The MEG experiment result and the MEGII status
charged Lepton Flavour Violation (cLFV)

- LFV observed in the neutral sector but **not** in the charged one (yet)
  - "accidentally" due to tiny neutrino masses compared to electroweak energy scale

- cLFV signal would **definitely** be due to BSM physics
Signal and background

Accidental background is dominant and determined by beam rate and resolutions

\[ B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma} \]

\[ B_{RMD} \approx 0.1 \cdot B_{acc} \]
Detector overview

Muon Beam

$E_Y, t_Y, \chi_Y$

$\theta_{eY}$

$\phi_{eY}$

$\bar{p}_e$

$\gamma$

$x, y, z$

$x, y, z$

ICHEP 2016
L. Galli, INFN Pisa
Analysis strategy

- Decided to extract CL to $B(\mu \rightarrow e\gamma)$ from a likelihood analysis in a wide signal box.

- Each event is described in terms of 5 kinematic variables:
  - $x_i = (E_{\gamma}, E_{e\gamma}, t_{e\gamma}, \varphi_{e\gamma}, \theta_{e\gamma})$

- Resolutions and PDFs evaluated on data outside the signal box.
  - Signal box closed until analysis is fixed.

- Use of sidebands.
  - Accidental background from Left and Right sidebands.
  - Radiative Muon Decay (RMD) studied in the $E_{\gamma}$ sideband.

- $BR(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$ @90% CL with half of the statistics.

“New constraint on the existence of the $\mu \rightarrow e\gamma$ decay”

PRL110, 201801 (2013)
Analysis improvements

- Major systematic error
  - 13% sensitivity worsening

- Positron AIF events
  - 2% bkg suppression
  - 1% sign inefficiency

- First missing turn recovery
  - +4% of tracking efficiency
Normalisation

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

- Two independent normalisation procedures
  - count positrons from \( \mu \rightarrow e \nu \nu 
    - dedicated pre-scaled trigger in DAQ
  - radiative decay events
    - in photon energy side-band
- Integrated normalisation = \( 1.73 \times 10^{13} \)
  - 4% uncertainty
Sensitivity

- **median 90% CL Upper Limit** on toy MC experiments with **null signal hypothesis**
- **Comparison** with **last publication** from 2009-2011 data
  - **no significative difference**
- **Checked** by **timing side-band** data fits
- 5.3 $10^{-13}$ for all data
  - 8 $10^{-13}$ for 2009-2011 data

- The **Blinded Box** was **opened** in December 2015

![Signal contours of 1, 1.64, 2σ are shown](image)
The 5(+1) observables & R_{sig}

\[ R_{sig} = \log_{10}(\frac{S}{0.1R + 0.9B}) \]

signal enhanced by a factor 100

\[ \text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \text{ @90\% CL} \]
Final MEG result and constraints

accepted by EPJ C, arXiv:1605.05081v3
MEG II at a glance

- Liquid Xenon Gamma-ray Detector
- COBRA Superconducting Magnet
- Gamma ray
- x2 resolution everywhere
- Drift Chamber single-volume He:iC\textsubscript{4}H\textsubscript{10} small stereo cells
- Positron Timing Counter 30ps resolution w/ multiple hits
- Radiative Decay Counter
- better uniformity w/ VUV-sensitive 12x12mm\textsuperscript{2} SiPM
- full available intensity 7x10\textsuperscript{7}/s
- Positron
- Muon
- further reduction of radiative BG

L. Galli, INFN Pisa
The first MEG II data...
LXe calorimeter first tests this fall

Drift Chamber Completed by Spring 2017

RDC tested with µbeam last July

Work in progress
Perspectives

"μ→eγ"-equivalent Branching Ratios

Data taking
Assembly
2013
2015
2017
2019
R&D
MEG II

New Physics
MEG
MEG II

Branching ratio upper limit (μ→eγ equivalent)

Year

ICHEP 2016
14
L. Galli, INFN Pisa
Conclusions

The final result of the MEG experiment is

\[ BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \ @90\% \ CL \]

