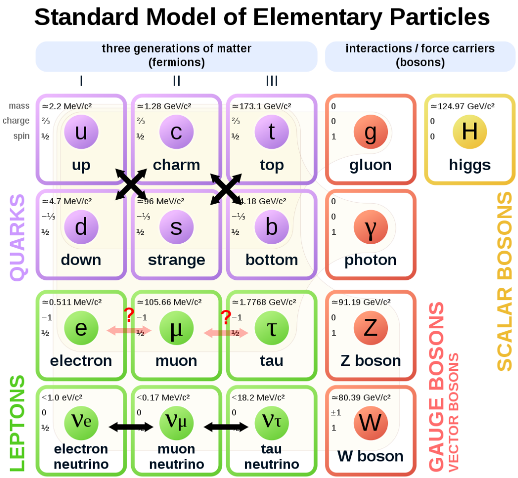
The Current Status of the Mu2e Experiment

Andrew Edmonds
on behalf of the Mu2e collaboration

55th Fermilab Users Meeting

Boston University

Why do muons conserve flavor?



Muons are interesting:

- magnetic anomaly from FNAL $g-2$,
- flavor anomalies from LHCb ($R_{K^{(*)}}$, P_5', ...)

Why do muons conserve flavor when nothing else does?

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

Flavor is not conserved in:

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

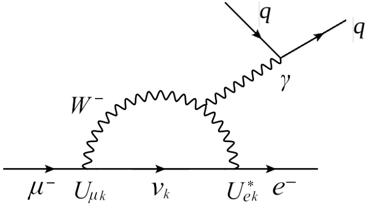
Charged Lepton Flavor Violation (CLFV)

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

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

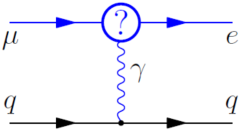
νSM Prediction

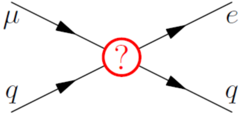
$$R_{\mu\to e} \propto \left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 < 10^{-52}$$



BSM Predictions

$$R_{\mu\to e} \sim 10^{-17} - 10^{-15} \ (\Lambda \sim 10^4 \text{ TeV})$$



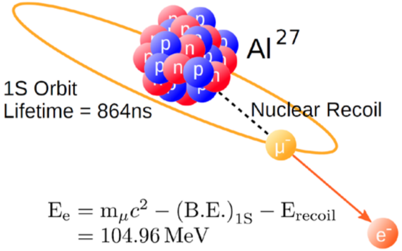


Any observation of CLFV would be clear evidence of New Physics!

Muon-to-electron Conversion

Neutrino-less $\mu \to e$ conversion violates charged lepton flavor conservation

- occurs in muonic atoms $\to$ stop low-energy muons in material



It has a very simple signal

- a mono-energetic electron

Current limit (SINDRUM II on Au): $R_{\mu\to e} < 7 \times 10^{-13}$, where

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

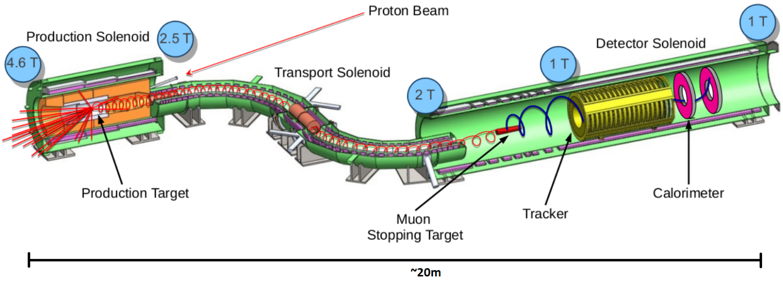
The Mu2e Experiment

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

$$R_{\mu\to e}\ (90\%\ \mathrm{CL}) < 8\times 10^{-17} \qquad R_{\mu\to e}\ (5\sigma\ \mathrm{discovery}) = 2\times 10^{-16}$$

