A New Charged Lepton Flavor Violation Program at Fermilab

Bertrand Echenard – Caltech

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

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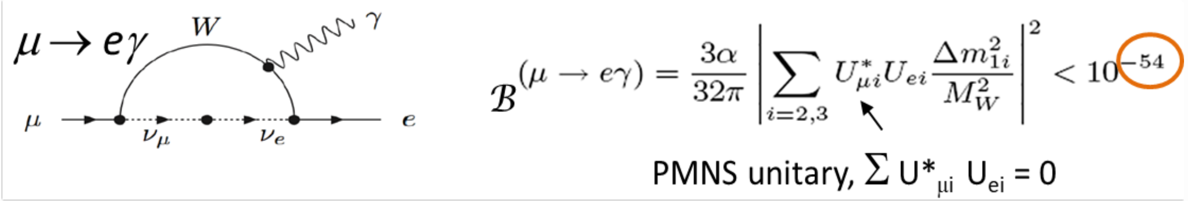
Introduction
Current muon CLFV landscape
A new muon CLFV program
Status and synergies with other efforts

CLFV and BSM physics

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

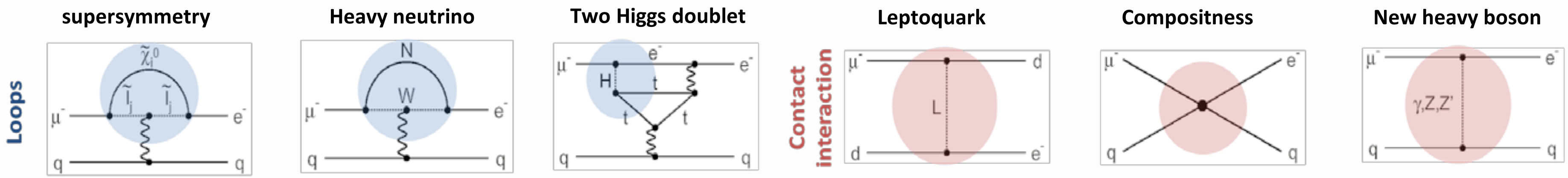
CLFV can be generated at loop level with massive neutrinos, but the rate is extremely suppressed due to GIM mechanism and tiny neutrino masses. For example:



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

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

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


supersymmetry **Heavy neutrino** **Two Higgs doublet** **Leptoquark** **Compositness** **New heavy boson**

