MEG実験2013とアップグレード計画の現状

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Physics Motivation of lepton flavor violation search

- Quark mixing is well described by CKM matrix in Standard Model.
- Neutrino oscillation is the first observed lepton flavor violating process.
- No LFV is found yet in charged lepton.
- SM + neutrino mass $\Rightarrow$ tiny BR($\mu \rightarrow e\gamma$).
- New physics like SUSY-GUT, SUSY-seesaw, Extra Dimensions etc. predict large BR.
- If muon g-2 discrepancy is really evidence for new physics, searches for $\mu \rightarrow e\gamma$ reveal that the “amount” of flavor violation in the new physics sector.

The current situation of LFV

- Higgs boson ~ 126GeV
- Non observation of SUSY particles
- Even if slepton masses O(10TeV), large LFV may occur by renormalization group effects
- Complementary with direct search of new physics

High-scale SUSY with right handed neutrino

\[ \tan \beta \]

\[ \text{Br}(\mu \rightarrow e\gamma) \]

\[ \begin{align*}
& \text{sign}(\mu) > 0 \\
& M_{1/2} = m_0 \\
& M_N = 3 \times 10^{15} \text{ GeV}
\end{align*} \]

\[ 125 \text{GeV} < m_\nu < 127 \text{GeV} \]

\[ m_0 \ [\text{TeV}] \quad \text{scalar mass} \]

Moroi et. al., arXiv:1305.7357[hep-ph]
MEG実験

- 1999 Proposal accepted by PSI
- R&D, Detector Construction
- 2008 Physics run started
- International collaboration
  - Japan, Italy, Switzerland, Russia, and USA
- ~60 physicists

$E_r, E_e \approx 52.8 \text{MeV}$
$\Theta_e r = 180^\circ, T_r = T_e$
Latest result

- 2009-2011 likelihood analysis
  - 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 ($1.2 \times 10^{-11}$)

- 51 < E_{\gamma} < 55.5 MeV
- 52.385 < E_{\text{Positron}} < 55 MeV
- $\pi - \Theta(e'\gamma) < 27.2$ mrad ($\cos \Theta_{e'\gamma} < -0.99963$)
- $|t(e'\gamma)| < 244.3$ ps
MEG2013

- Smooth physics run for 3.5 months
  - 6 DC modules are replaced, LXe purification for light yield recovery after MEG2012
- Calibrations: CEX by LXe 55MeV γ-ray for 10 days, e\(^+\) beam for 1 week
- Beam tests for upgrade (RDC) for 5 days
- MEG physics run finished successfully in Aug. 2013!
MEG analysis status

- An analysis of 2012+2013 data is going on.
- Data statistics will be doubled.
- The final result will be published next year. Stay tuned.

- Next -> Upgrade
Upgrade Status

- 2013/Jan- Upgrade proposal presented, and accepted by PSI (arXiv:1301.7225)
- 2013-2015 Design & Construction
- 2015- Engineering run
- 2016 - 2018 Physics run
Upgrade Concept

- What can be improved?
  - Higher muon beam rate
  - Larger acceptance
  - Better resolutions
  - Active background suppression
Expected Detector performance & Sensitivity

<table>
<thead>
<tr>
<th>PDF parameters</th>
<th>Present MEG</th>
<th>Upgrade scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$ energy (keV)</td>
<td>306 (core)</td>
<td>130</td>
</tr>
<tr>
<td>$e^+\theta$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$e^+\phi$ (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>$\gamma$ energy (%) $(w &lt; 2,\text{cm})/ (w &gt; 2,\text{cm})$</td>
<td>2.4 / 1.7</td>
<td>1.1 / 1.0</td>
</tr>
<tr>
<td>$\gamma$ position (mm) $u/v/w$</td>
<td>5 / 5 / 6</td>
<td>2.6 / 2.2 / 5</td>
</tr>
<tr>
<td>$\gamma$-$e^+$ timing (ps)</td>
<td>122</td>
<td>84</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>trigger</td>
<td>$\approx 99$</td>
<td>$\approx 99$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>$e^+$</td>
<td>40</td>
<td>88</td>
</tr>
</tbody>
</table>

![Graph showing branching ratios with 90% C.L. MEG 2011, 5σ Discovery, and 3σ Discovery curves, with a note on the expectation of $5 \times 10^{-14}$ and an upgraded MEG in 3 years.]

