A New Charged Lepton Flavor Violation Program at Fermilab

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with Robert Bernstein (FNAL) and Jaroslav Pasternak (ICL/RAL SCTF)

Potential Fermilab Muon Campus & Storage Ring Experiments Workshop
May 2021

Charged lepton flavor violating (CLFV) processes are interactions that do **not** conserve lepton family number(s)

- e.g. $\mu \to e$, $\tau \to \mu\mu\mu$, $K_L \to \mu e$, $H \to \tau\mu$, ...

Flavor in the Standard Model

- Quark flavor is violated in weak decays (CKM matrix)
- Neutral lepton flavor is violated (neutrino oscillations)

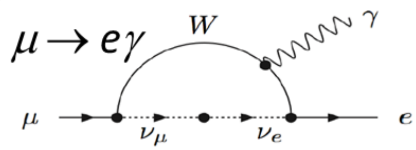
What about charged lepton flavor?

- Lepton flavor accidentally conserved in SM with massless neutrino
- Add Dirac neutrino masses to SM: lepton flavor violated, but unmeasurably small rates

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

CLFV and BSM physics

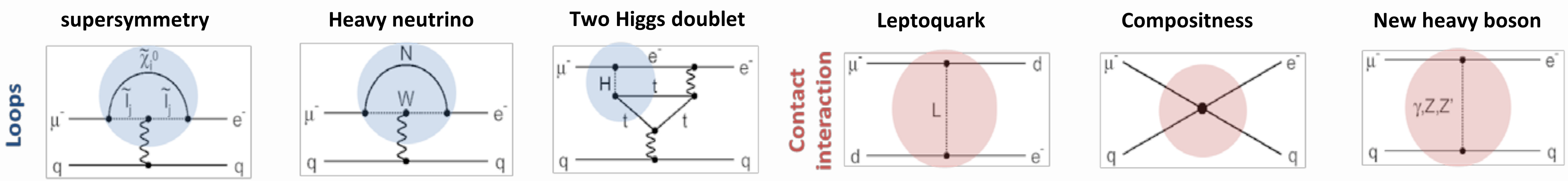
CLFV can be generated at loop level with massive neutrinos, but the rate is extremely suppressed due to GIM mechanism and tiny neutrino masses. For example:



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

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

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



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

Observation of CLFV could inform the choice of future high-energy colliders

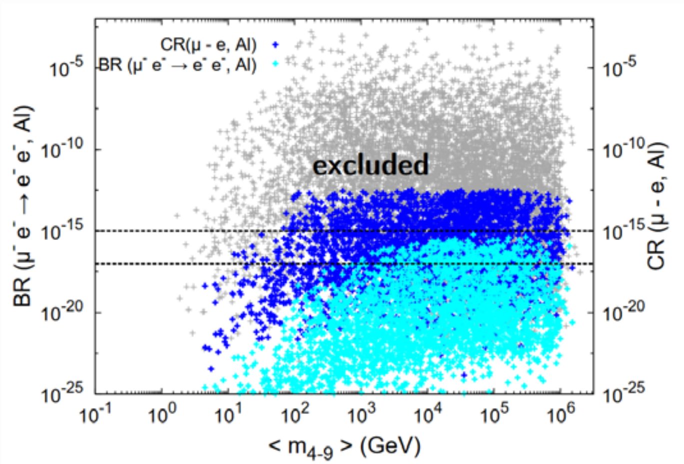
A future CLFV program has synergies with both muon colliders and neutrino factories, and could be a component of a comprehensive muon program at FNAL

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

- distinct new states realized at different scales

Low scale Seesaw: inverse seesaw

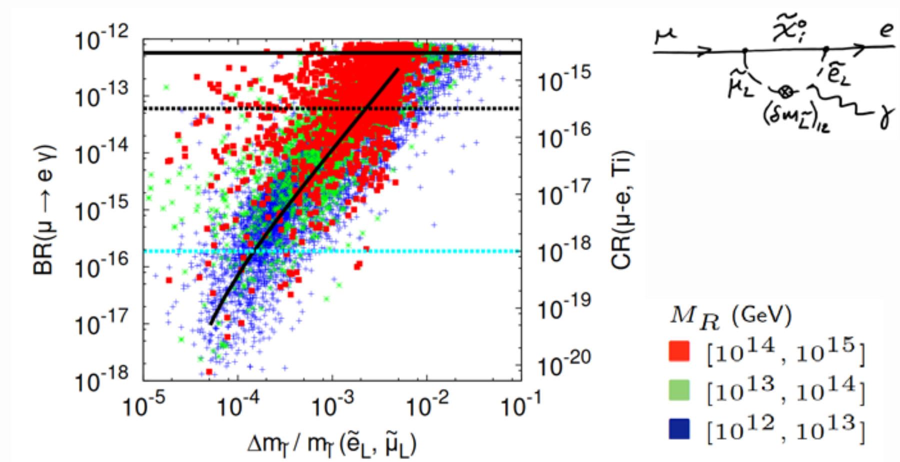
Addition of 3 “heavy” RH neutrinos and 3 extra “sterile” fermions to SM



