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The Mu2e Experiment

Tomo Miyashita

Caltech

On Behalf of the Mu2e Collaboration

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Overview

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Motivation

- Mu2e is searching for Charged Lepton Flavor Violation (CLFV)
 - Specifically, the neutrinoless conversion of a μ^- to an e^- in the field of a nucleus:

- Using the current Fermilab accelerator complex, we intend to achieve a sensitivity 4 orders of magnitude better than current limits:

Target Sensitivity:

$$R_{\mu e} = \frac{\Gamma [\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)]}{\Gamma [\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z - 1, N + 1)]} < 6.7 \times 10^{-17} (90\% \text{CL})$$

4 orders of magnitude better than current limits: SINDRUM II
[W. Bertl et al., Eur. Phys. J. C 47, 337-346 (2006)]

- We will have discovery sensitivity over a broad range of New Physics parameter space

CLFV in the Standard Model

- CLFV is not technically allowed in the SM because since charged lepton number is accidentally conserved when neutrinos are massless
- However, if we include massive neutrinos in our model then CLFV becomes possible at the loop level due to neutrino oscillations:

- This process is extremely suppressed:

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

- Therefore, any signal at our sensitivity would be a sign of new physics

New Physics Reach

- There are many possible new physics contributions to $\mu N \rightarrow e N$, either through loops or the exchange of heavy intermediate particles
- Many NP models predict rates observable at next gen CLFV experiments

Loops

Supersymmetry

Heavy Neutrinos

Two Higgs Doublets

Contact Terms

Compositeness

Leptoquarks

New Heavy Bosons /
Anomalous Couplings

Model-Independent Effective Lagrangian

$$L_{\text{CLFV}} = \frac{m_m}{(1+k)\Lambda^2} \bar{m}_R s_{mn} e_L F^{mn} + \frac{k}{(1+k)\Lambda^2} \bar{m}_L g_m e_L (\bar{u}_L g_m u_L + \bar{d}_L g_m d_L) + h.c.$$

Λ : effective mass scale of New Physics

k : relative contribution of the contact term

“Dipole term”

“Contact term”

Courtesy A. de Gouvêa, B. Bernstein, D. Hitlin

- CLFV can probe very high mass scales $O(1000 - 10,000 \text{ TeV})$

Experimental Concept

- Generate a beam of low momentum muons
 - Muons are stopped in an aluminum target
 - When stopped muons convert to electrons, the nucleus recoils and the electron is emitted at a specific energy
- Signal is mono-energetic electron at 104.9 MeV
 - Main intrinsic background is Decay In Orbit (DIO) events
- To achieve our target sensitivity, we need $\sim 10^{18}$ stopped muons over 3 year run
 - $\Rightarrow \sim 10^{10}$ stopped muons per second

Decay In Orbit Energy Distribution

- Although the maximum electron energy from free muon decay is far below our signal energy (104.9 MeV)...

Decay In Orbit Energy Distribution

- The decay spectrum is distorted by the presence of the nucleus...

Decay In Orbit Energy Distribution

- ...so the maximum energy for the DIO electrons can come very close to the signal energy:

- Therefore, it is important that we have good energy resolution

Design Overview

- **Production Target + Production Solenoid**
 - High intensity, pulsed, 8 GeV proton beam strikes tungsten production target producing pions
 - Pions are captured by the graded magnetic field and decay to muons
- **Transport Solenoid**
 - Selects low momentum, negative muons
 - Absorbers and Collimators eliminate high energy negative particles, positive particles, and line-of-sight neutrals
- **Stopping Target, Detector, and Detector Solenoid**
 - Muons are stopped on an aluminum target
 - Tracker measures momentum and trajectories of electrons from muonic atoms
 - Calorimeter measures energy/time
- **Cosmic Ray Veto detector surrounds detector solenoid**

