The Mu3e Experiment
Introduction and Current Status

Moritz Kiehn for the Mu3e Collaboration

Physikalisches Institut, Universität Heidelberg

The Mu3e Experiment

- Precision experiment
- Search for $\mu^+ \rightarrow e^+e^-e^+$
- Sensitivity $< 1$ in $10^{16}$ decays

In this talk
- Experimental Concept
- Current Status
- Pixel Sensor Prototypes
$\mu \rightarrow eee$ in the Standard Model

**Features**

- Charged lepton flavor violating
- Via neutrino mixing
- Expected $\text{BR}(\mu \rightarrow eee) \ll 10^{-50}$
- Current Limit from Sindrum $\text{BR}(\mu \rightarrow eee) < 1 \cdot 10^{-12}$ @90% CL

*Nucl.Phys. B299(1)*

**Importance**

- Observable rate only from *New Physics*
- Sensitive New Physics Search
Paul Scherrer Institute

- Villigen, Switzerland
- Currently hosts the MEG Experiment

Muon Beamlines

- Low energy DC beams
- Current beam lines: \( \approx 1 \cdot 10^8 \mu/s \) (\( \pi E5 \))
- Future high intensity beam: \( > 1 \cdot 10^9 \mu/s \)
2 \times 10^9 \, \mu/s
50 \, \text{ns integration}
Signal and Backgrounds

Signal
- Common vertex
- $\sum \vec{p}_i = 0$
- $p < 53 \text{ MeV}$

Backgrounds
- Internal Conversion
  - Common vertex
  - $\sum \vec{p}_i \neq 0$
  - In-time
  - Requires $\sigma_p < 0.5 \text{ MeV}$
  - $\sigma_t < 1 \text{ ns}$
- Combinatorial
  - No common vertex
  - Out-of-time
Multiple Scattering

\[ \theta_{MS} \sim \frac{1}{p} \sqrt{x/X_0} \]

Example

- \( p = 35 \text{ MeV} \)
- 200 µm Si
- \( \Omega R = 5 \text{ cm} \)
- \( \Delta y \approx 1 \text{ mm} \)

→ Low material budget
Detector Concept

Environment

- $> 10^9 \mu^+$ Decays/s
- Electrons $p < 53$ MeV
- Multiple scattering dominates
Environment

- $> 10^9 \mu^+$ Decays/s
- Electrons $p < 53$ MeV
- Multiple scattering dominates
Detector Concept

Environment

- $> 10^9 \mu^+$ Decays/s
- Electrons $p < 53$ MeV
- Multiple scattering dominates
Detector Concept

Environment

- $> 10^9 \mu^+$ Decays/s
- Electrons $p < 53$ MeV
- Multiple scattering dominates
Full Detector

Magnetic field $\sim 1$ T
Continuous readout

Tracker Requirements

- Fast serial readout $\sim 20$ MHz
- Thin $< 1 \% \times X_0$
- $80 \mu m \times 80 \mu m$ pixel
- $1$ cm $\times$ $2$ cm sensor area

Timing

- Resolution $< 1$ ns
Ultra-Lightweight Mechanics

- 50 µm Silicon sensor
- 25 µm Kapton flexprint
- 25 µm Kapton support frame
→ \( \sim 1\% \) Radiation length
Scintillating Fibres

Fibre and SiPM Array

- 3-5 layers of fibres
- Readout with SiPM and custom ASIC (StiC)
- Time resolution $\sim 1\,\text{ns}$ ($^{22}\text{Na}$-source)

Efficiency $> 98\%$
(2 photons or more)

Signal Spectrum
Scintillating Tiles

Tile Station

Tile Prototype

Time Resolution

- $\sigma = 79.2$ ps

- $\sim 0.5 \text{ cm}^3$ per tile
- Readout with SiPM and custom ASIC (StiC)
- Time resolution $\sim 80$ ps (testbeam)
HV $\sim 70$ V (HV-MAPS)
- Fast charge collection by drift
- Thin active zone $< 20$ $\mu$m
- Cheap, commercial process
HV-MAPS Prototypes

Design Specifications

- 80 µm × 80 µm pixel size
- 1 cm × 2 cm active area

MuPix2

- 39 µm × 30 µm pixel size
- 1.8 mm × 1 mm active area
- Proof of Concept

MuPix3/4

- 92 µm × 80 µm pixel size
- 2.9 mm × 3.2 mm active area
MuPix4 HV-MAPS Prototype

- 92 µm × 80 µm pixel size
- Global threshold
- Zero-suppressed digital readout
- Timestamps
- Additional readout FPGA
Single Hit Resolution

0° incidence angle
70 V high voltage
823 mV threshold
Global Efficiency

Effective thickness $\sim \frac{1}{\cos \alpha}$

- 0.0° incidence angle
- 22.5° incidence angle
- 45.0° incidence angle

HV = 70V
E = 5GeV
Pixel Efficiency

0° incidence angle
70 V high voltage
823 mV threshold
Subpixel Efficiency / 4x4 Pixels

0° incidence angle
70 V high voltage
823 mV threshold
Timing

- Hits per 10 ns bin
- Timestamp frequency 100 MHz
- $\sigma = 16.6$ ns
- Sensor + DAQ
- Resolution 17 ns
Future MuPix Prototypes

MuPix6

- Currently in the lab
- Updated analog part, e.g. 2-stage amplifier
- Same geometry

MuPix7

- Just submitted
- Fast serial readout
- Full digital logic
- Still small scale prototype
Cooling with Helium

Why Helium?

- Low density, low scattering
- High mobility

Temperature Gradient

3.5 m/s in air
**Reconstruction**

**Reconstruction Efficiency**

- > 90% efficiency for 4-hit tracks
- Dropoff is detector acceptance

**Momentum Resolution**

- 3-hit track, $\sigma \approx 1.5$ MeV
- 6-hit track, $\sigma \approx 0.2$ MeV

- Full GEANT4 simulation
- Custom reconstruction
- No energy loss correction
Phase IA: earliest 2016
- $2 \cdot 10^7 \mu/s$
- Central pixel layers

Phase IB: 2017+
+ Timing
+ 1st recurl stations

Phase II: 2019+
- $2 \cdot 10^9 \mu/s$
- Full detector
- Future Muon Beamline
Expected Sensitivity

Phase IA: earliest 2016
- $2 \cdot 10^7 \mu/s$
- Central pixel layers

Phase IB: 2017+
- $1 \cdot 10^8 \mu/s$
- Timing
- 1$^{st}$ recurl stations

Phase II: 2019+
- $2 \cdot 10^9 \mu/s$
- Full detector
- Future Muon Beamline
Expected Sensitivity

Phase IA: earliest 2016
- \(2 \cdot 10^7 \mu/s\)
- Central pixel layers

Phase IB: 2017+
- \(1 \cdot 10^8 \mu/s\)
- Timing
- 1\textsuperscript{st} recurl stations

Phase II: 2019+
- \(2 \cdot 10^9 \mu/s\)
- Full detector
- Future Muon Beamline
Summary and Outlook

Mu3e

- Search for $\mu^+ \to e^+e^-e^+$
- Sensitivity < 1 in $10^{16}$ decays

Features

- HV-MAPS silicon sensors
- Ultra-thin detector
- Down to 100 ps timing
- Up to $2 \cdot 10^9 \mu/s$

In the Future

- First data in 2016+
- Full rate not before 2019

http://www.psi.ch/mu3e
Backup
Silicon Pixel Sensors

Hybrid

- HV $\sim 700$ V
- Sensor thickness $\sim 250$ µm
- Extra material
- Complex and expensive

Monolithic Active Pixel Sensor

- HV $\sim 70$ V (HV-MAPS)
- Thin active zone $< 20$ µm
- Cheap, commercial process
Beyond the Standard Model

In Loops

- e.g. SUSY

At Tree Level

- e.g. new heavy boson
Global Efficiency / High Voltage

\[ \epsilon = \frac{N_{\text{matched}}}{N_{\text{tracks}}} \]

0° incidence angle
\[ E = 5 \text{GeV} \]

- HV = 50V
- HV = 70V