Search of Lepton Flavour Violation with the $\mu^+ \rightarrow e^+ \gamma$ decay: first results from the MEG experiment

Giovanni Signorelli
INFN Sezione di Pisa
on behalf of the MEG collaboration

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The MEG collaboration

Tokyo U.
Waseda U.
KEK

INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce

PSI

UCIrvine

JINR Dubna
BINP Novosibirsk
The MEG collaboration

X. Bai
T. Doke
T. Haruyama
Y. Hisamatsu
T. Iwamoto
D. Kaneko
A. Maki
S. Mihara
T. Mori
H. Natori
H. Nishiguchi
Y. Nishimura
W. Ootani
R. Sawada
S. Suzuki
Y. Uchiyama
S. Yamada
A. Yamamoto
S. Yamashita

A. Baldini
A. Barchiesi
C. Bemporad
G. Boca
P. W. Cattaneo
G. Cavoto
G. Cecchet
F. Cei
C. Cerri
A. De Bari
M. De Gerone
S. Dussoni
L. Galli
G. Gallucci
F. Gatti
M. Grassi
R. Nardò
D. Nicolò
M. Panareo

A. Papa
R. Pazzi
G. Piredda
F. Renga
M. Rossella
F. Sergiampietri
G. Signorelli
R. Valle
C. Voena
D. Zanello

J. Adam
J. Egger
M. Hildebrandt
P.-R. Kettle
O. Kiselev
S. Ritt
M. Schneebeli

E. Baracchini
B. Golden
W. Molzon
C. Topchyan
V. Tumakov
F. Xiao

D. N. Grigoriev
F. Ignatov
B. I. Khazin
A. Korenchenko
N. Kravchuk
D. Mzavia
A. Popov
Yu. V. Yudin

Tokyo U.
Waseda U.
KEK

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Outline

• Physics motivation for a $\mu \rightarrow e\gamma$ experiment
• The $\mu \rightarrow e\gamma$ decay
• The detector
  • Overview of sub-detectors
  • Calibration methods
• Analysis of 2008 run
• Status
  • Run 2009
• Next year(s)
The $\mu \rightarrow e\gamma$ decay

- The $\mu \rightarrow e\gamma$ decay in the SM is radiatively induced by neutrino masses and mixings at a negligible level

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

- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)

- Clear evidence for physics beyond the SM
- Restrict parameter space of SM extensions

Relative probability $\sim 10^{-54}$
Connections

• LHC
  • it is Super Symmetry + Grand Unification that predicts new particles in the loop.
  • alternate search for (E/M\text{SUSY}) suppressed effects

• neutrino oscillations
  • mixing matrix in charged sector can be proportional to
    - PMNS
    - CKM

• muon $g-2$
  • $a_\mu$ is the “diagonal” term
  • $\mu \rightarrow e \gamma$ diagram is the “off-diagonal”

Barbieri et al., Nucl. Phys B445 (1995) 225
...
Connections

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Each improvement linked to the technology either in the beam or in the detector. Always a trade-off between various elements of the detector to achieve the best "sensitivity".
**Signal and Background**

The accidental background is **dominant** and it is determined by the experimental resolutions.

The table below summarizes the results from various experiments:

<table>
<thead>
<tr>
<th>Exp./Lab</th>
<th>Year</th>
<th>$\Delta E_e/E_e$ (%)</th>
<th>$\Delta E_\gamma/E_\gamma$ (%)</th>
<th>$\Delta t_{e\gamma}$ (ns)</th>
<th>$\Delta \theta_{e\gamma}$ (mrad)</th>
<th>Stop rate (s$^{-1}$)</th>
<th>Duty cyc. (%)</th>
<th>BR (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIN</td>
<td>1977</td>
<td>8.7</td>
<td>9.3</td>
<td>1.4</td>
<td>-</td>
<td>$5 \times 10^5$</td>
<td>100</td>
<td>$3.6 \times 10^{-9}$</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>1977</td>
<td>10</td>
<td>8.7</td>
<td>6.7</td>
<td>-</td>
<td>$2 \times 10^5$</td>
<td>100</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>LANL</td>
<td>1979</td>
<td>8.8</td>
<td>8</td>
<td>1.9</td>
<td>37</td>
<td>$2.4 \times 10^5$</td>
<td>6.4</td>
<td>$1.7 \times 10^{-10}$</td>
</tr>
<tr>
<td>Crystal Box</td>
<td>1986</td>
<td>8</td>
<td>8</td>
<td>1.3</td>
<td>87</td>
<td>$4 \times 10^5$</td>
<td>(6..9)</td>
<td>$4.9 \times 10^{-11}$</td>
</tr>
<tr>
<td>MEGA</td>
<td>1999</td>
<td>1.2</td>
<td>4.5</td>
<td>1.6</td>
<td>17</td>
<td>$2.5 \times 10^8$</td>
<td>(6..7)</td>
<td>$1.2 \times 10^{-11}$</td>
</tr>
<tr>
<td>MEG</td>
<td>2010</td>
<td>1</td>
<td>4.5</td>
<td>0.15</td>
<td>19</td>
<td>$3 \times 10^7$</td>
<td>100</td>
<td>$2 \times 10^{-13}$</td>
</tr>
</tbody>
</table>
MEG experimental method

