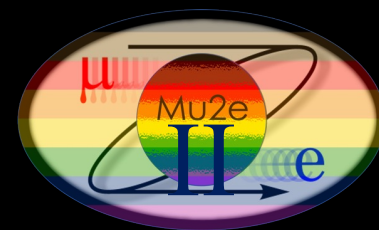# Mu2e-II: Sensitivity Summary

Sophie Middleton

March 2023

Future Muon Workshop

Mu2e-II: 2022 Snowmass Contributed Paper

2-year long effort resulted in Snowmass Contributed Paper

~100 co-signed
34 institutions
6 countries

Assumed:

- POT = 4.5×10^{22}
- 5 years of running
- **BaF$_2$ calorimeter crystals** - same dimensions as CsI
- **Straw tube tracker** - no gold layer and 8 μm straws
- **Carbon production target, conveyor design**.
- No $\bar{p}$ windows in TS.
- Mu2e Al stopping target with foil design.
- Mu2e reconstruction and trigger algorithms.
- Mu2e IPA dimensions.

Background	Mu2e	Mu2e-II (5 years)
Decay in orbit	0.144	0.263
Cosmics	0.209	0.171
Radiative Pion Capture (in-time)	0.009	0.033
Radiative Pion Capture (out-of-time)	0.016	< 0.0057
Radiative Muon Capture	< 0.004	< 0.02
Anti-protons	0.040	0.000
Decays in flight	< 0.004	< 0.011
Beam Electrons	0.0002	< 0.006
Total	**0.41**	**0.47**
N (*muon stops*)	6.7×10^{18}	5.5×10^{19}
SES	3.01×10^{-17}	3.25×10^{-18}
$R_{\mu e}$ (*discovery*)	1.89×10^{-16}	2.34×10^{-17}
$R_{\mu e}$ (90% *C.L.*)	6.01×10^{-17}	6.39×10^{-18}

Future Muons at Fermilab Workshop: Mu2e-II Sensitivity Summary

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29 March 2023

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Sensitivity Sessions Agenda

11:00 AM → 12:30 PM **Parallel Mu2e-II: Physics and Sensitivity** 📍 269 (Lauritsen)
Convener: Sophie Middleton (Caltech)

11:00 AM **Introduction** ⏱10m
Speaker: Sophie Middleton (Caltech)

11:10 AM **Stopping target** ⏱25m
Speaker: Leo Borrel (California Institute of Technology)

11:35 AM **Normalization** ⏱25m
Speaker: David Hitlin (Caltech)

12:00 PM **Exotic physics signatures** ⏱25m
Speaker: Ryan Plestid (Caltech)

1:30 PM → 3:30 PM **Parallel Mu2e-II: Physics and Sensitivity** 📍 269 (Lauritsen)
Convener: Sophie Middleton (Caltech)

1:30 PM **Implication of production target design on sensitivity** ⏱25m
Speaker: Michael Mackenzie

1:55 PM **Implication of tracker design on sensitivity** ⏱25m
Speaker: David Brown (LBNL)

2:20 PM **Challenges and on-going efforts** ⏱30m
Speaker: All

Stopping Target: A,Z Dependence (Leo Borrel)

Goal

Improve the calculation of the muon conversion rate by adding muonic x-ray experimental dataset and taking into account nuclear deformation

1. Previous calculation primarily use electron scattering data (Kitano, de Vries)
2. The conversion rate currently ignores nuclear deformation
3. Differentiate between proton and neutron distribution in the nucleus

R. Kitano et al., Phys. Rev. D 66 (2002)
H. De Vries et al., Atom. Data and Nucl. Data Tabl. 36 (1987)

Previous work (Kitano et al, Cirgliano et al, Heeck et al) uses electron scattering data only. Data is limited and doesn't take into account permanent quadruple deformations, Al-27 has large.

