CLFV Golden channel: $\mu^+ \rightarrow e^+ \gamma$

**Physics motivation:**

**Charged Lepton Flavour Violation** are key processes in SM:
lepton interactions can only couple within the same family

\[
\begin{align*}
\bar{\nu}_e & \leftrightarrow e^\pm \\
\bar{\nu}_\mu & \leftrightarrow \mu^\pm \\
\bar{\nu}_\tau & \leftrightarrow \tau^\pm
\end{align*}
\]

But neutrino oscillations shows that **Lepton family are violated**
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**World best upper limit by MEG I:**

$\text{BR}(\mu^+ \rightarrow e^+ + \gamma) \leq 4.2 \cdot 10^{-13} \ (\@ 90\% \ C.L.)$

*The European Physical Journal C 76.8 (2016): 434*

**MEG II experimental sensitivity:**

$\text{BR}(\mu^+ \rightarrow e^+ + \gamma) \leq 6 \cdot 10^{-14} \ (\@ 90\% \ C.L.)$

*Symmetry 13.9 (2021): 1591*

**One order of magnitude improvement!**

**Final statistic to be collected in 3 years:** $\sim 10^{16} \mu^+$ decays

Use world **most intense** continuous muon beam: $7 \cdot 10^7 \mu^+/s$ at PSI (CH)
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Signal

Physics Background:

Accidental Background:

\[ \alpha R_\mu BR(\mu \rightarrow e\nu\bar{\nu}\gamma) \]
\[ \alpha R^2_\mu \Delta T \]

Photon from: Radiative, AIF, Bremsstrahlung
Design of MEG II Experiment

Experiment tailored to $\mu^+ \rightarrow e^+ \gamma$ search

- Stop muon at center of experiment
  - exploit the simple 2-body decay kinematics
  - but harsh pileup environment from other muons
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Detectors must provide high resolution **charge** and **time** reconstruction despite the extreme occupancy

All **signals sampled at >=1.4 GHz**

+ Full waveform stored for **offline processing**

- Noise rejection
- Pileup identification and subtraction
- Feature extraction
- Hit clustering
- …
High speed digitization: the WaveDAQ system

Full MEG II experiment needs ~9000 channels: commercial FADCs too slow or too costly → DRS4 ASIC Chip

**Analog switched capacitor array**: analog memory with depth of 1024 sampling cells
Developed at PSI, provides a “snapshot” of signal before trigger time

Extensively used also in MEGI

800 MSPS ↔ 5 GSPS sampling speed

Strong constrain on trigger system:
decision must happen before 1024 samples are collected

\[ T^{Max} = \frac{1024}{f_{sampl}} \]

Trigger latency < 731ns @1.4 GHz
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---

WaveDREAM board:
16 ch Drs4 REA
dout Module (10cm x 16 cm)
Waveform digitizer with two DRS4 each with 80 MHz ADC for readout

Includes SiPM bias and amplification for Liquid Xenon detector and Timing Counter.

More details: Poster #6
“Design of the WaveDAQ System”
by S. Ritt
How to reduce the event rate?

MEG event size is 3 MB after **compression and data reduction**

At 20 Hz is ~500 TB every 3 month!
How to reduce the event rate?

MEG event size is **3 MB** after compression and data reduction
At 20 Hz is ~500 TB every 3 month!

**Physics observables:**
- Photon Energy $E_{\gamma}$
- Positron Momentum $P_e$
- Relative angle $\Theta_{e\gamma}$
- Time coincidence $T_{e\gamma}$

Require CDCH: Cannot be fully exploited by trigger
How to reduce the event rate?

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**Physics observables:**
- Photon Energy $E_\gamma$
- Positron Momentum $P_e$
- Relative angle $\Theta_{e\gamma}$
- Time coincidence $T_{e\gamma}$

**Trigger-level** requests:
- Estimate $E_\gamma$ through signals from Liquid Xenon photon detectors $\rightarrow$ **QSUM trigger**
- Estimate $T_{e\gamma}$ by comparing hit time in Timing Counter and in Liquid Xenon $\rightarrow$ **Time trigger**
- Combines $\Theta_{e\gamma}$ and $P_e$ by checking if the pair of hits is compatible with signal topology $\rightarrow$ **DirectionMatch trigger**

Starting from $\sim$100 kHz $\gamma$ rate in Liquid Xenon

- Reduction factor: $\sim$100 $\rightarrow$ 1 kHz rate
- Reduction factor: $\sim$10 $\rightarrow$ 100 Hz rate
- Reduction factor: $\sim$10 $\rightarrow$ 10 Hz rate
WaveDAQ trigger inputs

Each WaveDREAM board contains a dedicated **ADC** and **Discriminator** for all input signals.

