μ -> e γ
Experimental Aspects
History of $c$LFV searches

Hincks & Pontecorvo
[Phys. Rev. 73 (1948) 257]
*muon is not an “excited electron”*

Lokanathan & Steinberger
*lepton flavors*

MEG Experiment
$BR(\mu \rightarrow e \gamma) < 4.2 \times 10^{-13}$
$\mu \rightarrow e \gamma$ searches

28 MeV/c muons are stopped on a thin target

Positron and photon are monochromatic (52.8 MeV), back-to-back and produced at the same time;

**Accidental Background**

DOMINANT

**Radiative Muon Decay (RMD)**
\[ \mu \longrightarrow e \gamma \] searches

28 MeV/c muons are stopped on a thin target

Positron and photon are \textbf{monochromatic} (52.8 MeV), back-to-back and produced at the same time;

Radiative Muon Decay (RMD)

\[ \Gamma_{acc} \propto \Gamma_{\mu}^2 \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \Theta_{e\gamma})^2 \cdot \delta T_{e\gamma} \]

DOMINANT
Ingredients for a search of $\mu \rightarrow e \gamma$

- Reconstruct the Relative Angle
- Reconstruct the Photon Energy
- Reconstruct the Relative Time
- Reconstruct the Positron Energy
The MEG Experiment

Reconstruct the Relative Angle

Reconstruct the Photon Energy

Reconstruct the Positron Energy

LXe calorimeter (XEC)
16 Drift Chambers (DC) in a magnetic field
30 scintillating bars for timing & trigger (TC)

7.5 x 10^{14} \mu on target

BR(\mu \rightarrow e \gamma) < 4.2 x 10^{-13} @ 90\% C.L.
MEG-II

- The MEG experiment has been upgraded in all sub-detectors

- Larger LXe volume with finer light detector granularity

- Higher beam intensity

- Unique-volume Drift Chamber

- Scintillator Tile TC

- RMD Veto
MEG-II status

TC built and commissioned in 2016-2017
\( \sigma_T \approx 35 \text{ ps} \)

First photons in the upgraded XEC in 2017
\( \sigma_E \approx 1\% @ 52.8 \text{ MeV} \)

New DC under commissioning
Expected to be fully operational in 2021
\( \sigma_E \approx 130 \text{ keV} \)
MEG-II status

TC built and commissioned in 2016-2017

First photons in the upgraded XEC in 2017

$\sigma_T \sim 35 \text{ ps}$

New DC under commissioning

Expected to be fully operational in 2021

$\sigma_E \sim 130 \text{ keV}$

First physics run in 2021

Expected UL

$\sim 6 \times 10^{-14}$

in a 3-year run
What next?

G. Cavoto, A. Papa, FR, E. Ripiccini and C. Voena

Ingredients for a search of $\mu \rightarrow e \gamma$

- Reconstruct the Photon Energy
- Reconstruct the Relative Angle
- Reconstruct the Relative Time
- Reconstruct the Positron Energy
Ingredients for a search of $\mu \rightarrow e \gamma$

- Reconstruct the Photon Energy
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- Reconstruct the Relative Time
- Reconstruct the Positron Energy

**Continuous** (to avoid pileup)
**Positive** (to avoid capture by nuclei in the stopping target)
muon beams

$~ 10^8 \mu/s$ available at PSI now

PSI is considering a beamline with $> 10^9 \mu/s$

Prospects for DC muon beams at PIP-II (Fermilab) are under study
Ingredients for a search of $\mu \rightarrow e \gamma$

- **Reconstruct the Relative Angle**: Use a magnetic spectrometer to get the best resolutions. For instance, at 52.8 MeV/c, large multiple scattering results in a very low material budget, ideally a gaseous detector.

- **Reconstruct the Photon Energy**: The target itself contributes significantly to the angular resolution. To mitigate this, target should be as thin as possible, and the momentum beam should be as monochromatic as possible.
Positron Reconstruction at High Beam Rate

- MS makes useless an extreme position resolution (e.g. silicon detectors) and plays in favor of light gaseous detectors, but...