~$5 \times 10^{-14}$
PSI Accelerator (muon beam rate)

- PSI also has a plan to upgrade the accelerator
  - Mainly for Mu3e experiment
- MEG experiment doesn’t require the accelerator upgrade
  - We can quickly start whenever the detector upgrade finishes
- \(3.0 \times 10^7 \Rightarrow 7.0 \times 10^7 \, \mu/s\) stopped at the target are possible now
Drift chamber

- 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

**Expected Performance**

- Momentum: ~130 keV (350 keV)
- Angular: ~5 mrad; ~5 mrad
  (9 mrad; 11 mrad)
- Vertex: ~1.2 mm; ~0.7 mm
  (1.8 mm; 1.1 mm)
- DC-TC matching eff.: ~90 % (41%)
DC R&D Status

- Many prototypes
- Single hit resolution
- Aging
- Mechanical design & optimize the length etc.

Resolution study

\[ \frac{d_1 + d_3}{2} - d_2 = \pm \Delta \]

\[ \sigma_\Delta = \sqrt{\frac{3}{2}} \sigma_d \]

σ ~ 130 μm

Aging test

Mechanical design

Single full-length wire prototype

X-ray source

Lead shield

Nal x-ray monitor
New Pixelated Timing Counter

- Array of ultra-fast plastic scintillator counters
- SiPM readout
- High resolution with multiple counter hits
- Expected resolution 30-35ps

\[ \langle N_{\text{hit}} \rangle = 6.6 \]

> 15 scintillators x 2

![Upgrade](image)
Beam tests @ Frascati

- Single counter resolution \(\sim 70\)ps
  \((90\times40\times5\text{mm}^3, \text{BC418})\)
- Ultimate resolution with multi-counter hit
  - Reduce electronics, calibration contribution, and counter resolution
- Eight counters\((90\times40\times5\text{mm}^3, \text{BC418})\) with MPPC and six counters with AdvanSiD are prepared (still to be optimized)

Beam test condition @ Frascati

- repetition rate : 50Hz
- Bunch width : 10ns
- Positron 48MeV

Resolution improvement as a function of number of counters is confirmed!

- Measured resolution 30~35ps
LXe $\gamma$-ray detector

- Small photon sensors (12x12mm$^2$ MPPC) at $\gamma$-ray incident face
- ~4000ch MPPCs instead of 216 PMTs
- Better position, energy resolutions at shallow events
- Better identification of pile-up events
- Wider incident face, Change PMT angle at lateral face
- To reduce shower leakage, better uniformity
Possible improvements

Position Resolution

Position resolution (mm)

Distance from entrance (cm)

Red: PMT (present)
Blue: MPPC (upgraded)

Energy resolution

Red: present
Blue: upgraded

Energy [MeV]

$w < 2 \text{cm}$

$\sigma_{up}$

2.4% → 1.1%
MPPC R&D Status

- MPPC development in cooperation with Hamamatsu

- Achieved
  - UV(~175nm) sensitivity: PDE >15%
  - Large area (12x12mm²), single photoelectron peak resolved

- Remaining issues
  - To reduce long tail (~200ns)
Series or Parallel connection?

- Original plan was a single sensor with 12x12mm$^2$ large area, but it had a long tail ~ 200ns.

- To reduce a sensor capacitance, one sensor can be segmented into sectors, which will be connected in series.

- To simulate the concept works or not, 4 independent 6x6mm$^2$ samples are connected differently, and the waveforms are compared.

- Succeeded in obtaining shorter tail (30-50ns)!
• More channels, higher rate
  • XEC MPPC (inner face) : ~4000
  • XEC PMT (other faces) : 630
  • pTC MPPC : ~1200
  • DC : 2760 (1GHz bandwidth)

• WaveDREAM
  • Higher density, compact
  • Waveform digitizer(DRS) +bias voltage supply +amplifier+simple trigger
Background tagging detectors

- Tagging radiative muon decay events with \( \sim 50\text{MeV} \gamma \) (low energy \( e^+ \) is emitted \( \sim 4\text{MeV} \))

- Plastic scintillator + crystal with MPPC readout

- Beam test was performed at the end of MEG beam time in August with prototype
Summary

• The MEG experiment improved the BR(μ→eγ) upper limit this year, 5.7x10^{-13} at 90% C.L.

• MEG physics run finished in Aug. 2013.

• The statistics will be doubled by adding 2012-2013 data, and the analysis is ongoing. The final result will be published next year. Stay tuned.

• MEG upgrade proposal is approved by PSI in 2013. R&D for detector upgrade is ongoing.

