Experimental search for $\mu^+ \rightarrow e^+ \gamma$
present and future

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On behalf of MEG and MEG-2 collaborations

RENCONTRES DU VIETNAM
Quy Nhon, 31.07.2014
MEG Home

Switzerland
PSI, ETH-Z

Italy
INFN + Univ.: Pisa, Genova, Pavia, Roma I & Lecce

Russia
BINP, Novosibirsk, JiNR, Dubna

Japan
Univ. Tokyo, KEK, Waseda Univ., Kyushu Univ.

USA
University of California Irvine, UCI

MEG Collaboration
some 65 Physicists
5 Countries, 14 Institutes
Why $\mu^+ \rightarrow e^+\gamma$

- CLFV Forbidden in SM (background: $\text{Br}(\mu^+ \rightarrow e^+\gamma) < 10^{-45}$)
- So far, no CLFV signal has been observed.
- Many new physics beyond SM (e.g. SUSY, Extra dimensions etc.) predict observable $\text{Br} \ (10^{-14} — 10^{-11})$
- Discovery will be an unambiguous evidence of new physics.

- Complementary search of new physics,
  - LHC Run 2
  - New experiments to search for other muon channels ($\mu \rightarrow e$ conversion, $\mu \rightarrow eee$)
Signal and backgrounds

**Signal**  \( \mu^+ \) decay at rest
- 52.8 MeV (half of \( M_\mu \)) (\( E_\gamma, E_e \))
- Back-to-back (\( \theta_{e\gamma}, \varphi_{e\gamma} \))
- Timing coincidence (\( T_{e\gamma} \))

**Accidental background** (dominant)
Michel decay \( e^+ + \) random \( \gamma \)
Random timing, angle, \( E < 52.8 \text{MeV} \)

**Radiative muon decay**
\( \mu^+ \rightarrow e^+\nu\nu\gamma \)
Timing coincident, not back-to-back,
\( E < 52.8 \text{MeV} \)
Key points of the experiment

- High quality & rate stopped $\mu$-beam $\Rightarrow$ surface muon beam ($10^8$/s), $(E \times B)$ Wien filter, SC-solenoid+degrador

- $e^+$ magnetic spectrometer with excellent tracking & timing capabilities $\Rightarrow$ COBRA magnet, DCs & TCs

- Photon detector with excellent spatial, timing & energy resolutions $\Rightarrow$ 900 litre LXe detector (largest in world)

- Stable and well monitored & calibrated detector $\Rightarrow$ Arsenal of calibration & monitoring tools
Layout of the experiment
Beam line

- High-intensity DC surface muon beam - \( \pi E5+MEG \) capable of \( > 10^8 \mu^+/s \) at 28 MeV/c + \( \sim 10^9 \) beam \( e^+/s \)
- “pure” muon beam - Wien filter + Collimator system
  \( \Rightarrow \) \( \mu-e \) separation at collimator \( > 7.5\sigma \) (12 cm)
- Small beam-spot + high transmission – BTS
  \( \Rightarrow \) focus enhancement, beam \( \sigma \sim 10 \) mm at target
  \( \Rightarrow \) focus at centre BTS – degrader
- Thin stopping target + minimal scattering – end-caps
  \( \Rightarrow \) 18 mg/cm\(^2\) CH\(_2\) target + He COBRA environment + remote Target & End-cap insertion system
The important part – gradient field COBRA magnet: tracks radius is independent on incident angle at 52.8 MeV/c
Positron spectrometer

- SC COBRA Magnet
- Gradient Bfield \((1.27-0.5) \text{T}\)
- \(CO\)-\text{ntant Bending RA}dius
- \(0.2 X_0\) fiducial thickness
- \(\gamma\)-transparency 95%
- NC Compensations coils reduce Bfield at Calorimeter < 5mT at PMT positions
Positron spectrometer

- **Drift Chambers**
- 16 radial, staggered double-layered DCs
- each 9 cells with "Vernier" cathodes
- 50:50 He/C\textsubscript{2}H\textsubscript{6}
- Ultra-thin $2 \cdot 10^{-3}X_0$ along e\textsuperscript{+} path

