New limit on LFV searches from the MEG experiment
Nonetheless, we know it is not the ultimate theory. Some of the reasons:

- Neutrino oscillations
- Dark Matter/Energy
- No quantitative way to account for matter/antimatter asymmetry in universe
- Hierarchy, unification, flavour problems

Everybody is eager for New Physics!!
Going beyond the SM

Through the gauge sector
(Higgs, EWSB)

Through the flavour sector
(LFV, CPV, FCNC, ν mixing, EDM)

The High Energy Frontier

New particles produced increasing c.m. energy

The High Intensity Frontier

Virtual processes indirectly test the NP energy scale (sometimes further than LHC reach)

Full complementarity between the two approaches
Lepton Flavour Conservation is an accidental symmetry of SM:
- Not related to the gauge structure of the theory
- Naturally violated in SM extensions

LFV already observed in the neutral sector: neutrino oscillations

LFV in charged sector could be mediated by
- Neutrino oscillation in SM extensions with massive neutrinos
- Off-diagonal terms in the slepton mass matrix (through RG evolution) in SUSY

\[ \Gamma(\mu \rightarrow e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left( \frac{\alpha}{2\pi} \right) \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2}{M_W^2} \right) \]

\[ BR(\mu \rightarrow e\gamma) \sim 10^{-54} \]

\[ BR(\mu \rightarrow e\gamma) \sim 10^{-13} - 10^{-14} \]
Charged LFV processes

A new lepton-lepton coupling

\[ y_{ij} \ell_i F_{\mu\nu} \ell_j \sigma_{\mu\nu} \]

\[ \begin{array}{c}
\mu \rightarrow e\gamma \\
\tau \rightarrow \mu\gamma \\
\tau \rightarrow e\gamma \\
(g - 2)_\mu \\
\mu^- N \rightarrow e^- N \\
\mu \rightarrow eee
\end{array} \]

cLFV processes are a wide field of research

- LFV decays
- Muon to electron conversion in matter
- Anomalous magnetic moment
The cLFV wheel

$$\alpha \left( \frac{Z \alpha}{\pi} \right)$$

$$\mu \rightarrow e \gamma$$

$$\frac{m_{\tau}}{m_{\mu}} \left( \frac{2}{4} \right)$$

$$\equiv \mathcal{O}(1)$$

LFV couplings

$$\mu \rightarrow e e e$$

$$\mu \rightarrow N \rightarrow e \gamma$$

$$\tau \rightarrow \mu \gamma$$

$$\tau \rightarrow e \gamma$$

$$(g - 2)_{\mu}$$

$$\times \tan^2 \beta$$

$$\frac{B_{\mu e \gamma}}{10^{-12}} \propto \left( \frac{\Delta a_{\mu}}{10^{-9}} \right)^2$$

Common Models
Present Limits

- **SINDRUMII**
  - $B(\mu Ti \rightarrow e Ti) < 4.3 \times 10^{-12}$
  - $B(\mu Au \rightarrow e Au) < 7 \times 10^{-13}$

- **MEG@LAMPF**
  - $1.2 \times 10^{-11} \quad \mu \rightarrow e \gamma$

- **B-factories**
  - $3.3 \div 4.5 \times 10^{-8}$

- **BNL E821**
  - $a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (296 \pm 81) \times 10^{-11}$

- **SINDRUM**
  - $1 \times 10^{-12} \quad \mu \rightarrow e e e$

- **1988**

- **1999**
  - $\tau \rightarrow e \gamma$
  - $\tau \rightarrow \mu \gamma$

- **2004**
  - a hint for NP?

