Searching for a lepton flavour violating muon decay mediated by a new light particle with the MEG I full datasets

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Abstract

- We have searched for a **lepton flavor violating muon decay** mediated by a **new light particle** $X$, $\mu^+ \rightarrow e^+ X$, $X \rightarrow \gamma \gamma$, using the full datasets (2009–2013, $7.5 \times 10^{14} \mu^+ s$) of the MEG experiment.

- Statistics, reconstruction methods, and the decay search analysis are improved from the previous analysis in 2012 (2009, 2010 data was used).

- No significant excess was found in the mass region of 20–45 MeV, lifetime below 40 ps.
  - In particular, the upper limits are **pushed down to the level of $\mathcal{O}(10^{-11})$** for 20–30 MeV.

- It is at most **60 times more stringent** result than the bound from the Crystal Box experiment.
The MEG experiment

- The MEG experiment searched for charged lepton flavor violating muon decay ($\mu^+ \rightarrow e^+\gamma$).

- Physics data taking: **2009–2013**
  - 7.5x10^{14} stopped muons

- No excess was found and the most stringent upper limit, $4.2 \times 10^{-13}$ (90% C.L.) was set on $\mathcal{B}(\mu^+ \rightarrow e^+\gamma)$ in 2016.

**At Paul Scherrer Institut in Switzerland**

Physics motivation

- There is no clear evidence of new physics beyond the standard model to date (except for some anomalies).

- We try to tackle this situation by combining two different directions: charged lepton flavor violation and light new physics.
Physics motivation: charged lepton flavor violation

● There is no clear evidence of new physics beyond the standard model to date (except for some anomalies).

● We try to tackle this situation by combining two different directions: charged lepton flavor violation and light new physics.

● Inter-generational mixing in the charged lepton sector (= charged lepton flavor violation, CLFV) is clear evidence for new physics.

● The MEG experiment searched for charged lepton flavor violating muon decay ($\mu^+ \rightarrow e^+ \gamma$).

● No excess was found and the most stringent upper limit, $4.2 \times 10^{-13}$ (90% C.L.) was set (2016*).

Physics motivation: light new physics

- There is no clear evidence of new physics beyond the standard model to date (except for some anomalies).

- We try to tackle this situation by combining two different directions: **charged lepton flavor violation** and **light new physics**.

- LFV mediated by **new light particle** $X \sim O(10^{-1} - 100)$ MeV might be undiscovered as a loophole.

- A possible search in MEG: $\mu^+ \rightarrow e^+ X$, $X \rightarrow \gamma\gamma$ (hereafter we call it “MEx2G”)
  - $X$ is generated via LFV coupling and the on-shell $X$ decays back into SM particles.
  - In this search, we assume decay width is narrow and $X$ is long-lived.

- Possible candidates of $X$: axion-like particle, majoron, familon, flaxion, and strongly interacting DM (SIDM)
Previous studies (1/2)

- Direct search: MEG (2012) [1] (markers in bottom left plot)
  - $\mu^+ \rightarrow e^+X, X \rightarrow \gamma\gamma$ decay search using the MEG 2009/2010 datasets.
  - The first search in the world, available only in a Ph.D thesis [1].

- Inclusive search: Crystal Box (1988) [2] (solid lines in bottom left plot)
  - LFV $\mu$ decays including $\mu \rightarrow e\gamma\gamma$ were searched.
  - Limits on $\mu \rightarrow e\gamma\gamma$ can be converted to $\mu^+ \rightarrow e^+X, X \rightarrow \gamma\gamma$ [1].

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Previous studies (2/2)

- Direct search: MEG (2012) [1] (markers in bottom left plot)
  - $\mu^+ \rightarrow e^+ X, X \rightarrow \gamma \gamma$ decay search using the MEG 2009/2010 datasets.
  - The first search in the world, available only in a Ph.D thesis [1].

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  - LFV $\mu$ decays including $\mu \rightarrow e \gamma \gamma$ were searched.
  - Limits on $\mu \rightarrow e \gamma \gamma$ can be converted to $\mu^+ \rightarrow e^+ X, X \rightarrow \gamma \gamma$ [1].

  - “decay length <1 cm and $m_X >20$ MeV” is hot spot.

Target parameter space

- We have searched for the white region:
  - $m_X = 20 - 45 \text{ MeV}$
  - $\tau < 40 \text{ ps}$
**Signal**
- $p_X$ and $p_{e^+}$ is less than $m_\mu/2 = 52.8$ MeV.
- $E_{\gamma_1} + E_{\gamma_2}$ is larger than $m_\mu/2$.
- $2\gamma$s are boosted and opening angle between them is less than 180°.
- $e^+, \gamma, \gamma$ are coincident in time (at each vertex).

