\( \mu \rightarrow e\gamma \) search with MEG: results and perspectives

Luca Galli, INFN Pisa
Outline

• Physics motivations
• The experiment
  • detector and beam
  • signal and background
• Analysis scheme
• Results from Run 2009
  • normalization and sensitivity
  • results and upgrades
• Perspectives
  • Run 2010 data
  • 2011 and future
cLFV in the Standard Model and beyond

cLFV undetectably small in the Standard Model with $\nu$-oscillations

\[
\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e\nu\nu)} \approx \left( \frac{\alpha}{2\pi} \right) \sin^2(2\theta) \left( \frac{\Delta m^2}{M_W^2} \right)^2 \approx 10^{-54}
\]

- process enhanced in SUSY theories and others
- expected rate $\approx$ experimental sensitivities $10^{-12} \div 10^{-14}$
- no SM contamination: $\mu \rightarrow e\gamma$ New Physics clean probe

Scan in the LHC parameter space

G. Isidori, Phys Rev. D75 (2007) 115019
P. Paradisi, this conference
Experimental method

Detector OUTLINE

- **μ decay at rest**
  - Beam rate: $3 \times 10^7 \mu/s$
  - μ stopped in 205 μm target

- **γ detection**
  - Liquid Xenon calorimetry with scintillation light
    - fast: 4/22/45 ns
    - high LY: ~0.8 NaI
    - short $X_0$: 2.77 cm

- **e⁺ detection**
  - Magnetic spectrometer
    - non-uniform B field → constant bending radius and e⁺ swept rapidly away
    - ultra-thin drift chambers to limit matter effects ($X_0 \sim 0.0003$ per module)

- **TC detector**
  - time of flight with plastic scintillator counters
  - transverse scintillation fibers → hit position

~60 physicists, 12 Institutions, 5 Countries
Italy, Japan, Russia, Switzerland, USA
Location: Paul Scherrer Institut (CH)
Signal and background

**Accidental bkg** is **dominant** and determined by **beam rate** and **resolutions**

\[ B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma} \]

\[ B_{RMD} \approx 0.1 \cdot B_{acc} \]

<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 x 10(^5)</td>
<td>100</td>
<td>3.6 x 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 x 10(^5)</td>
<td>100</td>
<td>1 x 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 x 10(^5)</td>
<td>6.4</td>
<td>1.7 x 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 x 10(^5)</td>
<td>(6..9)</td>
<td>4.9 x 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 x 10(^8)</td>
<td>(6..7)</td>
<td>1.2 x 10(^{-11})</td>
</tr>
<tr>
<td>MEG</td>
<td>2008 - x</td>
<td>1</td>
<td>4.5</td>
<td>0.15</td>
<td>19</td>
<td>3 x 10(^7)</td>
<td>100</td>
<td>3.5 x 10(^{-13})</td>
</tr>
</tbody>
</table>
MEG key elements

- **MEG** is a *precision experiment* which *demands* for
  - *unprecedented detector resolution at these energies* for effective *background rejection*
  - *accurate monitoring* of detector *performances with time*
- The detector is *operated in conjunction* with an *impressive set of calibration tools*
LXe calibrations (subset...)

Artificial light source... ... events inside the detector... ... low energy $\gamma$s with beam...

**LED**
PMT gain

**$\alpha$ source**
PMT QE
Absorption length

**Ni $\gamma$ generator**
9 MeV $\gamma$-line
beam on/off calib.

**CEX**
$\gamma$-resolutions:
- energy
- time
- impact point

**XENON CALIBRATION**

**CW p-accel**
Light Yield
LXe-TC t-calib

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La Thuile, 04-03-2011
Luca Galli, INFN Pisa
Analysis strategy

- Decided to extract $\mathbf{C L}$ to $\mathbf{B(\mu \rightarrow e \gamma)}$ from a likelihood analysis in a wide signal box.

- Each event is described in terms of 5 kinematic variables:
  - $x_i = (E_{\gamma}, E_e, t_{\gamma e}, \varphi_{\gamma e}, \theta_{\gamma e})$

- Resolutions and PDFs evaluated on data outside the signal box.
  - Signal box closed until analysis is fixed.

