Search for Charged Lepton Flavour Violation with the MEG and MEG II experiments

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Charged Lepton Flavour Violation


\[ \mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 \sim 10^{-54} \]

Many new physics scenarios predict an enhanced probability, through mixing between new particles of the theory.

The existence of new physics at high energy scale may result in

\[ \mathcal{B} \sim 10^{-14} \div 10^{-12} \]

free from SM background!
CLFV channels

Lepton decays | μ-e conversion | Meson (or Higgs) decays | (Anomalous Magnetic Moment)

γ | N | q | e | μ | μ

Look out for discrepancies on lepton couplings at Hadron Colliders!

\[
R^\mu_e^K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to K\mu\mu)} \cdot \mathcal{B}(h \to \mu\tau)
\]

Muon channels

Due to the extremely-low accessible branching ratios, CLFV muon channels can strongly constrain new physics models and scales.

Model independent Lagrangian:

\[
\frac{m_\mu}{(\kappa + 1)\Lambda^2} + \frac{\kappa}{(\kappa + 1)\Lambda^2}
\]

Dipole term (e.g. SUSY) | Contact term (e.g. Z', LQ)

| \(\mu \rightarrow e\gamma\) | \(\mu \rightarrow eee\) |
| \(\mu - e\) conversion |

Sensitive to high-mass New Physics!
The MEG experiment

Search for the Lepton Flavour Violating process $\mu \rightarrow e\gamma$
The $\mu \rightarrow e\gamma$ decay

Clear kinematic signature (at rest):

1) $E_\gamma = m_\mu / 2$
2) $E_e = m_\mu / 2$
3) $\Theta_{e\gamma} = 180^\circ$
4) $t_{e\gamma} = 0$

with two sources of background:

Radiative Muon Decay

1) $E_\gamma \lesssim m_\mu / 2$
2) $E_e \lesssim m_\mu / 2$
3) $\Theta_{e\gamma} \lesssim 180^\circ$
4) $t_{e\gamma} = 0$

$\propto R_\mu$

Accidental Background

$\propto R^2_\mu$

$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e\gamma$
$e^+e^- \rightarrow \gamma\gamma$
$e^+ N \rightarrow e^+ N\gamma$
The MEG apparatus

Tailored to take advantage of the well-defined kinematics

- **Positive muons stopped** in a thin polyethylene target
- Positrons are detected by a **spectrometer** immersed in a non-uniform magnetic field
- Photons are detected by a **liquid Xenon** calorimeter

The MEG apparatus

- 16 drift chamber modules
- 15 plastic bars + scintillating fibres for timing

from PSI πE5 beam line

$3 \times 10^7 \mu^+/s$

$p = 29$ MeV/c

- fast: $\tau's = 4/22/45$ ns
- high Light Yield $LY \sim 0.8 LY_{NaI}$
- Short Radiation Length $X_0 = 2.77$ cm
Analysis strategy

- Events described by 5 variables:
  \[ \bar{x} = (E_\gamma, E_e, t_{e\gamma}, \vartheta_{e\gamma}, \varphi_{e\gamma}) \]

- **Probability Density Functions (PDFs)** for signal and backgrounds are determined starting from data outside the signal box.

- Two-fold use of **sidebands**
  - Evaluation of PDFs.
  - Estimate of the background events entering the signal box.
Probability density functions

**Positron Energy**
- Fit from Michel endpoint
- Left/right sidebands

**Photon Energy**
- Fit from 55 MeV calibration

**Relative Time**
- From lower sideband

\[ N_{\text{RMD}} = 16430 \pm 374 \]
\[ \sigma_{t_{\gamma}} = 130 \pm 4 \text{ ps} \]
Likelihood fit

\[ \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}}) = \frac{e^{-N}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \left[ N_{\text{sig}} S(\vec{x}_i) + N_{\text{RMD}} R(\vec{x}_i) + N_{\text{ACC}} B(\vec{x}_i) \right] \exp \left[ -\frac{(N_{\text{RMD}} - \langle N_{\text{RMD}} \rangle)^2}{2\sigma_{\text{RMD}}^2} \right] \exp \left[ -\frac{(N_{\text{ACC}} - \langle N_{\text{ACC}} \rangle)^2}{2\sigma_{\text{ACC}}^2} \right] \]

from this fit we get

\[ N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}} \]
Branching ratio

1) **Normalization**: obtained from Michel and radiative decays.

2) **Confidence interval** calculated with Feldman & Cousins approach with profile likelihood ratio ordering.

with half of the collected statistics:

\[ \mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13} \]

@ 90% C.L.


Final result from the MEG data set will be released in a few weeks, with an expected sensitivity of ~ 4x10^{-13} thanks to the **double statistics** and improvements on analysis.
MEG upgrade

1. Higher Muon Rate ⇔ better detector resolutions
2. Less energetic muons ⇒ thinner target
3. New tracker with higher resolution
4. Improved matching between drift chamber and timing counter
6. Larger XEC acceptance
7. Better XEC scintillation light collection

A new drift chamber

A new single-volume cylindrical drift chamber is under construction.