Easy signal selection with $\mu^+$ at rest:
$\mu$: stopped beam of $>10^7 \mu$ /sec in a 175 $\mu$m target

\[ \theta_{e\gamma} = 180^\circ \]

$e^+ \mu^+ \gamma$

$E_{e} = E_{\gamma} = 52.8$ MeV

• $e^+$ detection
  magnetic spectrometer composed of solenoidal magnet and drift chambers for momentum
  plastic counters for timing

• $\gamma$ detection
  Liquid Xenon calorimeter based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short $X_0$: 2.77 cm
**Beam line**

\( \pi E5 \) beam line at PSI

Optimization of the beam elements:
- Muon momentum \( \sim 29 \text{ MeV/c} \)
- Wien filter for \( \mu/e \) separation
- Solenoid to couple beam and spectrometer (BTS)
- **Degrader** to reduce the momentum for a 175 \( \mu \text{m} \) target

\( \mu/e \) separation 11.8 cm (7.2 \( \sigma \))

\( R_\mu \) (exp. on target)

\( \mu \) spot (exp. on target)

\( \sigma_x = 11 \text{ mm} \)

\( \sigma_y = 11 \text{ mm} \)

\( >6 \times 10^7 \mu^+/s \)
COBRA spectrometer

- The emitted positrons tend to wind in a uniform magnetic field
- the tracking detector becomes easily “blind” at the high rate required to observe many muons
- A non uniform magnetic field solves the rate problem
- As a bonus: CONstant Bending RAdius

| Uniform field | Constant $|p|$ track | High $p_T$ track |
|---------------|----------------------|------------------|
| CoBRa:        | Constant bending     | High $p_T$ track |
|               | quick sweep away     |                  |
The superconducting magnet is very thin \((0.2 \, X_0)\).

- Can be kept at 4 K with **GM refrigerators** (no usage of liquid helium)
Positron Tracker

- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C$_2$H$_6$ mixture
- Within one period, fine structure given by the Vernier circle
  \[ \sigma_R \approx 350 \, \mu m \]
  \[ \sigma_z \approx 500 \, \mu m \]

transverse coordinate (t drift)

longitudinal coordinate (charge division + Vernier)
Timing Counter

- Must give excellent rejection
- Two layers of scintillators:
  - Outer layer, read out by PMTs: timing measurement
  - Inner layer, read out with APDs at 90°: z-trigger
- Obtained goal $\sigma_{\text{time}} \sim 40$ psec (100 ps FWHM)

