First results from the MEG experiment: $\mu \rightarrow e \gamma$

Paolo Walter Cattaneo, INFN Pavia, Italy, 18-11-2009

International conference on Neutrino Physics in the LHC Era, Luxor, Egypt
The $\mu \rightarrow e\gamma$ decay

**SM with massive $\nu$**

\[ \text{BR}_{\text{SM}}(\mu \rightarrow e\gamma) \approx 10^{-14} \div 10^{-13} \]

**LFV induced by slepton mixing**


- SUSY SU(5) $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-14} \div 10^{-13}$
- SUSY SO(10) $\text{BR}_{SO(10)} \approx 100 \text{BR}_{SU(5)}$

<table>
<thead>
<tr>
<th>Lab.</th>
<th>Year</th>
<th>Upper limit</th>
<th>Experiment or Auth.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI</td>
<td>1977</td>
<td>&lt; $1.0 \times 10^{-9}$</td>
<td>A. Van der Schaaf et al.</td>
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<tr>
<td>TRIUMF</td>
<td>1977</td>
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<td>P. Depommier et al.</td>
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<tr>
<td>LANL</td>
<td>1979</td>
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<td>W.W. Kinnison et al.</td>
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<tr>
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<td>&lt; $4.9 \times 10^{-11}$</td>
<td>Crystal Box</td>
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<tr>
<td>LANL</td>
<td>1999</td>
<td>&lt; $1.2 \times 10^{-11}$</td>
<td>MEGA</td>
</tr>
<tr>
<td>PSI</td>
<td>~2011</td>
<td>$\sim 10^{-13}$</td>
<td>MEG</td>
</tr>
</tbody>
</table>

**Experimental limit**

- MEGA $\times 10^{-11}$
- PSI $< 1.2 \times 10^{-11}$
- LANL $< 4.9 \times 10^{-11}$
- TRIUMF $< 3.6 \times 10^{-9}$
- PSI $< 1.0 \times 10^{-9}$
Signal and background

**Signal**

\[ \mu \rightarrow e \gamma \]

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

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

\[ T_e = T_\gamma \]

**Background**

**Physical**

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

**Accidental**

\[ \mu \rightarrow e \nu \nu \nu \]

\[ e e \rightarrow \gamma \gamma \nu \nu \]

\[ e \gamma \rightarrow e \gamma \gamma \nu \]

Need \( \mu^+ \) to avoid muonic atoms
The sensitivity is limited by the accidental background

\[ n_{\text{sig}} \propto R_\mu T \quad n_{\text{phys,b}} \propto R_\mu T \quad n_{\text{acc,b}} \propto R_\mu^2 T \]

The n. of acc. backg events \( n_{\text{acc,b}} \) depends quadratically on the muon rate \( R_\mu \) and on the quality of the measurement of the experimental quantities:

- \( e^\gamma \) relative timing and angle, positron and photon energy
  \[ \text{BR}_{\text{acc}} \propto R_\mu \times \Delta t_{e\gamma} \times \Delta \theta_{e\gamma}^2 \times \Delta E_e \times \Delta E_{\gamma}^2 \]

DC beam, rather than pulsed beam, give lowest instantaneous rate \( R_\mu \) and thus lowest background
Required Performances

\[ BR(\mu \rightarrow e\gamma) \approx 10^{-13} \text{ reachable} \]

\[ BR_{\text{acc.b}} \approx 2 \times 10^{-14} \text{ and } BR_{\text{phys.b}} \approx 0.1 \times BR_{\text{acc,b}} \text{ with the following resolutions} \]

<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 ((\text{s}^{-1}))</th>
<th>Duty cyc. (%)</th>
<th>BR ((90% \text{ CL}))</th>
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</thead>
<tbody>
<tr>
<td>SIN</td>
<td>1977</td>
<td>8.7</td>
<td>9.3</td>
<td>1.4</td>
<td>-</td>
<td>5 \times 10^5</td>
<td>100</td>
<td>3.6 \times 10^{-9}</td>
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<td>1977</td>
<td>10</td>
<td>8.7</td>
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<td>1979</td>
<td>8.8</td>
<td>8</td>
<td>1.9</td>
<td>37</td>
<td>2.4 \times 10^5</td>
<td>6.4</td>
<td>1.7 \times 10^{-10}</td>
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<td>Crystal Box</td>
<td>1986</td>
<td>8</td>
<td>8</td>
<td>1.3</td>
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<td>(6.9)</td>
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</tr>
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<td>1999</td>
<td>1.2</td>
<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>2011</td>
<td>0.8</td>
<td>4</td>
<td>0.15</td>
<td>19</td>
<td>2.5 \times 10^7</td>
<td>100</td>
<td>1 \times 10^{-13}</td>
</tr>
</tbody>
</table>