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

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

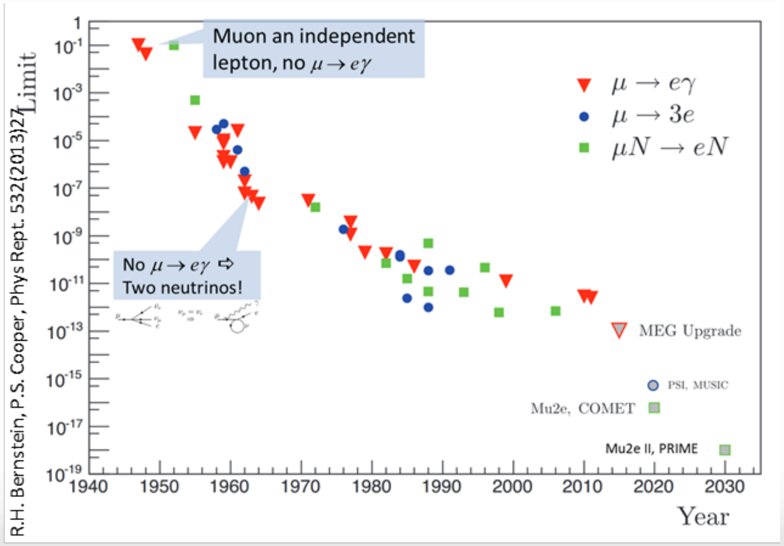
CLFV and muon transitions and decays

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

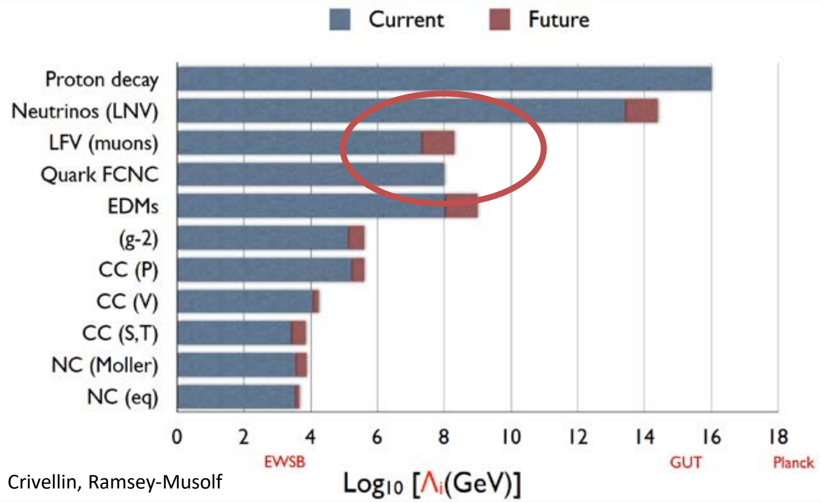
Three main modes

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

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



R.H. Bernstein, P.S. Cooper, Phys Rept. 532(2013)27



Crivellin, Ramsey-Musolf

CLFV and muon transitions and decays

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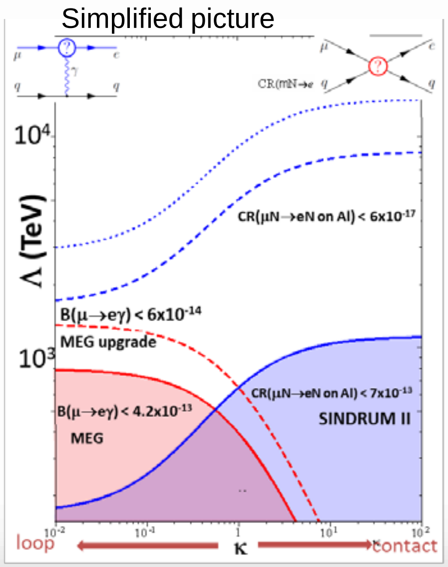
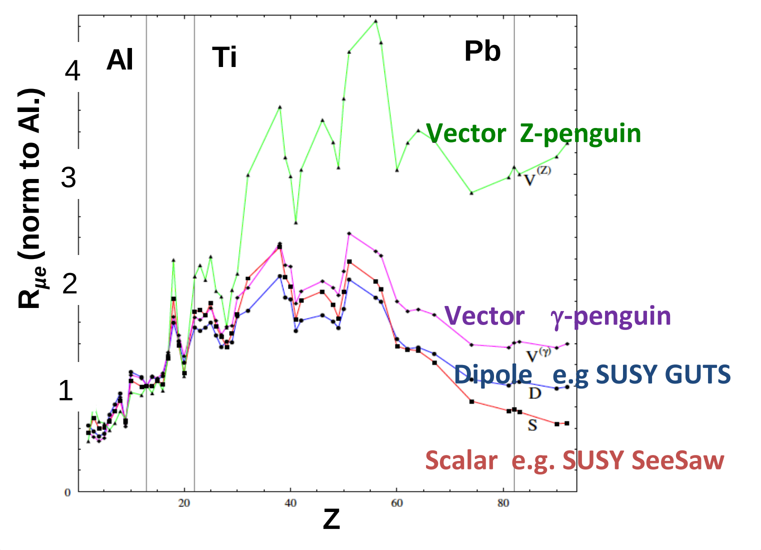
Complementarity is key – each reaction probes different NP operators

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)

Current experimental situation

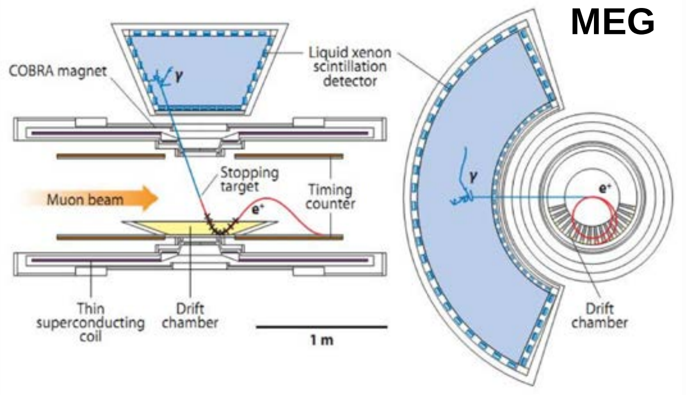
Decay experiments

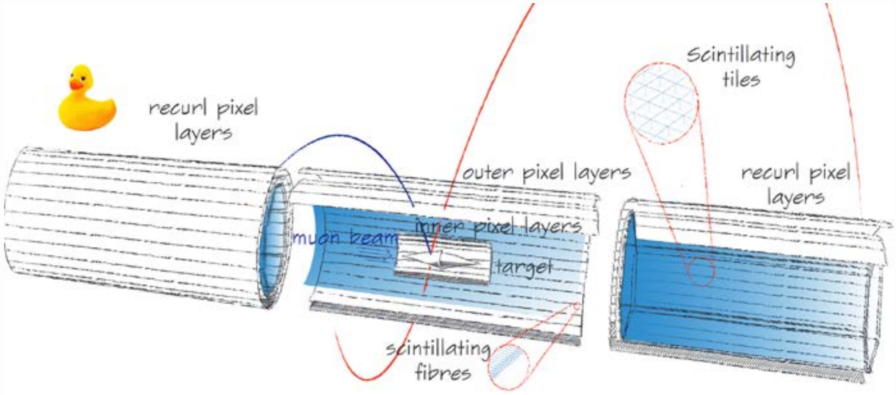
$\mu^+ \to e^+\gamma$ - MEG / MEG II at PSI

- 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++





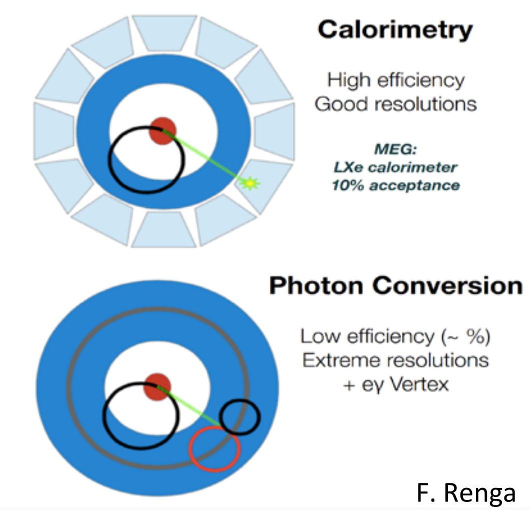
Muon decays – limiting factors

Increase muon rate

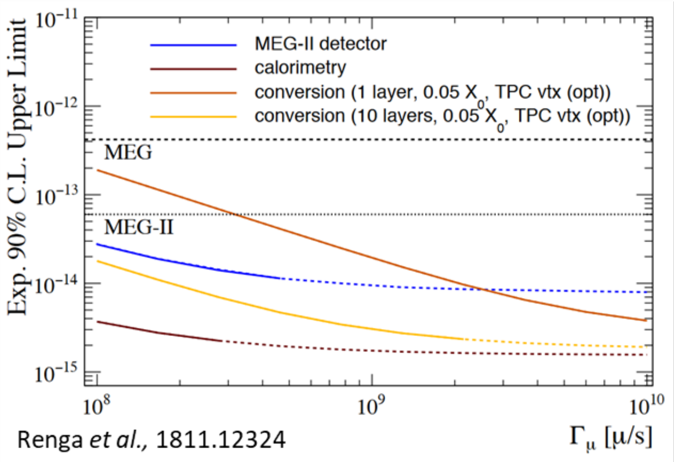
Current PSI muon beamline	2x10^8 μ/s
Proposed HiMB at PSI	~10^{10} μ/s
Mu2e (current design, positive mode)	~10^{11} μ/s

