Mu2e-II: Stopping Target Studies & Sensitivity Update

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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.
- 3 support wires suspending in a frame.

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

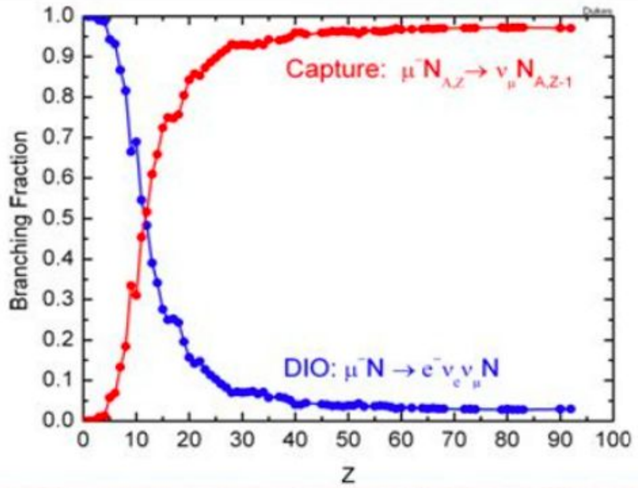
The resulting yields of Stopped Muons were recorded and simulations of the CE signal, DIO and RPC (Al only, internal and external) backgrounds were carried out.

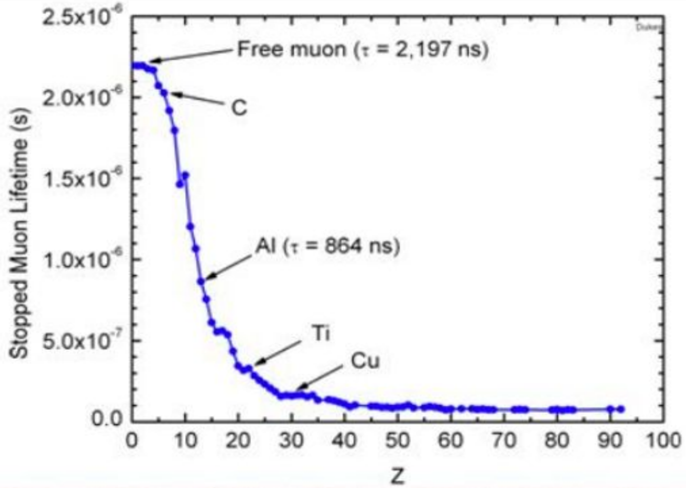
I developed new software tool, StatsTool2021, which takes input from the generated and reconstructed momenta spectra stored in TTrees for the signal and all background and calculates the projected BF upper limit (using Feldman-Cousins) and Single Event Sensitivity for each target.

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

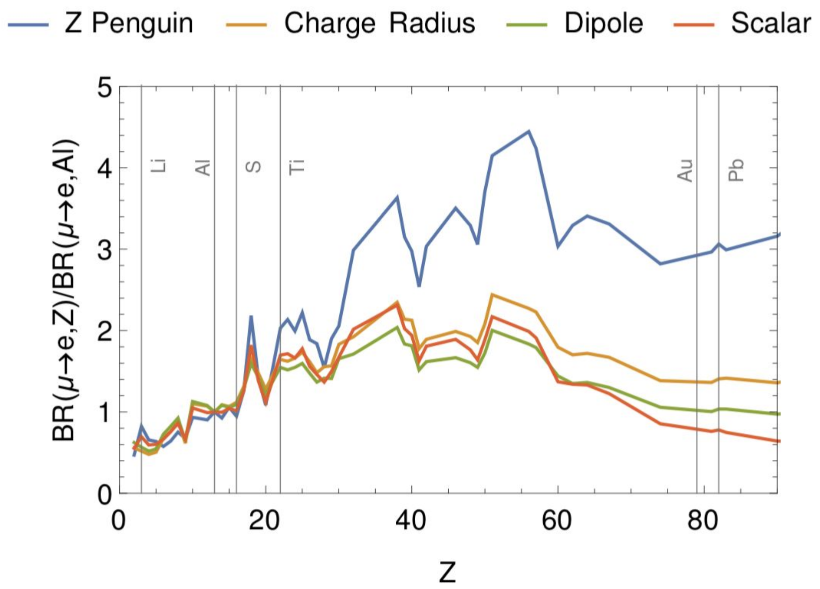
There are 2 possible outcomes from Mu2e:

