Up-to-Date Results and Upgrade Plans of the MEG Experiment

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on behalf of the MEG Collaboration

ICHEP2012, 04-11 Jul. 2012, Melbourne, Australia
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Why charged LFV has never been observed?

Why? : Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

SM + simple ν Oscillation
- charged LFV is possible
  e.g. $\nu_\mu \rightarrow \nu_e$
- but extremely rare
  \[
  B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i}^* U_{ei} \frac{m_{vi}^2}{m_W^2} \right|^2
  \]
- $B(\mu \rightarrow e\gamma) \approx 10^{-57} !!!$

Beyond SM (SUSY-GUT etc.)
- charged LFV is largely enhanced
  e.g. $\tilde{\mu} \rightarrow \tilde{e}$
- still rare but observable level
  \[
  B(\mu \rightarrow e\gamma) \simeq \frac{\alpha^3 \pi \theta_{\tilde{\mu}\tilde{e}^c}}{G_F^2 m^4}
  \]
- $B(\mu \rightarrow e\gamma) = 10^{-15} \sim 10^{-11} !!!$
Why charged LFV has never been observed?

Why? : Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

"charged LFV" = "NEW PHYSICS"

TeV-scale New Physics

competitive & complementary to LHC!

\[
B(\mu \rightarrow e\gamma) \approx 10^{-37} !!!
\]

\[
B(\mu \rightarrow e\gamma) = 10^{-15} \sim 10^{-11} !!!
\]

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Hunting for $\mu \rightarrow e \gamma$ and MEG Features

* Signal and Backgrounds

* Clear 2-body kinematics ($E_e = E_\gamma = 52.8$ MeV, $\theta_{e\gamma} = 180^\circ$, Time Coincidence)

* Sensitivity is Limited by “Accidental Overlap”

* **DC muon is the Best Solution**

* **Good Resolution (Energy, Spacial and Timing) under Very High Rate**
Hunting for $\mu \rightarrow e\gamma$ and MEG Features

- **Signal and Backgrounds**

  - **Clear 2-body kinematics ($E_e = E_\gamma = 52.8\text{MeV}, \#e_\gamma = 180^\circ, \text{Time Coincidence}$)**
  
  - **Sensitivity is Limited by “Accidental Overlap”**
  
  - **World Most Intense DC Muon Beam at PSI $10^8\text{ muon/sec}$**
  
  - **Liquid Xenon Scintillation Detector (gamma)**
  
  - **COBRA Spectrometer (positron)**

- **DC muon is the Best Solution**
  - **Good Resolution (Energy, Spatial, and Timing) under Very High Rate**
Analysis Procedure

- **Blind Analysis**
  - Signal region was hidden until analysis fixed
  - Any study (calibration, BG estimation, performance evaluation) can be done with events outside the box
  - Hidden parameters \((E_\gamma, T_{e\gamma})\)

- **Sideband Data**
  - Accidental BG can be studied with off-timing sideband data
  - Radiative decay can be studied with low energy sideband data

- **Normalization**
  - Unbiased Michel data mixed in physics data

- **Maximum likelihood fitting**
  - \(N_{\text{sig}}, N_{\text{RD}}\) and \(N_{\text{BG}}\) fitted with PDFs extracted from data for \(E_e, E_\gamma, t_{e\gamma}, \theta_{e\gamma}\) and \(\phi_{e\gamma}\)
After the Previous ICHEP

Event distribution after unblinding

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 other variables for roughly 90% window is applied.
Event distribution after unblinding

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 other variables for roughly 90% window is applied.

- Accumulate more statistics.
- Improve calibrations/alignments.
- Perform combined analysis on 2009+2010.
Results (2009+2010)

Based on $\sim 1.8 \times 10^{14}$ $\mu$ on target

$N_{\text{Sig}} = -0.5^{+7.9}_{-4.7}$

$N_{\text{BG}} = 882 \pm 22$

$N_{\text{RD}} = 76.5 \pm 12$

un-binned likelihood fitting on 5 discriminating observables
Results (2009+2010)

1.8×10^{14} muons stops on target

Result: \( \mathcal{B}(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12} \) (@90CL.)

Present world record!

