The Mu2e Experiment : A Search for Charged Lepton Flavour Violation in Muons

Andrew Edmonds
on behalf of the Mu2e collaboration

University of Birmingham Seminar, 1st June 2022

Boston University

Outline

Motivation

- The Muon in the Standard Model and Hints of New Physics
- Charged Lepton Flavour Violation and Muon-to-Electron Conversion

The Mu2e Experiment

- Producing and Stopping the Highly-Intense Muon Beam
- Detecting the Signal and Mitigating Backgrounds

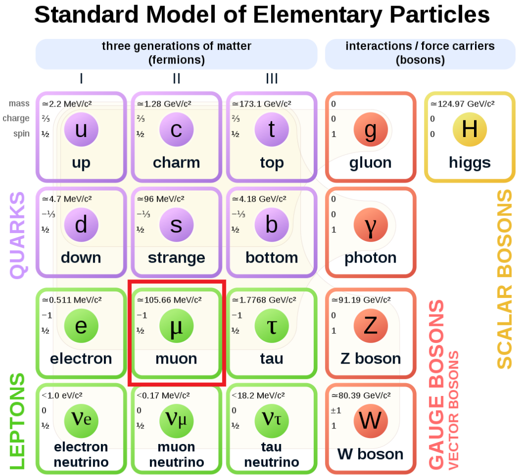
Conclusion

- Future Prospects

Motivation

The Muon in the Standard Model and Hints of New Physics

The Muon



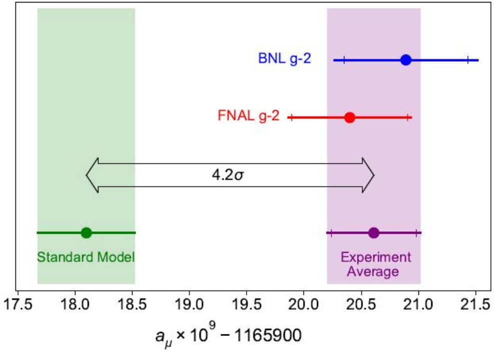
The muon is the second-generation charged lepton

In the Standard Model:

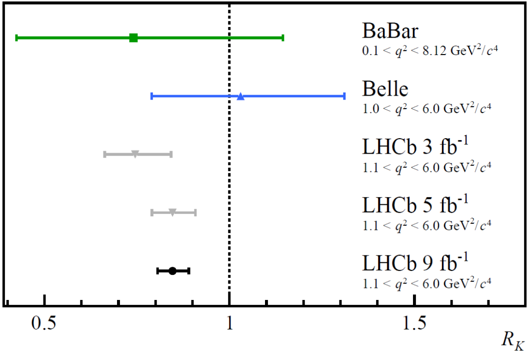
- one can calculate their properties to high precision,
- lepton interactions with gauge bosons are flavour independent (lepton universality), and
- lepton flavour is conserved

It’s an exciting time for muon physics!

Starting to see evidence that the Standard Model does not fully describe muons



anomalous magnetic moment measured again

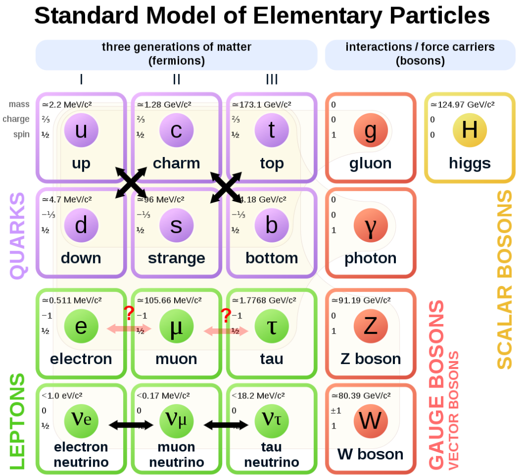


hints of lepton universality violation

Motivation

Charged Lepton Flavour Violation and Muon-to-Electron Conversion

Charged Lepton Flavour Conservation



Muons conserve lepton flavour:

	μ^-	$\rightarrow$	e^-	$\bar{\nu}_e$	ν_μ
L_μ:	$+1$		0	0	$+1$
L_e:	0		$+1$	-1	0

Flavour is not conserved in:

- quarks (via quark mixing); and
- neutrinos (via neutrino oscillations)

So why don't we see muons violate flavour conservation?

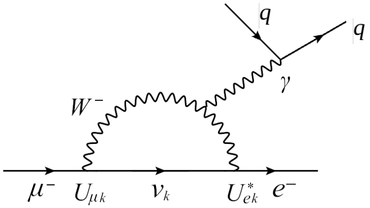
Charged Lepton Flavour Violation (CLFV)

The Standard Model with neutrino masses (νSM) says its unobservably rare...

