Pulsed Muon Beam Experiments

Yoshitaka Kuno
Department of Physics,
Osaka University, Japan

August 28th 2019
NuFACT2019,
Daegu, Korea
Introduction

Muon particle physics experiments and Beam time structure
Muon particle physics experiments and Beam time structure

Pulsed muon beam

for the experiments of

- delayed measurements
  (\(\mu \rightarrow e\) conversion)
- with storage ring and acceleration (muon g-2)
- with pulsed instruments
  (laser)
  - proton synchrotron
    (J-PARC, FNAL, RAL)
Introduction

Muon particle physics experiments and Beam time structure

Pulsed muon beam

for the experiments of
- delayed measurements ($\mu \rightarrow e$ conversion)
- with storage ring and acceleration (muon g-2)
- with pulsed instruments (laser)
- proton synchrotron (J-PARC, FNAL, RAL)

DC muon beam

for the experiments of
- coincidence measurements with low instantaneous intensity ($\mu \rightarrow e\gamma$, $\mu \rightarrow eee$)
- proton cyclotron (PSI, TRIUMF, MuSIC)
Introduction: World Map

DC muon beam experiments
pulsed muon beam experiments
Introduction: World Map

Fermilab

g-2 (E989)

Mu2e

DC muon beam experiments
pulsed muon beam experiments
Introduction: World Map

Fermilab

g-2 (E989)
Mu2e

PSI
MEG II
Mu3e
CREMA
MUSE
MuMASS
more

DC muon beam experiments
pulsed muon beam experiments
Introduction: World Map

Fermilab
- g-2 (E989)
- Mu2e

PSI
- MEG II
- Mu3e
- CREMA
- MUSE
- MuMASS
- more

J-PARC
- COMET
- DeeMe
- g-2/edm
- Museum

DC muon beam experiments
pulsed muon beam experiments
Outline

• Charged Lepton Flavour Violation (CLFV) with Muons
  • Physics Motivation
  • $\mu^- \rightarrow e^-$ conversion
  • $\mu^+ \rightarrow e^+ \gamma$, $\mu^+ \rightarrow e^+ e^+ e^-$ (just brief)
• Muon $g$-2
• Summary
Outline

• Charged Lepton Flavour Violation (CLFV) with Muons
  • Physics Motivation
  • $\mu^- \rightarrow e^-$ conversion
  • $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$ (just brief)
• Muon g-2
• Summary

Details are given in the WG4 sessions.
Charged Lepton flavour Violation (CLFV) with Muons
Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.
Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.

$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_l (V_{MNS})_{\mu l}^* (V_{MNS})_{el} \frac{m_{\nu_l}^2}{M_W^2} \right|^2$$

Lepton Mixing in the SM to CLFV

Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.

\[ B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_l (V_{MNS})^*_{\mu l} (V_{MNS})_{e l} \frac{m_{\nu l}^2}{M_W^2} \right|^2 \]


\[ \text{BR} \sim O(10^{-54}) \]
Lepton Mixing in the SM to CLFV

Neutral lepton flavour violation has been observed. Lepton mixing in the SM has been established.

\[ B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_l (V_{MNS})^*_{\mu l} (V_{MNS})_{el} \frac{m^2_{\nu_l}}{M_W^2} \right|^2 \]


BR \sim O(10^{-54})

Large window for BSM search without SM backgrounds
New Physics Energy Scale of CLFV Search

Effective Field Theory (EFT) Approach

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}} \]

\( \Lambda \) is the energy scale of new physics

\( C^{(d)} \) is the coupling constant.
Effective Field Theory (EFT) Approach

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{C^{(d)}}{\Lambda^{d-4}} \]

\( \Lambda \) is the energy scale of new physics
\( C^{(d)} \) is the coupling constant.

from BR(\( \mu \rightarrow e\gamma \)<4.2x10\(^{-13} \)

\[ \frac{C^{6}}{\Lambda^{2}} \mathcal{O}^{6} \rightarrow \frac{C^{6}}{\Lambda^{2}} \bar{e}_{L} \sigma^{\rho\nu} \mu_{R} \Phi F_{\rho\nu} \]

