The $\mu^+ \rightarrow e^+ \gamma$ decay as a sensitive probe for physics beyond the SM: first results from the MEG experiment

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on behalf of the MEG collaboration

Université Catholique de Louvain, 3 Décembre 2009
Outline

- Physics motivation for a $\mu \rightarrow e\gamma$ experiment
- The $\mu \rightarrow e\gamma$ decay
- The detector
  - Overview of sub-detectors
  - Calibration methods
- Analysis of 2008 run
- Status
  - Run 2009
  - Next year(s)
The $\mu \rightarrow e\gamma$ decay

- The $\mu \rightarrow e\gamma$ decay in the SM is radiatively induced by neutrino masses and mixings at a negligible level

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

- 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
- Restrict parameter space of SM extensions

Relative probability $\sim 10^{-54}$
Connections

- **LHC**
  - it is Super Symmetry + Grand Unification that predicts new particles in the loop.
  - alternate search for \((E/M_{\text{SUSY}})\) suppressed effects

- **neutrino oscillations**
  - mixing matrix in charged sector can be proportional to
    - PMNS
    - CKM

- **muon g–2**
  - \(a_\mu\) is the “diagonal” term
  - \(\mu\rightarrow e\gamma\) diagram is the “off-diagonal”

Barbieri et al., Nucl. Phys B445 (1995) 225
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Each improvement linked to the technology either in the beam or in the detector. Always a trade-off between various elements of the detector to achieve the best "sensitivity".
Signal and Background

• To better understand why MEG was designed the way it is we have to understand exactly:

  • what are we searching for? **signal**

  • in which environment? **background**

  • which **handles** can we use for discrimination?
Signal and Background

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

<table>
<thead>
<tr>
<th>Exp./Lab</th>
<th>Year</th>
<th>$\Delta E_e/E_e$ (%)</th>
<th>$\Delta E_\gamma/E_\gamma$ (%)</th>
<th>$\Delta t_{e\gamma}$ (ns)</th>
<th>$\Delta \theta_{e\gamma}$ (mrad)</th>
<th>Stop rate (s$^{-1}$)</th>
<th>Duty cyc. (%)</th>
<th>BR (90% CL)</th>
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<td>$4.9 \times 10^{-11}$</td>
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<td>4.5</td>
<td>1.6</td>
<td>17</td>
<td>$2.5 \times 10^8$</td>
<td>(6.7)</td>
<td>$1.2 \times 10^{-11}$</td>
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<td>MEG</td>
<td>2009</td>
<td>1</td>
<td>4.5</td>
<td>0.15</td>
<td>19</td>
<td>$3 \times 10^7$</td>
<td>100</td>
<td>$2 \times 10^{-13}$</td>
</tr>
</tbody>
</table>
**MEG experimental method**

Easy signal selection with $\mu^+$ at rest

$\theta_{e\gamma} = 180^\circ$

$e^+ \mu^+ \gamma$

$E_e = E_\gamma = 52.8$ MeV

- $\mu$: stopped beam of $>10^7 \mu$/sec in a 175 $\mu$m target
- $e^+$ detection
  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum
  plastic counters for timing
- $\gamma$ detection
  Liquid Xenon calorimeter based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: $\sim 0.8 \ast$ NaI
  - short $X_0$: 2.77 cm
Machine

- "Sensitivity" proportional to the number of muons observed
- Find the most intense (continuous) muon beam: Paul Scherrer Institut (CH)
- 1.6 MW proton accelerator
  - 2 mA of protons - towards 3 mA (replace with new resonant cavities)!
  - extremely stable
  - > $3 \times 10^8$ muons/sec @ 2 mA
πE5 beam line at PSI

Optimization of the beam elements:

- Muon momentum ~ 29 MeV/c
- Wien filter for $\mu/e$ separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 175 $\mu$m target

$\mu/e$ separation 11.8 cm (7.2 $\sigma$)