• The target sensitivity is 5x10^{-14}, and data taking for three years starting from 2016.
SUSY-Seesaw

Likelihood analysis

• Fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering

\[ \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{e^{-N}}{N_{\text{obs}}} e^{-\left[\frac{(N_{\text{RMD}} - \langle N_{\text{RMD}} \rangle)^2}{2\sigma_{\text{RMD}}^2}\right]} \]

\[ \times e^{-\left[\frac{(N_{\text{BG}} - \langle N_{\text{BG}} \rangle)^2}{2\sigma_{\text{BG}}^2}\right]} \prod_{i=1}^{N_{\text{obs}}} \frac{N_{\text{sig}} S(\tilde{x}_i)}{N_{\text{obs}}} \]

\[ + N_{\text{RMD}} R(\tilde{x}_i) + N_{\text{BG}} B(\tilde{x}_i) \],

\[ \tilde{x}_i = \{E_{\gamma}, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}\} \]

\[ \lambda_p(N_{\text{sig}}) = \frac{\mathcal{L}(N_{\text{sig}}, \hat{N}_{\text{RMD}}(N_{\text{sig}}), \hat{N}_{\text{BG}}(N_{\text{sig}}))}{\mathcal{L}(\hat{N}_{\text{sig}}, \hat{N}_{\text{RMD}}, \hat{N}_{\text{BG}})}, \]
New DC parameters

- 90% He + 10% Iso-Butane (iC$_4$H$_{10}$)
- Spatial resolution estimate ~130μm
- Momentum resolution ~ 130keV
- Angular resolution ~5mrad
- DC-TC matching eff. ~ 90%
- 10 layers, square projective cells of 0.7cm, stereo angle of ~8 deg with respect to Z (z resolution ~ 7 times the transverse resolution)
- 25 and 40μm anode and field wires
- Total length 180-190cm, outer radium 29.2cm, 1380 anode/7500 field wires
- Positron hit rate density by MC simulation
  - Michel e+ generated over 4π at 1×10$^8$ μstop/s, max rate 45kHz/cm$^2$
  - At 1×10$^5$ gain and 7×10$^7$ μstop/s, the maximum current is 6nA/cm(innermost wire), 3 years of running, the maximum integrated charge is 0.4C/cm
  - Free radical polymerization is regarded as the dominating mechanism of wire chamber aging
- Pisa aging up to 0.5C/cm
Hit resolution estimate

- Arrange 3 cells with the central one displaced by $\Delta$.
- Measure $t_i$ drift times, compute $d_i$ drift distances.
- For straight tracks it results independently of drift distance and angle (almost):
  \[
  \frac{d_1 + d_3}{2} - d_2 = \pm \Delta
  \]
  \[
  \sigma_\Delta \approx \sqrt{\frac{3}{2}} \sigma_d
  \]
- Measure single hit resolution averaged on all impact parameters and angles if $\sigma_\Delta << 2\Delta$.
Scintillator Type

- Test BC418, 420, and 422 which is 90x40x5mm with 4MPPCs

<table>
<thead>
<tr>
<th>Properties</th>
<th>BC-418</th>
<th>BC-420</th>
<th>BC-422</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Output [% Anthracene]</td>
<td>67</td>
<td>64</td>
<td>55</td>
</tr>
<tr>
<td>Rise Time [ns]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Decay Time [ns]</td>
<td>1.4</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Wavelength of Max. Emission [nm]</td>
<td>391</td>
<td>391</td>
<td>370</td>
</tr>
<tr>
<td>Bulk Light Attenuation Length [cm]</td>
<td>100</td>
<td>110</td>
<td>8</td>
</tr>
</tbody>
</table>

Properties of ultra-fast plastic scintillators from Saint-Gobain

<table>
<thead>
<tr>
<th>Scintillator Type</th>
<th>Single Resolution (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC422</td>
<td>51.2</td>
</tr>
<tr>
<td>BC420</td>
<td>57.7</td>
</tr>
<tr>
<td>BC418</td>
<td>55.8</td>
</tr>
</tbody>
</table>

13/09/17
Calibration

- Important item for actual operation
- Laser calibration
  - Light pulse from a laser system
    - Hamamatsu PLP10-040
      - 70 ps width, 405 nm wavelength
    - Distribute via optical fibers
- Michel (track-based)
  - in-situ calibration using data itself
  - Develop a technique similar to position alignment
    - like Millipede or Linear-fit algorithms
    - to calibrate all channels simultaneously
- Finally, with RMD
Example I

“Accidental” and “real” AIF candidates in the same event: