Latest results of the MEG experiment

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On behalf of the MEG Collaboration

EPS-HEP Conference, Stockholm, 18-24 July 2013
Outline

- Lepton Flavour Violation (LFV)
- The MEG Experiment
- Re-analysis of 2009/2010 Data
- Analysis of 2011 Data and combined results
- Impact on Beyond Standard Model Physics (BSM)
- Summary and Perspectives
In the SM of electroweak interactions, leptons are grouped in doublets and there is no space for transitions where the lepton flavour is not conserved.

However, lepton flavour is experimentally violated in neutral sector (neutrino oscillations) ⇒ needed to extend the standard model by including neutrino masses and coupling between flavours.

cLFV indicates non conservation of lepton flavour in processes involving charged leptons.
Including neutrino masses and oscillations in SM:

- Experimentally not measurable!

- Huge rate enhancement in all SM extensions ⇒ predicted rates experimentally accessible!

\[
\Gamma(\mu \to e\gamma) \approx \frac{G_F m_\mu^5}{192\pi^3} \left(\frac{\alpha}{2\pi}\right) \sin^2 \theta \sin^2 \left(\frac{1.27\Delta m^2}{M_W^2}\right)
\]

- \(\mu\) decay, \(\gamma\) – vertex, \(\nu\) – oscillation

\[
\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} c_{23}}{M_W^2}\right)^2
\]

≈ \(10^{-54}\)

⇒ Observation of cLFV clear evidence for physics beyond SM

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\( \tau \rightarrow \mu \gamma \) vs \( \mu \rightarrow e \gamma \) < 2013


Antusch et al. JHEP 0611 (2006) 090

MEG 2011 = PRL 107 (2011) 181201

\( \theta_{13} \) recently measured by Daya Bay, Reno, Double Chooz ... (7 \div 10^o)
The MEG Experiment

Goal: search for $\mu^+ \rightarrow e^+ \gamma$ decay with a sensitivity on $BR \leq 10^{-13}$
Signal and background

**Signal**

\[ E_e = E_\gamma = 52.8 \text{ MeV} = m_\mu/2 \]

180°

**Radiative muon decay (RMD)**

\[ E_e, E_\gamma < m_\mu/2 \]

\[ T_e = T_\gamma \]

**Accidental Background (ACC)**

\[ e^+ \text{ from Michel decay}, \gamma \]

from RMD, \( e^+e^- \) annihilation ..

Random \( \Delta T, \Delta \Theta, E_e, E_\gamma < m_\mu/2 \)

**Signal, RMD \( \propto R_\mu \), ACC \( \propto R_\mu^2 \) \( \Rightarrow \)**

- ACC is dominant (x 10 RMD in signal region);
- needed **continuous beam** and accurate choice of \( R_\mu \);
- needed **high precision experiments**.

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The Paul Scherrer Institute (PSI)

- The most powerful continuous machine (proton cyclotron) in the world;
- Proton energy 590 MeV;
- Power 1.4 MW;
- Nominal operational current 2.2 mA.

MEG beam line ($\pi$E5 secondary muon line):

- Wien filter
- Beam transport solenoid (BTS)
- Muon degrader
- 2-d beam spot on target: $\sim (1 \times 1) \text{ cm}^2$
Detector layout

Muon beam intensity $3 \times 10^7$ stopped $\mu^+/s$

## Summary of MEG performances

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma E [%]</td>
<td>1.89</td>
<td>1.90</td>
<td>1.65</td>
<td>Effective sigma (averaged on event depth)</td>
</tr>
<tr>
<td>Relative timing T_{e\gamma} [ps]</td>
<td>160</td>
<td>130</td>
<td>140</td>
<td>RMD with E_\gamma &lt; 48 MeV</td>
</tr>
<tr>
<td>Positron E [keV]</td>
<td>306 (86%)</td>
<td>306 (85%)</td>
<td>304 (86%)</td>
<td>Michel edge, core resolution</td>
</tr>
<tr>
<td>Positron ( \theta ) [mrad]</td>
<td>9.4</td>
<td>10.4</td>
<td>10.6</td>
<td>Double turn</td>
</tr>
<tr>
<td>Positron ( \phi ) at zero [mrad]</td>
<td>8.7</td>
<td>9.5</td>
<td>9.8</td>
<td>Double turn</td>
</tr>
<tr>
<td>Positron Z/Y [mm]</td>
<td>2.4/1.2</td>
<td>3.0/1.2</td>
<td>3.1/1.3</td>
<td>Double turn, Y core resolution</td>
</tr>
<tr>
<td>Gamma position [mm]</td>
<td>5 (transvers)</td>
<td>5 (transverse)</td>
<td>5 (transverse)</td>
<td>( \pi^0 ) measurement with lead collimators</td>
</tr>
<tr>
<td>Trigger/DAQ efficiency [%]</td>
<td>91/75</td>
<td>92/76</td>
<td>97/96</td>
<td></td>
</tr>
<tr>
<td>Gamma efficiency [%]</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>( \pi^0 ) sample</td>
</tr>
<tr>
<td>Positron efficiency [%]</td>
<td>43</td>
<td>36</td>
<td>36</td>
<td>From MC</td>
</tr>
</tbody>
</table>
Previous result:
(PRL 107 (2011) 181201)

