Recent + future MEG results (and LFV implications) in the “SuperB” era

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XVII SuperB Workshop and Kick-off Meeting

La Biodola (Isola d’Elba) 1 June 2011
Lepton flavor violation

- LFV decays in the SM is radiatively induced by neutrino masses and mixings at a negligible level

\[ \Gamma(\mu \rightarrow e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left( \frac{\alpha}{2\pi} \right) \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m_{23}^2}{M_W^2} \right) \]

\[ \mu \text{ - decay} \quad \gamma \text{ - vertex} \quad \nu \text{ - oscillation} \]

- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)

- Clear evidence for physics beyond the SM - background-free

- Restrict parameter space of SM extensions
Many processes

- LFV is related to a "new" lepton-lepton coupling
  \[ y_{ij} \bar{\ell}_i F^{\mu \nu} \ell_j \sigma_{\mu \nu} \]

- A wide field of research
  - LFV decays
  - Anomalous magnetic moment for the \( \mu, \tau \)
  - Muon-to-electron conversion
  - (LFV in B-meson decays)
Many processes

- LFV is related to a “new” lepton-lepton coupling

$$y_{ij} \bar{\ell}_i F^{\mu\nu} \ell_j \sigma_{\mu\nu}$$

- A wide field of research
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  - Muon-to-electron conversion
  - (LFV in B-meson decays)

- Tau’s from B-factory
Processes are correlated

Model-dependent correlations

Barbieri et al., Nucl. Phys B445 (1995) 225
...
The LFV wheel

\[ \alpha \left( \frac{Z \alpha}{\pi} \right) \]

\[ \mu \rightarrow e \gamma \]

\[ \mu \rightarrow e\overline{e}\overline{e} \]

\[ \mu \rightarrow N \rightarrow e \overline{N} \]

\[ \tau \rightarrow e \gamma \]

\[ \tau \rightarrow \mu \gamma \]

\[ \tau \rightarrow e \gamma \]

\[ \tau \rightarrow e e e \]

\[ \propto (g - 2)_\mu \]

\[ \propto (m_\tau/m_\mu)^{2/4} \]

\[ \propto O(1) \]

\[ B_{\mu e \gamma} \approx 10^{-12} \]

\[ \times \tan^2 \beta \]

\[ \propto \left( \frac{\Delta a_\mu}{10^{-9}} \right)^2 \]
Present limits

SINDRUM II
\( B(\mu \text{Ti} \rightarrow e \text{Ti}) < 4.3 \times 10^{-12} \)
\( B(\mu \text{Au} \rightarrow e \text{Au}) < 7 \times 10^{-13} \)

1999
\( \mu \rightarrow e \gamma \)
\( (g - 2)_{\mu} \times \tan^2 \beta \)

2004
a hint for NP?

2006
\( \mu \rightarrow e \text{ee} \)
\( \mu \rightarrow e \text{e} \rightarrow e \gamma \)

2000

1988
\( 1 \times 10^{-12} \)

B-factories
\( 3.3 \div 4.5 \times 10^{-8} \)

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

mu2e COMET

$10^{-16} \rightarrow 10^{-18}$

2016

MEG

few $\times 10^{-13}$

running

$\rightarrow 2013$

Heidelberg

$\sim 10^{-15} \div 16$

2015

SuperB

$1 \div 2 \times 10^{-9}$

2015

Gm2 FNAL

$\Delta a_\mu = (XXX \pm 34) \times 10^{-11}$

$3.6\sigma \rightarrow 8\sigma$
The MEG collaboration

KEK
Tokyo U.
Waseda U.
KEK

INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce

PSI
UCIrvine
JINR Dubna
BINP Novosibirsk
The MEG collaboration

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Tokyo U. Waseda U. KEK

INFN & U Pisa INFN & U Roma INFN & U Genova INFN & U Pavia INFN & U Lecce

PSI UCIrvine JINR Dubna BINP Novosibirsk

D. N. Grigoriev F. Ignatov B. I. Khazin A. Korenchenko N. Kravchuk D. Mzavia† A. Popov Yu. V. Yudin
Time scale

- A $\mu \to e\gamma$ experiment at the Paul Scherrer Institut (PSI)
- The $\mu \to e\gamma$ decay
- The detector
  - Overview of sub-detectors
  - Calibration methods
- Analysis of 2009 run
- Status
  - Run 2010
- 2011 and Next year(s)
Signal and Background