Need of a DC muon beam
Experimental method

Detector outline

- Stopped beam of $3 \times 10^7 \mu \text{sec}$ in a $205 \mu \text{m}$ target
- Solenoid spectrometer & drift chambers for $e^+$ momentum
- Scintillation counters for $e^+$ timing
- Scintillating fiber for $e^+$ $z$ position
- Liquid Xenon calorimeter for $\gamma$ detection (scintillation)

MEG proposal: September 2002: $10^{-13}$ goal: A. Baldini and T. Mori et al.,
Italy, Japan, Switzerland, Russia
The PSI πE5 DC beam

- 1.8 mA of 590 MeV/c protons (most intense DC beam in the world)
- 29 MeV/c muons from decay of π stop at rest: fully polarized

Particles intensity as a function of the selected momentum
The positron spectrometer: COBRA spectrometer

**CO**nstant B**e**nding R**a**dius (COBRA) spectrometer

- High $p_{\text{e}}$ positrons quickly swept out: reduced #DCH hits

- Constant bending radius independent of emission angles: ease of trigger
The drift chambers

- 16 chamber sectors aligned radially with 10° intervals
- Two staggered arrays of drift cells
- Chamber gas: He-C₂H₆ mixture
- Vernier pattern to measure z-position made of 15 μm kapton foils
- Embedded in He gas to reduce MS
- Elliptic thin target slanted ~ 20° to reduce MS

Goals:
\[ \sigma(X,Y) \sim 200 \, \mu m \] (drift time)
\[ \sigma(Z) \sim 300 \, \mu m \] (charge division vernier strips)
\[ \sigma(p) \sim 0.4\% \]
$2 \times 10^{-3} X_0$ along $e^+$ trajectory
The Timing Counter

- One (outer) layer of scintillating bars read by PMTs: $e^+$ timing
- One inner layer of scintillating fibers read by APDs: $e^+ z$ for trigger and analysis (longitudinal position is needed for a fast estimate of the $e^+$ direction)
- Goal $\sigma_{\text{time}} \sim 40$ ps (100 ps FWHM) $\sigma_z \sim 2$ mm
A plastic support structure arranges the scintillator bars as requested.

The bars are glued onto the support.

Interface elements are glued onto the bars and support the fibres.

Fibres are glued as well.

Temporary aluminium beams are used to handle the detector during installation.

PTFE sliders will ensure a smooth motion along the rails.
**The Liquid Xe calorimeter**

- 800 l of Liquid Xe
- 848 PMT immersed in LXe
- Only scintillation light
- High luminosity
- Unsegmented volume

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### Experimental check

In a Large Prototype

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<table>
<thead>
<tr>
<th>Density</th>
<th>2.95 g/cm³</th>
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<tbody>
<tr>
<td>Boiling and melting points</td>
<td>165 K, 161 K</td>
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<tr>
<td>Energy per scintillation photon</td>
<td>24 eV</td>
</tr>
<tr>
<td>Radiation length</td>
<td>2.77 cm</td>
</tr>
<tr>
<td>Decay-time</td>
<td>4.2 nsec, 22 nsec, 45 nsec</td>
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<tr>
<td>Scintillation light wave length</td>
<td>1.75 nm</td>
</tr>
<tr>
<td>Scintillation absorption length</td>
<td>&gt; 100 cm</td>
</tr>
<tr>
<td>Attenuation length (Rayleigh scattering)</td>
<td>30 cm</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.74</td>
</tr>
</tbody>
</table>
**LED**

(rough) relative timing calib.
< 2~3 nsec

**PMT Gain**
Higher V with light att.
Can be repeated frequently

**Laser**

(lower) relative timing calib.
< 2~3 nsec

**Proton Acc**

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

**Xenon Calibration**

- Laser
- LED
- Proton Acc
- Nickel γ Generator

**Nickel γ Generator**

Illuminate Xe from the back

Source (Cf) transferred by comp air

- 3 cm Polyethylene
- 0.25 cm Nickel plate

**α**

PMT QE & Att. L
Cold GXe
LXe

**Proton Acc**

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Calorimeter energy Calibration by Charge Exchange Reactions (CEX)