×5 more stringent limit than previous
\( \mathcal{B} < 1.2 \times 10^{-11} \) (MEGA, 1999))

Published in PRL 107 171801 (2011)

Un-binned likelihood fitting on 5 discriminating observables
Run 2011

- Run 2011 was successful. First long DAQ period.
- All subsystems were operational with reasonable performances during entire data-taking period.

- New DC HV
- New DC alignment
- More efficient LXe calibration
- Higher DAQ efficiency

Data Statistics Doubled!!

$$1.9 \times 10^{14} \mu \text{ stopped}$$

$$1.75 \times 10^{14} \mu \text{ in 2009+2010}$$
Analysis Status of Run 2011

- Analysis on data 2011 is in a good shape.
- Calibration / Alignment and optimization of analysis are almost finished.
- Estimated detector performance is comparable (even better) to previous years.

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ Energy $\sigma_{E_\gamma}$ (%)</td>
<td>1.9 (depth&gt;2cm)</td>
<td>1.7 (depth&gt;2cm)</td>
</tr>
<tr>
<td>$\gamma$ Position $\sigma_{x_\gamma}$ (mm)</td>
<td>5/6</td>
<td>←</td>
</tr>
<tr>
<td>$\gamma$ Efficiency $\varepsilon_{\gamma}$ (%)</td>
<td>59</td>
<td>63</td>
</tr>
<tr>
<td>$e^+$ Mom. $\sigma_{p_e}$ (%)</td>
<td>0.61(core 79%)</td>
<td>0.61(core 86%)</td>
</tr>
<tr>
<td>$e^+$ Angle $\sigma_{\theta_e}$ (mrad)</td>
<td>7.2($\phi$)/11($\theta$)</td>
<td>6.5($\phi$)/10.8($\theta$)</td>
</tr>
<tr>
<td>$e^+$ Efficiency $\varepsilon_{e}$ (%)</td>
<td>41</td>
<td>←</td>
</tr>
<tr>
<td>$\gamma$-$e^+$ Timing $\sigma_T$ (ps)</td>
<td>126(core)</td>
<td>133</td>
</tr>
<tr>
<td>$\mu^+$ decay vertex (mm)</td>
<td>2.0/1.1</td>
<td>1.9/1.0</td>
</tr>
<tr>
<td>Trigger Efficiency (%)</td>
<td>92</td>
<td>95</td>
</tr>
<tr>
<td># of stopped $\mu$</td>
<td>$1.1\times10^{14}$</td>
<td>$1.9\times10^{14}$</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$2.2\times10^{-12}$</td>
<td>next slide!</td>
</tr>
</tbody>
</table>

3 major updates on analysis
- new pile-up rejection
- noise reduction at offline
- new tracking code and PDF for $e^+$

Analysis on data 2011 is in a good shape. Calibration / Alignment and optimization of analysis are almost finished. Estimated detector performance is comparable (even better) to previous years.

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**Potential of Run2011 (preliminary)**

\[ \text{N}_{\text{sig}} = -0.3^{+6.0}_{-2.5} \]
\[ \text{N}_{\text{acc}} = 951^{+25}_{-25} \]
\[ \text{N}_{\text{RMD}} = 18^{+27}_{-24} \]

(1.645\sigma)

Expected Sensitivity

\(~1 \times 10^{-12}\)

(2011 data only)
MEG Upgrade → MEG-2

- MEG sensitivity is surely and steadily improving,
  - $2009+2010+2011 \rightarrow \text{Enter to } O(-13)$
  - Exploring $O(-13)$ region by adding 2012 data holds $3\sigma$ discovery potential, if $B \approx 10^{-12}$
  - but is moderately slowing down...
- Now it’s a time to consider the major upgrade of experiment!!
- Several R&Ds are ongoing to perform the experiment with
  - “$\times 3$ higher beam intensity”
  - “improved resolution/efficiency”
e^+-detector upgrade (tracker)

- **Unique volume cylindrical DC concept**, with very small cell & all stereo
- Avoid any material along the e^+ path → **improve efficiency/resolution**
- Track e^+ until the timing counter hit → **improve timing resolution**

* Intensive simulation work / prototyping are ongoing.
* Expected Performances; $\varepsilon_{e^+} = 91\sim92\%$, $\sigma_p = 140\text{keV}$, $\sigma_{\theta,\phi} = 6\sim8\text{mrad}$.
* Prototyping; Machinery Studies, Aging Study and Performance R&D
e⁺-detector upgrade (timing counter)

* **Scintillator pixel detector concept**
  * With small scintillator pixel (~20×30×5 mm³), Total # of pixels ~ 1500
  * Each pixel is readout by MPPCs from both ends.
  * **Less pileup, Improved time resolution** using multiple hits info.

