Future muon-to-electron conversion experiments

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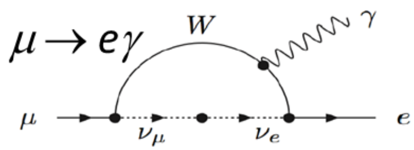
Fermilab - January 2022

Charged lepton flavor violating (CLFV) processes are interactions that do **not** conserve lepton family number(s), e.g. $\mu \to e$, $\tau \to \mu\mu\mu$, $K_L \to \mu e$, $H \to \tau\mu$, ...

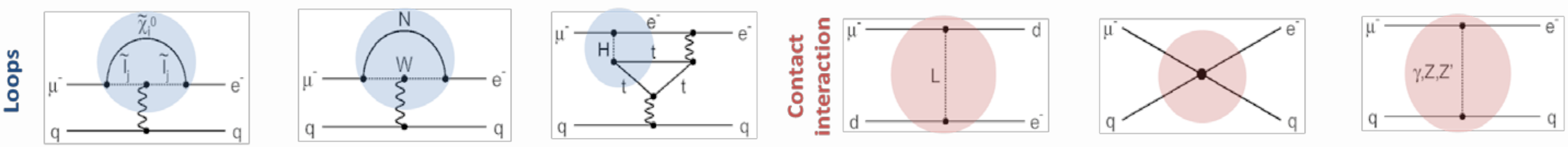
CLFV can be generated at loop level with massive neutrinos, but the rate is extremely suppressed due to GIM mechanism and tiny neutrino masses. For example:



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

PMNS unitary, $\Sigma\, U^*_{\mu i}\, U_{ei} = 0$

New physics could greatly enhance these rates, e.g.



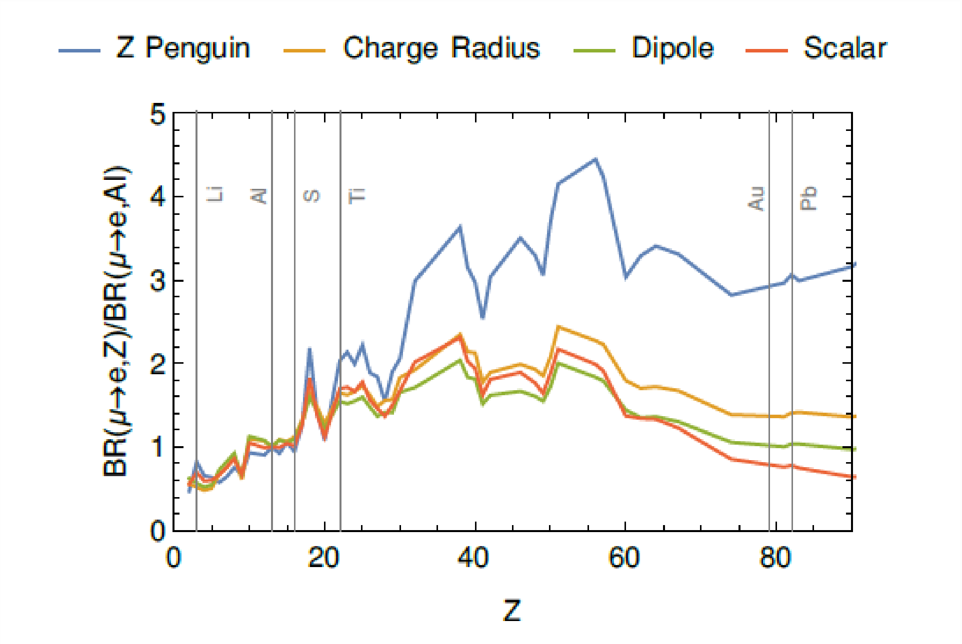
CLFV are very clean probes - an observation is an unambiguous sign of physics beyond νSM

CLFV searches share the stage with neutrino experiments in studying the origin of neutrino mass, flavors and families

The Z dependence provides information about the nature of the underlying NP

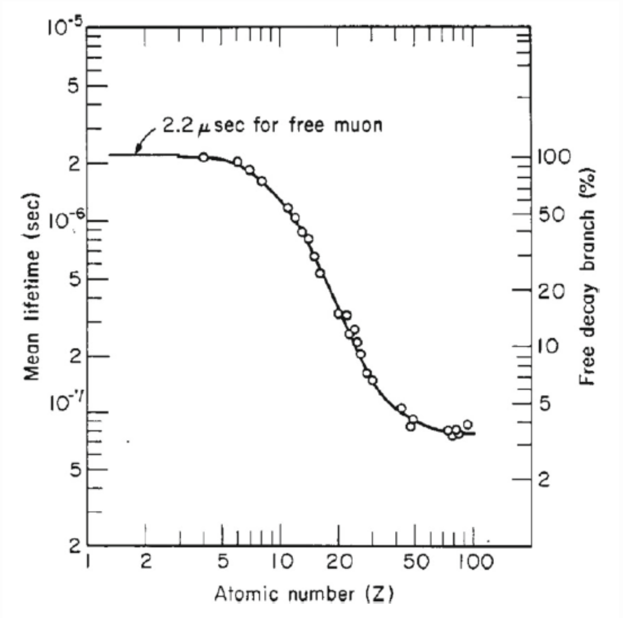
Effect more pronounced for high-Z material, cut corresponding muonic atom lifetime decreases → implication for experimental design

Z dependence $\mu \to e$ of conversion rates



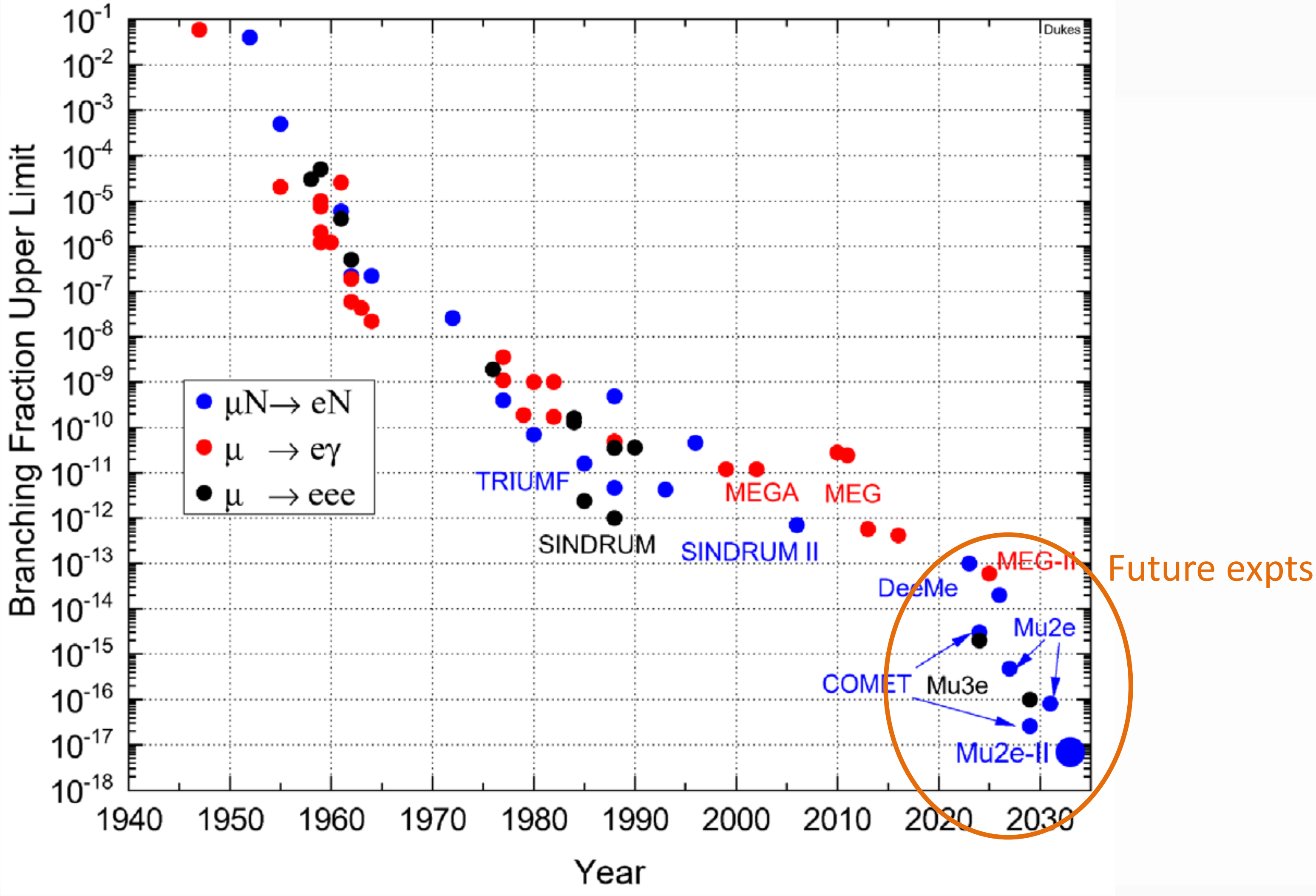
J. Heeck et al. (SNOWMASS21-RF5_RF0-TF6_TF0_Heeck-043.pdf)
based on
R. Kitano et al Phys. Rev. D 66 (2002) 096002
V. Cirigliano et al., Phys. Rev. D 80 (2009) 013002.