- 10 layers with wires at stereo angles ±7°÷8°.
- Drift cells with approximately squared shape 7x7 mm² (high granularity).
- Low mass gas mixture with helium and isobutane 85:15 (high transparency).
- Semi-automatic wiring robot with laser soldering tool developed for wiring >10000 wires.

Radiation hardness measured in laboratory tests

Spatial Resolution ~110 µm
The new timing counters

Good single pixel resolution is improved with **multiple hits** down to **35 ps**.

Each timing counter consists of 256 scintillator plates, read-out by 6 SiPMs.

- **Transparency**: thin scintillators for smaller multiple scattering contribution.
- **Segmentation**: less pile-up at even higher beam intensity.
The upgraded LXe detector

Replacement of the photosensors in the front face and rearrangement of those in the lateral faces.

2" PMTs

12x12mm$^2$ MPPCs
Trigger and DAQ

Custom system based on:
• 1-GHz waveform digitizers (**DRS chips**) for pile up rejection.
• **FPGAs** for online processing.
Resolution improvements

All the resolutions on the kinematic variables are improved by about a factor 2!

<table>
<thead>
<tr>
<th>Variable</th>
<th>MEG</th>
<th>MEG2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E_{\gamma}$ (%)</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>$\gamma$ position (mm)</td>
<td>5($u, v$), 6($w$)</td>
<td>2.6($u$), 2.2($v$), 5($w$)</td>
</tr>
<tr>
<td>$\Delta P_e$ (keV)</td>
<td>306</td>
<td>130</td>
</tr>
<tr>
<td>$e^+$ angle (mrad)</td>
<td>7($\varphi_e$), 9.4($\vartheta_e$)</td>
<td>5.3($\varphi_e$), 3.7($\vartheta_e$)</td>
</tr>
<tr>
<td>$\Delta t_{e\gamma}$ (ps)</td>
<td>122</td>
<td>84</td>
</tr>
<tr>
<td>$e^+$ efficiency (%)</td>
<td>40</td>
<td>88</td>
</tr>
<tr>
<td>$\gamma$ efficiency (%)</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>trigger efficient (%)</td>
<td>$\sim 99$</td>
<td>$\sim 99$</td>
</tr>
</tbody>
</table>
MEG2 expected sensitivity

- 3 DAQ years estimated
- \(~10x\) in stopped muons
- Schedule ongoing

\[ k \text{ factor} = \frac{\text{SES}_1}{50} \times 10^{12} \]

5 \times 10^{-14}

Upgraded MEG in 3 years
Conclusions

- **Charged Lepton Flavour Violation** experiments represent a powerful tool to investigate new physics scenarios with no SM background.

- Combined measurements on CLFV processes can significantly **constrain** new physics at **high energy scales**.

- The MEG experiment has recently set the most stringent limit on CLFV physics scenarios.

- Next year **MEG2** will start data taking with the goal of improving MEG results by an **order of magnitude**.
In the next decade...

MEG Final Result

MEG2 DAQ


Mu3e DAQ

COMET-II DAQ

J-PARC g-2 DAQ

Mu2e DAQ

FNAL g-2 DAQ

COMET-I DAQ

DeeMee DAQ

Mu2e DAQ

COMET-II DAQ

J-PARC g-2 DAQ

Mu3e DAQ

COMET-I DAQ

DeeMee DAQ
Spare Slides
"Table-top" experiments

- Dedicated experiments
- A long road in beam and detector technology improvements

Experiments looking for $\mu \rightarrow e\gamma$

Hincks-Pontecorvo 1948
Crystal-Box 1988
MEGA 1999

Probes to New Physics

Between the different processes **tight connections** are envisaged in several models

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Antusch et al., JHEP (2006), 0611:090
Hisano et al., JHEP (2009), 0912:030
Detector calibrations

Proton Accelerator

Li(p,γ)Be
LiF target at COBRA center
17.6MeV γ
~daily calib.
also for initial setup

\[ \pi^0 \rightarrow \gamma \gamma \]
\[ \pi^+ + p \rightarrow \pi^0 + n \]
\[ \pi^0 \rightarrow \gamma \gamma \text{ (55MeV, 83MeV)} \]
\[ \pi^+ + p \rightarrow \gamma + n \text{ (129MeV)} \]
LHe target

Alpha on wires

PMT QE & Att. L
Cold GxXe
LXe

Mott e\(^+\) scattering

Detector Calibration

Cosmic ray alignment

Nickel γ Generator

\( \gamma \rightarrow \mu^0 \rightarrow e^- + \nu_e \)

Lower beam intensity < 10\(^7\)
Is necessary to reduce pile-ups
A few days ~ 1 week to get enough statistics

9 MeV Nickel \_line

NaI

Illuminate Xe from the back
Source (Cf) transferred by comp air \rightarrow on/off
A new drift chamber

Radiation hardness

Laboratory tests showed that the expected accumulated charge of $0.5 \, \text{C/cm}$ correspond to a gain loss of $\sim 50\%$ in the whole data taking period in the hottest portion.

Performance

In low-mass gas mixtures spatial resolution is limited by poor ionisation statistics.

- Tests on small prototypes showed a single-hit resolution of $\sim 110 \, \mu\text{m}$.
- The high-bandwidth (1 GHz) electronic chain allows for the improvement of such results by means of the cluster timing technique.