Status and perspectives of MEG II experiment

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Muon4Future2025, 28/May/2025

<u>Outline</u>

- 1. Introduction to $\mu \rightarrow e\gamma$
- 2. MEG II experiment
- 3. Latest result
- 4. Perspective of experiment

1. Introduction to $\mu \rightarrow e\gamma$

Why $\mu \rightarrow e\gamma$ search?

- No SM process for $\mu \to e \gamma$
 - Even with ν -oscillation, Br($\mu \rightarrow e\gamma$) < 10^{-54}
- → Evidence of new physics if discovered

- BSM expectation for $\mu \rightarrow e \gamma$
 - E.g. SUSY in O(10 TeV): Br($\mu \rightarrow e\gamma$) ~ $10^{-14} - 10^{-12}$
- → Within experimental reach





 $10^{-14} - 10^{-12}$: In experimental reach

Context of this talk

- Most stringent limit so far: $Br(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ (90% CL)
 - MEG experiment: 5 years run (2009 2013)
 <u>Eur. Phys. J. C 76(8), 434 (2016)</u>
 - Search with 5.3×10^{-13} sensitivity

Today's new result:

- Achieved ×2.4 higher sensitivity than MEG
- With one-year-long MEG II data taken in 2022

<u>How to detect $\mu \rightarrow e\gamma$?</u>



Best facility for $\mu \rightarrow e\gamma$ @PSI

- $\pi E5$ beamline: DC muon beam of up to $10^8 \ \mu/s$
 - Most powerful beam suitable for $\mu \rightarrow e \gamma$
 - Available thanks to 1.4 MW proton accelerator





Proton ring cyclotron

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Operation and performance of the MEG II detector

The MEG II collaboration

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2. MEG II experiment

Details are published in Eur.Phys.J.C 84 (2024) 2, 190

MEG II overview



Positron detector



Tracking resolution

 $E_{\rm e^+}$ (keV) 89 5.2/6.2 $\phi_{\mathrm{e}^+}, \theta_{\mathrm{e}^+} \ \mathrm{(mrad)}$ 0.61/1.76 $y_{\mathrm{e}^+}, z_{\mathrm{e}^+} \ \mathrm{(mm)}$



Positron timing



- 512 plastic counters in total 110 ps resolution / hit
- 9 hits (average) / signal track

Positron tracking: Drift chamber



- Wire chamber with stereo geometry
- High-density readout (2 3 cells / cm²)
- Reduced material $(1.6 \times 10^{-3} X_0)$

Photon detector



Muon stopping target

- \bullet 174 μm thick plastic
 - Thin material to suppress scattering, etc.
- Alignment methods:
 - Photographic survey of printed markers
 - Analysis of 6 holes in reconstructed positron distribution on target
- \rightarrow Alignment precision of 50 μ m



Electronics & Trigger

- Use of custom integrated DAQ system
 - Full waveform data acquisition (GSPS)
 - Power supply to SiPMs & amplification
 - Triggering system





Highlight: Performance vs MEG



Timeline (since DAQ start)



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New limit on the $\mu^+ \rightarrow e^+ \gamma$ decay with the MEG II experiment

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3. Latest result

Preprint available: arxiv:2504.15711

(Submitted to PRL)

Analysis

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 $t_{\rm e\gamma}$ (ns)

• Extended un-binned likelihood fit to estimate N_{sia}

$$\times \frac{e^{-(N_{sig}+N_{Acc}+N_{RMD})}}{N_{obs}!} \times \prod_{dataset} \left(N_{sig} \cdot S(x) + N_{acc} \cdot A(x) + N_{RMD} \cdot R(x) \right)$$

$$= S(x), A(x), B(x): Multi-dimensional function of energy, time & BG-\gamma counter \\ = Confidence interval calculation with Feldman-Cousins method \\ = Solution = Solution$$

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46

-3

_2

_1

0

Blinding according to

of energy, time

- Time difference
- Photon energy

Sensitivity of this search

- Measured # of muons: $k = (1.34 \pm 0.07) \times 10^{13}$
 - Number of effectively measured muons
 - Evaluation by background positron counting in dedicated dataset
 - \rightarrow Automatic incorporation of positron efficiency & beam rate fluctuation

- Sensitivity to $Br(\mu \rightarrow e\gamma)$: **2**. **2**×**10**⁻¹³
 - Defined as median UL on null toy experiments



Event distribution

• No signal excess observed



Data vs Fit



<u>Result</u>



Comparison with MEG

- Number of observed muon decays
 - MEG: 1.71×10¹³ (in 5 years)
 - This result: 1.34×10^{13} (in 1 year+7 weeks)
 - i.e. Overall efficiency improved by $\times 4$
- Sensitivity on N_{sig}
 - MEG: $N_{sig}^{sens} \sim 9$ \rightarrow Limited by BG
 - This analysis: N^{sens}_{sig} ~ 2.9
 → Still BG-free

× 2.4 higher sensitivity achieved in a year!!