...but many Beyond Standard Model (BSM) theories predict enhanced rates of CLFV

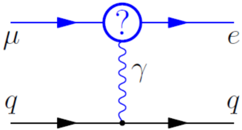
νSM Prediction

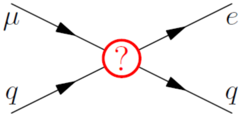
$$R_{\mu\to e} \propto (\frac{\Delta m_\nu^2}{M_W^2})^2 < 10^{-52}$$



BSM Predictions

$$R_{\mu\to e} \sim 10^{-17} - 10^{-15}$$





Any observation of CLFV would be clear evidence of New Physics!

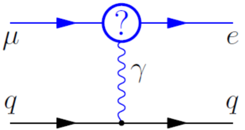
CLFV Searches

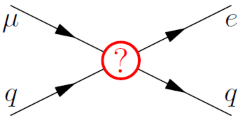
Muons are a great experimental tool because

- they have a long lifetime, and
- we can create a lot of them.

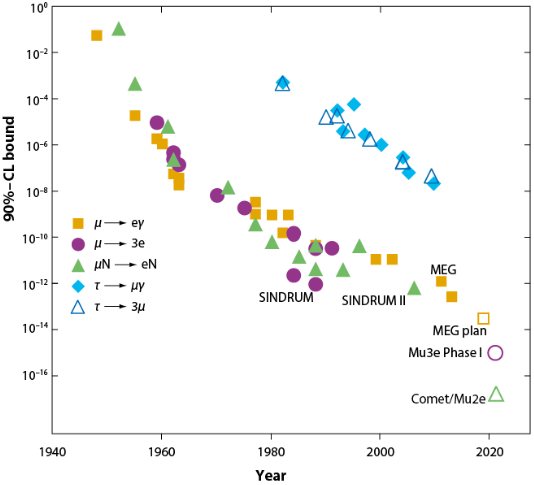
There are three possible CLFV processes:

- $\mu \to e\gamma$
- $\mu \to eee$
- $\mu^- + N(Z, A) \to e^- + N(Z, A)$



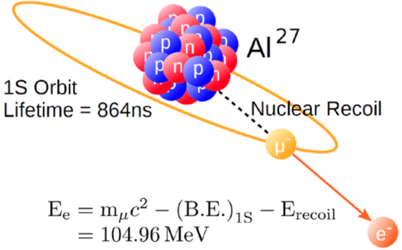


Muon-to-electron conversion sensitive to many different BSM models



History of CLFV Searches in Leptons

Muon-to-electron Conversion



Muon-to-electron conversion occurs in muonic atoms

- stop low-energy muons in a stopping target

It has a very simple signal

- a mono-energetic electron

Current limit (SINDRUM II on Au): $R_{\mu\to e} < 7\times10^{-13}$, where

$$R_{\mu\to e} = \frac{\Gamma\left(\mu^- + N(Z,A) \to e^- + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A)\right)}$$

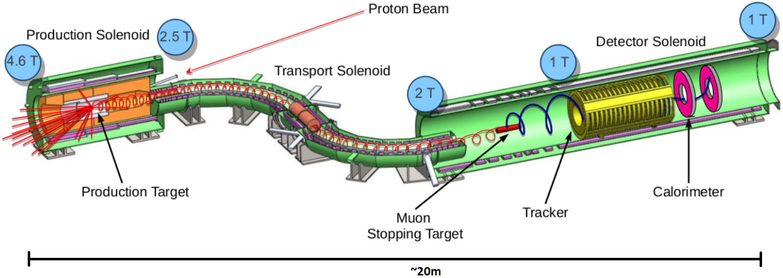
The Mu2e Experiment

The Mu2e experiment will search for this process in Al and improve on this limit by four orders of magnitude!

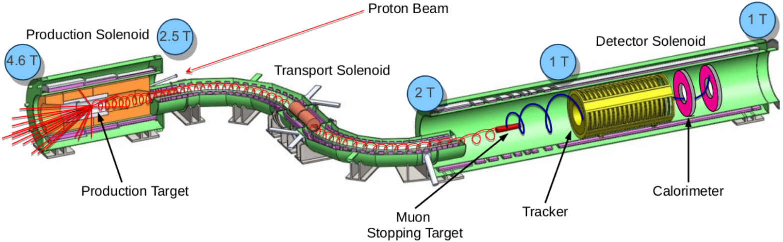
$$R_{\mu\to e} = \frac{\Gamma\left(\mu^- + N(Z,A) \to e^- + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A)\right)} < 8\times 10^{-17}\ (90\%\ \mathrm{CL})$$

$$\tau_{\mu\text{-Al}} = 864\ \mathrm{ns},\ E_{\mathrm{signal}} = 105\ \mathrm{MeV}$$

