



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

MEG II collaboration

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Abstract This letter reports the result of the search for the decay $\mu^+ \rightarrow e^+ \gamma$ undertaken at the Paul Scherrer Institut in Switzerland with the MEG II experiment using the data collected in the 2021–2022 physics runs. The sensitivity of the branching ratio measurement in this search is 2.2×10^{-13} , a factor of 2.4 better than that of the full MEG dataset and obtained in a data taking period of about one fourth that of MEG, thanks to the superior performances of the new detector. The observed data are consistent with the expected background, yielding an upper limit on the branching ratio of $\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 1.5 \times 10^{-13}$ (90% C.L.). Additional improvements are expected with the data collected during

the years 2023–2024. The data-taking will continue in the coming years.

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In the standard model (SM) of particle physics, charged lepton flavour-violating (CLFV) processes are almost forbidden, with extremely small branching ratio ($\sim \times 10^{-54}$ [1] when considering non-zero neutrino mass differences and mixing angles. Hence, the experimental searches for such decays are free from irreducible SM contributions and a positive signal would be unambiguous evidence for physics beyond the SM. Several SM extensions [2,3] predict experimentally accessible CLFV decay rates, with the channel $\mu^+ \rightarrow e^+\gamma$ being particularly sensitive.

The most stringent upper limit on the $\mu^+ \rightarrow e^+\gamma$ branching ratio was set by the MEG II collaboration, $\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 3.1 \times 10^{-13}$ (90% C.L.) [4] by combining the full dataset of the MEG experiment [5] with the dataset of the MEG II experiment collected in 2021. This letter presents a new limit on $\mathcal{B}(\mu^+ \rightarrow e^+\gamma)$ based on the analysis of the data collected in 2022 combined with an update analysis of the 2021 dataset.

1 Signal and background

A signal event is a back-to-back, monoenergetic, time coincident photon-positron pair from a decay $\mu^+ \rightarrow e^+\gamma$ at rest. The energy of both photon and positron is half the muon mass (52.83 MeV) for muons decaying at rest. The background consists of events from radiative muon decay (RMD) $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ and from accidental time coincidences of positrons from muon Michel decay $\mu^+ \rightarrow e^+\nu\bar{\nu}$ with photons from RMD, positron-electron annihilation-in-flight or bremsstrahlung (ACC).

2 The MEG II experiment

The MEG II detector and its performance are described in [6]. It consists of a positron spectrometer, formed by a cylindrical drift chamber (CDCH) and two semicylindrical sectors each with 256 scintillator pixels, one located upstream of the target and the other downstream (pTC), placed inside a superconducting solenoid with a gradient magnetic field along the beam axis, and of a liquid xenon (LXe) photon detector, outside the solenoid, viewed by VUV-sensitive SiPMs on the front face and photomultiplier tubes (PMTs) on the other faces. In addition, a radiative decay counter (RDC) is located downstream centred on the beam axis, to identify the ACC events with an RMD-originated high-energy γ -ray by tagging the corresponding low energy positron in coincidence. It consists of a scintillating plastic detector to measure the positron timing and a LYSO crystal calorimeter to measure the positron energy.

The muon stopping target is elliptical¹ [6]. Its position x_T and planarity are measured with a camera imaging dots printed on its surface and six holes bored in it. A continuous monochromatic μ^+ beam is delivered through a Beam Transport Solenoid onto the target where it is stopped. The trigger for $\mu^+ \rightarrow e^+\gamma$ events is based on the online estimates of the γ -ray energy E_γ , the relative time between the positron and the γ -ray $t_{e+\gamma}$ from the LXe and the pTC, and the positron- γ -ray relative direction from the same detectors.

A right-handed, Cartesian coordinate system is adopted, with the z -axis along the beam direction and the y -axis vertical and pointing upward. A polar spherical coordinate system is also used, with the θ angles referred as usual to the beam axis (z) and the ϕ angles lying in the (x, y) -plane. For the LXe, we defined a local system of curvilinear coordinates (u, v, w) , where u and v are tangent to the cylindrical inner surface of the calorimeter (with u parallel to z) and w is the depth inside the LXe fiducial volume.