\( \Lambda \sim \mathcal{O}(10^{4}) \text{ TeV} \)

c.f. \( \Delta m_{K}, \epsilon' \)

| \( C_{a} \) [\( \Lambda = 1 \text{ TeV} \)] | \( \Lambda \) (TeV) [\( |C_{a}| = 1 \)] | CLFV Process |
|-----------------|-----------------|----------------|
| \( C_{\mu e}^{\mu e} \) | \( 2.1 \times 10^{-10} \) | \( 6.8 \times 10^{4} \) | \( \mu \rightarrow e\gamma \) |
| \( C_{\mu e,\mu e e,\mu e}^{\mu e} \) | \( 1.8 \times 10^{-4} \) | \( 75 \) | \( \mu \rightarrow e\gamma \) [1-loop] |
| \( C_{\mu e,ee}^{\mu e} \) | \( 1.0 \times 10^{-5} \) | \( 312 \) | \( \mu \rightarrow e\gamma \) [1-loop] |
| \( C_{ee}^{e e} \) | \( 4.0 \times 10^{-9} \) | \( 1.6 \times 10^{4} \) | \( \mu \rightarrow eee \) |
| \( C_{ee,lee,ee}^{ee} \) | \( 2.3 \times 10^{-5} \) | \( 207 \) | \( \mu \rightarrow eee \) |
| \( C_{ee,lee,ee}^{ee} \) | \( 3.3 \times 10^{-5} \) | \( 174 \) | \( \mu \rightarrow eee \) |
| \( C_{ee,ee,ee}^{ee} \) | \( 5.2 \times 10^{-9} \) | \( 1.4 \times 10^{4} \) | \( \mu^{-}\text{Au} \rightarrow e^{-}\text{Au} \) |
| \( C_{\mu e,\nu_{\mu},\nu_{e},\nu_{e}}^{\mu e} \) | \( 1.8 \times 10^{-6} \) | \( 745 \) | \( \mu^{-}\text{Au} \rightarrow e^{-}\text{Au} \) |
| \( C_{ee,ee,ee}^{ee} \) | \( 9.2 \times 10^{-7} \) | \( 1.0 \times 10^{3} \) | \( \mu^{-}\text{Au} \rightarrow e^{-}\text{Au} \) |
| \( C_{e e,ee,ee}^{ee} \) | \( 2.0 \times 10^{-6} \) | \( 707 \) | \( \mu^{-}\text{Au} \rightarrow e^{-}\text{Au} \) |
Future planned CLFV experiments (with muons) expecting improvements by an additional factor of >10,000 or more (will be described later) would probe ....
Future planned CLFV experiments (with muons) expecting improvements by an additional factor of >10,000 or more (will be described later) would probe …. 

\[ \Lambda \sim \mathcal{O}(10^5) \text{ TeV} \]

It is crucial in establishing where is the next fundamental scale above the electroweak symmetry breaking.
“Golden” $\mu \rightarrow e$ CLFV Transition Processes

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^+ \rightarrow e^+e^+e^-$
- $\mu^-N \rightarrow e^-N$
“Golden” $\mu \rightarrow e$ CLFV Transition Processes

\[ \mu^+ \rightarrow e^+\gamma \]

\[ \mu^+ \rightarrow e^+e^+e^- \]

\[ \mu^-N \rightarrow e^-N \]
Some examples will be mentioned in section cients than the dipoles that can only be loop induced. Some examples will be mentioned in section cients of the operators in Table IV are in general not ects are encoded in a single operator. Although this can be approximately true of present and forecast limits on the coe cients. Such e cients of the operators in Table IV are in general not ects are encoded in a single operator. Although this can be approximately true of present and forecast limits on the coe observables is shown in Figure 5. supersymmetric frameworks that we will discuss in section (41) rates of (40) limit to the above observables at the 10 (41) For full calculations of the (40) limit to the above observables at the 10 order (41) with respect to (40) Therefore the MEG bound on BR(41) As a matter of fact, there are several new physics models where such operators arise at the source of CLFV is not the dipole operator (121), as it can be intuitively understood from Figure Conversion arising from a flavour-violating dipole operator and, conversely, to µe CLFV Transition Processes dipole interaction µ+ → e+γ contact interaction µ+ → e+e+e− μ−N → e−N
Some examples will be mentioned in section tree level, thus with much larger coefficients than the dipoles that can only be loop induced. The coefficients of the operators in Table IV are in general not independent due to radiative effects and supersymmetric frameworks that we will discuss in section tree level. Conversely, a measurement of the source of CLFV is not the dipole operator but rather arises from 4-fermion operators. This would rule out large classes of models, such as the typical contact interaction with respect to different nuclei, see [109, 122, 123].

\[ \mu^+ \rightarrow e^+ \gamma \]
\[ \mu^+ \rightarrow e^+ e^+ e^- \]
\[ \mu^- N \rightarrow e^- N \]
Some examples will be mentioned in section (ects. Such e-

cients than the dipoles that can only be loop induced. cients of the operators in Table IV are in general not

e in certain scenarios, yet the co-

rithms e

de

observables is shown in Figure 5. of present and forecast limits on the co-

ections – summarised by the renormalisation
ections. Such e-
cients than the dipoles that can only be loop induced.

cs – summarised by the renormalisation
ections. Therefore the MEG bound on BR($\mu \rightarrow e \gamma$)

cs – summarised by the renormalisation
ections. Therefore the MEG bound on BR($\mu \rightarrow e \gamma$)

Golden” $\mu \rightarrow e$ CLFV Transition Processes

dipole interaction

$\mu^+ \rightarrow e^+ \gamma$

$\mu^+ \rightarrow e^+ e^+ e^-$

$\mu^- N \rightarrow e^- N$

contact interaction

$e^- e^- e^- e^-$

$\mu^- e^- e^- e^-$

$\mu^- e^- e^- e^- e^-$

$\mu^- e^- e^- e^- e^- e^-$
Operator Mixing via RGE

EFT at high physics scale

The operators are mixed in RGE at the experiment scale

All processes are equally important (complementary).