- many improvements in reconstruction and systematics treatments developed

The MEG II is going to improve MEG sensitivity by one order of magnitude

construction on going

- first data taken last year with a part of the TC detector and the RDC counter with the first TDAQ system

- in 2016 is going to be crucial for the realisation of the new devices
Thank you... and stay tuned!
Backup
Detector overview

- $\mu$ decay at rest
  - Beam rate: $3 \times 10^7 \mu/s$
  - $\mu$ stopped in 205 $\mu$m target

- $\gamma$ detection
  - Liquid Xenon calorimetry with scintillation light
    - fast: 4/22/45 ns
    - high LY: $\sim$0.8 NaI
    - short $X_0$: 2.77 cm

- positron detection
  - magnetic spectrometer
    - non-uniform B field $\rightarrow$ constant bending radius and $e^+$ swept rapidly away
    - ultra-thin drift chambers to limit matter effects ($X_0 \sim 0.0003$ per module)

- TC detector
  - time of flight with plastic scintillator counters
Calibration system (a subset!)

Proton Accelerator

$\pi^+ \rightarrow \gamma \gamma$

$\pi^+ + p \rightarrow \pi^0 + n$

$\pi^0 \rightarrow \gamma \gamma$ (55MeV, 83MeV)

$\pi^+ + p \rightarrow \gamma + n$ (129MeV)

$LH_2$ target

Mott $e^+$ scattering

Lif$(p,\gamma)$Be

LiF target at COBRA center

17.6MeV $\gamma$

Daily calib.

Also for initial setup

Alpha on wires

PMT QE & Att. L

Cold GxXe

LXe

$\mu$ radiative decay

$\gamma \rightarrow \mu^+ + \nu$

Lower beam intensity $< 10^7$

Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

Cosmic ray alignment

Nickel $\gamma$ Generator

9 MeV Nickel line

Illuminate Xe from the back

Source (Cf)

Transferred by comp. air on/off

ICHEP 2016

L. Galli, INFN Pisa
Relevant example

\[ \gamma \] energy scale before and after calibration

uncertainty less than 0.5%
Target Alignment

- Position and target shape are surveyed by:
  - hole reconstructions from data
  - optical survey between runs

- worked well for the first part of the experiment
- problems arising in 2012-2013 data
**Target Alignment (2)**

- **Significant** target planarity deformation for 2012-2013 runs
  - *led to ~0.5 mm uncertainty on the target position* perpendicular to its plane
    - a factor 2 larger than other years
  - *treated with nuisance parameters in likelihood analysis*
- ~13% on average degradation in sensitivity
  - largest systematic effect
- A **few different** target materials being studied for MEG II

![Paraboloid shape from cross markers fit](image)

![Deformation measured by 3D scanner](image)
AIF Gamma-rays

- γ-rays from e+ annihilation inside DC were identified and rejected
  - overall BG rejection 1.9%
  - signal inefficiency 1.1%
- protection from high γ-rays outliers events
- Double check of DC-Target-LXe alignment
Missing 1st turn

- Possibility to **miss the first turn** in a **multiple hit event**
- Algorithm revised to recover **missing first turn**
  - *signal efficiency improved by ~4%*

![Graphs showing efficiency of missing first turn recovery](image)
One event in the box
Probability density functions

<table>
<thead>
<tr>
<th>Photon</th>
<th>Positron</th>
<th>Relative timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow \gamma\gamma$</td>
<td>$\mu \rightarrow e\nu\bar{\nu}$</td>
<td>$\mu \rightarrow e\nu\bar{\nu}\gamma$</td>
</tr>
<tr>
<td>$\gamma \gamma$</td>
<td>$\mu \rightarrow e\gamma$</td>
<td>RMD peak</td>
</tr>
</tbody>
</table>