3 Event reconstruction

In each event, positron and γ -ray candidates are described by five observables: E_{e^+} , E_γ , $t_{e+\gamma}$, $\theta_{e+\gamma}$ and $\phi_{e+\gamma}$, where $\theta_{e+\gamma}$ and $\phi_{e+\gamma}$ are the polar and azimuthal angles of the relative direction, respectively. The positron kinematics is reconstructed by tracking the trajectory in the magnetic spectrometer with the CDCH and extrapolating it backward to the decay vertex $(x_{e^+}, y_{e^+}, z_{e^+})$ on the muon stopping target and forward to the pTC. The interaction time of the track with the pTC is measured with the hit times of close pixels combined in a cluster, to be corrected for the time of flight to obtain the positron production time t_{e^+} .

The tracking efficiency depends on the stopped muon rate on target R_μ , from $(66.0 \pm 1.5 \pm 4.0_{R_\mu})\%$ at $R_\mu = 5 \times 10^7 \text{ s}^{-1}$ to $(77.0 \pm 1.5 \pm 4.0_{R_\mu})\%$ at $R_\mu = 2 \times 10^7 \text{ s}^{-1}$, limited by the track finding capability. In a high pileup rate with occupancy of up to 50%, the track seeding algorithm is affected by pileup hits. Improvements based on ML technique are under study for the future. Here, the R_μ -subscripted uncertainty arises from the 5% uncertainty on R_μ [6,7]. In addition, the positron efficiency is subject to the pTC acceptance and efficiency of $(91 \pm 2)\%$. In the statistical analysis (see Sect. 5.2), these efficiencies are taken into account along with their uncertainties.

The conversion point of the incident γ -ray inside LXe $(u_\gamma, v_\gamma, w_\gamma)$ and the conversion time are reconstructed by combining signals detected by sensors near the incident posi-

¹ The elliptical shape with small angle (15°) from the beam axis, is required to provide adequate stopping material for the incoming muons still minimizing the traversing the decaying photon and positron.

Table 1 Resolutions expressed in core Gaussian σ and efficiencies of the MEG II experiment in 2022 (2021) measured at $R_\mu = 3 \times 10^7 \text{s}^{-1}$

Resolutions	
E_{e^+} (keV)	89
ϕ_{e^+}/θ_{e^+} (mrad)	3.8/6.2
y_{e^+}/z_{e^+} (mm)	0.61/1.76
$E_\gamma(\%)$ ($w_\gamma < 2\text{cm}$)/($w_\gamma > 2\text{cm}$)	2.4(2.0)/1.9(1.8)
$u_\gamma/v_\gamma/w_\gamma$ (mm)	2.5/2.5/5.0
$t_{e^+\gamma}$ (ps)	78
Efficiencies (%)	
ε_γ	63
ε_{e^+}	67
ε_{TRG}	91(88)

tion. The γ -ray direction $(\theta_\gamma, \phi_\gamma)$ is then reconstructed by joining $(u_\gamma, v_\gamma, w_\gamma)$ with the reconstructed decay vertex. The γ -ray conversion time $t_{\gamma, \text{LXe}}$ is corrected for the time of flight to obtain the production time t_γ . The resolution on $t_{e^+\gamma} = t_{e^+} - t_\gamma$ is dominated by the time resolution of the LXe detector ($\sigma_{t_{\gamma, \text{LXe}}} = 65\text{ps}$). E_γ is determined by summing the number of photons in all photosensors and converting it into energy by means of calibration factors accounting for the energy scale of the detector and its non-uniformity. The RDC measures the time $t_{e^+, \text{RDC}}$ and energy loss $E_{e^+, \text{RDC}}$ of a low-energy positron in coincidence with a high-energy γ -ray in the LXe detector. Table 1 summarizes the detector performances used to build the probability density functions (PDFs) at $R_\mu = 3 \times 10^7 \text{s}^{-1}$, the most used value of stopped muon rate in this dataset, chosen in view of the conservative operation of the detector. For each value of R_μ , the performances change slightly and different PDFs are built.

In this analysis, the reconstruction for 2021 dataset was updated from the one in [4]. In the γ -ray reconstruction, the analysis of pileup γ -rays was revised [8] to increase the signal efficiency by 2%. In addition, γ -ray calibration was updated relying on the 17.6MeV γ -ray source [6], reducing the uncertainty in the energy scale due to temporal variation by 40%. The positron selection was updated to select higher quality tracks, improving the resolution for 15% for most of the variables. The table reports the average ϕ_{e^+} resolution while in [4] the value for $\phi_e = 0$ was reported.

