Status and prospects of charged lepton flavor violation searches with the MEG-II experiment

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INFN Roma
on behalf of the MEGII collaboration

The 19th International
Workshop on Neutrinos from Accelerators
Uppsala University, 25-30 September 2017
Charged lepton flavor violation

- Allowed but unobservable in the Standard Model (with neutrino mass \( \neq 0 \))

\[ BR(\mu \rightarrow e\gamma)_{SM} < 10^{-50} \]

- Enanced, sometimes just below the experimental limit, in many New Physics models

Observation of CLFV is a clean signal of Physics beyond the Standard Model

Crivellin et. al., 2017 (LQ model)

Crivellin et. al.

arXiv:1706.08511
History and future experiments

History of CLFV searches with muons

Future experiments
Why $\mu \to e\gamma$

- Theoretically can be favored or disfavored vs other CLFV processes depending on the New Physics model
- **Intense muon beams** available:
  - PSI presently: up to $10^8 \mu/s$, future perspectives: $10^9-10^{10} \mu/s$
- **Clean experimental signature**
  (positive muon decays at rest)

Simultaneous back-to-back $e^+$ and $\gamma$ with $E_\gamma=E_{e+}=52.8\,\text{MeV}$

**Discriminating variables:**

$E_{e+}, E_\gamma, T_{e\gamma}, \Theta_{e\gamma}$
• Accidental background
  - Accidental coincidence of $e^+$ and $\gamma$:
  - Proportional to $\Gamma_\mu^2$ while signal proportional to $\Gamma_\mu$ ($\Gamma_\mu$ = beam intensity)
  - Compromise between high signal and low background

• Radiative muon decay background
  - Proportional to $\Gamma_\mu$
  - Note: $e^+$ and $\gamma$ simultaneous as for signal
The MEG(II) location: PSI lab

The Paul Scherrer Institute
Continuous muon beam up to few $10^8 \mu^+/s$

Multi-disciplinary lab:
- fundamental research, cancer therapy, muon and neutron sources
- protons from cyclotron ($D=15m, E_{proton}=590\text{MeV}$, $I=2.2\text{mA}$)
The MEG experiment for $\mu \rightarrow e\gamma$ search

- liq. Xenon photon detector
  (~900 PMTs / ~900 L LXe, excellent resol.)
- muon stopping target
  (200um CH2 target)
- COBRA Solenoid
  (highly gradient B-field)
- Timing Counter
  (Very Fast, 45ps)
- Drift Chamber
  (Very Light, ~0.002x0)
- World Most Intense DC Muon
  (3x10^7 muon/sec)
- Muon transport

~65 physicists
(12 institutes / 5 countries)
MEG BR(µ→eγ) limit result

- 7.5 x 10^{14} stopped muons in 2009-2013
- 5 discriminating variables: E_e, E_γ, T_{eγ}, θ_{eγ}, φ_{eγ}
- likelihood analysis

BR (µ→eγ) < 4.2 x 10^{-13} at 90% C.L.

Extending the search of $\mu \rightarrow e\gamma$ is complementary to New Physics searches at the high energy frontier.

- Same detector concept as in MEG

Next: MEG upgrade: MEG-II

- Extending the search of $\mu \rightarrow e\gamma$ is complementary to New Physics searches at the high energy frontier
- Same detector concept as in MEG
MEG-II detector highlights: Liquid Xenon

Liquid Xenon Calorimeter with higher granularity in inner face: => better resolution, better pile-up rejection

- Developed UV sensitive MPPC (vacuum UV 12x12mm² SiPM)
- Detector assembled, filled with LXe (commissioning on-going, tests during 2017 pre-engineering run)
MEG-II detector highlights: Drift Chamber

- Single volume drift chamber with $2\pi$ coverage
  - 2m long
  - 1300 sense wires
  - stereo angle (6°-8°)
  - low mass
  - high trasparency to TC (double signal efficiency)

- Assembly: 78% (wiring~70%)
- Will be transported at PSI: Jan 2018
MEG-II detector highlights: Timing Counter

- High granularity: 2 x 256 BC422 scintillator plates read by SiPM
  - improved timing resolution: 35ps (70ps in MEG)
  - Assembly: completed
  - Installation in COBRA in progress
  - Full test during 2017 pre-engineering run
    (expected detector performances already confirmed in data)
MEG-II detector highlights: Radiative Decay Counter