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

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



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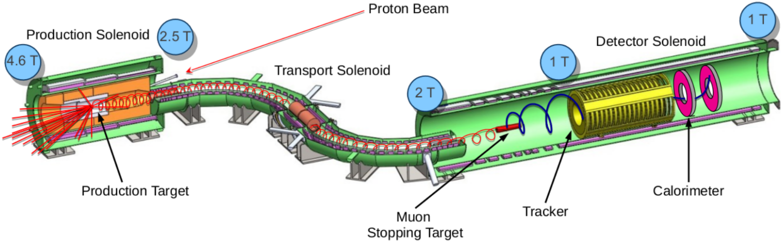


- Production Solenoid
  - pulsed proton beam hits production target
  - pions collected by the graded solenoidal magnetic field
- Transport Solenoid
  - pions decay to muons
  - charge and momentum selection
- Detector Solenoid
  - muons stop in thin Al foils
  - muonic atom decays
  - resulting electrons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

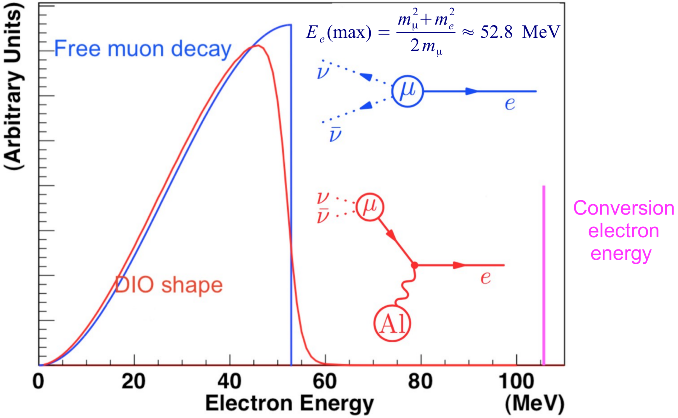
Decay-in-Orbit (DIO) Background

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

- 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



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

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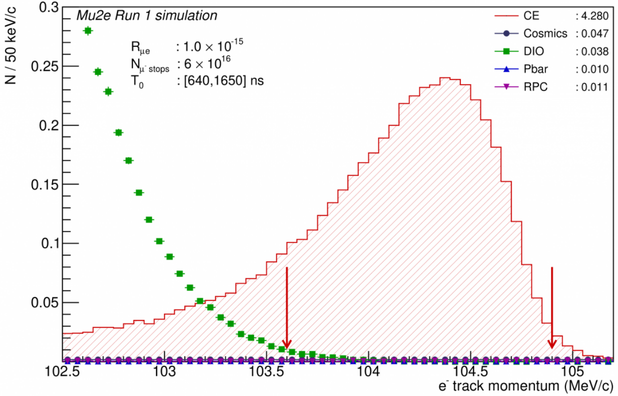
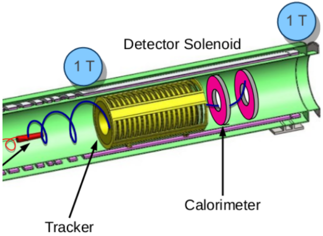


Expected signal ($R_{\mu \to e} = 10^{-15}$) and DIO spectra from Run 1 simulation (10% of final dataset, includes resolution and energy loss effects)

Tracker

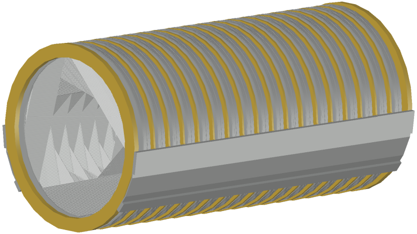
Need a high-resolution momentum measurement

- 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

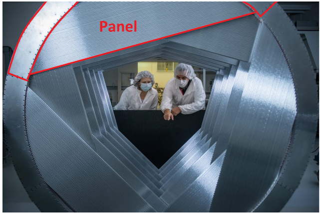


5 mm diameter, 15 μm thick walls

1 tracker = 36 planes = 20736 straws



plane with central hole



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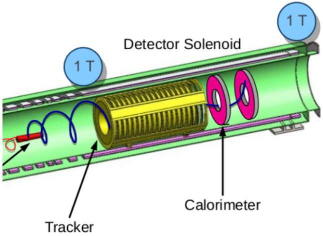