If possible prefer the discriminator: ADC conversion takes ~100 ns.

Flexibility to implement **charge** or **time** based selection within the onboard FPGA or on the global experiment.

**Signal examples:**

- **Liquid Xenon Detector**
- **Timing Counter**

DRS4 “**Transparent Mode**”: same ADC for Trigger and readout.

**Flexibility to implement charge or time based selection**

*If possible prefer the discriminator: ADC conversion takes ~100 ns.*
WaveDAQ trigger subsystem

Trigger information merging by a 3-layer three made of 45 Kintex 7 Trigger Concentrator FPGA Board [TCB] using low latency serial links
WaveDAQ trigger subsystem

Trigger information merging by a 3-layer three made of 45 Kintex 7 Trigger Concentrator FPGA Board [TCB] using low latency **serial links**

**Every clock cycle is important:** use shift registers instead of Multi-Gigabit Transceiver trade bandwidth (640 Mbit/s * 8 lines) for latency (~40 ns)

1 custom crate = 16 WaveDREAMs = 256 channels

Multi-crate systems up to 16384 channels
QSUM trigger computes the **weighted sum** of pedestal-subtracted signal amplitude

\[ E_{\gamma} \approx \sum_{i \in LXe} g_i (V_i - V_{i,\text{pedestal}}) \]

This selection have to account for **ADC conversion time**
- slowest path of trigger selection
- use amplitude: cannot afford to integrate signal charge

Pedestal estimated “on the fly” from previous samples to subtract low frequency noise

**Channel-by-channel weight** \(g_i\) to account for:
- Gain
- Detection efficiency
- Detector type (SiPM-PMT)
- Ageing speed
- ....
QSUM trigger: design

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\[ \rightarrow \text{slowest path of trigger selection} \]

\[ \rightarrow \text{use amplitude: cannot afford to integrate signal charge} \]

Pedestal estimated “on the fly” from previous samples to subtract low frequency noise

Use of **DSP48 primitives** of Xilinx FPGAs to compute difference, product and for the summation speedup

**Lesson learn:** Exploit your FPGA resources
QSUM trigger: performance

Two main **calibration sources** for Liquid Xenon detector

**C-W proton accelerator**
1 MeV proton on Li BO\(_4\) target

Energy calibration lines:
\[ p^6\text{Li} \rightarrow \ ^7\text{Be} \, \gamma (17.6 \text{ MeV}) \]
\[ \rightarrow ^7\text{Be} \, \gamma (14.6 \text{ MeV}) \]

Thee times a week

**Charge Exchange reaction**
Change from \( \mu^+ \) to \( \pi^- \) beam on liquid hydrogen target

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

Movable array of BGO Crystals

Once in the year

3.5% trigger energy resolution @17.6 MeV

2.4% trigger energy resolution @ 55 MeV

Current offline energy reconstruction: 1.8% @signal energy
QSUM trigger addendum: Q/A selection

Well-known property of Noble Gas scintillators:

Emission time of photons depends on energy deposit mechanism

- **α-like**
  - Fast
    - Xe + energy $\rightarrow$ Xe$^*$
    - Xe$^*$ + Xe $\rightarrow$ Xe$_2^*$ $\rightarrow$ 2 Xe + photon

- **γ-like**
  - Slow
    - Xe + energy $\rightarrow$ Xe$^+$ + e$^-$
    - Xe$^+$ + Xe $\rightarrow$ Xe$_2^+$
    - Xe$_2^+$ + e$^-$ $\rightarrow$ Xe$_2^{**}^*$ $\rightarrow$ Xe$_2^{**}^*$ + heat
    - Xe$_2^{**}^*$ $\rightarrow$ 2 Xe + photon

Graph showing mV vs. time (ns) for α-like and γ-like reactions.
QSUM trigger addendum: Q/A selection

Well-known property of Noble Gas scintillators:
Emission time of photons depends on energy deposit mechanism

