FERMILAB-SLIDES-18-788-E

Charged Lepton Flavor Violation search on Mu2e at Fermilab

在费米实验室Mu2e实验上寻找带电轻子味破坏

Zhengyun You (尤郑昀)

Sun Yat-Sen University (中山大学)

Workshop on Intensity Frontier of Particle Physics

9/9/2018, Institute of Theoretical Physics, CAS, Beijing

Overview

- Charged Lepton Flavor Violation (CLFV)
- CLFV measurements
- Muon to electron conversion search on Mu2e
- The experimental apparatus
- Current status
- Next plan – Mu2ell

Flavor Violation

Standard Model of Elementary Particles

- Quark Mixing (CKM)
- **Charged Lepton Flavor Violation?**
- Neutrino Oscillation

CLFV and BSM

- Ordinary muon decay

Lepton Flavor Conservation

	muon		muon neutrino		electron		electron antineutrino
equation:	μ	$\rightarrow$	ν_μ	$+$	e^-	$+$	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0

- CLFV could exist but is too tiny to be measurable

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

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

- Any CLFV observation implies **New Physics** Beyond the Standard Model (BSM)

CLFV searches

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

One of the most effective channels

μ channels

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu \eta$	$BR < 6.5 \text{ E-}8$	$10^{-9} - 10^{-10}$ (Belle II)
$\tau \rightarrow \mu \gamma$	$BR < 6.8 \text{ E-}8$	
$\tau \rightarrow \mu \mu \mu$	$BR < 3.2 \text{ E-}8$	
$\tau \rightarrow eee$	$BR < 3.6 \text{ E-}8$	
$K_L \rightarrow e \mu$	$BR < 4.7 \text{ E-}12$	
$K^+ \rightarrow \pi^+ e^- \mu^+$	$BR < 1.3 \text{ E-}11$	
$B^0 \rightarrow e \mu$	$BR < 7.8 \text{ E-}8$	
$B^+ \rightarrow K^+ e \mu$	$BR < 9.1 \text{ E-}8$	
$\mu^+ \rightarrow e^+ \gamma$	$BR < 4.2 \text{ E-}13$	10^{-14} (MEG)
$\mu^+ \rightarrow e^+ e^+ e^-$	$BR < 1.0 \text{ E-}12$	10^{-16} (PSI)
$\mu N \rightarrow e N$	$R_{\mu e} < 7.0 \text{ E-}13$	10^{-17} (Mu2e, COMET)

Muon CLFV search history

CLFV Searches History

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

Mu3e @PSI

MEG Upgrade @PSI

Mu2e @FNAL

COMET @KEK

Zhengyun You (SYSU)

Probing New Physics with CLFV

Effective CLFV Lagrangian

$$L = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu} R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$

- Relative strength κ , mass scale Λ
- ‘Loops’, electromagnetic operator, $\kappa \ll 1$, can be probed by $\mu \rightarrow e \gamma$ and $\mu N \rightarrow e N$
- ‘Contact terms’, direct coupling between quarks and leptons, $\kappa \gg 1$, accessible by $\mu N \rightarrow e N$
- Mu2e will probe mass scale Λ
2,000 ~ 10,000 TeV
 Beyond the reach of accelerators

CLFV and Theoretic Models

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

One of the most effective channels

Large effects

Visible, but small

No sizable effect

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

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

W. Altmannshofer , A.J.Buras, S.Gori, P.Paradisi, D.M.Straub, NPB 830, 17 (2010)

Current Best Limit in $\mu N \rightarrow e N$

- Current best limit
 - by SINDRUM II at PSI
 - $R_{\mu e}(\text{Au}) < 7 \times 10^{-13}$ (90%C.L.)
- Au target: different electron energy endpoint than Al

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

Fig. 11. Momentum distributions of electrons and positrons for the two event classes. Measured distributions are compared with the results of simulations of muon decay in orbit and $\mu - e$ conversion

$\mu \rightarrow e\gamma$ & $\mu N \rightarrow eN$

$\mu \rightarrow e\gamma$

- Signal particles ≤ 53 MeV
 - high background region
- Signal: **combination** of particles
 - Background rejection: cuts on track combinations
 - Accidental coincidences limit usable muon rate
- **Continuous** beam
- **μ^+**
 - Capture rates: $\Gamma_{\mu^+} = 0$

$\mu N \rightarrow eN$

- Signal particle at 105 MeV
 - Away from Michel peak
- Signal: **single** track
 - Fewer handles to reject background
 - Coincidences not a problem
- Use **pulsed** beam
 - suppress background between pulses
- Need **cosmic ray veto**
- **μ^-**
 - Capture rates: $\Gamma_{\mu^-} \sim Z^4$
 - Potential background

Mu2e Experiment

- Located at Fermi National Laboratory
- One of the U.S. Intensity Frontier top priority projects
- Cost ~\$275 M dollars (US accounting)

Mu2e Building

- Civil construction completed (2017/3)

The Proton Beam

- Use existing accelerator infrastructure
- Booster provides **8 GeV** protons
- Recycler stacks protons into 4 bunches
- Deliver Ring takes one bunch from Recycler
- Run simultaneously with neutrino programs NOvA.