Resolutions from Michel edge and double turns method

Background Left&Right sideband
Likelihood function

- **Likelihood** function in terms of **Signal**, **Radiative muon decay**, and accidental **Background number of events** and **PDFs**

\[
L(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{e^{-N}}{N_{\text{obs}}} \left( e^{-[(N_{\text{RMD}} - \langle N_{\text{RMD}} \rangle)^2 / 2\sigma_{\text{RMD}}^2]} \right) \times e^{-[(N_{\text{BG}} - \langle N_{\text{BG}} \rangle)^2 / 2\sigma_{\text{BG}}^2]} \prod_{i=1}^{N_{\text{obs}}} [N_{\text{sig}} S(\bar{x}_i) + N_{\text{RMD}} R(\bar{x}_i) + N_{\text{BG}} B(\bar{x}_i)],
\]

- **N$_{\text{S}}$, N$_{\text{R}}$, N$_{\text{B}}$** measured **simultaneously** with an **un-binned** Likelihood fit in the analysis box

- **B(μ→eγ) C.L.** with **profiled-likelihood ratio ordering**

- Cross-check:
  - **two independent analysis** with **different PDFs**
    - **Analysis A**: separated angles (θ$_{\text{eγ}}$, φ$_{\text{eγ}}$) and **event by event PDFs**
    - **Analysis B**: stereo angle θ$_{\text{eγ}}$, **constant PDF** (Pisa)
4D Event distribution

signal contours of 1, 1.64, 2σ are shown
## Final MEG result

<table>
<thead>
<tr>
<th>Dataset</th>
<th>2009-2011</th>
<th>2012-2013</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Fit</td>
<td>-1.3</td>
<td>-5.5</td>
<td>-2.2</td>
</tr>
<tr>
<td>90% CL Upper Limit</td>
<td>6.1 $10^{-13}$</td>
<td>7.9 $10^{-13}$</td>
<td>4.2 $10^{-13}$</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>8.0 $10^{-13}$</td>
<td>8.2 $10^{-13}$</td>
<td>5.3 $10^{-13}$</td>
</tr>
</tbody>
</table>

\[ BR(\mu \rightarrow e\gamma) < 4.2 \ 10^{-13} \ @ 90\% \ CL \]
MEG II at a glance

6. > LXe acceptance

7. > granularity on front face

1. > $\mu^+$

2. thinner target

5. > TC granularity

4. e+ tracking up to TC

3. > DC hits

3. < Multiple scattering
MEG II at a glance

1. $\mu^+$
2. Thinner target
3. $>\text{DC hits}$
4. $e^+$ tracking up to TC
5. $>\text{TC granularity}$
6. $>\text{LXe acceptance}$
7. $>\text{granularity on front face}$

PMTs $\rightarrow$ SiPM / MPPC

3. $<\text{Multiple scattering}$
**MEG II sensitivity**

<table>
<thead>
<tr>
<th>PDF parameters</th>
<th>Present MEG</th>
<th>Upgrade scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{E_{e^+}}$ (keV)</td>
<td>380</td>
<td>110</td>
</tr>
<tr>
<td>$e^+ \sigma_\theta$ (mrad)</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>$e^+ \sigma_\phi$ (mrad)</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>$e^+ \sigma_z / \sigma_\gamma$ (core) (mm)</td>
<td>2.0/1.0</td>
<td>1.2/0.7</td>
</tr>
<tr>
<td>$\frac{\sigma_{E_{e^+}}}{\sigma_\gamma}$ (% w&gt;2 cm)</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>$\gamma$ position at LXe $\sigma_{(u,v)}-\sigma_w$ (mm)</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$\gamma$-$e^+$ timing (ps)</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>≈ 99</td>
<td>≈ 99</td>
</tr>
<tr>
<td>trigger</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\gamma$ reconstruction</td>
<td>40</td>
<td>95</td>
</tr>
<tr>
<td>$e^+$ reconstruction</td>
<td>80</td>
<td>85</td>
</tr>
<tr>
<td>event selection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graphs:**
- Present upgrade
- Present upgrade

**MEG 2009-2010**
- MEG final (estimated)
- MEG final

**Upgraded MEG in 3 years**

**Weeks**
- 0
- 50
- 100
- 150

ICHEP 2016 32 L. Galli, INFN Pisa