"Signal"  

"RMD"  

"Accidental"

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

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

\[ e^+ e^- \rightarrow \gamma \gamma \]

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

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

\[ t_{e\gamma} \approx 0 \]

\[ B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}} \]

\[ B_{\text{acc}} \approx R_{\mu} \Delta E_{e} \Delta E_{\gamma}^2 \Delta \theta^2 \Delta t \]

The accidental background is dominant and it is determined by the experimental resolutions.
MEG experimental method

- $\mu$: stopped beam of $3 \times 10^7 \mu$ /sec in a 205 $\mu$m polyethylene target
  - PSI $\pi$E5 beam line

- $e^+$ detection
  - magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum
  - plastic counters for timing

- $\gamma$ detection
  - Liquid Xenon detector based on the scintillation light
    - fast: 4 / 22 / 45 ns
    - high LY: $\sim 0.8 \times$ NaI
    - short $X_0$: 2.77 cm

Easy signal selection with $\mu^+$ at rest
Some detector pictures

LXe detector

DC system

Beam Line
The photon detector

- $\gamma$ Energy, position, timing
- **Homogeneous 0.8 m$^3$ volume of liquid Xe**
  - 10% solid angle
  - $65 < r < 112$ cm
  - $|\cos\theta| < 0.35 \ |\phi| < 60^\circ$
- Only scintillation light
- Read by 848 PMT
  - 2” photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - **Low temperature** (165 K)
  - **Quartz window** (178 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
  - Pileup rejection
Xe properties

- **Liquid Xenon** was chosen because of its **unique** properties among radiation detection active media.
- $Z=54, \ \rho=2.95 \text{ g/cm}^3 (X_0=2.7 \text{ cm}), \ R_M=4.1 \text{ cm}$
- High **light yield** (similar to NaI)
  - 40,000 phe/MeV
- Fast response of the scintillation decay time
  - $\tau_{\text{singlet}} = 4.2 \text{ ns}$
  - $\tau_{\text{triplet}} = 22 \text{ ns}$
  - $\tau_{\text{recomb}} = 45 \text{ ns}$
- Particle **ID** is possible
  - $\alpha \sim \text{singlet+triplet, } \gamma \sim \text{recombination}$
- Large refractive index $n = 1.65$
- **No self-absorption** ($\lambda_{\text{Abs}}=\infty$)
Calibrations

**Proton Accelerator**

Li(p,γ)Be
LiF target at COBRA center
17.6MeV γ ~daily calib.
also for initial setup

**LED**
PMT QE & Att. L
Cold GXe
LXe

**Alpha on wires**

PMT QE & Att. L
Cold GXe
LXe

**Xenon Calibration**

π^0 → γγ
π + p → π^0 + n
π^0 → γγ (55MeV, 83MeV)
π^+ + p → γ + n (129MeV)
LH2 target

**Laser**

relative timing calib.

**Nickel γ Generator**

9 MeV Nickel _γ_-line

Illuminate Xe from the back
Source (Cf) transferred by comp air → on/off

**µ radiative decay**

Lower beam intensity < 10^7
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics
The precise knowledge of the calorimeter energy scale is crucial for the experiment.

