Mu2e-II: Stopping Target Studies & Sensitivity Update

Sophie Middleton
Lisa Goodenough
Yuri Oksuzian

Mu2e-II Workshop
3rd March 2021

Introduction

As part of the Snowmass 2022 Mu2e-II study one of the big questions is: What are the best materials as an alternative to the Al target? And is the design of the Al target optimal in this scenario?

Benchmark is current Mu2e Stopping Target:

- 37 foils of Al.
- 0.1056 mm thick.
- Total mass of ~170g.
- Each foil has a hole of ~21 micron radius.
- 3 support wires suspending in a frame.

In several recent studies I have altered either the geometry, mass or elementary material of ST.

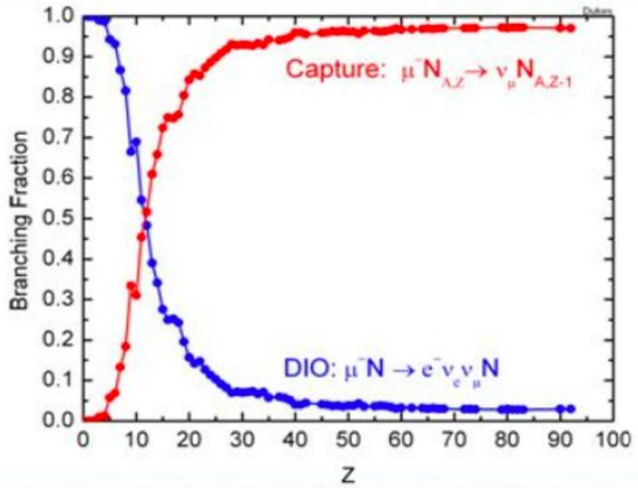
The resulting yields of Stopped Muons were recorded and simulations of the CE signal, DIO and RPC (Al only, internal and external) backgrounds were carried out.

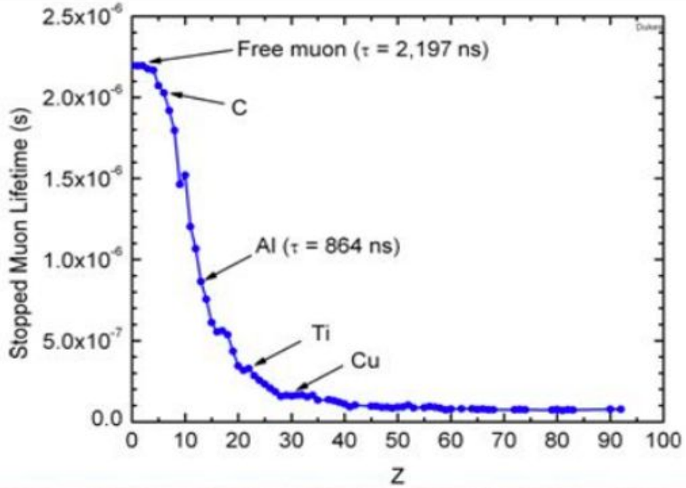
I developed new software tool, StatsTool2021, which takes input from the generated and reconstructed momenta spectra stored in TTrees for the signal and all background and calculates the projected BF upper limit (using Feldman-Cousins) and Single Event Sensitivity for each target.

Choosing a Target

- Target material must be chemically stable and available in the required size, shape, and thickness.
- Conversion energy such that only tiny fraction of photons produced by muon radiative capture.
- Muon lifetime long compared to transit time of prompt backgrounds.
- Conversion rate increases with atomic number, reaching maximum at Se and Sb, then drops. Lifetime of muonic atoms decreases with increasing atomic number.

→ Al best choices for Mu2e….but what about alternatives?





Possible Materials

Compiled a “library” of interesting papers
https://github.com/sophiemiddleton/TargetStudiesPapers