4 Data taking

The data analysed in this letter were collected in the years 2022 (2021) for 18 (7) weeks, for a total DAQ live time of $7.8 \times 10^6 \text{s}$ ($2.9 \times 10^6 \text{s}$). Data were taken at $R_\mu = (3 - 5) \times 10^7 \text{s}^{-1}$ ($(2 - 5) \times 10^7 \text{s}^{-1}$) for a total of 2.5×10^{14} (1.0×10^{14}) stopped μ^+ in 2022 (2021). The average frac-

tion of the DAQ live time with respect to the total time was 72% (63%) in 2022 (2021). During 2022, the fraction improved from 60% in the first 4 weeks to 80% in the last ones. These improvements were achieved thanks to the optimisation of the calibration DAQ scheme, which accounted for 20% and 10% of DAQ time at the beginning and end of 2022, respectively. The remaining 10% downtime in the end of 2022 was dominated by downtime periods of PSI proton accelerator.

The DAQ efficiency, defined as the fraction of recorded events out of all events meeting the trigger requirements, was on average 96% (82%) in 2022 (2021). This improvement was achieved thanks to the improvement of data recording bandwidth by replacing the data storage disk with a faster one. The trigger logic was also improved thanks to the use of PMTs instead of SiPMs in the online γ -ray time reconstruction because the formers have faster time response. As a result, the trigger efficiency for signal events improved from 88% in 2021 to 91% in 2022.

A degradation of the photon detection efficiency (PDE) of SiPMs in the LXe detector challenged the long-term operation [6]. Despite this, the average PDE was kept above 10.8% during 2022, thanks to annealing of SiPMs before the start of the data taking achieving an initial average PDE recovery to 14%. On the other hand, the energy resolution in 2022 data worsened compared to 2021 (see Table 1). The cause of this degradation is under study, a possibility is lower calibration quality, mainly due to the non-linear response of SiPMs with the largest PDEs.

5 Analysis

An extended unbinned maximum likelihood fit is performed to the dataset in the analysis region $48.0\text{MeV} < E_\gamma < 58.0\text{MeV}$, $52.2\text{MeV} < E_{e^+} < 53.5\text{MeV}$, $|t_{e^+\gamma}| < 0.5\text{ns}$, $|\phi_{e^+\gamma}| < 40\text{mrad}$, $|\theta_{e^+\gamma}| < 40\text{mrad}$. The confidence interval for the number of signal events N_{sig} is dictated by the Feldman–Cousins prescription [9], with ordering of the profile likelihood ratio [10]. To translate the result into the branching ratio, a normalisation factor N_μ , the number of effectively measured muon decays in the experiment, is required $\mathcal{B}(\mu^+ \rightarrow e^+\gamma) = N_{\text{sig}}/N_\mu$. A blind analysis was performed, hiding events in the region $48.0 < E_\gamma < 58.0\text{MeV}$ and $|t_{e^+\gamma}| < 1\text{ns}$, until the analysis strategy was finalised.

In order to estimate the background the analysis was also applied to four control analysis regions (the time side-bands) ($-3.0\text{ns} < t_{e^+\gamma} < -2.0\text{ns}$, $-2.0\text{ns} < t_{e^+\gamma} < -1.0\text{ns}$, $1.0\text{ns} < t_{e^+\gamma} < 2.0\text{ns}$, $2.0\text{ns} < t_{e^+\gamma} < 3.0\text{ns}$). Furthermore the region defined by $45\text{MeV} < E_\gamma < 48\text{MeV}$, called “ E_γ side-band”, is used for the estimation of the RMD events. A concise description of the analysis algorithm, which imple-

ments the approach presented in [4], is presented in the following. A detailed explanation of the blinding scheme is described in [5].

5.1 Likelihood function

A fit is performed with the set of observables $\vec{x} = (E_{e^+}, E_\gamma, t_{e^+\gamma}, \theta_{e^+\gamma}, \phi_{e^+\gamma}, t_{e^+, \text{RDC}} - t_{\gamma, \text{LXe}}, E_{e^+, \text{RDC}}, n_{\text{pTC}})$. The number of hits on the pTC, n_{pTC} , is introduced to incorporate the difference in its distribution between signal and background, as well as the dependence of $\sigma_{t_{e^+\gamma}}$ on n_{pTC} .