- **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)



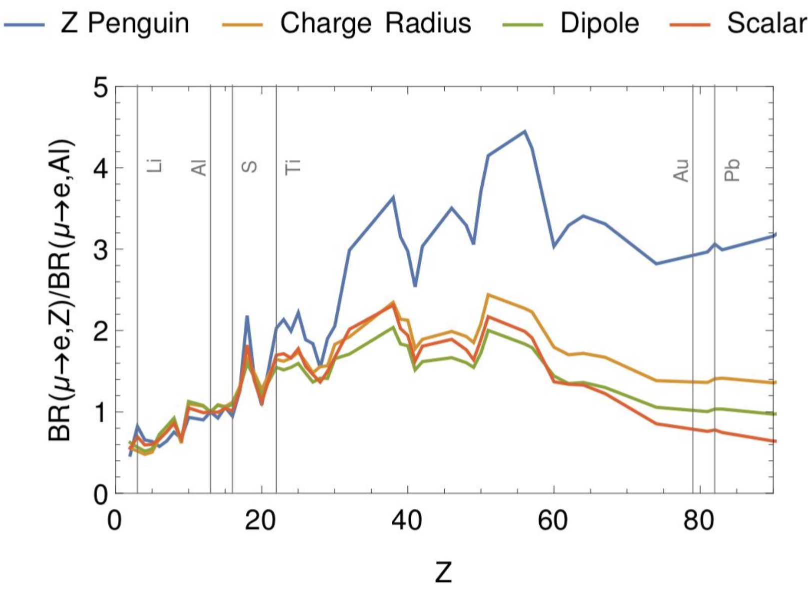
V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242
S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109

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)

Cuts

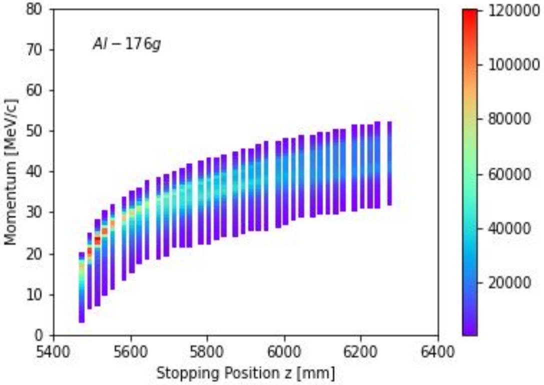
Use the SU2020 cuts as a start. Formal analysis will further optimize:

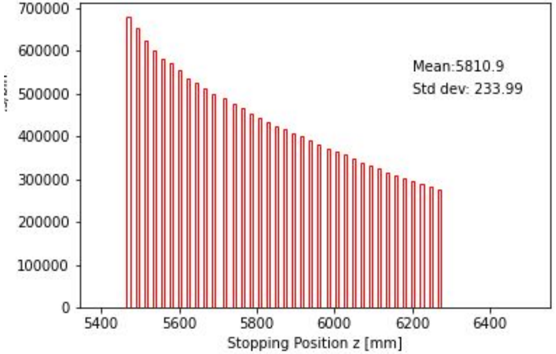
	cele0s61b1			cele0s71b2		
selection	N events	efficiency		N(events)	efficiency	
		incremental	total		incremental	total
N(generated events)	1000000		1.0	1000000		1.0
DAR track reconstructed	329584	0.3296	0.3296	324614	0.3246	0.3246
T > 700 ns	232959	0.7068	0.2330	230525	0.7102	0.2305
103.85 MeV/c < P < 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

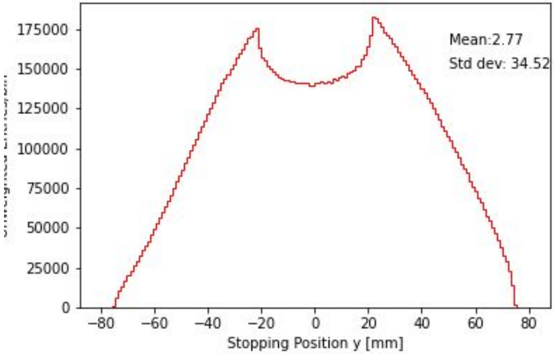
Cuts are optional in StatsTool, but applied in all results shown here.