Need to stop $O(10^{18})$ μ^- and have $\ll 1$ background event



The Mu2e Experiment



- Production Solenoid
  - pulsed proton beam hits production target
  - pions collected by the graded solenoidal magnetic field
- Transport Solenoid
  - pions decay to muons
  - charge and momentum selection
- Detector Solenoid
  - muons stop in thin Al foils
  - muonic atom decays
  - resulting electrons are detected by a tracker and a calorimeter
- Other Detectors (not shown)
  - cosmic ray veto
  - extinction and stopping target monitors

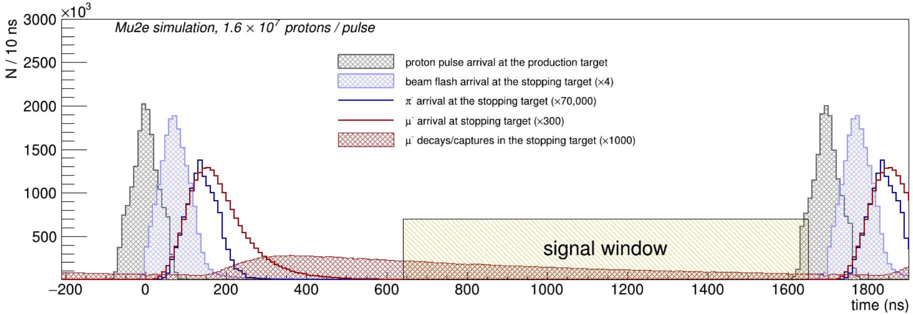
The Mu2e Experiment

Producing and Stopping the Highly-Intense Muon Beam

Proton Beam

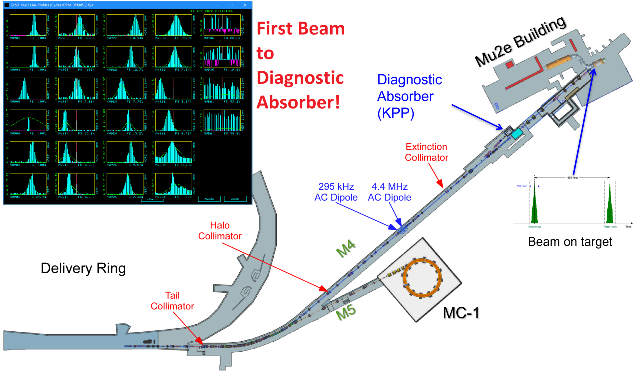
Backgrounds that are prompt with proton-on-target could be significant

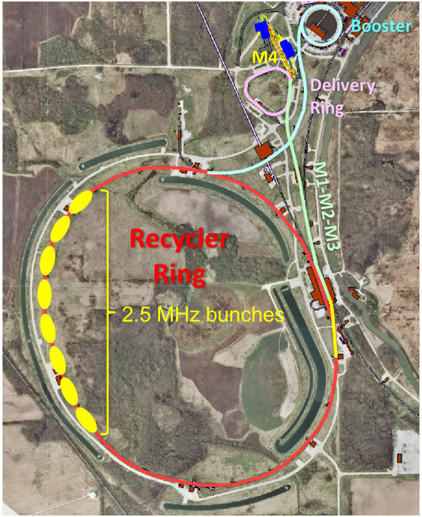
- take advantage of muonic atom's long lifetime and use a pulsed beam to greatly reduce beam-related backgrounds
- i.e. signal is emitted in the gaps between proton pulses



Accelerator

Protons will be slow extracted from the delivery ring to generate proton pulses

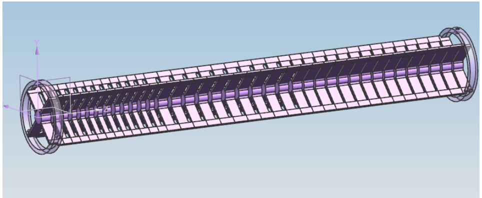




Production Target

Tungsten production target is in a very challenging environment (8 kW beam power, 8 GeV protons):

- design optimized for pion production, radiation cooling, and structural integrity $\rightarrow$ segmented target



CAD Drawing of Mu2e Production Target

Photo of Mu2e Production Target in Mounting Rig

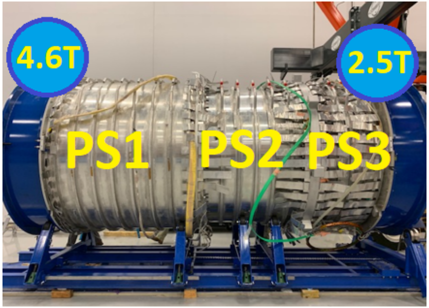
Production Solenoid

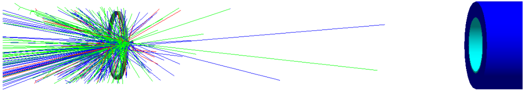
Graded magnetic field collects pions going backwards w.r.t proton beam

