A novel experiment searching for the lepton flavour violating decay

\[ \mu \rightarrow \text{eee} \]

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Overview

• **Why**
  searching for lepton flavour violation?

• **Where**
  can lepton flavour violation come from?

• **Why**
  do it in $\mu \rightarrow eee$?

• **How**
  to reach a sensitivity of $BR(\mu \rightarrow eee) < 10^{-16}$?
In the Standard Model of particle physics, lepton flavour is conserved.
Neutrino Oscillations!
Why searching for LFV?

- What about charged leptons?
- Charged lepton-flavour violation through neutrino oscillations heavily suppressed (BR < 10^{-50})
- Observation clear sign for new physics
Where to search for LFV?

Lepton decays
- $\mu \rightarrow e\gamma$
- $\mu \rightarrow eee$
- $\tau \rightarrow l\gamma$
- $\tau \rightarrow lll$ \hspace{1em} l = $\mu$, e
- $\tau \rightarrow lh$

Meson decays
- $\phi, K \rightarrow ll'$
- $J/\psi, D \rightarrow ll'$
- $Y, B \rightarrow ll'$

Conversion on Nucleus
- $\mu N \rightarrow e N$

Fixed target experiments (proposed)
- $e N \rightarrow \mu N$
- $e N \rightarrow \tau N$
- $\mu N \rightarrow \tau N$

Collider experiments
- $e p \rightarrow \mu (\tau) X$ \hspace{1em} (HERA)
- $Z' \rightarrow ll'$ \hspace{1em} (LHC)
- $\chi^{0,\pm} \rightarrow ll' X$ \hspace{1em} (LHC)
Experimental Status

Purely leptonic LFV

- $\text{BR}(\mu \to e\gamma) < 2.4 \times 10^{-12}$ (MEG 2011)
  $< 10^{-13}$ (MEG, projected)
- $\text{BR}(\tau \to e(\mu)\gamma) \sim 4 \times 10^{-8}$ (B-Factories)
- $\text{BR}(\mu \to eee) < 10^{-12}$ (SINDRUM)
  $< 10^{-16}$ (Our proposal)
- $\text{BR}(Z \to e\mu) < 10^{-6}$ (LEP)

Semi-hadronic LFV

- $\text{BR}(K \to \pi e\mu) \sim 10^{-11}$
- $\text{BR}(\mu N \to eN) \sim 10^{-12}$ (SINDRUM 2)
  $\sim 10^{-14}$ (DeeMe, projected)
  $< \text{down to } 10^{-17}$ (projected: Mu2e, COMET, Prism)
Models for physics beyond the standard model often naturally induce LFV, either through loops or exchange of heavy intermediates:

- Supersymmetric models with GUT with Seesaw
- Models with Leptoquarks
- Models with additional Higgs particles: Higgs triplet model
- Models with a Z' or large extra dimensions
Models for LFV: SUSY

- Supersymmetry with slepton mixing
- Lepton mixing is large; would naturally expect large slepton mixing
For these models:
\[ \text{BR}(\mu \rightarrow \text{eee}) = 0.006 \times \text{BR}(\mu \rightarrow \text{e}\gamma) \]

Points: SUSY LHC parameters

Constrained Minimal Supersymmetric Model with Seesaw neutrino masses and leptogenesis

General feature: Strong dependence on $\theta_{13}$

Leptoquarks can lead to $\mu \rightarrow eee$ at one-loop order.

