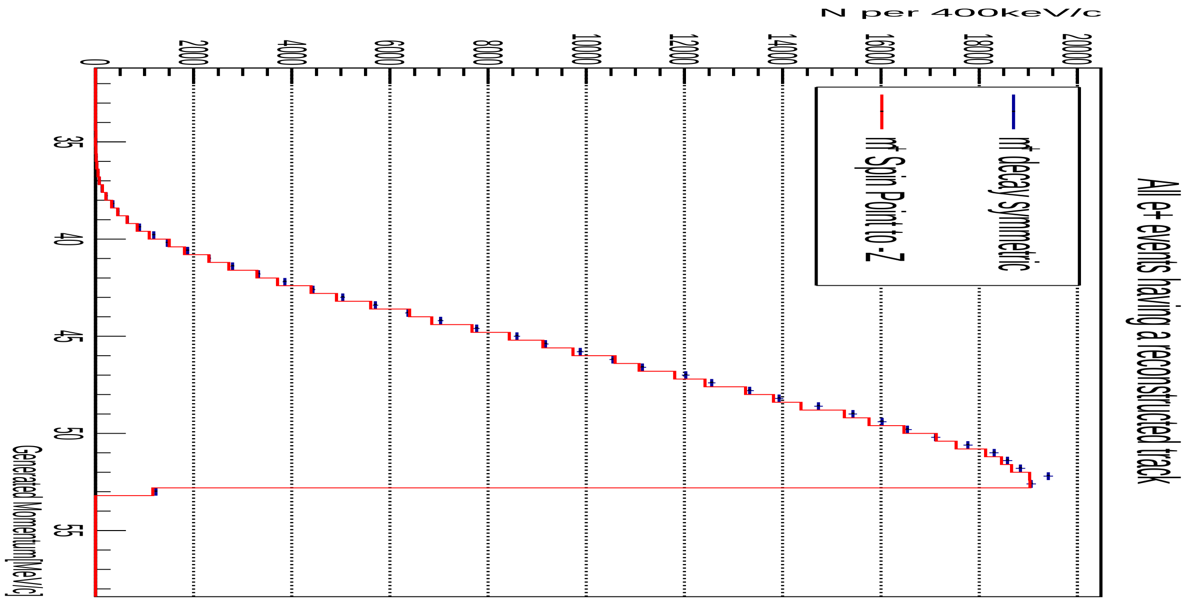


(Left) Michel decay positron acceptance under 50% B-field in the DS, simulated from 10^7 stopped muons, assuming isotropic emission. (Right) Momentum resolution of a 52.8MeV/c e+dataset. The red line is a multiple-parameter fit to the resolution line shape. The FWHM is 0.9 MeV/c and is shown as the shaded area.

Effect of μ^+ spin polarization

- Assume maximum decay asymmetry, i.e., 100% polarized μ^+ stop with polarization towards the –Z direction.





- Even at this extreme case, the effect of decay asymmetry cause the change in acceptance by less than 1 %.