New limit on the Lepton Flavor Violating decay $\mu \rightarrow e\gamma$

Flavio Gatti - University and INFN of Genoa, Italy

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61 collaborators/5 countries
Kinematics

\[ E_e = E_\gamma = 52.8 \text{ MeV} \]
\[ \theta_{e\gamma} = 180^\circ \]
\[ t_{e\gamma} \sim 0 \]

\[ B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}} \]

\[ B_{\text{acc}} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta \theta^2 \Delta t \]
Stopped $\pi E_5$ beam of $3 \times 10^7 \mu$ /sec in a 150 $\mu$m target

1. Drift Chambers for $e^+$ momentum (DCH) in Magnetic Field
2. Scintillation counters for $e^+$ timing (TC) in Magnetic Field
3. Liquid Xenon calorimeter for $\gamma$ energy and timing (LXe) (scintillation)
Paul Scherrer Institut (CH) ➔ Most intense continuous muon beam
1.6 MW proton accelerator
Presently, more than 2 mA of protons (possible upgrade to 3 mA)
Highly stable beam
> 3 x 10^8 muons/sec @ 2 mA
Beam line

πE5 beam line at PSI

Optimization of the beam elements:
- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 205 μm target

μ/e separation 11.8 cm (7.2 σ)
Rμ (exp. on target)
μ spot (exp. on target)

3 x 10^7 μ^+/s
σ_v ≈ σ_H ≈ 11 mm
σ_x = 11 mm
σ_y = 11 mm
### Constant Bending Radius solenoid (CoBRa)

| Uniform field | Constant $|\rho|$ track | High $\rho_T$ track |
|---------------|-------------------------|---------------------|
| CoBRa:        | ![Diagram 1](image1)     | ![Diagram 2](image2) |
| Constant bending quick sweep away | ![Diagram 3](image3)     | ![Diagram 4](image4) |
Tracking the Positrons: Drift Chambers

- 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-C₂H₆ mixture
- Within one period, fine structure given by the Vernier circle
  \[ \sigma_R \sim 300 \, \mu m \quad \text{transverse coordinate (t drift)} \]
  \[ \sigma_Z \sim 700 \, \mu m \quad \text{longitudinal coordinate (Vernier)} \]
A view of Drift chambers inside the Magnet CoBra

Drift Chambers  Mu-target

Gamma  e+

Gap for the Timing Counter

Inner surface of CoBRA
Timing (tracking) the positron

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

![Diagram showing timing resolution and counter dimensions](image)

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

*Best existing TC*
Fully Tested at BTF (LNF-ITALY)
Timing Counter

4x4 cm Scintillating bar

2" PMT coupler

Front-end electronics

Fibers-electronics assembly

Timing counter with fiber sexposed

Cooling system

Scintillating fibers
Timing Counter
The most important thing: a plastic bag against the He atmosphere of CoBra

Special new plastic used for "mozzarella"'s bag (EVAL) has been produced with a thickness of 250 um (typically 25-50 um)

EVAL has one of the lowest He diffusivity coefficient among plastics: With 2 m² surface expose to 1 atm He We achieve 1-10 times the natural atmospheric He partial pressure
TC before insertion in the Magnet
LXe

- γ Energy, position, timing
- Homogeneous 0.8 m³ volume of liquid Xe = 2.7 t
  - 10% solid angle
  - 65 < r < 112 cm
  - |cosθ| < 0.35, |

- Only scintillation light
  - Read by 848 PMT 2” photo-multiplier tubes
    - Maximum coverage
    - Immersed in liquid Xe
    - Low temperature (165 K)
    - Quartz window (178 nm)

- Thin entrance wall
- Waveform digitizing @ 2 GHz
  - Pileup rejection
Lxe cryostat

- Inner PMT array, Cryostat, final positioning
Digitizer for DAQ

- All channels are readout by a 1 GHz WFD

- DRS chip (Domino Ring Sampler)
  - Custom sampling chip designed at PSI (BW of 950 MHz)
  - 0.2 → 5 GHz sampling. → 40 ps timing resolution
  - Sampling depth 1024 bins for 9 channels/chip
  - Full waveform is a handle to do pile-up rejection
Calibrations and Monitoring

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

**Alpha on wires**
- PMT QE & Att. L
- Cold GXe
- LXe

**Xenon Calibration**
- $\pi^0 \rightarrow \gamma\gamma$
- $\pi^0 + p \rightarrow \pi^0 + n$
- $\pi^0 \rightarrow \gamma (55\text{MeV}, 83\text{MeV})$
- $\pi^0 + p \rightarrow \gamma + n (129\text{MeV})$
- LH$_2$ target

