The MEG/MEGII and Mu3e experiments at PSI

Angela Papa
Paul Scherrer Institut
on behalf of the MEG/MEGII and Mu3e collaborations
Contents

• Introduction

• The world’s most intense DC muon beam

• The MEG/MEGII experiment searching for the $\mu^+ \rightarrow e^+ \gamma$ decay

• The Mu3e experiment searching for the $\mu^+ \rightarrow e^+ e^+ e^-$ decay
Lepton Flavour Violation of Charged Leptons (cLFV)

- Lepton flavour is preserved in the SM ("accidental" symmetry)
  - not related to the theory gauge
  - naturally violated in SM extensions

LFV of neutral leptons confirmed
-neutrino oscillations-
Lepton Flavour Violation of Charged Leptons (cLFV)

- Lepton flavour is preserved in the SM ("accidental" symmetry)
- not related to the theory gauge
- naturally violated in SM extensions

LFV of neutral leptons confirmed
-neutrino oscillations-

LFV of charged leptons not yet observed

MEG (2009-2011)
The $\mu^+ \rightarrow e^+ \gamma$ decay as an example

- Taking neutrino oscillations into account

$$B(\mu^+ \rightarrow e^+ \gamma) \approx 10^{-54}$$

too small to access experimentally
The $\mu^+ \rightarrow e^+ \gamma$ decay as an example

- Taking neutrino oscillations into account
  
  $\Gamma(\mu \rightarrow e\gamma) = \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)$

  $B(\mu^+ \rightarrow e^+\gamma) \approx 10^{-54}$

  too small to access experimentally

- Beyond SM theories such as SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureable cLFV decay BR

  $\Gamma(l_1 \rightarrow l_2\gamma) = \frac{\alpha G_F^2 m_{l_1}^5}{2048\pi^4} (|D_R|^2 + |D_L|^2)$

  $10^{-14} < B(\mu^+ \rightarrow e^+\gamma) < 10^{-11}$

  an experimental evidence: a clear signature of New Physics
The role of low energy physics in the LHC era

Rare decay searches as a complementary way to unveil BSM physics and explore much higher energy scale w.r.t. what can be done at the high-energy frontiers

- **Direct/indirect production of BSM particles**
  - Real BSM particles produced in the final state
  - Energy frontier (LHC)
  - Virtual BSM particles produced in loops
  - Precision and intensity frontier

- **Effective field theory** approach

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)} \]

- \( \mathcal{L}_{\text{eff}} \) is in terms of inverse powers of heavy scale
Favorite place: the Paul Scherrer Institute

- MEG/MEGII and Mu3e: looking for rare decays with coincident particles in the final state
- The best choice for a beam: the most intense continuous positive (surface) muon beam at low momentum (28 MeV/c)
  - up to few \( \times 10^8 \) muon/s

1.2 MW PROTON CYCLOTRON
The MEG/MEGII experiment
The MEG experiment

• The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $\text{BR}(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)

• Five observables ($E_g$, $E_e$, $t_{eg}$, $\theta_{eg}$, $\phi_{eg}$) to characterize $\mu \rightarrow e \gamma$ events
Experimental set-up

- The most intense DC muon beam
- Gamma High energy and time resolutions
- Positron Very precise momentum and time resolutions
- High efficiency event selection and frequency signal digitization
- Complementary calibration and monitoring methods
## Detector performance and Data sample

<table>
<thead>
<tr>
<th>Resolutions (σ)</th>
<th>μ stopped</th>
<th>sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2009+10</strong></td>
<td>$1.75 \times 10^{14}$</td>
<td>$1.3 \times 10^{-12}$</td>
</tr>
<tr>
<td><strong>2011</strong></td>
<td>$1.85 \times 10^{14}$</td>
<td>$1.1 \times 10^{-12}$</td>
</tr>
<tr>
<td><strong>2009+10+11</strong></td>
<td>$3.60 \times 10^{14}$</td>
<td>$7.7 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

| Gamma Energy (%)         | 1.7 (depth>2cm), 2.4 |
| Gamma Timing (psec)      | 67 |
| Gamma Position (mm)      | 5(u,v), 6(w) |
| Gamma Efficiency (%)     | 63 |
| Positron Momentum (KeV)  | 305 (core = 85%) |
| Positron Timing (psec)   | 108 |
| Positron Angles (mrad)   | 7.5 (Φ), 10.6 (Θ) |
| Positron Efficiency (%)  | 40 |
| Gamma-Positron Timing (psec) | 127 |
| Muon decay point (mm)    | 1.9 (z), 1.3 (y) |
Event selection