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

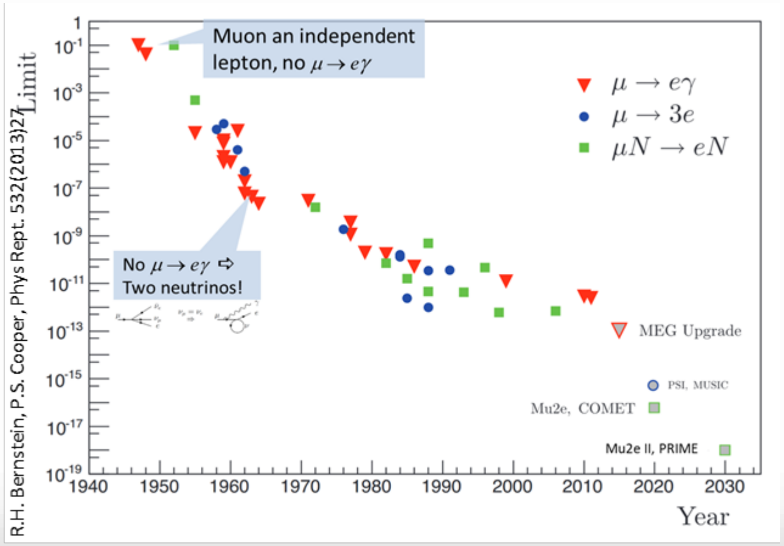
Non Standard Interactions might also impact neutrino oscillations

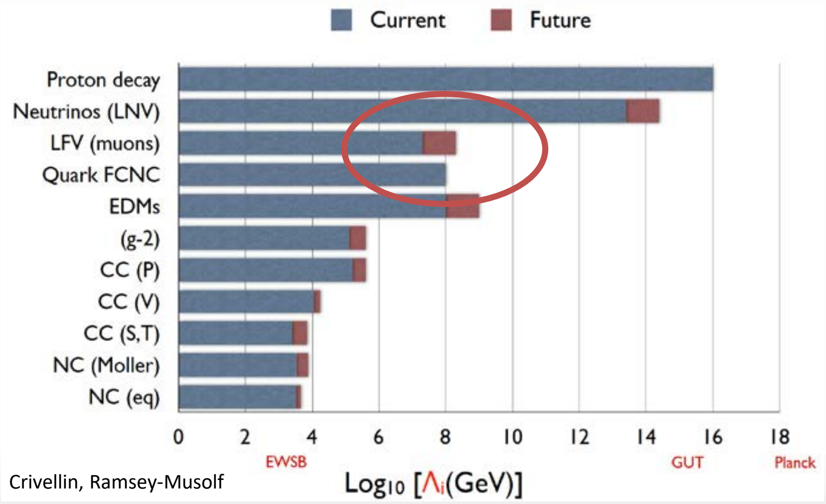
Why muons? Relatively easy to make high-intensity muon beams

Three main modes

- $\mu^+ \rightarrow e^+\gamma$ decays
- $\mu^+ \rightarrow e^+e^-e^+$ decays
- $\mu^- N \rightarrow e^- N$ conversion

Already probe new physics effective mass scale (Λ) at the level of 10^3 TeV
Significant improvements expected in the coming years





Why muons? Relatively easy to make high-intensity muon beams

Three main modes

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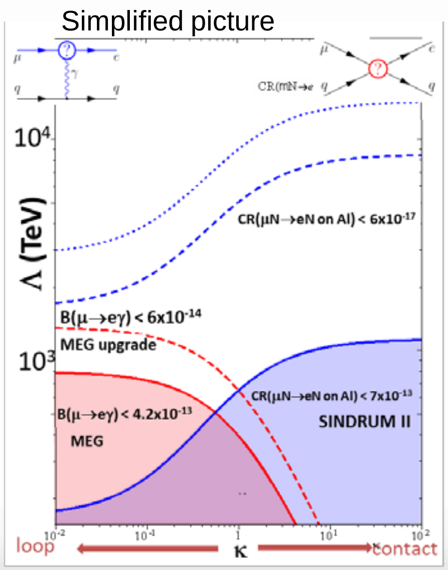
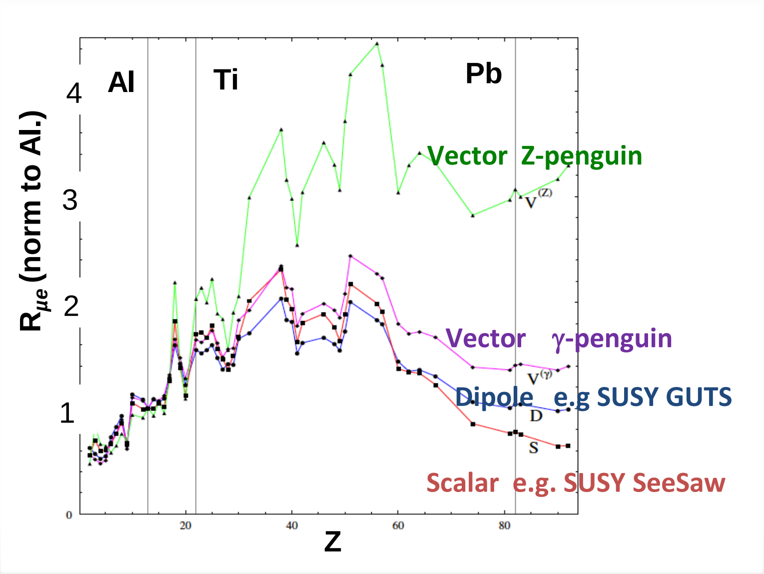
Complementarity is key – each reaction probes different NP operators

Z dependence of μ-e conversion provide information about the nature of new physics



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



Cirigliano, *et al*, PRD **80**, 013002 (2009)