BR ($\mu \rightarrow e\gamma$) < $2.4 \times 10^{-12}$ @90% C.L.

Data sample: $1.75 \times 10^{14}$ stopped $\mu^+$ (2009 + 2010)

Added in 2011: $1.85 \times 10^{14}$ $\mu^+$

Total data sample: $3.6 \times 10^{14}$ $\mu^+$

Hardware improvements in 2011:
- NaI replaced by BGO for $\pi^0$ measurements
- Laser tracker system for DCH/target alignment
- Multiple buffer readout
Reconstruction improvements

**γ-side:**
- improved pile-up rejection method:
  - reduced high energy tail
  - 7% higher signal efficiency

**e⁺-side:**
- FFT offline noise reduction:
  - few % better angle resolution
  - 6% higher signal efficiency
- New track fitter (Kalman filter):
  - reduced high energy tail
  - 7% higher signal efficiency

New algorithms applied to:
- reanalyze 2009-2010 sample;
- process data collected in 2011
Signal and background optimization done in sidebands

Events in the blind box (≈ 0.2%) are hidden up to the end of optimization procedure (only 2011)

Likelihood + Blind (only 2011) analysis

MEG analysis
MEG likelihood analysis

- Maximum likelihood analysis to extract $N_{\text{signal}}$
  - Observables: $E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \Phi_{e\gamma}$
  - PDFs are formed mostly from data.
    - Signal: Measured resolutions
  - Accidental BG: Measured spectrum in sidebands
  - RMD: Theoretical spectrum smeared by detector resolutions
- Different likelihood analyses performed to check systematics
  - PDF: Event-by-event PDF, different PDFs according to tracking quality, averaged PDF

Likelihood function

$$\mathcal{L}(x_1, \ldots, x_N, R_\phi, A_\phi | \hat{S}, \hat{R}, \hat{A}) = \frac{e^{-\hat{N}}}{N!} e^{-\frac{1}{2} \frac{(A_\phi - \bar{A})^2}{\sigma_A^2}} e^{-\frac{1}{2} \frac{(R_\phi - \bar{R})^2}{\sigma_R^2}} \prod_{i=1}^{N} \left( \hat{S}s(x_i) + \hat{R}r(x_i) + \hat{A}a(x_i) \right)$$

PDF = Probability Distribution Function

Most dangerous background is measured!
Sensitivity

Median upper bound of a sample of toy MC experiments generated with zero signal hypothesis using the measured background pdf’s.

Median (2009 - 2010) = $1.30 \times 10^{-12}$ (1.6 x $10^{-12}$ in previous analysis, 20% improvement)
Median (2009 - 2011) = $7.7 \times 10^{-13}$

10^{-13} level reached!
Re-analysis of 2009-2010

Event distributions; cuts on not shown variables

Signal PDF contours at 39.3, 74.2, 86.5%

No excess found

NSIG Best = 0.3 (+4.1, -1.5)

Comparison with previous analysis:
UL changed because of different reconstruction algorithms.
Statistical compatibility checked with toy MC: 31% probability.
2011 and 2009-2011 analysis

2011 data only
NSIG Best = -1.4 (±3.8, -1.3)

2009-2011 data
NSIG Best = -0.4 (±4.8, -1.9)

No excess observed in all samples
Unbinned maximum likelihood fit on \((E_e, E_\gamma, \Delta T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})\)

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

Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data
**Confidence level**

**Frequentistic analysis, Feldman-Cousins method**

\[
\text{BR} (\mu \rightarrow e\gamma) < 5.7 \times 10^{-13} \quad (90\% \text{ C.L.}) \quad \text{factor 4 improvement!}
\]

