The Mu3e Experiment @ PSI

searching for the neutrinoless muon decay $\mu^+ \rightarrow e^+e^-e^+$

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LFV in the “Standard Model”

Flavor Conservation in the charged lepton sector:

processes like \( \mu A \rightarrow e A \)
\( \mu \rightarrow e + \gamma \)
\( \mu \rightarrow e e e \) have not been observed yet (down to \( 10^{-13} \)).

In SM \( (m_\nu = 0) \) Lepton Flavor is conserved absolutely (not by principle but by structure !)

neutrino oscillations \( \rightarrow m_\nu \neq 0 \Rightarrow \) Lepton Flavor is not anymore conserved (\( \nu \) oscillations)
\( \rightarrow \) charged LFV possible via loop diagrams, but heavily suppressed

\( \mu \rightarrow e \) (or \( \mu \rightarrow \tau \)) via \( \nu \) oscillations

\( \mu \rightarrow e e e \) via a quantum loop

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\vartheta) \sin^2(\Delta m^2_{\alpha\beta} \frac{L}{4E}) \]

measurement not affected by SM processes

\[ \propto \frac{\Delta m^4_{\nu}}{M^4_W} \Rightarrow BR(\mu^\pm \rightarrow e^\pm e^e e^-) < 10^{-54} \]
New Physics in $\mu \rightarrow eee$

several cLFV models predict sizeable effects, accessible to the next generation of experiments!

if cLFV seen, unambiguous signal for new physics (going beyond Dirac $m_\nu > 0$)

explore physics up to the PeV scale complementary to direct searches at LHC

Dipole (Loop Diagrams)
- Supersymmetry
- Little Higgs Models
- Seesaw Models
- GUT models (Leptoquarks)
- many other models …

Contact (Tree Diagrams)
- Higgs Triplet Models
- New Heavy Vector Bosons (Z‘)
- Extra dimensions (K-K towers)
- many other models …

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Model Comparison ($\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$)

effective charge LFV Lagrangian ("toy" model) Kuno & Okada

$$L_{\text{LFV}} = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{\text{dipole}} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J^{e,\mu} J^{\sigma,\gamma}$$

$\Lambda =$ common effective scale
$\kappa =$ “contact” vs “loop”

de Gouvea & Vogel

explore physics up to PeV scale

$e \gamma / Z^*$

$\kappa \rightarrow 0$

$\kappa \rightarrow \infty$
LFV $\mu$ Decays : Experimental Signatures

**Kinematics**:

- 2-body decay
  - Monochromatic $e^+$, $\gamma$
  - Back to back

- Quasi 2-body decay
  - Mono-energetic $e^-$

- 3-body decay
  - Coplanar, $\sum p_i = 0$
  - $\sum E_i = m_\mu$

**Backgrounds**:

- Accidentals

- Decay in orbit
  - Antiprotons, pions

- Radiative decay
  - Accidentals

**Beam**:

- Continuous beam

- Pulsed beam

- Continuous beam

None of these decays, however, have been yet observed experimentally.
search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity $\text{BR} \sim 10^{-16}$ (PeV scale)

$\tau_{(\mu \rightarrow eee)} > 1000 \text{ years} \ (\tau_{\mu} = 2.2 \ \mu\text{s})$

using the most intense DC (surface) muon beam in the world ($p \sim 28 \ \text{MeV/c}$)

suppress backgrounds below $10^{-16}$

find or exclude $\mu^+ \rightarrow e^+ e^- e^+$ at the $10^{-16}$ level

4 orders of magnitude over previous experiments (SINDRUM @ PSI)

aim for sensitivity / staged approach

$10^{-15}$ in Phase I

$10^{-16}$ in Phase II

(i.e. find one $\mu^+ \rightarrow e^+ e^- e^+$ decay in $10^{16}$ muon decays)

$\rightarrow$ observe $\sim 10^{17} \mu$ decays (over a reasonable time scale)

rate $\sim 2 \times 10^9 \mu$ decays / s

$\rightarrow$ build a detector capable of measuring $2 \times 10^9 \mu$ decays / s

minimum material, maximum precision

project (Phase I) approved in January 2013
Mu3e Baseline Design – Phase I

- Thin (< 0.1% $X_0$), fast, high resolution detectors
  (minimum material, maximum precision)

- 175 M HV-MAPS channels (Si pixels w/ embedded amplifiers)

- 10 k ToF channels (SciFi and Tiles)

- Surface $\mu$
  $p \sim 28 \text{ MeV/c}$
  $10^8 \mu / \text{s}$

- Acceptance ~ 70% for $\mu^+ \rightarrow e^+ e^- e^+$ decay (3 tracks!)