**Background**
- one of $\gamma$ is accidental
- $e^+$ is accidental
- $e^+, \gamma, \gamma$ is accidental
- physics backgrounds are negligible
$\mu^+ \rightarrow e^+X, X \rightarrow \gamma\gamma$ decay search analysis

- Blind analysis
  - A blind analysis is used to reduce the experimenters's bias.

- Cut-counting-based analysis
  - We apply several cuts to reduce BGs while keeping the number of signal events.
  - The number of signals and BGs in the signal region are simultaneously estimated by a maximum likelihood fit.

- The confidence interval of the number of signal events and its significance are calculated in a frequentist approach.

- Branching ratio: $\mathcal{B}_{\text{ME}_{\text{Ex}2G}} = N_{\text{Signal}} \times \frac{1}{k}$
  - $N_{\text{Signal}}$: the number of signal
  - $k$: normalization factor, $1/k$: single event sensitivity
Blind analysis

- Blind analysis
  - A blind analysis is used to reduce the experimental bias.
- Blind region: $|t_{e\gamma_1}| < 1 \text{ ns} \land |t_{\gamma\gamma}| < 1 \text{ ns}$
  - $t_{e\gamma_1}$: time difference between $e^+$ and $\gamma_1$.
  - $t_{\gamma\gamma}$: time difference between two $\gamma$s.
Signal selection

- Geometrical cuts
  - $|u_{\gamma 1,2}| < 25 \text{ cm (}\gamma\text{ acceptance), fixed}$
  - $|v_{\gamma 1,2}| < 71 \text{ cm (}\gamma\text{ acceptance), fixed}$
  - $\sqrt{(u_{\gamma 1} - u_{\gamma 2})^2 + (v_{\gamma 1} - v_{\gamma 2})^2}$

- Energy cuts
  - $E_{\text{sum}} \equiv E_{e^+} + E_{\gamma_1} + E_{\gamma_2}$
  - $E_{\gamma 1,2} > 10 \text{ MeV, fixed}$
  - $|P_{e^+} - P_X| < 1 \text{ MeV, fixed}$

- $X \rightarrow \gamma\gamma$ vertex quality cuts
  - $P_{\text{sum}} \equiv P_{e^+} + P_{\gamma_1} + P_{\gamma_2}$
  - Vertex $\chi^2$ cut

- Time difference
  - $t_{\gamma\gamma} = (t_{\gamma 1} - \frac{r_1}{c}) - (t_{\gamma 2} - \frac{r_2}{c})$
  - $t_{\gamma 1e} = (t_{\gamma 1} - \frac{r_1}{c} - \frac{l}{\beta c}) - t_e$
After the signal selections, we estimate the number of signal from the survived events.

Likelihood function: \( \mathcal{L}(N_{\text{signal}}, N_{\text{BG}}, k | N_{\text{obs}}, k_0) \)

- \( N_{\text{signal}} \): number of signal
- \( N_{\text{BG}} \): number of background
- \( N_{\text{obs}} \): number of observed events in the analysis region (after unblinding).

\( N_{\text{BG}} \) can be estimated from number of events in the sidebands (see next).
Background estimation

- $N_{BG}$ can be estimated from number of events in the sidebands
- table: BG types. The same symbol indicates the same physics origin.

**Accidental**

**Physics**

→ negligible

<table>
<thead>
<tr>
<th>type</th>
<th>e$^+$</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>source</th>
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<td>1</td>
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<td>☐</td>
<td>☐</td>
<td>○: RMD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\triangle$: RMD, AIF, brems.</td>
</tr>
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<td>☐</td>
<td>☐</td>
<td>○: Michel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>☐</td>
<td>☐</td>
<td>$\triangle$: AIF / RMD, AIF or brems. from RMD $e^+$</td>
</tr>
<tr>
<td>3</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>○: Michel</td>
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<tr>
<td></td>
<td></td>
<td>☐</td>
<td>☐</td>
<td>$\triangle$, $\diamond$: RMD, AIF, or brems.</td>
</tr>
<tr>
<td>4</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>Doubly radiative muon decay, RMD associated BG</td>
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</tbody>
</table>

Blind region

Signal region

ex)

$A_1$ has contribution from BG type2 and type3.