**LED**
- PMT Gain
- Higher V with tight att.

**Laser**
- relative timing calib.

**Nickel γ Generator**
- 9 MeV Nickel
- Source (Cf) transferred by comp air → on/off

**μ radiative decay**
- Lower beam intensity < 10$^7$
- Is necessary to reduce pileups
- A few days ~ 1 week to get enough statistics

**NaI**
- NaI crystal
An example: the alpha sources

- It is understood that in such a complex detector a lot of parameters must be constantly checked.
- We have prepared several and redundant calibration and monitoring tools:
  - Single detector
  - PMT equalization for LXe and TIC
  - Inter-bar timing (TIC)
  - Energy scale
  - Multiple detectors
  - Relative timing
Alpha-rings,
Reconstructed signal from alpha source onto thin wire in LXe
An example: the Lxe Calibration

- This calibration is performed routinely
- Muon target moves away and a crystal target is inserted
- Hybrid target (Li₂B₄O₇)
- 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>σ peak</th>
<th>γ-lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li(p,γ)Be</td>
<td>440 keV</td>
<td>5 mb</td>
<td>(17.6, 14.6) MeV</td>
</tr>
<tr>
<td>B(p,γ)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>
Gamma Energy stability

The graph shows the energy scale over time, with two sets of data: CW-Li peak history (black dots) and MEG BG scale history (red dots). The energy scale is measured in arbitrary units (a.u.).

The data indicates a stability within ±1%.
Gamma Energy Calibration

\[ \pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n \]

- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons
- Dalitz decays were used to
- study positron-photon synchronization and time
- resolution: \( \pi_0 \rightarrow \gamma e^+ e^- \)
Gamma Position Resolution

Hit point resolution for photon conversion position was evaluated by CEX run with Pb collimators ~ 5mm
Positron time measured by TC and corrected by ToF (DC trajectory)

LXe time corrected by ToF to the conversion point

RMD peak in a normal physics run corrected by small energy dependence;

stable < 20ps
Alignements

- alignment by CR & Michel e+
- DC - B field - target - LXe
- optical surveys
- DC: MILLEPEDE (like in CMS)
- target holes
- LXe: Pb collimators
- more detailed implementation of e+ correlation
The Blind Analysis

Parameters:
\((E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})\)

Outputs:
signal, acc BG, RD BG

PDFs mostly from data
accidental BG: side bands
signal: measured resolution
radiative BG: theory + resolution
Fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering
PDF: methods of calculation

**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 $E_g$)

**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 ($E_\gamma$)
PDF plots and resolutions

- **$E_Y$**
  - Resolution functions of core and tail components
    - $\text{core} = 390 \text{ keV (0.74\%)}$
  - Positron angle resolution measured using multi-loop tracks
    - $\sigma(\varphi) = 7.1 \text{ mrad (core)}$
    - $\sigma(\theta) = 11.2 \text{ mrad}$

- **$E_{e^+}$**
  - Average upper tail for deep conversions
    - $\sigma_R = (2.1 \pm 0.15) \%$
  - Systematic uncertainty on energy scale $< 0.6\%$

- **$t_{eY}$**
  - 40 MeV $< E_Y < 48 \text{ MeV}$
  - $\sigma_t$ is corrected for a small energy-dependence
    - $(142 \pm 15) \text{ ps}$
    - Stable within 15 ps along the run
  - MEGA had on RMD
    - 700 ps resolution

- **$\gamma_{bck}$**
  - Overall angular resolution combining
    - XEC+DCH+target
      - $\sigma(\varphi) = 12.7 \text{ mrad (core)}$
      - $\sigma(\theta) = 14.7 \text{ mrad}$

- **Michel**
  - Systematic uncertainty on energy scale $< 0.6\%$
The normalization factor is obtained from the number of observed Michel positrons taken simultaneously (pre-scaled) with the $\mu\rightarrow e\gamma$ trigger:

- Cancel at first order
- Absolute $e^+$ efficiency and DCH instability
- Instantaneous beam rate variations

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

Approximately $18k$ and $10^7$.