Simulation works are ongoing
* Optimization of scintillator size, tilt, layout, and MPPC studies
* **Expected timing resolution = ~35 psec.**
Replace inner face PMTs by smaller photosensors in the present LXe detector

- candidate-1: MPPC
- candidate-2: 1” square shape PMT
- candidate-3: 2” flat panel multi-anode PMT

Good pile-up elimination power and resolutions are expected.

Simulation works and photosensor R&Ds are ongoing.

- Estimated resolutions: $\sigma_E = 0.7\sim0.9\%$, $\sigma_x = 2\sim4$mm
Alternative Upgrade R&Ds

Many alternatives are under studies, for example...

- **Radial TPC base e^+ tracker**
  - [Diagram of Radial TPC base e^+ tracker]
  - Description of the tracker's design and functionalities.

- **SVD option**
  - [Diagram of SVD option]
  - Explanation of the SVD option's advantages and implementation.

- **Active Target idea**
  - [Diagram of Active Target idea]
  - Description of the active target concept and its potential applications.

- **Radiative decay Veto**
  - [Diagram of Radiative decay Veto]
  - Explanation of the radiative decay veto mechanism and its benefits.

Reminder (previous configuration):

- **Plastic counter**
  - **z = 12 cm**
  - **r = 4 cm**
  - **t = 1 cm**
  - Reduction in BG gamma rate by detecting low energy e^+.

- **Beam γ BG reduction**
  - Veto counter hit time from muon decay
  - Energy deposit in LXe
    - Without cut
    - With veto, time window = 2 nsec
    - With veto, time window = 4 nsec
  - Veto counter energy threshold = 30 keV
  - Muons are forced to decay with gamma with Eg > 45 MeV. Therefore no AIF events are included.
# MEG prospects

## 1. Analysis

- **Almost Finished**
- **Box will be opened in this Autumn**

- Improved analysis is applied on 2009+2010, and then it will be re-processed.
- After reprocess, blind box will be opened with old data.
- All combined analysis (2009+2010+2011) will be published in this autumn → $O(-13)$ !!

## 2. Physics Run

- **Will Re-Start Soon**
- **Long Shutdown will start in 2013**

- Detector Maintenance is almost finished.
- Extra run (3 months) are planned at begin of 2013 → Enough statistics to achieve $6 \times 10^{-13}$
- Long Shutdown (~2 y) for Major Upgrade

## 3. Upgrade

- **R&D Started**
- **Goal : $5 \times 10^{-14}$ Sensitivity**

- Many Activities are ongoing for upgrade
- Proposals are under preparation for INFN (Jul.) and PSI (Dec.)
- MEG-II will start ~2015(16) and run ~3 y
Conclusions

- After the previous ICHEP (2010, Paris), MEG renewed the Upper limit of $\bar{B}(\mu \to e\gamma)$ as $2.4 \times 10^{-12}$ (@90CL.) which is $\times 5$ more stringent than previous limit $1.2 \times 10^{-11}$ (MEGA, 1.2 $\times 10^{-11}$, 1999)
  - MEG 2009+2010 data ($\sim 1.75 \times 10^{14}$ $\mu$ stops) were analyzed for that result.
  - **MEG 2011 was successfully done**, and analysis is almost verging to a close.
    - According to the side-band samples, $\sim 1 \times 10^{-12}$ of sensitivity is expected
    - Improved analysis will also be applied on 2009/2010 data.
    - All combined analysis will be published this autumn $\rightarrow O(-13)$
  - MEG 2012 will start soon.
    - To compensate the shorter DAQ period, extra runs will be performed at the beginning of 2013, and then we will have a long break for upgrade.
  - **MEG Upgrade**
    - Many upgrade R&Ds are ongoing in parallel with MEG 2012 run
    - Aiming $\sim 5 \times 10^{-14}$ of UL sensitivity, can be a good competitor for LHC.
appendix
Long History of “μ→eγ” Search

“μ→eγ” Search Experiment has started right after μ discovery

Very Long Tradition

Now already sensitive to the predicted region.