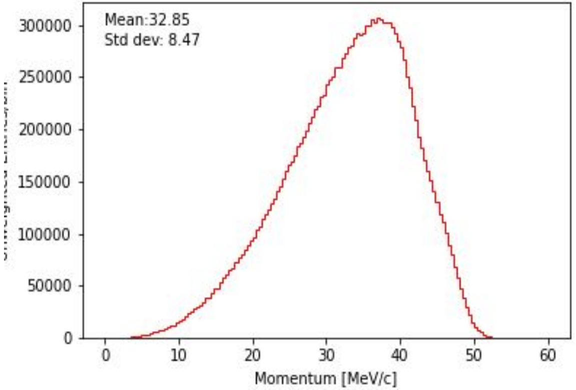
Distributions of Stopped Muons in Al 37 foils

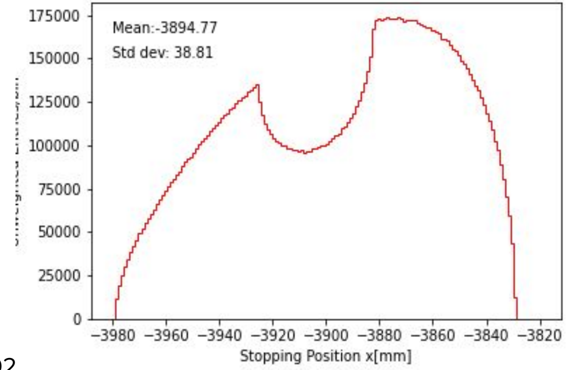
- Position and Momentum distributions same shape as in Mu2e:











202.

Titanium

Expected nPOT: 5e22

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

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

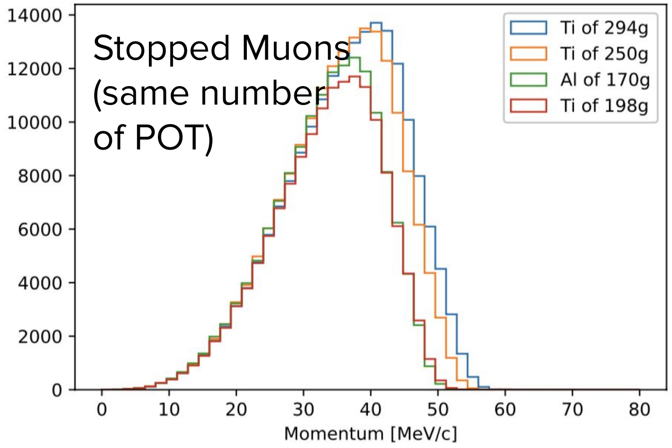
- Assuming foils style target
- Begin with same design as Al (i.e. 37 foils of same thickness)
- Alter to other masses in attempt to improve SES.

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

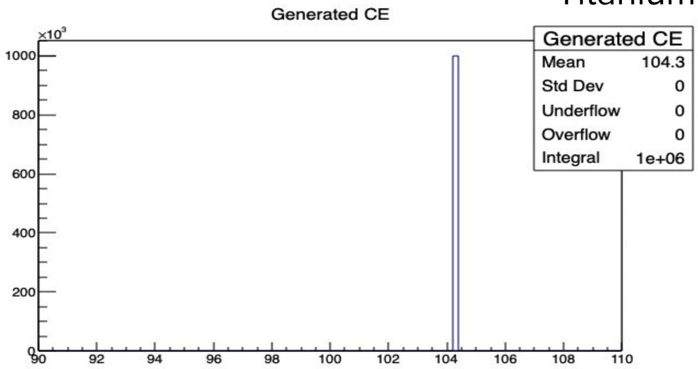
Name	Stops Rate	CE Eff	DIO Eff	SES
Al 37 foils (176g)*	0.000089	0.12 +/- 0.0003	0.197 +/- 0.005	3.06 e-18 +/- 7.49 e-21
34 foils (275g)	0.0001077	0.055 +/- 0.0002	0.12+/- 0.002	3.95e-18 +/- 1.36e-20
25 foils (198g)	0.0000886	0.073+/-0.002	0.122+/-0.002	2.98e-18 +/- 9.00e-21
17 foils (138g)	0.0000667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