A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, arXiv:1611.03409
A. Crivellin, S. Davidson, G.M. Pruna and A. Signer, JHEP 117 (2017) no.5
Model dependent CLFV

- SM + NHL (neutral heavy lepton)
- large extra dimensions
- extended Higgs sector
- additional vector boson (Z’)
- leptoquark
- SUSY-GUT and SUSY seesaw
- R-parity violating SUSY
- low-energy seesaw
- etc. etc.

Extra dimension model

SUSY-GUT

Little Higgs

SM+HNL
Model dependent CLFV

- SM + NHL (neutral heavy lepton)
- large extra dimensions
- extended Higgs sector
- additional vector boson (Z’)
- leptoquark
- SUSY-GUT and SUSY seesaw
- R-parity violating SUSY
- low-energy seesaw
- etc. etc.
$\mu \rightarrow e$ conversion in a muonic atom
What is $\mu \rightarrow e$ Conversion?

1s state in a muonic atom

$nucleus$

$\mu^-$

muon decay in orbit

$\mu^- \rightarrow e^- \nu \bar{\nu}$

nuclear muon capture

$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)$
What is $\mu \rightarrow e$ Conversion?

1s state in a muonic atom

- $\mu^-$ decay in orbit: $\mu^- \rightarrow e^- \nu \bar{\nu}$
- Nuclear muon capture: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)$

Neutrino-less muon nuclear capture

$$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$$

Coherent process: $\propto Z^5$

Event Signature:
a single mono-energetic electron of 105 MeV

$$\text{CR}(\mu^- N \rightarrow e^- N) \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \text{all})}$$
Backgrounds for μ-e conversion

intrinsic physics backgrounds

Muon decay in orbit (DIO)
Radiative muon capture (RMC)
Neutrons from muon nuclear capture
Protons from muon nuclear capture
## Backgrounds for μ-e conversion

<table>
<thead>
<tr>
<th>intrinsic physics backgrounds</th>
<th>beam-related backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon decay in orbit (DIO)</td>
<td>Radiative pion capture (RPC)</td>
</tr>
<tr>
<td>Radiative muon capture (RMC)</td>
<td>Beam electrons</td>
</tr>
<tr>
<td>neutrons from muon nuclear capture</td>
<td>Muon decay in flights</td>
</tr>
<tr>
<td>Protons from muon nuclear capture</td>
<td>Neutron background</td>
</tr>
</tbody>
</table>

Antiproton induced background
## Backgrounds for μ-e conversion

<table>
<thead>
<tr>
<th>Intrinsic Physics Backgrounds</th>
<th>Beam-Related Backgrounds</th>
<th>Cosmic-Ray and Other Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon decay in orbit (DIO)</td>
<td>Radiative pion capture (RPC)</td>
<td>Cosmic-ray induced background</td>
</tr>
<tr>
<td>Radiative muon capture (RMC)</td>
<td>Beam electrons</td>
<td>False tracking</td>
</tr>
<tr>
<td>Neutrons from muon nuclear capture</td>
<td>Muon decay in flights</td>
<td></td>
</tr>
<tr>
<td>Protons from muon nuclear capture</td>
<td>Neutron background</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Antiproton induced background</td>
<td></td>
</tr>
</tbody>
</table>
Current Limits on $\mu \rightarrow e$ Conversion

SINDRUM-II (PSI)

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>S</th>
<th>CR limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>sulfur</td>
<td>16</td>
<td>0</td>
<td>$7 \times 10^{-11}$</td>
</tr>
<tr>
<td>titanium</td>
<td>22</td>
<td>0,5/2,7/2</td>
<td>$4.3 \times 10^{-12}$</td>
</tr>
<tr>
<td>copper</td>
<td>39</td>
<td>3/2</td>
<td>$1.6 \times 10^{-8}$</td>
</tr>
<tr>
<td>gold</td>
<td>79</td>
<td>0,5/2</td>
<td>$7 \times 10^{-13}$</td>
</tr>
<tr>
<td>lead</td>
<td>82</td>
<td>0 (1/2)</td>
<td>$4.6 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
In order to make a new-generation experiment to search for $\mu$-e conversion ...