The likelihood fit has four parameters: a floated parameter, N_{sig} , and three constrained parameters, N_{BG} , N_{RMD} , x_{T} . The likelihood function is obtained from PDFs for the signal ($S(\vec{x})$), RMD ($R(\vec{x})$) and ACC background events ($A(\vec{x})$) as

$$\begin{aligned} \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}}) &= \frac{e^{-(N_{\text{sig}} + N_{\text{RMD}} + N_{\text{ACC}})}}{N_{\text{obs}}!} C(N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}}) \\ &\times \prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}} S(\vec{x}_i) + N_{\text{RMD}} R(\vec{x}_i) + N_{\text{ACC}} A(\vec{x}_i)), \end{aligned}$$

where $\vec{x}_i$ is the set of the observables for the i th event; N_{sig} , N_{RMD} and N_{ACC} are the numbers of signal, RMD and ACC background events in the analysis region; x_{T} is a parameter representing the misalignment of the muon stopping target; N_{obs} is the total number of events observed in the analysis region; $C(N_{\text{RMD}}, N_{\text{ACC}}, x_{\text{T}})$ is a constraint term on the nuisance parameters, a product of three independent Gaussian functions, one for each parameter. N_{RMD} is constrained by extrapolating the number of RMD events in the energy sideband, N_{BG} is constrained by counting the number of accidental events in the timing sideband, and x_{T} is constrained according to the estimated alignment precision.

The signal PDFs are modelled according to the measured resolutions including non-Gaussian tails. The ACC E_{e^+} PDF is the convolution of the theoretical Michel spectrum with acceptance and resolution effects, fitted to data in the sidebands [7]. The ACC E_γ PDF is obtained from the Monte Carlo spectrum, with a Gaussian smearing and verified in the data. The ACC angular PDFs are modelled with polynomials, fitted to data in the side-bands. The RMD PDFs are obtained by convolving the theoretical spectra with the experimental resolutions. The n_{pTC} PDFs are taken from the side-bands for the ACC background, and from the Monte Carlo for signal and RMD.

As a cross-check, two independent analyses are performed with differently constructed PDFs: “per-event PDFs” and “constant PDFs”. In the “per-event PDF” approach, the PDF parameters depend on the single event allowing the maximisation of the sensitivity. Here, the event by event difference is

modelled with parameters that represent the reconstruction performance for each event. The positron PDFs are modelled with the tracking precision estimated by a Kalman filter technique. The γ -ray PDFs depend on the conversion position; the resolution of the γ -ray measurement becomes worse when γ -rays are converted near the end of the detectors fiducial volume. In the other approach, “constant PDFs” are constructed by averaging such dependencies (except that different γ -ray PDFs are used for $w_\gamma < 2\text{cm}$ and $w_\gamma > 2\text{cm}$). Moreover, the angle PDF is also modelled differently: the stereo angle $\Theta_{e^+\gamma}$ between the positron and the γ -ray directions is used instead of the two separate components, $\phi_{e^+\gamma}$ and $\theta_{e^+\gamma}$ and the RDC observables are not used.

5.2 Normalisation

The normalisation factor, $N_\mu = (1.34 \pm 0.07) \times 10^{13}$, is evaluated from the number of Michel positrons counted with a dedicated trigger [5]. The normalisation dataset is collected in parallel with the physics data-taking, such as to account for possible variations of the detector condition and of R_μ . For the purpose of this analysis, the 2021 dataset accounts for $N_\mu^{2021} = (0.28 \pm 0.01) \times 10^{13}$ with the trigger efficiency of $88 \pm 2\%$, which increased from $80 \pm 2\%$ in [4] as a result of improvements in its evaluation. Among the factors contributing to the improvement, the two most relevant are a more refined estimate of trigger direction match efficiency, driven by a better modelling of γ -ray and positron behavior at the trigger level, and an additional analysis selection that rejects events with a large expected energy deposit on dead channels.

5.3 Results

To evaluate the sensitivity, pseudo-experiments with a null-signal hypothesis were generated according to the PDFs and the evaluated number of background events from the sidebands. With the “per-event PDFs” the median of the simulated 90% C.L. upper limit distribution is $S_{90} = 2.2 \times 10^{-13}$ including systematic uncertainties. The contribution to the sensitivity due to systematic uncertainties, mainly due to detector misalignment, uncertainty on detector position, γ -ray energy scale and normalisation, is 3%.