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

- \( \pi^- \) stopped in liquid H\(_2\) target
- Tagging \( \gamma \) at 180\(^\circ\) provides monochromatic \( \gamma \)
- NaI crystal array to tag the other \( \gamma \)
- Dalitz decay \( \pi^0 \rightarrow \gamma e^+e^- \) to study \( e^+\gamma \) synchronization and time resolution

\( \sigma_R = 1.5\% \)
\( \text{FWHM} = 4.6\% \)
• Sub-Mev proton beam by a Cockcroft-Walton (CW) impinge on a Li$_2$B$_3$O$_7$ target
• 17.6 MeV from $^7$Li
• 2 coincidence $\gamma$ (4.4, 11.6) MeV from $^{11}$B: synchronization of LXe and TC
• Short runs thrice a week
**DAQ: trigger**

Uses easily quantities:

- $e^+ - \gamma$ coincidence in time and direction
- $\gamma$ energy
- Built on a **FADC-FPGA** architecture
- More complex algorithms implementable

**Trigger:**

Signals from Calorimeter and TC bar are sampled at 100 MHz with separate ADC

Several trigger combinations available to study trigger and detector efficiency for all subdetectors

- **Beam rate**  \[10^8 \text{ s}^{-1}\]
- **Fast LXe energy sum > 45MeV**  \[2 \times 10^3 \text{ s}^{-1}\]
- $\gamma$ interaction point (PMT of max charge)
- $e^+$ hit point in TC
- **time correlation $\gamma - e^+$**  \[200 \text{ s}^{-1}\]
- **angular correlation $\gamma - e^+$**  \[20 \text{ s}^{-1}\]
- ~5 Hz trigger rate in 2008 data taking
**Readout electronics: the Domino Principle**

- **Waveform digitizing for all channels (pile-up rejection);**
- **Custom sampling chip** Domino Ring Sampler (DRS) designed at PSI;
- **2.5 GHz** sampling speed @ 40 ps timing resolution;
- Sampling depth **1024** bins;
- Readout similar to trigger;
- **Trigger:**
  - Signals from Calorimeter and TC bar are sampled at 100 MHz with separate ADC
  - Several trigger combinations available to study trigger and detector efficiency for all subdetectors
The 2008 Physics run

- Long calibration run in summer with $\pi$ charge exchange (CEX)
- First 3 months physics data taking (September-December 2008)
- During physics run, frequent calibration runs (CW, RMD) were conducted frequently
- Another CEX run performed at end of run

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

Programmed beam shutdowns

Air test in COBRA

Cooling system
Drift chamber instability

• DC showed frequent HV trips after 2-3 months of operation

• Increased #DCs had to be operated with reduced HV

• Reduced efficiency and resolution for e+ measurement

• Problem related to long term exposure to He

• The DC instability uncertainty cancels out in the $\mu^+\rightarrow e^+\gamma$ analysis: $BR = \#\mu^+\rightarrow e^+\gamma/#$ Michel

• DC modules are now modified and runs without problems in the laboratory and in the experiment since several months.
Light yield of LXe calorimeter

- LXe has been purified during the run monitoring the increase of the light yield with calibration tools (CW, alpha, LED, cosmic rays)

- Overall energy scale uncertainty during the whole run period: ~0.4%

- The light yield at the end of the run was 70% of the expectation
Tracks with two turns in the spectrometer are used to estimate the angular resolutions.

The edge of Michel positrons used to determine momentum resolution.

\[ \sigma(\Delta \theta) = 25 \text{ mrad} \]  
\[ \Rightarrow \sigma(\theta) = 18 \text{ mrad} \]

\[ \sigma(\Delta \phi) = 14 \text{ mrad} \]  
\[ \Rightarrow \sigma(\phi) = 10 \text{ mrad} \]

\[ \sigma_{\text{core}} = 374 \text{ keV (60\%)} \]  
\[ \sigma_{\text{tail1}} = 1.06 \text{ MeV (33\%)} \]  
\[ \sigma_{\text{tail2}} = 2 \text{ MeV (7\%)} \]
**γ-e⁺ Timing resolutions from 2008 data**

**Intrinsic timing resolution using e⁺ hitting several bars**

\[ \Delta T \sim 80 \text{ ps} \]

**γ-e⁺ timing resolution by using Radiative Muon Decay**

\[ \sigma_{t_{\gamma}} = 148 \pm 17 \text{ ps} \]

*e⁺ time hit measured by TC corrected by ToF (DCH trajectory) to target
LXe corrected by ToF from target to conversion point
Blind analysis: $E_\gamma$ vs $\Delta t_{\gamma e}$ window
Sidebands ($|\Delta T_{\gamma}| > 1 \text{ ns}$) are used to measure accidental background distributions.