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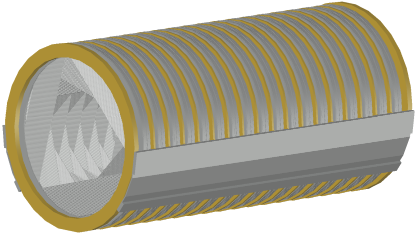

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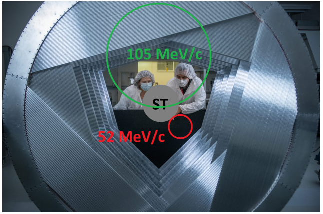


*not to scale

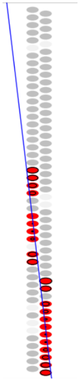
Tracker: Current Status

All straws produced

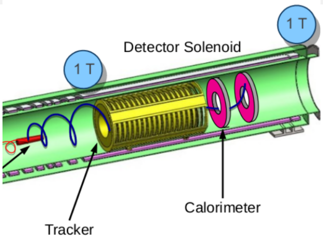
167 / 216 panels produced

16 / 36 planes are built

Cosmic ray tests with a single plane



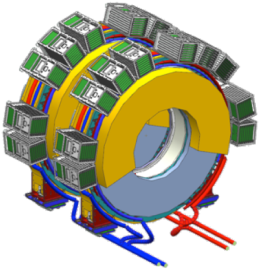
Calorimeter



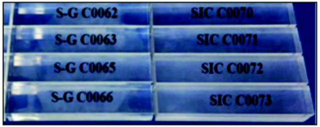
Want a fast energy measurement

- 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

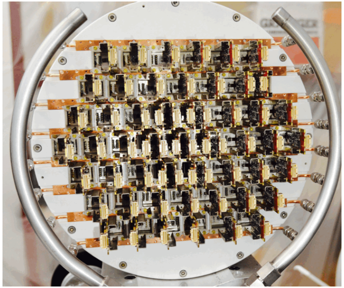
Two disks, each 674 crystals



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



Module 0 prototype

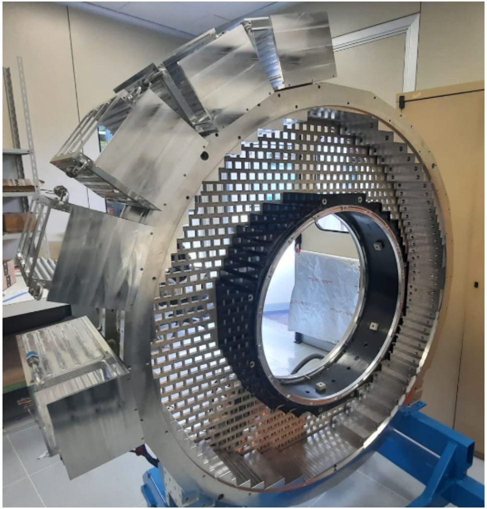


Calorimeter: Current Status

All crystals, SiPMs, and FEEs produced

All mechanical parts in hand to build the first disk

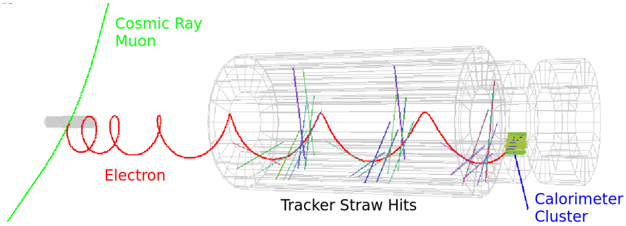
Cosmic ray test underway with subset of crystals