- **2006**
  - $\mu \rightarrow e N \rightarrow e N$

- **2010**
Future Prospects

- **mu2e COMET**: $10^{-16} \rightarrow 10^{-18}$
  - **2017**

- **Heidelberg**: $\sim 10^{-15/16}$
  - **2015**

- **MEG**: few $\times 10^{-13}$
  - **running**
  - **2013**

- **SuperB**: $1/2 \times 10^{-9}$
  - **2015**

- **g-2 JPARC**: $2017^?$
  - **2017?**
  - $0.1$ ppm

- **g-2 FNAL**: $2017^?$
  - **2017?**
  - $3.6\sigma \rightarrow 8\sigma$
$\mu \rightarrow e \gamma$: experimental signature

**Signal**
- 52.8 MeV
- Back-to-back
- Time coincidence

**Physics BG**
- (radiative muon decay)
- $<$ 52.8 MeV
- Any angle
- Time coincidence

**Accidental BG**
- $<$ 52.8 MeV
- Any angle
- Random
In order to reach $O(10^{-13})$ sensitivity, unprecedented detector resolution at these energies and accurate monitoring and calibration of detectors needed.
MEG in a nutshell

- Most intense DC muon beam of $3 \times 10^7$ muon/s at PSI
- Quasi-solenoidal spectrometer & low mass drift chamber for $e^+$ kinematic measurement
- Scintillator bars and fibers for $e^+$ timing
- Liquid Xenon calorimeter for photon detection
- $~10^7$ fully efficient trigger bkg suppression

~ 60 collaborators

INFN Genova
INFN Lecce
INFN Pavia
INFN Pisa
INFN Roma
KEK
Tokyo Univ.
Waseda Univ.
UC Irvine
PSI
BINP - Novosibirsk
JINR - Dubna
The PSI $\pi E5$ beam & target

Most intense proton DC beam in the world: 2 mA @ 1.3 MW
28 MeV/c “surface muons” from decay of $\pi$ at rest
Wien filter for e/$\mu$ separation
Solenoid to couple beam with the COBRA magnetic field

Need enough material for stopping muons but low bremsstrahlung for signal positron:
- degrader 200/300 $\mu$m + target 205 $\mu$m
- 20.5° angle between beam and target
- material with high radiation length $X_0$ (CH$_2$)
Liquid Xenon γ detector

First ton-scale (~ 900 L) LXe calorimeter in use in the world

Pros

- High light yield (~ 75% NaI)
- Fast response ($\tau_{\text{decay}} = 45$ ns)
- High stopping power ($X_0 = 2.8$ cm)
- No self absorption
- Uniform, no segmentation, no aging

Challenges

- Vacuum ultra violet (178 nm)
- Low temperature (165 K)
- Need high purity

Measure photon energy and time and position of conversion inside the LXe

$\sigma_E/E < 2 \% @ 52.8$ MeV
$\sigma_t = 67$ ps
$\sigma_x = 5$-6 mm

Proposal

$1.2 \%$
$43$ ps
$3.8$-5.1 mm
Experimental requirements:

- Very good momentum and angular resolution (~ 200 KeV @ 52.8 MeV and ~ 5 mrad)
- Low pile-up for efficient background rejection

Low mass drift chambers in graded magnetic field (COBRA)
Drift Chambers

- 16 chamber sectors, 2 planes each
- Staggered array of drift cells
- Helium:Ethane 50/50 mixture
- Ultra low mass chamber to suppress MS that limits momentum and angular resolutions
  - 12.5 µm cathode foils with Vernier pattern for Z hit position
  - ~ 0.2 % $X_0$ along $e^+$ trajectory
- Reconstruct $e^+$ momentum vector at target with Kalman filter technique
  - $\sigma_E/E \sim 0.6 \%$
  - $\sigma_\theta \sim 10 \text{ mrad}$
  - $\sigma_\phi \sim 7 \text{ mrad}$

Proposal
  - $\sigma_E/E = 0.3 \%$
  - $\sigma_\theta = 5 \text{ mrad}$
  - $\sigma_\phi = 5 \text{ mrad}$
Time Measurement

- Positron time measured by timing counter: 2 sections (upstream & downstream) of 15 bars each read by fine mesh PMTs.
- Further z impact position measurement with scintillating fibers read by APDs.
- Crucial for positron time measurement: intrinsic time resolution: current ~ 70 ps/goal ~ 50 ps.