Radiative decay + In flight positron annihilation + resolution + pileup: in agreement with MCs.
Likelihood analysis: accidentals + radiative + signal PDFs to fit data + Feldman Cousins

$0 \leq N_{\text{Sig}} \leq 14.6$

Best fit in the signal region
Note: all the other parameters are cut to select ~90% of signal events in these plots.
Normalization with Michel events measured simultaneously with the MEG trigger

\[ N_{e\gamma} = BR(\mu^+ \rightarrow e^+\gamma) \times k \]

- Independent of instantaneous beam rate
- Nearly insensitive to \( e^+ \) acceptance and efficiency factors related to DCH and TC
90% CL limit

- $90\% \, C.L. N_{\text{sig}} \leq 14.6$ corresponds to $BR(\mu \rightarrow e\gamma) \leq 3.0 \times 10^{-11}$
- Computed sensitivity $1.3 \times 10^{-11}$
- Statistical fluctuation 5%
- From sidebands analysis we expected 0.9 (left) and 2.1 (right) $\times 10^{-11}$
- Bad luck
Future prospects

• Re-start of data taking in october, until december (as in 2008)
• Instabilities eliminated: DRS2 ➔ DRS4 (timing improvement + noise reduction)
• Data taking and trigger efficiencies: 3-4 factor improvement
• Corresponding improvement in sensitivity: 3-4 * 10^{-12} for 2009 run
• Continue running in 2010 + 2011 for the final (10^{-13}) goal

More details at

http://meg.psi.ch
http://meg.pi.infn.it
http://meg.icepp.s.u-tokyo.ac.jp
Backup Slides
Beam studies

Optimization of the beam elements:

- **Wien filter** for $\mu/e$ separation
- **Degrader** to reduce the momentum stopping in a 205 $\mu$m $\text{CH}_2$ target
- **Solenoid** to couple beam with COBRA spectrometer

Results (4 cm target):

- $R_\mu$ (total) $1.3 \times 10^8 \mu^+ / s$
- $R_\mu$ (after W.filter & Coll.) $1.1 \times 10^8 \mu^+ / s$
- $R_\mu$ (stop in target) $6 \times 10^7 \mu^+ / s$
- **Beam spot** (target) $\sigma \approx 10 \text{ mm}$

$\forall \mu/e$ separation (at collimator) $7.5 \sigma$ (12 cm)

$10^8 \mu / s$ could be stopped in the target but only $3 \times 10^7$ are used because of accidental background
Detection efficiency

- The probability to detect a signal $\gamma$-ray within the detector acceptance is computed using the Monte Carlo simulation;
- The probability that the energy of a 52.8 MeV $\gamma$-ray is reconstructed $>46$ MeV (0.66) is corrected by taking into account:
  - position resolution smearing for the acceptance;
  - positron direction smearing;
- $\mathcal{E}_{(\gamma)} = 0.61 \pm 0.03$
- confirmed by $\pi^0$ and RD spectra
On-line $E_\gamma$ resolution

55 MeV line from $\pi^0$-decay

45 MeV threshold

(@4\sigma from signal)

$\sigma = 3.8\%$
Liquid xenon: waveforms: 2 digitizers

Trigger@100 MHz

DRS2 @ 500 MHz or 2 GHz
**α-source and Li line**

- The position of the **α-source peak** is ~the same as year 2008.
- The **Li peak** (17.6 MeV) is higher!
  - around ~ 30k phe
  - it was at < 22k phe
  - integration still not optimized for this year’s waveform

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**Graphs:**
- Full spectrum
- γ-ray cut
- α-particle cut

**2008 peak**

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2008

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2009
In 2009 xenon scintillation waveforms have the right time decay constant: longer for gammas
Dedicated RMD runs at lower thresholds

\[ \text{mean} = 2 \pm 8 \text{ ps} \]
\[ \text{sigma} = 184 \pm 7 \text{ ps} \]
The magnet

- $B_c = 1.26T$ current = 359A
- Five coils with three different diameters
- Compensation coils to suppress the stray field around the LXe detector
- High-strength aluminum stabilized superconductor