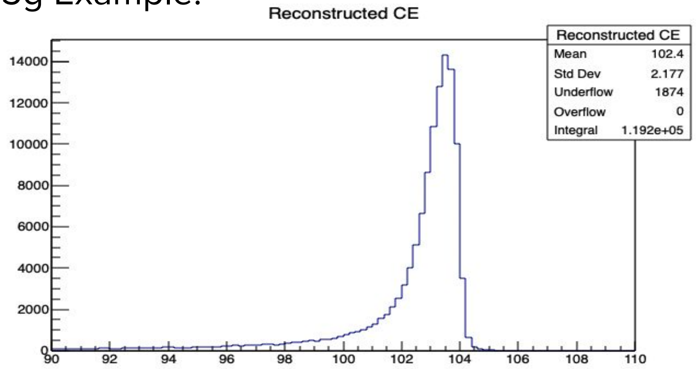
Lower mass ➔ better!

- 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.
- All Titanium CE Efficiencies are low…..requires analysis!
- Higher masses previously found to be worse.

Reconstructed .v. Generated Momentum

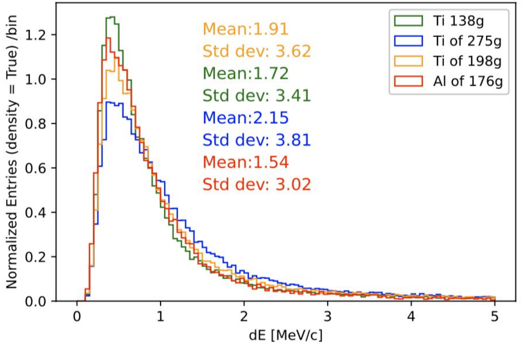
Titanium 275g Example:





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

Titanium: Lower Mass Results

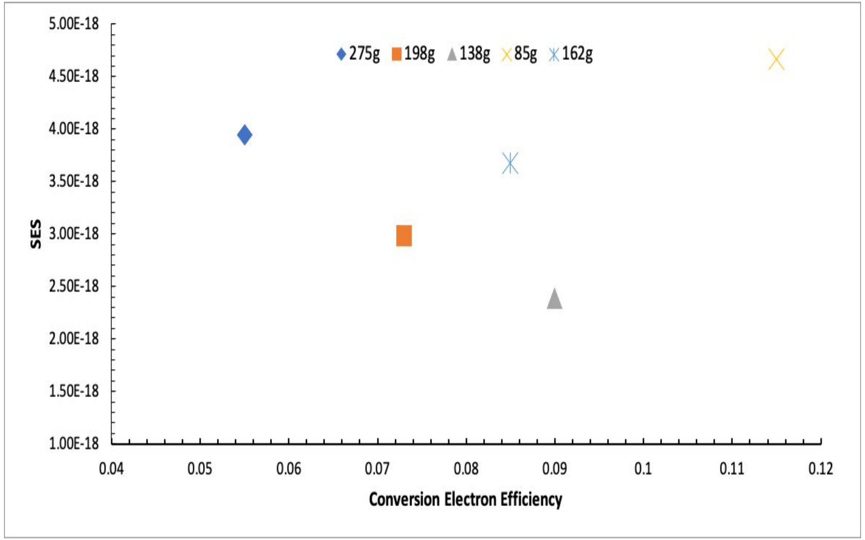
For fixed signal window definition of 103.0-104.25 MeV/c → Not optimized yet!