$R_\mu$ (exp. on target) $>6 \times 10^7 \mu^+/s$

$\mu$ spot (exp. on target) $\sigma_x \approx \sigma_y \approx 11$ mm

Beam line

$\mu$ ejection point

Quadrupole triplet

collimator, steering & degrader

Electrostatic separator

Transport solenoid

175 $\mu$m of CH$_2$

Z-Branch Momentum Spectrum

Horizontal Profile with Beam Size mm

Vertical Profile with Beam Size mm

$\sigma_x = 11$ mm

$\sigma_y = 11$ mm
Target

- **Stop** muons on the **thinnest** possible target 175 μm CH$_2$:
  - need **low energy** muons (lots of multiple scattering) but...
  - the **MS** of the decaying positron is minimized: precise direction/timing
  - **bremsstrahlung** reduced
  - the **conversion** probability of the photon in the target is negligible

Holes to study position reconstruction resolution
COBRA spectrometer

- The emitted **positrons** tend to wind in a **uniform** magnetic field
- the tracking detector becomes easily “blind” at the high rate required to observe many muons
- A **non uniform magnetic field** solves the rate problem
- As a bonus: **CO**nstant **B**ending **R**Adius

|          | Constant $|p|$ track | High $p_T$ track |
|----------|--------------|-----------------|
| **Uniform field** | ![Diagram](image1) | ![Diagram](image2) |
| **CoBRa:** Constant bending quick sweep away | ![Diagram](image3) | ![Diagram](image4) |
COBRA spectrometer

Non uniform magnetic field decreasing from the center to the periphery

| $\vec{B}$ | < 50 G |

- The superconducting magnet is very thin ($0.2 \ X_0$)
- Can be kept at 4 K with GM refrigerators (no usage of liquid helium)
Positron Tracker

- **16 chambers** radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 *vernier cathode* strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C₂H₆ mixture

Within one period, fine structure given by the Vernier circle

**transverse coordinate (t drift)**

**longitudinal coordinate (charge division + Vernier)**
Drift chambers

- Drift chambers
- Drift chambers
- Final step
- R Position Resolution - transverse -
  - R resolution is studied by using CR alignment data.
  - Residual "reconstruct - fit"
  - Slice by 0.5 mm intervals in drift distance, position dependence of R resolution is studied.
  - 170~350 micron in sigma is achieved (good DC).
Timing Counter

- Must give excellent rejection
- **Two layers** of scintillators:
  - **Outer** layer, read out by **PMTs**: timing measurement
  - **Inner** layer, read out with **APDs** at 90°: z-trigger
- Obtained goal $\sigma_{\text{time}} \approx 40$ psec (100 ps FWHM)

<table>
<thead>
<tr>
<th>Exp. application</th>
<th>Counter size (cm)</th>
<th>Scintillator</th>
<th>PMT</th>
<th>$\lambda_{\text{m}}$ (cm)</th>
<th>$\sigma_{\text{meas}}$</th>
<th>$\sigma_{\text{exp}}$</th>
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<tr>
<td>G.D. Agostini</td>
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<td>XP2020</td>
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<td>R. Stroynowski</td>
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<td>420</td>
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<td>Belle</td>
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<td>143</td>
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<td><strong>38</strong></td>
<td></td>
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</table>

*Best existing TC*
The photon detector

- γ Energy, position, timing
- Homogeneous 0.8 m³ volume of liquid Xe
  - 10% solid angle
  - 65 < r < 112 cm
  - |cosθ| < 0.35  |ϕ| < 60°
- 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
γ-detector construction
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)
  - 40000 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 ($\lambda_{\text{Abs}}=\infty$)
Readout electronics

2 GHz waveform digitization for all channels

DRS chip (Domino Ring Sampler)

- Custom sampling chip designed at PSI
- 2 GHz sampling speed @ 40 ps timing resolution
- Sampling depth 1024 bins for 8 channels/chip
- Full waveform is a unvaluable handle to do pile-up rejection
Trigger

- 100 MHz waveform digitizer on VME boards that perform online pedestal subtraction
- Uses:
  - $\gamma$ energy
  - $e^+$ - $\gamma$ time coincidence
  - $e^+$ - $\gamma$ collinearity
- Built on a FADC-FPGA architecture
- More performing algorithms could be implemented

- Beam rate $\sim 3 \times 10^7$ s$^{-1}$
- Fast LXe energy sum $> 45$ MeV $2 \times 10^3$ s$^{-1}$
  - gamma interaction point (PMT charge)
  - $e^+$ hit point in timing counter
  - time correlation $\gamma - e^+$ 100 s$^{-1}$
  - angular correlation $\gamma - e^+$ 10 s$^{-1}$
TRG + DAQ example

- For (almost) all channels, for each sub-detector we have two waveform digitizers with complementary characteristics.