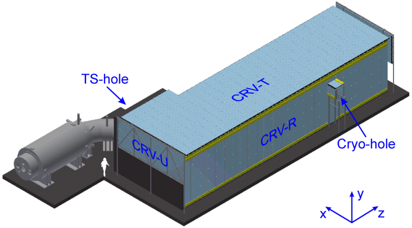


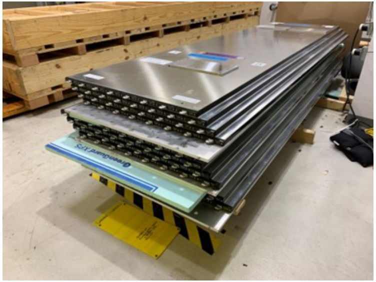
Cosmic Ray Veto

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







Cosmic Ray Veto: Current Status

$\sim$2200 / 2700 di-counters produced

67 / 83 modules produced

Cosmic ray tests underway at Wideband

Module Assembly at UVA

Other Recent Achievements

Accelerator:

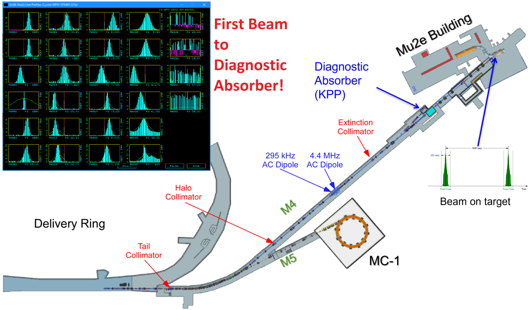
- recently delivered protons to diagnostic absorber (just upstream of production target)

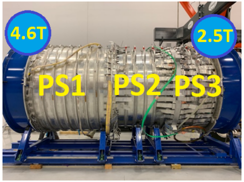
Solenoids:

- all coils for PS and TS are fabricated
- cold mass fabricated for TS
- everything else under construction

Targets:

- production and stopping targets assembled





Timeline

- Detector commissioning through to 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 improvements over SINDRUM-II

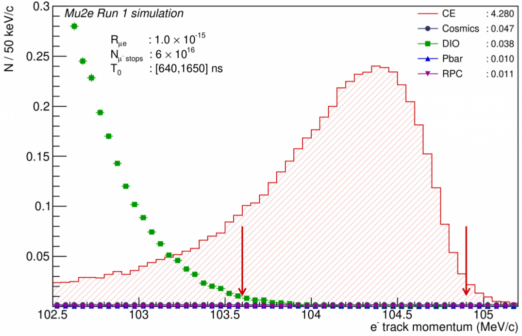
Run 1 Sensitivity Estimate

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

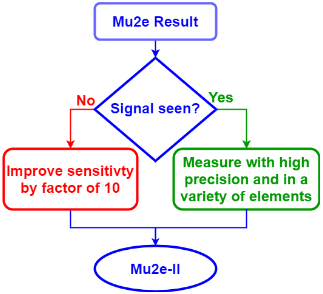


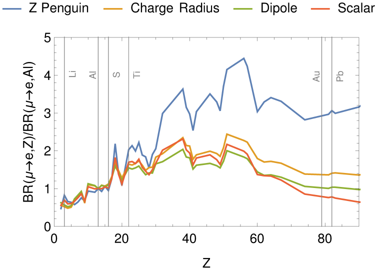
Signal and Background PDFs for $R_{\mu\to e} = 10^{-15}$

Beyond Mu2e

An upgraded Mu2e-II has been proposed (link)

- takes advantage of PIP-II upgrade at Fermilab
- use as much of Mu2e as possible but would need
  - upgraded detectors (e.g. thinner straws)
  - upgraded production target (to handle higher beam power)
- x10 improvement in sensitivity, or measure in other muonic atoms





Conclusion

Mu2e will search for the charged lepton flavor 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

- plenty of opportunities for postdocs and new collaborators to commission a new experiment!
- `https://mu2e.fnal.gov/`

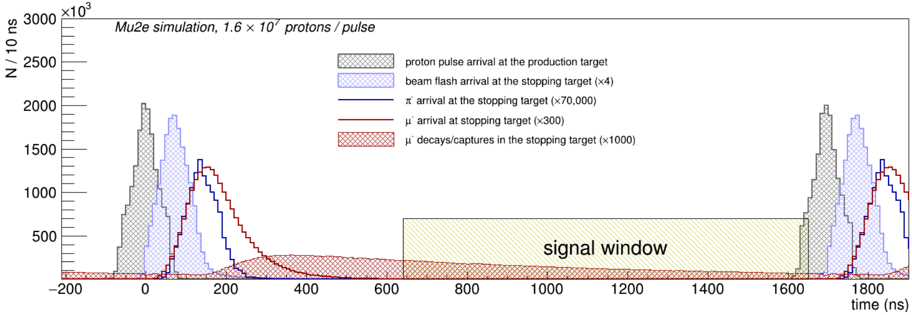
Thanks for listening! Any questions?

Back Up

Beam-related Backgrounds

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
- we need extinction level (ratio of protons in and out of pulse) to be $< 10^{-10}$



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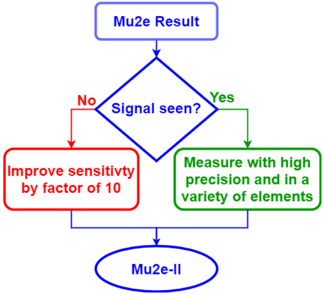
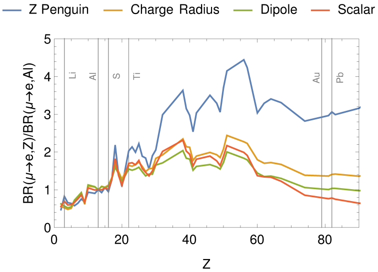


Beyond Mu2e-II, a fuller CLFV program for Fermilab is being pursued as part of Snowmass (link)

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



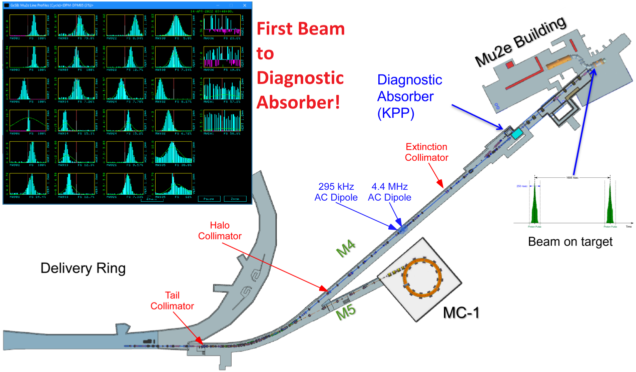
Run 1 Background Table

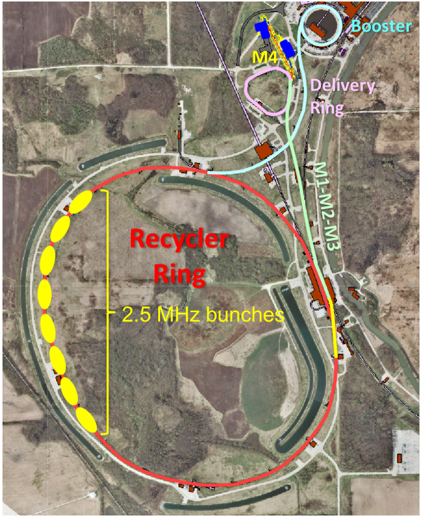
We expect 0.11 ± 0.03 background events for Run 1 based on our hit level Monte Carlo simulation

Channel	Mu2e Run 1 Background Expectation
Cosmics	0.048 ± 0.010 (stat) ± 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)