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

——— Bkg <= 10 evts ------ bkg > 10 evts

Current experimental situation

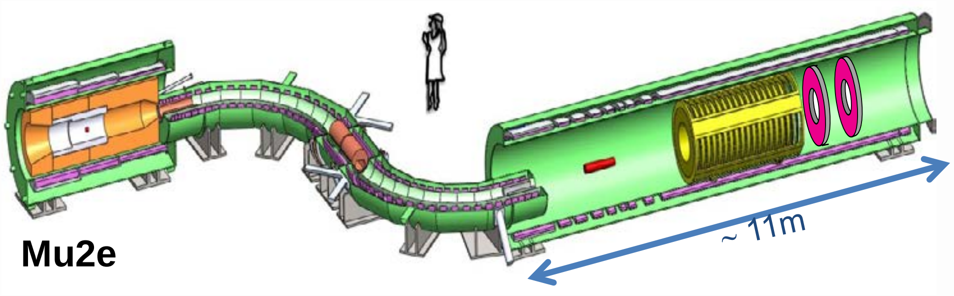
Conversion experiments

Mu2e at FNAL and COMET at J-PARC

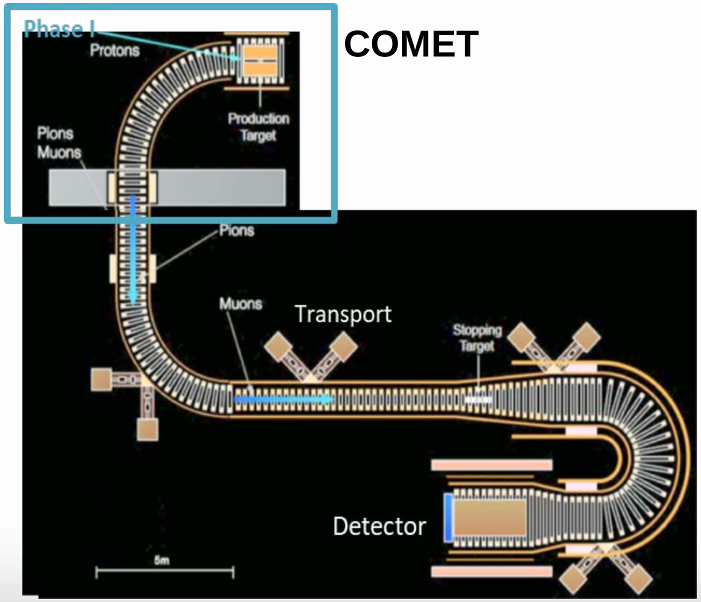
- Aim to achieve single event sensitivity $R_{\mu e} \sim 10^{-17}$ by the end of the decade

Mu2e-II at PIP II (proposal)

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



Mu2e

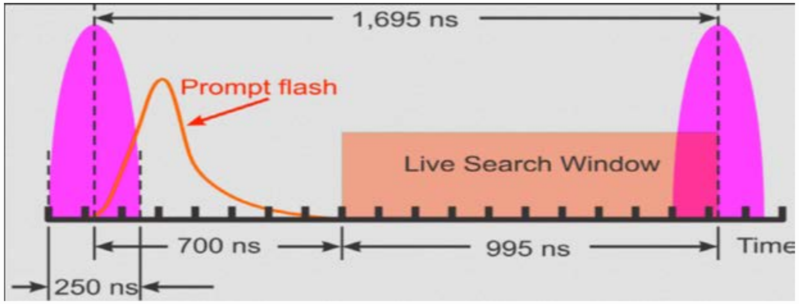


COMET

Muon conversion – limiting factors

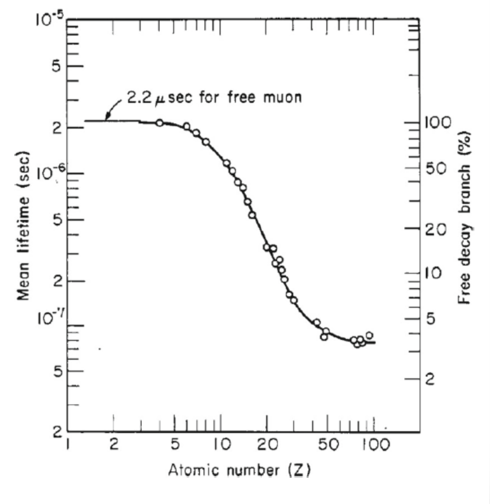
Current approach

- 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

A new CLFV program at Fermilab

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 at FNAL

PIP II

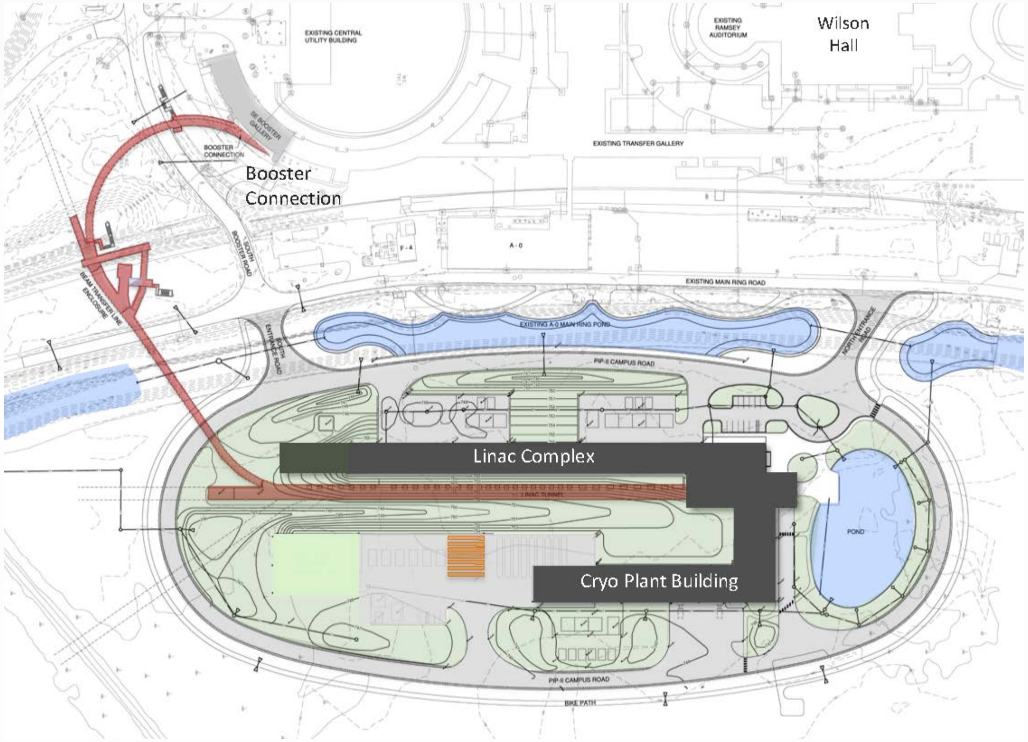
- 800 MeV H− linac
  - Up 165 MHz bunches
  - Up to 2 mA CW
  - Up 1.6 MW