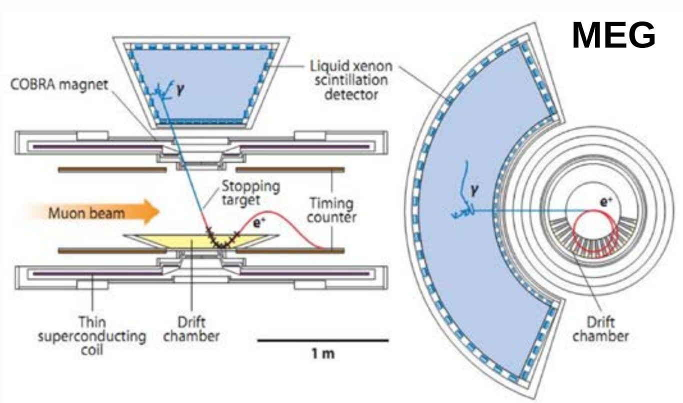
Decay experiments

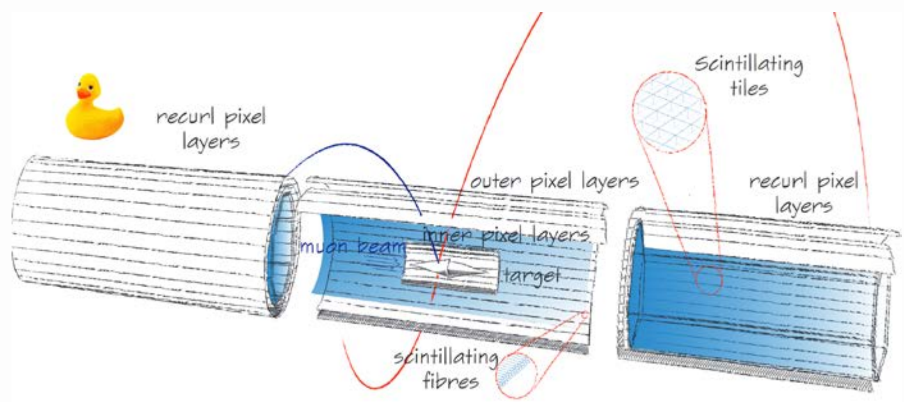
$\mu^+ \to e^+\gamma$ - MEG / MEG II at PSI

- Expected sensitivity at the level of 10^{-14} (3 year run)
- Expect data taking in 2021

$\mu^+ \to e^+e^-e^+$ - Mu3e at PSI

- Expected sensitivity at the level of 10^{-15} to 10^{-16} (with HiMB)
- Expect data taking in 2022++





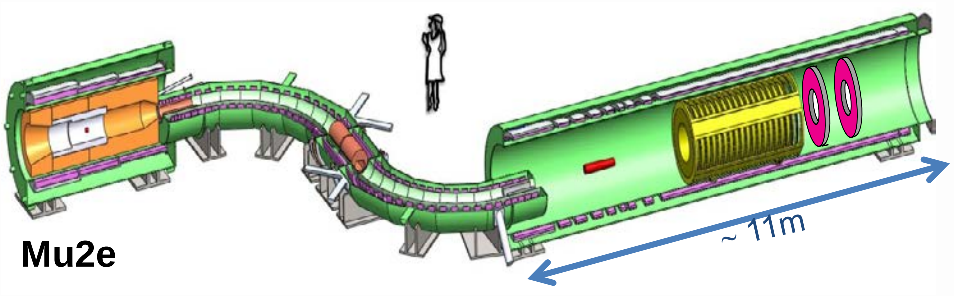
Conversion experiments

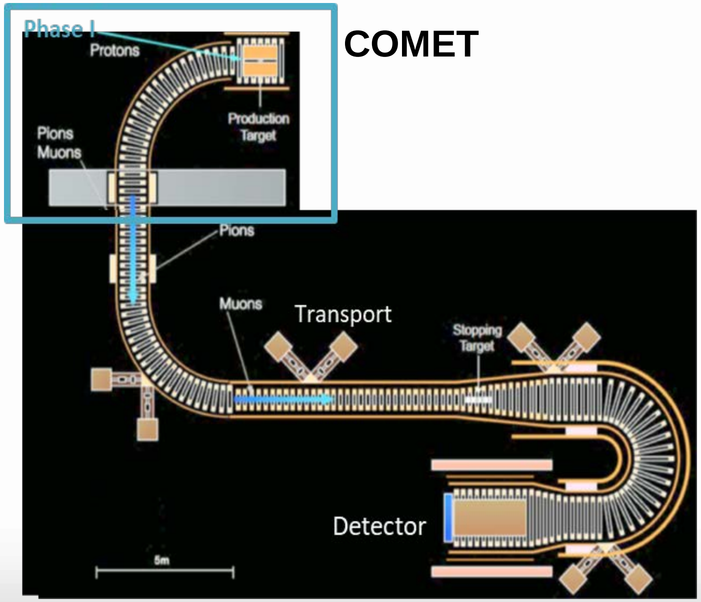
Mu2e at FNAL and COMET at J-PARC

- Aim to achieve single event sensitivity $R_{\mu e} \sim 10^{-17}$ by the end of the decade

Mu2e-II at PIP II (proposal, see S. Middleton talk on Wedneday)