→ type2 component of $N_{BG}$ can be estimated from $A_1$ and $A_2$. 
We observed 1, 2 events in some mass regions:

<table>
<thead>
<tr>
<th>mass (MeV)</th>
<th>sideband</th>
<th>expected $N_{BG}$ in signal region</th>
<th>nObs</th>
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<tr>
<td></td>
<td>$A(=A_1+A_2)$</td>
<td>$B(=B_1+B_2)$</td>
<td>$C(=C_1+C_2+C_3+C_4)$</td>
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<td>20</td>
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<td>0</td>
<td>1</td>
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<tr>
<td>21</td>
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<tr>
<td>45</td>
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</table>
The Feldman-Cousins approach is used to estimate the interval.
  - Note that Feldman-Cousins can give both upper and lower limits.
- Some masses have both upper and lower limits.
• The Feldman-Cousins approach is used to estimate interval.
• Some masses have both upper and lower limits.
• The excess is not statistically significant.
Normalization

- To get the relative normalization, Michel events ($\mathcal{B}(\mu^+ \rightarrow e^+\nu\bar{\nu}) \sim 100\%$) are used.
  
  \[
  \begin{align*}
  \mu^+ & \rightarrow e^+\nu\bar{\nu} & : & \text{Michel decay, } Br \sim 100\% \\
  \mu^+ & \rightarrow e^+X, X \rightarrow \gamma\gamma & : & \text{MEx2G signal}
  \end{align*}
  \]

  \[
  \mathcal{B}_{\text{MEx2G}} = N_{\text{Signal}} \times \frac{1}{k}
  \]

  \[
  \frac{1}{k_0} = \frac{1}{N_{\text{Michel}}} \times \mathcal{B}_{\text{Michel}} \times f_{\text{Michel}} \times \frac{\epsilon_{\text{Michel}}}{\epsilon_{e^+}} \times \frac{1}{\mathcal{E}_{\text{MEx2G}/e^+}}
  \]

  *$k_0$: measured value of $k$

  - The number of Michel events
  - Fraction of Michel events (7\%–10\%)
  - Ratio of trigger
  - Relative $e^+$ efficiency (90\%)
  - Efficiency of $\gamma$, direction match trigger, and cut. 0.2\%–1.4\%

- By using Michel $e^+$s as a normalization, the estimation is independent of beam rate (stopped muons), and insensitive to absolute positron detection efficiency.
Uncertainty on normalization

- Main source: systematic uncertainty coming from MC smearing and $\gamma$ detection efficiency.
  - MC smearing is estimated from differences of the efficiency with different smearing parameters (mean, mean±systematics).
  - $\gamma$ detection efficiency from MEG1 study.
- The uncertainty is incorporated into the signal likelihood function;
  - normalization factor $k$ is also fitted

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(2013)</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Michel events</td>
<td>53841</td>
<td>0.43 % (stat)</td>
</tr>
<tr>
<td>branching ratio of Michel</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>energy fraction of Michel</td>
<td>0.104</td>
<td>0.01 % (sys)</td>
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<tr>
<td>prescale</td>
<td>$10^7$</td>
<td>0</td>
</tr>
<tr>
<td>prescale correction</td>
<td>1.12</td>
<td>0.89 % (stat)</td>
</tr>
<tr>
<td>Relative positron efficiency correction</td>
<td>1.024</td>
<td>1.3 % (sys)</td>
</tr>
<tr>
<td>Missing turn correction</td>
<td>0.957</td>
<td>0.21 % (sys)</td>
</tr>
<tr>
<td>Signal efficiency ($\gamma$, DM, selection)</td>
<td>0.0135</td>
<td>2.1 % (stat) 9.5 % (sys)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>acceptance</td>
<td>1.3%</td>
</tr>
<tr>
<td>trigger efficiency</td>
<td>0.98%</td>
</tr>
<tr>
<td>pileup inefficiency</td>
<td>2.8%</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>7.4%</td>
</tr>
<tr>
<td>MC Smearing</td>
<td>4.8%</td>
</tr>
</tbody>
</table>
BR limits (1/2)

- BR limits is improved by a factor of 4.4–13 depending on $m_X$ from MEG2012 (2009/2010 MEG data is used).
  - SES is improved by a factor of 5.6–13 depending on $m_X$
  - Statistics (and positron analysis updates) contributes (at most) ~5.
  - Optimization of selection efficiency at higher $m_X$ contributes (at most) ~3.
  ✓ In the previous analysis in MEG2012, selection conditions are not optimized.

