The ultra-light Mu3e Tracker & possibilities for future trackers

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https://www.psi.ch/mu3e/
History of LFV Decay experiments

- **Mu3e I**
- **Mu3e II**

4 orders of magnitude
**LFV Decay** $\mu^+ \rightarrow e^+e^+e^-$

- Supersymmetry
- Little Higgs Models
- Seesaw Models
- GUT models (Leptoquarks)
- many other models

- Higgs Triplet Model
- New Heavy Vector bosons ($Z'$)
- Extra Dimensions (KK towers)

Most models “naturally” induce lepton flavor violation!
Mu3e Experiment @ PSI

• World’s most intense continuous muon beam \( (f_{\text{cycl.}} = 50\text{MHz}) \)
• 2.4 mA protons at \( 590 \text{ MeV} = 1.5 \text{ MW} \) → \( O(10^{10-11}) \) muons

Aiming for sensitivity (SES)

\[
\begin{align*}
\text{BR}(\mu \rightarrow e e e) &< 2 \cdot 10^{-15} \quad \text{ (phase I)} \quad \rightarrow \quad 10^8 \text{ muons/s} \quad \text{(PiE5)} \\
\text{BR}(\mu \rightarrow e e e) &< 10^{-16} \quad \text{ (phase II)} \quad \rightarrow \quad >10^9 \text{ muons/s} \quad (\rightarrow \text{new HiMB})
\end{align*}
\]
PiE5 Muon Beamline @ PSI

- $O(10^8)$ muons per second
- Low momentum muons 28 MeV/c
- PiE5 beamline shared between MEG2 and Mu3e
PiE5 Area

Compact Muon Beamline (CMBL) for Mu3e
Signal $\mu^+ \rightarrow e^+ e^+ e^-$

- 3-prong signature
- muons decay at rest:
  - two positrons and electron in common plane

Exotic Physics

$\sum_i E_i = m_\mu$
$\sum_i \vec{p}_i = 0$
Irreducible Background

Radiative decay with internal conversion

\[ B(\mu^+ \rightarrow e^+e^+e^-\nu\nu) = 3.4 \cdot 10^{-5} \]

\[ \sum_i E_i = m_\mu \]

\[ \sum_i \vec{p}_i = 0 \]
Irreducible Background

Radiative decay with internal conversion

\[ B(\mu^+ \rightarrow e^+e^-e^-\nu\nu) = 3.4 \cdot 10^{-5} \]

Davey, A. Schöning

very good momentum +
total energy resolution required!

Branching Ratio as a function of cut on \( m_\mu - E_{\text{tot}} \)

missing energy from two neutrinos
steeply falling!

R.M. Djilkibaev,
R.V. Konoplich
PRD79 (2009)

missing energy taken
by neutrinos

very good momentum +
total energy resolution required!
Accidental Backgrounds

- **Overlays** of two ordinary $\mu^+$ decays with a (fake) electron ($e^-$)
- Electrons from: **Bhabha** scattering, photon conversion, mis-reconstruction

Need excellent:
- Vertex resolution
- Timing resolution
- Kinematic reconstruction

+ little material (avoid high Z)
Muon decay ($m = 105.6$ MeV):

$$\rightarrow \text{electrons at low momentum:}$$

$$p < 53 \text{ MeV/c}$$

Multiple scattering is dominant!

- Need **thin**, **fast** and **high** resolution tracking detectors operated at **high rate** ($>10^9$ particles/s @ phase II)

$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X/X_0}$$
Mu3e Experiment

Aiming for a sensitivity (SES)

\[ \text{BR}(\mu \rightarrow e e e) < 2 \cdot 10^{-15} \] (phase I)
\[ \text{BR}(\mu \rightarrow e e e) < 10^{-16} \] (phase II)

requires:
\[ \rightarrow 10^8 \text{ muons/s} \] (PiE5)
\[ \rightarrow >10^9 \text{ muons/s} \] (→ HiMB)
Momentum Resolution in MS Regime

Standard spectrometer:

\[ \sigma_p \sim \frac{\Theta_{MS}}{\Omega} \sim \frac{\sqrt{X}}{\Omega} \]