- Aim to achieve $R_{\mu e} \sim 10^{-18}$ in the next decade



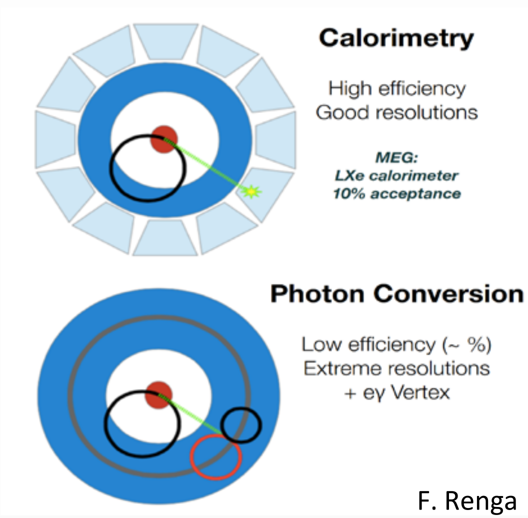


Increase muon rate

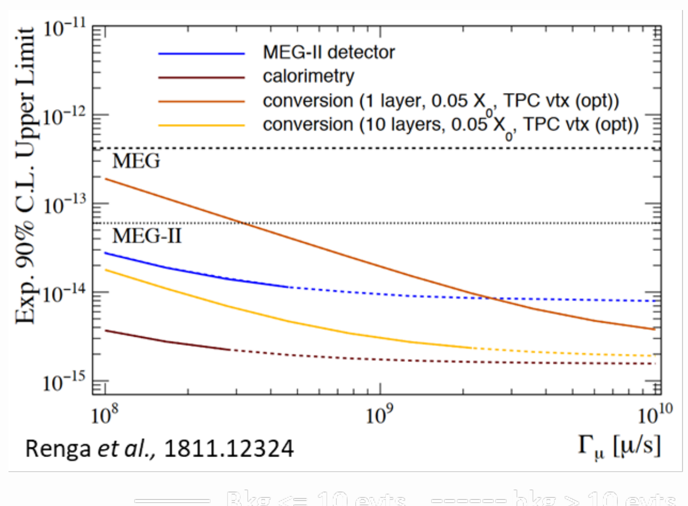
- Current PSI muon beamline — 2×10^{8} μ/s
- Proposed HiMB at PSI — $\sim10^{10}$ μ/s
- Mu2e (current design, positive mode) — $\sim10^{11}$ μ/s

Improve detector performance to reduce backgrounds

- Background level depends on the photon energy and angular resolution (among others)
- High-efficiency calorimeter or photon conversion to improve energy and angular resolution



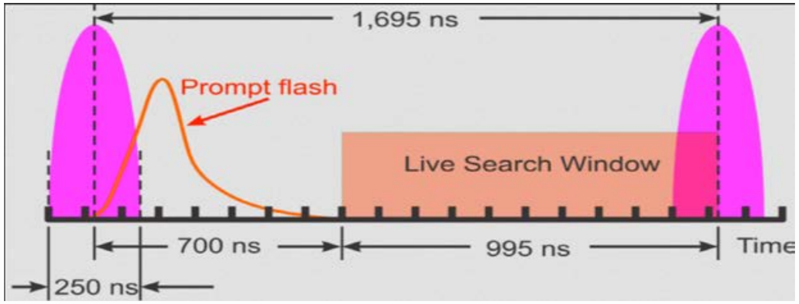
F. Renga



Renga *et al.*, 1811.12324

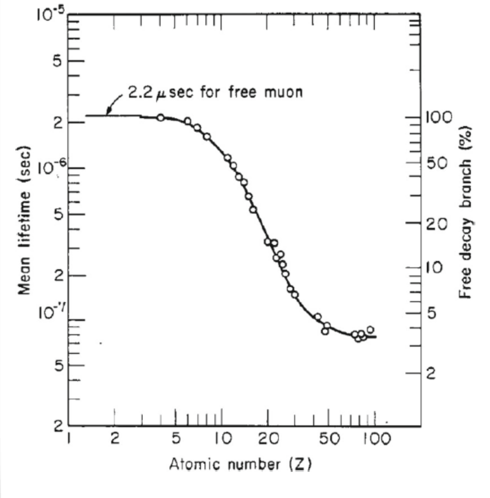
Current approach

- Protons hit the production target, pions → muons captured by production solenoid (pulsed beam)
- Muons transported towards stopping target
- Muon conversion or decay products measured by detector (tracker + calorimeter)



Main limiting factors

- Dead time to wait for beam-associated backgrounds to decrease to negligible level → cannot measure conversions in atoms with short muonic lifetimes (high Z)
- Need well-defined pulse beam (extinction)
- Available beam power limits muon rate
- Mu2e-II is based on same concept with increased beam power (100 kW), prompt backgrounds continue to limit studying high-Z targets



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

ENIGMA is a new facility for a next generation of muon experiments at FNAL based on the PIP-II accelerator with a

Surface muon beam for muon decay experiments

- Similar to what is done at PSI (1.4MW target, well known technology)
- Dedicated beam with higher intensity – up to 10^{12} μ/s with PIP II
- Potentially improve sensitivity by a factor x100 w.r.t MEG-II

New beam for muon conversion experiments

- Probe $R_{\mu e}$ sensitivity down to 10^{-19}, with the ultimate objective to reach 10^{-20} and probe O(10^4 - 10^5) TeV effective mass scale
- Probe high-Z target (e.g. Au) to explore underlying new physics if CLFV is observed
- Based on the PRISM concept to provide a low momentum, quasi-mono-energetic muons beam with extremely low pion contamination