![BR limits (90%), $\tau = 20$ ps](image)

Lower limits of BR due to excess events.
BR limits (2/2): 3 key features

1. Improved BR upper limits in all $m_X$ from the previous analysis using 2009 and 2010 data (MEG2012).

2. Set BR upper limits down to $\mathcal{O}(10^{-11})$.

3. Improved BR upper limits in $m_X > 30$ MeV, which was not improved by MEG2012.
Conclusion

- We have searched for a lepton flavor violating muon decay mediated by a new light particle $X$, $\mu^+ \rightarrow e^+X, X \rightarrow \gamma\gamma$, using the full datasets (2009–2013, $7.5 \times 10^{14}\mu^+s$) of the MEG experiment.

- No significant excess was found in the mass region of 20–45 MeV, lifetime below 40 ps.
  - In particular, the upper limits are pushed down to the level of $\mathcal{O}(10^{-11})$ for 20–30 MeV.

- It is at most 60 times more stringent result than the bound from the Crystal Box experiment.

- The MEG II experiment is planned and the sensitivity is expected to be improved by one order of magnitude.

- A further update can be possible in the future CLFV experiments.
Backup slides
MEG Apparatus

COBRA Magnet

Drift chamber

Muon Beam

Stopping Target

Liquid Xenon Scintillation Detector

Timing counter

1m

Drift chamber

γ

e^+

e^+
μ\(^+\) Beam & target

- The world most powerful proton ring cyclotron @PSI in Switzerland:
  - 2.2-2.4 mA, 1.4 MW, 590 MeV proton, RF: 50.7 MHz.

- The πE5 beamline
  - provides \(3 \times 10^8\mu^+/s\) at 28 MeV/c, operated at \(3 \times 10^7\mu^+/s\) for the MEG data taking.

- Stopping target
  - 205 \(\mu\)m thick polyethylene and polyester sheet (density: 0.895 g/cm\(^3\)).
  - Slanted angle of 20°
**e\(^+\): COBRA magnet**

- COBRA = COnstant Bending RAdius

- Specially graded B field
  - The diameter of the trajectories depend on e\(^+\) momenta independent of their emission angles.
  - Low momentum e\(^+\)s are quickly swept out
    - ✔ Low hit rate in the drift chambers
  - e\(^+\)s whose momenta are more than \(~45\) MeV come into the acceptance

![Diagram of COBRA magnet with trajectories and hit rate comparison]

(a) (b)
e⁺: Drift Chamber

- Track e⁺s.
- Made of ultra low mass materials
  - Minimize the multiple scattering.
  - Suppress γ BG.
  - in total, $2.6 \times 10^{-4} X_0$
- 16 modules consist of two staggered layers.
- Vernier method is used for z reconstruction.
- Helium-based chamber gas.
  - He:C₂H₂ = 1:1
e\(^+\): Timing Counter

- Measure hit timing of \( e^+ \)s.
- 15 scintillator bars for both upstream and downstream.
- Scintillation light are detected by using fine-mesh PMTs at both end.
\( \gamma \): Liquid xenon detector

- Detect \( \gamma \) using liquid xenon (active volume 800 L).
  - Determine timing, energy, and position of \( \gamma \)
- Good stopping power (Liquid xenon).
- Fast scintillation timing (Liquid xenon).
- VUV-sensitive (178 nm) PMTs (846 tubes).
  - Newly developed for MEG by Hamamatsu.

![Diagram of liquid xenon detector](image)
Event reconstruction

1. $e^+$ reconstruction
   - TC: time
   - DCH: momentum, position

2. $2\gamma$ reconstruction
   - Energy & position: simultaneous least square fit using light yield of all PMTs.
   - Time: least square fit using selected PMTs.

3. Combined reconstruction
   - $X \rightarrow \gamma\gamma$ vertex position: maximum likelihood fit assuming $m_X$.
   - Momentum: $\vec{P}_{\gamma_1}, \vec{P}_{\gamma_2}, (\vec{P}_X)$
   - Time differences: $t_{\gamma_1} - t_{\gamma_2}, t_{\gamma_1} - t_{e^+}$
• DRS4 (Domino Ring Sampler)
  ▸ Switched capacitor array specially developed at PSI.
  ▸ Take the data from all detectors as waveforms.

• Trigger
  ▸ Trigger rate below 10 Hz.
  ▸ $\gamma$ energy, time difference between $e^+$ and $\gamma$, and relative direction of $e^+$ and $\gamma$ are used in the trigger algorithm.
  ▸ Not optimized for the ME$\times$2G search and the direction match trigger condition loses the ME$\times$2G signal (down to 50–90 %).
Dataset

- $7.5 \times 10^{14} \mu^+$ stopped on the target in 5 years.
  - $1.8 \times 10^{14} \mu^+$ (2009 and 2010) was used for the previous MEx2G analysis in 2012.

- $\mu^+ \rightarrow e^+ \gamma$ data is reused for the MEx2G search.