Access to Leptoquark masses up to $\sim 5$ TeV

LFV in Higgs triplet models

Hierarchical case

- Dependence on neutrino mass hierarchy and $\theta_{13}$

LFV in Higgs triplet models

• Dependence on neutrino mass hierarchy and $\theta_{13}$

Recent result from Daya Bay

- $\theta_{13}$ is $\sim 9^\circ$
- Leads to large BF predictions for $\mu \rightarrow eee$
Recent result from Daya Bay

- $\theta_{13}$ is $\sim 9^\circ$
- Leads to large BF predictions for $\mu \rightarrow eee$

Even more recent result from RENO:

- $\theta_{13}$ is indeed $\sim 9^\circ$
Tree-Level LFV

• Models with a $Z'$ with flavour off-diagonal couplings
• Models with large extra dimensions (Kaluza-Klein states)
Predictions: $\mu \rightarrow$ $\text{eee}$ vs. $\mu \rightarrow$ $\text{e}\gamma$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\frac{B(\mu \rightarrow \text{eee})}{B(\mu \rightarrow \text{e}\gamma)}$ (predicted)</th>
<th>$B(\mu \rightarrow \text{eee})$ (experimental constraint)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSugra with seesaw</td>
<td>$\sim 10^{-2}$</td>
<td>$&lt; 2.5 \times 10^{-14}$</td>
</tr>
<tr>
<td>SUSY with SO(10) GUT</td>
<td>$\sim 10^{-2}$</td>
<td>$&lt; 2.5 \times 10^{-14}$</td>
</tr>
<tr>
<td>SUSY + Higgs</td>
<td>$\sim 10^{-2}$</td>
<td>$&lt; 2.5 \times 10^{-14}$</td>
</tr>
<tr>
<td>$Z'$, Kaluza-Klein</td>
<td>$&gt; 1$</td>
<td>$&lt; 10^{-12}$</td>
</tr>
<tr>
<td>Little Higgs</td>
<td>$0.1 - 1$</td>
<td>$&lt; 10^{-12}$</td>
</tr>
<tr>
<td>Higgs Triplet</td>
<td>$10^{-3} - 10^{3}$</td>
<td>$&lt; 10^{-12}$</td>
</tr>
</tbody>
</table>
A general effective Lagrangian

\[ L_{\mu \rightarrow eee} = 2 G_F (m_{\mu} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L^\dagger F_{\mu\nu} + m_{\mu} A_L \bar{\mu}_L \sigma^{\mu\nu} e_R^\dagger F_{\mu\nu} + m_{\mu} A_{\mu} \sigma^{\mu\nu} e_R^\dagger F_{\mu\nu} + m_{\mu} A_{\mu} \sigma^{\mu\nu} e_L^\dagger F_{\mu\nu} + H. C.) \]

Tensor terms (dipole) e.g. supersymmetry

- \[ + g_1 (\bar{\mu}_R e_L^\dagger) (\bar{e}_R e_L) \]
- \[ + g_2 (\bar{\mu}_L e_R^\dagger) (\bar{e}_L e_R) \]
  scalar

- \[ + g_3 (\bar{\mu}_R \gamma^\mu e_R^\dagger) (\bar{e}_R \gamma^\mu e_R) \]
- \[ + g_4 (\bar{\mu}_L \gamma^\mu e_L^\dagger) (\bar{e}_L \gamma^\mu e_L) \]
  vector

- \[ + g_5 (\bar{\mu}_R \gamma^\mu e_R^\dagger) (\bar{e}_L \gamma^\mu e_L) \]
- \[ + g_6 (\bar{\mu}_L \gamma^\mu e_L^\dagger) (\bar{e}_R \gamma^\mu e_R) \]
  vector

Four-fermion terms e.g. Higgs, Z', doubly charged Higgs....

\[(Y. Kuno, Y. Okada, Rev. Mod. Phys. 73 (2001) 151)\]
And a simpler Lagrangian

\[
L_{\text{LFV}} = \frac{m_\mu}{(k+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(k+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_L \gamma^\mu e_L)
\]

- Retain only one loop term and one contact term
- Ratio \(\kappa\) between them
- Common mass scale \(\Lambda\)
- Allows for sensitivity comparisons between \(\mu \to eee\) and \(\mu \to e\gamma\)
- In case of dominating dipole couplings (\(\kappa = 0\)):

\[
\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})
\]
Why $\mu \rightarrow eee$?