Muonic atom lifetime



A. Knecht et al., EPJ. Plus (2020) 135

Huge leap in sensitivity by the end of this decade

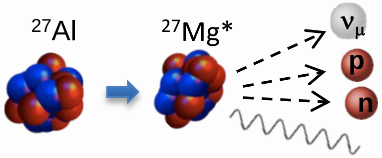


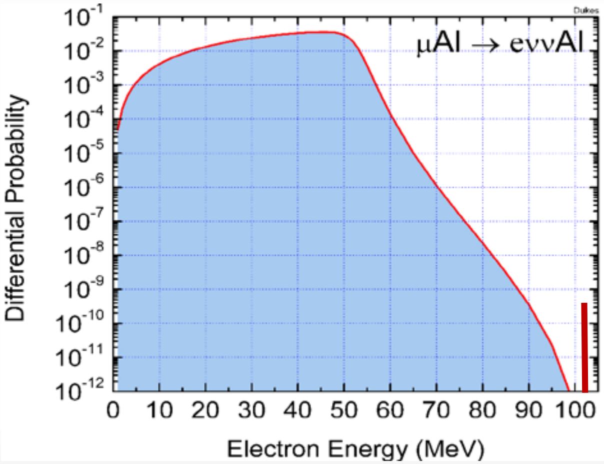
courtesy C. Dukes

Experimental concept to search for muon-to-electron conversion

- Produce beam of muons via pion decays by hitting protons on target :
  $p + nucleus \rightarrow \pi^- \rightarrow \mu^- \nu_\mu$
- Collect and stop low momentum muons in stopping target
- Muon are captured and cascade to K shell (<ps) firing off X rays
  measure X rays spectrum to estimate the number of captures
- The muon circles the nucleus up to 2.2 μsec, and will
  1) Be captured by the nucleus (~61% for Al): $\mu N \rightarrow \nu_\mu N'^*$.
     The excited nucleus can emit particle that would produce background electron
  2) Decay in orbit $\mu \rightarrow e\, \nu_\mu \bar{\nu}_e$ (~39% for Al).
     The free muon spectrum (Michel spectrum) is distorted by the presence of the nucleus and the electron can be at the conversion energy
  3) Convert into an electron, the signal is a mono-energetic electron with energy

$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\rm recoil} \\ &= 104.973 \text{ MeV} \quad (\text{for Al}) \end{aligned}$$





Experimental aspects – other background

Beam-induced background

Particles produced in addition to the muons by primary protons, which can produce electrons having the conversion energy

- Radiative pion capture (RPC)
  $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$
  $\pi^- N \rightarrow e^+e^- N'$
- Pion/muon decays in flight
- Antiprotons producing pions when annihilating
- Delayed beam electrons
- ….

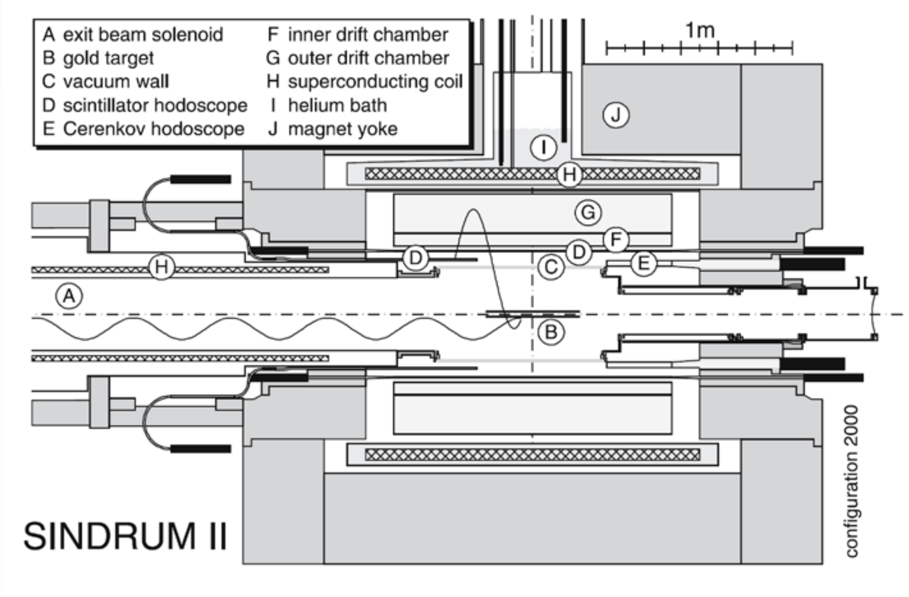
Other background

- Cosmic rays interacting with detector material and producing conversion-like electron or cosmic muon mimicking signal (~1 / day at Mu2e)

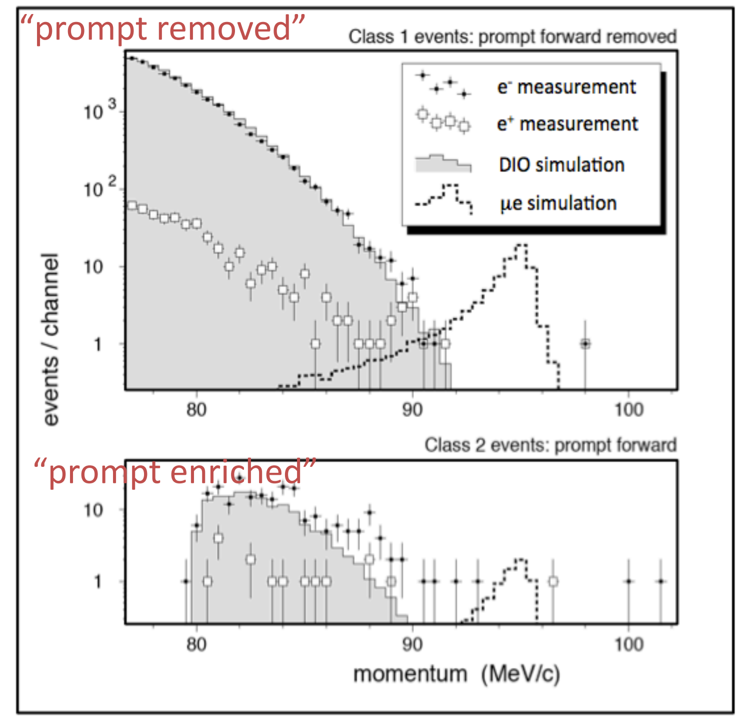
Need to control these backgrounds extremely well to keep the experiment background free !!!

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

SINDRUM II at PSI (2006)



Fast beam repetition rate: 0.3ns bunch every 20ns



Final results on gold:

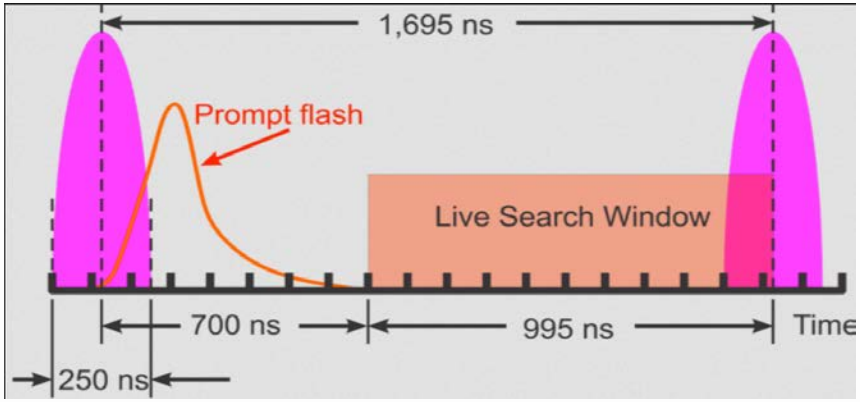
$R_{\mu e} < 7\times10^{-13}$ @ 90% CL

Timing cut ($|t_0$-10ns$| > 4.5$ ns) used to separate contribution of prompt bkg induced by radiative pion capture and pion decay in flight

Muon intensity and prompt backgrounds are limiting factors

Pulse proton beam

Pulse proton beam with a long interval between pulses to suppress prompt background (beam flash, RPC,…)



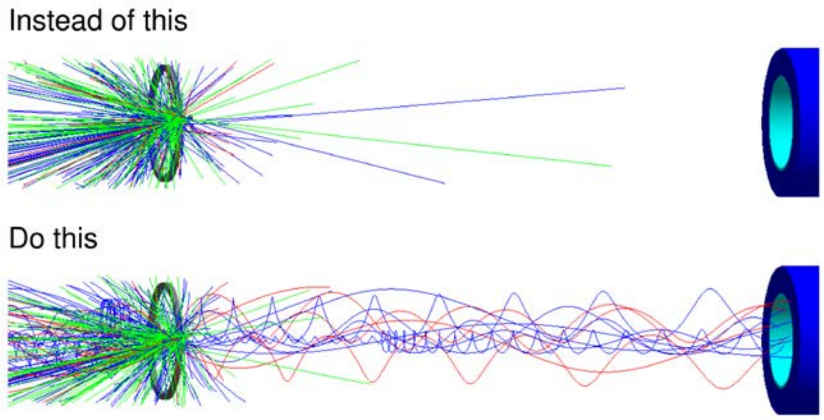
Challenges

Need to suppress out-of-time proton by $O(10^{10})$ or more

Restrict measurement to muonic atom lifetime large enough to have good signal efficiency