Muon decay time:
- TC hit time + e⁺ flight length from DC
- LXe hit time + γ flight length
- \( t_{e\gamma} = t_{e+} - t_\gamma \)
- \( \sigma_{t_{e\gamma}} = 122 \text{ ps from RMD} \)
**Trigger & DAQ**

**DAQ**
- Custom WF digitizer DRS chip design at PSI
- Sampling speed [800 MHz, 5 GHz]
- Bandwidth 1 GHz
- Inter-chip synchronization < 30 ps

**Trigger experimental requirements**
- \( O(10^7) \) background suppression
- > 95% efficiency on signal
- Maximum latency ~ 450 ns
- Flexibility for physics analysis as well as calibrations

**MEG choices**
- 100 MHz digital conversion of input signals
- Selection algorithms on FPGAs
- Use of fast detector, LXe and TC:
  - \( E_\gamma > 45 \text{ MeV} \) --> rate \( 2 \times 10^3 \) Hz
  - \( \Delta t \) between LXe and TC --> rate 100 Hz
  - Collinearity based on LUT tables --> 10 Hz

**Trigger improvements through time**
- thanks to improved online resolutions (DM improvement) and multiple buffer readout implementation (MB)
Detector Pictures

LXe detector

DC system

Beam Line

TC with fibers exposed
Calibrations

**Calibrations**

- **LED**
  - PMT gain

- **α source**
  - PMT QE
  - Absorption length

- **Ni γ generator**
  - 9 MeV γ-line
  - beam on/off calib.

- **CEX**
  - γ-resolutions:
    - energy
    - time
    - impact point
  - LH₂ target

- **XENON CALIBRATION**

- **CW p-accel**
  - Light Yield
  - LXe-TC t-calib

**TRACKER CALIBRATION**

- **Cosmic Ray**
  - DC alignment
  - TC uniformity
  - LXe monitoring

- **e⁺ Mott-scatter**
  - Monochromatic, tunable momentum beam

- **Michel decays**
  - μ → e νν for momentum energy scale

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E. Baracchini - New limit on LFV searches from the MEG experiment - 27th January 2012 - QMUL
CW and CEX calibrations

\[ p + ^{11}\text{B} \rightarrow ^{12}\text{C}^{*}\gamma + \gamma \]
\[ p + ^{7}\text{Li} \rightarrow ^{4}\text{Be} + \gamma \]

Target of \( \text{Li}_2\text{B}_4\text{O}_7 \) allows both calibrations at same time

Cockcroft-Walton accelerator

Photons from \( \pi^- \) Charge EXchange reaction

\[ 17.6, 14.6 \text{ MeV} \]
Alignment

Good alignment is crucial to reduce systematics on relative photon-positron angle

- No back to back source for calibration
- Nonetheless, we improved alignment inside and among detectors
  - DC - B field - target - LXe

Tools:
- Optical surveys
- DC: Millipede (a la CMS) with cosmic rays + Michel e+
- Target holes
- LXe: Pb collimators
- B field: resolutions and correlations

Cosmic Rays

Target holes
Reconstruct Y/Z in Z/Y slices as a function of φ/θ

Pb collimators in CEX run
Blind analysis technique adopted:

- Events inside a signal region of $E_\gamma$ and $t_{e\gamma}$ not used for analysis development

Background characterization from sidebands:

- accidental bkg from off-time sidebands,
- RMD from low energy $E_\gamma$ sideband

Extended unbinned ML fit of $N_{\text{sig}}, N_{\text{RMD}}$ and $N_{\text{bkg}}$

Observables $E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$

Number of muons stopped on target: $1.7 \times 10^{14}$ \((6.5 \times 10^{13} (2009) + 1.1 \times 10^{14} (2010))\)

