A Novel Experiment Searching for the Lepton Flavor Violating Decay 

\[ \mu \rightarrow eee \]

Dirk Wiedner, Heidelberg
On Behalf of the Mu3e Proto-Collaboration
July 17\textsuperscript{th} 2012
Overview

• Physics Motivation
• Mu3e Experiment
• HV-MAPS
• Construction
• Timing detectors
• DAQ
• Summary
Physics Motivation

Lepton flavor violation?

Standard model:
• No lepton flavor violation
Physics Motivation

Lepton flavor violation?

Standard model:
• No lepton flavor violation
Physics Motivation

Lepton flavor violation: $\mu^+ \rightarrow e^+ e^- e^+$

Standard model:

• No lepton flavor violation, but:
  o Neutrino mixing
  o Branching ratio $<10^{-50} \rightarrow$ unobservable
The Mu3e Signal

- $\mu \rightarrow eee$ rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions
The Mu3e Signal

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- Rare decay (BR$<10^{-12}$, SINDRUM)
- For BR $O(10^{-16})$
  - $>10^{16}$ muon decays
  - High decay rates $O(10^9$ muon/s)
The Mu3e Signal

→ Maximum electron energy 53 MeV
The Mu3e Background

- Combinatorial background
  - $\mu^+ \rightarrow e^+\nu\nu$ & $\mu^+ \rightarrow e^+\nu\nu$ & $e^+e^-$
  - many possible combinations

- Good time and
- Good vertex resolution required
The Mu3e Background

- $\mu^+ \rightarrow e^+ e^- e^+ \nu \nu$
  - Missing energy ($\nu$)
  - Good momentum resolution

Challenges
Challenges

• High rates
• Good timing resolution
• Good vertex resolution
• Excellent momentum resolution
➢ Extremely low material budget
Challenges

- High rates: $10^9 \, \mu/s$
- Good timing resolution: 100 ps
- Good vertex resolution: $\sim 100 \, \mu m$
- Excellent momentum resolution: $\sim 0.5 \, MeV/c^2$
- Extremely low material budget:
  - $1 \times 10^{-3} \, X_0$ (Si-Tracker Layer)
- HV-MAPS spectrometer
  - 50 \, \mu m thin sensors
  - B $\sim 1$ T field
- + Timing detectors
The Mu3e Experiment

- Muon beam $O(10^9/s)$
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Tile hodoscope
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PSI $\mu$-Beam

Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Phase I:
  - Surface muons from target E
  - Up to a few $10^8 \mu/s$
- Phase II:
  - New beam line at the neutron source
  - Several $10^9 \mu/s$ possible
  - $>10^{16}$ muon decays per year
  - BR $10^{-16}$ (90% CL)

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**HV-MAPS**

- **High Voltage Monolithic Active Pixel Sensors**
- Pixel sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased

**by Ivan Peric**

I. Peric, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology

*Nucl.Instrum.Meth.*, 2007, A582, 876
HV-MAPS

- **High Voltage Monolithic Active Pixel Sensors**
- Pixel sensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased ~60V
  - Depletion layer
  - Charge collection via drift
  - Fast $O(100 \text{ ns})$ charge collection
  - Thinning to < 50 μm possible

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  - Thinning to < 50 $\mu$m possible
- Integrated readout electronics

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Sensor + Analog + Digital

Pixel

Periphery

Readout

Sensor

Injection

CSA

source follower

tune DAC

BL

Comparator

threshold
Sensor + Analog + Digital

Pixel

- Sensor
- CSA
- Source follower
- Injection
- Amplification
- Integrate charge
- Drive high C of signal line

Periphery

- Comparator
- BL
- Tune DAC
- AC coupling via CR filter
- Set individual threshold
- Digital output (ToT)

Readout

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Digital Logic

- **Pixel logic:**
  - Address generation
  - Time stamp
  - Column bus logic

- **Column logic**
  - Priority logic
  - ... using tri-state bus
  - Fifo buffer

- **Chip wide logic**
  - Data frame generation

- **Serializer(s)**
  - 800 Mbit/s LVDS
Digital Logic

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Test Results
Current Chip Prototype

- 180 nm HV-CMOS
- Pixel matrix:
  - 42 x 36 pixel
  - 39 x 30 μm² each
- Ivan Peric ZITI
  - Analog part almost final
  - Digital part in next submission
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Test Setup

- Laptop
- Readout Board
- FPGA
- HV-MAPS

USB connection
Test Setup
Test Setup
Timing Tests

• Timing critical
  o $10^9 \mu$s
  ➢ $O(10 \text{ ns})$ resolution
• LED pulsed sensor
• Double pulse resolution
Timing Tests

- LED pulsed sensor
- Double pulse resolution
  - Visible in oscilloscope
Timing Tests

- LED pulsed sensor
- Double pulse resolution
  - Visible in oscilloscope
  - ... or time over threshold
Double Pulse Resolution

- Ratio of
  - resolved to
  - unresolved double pulses
- Default: $5.27 \pm 0.01 \mu s$
Double Pulse Resolution

- Ratio of
  - resolved to unresolved double pulses
- Default: $5.27 \pm 0.01 \, \mu s$
  - Pixel bias current adjustment
  - Optimized: $3.23 \pm 0.01 \, \mu s$
    - Further reduction required
Pulse Shape

- LED setup
- Test pulse latency
- + time over threshold
- ... for different thresholds
Pulse Shape

- LED setup
- Test pulse latency
- + time over threshold
- ... for different thresholds
Pulse Shape

• LED setup
• Test pulse latency
• + time over threshold
• ... for different thresholds
Pulse Shape

- LED setup
- Test pulse latency
- + time over threshold
- ... for different thresholds
  - faster shaping needed
Construction
• Conical target
• Inner double layer
  o 12 and 18 sides of 1 x 12 cm
• Outer double layer
  o 24 and 28 sides of 2 x 36 cm
• Re-curl layers
  o 24 and 28 sides of 2 x 72 cm
  o Both sides (x2)
Mu3e Silicon Detector

- Conical target
- Inner double layer
  - 12 and 18 sides of 1 x 12 cm
- Outer double layer
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180 inner sensors
4680 outer sensors
➢ 274 752 000 pixel
Cooling

- 2 m$^2$ silicon detector
- Up to 200mW/cm$^2$
- 60 °C maximum
- Gaseous helium
- Laminar flow
- Tests:
  - Inductive heating
  - Aluminum foil
Thinning

- 50 μm Si-wafers
  - Commercially available
  - HV-CMOS 75 μm (AMS)
- Single die thinning
  - For chip sensitivity studies
  - < 50 μm desirable
  - In house grinding?
Material

- HV-MAPS
- Flex print
- Kapton Frame
Inner Double Layer

Very stable self supporting structure
Inner Double Layer

Spokes give extra stiffness
Outer Double Layer

Minimal material in sensitive region
Outer Double Layer

4 flex prints per modules
End Pieces

6 plus 7 modules per layer
End Pieces

• End pieces for modules
  o PVC
  o PEEK in future?
• Production done
Frame Support

- Support design light weight
  - Spokes combine all separate modules
  - Connected by metal beams
  - ... running in bushings
Frame Support

- Support design light weight
  - Spokes combine all separate modules
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Spoke Assembly
Spoke Assembly
Timing Detectors

- **Fiber hodoscope**
  - Before outer pixel layers
  - 250 μm scintillating fibers
  - SiPMs
  - 1 ns resolution

- **Tile detector**
  - After recurl pixel layers
  - 1x1 cm² scintillating tiles
  - SiPMs
  - 100 ps resolution
Timing Detectors
Timing Detectors
Fiber Hodoscope

- 250 μm scintillating fibers
  - Kuraray SCSF-81M
  - double cladding
  - 7500 in total
- Very high occupancies:
  - 24% in 50ns time frame
- Sampling readout
  - SiPM
  - DRS5 chip
  - From Stefan Ritt, PSI

Kuraray
Fiber Hodoscope

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Tile Detector

- 1x1 cm² scintillating tiles
  - O(7000)
- GosSip simulation
  - MPPC with 3600 pixels
  - 100 ps resolution (RMS)
  - 97% efficiency

Kirchhoff-Institut für Physik
Tile Detector

- 1x1 cm² scintillating tiles
  - O(7000)
- GosSip simulation
  - MPPC with 3600 pixels
  - 100 ps resolution (RMS)
  - 97% efficiency
Data Acquisition

- 2.5 GHz muon decays
- 50 ns readout frames
- $O(5000)$ pixel chips
  - 800 Mb/s readout links
- $O(7500)$ scintillating fibers
- $O(7000)$ timing tiles
  - DRS readout
- 3 layers switching FPGAs
  - Optical data links
- Online filtering
Data Acquisition

- 2.5 GHz muon decays
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Diagram:
- Pixel Sensor
- Silicon FPGAs
- Readout board
- PC

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Event Filter Farm

- Triggerless readout
- GPU computers
  - PCIe FPGA/optical input
  - Tflop/s GPU
- 10x faster than CPU
  - Requires custom code
  - Makes farm affordable

Optical mezzanine connectors

GPU computer

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Schedule

- **2012** Letter of intent to PSI, tracker prototype, technical design, technical design report
- **2013** Detector **construction**
- **2014** Installation and **commissioning** at PSI
- **2015** Data taking at up to a few $10^8 \mu/s$
- **2016+** Construction of **new beam-line** at PSI
- **2017++** Data taking at up to $3 \cdot 10^9 \mu/s$
Institutes

• Mu3e proto-collaboration:
  o DPNC Geneva University
  o Paul Scherrer Institute
  o Particle Physics ETH Zürich
  o Physics Institute Zürich University
  o Physics Institute Heidelberg University
  o ZITI Mannheim
  o KIP Heidelberg

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Summary

- Mu3e searches for lepton flavor violation
- $> 10^{16}$ $\mu$-decays $\rightarrow$ BR $< 10^{-16}$ (90% CL)
- Silicon tracker with $\sim$275M pixel
- HV-MAPS 50 $\mu$m thin
- Two SiPM based timing systems
- Prototypes look encouraging
Backup Slides
Si-Layer Rad Length

- Radiation length per layer
  - 2x 25 μm Kapton
    - $X_0 = 1.75e^{-4}$
  - 15 μm thick aluminum traces (50% coverage)
    - $X_0 = 8.42e^{-5}$
  - 50 μm Si MAPS
    - $X_0 = 5.34e^{-4}$
  - 10 μm adhesive
    - $X_0 = 2.86e^{-5}$
- Sum: $8.22e^{-4}$ (x4 layers)
  - For $\theta_{min} = 22.9^\circ$
    - $X_0 = 21.1e^{-4}$

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MAPS Tiles

- MAPS
  - 2 cm x 1 cm for inner layers
  - 2 cm x 2 cm for outer layers
  - Pixel size 80 μm x 80 μm
- Size defined by reticle: 2 cm x 2 cm
  - Cut 6 cm x 2 cm stripes from wafer
  - Bond to flex print
  - Mount sensor-equipped flex print on carrier
Flex Print

- Single Layer in active region
- Multilayer in “cable” end
- LVDS buffers at edge
Tools

• Kapton-Frame tools:
  o Sensor on Flex print
    • Gluing groove
    • Vacuum lift
  o Tools are tested with
    • 25 μm Kapton foil
    • 50 μm glass
Inner Double Layer

- 25 µm Kapton frame
- 25 µm Kapton strip
- 50 µm glass
Outer Doublet Design

Modular design
Spokes Between Layers 1+2

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Mu3e vs. MEG

- $\mu \rightarrow eee$
- Proposal
- $5 \times 10^{-13}$
- $2.4 \times 10^{-12}$
- $\mu \rightarrow e\gamma$ (MEG)
- $\mu \rightarrow eee$ (Sindrum)
Momentum Resolution

- Multiple scattering only
- Current design:
  - 50 µm silicon
  - 50 µm Kapton
  - Helium gas cooling
  - 3 layer fiber tracker