Beam Time Structure

- 4×10^7 protons per bunch, bunch spacing 1695 ns
- 700 ns delay before 1 ms live gate
- Extinction factor (Out-Of-Time proton rate) $< 10^{-10}$.

Mu2e Collaboration

- > 220 scientists from 38 institutions
- Sun Yat-Sen University joined Mu2e in 2016

Argonne National Laboratory,
Boston University,
University of California Berkeley,
University of California Irvine,
California Institute of Technology,
City University of New York,
Joint Institute of Nuclear Research Dubna,
Duke University,
Fermi National Accelerator Laboratory,
Laboratori Nazionale di Frascati,
University of Houston,
Helmholtz-Zentrum Dresden-Rossendorf,
INFN Genova,
Institute for High Energy Physics, Protvino,
Kansas State University,
Lawrence Berkeley National Laboratory,
INFN Lecce, University Marconi Rome,
Lewis University,
University of Liverpool,

University College London,
University of Louisville,
University of Manchester,
University of Michigan,
University of Minnesota,
Muon Inc.,
Northwestern University,
Institute for Nuclear Research Moscow,
INFN Pisa,
Northern Illinois University,
Purdue University,
Rice University,
Sun Yat-Sen University,
University of South Alabama,
Novosibirsk State University
Budker Institute of Nuclear Physics,
University of Virginia,
University of Washington,
Yale University

$\mu N \rightarrow e N$ Conversion

What to measure

- The ratio of muon to electron conversions to the number of muon captures by nuclei

$$R_{\mu e} = \frac{\mu^- + {}_{13}^{27}\text{Al} \rightarrow e^- + {}_{13}^{27}\text{Al}}{\mu^- + {}_{13}^{27}\text{Al} \rightarrow \text{nuclear capture}}$$

- Signal: Neutrinoless conversion of a muon to electron in the field of a nucleus
- Experimental signature
 - Mono-energetic electron
 - $E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$
 - For Al, $E_e = 104.97 \text{ MeV}$

Mu2e Apparatus

**Production
Solenoid**

Proton Beam

Tracker **Calorimeter**

4.5 T

2.0 T

1.0 T

2.5 T

**Production
Target**

Transport Solenoid

Detector Solenoid

Three functional solenoids
with graded fields (4.5T – 1T)

Target and Shield

- Production Target

- Protons + target $\rightarrow \pi + X$; π decay into muons
- High A and high density material Tungsten to maximize muons production
- High melting temp, radiative cooling ($\sim 1600^\circ\text{C}$), with 8kW beam (700w in target)

- Heat Radiation Shield

- To protect superconductor of PS and upstream TS
- To limit heat load and radiation damage
- ~ 25 tons of Bronze

Transport Solenoid

- Gradient magnetic field from 2.5 T to 2.0 T
- S-shaped magnetic channel to transmit low-momentum negatively charged particles in helical trajectories
- Collimators to remove positively charged and high-momentum particles

Detector Solenoid

- Stopping target to capture muons
- Graded magnetic field from 2 T to 1 T, captures conversion electrons with bigger acceptance
- Tracker and Calorimeter in a uniform field to reconstruct and identify electrons.

Tracker

Tracker Structure

105 MeV
Conversion
electrons

DIO
electrons

Straw Tube

- 5 mm diameter straw drift tubes
- 15 μm Mylar walls, filled with $\text{Ar}:\text{CO}_2$ (80:20)
- 18 stations, 2 planes/station, 6 panels /plane
- Blind to beam flash and $>97\%$ DIO
- Expect 100 μm hit resolution
- Momentum resolution $< 180 \text{ keV}/c$ (@105MeV/c)

Calorimeter

- Two disks separated by 70 cm ($1/2 \lambda$), ~ 674 CsI crystals/disk
- Provides independent energy ($\sigma_E/E < 5\%$), time ($\sigma_t < 0.5\text{ns}$) and position ($\sigma_{\text{pos}} \sim 1\text{cm}$) measurements
- Particle ID, Cosmic Ray rejection, tracking seed
- Independent trigger

Extinction Monitor

- Extinction definition: protons between pulses / protons in pulse
- Extinction requirements $< 10^{-10}$
- Extinction measurement is important to success

