Search for LFV with Mu3e experiment

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on behalf of the Mu3e Collaboration
Search for Lepton Flavor Violation (LFV)

- Searching for a decay $\mu^+ \rightarrow e^+ e^+ e^-$
- This decay is not observable in the Standard Model ($\text{Br} < 10^{-54}$)
- *Any observed decay will point to New Physics*
Current experimental status:

- $\text{Br} < 10^{-12}$ at 90% c.l

Mu3e aims for Single Event Sensitivity (SES) of $2 \cdot 10^{-15}$

- Use existing beam line ($\pi E5, 10^8 \mu/s$) at Paul Scherrer Institute
- Factor $10^3$ improvement compared to SINDRUM result
- At Phase II aim for $10^{-16}$ sensitivity
  - New High Intensity Muon Beamline (HIMB) at PSI
  - See "The HIMB project at PSI" talk on Thursday by Andreas Knecht
Signal ($\mu \rightarrow 3e$):

- Three tracks (two positrons and one electron)
- Muon decays at rest
  - $\sum \mathbf{p}_e = 0 \rightarrow$ need good momentum resolution
  - Invariant mass: $M_{e^+e^-e^-} = m_\mu$
  - $|\mathbf{p}_e| < 53$ MeV/c $\rightarrow$ large Multiple Scattering (MS) $\rightarrow$ need to reduce material
- Common vertex & time $\rightarrow$ need good vertex resolution
Background:

- **Random combinations:**
  - Overlap of $\mu^+ \to e^+ + 2\nu$, $e^\pm$ scattering
  - *Fake* tracks
  - Not same vertex, time, etc.

- **Internal conversion:**
  - $\mu^+ \to e^+ e^+ e^- + 2\nu$
  - Missing momentum & energy

\[ \mu \to e + 2\nu + e^- \quad \mu \to 3e + 2\nu \]
Mu3e Detector

Central station
(target, sensors, fibres)

Recurl station
(sensors, tiles)

$e^+$

$e^-$

$e^+$
Detector - central station

Helium atmosphere
mag. field: \( B = 1 \, \text{T} \)

\[ R \approx 8 \, \text{cm} \]
\[ L \approx 36 \, \text{cm} \]

Double cone hollow target:
- Muons stop on target and decay at rest
- Vertices are distributed over surface of the target for better vertex separation

4 pixel layers:
- Provide hits for track reconstruction
- HV-MAPS technology (minimize material budget to reduce Multiple Scattering)
- Commercially available (HV-CMOS) process (AMS & TSI 180 nm)
- Combination of matrix + readout, in-pixel electronic
- Large area (2 × 2 cm²)
- High granularity (pixel size 80 × 80 µm²)
- High efficiency (> 99%)
- Fast charge collection via drift (HV, \( \sigma_t < 15 \text{ ns} \))
- Can be thinned to 50 µm

- See "HV-MAPS" talk on Wednesday by Andre Schöning

*I.Peric, NIM A582(2007)876*
MuPiX 10

Design:
- Substrate: 20, 200 $\Omega$ cm
- Thickness: 50-70, 100, 650 $\mu$m
- Matrix: 256 × 250
- Pixes size: 80 × 80 $\mu$m$^2$
- Active area: 20.48 × 20 mm$^2$

Performance:
- Efficiency > 99%
- Noise rate < 2 Hz/Pixel
- Power consumption < 350 mW/cm$^2$
- Time resolution $O(13)$ ns
Inner/vertex tracker

- Sensors are mounted on High Density Interconnect (polyimide substrate with aluminum traces)
- First Layer - 8 ladders (placed close to target), second layer - 10 ladders (about 1 cm distance from first layer)
- Each ladder made of 6 sensors (12 cm length)
Helium atmosphere
mag. field: $B = 1$ T

Detector - central station

Scintillating fibres:
- Time measurement to reduce combinatorial background
- Required resolution of better than 1 ns
- Placed just before outer layers
Scintillating fibres

• 3 layers of fibres (Kuraray SCSF-78MJ, diameter 250 µm)
• $X/X_0 \approx 0.2\%$

• 12 fibre ribbons coupled at both end to SiPM arrays (Hamamatsu S13552-HRQ)
• The SiPM arrays are read out by MuTRIG ASIC
• Prototype time resolution of 250 ps
Particles bend back in magnetic field:
- Dedicated ‘recurl’ stations
- Improve momentum resolution
  (factor 5-10 improvement)

Two recurl stations:
- Two pixel layers (same as outer layers of central station)
- + scintillating tiles
  - $\sigma_t < 100$ ps
  - Suppress accidentals

constraint on radius:
  pixel size (min $\sigma_p$)
Scintillating tiles

- Tile detector station: 7 modules
- Module:
  - 13 sub-modules
  - Read out by 13 MuTRIG ASICs
- Sub-module: 32 scintillator tiles
- Prototype performance (DESY testbeam):
  - Efficiency above 99%
  - Single channel (tile) resolution $\approx 45$ ps
The detector is assembled on a beam pipe within the rigid cage:

- Allows for easy mounting and extraction from the magnet by use of rail system
- Supports additional infrastructure, such as power converters, front-end boards, cables, etc.

The cage is inserted inside the magnet:

- Magnetic field: $B = 1$ T
- Inhomogenity below $10^{-3}$ and stability better than $10^{-4}$ over 100 days
- Produced by Cryogenic and delivered to PSI in summer 2020
Large data rate:

- $10^8$ Hz muon stopping rate
- Pixel sensors: up to 740 Mbit/s per link at inner layer (occupancy of 1.3 MHz/cm$^2$)
- Fibre detector average hit rate of 620 kHz per channel $\rightarrow$ 700 Mbit/s per link + noise
Reconstruction
10^8 \mu/s stop and decay on target
• Hit rate of 10^9 per second + fibre and tile hits
• Due to limited storage need fast online reconstruction to reduce rate by factor 100
• Continuous readout (DC beam), no trigger
• Data divided into 64 ns time slices

Reconstruction:
• Fast (triplet) fit for MS dominated environment
• Use same algorithms online and offline
Track in magnetic field:
• Described by helical trajectory
• Require minimum 3 hits to reconstruct track (triplet)

Triplet - trajectory with Multiple Scattering (MS) in middle point
• No pixel uncertainty and no energy loss
• Only one parameter - curvature $r$ (momentum $p$)
• Triplet fit: minimize MS angle
  • No analytical solution
  • Small MS angles $\rightarrow$ linearization
Track fit

Track:
- Sequence of triplets (2 consecutive triplets share pair of hits)
- Minimize combined $\chi^2$
  - $r =$ weighted average of individual triplet solutions

Offline reconstruction includes effects of pixel size and energy loss
Reconstruction: from triplets to short tracks

Triplet (3 hits) seeds:
- Combine hits from first 3 layers
- 10-20 hits per layer per 64 ns time slice, $O(1K)$ combinations
- Total $10^9$ triplet fits each second
- Fake rate $\approx 1$ (1 per truth track)

Short (4 hits) tracks:
- Combination of triplet and hit in outer layer
- Fake rate $\approx 1.0\%$
Reconstruction: long tracks

Long 6-hit tracks:
- Combine short track with pair of hits in outer layers

Long 8-hit tracks:
- Combine 2 short tracks with opposite curvature
- Ambiguity in direction (charge)
- Fake rate $\approx 3.7\%$ - combination of short tracks from wrong turns
Time information from fibres and tiles:

- Link fibre and tile clusters to reconstructed tracks
- Use time difference between two fibre hits to identify track charge
- Reconstruct time at first layer that is used to reduce number of wrong combinations during vertex fit
Acceptance and efficiency

- Acceptance: $\varepsilon_{acc} \approx 70\%$ (1 hit per layer, min $p_T$, etc.)
- Short tracks: $\varepsilon_{short} \approx 90\% \cdot \varepsilon_{acc}$ ($\chi^2$ cut)
- Long tracks: $\varepsilon_{long} \approx 70\% \cdot \varepsilon_{short}$ (gaps, etc.) → analysis
Momentum resolution

Short tracks (4 hits)
• $\langle \sigma_p \rangle \approx 1.4$ MeV/c
• Depends linearly on momentum

Long tracks (6 and 8 hits)
• $\langle \sigma_p \rangle \approx 0.2$ MeV/c
  • ($\times 10$ better than short tracks)
• min $\sigma_p \approx 100$ KeV/c
Sensitivity

- Combine 3 long tracks
- Fit vertex and apply cut on vertex time
- + other cuts to suppress Bhabha background

Mu3e Phase I Simulation

<table>
<thead>
<tr>
<th>Events / 0.2 MeV/c²</th>
<th>10^{15} muon stops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 10^8 muons/s</td>
</tr>
</tbody>
</table>

\[ \mu \to eee \nu \]

Bhabha + Michel

at 10^{-12}

at 10^{-13}

at 10^{-14}

at 10^{-15}

\[ \mu \to eee \rightarrow \nu \nu \]

Mu3e Phase I Simulation

\[ \text{muons/s} \]

Events / 0.2 MeV/c² vs. m_{rec} [MeV/c²]
Integration run

Successfull integration run campaign from May to July 2021 with reduced detector: 2 pixel layers + fibre detector
Integration run

Mounted in a cage with all the readout electronics, services (cooling pipes), power converters, etc.
Integration run

- Inserted into magnet
- Run with helium cooling, in magnetic field and with a muon beam
- Almost full data readout chain
  - From detectors to front-end boards
  - Then optically from inside the magnet to switching boards in the counting room
  - Finally transfer data to PC and store to disk
- See "Mu3e Integration Run 2021" poster by Marius Köppel
Summary

• Search for $\mu^+ \rightarrow e^+e^+e^-$ decay (LFV)
• Single event sensitivity of $2 \cdot 10^{-15}$
• Successfull integration run this summer (2 pixel layers, fibres, magnet, beam)
• TDR published in NIM A
  <https://doi.org/10.1016/j.nima.2021.165679>
• Construction and commissioning is under way
• "The HIMB project at PSI" talk on Thursday by Andreas Knecht
• "HV-MAPS" talk on Wednesday by Andre Schöning
• "Mu3e Integration Run 2021" poster by Marius Köppel
• "The Power Distribution System for the Mu3e Experiment" poster by Sophie Gagneur
Experimental area
Target

Muon stopping rate distribution:

Entries

0 100 200 300 400 500 600 700 800 900

-40 -20 0 20 40

z of muon stop [cm]
## Simulation performance

<table>
<thead>
<tr>
<th>Category</th>
<th>Efficiency</th>
<th>Total efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon stops</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Geometrical acceptance, short tracks</td>
<td>38.1%</td>
<td>38.1%</td>
</tr>
<tr>
<td>Geometrical acceptance, long tracks</td>
<td>68.0%</td>
<td>25.9%</td>
</tr>
<tr>
<td>Long track reconstruction</td>
<td>67.2%</td>
<td>17.4%</td>
</tr>
<tr>
<td>Recurler rejection/Vertex fit convergence</td>
<td>99.4%</td>
<td>17.3%</td>
</tr>
<tr>
<td>Vertex fit $\chi^2 &lt; 15$</td>
<td>91.3%</td>
<td>15.8%</td>
</tr>
<tr>
<td>CMS momentum $&lt; 4\text{ MeV/c}$</td>
<td>95.6%</td>
<td>15.1%</td>
</tr>
<tr>
<td>$m_{ee,\text{low}} &lt; 5\text{ MeV/c}^2$ or $&gt; 10\text{ MeV/c}^2$</td>
<td>98.0%</td>
<td>14.9%</td>
</tr>
<tr>
<td>$103\text{ MeV/c}^2 &lt; m_{\text{rec}} &lt; 110\text{ MeV/c}^2$</td>
<td>97.0%</td>
<td>14.4%</td>
</tr>
<tr>
<td>Timing</td>
<td>90.0%</td>
<td>13.0%</td>
</tr>
</tbody>
</table>
Sensitivity

Mu3e Phase I Simulation

- $\mu \rightarrow eee\nu\bar{\nu}$
  - 1 dot: 1 event per $10^{18}$ $\mu$ stops

- Michel + Bhabha
  - 1 dot: 1 event per $10^{16}$ $\mu$ stops

$\mu \rightarrow eee$
Sensitivity

Mu3e Phase I
10^8 muon stops/s
13.0% signal efficiency

SINDRUM 1988

2 x 10^{-15}

Data taking days

Sensitivity