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- Online pedestal subtraction for LXe.

- Info from all subdetectors is combined.
Calibrations

• It is understood that in such a complex detector a lot of parameters must be constantly checked

• We are prepared for redundant calibration and monitoring

• **Single** detector
  - PMT equalization for LXe and TIC
  - Inter-bar timing (TIC)
  - Energy scale

• **Multiple** detectors
  - relative timing
Calibrations

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

Alpha on wires
- PMT QE & Att. L
- Cold GXe
- LXe

Xenon Calibration
- Li(p, γ)Be
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- also for initial setup

LED
- PMT Gain
- Higher V with light att.

Laser
- relative timing calib.

Nickel γ Generator
- 9 MeV Nickel γ-line
- 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

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Example: $\alpha$-sources in Xe

- **Specially developed Am sources:**
- 5 dot-sources on thin (100 $\mu$m) tungsten wires
- SORAD Ltd. (Czech Republic)

This photon is lost

\[ R_\alpha = 7 \text{ mm} \]
\[ d_{\text{wire}} = 100 \text{ um} \]

\[ R_\alpha = 40 \text{ um} \]
\[ d_{\text{wire}} = 100 \text{ um} \]
γ-energy scale calibration

- A reliable result depend on a constant calibration and monitoring of the apparatus
- We are prepared for continuous and redundant checks
  - different energies
  - different frequency

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>Charge exchange</td>
<td>$\pi^- p \rightarrow \pi^0 n$</td>
<td>55, 83, 129 MeV</td>
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<tr>
<td></td>
<td>$\pi^0 \rightarrow \gamma \gamma$</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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<tr>
<td>Nuclear reaction</td>
<td>$^{58}\text{Ni}(n, \gamma_9)^{59}\text{Ni}$</td>
<td>9 MeV</td>
</tr>
<tr>
<td>Radioactive source</td>
<td>$^{60}\text{Co, AmBe}$</td>
<td>1.1 - 4.4 MeV</td>
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</table>
CEX measurement

\[ \pi^- p \rightarrow \pi^0 n \]
\[ \pi^0 \rightarrow \gamma \gamma \]

- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab.
- In the back-to-back configuration the energies are 55 MeV and 83 MeV.
- Even a modest collimation guarantees a sufficient monochromaticity.
- Liquid hydrogen target to maximize photon flux.
- An “opposite side detector” is needed (NaI array).
• In the back-to-back raw spectrum we see the correlation
  • $83\,\text{MeV} \Leftrightarrow 55\,\text{MeV}$
  • The $129\,\text{MeV}$ line is visible in the NaI because Xe is sensitive to neutrons ($9\,\text{MeV}$)
The Cockcroft-Walton accelerator
Reactions

- The **Cockcroft-Walton** is an extremely powerful tool, installed for monitoring and calibrating *all* the MEG experiment.
- Protons of up to 1 MeV on Li or B
  - Li: high rate, higher energy photon
  - B: two (lower energy) time-coincident photons

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Peak energy</th>
<th>$\sigma$ peak</th>
<th>$\gamma$-lines</th>
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<tbody>
<tr>
<td>Li(p,$\gamma$)Be</td>
<td>440 keV</td>
<td>5 mb</td>
<td>(17.6, 14.6) MeV</td>
</tr>
<tr>
<td>B(p,$\gamma$)C</td>
<td>163 keV</td>
<td>$2 \times 10^{-1}$ mb</td>
<td>(4.4, 11.7, 16.1) MeV</td>
</tr>
</tbody>
</table>

- $17.6$ MeV
- $\sim 14.8$ MeV
- $>16.1$ MeV
- $>11.7$ MeV
- $4.4$ MeV
CW - daily calibration

- This calibration is performed every other day
- Muon target moves away and a crystal target is inserted
- Hybrid target (Li$_2$B$_4$O$_7$)
- Possibility to use the same target and select the line by changing proton energy
The simultaneous emission of two photons in the Boron reaction is used to:

- determine relative timing between Xe and TIC
- Inter-calibrate TIC bar

Graph:

- Xe energy vs. TICP cluster energy
- 4.4 and 11.6 MeV Compton Edges

Graph:

- Offset vs. Xe energy
- Bar number
2008: First run of the experiment

(... after a short engineering run in 2007)

**Time schedule**

**Winter - Spring**
- detector dismantling
- improvement (after run 2007)
- re – installation

**Spring - Summer**
- LXe purification
- CW and $\pi^0$ calibration
- beam line setup

**September – December**
- MEG run
- short $\pi^0$ calibration

**Running conditions**

**MEG run period**
- Live time $\sim 50\%$ of total time
- Total time $\sim 7 \times 10^6$ s
- $\mu$ stop rate: $3 \times 10^7$ $\mu$/s
- Trigger rate 6.5 ev/s ; 9 MB/s

The missing 50% is composed of:
- 17% DAQ dead time
- 14% programmed beam shutdowns
- 7% low intensity Radiative muon decay runs (RMD)
- 11% calibrations
- 2% unforeseen beam stops
Muons on target

We also took RMD data once/week at reduced beam intensity

Programmed beam shutdowns

Cooling system repair

Air test in COBRA
2008 run DCH instabilities

• DCH started to show frequent HV trips after 2–3 months of operation
  • an increasing number of DCH had to be operated with reduced HV settings
    – reduced efficiency and resolution
    – problem due to long-term exposure to helium
  • the DC instability cancels out in the evaluation of the branching ratio
    – normalized to Michel decays

• The DCH modules have now been modified and are successfully being operated in this 2009 run

• HV spark reproduced in lab
Sep. 2008
Analysis

• We decided to adopt a **blind-box likelihood analysis** strategy

• Three independent blind likelihood analyses

• The blinding variables are $E_\gamma$ and $t_{e\gamma}$

• Use of the **sidebands** justified by the fact that our **main background** comes from accidental coincidences

![Graph showing blind box (0.2%) and sidebands]
A $\mu \rightarrow e\gamma$ event is described by 5 kinematical variables:
- $E_e$, $E_\gamma$, $(\Delta \vartheta, \Delta \varphi)$, $t_{e\gamma}$

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

$$\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{N^{N_{\text{obs}}}}{N_{\text{obs}}!} \exp^{-N} \prod_{i=1}^{N_{\text{obs}}} \left[ \frac{N_{\text{sig}}}{N} S + \frac{N_{\text{RMD}}}{N} R + \frac{N_{\text{BG}}}{N} B \right]$$

PDFs taken from:
- data
- MC tuned on data
Probability Density Functions

- **SIGNAL**
  
  - $E_{\gamma}$: from full signal MC (or from fit to endpoint)
  - $E_e$: 3-gaussian fit on data
  - $\theta_{e\gamma}$: combination of $e$ and gamma angular resolution from data
  - $t_{e\gamma}$: single gaussian from MEG trigger Radiative Decay (no cut on $E_g$)

- **RADIATIVE**
  
  - $E_e, E_{\gamma}, \theta_{e\gamma}$: 3D histo PDF from toy MC that smears and weighs Kuno-Okada distribution taking into account resolution and acceptance
  - $t_{e\gamma}$: single gaussian with same resolution as signal

- **ACCIDENTAL**

  - $E_{\gamma}$: from fit to $t_{e\gamma}$ sideband
  - $E_e$: from data
  - $\theta_{e\gamma}$: from fit to $t_{e\gamma}$ sideband
  - $t_{e\gamma}$: flat

*Alternative observables definition*

1) different algorithm for LXe Timing
2) Trigger LXe waveform digitizing electronics ($E_{\gamma}$)
Some examples: γ-ray energy

- The energy resolution and energy scale is extracted by the CEX data (55 MeV photons)
  - verified by RMD (+AIF) spectrum
- Average upper tail for deep conversions
  - $\sigma = 2.0 \pm 0.15 \%$
- Systematic uncertainty on energy scale < 0.6%
Positron momentum

- **e⁺ energy scale and resolution** are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8 MeV
- Resolution functions of core and tail components
  - core = 374 keV (60%)
  - tail = 1.06 MeV (33%) and 2.0 MeV (7%)
- Positron angle resolution measured using multi-loop tracks
  - $\sigma(\phi) = 10$ mrad
  - $\sigma(\theta) = 18$ mrad