A total of 357 events were observed in the analysis region. The event distributions in each of E_{e^+} , E_γ , $t_{e^+\gamma}$, $\theta_{e^+\gamma}$, $\phi_{e^+\gamma}$, and R_{sig} are shown in Fig. 1, where R_{sig} is defined on the basis of [11] as

$$R_{\text{sig}} = \log_{10} \left(\frac{S(x_i)}{f_{\text{RMD}} R(x_i) + f_{\text{ACC}} A(x_i)} \right),$$

with f_{RMD} and f_{ACC} being the fractions of the RMD and ACC background events, evaluated to be 0.027 and 0.973 in

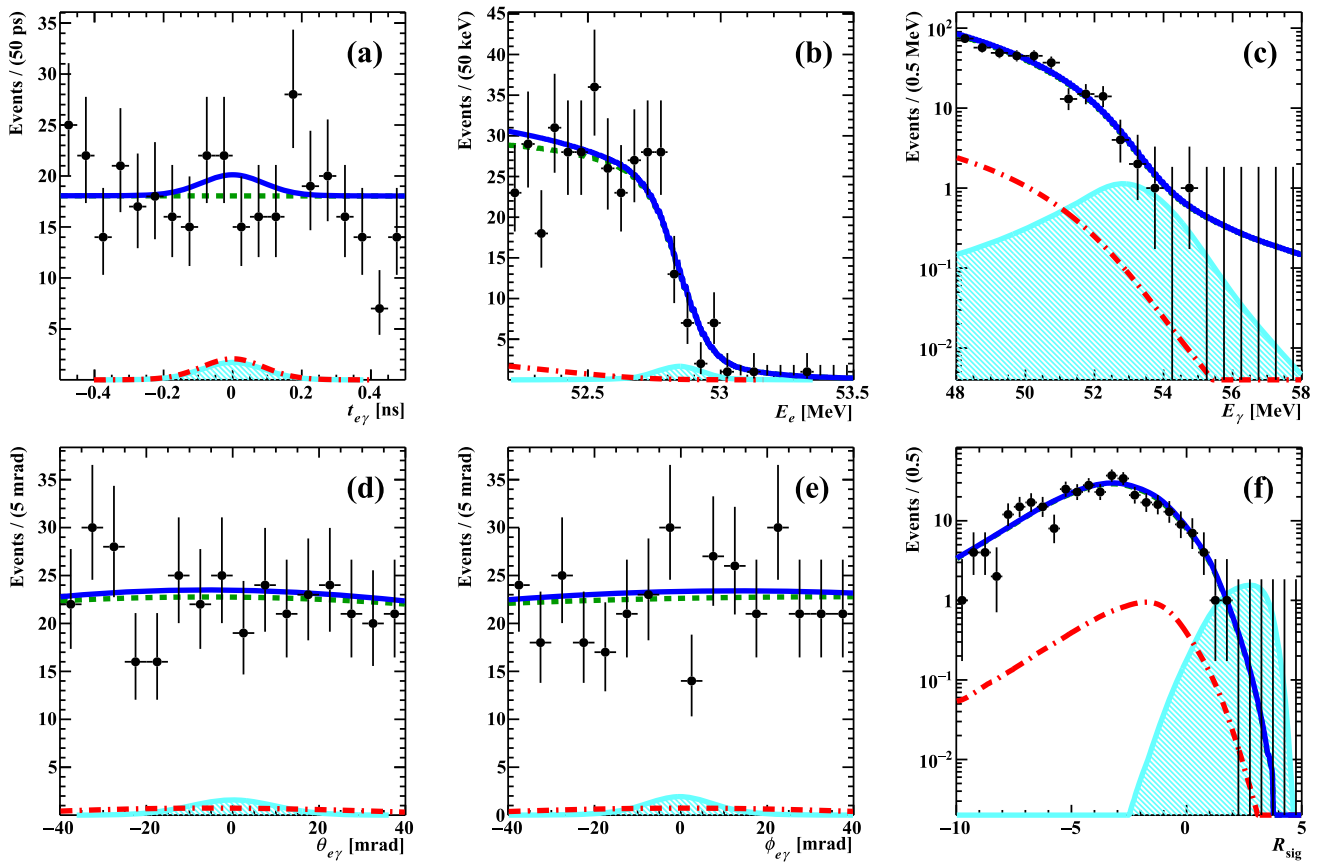


Fig. 1 The projections of the best-fitted PDFs to the five main observables and R_{sig} , together with the data distributions (black dots). The green dash and red dot-dash lines are individual components of the fit-

ted PDFs of ACC and RMD, respectively. The blue solid line is the sum of the best-fitted PDFs. The cyan hatched histograms show the signal PDFs corresponding to the four times magnified N_{sig} upper limit