Count unbiased Michel sample in physics data simultaneously with the signal

Count RMD sample in $E_\gamma$ sideband (independent sample) for consistency check

Independent of instantaneous beam rate and insensitive to acceptance and efficiency

$$\text{BR}(\mu^+ \rightarrow e^+\gamma) = \frac{N_{\text{sig}}}{N_{\text{ev}}} \times \frac{f_{e\nu}}{P} \times \frac{\epsilon_{e\gamma}^{\text{trig}}}{\epsilon_{e\gamma}} \times \frac{A_{e\gamma}^{\text{TC}}}{A_{e\gamma}^{\text{TC}}} \times \frac{\epsilon_{e\gamma}^{\text{DCH}}}{\epsilon_{e\gamma}} \times \frac{1}{A_{e\gamma}^{\text{g}}} \times \frac{1}{\epsilon_{e\gamma}},$$
PDFs

- Signal $E_e$ PDF from fit to Michel edge data
- Signal angle PDFs measured on data from tracks which make two turns inside the spectrometer
- Background angle PDFs measured on time sideband
- RMD PDFs from theoretical distributions convoluted with measured resolutions

Fit variables: $E_\nu, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$
Signal Positron PDFs & Correlations

Signal positron PDFs are evaluated from tracks which make 2 turns inside the spectrometer, treating each turn as an independent pseudo track.

Since all positrons must come from the target (~200 µm thick, fairly considered bidimensional in our analysis), this constraint removes one degree of freedom from the problem, introducing correlations among all positrons track parameters and resolutions.

This geometrical effect worsen resolutions, which can nevertheless be partially recovered taking correlations into account in the likelihood analysis.

Evaluating resolution at the 2-turn track turning point on a fictitious plane with same inclination as the target allows to extract correlations from data.
# Performances

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>γ energy</strong></td>
<td>1.9% (w&gt; 2 cm), 2.4% (w&lt; 2 cm)</td>
<td>1.9% (w&gt; 2 cm), 2.4% (w&lt; 2 cm)</td>
</tr>
<tr>
<td><strong>γ timing</strong></td>
<td>96 ps</td>
<td>67 ps</td>
</tr>
<tr>
<td><strong>γ position</strong></td>
<td>5 mm (u,v), 6 mm (w)</td>
<td>5 mm (u,v), 6 mm (w)</td>
</tr>
<tr>
<td><strong>γ efficiency</strong></td>
<td>58%</td>
<td>59%</td>
</tr>
<tr>
<td><strong>e⁺ timing</strong></td>
<td>107 ps</td>
<td>107 ps</td>
</tr>
<tr>
<td><strong>e⁺ energy</strong></td>
<td>0.31 MeV (80% core)</td>
<td>0.32 MeV (79% core)</td>
</tr>
<tr>
<td><strong>e⁺ angle (θ)</strong></td>
<td>9.4 mrad</td>
<td>11.0 mrad</td>
</tr>
<tr>
<td><strong>e⁺ angle (φ)</strong></td>
<td>6.7 mrad</td>
<td>7.2 mrad</td>
</tr>
<tr>
<td><strong>e⁺ vertex (Z/Y)</strong></td>
<td>1.5 mm/1.1 mm (core)</td>
<td>2.0 mm/1.1 mm (core)</td>
</tr>
<tr>
<td><strong>e⁺ efficiency</strong></td>
<td>40%</td>
<td>34%</td>
</tr>
<tr>
<td><strong>e⁺ - γ timing</strong></td>
<td>146 ps</td>
<td>122 ps</td>
</tr>
<tr>
<td><strong>Trigger efficiency</strong></td>
<td>91%</td>
<td>92%</td>
</tr>
<tr>
<td><strong>e⁺ - γ angle (θ)</strong></td>
<td>14.5 mrad</td>
<td>17.1 mrad</td>
</tr>
<tr>
<td><strong>e⁺ - γ angle (φ)</strong></td>
<td>13.1 mrad</td>
<td>14.0 mrad</td>
</tr>
<tr>
<td><strong>Stopping µ rate</strong></td>
<td>$2.9 \times 10^7$ s⁻¹</td>
<td>$2.9 \times 10^7$ s⁻¹</td>
</tr>
<tr>
<td><strong>DAQ time/ Real time</strong></td>
<td>35 days/43 days</td>
<td>56 days/67 days</td>
</tr>
<tr>
<td><strong>Total stopped µ</strong></td>
<td>$6.5 \times 10^{13}$</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
</tbody>
</table>