- 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



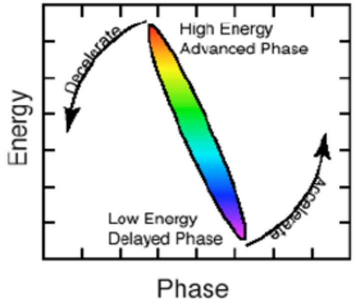
PIP-II will deliver 1.2 MW proton beam for LBNF, but that program uses a very small fraction of the available beam → opportunity for a muon facility

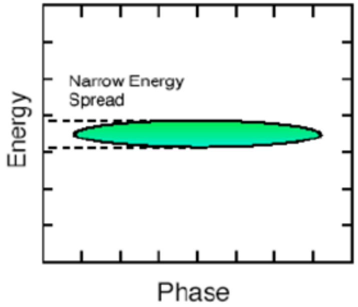
New beam for muon conversion - PRISM

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 $\pi \to \mu$
- 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
$\to$ PIP II with a compressor ring (bunch size limit is much too small for the FFA)

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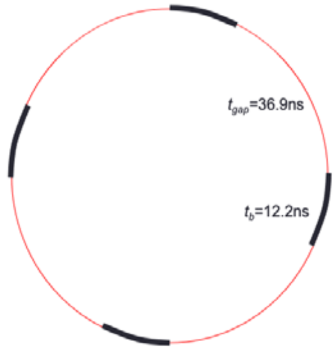
*https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

PRISM – conceptual design

Compressor ring and FFA accelerator complex + detector

E. Prebys



Circumference: $C = 49.7$ m

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

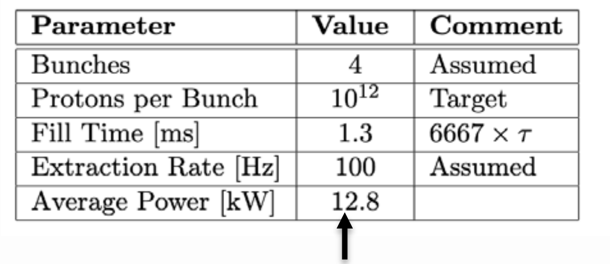
harmonic: $h = 8$ or 4

Protons/bunch: $n_b = 1\times10^{12}$

Bunch length: $t_b = 12.2$ ns

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

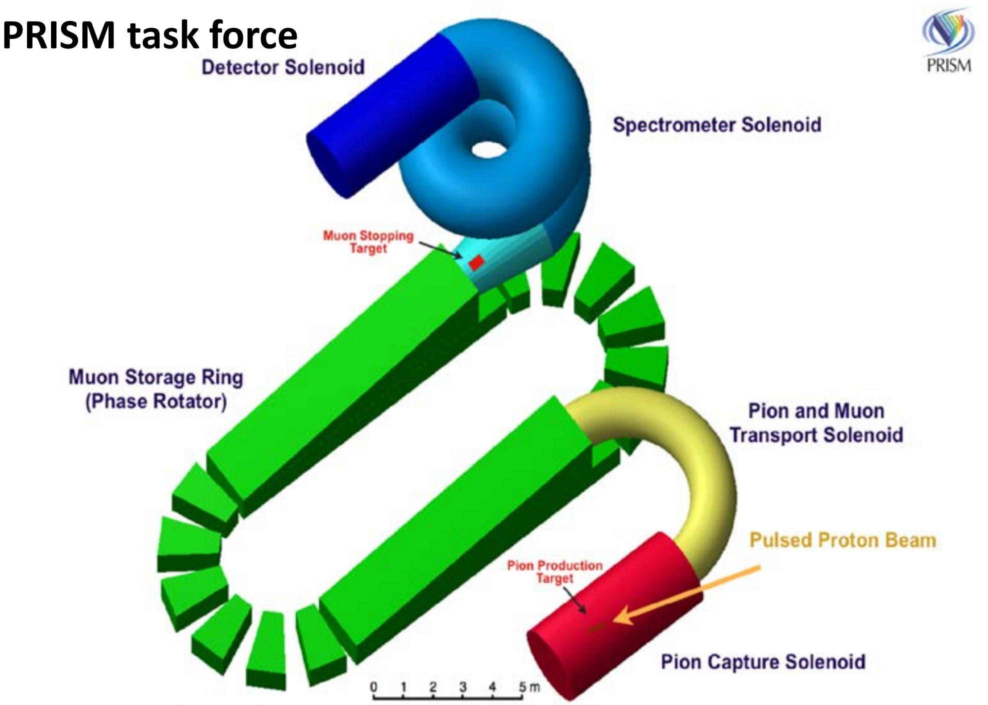
https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys-071.pdf



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

MUSIC - proof of PRISM FFA concept at Osaka with a 10 cell DFD ring

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

Study groups – Snowmass process

Forming groups to study these possibilities in the context of Snowmass process

Muon decays experiments

- Use HiMB at PSI as starting point for a next generation beamline
- R&D to improve detector performance (tracking? Converter design?)
- Can we build a detector for both $\mu^+ \to e^+\gamma$ *and* $\mu^+ \to e^+e^-e^+$?