Capture solenoids to increase muon flux*

Place production target inside magnetic field to trap more pions, and muons



Challenges

Need to design a magnetic system that can cope with beam power

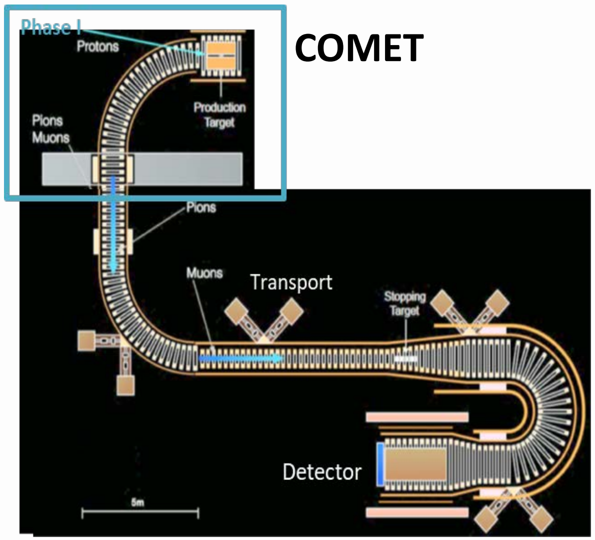
*Dzhilkibaev and Lobashev, Sov.J.Nucl.Phys 49, 384 (1989)

Two new experiments taking advantage of these ideas, to run before the end of the decade

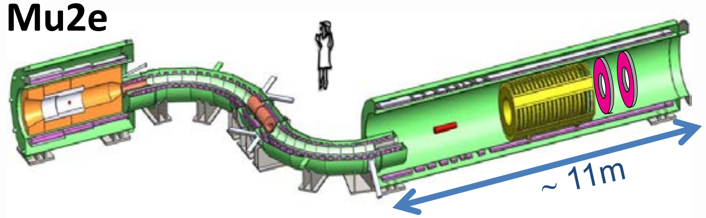
- COMET at J-PARC, expected SES ~ 10^{-17} (bkg<<1)
- Mu2e at FNAL, expected SES ~ 10^{-17} (bkg<<1)

SES=Single Event Sensitivity

COMET



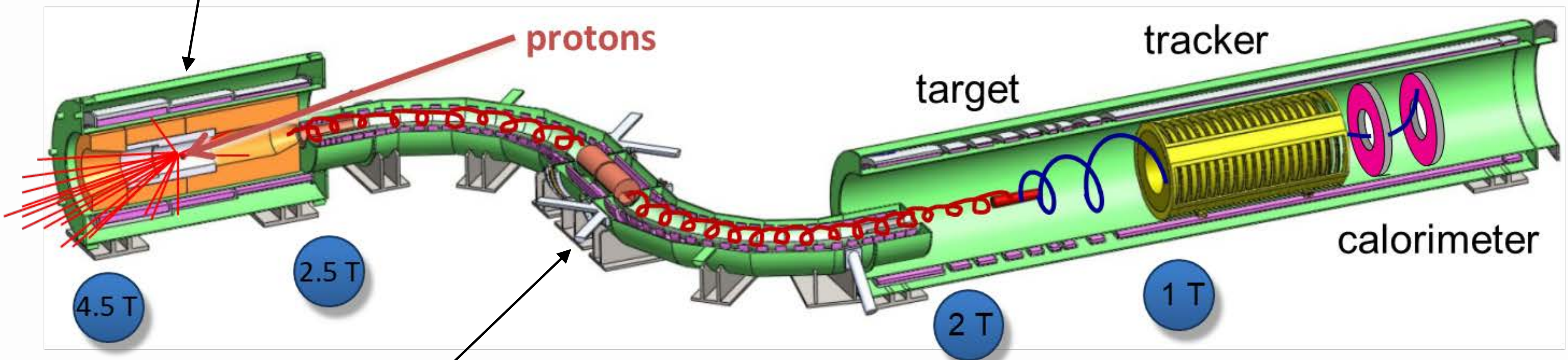
Mu2e



There is also an effort at J-PARC with a different design – DeeMe experiment, with a lower expected SES ~ 10^{-14} - see backup slides

Production Target / Solenoid

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid → high muon intensity



Transport Solenoid

- Collimator selects low momentum, negative muons
- Antiproton absorber
- The S shape eliminates photons and neutrons, and restore beam at center of detector magnet

The center of the helical trajectory in a curved solenoidal field drifts vertically as

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

Oppositely charged muons drift in opposite directions → collimator to select specific charge

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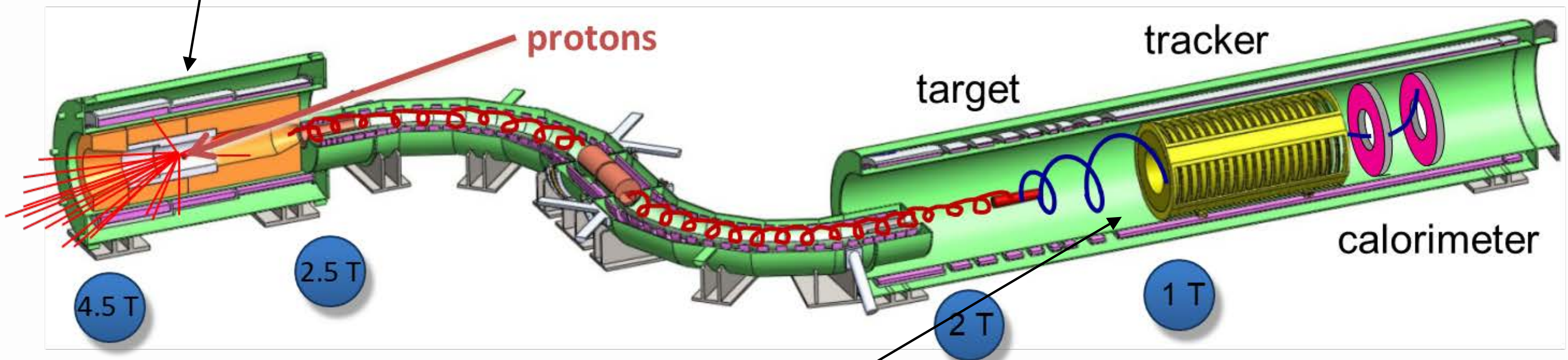
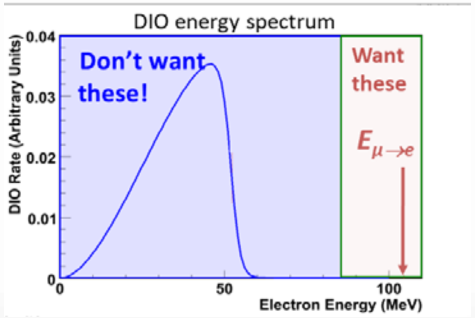
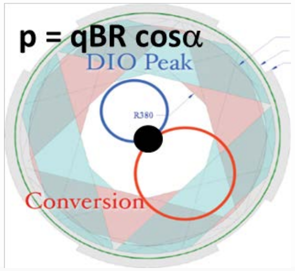


