Background in the Mu3e Experiment
Searching for Lepton Flavour Violation

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The Mu3e Experiment

Indirect search for the lepton flavour violating decay $\mu^+ \rightarrow e^+ e^- e^+$

In this talk
- Introduction to Mu3e
- Detector Concept
- Background Studies
The Mu3e Experiment
Charged Lepton Flavour Violating Decay $\mu^+ \rightarrow e^+ e^- e^+$

Lepton Flavour conserved in Standard Model

... but $\nu$ oscillations

Expectation from lepton mixing: $\text{BR}_{\mu \rightarrow eee} \sim \left( \frac{\Delta m_\nu}{m_W} \right)^4 < 10^{-54}$
The Mu3e Experiment
Charged Lepton Flavour Violating Decay $\mu^+ \rightarrow e^+ e^- e^+$

Observation of $\mu \rightarrow eee$ is a clear sign for New Physics
SUSY, extra heavy vector bosons ($Z'$), ...

$\mu$ is sensitive to one in $10^{15} \mu$ decays
Current limit: $\text{BR}_{\mu \rightarrow eee} < 1.0 \cdot 10^{-12}$ at 90% CL [SINDRUM, 1988]
Signal Decay $\mu \rightarrow eee$

Signature for $\mu$ decay at rest

- Common vertex
- Coincident in time
- $\sum E_e = m_\mu c^2$
- $\sum \vec{p}_e = 0$
- $E_e = (0 - 53) \text{ MeV}$

Multiple Coulomb scattering limits momentum resolution
Overlays of Michel decay, Bhabha scattering, photon conversion, . . .

No common vertex
Not coincident
\[ \sum E_e \neq m_\mu c^2 \]
\[ \sum \vec{p}_e \neq 0 \]

Increases with beam intensity
Background
Internal Conversion Decay $\mu \rightarrow eee\nu\bar{\nu}$

$$\text{BR}_{\mu^+ \rightarrow e^+e^-e^+\nu_\mu \nu_e} = (3.4 \pm 0.4) \cdot 10^{-5} \text{[Nucl.Phys.B260, 1985]}$$

Common vertex
Coincident in time
$$\sum E_e < m_\mu c^2$$
$$\sum \vec{p}_e \neq 0$$
$\rightarrow$ Missing energy due to neutrinos

Need very good momentum resolution
The Mu3e Detector

Tracking detector:
50 µm Si pixel sensors (HV-MAPS)
+ Lightweight mechanics

+ Timing detector:
Scintillating fibres and tiles

Paul-Scherrer Institute (CH)
Polarized µ beam with $10^8 \mu /s$
The Mu3e Detector

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Paul-Scherrer Institute (CH)
Polarized μ beam with $10^8 μ/\text{s}$

Full Geant4-based simulation
Background decays

Michel decay $\mu \rightarrow e\nu\bar{\nu}$

Radiative decay $\mu \rightarrow e\gamma\nu\bar{\nu}$

Internal conversion $\mu \rightarrow eee\nu\bar{\nu}$

Signal $\mu \rightarrow eee$

3-body decay

Other effects

Multiple Coulomb scattering

Bhabha scattering
Internal Conversion Decay $\mu \rightarrow eee\nu\bar{\nu}$ in Simulation

$$\Gamma_{\mu \rightarrow eee\nu\bar{\nu}} \propto |T_{\mu \rightarrow eee\nu\bar{\nu}}|^2 \rho$$


Only unpolarized muons
Internal Conversion Decay $\mu \rightarrow eee\nu\bar{\nu}$ in Simulation

\[\Gamma_{\mu \rightarrow eee\nu\bar{\nu}} \propto |T_{\mu \rightarrow eee\nu\bar{\nu}}|^2 \rho\]

New calculations by A. Signer et al. (PSI) take polarisation into account

High-energy positrons in acceptance

A. Perrevoort (Heidelberg)
Internal Conversion Decay $\mu \rightarrow eee\nu\bar{\nu}$ in Simulation

Suppress $\mu \rightarrow eee\nu\bar{\nu}$ by cuts on electron energy

$$E_{tot} = \sum E_e \xrightarrow{\mu \rightarrow eee} m_\mu c^2$$
Internal Conversion Decay $\mu \rightarrow eee\nu\bar{\nu}$ in Simulation