Momentum resolution $<\sigma p/p)$ 6\%
Angular resolution (e\textsuperscript{+}) $\phi \sim 7$ mr $\theta \sim 10$ mr
Positron spectrometer

• **Timing Counter Arrays**

• 2 arrays of each –
  15 axial scintillator bars
  BC404 $e^+$ impact point + timing
  intrinsic $\sigma_t \approx 70$ps over 90 cm

• 256 orthogonal radial
  scintillating fibres
  BCF-20 + APDs
  triggering (angular matching)
Calorimeter

- Largest LXe calorimeter in the world 900 litres $\Delta\Omega/4\pi = 10\%$
- Fast response (4, 22 ns) - minimize “pileup”
- Large light-yield $\sim 80\%$ NaI
- High density, short $\chi_0$
- Homogeneous medium uniform response, no segmentation needed
- Sensitive to impurities at sub –ppm level (mainly $\text{H}_2\text{O}$, $\text{O}_2$, $\text{N}_2$)
- Scintillation light used for shower reconstruction $\lambda = 175$ nm
- 846 PMTs wall-mounted inside LXe-volume signals digitized @ 1.6 GHz

Energy resolution $\langle \sigma_E/E \rangle < 2\%$ at 52.8 MeV
Timing resolution $= 67$ ps
Position resolution $(X,Y)$ 5 mm, (depth) 6 mm
$\gamma$-efficiency $59\%$ ($\varepsilon_{\text{Detect}} \times \varepsilon_{\text{Anal}}$)
Calibration and Monitoring

PMT: Gain, QE, 
LXe: Light-yield, Attenuation-length 
Calorimeter: Energy-scale 
Calo.+TC: Relative detector timing, Alignment 
e.g. $\alpha$s, LED, $\pi p \rightarrow \pi^0 n$ or $\gamma n$, "Dalitz-decay, 
RMD, protons from C-W accelerator on Li$_2$B$_4$O$_7$, 
n-generator+ Ni, cosmics, Mott e+ beam

Cosmic rel. 
alignment LXe + spectrometer

Radiative Muon Decay 
RMD $\rightarrow t_{\mu\gamma}$ 

Mott mono. 
e+ scattering
Detector Stability

Lxe Detector Light Yield Stability

Detector Stability permanently monitored

- Light Yield stable to $< 1\%$ rms $< 2\%$
- Photon energy-scale cross-checked using BG-spectrum from LXe side-bands
- Timing stability checked using radiative muon decay events (RMD) taken simultaneously during run (multi-trigger) $T_{e\gamma}$ stable $\sim 15$ ps over whole run
Analysis Principle

Blind likelihood Analysis:

Data Sample defined by 5 Observables:
\[ E_{e^+}, E_\gamma, \theta_{e\gamma}, \phi_{e\gamma}, T_{e\gamma} \]

Analysis-box for Likelihood fit
Defined in 5D-space as:

- Left Time Sideband
- Right Time Sideband
- \( E_\gamma - \text{Sideband} \)
- \( T_{e\gamma} \text{ resolution} \)

Analysis Region shown in 2D
(No Selection)

Analysis Box vs 5 Observables

(\( \sim 10\sigma \) wide windows cf. res.)
- \( 48 \leq E_\gamma \leq 58 \text{ MeV} \)
- \( 50 \leq E_e \leq 56 \text{ MeV} \)
- \( |T_{e\gamma}| \leq 0.7 \text{ ns} \)
- \( |\phi_{e\gamma}|, |\theta_{e\gamma}| \leq 50 \text{ mrad} \)

(angles between e\(^+\) & flipped \( \gamma \) vec.)