Caltech group have added in muonic x-ray data

Previous work
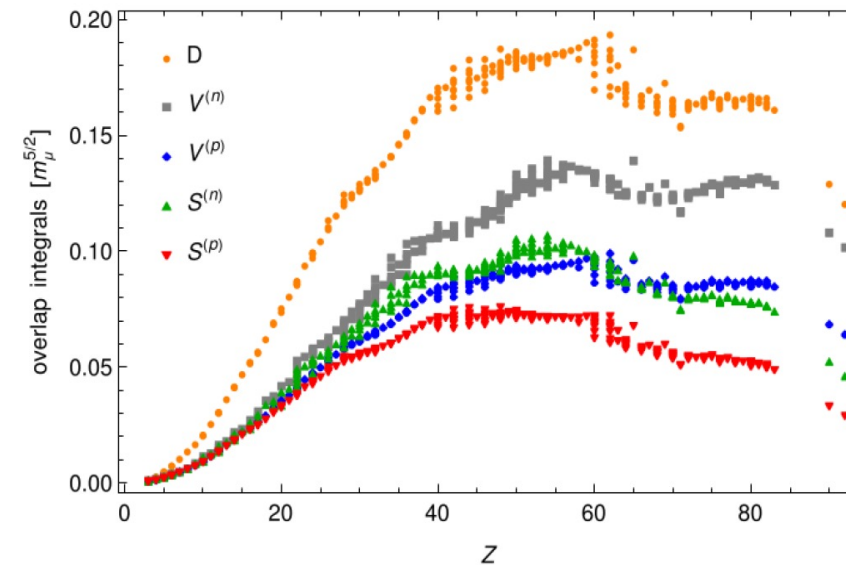
J. Heeck et al., Nucl. Phys. B 980 (2022)

- Neutron distribution is equal to the proton distribution scaled by N/Z
- The nucleon distribution is computed from the rms radius only for a number of isotopes

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Stopping Target: A,Z Dependence (Leo Borrel)
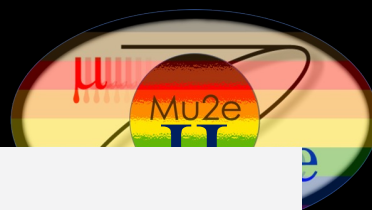
Slides give nice details of method:

Including nuclear deformation

- Start with 2pF (2-parameter Fermi distribution) $\rho(r) = \frac{\rho_0}{1+\exp\left[\frac{r-c}{t}\right]}$ (or Fourier-Bessel distribution from literature)

- include quadrupole deformation parameter β into the deformed 2pF (non-spherically symmetric) $\rho(r,\theta) = \frac{\rho_0}{1+\exp\left[\frac{r-c(1+\beta Y_{20}(\theta))}{t}\right]}$

- adjust the t parameter in the (spherically symmetric) 2pF to have the same **rms radius** as the deformed 2pF: $<r^2> = \frac{4\pi}{Z}\int_0^\infty \rho(r)r^4 dr$

- solve (spherically symmetric) Dirac equation with the (spherically symmetric) equivalent 2pF

Using Barrett Moment

- Start with 2pF (2-parameter Fermi distribution) $\rho(r) = \frac{\rho_0}{1+\exp\left[\frac{r-c}{t}\right]}$

- include quadrupole deformation parameter β into the deformed 2pF (non-spherically symmetric) $\rho(r,\theta) = \frac{\rho_0}{1+\exp\left[\frac{r-c(1+\beta Y_{20}(\theta))}{t}\right]}$

- adjust the t parameter in the (spherically symmetric) 2pF to have the same **Barrett Moment** as the deformed 2pF: $<e^{-\alpha r}r^k> = \frac{4\pi}{Z}\int_0^\infty \rho(r)e^{-\alpha r}r^{k+2}dr$

- solve (spherically symmetric) Dirac equation with the (spherically symmetric) equivalent 2pF

R.C. Barrett, Rep. Prog. Phys. 37 (1974)

Adding neutron distribution
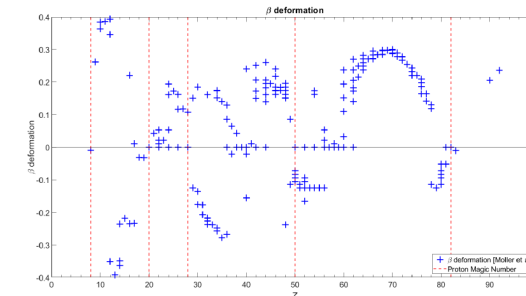
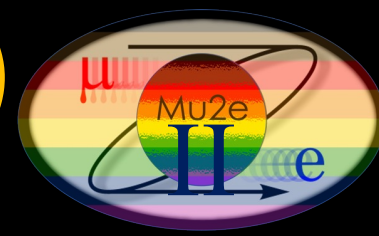P. Moller et al., Atom. Data Nucl. Data Tabl. 109 (2016)
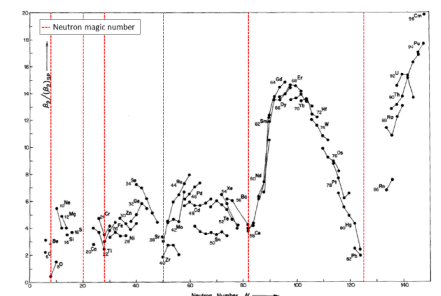
P. Stelson and L. Grodzins, Nucl. Data Sheets 1 (1965)

Calculation based on relativistic Hartree-Bogoliubov model for even-even nuclei
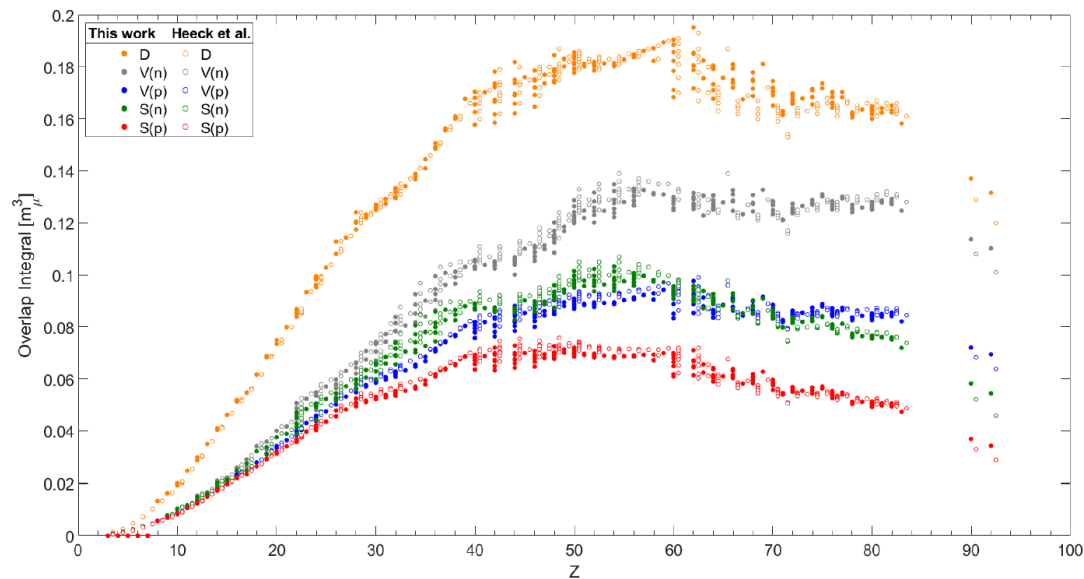
Caltech group have:
1. included muonic X-ray determinations of the nuclear charge distributions
2. explicitly accounted for permanent quadrupole moments
3. used a collective model for neutron distributions.

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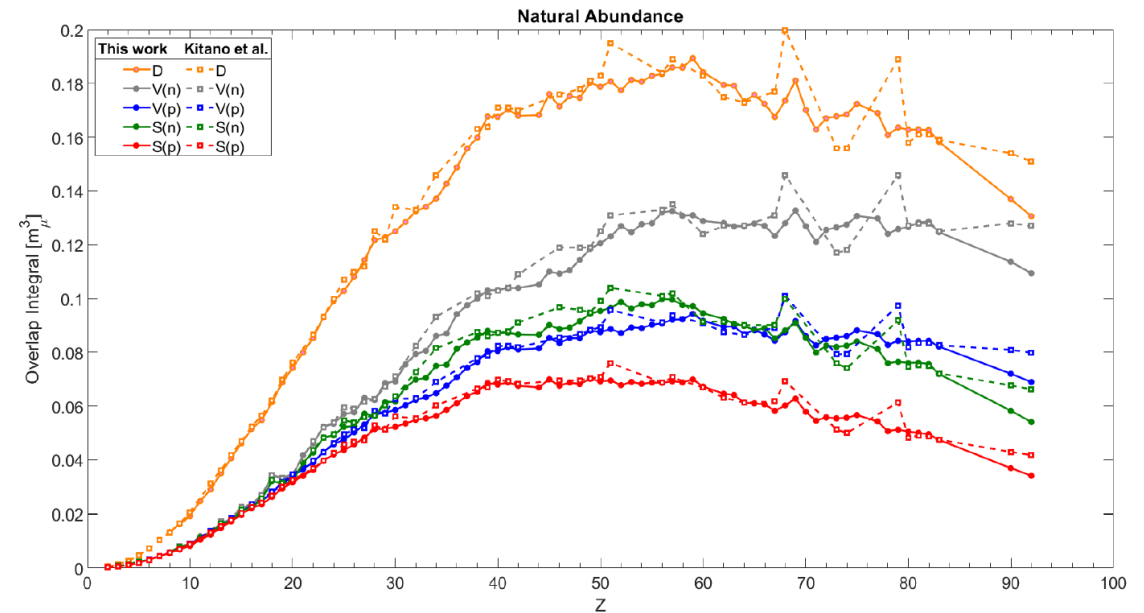# Stopping Target: A,Z Dependence (Leo Borrel)

