LFV: mu–e gamma experiment

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Lepton Flavor Violation

• The Standard Model can explain most of the experimental results, and the Higgs boson has been found.

• However, many parameters and issues remain in SM. Is the SM incomplete, and is there new physics beyond the SM?

• Lepton flavor violation
  • Neutrino: Neutrino oscillation is a lepton flavor violating process. Neutrino oscillation might be a hint for new physics
  • Charged lepton: No LFV has been observed yet.

**SM+M_{\nu}**

In SM with neutrino mass, \( BR(\mu \rightarrow e \gamma) \sim 10^{-54} \)
(No background from SM!)

Observation of \( \mu \rightarrow e \gamma \) decay is a clear sign of new physics beyond SM

**New physics**

Many new physics such as SUSY–GUT, SUSY–seesaw, Extra Dimensions etc. predict large \( BR(\mu \rightarrow e \gamma) \)
LFV from new physics


- $\mu \rightarrow e\gamma$ search experiments are already constraining some of new physics scenarios
- $\mu \rightarrow e\gamma$ searches have real chances to discover new physics / to make strong restriction
Muon LFV experiment

Many new experiments will start, and important results will come soon.

Once a LFV process is discovered, it is very important to see other processes because ratios of the branching fraction of various LFV processes give information on nature of LFV and new physics.

ArXiv: 1307.5787[hep-ex]
μ→eγ signal & background

**Signal**

- Simple two body decay

\[ E_\gamma, E_e \approx 52.8\text{MeV} \]

\[ \Theta_{e\gamma} = 180^\circ, \ T_\gamma = T_e \]

**Radiative muon decay background**

- if two neutrinos have low energy and e+ and γ are emitted back-to-back

- timing coincident, can be used for timing calibration

**Accidental background**

- Usual muon decay Michel e+ + random γ from RMD/Annihilation in flight (AIF)

- dominant for us

- To get good sensitivity, all the resolutions should be good!

\[ N_{acc} \propto R_\mu^2 x \Delta E_\gamma^2 x \Delta E_x x \Delta \Theta_{e\gamma}^2 x \Delta t_{e\gamma} x T \]
MEG Experiment

• 1999 Proposal to PSI

• 2008–2013 Physics run

• The latest result based on 2009–2011 data set upper limit of $\text{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13} @90\%CL$

• 2012–2013 data will double the statistics, and the new result with our full statistics would be published at winter conferences

• MEG Collaborator ~ 60 physicists from Japan, Italy, Switzerland, Russia, and USA

1.3MW high intensity proton accelerator
World most intense DC $\mu^+$ beam
$>1 \times 10^8 \mu^+/s$
MEG detector

- Superconducting magnet
- Drift
- Timing

Positron spectrometer

- 3x10^7 μ⁺/s

Liquid xenon γ-ray calorimeter

- 900L LXe
- 846 PMTs
Event distribution

- 2009–2011 data

- $51 < \text{EGamma} < 55.5 \text{ MeV}$
- $52.385 < \text{EPositron(\gamma')} < 55 \text{ MeV}$
- $\pi - \Theta(\gamma') < 27.2 \text{ mrad (cos} \Theta_{\gamma'} < -0.99963)$
- $|t(\gamma')| < 244.3 \text{ ps}$
Likelihood analysis

2009-2011 likelihood fit

Total
Accidental : $2413.6^{+37.1}_{-37.0}$
Radiative : $167.5^{+24.2}_{-24.0}$
Signal : $-0.4^{+4.8}_{-1.9}$

- BR < $5.7 \times 10^{-13}$ @ 90% C.L., PRL110, 201801(2013)
- 4x improved upper limit than previous MEG result ($2.4 \times 10^{-12}$),
  20x improved than previous experiment MEGA ($1.2 \times 10^{-11}$)
Impact on new physics

SO(10) SUSY-GUT

Lorenzo Calibbi et al JHEP12(2009)057

MSSM with large $\tan\beta$

heavy squarks


SUSY-Seesaw


Split family SUSY

What can be improved?

• Statistics improvement:
  • Muon beam rate ($3 \times 7 \times 10^7 \mu^+$/s stopped on target), Positron detection efficiency (CDC, pixelated TC)

• Accidental background reduction:
  • Resolution of positron spectrometer (CDC, pixelated TC), Resolution of LXe $\gamma$-ray calorimeter for shallow events

$$N_{\text{acc}} \propto R_\mu^2 \Delta E_\gamma \Delta E_e \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma} T$$
MEG upgrade (MEG II)

- 2013 Upgrade proposal presented to PSI
- 2013–2015 R&D / detector construction
- 2016–2018 physics run
- Target sensitivity down to $5 \times 10^{-14}$

**LXe**
Inner face 2” PMTs -> 12x12mm

**CDC**
16 segmented DC -> single volume

**pTC**
15 Scinti. bars with PMTs -> 256 pixelated scinti. with SiPMs
CDC

• Single volume gaseous detector
• Stereo wires along z
• Finer granularity, better resolution
• Larger acceptance DC + TC

Challenging

Long wires: ~200cm
High rate environment

Large number of hits

Red: new tracker
$<N> \approx 64$
(Black: current one)

Expected Performance

Momentum $\sim 130$ keV (350 keV)
Angular $\sim 5$ mrad; $\sim 5$mrad
(9mrad; 11mrad)
Vertex $\sim 1.2$ mm; $\sim 0.7$ mm
(1.8 mm; 1.1 mm)
DC-TC matching eff. $\sim 90\%$ (41%)
What can be improved for Timing counter?