- A search for $\mu \rightarrow eee$ with a sensitivity of $10^{-16}$ has a large potential to discover LFV or to set very stringent bounds on new physics.

- Complementary to LFV searches in conversion or $\mu \rightarrow e\gamma$.

- Complementary to quark flavour physics and LHC.

- Reaching mass scales way beyond direct reach of LHC.
Why $\mu \rightarrow eee$?

- Muons are plentiful and clean
- Advances in detector technology allow for high rate & high precision experiments
- Three body decay offers more constraints and options to study LFV mechanism and CP violation in case of a discovery
- A search for $\mu \rightarrow eee$ with a sensitivity of $10^{-16}$ has a large potential to discover LFV or to set very stringent bounds on new physics
An experiment searching for

\[ \mu \rightarrow eee \]
A $\mu \rightarrow eee$ experiment sensitive to $10^{-16}$

Need a lot of muons

Need to suppress background by $10^{16}$
The Paul Scherrer Institut (PSI) in Villigen, Switzerland has the world’s most powerful DC proton beam (2.2 mA at 590 MeV).

Pions and then muons are produced in rotating carbon targets.
DC muon beams at PSI:

- $\mu$E1 beamline: $\sim 5 \times 10^8$ muons/s
- $\pi$E5 beamline: $\sim 10^8$ muons/s  
  (MEG experiment)
- $\mu$E4 beamline: $\sim 10^9$ muons/s
- SINQ (spallation neutron source) target could even provide $\sim 5 \times 10^{10}$ muons/s

- The $\mu \rightarrow eee$ experiment (final stage) requires $2 \times 10^9$ muons/s focused and collimated on a $\sim 2$ cm spot
• Two positrons and one electron
• Coincident in time and vertex
• In a plane
• Energies sum up to muon mass
Accidental Background

- Overlays of two normal muon decays with an electron
- Electrons from Bhabha-scattering, photon conversion, mis-reconstruction

Need excellent:

- Vertex resolution
- Timing resolution
- Kinematics reconstruction
Internal Conversion Background

Radiative muon decay with internal conversion

- Looks like signal
- Except for missing energy
Internal Conversion Background

- Branching fraction $3.4 \times 10^{-5}$
- Need excellent momentum resolution to reject this background

Last Experiment: SINDRUM

SINDRUM (1988)

- $\sigma_p/p$ (50 MeV/c) = 5.1%
- $\sigma_p/p$ (20 MeV/c) = 3.6%
- $\sigma_\theta$ (20 MeV/c) = 28 mrad
- Vertex: $\sigma_d \approx 1$ mm
- $\chi_0$ (MWPC) = 0.08 - 0.17% per layer
State of the art: MEG

MEG (2010)

- $\sigma_p/p$ (53 MeV/c) = 0.6%
- $\sigma_\theta$ (53 MeV/c) = 11 mrad
- $\sigma_\phi$ (53 MeV/c) = 7 mrad
- Vertex: $\sigma_r \approx 1.1$ mm, $\sigma_z \approx 2.0$ mm
The challenge: Rates and precision

Tracking of $2 \times 10^9$ electrons/s

With sub-MeV momentum resolution

In a multiple scattering dominated regime
Multiple scattering

- Decay particles are electrons with momenta $< 53$ MeV/c

- Strong multiple scattering
  \[ \propto \sqrt{X/X_0} \times 1/p \]

- Need a thin, fast, high resolution detector

- Rates and aging speak against a gaseous detector

- Silicon is heavy - or is it?
## Silicon detector technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Thickness</th>
<th>Speed</th>
<th>Readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS pixel</td>
<td>260 μm</td>
<td>25 ns</td>
<td>extra RO chip</td>
</tr>
<tr>
<td>DEPFET (Belle II)</td>
<td>50 μm</td>
<td>slow (frames)</td>
<td>extra RO chip</td>
</tr>
<tr>
<td>MAPS</td>
<td>50 μm</td>
<td>slow (diffusion)</td>
<td>fully integrated</td>
</tr>
<tr>
<td>HV-MAPS</td>
<td>&gt; 30 μm</td>
<td>O(100 ns)</td>
<td>fully integrated</td>
</tr>
</tbody>
</table>
High voltage monolithic active pixel sensors