Theory, resolution, acceptance.

\[
\text{B.R.} = N_{\text{sig}} \times (1.01 \pm 0.08) \times 10^{-12}
\]
A $\mu \rightarrow e\gamma$ event is described by 5 kinematical variables

$$x_i = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$$

Likelihood function is built in terms of Signal, radiative Michel decay RMD and background BG number of events and their probability density function PDFs

$$-\ln \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = N_{\exp} - N_{\text{obs}} \ln (N_{\exp})$$

$$- \sum_{i=1}^{N_{\text{obs}}} \ln \left[ \frac{N_{\text{sig}}}{N_{\exp}} S(x_i^\gamma) + \frac{N_{\text{RMD}}}{N_{\exp}} R(x_i^\gamma) + \frac{N_{\text{BG}}}{N_{\exp}} B(x_i^\gamma) \right]$$

Extended unbinned likelihood fit: $\text{mfit}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}})$ in a wide region

PDFs taken from
- data
- MC tuned on data

Cuts:
- $48 \leq E_\gamma \leq 58 \text{ MeV}$
- $50 \leq E_e \leq 56 \text{ MeV}$
- $|T_{e\gamma}| \leq 0.7 \text{ ns}$
- $|\phi_{e\gamma}|, |\theta_{e\gamma}| \leq 50 \text{ mrad}$
The Likelihood plots for 2009

- $N_{\text{sig}} < 14.5$ @ 90% C.L., $N_{\text{sig}}$ best-fit value = 3.0
- $N_{\text{sig}} = 0$ is in 90% confidence region
  - C.L @0: 40÷60% depending on the statistical approach

Accidental BG
RMD
Signal
Total

Dashed lines: 90% C.L. UL of Nsig
Sidebands for 2009 data

**Blind Box**

Blue lines are the 1(39.3 % included inside the region w.r.t. analysis window), 1.64(1.42%) and 2(0.03%) sigma regions. For each plot, cut on other variables for roughly 90% window is applied.
... with event ranking
...a high ranked event...

- Events in the signal region were checked carefully
- An event in the signal region
2009 data update

\[ N_{\text{sig}} = 3.0 \quad \Rightarrow \quad N_{\text{sig}} = 3.4 \]
2009 updated likelihood analysis

Best Fit $BR = 3.2 \times 10^{-12}$

$1.7 \times 10^{-13} < BR < 9.6 \times 10^{-12}$

90\% C.L.

updated 2009 data
2010 analysis

consistent with expected sensitivity = $2.2 \times 10^{-12}$ @90% C.L.
2010 data after unblinding
Likelihood 2010 data

$T_{e\gamma}$

$E_e$

$E_\gamma$

$\theta_{e\gamma}$

$\phi_{e\gamma}$

Total
Accidental
Radiative
Signal

2010 data
Likelihood Analysis

$\text{BR} < 1.7 \times 10^{-12}$

90% C.L.

2010 data
## Performance summary

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<tr>
<th></th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gamma Energy (%)</strong></td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Gamma Timing (psec)</strong></td>
<td>96</td>
<td>67</td>
</tr>
<tr>
<td><strong>Gamma Position (mm)</strong></td>
<td>5 (u,v), 6 (w)</td>
<td>5 (u,v), 6 (w)</td>
</tr>
<tr>
<td><strong>Gamma Efficiency (%)</strong></td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td><strong>e⁺ Timing (psec)</strong></td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td><strong>e⁺ Momentum (keV)</strong></td>
<td>310 (80% core)</td>
<td>330 (79% core)</td>
</tr>
<tr>
<td><strong>e⁺ θ (mrad)</strong></td>
<td>9.4</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>e⁺ φ (mrad)</strong></td>
<td>6.7</td>
<td>7.2</td>
</tr>
<tr>
<td><strong>e⁺ vertex Z/Y (mm)</strong></td>
<td>1.5 / 1.1 (core)</td>
<td>2.0 / 1.1 (core)</td>
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<tr>
<td><strong>e⁺ Efficiency (%)</strong></td>
<td>40</td>
<td>34</td>
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<td><strong>e⁺-gamma timing (psec)</strong></td>
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<td>122</td>
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<tr>
<td><strong>Trigger efficiency (%)</strong></td>
<td>91</td>
<td>92</td>
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<tr>
<td><strong>Stopping Muon Rate (sec⁻¹)</strong></td>
<td>2.9×10⁷</td>
<td>2.9×10⁷</td>
</tr>
<tr>
<td><strong>DAQ time/ Real time (days)</strong></td>
<td>35/43</td>
<td>56/67</td>
</tr>
<tr>
<td><strong>Expected 90% C.L. Upper Limit</strong></td>
<td>3.3×10⁻¹²</td>
<td>2.2×10⁻¹²</td>
</tr>
</tbody>
</table>
2009 and 2010 data
systematic errors (in total 2% in UL) include:
- relative angle offsets
- correlations in e+ observables
- normalizati

(2009+2010 expected UL = 1.6×10-12)
Summary

- New physics is now constrained by 5× tighter upper limit: \( BR < 2.4 \times 10^{-12} @90\% \text{ C.L.} \)
- (Preprint available in arXiv)
- MEG is accumulating more data this and next year to reach O(10-13) sensitivity;
- Detector improvements/upgrade