Status of the MEG II Experiment

Dylan Palo – On Behalf of the MEG II Collaboration
Overview

• Goal:
  • Describe MEG II experimental technique and show results from the first MEG II run

• Discuss:
  • Charged Lepton Flavor Violation (CLFV) background
  • MEG II experimental overview
  • MEG II physics data
    • Detector resolutions
    • Sensitivity projections
Charged Lepton Flavor Violation
\( \mu \rightarrow e \gamma \) Decay

- \( \mu \rightarrow e \gamma \) decay is an example of charge lepton flavor violation (CLFV)

- The SM \( \mu \rightarrow e \gamma \) BR is **negligible**: \( \sim 10^{-54} \); proportional to \( \left[ \frac{\Delta (m_\nu^2)}{m_W^2} \right]^2 \)

- SM extensions (e.g. SUSY) allow for other \( \mu \rightarrow e \gamma \) decay channels

- Theorized SUSY \( \mu \rightarrow e \gamma \) is detectable (\( \text{BR} \sim 10^{-11}: 10^{-15} \)) since the mass splittings can be comparable to masses

- Detecting \( \mu \rightarrow e \gamma \) would be a clear indication of new physics
The MEG II collaboration searches for the $\mu \rightarrow e \gamma$ decay; one of several ongoing searches for charged lepton flavor violation (CLFV).

- The current $\mu \rightarrow e \gamma$ decay sensitivity is $4.2 \times 10^{-13}$ (90% Confidence Level), set by MEG I.
- The MEG II collaboration aims to increase the sensitivity by an order of magnitude.
MEG II Experimental Overview
MEG II Experiment

- International collaboration of ~ 60 physicists
- Based at Paul Scherrer Institut located in Villigen, CH near Zurich
- Uses the PSI proton ring cyclotron
  - 590 MeV protons
  - Unbunched surface muon beam produced: $R_\mu \approx 7 \times 10^7$ Hz
The experiment relies on precise kinematic measurements of the decay products to distinguish between signal/background decays.

The $\mu \rightarrow e\gamma$ signal is a two-body decay at rest, signal $e/\gamma$ have equal and opposite momentum ($m_\mu/2$).

Background does not have these characteristics:

- RMD (radiative muon decay): $\mu^+ \rightarrow \gamma e^+\nu_\mu\bar{\nu}_e$ (small $E_\mu\nu_\mu\bar{\nu}_e$)

- Accidental background: high $p_{e^+}$ coincident with $\gamma$ from RMD (dominant background), AIF ($e^+ e^- \rightarrow \gamma\gamma$) or bremsstrahlung
- The experiment stops $\mu^+$ in a thin film target ($R_\mu \sim 7 \times 10^7$ Hz)
- Stopped $\mu^+$ decay in target; decay products ($e$, $\gamma$) are measured in various detectors
- Similar design to MEG I, but all detectors have been upgraded
- Kinematic estimates at target by $e^+$ Kalman propagation to target, then $\gamma$ propagation to $e^+$ target vertex ($\Delta \theta_{e+\gamma}, \Delta \phi_{e+\gamma}, \Delta t_{e+\gamma}, \Delta E_{\gamma}, \Delta p_{e+}$)

\[
N_{acc} \propto R_{\mu+}^2 \cdot \Delta E_{\gamma}^2 \cdot \Delta p_{e+} \cdot \Delta \phi_{e+\gamma} \cdot \Delta \theta_{e+\gamma} \cdot \Delta t_{e+\gamma} \cdot T
\]
CDCH Detector

- Upgrades:
  - New ultra-light stereo drift chamber to improve efficiency and resolution
  - More track space points in drift chamber to improve resolution (1150 readout drift cells)
  - In 2021, the chamber was filled with He: C₄H₁₀ : C₃H₈O : O₂ (88.2 : 9.8 : 1.5 : 0.5)
  - High voltage wires surrounding sense wire creates drift cell geometry

<table>
<thead>
<tr>
<th>Kinematic Core σ</th>
<th>MEG I</th>
<th>MEG II Goal</th>
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<tbody>
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<td>$p_{e^+}$ (keV)</td>
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<td>$\theta_{e^+}/\varphi_{e^+}$ (mrad)</td>
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<td>e+ Efficiency</td>
<td>30</td>
<td>70</td>
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pTC Detector

- Upgrade: higher hit multiplicity
- Two semi-cylindrical modules, each consisting of 256 timing counters
- Counter consists of a scintillation tile with double-sided SiPM readout
- Individual counter timing precision ~90 ps
- Signal $e_+ < n$ counters $\sim 9$; $\sigma_{t_{e+}} = 30$ ps

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LXe Detector

- One of world’s largest liquid Xe detector
- Upgrade: inner face is now covered by 4092 MPPCs (Multi-Pixel Photon Counters)
- Other 5 sides covered by PMT photon counters

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MEG II 2021 Physics Run
MEG II 2021 Physics Run/Trigger