Muon conversion experiments

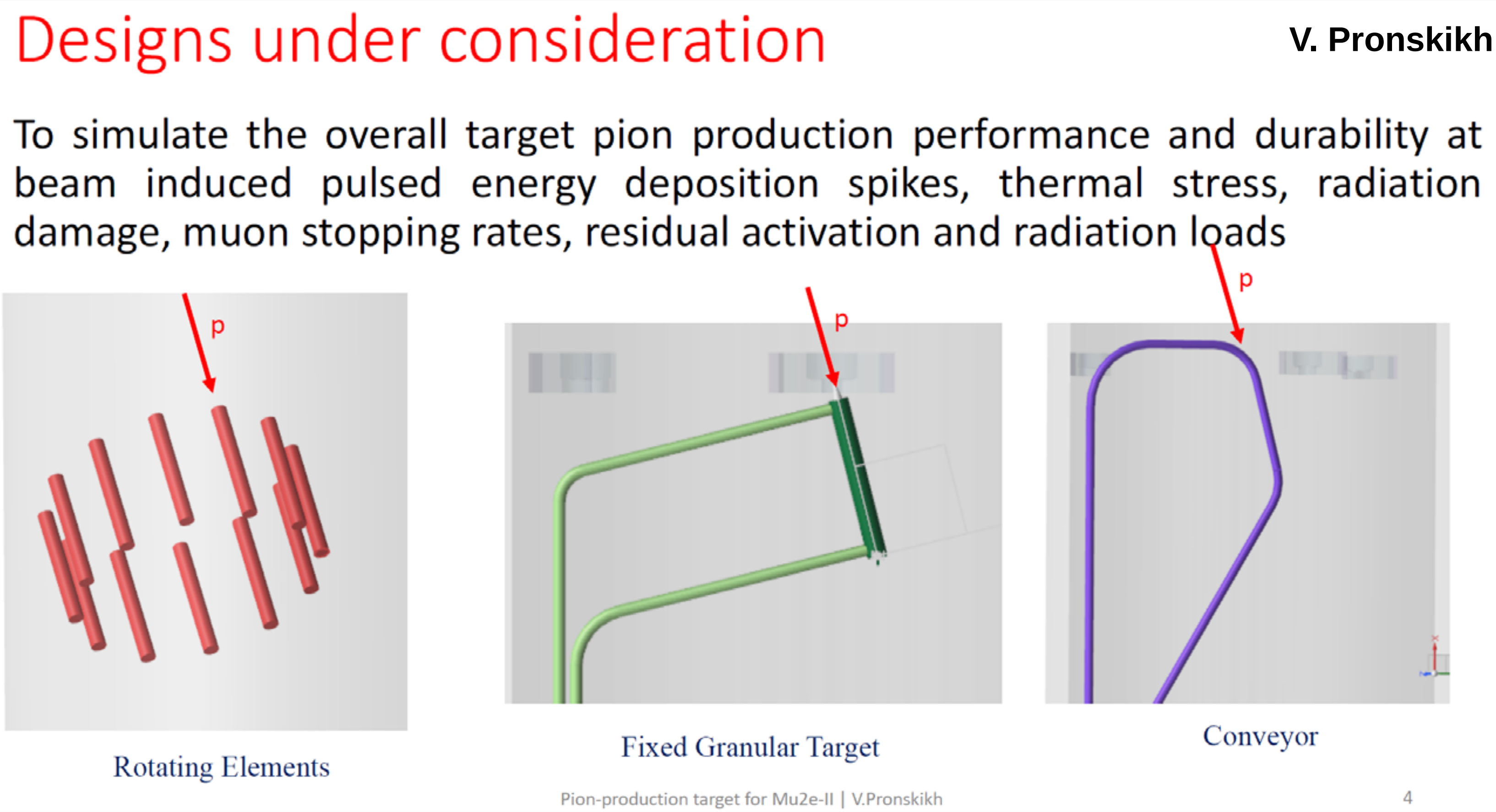
- Preliminary design for compressor ring, but need R&D to increase power
- **R&D for MW target in solenoid (synergies with MUC / NF)**
- Adapt FFA design from PRISM group, interface with compressor ring
- Explore potential design for detector (Mu2e/COMET, something else?)
- Set requirements for performance and background rejection

And many other efforts, including

- Pion-production target design for Mu2e-II (FNAL LDRD)

Opportunities for synergistic activities

Design study of a pion-production target inside a solenoid for the 100-kW 800-MeV proton beam (PIP II) for Mu2e-II