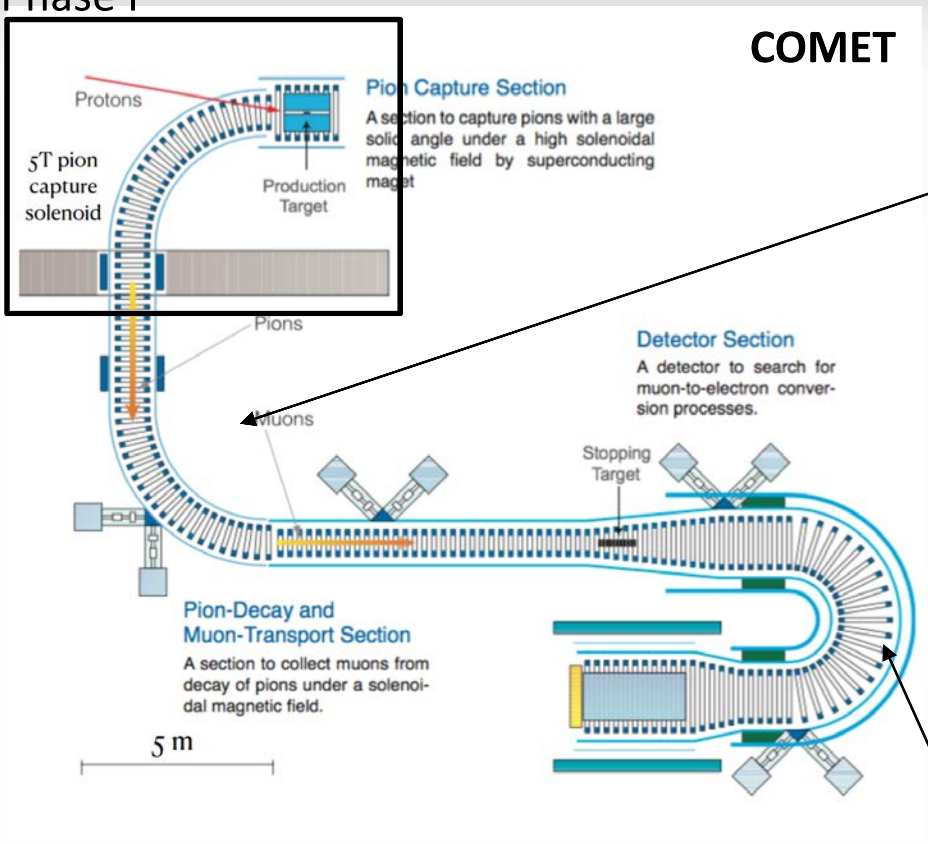
Target, Detector and Solenoid

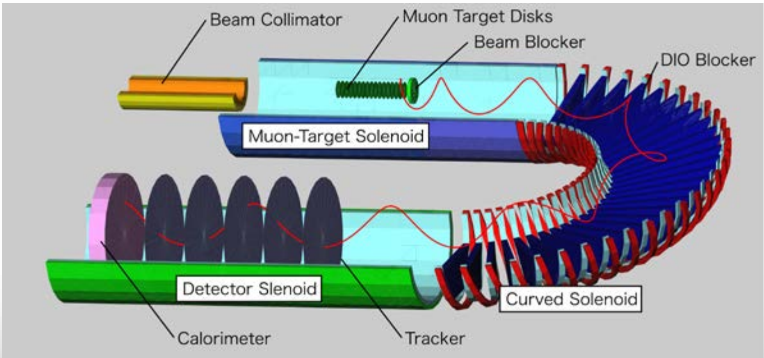
- Capture muons on Al target
- Annular detector let low-momentum particles (beam flash, DIO,…) go through w/o interacting
- Large background from particles produced in stopping target, but charge symmetric detector → study positrons to estimate background in-situ and measure $\Delta L=2$ process $\mu^- \rightarrow e^+$





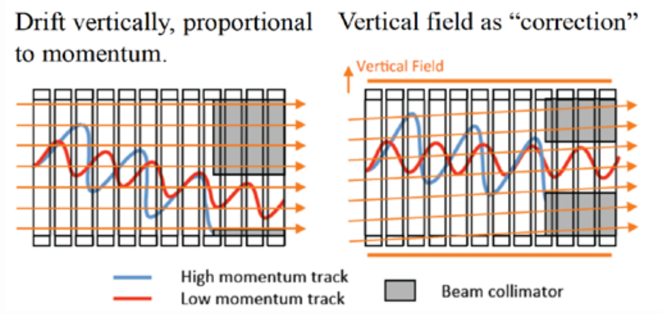
Phase I





Curved solenoids – same directions

Use additional dipole magnet to select low-momentum particles and eliminate bkg from muon decay in flight



Electron spectrometer

Use solenoid to filter out low-momentum particles and neutrals.

No need for annular detector, but only sensitive to either positively or negatively charged particles at a given time

Going beyond COMET/Mu2e – Mu2e-II

Mu2e-II is a proposed Mu2e upgrade to take full advantage of PIP-II and improve the SES by an order of magnitude over Mu2e (i.e. SES $\sim 10^{-18}$)

Re-use as much of Mu2e infrastructure as possible, and upgrade components required to handle higher beam intensity. In particular:

- Beam delivery: higher beam intensity, lower beam energy, beam extinction (# protons out of time / # proton in time)
- Tracker: higher occupancy and limited resolution
- Calorimeter: high rate and radiation damage
- Cosmic ray veto: higher occupancy and background from neutrals
- DAQ system: higher rate and throughput

Dedicated R&D efforts in all these domains (and others) to meet the requirements

Improving tracker resolution

The DIO contribution would increase by a factor x10 with higher beam intensity

Need to improve momentum resolution to mitigate this bkg, and adapt electronics to handle higher radiation dose

One solution is to reduce the straw tracker mass

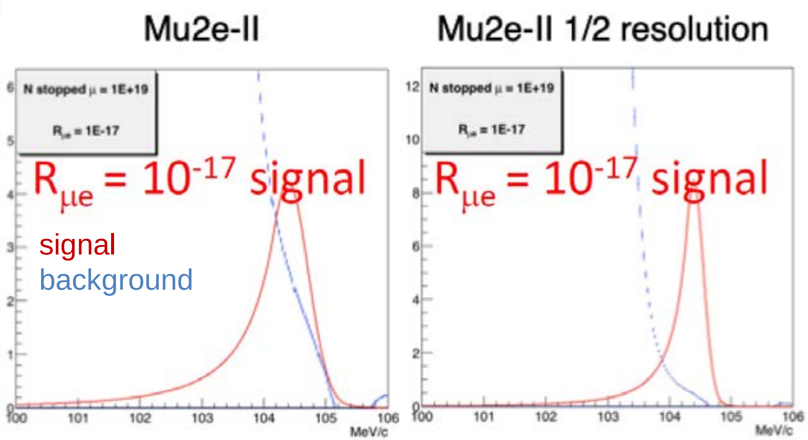
- Thinner straws (15 μm → 8μm)
- Remove gold layer inside straw
- On-going R&D effort

Other ideas in a few slides…

Tracking is only part of the problem: a cold muon beam to the rescue

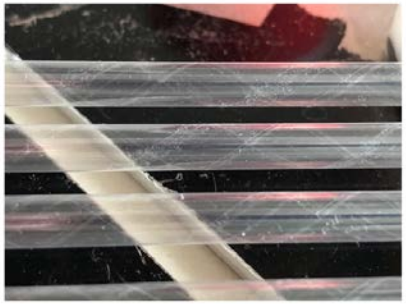
A large contribution to the resolution arise from energy loss fluctuations in the stopping target, and a colder muon beam can be stopped in thinner and less foils

→ big advantage of FFA design



D. Brown


8 μm Mylar Straw


Pressurized 8 μm Mylar Straws

Improving calorimeter performance

Rate and radiation dose are too high for pure CsI in Mu2e

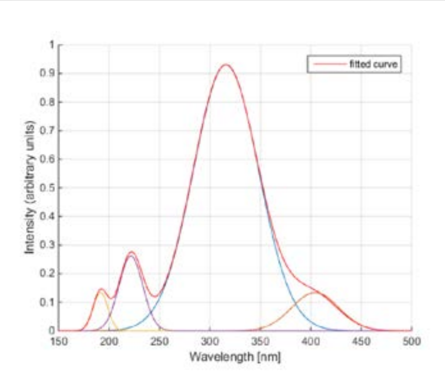
- Up to ~ 1Mrad and 1E13 n [1MeVeq/cm2]

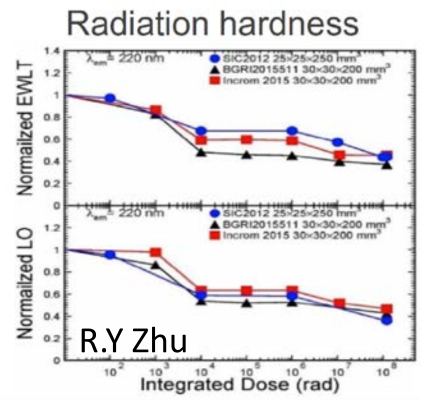
BaF_2 is an excellent candidate for ultra fast, high rate, radiation hard crystal calorimeter

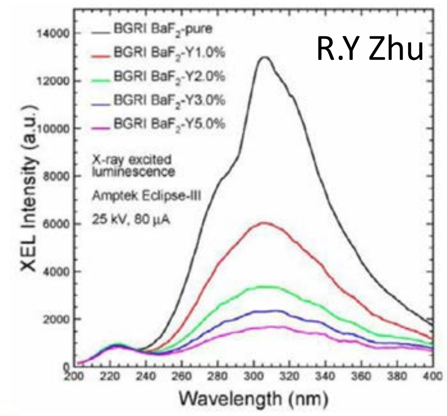
- Fast components (<1 ns) at 195 and 200 nm
- Can support > 1 Mrad radiation dose

Must use fast component at 200 nm without undue interference from slow 320 nm component. Two complementary approaches:

- Yttrium doping can suppress slow component by factor x5 without reducing fast signal
- Develop photo-sensor only sensitive to fast component: solar blind UV-sensitive SiPM /APD, nano-particle wavelength shifting filter,…



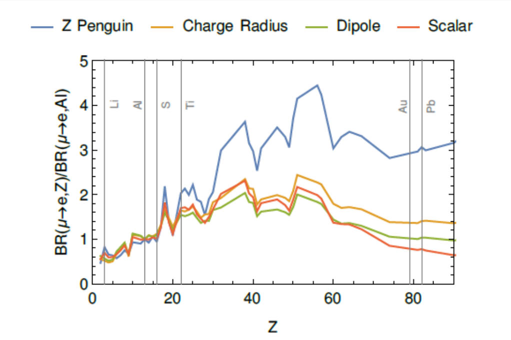


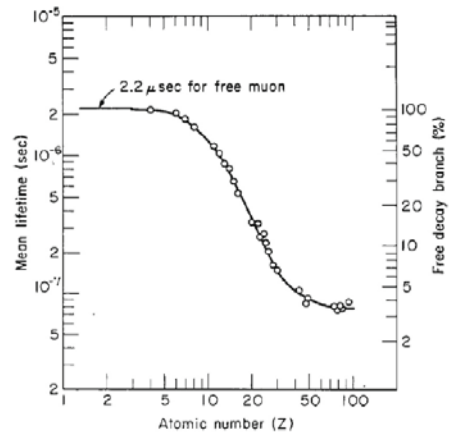


More about Mu2e-II detector/target development in backup slides

Going beyond Mu2e-II requires overcoming the following limiting factors

- Dead time to wait for beam-associated backgrounds to decrease to negligible level
  $\rightarrow$ cannot measure conversions in atoms with short muonic lifetimes (high Z)
- Need well-defined pulse beam (extinction) to avoid beam-related background in the search window
- Need to further improve energy resolution to reject DIO background
- Radiation dose in the detector area (depending on the design)



