Charged Lepton Flavor Violation and the new Mu2e and COMET experiments

Bertrand Echenard - Caltech

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Introduction

Charged lepton flavor violating (CLFV) processes are reactions involving e, μ and τ lepton states that don't conserve lepton family number(s).

- CLF conserving reaction: $\mu \rightarrow e \nu_\mu \bar{\nu}_e$
- CLF violating reaction:
 - $\mu \rightarrow e$
 - $\tau \rightarrow \mu \mu \mu$
 - $K_L \rightarrow \mu e$
 - $H \rightarrow \tau \mu$
 - ...

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CLFV are very sensitive and generic probes of new physics, exploring the underlying symmetries, and more generally the physics of flavor and families

Complementary to other searches at low- and high-energies

Exciting new initiatives searching for mu-e conversion: COMET and Mu2e

Family number: not a fundamental symmetry

Family number is not a fundamental symmetry of the SM.

We know that quark family number is violated in weak decays

mixing strength encoded in CKM matrix

We observed neutrino mixing, which implies neutral lepton flavor violation, and evidence for BSM physics

mixing parameters encoded in PMNS matrix

What about charged leptons?

Strictly speaking, CLFV is forbidden in the SM, since charged lepton number is accidentally conserved when neutrinos are massless.

But...

CLFV and BSM physics

CLFV can be generated at least at loop level with massive neutrinos:

these processes are extremely suppressed in the SM, due to GIM mechanism and tiny neutrino masses. For example:

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

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

Effectively zero in the SM – background free !!!

By comparison, this mechanism is much less efficient in the quark sector

$$\text{Br}(b \rightarrow s\gamma) \simeq \frac{6\alpha}{\pi} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} f(m_t/m_W, \alpha_S) \right|^2 \xrightarrow{\text{NNLO QCD}} (3.36 \pm 0.23) \times 10^{-4}$$

A. Zupan Asatrian et al., 1503.01789

Observation of CLFV is an unambiguous sign of BSM physics

CLFV and BSM physics

Many BSM scenarios predict observable CLFV rates.

A measurement only provide indirect information, you don't directly observe the new particle(s).

Need multiple measurements to pinpoint the BSM physics and extract the CLFV couplings (the Yukawas)

Model discrimination

SUSY GUT

Sterile neutrino model

LITTLEST HIGGS

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\text{Br}(\mu^- \rightarrow e^- e^+ e^-)}{\text{Br}(\mu \rightarrow e \gamma)}$	0.02 ... 1	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$	0.06 ... 2.2
$\frac{\text{Br}(\tau^- \rightarrow e^- e^+ e^-)}{\text{Br}(\tau \rightarrow e \gamma)}$	0.04 ... 0.4	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	0.07 ... 2.2
$\frac{\text{Br}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{\text{Br}(\tau \rightarrow \mu \gamma)}$	0.04 ... 0.4	$\sim 2 \cdot 10^{-3}$	0.06 ... 0.1	0.06 ... 2.2
$\frac{\text{Br}(\tau^- \rightarrow e^- \mu^+ \mu^-)}{\text{Br}(\tau \rightarrow e \gamma)}$	0.04 ... 0.3	$\sim 2 \cdot 10^{-3}$	0.02 ... 0.04	0.03 ... 1.3
$\frac{\text{Br}(\tau^- \rightarrow \mu^- e^+ e^-)}{\text{Br}(\tau \rightarrow \mu \gamma)}$	0.04 ... 0.3	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	0.04 ... 1.4
$\frac{\text{Br}(\tau^- \rightarrow e^- e^+ e^-)}{\text{Br}(\tau^- \rightarrow e^- \mu^+ \mu^-)}$	0.8 ... 2	~ 5	0.3 ... 0.5	1.5 ... 2.3
$\frac{\text{Br}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{\text{Br}(\tau^- \rightarrow \mu^- e^+ e^-)}$	0.7 ... 1.6	~ 0.2	5 ... 10	1.4 ... 1.7
$\frac{\text{R}(\mu \text{Ti} \rightarrow e \text{Ti})}{\text{Br}(\mu \rightarrow e \gamma)}$	$10^{-3} \dots 10^2$	$\sim 5 \cdot 10^{-3}$	0.08 ... 0.15	$10^{-12} \dots 26$

Buras, Duling, Feldmann, Heidsieck, Promberger, 1006.5356

CLFV searches – a worldwide hunt

Worldwide effort to search for experimental signatures in many different channels.