$\Rightarrow$ thin magnet \hspace{1cm} (1.46 cm Aluminum, 0.2 $X_0$)
Background and Sensitivity

**Single Event Sensitivity**

Limited by Accidental Background hence Detector Performance

\[
\text{BR}(\mu \rightarrow e\gamma) = \left( R_\mu \cdot T \cdot \Omega/4\pi \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{\text{sel}} \right) \left( \Delta E_e \cdot \Delta t_{e\gamma} \cdot \Delta \theta_{e\gamma} \right) \approx 3 \cdot 10^{-14}
\]

Accidental Background

Upper Limit at 90% C.L. for BR

\[
\text{BR}_{\text{acc}} \approx 1 \cdot 10^{-15}
\]

1 week = 4 x 10⁵ s

* The muon rate can be optimized to improve the limit
**MEG detection concept**

$\mu^+ \text{ decay at rest}$

$\theta e\gamma = 180^\circ$

$e^+ \quad \mu^+ \quad \gamma$

$E_e = E_\gamma = 52.8 \text{ MeV}$

**Stopped beam** of $3 \times 10^7 \mu$/sec in a 205 $\mu$m target

**Liquid Xenon calorimeter** for $\gamma$
detection (scintillation):
- fast: $4 / 22 / 45$ ns
- high $LY$: $\sim 0.8 * \text{NaI}$
- short $X_0$: 2.77 cm

**Solenoid spectrometer** (COBRA) & drift chambers for $e^+$ momentum measurement

**Scintillation counters** for $e^+$ timing

More on Lxe Calorimeter in R. Sawada talk
Energy release in Liquid Xenon

Positron track

A simulated $\mu \rightarrow e\gamma$ event

Hits on Timing Counter
Timing Counter 2)

Two sectors upstream and downstream the target
Two layers of scintillation counters placed at right angles with each other.

Outer layer: scintillator bars devoted to trigger, $\phi$ and time measurement.

Two sectors of 15 bars each, read by 2 PMTs, on the inner and outer sides

Full PMT waveforms read out for dedicated charge and time analysis

Inner layer: scintillating fibres providing trigger and $z$ information

Two sectors of 256 fibers, read by APDs

Only digital signals (on/off)

Measurements of TC bars timing resolution in dedicated test beams at several positions and impact angles

$\text{FWHM}(T) = 91 \text{ ps (} \pm 5\% \text{)}$

MEG Goal 100 ps
Readout electronics

- **Waveform digitizing for all channels (pile-up rejection);**
- Custom *domino sampling chip (DRS)* designed at PSI;
- **2.5 GHz** sampling speed @ 40 ps timing resolution;
- Sampling depth **1024 bins**;
- Readout similar to trigger;
- **Trigger:**
  - Signals from Calorimeter and TC bar are sampled at 100 MHz with separate ADC
  - Several trigger combinations are available to study trigger and detector efficiency for all subdetectors
**Spectrometer calibration**

- **MEG is a precision experiment**
- **High experimental resolutions to reject background**
- **Stable for a ~ 4 year scale**

- **PMT time walk correction**
  - Michel

- **Same bar PMT time offset**
  - Cosmics, Laser

- **Interbar time offset**
  - Boron, Laser, Dalitz

- **XEC-TC time offset**
  - Dalitz

- **Bar V\textsubscript{eff}**
  - Cosmics
Reactions induced by Cockroft-Walton protons

$\text{(E \sim 1 \text{ MeV}) \text{ on Li and B targets}}$

<table>
<thead>
<tr>
<th>Reactio</th>
<th>Peak energy</th>
<th>$\sigma$ peak</th>
<th>$\gamma$-lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Li(p,}\gamma\text{Be)}$</td>
<td>$440 \text{ keV}$</td>
<td>$5 \text{ mb}$</td>
<td>$(17.6, 14.6) \text{ MeV}$</td>
</tr>
<tr>
<td>$\text{B(p,}\gamma\text{C)}$</td>
<td>$163 \text{ keV}$</td>
<td>$2 \times 10^{-1} \text{ mb}$</td>
<td>$(4.4, 11.6, 16.1) \text{ MeV}$</td>
</tr>
</tbody>
</table>

**Boron target:**
- Lower cross section
- Two gamma’s emitted simultaneously $\Rightarrow$ tool for relative timing calibration