- typically lower momentum → will stop in the stopping target later

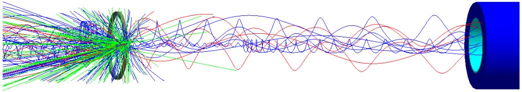
Current status: all coils fabricated, testing and cold mass assembly underway

Photo of Production Solenoid Coils





Without PS Field



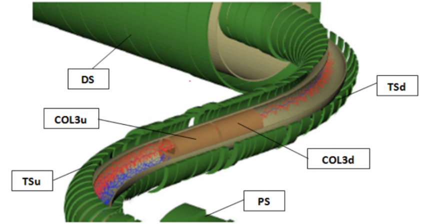
With PS Field

Transport Solenoid and Collimators

Transport solenoid separates positive and negative pions/muons

- rotatable collimator blocks positive muons

Current status: all coils delivered, TSu and TSd cold masses assembled (right)



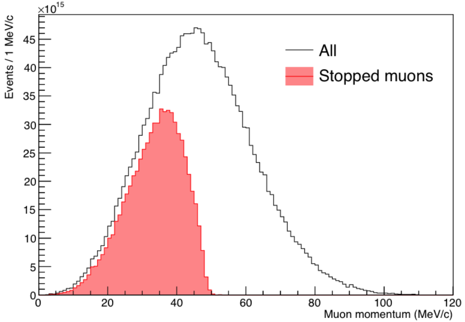
Example negative and positive muons travelling around Transport Solenoid

Transport Solenoid Cold Masses

Stopping Target

In the detector solenoid, we have the stopping target

- 37 thin aluminium foils, 100 μm thick
- we will stop 10^{10} μ^{-} / s



Momentum distribution of stopped (all) muons at stopping target

Photo of the Stopping Target

The Mu2e Experiment

Detecting the Signal and Mitigating Backgrounds

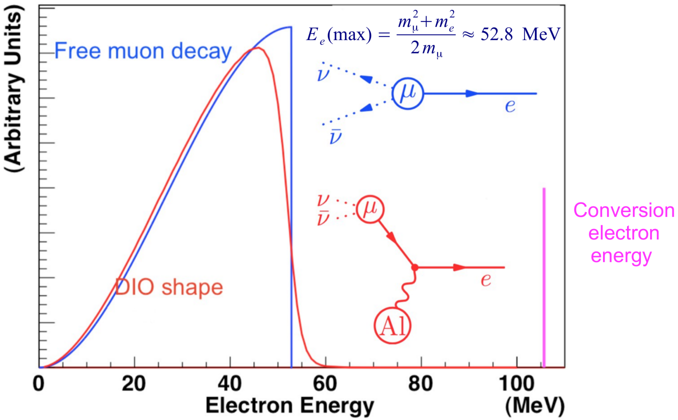
Decay-in-Orbit (DIO) Background

When the muon is bound in a muonic atom, it could also decay to an electron and two neutrinos ($\mu^- \to e^- \nu_\mu \bar{\nu}_e$)

- happens $\sim$ 40% of the time in muonic-Al

Nuclear recoil modifies energy spectrum:

- still has a peak at $\sim$ 50 MeV, but
- tail extends up to the conversion energy



Cartoon of DIO Energy Spectrum
(see Szafron, Czarnecki PhysRevD.94.051301 + others)

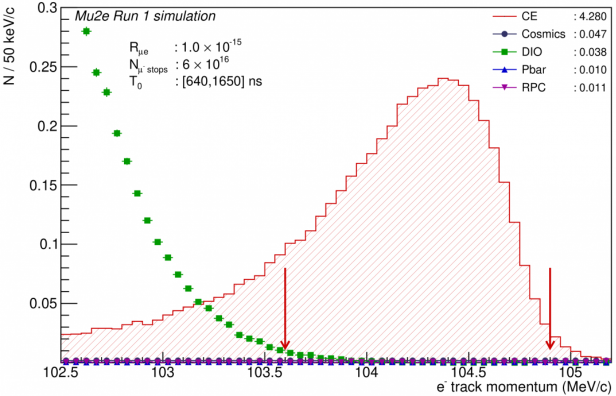
Decay-in-Orbit (DIO) Background

When the muon is bound in a muonic atom, it could also decay to an electron and two neutrinos ($\mu^- \to e^- \nu_\mu \bar{\nu}_e$)

- happens $\sim 40\%$ of the time in muonic-Al

Nuclear recoil modifies energy spectrum:

- still has a peak at ~ 50 MeV, but
- tail extends up to the conversion energy

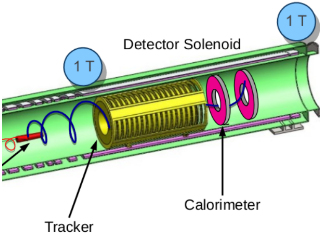


Expected signal ($R_{\mu \to e} = 10^{-15}$) and DIO spectra from simulation (with resolution and energy loss)

Tracker

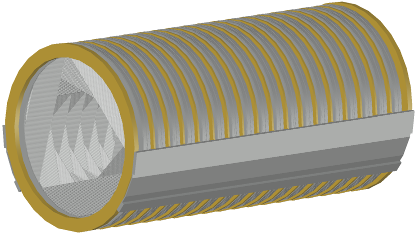
Need a high-resolution momentum measurement

- minimize energy loss by operating in vacuum and using low mass straws
- extra hit position information with high-angle stereo overlaps and readout on both ends of straw
- reduce background hits with a central hole

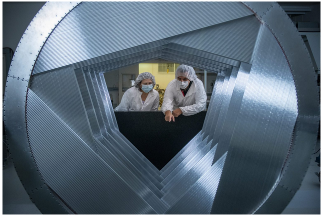


5 mm diameter, 15 μm thick walls

1 tracker = 36 planes = 20736 straws



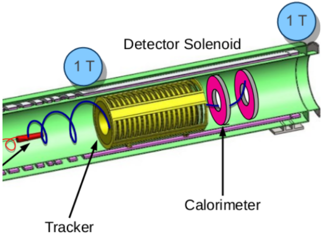
planes with central hole



Tracker

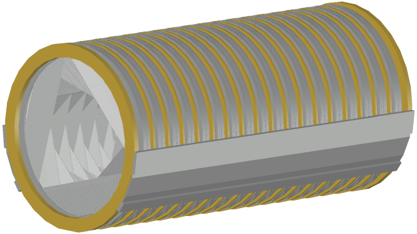
Need a high-resolution momentum measurement

- minimize energy loss by operating in vacuum and using low mass straws
- extra hit position information with high-angle stereo overlaps and readout on both ends of straw
- reduce background hits with a central hole

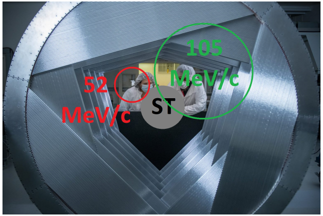


5 mm diameter, 15 μm thick walls

1 tracker = 36 planes = 20736 straws



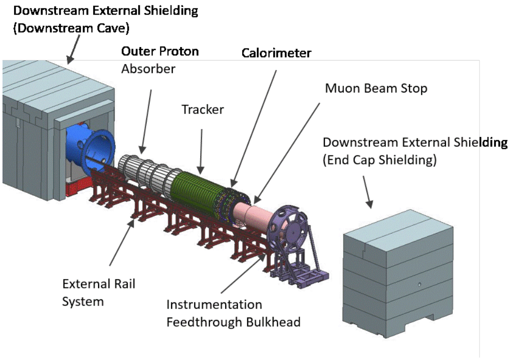
planes with central hole



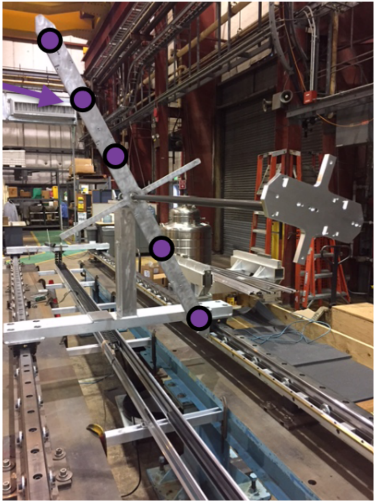
Detector Solenoid

Need to measure the magnetic field to 10^{-4} T

- dedicated DS field mapping runs



Detector extracted position for field mapping

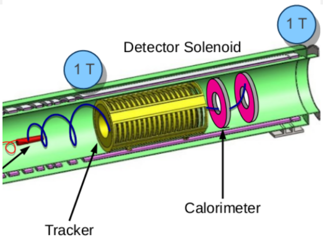


DS Field Mapper with Hall probe locations

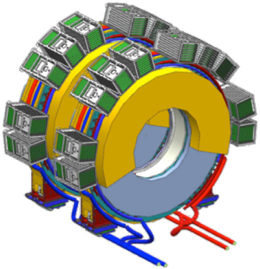
Calorimeter

Want a fast energy measurement

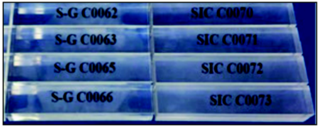
- can be used for the trigger
- combine with momentum measurement for e/μ separation
- energy clusters can also be used to seed the track fit