- New auxiliary detector for background rejection purpose => improve sensitivity by 15%
- Commissioned during 2016 run
- Ready for 2017 pre-engineering run
MEG-II new trigger and DAQ system

- **New version of DRS (Wavedream)** custom digitization board integrating both digitization, triggering and some HV
  
  - ~9000 channels (5GSPS)
  - 256 channels (1crate) tested during 2016 pre-engineering run
  - > 1000 channels available for the upcoming 2017 pre-engineering run

- **Final production expected in winter 2018**
MEG-II goals and schedule

- MEG-II is expected to start taking data with the full detector next year (full engineering run)
- Final sensitivity: $4 \times 10^{-14}$
  (1 order of magnitude improvement vs MEG)

<table>
<thead>
<tr>
<th>PDF parameters</th>
<th>MEG</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{e^+}$ (keV)</td>
<td>380</td>
<td>130</td>
</tr>
<tr>
<td>$\theta_{e^+}$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$\phi_{e^+}$ (mrad)</td>
<td>8.7</td>
<td>3.7</td>
</tr>
<tr>
<td>$z_{e^+}/y_{e^+}$ (mm) core</td>
<td>2.4/1.2</td>
<td>1.6/0.7</td>
</tr>
<tr>
<td>$E_\gamma(%)$ ($w &gt; 2$ cm)/($w &lt; 2$ cm))</td>
<td>2.4/1.7</td>
<td>1.1/1.0</td>
</tr>
<tr>
<td>$u_\gamma, v_\gamma, w_\gamma$ (mm)</td>
<td>5/5/6</td>
<td>2.6/2.2/5</td>
</tr>
<tr>
<td>$t_{e^+\gamma}$ (ps)</td>
<td>122</td>
<td>84</td>
</tr>
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</table>

**Efficiency (%)**

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>MEG II</th>
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</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>$\approx$ 99</td>
<td>$\approx$ 99</td>
</tr>
<tr>
<td>Photon</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>$e^+$ (tracking × matching)</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>
Next generation of $\mu \rightarrow e\gamma$ searches

- Activities around the world to increase the muon beam rate to $10^9 \text{-} 10^{10}$ muons/s
- Crucial to understand which factors will limit the sensitivity

\[
B_{\text{sig}} \propto \Gamma_\mu \\
B_{\text{acc}} \propto \Gamma_\mu^2 \cdot \delta E_\gamma \cdot (\delta E_\gamma)^2 \cdot \delta T_{\gamma\gamma} \cdot (\delta \Theta_{\gamma\gamma})^2
\]

- For a given detector, there is no advantage in the increase of $\Gamma_\mu$ over a certain limit since at some point the sensitivity becomes constant (background dominated regime)

- MEGII, for example exploits $7 \times 10^7$ muon/s (available $10^8$ muon/s)
Next generation of $\mu \rightarrow e\gamma$ searches: photon

**Calorimeter**

- high efficiency
- good resolution

Requirements:
- high light yield
- fast response

**Photon conversion**

- low efficiency (%)
- extreme resolution
- photon direction

Requirements:
- optimization of converter thickness
  (efficiency vs pair energy and angle resolution)

Sensitivity trend vs beam intensity

blue = pair conversion design
black = calorimeter design
red = calorimeter design with x2 resolution

Sensitivity $\Gamma_\mu$ [a.u.]

$\mu$-production by a proton beam impinging on a graphite target.

Muons originate from the decay of pions produced by the decay of pions decaying right at the surface.

One of the limiting factors for the production of $\mu^+ E_4$ channel is tuned to select positive muons with $E_5$ channel.

At PSI, the High-intensity Muon Beam (HiMB) project intends to exploit:
- a higher muon capture efficiency at the production target (26% versus 6% in the existing target (20 mm), since the beam has to be preserved surrounded by a high-strength solenoidal magnetic field.

In the meanwhile, an intense activity is ongoing at PSI and elsewhere to design channels for continuous muon beams with $\mu E_4$ is also operated at PSI, with the capability of exceeding 9 $\mu E_4$ muons/s. Thanks to the improved optics.