**trigger MEG**

\[ E_g > 40 \text{ MeV} \& |\Delta t_{eg}| < 10 \text{ ns} \& |\Delta \varphi| < 7.5^\circ \]

**pre-selected events**

At least 1 reconstructed track on DCHs

short relative time between LXe-TC

\((\sim 16\% \text{ of the original sample})\)

**Side-boxes** \(\Rightarrow\) **Blind box**

to study the background and to optimize the algorithm

**hidden events**

RMD: radiative michel decay

\[ \mu^+ \rightarrow e^+ \nu \nu \gamma \]
Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>Best fit</th>
<th>Upper Limit (90% C.L.)</th>
<th>Sensitivity **</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009+10</td>
<td>0.09x10^{-12}</td>
<td>1.3x10^{-12}</td>
<td>1.3x10^{-12}</td>
</tr>
<tr>
<td>2011</td>
<td>-0.35x10^{-12}</td>
<td>6.7x10^{-13}</td>
<td>1.1x10^{-12}</td>
</tr>
<tr>
<td>2009+10+11</td>
<td>-0.06x10^{-12}</td>
<td>5.7x10^{-13}</td>
<td>7.7x10^{-13}</td>
</tr>
</tbody>
</table>

\[ \mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13} \quad \text{(all combined data)} \quad *\]

* x4 more stringent than the previous upper limit
  \((\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12} \quad \text{-MEG 2009-10})\)

* x20 more stringent than the MEGA experiment result
  \((\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11} \quad \text{-MEGA 2001})\)

(**) 90% C.L. upper limit averaged over pseudo-experiments based on null-signal hypothesis with expected rates of RMD and BG
MEGII

- An upgrade of MEG, aiming at a sensitivity improvement of one order of magnitude (down to $5 \times 10^{-14}$) approved by PSI and funding agencies is ongoing.
MEGII vs MEG

Kept the key elements of MEG

1. World’s most intense DC muon beam @ PSI
2. Innovative LXe γ-ray detector
3. Gradient B-field e⁺-spectrometer
4. Thousands virtual oscilloscopes (DAQ)
5. Sophisticated calibration methods

Upgraded MEG

LXe with MPPC in VUV

Fast read-out DC

7×10⁷ Muon/s

pixelized TC

MEG Now
The new re-designed spectrometer: the single volume chamber

- High granularity/Increased number of hits per track
- Less material (helium:isobutane = 85:15, $2 \times 10^{-3} X_0$)
- High transparency towards the TC

<table>
<thead>
<tr>
<th>Resolutions</th>
<th>MEG</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_e$ (keV)</td>
<td>306</td>
<td>130</td>
</tr>
<tr>
<td>$\varphi_e$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$\varphi_e$ (mrad)</td>
<td>8.7</td>
<td>4.8</td>
</tr>
<tr>
<td>$e^+$ efficiency (%)</td>
<td>40</td>
<td>88</td>
</tr>
</tbody>
</table>

Ageing tests:

Front End Electronics:
3dB bandwidth around 1GHz
A new re-designed spectrometer: the pixelized Timing Counter

- Higher granularity: 2 x 256 of scintillator plates (120 x 50 x 5 mm$^3$) readout by SiPMs
- Improved timing resolution: from 70 ps to 35 ps
- Less multiple scattering and pile-up

Timing resolution:
35 ps at the MEGII rate conditions
The upgraded Liquid Xenon calorimeter

- High uniformity/Increased resolutions
- High pile-up rejection capability
- High acceptance and detection efficiency
The new waveDAQ

- Based on the DRS4 chip
- Waveform Sampling: 5 GS/s
- SiPM power supply included
Where we will be

\[ k \text{ factor (x}10^{11}\text{)} \approx 5 \times 10^{-14} \]
The Mu3e experiment
The Mu3e experiment

- The Mu3e experiment searches for $\mu^+ \rightarrow e^+ e^+ e^-$ and aims a sensitivity of $\sim 10^{-16}$ (current best upper limit $\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by the SINDRUM experiment)

$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2} \bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f$$
The Mu3e experiment

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-16}$ (current best upper limit $\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by the SINDRUM experiment)

**Case 1**: dominant dipole coupling ($k \rightarrow 0$)

$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k + 1) \Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k + 1) \Lambda^2} \bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f$$

- $\mu^+ \rightarrow e^+ \gamma$ most sensitive channel!
The Mu3e experiment

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-16}$ (current best upper limit $\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by the SINDRUM experiment).

**Case 2:** tree level interaction ($k > 10$)

$$L_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2} \bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f$$

$$\frac{\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-)}{\text{BR}(\mu^+ \rightarrow e^+ \gamma)} \gg 1$$

tree level interaction accessible only via $\mu^+ \rightarrow e^+ e^+ e^-$!
cLFV search: complementary approach

\[ B(\mu \to \text{ee}) = 10^{-16} \]
\[ B(\mu \to e\gamma) = 10^{-13} \]
\[ B(\mu \to e\gamma) = 10^{-14} \]

\[ B(\mu \to e \text{ conv in } ^{27}\text{Al}) = 10^{-18} \]

\[ \Lambda \ (\text{TeV}) \]

EXCLUDED (90% CL)
The Mu3e experiment

- The $\mu^+ \rightarrow e^+ e^+ e^-$ signature
  - 3 charged particle in the final state
  - no neutral particle in the final state allows for higher detector performances

- The $\mu^+ \rightarrow e^+ e^+ e^-$ main backgrounds
  - $\mu^+ \rightarrow e^+ e^+ e^- \nu \nu$
  - combinatorial e.g. $\mu^+ \rightarrow e^+ \nu \nu$, $\mu^+ \rightarrow e^+ \nu \nu$, $e^+ e^-$

- Excellent momentum resolution
- Good vertex resolution
- Good timing resolution
Mu3e staging approach

- Phase IA 201x (piE5 beam line: $O(10^7)$ mu/s)
- Phase IB 201x+1 (piE5 beam line: $O(10^8)$ mu/s)
- Phase II 202x (new beam line: $O(10^9)$ mu/s)

Feasibility study of a High Intensity Muon Beam (HIMB) line.
Aim: $O(10^{10})$ mu/s

HIMB@SINQ
The compact muon beam line (CMBL)

- The MEGII and the phase IA and IB of Mu3e have similar beam requirements $O(10^8)$ mu/s, 28 MeV/c
- the CMBL allows both experiments to co-exist
The compact muon beam line (CMBL)
The tracker detector: Mupix

- Based on the High Voltage Monolithic Active Pixel Sensors (HV-MAPs)
- HV-CMOS technology
- Reversely biased ~60 V
  - fast charge collection via drift <1 ns
  - thinned ~50 μm
- Integrated readout electronics
- 5 generation of prototype
  - Mupix 7 is the current version with all features of the final sensors
- Full detection efficiency (> 99%)
- High rate capability (> 1 MHz)
- Timing resolution < 17 ns
The tracker detector: Mupix

- Based on the High Voltage Monolithic Active Pixel Sensors (HV-MAPs)
- HV-CMOS technology
- Reverserly biased ~60 V
  - charge collection via drift
  - fast <1ns
  - thinning to ~50 μm
- Integrated readout electronics
- 5 generation of prototype
  - Mupix 7 is the current version with all features of the final sensors
- Full detection efficiency (> 99%)
- High rate capability (> 1 MHz)
- Timing resolution < 17 ns
The timing detector: SciFi

- Precise timing measurement is critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) \(O(1\ \text{ns})\), full detection efficiency (>99%)
  - Scintillating tiles \(O(100\ \text{ps})\), full detection efficiency (>99%)
The timing detector: Tiles

- Precise timing measurement is critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) $O(1\, \text{ns})$, full detection efficiency ($>99\%$)
  - Scintillating tiles $O(100\, \text{ps})$, full detection efficiency ($>99\%$)
Summary

- Unique DC muon beam at PSI
  - high intensity $O(10^8)$ muon$^+$/s
  - feasibility studies ongoing to increase it, aiming at $O(10^{10})$ muon$^+$/s

- MEG completed successfully
  - data sample 2009-2011: best upper limit of any particle decay $B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$
  - data sample 2009-2013: final result just around the corner

- MEGII preparation in good shape
  - improved sensitivity by a factor of 10 reaching $5 \times 10^{-14}$

- Mu3e detector R&D in progress
  - an experiment completely based on new technologies
  - improved sensitivity on $B(\mu^+ \rightarrow e^+ e^+ e^-)$ by 4 order of magnitude aiming at $\text{few } 10^{-16}$
Back-up
Maximum Likelihood Analysis

- **Analysis region:** $48 < E_\gamma < 58 \text{MeV}$, $50 < E_e < 56 \text{MeV}$, $|\theta_e| < 50 \text{mrad}$, $|\Phi_e| < 50 \text{mrad}$, $|T_e| < 0.7 \text{ns}$

- **Maximum likelihood analysis to estimate # of signal**
  
  - Event-by-event PDF
    
    - gamma: position dependent resolutions
    
    - positron: per-event error matrix from Kalman filter

$$
\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{e^{-N}}{N_{\text{obs}}!} e^{-\frac{(N_{\text{RMD}} - \langle N_{\text{RMD}} \rangle)^2}{2\sigma_{\text{RMD}}^2}} e^{-\frac{(N_{\text{BG}} - \langle N_{\text{BG}} \rangle)^2}{2\sigma_{\text{BG}}^2}} \times \prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}} S(\bar{x}_i) + N_{\text{RMD}} R(\bar{x}_i) + N_{\text{BG}} B(\bar{x}_i))
$$

- **Confidence interval of $N_{\text{sig}}$ (or $B$ )**

  - Frequentist approach with profile likelihood ratio ordering
Probability Density Functions

- **Probability density functions (PDF)** for likelihood function are mostly extracted from data.

  The signal PDF $S$ is the product of the PDFs for $E_e$, $\theta_e\gamma$, $\Phi_e\gamma$, $T_e\gamma$, which are correlated variables, and the $E\gamma$ PDF.

  The RMD PDF $R$ is the product of the same $T\gamma$ PDF as that of the signal and the PDF of the other four correlated observables, which is formed by folding the theoretical spectrum with the detector response functions.

  The BG PDF $B$ is the product of the five PDFs, each of which is defined by the single background spectrum, precisely measured in the sideband.

---

**Signal $E\gamma$ (CEX)**

- $\sigma_{E\gamma} = 1.56 \pm 0.03 \%$
- $\text{FWHM}_{E\gamma} = 4.54 \pm 0.11 \%$

**Signal $E_e$ /BG (Michel)**

**Signal $T_{e\gamma}$ (RMD)**

- $N_{\text{RMD}} = 16430 \pm 374$
- $\sigma_{t_{e\gamma}} = 130 \pm 4 \text{ ps}$
Likelihood Fit (2009-2011)

- Green: Signal
- Red: RMD
- Purple: BCK
- Blue: Total
- Black: Data

NSIG = -0.4(+4.8 -1.9)
NRMD = 167.5 ± 24
NBCK = 2414 ± 37
Confidence Interval

- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering

Consistent with null-signal hypothesis
The MEGII experiment - 3D view
VUV-sensitive SiPM (MPPC using Hamamatsu convention)

We have successfully developed VUV-MPPC in collaboration with Hamamatsu Photonics. K.K.

- **Sensitive to VUV-light**
  - Protection coating is removed, VUV-transparent quartz window is used for protection.

- **Large area (12x12 mm²)**
  - Signal tail become long due to large capacitance.
  - Reduce capacitance by connecting 4 chips in series.

![Diagram of VUV-sensitive SiPM](image)

- 50 μm pitch pixel
- 4 independent chips
- Metal quench resister

Hamamatsu S10943-3186(X)
The Mu3e experiment

- Pixel dimension: 80 x 80 um$^2$
- Thinning to 50 um
- The sensor and read-out are integrated on the same device
- Momentum resolution < 0.5 MeV/c over a large phase space
- Vertex resolution < 200 um
Cooling concept

- Gaseous He cooling
  - for silicon tracker
  - low radiation length
  - global flow
  - local direct cooling
- Liquid cooling
  - for readout electronics
  - integrated in beam-pipe
Beam Pipe

- Stainless steel pipe
  - Shields against background
- Mechanical support
  - Detectors attached to beam pipe
  - Via end rings
- Read-out PCBs attached
  - FPGAs mounted directly
  - Integrated cooling