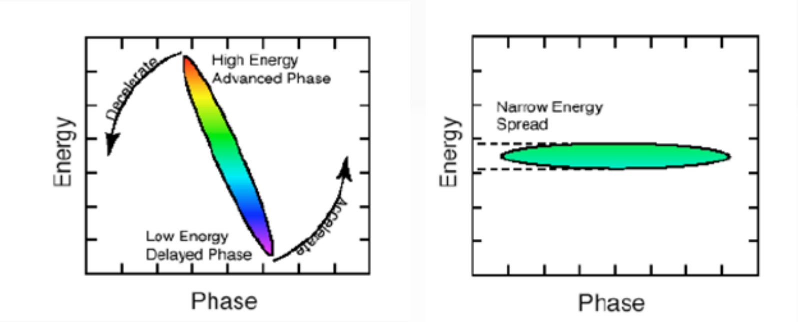


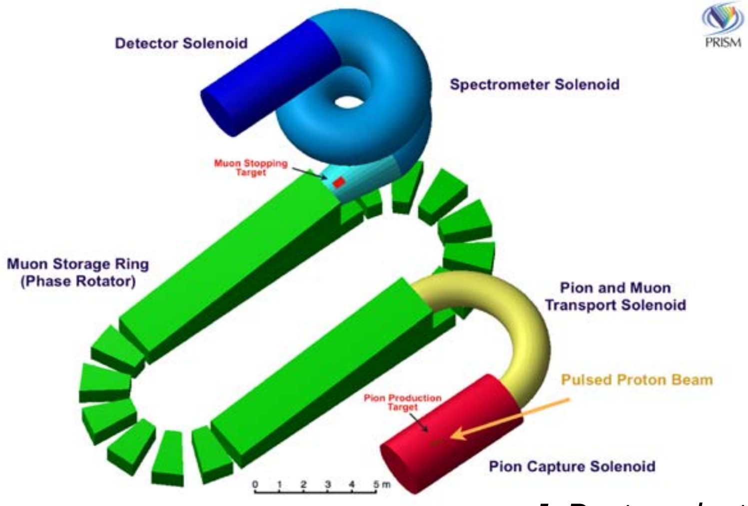
Need new concept to further push sensitivity down to 10^{-19}, with the ultimate ambition to reach 10^{-20} one day….

New beam for conversion experiment*, based on the PRISM concept (see J. Pasternak's talk)

PRISM concept:

- High intensity (MW) proton beam with very short pulse duration hit target in a capture solenoid, producing $\pi \rightarrow \mu$
- Inject muons into a fixed-field alternating gradient (FFA) ring
- Phase rotates to reduce the beam energy spread (slow down leading edge, accelerate trailing edge)
- Pion contamination is drastically reduced during phase rotation (O(μs))
- Extract purified muon beam to detector





J. Pasternak et al.

Requires a compressed proton bunch and high power beam to achieve high μ rate

$\rightarrow$ PIP II with a compressor ring (see E. Prebys' talk)

*https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

Next-to-next generation experiment

Take advantage of cold, monochromatic, purified muon beam at the exit of the FFA

No beam-induced background – notably pion contamination

- No need to wait for pions to decay anymore, RPC is extremely suppressed
- No background from antiprotons, delayed electrons,…
- Can measure short muonic atom lifetime -> high Z material (e.g. Au)
- No stringent requirements on out of time protons
- Less radiation and occupancy

Cold beam

- Use thinner stopping target to stop muons (ideally a single thin foil)
- Reduce energy loss fluctuations in target material
- Improve momentum resolution

Still need to handle DIO background, cosmic induced background and secondary particles produced from muon captures

Spectrometer solenoid + detector (aka Guggenheim scheme, à la PRIME concept)

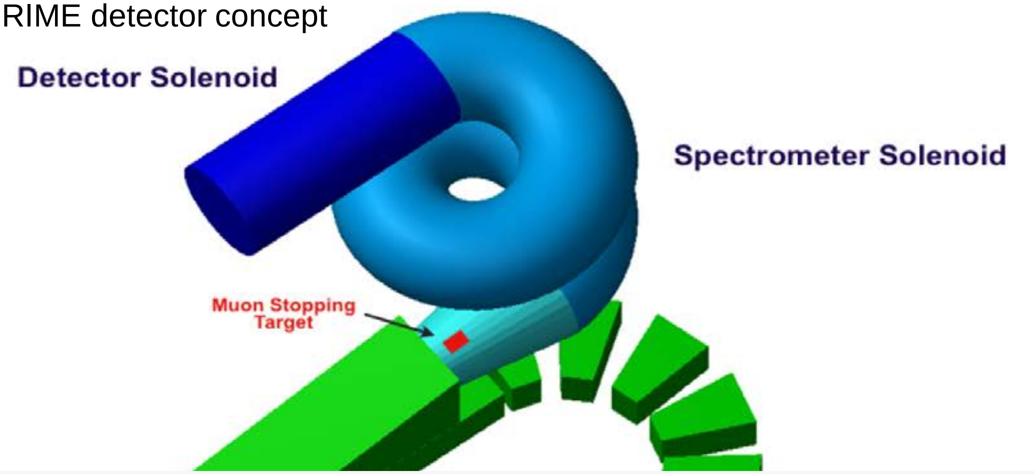
+ Greatly reduce muon capture induced background with beam blocker and magnetic field (including neutrals)

+ Greatly reduce DIO contribution

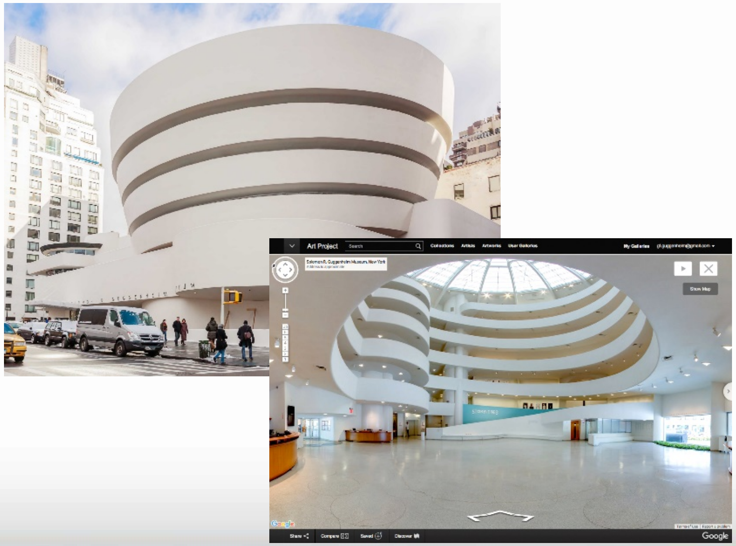
+ Detector occupancy is much lower and could be leveraged to design detector with improved momentum resolution and faster trigger system

- Not charge symmetric, so cannot measure simultaneously $\mu^- \to e^-$ and $\mu^- \to e^+$, but no need to measure in-situ background with positrons since RPC background is negligible

PRIME detector concept



Guggenheim museum (NYC)

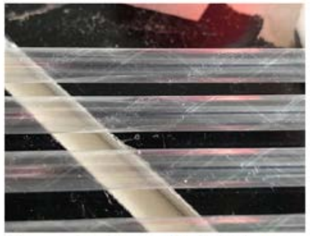


Spectrometer solenoid + detector (aka Guggenheim scheme, à la PRIME concept)

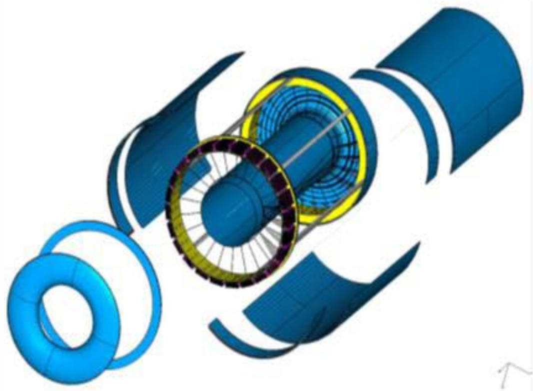
Need to improve tracking resolution to reject DIO. Possible solution include:

- Straw tracker with thinner straws
- Use ultra-light pressure vessel to ease requirements on straw leakage
- Construct a high granularity and high transparency drift chamber à la MEG II.
- Investigate potential of low-mass silicon sensors (e.g. HVMaps), MPGD, ….

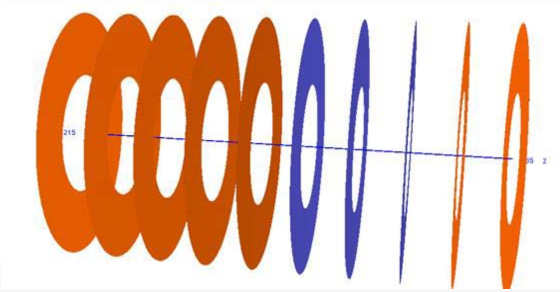
8 μm Mylar Straw



Pressurized 8 μm Mylar Straws



G.F Tassielli et al.