<table>
<thead>
<tr>
<th>Exp. application (*)</th>
<th>Counter size (cm) $(T \times W \times L)$</th>
<th>Scintillator</th>
<th>PMT</th>
<th>$\lambda_{\text{in}}$ (cm)</th>
<th>$\sigma_{\text{meas}}$</th>
<th>$\sigma_{\text{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.D. Agostini</td>
<td>3 x 15 x 100</td>
<td>NE114</td>
<td>XP2020</td>
<td>200</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>T. Tanimori</td>
<td>3 x 20 x 150</td>
<td>SCSN38</td>
<td>R1332</td>
<td>180</td>
<td>140</td>
<td>110</td>
</tr>
<tr>
<td>T. Sugitate</td>
<td>4 x 3.5 x 100</td>
<td>SCSN23</td>
<td>R1828</td>
<td>200</td>
<td>50</td>
<td>53</td>
</tr>
<tr>
<td>R.T. Gile</td>
<td>5 x 10 x 280</td>
<td>BC408</td>
<td>XP2020</td>
<td>270</td>
<td>110</td>
<td>137</td>
</tr>
<tr>
<td>TOPAZ</td>
<td>4.2 x 13 x 400</td>
<td>BC412</td>
<td>R1828</td>
<td>300</td>
<td>210</td>
<td>240</td>
</tr>
<tr>
<td>R. Sroynowski</td>
<td>2 x 3 x 300</td>
<td>SCSN38</td>
<td>XP2020</td>
<td>180</td>
<td>180</td>
<td>420</td>
</tr>
<tr>
<td>Belle</td>
<td>4 x 6 x 255</td>
<td>BC408</td>
<td>R6680</td>
<td>250</td>
<td>90</td>
<td>143</td>
</tr>
<tr>
<td>MEG</td>
<td>4 x 4 x 90</td>
<td>BC404</td>
<td>R5924</td>
<td>270</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>

Best existing TC
The photon detector

- γ Energy, position, timing
- Homogeneous 0.8 m³ volume of liquid Xe
  - 10% solid angle
  - 65 < r < 112 cm
  - |cosθ| < 0.35  |Φ| < 60°
- Only scintillation light
- Read by 848 PMT
  - 2” photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low temperature (165 K)
  - Quartz window (178 nm)
- Thin entrance wall
- Singly applied HV
- Waveform digitizing @2 GHz
- Pileup rejection
Xe properties

- **Liquid Xenon** was chosen because of its **unique** properties among radiation detection active media
- \( Z=54, \ \rho=2.95 \text{ g/cm}^3 \) \((X_0=2.7 \text{ cm}), \ \text{R}_M=4.1 \text{ cm}\)
- High light yield (similar to NaI)
  - \(40000 \text{ phe/MeV}\)
- Fast response of the scintillation decay time
  - \(\tau_{\text{singlet}}=4.2 \text{ ns}\)
  - \(\tau_{\text{triplet}}=22 \text{ ns}\)
  - \(\tau_{\text{recomb}}=45 \text{ ns}\)
- Particle ID is possible
  - \(\alpha \sim \text{singlet+triplet}, \ \gamma \sim \text{recombination}\)
- Large refractive index \(n = 1.65\)
- No self-absorption \((\lambda_{\text{Abs}}=\infty)\)
γ-detector construction
TRG + DAQ example

- For (almost) all channels, for each sub-detector we have two waveform digitizers with complementary characteristics.

![Graph showing trigger waveform and online pedestal subtraction for LXe]

- Custom DRS2 chip (PSI)
  - 2 GHz: offline DAQ

- 100 MHz: trigger and redundancy
  - FADC-FPGA VME boards (Pisa)

- info from all sub-detectors is combined

![Graph showing TGEN bits and trigger types]

- Trigger!

- Beam rate \( \sim 3 \times 10^7 \) s\(^{-1}\)
- Acquisition rate 7 s\(^{-1}\)
Calibrations

- It is understood that in such a complex detector a lot of parameters must be constantly checked.
- We are prepared for redundant calibration and monitoring.
- Single detector
  - PMT equalization for LXe and TIC
  - Inter-bar timing (TIC)
  - Energy scale
- Multiple detectors
  - relative timing
Calibrations

**Proton Accelerator**

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

**Alpha on wires**

PMT QE & Att. L
Cold GXe
LXe

**Xenon Calibration**

π⁺ + p → π⁰ + n
π⁰ → γγ (55MeV, 83MeV)
π⁻ + p → γ + n (129MeV)
LH₂ target

**LED**

PMT Gain
Higher V with light att.

**Laser**

relative timing calib.