PIP II

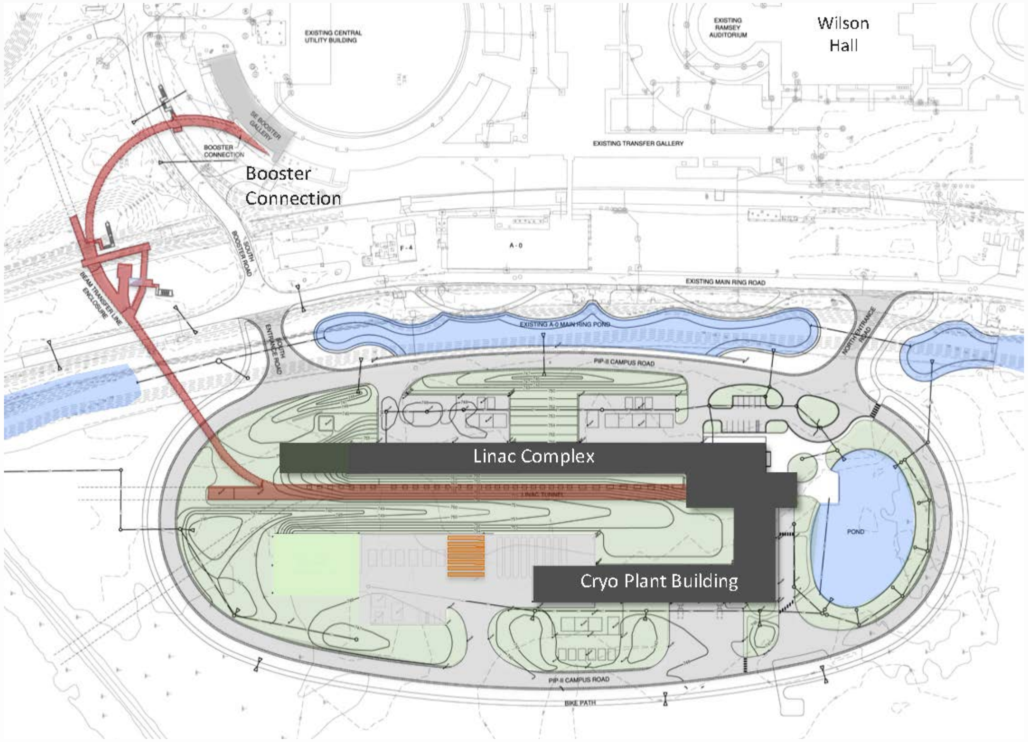
800 MeV H− linac
- Up 165 MHz bunches
- Up to 2 mA CW
- Up 1.6 MW

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Protons for the High Energy Program
- ~1% of available beam!

Groundbreaking for project
- March 2019

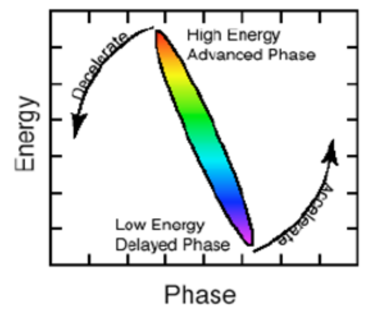


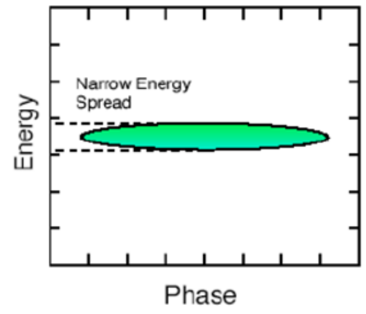
PIP-II will deliver 1.2 MW proton beam for LBNF, but that program uses a very small fraction of the available beam → opportunity for a muon facility

New beam for conversion experiment*, based on the PRISM (Phase Rotated Intense Slow Muon beam) concept proposed by Y. Kuno and Y. Mori

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



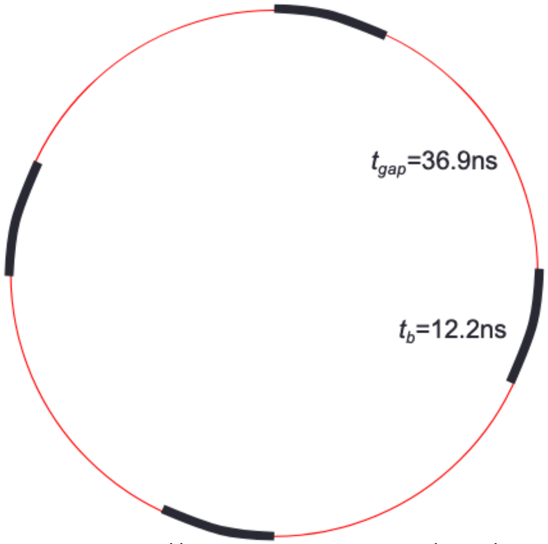


Requires a compressed proton bunch and high power beam to achieve high μ rate
$\rightarrow$ PIP II with a compressor ring.

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

PIP II beam power is sufficient, but the $2x10^8$ bunch size limit is much too small for the FFA and requires a compressor ring