Due to Missing DCH

Worse than expected
Relative time resolution

- Quote directly the $t_{e\gamma}$ from RMD resolution (recall: MEGA 700 ps) $\mu \rightarrow e\bar{\nu}\nu\gamma$
- $e^+$ time from TC and corrected by ToF (DCH trajectory)
- LXe time corrected by ToF to the conversion point

- $\sigma_t$ is corrected for a small energy-dependence
  - $(148 \pm 17)$ ps
  - stable within 20 ps along the run
Likelihood fit

- A “Feldman-Cousins” approach was adopted for the likelihood analysis
- The sensitivity (average expected 90% CL upper limit) on $N_{\text{sig}}$ assuming no signal by means of toy MC:
  - $N_{\text{sig}} < 6$
- 90% CL upper limit from the sidebands
  - $N_{\text{sig}} < (4.2 \div 9.7)$
A "Feldman-Cousins" approach was adopted for the likelihood analysis. The sensitivity (average expected 90% CL upper limit) on \( N_{\text{sig}} \) assuming no signal by means of toy MC:
- \( N_{\text{sig}} < 6 \)

90% CL upper limit from the sidebands:
- \( N_{\text{sig}} < (4.2 \div 9.7) \)

\( N_{\text{sig}} < 14.7 \) @90% CL

\( N_{\text{RMD}} \) consistent with sideband estimate: \( 25^{+17}_{-16} \)
The $N_{\text{sig}}$ are normalized to the detected Michel positrons.

$$\text{BR}(\mu^+ \rightarrow e^+\gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^{E}_{\nu\bar{\nu}}}{P} \times \frac{\epsilon_{e\nu\bar{\nu}}^{\text{trig}}}{\epsilon_{e\gamma}^{\text{trig}}} \times \frac{A_{\text{TC}}^{e\nu\bar{\nu}}}{A_{e\gamma}^{\text{TC}}} \times \frac{\epsilon_{e\nu\bar{\nu}}^{\text{DC}}}{\epsilon_{e\gamma}^{\text{DC}}} \times \frac{1}{A_{e\gamma}^{LXe}} \times \frac{1}{\epsilon_{e\gamma}^{LXe}}$$

- count # of Michel decays in the analysis window with a pre-scaled trigger
- theory resolution acceptance

$E_{e}$ (MeV)
Normalization

- The $N_{\text{sig}}$ are normalized to the detected Michel positrons

$$BR(\mu^+ \rightarrow e^+\gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon_{e\gamma}^{\text{trig}}}{\epsilon_{e\gamma}} \times \frac{A_{e\gamma}^T}{A_{e\gamma}^{e\nu\bar{\nu}}} \times \frac{\epsilon_{e\gamma}}{\epsilon_{e\gamma}^{DC}} \times \frac{1}{A_{e\gamma}^{LX_e}} \times \frac{1}{\epsilon_{e\gamma}^{LX_e}}$$

= \sim 1

Average absolute efficiency $> 30$

- The fraction of events with at least one reconstructed track at high momentum is a measure of relative tracking efficiency
Normalization

- The $N_{\text{sig}}$ are normalized to the detected Michel positrons

$$\text{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f_{\text{ev}}}{P} \times \frac{\epsilon_{\text{trig}}}{\epsilon_{e\gamma}} \times \frac{A_{TC}}{A_{e\gamma}} \times \frac{\epsilon_{DC}}{\epsilon_{e\gamma}} \times \frac{1}{A_{e\gamma}} \times \frac{1}{\epsilon_{LXe}}$$

- The probability to detect a signal $\gamma$-ray computed using the MC simulation:
  - corrected for smearing and acceptance
    - $\epsilon(\gamma) = 0.61 \pm 0.03$, confirmed by $\pi^0$ and RD spectra
  - $\text{Norm} = (2.0 \pm 0.2) \times 10^{-12}$
Likelihood fit

• A “Feldman-Cousins” approach was adopted for the likelihood analysis.
• The sensitivity (average expected 90% CL upper limit) on $N_{\text{sig}}$ assuming no signal by means of toy MC:
  - $BR < 1.3 \times 10^{-11}$
• 90% CL upper limit from the sidebands:
  - $BR < (0.9 \div 2.1) \times 10^{-11}$