Muon decays (MEG, Mu3e)

$$\mu \rightarrow e\gamma, \mu \rightarrow eee$$

Tau decays (Belle-II, LHCb)

$$\tau \rightarrow l\gamma, \tau \rightarrow ll, \tau \rightarrow lh$$

Muon Conversion (Mu2e, COMET)

$$\mu N \rightarrow eN$$

Meson decays (Belle-II, LHCb, J-PARC, CERN,...)

$$e.g. K, \phi, \dots, B \rightarrow ll'$$

Higgs, SUSY,... (LHC)

$$Z, Z', H \rightarrow ll'$$

$$H \rightarrow e, \mu, \tau + X$$

Some reviews:

Calibi and Signorelli, arxiv: 1709.00294

Bernstein and Cooper, arxiv:1307.5787

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

Current and future sensitivities

Process	Current Limit	Next Generation exp
$\tau \rightarrow e\gamma$	$\text{BR} < 3.3 \times 10^{-8}$	$10^{-9} - 10^{-10}$ (Belle II)
$\tau \rightarrow \mu\gamma$	$\text{BR} < 4.4 \times 10^{-8}$	
$\tau \rightarrow \mu\mu\mu$	$\text{BR} < 2.1 \times 10^{-8}$	
$\tau \rightarrow eee$	$\text{BR} < 2.7 \times 10^{-8}$	
$K_L \rightarrow e\mu$	$\text{BR} < 4.7 \times 10^{-12}$	
$K^+ \rightarrow \pi^+ e^- \mu^+$	$\text{BR} < 1.3 \times 10^{-11}$	
$B^0 \rightarrow e\mu$	$\text{BR} < 2.8 \times 10^{-9}$	LHCb / Belle II
$B^+ \rightarrow K^+ e\mu$	$\text{BR} < 3.8 \times 10^{-8}$	LHCb / Belle II
$\mu^+ \rightarrow e^+ \gamma$	$\text{BR} < 4.2 \times 10^{-13}$	10^{-14} (MEG)
$\mu^+ \rightarrow e^+ e^+ e^-$	$\text{BR} < 1.0 \times 10^{-12}$	10^{-16} (PSI)
$\mu N \rightarrow e N$	$R_{\mu e} < 7.0 \times 10^{-13}$	10^{-17} (Mu2e, COMET)

New physics effects could be larger for taus than muons, but colliders produce $O(10^{10})$ τ /year, while dedicated muon experiments can produce $O(10^{10})$ μ /s.

I'll now focus on CLFV in the muon sector

Already a long history...

There have been many searches for CLFV in muon decays

Muon an independent lepton, no $\mu \rightarrow e\gamma$

$\mu \rightarrow e\gamma \sim 10^{-4}/10^{-5}$ or two ν
Feinberg (1958)

No $\mu \rightarrow e\gamma \Leftrightarrow$ Two neutrinos!

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

New experimental initiatives will improve upon current limits on $\mu N \rightarrow eN$ conversion by four orders of magnitude !

Possible contributions to mu-e conversion

A wide array of BSM physics induce $\mu N \rightarrow e N$ conversion, either through loops or exchange of heavy intermediate particles

Loops

Supersymmetry

Heavy neutrino

Two Higgs doublet

Contact
interaction

Leptoquarks

Compositeness

New heavy bosons / anomalous coupling

Generic parametrization of CLFV process

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

Λ : effective mass scale of new physics κ : relative contribution of the contact term

“Dipole term”

Contributes to
 $\mu \rightarrow e\gamma$

“Contact term”

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

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

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

Different BSM scenarios predict
different value of $\kappa \rightarrow$ model
diagnosis

MUON-TO-ELECTRON CONVERSION

Experimental concept

Muon-to-electron conversion experiments

Search for neutrinoless muon-to-electron conversion

Measure ratio of signal to all muon captures

Signal is mono-energetic electron and nothing else.

Electron energy is Z dependent, $E_e = 105 \text{ MeV}$ for N=Al

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z) \rightarrow e^- + N(A, Z))}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon captures})}$$

D. Hitlin

Currently four experiment in various stages of execution:

DeeMee at J-PARC

COMET at J-PARC*

Mu2e at FNAL*

PRISM/Prime

} Aim to achieve single event sensitivity $R_{\mu e} \sim 10^{-17}$

*Origins trace to MELC and MECO proposals

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Experimental concept to search for muon-to-electron conversion

- Produce beam of low-momentum muons by hitting protons on target:

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measure X rays spectrum to estimate the number of captures

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coherent process, the nucleus remains intact
- Signal is a mono-energetic electron

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

This sounds simple, but what happens most of the time...