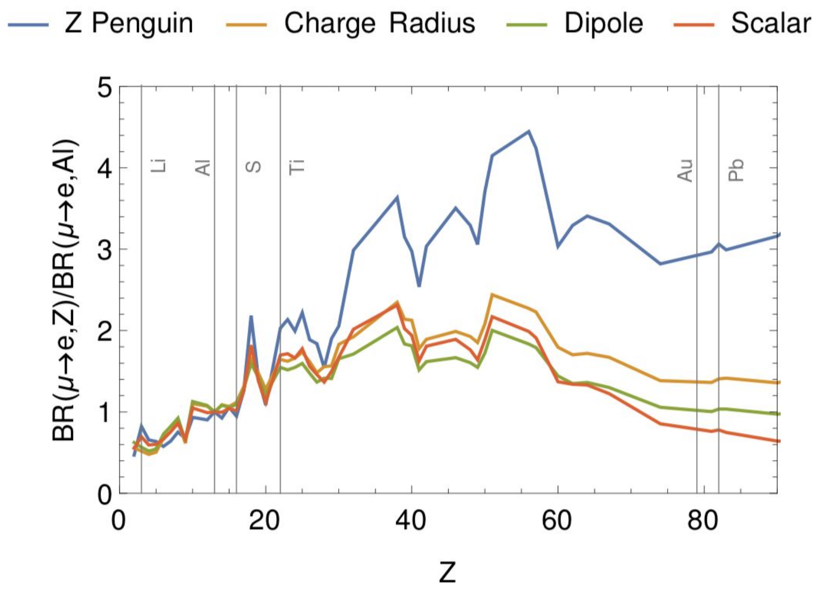
There are 2 possible outcomes from Mu2e:

- **Conversion not observed** - motivates pushing to higher mass scales.
- **Conversion observed** - motivates more precise measurements with different targets.

Various operator coefficients add coherently in the amplitude. Weighted by nucleus-dependent functions.

→ Requires measurements of conversion rate in other target materials in order to understand nature of New Physics.

2 Contributions: Spin-Independent (SI) (A^2 rate enhancement) and Spin-Dependent (SD) (does not benefit from A^2 enhancement but probes different operators to coherent)



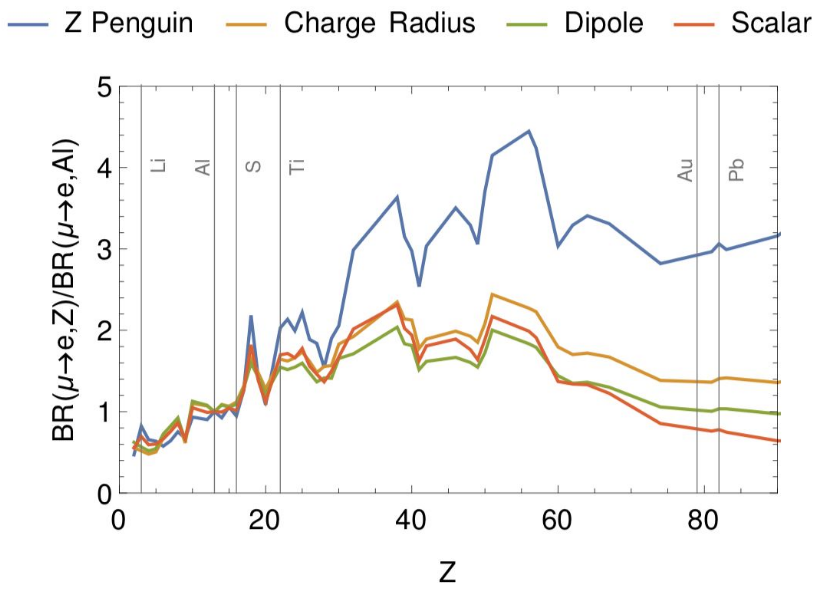
V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242
S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109

Comparing Targets

Compiled a “library” of interesting papers

https://github.com/sophiemiddleton/TargetStudiesPapers

- Lithium:
  - No detailed study, hard to contain, but not impossible.
  - Weak signal, low discrimination power.
  - (see Davidson et al 2019)
- Aluminum:
  - Single stable isotope
  - Al(27) (spin 5/2)
- Sulphur:
  - Advantageous for e+ channel (see Beomki et al 2017)
- Titanium:
  - Multiple isotopes
  - Ti(48) Ti(46)Ti(50) (spin-0)→ no SD contribution
  - Ti (47) (spin-5/2) or Ti(49)(spin-7/2) can measure SI contribution.
- Vanadium:
  - Single isotope: V(51) makes up > 99% (spin-7/2)
- Heavy Nuclei (Au or Pb):
  - Strong discrimination.
  - Short muon lifetime (increased pion backgrounds).
  - Low sensitivity to spin-dependent contribution.



R. Kitano, M. Koike and Y. Okada, Detailed calculation of lepton flavor violating muon electron conversion rate for various nuclei, Phys. Rev. D 66 (2002)

V. Cirigliano, R. Kitano, Y. Okada and P. Tuzon , On the model discriminating power of μ → e conversion in nuclei, Phys. Rev. D 80 (2009)

Comparing Targets

Material	CE [MeV/c]	Lifetime [ms]	Capture Rate	Decay Rate	Density [g/cm^3]	Atomic Number	Equivalent mass [g]
Aluminum	104.97	864	0.61	0.39	2.7	13	1
Titanium	104.29	329	0.85	0.15	4.5	22	~290
Vanadium	104.05	300	0.87	0.13	6.1	23	~310

Fixed Signal Regions t > 700ns and:

Material	Upper [MeV/c]	Lower [MeV/c]
Al	**103.85**	**105.1**
Ti	**103.25**	**104.5**
V	**103.0**	**104.25**

StatsTool can optimize this.