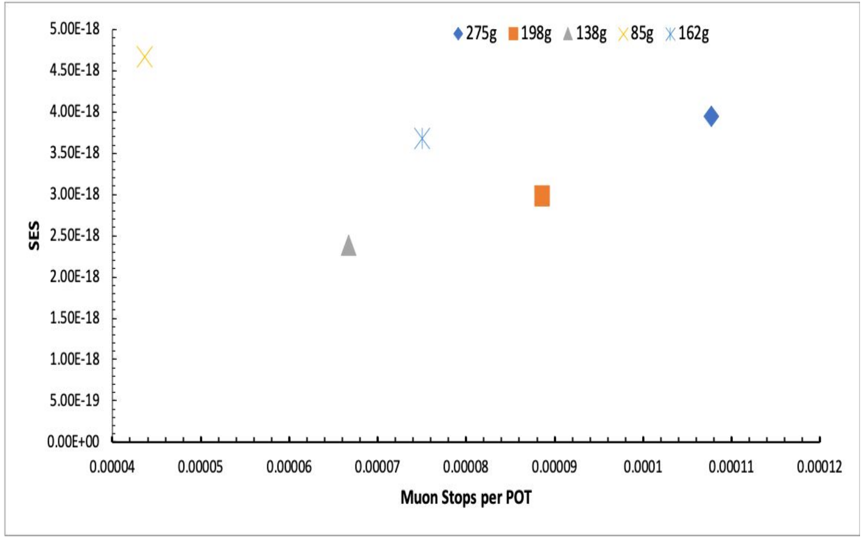
Optimal mass → 138g +/- 10g

Name	Stops Rate	CE Eff (cuts)	SES (cuts)
Al 37 foils (176g)*	0.000089	0.12 +/- 0.0003	3.06 e-18 +/- 7.49 e-21
34 foils (275g)	0.0001077	0.055 +/- 0.0002	3.95e-18 +/- 1.36e-20
25 foils (198g)	0.0000886	0.073+/- 0.002	2.98e-18 +/- 9.00e-21
20 foils (162g)	0.000075	0.085+/- 0.0003	3.68e-18 +/- 1.088e-20
17 foils (138g)	0.0000667	0.09+/- 0.0002	2.39e-18 +/- 6.33e-21
10 foils (81g)	0.0000437	0.115 +/- 0.0003	4.67e-18 +/- 1.24e-20

Optimization

Minimum point found but further refinements needed





Vanadium

Expected nPOT: 5e22

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

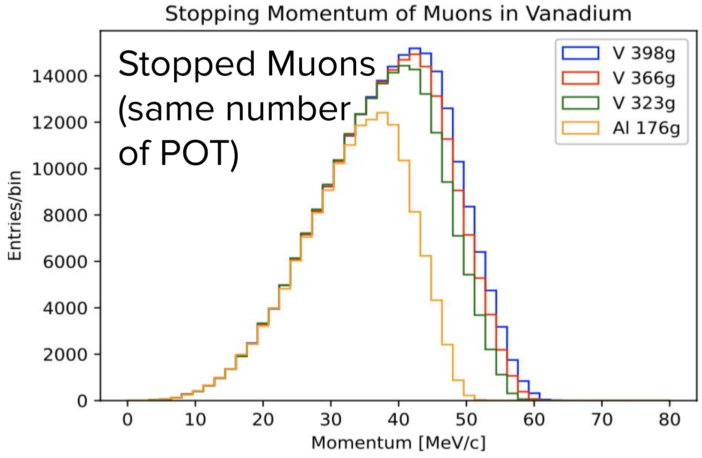
+47% more Stopped Muons for 323g for same foil design

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

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

$\longrightarrow$ Driving factor for achievable SES is the efficiency!

- 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.