Muonic atom decay

Nuclear capture (~61% for Al)

$$\mu N \rightarrow \nu_\mu N'^*$$

Could produce signal-like electron

Muon decay in orbit (~39% for Al)

$$\mu \rightarrow e \nu_\mu \bar{\nu}_e$$

See e.g. Czarnecki et al., Phys. Rev. D 84, 013006 (2011)

The Michel spectrum is distorted by the presence of the nucleus and the electron can be at the conversion energy if the neutrinos are almost at rest

And other backgrounds...

Prompt background

Particles produced in addition to the muons by primary protons which interact almost immediately when they hit the stopping target: pions, neutrons, antiprotons.

- Radiative pion capture (RPC)

$$\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$$

$$\pi^- N \rightarrow e^+ e^- N'$$

- Pion/muon decays in flight

Other background

- Antiprotons producing pions when annihilating in the target
- Cosmic rays induced,...

Need to control the backgrounds extremely well !!!

Key elements for success

Pulse muon beam

Pulse muon beam with a long interval between bunches to suppress prompt background

Prompt background decreases rapidly and becomes negligible in the search window - must suppress out-of-time proton by $O(10^{10})$

Muonic atom lifetime large enough to have good signal efficiency

Capture solenoids*

Place production target inside magnetic field to trap more pions

Large number of muons with reasonable beam current

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

MUON-TO-ELECTRON CONVERSION

New experiments

New experimental efforts

Mu2e at FNAL

Over 200 scientists
37 institutions,
5 countries

COMET at JPARC

Over 150 collaborators
33 institutes,
15 countries

Mu2e experiment - overview

Production Target / Solenoid (PS)

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

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- Antiproton absorber
- The S shape eliminates photons and neutrons

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Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field “reflects” conversion electrons, improving efficiency

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- Proton beam strikes target, producing mostly pions
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REPEAT

- next proton bunch 1695 ns later

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- Antiproton absorber
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Target, Detector and Solenoid (DS)

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Mu2e experiment - tracker

The tracker is designed to measure the momentum of charged particles with high precision and ensure operability in a high background environment.

Since track radius is proportional to energy, design the tracker to only detect tracks with large enough radii.

Low-mass, annular tracker made of straw panels

Excellent rate capabilities and resolution ($\sigma_p/p < 180$ keV/c at 105 MeV/c)

Mu2e experiment - expected sensitivity

3 years running period with 1.2×10^{20} protons on target per year

Estimated background

Process	Expected event yield
Cosmic rays	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
DIO	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

Reconstructed e^- momentum

Bottom line:

Almost background free:
Single event sensitivity:

background < 0.5 event
 $R_{\mu e} = 3 \times 10^{-17}$

COMET experiment - Phase I

Production target

Proton beam produces pions by striking target
Pions captured by high solenoidal magnetic field

Transport section

Pion decays to muon
Momentum and charge selection

Stopping target and detector

Muon stops into target
Detector to search for mu-to-e conversion

COMET experiment - Phase I

Transport solenoid

Central detector

COMET experiment - Phase II

COMET – expected sensitivity

Estimated sensitivity for Phase I for 150 days of running

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
Delayed Beam	Neutrons	$\sim 10^{-9}$
	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays [†]	< 0.01
Total		0.032

[†] This estimate is currently limited by computing resources.

Single event sensitivity:

Phase I : $R_{\mu e} \sim 3 \times 10^{-15}$ for 150 days of data taking

Phase II : $R_{\mu e} \sim 2 \times 10^{-17}$ for 2-3 years of running

Schedule

COMET Schedule

Mu2e Schedule

**COMET and Mu2e
will start taking data
in the coming years**

What's next

Z dependence of μ -to- e conversion

Study underlying BSM physics with different targets if signal is seen

PIP2 is a superconducting linac for LBNF and the muon campus at FNAL

- 800 MeV, 100s kW available for muon campus
- Currently under design

Mu2e II, active study of Mu2e upgrade

- Order of magnitude increase in muon stops with a modest increase in instantaneous rate
- Beamline and detector upgrade
- Improve sensitivity by an order of magnitude
- Presented to Fermilab PAC 2018

PRISM / PRIME

Phase Rotated Intense Slow Muon source

PRISM Muon Electron conversion

A muon storage ring (FFAG),
feeding a COMET-like detector

Very high muon intensity 10^{11} - 10^{12} μ^- /s

Low momentum, quasi-mono-energetic muons

Very low pion contamination $< 10^{-18}$

Aims for a single event sensitivity at the level of 10^{-19}

Timescale > 2030

CLFV processes:

Generic and powerful probes of BSM physics, touching on the question of flavor and families.