$$B(\mu N \rightarrow eN) \leq 10^{-16}$$
Highly Intense Muon Source

**pion capture in superconducting solenoids**

- proton target in a solenoidal field (~5T)
- a long proton target (1.5~2 interaction length) of heavy material

\[
\text{\(2 \times 10^{11}\) \(\mu^-/s\) for 56 kW protons}
\]

\[
\text{muon yield} > 1000 \text{ increase}
\]
Improvements for Background Rejection

Beam-related backgrounds
- Beam pulsing with separation of 1μsec
  - measured between beam pulses
  - proton extinction = #protons between pulses/#protons in a pulse < 10^{-10}

Muon DIO background
- low-mass trackers in vacuum & thin target
  - improve electron energy resolution

Muon DIF background
- curved solenoids for momentum selection
  - eliminate energetic muons (>75 MeV/c)

based on the MELC proposal at Moscow Meson Factory
Pulsed Muon Beam for $\mu$-e conversion

Selection windows turn on late, significantly reducing prompt backgrounds.

Requirements:
Proton extinction factor during pulses $< 10^{-10}$
J-PARC (MUSE@MLF)

Accelerator-driven Transmutation exp facility

Linac (330m, 400MeV)

3GeV Synchrotron (RCS) (350m ring, 25Hz, 1MW)

30GeV Synchrotron (MR) (1600m ring, 0.75MW)

Material/Life-Science Facility (MLF) (muon source, pulse neutron source)

Hadron Experiment Facility

Neutrino Experiment Facility (T2K, towards SK)
J-PARC (MUSE@MLF)

Linac (330m, 400MeV)
3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)
30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)

Hadron Experiment Facility

Neutrino Experiment Facility
(T2K, towards SK)

Muon beam @ Material Life-science Facility (MLF)

Four Secondary Beam-Lines
1. D-Line: Decay Surface Muon Beam Line
2. U-Line: Ultra Slow Muon Beam Line

D, U and S are in operation
H-Line is under construction and dedicated for High Energy Physics Experiment

Decay \( /e \) (<120MeV/c) and surface \( (30\text{MeV/c}) \)

H1 area for DeeMe & MuSEUM
H2 area for \( g-2/EDM \) and transmission muon microscopy
H2 needs extra-building to re-accelerate ultra slow muons up to 300 MeV/c

10^8 muons/s
J-PARC (MUSE@MLF)

Linac (330m, 400MeV)
3GeV Synchrotron (RCS) (350m ring, 25Hz, 1MW)
30GeV Synchrotron (MR) (1600m ring, 0.75MW)

Neutrino Experiment Facility (T2K, towards SK)

Accelerator-driven Transmutation exp facility
Material/Life-Science Facility (MLF) (muon source, pulse neutron source)

Hadron Experiment Facility

Muon beam @ Material Life-science Facility (MLF)

Four Secondary Beam-Lines
1. D-Line : Decay Surface Muon Beam Line
2. U-Line : Ultra Slow Muon Beam Line

D, U and S are in operation
H-Line is under construction and dedicated for High Energy Physics Experiment
Decay !/e (<120MeV/c) and surface !/(30MeV/c)
H1 area for DeeMe & MuSEUM
H2 area for g-2/EDM and transmission muon microscopy
H2 needs extra-building to re-accelerate ultra slow muons up to 300 MeV/c
DeeMe (Direct emission of electron from Muon to electron conversion)

DeeMe at J-PARC MLF

3 GeV J-PARC RCS protons
- beamline and spectrometer to select 100 MeV e-
- 4 MWPCs with $\Delta p=0.5$ MeV

with carbon target
CR<$1 \times 10^{-13}$ (1 year)
with SiC target
CR<$3 \times 10^{-14}$ (1 year)
DeeMe (Direct emission of electron from Muon to electron conversion)

DeeMe at J-PARC MLF

3 GeV J-PARC RCS protons
- beamline and spectrometer to select 100 MeV e⁻
- 4 MWPCs with Δp=0.5 MeV

N. Teshima on Thursday
J-PARC (COMET@Main Ring)

Linac
(330m, 400MeV)

3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)

30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)

Neutrino Experiment Facility
(T2K, towards SK)

Hadron Experiment Facility

Accelerator-driven
Transmutation exp facility
J-PARC (COMET@Main Ring)

Accelerator-driven Transmutation exp facility

Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)

Hadron Experiment Facility

3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)

30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

Neutrino Experiment Facility (T2K, towards SK)

Accelerator-driven
Transmutation exp facility

2x10^{11} muons/s from 56 kW

Phase II Geometry
COMET = COherent Muon to Electron Transition

COMET Phase-I : J-PARC E21

Phase-I
proton beam power = 3.2 kW

Single event sensitivity : $2 \times 10^{-15}$
a factor of 100 improvement
Running time: 0.4 years ($1.2 \times 10^7$ s)
Phase-II
proton beam power = 56 kW