Changing the Stopping Target in Mu2e-II/Offline

Many places to check:

1. Mu2eG4/geom: Make a stopping target config file and include in main geometry file (replacing current ST)
2. Mu2eG4/src/construct_StoppingTarget.cc: changes here for geometry changes (no need to edit if only changing element/foil numbers)

If changing material too:

3. EventGenerator/src and prolog.fcl: need to define CE signals here
4. globalConstants01.txt: Ti already here, any other materials must be added

Note: In the following analyses the detectors remain Mu2e. Only the Production Target (and Stopping Target) is upgraded.

StatsTool

A work in progress, current code visible here:

https://github.com/sophiemiddleton/StatsTool2021

- Python based code, uses uproot to port Mu2e-II TrkAna and myGen (my thing) data.
- Easily adapted for Mu2e or Mu2e-II and for any target choice.
- User inputs .root TTrees containing Momentum of generated and reconstructed signal or background.
- Several optional cut lists available (cd3, su2020, any mu2e-II specific cuts)
- Calculates expected yield of CE, RPC, DIO (options for Al or Ti DIO)
- Interface for DIO and RPC allowing main code to be user friendly
- Calculates efficiencies, SES and Branching Fraction Upper Limit (using Feldman Cousins 90% CL) → Working on making this more robust!
- Optimizes signal region in terms of momentum window only → No time cut optimization yet (but RPC has been shown to be <<1 for all Al targets)
- Input from FlatElectron and re-weights according to Czernecki for Al or Ti (V is currently using Ti with some edits).
- Outputs optimal window and histograms for analysis.

Cuts

Use the SU2020 cuts as a start. Formal analysis will further optimize:

	cele0s61b1			cele0s71b2		
selection	N events	efficiency		N(events)	efficiency	
		incremental	total		incremental	total
N(generated events)	1000000		1.0	1000000		1.0
DAR track reconstructed	329584	0.3296	0.3296	324614	0.3246	0.3246
T > 700 ns	232959	0.7068	0.2330	230525	0.7102	0.2305
103.85 MeV/c < P < 105.1 MeV/c	136893	0.7708	0.1369	134724	0.5844	0.1347
(N-1) 0.5 < tan(dip) < 1	129947	0.8719	-	126938	0.8775	-
(N-1) $\|d_0\| < 100$ mm	113343	0.9996	-	111431	0.9996	-
(N-1) $S_{TRQ} > 0.2$	118812	0.9536	-	11757	0.9474	-
passed all cuts	113299	0.8276	0.1133	111387	0.8268	0.1114

Cuts are optional in StatsTool, but applied in all results shown here.

Design of Al Stopping Target Studies

Is the foil target optimal for Mu2e-II:

- **Nominal POT: 5e22**
- **Stopped Muon Rate:**

  0.000089 stops/per POT

- **Stopped Pion Rate:**

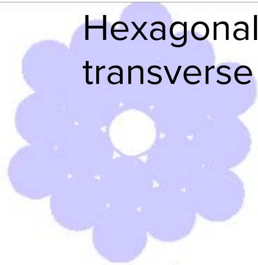
  0.000096 stops/per POT

Compare to Mu2e:

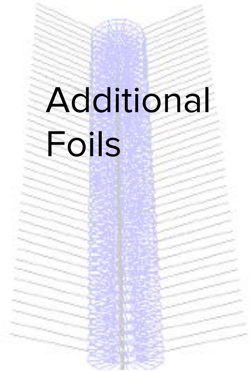
- Muons: 0.00152 stops/POT
- Pions: 0.00211 stops/POT

Cylinder design i.e tubes with differing radi - muons still captured but easier for CE to get through.

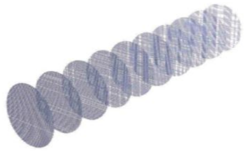
Screen Disks with holes



Hexagonal transverse view



Additional Foils

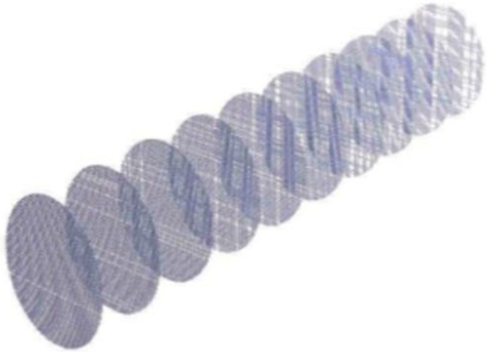


Screen Disks without holes. Screens made of strings - vary strings = mesh style alternative.