**Lithium spectrum on NaI**

- $17.6 \text{ MeV line}$
- $14.6 \text{ MeV broad resonance}$

Counts / 40 keV

$E(\text{MeV})$

$>16.1 \text{ MeV}$

$>11.6 \text{ MeV}$

$4.4 \text{ MeV}$
TC bar measurements

\[ t_0 = T + \frac{z}{v_{\text{eff}}} + b_0 + \frac{c_0}{\sqrt{A_0}} \]

\[ t_1 = T + \frac{L - z}{v_{\text{eff}}} + b_1 + \frac{c_1}{\sqrt{A_1}}. \]

- **T**: time of \( e^+ \) at the impact point on first hit bar
- **z**: impact point along bar length
- **b_{0,1}**: PMT time offsets
- **c_{0,1}**: PMT Time Walk coefficients

amplitude of PMT
effective velocity
Detector calibration and performances: TC 1)

**Timing counter parameters:**
- **PMT Gain → charge response**
- **Effective velocity** $v_{\text{eff}}$
- **Effective attenuation length** $\lambda_{\text{eff}}$

PMT relative gain from CR, LIF and B Runs

**Graph:**
- PMT Gain
- $\lambda_{\text{eff}}$ (cm)

$T = \frac{t_1 + t_0}{2} - \frac{L}{2 \cdot v_{\text{eff}}}$

$z = \frac{v_{\text{eff}} \cdot (t_0 - t_1)}{2}$

$\ln \left( \frac{Q_1}{Q_0} \right) = \ln \left( \frac{G_1}{G_0} \right) + \frac{2z}{\lambda_{\text{eff}}}$

40% Spread
Detector calibration and performances: TC 2

Effective velocity measurement (cm/ns)

\[ V_{\text{eff}} \] determined with < 1% precision by using bar and fibre information simultaneously.

Events with \(|\Delta Z|<10\):

- **bar1**
  - \( Z \) (cm): 13.72 +/- 0.08
  - \( \Delta t \) (ns):
    - bar0: 14.62 +/- 0.17
    - bar2: 14.31 +/- 0.11

- **bar0**
  - \( Z \) (cm):
  - \( \Delta t \) (ns):

- **bar2**
  - \( Z \) (cm):
  - \( \Delta t \) (ns):
Inter-PMT offsets

\[ t_1 - t_0 \ [\text{ns}] \]

Average $\Delta t$ is PMT offset in cosmic runs

MEG physics runs TC hitmap

Before

After

$\text{US}$

$\text{DS}$

\[ t_1 - t_0 \ [\text{ns}] \]
Inter-bar offset extraction

Boron 4.4MeV (XEC) and 11.7MeV(TC)

\[ DT_{gg} = \left( T_{XEC} - \frac{L_{XEC}^g}{c} \right) - \left( \frac{t_0 + t_1}{c} - \frac{L_{TC}^g}{c} \right) \]

\[ \Delta T_{\gamma\gamma} [ns] \]

Bar17
\[ \text{-signal} \]
\[ \text{-bkg (rescaled)} \]

Sep 08/10
08/10
13/10
20/10
25/10
10/11
24/11
01/12

Stable in time!
On sample of two hit adjacent bars (‘doubles’) test time walk correction ($c_0$ and $c_1$)

$$DT = T_A - T_B$$

On events with three adjacent hit bars (triples)
minimize the differences (for all the bars)

$$\frac{t_{0C} + t_{OB}}{2} - t_{0A} - \left[ \frac{1}{2} \left( \frac{c_{0C}}{\sqrt{A_{0C}}} + \frac{c_{0B}}{\sqrt{A_{0B}}} \right) - \frac{c_{0A}}{\sqrt{A_{0A}}} \right].$$
Detector calibration and performances: TC resolution

**Timing resolution** (timing difference between adjacent bars)

<table>
<thead>
<tr>
<th>$\Delta T$</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>$\chi^2$/ndf</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>988</td>
<td>3.458e-010</td>
<td>4.39e-010</td>
<td>183.7 / 77</td>
<td>131.9 ± 8.4</td>
<td>2.392e-010 ± 2.736e-012</td>
<td>5.435e-011 ± 2.318e-012</td>
</tr>
</tbody>
</table>

$\sigma_T = 54$ ps, close to project goal (100 ps FWHM)
Dalitz $\pi^0$ events $\pi^0 \to \gamma e^+e^-$

- Same topology as signal!
- Gamma/positron energy range (can be chosen) same as for signal
- Worse resolution due to LH$_2$ target

**Comparison with signal is not exact**

$$DT = \left( T - \frac{L^{XEC}}{c} \right) - \left( T - \frac{L^{TC}}{c} \right)$$

**Centre of signal window**

Control sample (flight length correction)

MC validation

Bar17

$\quad = 26.06 \pm 0.01 \text{ns}$

$\sigma = 267 \pm 10 \text{ps}$
Tracking efficiency in the Drift Chamber was severely limited by HV trips. A substantial and growing with time number of DCH planes had low or no efficiency. More details in the dedicated talk on Drift Chambers.