Single event sensitivity : $2.6 \times 10^{-17}$
a factor of 10,000 improvement
Running time: 1 years ($2 \times 10^7$ sec)
**COMET Phase-II : J-PARC E21**

Phase-II

proton beam power = 56 kW

Single event sensitivity : $2.6 \times 10^{-17}$

a factor of 10,000 improvement

Running time: 1 years ($2 \times 10^7$ sec)

---

proton beam

---

Single event sensitivity : $\mathcal{O}(10^{-18})$

a factor of 100,000 improvement

Running time: 1 years ($2 \times 10^7$ sec)

COMET collaboration, arXiv:1812.07824, 2018
COMET Phase-II : J-PARC E21

Phase-II
proton beam power = 56 kW

Single event sensitivity : $2.6 \times 10^{-17}$
a factor of 10,000 improvement
Running time: 1 years ($2 \times 10^7$sec)

Single event sensitivity : $O(10^{-18})$
a factor of 100,000 improvement
Running time: 1 years ($2 \times 10^7$sec)
COMET collaboration, arXiv:1812.07824, 2018

T. Xing on Thursday
COMET Phase-I: Preparation

Transportation solenoid
Finished in 2015

High-p

B line in Jan 2018
To be finished in 2019

Winding of CS

Inside the experimental hall

Prototype for stopping target

Detector solenoid

CRV design fixed

The Mu2e experiment
Muon to electron conversion at Fermilab
Andrei Gaponenko
Fermilab
CIPANP-2012
http://mu2e.fnal.gov
The Mu2e experiment
Muon to electron conversion at Fermilab
Andrei Gaponenko
Fermilab
CIPANP-2012
http://mu2e.fnal.gov

6x10^{10} muons/s from 8 kW
Mu2e at Fermilab

A search for Charged Lepton Flavor Violation: $\mu N \rightarrow eN$
- Expected sensitivity of $6 \times 10^{-17}$ @ 90% CL, x10,000 better than SINDRUM-II
- Probes effective new physics mass scales up to $10^4$ TeV/c$^2$
- Discovery sensitivity to broad swath of NP parameter space

Experiment scope includes
- Proton Beam line
- Solenoid systems
- Detector elements
  (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
- Experimental hall
- Commissioning begins in 2022
Mu2e at Fermilab

A search for Charged Lepton Flavor Violation: $\mu N \rightarrow eN$

- Expected sensitivity of $6 \times 10^{-17}$ @ 90% CL, $x10,000$ better than SINDRUM-II
- Probes effective new physics mass scales up to $10^4$ TeV/c$^2$
- Discovery sensitivity to broad swath of NP parameter space

Experiment scope includes

- Proton Beam line
- Solenoid systems
- Detector elements (tracker, calorimeter, cosmic veto, DAQ, beam monitoring)
- Experimental hall
- Commissioning begins in 2022

R. Bonventre on Thursday
Mu2e at Fermilab

Completed:
- 75 km of superconductor
- 30 km of extruded scintillator
- 25 km of aluminized mylar straws
Mu2e at Fermilab

Progress across sub-systems:

- 68% of Calorimeter CsI crystals received & tested
- 37% of Cosmic Veto di-counters built & tested
- 75% of pre-production Tracker panels built & tested
- Delivery Ring installed and working
- M4 Beam line installation in progress

Transport Solenoid: Testing & assembly in progress!

Production Solenoid - coil windings have begun for the first coil!
Mu2e-II - a next generation $\mu \rightarrow e$ conversion experiment at FNAL

Mu2e-II is an upgrade that will:

- Use $\approx 100$ kW of PIP-II protons @800 MeV
- Achieve an order of magnitude improvement in sensitivity
  - probe $R_{\mu e} \sim 10^{-18}$ level,
  - extend $\Lambda_{NP}$ reach by $x2$

EOI Submitted to Fermilab PAC in 2018
130 Signatories, 36 Institutions

PAC: “physics case is compelling” “endorse request for R&D funding”

Status: Pursuing high priority R&D. Data taking $\sim 2030$ timescale.
Mu2e-II is an upgrade that will:

- Use \( \sim 100 \text{ kW} \) of PIP-II protons @800 MeV
- Achieve an order of magnitude improvement in sensitivity
  - probe \( R_{\mu e} \sim 10^{-18} \) level,
  - extend \( \Lambda_{NP} \) reach by x2

- EOI Submitted to Fermilab PAC in 2018
- 130 Signatories, 36 Institutions

PAC: “physics case is compelling” “endorse request for R&D funding”

Status: Pursuing high priority R&D. Data taking ~2030 timescale.