$N_{\text{sig}} < 14.7$ @90% CL
$N_{\text{RMD}}$ consistent with sideband estimate: $25^{+17}_{-16}$
Result on BR

\[ \text{BR}(\mu^+ \rightarrow e^+\gamma) < 3.0 \times 10^{-11} \]

- Effect of \textit{systematics} on evaluation of limit on \(N_{\text{sig}}\)
  - \(E_\gamma\) energy scale (~0.6)
  - \(e^+\) angle (~0.35)
  - \(e^+\) energy spectrum (~1.18)

- ~2 times \textit{worse} than expected sensitivity
- Probability of getting this result by statistical fluctuations is ~5%

- see arXiv:0908.2594v1 [hep-ex]
Conclusion

• Data from the first three months of operation of the MEG experiment give a result competitive with the previous limit
  – 2008 run suffered from detector instabilities
• During 2009 shutdown the problem with the DCH instability was solved
  – DCH operated for 6 months with no degradation
• Data taking restarted in October 2009 till 23 December
  – improved efficiency
  – improved read-out electronics (DRS2 → DRS4)
  – improved resolutions (tracking, timing...)
• Confident in a sensitivity $\sim 5 \times 10^{-12}$ for this year’s data
• We will need to run until the end of 2011 for reaching the target sensitivity
Thank you

- Visit us on [http://meg.psi.ch](http://meg.psi.ch)
Back-up slides
**CW - daily calibration**

- This calibration is performed **every other day**
- Muon target moves away and a crystal target is inserted
- Hybrid target (Li$_2$B$_4$O$_7$)
- Possibility to use the same target and select the line by changing proton energy

When p energy increases B lines appear

---

**LXe spectrum**

- $^7$Li
- $^{10}$B

**Preliminary**
γ hit resolution

- We use the response shape from the Monte Carlo folded with an additional component estimated from data using a lead collimator

- $\sigma(u,v) \sim 5.0 \text{ mm}$
- $\sigma(w) \sim 6.0 \text{ mm}$
Typical resolutions and eff

- are summarized in this table

<table>
<thead>
<tr>
<th></th>
<th>peak</th>
<th>error</th>
<th>spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_E$ (%)</td>
<td>2.0</td>
<td>0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>$\sigma_{(u,v)}$ (mm)</td>
<td>5.0</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_{\text{teV}}$ (ps)</td>
<td>148</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td><strong>Energy scale</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>61%</td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>

\[
\frac{3\alpha}{32\pi} \left( \frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2} \right)^2
\]
Normalization numbers

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{evv}}$</td>
<td>11414</td>
</tr>
<tr>
<td>Prescale</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Michel fraction</td>
<td>1/0.1008</td>
</tr>
<tr>
<td>$\varepsilon_{e^+}$ ratio</td>
<td>1.14</td>
</tr>
<tr>
<td>$\varepsilon_\gamma$</td>
<td>0.98 x 0.66</td>
</tr>
<tr>
<td>$\varepsilon_{\text{trigger}}$</td>
<td>0.66</td>
</tr>
<tr>
<td>$\varepsilon_{\text{selection}}$</td>
<td>0.99 x 0.91</td>
</tr>
<tr>
<td>SES</td>
<td>$(2 \pm 0.2) \times 10^{-12}$</td>
</tr>
</tbody>
</table>

- **Best fit in likelihood fit**
- **Sample point**
- **Simulated experiments taking sample point as true point**

**NRMD vs Nsignal**

<table>
<thead>
<tr>
<th>$\Omega/4\pi$</th>
<th>0.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>0.66 x 0.91 (E$_\gamma$&gt;46MeV)x(pileup, CR)</td>
</tr>
<tr>
<td>$e^+$</td>
<td>0.15 (DCH x DC-TC match)</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.66 (DM)</td>
</tr>
<tr>
<td>Selection</td>
<td>0.99 x 0.98 (DCH x $\gamma$ acc.)</td>
</tr>
<tr>
<td>$N_{\mu}$</td>
<td>9.4x10$^{13}$ $\mu$ stops (3.0x10$^7$ $\mu$/s/2mA·6290C)</td>
</tr>
<tr>
<td>SES</td>
<td>2.0x10$^{-12}$</td>
</tr>
</tbody>
</table>
DCH repair

1) The chambers are dismounted and operated in laboratory in He atmosphere

2) The potting glue for the HV protection was inadequate: change on all chamber to epoxy glue