- 2x array of 15 scintillating bars readout by PMTs
- 40x40x800mm$^3$ scintillator
- Mean resolution $\sim 65$ps

- Higher granularity 2x256 of small scintillator plates (90x(40–50)x4mm$^3$) readout by SiPM
- Resolution down to 30ps
  - High single pixel resolution
  - Further improvement with multi-counter hits
- Thin scintillator for less multiple scattering
- Less pile-up also with higher beam intensity
LXe upgrade concept

Wider incident face, different PMT angle at lateral face
### Sensitivity

<table>
<thead>
<tr>
<th>PDF parameters</th>
<th>Present MEG</th>
<th>Upgrade MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+ energy (keV)</td>
<td>306 (core)</td>
<td>130</td>
</tr>
<tr>
<td>e+ θ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>e+ φ (mrad)</td>
<td>8.7</td>
<td>3.7</td>
</tr>
<tr>
<td>e+ vertex (mm) Z/Y (core)</td>
<td>2.4/1.2</td>
<td>1.6/0.7</td>
</tr>
<tr>
<td>γ energy (%) (w&lt;2cm)/(w&gt;2cm)</td>
<td>2.4/1.7</td>
<td>1.1/1.0</td>
</tr>
<tr>
<td>γ position (mm) u/v/w</td>
<td>5/5/6</td>
<td>2.6/2.2/5</td>
</tr>
<tr>
<td>γ-e+ timing (ps)</td>
<td>122</td>
<td>84</td>
</tr>
</tbody>
</table>

#### Efficiency

| trigger | ≃99 | ≃99 |
| γ | 63 | 69 |
| e+ | 40 | 88 |

![Graph showing 90% C.L. MEG 2011 and 2013 bounds with 5σ and 3σ discovery limits.](image)
Summary

• The most stringent upper limit of $\text{BR}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$ @90%CL has been set by MEG based on 2009–2011 data. Including 2012–2013 data, the statistics will be doubled. We are finalizing the analysis, and aiming at publishing the final results at winter conferences.

• MEG upgrade proposal was accepted by PSI committee in 2013. The target sensitivity of MEG II will be $5 \times 10^{-14}$ (10 times better than MEG).

• The muon beam intensity will be increased, and the MEG detector components will be upgraded to reduce accidental backgrounds.

• All the detector components will be ready in 2015, and physics run will continue 2016–2018 to reach our target sensitivity.
Single Pixel Study

3 SiPMs in series connection

Smaller counter has better resolution

Multiple hit scheme

• Overall timing counter resolution is

\[
\sigma^2_{total}(N_{hit}) = \frac{\sigma^2_{single}}{N_{hit}} + \frac{\sigma^2_{inter-counter}}{N_{hit}} + \sigma^2_{MS}(N_{hit})
\]

\[30-40 \text{ ps} \quad \sim 5 \text{ ps}\]

• Optimization

  • Good single counter resolution → smaller counter
  • Many counter hits → larger counter

• The best performance (at fixed cost) with 90x(40–50)x4 mm\(^3\)

![Simulated signal positron]

![Optimized histogram]

Mean 6.557
Beam test with multi-counters

DAΦNE Beam Test Facility @Frascati

To confirm the multi hit scheme
Multiple hit resolution

- 1/$\sqrt{N_{\text{hit}}}$ behavior confirmed

- A resolution of ~30ps with 6–7 pixel is achieved, both with Hamamatsu and AdvanSiD devices
The current status of pTC:

- AdvanSiD SiPMs (6500) are ordered. We can increase #ch (6SiPMs/side from 3SiPMs/side) which improves time resolution further.

- Series of 3 couples of SiPMs in parallel connection has been tested. It shows better resolution than 3–SiPM series connection.

- Two beam test this year
  - A larger number of counters
  - High rate environment
  - Final electronics

- Final pTC will be ready in 18 months.
Limitation of the Current LXe Detector

• Limited resolutions for shallow events due to non-uniform PMT coverage

• Idea to improve LXe detector in MEG II
  • Smaller photo sensors (~4000 12x12mm² SiPM) for gamma-ray incident face instead of 216 2” PMTs
  • Wider incident face, different PMT angle at lateral face

# of photons collected by PMTs as a function of depth

LXe detector event display
Expected performance

- Detection efficiency
  - improved by 10%
- Position resolution
- Energy resolution

Energy spectra

Conversion depth < 2cm
- Energy resolution: 2.4% → 1.1%

Conversion depth > 2cm
- Energy resolution: 1.7% → 1.0%
UV-sensitive MPPC

- Requirements
  - Sensitive to UV light (175nm)
    - Photon Detection Efficiency of commercial SiPM (PDE) for UV (175nm)
  - Large area sample (12x12mm²) to reduce #ch.

- We developed UV-sensitive MPPCs with HPK
  - Remove protection layer
  - Optimize anti-reflection coating
  - Thinner insensitive layer
  - Matching of refractive index
  - Metal quench suitable at low temp.

Photon Detection Efficiency

![Graph showing photon detection efficiency vs. over voltage for different samples.](image)
Large area MPPC

- We tested a series connection with 4-segmented 6x6mm MPPCs to get one 12x12mm² MPPC
- Signal tail became 30–50ns
- Single photoelectron peaks are resolved
- Still 4–5x10⁵ gain is available
- Signal is connected in series, and bias is connected in parallel.
• Four independent sensor chips are connected in a PCB

• In March 2014, 600 MPPCs will be delivered.

• Mass test at room temp.

• The 100L LXe prototype will be used to test the MPPCs.

• In November, a beam test with charge exchange reaction ($\pi^0 \rightarrow \gamma\gamma$) will be done to evaluate energy, position, and timing at 55MeV $\gamma$-ray