The MEG experiment
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New Physics processes

BSM?

Different $\mu$-beam concept

Is Lepton Family a fundamental symmetry of nature? Bilenky, Petcov, Pontecorvo 1977
Bjorken, Lane, Weinberg 1977

$\text{BR}(\mu \rightarrow e\gamma) \approx 5 \times 10^{-10}$

Establishing the family structure of elementary particles ($\nu_\mu \neq \nu_e$)

charged Lepton Flavor Violating (cLFV)

New Physics processes BSM?
Why are these processes so sensitive to BSM?
First: cLFV in the SM are NOT observable

In pre-$\nu$ oscillations SM cLFV (charged Lepton Flavor Violating) amplitudes are 0 due to the fact that neutrino masses are 0

$\mu \rightarrow e\gamma$ rate in the standard model after neutrino oscillations

$$P_{osc} \approx \sin^2 \left( \frac{\delta m^2_{\nu} L}{E} \right); \quad L \approx \frac{1}{M_W}; \quad E \approx M_W$$

$$BR \sim \alpha P_{osc} \sim \alpha \left( \frac{\delta m^2_{\nu}}{M_W^2} \right)^2; \quad \delta m^2_{\nu} \sim 10^{-5} eV^2 \Rightarrow BR \sim 10^{-55}$$

$$\frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k}U_{e k}^* m_{\nu k}^2}{M_W^2} \right|^2$$

cLFV are VERY clean channels for new physics searches
Second: as soon as one starts adding new (BSM) terms to the SM Lagrangian:

- **Heavy Neutrinos** (see saw)
- **Supersymmetry**
- **Compositeness**
- **Leptoquarks**
- **New Heavy Bosons / Anomalous Couplings**

Charged Lepton flavor violating amplitudes arise at measurable levels in the same way in which $V_{PMNS}$ and $V_{CKM}$ arise (Yukawa mass terms diagonalization)
SUSY seesaw SO(10) with PMNS slepton mixing; Calibbi, Signorelli 2017 and references therein.
In case model prefer dipole operator (Supersymmetry) $\mu \rightarrow e\gamma$ is enhanced by roughly a factor $1/\alpha$ wrt $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$.

In other cases $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$ dominate $\Rightarrow$ Complementarity $+$ possibility of distinguishing among different models.

New Heavy Bosons / Anomalous Couplings.

Compositeness

Leptoquarks
Comparison with SUSY searches at LHC: a particular case

\[ \frac{g-2}{\mu} \rightarrow e \gamma \]

Focus only on the particles relevant for CLFV observables (limits from LHC on coloured sparticles much stronger)
The distinction of Signal from background

**signal**

\[ \mu \rightarrow e \gamma \]

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

\[ T_e = T_\gamma \]

\[ \theta_{e\gamma} = 180^\circ \]

**background**

**physical**

\[ \mu \rightarrow e \gamma \nu \nu \]

\[ ee \rightarrow \gamma \gamma \]

\[ eZ \rightarrow eZ \gamma \]

**accidental**

\[ \mu \rightarrow e \nu \nu \]

4 variables measured: measure them in the best possible way in order to separate signal from background
The MEG experiment...

1. Stopped beam of $3 \times 10^7 \mu$\(/{\text{sec}}\) in a 150\(\mu\text{m}\) target

2. Solenoid spectrometer & drift chambers for $e^+$ momentum

3. Scintillation counters for $e^+$ timing

4. Liquid Xenon calorimeter for $\gamma$ detection (scintillation)
The interesting 4D region split in 2 bidimensional plots
A more quantitative comparison...

The relative angle is split into zenith and azimuth.

Magnified signal ($BR = 4 \times 10^{-11}$)

The relative angle is split into zenith and azimuth.

$N_{ACC} = 7684 \pm 103$

$N_{RMD} = 663 \pm 59$

$N_{SIG}$ (best fit) = -2.2

$BR < 4.2 \times 10^{-13}$

@ 90% C.L.

The MEG Collaboration

University of Tokyo
KEK

INFN & University of Genova
INFN & University of Lecce
INFN & University of Pavia
INFN & University of Pisa
INFN & University of Roma 1

Paul Scherrer Institut

JINR Dubna
BINP Novosibirsk

University of California
Irvine
The MEG II detector

Liquid Xenon Gamma-ray Detector

COBRA Superconducting Magnet

Gamma ray

x2 resolution everywhere

Drift Chamber

single-volume He:iC₄H₁₀ small stereo cells

Positron Timing Counter

30ps resolution w/ multiple hits

Radiative Decay Counter

Muon

Positron

Further reduction of radiative BG

Full available intensity 7x10⁷/s

Better uniformity w/ VUV-sensitive 12x12mm² SiPM
$P_\mu \sim 29\text{MeV}/c$

$\pi \rightarrow \mu\nu$

at rest

$- 10^8 \mu/s$ from the decay at rest of $\pi^+$ on the target surface (the $\mu$ range is approx. .1 gr/cm$^3$): almost completely polarized

2 systems for almost “continuous” beam monitoring:
scintillating fibers and scintillating target
Measuring possible deformations with a camera

New target
New Pixelated Timing Counter

2017: ready

first insertions tests and positrons already in 2015 with 1/2 detector
Liquid Xenon detector 2017: ready

- Same detector as MEG
- homogenous
  - LXe as scintillator
    - bright: 40 photons/keV
    - fast: 4/22/40 ns
  - VUV MPPC replacing PMTs in the inners face
    - 4192 channels instead of 216!!
    - uniform response in particular for shallow events
Liquid Xenon detector (2)