E. Prebys



Circumference: $C = 49.7$ m

RF Frequency: $f_{RF} = 40.62$ or 20.31 MHz

harmonic: $h = 8$ or 4

Protons/bunch: $n_b = 1 \times 10^{12}$

Bunch length: $t_b = 12.2$ ns

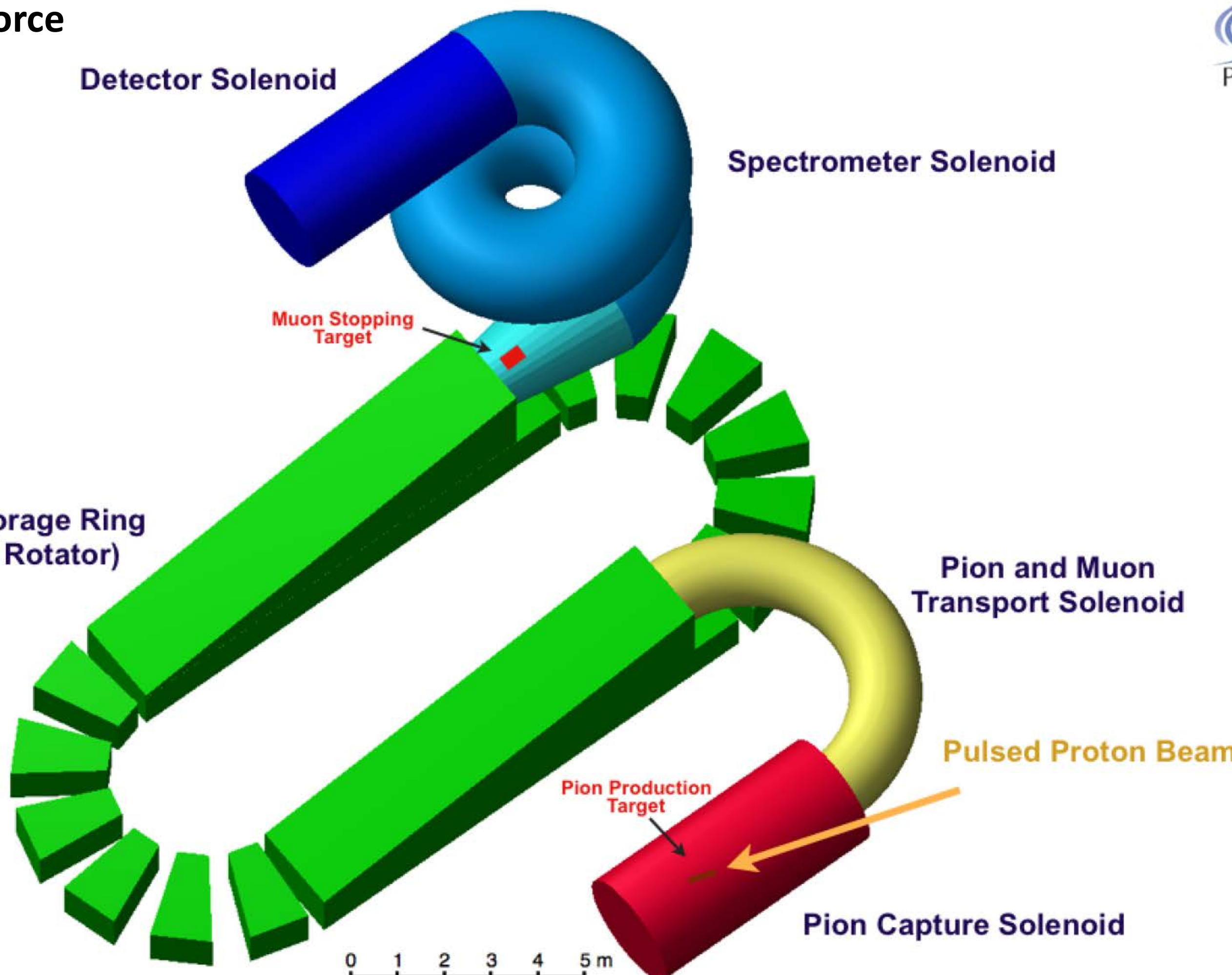
Fill time: $t_{fill} = 1.3$ ms

https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys-071.pdf

Parameter	Value	Comment
Bunches	4	Assumed
Protons per Bunch	10^{12}	Target
Fill Time [ms]	1.3	$6667 \times \tau$
Extraction Rate [Hz]	100	Assumed
Average Power [kW]	12.8	

This is too low! Need R&D to push repetition rate or bunch size!

PRISM task force



J. Pasternak et al.

https://indico.phys.vt.edu/event/34/contributions/685/attachments/529/625/PRISM_nufact18.pdf

PRISM – challenges and synergies

FFA ring design

- in full synergy with the Neutrino Factory and a Muon Collider

Target and capture system

- MW class target in a solenoid
- in full synergy with the Neutrino Factory and a Muon Collider

Design of the muon beam transport from the solenoidal capture to the PRISM FFA ring

- very different beam dynamics conditions
- very large beam emittances and the momentum spread

Muon beam injection/extraction into/from the FFA ring

- very large beam emittances and the momentum spread

Compressor ring

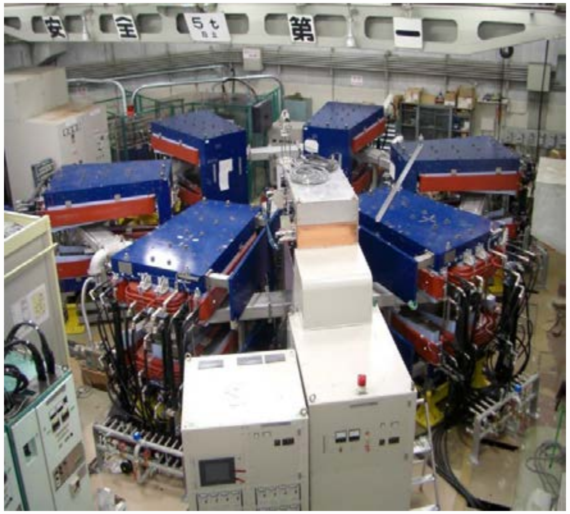
- Fast kicker to transfer beam from compressor ring at 1kHz

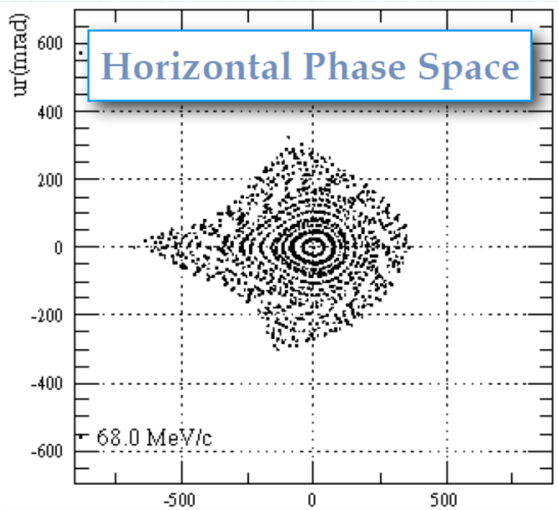
Many synergistic activities with muon collider and neutrino factory R&D

PRISM is in a position to be one of the incremental steps of the muon program and a component of a global muon program at FNAL to exploit the full potential of PIP-II

PRISM FFA - proof of concept

- 10 cell DFD ring has been designed
- FFA magnet-cell has been constructed and verified
- RF system has been tested and assembled
- 6 cell ring was assembled and its optics was verified with α particles
- Phase rotation was demonstrated for α particles





Pasternak et al., https://indico.phys.vt.edu/event/34/contributions/685/attachments/529/625/PRISM_nufact18.pdf
A. Alekou et al., arxiv: 1310.0804

Study groups – muon decays

Forming groups to study beam and detector for muon decay experiments

Beam

- Use HiMB at PSI as starting point for a next generation beamline (HiMB project 2025-2028, operations 2029+)

Detector

- R&D to improve detector performance to fully exploit high intensity beam (tracking? Converter design?)
- New approaches? Multiple stopping targets?
- Can we build a detector for both $\mu^+ \to e^+\gamma$ *and* $\mu^+ \to e^+e^-e^+$?