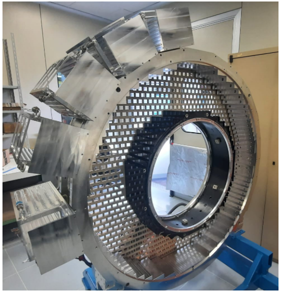
Two disks, each 674 crystals



undoped CsI crystals
(20 x 3.4 x 3.4 cm^3)



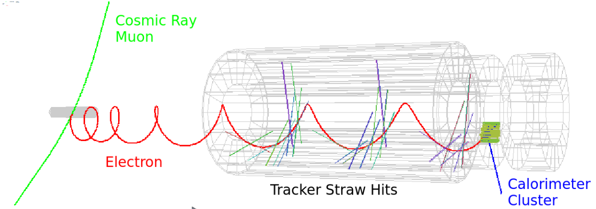
Calorimeter Disk

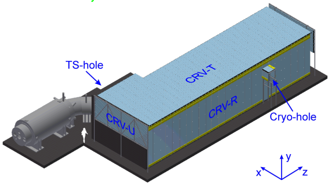


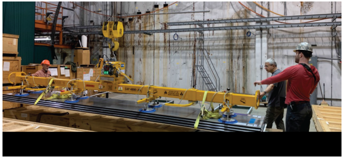
Cosmic Ray Veto

Need to know when cosmic rays enter experiment

- expect 1 Ce-like electron per day from cosmic muons
- CRV covers full detector solenoid and half the transport solenoid
- must be 99.99% efficient



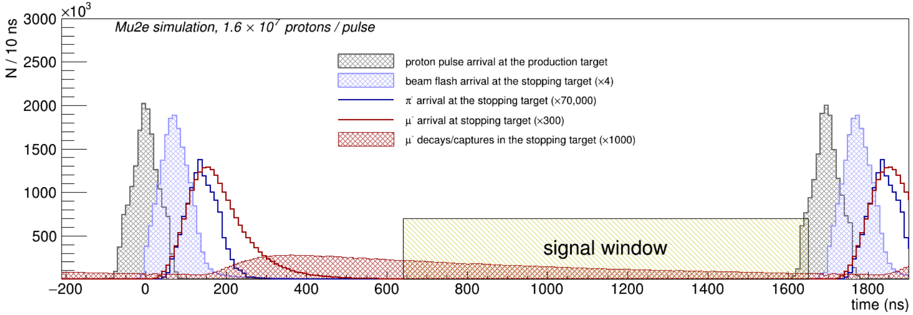




Beam-related Backgrounds

Backgrounds that are prompt with proton-on-target could be significant

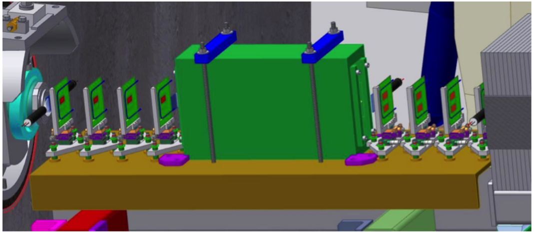
- we are looking for something so rare, that any protons that arrive at production target between proton pulses could produce a large background
- we need extinction level (ratio of protons in and out of pulse) to be $< 10^{-10}$

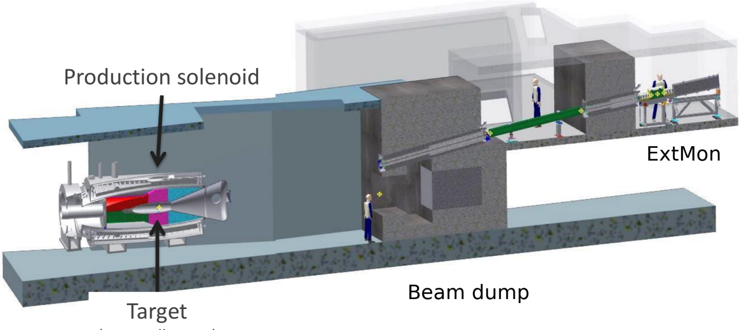


Extinction Monitor

Ensure extinction meets requirements by tracking protons that scatter off production target

- uses pixel sensors and trigger scintillators





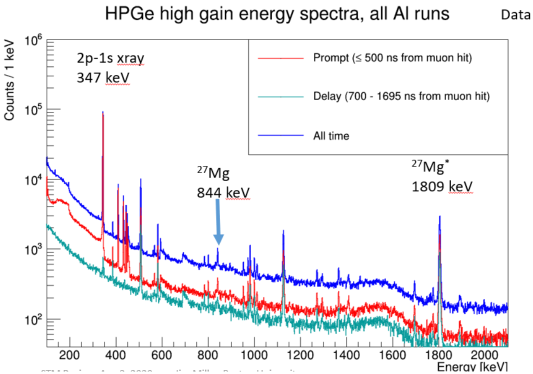
The Denominator of $R_{\mu-e}$

Need to know the denominator of $R_{\mu-e}$:

$$R_{\mu\to e} = \frac{N_{\text{signal}}}{N_{\text{captures}}}$$

We count the number of stopped and captured muons by detecting characteristic x- and γ-rays from:

- stopped muons
  - $2p - 1s$ x-ray (347 keV)
- captured muons ($\mu + {}^{27}\text{Al} \to {}^{27}\text{Mg} + \nu_\mu$)
  - ${}^{27}\text{Mg} \to {}^{27}\text{Al} + \gamma$ (844 keV)
  - ${}^{27}\text{Mg}^* \to {}^{27}\text{Mg} + \gamma$ (1809 keV)

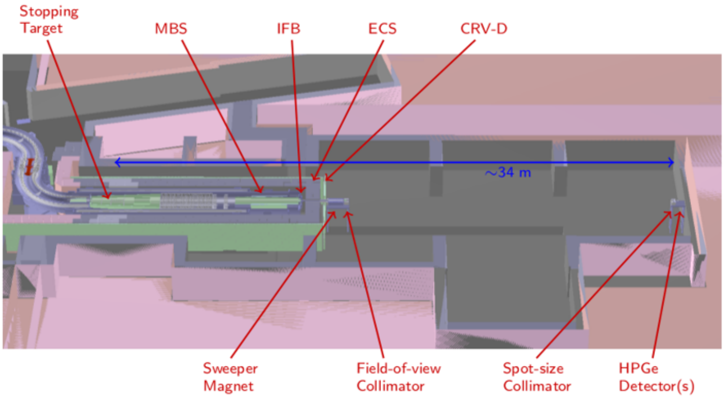


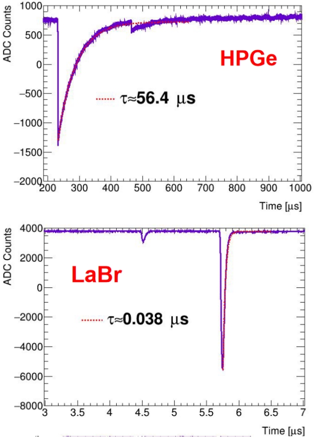
Data from the AlCap experiment

Stopping Target Monitor

The stopping target monitor consists of a HPGe and an LaBr detector

- LaBr can handle higher rates at expense of energy resolution





Test Beam Data

Detectors located far downstream because beam flash is too bright

Conclusion

Future Prospects

Mu2e Schedule

- Detector commissioning with cosmic rays in 2023
- Beam on production target in late 2024
- Take Run 1 data in 2025 and 2026 until LBNF/PIP-II shutdown
  - x1000 improvement over SINDRUM-II
- Resume data collection in 2029 after long shutdown
  - x10000 improvement over SINDRUM-II

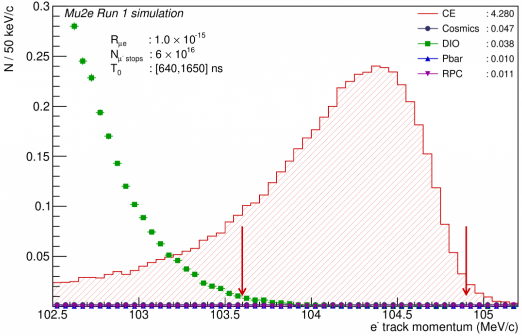
Run 1 Sensitivity Estimate

We recently completed a sensitivity estimate for Run 1

- 5σ discovery $R_{\mu\to e} = 1.1 \times 10^{-15}$
- 90% CL $R_{\mu\to e} < 5.9 \times 10^{-16}$
- 1000x better than SINDRUM-II limit
- paper to be submitted to *Universe*

Total background:

- 0.11 ± 0.03 (stat.+syst.) events
  - cosmics $= 0.05 \pm 0.01$ events
  - DIO $= 0.04 \pm 0.02$ events



Signal and Background PDFs for $R_{\mu\to e} = 10^{-15}$

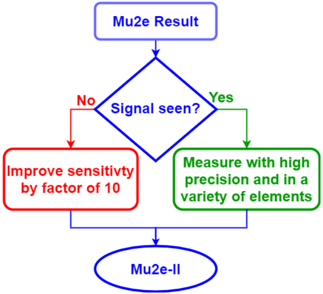
Beyond Mu2e

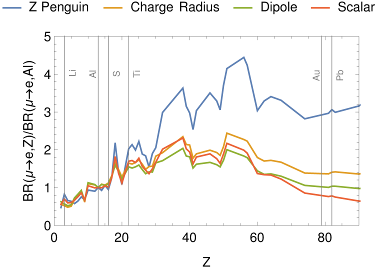
An upgraded Mu2e-II has been proposed (link)