D. Ambrose et al.

Spectrometer solenoid + detector (aka Guggenheim scheme, à la PRIME concept)

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Need to design cosmic ray veto to ensure the cosmic induced background remains <<1 evt. Likely need multiple systems to achieve required inefficiency, but that seems doable.

Annular detector (à la Mu2e)

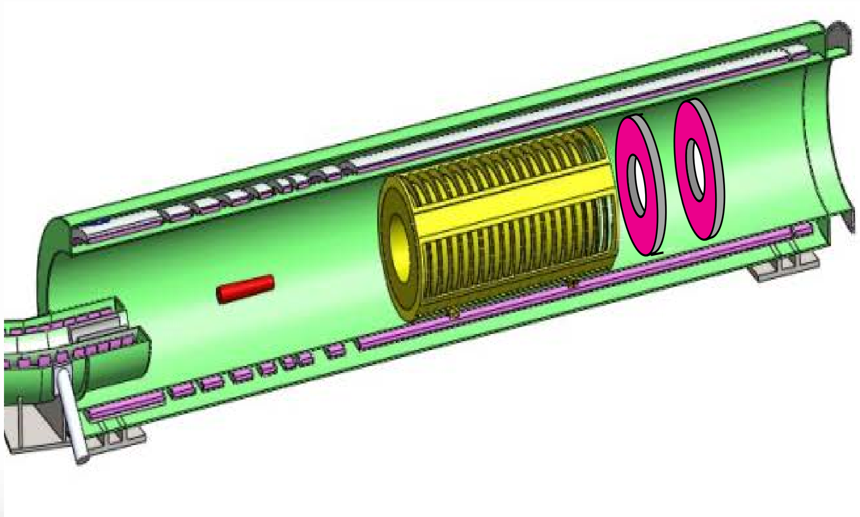
+ Simpler solenoid system

+ Charge symmetric detector, simultaneously in-situ measure $\mu^- \to e^-$ and $\mu^- \to e^+$

- Need to mitigate particles from muon captures, more constraints on detector design to achieve the required resolution

- Larger occupancy and radiation dose

Also need to improve tracking and cosmic ray veto design (same considerations as discussed for Guggenheim scheme)



And more speculative ideas

Place the stopping target directly inside a drift chamber without inner walls – extension of MEG II design (i.e. muons stop inside the drift chamber)

Use Mu2e straw layout: annular panel design with wires held along the outer radial wall

No material between the conversion electron production point and the sensing volume, resulting in improved resolution

Do we blow the chamber after a few seconds, minutes, days or years?

Any many other audacious ideas….

The detector design effort has barely started, now is the time to be bold and creative

Summary

CLFV processes are very clean probes of new physics, and an observation would be transformative

Current experiment and their upgrades (COMET, Mu2e and Mu2e-II) will improve upon existing limits by several orders of magnitude, but concept has several limiting factors

A new large scale muon facility at PIP II would be needed to go beyond, and explore the underlying new physics in detail if CLFV is observed

Several technologies are being explored to improve the detector capabilities, and some of them sound quite promising…

… but now is the right time to keep exploring ideas and be bold. Feel free to contact us if you are interested!

We would like to include a discussion of the physics case and the opportunity of a new large muon facility at PIP II in the Snowmass report – white paper in progress – and we would like P5 to endorse the physics concept to pursue further design studies

Thank you for your attention

Extra material

Solar-blind UV-sensitive SiPM

Add anti-reflection filter to SiPM surface

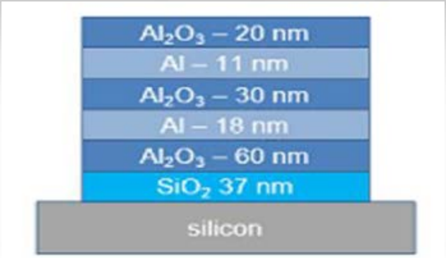
- Select fast component, further suppress slow component
- Improve overall efficiency (light bounces back)

Add superlattice by implementing boron layer just below the Si surface with molecular beam epoxy

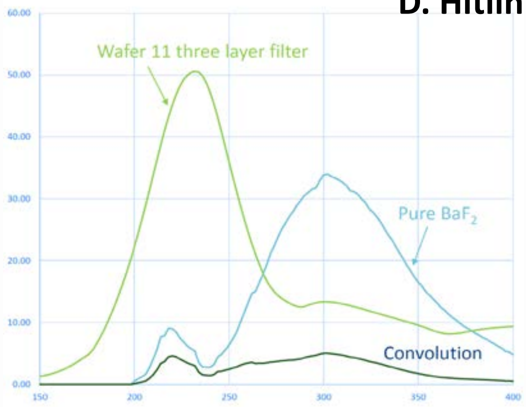
- Improve quantum efficiency and timing performance by reducing undepleted region near surface
- Provide stability under intense UV illumination

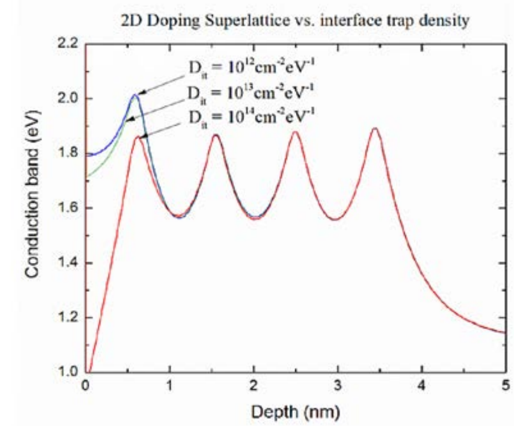
Currently under R&D from Caltech, JPL and FBK

- First tests with 3 layer filter (no superlattice) show good sensitivity to fast component.
- Further R&D to include 5 layer filter and superlattice



D. Hitlin





Other possibilities

- MCP not yet suitable for reading crystal in high-rate environment, as charge collected by anode is orders of magnitude too large for device capabilities (max few C/cm^2). Would need further R&D.
- Nano-particle WLS filter require more R&D to understand QE and timing performance

https://indico.fnal.gov/event/46746/contributions/210202/attachments/141121/177609/Hitlin_CPAD__210318-.pdf

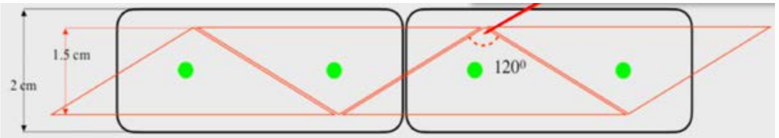
Improving cosmic ray rejection

Largest source of background due to interaction of cosmic ray muon with detector (1 evt / day) $\rightarrow$ need extremely efficient veto to maintain zero background environment

Main challenges come from managing high radiation rate ($\rightarrow$ dead time), production of neutron interacting with detector or muon sneaking through cracks (and they are sneaky!)

Improve veto by using different bar geometry: rectangular $\rightarrow$ triangular

- less inefficiency due to gap
- lower dead time and occupancy
- Fill hole around fiber with silicon resin or epoxy



Investigate alternative technologies for high-occupancy regions

- Resistive plate chambers
- High-rate wire chambers

Add low-mass silicon detector around stopping target to flag incoming muons ?

Production target

Investigate design of pion production target inside solenoid to handle increase beam power

Explore rotation target, fixed granular target or conveyor belt with small target elements

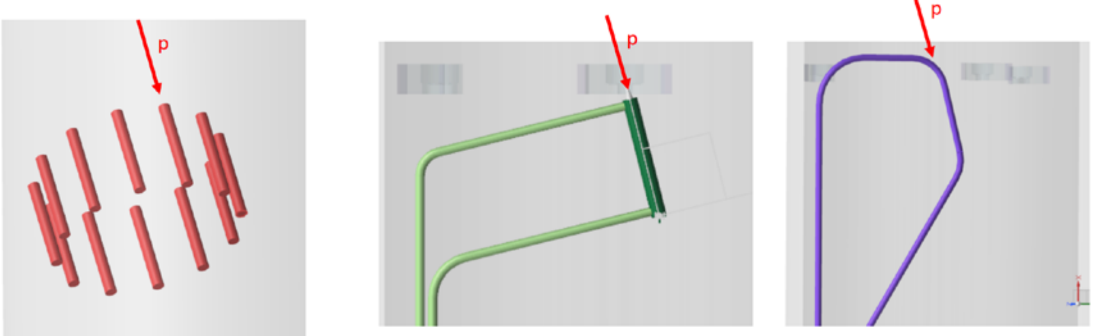
Understand solenoid shielding requirements

Current LDRD program at FNAL, conveyor belt seem the favored solution so far

Designs under consideration

V. Pronskikh

To simulate the overall target pion production performance and durability at beam induced pulsed energy deposition spikes, thermal stress, radiation damage, muon stopping rates, residual activation and radiation loads



Rotating Elements — Fixed Granular Target — Conveyor

Pion-production target for Mu2e-II | V.Pronskikh 4

	Tungsten/WC	Lower-density bent (Carbon)
Rotated	Requires a large hardware in HRS	Too large to fit HRS
Fixed granular	DPA is too high	DPA is high; lower pion production
Conveyor	Thermal analysis is ongoing	Lower pion production; thermal analysis is ongoing

