Status of the Mu3e Experiment at PSI

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The Mu3e Experiment

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

In this talk

• Introduction to Mu3e
• Experimental Concept
• Current Status and Outlook
Charged Lepton Flavour Violation
Searching for New Physics in the Decay $\mu \rightarrow eee$

Lepton Flavour conserved in Standard Model

... but $\nu$ oscillations

Expectation from lepton mixing: $\text{BR}_{\mu \rightarrow eee} \sim \left(\frac{\Delta m_{\nu}}{m_W}\right)^4 < 10^{-54}$
Charged Lepton Flavour Violation
Searching for New Physics in the Decay $\mu \to eee$

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

Current limit: $\text{BR}_{\mu \to eee} < 1.0 \cdot 10^{-12}$ at 90% CL [SINDRUM, 1988]

Mu3e: New experiment sensitive to BR’s of $10^{-15}$ ($10^{-16}$)
Charged Lepton Flavour Violation

Searching for New Physics in the Decay $\mu \to eee$

\[ \mathcal{L}_{\text{CLFV}} = \left[ \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu} R \sigma_{\mu\nu} e_L F_{\mu\nu} \right]_{\text{dipole-like}} + \left[ \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu} L \gamma_\mu e_L)(\bar{e} L \gamma^\mu e_L) \right]_{\text{four-fermion}} \]

A. Gouvêa, P. Vogel, Prog.Part.Nucl.Phys. 71 (2013)
Signal and Background

**Signal**

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

Common vertex
Coincident
\[ \sum E_e = m_\mu \]
\[ \sum \vec{p}_e = 0 \]

**Background**

**Accidental combinations**

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

**Internal conversion**

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

Common vertex
Coincident
\[ \sum E_e < m_\mu \]
\[ \sum \vec{p}_e \neq 0 \]
Signal and Background

Background

Internal conversion
\[ \mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e \]
Common vertex
Coincident
\[ \sum E_e \ < \ m_\mu \]
\[ \sum \vec{p}_e \neq 0 \]
Signal and Background

Signal

Background

Detector requirements:

• Very good vertex (~ 200 µm) and time resolution (~ 100 ps)
• Excellent momentum resolution (~ 0.5 MeV)
• Minimal material amount

+ High muon stopping rates (10^8 to 10^9 muons/s)

Thin silicon pixel sensors
+ Scintillating fibres/tiles
Experimental Concept

Phase I: Detector Configuration A

Tracking detector with Si pixel sensors

Phase IA

$10^7$ muons/s
BR $\sim 10^{-14}$
2017
Experimental Concept
Muon Beam

Paul-Scherrer Institute in Switzerland

2.2 mA proton beam with 590 MeV
Secondary beamlines: $\mu^+$ with 28 MeV

$10^8$ muons/s at existing beamline
$10^9$ muons/s at future beamline under investigation
Experimental Concept
High-Voltage Monolithic Active Pixel Sensors

- High voltage of > 60 V
- Fast charge collection via drift
- Depletion zone of $\sim 10 \, \mu m$
  Thinning possible ($\lesssim 50 \, \mu m$)
- Integrated readout electronics
- Pixel size $80 \times 80 \, \mu m^2$
  Sensor size $2 \times 2 \, cm^2$

Thin and granular
Experimental Concept
High-Voltage Monolithic Active Pixel Sensors

Latest prototype: MuPix7

- Pixel size 103 × 80µm²
  Sensor size 2.9 × 3.2mm²
- Zero-suppressed hit addresses and timestamps via fast serial link
- Successfully tested in lab and in testbeam campaigns
Experimental Concept

Lightweight Mechanics

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

→ ~ 1 % of radiation length

Cooling with gaseous helium
Experimental Concept

Data Acquisition

Triggerless data acquisition

Front-end board
- Buffer and merge data of $O(15)$ sensors
- Time-sorting
- Slow control

Switching board
- Switch between front-end and filterfarm
- Merge data of sub-detectors

GPU filterfarm
- Fast track finding and online reconstruction
- Reduce data rate from $\sim 1 Tbit/s$ to $\sim 100$ MB/s
Experimental Concept
Phase I

Increase muon rate to $10^8$ muons/s → precise time measurement required

Tracks expected within readout frame of 50 ns

Matching with time information of scintillating fibres and tiles
Experimental Concept

Phase I: Detector Configuration B

Scintillators improve time resolution
Experimental Concept
Phase I: Detector Configuration B

Improve momentum resolution by measuring re-curling particles
Increase acceptance for re-curlers
Experimental Concept

Phase I: Detector Configuration B

Phase IB

$10^8$ muons/s
BR $\sim 10^{-15}$
2018
Experimental Concept

Scintillating Fibres

- ∼ 3 layers of fibres with diameter of 250 µm
- Round and squared fibres under investigation
- Photon detection at both ends with SiPM array
- Readout with custom-designed STiC chip

Time resolution:

\[
\frac{\sigma_{\text{round}}}{\sqrt{2}} \approx 1.5 \text{ ns}
\]

\[
\frac{\sigma_{\text{squared}}}{\sqrt{2}} \leq 500 \text{ ps}
\]
Experimental Concept
Scintillating Tiles

- Size $\sim 1 \times 1 \times 1\text{cm}^3$
- Each tile has a SiPM
- Readout with custom-designed STiC chip
- Time resolution $\lesssim 100\text{ps}$
Phase II

$10^9$ muons/s at future beamline
BR $\sim 10^{-16}$
2020+
Sensitivity Studies

Reconstructed mass for signal and background events

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

Reconstructed Mass (MeV)

96 98 100 102 104 106 108 110

Events per 100 keV

-4 $10^{-4}$
-3 $10^{-3}$
-2 $10^{-2}$
-1 $10^{-1}$

Internal Conversion Background

+$\mu$ eee at $10^{-12}$
+$\mu$ eee at $10^{-13}$
+$\mu$ eee at $10^{-14}$
+$\mu$ eee at $10^{-15}$

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

SIMULATION
Summary

Mu3e

Precision experiment searching for LFV decay $\mu \rightarrow eee$
Aiming at a sensitivity of BR $\sim 10^{-15}(10^{-16})$

Lightweight pixel detector made of HV-MAPS
Precise timing by scintillating fibres/tiles
Triggerless readout
Operated at $10^8$ muons/s
Status and Outlook

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
- Phase IA: BR $\sim 10^{-14}$ (2017)
- Phase IB: BR $\sim 10^{-15}$ (2018)
- Phase II: BR $\sim 10^{-16}$ (2020+)
  - requires muon rates of $10^9$ muon/s
Appendix
History of LFV Searches in $\mu$ and $\tau$ Decays

Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]
Tuesday 16/12/2014
“Compact Muon Beam Line” Test Setup achieved “Proof-of-Principle”
$1 \times 10^8$ Muons/s at
Mu3e Solenoid Injection Point
Decay electrons have low momentum $< 53 \text{ MeV/c}$

Momentum resolution is dominated by multiple scattering

$$\frac{\sigma}{p} \sim \frac{\theta_{\text{MS}}}{\Omega}$$

$$\theta_{\text{MS}} \propto \frac{1}{\beta cp} \sqrt{\frac{x}{X_0}}$$
Multiple Coulomb Scattering

Decay electrons have low momentum < 53 MeV/c

Momentum resolution is dominated by multiple scattering

$$\frac{\sigma}{p} \sim \frac{\theta_{\text{MS}}}{\Omega}$$

$$\theta_{\text{MS}} \propto \frac{1}{\beta c p} \sqrt{\frac{x}{X_0}}$$
Layout of MuPix7

Pixel Matrix

Readout Control  Periphery

A. Perrevoort (Heidelberg)  Mu3e

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Readout Concept

4860 Pixel Sensors

- 4860 Pixel Sensors
- up to 56 1250 Mbit/s links
- FPGA
- FPGA FPGA
- ... 82 FPGAs
- RO Board
- Group A
- RO Board
- Group B
- RO Board
- Group C
- RO Board
- Group D
- 1.6 Gbit/s link each
- 12 10 Gbit/s links per RO Board

~ 4000 Fibres

- ~ 4000 Fibres
- FPGA
- 16 FPGAs
- RO Board
- Group A
- RO Board
- Group B
- RO Board
- Group C
- RO Board
- Group D
- 12 PCs

~ 7000 Tiles

- ~ 7000 Tiles
- FPGA
- 14 FPGAs
- RO Board
- Group A
- RO Board
- Group B
- RO Board
- Group C
- RO Board
- Group D
- 12 PCs

12 PCs

- 12 PCs
- Gbit Ethernet
- Subfarm A
- Subfarm B
- Subfarm C
- Subfarm D

Data Collection Server

Mass Storage

A. Perrevoort (Heidelberg)  Mu3e  FCCP 2015  6 / 7
Mu3e Collaboration

DPNC, Geneva University
KIP, Heidelberg University
Physics Institute, Heidelberg University
IPE, Karlsruhe Institute of Technology
Institute for Nuclear Physics, JGU Mainz
Paul Scherrer Institute
Institute for Particle Physics, ETH Zürich
Physics Institute, Zürich University