- In spite of that DCH were adequate for many studies.
  Highly pre-scaled TC trigger \(~6000\) C total live protons on target \(2.8 \times 10^7\) \(\mu/s/2mA\)
  Implies \(~8400 \times 10^{10}\) total muon stops

\[N_{\mu \rightarrow \nu \nu} = 11895\] satisfying selection cuts

\[= 8.4 \times 10^{13}\] Number of muon stops calculated

\[\times 10^7\] prescale factor known

\[\times 0.30\] TIC acceptance \(\times\) efficiency for Michel measured

\[\times 0.182\] fraction of Michel spectrum \(> 48\) MeV calculated

\[\times (0.92-1.0)\] conditional trigger efficiency for TIC measured*

\[\times 0.091\] Michel geometric acceptance assumed

\[\times \varepsilon_{DCH}\] drift chamber reconstruction \& cuts unknown

\[\varepsilon_{DCH} = 11895 \times 10^7 / 0.3 / 0.182 / 0.92 / 0.091 / 8.4 / 10^{13} = 0.28-0.31\]
Momentum resolution from MC

- No source of fixed momentum particles – fit to edge of Michel spectrum
- Generate Michel spectrum without inefficiencies
- Fit convolution of generated MC spectrum with Gaussian to reconstructed MC spectrum
  - Fit range (51.5-54.0) MeV/c
  - Done for “tight cuts”
- Resolution worse than original MEG predictions: DRS noise + ?
- Tails from large angle scattering, pattern recognition?, others?

\[ \sigma_{\text{RMS}} = 420 \text{ keV} \]
• No fixed momentum particles to measure response function
• Fit to edge of Michel spectrum to demonstrate resolution
  Edge of spectrum most sensitive to Gaussian part of resolution function
  – fit of high energy tail very dependent on model for tail in resolution function
  Currently worse than MC by a factor of 2, but inefficiencies not yet in MC resolution

\[ \sigma_{\text{RMS}} = 772 \text{ keV} \]  
\[ \sigma_{\text{RMS}} = 830 \text{ keV} \]  
\[ \sigma_{\text{RMS}} = 1002 \text{ keV} \]  
\[ \sigma_{\text{RMS}} = 795 \text{ keV} \]
• Need to correct for track propagation delay to precision of 50 ps ⇒ track length to 1.5 cm
• Trajectory known from target plane through spectrometer to very good precision
• Projection to TIC complicated by material after spectrometer causing scattering, energy loss
• Currently, project to fixed $\phi$ of timing counter with using propagation of Kalman state vector
  No correction for mismatch with reconstructed position in timing counter
  Typical propagation distance is of order 1 m
  Systematic uncertainties in dR, dZ seen, of order 1 cm

• Fully corrected photon-positron timing difference currently at level of 150 ps in RD signal with photon
  energy above 40 MeV
Using DCH to Study Timing Counter

- Use DCH trigger data
  - Require 4 hits in 5 contiguous chambers
  - Run standard analysis, positron selection criteria
  - Measure probability of having a TIC hit
Radiative Decay peak is searched in:

- Dedicated Low Intensity run
- Standard Intensity

The distribution $T_{e^+} - T_{\gamma}$ shows a clear peak!!

Selecting high $E_\gamma$ time resolution is close to design value!!
Conclusions

- Tracking efficiency in current run is poor, mostly due to DCH performance
- Momentum resolution not yet corresponding to MC (Inefficiency?)
- TC fibre performance limited by malfunctioning digital electronics, adequate otherwise
- TC bar performance in line with design parameters
- Radiative Decay peak cleanly detected with good time resolution
- Analysis currently adequate for data with MEG sensitivity of order few \( 10^{-12} \)
- Significant improvement in MEG sensitivity per day can be achieved
  - Replacing TC fibre electronics
  - Improvements in DCH resolution function
    - improved chamber efficiency (hardware)
    - Improved noise performance (hardware)
    - some tuning (software)
  \[\Rightarrow\text{ increase in sensitivity per day by 3}\]