Study groups – muon conversion

Forming groups to study beam and detector for muon conversion experiments

Beam

- Preliminary design for compressor ring, but need more R&D to increase power delivered on target
- **R&D for MW target in solenoid (synergies with muon collider)**
- Adapt FFA design from PRISM group, interface with compressor ring
- Understand synergies and form connection with muon collider and neutrino factories

Detector

- Explore potential design for detector (Mu2e/COMET style or something else?)
- Set requirements for performance and background rejection

Muon community at FNAL

This effort is part of a global muon program under study within Snowmass

- Muon decays (MEG and Mu3e)
- Muon conversion (Mu2e / COMET and Mu2e II)
- $\Delta L=2$ processes $\mu^- N \rightarrow e^+ N$
- Muonium – antimuonium (MACE)
- General Low Energy Muon Facility (FNAL)
- Light new physics in muon decays (MEG-Fwd)

A large community committed to muon physics at FNAL and around the world

Summary

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

A new large scale muon facility at PIP II could improve the sensitivity by orders of magnitude and explore the underlying new physics if CLFV is observed

This program has many synergies with the muon collider and neutrino factory, and could be part of a comprehensive muon program at FNAL to fully exploit the potential of PIP II

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, and we would like P5 to endorse the physics concept and provide resources for design studies

People interested in exploring synergies or contributing to this program are welcomed to contact us

Thank you for your attention

Extra material

Some references

Next generation MW muon facility at FNAL

A New Charged Lepton Flavor Violation Program at Fermilab
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

A Phase Rotated Intense Source of Muons (PRISM) for a $\mu \rightarrow e$ Conversion Experiment
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_J_Pasternak-096.pdf

Bunch Compressor for the PIP-II Linac
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf

Muon decays

The MEG II experiment and its future development
https://www.snowmass21.org/docs/files/summaries/ RF/SNOWMASS21-RF5_RF0_MEGII-062.pdf

A new experiment for the $\mu \rightarrow e\gamma$ search
https://www.snowmass21.org/docs/files/summaries/ RF/SNOWMASS21-RF5_RF0_Tassielli-067.pdf

Mu2e-II

Mu2e-II
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Frank_Porter-106.pdf

Low-E facility at FNAL

Upgraded Low-Energy Muon Facility at Fermilab
https://www.snowmass21.org/docs/files/summaries/ RF/SNOWMASS21-RF0-AF0-007.pdf

High intensity muon beam (HiMB) at PSI

Towards an High intensity Muon Beam (HiMB) at PSI
https://indico.cern.ch/event/577856/contributions/3420391/attachments/1879682/3097488/Papa_HiMB_EPS2019.pdf

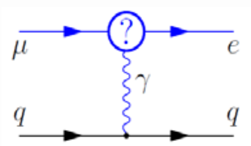
HIMB Physics Case Workshop
https://indico.psi.ch/event/10547/timetable/?view=standard

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

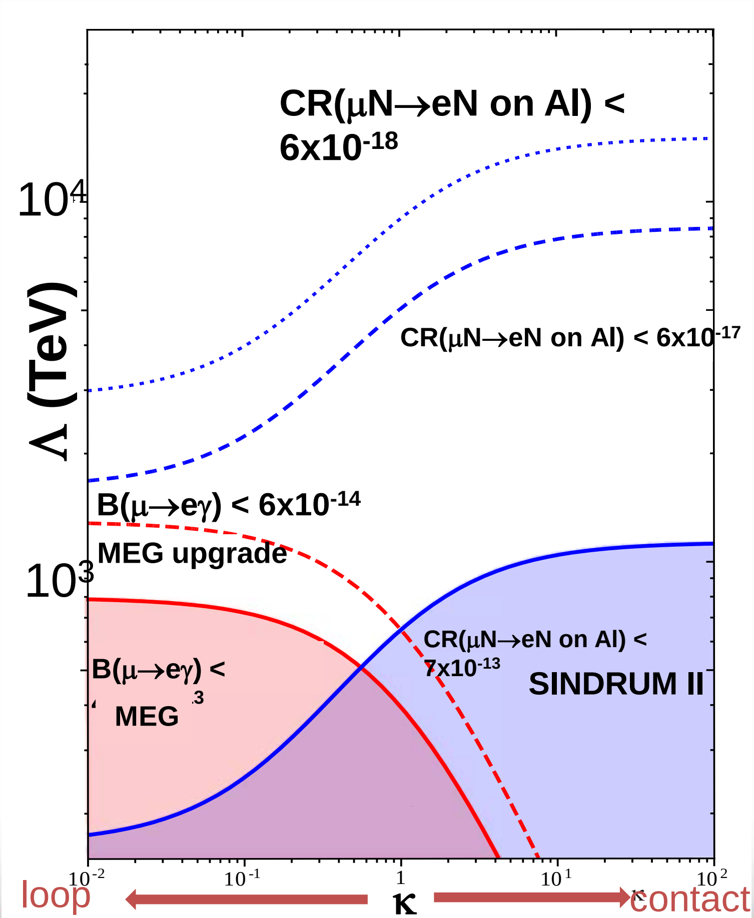
L: effective mass scale of new physics

k: relative contribution of the contact term

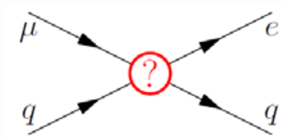
"Dipole term"