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!!! Time and \( E_\gamma \) sidebands Important Ingredient to Analysis also angular sidebands introduced

⇒ Since our background is dominated by “accidentals” the side bands can be used to 
estimate the background in the signal region, check of experimental sensitivity &
measure the timing resolution using RMD in the \( E_\gamma \)-sideband
## Results


Data taking finished at 31.08.2013
Statistics is doubled compare to published

<table>
<thead>
<tr>
<th>year</th>
<th>$N_{\text{stop}} \mu$, x10$^{13}$</th>
<th>Sensitivity, x10$^{-13}$</th>
<th>Br, Upper limit (CL 90%), x10$^{-13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009+2010</td>
<td>17.5</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>2011</td>
<td>18.5</td>
<td>11</td>
<td>6.7</td>
</tr>
<tr>
<td>2009+2010+2011</td>
<td>36.0</td>
<td>7.7</td>
<td>5.7 (20 times better than MEGA)</td>
</tr>
<tr>
<td>All data (expected)</td>
<td>~80</td>
<td>~5</td>
<td></td>
</tr>
</tbody>
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Final result of analysis is expected by the end of 2014

Published
MEG-2

• Goal to reach sensitivity in order of magnitude better than MEG:
  – More statistics (double beam rate)
  – Improve efficiency ~2 and background rejection ~30 (upgrade of LXe calorimeter, new cylindrical Drift Chamber, new Timing counters).
Layout of MEG-2 detector

- Calorimeter
- Drift chamber
- Timing counters
- Thinner target active?
- Twice more intense beam
- Radiative Decay Counter?
- Identify gammas from muon radiative-decays
Calorimeter upgrade

- Improved layout of PMTs
- Replace 2” PMTs on inner face with newly developed VUV-sensitive SiPMS

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Upgraded</th>
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<tbody>
<tr>
<td>Energy resolution [%]</td>
<td>2.4 / 1.7</td>
<td>1.1 / 1.0</td>
</tr>
<tr>
<td>Position resolution [mm]</td>
<td>5 / 5</td>
<td>2.6 / 2.2</td>
</tr>
<tr>
<td>Detection Efficiency</td>
<td>63%</td>
<td>69%</td>
</tr>
</tbody>
</table>

- 2 inch PMT
- 216 ch
- shallow / deep events (d = 2cm)
- horizontal / vertical
- 12×12 mm² MPPC
- ~ 4000 ch
- Factor 2 better energy and position resolutions
- 10% higher efficiency
New drift chamber

Gas volume
- Lower Z gas mixture (85% He + 15% iso-butane)
- Unique 2m-long chamber-gas volume, improved transparency to timing-counters.
  - Double the detection efficiency
  - Improve the Time-Of-Flight error down to 10 psec

Wire configuration
- Stereo-angle configuration for longitudinal position
- Finer granularity (7 mm cell) and higher multiplicity (15 → 60 hits per track)
- Single hit spacial resolution of 120~μm
New timing counters

- Many small plastic counters.
- Six SiPMs are directly attached on both sides for high light-collection efficiency.
- SiPMs on the same side are attached in series to read with a single channel.
- In average, ~8 counters hit by a signal positron.
- 30 psec time resolution by averaging the hit-times
Current status

- **Xenon calorimeter**
  - Development of LXe MPPC is finished. PDE of 15% is achieved for LXE light. Production of 600 MPPCs for a prototype is done.
  - Mass test of MPPCs and the performance study of the calorimeter will be done with a prototype detector.

- **Drift chamber**
  - Geometrical parameters have been fixed.
  - Prototype R&D on-going (aging, resolution).
  - Good (~110 μm) spacial resolution for cosmic-rays was confirmed

- **Timing counters**
  - Prototype R&D on-going. 30 ps resolution is achieved at test beam.

**GOAL** - start physical run at 2016
Near future

Nstop muons x10^{13}
Conclusion

• MEG experiment successfully finished data taking 31.08.2013.
• The statistics is double compare to published result. The data analysis will be finished at 2014.
• Expected improvement of sensitivity from $7.7 \times 10^{-13}$ to $\sim 5 \times 10^{-13}$.
• Preparation of MEG-2 is in good shape.
• Expected MEG-2 sensitivity after data taking in 2016-2018 is $\sim 5 \times 10^{-14}$. 
Thanks for your attention!
Backup
Confidence Interval

• Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering

Consistent with null-signal hypothesis