Straw R&D (FNAL LDRD program)

Develop 8 μm Mylar straws using 3.5 μm Mylar + 1 μm adhesive + 3.5 μm Mylar double helical wrap

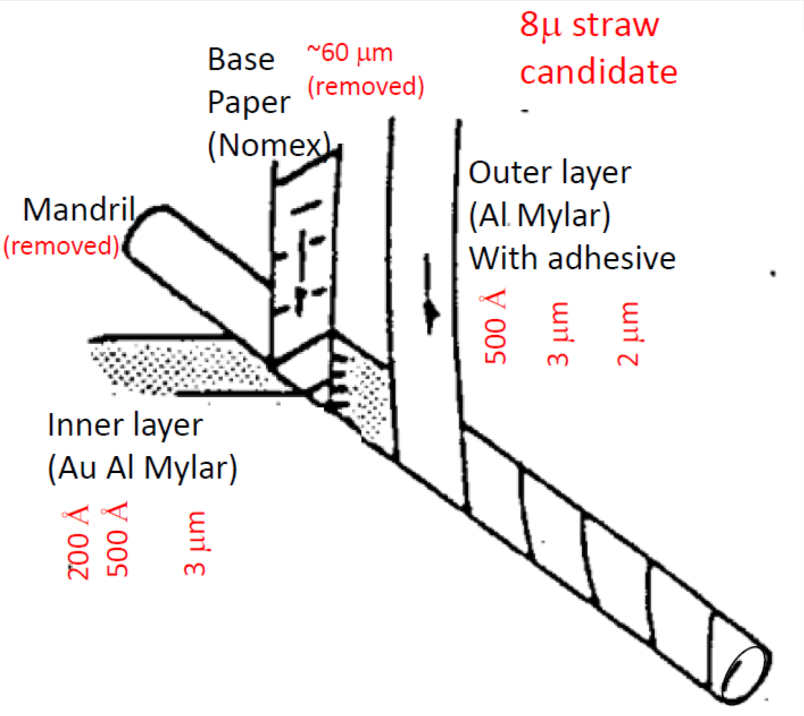
Held 15 PSI for multiple days and 400 g tension without visible distortion

Handling straws with internal outward force without causing obvious damage

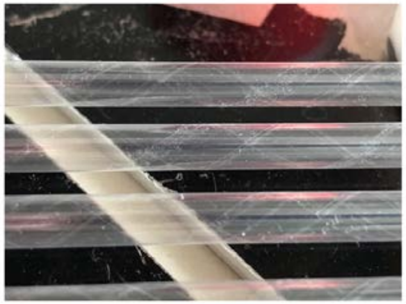
- Paper is inside
- Inflated straws

Almost no compression force can be applied, making the installation of straw termination challenging

Integrated readout electronics must be able to handle large radiation dose



8 μm Mylar Straw



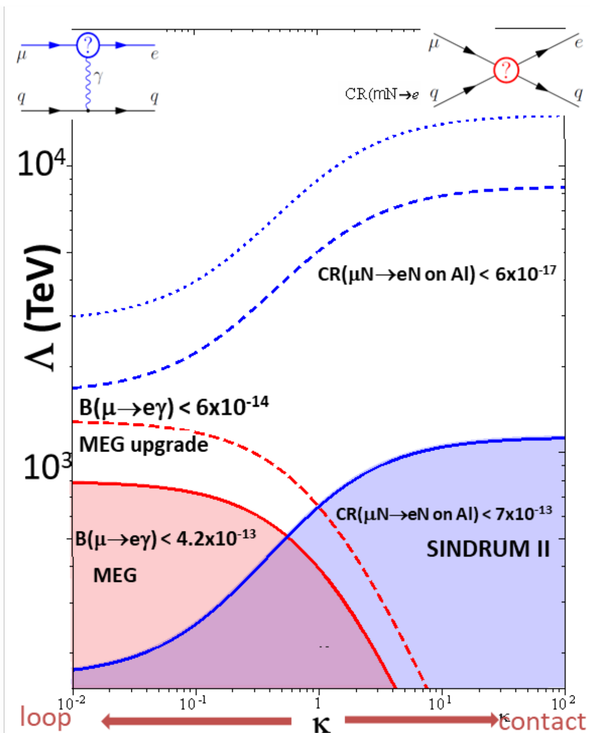
Pressurized 8 μm Mylar Straws

Why muon-to-electron conversion

Sensitive to a wide variety of new physics models (both loop and contact terms), offer model diagnosis in conjunction with additional measurements

Simple effective Lagrangien

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$



From A. de Gouvêa, P. Vogel, arXiv:1303.4097

SUSY – a selection of models

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

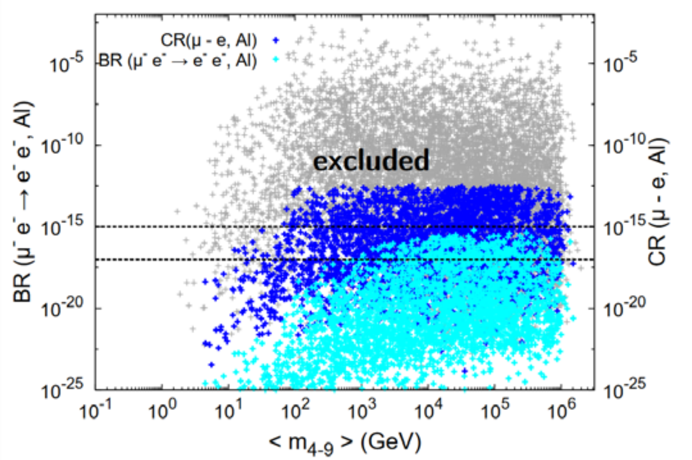
W. Altmannshofer et al. - 0909.1333

Many mechanisms to generate ν mass: seesaw, Zee models, RPV SUSY,…

- distinct new states realized at different scales

Low scale Seesaw: inverse seesaw

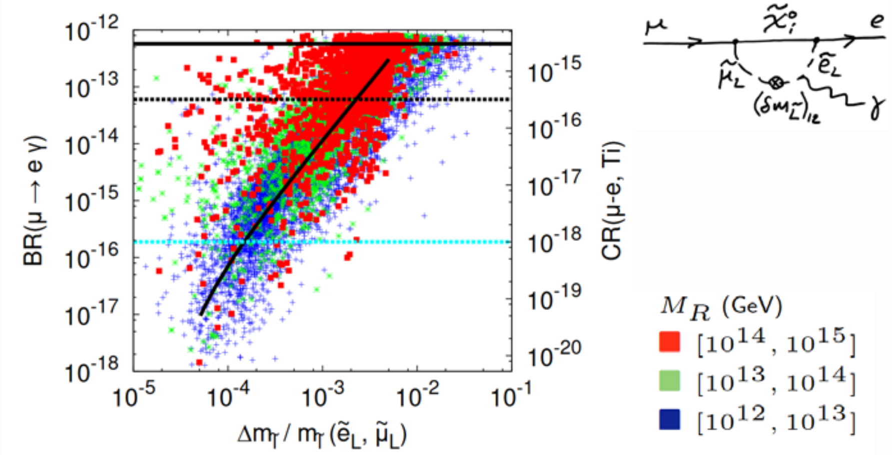
Addition of 3 “heavy” RH neutrinos and 3 extra “sterile” fermions to SM



Teixeira et al., JHEP02 (2016) 083

SUSY Seesaw

CLFV induced by exchange of SUSY particles

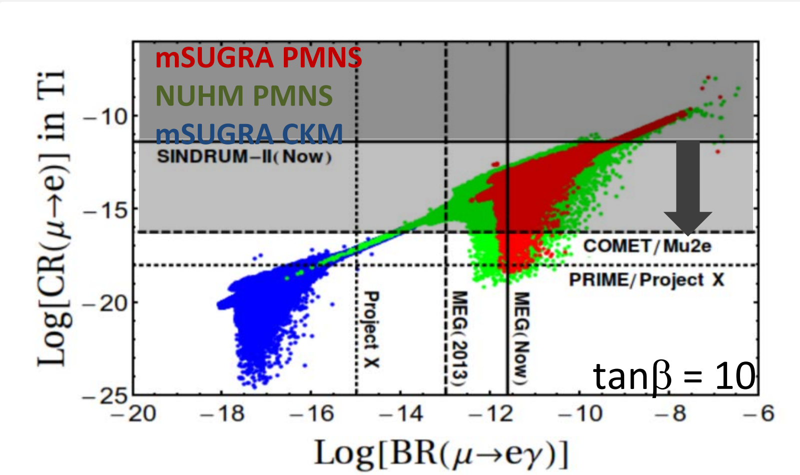


Figueiredo & Teixeira, JHEP 1041(2014) 015

Induces sizeable CLFV rates and helps differentiate models

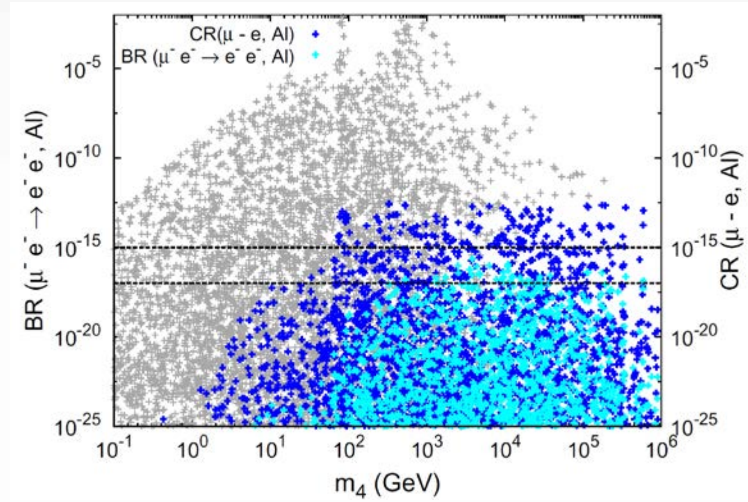
Non Standard Interactions might also impact neutrino oscillations