(linearised)

precision requires large lever arm

→ large bending angle \( \Omega \)
“Half turn” spectrometer:

$\frac{\sigma_p}{P} \sim O(\Theta_{MS}^2) \sim \frac{X}{X_0}$

- best precision for half turn tracks
- measure recurlers
Tracking Design Considerations

\[ \mu \bar{\mu} \]

muon mass \( \sim 105 \text{ MeV}/c^2 \)

50 MeV/c 25 MeV/c 12 MeV/c
Tracking Design Considerations

- $50 \text{ MeV/c}$
- $25 \text{ MeV/c}$
- $12 \text{ MeV/c}$
Tracking Design Considerations
Tracking Design Considerations
Mu3e Baseline Design

$10^8$ muons per second (phase I)

$p = 28$ MeV/c
Mu3e Baseline Design

inner pixel layers

μ Beam

Target
Mu3e Baseline Design

Long cylinder!

~180 cm

Recurl pixel layers
Scintillator tiles

~15 cm

Inner pixel layers
Target
Scintillating fibres
Outer pixel layers

not to scale!
Mu3e Baseline Design

Recur pixel layers

Scintillator tiles

μ Beam

Inner pixel layers

Target

Scintillating fibres

Outer pixel layers

solenoid B=1 T
Mu3e Design

Features:
- surface muons \( (p=29 \text{ MeV/c, DC}) \) stopped on target at high rate: \( 10^8 - 10^9 \text{ /s} \)
- ultra thin **silicon pixel detector** \((\text{HV-MAPS})\) with **1 per mill radiation length** / layer
- high precision tracking using **recurling tracks** in strong magnetic field
- **fast timing** detectors (scintillating fibers & tiles)
- **helium gas cooling**

\[ E_k \sim 4 \text{ MeV} \]
A light-weight pixel tracker

Mu3e: SES scales with the third power of the tracker material!

\[ SES \sim \left( \frac{X_{\text{layer}}}{X_0} \right)^3 \]

→ goal Mu3e: \( \frac{X}{X_0} = 0.001 \)
  - 50 µm HV-MAPS
  - ~150 µm flexprint + mechanical support

In addition:
  - helium atmosphere → reduces multiple scattering
  - cooling of pixel tracker with helium gas

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Material per layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS IBL</td>
<td>1.9% ( X_0 )</td>
</tr>
<tr>
<td>ALICE ITS mid/outer</td>
<td>0.8% ( X_0 )</td>
</tr>
<tr>
<td>ALICE ITS inner</td>
<td>0.3% ( X_0 )</td>
</tr>
<tr>
<td>STAR</td>
<td>0.4% ( X_0 )</td>
</tr>
<tr>
<td>BELLE II vertex</td>
<td>0.2% ( X_0 )</td>
</tr>
<tr>
<td>Mu3e (all layers)</td>
<td>0.1% ( X_0 )</td>
</tr>
</tbody>
</table>
(Outer) Pixel Tracker Module

MuPix chips, 20 x 23 mm²

Overlap

HDI

Interposer

Flexprint

MuPix (HV-MAPS)

Endpiece

High Density Interconnect (LTU, Ukraine)

180 nm HV-CMOS (AMS)

50 µm
Mechanical Mockups

Ultra-thin mechanical mockup:
- sandwich of 25 µm Kapton®
- 50 µm glass (instead of Si)

Even larger stable structures possible

by using Kapton V-folds
Flexprint Production and Bonding

FPC Production by LTU Ltd (Ukraine)

spTAB bond zoomed in

→ bonding yield 100%

FPC spTAB-bonded on test board and qualified

spTAB = single point tape automated bonding
FPC = flexible printed circuit

6.85 cm
Ultralight Pixel Ladder

Mupix sensor 50µm

HDI ~100µm

tap-bonds

polyimide 15µm

Mupix periphery

2 Al layers

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>14</td>
</tr>
<tr>
<td>PI</td>
<td>10</td>
</tr>
<tr>
<td>Glue</td>
<td>5</td>
</tr>
<tr>
<td>PI</td>
<td>25</td>
</tr>
<tr>
<td>Glue</td>
<td>5</td>
</tr>
<tr>
<td>Al</td>
<td>14</td>
</tr>
<tr>
<td>PI</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer 1-2</th>
<th>Layer 3-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness [µm]</td>
<td>X/X₀</td>
</tr>
<tr>
<td>MuPix Si</td>
<td>45</td>
</tr>
<tr>
<td>MuPix Al</td>
<td>5</td>
</tr>
<tr>
<td>HDI polyimide &amp; glue</td>
<td>45</td>
</tr>
<tr>
<td>HDI Al</td>
<td>28</td>
</tr>
<tr>
<td>polyimide support</td>
<td>25</td>
</tr>
<tr>
<td>adhesives</td>
<td>10</td>
</tr>
<tr>
<td>total</td>
<td>158</td>
</tr>
</tbody>
</table>

pixel layer: ~ 1.15 per mille radiation length
High Voltage-Monolithic Active Pixel Sensor (HV-MAPS)

- transistor logic embedded in N-well ("smart diode array")

Active sensors
- hit finding + digitisation + readout

HV-CMOS: 60-120 V, commercial process (AMS, GlobalFoundry, TSI)

- different substrates possible 20-1000 Ω cm
- thickness ~50 μm (~ 0.0005 X₀)

MuPix8 prototype

MuPix has been characterized in the lab and at test beams
- efficiency
- noise
- rate
- temperature-dependence
- (radiation hardness)

I. Peric et al., NIM A 582 (2007) 876
MuPix Chip Design

![Diagram of pixel matrix and periphery]

- **Pixels**: "active" cells
- **Periphery**: "mirror" cells
  - State machine
  - VCO, PLL, ...

**Periphery** (5-10% total area):
MuPix Chip Design

analog cell:
- reverse biased ~ 85V
- charge sensitive amplifier
- source follower
transmission line:
- send signal to corresponding mirror cell
MuPix Chip Design

mirror cell:

- comparator for discrimination
- threshold and baseline by tune DACs
MuPix Hit Detection

hit sequence:
- signal generation
MuPix Hit Detection

hit sequence:
• signal generation
• amplification
MuPix Hit Detection

hit sequence:
- signal generation
- charge amplified
- received in mirror pixel
MuPix Hit Detection

hit sequence:
- signal generation
- charge amplified
- received in mirror pixel
- discriminated
hit sequence:
- signal generation
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
MuPix Hit Detection

hit sequence:
- signal generation
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation
MuPix Hit Detection

hit sequence:
- signal generation
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation
- hit address and timestamp are sent to serializer
MuPix Hit Detection

Finally, all detected hits are sent out via a 1.25 (1.6) Gbit/s serial link.

Eye diagram measured with Mupix7 prototype

Maximum readout rate is 33 Mhits/s per link.
Integration & Connectivity

MuPix chips, 20 x 23 mm²

Overlap

HDI

Interposer

Flexprint

High Density Interconnect (HDI) has only two metal layers!

→ Routing of power, control and signal lines is critical!

Mupix pinout with ~ 21 pins including 3 serial links

HDI design (prel.)

Mupix7 prototype ~100 pins (incl. test)

Requires high level of chip integration:
- power regulators
- state machine
- clock management
- etc.
MuPix8 Performance Maps

Efficiency

Noise

Mupix8 is the first large scale prototype

A. Schöning
MuPix8 Efficiency and Noise

→ almost 100% efficient

untuned & unmasked sensor

1000 e

→ 100% efficient
MuPix8 Timing Resolution

After offline timewalk correction:

\[ \sigma_{\text{time}} = 6.4 \text{ ns} \]
Phase I design

~15 cm

- about 200 million pixels
- power dissipation: $\sim 200-300$ mW/cm$^2$

He cooling in gaps between layers and detectors
V-Fold Cooling Channels

MuPix chip

Endpiece

Flexprint

Interposer

V-fold

He distribution chamber
Mechanics Prototype with V-folds

V-shapes for local cooling channels

Helium cooling:
- global flow
- flow between layers
- flow in V-shapes

early pixel module prototype
Preliminary Simulation Results

Velocity map layer 4

max flow
20 m/s

Temperature map layers 1+2

→ goal $\Delta T = 20-50 \, ^\circ C$

CFD Simulations are validated by lab-measurements

- Targeted power consumption ($P=250 \, mW/cm^2$)
- Maximum allowed power consumption ($P=400 \, mW/cm^2$)
Light-Weight Gas Cooling System

Considerations

- Gas supply lines (pipes) require significant space
- Significant pressure drop of 50-100 mbar in detector
- He-gas needs to be pumped in and out

Example:

- Mupix power dissipation is max. 4 kW in Mu3e 1
- For $1\text{m}^2$ active area and $<\Delta T>=15K \rightarrow 50 \text{ g/s He}$

(corresponds to about $20 \text{ m}^3$ per minute at atmospheric pressure)

I believe up to $100 \text{ m}^3$ per minute (or maybe more) could be realized in future experiments $\rightarrow 20 \text{ kW cooling power}$!
Lessons and Final Remarks

Mu3e ultralight pixel tracker is based on

- monolithic pixel sensors → HV-MAPS
- ultra-light polyimide/aluminium HDIs
- polyimide mechanical support
- He-gas cooling system

Critical points:

- precision of pixel modules + vibration due to gas cooling
  - vibrations measured in lab to be < 5µm
  - Mu3e will constantly monitor alignment online (studied in PhD thesis)

- Aging of polyimide in helium atmosphere in presence of radiation
  - currently under study

- Would like to have longer modules (>36 cm) for Mu3e phase II
  - we believe that is possible if modules are strained (tbc)
Momentum resolution in Mu3e is $100 \text{ keV/c}$ for $20 \text{ MeV/c}$ positrons due to the recurler design.

Similar “trick” works also for HEP experiments → next page
Last Comment II

Momentum resolution of an “ATLAS-like” detector with $B=2T$ for different designs of barrel layers

... might be interesting for physics at the “soft scale” ...

A. Schöning
Mu3e Status and Plans

Phase I
- Comprehensive R&D (HV-MAPS, SciFi) program completed
- Detector construction starting this year
- Magnet will be delivered by Cryogenic Ltd. mid 2019
- First data taking in 2020

Phase II
- requires design and approval of High Intensity Muon Beam Line (HiMB)
  - not before 2025, physics program up to ~2030
Backup
The Mu3e Mass Plot (Phase I) displays the expected number of events per 0.2 MeV/c² as a function of the reconstructed mass, $m_{rec}$, in the range of 96 to 110 MeV/c². The plot includes a shaded region representing the expected number of muon stops at $10^8$ muons/s, with an upper limit of $10^{15}$ muon stops.

The plot features several key processes:

- $\mu \rightarrow eee + \nu \bar{\nu}$
- Bhabha scattering
- Michel effect

The plot also highlights the observed events at different muon decay rates:

- $\mu \rightarrow eee$ at $10^{-12}$
- $\mu \rightarrow eee$ at $10^{-13}$
- $\mu \rightarrow eee$ at $10^{-14}$
- $\mu \rightarrow eee$ at $10^{-15}$
Mu3e Collaboration

Germany (Deutsche Forschungsgemeinschaft, Germany)
- University Heidelberg
- Karlsruhe Institute of Technology
- University Mainz

Switzerland (Swiss National Font, Switzerland)
- University of Geneva
- Paul Scherrer Institute
- ETH Zurich
- University Zurich

United Kingdom (STFC Council, UK)
- Bristol
- Liverpool
- Oxford
- UC London

about 60 members including 14 PhD students
High Intensity Muon Beamline (HiMB)

Proton cyclotron

\[ I_p = 2.4 \text{ mA} \]
\[ @ \ 590 \text{ MeV} \]

World-highest intensity beam!

**HiMB Studies:**

- **refurbish target M**
  - \( \mu \) rates >> \( 10^9 \text{/s} \)
  - promising!
- **SINQ target:**
  - rates >\( 10^{10} \text{/s} \) possible
  - but extremely difficult

PiE5 beamline: MEG+Mu3e experiments