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

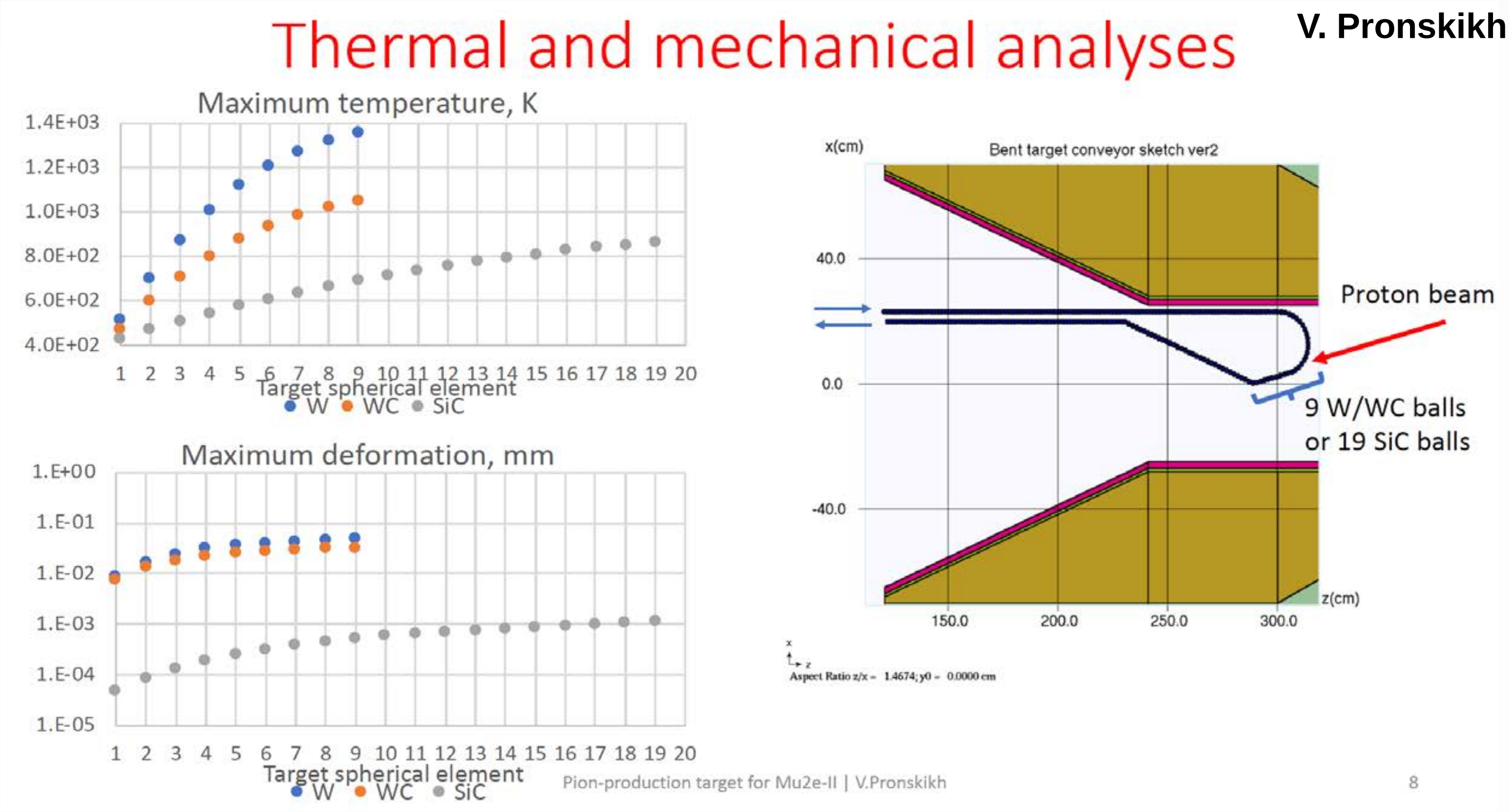
Conveyor

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

1st Muon Community Meeting, https://indico.cern.ch/event/1030726/contributions/4370902/attachments/2247841/3812745/Mu2e-II_CERN__052021_VP.pdf

Design study of a pion-production target inside a solenoid for the 100-kW 800-MeV proton beam (PIP II) for Mu2e-II

V. Pronskikh



Thermal and mechanical analyses

Pion-production target for Mu2e-II | V.Pronskikh 8

1st Muon Community Meeting, https://indico.cern.ch/event/1030726/contributions/4370902/attachments/2247841/3812745/Mu2e-II_CERN__052021_VP.pdf

Need substantial R&D effort to reach MW level !!!

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 (especially target development), and could be part of a comprehensive muon program

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 to pursue further design studies

It might be the right time to start exploring synergies (e.g. Muon collider workshop a few weeks ago). Feel free to contact us to start the discussion!

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

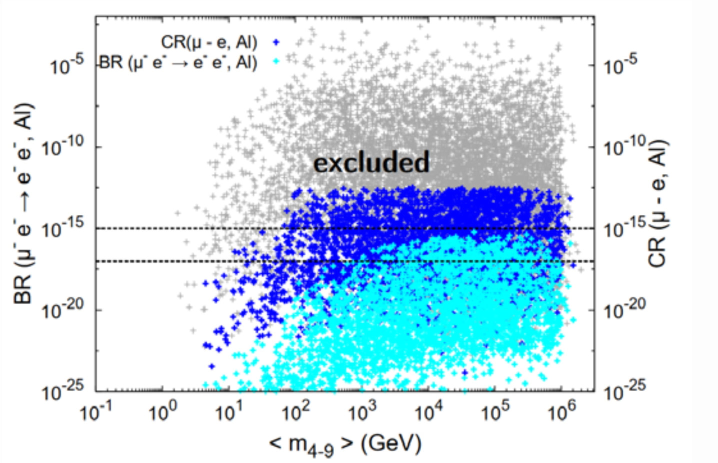
CLFV and neutrino mass

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

- distinct new states realized at different scales

Low scale Seesaw: inverse seesaw

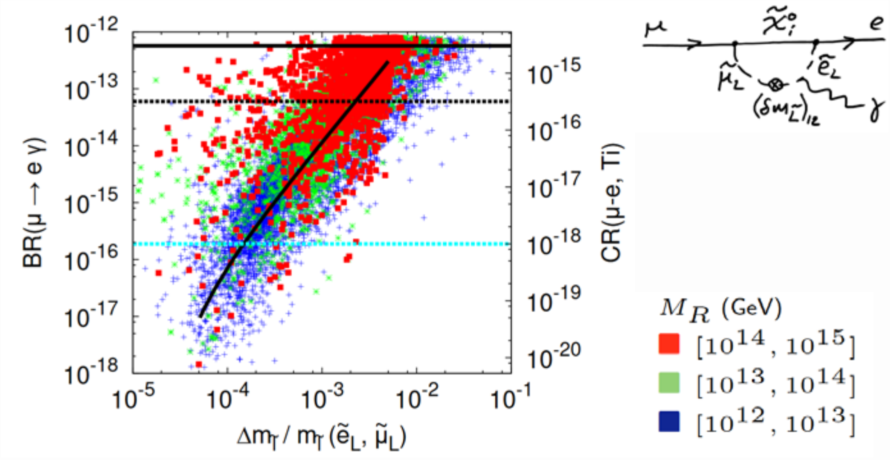
Addition of 3 “heavy” RH neutrinos and 3 extra “sterile” fermions to SM



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

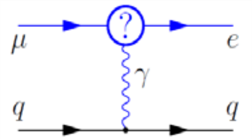
Non Standard Interactions might also impact neutrino oscillations

Simplified Lagrangian

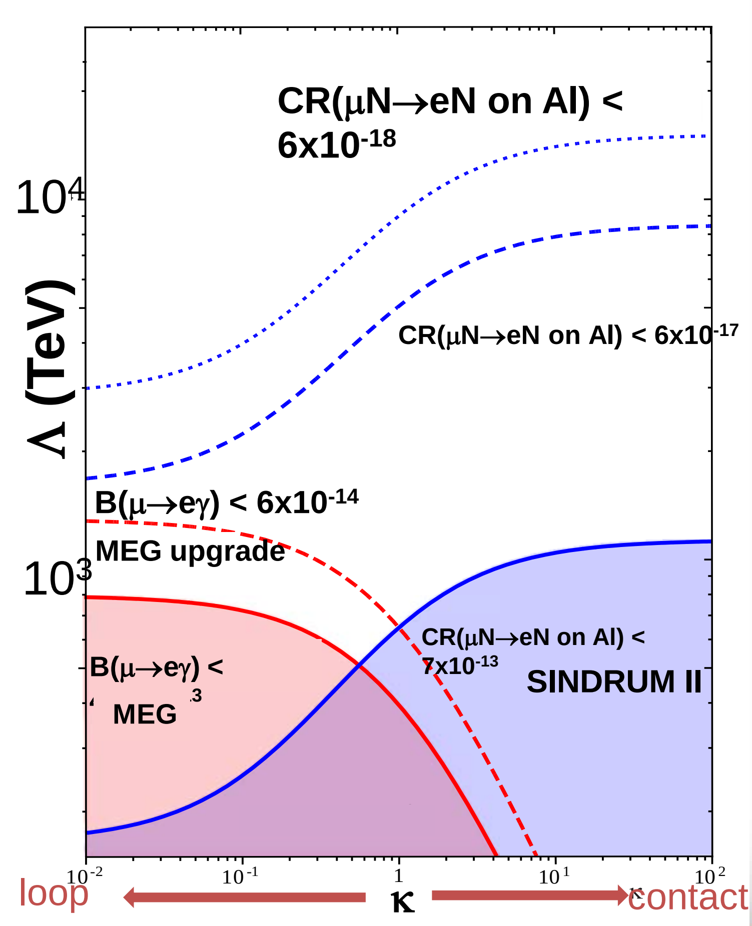
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