α-like Fast
Xe + energy → Xe*
Xe* + Xe → Xe2* → 2 Xe + photon

γ-like Slow
Xe + energy → Xe\(^+\) + e\(^-\)
Xe\(^+\) + Xe → Xe\(_2\)^\(^+\)
Xe\(_2\)^\(^+\) + e\(^-\) → Xe\(_2\)^\(*\) → Xe\(_2\)^\(*\) + heat
Xe\(_2\)^\(*\) → 2 Xe + photon

Online pulse shape discrimination

Preliminary

25 point-like alfa sources on wires in LXe
Localized energy deposit (40μm range) for detection efficiency monitoring & calibration

Charge/Height ratio provides discrimination capability online using DSP48 resources in TCBs

Good enough for triggering: further selection offline with template fitting
DirectionMatch trigger: design

Online track fitting is not feasible: rely only on Liquid Xenon - Timing Counter channel correlation

1. Search Max on the inner face of Liquid Xenon detector
   - Inner face
   - Reduce combinatorial: group channels in 4x4 SiPM “Patches” (6x6 cm)

2. Search Hit position in Timing counter
   - Reduce fake combinatorial: Select only first “Tile” hit

Single sensor in Liquid Xenon detector is sensitive to shower fluctuations ($R_{\text{Molière}}^{\text{LXe}} = 5.2 \text{ cm}$)
DirectionMatch trigger: design

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3. Check position of TC hit is consistent with signal positrons (Lookup Table from MC)
   - 97% efficiency requested on MC

Single sensor in Liquid Xenon detector is sensitive to shower fluctuations ($R_{\text{Molière}}^{\text{LXe}} = 5.2$ cm)

Lesson learn: Exploit your detector strengths!
DirectionMatch trigger: performance

Operated for the first time in MEG II during 2021 beam time:
Availability of all electronics channel was crucial to explore the whole solid angle

Strategy: check bias induced using dedicated reduced bias trigger

<table>
<thead>
<tr>
<th>Num</th>
<th>Trigger</th>
<th>Enabled</th>
<th>Prescaling</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>MEG</td>
<td></td>
<td>2</td>
<td>16.308645</td>
</tr>
<tr>
<td>1</td>
<td>MEG low Q</td>
<td></td>
<td>86</td>
<td>80.847122</td>
</tr>
<tr>
<td>2</td>
<td>MEG wide Angle</td>
<td></td>
<td>60</td>
<td>60.56076</td>
</tr>
<tr>
<td>3</td>
<td>MEG wide Time</td>
<td></td>
<td>31</td>
<td>28.639572</td>
</tr>
</tbody>
</table>

Physics trigger
“Reduced bias”

Caveat: Sensitive to offline reconstruction performance of Liquid Xenon detector and Positron Spectrometer
Offline algorithm development still ongoing

Clear effect of reduction of events with opening angle < 3 srad
Modern FPGA input tiles have integrated shift registers: **Oversampling** of input signals

Can get signal timing timing at 1/n of the clock cycles resolution (n=8)

**Minimal logic and latency** need: encoder at output to identify transitions

Resolution @80 MHz: $12.5\, \text{ns}/8 \sim 1.56\, \text{ns}$

Single channel $\sigma = \frac{1.56\, \text{ns}}{\sqrt{12}} \sim 450\, \text{ps}$

**Lesson learn:** Do not over-engineer
Time trigger: design

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To Hit identification logic

**Lesson learn:**
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Resolution @80 MHz: 12.5 ns/8 ~ 1.56 ns

Single channel $\sigma = \frac{1.56 \text{ ns}}{\sqrt{12}} \sim 450$ ps

LXe Inner face: 4092 VUV SiPMs

Timing counter scintillator:
Two side SiPM readout

average both ends

average all channels within this region
Time trigger: performance

Detector time resolution (<100ps) much better than trigger one: only relevant effect is trigger

Extract trigger effect from ratio of two distribution

~3ns coincidence resolution
Time trigger: performance

Detector time resolution (<100ps) much better than trigger one: only relevant effect is trigger

Source of bias observed in depth dependence of time reconstruction:
Time walk on discriminator because of slow MPPC risetime (0.1 mV/ns)

~3ns coincidence resolution

Extract trigger effect from ratio of two distribution
Conclusions and prospects

MEG II ended its first **Physics run** in 2021.
Data sanity check: radiative decays observed!