**Nickel γ Generator**

Lower beam intensity < 10⁷
Is necessary to reduce pile-ups
A few days ~ 1 week to get enough statistics

Illuminate Xe from the back
Source (Cf) transferred by comp air → on/off

µ radiative decay

9 MeV Nickel _-line

NaI
• A reliable result depend on a constant calibration and monitoring of the apparatus
• We are prepared for continuous and redundant checks
  • different energies
  • different frequency

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy</th>
<th>Frequency</th>
</tr>
</thead>
</table>
| Charge exchange          | $\pi^- p \rightarrow \pi^0 n$
                          | $\pi^0 \rightarrow \gamma \gamma$ | 55, 83, 129 MeV | year - month |
| Proton accelerator       | $^7\text{Li}(p, \gamma_{17.6})^8\text{Be}$ | 14.8, 17.6 MeV | week          |
| Nuclear reaction         | $^{58}\text{Ni}(n, \gamma_9)^{59}\text{Ni}$ | 9 MeV          | daily         |
| Radioactive source       | $^{60}\text{Co, AmBe}$ | 1.1 -4.4 MeV   | daily         |
**CW - daily calibration**

- This calibration is performed *every other day*
- Muon target moves away and a crystal target is inserted
- Hybrid target \((\text{Li}_2\text{B}_4\text{O}_7)\)
- Possibility to use the same target and select the line by changing proton energy

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Peak energy</th>
<th>(\sigma) peak</th>
<th>(\gamma)-lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Li}(p,\gamma)\text{Be})</td>
<td>440 keV</td>
<td>5 mb</td>
<td>((17.6, \ 14.6)) MeV</td>
</tr>
<tr>
<td>(\text{B}(p,\gamma)\text{C})</td>
<td>163 keV</td>
<td>(2 \times 10^{-1}) mb</td>
<td>((4.4, \ 11.7, 16.1)) MeV</td>
</tr>
</tbody>
</table>

*Graph showing number of events as a function of date for \(\gamma\)-lines.*

*Graph showing \(\gamma\)-lines peaks for different dates.*
2008: First run of the experiment
(... after a short engineering run in 2007)

Time schedule

Winter - Spring
- detector dismantling
- improvement (after run 2007)
- re – installation

Spring - Summer
- LXe purification
- CW and \( \pi^0 \) calibration
- beam line setup

September – December
- MEG run
- short \( \pi^0 \) calibration

Running conditions
MEG run period
- Live time \(~50\%\) of total time
- Total time \(~7 \times 10^6\) s
- \( \mu \) stop rate: \(3 \times 10^7\) \( \mu \)/s
- Trigger rate 6.5 ev/s ; 9 MB/s

The missing 50\% is composed of:
- 17\% DAQ dead time
- 14\% programmed beam shutdowns
- 7\% low intensity Radiative muon decay runs (RMD)
- 11\% calibrations
- 2\% unforeseen beam stops
We also took RMD data once/week at reduced beam intensity.
2008 run DCH instabilities

- DCH started to show frequent HV trips after 2–3 months of operation
- an increasing number of DCH had to be operated with reduced HV settings
  - reduced efficiency and resolution
  - problem due to long-term exposure to helium
- the DC instability cancels out in the evaluation of the branching ratio
  - normalized to Michel decays

- The DCH modules have now been modified and have been successfully operated in the 2009 run
- HV spark reproduced in lab
Analysis

• We decided to adopt a **blind-box likelihood analysis** strategy

  • Three independent blind likelihood analyses

  • The blinding variables are $E_\gamma$ and $t_{e\gamma}$

• Use of the **sidebands** justified by the fact that our **main background** comes from **accidental coincidences**
Analysis principle

- A $\mu \rightarrow e\gamma$ event is described by 5 kinematical variables
  - $E_e$, $E_\gamma$, $(\Delta \theta, \Delta \phi)$, $t_{e\gamma}$
- Likelihood function is built in terms of Signal, radiative Michel decay RMD and background BG number of events and their probability density function PDFs

\[
\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{N^{N_{\text{obs}}} \exp^{-N}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \left[ \frac{N_{\text{sig}}}{N} S + \frac{N_{\text{RMD}}}{N} R + \frac{N_{\text{BG}}}{N} B \right]
\]

- PDFs taken from
  - data
  - MC tuned on data
Probability Density Functions

• SIGNAL
  \( E_\gamma \): from full signal MC (or from fit to endpoint)
  \( E_e \): 3-gaussian fit on data
  \( \theta_{e\gamma} \): combination of e and gamma angular resolution from data
  \( t_{e\gamma} \): single gaussian from MEG trigger Radiative Decay (no cut on Eg)

• RADIATIVE
  \( E_e, E_\gamma, \theta_{e\gamma} \): 3D histo PDF from toy MC that smears and weighs Kuno-Okada
distribution taking into account resolution and acceptance
  \( t_{e\gamma} \): single gaussian with same resolution as signal