Screen & Mesh Designs

The difference between the 2 "screen" ("Mesh" and "Screen") designs comes from the thickness of the strings. These are based on commercially available products so further optimization was not done:

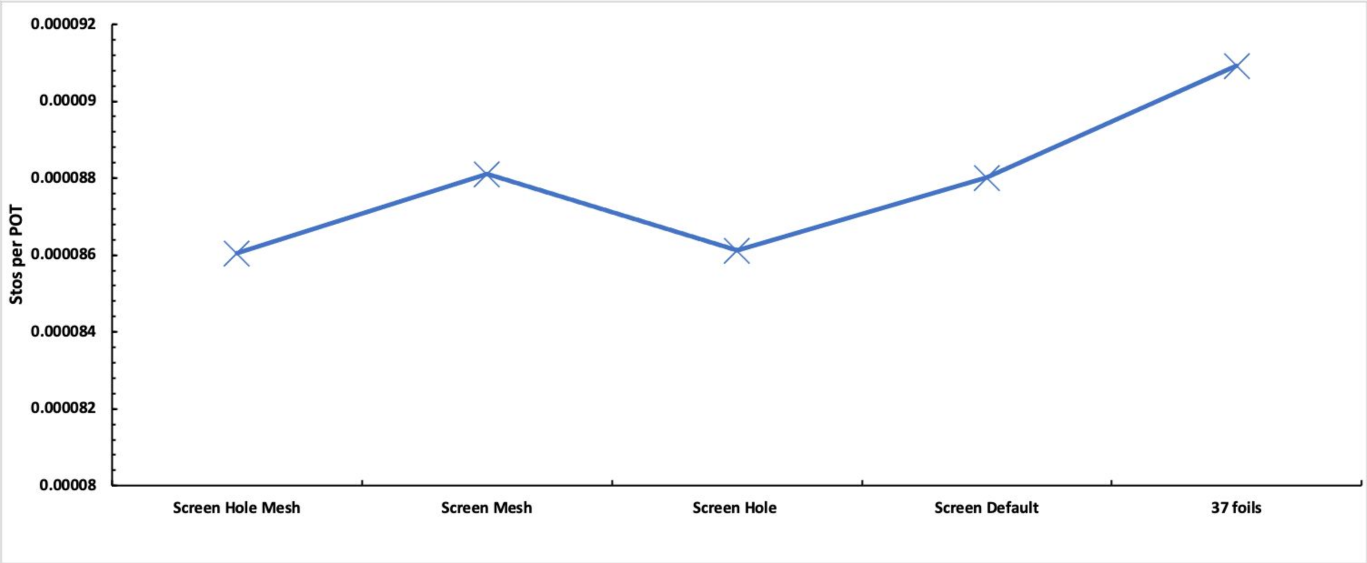
Feature	Mesh	Screen
ST Outer radius [mm]	75	75
Screen Layers	53	97
String Radius [mm]	0.1143	0.02665
String Target Opening Size	1.0414	0.07366
Target Length [mm]	800	800
Total Mass [g]	163.476	162.665



Stopped Muons

$$SES = \frac{1}{(POT \times \frac{stop}{POT} \times \frac{Capture}{stop} \times \frac{N^{CE}_{rec}}{N^{CE}_{gen}})}$$

The Mu2e style foil target appears to stop the largest fraction of muons....
The stopping rate is an important factor in SES calculation, but we **also need to consider efficiency**.



Results for AI Stopping Target Studies

$$SES = \frac{1}{(POT \times \frac{stop}{POT} \times \frac{Capture}{stop} \times \frac{N^{CE}_{rec}}{N^{CE}_{gen}})}$$

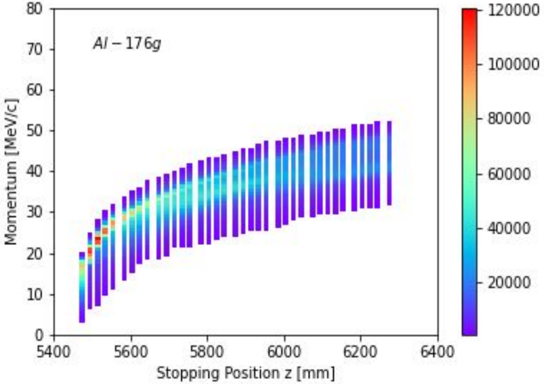
Momentum window optimized for BFUL.