The Mu2e Proton Beam

- Mu2e will take advantage of the existing Booster, Recycler, Accumulator, and Antiproton Source Debuncher rings at Fermilab
- Mu2e will run in parallel with NOvA
- Mu2e cannot be simultaneously run with g-2, but could run after g-2 or alternate with it

Radiative Pion Capture

- As previously described, we generate pions in order to make muons
 - However, sometimes the pions live long enough to reach the stopping target
- Pions arriving at the stopping target can undergo radiative pion capture (RPC):
 - $\pi N \rightarrow N' \gamma, \quad \gamma \rightarrow e^+ e^-$
 - $\pi N \rightarrow N' e^+ e^-$

potentially producing an electron at the signal energy
- In order to suppress this background, we use a pulsed beam structure with a delayed data-taking window

Proton Pulse Structure

- Proton Pulse Structure:

- We wait for the “prompt” pion backgrounds to subside before opening the live window
- A 700 ns delay reduces pion background by $> 10^{-11}$
- We need a 10^{-10} out-of-pulse/in-pulse proton ratio (extinction)
- This “extinction ratio” is measured and monitored throughout the experiment

Production Target

- Production Target
 - Radiatively cooled tungsten target suspended by wires
 - Produces pions when struck by the proton beam
 - Muons are guided to the stopping target by the production and transport solenoids

Stopping Target

- Stopping Target
 - Aluminum stopping target composed of foils suspended by wires
 - If a signal is seen, other stopping target materials may be used to narrow down what kind of physics is responsible
 - Design is still being optimized, but it will probably consist of something like aluminum foil annuli suspended at intervals in a cylindrical volume

Solenoid Status

- Solenoid production is underway
 - All superconducting cables for solenoids have been manufactured
 - A production module for the transport solenoid (TS) have been constructed and cold tests are being performed
 - Warm bores for the production and detector solenoid have been delivered to General Atomics

Solenoid Status II

- Warm Bores en route to Tupelo, MS

Tracker I

- A low-mass annular tracker provides us with high-precision measurements of charged particle momenta
- Designed to function in a high background environment
- Within the detector solenoid, track radius is proportional to transverse momentum so we use an annular design that only detects particles with large enough radii

- Expect $< 180 \text{ keV/c } p_T$ resolution at $105 \text{ MeV/c } (< 0.18\%)$

Tracker II

- Tracker Construction:

- Tracker is constructed from self-supporting **panels** of low mass straws tubes detectors:

- 5 mm diameter straw
- Spiral wound
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al
- 25 mm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO₂ with HV < 1500 V

96 straws/panel

- Sets of 6 panels are attached to form a **plane**, 2 planes are combined to form a **station**, and 18 stations are arranged in a cylindrical volume to form the tracker:

plane

6 panels/plane

station

2 panels/station

18 station tracker

Tracker III

- Tracker Construction:

Calorimeter I

- Calorimeter Serves to
 - Distinguish muons from electrons
 - Aid in track pattern recognition
 - Provide tracker-independent trigger
 - Provide accurate timing information for bkg rejection

- Calorimeter Design:

- Two annuli with radius 37-66 cm
- Disks separated by 70 cm ($1/2 \lambda$)
- ~674 CsI crystals per disk
- Two $14 \times 20 \text{ mm}^2$ six-element SiPMs / crystal
- Square crystals ($34 \times 34 \times 200 \text{ mm}^3$)

Calorimeter II

- Wrap crystals in Tyvek and stack in annulus
- A backplane assembly provides cooling and slots mounting crystal readout electronics
- Insert SiPM holders with front end electronics (FEE) into the backplane (air-gap coupling)
- FEE are read out by readout controllers housed in crates

Crystal Stacking

SiPM Holder

Calorimeter Prototype

Calorimeter Prototype Test Beam

- May 2017 test beam with 70-115 MeV electrons at INFN Frascati
 - 51 30x30x200 mm³ CsI crystals
 - Readout: Hamamatsu, SNESSL, and Advansid SiPMs

- Results:

PM2018 – 14th Pisa Meeting on Advanced Detectors
<https://agenda.infn.it/materialDisplay.py?contribId=44&sessionId=14&materialId=slides&confId=13450>

Energy Resolution

Calibration with e⁻ at 0°
For 100 MeV e⁻ at 50°:
Energy resolution ~7%

Time Resolution

Δt : Time difference between two sensors reading the same crystal.

For 100 MeV e⁻ at 50°:
 Δt resolution ~340 ps
Single sensor resolution ~240 ps

- Energy and time resolutions satisfy our requirements (~10% and 500ps, resp.)

Cosmic Ray Veto I

- The Cosmic Ray Veto (CRV) system surrounds the detector solenoid and half the transport solenoid
- CRV identifies cosmic ray muons

- Each day, ~ 1 conversion-like electron is produced by cosmic rays
- Need the CRV to suppress this background

Cosmic Ray Veto II

- The CRV is composed of 4 layers of overlapping panels of extruded polystyrene scintillator

- Each panel is composed of $5 \times 2 \times \sim 450 \text{ cm}^3$ scintillator bars
 - 2 embedded wavelength-shifting fibers per bar
 - Both ends of the bars are readout by SiPMs
 - In testing, the veto achieves $\varepsilon > 99.4\%$ per layer

DAQ/Trigger

- Data Acquisition (DAQ) system provides readout and control for all the detector subsystems

- Trigger processing is handled almost entirely in software (with some FPGA-based pre-processing)
 - Allows us to take advantage of commercial computing hardware
 - Filters designed and tested in the offline environment can be run in the online trigger environment

Mu2e Building

The Mu2e Collaboration

Over 200 Scientists from 37 Institutions

Argonne National Laboratory • Boston University • Brookhaven National Laboratory • Lawrence Berkeley National Laboratory and University of California, Berkeley • University of California, Davis • University of California, Irvine • California Institute of Technology • City University of New York • Joint Institute for Nuclear Research, Dubna • Duke University • Fermi National Accelerator Laboratory • Laboratori Nazionali di Frascati • INFN Genova • Helmholtz-Zentrum Dresden-Rossendorf • University of Houston • Institute for High Energy Physics, Protvino • Kansas State University • INFN Lecce and Università del Salento • Lewis University • University of Liverpool • University College London • University of Louisville • University of Manchester • Laboratori Nazionali di Frascati and Università Marconi Roma • University of Minnesota • Institute for Nuclear Research, Moscow • Muons Inc. • Northern Illinois University • Northwestern University • Novosibirsk State University/Budker Institute of Nuclear Physics • INFN Pisa • Purdue University • University of South Alabama • Sun Yat Sen University • University of Virginia • University of Washington • Yale University

Detector Hall (Lower Level)

Mu2e Schedule

Z-Dependence of $\mu \rightarrow e$ Conversion

Lepton flavor violating $\mu - e$ conversion rate for various nuclei
 M. Koike et al., J. Phys. G29 (2003) 2051-2054
 DOI: 10.1088/0954-3899/29/8/401

Mu2e II Introduction

- As Mu2e approaches commissioning, we are also looking toward future upgrades
- The proposed Mu2e II experiment aims to achieve an order of magnitude improvement in sensitivity over Mu2e
 - **If there is no signal at Mu2e:** We could extend our sensitivity to find a signal or set new limits
 - **If Mu2e does see something:** We can improve our statistical significance and use different target materials to narrow down the NP processes involved
- To achieve a 10X improvement, we need:
 - An upgraded proton source (already approved)
 - Other upgrades to parts of the detector
- We aim to reduce costs by reusing parts of mu2e wherever feasible

Mu2e II Plans

- So far, various studies of Mu2e II backgrounds, sensitivity, and radiation damage have been performed
- A series of Mu2e II workshops has been held and the collaboration is involved in the Fermilab PIP-II planning process (a superconducting linac for LBNF and the muon campus)
 - PIP-II will have an energy of 800 MeV (Mu2e's proton source is 8 GeV) which is below the anti-nucleon production threshold and will result in less background
- An expression of interest was recently submitted to the Fermilab PAC
- Timecale:
 - Mu2e is expected to run for 4 years of data-taking at full intensity
 - Assuming 2-3 years from the end of Mu2e to the start of Mu2e II, Mu2e II could begin taking data around 2030

Summary

- The Mu2e experiment will improve current $\mu^- N \rightarrow e^- N$ CLFV sensitivity limits by 4 orders of magnitude (and thereby constrain many NP models at mass scales up to $\sim 10,000$ TeV)
- Mu2e will be sensitive to a broad range of NP models
- If we see a signal, switching to another stopping target material will provide further information about the Lorentz structure of the NP
- Progress is on schedule and we plan to begin commissioning in 2020

Backup Slides

Example CLFV Processes

- Potential channels for CLFV searches:

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu \eta$	$\text{BR} < 6.5 \times 10^{-8}$	$10^{-9} - 10^{-10}$ (Belle II)
$\tau \rightarrow \mu \gamma$	$\text{BR} < 6.8 \times 10^{-8}$	
$\tau \rightarrow \mu \mu \mu$	$\text{BR} < 3.2 \times 10^{-8}$	
$\tau \rightarrow e e e$	$\text{BR} < 3.6 \times 10^{-8}$	
$K_L \rightarrow e \mu$	$\text{BR} < 4.7 \times 10^{-12}$	
$K^+ \rightarrow \pi^+ e^- \mu^+$	$\text{BR} < 1.3 \times 10^{-11}$	
$B^0 \rightarrow e \mu$	$\text{BR} < 7.8 \times 10^{-8}$	
$B^+ \rightarrow K^+ e \mu$	$\text{BR} < 9.1 \times 10^{-8}$	
$\mu^+ \rightarrow e^+ \gamma$	$\text{BR} < 4.2 \times 10^{-13}$	10^{-14} (MEG Upgrade)
$\mu^+ \rightarrow e^+ e^+ e^-$	$\text{BR} < 1.0 \times 10^{-12}$	10^{-16} (Mu3e)
$\mu N \rightarrow e N$	$R_{\mu e} < 7.0 \times 10^{-13}$	10^{-17} (Mu2e, COMET)

- Although CLFV τ processes could have larger branching ratios than μ processes, dedicated muon experiments can produce $O(10^{10}) \mu/\text{s}$ whereas colliders produce $O(10^{10}) \tau/\text{year}$

Mu2e Discovery Potential

- Mu2e has discovery sensitivity across a wide range of models:

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

★★★★ = Discovery Sensitivity

	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.

arXiv:0909.1333[hep-ph]

Calorimeter Calibration

- The calorimeter will be calibrated using activated Fluorine-rich fluid
 - Fluorinert is activated using neutrons from a DT generator
 - Fluid is pumped through pipes in front of the disks
 - Calibrate energy scale to $< 0.5\%$ in a few minutes
- A UV laser system will continuously monitor SiPM gains
 - Distribute light using silica optical fibers

Prototype Spectrum

DAQ Server Setup

- Online processing provided by 40 commercial 3U rack-mount servers
- Each server houses 1 or 2 PCIe cards with onboard FPGA and custom firmware that provide detector readout/control as well as data pre-processing

Average Data Rates

pre-event building fraction pass: A
 Level 0 pre-processing fraction pass: B
 Level 1 Filter fraction pass: C

Total Required Rejection Ratio: ~125:1

Requirement: Process 200k events/s

Therefore, trigger algorithm must run in:

$$1 / 200K \frac{\text{events}}{s} * 40 \text{ nodes} * 20 \frac{\text{art threads}}{\text{nodes}} = 4.0 \frac{\text{ms}}{\text{events}}$$