MEG reseted UL on $\mathcal{B}(\mu\rightarrow e\gamma)<2.4	imes10^{-12}$ in 2011, and is aiming to improve it down to the order of $10^{-13}$
Liquid Xenon Scintillation $\gamma$ Detector

- Homogeneous Volume (~800 l) is surrounded by PMTs on all faces
- 846 PMTs submerged in the liquid
- Energy Measurement
  - All PMT outputs
  - $\sigma_E/E \sim 2\%$ (@52.8 MeV)
- Position Measurement
  - PMTs on the inner face
  - $\sigma_x = 5$-6 mm (@52.8 MeV)
- Timing Measurement
  - Averaging of signal arrival time of selected PMTs
  - $\sigma_t \sim 70$ ps (@52.8 MeV)
COBRA Positron Spectrometer

**Solenoid**
- superconducting solenoid
- gradient B-field (0.5-1.7 T)
- very thin conductor and cryostat wall (0.2X₀)

**Drift Chamber**
- segmented radially (16 sectors)
- helium:ethane (50:50)
- opened-frame
- very thin cathode foil with pads

**Timing Counter**
- 2-layers of scintillators
  - scintillator bars (outer)
  - scintillator fibres (inner)

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MEG Time line

- Proposal to PSI
- Proposal to INFN
- Detector R&D
- Magnet construction
- Detector construction
- Beam line commissioning
- Engineering run
- Physics run (1)
- Physics run (2)
- Physics run (3)
- Physics run (4)
- 1st publication: $1.5 \times 10^{11} (90\text{CL.})$
  Nucl.Phys.B834.p1
- 2nd publication: $2.4 \times 10^{12} (90\text{CL.})$
  Phys.Rev.Let 107. 171801

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Likelihood Analysis

* Extended unbinned maximum likelihood analysis on number of events
  \[ \mathcal{L}(N_{\text{sig}}, N_{\text{RD}}, N_{\text{BG}}) \]
  
  \[ = \frac{N^{N_{\text{obs}}} e^{-N}}{N_{\text{obs}}} \prod_{i=i}^{N_{\text{obs}}} \left[ \frac{N_{\text{sig}}}{N} S + \frac{N_{\text{RD}}}{N} R + \frac{N_{\text{BG}}}{N} B \right] \]

* Fit Parameters: # of events \(N_{\text{sig}}, N_{\text{RD}}\) and \(N_{\text{BG}}\) (\(N = N_{\text{sig}} + N_{\text{RD}} + N_{\text{BG}}\))

* Observables: Energy \(E_{\gamma}, E_e\), Relative time \(T_{\gamma}\) and Opening angle \(\theta_{\gamma}, \phi_{\gamma}\)

* Probability Density Function for each event type \((S, R, B)\)
  * PDFs are extracted from data

* Fit in Wide region (10\(\sigma\))
  * Fit Signal and Background simultaneously

* Three Independent Analysis Tools
  * Different PDF implementation
  * \textbf{Fit or Input} \(N_{\text{RD}}\)
  * Different Statistical treatment (Frequentist or Bayesian)

check, understanding or find bug

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PDFs - Energies, Angles and Timing -

- **Ee Signal PDF**: (from measured resolution)
  - **Eγ Signal PDF**: (from 55MeV γ) (using π⁰ beam)
  - **Tγ Signal PDF**: (from RD peak)
  - **Relative Angle (θ_eγ, φ_eγ) PDF**: Signal : from measured resolution
    Background : from L/R sideband
- **Ee BG PDF**: (from L/R sideband)
- **Eγ BG PDF**: (from L/R sideband)
Normalization - # of Muon Decay -

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

* # of Michel Positrons is counted simultaneously using highly pre-scaled trigger applying the same event selection as for the physics data sample.
* Advantage: Independent of beam-rate & in 1st-order insensitive to acceptances & efficiencies (ratios)
* Branching ratio is represented by obtained normalization factor "k" and the # of signal which will be obtained by the final analysis

\[
\mathcal{B}(\mu^+ \rightarrow e^+\gamma) = \frac{k}{N_{\text{sig}}}
\]