Better position resolution ➞ angular resolution
Better uniformity ➞ energy resolution
Liquid Xenon detector (3): MMPC (SiPM) positions measurement

- Scaling factor is consistent with thermal coefficient of stainless steel (cryostat material ~0.0016), and no position dependent deviation observed.

\[ \Delta Z = Z_{\text{Xray}} - Z_{\text{Faro}} \text{[mm]} \]

Blue: before transformation  
Red: after transformation

\[ \Delta \phi = \phi_{\text{Xray}} - \phi_{\text{Faro}} \text{[deg]} \]

Blue: before transformation  
Red: after transformation
New Cylindrical Drift Chamber

- Stereo u-v wires, based on the Kloe experience
- **single** volume DC
- **He-Isobuthane** (85-15) **low mass** gas mixture
  - $2 \times 10^{-3}$ radiation length per track (20% less than MEG)
- **1728 anode** wires + ~10000 cathodes
  - **anode: 20\mu m W/Au,** **cathode: 40/50 \mu m Al/Ag**
  - **7 degree stereo angle**

Ready in **2018** due to a problem of 40 \mu m cathodes fragility
New Cylindrical Drift Chamber (2)

4 times the number of hits in MEG DC ➞ improved momentum resolution

Tracks are followed down to the TC ➞ higher matching efficiency

Single hit resolution measured in dedicated facility

\[ \text{integrated on all impact parameters} \]

\[
\begin{align*}
\text{events/20 \mu m} & \quad 1277 \pm 31 \\
A & \quad 8999 \pm 13 \\
\mu & \quad -0.0155 \pm 0.002 \\
\sigma & \quad 0.106 \pm 0.002 \\
\delta & \quad 0.078 \pm 0.003 \\
\end{align*}
\]

A. M. Baldini et al., JINST, 2016

L. Galli et al., TNS, 2015

filled with He to check sealing

HV tests
New detector: Radiative Decay Counter

- Tags BG gamma rays from radiative decays by measuring low energy positrons
- Improves sensitivity by 15%
Completely New Trigger and DAQ electronics

- Fully custom
- Trigger and DAQ integrated
  - *wfm digitiser* @2GSPS with DRS chip
  - SiPM power supply and amplification included
  - Complex FPGA based trigger with latency <450ps

System demonstrator successfully tested in 2017 with LXe, TC and RDC

≈20% of the 8000 needed channels available; complete production by spring 2020
Final sensitivity of $6 \times 10^{-14}$

<table>
<thead>
<tr>
<th>PDF parameters</th>
<th>MEG</th>
<th>MEG II</th>
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<tbody>
<tr>
<td>$E_{e^+}$ (keV)</td>
<td>380</td>
<td>130</td>
</tr>
<tr>
<td>$\theta_{e^+}$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$\phi_{e^+}$ (mrad)</td>
<td>8.7</td>
<td>3.7</td>
</tr>
<tr>
<td>$z_{e^+}/y_{e^+}$ (mm) core</td>
<td>2.4/1.2</td>
<td>1.6/0.7</td>
</tr>
<tr>
<td>$E_{\gamma}(%)$ ($w&gt;2$ cm)/($w&lt;2$ cm)</td>
<td>2.4/1.7</td>
<td>1.1/1.0</td>
</tr>
<tr>
<td>$u_\gamma$, $v_\gamma$, $w_\gamma$ (mm)</td>
<td>5/5/6</td>
<td>2.6/2.2/5</td>
</tr>
<tr>
<td>$t_{e^+\gamma}$ (ps)</td>
<td>122</td>
<td>84</td>
</tr>
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**Efficiency (%)**

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Trigger</td>
<td>$\approx$ 99</td>
<td>$\approx$ 99</td>
</tr>
<tr>
<td>Photon</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>$e^+$ (tracking $\times$ matching)</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
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$$B_{acc} \propto R_\mu \Delta E_e \Delta E_{\gamma}^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma}$$
Schedule of the muon LFV experiments

Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams

- $\mu^- N \rightarrow e^- N$ ($7 \times 10^{13}$)
  - COMET Phase-I
  - Sensitivity: $10^{15}$

- $\mu^+ \rightarrow e^+ e^+ e^-$ ($1 \times 10^{12}$)
  - Mu3e Phase-I
  - Sensitivity: $10^{14}$

- $\mu^+ \rightarrow e^+ \gamma$ ($4.2 \times 10^{13}$)
  - MEG II
  - Sensitivity: $10^{14}$

- COMET Phase-II
  - Sensitivity: $10^{17}$

- Mu3e Phase-II
  - Sensitivity: $10^{16}$

- Mu2e-II with PIP-II
  - Sensitivity: $10^{18}$

- PRISM
  - Sensitivity: $10^{19}$

Input to Eur. Particle Physics Strategy
“Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities”
Summary

$\mu \rightarrow e \gamma$ (CLFV) is an excellent probe for search of physics Beyond the Standard Model

Complementary search (high intensity or precision frontier) of BSM wrt to the high energy frontier (LHC)

MEG II, largely improved with respect to MEG, should soon start data taking

Delay in the schedule due mostly to DAQ electronics complexity: 2018/2019 test of detectors with subset of DAQ electronic channels

Three years of data taking to reach a final sensitivity of $6 \times 10^{-14}$

Thank you for your attention