L: effective mass scale of new physics   k: relative contribution of the contact term

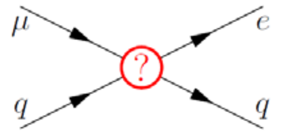
"Dipole term"



Contributes to $\mu \to e\gamma$



"Contact term"



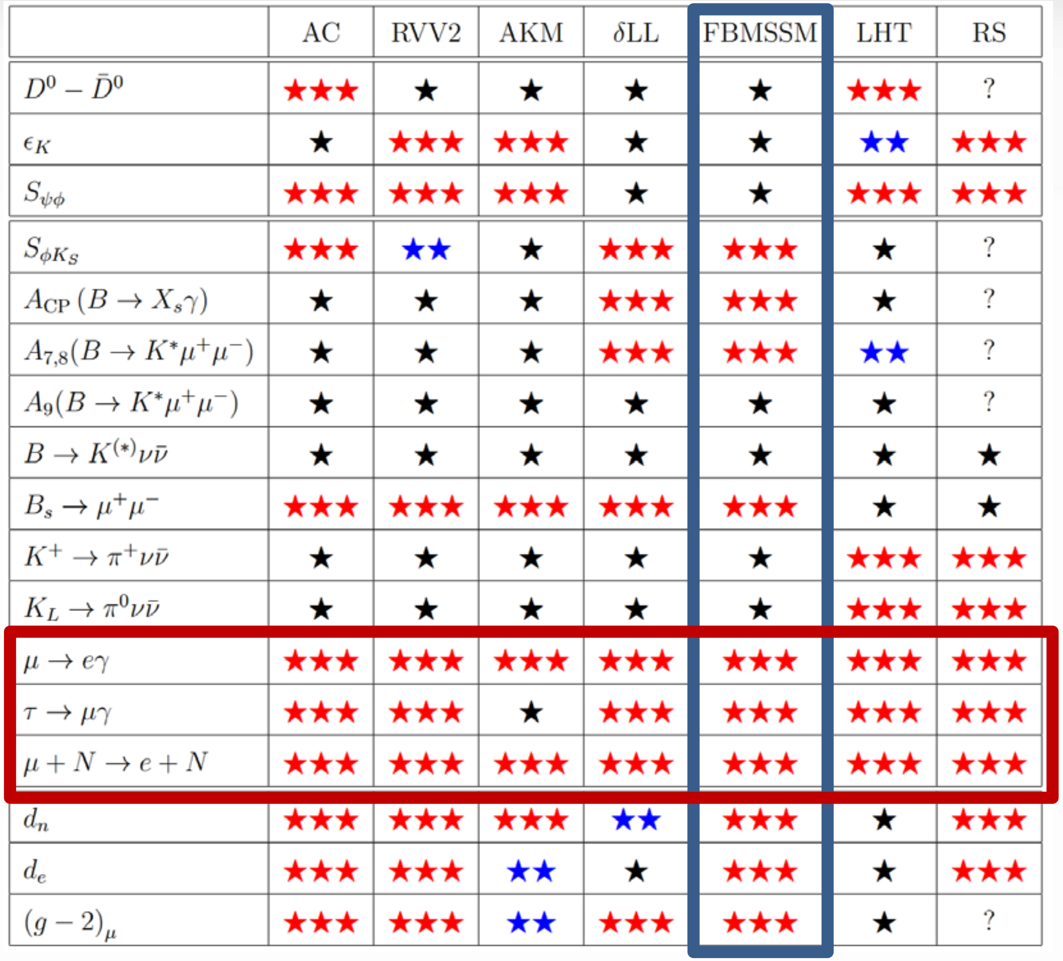
No contribution to $\mu \to e\gamma$

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	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
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

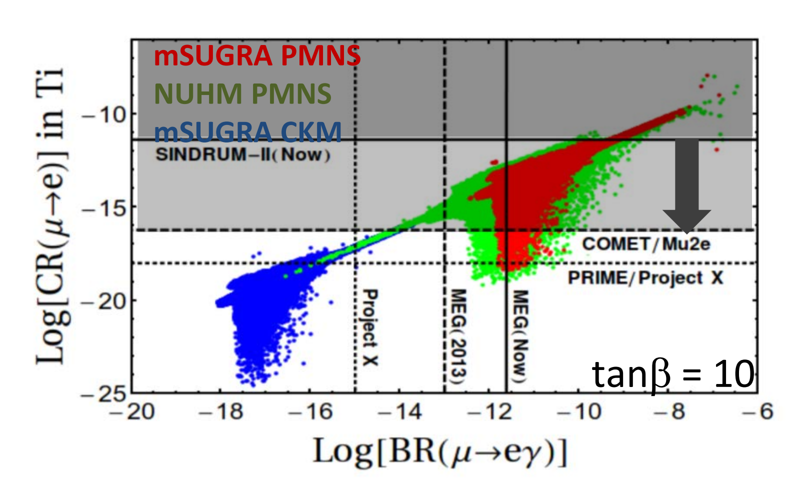
Glossary

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)

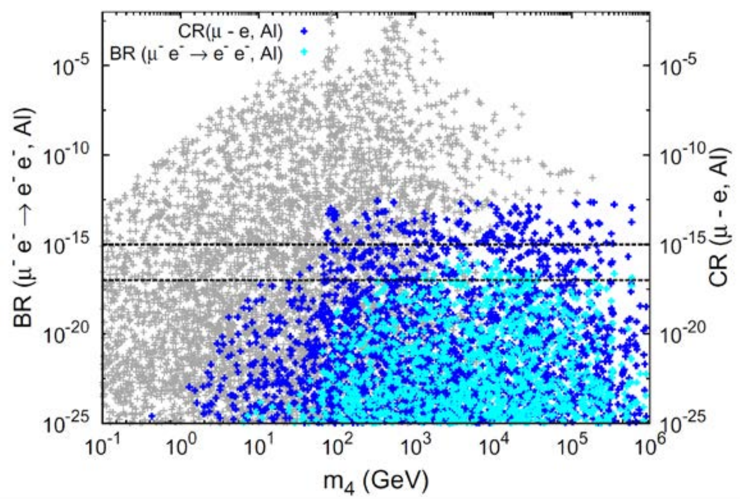
Model discrimination

SUSY GUT



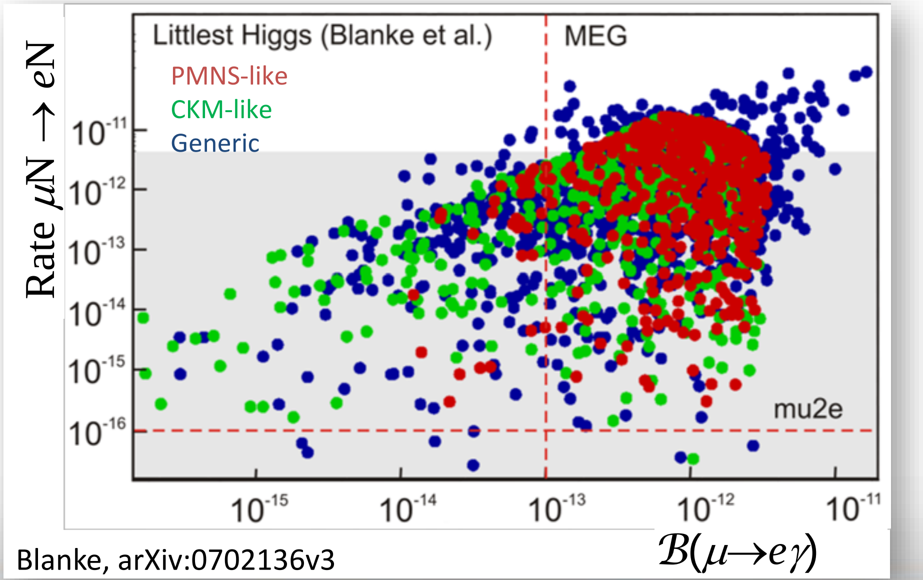
L. Calibbi et al., JHEP 1211 (2012) 040

Sterile neutrino model

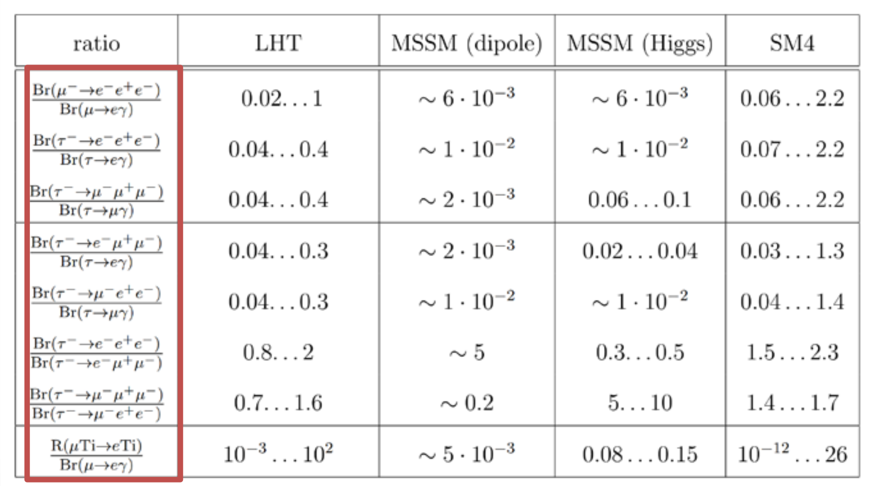


Teixeira et al., JHEP02 (2016) 083

LITTLEST HIGGS



Blanke, arXiv:0702136v3



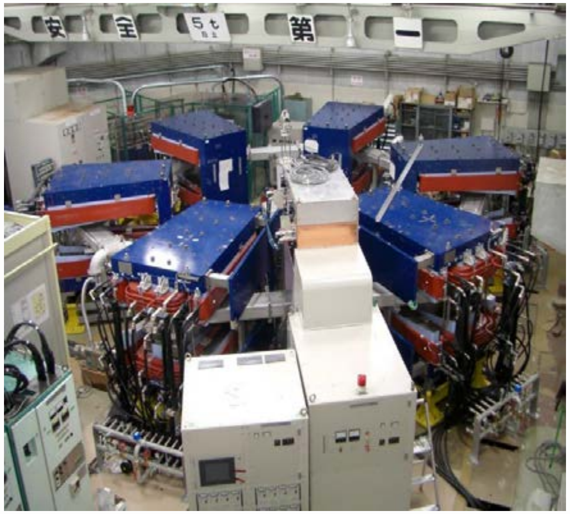
ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{Br(\tau^-\to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

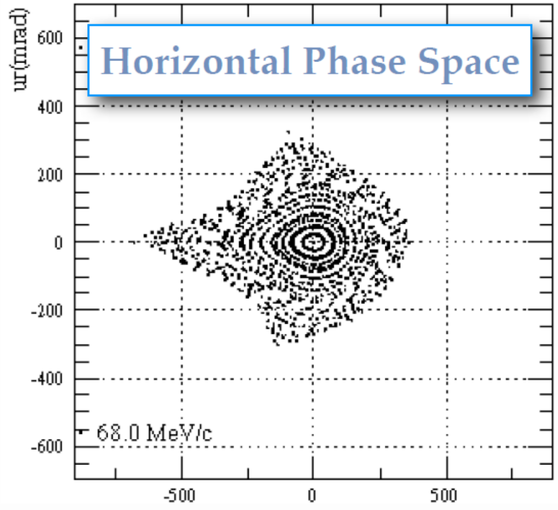
Buras, Duling, Feldmann, Heidsieck, Promberger, 1006.5356

FFA – R&D work in Osaka (MUSIC)

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