- takes advantage of PIP-II upgrade at Fermilab
- upgraded detectors (e.g. thinner straws)
- x10 improvement in sensitivity, or measure in other muonic atoms

Beyond Mu2e-II, a fuller CLFV program for Fermilab is being pursued as part of Snowmass (link)

- $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$





Conclusion

Observation of charged lepton flavour violation would be an unambiguous sign of new physics

Mu2e will search for the charged lepton flavour violating process of $\mu \to e$ conversion with a 90% CL upper limit of $R_{\mu \to e} < 8 \times 10^{-17}$

The experiment is under construction with beam commissioning to take place in 2024, and data-taking to begin in 2025

Thanks for listening! Any questions?

Back Up

Run 1 Background Table

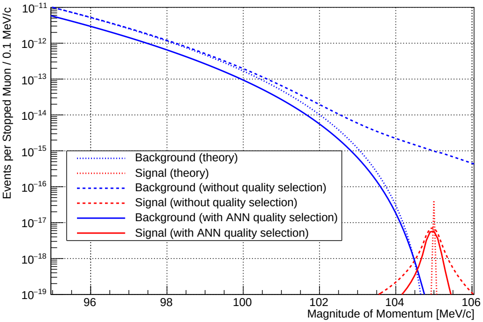
We expect 0.11 $\pm$ 0.03 background events for Run 1 based on our hit level Monte Carlo simulation

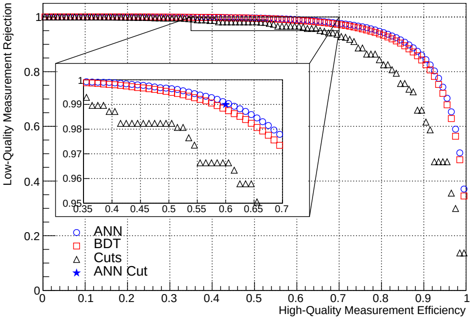
Channel	Mu2e Run 1 Background Expectation
Cosmics	0.048 ± 0.010 (stat) $\pm$ 0.010(syst)
DIO	0.038 ± 0.002 (stat)$^{+0.026}_{-0.016}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) $^{+0.010}_{-0.004}$ (syst)
RPC in-time	0.011 ± 0.002 (stat) $^{+0.001}_{-0.002}$ (syst)
RPC out-of-time	negligibly small
RMC	negligibly small
Beam electrons	negligibly small
Total	0.107 ± 0.032 (stat$\oplus$syst)

ML for Track Quality

We need to understand the far tails of our resolution function

- we found that using ML methods to select high-quality tracks produces larger background reduction than simple cuts[1]



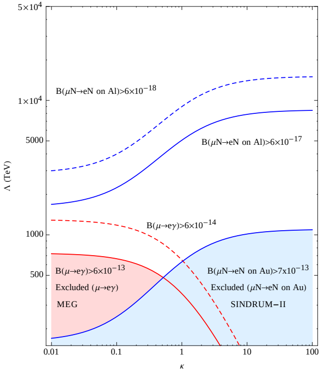


[1] A. Edmonds et al 2021 JINST 16 T08010

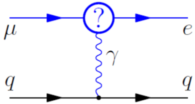
Sensitivity Reach

If we assume a toy Lagrangian of the form:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\overline{q_L}\gamma^\mu q_L\right)$$

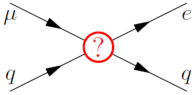


Bernstein, de Gouvea



$\kappa << 1$

(loop term)



$\kappa >> 1$

(four-point contact term)

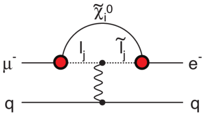
Complementary to the LHC

- can probe mass scales up to 10^4 TeV
- (assuming maximal mixing and unit coupling – $R_{\mu\to e} \sim \frac{g\theta_{e\mu}}{\Lambda^2}$)

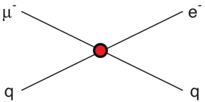
BSM Theories

A selection of BSM theories that predict enhanced rates of CLFV processes:

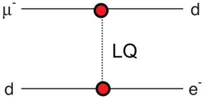
Supersymmetry



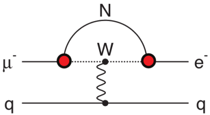
Compositeness



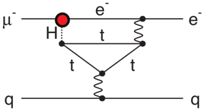
Leptoquark



Heavy Neutrinos



Second Higgs Doublet



Heavy Z’ Anomal. Z Coupling