- Use of sidebands:
  - Accidental background from Left and Right sidebands.
  - RMD studied in the $E_{\gamma}$ sideband.
Run 2009: PDFs

<table>
<thead>
<tr>
<th>( E_Y )</th>
<th>Tracking</th>
<th>( t_{eY} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td>( \pi^0 \rightarrow \gamma \gamma )</td>
<td>( \mu \rightarrow e\nu \bar{\nu} )</td>
<td>( \mu \rightarrow e\nu \bar{\nu} \gamma )</td>
</tr>
<tr>
<td>Left&amp;Right sideband</td>
<td>( \sigma(p) = 390 \text{ keV} ) (core 0.74%, double gaussian)</td>
<td>( \sigma(t_{eY}) = 142 \text{ ps} ) (core)</td>
</tr>
<tr>
<td></td>
<td>( \sigma(\varphi_e) = 7.1 \text{ mrad} ) (core)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \sigma(\theta_e) = 11.2 \text{ mrad} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \sigma(Z)_{\text{vertex}} = 3.4 \text{ mm} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \sigma(Y)_{\text{vertex}} = 3.3 \text{ mm} )</td>
<td></td>
</tr>
</tbody>
</table>

- \( \sigma_R = 2.1 \pm 0.15\% \) measured with CEX events
- **Sys** uncertainty in energy scale 0.6%
Likelihood function

- **Likelihood** function in terms of **Signal**, **Radiative muon decay**, and accidental **Background** number of events and **PDFs**

\[
L(N_S, N_R, N_B) = \frac{N_{obs} e^{-N}}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[ \frac{N_S}{N} S + \frac{N_R}{N} R + \frac{N_B}{N} B \right]
\]

- **N_S**, **N_R**, **N_B** measured **simultaneously** with an **un-binned** Likelihood fit in the analysis box
- **B(μ→eγ)** C.L. with **Feldman and Cousins**
- Cross-check:
  - two independent **frequentistic analysis** with different **PDFs**
    - **Analysis A**: separated angles (θeγ, φeγ) and event by event PDFs
    - **Analysis B**: stereo angle θeγ
  - **third analysis** based on **Bayesian statistics**
Normalization and sensitivity

Normalization from $N_{\mu \rightarrow e \nu \bar{\nu}}$ events counted simultaneously with the signal with pre-scaled trigger

$$\frac{B(\mu^+ \rightarrow e^+ \gamma)}{B(\mu^+ \rightarrow e^+ \nu \bar{\nu})} = \frac{N_{\text{sig}}}{N_{\text{ev}\nu}} \times \frac{f_{\text{ev}\nu}}{P \cdot \epsilon_{\text{pu}}} \times \frac{\epsilon_{\text{ev}\nu}}{\epsilon_{\text{trig}}} \times \frac{\epsilon_{\text{DC}}}{\epsilon_{e\gamma}} \times \frac{1}{A_{\text{geo}}} \times \frac{1}{\epsilon_{e\gamma}} = \frac{N_{\text{sig}}}{k}$$

$k = 1.0 \pm 0.1 \times 10^{12}$

Sensitivity = $6.1 \times 10^{-12}$

average 90% CL upper limit of toy MC with 0 signal

consistent with sideband results $4 \div 6 \times 10^{-12}$
Fit result

**Best Fit:** $N_S = 3, \quad N_R = 35^{+24}_{-22}$

$N_S < 14.5 \text{ at } 90\% \text{ C.L. (Feldman-Cousins)}$

**Signal**
**RADIATIVE DECAY**
**ACCIDENTAL**
**TOTAL**

(dashed: $N_S$ 90% U.L.)
The effect of **systematics** is taken into account in the calculation of the confidence region by **fluctuating the PDFs** according to uncertainty values.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>8%</th>
<th>( \epsilon_e ), ( \epsilon_{\gamma} ), ( \epsilon_{\text{TRG}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalization</td>
<td>0.4%</td>
<td>Light yield stability, gain shift</td>
</tr>
<tr>
<td>( E_{\gamma} ) scale</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>( E_{\gamma} ) resolution</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>( E_e ) scale</td>
<td>7%</td>
<td>from Michel edge</td>
</tr>
<tr>
<td>( E_e ) resolution</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>( t_{\gamma} ) center</td>
<td>15 ps</td>
<td></td>
</tr>
<tr>
<td>( t_{\gamma} ) resolution</td>
<td>10%</td>
<td>RMD peak</td>
</tr>
<tr>
<td>Angle</td>
<td>7.5 mrad</td>
<td>Tracking + LXe position</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>( E_e - \phi_e ) correlation</td>
<td>50%</td>
<td>MC evaluation</td>
</tr>
</tbody>
</table>

Greater systematics from positron reconstruction code

**Overall effect \( \sim 10\% \) on \( N_s \) C.L.**
Preliminary result

• A preliminary result of 2009 data for the MEG experiment
  • \( B(\mu \rightarrow e\gamma) < 1.5 \times 10^{-11} \) @90% C.L. (ICHEP 2010)

• Notes:
  • the three analysis are consistent
  • the null hypothesis has a probability of 20-60%

• The MEG published result on 2008 data was (Nucl.Phys B 834(2010) 1)
  • \( B(\mu \rightarrow e\gamma) < 2.8 \times 10^{-11} \) @90% C.L.