Equivalent mass is ~310g

Vanadium: Preliminary Results

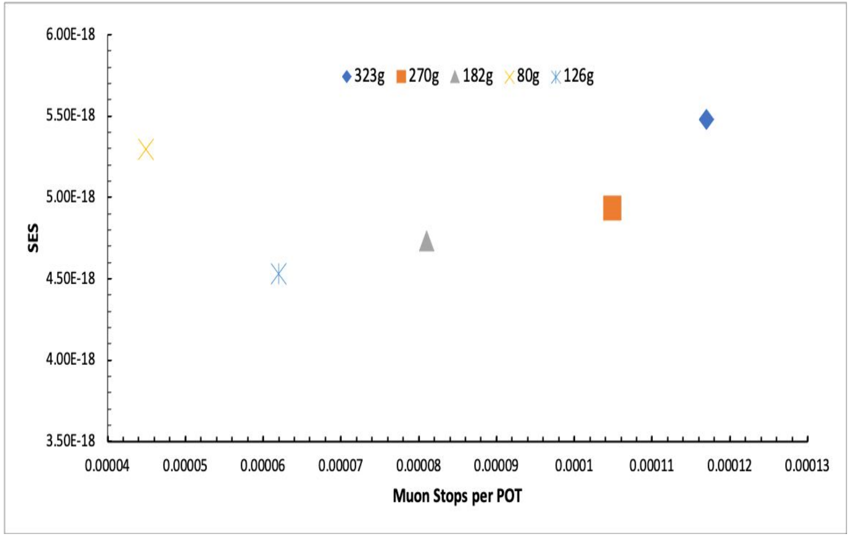
For fixed signal window definition of 103.0-104.25 MeV/c ➔ Not optimized yet!

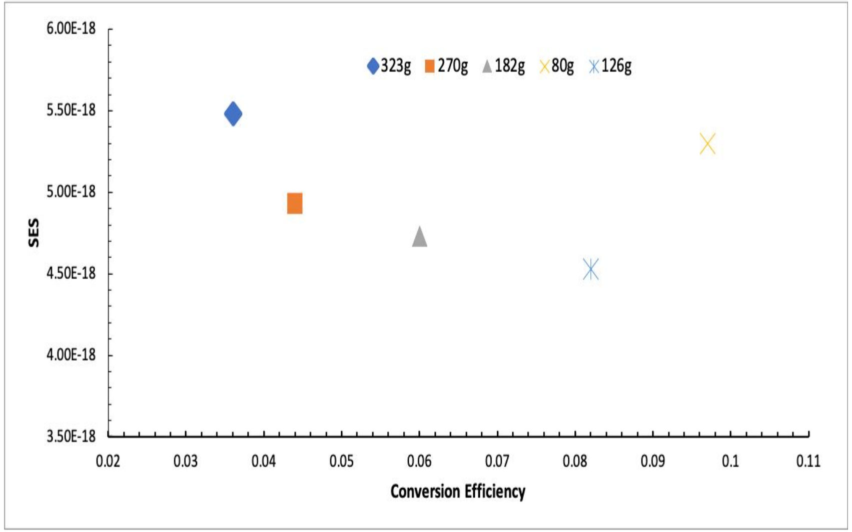
Optimal mass ➔ 126g +/- 10g

Name	Stops Rate	CE Eff	SES
Al 37 foils (176g)*	0.000089	0.12 +/- 0.0003	3.06 e-18 +/- 7.49 e-21
30 foils (323g)	0.000117	0.0361 +/- 0.0001	5.48e-18 +/- 2.52e-21
25 foils (270g)	0.000105	0.044 +/- 0.0002	4.93e-18 +/- 2.06e-21
17 foils (182g)	0.000081	0.060 +/- 0.0002	4.73e-18 +/- 1.68e-20
12 foils (126g)	0.000062	0.082 +/- 0.0003	4.529e-18 +/- 1.516e-20
8 foils (86g)	0.0000449	0.097+/- 0.0003	5.298e-18 +/- 1.545e-20

Optimization

Minimum's have been found but further refinements might be necessary:





Lithium: Preliminary Results

For fixed signal window definition of 103.66-104.91 MeV/c ➔ Not optimized yet!

Name	Stops Rate	CE Eff	SES
Al 37 foils (176g)*	0.000089	0.12 +/- 0.0003	3.06 e-18 +/- 7.49 e-21
37 foils	0.000025	0.228 +/- 0.0003	1.76e-16 +/- 2.45e-19
400 foil	0.000143	0.0948 +/- 0.00014	7.38e-17 +/- 1.06e-19
800 foils	0.000178	0.0227+/- 0.00013	2.476e-16 +/- 1.457e-18
1600foils	0.000224	0.0086 +/- 4.135e-05	5.21e-16 +/- 2.5173e-18