- Scintillating tiles

- Scintillating fibers

- Solenoid $B = 1 \text{ T}$

- Distance ~ 1.2 m

- Distance ~ 15 cm
Muons @ PSI

most intense DC muon beam

590 MeV/c proton cyclotron, 1.4 MW

πE5 beamline \( \sim 10^8 \mu / s \)
- surface muons \( \sim 28 \text{ MeV/c} \)
- high intensity monochromatic beam
  \( (\Delta P/P < 8\% \text{ FWHM}) \)
- polarization \( \sim 90\% \)
  (MEG exp., Mu3e phase I)

SINQ (spallation neutron source)
could even provide \( 5 \times 10^{10} \mu / s \)
High-intensity Muon Beamline (HiMB)

\( > 8\sigma \) separation

\( e / \mu \) 12 cm separation at last collimator
Mu3e – Phase I

MEGII and Mu3e (phase I) have similar beam requirements and will share the same beam-line.

\[ \pi E5 \text{ beamline} \]

\[ \pi E5 \text{ beamline} \]

can easily switch between the two experiments:
intensity \( O(10^8 \text{ muon/s}) \)
low momentum \( p = 28 \text{ MeV/c} \)
small straggling

Proof-of-Principle:
delivered \( 8 \times 10^7 \text{ muon/s} \) during 2016 test beam
Signal and Backgrounds

**signal**

- Internal conversion
- Accidental

**backgrounds**

- In time
- Out of time

**features**

<table>
<thead>
<tr>
<th>Common Vertex</th>
<th>No Common Vertex</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma p_i = 0, \ \Sigma E_i = m_\mu$</td>
<td>$\Sigma p_i \neq 0, \ \Sigma E_i &lt; m_\mu$</td>
</tr>
<tr>
<td>In time</td>
<td>Out of time</td>
</tr>
</tbody>
</table>

$$\text{BR} (\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu) = 3.5 \times 10^{-5}$$

rejecting the background requires

\[ \sigma_{\text{vtx}} < 300 \ \mu \text{m}, \quad \sigma_p < 0.5 \ \text{MeV/c}, \quad \sigma_t < 0.5 \ \text{ns} \]
Irreducible Background

$\mu$ radiative decay with internal conversion

$$\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$$ fraction in signal region as a function of $\Delta m_\mu$

$$\text{BR} (\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu) = 3.5 \times 10^{-5}$$

high momentum and energy resolution required to suppress this background

$\sigma_p < 0.5 \text{ MeV}/c$ and $\Delta m_\mu < 0.5 \text{ MeV}/c^2$
Background Suppression

Mu3e Phase I  $1 \cdot 10^{15}$ $\mu$ on Target; $10^8$ $\mu$/s

Internal Conversion Background

$\mu \rightarrow \text{eee}$ at $10^{-12}$

$\mu \rightarrow \text{eee}$ at $10^{-13}$

$\mu \rightarrow \text{eee}$ at $10^{-14}$

$\mu \rightarrow \text{eee}$ at $10^{-15}$

Events per 100 keV/c²

Reconstructed Mass [MeV/c²]

background rejected with tracking and timing

(tracking alone not sufficient to reject accidental background)
The Pixel Tracker

central tracker: four layers
re-curl tracker: two layers

minimum material budget: tracking in multiple scattering dominated regime
momentum resolution $< 0.5$ MeV/$c$ over a large phase space
geometrical acceptance $\sim 70$
$X/X_0$ per layer $\sim 0.011\%$
Silicon Pixel Detector HV-MAPS