- Implement logic directly in N-well in the pixel - smart diode array
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Can be thinned down to < 50 μm
- Low power consumption

(I. Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg))
Sensor Specs

- Module size $6 \times 1$ cm (inner layers)
  $6 \times 2$ cm (outer layers)
- Pixel size $80 \times 80$ μm
- Goal for thickness: 50 μm
- 1 bit per pixel, zero suppression on chip
- Power: 150 mW/cm$^2$
- Data output up to 3.2 Gbit/s
- Time stamps every 50 ns
  (20 MHz clock for low power consumption, gas cooling)
Momentum resolution given by (linearised):

\[ \frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega} \]

- Precision requires large lever arm (large bending angle \( \Omega \))
Momentum resolution for half turns given by

\[ \frac{\sigma_p}{p} \sim O(\theta_{MS}^2) \]

- Best precision for half turns
- Design tracker to measure recurlers
Detector concept

$\mu_3e$ Beam

Target
Detector concept

- Target
- Inner pixel layers
- Outer pixel layers
- $\mu$ Beam
Detector concept

- **μ Beam**
- **Scintillating fibres**
- **Inner pixel layers**
- **Target**
- **Outer pixel layers**
Detector concept

Recurl pixel layers

Scintillating fibres

Inner pixel layers

Target

Outer pixel layers

μ Beam
Detector concept

Recurl pixel layers

Scintillator tiles

Scintillating fibres

Inner pixel layers

Target

Outer pixel layers

μ Beam

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Detector Concept
Mechanics

- 50 \mu m silicon is not self-supporting...
- Use 25 \mu m Kapton flexprints for support and connection
- Very light and surprisingly sturdy
Mechanics
Sensor prototype

University of Heidelberg/ZITI Mannheim

- Prototype in IBM 180 nm process under test
Prototype sensors perform well

- Signal/Noise > 40
- Nice time-over-threshold spectra (X-ray fluorescence)
Timing

- The silicon detector is read out with 20 MHz (power consumption)
- Hundred electron tracks in one frame
- Can be resolved by hodoscope
- Scintillating fibres in central part ~ 1 ns
- Scintillating tiles in extensions ~ 100 ps
- Resolution ~ 100 ps - on average one electron
The silicon detector is read out with 20 MHz (power consumption)

- Hundred electron tracks in one frame
- Can be resolved by hodoscope
- Scintillating fibres in central part ~ 1 ns
- Scintillating tiles in extensions ~ 100 ps
- Resolution ~ 100 ps - on average one electron
Scintillating fibres

- High spatial resolution for matching with pixels
- 200-250 μm fibres
- Photosensor: SiPM array; high gain, high frequency
- Readout via switched capacitor array (PSI developed DRS5 chip)
Data acquisition

Pixel detector:
- 250 million (zero suppressed) channels
- ~ 2000 hits per 50 ns frame

Fibre tracker:
- ~ 10'000 (zero suppressed) channels

For a muon stop rate of $2 \times 10^9$/s:
- Data rate ~ 150 Gbyte/s
Internet software filter farm

- Continuous front-end readout (no trigger)
- FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s
• Send data to GPU - process - return results (double buffered)

• Fit circle to four points

• Using non-iterative algorithm by V. Karimäki (~400 FLOPS/ 32 bytes input)