SUSY GUT



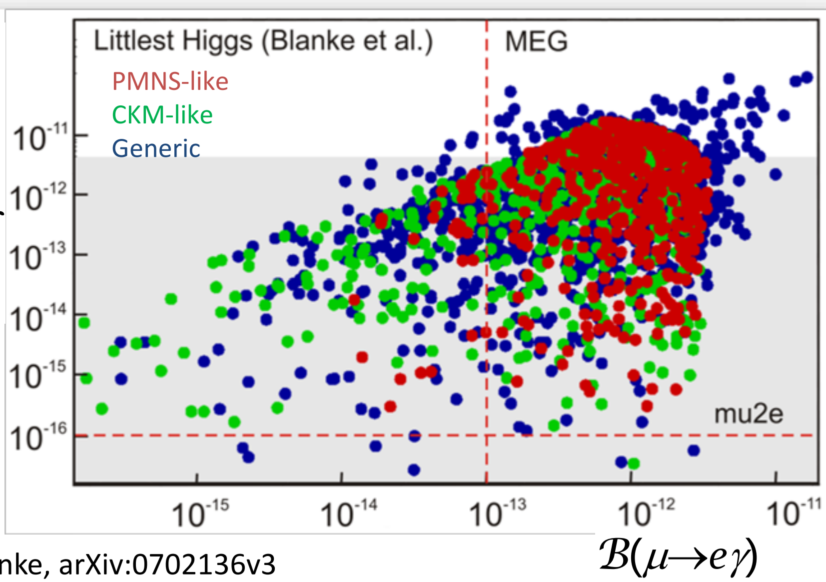
L. Calibbi et al., JHEP 1211 (2012) 040

Sterile neutrino model



Teixeira et al., JHEP02 (2016) 083

LITTLEST HIGGS



Blanke, arXiv:0702136v3

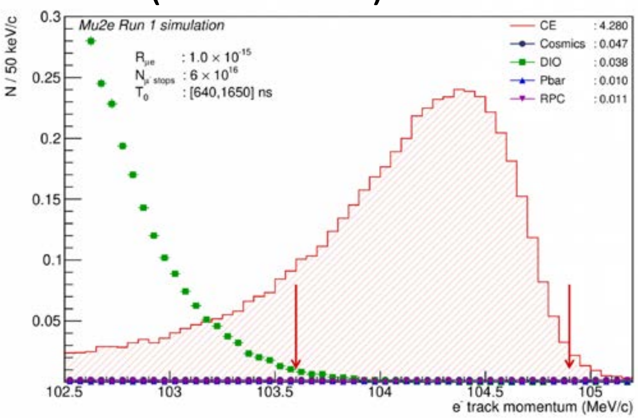
ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$	$0.06\ldots2.2$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$	$0.03\ldots1.3$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2$	~ 5	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{R(\mu Ti\to e Ti)}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

Buras, Duling, Feldmann, Heidsieck, Promberger, 1006.5356

Expected performance: single event sensitivity (SES) and upper limits

Mu2e*

Run1 (2025-2026)



SES $R_{\mu e} = 1.1 \times 10^{-15}$

90% CL upper limit $R_{\mu e} < 5.9 \times 10^{-15}$

Run2 (start 2029)

The goal is a x10^4 improvement over SINDRUM-II

COMET**

Phase I (start 2024)

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

SES: $R_{\mu e} = 3 \times 10^{-15}$ after 150 days of run

Phase II

The goal is a SES of 2.6×10^{-17}

* https://indico.cern.ch/event/855372/contributions/4441322/attachments/2304546/3920529/Pezzullo-Mu2e-talk-20210907-NuFact2021.pdf

** https://indico.cern.ch/event/855372/contributions/4429252/attachments/2305772/3922703/210908-NuFact_COMET.pdf

Muon to positron conversion μ^- (A,Z) $\rightarrow$ e^+ (A,Z-2)

This process violates both charged lepton flavor conservation but also lepton number conservation

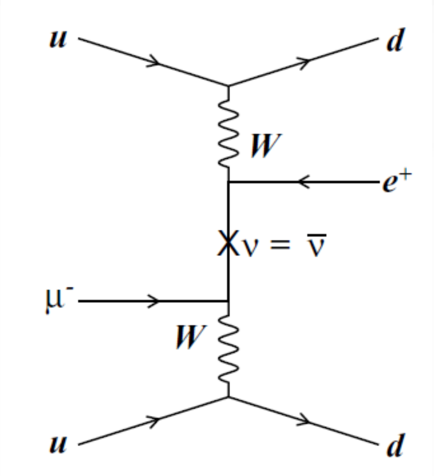
Analogous to neutrinoless double beta decay, and favored if the flavor off-diagonal sectors (eμ or eτ) dominate over the diagonal sector (ee)

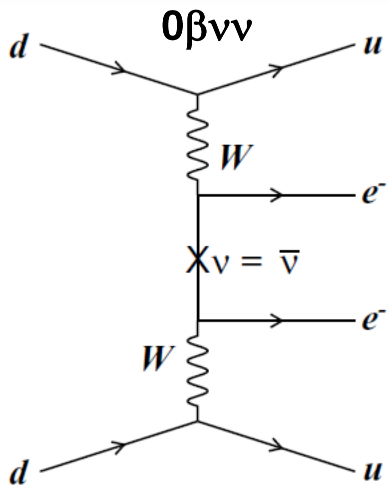
For Al, the signal is a mono-energetic electron of 92.3 MeV. However, the background for radiative muon capture is still important at this energy, making the measurement challenging.

Current experimental bound from Sindrum II:

CR($\mu^- \rightarrow e^+$) < 1.7×10^{-12} at 90% CL (on Ti)

μ^- (A,Z) $\rightarrow$ e^+ (A,Z-2)

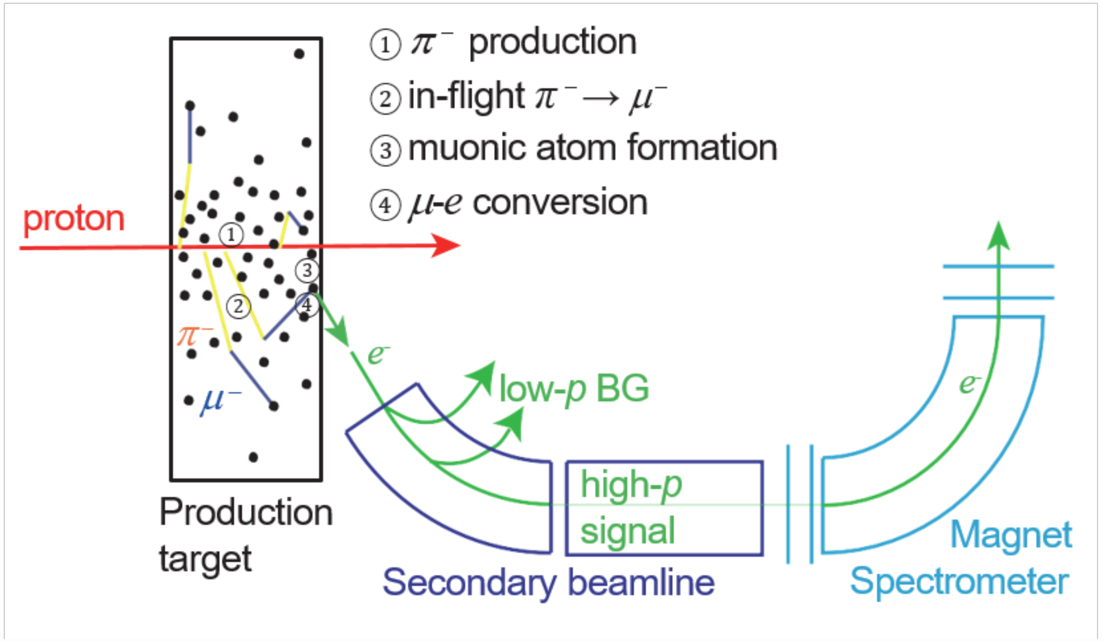




M. Lee and M. Mackenzie

Search for $\mu \to e$ conversion with a high power, high purity proton beam at J-PARC

Conversion happens in production target. Initially graphite target, upgrade to SiC



Single event sensitivity with 1 MW beam :

1 year: $1.2\text{x}10^{-13} \to 2.1 \text{ x } 10^{-14}$ upgrade

4 years: $2.5\text{x}10^{-14} \to 5 \text{ x } 10^{-15}$ upgrade