3) The PCB has vias close to ground plane, partially filled with araldite to fix PCB to the Carbon fiber frame: new PCB design

4) Open all chambers, replace the PCB and the wires, saving the cathodes

5) Test of the chambers in laboratory as soon as they are ready

Estimated time: ready to mount in August
Radiative decay signal

The radiative $\mu$-decay events are:
- good sample to check the LXe-TC timing
- good sample to control the efficiencies
- the second source of background: we want to validate our pdf
Search in dedicated low $\mu$-beam intensity runs

Event selection
1. Reject cosmic muons
2. Reconstructed track matching the TC
3. LXe energy $>30$ MeV
   \[ S/N \text{ ratio} = 0.8 \]
4. Kinematical constraint
   \[ S/N \text{ ratio} = 2.8 \]

\[
M_{2\nu}^2 = E_{2\nu}^2 - \tilde{p}_{2\nu}^2 = (M_\mu - E_e - E_\gamma) - (\tilde{p}_e + \tilde{p}_\gamma)
\]
\[
= M_\mu^2 - 2(E_e + E_\gamma)M_\mu + 2E_eE_\gamma \sin^2 (\theta/2) \geq 0
\]
\[
\Rightarrow xy \sin^2 (\theta/2) \geq x + y - 1
\]
Analysis schemes

- The 90% confidence levels are calculated by 3 independent likelihood fitting tools, all based on the Feldman-Cousins approach (*).
- All results are consistent.

1\textsuperscript{st} scheme
- uses an a-priori estimates of \(N_{\text{RMD}}\) and \(N_{\text{BG}}\)
- A likelihood ratio LR table is built as a function of \(N_{\text{sig}}\)
- The 90% confidence level for BR comes from the LR for experimental data vs tabulated values.

2\textsuperscript{ND}-3\textsuperscript{rD} scheme
- extract \(N_{\text{S}}, N_{\text{RMD}}\) and \(N_{\text{BG}}\) by likelihood fit on the observed events in the signal region, with two independent algorithms
- 90% confidence level of \(N_{\text{S}}\) comes from \((N_{\text{S}} N_{\text{RMD}})\)-plane, with \(N_{\text{BG}}\) fixed
- BR from the LR ordering technique

Signal region vs PDFs:

**Legend (*)&:**

- **Black:** data
- **Red:** Signal PDF
- **Blue:** RMD PDF
- **Green:** BG PDF

(*)Note:

All curves normalized to the event number
ACC BKG
Rad Muon Decay SIG

Fit with alternative observable definition gives very compatible results
Pedestal

- Residual large (2%) contribution of pedestal due to ghost pulses in DRS2
- Solved with new version of chip (installed in 2009)
Positron tracker

- Excellent momentum **resolution** at ~50 MeV
- The energy is very low hence the **multiple scattering** is important
  - we tend to **loose** position/energy **resolution**
  - $MS \sim \sigma$
- The **volumes** of the chambers are **independent**
  - too much high-Z gas otherwise (He/C$_2$H$_6$ vs He)
  - find a clever way for a good z-reconstruction
LXe: $g$ and QE

- The calorimeter is equipped with blue LEDs and alpha sources.
- Measurements of light from LEDs:
  - $\sigma^2 = g ( q - q_0 ) + \sigma_0^2$
- Absolute knowledge of the GAIN of ALL PMTs within few percents
- $g = 10^6$ for a typical HV of 800 V
- QE determined by comparison of alpha source signal in cold gaseous xenon and MC determined at a 10% level
Xenon purity

- Energy resolution strongly depends on absorption
- We developed a method to measure the absorption length with alpha sources
- We added a liquid and gas purification system (molecular sieve + gas getter) to reduce impurities below ppb
Xe light yield

- Large light yield increase (40%) during MEG run
- LY change monitored with the calibration system
  - three times per week @ 4.4, 11.6 and 17.6 MeV

17.6 MeV peak as a function the date

- CW
- $\pi^0$ data
- $\mu$ data taking
- purification & stability test

PRELIMINARY
α-sources in Xe

- Used to
  - QE determination
  - Monitor Xe stability
  - Measure absorption
  - Measure Rayleigh scattering

GXe: MC & data

LXe: MC & data

λ_{Abs} > 300 cm