Here: new work offset by 0.5 in Z, clear differences from earlier work

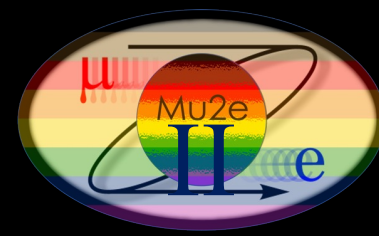**Paper out soon!**

Normalization: How to present our results (David Hitlin)

Normalization of $\mu \rightarrow e$ conversion results

- The issue comes down to the method of normalization
  - There is an approach to presenting the results that clarifies the physics and minimizes the nuclear physics complications (Z, A) dependence, coherent *vs* incoherent
  - This also facilitates the comparison to $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ measurements that are manifestly reported as decay branching fractions
- We actually measure the number of conversion electron candidates for a given number of muons stopped in the Al target in our live window
  - This requires knowledge of the muon lifetime in the Al atom

2218   T. SUZUKI, D. F. MEASDAY, AND J. P. ROALSVIG   35

TABLE IV. Compendium of total muon capture results for medium and heavy nuclei. (Z_{eff} is taken from Ref. 77. When it is underlined, it is an estimate. Entries in parentheses in column 4 are not given in the original reference.)

Z (Z_{eff})	Element	Mean life (ns)	Total capture rate (10^6/s)	Huff factor	Refs.
13 (11.48)	Al	880 ±10	0.691 ±0.020	0.993	40
		864 ±2	0.662 ±0.003		42
		905 ±12	0.650 ±0.015		45
		864.0±1.0	0.7054±0.0013		a

- The muon mean life and the total capture rate are, of course, related, but it is the muon lifetime that is relevant for our measurement

David Hitlin   Workshop on a Future Program at Fermilab   March 27, 2023   11

Coherent *vs* incoherent processes

- The "Conversion Rate" à la Weinberg and Feinberg $CR = \frac{\Gamma(\mu \rightarrow e \text{ conversion})}{\Gamma(\text{nuclear capture})}$ yields the fraction of all nuclear encounters that result in conversion
- However, exclusive $\mu \rightarrow e$ conversion is a coherent process over the nucleus while μ capture $\mu^- + p \rightarrow \nu_\mu + n$ in a nuclear environment is an incoherent process involving excitation of the residual nucleus via giant dipole excitation, multi-neutron production, fission, …

Reaction	Observed γ-ray yield	Estimated ground-state transition	Missing yields	Total yield
$^{27}\text{Al}(\mu^-, \nu)^{27}\text{Mg}$	10(1)	0	3	13
$^{27}\text{Al}(\mu^-, \nu n)^{26}\text{Mg}$	53(5)	4	4	61
$^{27}\text{Al}(\mu^-, \nu 2n)^{25}\text{Mg}$	7(1)	3	2	12
$^{27}\text{Al}(\mu^-, \nu 3n)^{24}\text{Mg}$	2	3	1	6
$^{27}\text{Al}(\mu^-, \nu pxn)^{26-23}\text{Na}$	2	2	1	5
$^{27}\text{Al}(\mu^-, \nu \alpha xn)^{23-21}\text{Ne}$	1	2	0	3
Total	75(5)	14	11	100

Measday, Stocki, Moftah and Tam
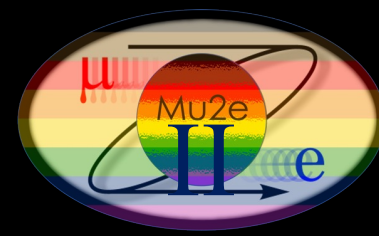Phys. Rev. C**76**, 035504 (2007)