Definitely a major step toward the $\mu \rightarrow e\gamma$ physics data taking next years

The **WaveDAQ system** was successfully deployed (x8 more channels than 2020) and the DAQ side performed extremely well.

**MEG II trigger system performed very smoothly for the first time with all electronics.**
Refinements planned for 2022, especially on the timing of the Liquid Xenon signals.

WaveDAQ application to other experiments:
poster #49 → “The fragmentation trigger of the FOOT experiment”
poster #257 → “Looking for Cherenkov light in liquid Xenon with LoLX”
**Dipole and 4-lepton operator**

Additional EM vertex needed to convert an operator to the other

---

**Dipole operator**

\[ \mu \rightarrow e\gamma \]

\[ \mu \rightarrow \text{ee} \]

**4 lepton operator**

\[ \mu \rightarrow \text{eee} \]

\[ \mu N \rightarrow eN \]

---

**Huge theoretical effort on combining results from various processes**

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_{\alpha} C^{(5)}_{\alpha} O^{(5)}_{\alpha} + \frac{1}{\Lambda^2} \sum_{\alpha} C^{(6)}_{\alpha} O^{(6)}_{\alpha} + \ldots
\]

\( C^{(i)}_{\alpha} \) = coupling associated to operator \( O^{(i)}_{\alpha} \)

\( \Lambda \) = scale of physics being integrated

\( \Lambda = 1 \text{ TeV} \)

---

<table>
<thead>
<tr>
<th>Model</th>
<th>( \mu \rightarrow \text{eee} )</th>
<th>( \mu N \rightarrow eN )</th>
<th>BR(( \mu \rightarrow \text{eee} )) / BR(( \mu \rightarrow e\gamma ))</th>
<th>CR(( \mu N \rightarrow eN )) / BR(( \mu \rightarrow e\gamma ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>Loop</td>
<td>Loop</td>
<td>( \approx 6 \times 10^{-3} )</td>
<td>( 10^{-3} - 10^{-2} )</td>
</tr>
<tr>
<td>Type-I seesaw</td>
<td>Loop*</td>
<td>Loop*</td>
<td>( 3 \times 10^{-3} - 0.3 )</td>
<td>( 0.1 - 10 )</td>
</tr>
<tr>
<td>Type-II seesaw</td>
<td>Tree</td>
<td>Loop</td>
<td>( (0.1 - 3) \times 10^{3} )</td>
<td>( O(10^{-2}) )</td>
</tr>
<tr>
<td>Type-III seesaw</td>
<td>Tree</td>
<td>Tree</td>
<td>( \approx 10^{3} )</td>
<td>( O(10^{3}) )</td>
</tr>
<tr>
<td>LFV Higgs</td>
<td>Loop\dag</td>
<td>Loop*\dag</td>
<td>( \approx 10^{-2} )</td>
<td>( O(0.1) )</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>Loop*</td>
<td>Loop*</td>
<td>( 0.05 - 0.5 )</td>
<td>( 2 - 20 )</td>
</tr>
</tbody>
</table>

---

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17 / 15

Pisa Meeting on advanced detector, 27-05-2022

https://doi.org/10.1393/ncr/i2018-10144-0
MEG experiment: signature and backgrounds

**Signal**

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

Physics Background:

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

Accidental Background:

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

\[ R_{\text{Rad}} = R_\mu \text{BR}(\mu \rightarrow e\nu\bar{\nu}\gamma | \Delta E_\gamma, \Delta E_e, \Delta \Theta_{e\gamma}) \]

\[ R_{\text{Acc}} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_{\gamma}^2 \cdot \Delta \Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma} \]

**Dominating for high muon rates**

\[ R_\mu \]

Photon from: Radiative, AIF, Bremsstrahlung

Marco Francesconi
MEG I - MEG II comparison

Design performances

<table>
<thead>
<tr>
<th></th>
<th>MEG I</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{e^+}$ (keV)</td>
<td>380</td>
<td>130</td>
</tr>
<tr>
<td>$\theta_{e^+}$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$\phi_{e^+}$ (mrad)</td>
<td>8.7</td>
<td>3.7</td>
</tr>
<tr>
<td>$E_{\gamma}$ $w_{\gamma} &gt; 2;\text{cm}(%)$</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>$E_{\gamma}$ $w_{\gamma} &lt; 2;\text{cm}(%)$</td>
<td>2.4</td>
<td>1.0</td>
</tr>
<tr>
<td>$u_{\gamma}$ (mm)</td>
<td>5</td>
<td>2.6</td>
</tr>
<tr>
<td>$v_{\gamma}$ (mm)</td>
<td>5</td>
<td>2.2</td>
</tr>
<tr>
<td>$t_{e^+\gamma}$ (ps)</td>
<td>122</td>
<td>84</td>
</tr>
</tbody>
</table>

Liquid Xenon Drift Chamber Timing Counter
Photon detector: the Liquid Xenon detector

- 4092 UV SiPMs 12mmx12mm
- Optimised positions of the remaining 668 PMTs

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>5 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Energy</td>
<td>2.4%-1.7%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Timing</td>
<td>67 ps</td>
<td>60 ps</td>
</tr>
</tbody>
</table>

More details: Poster #332
“Commissioning of Liquid Xenon Gamma-Ray Detector for MEG II Experiment” by A. Matsushita
The Cylindrical Drift Chamber

Single volume stereo drift chamber with He:Isobutane
- $1.5 \times 10^{-3} X_0$ per turn
- Drift cells 6mm x 6mm to cope with pileup (PCB-based construction)
- ~65 hits per track (MEG: ~12)

More details: Poster #236
“Analysis and study of the problems on the wires used in the MEG CDCH and the construction of the new drift chamber”
by G. Chiarello

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>29%</td>
<td>65%</td>
</tr>
<tr>
<td>Theta</td>
<td>9.4 mrad</td>
<td>6.7 mrad</td>
</tr>
<tr>
<td>Momentum</td>
<td>306 keV/c</td>
<td>100 keV/c</td>
</tr>
</tbody>
</table>
The pixelated Timing Counter

Final detector fully tested with **full beam intensity**

(7 \( 10^7 \) \( \mu \)s):

- 256 scintillating “Tiles” per module
- Multiple hits belonging to the same **positron track**
- Tracking capability to seed CDCH tracks
- Auxiliary Laser for stability monitoring

More details: Poster #184

“Operational results with the pixelated timing Counter (pTC) of the MEGII experiment during the first year of physics data taking”

by P.W. Cattaneo

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing</td>
<td>62 ns</td>
<td>30 ns</td>
</tr>
</tbody>
</table>
WaveDREAM detail

Analog Frontend

- 2 x 8 channels...
- SiPM biasing

Ethernet readout

- Ethernet readout
- Crate connector
Serial links

- **8 bit word sent each clock period:** 640 Mbps with 3 clk cycles latency
- Backplane track length different for each slot
- Delay to sample “value” stable moment
- Bitslip to align characters within each word
- Automatic slot by slot calibration needed → Finite State Machine
Trigger latency translate in peak position in the DRS4 window

If it exceed $1024/f_{\text{DRS}}$ the signal falls outside DRS snapshot window

Final WaveDREAMs have a quicker ADC:
- Still 80 MHz speed but smaller latency
- Trigger latency improved by $\sim 120$ ns
- Current algorithms run in 560 ns
- 1.8 GHz sampling speeds possible

Constraint on additional baseline for offline analysis
Multithreaded DAQ system

TDAQ Software completely written in c++11:

- High parallelization
- Tailored to MEG II TDAQ needs
- Use new c++ thread interface
- Provides key-value storage of board parameters
- Can add other stages (zero suppression, feature extraction…)
- Optional disk writing or interface with other DAQ software (MIDAS for MEG II)
- Flexibility to face system scaling:
  - More packet collectors
  - More Waveform Calibration threads
The challenge of datasize and dead time

Main drawbacks of high speed digitizers approach:

Huge single-channel data size: 1.5 KB/waveform

Enormous uncompressed event: 12.4 MB/event

DRS4 does not convert data in real time

Takes 375 μs to download the samples after a trigger is generated

Continuous beam: dead time = event loss

Goal 24 Hz Trigger rate:
Live time fraction is 99%
Data taking perspectives, depending on annealing

Three DAQ scenarios

- A: MEG II intensity run w/o annealing
- B: Half of MEG II intensity run w/o annealing
- C: MEG II intensity run w/ annealing at PDE 5% during run

Assumption

- Worst case of PDE decrease (2% after 60 days MEG II intensity, measured speed in 2019)
- 140 days beam time per year (84% live time)
- Annealing requires 60 days