High Voltage Monolithic Active Pixel Sensors: HV-MAPS

Readout logic and amplifiers embedded in the pixel n-well

Thin active region (10 μm) → fast charge collection via drift

< 50 μm thickness

Final pixel size 80 x 80 μm²

Final chip size 2 x 2 cm²

Time resolution < 15 ns

Efficiency > 99%

175 M pixels

Radiation hard

Operated at −85 V

1 Gb/s LVDS readout (30 M hits /s)

Peric NIMA731 (2008) 131
Latest prototype: MUPIX 8 (→ MUPIX X)

**characteristics**
- thickness 50 \( \mu \text{m} \)
- pixel size 80 x 80 \( \mu \text{m}^2 \)
- chip size 19 x 10 mm\(^2\)

**performance**
- efficiency > 99 %
- time resolution < 14 ns
Timing

50 ns snapshot (readout frame): 100 μ decays

additional ToF information < 500 ps

to suppress accidental backgrounds requires excellent timing

< 500 ps SciFis

< 100 ps scint. tiles
The Timing Detectors: Fibers and Tiles

precise timing measurement: critical to reduce accidental BKGs
determine sign of re-curling tracks (SciFi)

scintillating fibers (SciFi) \(\sim 250\) ps, detection efficiency \(> 95\%\)

scintillating tiles \(\sim 70\) ps, detection efficiency \(> 99\%\)
The SciFi Detector

Design

cylindrical
~12 cm diameter
length ~30 cm
3 staggered layers round fibers
multi-clad 250 μm round fibers
readout with Si-PM arrays on both ends
MuSTiC ASIC

Requirements

high detection efficiency > 95%
time resolution < 0.5 ns
thickness X/X₀ ~ 0.2 % (< 700 μm)
handle high occupancy: up to 250 KHz/fiber
limited space for electronics and cabling
SciFi Performance

different fibers have been evaluated
SCSF 78 MJ, SCSF 81 MJ, NOL 11, BCF 12 w/ and w/o TiO₂ coating, 3 & 4 layers, …

detection efficiency > 96 % @ 0.5 phe thr
timing resolution ~200 ps (mean time)

Si-PM array 2 x 64 ch., 250 μm pitch common cathode

.full size SciFi ribbon prototype

light yield

time resolution

[Graphs showing light yield and time resolution for different fibers]
Summary

Mu3e will search for the neutrinoless muon decay $\mu \rightarrow e^+e^-e^+$
with a sensitivity at the level of $10^{-16}$ i.e. at the PeV scale
$\rightarrow$ suppress backgrounds below $10^{-16}$ (16 orders of magnitude !)

Novel technologies:
- HV-MAPS (Si pixels, 50 $\mu$m thickness)
- Si-PMs (scintillating fibers and tails)
  they meet the requirements

Staged approach
- Stage I (2020 – 2024)
  $\sim 10^8 \mu$ decays / s
  BR($\mu \rightarrow eee$) < $10^{-15}$
  approved in January 2013

- Stage II (> 2025)
  $\sim 2 \times 10^9 \mu$ decays / s
  BR($\mu \rightarrow eee$) < $10^{-16}$
  HiMB feasibility study already started

Construction in 2018/2019 (incl. magnet)
Commissioning 2020
The best limits on LFV come from PSI muon experiments:

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

BR < 1 \times 10^{-12}
SINDRUM 1988

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

BR < 7 \times 10^{-13}
SINDRUM II 2006

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

BR < 4.2 \times 10^{-13}
MEG 2016

Mu3e \[ \mu^+ \rightarrow e^+e^-e^+ \]

Phase I: BR < 10^{-15}
Phase II: BR < 10^{-16}
SINDRUM @ PSI (~ 80s)

beam (πE3 beamline @ PSI):
  $5 \times 10^6 \mu / \text{sec}$
  28 MeV/c surface muons

resolution:
  $\sigma(p_T) = 0.7 \text{ MeV/c}^2$
  vertex ~ 1 mm
  statistics limited!

$$\frac{\Gamma(\mu^+ \rightarrow e^+ e^- e^+)}{\Gamma(\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e)} < 10^{-12} \quad (90\% \text{ CL})$$

$K = \sum_i E_i + |\sum_i \vec{p}_i c|$, $\mu \rightarrow 3e2\nu$

$m_\mu = 105.7 \text{ MeV} \pm 0$

e$^+$ spectrum $\mu^+ \rightarrow e^+2\nu$