- Thus the calculation of the μ capture rate involves matrix elements involving transitions to Mg, Na and Ne which have nothing to do with $\mu \rightarrow e$ conversion
- It is true that normalizing to $\omega_{capture}$ yields the fraction of the New Physics over all the things that the μ does in interacting with the nucleus, but this has the effect of mixing complex, and irrelevant, nuclear processes into a study of Z dependence

12

- Gave a comprehensive discussions of the origins of how CLFV searches present results.
- He emphasized that when we use the convention of dividing by capture, we introduce an incoherent process and structures into our Z dependence plot.
- It is lifetime we care about, why use capture rate? It is just convention, and we should re-think!

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Normalization: How to present our results (David Hitlin)

Conclusions

New normalization proposal

Theory ramifications

- Present the results that you actually calculate
- Present either calculated rate (Γ) or normalize to muon decay rate (BR) or (CR)
- Eliminates artificial normalization of a calculated coherent process to a measured incoherent process
- Facilitates comparison of conversion rates to decay rates in various models

Experimental ramifications

- Present the conversion fraction (or limit) normalized to the free muon decay rate, or just the conversion rate
- Normalize the conversion rate by what is actually measured:
  - Determine the number of muon stops in the target using the $2P$-$1S$ muonic x-ray (and/or muon capture γs)
  - Avoid presentation of experimental results divided by a looked-up muon capture rate, which results in extraneous Z,A structure dependence
- Corollary: NP limit comparisons such as the DeGouvea-Vogel or Davidson-Echenard plots should be revised to remove division by μ capture rate (.61 for Al)
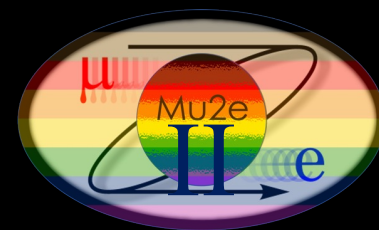
Comparison

$$B_{\mu \to e}(Z) = \Gamma_{conversion}(Z, A)$$

$$B_{\mu \to e}(\text{Al}) \equiv \Gamma_{conversion}(13,27)$$
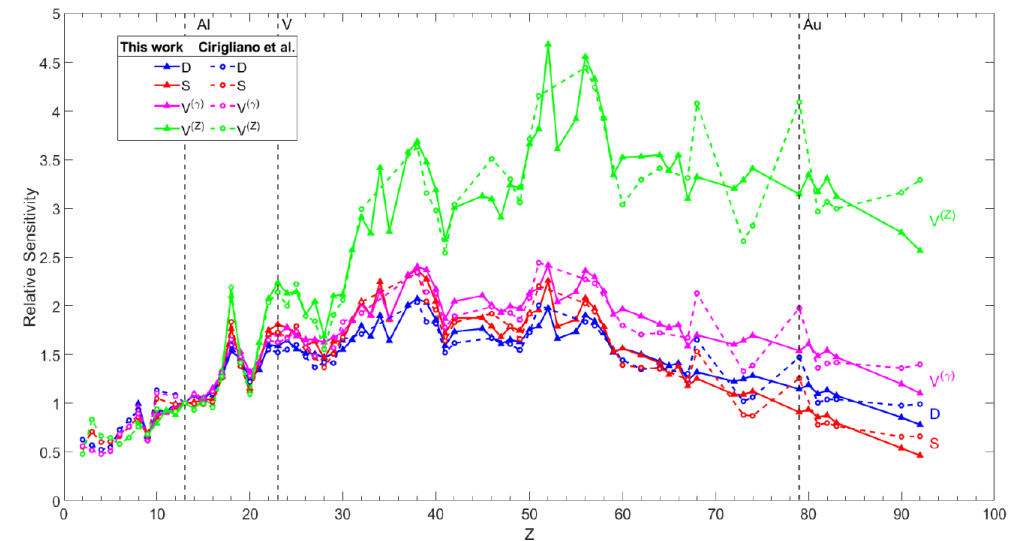
- We should present what we calculate
- Instead we should present a conversion fraction normalized to free muon decay rate, or just the conversion rate.
- How to convince other experiments?

Physics Signatures (Ryan Plestid)

Light New Physics

- Data demands that new physics be heavy, or weakly coupled

- What could we see in a ~100 MeV experiment?