• ACCIDENTAL
  \( E_\gamma \): from fit to \( t_{e\gamma} \) sideband
  \( E_e \): from data
  \( \theta_{e\gamma} \): from fit to \( t_{e\gamma} \) sideband
  \( t_{e\gamma} \): flat

Alternative observables definition

1) different algorithm for LXe Timing
2) Trigger LXe waveform digitizing electronics (\( E_\nu \))
Some examples of pdfs

- Resolution functions of core and tail components
  - core = 374 keV (60%)
  - tail = 1.06 MeV (33%) and 2.0 MeV (7%)

- Positron angle resolution measured using multi-loop tracks
  - $\sigma(\varphi) = 10$ mrad
  - $\sigma(\vartheta) = 18$ mrad

- Average upper tail for deep conversions
  - $\sigma = 2.0 \pm 0.15$ %

- Systematic uncertainty on energy scale < 0.6%

- $\sigma_t$ is corrected for a small energy-dependence
  - (148 ± 17) ps
  - stable within 20 ps along the run
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- $\sigma_t$ is corrected for a small energy-dependence
  - (148 ± 17) ps
  - stable within 20 ps along the run
- MEGA had on RMD
  - 700 ps resolution
Likelihood fit

• A “Feldman-Cousins” approach was adopted for the likelihood analysis
• The sensitivity (average expected 90% CL upper limit) on $N_{\text{sig}}$ assuming no signal by means of toy MC:
  – $N_{\text{sig}} < 6$
• 90% CL upper limit from the sidebands
  – $N_{\text{sig}} < (4.2 \div 9.7)$
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$N_{\text{sig}} < 14.7 \ @ 90\% \ CL$

$N_{\text{RMD}}$ consistent with sideband estimate: $25^{+17}_{-16}$
Normalization

- The $N_{\text{sig}}$ are normalized to the detected Michel positrons

$$BR(\mu^+ \rightarrow e^+\gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon_{\text{trig}}}{\epsilon_{e\gamma}} \times \frac{A_{TC}}{A_{e\gamma}} \times \frac{\epsilon_{DC}}{\epsilon_{e\gamma}} \times \frac{1}{A_{LXE}} \times \frac{1}{\epsilon_{LXE}}$$

- Count # of Michel decays in the analysis window with a pre-scaled trigger

- $\epsilon(\gamma) = 0.61 \pm 0.03$, confirmed by $\pi^0$ and RD spectra

- Norm $= (2.0 \pm 0.2) \times 10^{-12}$
Likelihood fit

- A “Feldman-Cousins” approach was adopted for the likelihood analysis.
- The sensitivity (average expected 90% CL upper limit) on $N_{\text{sig}}$ assuming no signal by means of toy MC:
  - $BR < 1.3 \times 10^{-11}$
- 90% CL upper limit from the sidebands:
  - $BR < (0.9 \div 2.1) \times 10^{-11}$

$N_{\text{sig}} < 14.7 \text{ @90\% CL}$

$N_{\text{RMD}}$ consistent with sideband estimate: $25^{+17}_{-16}$
Result on BR

\[ BR(\mu^+ \rightarrow e^+\gamma) < 3.0 \times 10^{-11} \]

- Effect of systematics on evaluation of limit on \(N_{\text{sig}}\)
  - \(E_\gamma\) energy scale (~0.6)
  - \(e^+\) angle (~0.35)
  - \(e^+\) energy spectrum (~1.18)

- ~2 times worse than expected sensitivity
- Probability of getting this result by statistical fluctuations is ~5%

see arXiv:0908.2594v1 [hep-ex]
Conclusion

- Data from the **first three months** of operation of the MEG experiment give a result competitive with the previous limit
  - 2008 run suffered from detector instabilities
- During 2009 shutdown the problem with the DCH instability was solved
  - DCH operated for all the 2009 run with no degradation
- Data taking in Nov-Dec/2009
  - improved efficiency
  - improved electronics (DRS2 → DRS4)
  - improved resolutions (track, time...)
- Confident in a sensitivity $\sim 5 \times 10^{-12}$ for this year’s data
- We will need to **run until** the end of **2011** for reaching the target sensitivity
Thank you

- Visit us on [http://meg.psi.ch](http://meg.psi.ch)
Back-up slides