I. Oksuzian on Thursday
If found …
Effective Field Theory for \( \mu \rightarrow e \) Conversion

two-lepton and two-nucleon operators and dipole operators

\[
\mathcal{L}_{\mu A \rightarrow e A}(\Lambda_{\text{expt}}) = -\frac{4G_F}{\sqrt{2}} \sum_{N=p,n} \left[ m_\mu \left( C_{DL} \bar{e}_R \sigma^{\alpha\beta} \mu_L F_{\alpha\beta} + C_{DR} \bar{e}_L \sigma^{\alpha\beta} \mu_R F_{\alpha\beta} \right) \right]
\]

- **scalar**
  \[
  \text{dipole} + \left( \tilde{C}_{SL}^{(NN)} \bar{e}_P \mu_L + \tilde{C}_{SR}^{(NN)} \bar{e}_P \mu_R \right) \bar{N} N
  \]

- **pseudo-scalar**
  \[
  \text{dipole} + \left( \tilde{C}_{PL}^{(NN)} \bar{e}_P \mu_L + \tilde{C}_{PR}^{(NN)} \bar{e}_P \mu_R \right) \bar{N} \gamma_5 N
  \]

- **vector**
  \[
  \text{dipole} + \left( \tilde{C}_{VL}^{(NN)} \bar{e}_P \gamma^\alpha \mu_L + \tilde{C}_{VR}^{(NN)} \bar{e}_P \gamma^\alpha \mu_R \right) \bar{N} \gamma_\alpha N
  \]

- **axial-vector**
  \[
  \text{dipole} + \left( \tilde{C}_{AL}^{(NN)} \bar{e}_P \gamma^\alpha \mu_L + \tilde{C}_{AR}^{(NN)} \bar{e}_P \gamma^\alpha \mu_R \right) \bar{N} \gamma_\alpha \gamma_5 N
  \]

- **(derivative)**
  \[
  \text{dipole} + \left( \tilde{C}_{DL}^{(NN)} \bar{e}_P \gamma^\alpha \mu_L + \tilde{C}_{DR}^{(NN)} \bar{e}_P \gamma^\alpha \mu_R \right) i(\bar{N} \not\partial_\alpha \gamma_5 N)
  \]

- **tensor**
  \[
  \text{dipole} + \left( \tilde{C}_{TL}^{(NN)} \bar{e}_P \sigma^{\alpha\beta} \mu_L + \tilde{C}_{TR}^{(NN)} \bar{e}_P \sigma^{\alpha\beta} \mu_R \right) \bar{N} \sigma_{\alpha\beta} N + h.c.
  \]
Discrimination of the interactions by different targets

![Graph showing the conversion rates normalized to the rate in aluminum as a function of the atomic number Z.](image)

- **Vector interaction (with Z boson)**
  - with Z penguin
- **Vector interaction (with photon - charge radius)**
  - left-right models
- **Dipole interaction**
  - SUSY-GUT
- **Scalar interaction**
  - SUSY seesaw

References:


Spin Dependent $\mu$-e conversion and Spin Independent $\mu$-e conversion

- dipole interaction
- vector interaction
- scalar interaction

Spin Independent $\mu$-e Conversion (coherent)
Spin Dependent $\mu$-e conversion and Spin Independent $\mu$-e conversion

- Dipole interaction
- Vector interaction
- Scalar interaction
- Pseudo-scalar interaction
- Axial vector interaction
- Tensor interaction

Spin Independent $\mu$-e Conversion (coherent)

Spin Dependent $\mu$-e Conversion (incoherent)

Compare zero-spin and non-zero-spin nuclear targets

LNV/CLFV
\( \mu^- \) to \( e^+ \) conversion in muonic atom

\[
\mu^- + N(A, Z) \rightarrow e^+ + N(A, Z - 2)
\]

ground or excited final states.

Lepton number violation (LNV) and Lepton flavour violation (LFV)

signal signature

\[
E_{\mu e^+} = m_\mu - B_\mu - E_{\text{rec}} - (M(A, Z - 2) - M(A, Z))
\]

backgrounds

- radiative muon nuclear capture (RMC)

\[
\mu^- + N(A, Z) \rightarrow N(A, Z - 1) + \nu + \gamma
\]

\[
E_{\text{RMC}} = m_\mu - B_\mu - E_{\text{rec}} - (M(A, Z - 1) - M(A, Z))
\]
**μ⁻ to e⁺ conversion in muonic atom**

\[ \mu^- + N(A, Z) \rightarrow e^+ + N(A, Z - 2) \]

Lepton number violation (LNV) and Lepton flavour violation (LFV)

**signal signature**

\[ E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - (M(A, Z - 2) - M(A, Z)) \]

**backgrounds**

- radiative muon nuclear capture (RMC)
  \[ \mu^- + N(A, Z) \rightarrow N(A, Z - 1) + \nu + \gamma \]
  \[ E_{RMC} = m_\mu - B_\mu - E_{rec} - (M(A, Z - 1) - M(A, Z)) \]