Z-Prime

$$\mathscr{L} \subset g' \bar{\mu} \Gamma_\mu e \, Z'^\mu$$

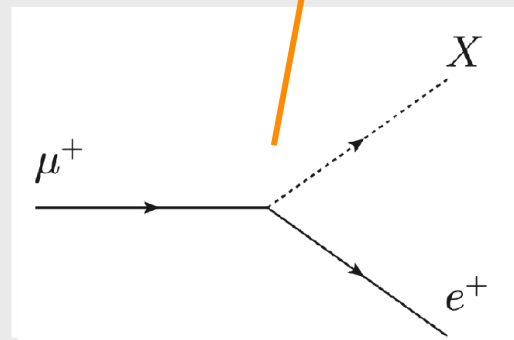$$\mathscr{L} \subset \frac{1}{\Lambda} \bar{\mu} \Gamma_\mu e \, \partial^\mu a$$
Axions

HNLs

$$\mathscr{L} \subset U_{eN} \left[f_\pi G_F \left(\partial_\mu \pi \right) \bar{N} \gamma^\mu P_L e \right]$$

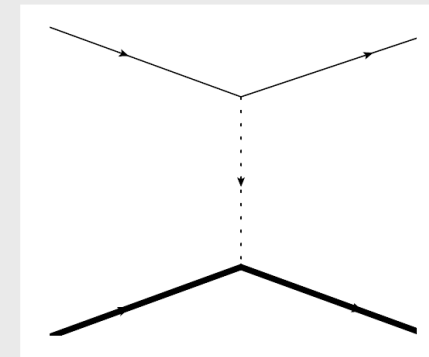**Mu2e and Mu2e-II can also probe light new physics, examples listed here.**
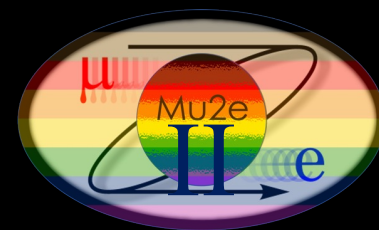
Use μ^+ channel
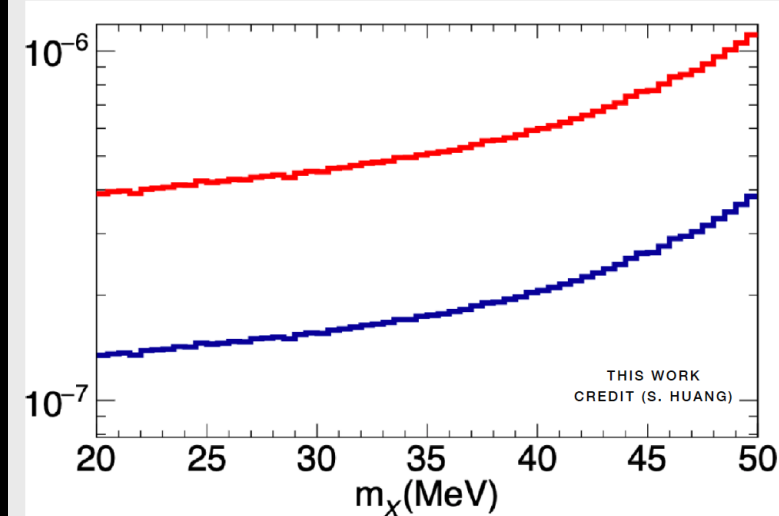
On-Shell Vs Off-Shell Processes

$$\Gamma \sim O(g^2)$$
THIS WINS

$$\Gamma \sim O(g^4)$$

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Physics Signatures (Ryan Plestid)

Estimates For $\mu^+ \to e^+ X$ $m_X > 20$ MeV


THIS WORK
CREDIT (S. HUANG)

- Estimates with 2 weeks of data taking.

- Improve on world leading limit by a factor of 40.

- Constrains LFV models with ALPs, and Z'.

HNLs are an active area of research, with Mu2e we could ne competitive to upcoming projections in mixing between HNL and electron neutrino in MeV range. With Mu2e-II being able to do even better.

Results For Heavy Neutral Leptons

- No planned experiment will probe the region of parameter space sketched here.