- Constant check of Xe light yield and purity
  - Trigger threshold
  - Systematic error on energy scale
- Different calibrations have different time-scales

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<tr>
<th>Process</th>
<th>Energy</th>
<th>Frequency</th>
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<tr>
<td>Charge exchange</td>
<td>$\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow \gamma \gamma$</td>
<td>55, 83, 129 MeV</td>
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<tr>
<td>Proton accelerator</td>
<td>$^7\text{Li}(p, \gamma_{17.6})^8\text{Be}$</td>
<td>14.8, 17.6 MeV</td>
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<td>Nuclear reaction</td>
<td>$^{58}\text{Ni}(n, \gamma_9)^{59}\text{Ni}$</td>
<td>9 MeV</td>
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<td>Radioactive source</td>
<td>$^{60}\text{Co}, ^{\text{AmBe}}$</td>
<td>1.1 - 4.4 MeV</td>
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2009: efficient physics run

- 2008 run BR<2.8 x 10^{-11}

  January - October
  - detector dismantling
  - improvement (after run 2008)
    - DCH
    - Electronic
  - re-installation
  - LXe purification
  - CW calibration
  - another experiment in the area had “exciting results” (μp)

  October
  - π⁰ calibration

  November – December
  - MEG run

Running conditions
MEG run period
- Live time ~84% of total time
- Total time ~ 7 weeks
- μ stop rate: 3x10^7 μ/s
- Trigger rate 6.5 ev/s ;
- Total data taken: 93 TB

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Programmed beam shutdowns

Beam line tests and Maintenance
Analysis principle

- A $\mu \rightarrow e\gamma$ event is described by 5 kinematical variables
  
  $\vec{x}_i = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$

- Likelihood function is built in terms of Signal, radiative Michel decay RMD and background BG number of events and their probability density function PDFs

$$- \ln \mathcal{L} (N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = N_{\text{exp}} - N_{\text{obs}} \ln (N_{\text{exp}}) - \sum_{i=1}^{N_{\text{obs}}} \ln \left[ \frac{N_{\text{sig}}}{N_{\text{exp}}} S(\vec{x}_i) + \frac{N_{\text{RMD}}}{N_{\text{exp}}} R(\vec{x}_i) + \frac{N_{\text{BG}}}{N_{\text{exp}}} B(\vec{x}_i) \right]$$

- Extended unbinned likelihood fit
  - fit $(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}})$ in a wide region

- PDFs taken from
  - data
    - $48 \leq E_\gamma \leq 58$ MeV
    - $50 \leq E_e \leq 56$ MeV
    - $|T_{e\gamma}| \leq 0.7$ ns
    - $|\phi_{e\gamma}|, |\theta_{e\gamma}| \leq 50$ mrad
  - MC tuned on data
• We adopt a blind-box likelihood analysis strategy
• The blinding variables are $E_\gamma$ and $t_{e\gamma}$
  - Hidden until analysis is fixed
• Three independent analyses
  - different pdf implementation
  - Fit or input $N_{\text{RMD}}, N_{\text{BG}}$
  - Different statistical treatment (Freq. or Bayes)
• Use of the sidebands
  - our main background comes from accidental coincidences
  - RMD can be studied in the low $E_\gamma$ sideband
Pdfs and resolutions

- Resolution functions of core and tail components
  - core = 390 keV (0.74%)
- Positron angle resolution measured using multi-loop tracks
  - $\sigma(\varphi) = 7.1$ mrad (core)
  - $\sigma(\vartheta) = 11.2$ mrad
- Average upper tail for deep conversions
  - $\sigma_R = (2.1 \pm 0.15)\%$
- Systematic uncertainty on energy scale < 0.6%

- Overall angular resolution combining
  - XEC+DCH+target
    - $\sigma(\varphi)$ = 12.7 mrad (core)
    - $\sigma(\vartheta)$ = 14.7 mrad

- 40 MeV $< E_\gamma < 48$ MeV
- $\sigma_t$ is corrected for a small energy-dependence
  - (142 $\pm$ 15) ps
  - stable within 15 ps along the run
- MEGA had on RMD
  - 700 ps resolution

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**$E_\gamma$**

- Number of events (0.5 MeV)

**$E_{e^+}$**

- Number of events (0.10 MeV)