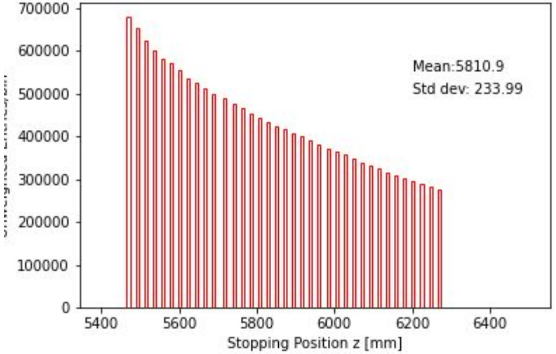
Targets ranked according to final column i.e. improvement on current Mu2e target.

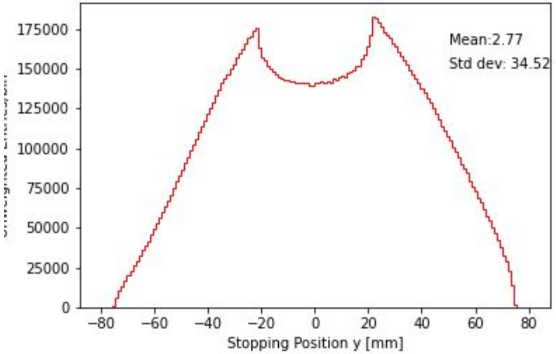
Name	Stops Rate	CE Eff	DIO Eff	SES	BFUL	Ratio
37 Foils (mu2e)	0.000089	0.125+/-0.0003	0.31+/-0.007	2.97e-18+/-6.98e-21	8.98e-18+/-4.64e-20	1
Screen Default	0.000089	0.135+/-0.0003	0.326+/-0.0078	2.73e-18+/-6.28e-21	8.602e-18+/-4.96e-20	0.92
Screen Hole	0.000092	0.131+/-0.0030	0.328+/-0.008	2.90e-18+/-6.34e-21	8.664e-18+/-5.686e-20	0.976
Screen Mesh	0.000092	0. 137+/-0.0003	0.327+/-0.007	2.76e-18+/-6.32e-21	9.145e-18+/-5.54e-20	0.93
Screen Hole Mesh	0.000089	0.133+/-0.0003	0.319+/-0.008	3.05e-18+/-7.16e-21	9e-18 +/-4.87e-20	1.0272

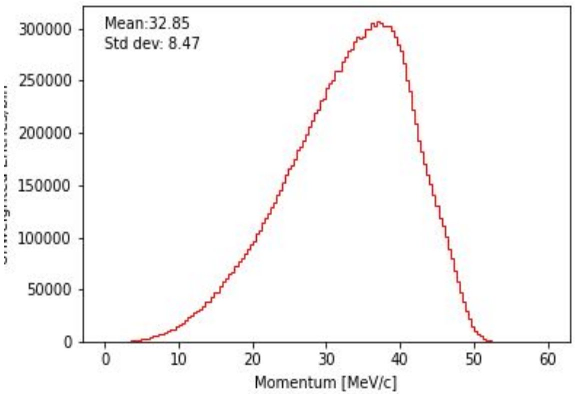
Distributions of Stopped Muons in Al 37 foils

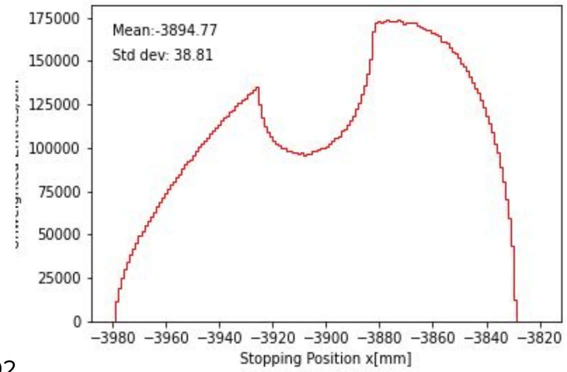
- Position and Momentum distributions same shape as in Mu2e:











202.

Summary for Aluminum

- Staying with foil design for now.
- Can we alter incoming muon momentum?
    - All values shown here are only meaningful for the current settings. If we modify incoming momentum we could get different profile and this might help...
- Still features to optimize:
    - Radii
    - Hole diameter
    - Thickness ➔ more mass in the z direction - more Multiple Coulomb Scattering (MCS)
    - Number of foils ➔ more mass - more MCS
- Need to improve efficiency. And understand differences.
- Optimization studies are ongoing.