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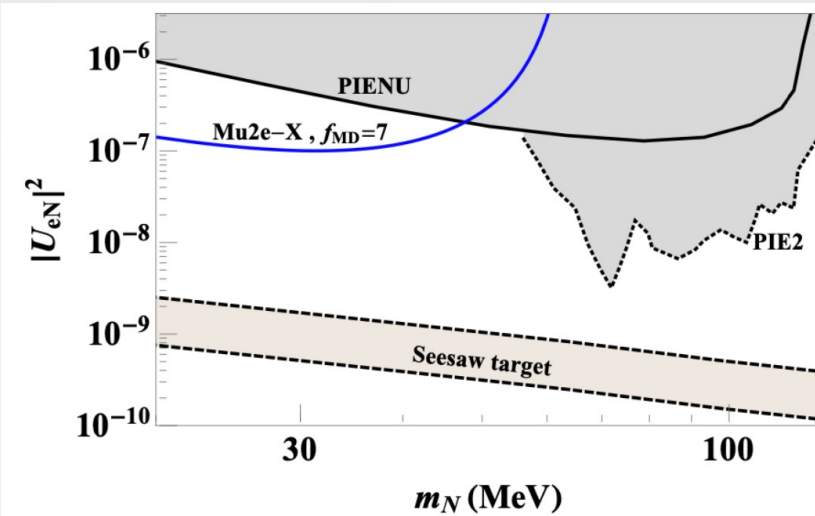
# Implications of Production Target Design (Michael Mackenzie)
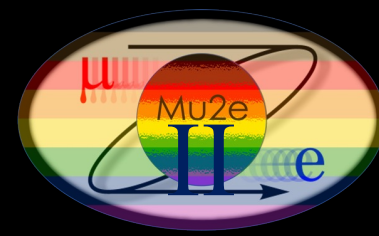
Muon stopping rate

Target	Proton KE (MeV)	R(muon stops / POT)
Carbon	800	$(9.044 \pm 0.095) \times 10^{-5}$
conveyor	8000	$(3.824 \pm 0.062) \times 10^{-4}$
Tungsten	800	$(7.190 \pm 0.085) \times 10^{-5}$
conveyor	8000	$(1.132 \pm 0.016) \times 10^{-3}$
Hayman	800	$(1.034 \pm 0.032) \times 10^{-4}$
	8000	$(1.866 \pm 0.014) \times 10^{-3}$

- The tungsten conveyor target performs worse than the Mu2e era tungsten Hayman target, though the Hayman target would not survive the higher beam power used at Mu2e-II
- The stopping rate is higher for the carbon conveyor target, but this could be a feature of the Geant4 modeling used in Offline as MARS/FLUKA predicted lower particle production rates for carbon
- We should be able to achieve a stopping rate of $\mathcal{O}(10^{-4})$
- Depending on the target's and the detector's ability to survive the high beam power, it's possible to increase the 800 MeV beam power to compensate for low muon production rates but this needs to be investigated
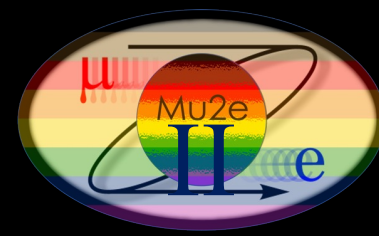
Mu2e-II sensitivity vs stopping rate
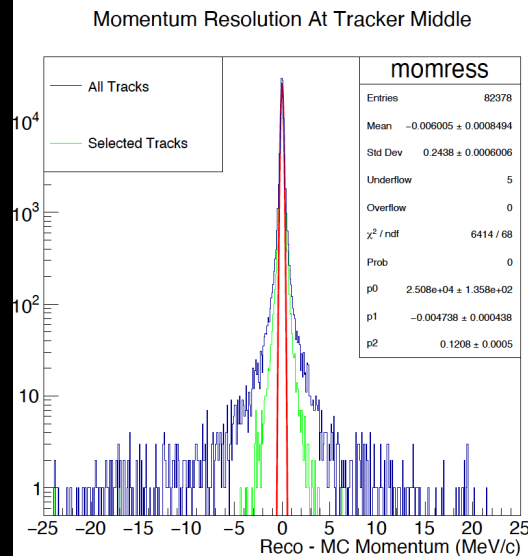