Slightly worse e⁺ tracking in 2010 due to noise problem.

Photon timing improvement thanks to WF digitizer upgrade in 2010.
This result

- 2009 + 2010 dataset combined analysis (2010 data ~ 2 x 2009 data)

Improved understanding of the experiment w.r.t. ICHEP 2010:
- Improved alignment inside and among detectors through newly developed techniques
- Improved magnetic field map
- Implementation of correlations at the target in likelihood analysis, strongly reducing the systematics and the effective resolutions

Improvements in the likelihood analysis technique w.r.t. ICHEP 2010
- $N_{\text{bkg}}$ constrained from sideband data
- Profile-likelihood interval with Feldman-Cousins method

Sensitivity of combined data $1.6 \times 10^{-12}$ @ 90% CL

$3.3 \times 10^{-12}$ in 2009 + $2.2 \times 10^{-12}$ in 2010
2009 and 2010 results

2009 data re-analyzed with improvements: best $N_{\text{sig}}$ fit 3.4 (ICHEP '10 best $N_{\text{sig}}$ fit 3.0) ---> STABLE RESULT

$1.7 \times 10^{-13} < \text{BR} < 9.6 \times 10^{-12}$ @ 90% CL

p-Value for null signal 8%

2010 data best $N_{\text{sig}}$ fit -2.2

$\text{BR} < 1.7 \times 10^{-12}$ @ 90% CL

Sensitivity $2.2 \times 10^{-12}$
**Combined Result**

<table>
<thead>
<tr>
<th></th>
<th>expected</th>
<th>best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sig}}$</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>$N_{\text{RMD}}$</td>
<td>79.4 ± 7.9</td>
<td>76 ± 12</td>
</tr>
<tr>
<td>$N_{\text{bkg}}$</td>
<td>881.7 ± 15.1</td>
<td>882 ± 22</td>
</tr>
</tbody>
</table>

**UL @ 90% CL**

$BR < 2.4 \times 10^{-12}$

<table>
<thead>
<tr>
<th>Data set</th>
<th>$B_{\text{fit}}$</th>
<th>LL</th>
<th>UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>$3.2 \times 10^{-12}$</td>
<td>$1.7 \times 10^{-13}$</td>
<td>$9.6 \times 10^{-12}$</td>
</tr>
<tr>
<td>2010</td>
<td>$-9.9 \times 10^{-13}$</td>
<td>$-$</td>
<td>$1.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>2009 + 2010</td>
<td>$-1.5 \times 10^{-13}$</td>
<td>$-$</td>
<td>$2.4 \times 10^{-12}$</td>
</tr>
</tbody>
</table>
Implications


MSSM @ large tanβ with LFV through SUSY seesaw

additional constraints from B physics

Δa_μ ± 1 (2) σ constraint


CMSSM with ν_R and SUSY seesaw

MEG limit

latest results from T2K/Double Chooz suggests θ_{13} ~ 8°

SUSY GUT

PMNS-like

CKM-like

MEGA limit

MEG proposal
2011 Run

- 2011 dataset > 2009 + 2010 datasets
- Improved DAQ & trigger efficiency up to >99% live time with >95% efficiency
- Improved noise conditions in DC thanks to new HV power supplies
- TC fibers APDs operational

All positron and photon resolutions consistent with 2010 already with preliminary alignment and calibrations
MEG data taking will continue through 2012

Sensitivity projection in the $5 \times 10^{-13}$ range
Several proposals for LXe and tracker short and long term upgrades

**LXe:**
- **Short term:** low reflectivity internal surface
- **Long term:** replacement of internal window PMTs and use of charge information (Italian MIUR independent R&D)

**Tracker:**
- **Short term:** change DC gas, target inclination and TC cables
- **Long term:** replace tracker, either full volume DC (capable of isolating primary ionization clusters) or set of scintillating films, active target, vertex detector
- R&D now starting
Conclusions & Prospects

- 2009 + 2010 MEG data analysis consistent with null signal
- Most stringent UL on LFV improved by a factor 5
- \[ \text{BR}(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12} \] @ 90% CL
- MEG 2011 dataset > 2010 + 2009 statistic with improved trigger, DAQ and DC noise conditions
- Expected sensitivity at the end of 2012: a few \(10^{13}\)
  
  Stay tuned!!
- Several proposal for a short (2012-2013) and long term (2015-2016?) upgrades to further improve sensitivity
Thank you!!

The MEG Collaboration
Backup slides
Target Holes

Method 1:
Reconstruct Y-coordinate in Z-slice as a function of \( \varphi \):

\[ \Delta Y \sim \tan(\varphi) \cdot \Delta P \]

Method 2:
Reconstruct Z-coordinate in Y-slice as a function of \( \theta \):

\[ \Delta Z \sim \tan(\theta - 90 + \alpha) \cdot \cos(\alpha) \cdot \Delta P \]
Correlations and Resolutions

\[ \delta \phi_e = -2 \tan \phi_e \frac{\delta R}{R} = -2 \tan \phi_e \frac{\delta E}{E} \]

\[ \delta Y = 2 \delta R \cos \phi_e + R \sin \phi_e \delta \phi_e = \frac{2R}{\cos \phi_e} \frac{\delta E}{E} \]

\[ \delta Z = \frac{2R}{\sin^2 \theta_e} \frac{\delta \theta}{\delta \phi_e} - 2R \cot \theta_e \frac{\delta E}{E} \]
Some more numbers :)
Systematics

Systematics effect taken into account in the calculation of confidence interval by profiling on \((N_{RD}, N_{BKG})\) and by fluctuating PDFs according to the uncertainty values.

All the results shown have systematic effects taken into account.

Size of systematic uncertainty in total 2\% on the UL: \(2.3 \times 10^{-12} \rightarrow 2.4 \times 10^{-12}\).

Contribution of each item in the list was studied with toy MC experiments by comparing the results with the nominal PDFs and the one with the fluctuated ones.

Relative contributions on UL

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of (\theta_{e\gamma}) and (\phi_{e\gamma})</td>
<td>0.18</td>
</tr>
<tr>
<td>Positron correlations</td>
<td>0.16</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.13</td>
</tr>
<tr>
<td>(E_{\gamma}) scale</td>
<td>0.07</td>
</tr>
<tr>
<td>(E_{e}) bias, core and tail</td>
<td>0.06</td>
</tr>
<tr>
<td>(t_{e\gamma}) center</td>
<td>0.06</td>
</tr>
<tr>
<td>(E_{\gamma}) BG shape</td>
<td>0.04</td>
</tr>
<tr>
<td>(E_{\gamma}) signal shape</td>
<td>0.03</td>
</tr>
<tr>
<td>Positron angle resolutions ((\theta_{e}, \phi_{e}, z_{e}, y_{e}))</td>
<td>0.02</td>
</tr>
<tr>
<td>(\gamma) angle resolution ((u_{\gamma}, v_{\gamma}, w_{\gamma}))</td>
<td>0.02</td>
</tr>
<tr>
<td>(E_{e}) BG shape</td>
<td>0.02</td>
</tr>
<tr>
<td>(E_{e}) signal shape</td>
<td>0.01</td>
</tr>
</tbody>
</table>