- First MEG II physics run with a complete set of instrumented electronics

- Dataset:
  - 3.4 M @ 2 * 10^7 μ/s
  - 8.8 M @ 3 * 10^7 μ/s
  - 5.7 M @ 4 * 10^7 μ/s
  - 6.2 M @ 5 * 10^7 μ/s
  - 24M Total

- Trigger Conditions:
  - LXe $E_\gamma > E_{\text{Threshold}}$ (40-45 MeV)
  - Time Match: pTC/LXe $|T_{e+/\gamma}| < 12.5$ ns
  - Spatial Match: pTC/LXe based on μ→eγ decays simulated in Geant4
MEG II 2021 Positron Analysis
2021 Positron Tracks

CDCH Hits
2021 Positron Tracks

pTC Counters
2021 Positron Tracks

Z Slice
On-going work to improve tracking efficiency, \textit{nhits/track}, hit residuals (distance of closest approach/B), etc.

- e.g. CNN (Convolutional Neural Network) model using CDCH digitized voltages to improve DOCA residuals (B)
- Still require optimization of CDCH wire alignment/ optimal magnetic field map

2021 Data

Entries: 70467
Mean: 42.16
Std Dev: 12.16

$3 \times 10^7 \mu/s$
On-going work to improve tracking efficiency, nhits/track, hit residuals (distance of closest approach/B), etc.

- e.g. CNN (Convolutional Neural Network) model using CDCH digitized voltages to improve DOCA residuals (B)

Still require optimization of CDCH wire alignment/ optimal magnetic field map

\[3 \times 10^7 \mu/s\]

2021 Data

\[\text{CNN [\mu m]}\]
\[\sigma_1 = 133, \sigma_2 = 338\]
\[\mu_1 = 1, \mu_2 = 36\]
\[A_2/A_1 = 0.36\]

\[\text{STD [\mu m]}\]
\[\sigma_1 = 133, \sigma_2 = 351\]
\[\mu_1 = 25, \mu_2 = 67\]
\[A_2/A_1 = 0.49\]
2021 Double Turn Analysis

- e.g. data-driven $e^+$ kinematic resolution estimate compares two independently measured/fit turns on a single $e^+$ track
- Compare kinematics at a common plane between the turns
Double Turn Analysis

- Turn kinematic comparison at target plane
- \( \sigma^2_{\Delta} = \sigma^2_{\text{Turn} 2} + \sigma^2_{\text{Turn} 1} \)
- \( <P_2 - P_1> \approx -100 \text{ keV} \), still under investigation... suspect alignment or magnetic field

\[ \phi_{e^+} \text{ estimated at plane perpendicular to track} \]
Double Turn Analysis

- **Preliminary** double turn (DT) resolution estimates are all improved with respect to MEG I

- Improving single hit resolution, wire alignment, magnetic field map, etc. aim to achieve the MEG II goal resolutions

- *Goal resolutions are based on signal $e_+$; double turn resolutions are corrected by MC $\sigma_{signal}/\sigma_{michel}$ ratio

### Kinematic Resolution

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<tr>
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<th>MEG I Core $\sigma$</th>
<th>MEG II Goal Core $\sigma$</th>
<th>MEG II 2021 Preliminary DT Core $\sigma$</th>
<th>MEG II 2021 Preliminary DT Single $\sigma$</th>
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<tr>
<td>$p_{e+}$ (keV)</td>
<td>380</td>
<td>130</td>
<td>94</td>
<td>105</td>
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<td>$\theta_{e+}/\varphi_{e+}$ (mrad)</td>
<td>9.4 / 8.7</td>
<td>5.3/ 3.7</td>
<td>7.4/ 5.3</td>
<td>8.1/ 5.9</td>
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<td>2.4/ 1.2</td>
<td>1.6/ 0.7</td>
<td>1.9/ 0.7</td>
<td>2.1/ 0.8</td>
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$\varphi_{e+}$ estimated at plane perpendicular to track

$3 \cdot 10^7 \mu/s$
2021 pTC Time Resolution

- pTC $\sigma_{t_{e+}}$ estimated by comparing time of even/odd hits in the same “cluster” of SPX hits
- Signal $e_+ <n\text{ hits}> \sim 9$

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<th>Kinematics/Core $\sigma$</th>
<th>MEG I</th>
<th>MEG II Goal</th>
<th>MEG II Preliminary 2021</th>
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<td>$t_{e+}$ (ps)</td>
<td>70</td>
<td>30</td>
<td>35</td>
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MEG II 2021 Photon Analysis
Example Pileup Event

- Image highlights the LXe detector’s ability to discriminate between two time-coincident γ using the inner face
2021 XEC Resolutions

- CEX Reaction:
  - $\pi^- p \rightarrow \pi^0 n$; $\pi^0 \rightarrow \gamma \gamma$
  - $E_\gamma = 0.5m_{\pi^0} \gamma(1 \pm \beta \cos \theta_{\text{rest}})$
  - $\theta_{\text{rest}} = 0$; $\beta \sim 0.2$; $E_\gamma = 55/83$ MeV