A. Baldini et al., EPJ C 78 (2018) 5, 380

Expected aging (gain loss) in the MEG-II Drift Chamber

...would a gaseous detector be able to cope with the very high occupancy at > 10^9 μ/s?

- Solutions for a gaseous detector with high rate capabilities are also under study (new geometries, optical readout,...)
Muon Stopping Target

- The target plays a crucial role in determining the positron angular resolution, due to the Multiple Coulomb Scattering:
  - target must be as thin as possible

- In order to stop a significative fraction of muons, it must be at the Bragg peak:
  - muons not stopped by the target are stopped in the gas right after, giving background without contributing to the signal
  - enough thickness to stop ~ all muons

Optimal target
Be, 90 µm

$\theta_{MS}(e^+) \sim 2.5 - 3$ mrad
Ingredients for a search of $\mu \rightarrow e \gamma$

Reconstruct the Photon Energy
Reconstruct the Relative Angle
Reconstruct the Relative Time
Reconstruct the Positron Energy

$\mu^+ \rightarrow e^+ \gamma$
Calorimetry vs. Photon Conversion

**Calorimetry**

High efficiency
Good resolutions

*MEE:*
* LXe calorimeter
* 10% acceptance

**Photon Conversion**

Low efficiency (~ %)
Extreme resolutions
+ εγ Vertex
Calorimetry vs. Photon Conversion

**Calorimetry**
- High efficiency
- Good resolutions

*MEG: LXe calorimeter 10% acceptance*

**Photon Conversion**
- Low efficiency (~ %)
- Extreme resolutions
  - + eγ Vertex

![Graph showing comparison between Calorimetry and Photon Conversion](image)
Ingredients for a search of \( \mu \rightarrow e \gamma \)

Reconstruct the Photon Energy

Reconstruct the Relative Angle

Reconstruct the Positron Energy

Reconstruct the Relative Time

\( \mu^+ \rightarrow e^+ \gamma \)
Photon and Positron timing

• Timing plays a crucial role in $\mu \rightarrow e \gamma$ searches (accidental coincidences!!!):
  - need a very good positron and photon timing
  - $\sigma(Te\gamma) \sim 80$ ps in MEG-II

• LiBr$_3$(Ce) calorimeters + positron scintillating counters like in MEG can give the required performances

• For photon conversion, need to detect $e^+$ or $e^-$ in a fast detector

What about stacking multiple layers?
Photon and Positron timing

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   ![Diagram](image)

   *Effective converter material with lower Z*

   *Worse compromise of efficiency vs. resolution*
A conceptual design
Expected Sensitivity

A few $10^{-15}$ seems to be within reach for a 3-year run at $\sim 10^8 \, \mu/s$ with calorimetry (expensive) or $\sim 10^9 \, \mu/s$ with conversion (cheap)

Fully exploiting $10^{10} \, \mu/s$ and breaking the $10^{-15}$ wall seem to require a **novel experimental concept**
A beam for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ at FNAL

Credit: R. Bernstein
Muon beam for muon LFV decays at FNAL

- PIP-II can provide a huge amount of muons - is it reasonable to think about a $\mu \rightarrow e \gamma / \mu \rightarrow 3e$ program at FNAL?

1. Start from the Mu2e beam line

2. make the beam positive (easy), continuous (easy - propagation in the beam line spread the muon arrival times, muon lifetime makes the rest), low momentum (difficult) and monochromatic (very difficult)

- Some ideas came out recently to get the necessary low-momentum, monochromatic beam (time-varying deceleration) — can get $> 10^{10} \mu/s$
Muon beam for muon LFV decays at FNAL

• Alternate running of $\mu \rightarrow e$ conversion, $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ experiments would be possible in the same place, with great advantages in terms of community building and return on investment.

• An application for a staff exchange project (aMUSE), including activities related to this opportunity, has been submitted to the European Community (ERC RISE program).
Backup
High Intensity Muon Beams

- High intensity muon beams are crucial in the search for cLFV

- A few projects to get muon beams 1 or 2 orders of magnitude more intense than now are under study around the world:

  - HiMB @ PSI

  - MuSIC @ RCNP (Osaka, Japan)

  - prospects for DC muon beams at PIP-II (Fermilab, USA) are under studies
The HiMB Project @ PSI

- PSI is designing a high intensity muon beam line (HiMB) with a goal of $\sim 10^{10}$ $\mu$/sec (x100 the MEG-II beam)

- Optimization of the beam optics:
  - improved muon capture efficiency at the production target
  - improved transport efficiency to the experimental area

x4 $\mu$ capture eff.

x6 $\mu$ transport eff.

$1.3 \times 10^{10}$ $\mu$/s

in the experimental area

with 1400 kW beam power

A. Knecht, SWHEPPS2016
Production target

- The ring cyclotron at PSI also serves a **neutron spallation source** (SINQ) downstream of the π/µ production target

  - the proton beam need to be mostly preserved
  -> **thin production target**
The MuSIC Project @ RCNP

- At RCNP in Osaka (Japan) the goal is to fully exploit the proton beam power with a thick production target:

  - $10^6 \mu$ per Watt of beam power (vs. $10^4 \mu/W$ at HiMB)

µ -> e γ searches

**Efficiency-dominated regime**

\[ 1/UL \sim \Gamma_{\mu} \epsilon \]

**Background-dominated regime**

\[ 1/UL \sim S/\sqrt{B} \sim \sqrt{\left(\Gamma_{\mu} \epsilon\right)/\left(\Gamma_{\mu}^2 \epsilon \delta E_e \ldots\right)} = \sqrt{\epsilon/\delta E_e \ldots} \]

MEG was operated with \(3 \times 10^7\) µ/s

MEG-II will be operated with \(7 \times 10^7\) µ/s
γ Reconstruction: Limiting factors — Calorimetry

- Photon Statistics
- Scintillator time constant
- Detector segmentation

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density [g/cm³]</th>
<th>Light Yield [ph/keV]</th>
<th>Decay Time [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr₃(Ce)</td>
<td>5.08</td>
<td>63</td>
<td>16</td>
</tr>
<tr>
<td>LYSO</td>
<td>7.1</td>
<td>27</td>
<td>41</td>
</tr>
<tr>
<td>YAP</td>
<td>5.35</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>LXe</td>
<td>2.89</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>38</td>
<td>250</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>9</td>
<td>300</td>
</tr>
</tbody>
</table>

- LaBr₃(Ce) — a.k.a. *Brilliance* looks a very good candidate:
  - our simulations & tests indicate that ~ 800 keV resolution can be reached
  - extreme time resolution (~ 30 ps)
  - large acceptance
  - very expensive
γ Reconstruction: Limiting factors — Conversion

- Interactions in the converter (conversion probability, e+e- energy loss and MS)
- Large Z materials (Pb, W) give the best compromise of efficiency vs. resolution

- Can take advantage of the photon direction determination from the e+e- reconstruction

\[ d_{e}\gamma^{\text{vtx}} = \sqrt{\left(\frac{X_e - X_\gamma}{\sigma_X}\right)^2 + \left(\frac{Y_e - Y_\gamma}{\sigma_Y}\right)^2} \]
Toward the next generation of \( \mu \rightarrow e \gamma \) searches: Positron Reconstruction

- Tracking detectors in a magnetic field are the golden candidates:
  - high efficiency
  - better resolutions w.r.t. calorimetry \((\sigma(E_e) \text{ down to } 0.2\% \text{ vs. } > 1\%)\)
- Performances are limited by Multiple Scattering of 52.8 MeV positrons in target and tracker materials
  - Need a very light detector (the MEG drift chambers gave \(~ 2 \times 10^{-3} X_0\) over the whole positron trajectory, 200 \(\mu\)m silicon equivalent)
  - Silicon trackers are likely to be not competitive with gaseous detectors in terms of resolutions (C-H. Cheng et al. arXiv: 1309.7679)
Positron Reconstruction at High Beam Rate

Expected aging (gain loss) in the MEG-II Drift Chamber

Would a gaseous detector be able to cope with the very high occupancy at $> 10^9 \mu/s$?