A further beam increase to 7 $\mu E_4$ seems to be within reach.
Next generation of $\mu \rightarrow e\gamma$ searches: positron

- Tracking detectors in a magnetic field are the gold candidates: high efficiency, good resolution

- Need very light detector ($\text{MEGII} \sim 10^{-3}X_0$) : positron reconstruction is ultimately limited by MS:
  
  - in the target & tracker-> angular resolution
  - in the tracker -> momentum resolution

- Silicon trackers are not competitive with gaseous detector in terms of resolution but could be the solution at very high rate

![Expected aging in MEG-II DCH](image-url)
Next generation of $\mu \rightarrow e\gamma$ searches: relative time

- Timing plays a crucial role to avoid accidental coincidences

- Calorimetric approach: calorimeters+positron scintillating counters (MEG-II: $T_{e\gamma} \sim 80$ps)

- Photon conversion approach: need to measure $e^+$ or $e^-$ time with a fast detector for photon timing

- Several conversion layers imply to have active material behind the converter
Next generation of $\mu \rightarrow e\gamma$ searches: possible scenarios

**CALORIMETRY** (R&D with LaBr$_3$(Ce))

<table>
<thead>
<tr>
<th>Variable</th>
<th>w/o vtx detector</th>
<th>w/ TPC vtx detector</th>
<th>w/ silicon vtx detector</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>conservative</td>
<td>optimistic</td>
</tr>
<tr>
<td>$\theta_{e\gamma} / \phi_{e\gamma}$ [mrad]</td>
<td>7.3 / 6.2</td>
<td>6.1 / 4.8</td>
<td>3.5 / 3.8</td>
</tr>
<tr>
<td>$T_{e\gamma}$ [ps]</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>$E_e$ [keV]</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$E_\gamma$ [keV]</td>
<td></td>
<td>850</td>
<td></td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td></td>
<td>42%</td>
<td></td>
</tr>
</tbody>
</table>

**PHOTON CONVERSION**

<table>
<thead>
<tr>
<th>Variable</th>
<th>w/o vtx detector</th>
<th>w/ TPC vtx detector</th>
<th>w/ silicon vtx detector</th>
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<tr>
<td></td>
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<tr>
<td>$\theta_{e\gamma} / \phi_{e\gamma}$ [mrad]</td>
<td>7.3 / 6.2</td>
<td>6.1 / 4.8</td>
<td>3.5 / 3.8</td>
</tr>
<tr>
<td>$T_{e\gamma}$ [ps]</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>$E_e$ [keV]</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$E_\gamma$ [keV]</td>
<td></td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

(1 LAYER, 0.05 $X_0$)
A few $10^{-15}$ level seems to be within reach for 3 years running at $10^8$ muon/s with calorimetry or $10^9$ muons/s with photon conversion.
Conclusion

- Best constraint on the $\mu \rightarrow e \gamma$ decay set by the MEG experiment with its final dataset: $7.5 \times 10^{14}$ stopped $\mu^+$

$$\text{BR} (\mu \rightarrow e \gamma) < 4.2 \times 10^{-13} \text{ at 90\% C.L.}$$

submitted to EPJC

- **MEG-II detector** is in the construction phase
  - same design of MEG but better resolution and higher beam rate

- Engineering run in 2018, sensitivity pushed to $\sim 4 \times 10^{-14}$ in 3 years

- **Ultimate $\mu^+ \rightarrow e^+ \gamma$?**
  - $10^9$-$10^{10}$ $\mu$/s seems possible (HiMB, MUSIC..)
  - A few $10^{-15}$ level seems to be within reach for 3 years running at $10^8$ muon/s with calorimetry or $10^9$ muons/s with photon conversion approach
  - Further improvements require new detector concepts
Backup
Calibrations

Proton Accelerator

$\pi^0 \rightarrow \gamma \gamma$

$\pi^- + p \rightarrow \pi^0 + n$

$\pi^0 \rightarrow \gamma \gamma$ (55MeV, 83MeV)

$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH$_2$ target

$\mu$ radiative decay

$\gamma \rightarrow \mu^- + e^+$

$\nu \rightarrow \nu$

$\mu$ relative timing calib.

Lower beam intensity $< 10^7$

Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

$\text{Li(p,}\gamma)\text{Be}$

LiF target at COBRA center

17.6MeV $\gamma$

~daily calib.

also for initial setup

Alpha on wires

PMT QE & Att. L

Cold GxNe

LXe

Xenon Calibration

LED

PMT Gain

Higher $V$ with light att.