- Separate detector (BGO) selects back-to-back $\gamma$ pair ($dt_{BGO-LXe}, E_{BGO}$, Opening angle > 170 deg)

- CEX reaction used to
  - Calibrate $E_\gamma, t_\gamma$
  - Estimate $\sigma_{E_\gamma}, \sigma_{t_\gamma}$

- Still much ongoing work to calibrate LXe to achieve MEG II goal resolutions

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<td>$E_\gamma$ (%)</td>
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<td>1.1</td>
<td>1.8</td>
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<tr>
<td>$t_\gamma$ (ps)</td>
<td>60</td>
<td>60</td>
<td>85</td>
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2021 RMD Timing Peak

- Use true non-accidental RMD $e^+/\gamma$ pairs at standard beam intensity to estimate $\sigma_{t_{e+\gamma}} \sim 107$ ps
- Direct measurement of signal $\sigma_{t_{e+\gamma}}$ with small corrections ($\gamma$ energy, number of pTC hits)
- Already improved with respect to MEG I
- Timing calibration/optimization is still ongoing to improve resolution
Preliminary Sensitivity Estimates

- MEG II 2021 dataset expected to approach the sensitivity limit set by MEG I
- MEG II 2021+2022 expected to surpass MEG I by a factor of ~4
- *Sensitivity hasn’t yet been updated to reflect updated resolutions

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<th>Dataset</th>
<th>Sensitivity ($10^{-13}$)</th>
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<tr>
<td>MEG I Sensitivity</td>
<td>5.3</td>
</tr>
<tr>
<td>MEG II Preliminary 2021 Sensitivity Estimate</td>
<td>5.3-6.1</td>
</tr>
<tr>
<td>MEG II Preliminary 2021+2022 Sensitivity Estimate</td>
<td>1.2-1.4</td>
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Conclusions

• Much work ongoing to improve detector resolution (CDCH wire alignment, magnetic field, LXe calibration, algorithm optimization, etc.). The mentioned improvements aim to achieve MEG II goal resolutions (some already achieved e.g. $\sigma_{p_{e+}}$)

• MEG II 2021 dataset expected to approach the $\mu \rightarrow e \gamma$ decay sensitivity limit originally set by MEG I

• MEG II 2021+2022 expected to achieve the most stringent limit on the CLFV $\mu \rightarrow e \gamma$ decay
• Unexpected events cause higher rate of $e_+$ inefficiency in some phase space regions
• Events cluster into two categories:
  • $-0 < Z < 50$ cm, SPX hits $\leq 2$
  • $-40 < Z < 75$ cm, $\varphi \approx 0$ rad
• These inefficient events are not observed in the MC
• Results in a lower “purity”
  i.e. % events with a reconstructed $e_+$
• Relevant when discussing the single event sensitivity or the efficiency
• $\sigma_\varphi$ degraded at large $\varphi$
• Track continues propagating (and curving due to B Field);
• Easier to get a larger $\varphi$ error in case 2
• e.g. energy error causes $\varphi$ error; magnified by plane $\perp$ to track

\[<\varphi_1 - \varphi_0>^2 \text{ [mrad}^2] \]
Backup: MEG II Experiment Upgrade

- MEG II upgrade based on MEG I experiment limitations
  - **Ultra-light drift chamber to improve efficiency and resolution**
  - **More track space points in drift chamber to improve \( e^+ \) resolution**
  - New \( e^+ \) timing counter design with higher hit multiplicity to improve \( e^+ \) timing
  - Upgraded LXe inner-face with improved granularity for improved \( \gamma \) resolution
  - Higher beam intensity
  - Target position monitoring
  - RMD counter
  - Improved trigger DAQ
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  - Higher beam intensity
  - Target position monitoring
  - RMD counter
  - Improved trigger DAQ

![MEG I](image1)

![MEG II](image2)
Backup: 2021 CDCH Track Properties

- Preliminary track properties for $3 \cdot 10^7 \mu/s$
- On-going work to improve tracking efficiency, nhits/track, hit residuals (B), etc.
- e.g. CNN (Convolutional Neural Network) model using CDCH digitized voltages to improve DOCA residuals (B)
- Still require optimized tuning of CDCH wire alignment/ improve upon magnetic field map
Here, we show the ratio of the MC resolutions for signal/Michel $e_+$

Fit (Reconstructed - MC) to a single gaussian in a truncated region

Older analysis code, not as optimized

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<th>Kinematic Resolution</th>
<th>MEG II MC Signal/Michel</th>
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<td>$p_{e_+}$ (keV)</td>
<td>1.03</td>
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<td>$\theta_{e_+}/\varphi_{e_+}$ (mrad)</td>
<td>0.92/0.94</td>
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