**Summary of all samples**

<table>
<thead>
<tr>
<th>Data set</th>
<th>(B_{\text{fit}} \times 10^{12})</th>
<th>(B_{90} \times 10^{12})</th>
<th>(S_{90} \times 10^{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009–2010</td>
<td>0.09</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>2011</td>
<td>-0.35</td>
<td>0.67</td>
<td>1.1</td>
</tr>
<tr>
<td>2009–2011</td>
<td>-0.06</td>
<td>0.57</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Result published in PRL 110 (2013) 201801

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$\tau \rightarrow \mu \gamma$ vs $\mu \rightarrow e \gamma$ NOW


Antusch et al. JHEP 0611 (2006) 090

$\theta_{13}$ recently measured by Daya Bay, Reno, Double Chooz ... ($7 \div 10^o$)
Number of $\mu^+ \rightarrow e^+\gamma$ events = (k factor) x BR ($\mu^+ \rightarrow e^+\gamma$)

- Estimated final sensitivity (toy MC) $\sim 5 \times 10^{-13}$
- Expected $BR < 5.7 \times 10^{-13}$  
  $S = 7.7 \times 10^{-13}$
- Expected $BR < 2.4 \times 10^{-12}$  
  $S = 1.6 \times 10^{-12}$

(2012 + 2013) $\approx$ (2009 + 2010 + 2011)  
$\Rightarrow$ Double statistics!

Final data and sensitivity
The MEG experiment analyzed data collected in the years 2009-2011, corresponding to a total sample of $3.6 \times 10^{14} \mu^+$ stopped on target.

No excess was found $\Rightarrow$ MEG established a new upper limit on $\text{BR}(\mu^+\rightarrow e^+\gamma) < 5.7 \times 10^{-13}$ (90% C.L.):
- 4 times better than previous MEG limit (MEG 2011)
- 20 times better than pre-MEG limit (MEGA, 2001)

**Sensitivity was** $7.7 \times 10^{-13}$ (negative fluctuation observed);

Data acquisition will end on late summer 2013;

Data collected in 2012+2013 will double the statistics $\Rightarrow$ expected final sensitivity $5 \times 10^{-13}$.

Detector upgrade proposal approved $\Rightarrow$ see Y. Uchiyama talk!
Backup slides
Several LFV processes, sensitive to New Physics (NP) through "new" lepton-lepton coupling

\[ y_{ij} \bar{\ell}_i F^{\mu\nu} \ell_j \sigma_{\mu\nu} \]

\[ \mu \to e\gamma \]
\[ \tau \to \mu\gamma \]
\[ \tau \to e\gamma \]
\[ \mu \to eee \]
\[ \mu^- N \to e^- N \]
\[ (g - 2)_{\mu} \]

\( \mu, \tau \) anomalous decays

\( \mu \to e \) conversion

Anomalous magnetic moment

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Indirect vs direct searches < 2013

Adapted from L. Calibbi et al., JHEP 1211 (2012) 040

MEG 2011 excluded

Log[BR(\mu\to e\gamma)]

$M_{1/2}$ [GeV]

$mSUGRA$, $\tan \beta = 10$, $U_{e3} = 0.11$

**Red points**: mixing based on PMNS

**Blue points**: mixing based on CKM

MEG 2011 = PRL 107 (2011) 181201

Models below this line excluded by direct LHC searches

Models compatible with MEG 2011 result

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Sensitivity of different experiments 2)

**μ → eγ vs μ → eee**

Effective lagrangian

\[ \mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa + 1)^2} \bar{\mu} R \sigma_{\mu \nu} e_L F^{\mu \nu} + h.c. \]

\[ + \frac{\kappa}{(1 + \kappa) \Lambda^2} \bar{\mu} L \gamma_\mu e_L (\bar{e} \gamma^\mu e) + h.c. \]

- Magnetic dipole interaction
- Four lepton interaction

\[ \Lambda = \text{New Physics scale} \]
\[ k = \text{Relative weight of two terms} \]

A μ → eγ experiment with sensitivity of \( \sim 10^{-14} \) is competitive with a μ → eee experiment with sensitivity \( \sim 10^{-16} \) for \( k \leq 1 \); for large \( k \), only μ → eee survives.