Titanium

Expected nPOT: 5e22

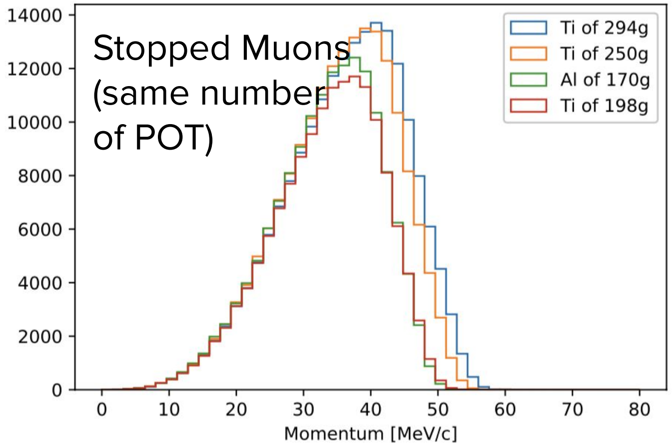
Stopped Muon Rate in Al (37 foils) : 9.1e-5 stops/per POT

- Assuming foils style target
- Begin with same design as Al (i.e. 37 foils of same thickness)
- Alter to other masses in attempt to improve SES.

$$SES = \frac{1}{(POT \times \frac{stop}{POT} \times \frac{Capture}{stop} \times \frac{N^{CE}_{rec}}{N^{CE}_{gen}})}$$

Initial study in Mu2e:

- Titanium target 37 foils, mass = 294 g simulated i.e. same number of nuclei as the 37 foil Al target. +26% more stops for same Al style target)



This study begins with assumption that we want to match number of nuclei

→ this might not be the best approach...

Equivalent mass is ~290g

Titanium: Preliminary Results

$$SES = \frac{1}{(POT \times \frac{stop}{POT} \times \frac{Capture}{stop} \times \frac{N^{CE}_{rec}}{N^{CE}_{gen}})}$$

For fixed signal window definition of 103.25-104.5 MeV/c → Not optimized yet!

*Al uses signal region:103.85-105.1
Uses CeMLL not just an endpoint

Name	Stops Rate	CE Eff	DIO Eff	SES
Al 37 foils (176g)*	0.000089	0.12 +/- 0.0003	0.197 +/- 0.005	3.06 e-18 +/- 7.49 e-21
34 foils (275g)	0.0001077	0.055 +/- 0.0002	0.12+/- 0.002	3.95e-18 +/- 1.36e-20
25 foils (198g)	0.0000886	0.073+/-0.002	0.122+/-0.002	2.98e-18 +/- 9.00e-21
17 foils (138g)	0.0000667	0.09+/- 0.0002	0.13+/-0.003	2.39e-18 +/- 6.33e-21

Lower mass → better!

- **Errors are statistical**
- **Cuts remove a lot of CE's**
- **Without track cuts allows 20% efficiency on Al but lower efficiency on Ti - would require cut optimization on Ti?**
- **Resolution function (DSCB) for tracker is the same.**
- **<u>All Titanium CE Efficiencies are low.....requires analysis!</u>**
- **Higher masses previously found to be worse.**

What makes the efficiency?

Efficiency is simply:

```
def GetRecoEff(self, Nrec, Ngen):
    efficiency = (Nrec) / Ngen
    print("rec, gen", Nrec, Ngen)
    return efficiency

def GetRecoEffError(self, Nrec, Ngen):
    """
    use Glen Cowan derivation of efficiency error based on a binomial distribution
    http://www.pp.rhul.ac.uk/~cowan/stat/notes/efferr.pdf
    """
    efficiency_error = math.sqrt(Nrec * (1. - Nrec/Ngen)) / Ngen
    return efficiency_error
```

N_{rec}: number of reconstructed events in the momentum region

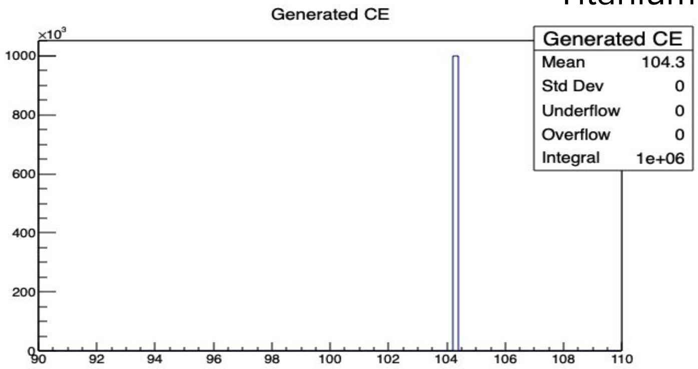
N_{gen}: number of generated events in momentum region (use mostly CeEndpoint so usually all CEs generated)