Due to low density and low capture rate the SES is x10 lower than Al, Ti and V

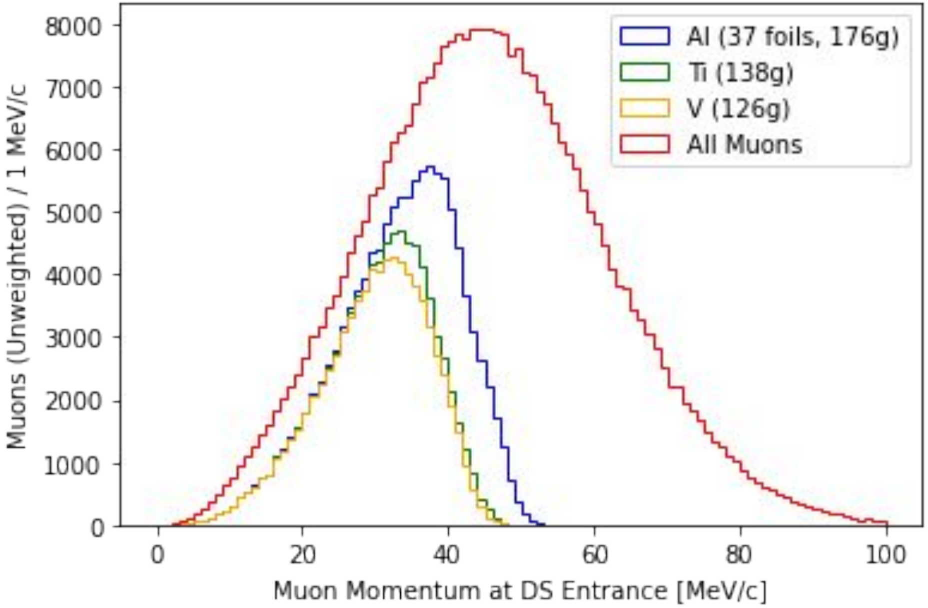
Momentum Distributions

Compare Incoming Muons to those stopped

% of DS Muons Stopped:

Al: 37%
Ti: 27%
V: 25%

Can we improve these numbers?

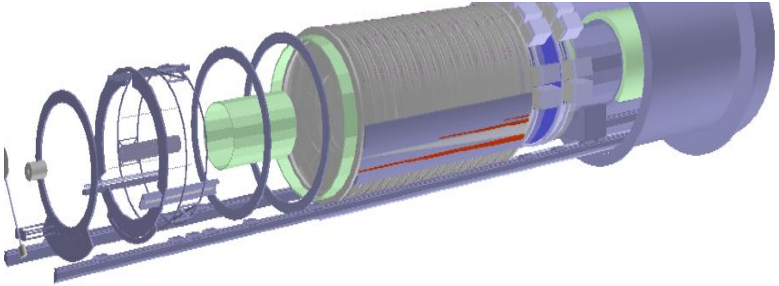


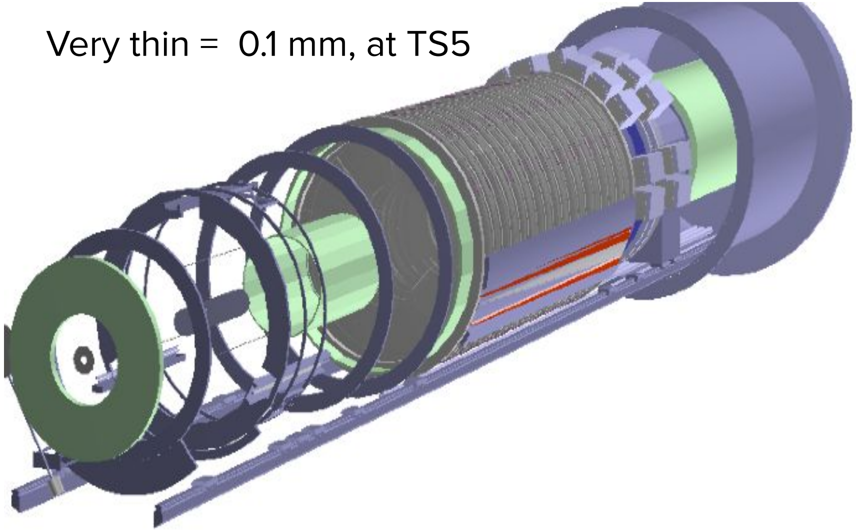
Changing the Incoming Momentum

- Added a Primary Absorber at the entrance of the DS made of LiH of various thicknesses
- Can we catch more muons by slowing them down before the ST?