Nickel $\gamma$ Generator

Illuminate Xe from the back

Source (Cl) transferred by comp air $\rightarrow$ on/off

Laser

relative timing calib.
### Present CLFV limits

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Present limit</th>
<th>C.L.</th>
<th>Experiment</th>
<th>Year</th>
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</thead>
<tbody>
<tr>
<td>$\mu^+ \rightarrow e^+\gamma$</td>
<td>$&lt; 4.2 \times 10^{-13}$</td>
<td>90%</td>
<td>MEG at PSI</td>
<td>2016</td>
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<tr>
<td>$\mu^+ \rightarrow e^+e^-e^+$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
<td>90%</td>
<td>SINDRUM</td>
<td>1988</td>
</tr>
<tr>
<td>$\mu^-\text{Ti} \rightarrow e^-\text{Ti}^+$</td>
<td>$&lt; 6.1 \times 10^{-13}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>1998</td>
</tr>
<tr>
<td>$\mu^-\text{Pb} \rightarrow e^-\text{Pb}^+$</td>
<td>$&lt; 4.6 \times 10^{-11}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>1996</td>
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<tr>
<td>$\mu^-\text{Au} \rightarrow e^-\text{Au}^+$</td>
<td>$&lt; 7.0 \times 10^{-13}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>2006</td>
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<tr>
<td>$\mu^-\text{Ti} \rightarrow e^+\text{Ca}^+$</td>
<td>$&lt; 3.6 \times 10^{-11}$</td>
<td>90%</td>
<td>SINDRUM II</td>
<td>1998</td>
</tr>
<tr>
<td>$\mu^+e^- \rightarrow \mu^+e^+$</td>
<td>$&lt; 8.3 \times 10^{-11}$</td>
<td>90%</td>
<td>SINDRUM</td>
<td>1999</td>
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<tr>
<td>$\tau \rightarrow e\gamma$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2010</td>
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<tr>
<td>$\tau \rightarrow \mu\gamma$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2010</td>
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<td>$\tau \rightarrow eee$</td>
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<td>2010</td>
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<td>$\tau \rightarrow \mu\mu\mu$</td>
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<td>90%</td>
<td>Belle</td>
<td>2010</td>
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<td>$\tau \rightarrow \pi^0\mu$</td>
<td>$&lt; 8.0 \times 10^{-8}$</td>
<td>90%</td>
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<td>2007</td>
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<td>$\tau \rightarrow \pi^0\mu$</td>
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<td>2007</td>
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<td>$\tau \rightarrow \rho^0\mu$</td>
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<td>2011</td>
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<tr>
<td>$\tau \rightarrow \rho^0\mu$</td>
<td>$&lt; 1.2 \times 10^{-8}$</td>
<td>90%</td>
<td>Belle</td>
<td>2011</td>
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<td>$\pi^0 \rightarrow \mu e$</td>
<td>$&lt; 3.6 \times 10^{-10}$</td>
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<td>KTeV</td>
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<td>$K_L^0 \rightarrow \mu e$</td>
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<td>BNL E871</td>
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<td>$K_L^0 \rightarrow \pi^0\mu^+e^-$</td>
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<td>KTeV</td>
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<td>$K^+ \rightarrow \pi^+\mu^+e^-$</td>
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<td>BNL E865</td>
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<td>$J/\psi \rightarrow \mu e$</td>
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<td>$J/\psi \rightarrow \tau e$</td>
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<td>$J/\psi \rightarrow \tau\mu$</td>
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<td>2004</td>
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<td>$B^0 \rightarrow \mu e$</td>
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<td>BaBar</td>
<td>2008</td>
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<td>$B^0 \rightarrow \tau\mu$</td>
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<td>90%</td>
<td>BaBar</td>
<td>2008</td>
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<td>$B \rightarrow K\mu\mu^+$</td>
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<td>90%</td>
<td>BaBar</td>
<td>2006</td>
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<td>BaBar</td>
<td>2006</td>
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<td>$B^+ \rightarrow K^+\tau\mu$</td>
<td>$&lt; 4.8 \times 10^{-5}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2012</td>
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<td>$B^+ \rightarrow K^+\tau\mu$</td>
<td>$&lt; 3.0 \times 10^{-5}$</td>
<td>90%</td>
<td>BaBar</td>
<td>2012</td>
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<td>$B_{s}^0 \rightarrow \mu e$</td>
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<td>LHCb</td>
<td>2013</td>
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<tr>
<td>$\Upsilon(1s) \rightarrow \tau\mu$</td>
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<td>2008</td>
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<td>$Z \rightarrow \mu e$</td>
<td>$&lt; 7.5 \times 10^{-7}$</td>
<td>95%</td>
<td>LHC ATLAS</td>
<td>2014</td>
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<td>$Z \rightarrow \tau e$</td>
<td>$&lt; 9.8 \times 10^{-6}$</td>
<td>95%</td>
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<td>1995</td>
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<td>$Z \rightarrow \tau\mu$</td>
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<tr>
<td>$h \rightarrow e\mu$</td>
<td>$&lt; 3.5 \times 10^{-4}$</td>
<td>95%</td>
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<td>95%</td>
<td>LHC CMS</td>
<td>2017</td>
</tr>
<tr>
<td>$h \rightarrow \tau e$</td>
<td>$&lt; 6.1 \times 10^{-3}$</td>
<td>95%</td>
<td>LHC CMS</td>
<td>2017</td>
</tr>
</tbody>
</table>
Comparison with SUSY searches at LHC