Mu2e Signal

To find a signal electron near 105 MeV/c from a bunch of track candidates

Background(1): Intrinsic

➤ Muon Decay-in-orbit (DIO)

- $\mu \rightarrow e \nu_{\mu} \bar{\nu}_e$
- Dominant background
- 39% of stopped muons
- DIO Rate $\sim (E_{\text{MAX}} - E_e)^5$, $E_{\text{MAX}} \sim 105$ MeV
- Requires good energy resolution

➤ Radiative Muon Capture (RMC)

- $\mu N \rightarrow \gamma \nu_{\mu} N'^*$
- 61% of stopped muons
- 3 MeV under DIO end point
- Negligible

Background(2): Prompt

➤ Radiative Pion Capture (RPC)

- $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$
 $\pi^- N \rightarrow e^+e^- N'$
- 2% of captured π^-
- Mitigate by waiting

➤ Beam and free decays

- Beam Electrons
- Muon Decay In Flight
- Pion Decay In Flight

Delayed search time window help to mitigate prompt backgrounds

Background(3): Anti-protons

➤ The 8GeV proton is above anti-proton production threshold

- $pp \rightarrow \bar{p}ppp$,
- Anti-proton annihilate, produce $\pi^0 \rightarrow e^+e^-$,
 π^- contribute to RPC backgrounds
- Anti-protons travel 10x more slowly
- Do not decay, time rejection does not help

Add absorbers at some locations in the muon beamline to absorb anti-protons

Background(4): Cosmic Rays

- Cosmic ray background ~ 1 event / day
- Requires $< 10^{-4}$ inefficiency $\rightarrow$ 0.1 event in 3 years
- **Cosmic Ray Veto (CRV)** made of 4 layers of overlapping scintillators
- Surrounding DS & part of TS area

All Backgrounds

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	$0.41 \pm 0.13(\text{stat}+\text{syst})$

Numbers normalized to 3 years run, 3.6×10^{20} POT events

Signal and Backgrounds

- Full Geant4 simulation and reconstruction, background overlaid with signal
- Discovery sensitivity accomplished with 3 years of running and suppressing backgrounds to < 0.4 event total, (5σ) 2×10^{-16}
- Single event sensitivity 3×10^{-17}
- Null signal upper limit 8×10^{-17} @ 90% C.L.

Mu2e Prototypes

Completed TS Module

PS Shell forging

Tests of a prototype tungsten production target at RAL

Straw tracker fabrication

Prototype counter for cosmic veto

Timeline

Mu2e II

- **If NO signal:**
Higher sensitivity search;
X10 improvement
 - Proton source upgrade
 - Detector upgrade
- **If signal:**
Precision measurement;
Measure different target materials
to discriminate between new
physics models;
- Expression of interest **(EOI)**
submitted to Fermilab PAC in
2018
(arXiv:1802.02599)

M. Koike et al., J. Phys. G29 (2003) 2051-2054

Summary

- CLFV has great potentials to probe new physics at the Intensity Frontier
- Mu2e will search for CLFV with $\mu N \rightarrow e N$
 - Address compelling science
 - Single event sensitivity $R_{\mu e} = 3 \times 10^{-17}$
 - Improve the current limits by a factor of 10^4
 - Search for New Physics with mass scale up to 10^4 TeV
- Project is going well
 - Complete construction in 2021
 - Progressing on schedule for data taking

Backup Slides

New Physics in $\mu \rightarrow e$

Loops

Supersymmetry

rate $\sim 10^{-15}$

Heavy Neutrinos

$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$

Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$

Contact Terms

Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$

Leptoquark

$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{1/2} \text{ TeV}/c^2$

Heavy Z'
Anomal. Z Coupling

$M_{Z'} = 3000 \text{ TeV}/c^2$

Flavor physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)

Mu2e Status

- TDR published in Oct. 2014
 - <http://arXiv.org/abs/1501.05241>
- DOE CD-2/3b received in March 2015
- DOE CD-3 awarded in July 2016
- First beam delivered in 2017 (Muon g-2)
- Detector construction starts in 2018

Mu2e Technical Design Report

October 2014
 Fermi National Accelerator Laboratory
 Batavia, IL 60510
www.fnal.gov
 Managed by
 Fermi Research Alliance, FRA
 For the United States Department of Energy under
 Contract No. DE-AC02-07-CF1-11359

Mu2e keeps as priority funding on DOE's funding for large projects

Report of the Particle Physics Project Prioritization Panel
 May 2014

Summary of Scenarios									
Project/Activity	Scenarios			Science Drivers					Technique (Frontier)
	Scenario A	Scenario B	Senario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I, C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medum Projects									