  • \( B(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11} \) @90% C.L
Blue lines are 1(39.3% included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions. For each plot, cut on the other variables for roughly 90% window is applied.
1. **Increase statistics!!**
   - Run **2010** with double statistics w.r.t. **2009** $k \approx 2 \times 10^{12}$
     - analysis on going
     - **2009 & 2010** data together
   - *In 2011 and 2012* dedicated to intensive DAQ, integrated $k \approx 3 \times 10^{13}$

2. **Improve detector (and) resolutions:**
   - **better understanding** of spectrometer and B-field related systematics
   - **improved** $e^+$ resolutions, from **2009 data**
   - **LXe simulation**
     - better PMT QE evaluation to improve $\gamma$ reconstruction, from **2009 data**
   - **New calibration technique**
   - **Mott scattering** with monochromatic $e^+$ beam, from **2010 data**
   - **new HV distributor** for DC
     - **20-30%** lower noise $\rightarrow$ better angular resolution, from **2011 data**
   - **new DAQ read out scheme**
     - $\sim$99% Live Time with trigger efficiency $>95\%$, from **2011 data**
New result with 2009 data

- What’s new?
  - **systematic** in the COBRA B-field measurement
  - φ component in the measured B-field not taken into account in reconstruction
    \[ \frac{B_\varphi}{B_z} \sim 2 - 3 \times 10^{-3} \]
  - use of calculated B-field
  - better resolution and lower systematics

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### e⁺ resolutions

<table>
<thead>
<tr>
<th></th>
<th>1st processing</th>
<th>2nd processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(p) ) (%)</td>
<td>0.74 (core)</td>
<td>0.61 (core)</td>
</tr>
<tr>
<td>( \sigma(\varphi) ) (mrad)</td>
<td>7.4 (core)</td>
<td>6.2 (core)</td>
</tr>
<tr>
<td>( \sigma(\theta) ) (mrad)</td>
<td>11.2</td>
<td>9.4</td>
</tr>
</tbody>
</table>

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NEW RESULT ready **SOON**

- 1st processing
- 2nd processing
Conclusions

• In 2009 MEG took data for 2 months in a stable detector condition

• Preliminary result
  • Sensitivity: $6.1 \times 10^{-12}$
  • 90% C.L. upper limit: $1.5 \times 10^{-11}$

• Update about 2009 data
  • calculated B-field in tracking
  • $e^+$ resolutions improved
    • result ready soon

• 2010: 2x statistics w.r.t. 2009
  • $k \sim 2 \times 10^{12}$ (+ 2009 data...)

• 2011-2012: ~5x statistics w.r.t 2009$\oplus$2010
Thanks for you attention!

The MEG Collaboration
Backup slides
μ-beam

Intensity (μ-stop/s)
- Low: $2.5 \times 10^6$
- Normal: $3.2 \times 10^7$
- Max: $2 \times 10^8$

Characteristics
- $P = 27.7$ MeV/c
- $\Delta P = 0.3$ MeV/c
- $\sigma_x = 9.5$ mm
- $\sigma_y = 10$ mm

MEG Target
- Material: CH$_2$
- $\theta = 22.5^\circ$
- thick: $205 \mu$m
- Size: $15 \times 25$ cm$x$cm
Positron spectrometer

Gradient magnetic field:
- $e^+$ rapidly swept away from detector
- bending radius $\propto |p|$

$e^+$ momentum
- 16 staggered ultra-thin DC ($\sim 0.0003 X_0$)
  $\sigma(p) = 200 \text{ keV}/c$ (design)
  direction = 5 mrad (design)

$e^+$ timing
- plastic scintillator counters
  $\sigma(t) = 45 \text{ ps}$ (design)
Events in the signal region were checked carefully.

An event in the signal region.
Uniformity

Calorimeter uniformity
- 55 MeV $\gamma$ (from $\pi^0$ decay)
- $E_\gamma$ resolution vs conversion point
- Close to design value

Timing uniformity and stability
- Events from raditive $\mu$ decay (RD)
- Requires LXe+TC+track
- Close to design value (if rescaled for the different $E_\gamma$ energy)