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Djilkibaev, Konoplich
Sensitivity Studies

Reconstructed mass for signal and background events

Mu3e: $1 \cdot 10^{15}$ μ on Target; Rate $10^8$ μ/s

Events per 100 keV/c

Reconstructed Mass [MeV/c$^2$]

Internal Conversion Background

Simulations: μ → eee at $10^{-12}$

Simulations: μ → eee at $10^{-13}$

Simulations: μ → eee at $10^{-14}$

Simulations: μ → eee at $10^{-15}$

Bhabha e$^+$e$^-$ + Michel e$^+$
Summary

Mu3e

Precision experiment searching for LFV decay $\mu \rightarrow eee$
Aiming at a sensitivity of $\text{BR} \sim 10^{-15}$

Simulation
Full description of the experiment
All background processes consider $\mu$ polarization

Next steps
Higher order corrections for background
Sensitivity studies for different models beyond SM
Status

Current status

Research proposal approved in 2013
Technical design report in preparation (Q1 2016)
Research and development of subsystems
Preparation of detector construction

Outlook

Commissioning and first data in 2017
History of LFV Searches in $\mu$ and $\tau$ Decays

Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]
Loop and Tree Level Contributions

\[ L_{LFV} = \left[ \frac{m_\mu}{(\kappa+1)\Lambda^2} \mu_R \sigma^{\mu\nu} e_L F_{\mu\nu} \right]_\gamma \text{penguin} + \left[ \frac{\kappa}{(\kappa+1)\Lambda^2} (\mu_L \gamma^\mu e_L) (\bar{e}_L \gamma_\mu e_L) \right]_\text{tree} \]

Adapted from A. de Gouvêa [Nucl.Phys.B188 2009]
Mu3e Simulation
Radiative Muon Decay $\mu \to e\gamma\nu\bar{\nu}$

$$\text{BR}_{\mu \to e\gamma\nu\bar{\nu}} = (1.4 \pm 0.4)\% \text{ for } E_{\gamma}^{\text{min}} > 10 \text{ MeV}$$

Use BR calculated by Kuno et al. [Rev.Mod.Phys 73, 2001]

Divergence for $E_{\gamma} \to 0$

Generate $\gamma$ momentum distributed according to $\sim \frac{1}{E_{\gamma}}$

Accept/reject events based on BR

Assign minimum $E_{\gamma}^{\text{min}}$, typ. 10 MeV

Scale BR using MC integration for $E_{\gamma}^{\text{min}} \neq 10 \text{ MeV}$

Distribution of photon momentum $y = \frac{2p_\gamma}{m_\mu}$
Pixel Sensors

High Voltage Monolithic Active Pixel Sensors

- High voltage of $> 50$ V
- Fast charge collection via drift
- Depletion zone of $\sim 10 \mu m$
- Thinning possible ($\lesssim 50 \mu m$)
- Integrated readout electronics
- Pixel size $80 \times 80 \mu m^2$

Thin and highly granular
Lightweight Mechanics

- 50 µm silicon sensor
- 25 µm Kapton flexprint with aluminum traces
- 25 µm Kapton support structure

→ ~ 1‰ of radiation length
Paul-Scherrer Institute in Switzerland

2.2 mA proton beam 590 MeV

Secondary beamlines: $\mu^+$ with 28 MeV/c

$10^8$ muons/s at existing beamline → Phase I

$10^9$ muons/s at future beamline → Phase II
Phase II Detector

Reach $\text{BR} \sim 10^{-16}$ with a muon rate of $10^9 \mu/s$
Simulation of 50 ns of Beam Time (Phase II)

Tracks per readout frame of 50 ns

Exploiting time resolution of scintillating fibres (1 ns) and tiles (0.1 ns)
Readout Concept

4860 Pixel Sensors

~ 4000 Fibres

~ 7000 Tiles

4 Subfarms

Data Collection Server

Mass Storage