Reach mass scales far beyond the direct production of new particles at the current colliders.

Existing searches already provide useful constraints, and new experiments will explore the regime predicted by many BSM physics.

Analysis of correlations between measurements provide model diagnosis.

Tremendous improvements in several channels is expected over the next decade, e.g. μ - e conversion sensitivity increased by four orders of magnitude.

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THANK YOU FOR YOUR ATTENTION

EXTRA MATERIAL

Higgs mediated CLFV decays

Bounds on CLFV couplings to the Higgs are derived from many measurements

$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

CLFV Higgs decay $\Gamma(h \rightarrow \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi} (|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2)$

$\tau \rightarrow \mu \gamma (\mu \rightarrow e \gamma)$

$\tau \rightarrow l' l l (\mu \rightarrow e e e)$

$\mu N \rightarrow e N$

$g-2$

CMS-HIG-14-005, PLB 749 (2015) 337

Channel	Coupling	Bound
$\mu \rightarrow e \gamma$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 3.6 \times 10^{-6}$
$\mu \rightarrow 3e$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	< 0.31
electron $g-2$	$\text{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \dots 0.026$
electron EDM	$ \text{Im}(Y_{e\mu} Y_{\mu e}) $	$< 9.8 \times 10^{-8}$
$\mu \rightarrow e$ conversion	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 4.6 \times 10^{-5}$
$M-\bar{M}$ oscillations	$ Y_{\mu e} + Y_{e\mu} $	< 0.079
$\tau \rightarrow e \gamma$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.014
$\tau \rightarrow e \mu \mu$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.66
electron $g-2$	$\text{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \dots 2.9] \times 10^{-3}$
electron EDM	$ \text{Im}(Y_{e\tau} Y_{\tau e}) $	$< 1.1 \times 10^{-8}$
$\tau \rightarrow \mu \gamma$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	$< 3.16 \times 10^{-3}$
$\tau \rightarrow 3\mu$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	< 0.52
muon $g-2$	$\text{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\text{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \dots 1.0$
$\mu \rightarrow e \gamma$	$(Y_{\mu\tau} Y_{\tau e} ^2 + Y_{\mu\tau} Y_{e\tau} ^2)^{1/4}$	$< 3.4 \times 10^{-4}$

CLFV physics reach

$$\mathcal{L}_{\text{CLFV}} = \frac{m_m}{(1+k)\Lambda^2} \bar{m}_k s_m e_L F^{mm} + \frac{k}{(1+k)\Lambda^2} \bar{m}_L g_m e_L (\bar{e}_L g_m e_L) + h.c.$$

CLFV tau decays

Current best limits – SINDRUM II at PSI

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

SINDRUM II at PSI

Final results on Au:

$$R_{\mu e} < 7 \times 10^{-13} \text{ @ 90\% CL}$$

Timing cut shows the contribution of prompt background (0.3 ns muon pulse separated by 20 ns)

One candidate event past the end of the spectrum. Pion capture, cosmic ray?

Mu2e experiment – inside a microbunch

Particles produced in an event, integrated over a window of 500 – 1695 ns after the protons hit the primary target

Pattern recognition

A window of ± 50 ns around a potential signal candidate

Fermilab accelerator complex

Fermilab ideally suited for Mu2e

Booster: batch of 4×10^{12} protons every $1/15^{\text{th}}$ second

Booster “batch” is injected into the Recycler ring and rebunched into 4 bunches

These are extracted one at a time to the Debuncher ring

Protons are extracted into bunches of $\sim 3 \times 10^7$ protons each, separated by $1.7 \mu\text{s}$ (debuncher ring period)

Achieve an extinction:
#protons out of bunches/#proton in bunch $\sim 10^{-10}$ or better

Pulse structure: width $\ll \tau_{\mu}(\text{Al})$ with separation $\sim 2 \times \tau_{\mu}(\text{Al})$

Search for $\mu \rightarrow e$ 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: $1.2 \times 10^{-13} \rightarrow 2.1 \times 10^{-14}$ upgrade

4 years: $2.5 \times 10^{-14} \rightarrow 5 \times 10^{-15}$ upgrade