How N_{BG} reduced?



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4. Perspective of experiment

Additional data samples

- Analysis of 2023 + 2024
 - Optimized $R_{\mu} = 4 \times 10^7 \ \mu/s$
 - Observed $\times 2$ more muon decays $\rightarrow O(10^{-14})$ in reach
 - Analysis ongoing
- DAQ planned until 2026
 - 20 weeks assigned in 2025

- 1. Increase in BG: $N_{BG} \propto R_{\mu}^2$
- Declining performance of detector (In particular, positron tracking efficiency)



Expected sensitivity



Foreseen analysis improvement

- (Disclaimer: Here, I selected my own work)
- Developing Transformer-based ML algorithm for positron tracking
 - Transformer: Good at associating queries through attention mechanism
 - Input query: Tracker hits & timing counter hits
 - Outputs: Classification of each tracker hits, "Track hits" or "Pileup hits"



Attention mechanism tries to connect different CDCH hits belonging to the same track

Classification: Do CDCH hits belong to the same track as timing counter hits?

ML-tracking

- ML-output used to filter out pileup hits
 - Demonstrating application to data
 - Expecting O(10%) efficiency improvements

MEG II is not just adding new data samples!!



<u>Summary</u>

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- MEG II aiming at 6×10^{-14} sensitivity
 - Started in 2021 & planned until 2026
- Latest result from 2021 + 2022
 - Search with $\times 2.4$ better sensitivity than MEG final result only in 1 year+7 weeks data
 - Updated limit: ${\rm Br}(\mu \to e \gamma) < 1.5 \times 10^{-13}$ at 90% CL
- Prospects
 - Planned analysis improvement & Some are already demonstrated for coming analysis
 - Possible discussion to increase of beam rate in 2025 & 2026

Backup

Beam rate optimization (since 2023)

- DAQ in 2021 & 2022 was done at different muon beam rate
 - To evaluate detector performance & compare sensitivity
 - $2-5 \times 10^7 \ \mu$ /s stopping rate on target
- Sensitivity vs muon rate
 - 1. Increase in BG: $N_{BG} \propto R_{\mu}^2$
 - 2. Declining performance of detector (Pileup)
 - Rate capability of detector operation (As well as detectors, trigger rate increases)
- → Operation at $4 \times 10^7 \ \mu$ /s was found optimal
 - Dictated by positron track efficiency



Challenge in 2024 run

- Beam collimation magnet runs on LHe supplied by PSI
 - Not having self-contained refrigerator
 - Last summer, LHe plant at PSI was out of service
 - So, start of DAQ was delayed until November
- For coming years, counter measures under discussion with PSI



Normalization breakdown

- Normalization factor: k
 - Number of effectively measured muons

$$Br(\mu o e\gamma) = rac{N_{sig}}{k}$$

• $k_{2021+22} = (1.34 \pm 0.07) \times 10^{13}$

- Evaluation by background positron counting in dedicated dataset
- \rightarrow Can automatically incorporate efficiency factors, minimizing systematics

<u>nough breakdown of contributions to h</u>		
	Value	Incorporation in positron counting
Stopped muons	3.2×10^{14}	Automatically incorporated in positron counting
Geometrical acceptance	11%	Automatically incorporated in positron counting
$\epsilon_{positron}$ (average)	67%	Automatically incorporated in positron counting
ϵ_{photon}	63%	Included in $\mu \rightarrow e \nu \nu \gamma$ count
$\epsilon_{trigger}$	~90%	Partly included in $\mu \rightarrow e \nu \nu \gamma$ count

Rough breakdown of contributions to k

How N_{BG} reduced?

• a



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Use of ML in MEG II tracking

- Idea: Exploit matching to timing counter
 - Good time resolution to separate pileup, so hits are reliably clustered
 - Positron reconstruction always needs to be matched with timing counter hits



Use of ML in MEG II tracking

- ML designed as chamber hit classifier
 - Idea similar to object detection application
 - One inference for each timing counter cluster (Not one inference for one event)
 - If CDCH hits likely belong to track matched with given timing counter cluster, so labeled
 - If not, labeled as "noise"



Original Transformer vs MEG II use

- We always require chamber-scintillator matching to reconstruct positron
 → Use of cross-attention b/w them
- Hit assignment to track label according to decoder output