**$t_{e\gamma}$**

- Number of events (0.080 nsec)
Normalization

- The normalization factor is obtained from the number of observed Michel positrons taken simultaneously (pre-scaled) with the $\mu \rightarrow e \gamma$ trigger.
- Cancel at first order:
  - Absolute $e^+$ efficiency and DCH instability
  - Instantaneous beam rate variations

$$\frac{B(\mu^+ \rightarrow e^+\gamma)}{B(\mu^+ \rightarrow e^+\nu\bar{\nu})} = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f_{e\nu\bar{\nu}}}{P \cdot \epsilon_{pu}} \times \frac{\epsilon_{e\nu\bar{\nu}}^{\text{trig}}}{\epsilon_{e\gamma}^{\text{DC}}} \times \frac{\epsilon_{e\nu\bar{\nu}}^{\text{DC}}}{\epsilon_{e\gamma}^{\text{DC}}} \times \frac{1}{A_{e\gamma}^{\text{geo}}} \times \frac{1}{\epsilon_{e\gamma}}$$

$\sim 18k$ $10^7$

- B.R. = $N_{\text{sig}} \times (1.01 \pm 0.08) \times 10^{-12}$
Likelihood fit result

- $N_{\text{sig}} < 14.5$ @ 90% C.L., $N_{\text{sig}}$ best-fit value = 3.0
- $N_{\text{sig}} = 0$ is in 90% confidence region
  - C.L @0: 40±60% depending on the statistical approach

Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent ($N_{\text{sig}}$ best fit = 3.0-4.5, UL = $1.2-1.5 \times 10^{-11}$)
Upper limit

• From the analysis of the **2009 data** our limit on the BR is the following:

\[
\frac{\mathcal{B}(\mu^+ \rightarrow e^+\gamma)}{\mathcal{B}(\mu^+ \rightarrow e^+\nu\bar{\nu})} < 1.5 \times 10^{-11}
\]

**Preliminary**

- cfr. MEGA limit \( BR < 1.2 \times 10^{-11} @ 90\% \text{ C.L.} \)

• Sensitivity:
  - \( 6.1 \times 10^{-12} \) average 90\% upper limit on null-signal toy experiments
  - \( BR < (4 \div 6) \times 10^{-12} \) from the SideBands

• On going activity
  - better understanding of the **spectrometer**
  - reduction of systematics on back-to-back **alignment**
  - better usage of **sideband** information in the likelihood

• We plan to present a **combined 2009/2010** analysis this summer
Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions. 
For each plot, cut on other variables for roughly 90% window is applied.
Event display

- Events in the **signal region** were **checked** carefully
- An event in the signal region
What’s next?

• Data taking was restarted from Aug. 5 to Nov. 6 2010
  – \( \pi^0 \) calibration from 23/8 to 9/9
  – accident to the beam transport solenoid on Nov. 6
  – \(~ 2 \times 2009\) statistics

• An accident on Nov. 6 put a premature end to the 2010 run

• Analysis ongoing
  – 2009 & 2010 data together

• Run 2011 soon starting
  – physics data taking from June to December
Sensitivity prospect

- Data from the two months of stable data taking of the MEG experiment in 2009 give a result competitive with the previous limit.
- Plans to reach its design sensitivity (few x $10^{-13}$) within 2013.
Back to the wheel...

\[ \mu \rightarrow e\gamma \]

MEG
few \( \times 10^{-13} \)
running \( \rightarrow 2013 \)

SuperB
\( 2 \times 10^{-9} \)
\( \rightarrow 2015 \)

mu2e COMET
\( 10^{-16} \rightarrow 10^{-18} \)
\( \rightarrow 2014 \)

Heidelberg
\( \sim 10^{-15} \div 16 \)
\( \rightarrow 2015 \)

\[ \mu \rightarrow eee \times \tan^2 \beta \]

Gm2 FNAL
\( \Delta a_\mu = (XXX \pm 34) \times 10^{-11} \)
3.6\( \sigma \rightarrow 8\sigma \)
\( \rightarrow 2015 \)
Thank you
Back-up slides