\[
(\delta_{LL})_{ij} = \frac{(\Delta_{LL})_{ij}}{\sqrt{(m_{L}^{2})_{ii}(m_{L}^{2})_{jj}}}
\]

Calibbi, Signorelli, NC 2017
<table>
<thead>
<tr>
<th>Process</th>
<th>Energy</th>
<th>Main Purpose</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>$\mu^\pm$ from atmospheric showers</td>
<td>Wide spectrum $O$(GeV)</td>
<td>Annually</td>
</tr>
<tr>
<td>Charge exchange</td>
<td>$\pi^- p \rightarrow \pi^0 n$</td>
<td>55, 83, 129 MeV photons</td>
<td>LXe–CDCH relative position</td>
</tr>
<tr>
<td>Radiative $\mu$–decay</td>
<td>$\mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma$</td>
<td>Photons &gt; 40 MeV, Positrons &gt; 45 MeV</td>
<td>LXe–pTC relative timing</td>
</tr>
<tr>
<td>Normal $\mu$–decay</td>
<td>$\mu^+ \rightarrow e^+ \nu \bar{\nu}$</td>
<td>52.83 MeV end-point positrons</td>
<td>CDCH energy scale/resolution</td>
</tr>
<tr>
<td>Mott positrons</td>
<td>$e^+ target \rightarrow e^+ target$</td>
<td>$\approx 50$ MeV positrons</td>
<td>CDCH energy scale/resolution</td>
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<tr>
<td>Proton accelerator</td>
<td>$^7$Li(p, $\gamma$)$^8$Be</td>
<td>14.8, 17.6 MeV photons</td>
<td>LXe uniformity/purity</td>
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<tr>
<td></td>
<td>$^{11}$B(p, $\gamma$)$^{12}$C</td>
<td>4.4, 11.6, 16.1 MeV photons</td>
<td>LXe–pTC timing</td>
</tr>
<tr>
<td>Neutron generator</td>
<td>$^{58}$Ni(n, $\gamma$)$^{60}$Ni</td>
<td>9 MeV photons</td>
<td>LXe energy scale</td>
</tr>
<tr>
<td>Radioactive source</td>
<td>$^{241}$Am((\alpha, \gamma)$^{237}$Np</td>
<td>5.5 MeV $\alpha$’s</td>
<td>LXe PMT/SiPM calibration</td>
</tr>
<tr>
<td>Radioactive source</td>
<td>$^9$Be((\alpha^{241}$Am, n)$^{12}$C$^*$</td>
<td>4.4 MeV photons</td>
<td>LXe purity</td>
</tr>
<tr>
<td></td>
<td>$^{12}$C$^*$($\gamma$)$^{12}$C</td>
<td></td>
<td>On demand</td>
</tr>
<tr>
<td>Radioactive source</td>
<td>$^{57}$Co(EC, $\gamma$)$^{57}$Fe</td>
<td>136 (11 %), 122 keV (86 %) X-rays</td>
<td>LXe–spectrometer alignment</td>
</tr>
<tr>
<td></td>
<td>LED</td>
<td>UV region</td>
<td>LXe PMT/SiPM calibration</td>
</tr>
<tr>
<td></td>
<td>Laser</td>
<td>401 nm</td>
<td>pTC inter-counter timing</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Continuously</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Annually</td>
</tr>
</tbody>
</table>

**MEG-II calibrations**