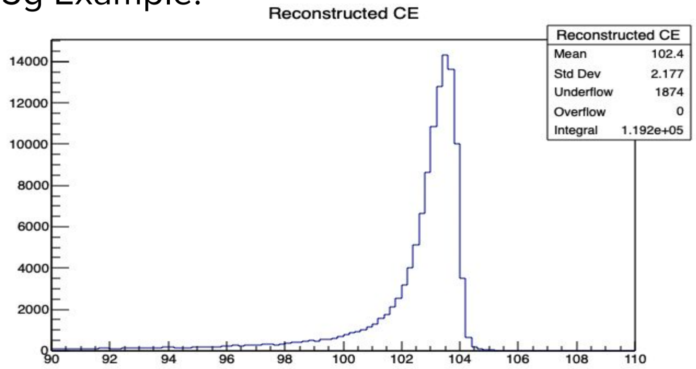
What would cause a lower efficiency?

- If less electrons are reconstructed in a given bin than were generated.
- Obviously we expect some distortions due to MCS and energy loss in the target, this will cause CE's to be reconstructed in a lower momentum bin (assuming they make it into signal region at all)
- <u>This will be a greater effect for higher masses!</u>

Reconstructed .v. Generated Momentum

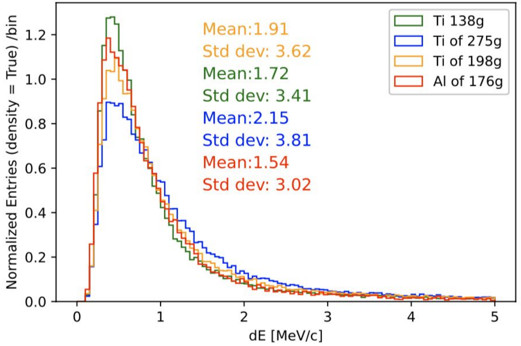
Titanium 275g Example:





For Total Events: CE Eff = 12%
In signal region (103.25-104.5) = 5.5%
Broader signal region = more DIOs

Means show average energy loss in target:



How can we regain efficiency?
➔ Need to optimize signal region for Sensitivity

Vanadium

Expected nPOT: 5e22

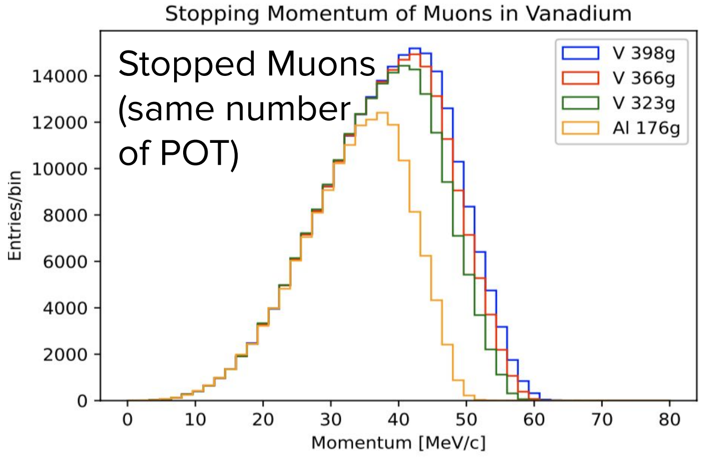
Stopped Muon Rate in Al (37 foils) : 9.1e-5 stops/per POT

+47% more Stopped Muons for 323g for same foil design

$$SES = \frac{1}{(POT \times \frac{stop}{POT} \times \frac{Capture}{stop} \times \frac{N^{CE}_{rec}}{N^{CE}_{gen}})}$$

- Factors for SES:
  - POT: normalized to the same as Al
  - stop/POT = 47% higher than Al
  - Capture/stop = 26% higher than Al

⟶ Driving factor for achievable SES is the efficiency!



Equivalent mass is ~310g

- The only factor which will cause deviations in the efficiency from that of Al (since CE's are only < 1MeV different) will be if there is significant increase in MCS or Energy Loss in the target…
- BFUL affected by DIO radiative correction but lower decay rate, so expect reduction.

Vanadium: Preliminary Results

For fixed signal window definition of 103.0-104.25 MeV/c ➔ Not optimized yet!