Needed all types of experiments

A. de Gouvea & P. Vogel, hep-ph 1303.4097

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Sensitivity of different experiments 1)

**Effective lagrangian**

\[
\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + h.c. + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma^\mu e_L \left( \bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L \right) + h.c.
\]

**Magnetic dipole interaction**

\[ B(\mu \rightarrow e \text{ conv in } ^{27}\text{Al}) = 10^{-14} \]

\[ B(\mu \rightarrow e \gamma) = 10^{-13} \]

\[ B(\mu \rightarrow e \text{ conv in } ^{27}\text{Al}) = 10^{-16} \]

**$\Lambda =$ New Physics scale**

**$k =$ Relative weight of two terms**

A $\mu \rightarrow e\gamma$ experiment with sensitivity of $\sim 10^{-14}$ is competitive with a $\mu \rightarrow e$ experiment with sensitivity $\sim 10^{-16}$ for $k < 1$; for $k >> 1$ $\mu \rightarrow e\gamma$ sensitivity drops and $\mu \rightarrow e$ conversion is the unique sensitive process.

A. de Gouvea & P. Vogel, hep-ph 1303.4097

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Part of
The MEG collaboration
Total ≈ 60 physicists
Superconducting solenoid with gradient field \((\text{COBRA})\)

- Sweeps out low \(P_z\) positrons.
- **Bending radius independent of \(\theta\) emission angle.**

205 \(\mu\)m polyethylene target, 20.5\(^\circ\) slanted angle, stopping efficiency 82%.

16 DCH with staggered anodic wires and cathodic strips in Vernier pattern.

Gas mixture \(\text{He}:\text{C}_2\text{H}_6 = 50:50\)

**Positron momentum vector measurement.**
900 l Liquid Xenon detector
846 UV sensitive PMTs
Light yield $\approx 0.8 \text{ NaI}$.
Fast timing response (45 ns)
$\Delta \Omega/4\pi \approx 0.12$
**Photon energy, timing and interaction point measurement.**

15 x 2 scintillator bars with fine mesh PMTs at both ends.
**Positron timing measurement.**
Overview of calibration system

Needed to ensure:

- Required precision
- Long term detector stability
- Continuous checks for a detector based on innovative technology (Liquid Xenon).

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Trigger

FPGA based system designed to reduce the trigger rate by using fast estimates:

- $\gamma$-energy: $\rightarrow 2 \times 10^3$ Hz
- $e^+\gamma$ timing: $\rightarrow 100$ Hz
- $e^+\gamma$ direction: $\rightarrow 10$ Hz

**Signal efficiency > 95%**
**Live Time fraction 99%**

Readout

DRS digitizer chip developed at PSI

- Maximum sampling speed 5 GHz, used in MEG **0.8 and 1.6 GHz**.
- 12 bit voltage digitization
Normalization

\[ N_{e\gamma} = BR(\mu^+ \rightarrow e^+\gamma) \cdot k \]

where:

\[ k \equiv N_{e\nu\nu} \times \left[ \frac{f_S}{f_M} \right] \times \frac{\varepsilon(\text{TRG} = 0 | e^+\gamma)}{\varepsilon(\text{TRG} = 22 | \text{track} \cap e^+_m \cap TC)} \times A(\gamma | \text{track}) \cdot \varepsilon(\gamma) \cdot Psc(22) \]

\[ f_S \equiv A(\text{DC}) \cdot \varepsilon(\text{track}, p_e > 50\text{MeV} | \text{DC}) \cdot \varepsilon(\text{TC} | p_e > 50\text{MeV}) |_S \]

\[ f_M \equiv \ldots | \ldots \]

TRG = 22: Michel events trigger (only DCH track required)
TRG = 0: MEG events trigger

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Per-event error matrix for positron introduced in 2011. Improvement of 10% in analysis sensitivity.
Indirect vs direct searches  NOW

Adapted from L. Calibbi et al., JHEP 1211 (2012) 040

MEG 2013 excluded

Log[BR(μ→eγ)] vs $M_{1/2}$ [GeV]

Red points: mixing based on PMNS
Blue points: mixing based on CKM

mSUGRA, tan $β = 10, U_{e3} = 0.11$

Models below this line excluded by direct LHC searches

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A 70 year history ..

Cosmic $\mu$’s

Stopped $\pi$’s

Muon beams

Gained twelve orders of magnitude!

5.7 x $10^{-13}$ Result in this talk (2013)


Empty symbols: future experiments

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