A glance beyond the Standard Model: the MEG experiment

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MEG’s “5W” rule (outline)

WHY?
- role of $\mu \rightarrow e\gamma$ and Lepton Flavor phenomena as a tool to explore New Physics (in brief)

WHO?
- “the MEG experiment, I suppose”: a tiny collaboration of ~60 researchers from Italy, Japan, Russia, USA and Switzerland

WHERE?
- At Paul Scherrer Institut, with the most intense DC muon beam worldwide

WHAT?
- signal, backgrounds and experimental challenges, final results

WHEN?
- now and future, constraining even further NP with MEG_II
Lepton Flavor Violation (LFV) is strictly forbidden in “original” SM with vanishing $\nu$ masses

- **modified SM** to account for $\nu$ oscillations (neutral LFV process): $\mu \rightarrow e \gamma$ (and all charged LFV processes) still heavily suppressed, $\mathcal{BR}_{\mu \rightarrow e \gamma} \sim 10^{-50}$

- in proposed extensions of SM, charged LFV is **enhanced**: $\mu \rightarrow e \gamma$ rises up to (hardly) detectable levels $\mathcal{BR}_{\mu \rightarrow e \gamma} \sim 10^{-15} - 10^{-11}$
  - hints on lepton sector, non-SM dark matter candidates and cosmology problems through lepton number violation;
  - $\mu \rightarrow e \gamma$ and other cLFV processes can test “new Physics” happening at an energy scale far out of LHC capability;
  - $\mu \rightarrow e \gamma$ is the cleanest channel;
  - this remains a tough challenge for experimenters.
\( \mu \rightarrow e\gamma \) and cLFV-mates

In the muon sector cLFV can be observed in:

- \( \mu \rightarrow e\gamma \), no neutrinos emitted (analog processes \( \tau \rightarrow \mu\gamma \) and \( \tau \rightarrow e\gamma \))
- \( \mu \rightarrow eee \) muon to three electrons
- \( \mu \rightarrow e N \) muon conversion in nuclei
- anomalous muon magnetic moment

All of them can be modeled with a general effective Lagrangian of the form:

\[
\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \text{h.c.}
\]

**SPOILER!**
This representation has some implications, as we will see...
\( \mu \rightarrow e \gamma \) and cLFV-mates

MEG already eroded place for Beyond Standard Model theories

Especially, one can notice that with the best estimate for \( \theta_{13} \) from recent neutrino oscillation experiments (Daya Bay, DoubleChooz...), the \( \mu \) cLFV is favoured against \( \tau \) channels!

Furthermore, MEG (and cLFV searches) are an ideal complement to LHC measurements looking for BSM effects, capable to explore higher energy region.

 RED: PMNS mixing  
 BLUE: CKM mixing  

favoured \( \theta_{13} \) value is here....
MEG keywords

- **High rate** (*rare* events, large statistics...)
  - *most intense continuous* Muon Beam in the world (PSI)
  - stringent trigger/DAQ requirements

- **Light and precise** (lowest *background* possible)
  - light *target*, light *Drift Chambers* for positron tracking with minimum multiple scattering
  - thin *magnet* for reduced gamma interaction probability (high efficiency)

- **Reliable** over long time multi-year data-taking
  - Several *calibration* and monitoring methods

- **Innovative detectors** with outstanding performances
  - *Liquid Xenon* calorimeter,
  - *Drift Chambers*,
  - high-speed *digitizers* (DRS),
  - *COBRA* magnet,
  - high resolution time measurements in magnetic field

- Optimized for looking at the $\mu \rightarrow e\gamma$ channel

- Small (~60 researchers involved, from many countries)
The MEG crew
The experimental method

\[ \mu \rightarrow e \gamma \text{ signature: photon and positron simultaneously emitted back-to-back and with equal energies in Center-Of-Mass system (} \mu \text{ decays at rest)} \]

signal will be hindered by a huge background:

- **“physics”:** \( \mu \rightarrow e \nu \nu \gamma \) radiative decay with “end-point” \( \gamma \) and \( e \) and low energy \( \nu \)’s
- **“accidental”:** \( e \) and \( \gamma \) from different sources but with compatible kinematics to the \( \mu \rightarrow e \gamma \) one
- in our conditions \( BR_{\text{phys}} \sim 0.1 \times BR_{\text{acc}} \) (dominant)

\[
\hat{BR}_{\text{acc}} \sim (R_\mu)^2 (\delta E_{\gamma})^2 \delta E_{\text{pos}} \delta t (\delta \omega)^2
\]

✓ squared rate dependence
✓ crucial dependence on detector resolutions

\[ T_e = T_\gamma \]

\[ E_e = E_\gamma = 52.8 \text{ MeV} \]

\[ \theta_{\text{e}\gamma} = 180^\circ \]
A MEG overview

Muons are stopped in a **THIN polyethilene TARGET** from which a **positron** and a **photon** emerge.

The positron is bent in the **COBRA** magnetic field and detected with the positron tracker (**DRIFT CHAMBERS, 16 modules**) and the time detector (**TIMING COUNTER: 2 sectors with 15 scintillator bars each**).

The photon escapes COBRA and is detected in the **LXE Calorimeter**, a C-shaped 880 liters vessel equipped with 848 PMTs.

Detector Paper:

MEG montage pics 😊
Winning the challenge

We have several constraints for the MEG detector given the extreme rarity of the searched events:

- **high statistics**, need for detector efficiency and huge $\mu$ stop rate $R_\mu = 3 \times 10^7 \mu/s$
- accidental bck rejection: ultimate resolutions
- trigger system and algorithms capable of selecting interesting events online with high live time and efficiency (total trigger rate $\sim 10$ Hz, from 2011 livetime is $\sim 99\%$)

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma E [%]</td>
<td>1.89</td>
<td>1.90</td>
<td>1.65</td>
<td>Effective sigma (averaged on event depth)</td>
</tr>
<tr>
<td>Relative timing $T_{\gamma}$ [ps]</td>
<td>160</td>
<td>130</td>
<td>140</td>
<td>RMD with $E_\gamma &lt; 48$ MeV</td>
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<tr>
<td>Positron E [keV]</td>
<td>306 (86%)</td>
<td>306 (85%)</td>
<td>304 (86%)</td>
<td>Michel edge, core resolution</td>
</tr>
<tr>
<td>Positron $\theta$ [mrad]</td>
<td>9.4</td>
<td>10.4</td>
<td>10.6</td>
<td>Double turn</td>
</tr>
<tr>
<td>Positron $\phi$ at zero [mrad]</td>
<td>8.7</td>
<td>9.5</td>
<td>9.8</td>
<td>Double turn</td>
</tr>
<tr>
<td>Positron Z/Y [mm]</td>
<td>2.4/1.2</td>
<td>3.0/1.2</td>
<td>3.1/1.3</td>
<td>Double turn, Y core resolution</td>
</tr>
<tr>
<td>Gamma position [mm]</td>
<td>5 (transvers)</td>
<td>5 (transverse)</td>
<td>5 (transverse)</td>
<td>$\pi^0$ measurement with lead collimators</td>
</tr>
<tr>
<td>Trigger/DAQ efficiency [%]</td>
<td>91/75</td>
<td>92/76</td>
<td>97/96</td>
<td>$\pi^0$ sample</td>
</tr>
<tr>
<td>Gamma efficiency [%]</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>$\pi^0$ sample</td>
</tr>
<tr>
<td>Positron efficiency [%]</td>
<td>43</td>
<td>36</td>
<td>36</td>
<td>From MC</td>
</tr>
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Calibrate at a glance

We need to

- ensure a stable operation throughout the whole data taking period which is split in more years
- set up the detector at the beginning
- validate the energy scale and time response

We developed several different calibration methods to do this.

Once a year, with lower beam intensity

- avoid pile up
- study of signal/background PDFs
- time calibration
- by-product: study of radiative muon decay

### Protons on Light Elements

- Li, F:
- Exothermic reaction with emitted γs
- Energies: 4.4, 11.7, 17.6 MeV
- Energy calibration and monitoring
- Start-up trigger threshold setting

### Daily Calibration

- Am sources, 5 MeV
- PMT QE study
- Xe purity monitor

### Mott scattering

- Once every year, ~2 weeks
- Possibility to exploit also Dalitz decays and pair production

### Cosmic Ray Alignment

- 9 MeV γ on Xe, from back side
- Switchable by moving the source with compressed air system

### Nickel γ Generator

- Radiative decay
- Study of signal/background PDFs
- Time calibration
- By-product: study of radiative muon decay

### Calibration at a Glance

- We need to ensure a stable operation throughout the whole data taking period which is split in more years by setting up the detector at the beginning and validating the energy scale and time response. We developed several different calibration methods to do this.

- Once a year, with lower beam intensity, we avoid pile up, study signal/background PDFs, and time calibration. A by-product of this study is the study of radiative muon decay.

- For cosmic ray alignment, we use 9 MeV γ on Xe, which is switchable by moving the source with compressed air system.

- For daily calibration, we use Am sources, 5 MeV, PMT QE study, and Xe purity monitor.
Calibrations: effects!

Reconstructed energy scale in the LXe detector before and after the correction evaluated from periodic calibration.

Final stability is within 0.2% to be compared with energy resolution of 1.6÷1.9%

RED: RMD edge estimate
Black: CW data
muon counting

precise estimate of DETECTED MUONS from the TOTAL STOPPED MUONS:

- normalization of the final results
- estimate of full detector efficiency

obtained with smart use of cross-efficiencies (TC|DC) combined with the flexible trigger setup

every data set is circa doubling the preceding

End of MEG Data-taking: Aug. 28th, 2013

1/2 of the full data taken still to be analyzed

This talk: up to 2011
muon counting stopping

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Analysis of 2009 - 2010 data:
*PRL 107 (2011) 171801*
\[\text{Br}(\mu^+ \rightarrow e^+\gamma) < 2.4 \cdot 10^{-12} \text{ (90\% CL)}\]

Analysis of 2009 - 2011 data:
*PRL 110 (2013) 201801*
Data Analysis

In order to combine the 5 observables:

\[ \overrightarrow{x} = (E_\gamma, E_e, t_{e\gamma}, \phi_{e\gamma}, \theta_{e\gamma}) \]

we used a Blind Box approach to extract all useful information before looking at the rare events searched.

The Blind Box definition was based on the photon energy and the relative positron-photon time. The analysis was developed on events outside the BB and the obtained resolutions were used to give Probability Density Functions for signal-like events (d-functions for all observables, convoluted with detector responses).

A Maximum Likelihood fit, to determine

- number of signal events \( N_{\text{sig}} \)
- number of radiative \( N_R \) \( m \rightarrow e\nu\nu\gamma \)
- number of accidental \( N_A \) bck

expected in the blind box, is then performed:

\[
\mathcal{L}(N_{\text{sig}}, N_R, N_A) = \frac{e^{-N}}{N_{\text{obs}}!} e^{-\left( \frac{(N_R - \langle N_R \rangle)^2}{2\sigma_R^2} + \frac{(N_A - \langle N_A \rangle)^2}{2\sigma_A^2} \right)} \prod_{i=1}^{N_{\text{obs}}} \left( N_{\text{sig}} S(\overline{x}_i) + N_R R(\overline{x}_i) + N_A A(\overline{x}_i) \right)
\]

normalization

\( S, R, A \): PDFs for different event types
Opening the Blinding Box

2011 data only
NSIG Best = -1.4 (+3.8, -1.3)

Event distributions: cuts on not shown variables
Signal PDF contours at 39.3, 74.2, 86.5%
No excess found

2009-2011 data
NSIG Best = -0.4 (+4.8, -1.9)
Opening the Blinding Box

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PDFs and Likelihood Fit

Each PDF obtained from different processes:

- **relative time**: fit of Radiative Muon Decay peak (scaled for different photon energy)
- **positron energy**: fit of Michel Edge for BCK, \( \delta \)-function convoluted with experimental resolution for signal (Mott scattering and double turn method)
- **gamma energy**: Background spectrum from time sidebands, Radiative Muon Decay theoretical shape, detector response to \( \pi^0 \) 55 MeV Photon (signal)
- **relative angles** from double turns tracks in spectrometer
- **Sideband Fit** before the unblinding to estimate expected number of bck events

<table>
<thead>
<tr>
<th>FIT Results</th>
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<tbody>
<tr>
<td>NSIG = -0.4(±4.8 -1.9)</td>
</tr>
<tr>
<td>NRMD = 167.5 ± 24</td>
</tr>
<tr>
<td>NBCK = 2414 ± 37</td>
</tr>
<tr>
<td>NOBS = 2574</td>
</tr>
</tbody>
</table>

Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data
Result: a new Upper Limit

A factor 20 better than pre-MEG limit (MEGA 2002), 4 times better than MEG 2009-2010.

Slightly better than the expected sensitivity ($7.7 \times 10^{-13}$) evaluated with Toy MC.

Confidence interval of $N_{\text{sig}}$ evaluated in a Feldman-Cousins fashion taking into account PDF uncertainties and fluctuations of signal and background.

Normalization: through the use of independent unbiased trigger on reference events (Michel decays) we can estimate total number of detected muons by applying the same cuts. A comparison with RMD data shows consistent values for the $k$-factor.

$BR = \frac{\text{Number of events}}{\text{total number of muons}}$

Limit published in: PRL 110 (2013) 201801
Next: why a MEG upgrade?

• MEG saturates its sensitivity with 2013 run
• interesting to go further by another order of magnitude
• needed a re-design of the detector to gain this (MEG is limited by current performances)
• quick process: we identified weak points of MEG detector and our expertise allows to implement modifications “easily”
• short time scale compared to other cLFV experiments
• competitive tool for New Physics for low values of $\bar{K}$ in the “effective Lagrangian”:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L \bar{F}_{\mu\nu} + h.c.$$  

• as already stated, growing interest is pinned on the $\mu \rightarrow e\gamma$ decay by large $\theta_{13}$ value
MEG_UP is going to implement several improvement in the experimental apparatus:

1. higher beam rate (more statistic)
2. thinner target (less background)
3. more points for a better track reconstruction (improve positron resolutions)
4. shorter path from last DC point to Timing Counter (time resolution)
5. segmented Timing Counter, for better matching with DC volume and multi-hit exploitation
6. different Calorimeter shape within the existing cryostat
7. finer inner face granularity with new readout devices (SiPM) for better energy reconstruction and pile-up rejection
DC upgrade

A unique cylindrical volume, with stereo wires

- full active volume, less dead layers giving multiple scattering problems
- extends closer to the target for better vertex reconstruction
- high bandwidth readout with fast counting gas: possibility to exploit Cluster Counting and Timing for better single-hit performances
- higher rate means severe constraints on central wires: demonstration of a 3 years operation for the worst case (inner cell, central position) by means of an accelerated ageing test
DC R&D examples

different prototypes prepared, each dedicated to different studies:

✧ **Long prototype** for signal/noise issues and wiring tests

✧ **small prototype** with a single cell for ageing measurements

✧ **three-tube and three-cells configuration** for hit resolution

✧ **dedicated preamplifier** developed for the upgraded detector

✧ **facility for high precision tracking** (Cosmic Ray telescope) for detector resolution and alignment procedures studies
XEC upgrade

In the existing calorimeter, due to 2” size of PMTs:
- spatially close photons cannot be disentangled: residual Pile-up
- poorer energy resolution for shallow events (conversion depth < 3 cm)
- limit on conversion point resolution (angular matching)

Main improvement:
- substitute inner face PMT with 12x12mm² SiPMs/G-APDs/MPPCs (name depends on brand!)
- R&D for VUV detection, after-pulsing and linearity issues, mechanical coupling to the structure, feedthroughs….
TC upgrade

Positron timing limited by:

- **Long path** from the last tracker point to the TC, with much material (structures, cabling, gas system, DC PCB)
- **large thickness** of TC bars needed for photo-statistic to limit PMT jitter contribution: large energy loss of positrons with path fluctuation

Furthermore, with the new tracker, the room for TC is smaller

- **solution**: replace large bars (4x4x80 cm$^3$) with small scintillator counters read out with SIPM
- **possible to use multiple hit lowering the time resolution thanks to high multiplicity**
- **optimize the orientation of each pixel independently**
- **the TC structure is just outside the tracking volume!**
A new DAQ

For a continuous beam experiment, there is a livetime to online selection efficiency tradeoff
- solved in MEG for the current beam intensity: up to 99% live time with >95% efficiency
- not sufficient in MEG_UP due to higher beam rate
- moreover, MEG_UP has an higher number of channels to be acquired

Need to rethink the DAQ structure
- digitizer: DRS sampling chip developed at PSI, working up to 5 GHz
- existing trigger system: dedicated boards with 100 MS/s sampling speed and FPGA processing of trigger algorithms
- a bottleneck is the limited communication speed between the two class of boards
- Our solution: have one type of board capable of handling complex trigger decisions: the WAVEDREAM concept
Synthesizing MEG_UP

MEG_UP is intended to give an order of magnitude better constraint on the $\mu \rightarrow e \gamma$ Branching Ratio in a few years

✧ re-design of full detector based on existing know-how
✧ new concept for DAQ: board with integrated high-speed digitizer and trigger
✧ fast R&D process (3 years study and construction, 3 years data taking)
✧ to be compared with ambitions and timescales of other muon-based Lepton Flavor searches e.g. mu2e, Comet...

<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 (%) ($w &lt; 2 cm)/(w &gt; 2 cm)$</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>
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<tr>
<td>$\gamma$</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>$e^+$</td>
<td>40</td>
<td>88</td>
</tr>
</tbody>
</table>
In conclusion…

The MEG experiment had a successful run in the period 2009-2013, with a total number of $\sim 1.5 \times 10^{13}$ accumulated muons.

The current best limit, using only 2009-2011 data, is already 20 times better than the previous limit from MEGA and 4 times better than the first released MEG limit.

With the current detector there is no room to improve the limit with further data taking after 2013; so we envisage an upgrade:

- new positron tracker and time detector
- modification of the photon detector
- major improvements in the DAQ system
- higher beam intensity

The upgrade will be able to detect the $\mu \rightarrow e\gamma$ decay with an order of magnitude better sensitivity in a timely fashion.

THANK YOU FOR THE ATTENTION!
spares
MEG Sensitivity:

Toy MC produced starting from the measured background PDFs + null signal hypothesis

Distribution of “measured” Branching Ratio Upper Limits (i.e. background fluctuations)

The sensitivity is defined as the median of this distribution
photon detector upgrade

top: Photon Detection Efficiency for SIPMs
bottom: gamma energy PDF for upgraded XEC

final MEG sensitivity vs MEGUP