- Current limits:
  \[ \mu^- + Ti \rightarrow e^+ + Ca(gs) \leq 1.7 \times 10^{-12} \]
  \[ \mu^- + Ti \rightarrow e^+ + Ca(ex) \leq 3.6 \times 10^{-11} \]

  J. Kaulard et al. (SINDRUM-II)

- Future prospects:
  - Mu2e or COMET can improve with proper targets,


**Future prospects:**

- Mu2e or COMET can improve with proper targets,
DC muon beam experiments are ...
CLFV Decay of Muons: $\mu^+ \rightarrow e^+\gamma$

**MEG @ PSI** (2016)

- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI

\[ B(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13} \]

- a factor of 30 improvement

$A.M.\ Baldini\ et\ al.\ (MEG\ Collaboration),\ Eur.\ Phys.\ J.\ C73\ (2013)\ 2365 (2016)$
CLFV Decay of Muons: $\mu^+ \rightarrow e^+\gamma$

**MEG @ PSI (2016)**
- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI

**MEG II**
- all detectors upgraded
- full muon beam intensity
- Goal $\sim 6 \times 10^{-14}$ (2020-2023)

$B(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$
- a factor of 30 improvement
CLFV Decay of Muons: \( \mu^+ \rightarrow e^+ \gamma \)

**MEG @ PSI (2016)**
- drift chamber for positrons
- liquid Xe detector for gammas
- DC muon beam at PSI

**MEG II**
- all detectors upgraded
- full muon beam intensity
- Goal \( \approx 6 \times 10^{-14} \) (2020-2023)

\[
B(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}
\]
- a factor of 30 improvement

---

S. Mihara on Thursday
Mu3e at PSI

BR(μ → e e e) < 2 \cdot 10^{-15} \quad \text{(phase I)} \quad \rightarrow 10^8 \text{ muons/s (PiE5)}

BR(μ → e e e) < 10^{-16} \quad \text{(phase II)} \quad \rightarrow >10^9 \text{ muons/s (HiMB)}

Features:

- surface muons (p=29 MeV/c, DC) stopped on target at high rate: 10^8 - 10^9 /s
- ultra thin silicon pixel detector (HV-MAPS) with 1 per mill radiation length / layer
- high precision tracking using recurling tracks in strong magnetic field
- fast timing detectors (scintillating fibers & tiles)
- helium gas cooling
Mu3e at PSI

$\text{BR}(\mu \rightarrow e e e) < 2 \cdot 10^{-15}$ (phase I) → $10^8$ muons/s (PiE5)
$\text{BR}(\mu \rightarrow e e e) < 10^{-16}$ (phase II) → $>10^9$ muons/s (HiMB)

Features:
- surface muons ($p=29$ MeV/c, DC) stopped on target at high rate: $10^8 - 10^9$/s
- ultra thin silicon pixel detector (HV-MAPS) with 1 per mill radiation length / layer
- high precision tracking using recurling tracks in strong magnetic field
- fast timing detectors (scintillating fibers & tiles)
- helium gas cooling

A. Schöning on behalf of Mu3e

PhiPsi'19 Workshop
Budker Institute
25.2-1.3. 2019, Novosibirsk

https://www.psi.ch/mu3e/

Search for $\mu^+ \rightarrow e^+ e^+ e^-$

S. Dittmeier on Thursday
Schedule of “golden” $\mu \rightarrow e$ Transition processes in 2025 and beyond

Timeline submitted to EPPSU 2020

Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Phase</th>
<th>Sensitivity</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^- N \rightarrow e^- N$</td>
<td>COMET Phase-I</td>
<td>$10^{15}$</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>Mu2e</td>
<td>$10^{17}$</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td>Mu2e-II with PIP-II</td>
<td>$10^{18}$</td>
<td>2030</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ e^+ e^-$</td>
<td>COMET Phase-II</td>
<td>$10^{15}$</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td>Mu3e Phase-I</td>
<td>$10^{14}$</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>Mu3e Phase-II</td>
<td>$10^{16}$</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td>PRISM</td>
<td>$10^{19}$</td>
<td>2035</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ \gamma$</td>
<td>MEG II</td>
<td>$10^{14}$</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{15}$</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{16}$</td>
<td>2030</td>
</tr>
</tbody>
</table>

Improvement : $> 10,000$

COMET, MEG, Mu3e, Mu2e, arXiv:1812.06540
Muon g-2
Muon g-2 : Spin precession

Under a magnetic field

Spin vector precession

\[ \omega_S = \frac{eB}{m_\mu \gamma} \left[ 1 + \frac{(g - 2)}{2} \gamma \right] \]

Momentum vector motion

\[ \omega_C = \frac{eB}{m_\mu \gamma} \]
Muon g-2: Spin precession

Under a magnetic field

Spin vector precession

\[ \omega_S = \frac{eB}{m_\mu\gamma} \left[ 1 + \frac{(g - 2)}{2} \right] \]

Momentum vector motion

\[ \omega_C = \frac{eB}{m_\mu\gamma} \]

Spin precession with respect to the momentum vector

\[ \omega_S - \omega_C = \omega_a = \frac{a_\mu eB}{m_\mu} \]

\[ a_\mu = \frac{1}{2} (g - 2) \]

At the BNL experiment, spin precesses around momentum once every 30 turns.
Muon g-2

\[ \omega_a = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] \]

FNAL/BNL approach: effect of focusing E-field cancelled by using “magic” 3.09 GeV momenta muons.

J-PARC approach: 300 MeV beam with very low transverse momenta requiring no E-field to focus.
$\omega_a = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$ 

- FNAL/BNL approach: effect of focussing E-field cancelled by using “magic” 3.09 GeV momenta muons.
- J-PARC approach: 300 MeV beam with very low transverse momenta requiring no E-field to focus.

$\omega_p$ is measured using NNR in terms of the proton Larmor frequency.
\[ \omega_a = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] \]

**FNAL/BNL approach**: effect of focusing E-field cancelled by using “magic” 3.09 GeV momenta muons.

**J-PARC approach**: 300 MeV beam with very low transverse momenta requiring no E-field to focus.

\[ \frac{g - 2}{2} = a_\mu = \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \]

B is measured using NNR in terms of the proton Larmor frequency

- 3ppb
- 22ppb
- 0.26ppt
Muon g-2 Prediction

\[ a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM) \]

\[ a_\mu^{SM} = 116591820.5(35.6) \times 10^{-11} \]
Muon g-2 Prediction

\[
a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(\text{BSM})
\]

\[
a_\mu^{\text{SM}} = 116591820.5(35.6) \times 10^{-11}
\]

\[
a_\mu^{\text{exp}} = 116595208.9(63) \times 10^{-11}
\]

BNL E821

3.7\sigma deviation from the SM expectation
Muon g-2 Prediction

\[ a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM) \]

\[ a_\mu^{SM} = 116591820.5(35.6) \times 10^{-11} \]

\[ a_\mu^{exp} = 116595208.9(63) \times 10^{-11} \quad \text{BNL E821} \]

3.7\sigma deviation from the SM expectation

D. Nomura on Tuesday
Muon g-2 (E989) at FNAL

- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year
Muon g-2 (E989) at FNAL

- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year
Muon g-2 (E989) at FNAL

- aim at 0.14 ppm (x4 improvement)
- significant improvements over BNL E821
- run 1 data (2018) ~ 1.4xBNL
- run 2 data (2019) ~ 1.8xBNL
- run 1 result by the end of this year
J-PARC g-2/edm

- new technique: slow muons from laser ionization of muonium.
- aim at 0.45 ppm
- different systematics

Experiment Overview

- Muon g-2/EDM experiment at J-PARC (Japan)
- 3 GeV proton beam (1 MW, double pulse, 25 Hz)
- Surface muon beam (27 MeV/c, \(\varepsilon \sim 1000 \pi \text{mm}\cdot\text{mrad}\))
- Muonium Production (300 K ~ 2.3 keV/c)
- Thermal muon production by resonant laser ionization of muonium (~10⁶ \(\mu^+\)/s)
- Muon reacceleration (300 MeV/c, \(\varepsilon \sim 1 \pi \text{mm}\cdot\text{mrad}\))
- 3D spiral injection
- 3 T storage magnet
- Silicon Tracker

J-PARC g-2/edm
J-PARC g-2/edm

- new technique: slow muons from laser ionization of muonium.
- aim at 0.45 ppm
- different systematics
Muon g-2 Anomaly and Muon CLFV

Muon g-2 anomaly
flavour conserving component of the BSM dipole operator

Muon CLFV ($\mu \rightarrow e\gamma$ etc.)
flavour violating component of the BSM dipole operator
If the Muon g-2 anomaly is confirmed, it will establish the presence of a BSM muon interaction which may induce sizable effects of muon CLFV.

M. Lindner, M. Platscher, and F.S. Queiroz, arXiv:161006587
Summary

- Physics prospects with muons are rich.
- Study of charged leptons has sensitivity to BSM physics extending and complementing the reach of the LHC with a significant synergy with the neutrino program.
- Many projects will have their first results/start data taking in the next 2-3 years.
Summary

- Physics prospects with muons are rich.
- Study of charged leptons has sensitivity to BSM physics extending and complementing the reach of the LHC with a significant synergy with the neutrino program.
- Many projects will have their first results/start data taking in the next 2-3 years.

Thank you for your attention!