A Novel Experiment Searching for the Lepton Flavor Violating Decay $\mu \rightarrow eee$

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On Behalf of the Mu3e Proto-Collaboration
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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

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

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

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The Mu3e Background

• Combinatorial background
  o $\mu^+ \to e^+\nu\nu$ & $\mu^+ \to e^+\nu\nu$ & $e^+e^-$
  o 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

• 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
- Recurl station
- Tile hodoscope
The Mu3e Experiment

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PSI μ-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: HIMB project (2y application)
  - 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**
- HV-CMOS technology
- 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**
- HV-CMOS technology
- Reversely biased ~60V
  - Charge collection via drift
    - Fast $O(100 \text{ ns})$
  - Thinning to $< 50 \mu\text{m}$ possible

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HV-MAPS

- **High Voltage Monolithic Active Pixel Sensors**
- HV-CMOS technology
- Reversely biased $\sim 60V$
  - Charge collection via drift
    - Fast $O(100 \text{ ns})$
  - Thinning to $< 50 \mu m$ possible
- Integrated readout electronics

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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
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

![ToT Spectrum of Double Pulses]

- Delay 4.7 μs

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Double Pulse Resolution

- Ratio of
  - resolved to unresolved double pulses
- $5.27 \pm 0.01 \, \mu s$
Construction
Mu3e Silicon Detector

- Conical target
- Inner double layer
  - 12 and 18 sides of 1 x 12 cm
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm
- Re-curl layers
  - 24 and 28 sides of 2 x 72 cm
  - Both sides (x2)

180 inner sensors
4680 outer sensors
➢ 274 752 000 pixel
Material

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

Very stable self supporting structure
Timing Detectors
Timing Detectors
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
Schedule

- **2012** Letter of intent to PSI, tracker prototype, technical design, research proposal
- **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
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

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Backup Slides
The Mu3e Experiment

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

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Sensor + Analog + Digital

Pixel

- Sensor
- Injection
- CSA
- Source follower
- Amplification
- Integrate charge

Periphery

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

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Pulse Shape

- LED setup
- Test pulse latency
- + time over threshold
- ... for different thresholds
  - faster shaping needed
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
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
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
Cooling

- 2 m² silicon detector
- Up to 200mW/cm²
- ≤ 4 kW cooling
- 60 °C maximum
- Gaseous helium
- Laminar flow
- Tests:
  - Inductive heating
  - Aluminum foil
Thinning

- 50 $\mu$m Si-wafers
  - Commercially available
  - HV-CMOS 75 $\mu$m (AMS)
- Single die thinning
  - For chip sensitivity studies
  - $< 50$ $\mu$m desirable
  - In house grinding?
  - Local company
Si-Layer Rad Length

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

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Flex Print

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

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

Minimal material in sensitive region
Outer Doublet Design

Modular design
Frame Support

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

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Tile Detector

- 1x1 cm$^2$ scintillating tiles
  - $O(7000)$
- GosSip simulation
  - MPPC with 3600 pixels
  - 100 ps resolution (RMS)
  - 97% efficiency
Momentum Resolution

- Multiple scattering only
- Current design:
  - 50 µm silicon
  - 50 µm Kapton
  - Helium gas cooling
  - 3 layer fiber tracker
Mu3e complementary to MEG