All results are preliminary…uses slightly edited DIO radiative corrects based on Ti, awaiting theory calculations for V, and for a Mu2e geometry

Name	Stops Rate	CE Eff	DIO Eff	SES
Al 37 foils (176g)*	0.000089	0.12 +/- 0.0003	0.197 +/- 0.005	3.06 e-18 +/- 7.49 e-21
30 foils (323g)	0.000117	0.0361 +/- 0.0001	0.11 +/- 0.002	5.48e-18 +/- 2.52e-21
25 foils (270g)	0.000105	0.044 +/- 0.0002	0.111+/- 0.002	4.93e-18 +/- 2.06e-21
17 foils (182g)	0.000081	0.060 +/- 0.0002	0.12 +/- 0.003	4.73e-18 +/- 1.68e-20

Need to explore lower mass!

Next Steps: Target Studies

- Analyze multiple scattering in more detail.
- Need to explore lower masses (for foil design)
- Need to explore changes in other foil dimensions
- Are there other targets we could also use?
- What has biggest effect on the SES and BFUL calculations when altering the material (.i.e. Digging into Energy Loss and MCS in the target) ➔ where does our loss in efficiency come from?
- Other more "exotic" targets .e.g. Lithium: Are these viable? A much more detailed simulation effort needed here...

Next Steps for the broader Mu2e-II Study

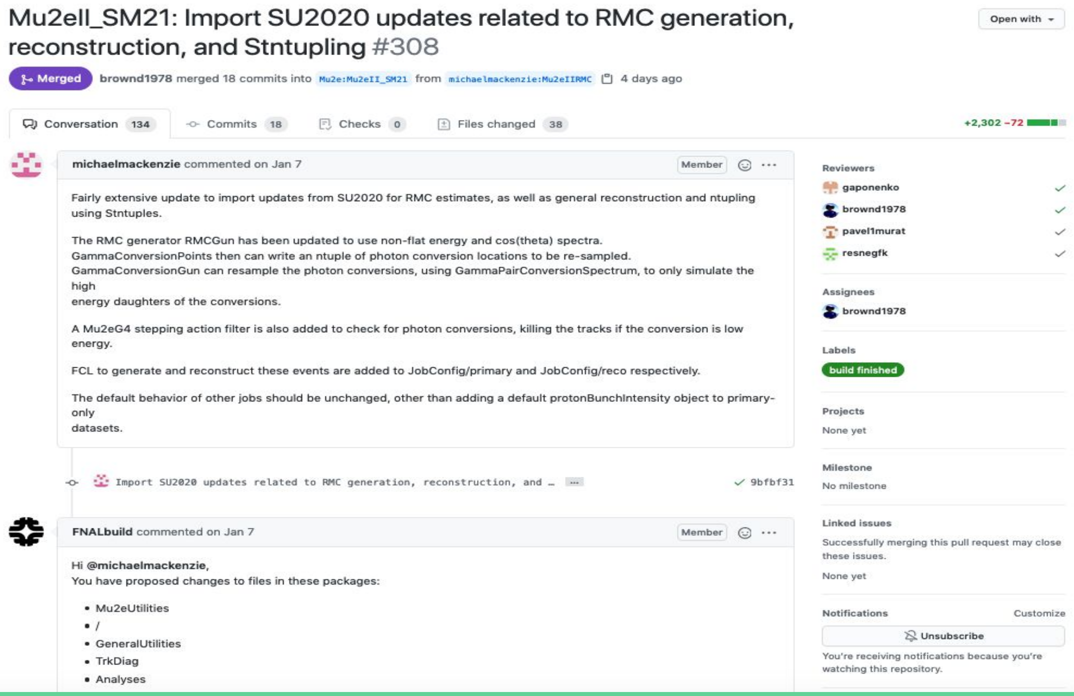
- We are beginning preliminary physics runs:
- Details: https://mu2eiiwiki.fnal.gov/wiki/Sensitivity_Estimates#beam:_stage2_.28DS.29

Process	Status	Volunteers Needed
DIO	Ready	Ask Sophie
Cosmics	-	Ask Yuri
RPC	Ready	Ask Sophie
RMC	In progress	Ask Michael M.
Signals *e+/e-	CE Ready/CP In Progress	Ask Convenors

As we begin this process we will develop our analysis infrastructure & optimize our cuts. Everyone is welcome to help our - we currently have a basic

Next Steps: Recent PR

- Lots of activity on GitHub following Michael M's RMC code improvements
- Code is merged in, we are ready!



Estimated Timeline

An updated timeline: