The MEGII experiments at PSI

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on behalf of the MEGII collaboration
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- Introduction
- The MEGII experiment searching for the $\mu^+ \rightarrow e^+ \gamma$ 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

\[ \Gamma(\mu \rightarrow e\gamma) = \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]
The $\mu^+ \to e^+ \gamma$ decay as an example

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

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

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

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
- 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

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

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ at 90 C.L. by MEGA experiment)
- Five observables ($E_g, E_e, t_{eg}, \vartheta_{eg}, \phi_{eg}$) 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
How the sensitivity can be pushed down?

- More sensitive to the **signal**...

\[
\text{SES} = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon(\text{gamma}) \times \varepsilon(\text{TRG}) \times \varepsilon(\text{sel})}
\]

- More effective on rejecting the **background**...

\[
B_{\text{acc}} \sim R \times \Delta E_e \times (\Delta E_{\text{gamma}})^2 \times \Delta T_{\text{egamma}} \times (\Delta \Theta_{\text{egamma}})^2
\]
Towards and upgrade

• Higher beam intensity $7 \times 10^7$ mu/s ($3 \times 10^7$ mu/s)
  • all detector should be able to sustain that rate

• Higher detector efficiency
  • Chamber transparency towards TC 80% (40%)
  • LXe detector 75% (65%)

• Better signal selection and background rejection
  • higher resolution
  • pile-up rejection
MEGII vs MEG

Upgraded MEG

Fast read-out DC

7x10^7 Muon/s

LXe with MPPC in VUV

pixelized TC

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

MEG Now
The MEGII experiment

- 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.
The MEGII experiment - 3D view

- Liquid Xenon Gamma-ray Detector
- COBRA Superconducting Magnet
- Gamma ray
- Drift Chamber: single-volume He:iC₄H₁₀, small stereo cells
- Positron Timing Counter: 30ps resolution w/ multiple hits
- Radiative Decay Counter
- Positron
- Muon
- Better uniformity w/ VUV-sensitive 12x12mm² SiPM
- Full available intensity 7x10⁷/s
- Further reduction of radiative BG
The new re-designed spectrometer: the single volume chamber

- High granularity/Increased number of hits per track
- Less material (helium:isobutane = 85:15, 2x10^{-3} X_0)
  - better momentum and angular resolutions
- High transparency towards the TC
The new re-designed spectrometer: the single volume chamber (in numbers)

- Positron momentum and direction measurement
- Unique volume gas chamber
  - Single hit resolution $50 \div 100 \ \mu m$ in $r$ ($250 \ \mu m$)
  - Momentum resolution $\sim 130 \ \text{KeV}$ ($310 \ \text{KeV}$)
  - Angular resolution $\sim 5 \ \text{mrad}$ ($8-11 \ \text{mrad}$)
  - Transparency towards TC $\sim 80 \%$ ($40\%$)
- Target (default solution)
  - Thinner passive target 140 um ($205 \ \text{um}$)

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 (with multiple hits): from 70 ps to 35 ps
- Less multiple scattering and pile-up
A new re-designed spectrometer: the pixelized Timing Counter (in numbers)

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

- Replacement of the inner face PMT (2”) with SiPM (12x12 mm²)
  - Higher granularity and uniformity
    - Increased energy, timing and position resolutions
  - Higher pile-up rejection capability
  - Higher detection efficiency
- Increased acceptance
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  - Higher detection efficiency
- Increased acceptance
The upgraded Liquid Xenon calorimeter (in numbers)

<table>
<thead>
<tr>
<th>Resolution</th>
<th>MEGI</th>
<th>MEGII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ (mm)</td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>$v$ (mm)</td>
<td>5</td>
<td>2.2</td>
</tr>
<tr>
<td>$w$ (mm)</td>
<td>6</td>
<td>3.1</td>
</tr>
<tr>
<td>$E_\gamma$ ($w&lt;2\text{cm}$)</td>
<td>2.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$E_\gamma$ ($w&gt;2\text{cm}$)</td>
<td>1.7%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$t_{\gamma}$ (ps)</td>
<td>67</td>
<td>60</td>
</tr>
</tbody>
</table>
R&D in collaboration with Hamamatsu: 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.

Hamamatsu S10943-3186(X)
The new waveDAQ

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

\[ k \text{ factor (x10^{11})} \approx 5 \times 10^{-14} \]
cLFV search: complementary approach
Summary

• 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 \( 5 \times 10^{-14} \)

• 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
Back-up
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>Gamma Energy (%)</strong></td>
<td>1.7(depth&gt;2cm), 2.4</td>
<td></td>
</tr>
<tr>
<td><strong>Gamma Timing (psec)</strong></td>
<td>67</td>
<td></td>
</tr>
<tr>
<td><strong>Gamma Position (mm)</strong></td>
<td>5(u,v), 6(w)</td>
<td></td>
</tr>
<tr>
<td><strong>Gamma Efficiency (%)</strong></td>
<td>63</td>
<td></td>
</tr>
<tr>
<td><strong>Positron Momentum (KeV)</strong></td>
<td>305 (core = 85%)</td>
<td></td>
</tr>
<tr>
<td><strong>Positron Timing (psec)</strong></td>
<td>108</td>
<td></td>
</tr>
<tr>
<td><strong>Positron Angles (mrad)</strong></td>
<td>7.5 (Φ), 10.6 (Θ)</td>
<td></td>
</tr>
<tr>
<td><strong>Positron Efficiency (%)</strong></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>Gamma-Positron Timing (psec)</strong></td>
<td>127</td>
<td></td>
</tr>
<tr>
<td><strong>Muon decay point (mm)</strong></td>
<td>1.9 (z), 1.3 (y)</td>
<td></td>
</tr>
</tbody>
</table>

- **2009+10**: 1.75x10^{14}, 1.3x10^{-12}
- **2011**: 1.85x10^{14}, 1.1x10^{-12}
- **2009+10+11**: 3.60x10^{14}, 7.7x10^{-13}
Event selection

**trigger MEG**

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

**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** ➙ ➙ **Blind box**

to study the background and to optimize the algorithm

**RMD: radiative michel decay**

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

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

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

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

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

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

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

- 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 $E_e$, $\theta_{e\gamma}$, $\Phi_{e\gamma}$, and $T_{e\gamma}$, which are correlated variables, and the $E_\gamma$ PDF.

The RMD PDF $R$ is the product of the same $T_{e\gamma}$ 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)**
  - $N_{RMD} = 16430 \pm 374$
  - $\sigma_{t_{e\gamma}} = 130 \pm 4$ 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