Very thin = 0.1 mm, at TS5

Thick = 100mm, at TS5





Changing incoming Momentum

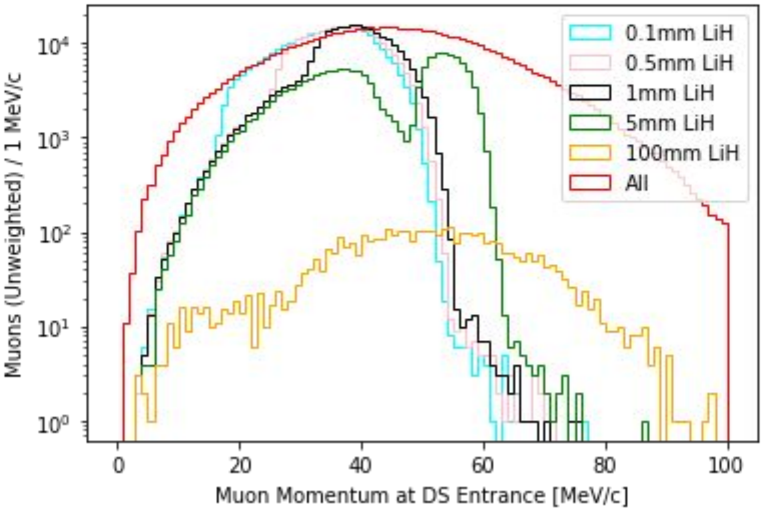
Results show how incoming momentum of stops changed relative to the “no absorber” entrance distribution

Distributions require understanding….

Number of Muons at ST:

100mm - 306683
5mm - 163199
1mm - 258723
0.5 mm - 280011
0.1 mm - 300668

Next steps: thinner absorbers, maybe Beryllium



Next Steps in the Sensitivity Study

We will soon begin making the mixed samples for the “old” geometry.

We plan to utilize the SU2020 python submission scripts but will make significant updates to make sure they are compatible with our code-base

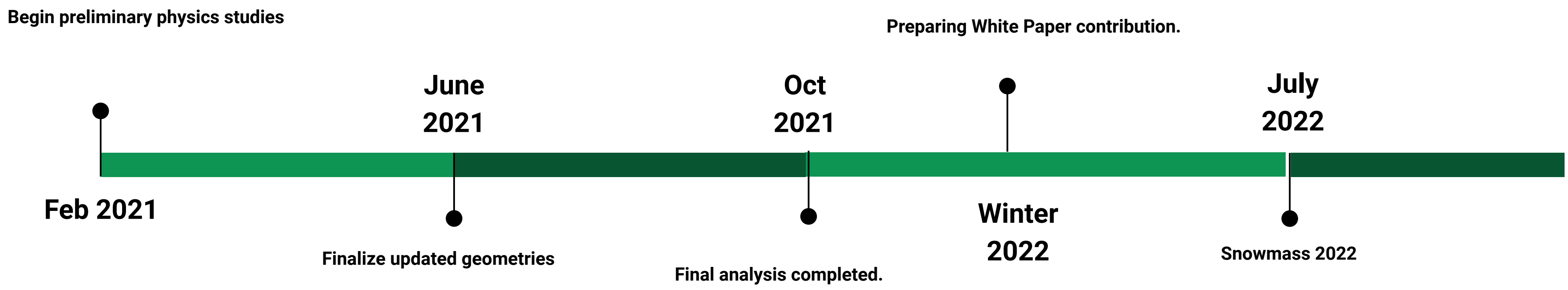
We will make a new Repo for our production scripts and store it in the Mu2e code page on GitHub (if approved)

Plan:

1. Full set of mixed samples for current setup (new PS/TS, same detectors)
2. Full set of samples with updated detectors too

Estimated Timeline

An updated timeline:



Comparing Targets

Material	CE [MeV/c]	Lifetime [ms]	Capture Rate	Decay Rate	Density [g/cm³]	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.

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.

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.