Design sensitivity is within reach in three years data taking!
Backup slides
Drift Chambers 1)

MEG target

DC planes
Timing Counter 3)

TC after installation in MEG
Detector calibration and performances: DC & target

- Target position and drift chambers alignment checked by optical survey. Target orientation known within 0.2°.
- Final alignment based on tracks:
  - cosmic rays;
  - Michel positrons → x-t calibration, algorithm refinement
Waveform Analysis

- Based on waveforms on 2 anode ends and 4 pads associated with each cell

waveform noise limits resolution

hardware improvements anticipated
- Improvement in noise level would significantly improve resolution
Check of Angular Resolution

- No source of positrons of known direction
- Fitting provides event-by-event estimate of $\delta \theta$, $\delta \phi$

- Target designed with holes to test of resolution in projection to the target
  $\Rightarrow$ infer $\delta \theta$, $\delta \phi$
- Take slice in target projection around hole, try to match depth of dip data to MC
- Position of hole vs. angle of track with respect to target normal sensitive to target position
- Difficult to quantitatively match distributions
  - Beam spot has different shape
  - Hole on falling distribution
  - Work in progress
  - First try requires increasing resolution in $\delta Z$, $\delta Y$ by 50%
- Position of hole good to at least 1 mm – negligible contribution to $\theta_e^\gamma$ uncertainty
Detector calibration and performances: DC resolution

DC performances: momentum resolution

Reconstructed Spectrum (Michel Trig.)

- $E_{\text{edge}} = 52.84 \pm 0.02$ MeV/c
- $\sigma_p = 0.48 \pm 0.01$ MeV/c

**FWHM** $p$ (meas.) = 2.1%

**FWHM** $p$ (MC) = 0.9%

Expected improvements in:
- detector resolution
- tracking efficiency

Decay vertex resolution

$\sigma_v \approx 1$ mm
as required (holes on target)
Drift Chamber Performance from Tracking

- **Rφ position resolution**
  - Look at difference in hits in 2 planes in chamber projected to central plane using trajectory information: insensitive to multiple scattering
  - Typical spatial resolution of 260 microns
  - Systematic effects with drift distance and angle – ad-hoc corrections applied

- **Z position resolution**
  - Similar technique to that for Rφ resolution

Inferred $\sigma_z = 0.15$ cm
**TC time resolution stability**

- Same TW calibration constants
- Stable over time
  no need of different sets of constants
Extrapolate tracks from DCH to TC bars

Given a track and a TC bar hit matching efficiency is 91%
Some data/MC discrepancy
Inter-bar offsets monitoring

$\Delta T\gamma\gamma$ mean [ns]

Bar15: change in DRS board

- No clear trend vs time

Weekly monitoring (periodic DB updates)
**Effective velocity with TICZ**

Pass-thru cosmics, 2 hit fibers (clusters) expected  
Single-cluster inefficiency: 27%  

due to cosmics geometrical inefficiency  
and dead/not fibers (5%)  

Using  
\[
Z_{fiber} = \frac{1}{2} v_{eff} \cdot (t_1 - t_0)
\]
**TC – LXe relative timing calibration with Boron**

4.4 MeV in LXe = 1180 ps

For coincident gamma’s at the target, $T_{TC} - T_{LXe} = -32$ ns

11.6 MeV in LXe = 885 ps

TC-LXe timing difference at target

Correlation between energy and timing resolution

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<tr>
<td>5518</td>
<td>-3.159e-08</td>
<td>3.614e-09</td>
<td>11.23 / 8</td>
<td>462.4 ± 10.7</td>
<td>-3.198e-08 ± 2.1</td>
<td>1.18e-09 ± 3.</td>
</tr>
</tbody>
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<tr>
<td>2662</td>
<td>-3.145e-08</td>
<td>2.897e-09</td>
<td>4.503 / 5</td>
<td>272 ± 9.7</td>
<td>-3.199e-08 ± 2.953e-11</td>
<td>8.847e-10 ± 3.769e-11</td>
</tr>
</tbody>
</table>
**TC time resolution**

\[
\frac{S_{DT}}{\sqrt{2}} \quad \text{Estimate of single bar time resolution}
\]

Assuming the two bars to have the same intrinsic time resolution

\[s_{DT} = \sqrt{2}\]

Upper limit on average time resolution (\(\sigma\)) in 60-90ps range

Includes effect of DRS digitization (~10 ps)