A. Baldini et al., MEG Upgrade Proposal, arXiv:1301:7225
An active conversion layer

- Low Z active material for timing deteriorates the best efficiency/resolution configuration
  - the active layer must be as thin as possible
- Scintillators have poor “timing to thickness” figures (~ 1 ns for 250 µm fibers)

FAST SILICON DETECTORS

- R&D on going for PET application (TT-PET)

M. Benoit et al., JINST 11 (2016) no. 03, P03011
Possible Scenarios

**CALORIMETRY**

<table>
<thead>
<tr>
<th>Variable</th>
<th>w/o vtx detector</th>
<th>w/ TPC vtx detector</th>
<th>w/ silicon vtx detector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>conservative</td>
<td>optimistic</td>
<td>conservative</td>
</tr>
<tr>
<td>$\theta_{e\gamma} / \phi_{e\gamma}$ [mrad]</td>
<td>7.3 / 6.2</td>
<td>6.1 / 4.8</td>
<td>3.5 / 3.8</td>
</tr>
<tr>
<td>$T_{e\gamma}$ [ps]</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_e$ [keV]</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\gamma}$ [keV]</td>
<td>850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>42% (70% $\gamma$ acceptance)</td>
<td></td>
<td></td>
</tr>
</tbody>
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**PHOTON CONVERSION**

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</tr>
<tr>
<td>$T_{e\gamma}$ [ps]</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_e$ [keV]</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\gamma}$ [keV]</td>
<td>320</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>1.2 (1 LAYER, 0.05 $X_0$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MEG-II Highlights - The LXe Calorimeter

We developed large-area (12x12 mm$^2$), UV-sensitive MPPCs to cover the inner face of the LXe calorimeter.

Better Resolution, better pile-up rejection

$\sigma_E \sim 1\%$, $\sigma_{\text{position}} \sim 2/5$ mm (x,y/z)

First events/spectra from 2017 data
MEG-II Highlights - The Timing Counters

5mm-thick Scintillator Tiles read out by 3x3 mm² SiPM

Complete detector took data in 2017

Calibration with dedicated laser
MEG-II Highlights - The Timing Counters

5mm-thick Scintillator Tiles read out by 3x3 mm$^2$ SiPM

Complete detector took data in 2017

$\sigma_T \sim 35$ ps

Already reached the design resolution
MEG-II Highlights - The Drift Chamber

Wiring, assembly and sealing have been completed

Had to face severe problems of wire fragility in presence of contaminants + humidity

On beam in Fall 2018

$$\sigma_E \sim 130 \text{ keV}, \sigma_{\text{angles}} \sim 5 \text{ mrad}, 2x \text{ larger positron efficiency}$$
MEG-II Highlights - RDC, DAQ, Trigger

50% of acc. background photons come from RMD w/ positron along the beam line

Can be vetoed by detecting the positron in coincidence with the photon

A new detector (LYSO + plastic scint.) built and tested in 2017 -> 16% better sensitivity

Trigger and DAQ will be integrated in a single, compact system (WaveDAQ)

Also provides power and amplification for SiPM/MPPC

Successfully tested in 2017 with XEC, TC and RDC
MEG-II schedule & sensitivity

![Timeline showing the schedule and sensitivity of MEG-II project from 2013 to 2022. The timeline includes stages such as Proposal, R&D, Construction & Commissioning, Engineering Runs, Physics Runs, and the final result of the MEG-II experiment, which is shown as $6 \times 10^{-14}$.](https://example.com/timeline.png)
Silicon detector momentum resolution

Mu3e momentum resolution (B = 1T)  
4x worse than MEG-II

A. Kozlinskiy, Mu3e Collaboration, CTD/WIT 2017
DeeMee / COMET / Mu2e

DeeMee: will start data taking soon
SES $\sim 10^{-14}$

COMET: Will start phase-I commissioning $\sim 2019$
phase-II SES $\sim 10^{-17}$

Mu2e: Data taking expected $\sim 2022$
SES $< 10^{-16}$
Mu3e

R&D almost completed
Commissioning will start soon
Data taking expected > 2020

Expected BR UL $\sim 10^{-16}$