• OpenCL implementation on AMD Radeon HD 7990 (3 GB) on an AMD FX 8150 system

• Factor 7 faster than 8 core CPU
Starting simple: GPU circle fits

- Send data to GPU - process - return results (double buffered)
- Fit circle to four points
- Using non-iterative algorithm by V. Karimäki (~400 FLOPS/ 32 bytes input)
- OpenCL implementation on AMD Radeon HD 7990 (3 GB) on an AMD FX 8150 system
- Factor 7 faster than 8 core CPU
- Needs lots of data
- Limited by PCI bus

Graph showing performance with different numbers of Fits/write vs. Tracks/Batch.
Technical challenge: Getting data into and out of GPU fast enough

- PCIe 3.0
- PCI cards with optical links will do DMA to GPU memory (PANDA development)

Floating point power sufficient to fit $O(10^{10})$ tracks on $O(50)$ devices

M. Turany et al., GSI/Giessen University
• Use both analytical estimates and a full Geant4 simulation
• Momentum resolution below 0.5 MeV/c achievable over large phase space
• Fully 3D track fit in preparation
• Track finding with 100 tracks/frame interesting challenge
• Geometrical acceptance ~70%
Performance: background rejection

- Suppressing accidental background fairly straightforward
- Internal conversion background is limiting
- Sensitivity down to $10^{-16}$ achievable with $< 0.5$ MeV/c momentum resolution

![Graph showing sensitivity versus energy resolution](image)

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A proto-collaboration has formed and submitted a letter of intent to PSI

- University of Geneva
- University of Heidelberg
- Paul Scherrer Institut (PSI)
- University of Zurich
- ETH Zurich

Also in contact with other interested groups

Goal: Detailed Research Proposal by 2013
Summary

- Lepton flavour violation might be just around the corner
- Novel concept for an experiment searching for $\mu \rightarrow eee$
- Technologies: HV monolithic pixel sensor and fibre tracker
- Sensitivity of $10^{-16}$ feasible
- After more than 20 years, time has come to go beyond the very successful SINDRUM experiment
Acceptance

Track electrons from with $p = 15 \, \text{to} \, 53 \, \text{MeV/c}$

- Acceptance depends on the model
- Generally better for four-fermion (red) than for photon penguin graphs
- Low minimum momentum required

\[
L_{\mu \to eee} = 2 \, G_F \left( m_\mu A_R \, \bar{\mu}_R \, \sigma^{\mu\nu} \, e_L \, F_{\mu\nu} \right) \\
+ g_1 \left( \bar{\mu}_R \, e_L \right) \left( \bar{e}_R \, e_L \right) \\
+ g_3 \left( \bar{\mu}_R \, \gamma^{\mu} \, e_R \right) \left( \bar{e}_R \, \gamma^{\mu} \, e_R \right) \\
+ g_5 \left( \bar{\mu}_R \, \gamma^{\mu} \, e_R \right) \left( \bar{e}_L \, \gamma^{\mu} \, e_L \right) \\
+ g_6 \left( \bar{\mu}_R \, \gamma^{\mu} \, e_L \right) \left( \bar{e}_R \, \gamma^{\mu} \, e_R \right) + \text{H. C.}
\]
Can derive $\mu \rightarrow eee$ branching ratio from fitting neutrino masses and constraints from $\mu \rightarrow e$ conversion on nuclei


Sensitive to multi-TeV leptoquarks
LFV in Little Higgs Models

\[ \mu e \rightarrow \mu e \]

\[ \nu_j \rightarrow \nu_j \]

\[ Z \rightarrow Z \]

\[ X \rightarrow X \]

\[ N_i \rightarrow N_i \]

\[ \phi \rightarrow \phi \]

\[ Z/Z'/\gamma \rightarrow Z/Z'/\gamma \]

\[ \mu \rightarrow \mu \]

\[ N_i \rightarrow N_i \]

\[ N_j \rightarrow N_j \]
LFV in Little Higgs Models

- Simplest Little Higgs Model
- Conversion experiments provide strongest constraints
- Access to scales > 50 TeV (curves)

(F. del Aguila, J.I. Illana, M.D. Jenkins, JHEP 1103 (2011) 080)