Accelerator

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





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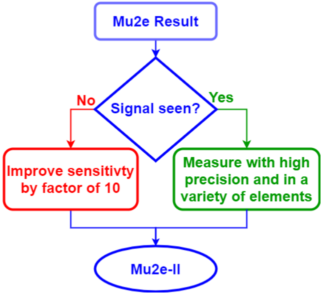
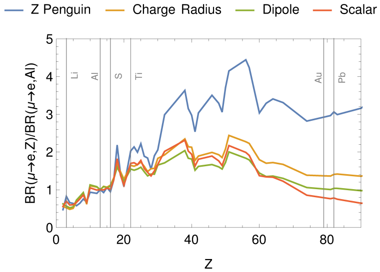
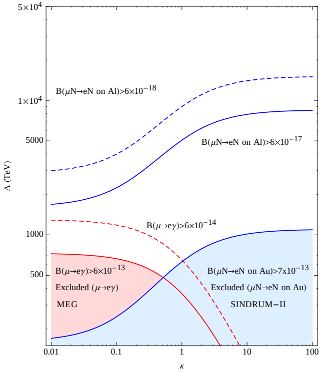




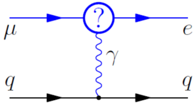
Sensitivity Reach

If we assume a toy Lagrangian of the form:

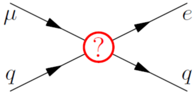
$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\bar{q}_L\gamma^\mu q_L\right)$$



Bernstein, de Gouvea



$\kappa \ll 1$
(loop term)



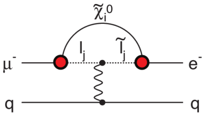
$\kappa \gg 1$
(four-point contact term)

Complementary to the LHC

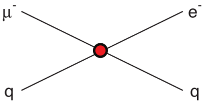
- can probe mass scales up to 10^4 TeV
- (assuming maximal mixing and unit coupling – $R_{\mu\to e} \sim \frac{g\theta_{e\mu}}{\Lambda^2}$)

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

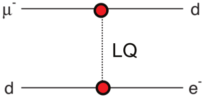
Supersymmetry



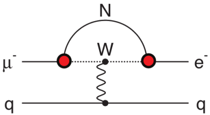
Compositeness



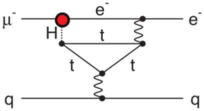
Leptoquark



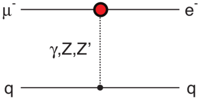
Heavy Neutrinos



Second Higgs Doublet

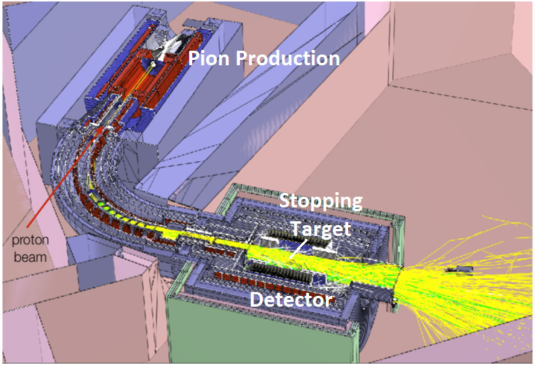


Heavy Z' Anomal. Z Coupling



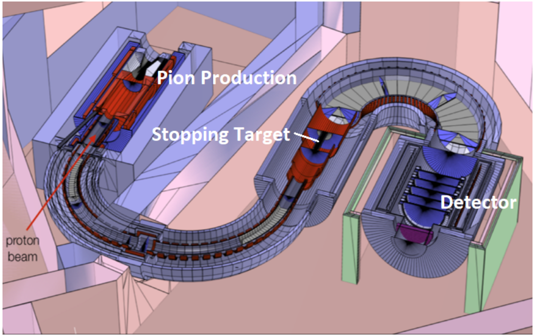
COMET @ J-PARC

COMET Phase-I



- commissioning 2023
- 90% CL $R_{\mu\to e} < 7 \times 10^{-15}$
    - $\times$100 improvement over SINDRUM-II

COMET Phase-II



- follows COMET Phase-I
- 90% CL $R_{\mu\to e} < 7 \times 10^{-17}$
    - $\times$10000 improvement over SINDRUM-II