Median 90% CL vs stopping rate
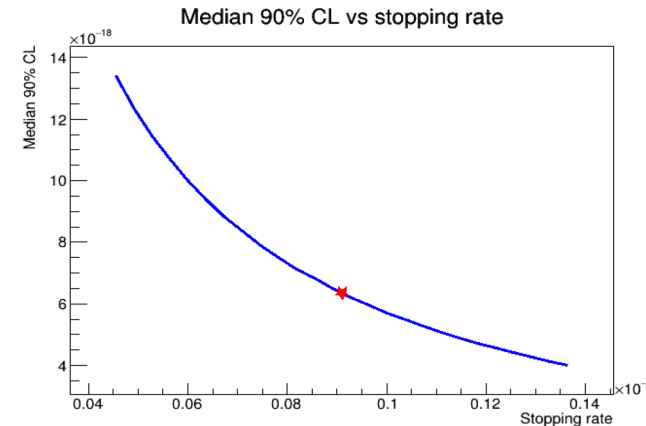
- The above plot shows the median expected 90% CL using Feldman Cousins while varying the muon stopping rate at Mu2e-II
- Clearly the stopping rate has a significant impact on the experiment sensitivity
- This does not include re-optimizing the search window, which would improve the expected sensitivity, or the change in the detector pileup with different production target particle yields

Production target design practicalities need to also consider effect on sensitivity – further studies needed!

Implications of Tracker Design
(David Brown)

Momentum Reconstruction Resolution

Momentum Resolution At Tracker Middle

| momress	
Entries	82378
Mean	−0.006005 ± 0.0008494
Std Dev	0.2438 ± 0.0006006
Underflow	5
Overflow	0
χ^2 / ndf	6414 / 68
Prob	0
p0	2.508e+04 ± 1.358e+02
p1	−0.004738 ± 0.000438
p2	0.1208 ± 0.0005

- The core resolution (120 KeV/c) is less than expected (270 KeV/c)
  - The fit corrects for energy loss in each straw crossing
    - Using the predicted trajectory
  - This removes the (dominant) resolution contribution due to **variation in the amount of material intersected**
- The resolution tails can be greatly reduced by fit quality cuts
  - RMS after selection is ~2X core resolution

How to Improve the Sensitivity (Tracker)

- Mitigate the target energy loss impact
  - **Predict the target material (number and paths of foil intersections) using the track fit**
  - **Optimize the target geometry for predicting the target energy loss**
  - Investigate how to improve the # of μ-stops/gm
    - Can the muon beam be optimized?
  - Actively count the target intersections
    - NB: the target foil energy deposition is not intrinsically useful as E_{ce} > critical energy
- Reduce the reconstruction artifacts causing high-side tails
  - **Improve the hit information quality and quantity**
  - Improve the drift calibration (T2D)
  - Improve the pattern recognition algorithm (LR ambiguity assignment)
  - Improve the track selection algorithms
- Reduce the tracker (straw) mass
  - Reduced mass will improve the fit quality and extrapolation accuracy
- Mitigate the IPA energy loss impact
  - Predict the material path using the track fit

Target, IPA and tracker design all effect resolution. See list of future project!

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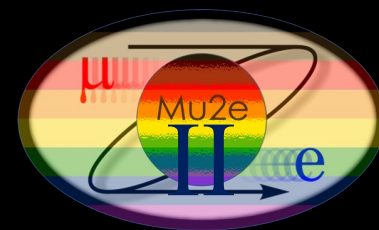
How to get involved? Next Steps

- Projects (in order of priority):

  - Stopping target studies – extrapolating tracks to ST using KinKal – contacts: Sophie*, Dave Brown

  - Incoming muon beam studies – play with absorbers, wedges, cooling and TS (as below) to alter incoming muon beam. Contacts: Sophie*

  - PS and TS field studies – for the PS what about radiation levels? For the TS main study is just playing with incoming beam via changing currents. Contacts: Sophie*

  - Production target studies – simulations based on on-going R&D. Contacts: Vitaly

  - Tracker Design – alternative designs modelling in G4. Contacts: Dave Brown.

  - Physics studies – contacts: Sophie*, Ryan Plestid

  - Notes:
    https://docs.google.com/document/d/1A9Svwji3Bg4WVGkR1S0fIciyRWj7YsnN_uQwfCF742Y/edit?usp=sharing

  - Please add if I missed anything. Plan to hold a simulation meeting at some point for people involved in projects listed, so get in touch if you'd like to be involved. Several projects good for graduate students and summer students. **Still many opportunities to help mold design of the Mu2e-II experiment!**

  - *email: sophie@fnal.gov (also Yuri Oksuzian & Lisa Goodenough)

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