Contributes to
$\mu \to e\gamma$



"Contact term"



No contribution
to $\mu \to e\gamma$

CLFV can probe very high mass scales O(1000-10000 TeV)

Different BSM scenarios predict different value of k → model diagnosis

Derived from A. de Gouvêa, P. Vogel, arXiv:1303.4097

CLFV and SUSY (subset of models)

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

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi & D.M. Straub - 0909.1333

★★★ Large
★★ Small but observable
★ Unobservable

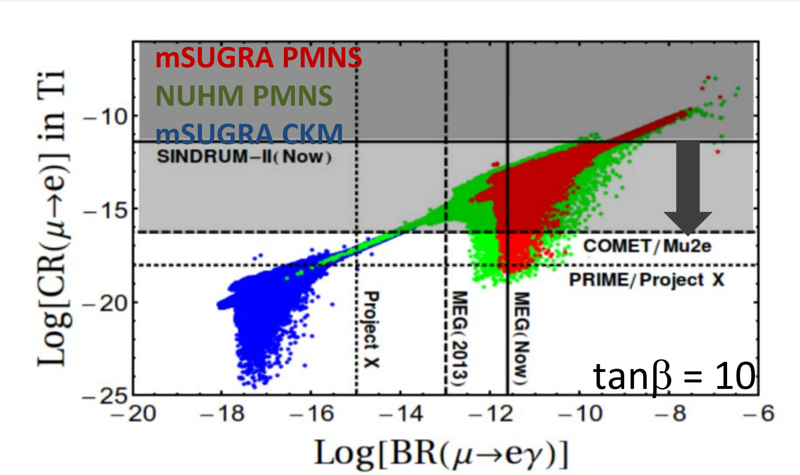
Glossary

AC	RH currents & U(1) flavor symmetry
RVV2	SU(3) flavored MSSM
AKM	RH currents & SU(3) family symmetry
δLL	CKM like currents
FBMSSM	Flavor-blind MSSM
LHT	Little Higgs with T parity
RS	Warped extra dimensions

Pattern characteristic of model,
diagnosis with multiple observables (not only CLFV)

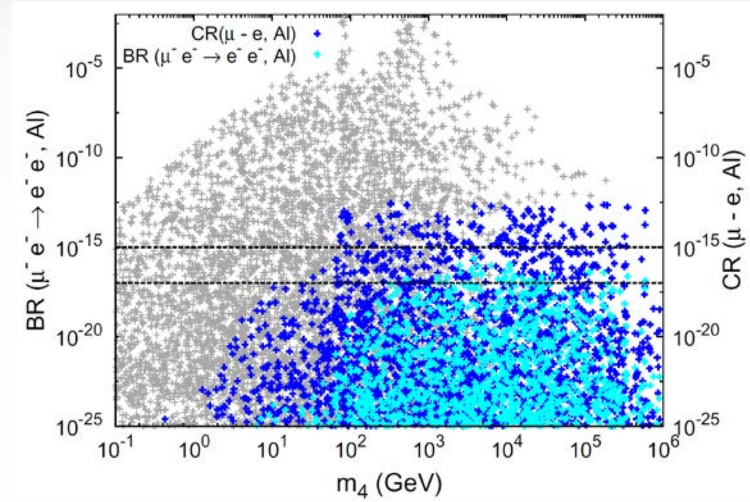
Model discrimination

SUSY GUT



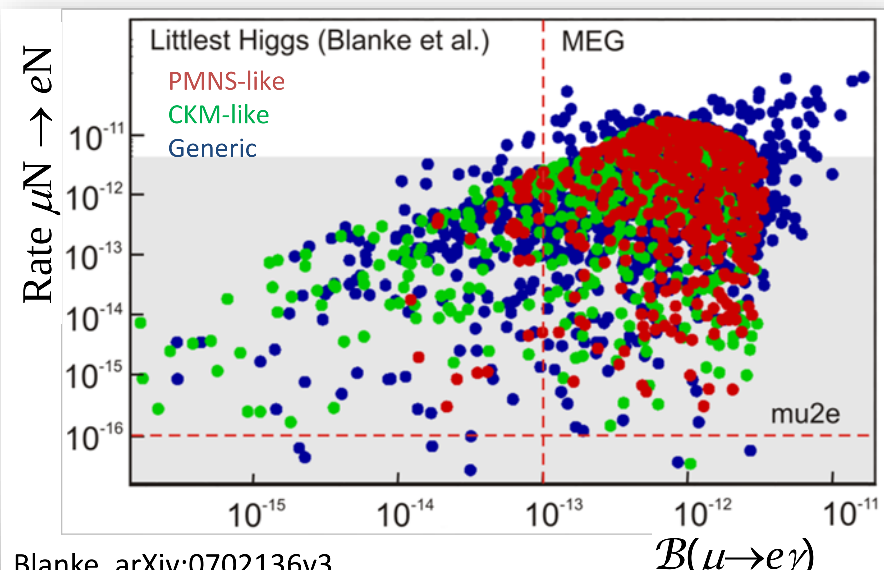
L. Calibbi et al., JHEP 1211 (2012) 040

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	$5\ldots10$	$1.4\ldots1.7$
$\frac{R(\mu Ti\to eTi)}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

Buras, Duling, Feldmann, Heidsieck, Promberger, 1006.5356