the side-bands, respectively. Scatter plots in the (E_{e^+}, E_γ) and $(\cos \Theta_{e^+\gamma}, t_{e^+\gamma})$ planes are shown in Fig. 2, with the marker colour and size depending on R_{sig} . The contours of the averaged signal PDFs are also shown. No excess of events is observed in the signal region. Figure 3 shows the observed profile likelihood ratios as a function of the branching ratio for the 2021–2022 dataset of MEG II, compared with the full dataset of MEG. The best estimate of and the 90% C.L. upper limit on the branching ratio for the 2021–2022 MEG II dataset are $\mathcal{B}_{\text{fit}} = -3.8 \times 10^{-13}$ and $\mathcal{B}_{90} = 1.5 \times 10^{-13}$, respectively. This upper limit, that includes the systematic uncertainties, is consistent with the sensitivity calculated from the pseudo-experiments with a null-signal hypothesis. Since the combination of MEG/MEGII data analysis improves the upper limit by a few % only, we decided to not report a separate result.

The sensitivity of the analysis using the “constant PDFs” approach, evaluated with the same estimator, is $\mathcal{S}_{90} = 2.5 \times 10^{-13}$ with 339 events in the analysis region. The best estimate of and the 90% C.L. upper limit on the branching ratio, including systematic uncertainties, are $\mathcal{B}_{\text{fit}} =$

-5.0×10^{-13} and $\mathcal{B}_{90} = 1.9 \times 10^{-13}$. This result is consistent with the expected $\sim 15\%$ better sensitivity of the “per-event PDFs” analysis.

Both analyses were also applied to four fictitious analysis regions inside the time side-bands ($-3 < t_{e^+\gamma} < -2\text{ns}$, $-2 < t_{e^+\gamma} < -1\text{ns}$, $1 < t_{e^+\gamma} < 2\text{ns}$, $2 < t_{e^+\gamma} < 3\text{ns}$) and the results are consistent with the null hypothesis. In Fig. 4 those results are shown together with the upper limits from an ensemble of pseudo-experiments; the vertical green and horizontal orange lines represent the sensitivities of the two analyses.

Finally, the likelihood fit in the analysis region was also performed without the constraints on N_{RMD} and N_{ACC} . The best estimates of $N_{\text{RMD}} = 0 \pm 8$ and $N_{\text{ACC}} = 357 \pm 19$ are consistent with the side-band estimates of $N_{\text{RMD}} = 10.1 \pm 1.7$ and $N_{\text{ACC}} = 364.0 \pm 9.5$, respectively.

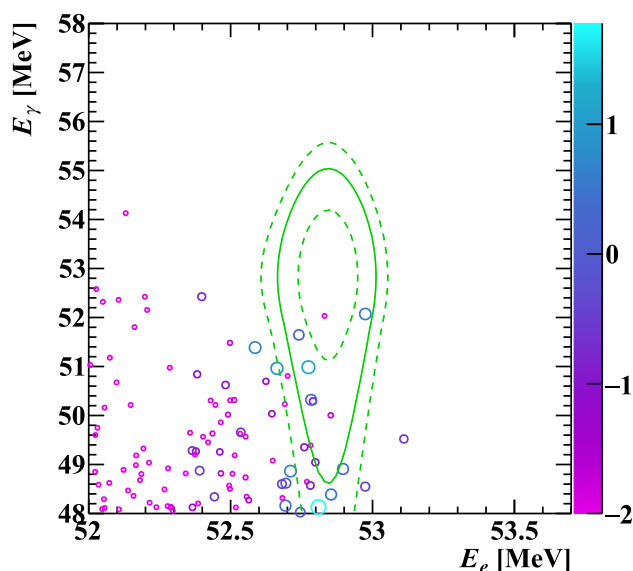


Fig. 2 Event distributions on the (E_{e^+}, E_γ) - and $(\cos \Theta_{e^+\gamma}, t_{e^+\gamma})$ -planes with marker size and colour based on R_{sig} , where events with $R_{\text{sig}} < -2$ are clipped to be displayed as $R_{\text{sig}} = -2$. Selections of $\cos \Theta_{e^+\gamma} < -0.9995$ and $|t_{e^+\gamma}| < 0.2\text{ ns}$, which have 97% signal efficiency for each observable, are applied for the (E_{e^+}, E_γ) -plane, while selections of $49.0 < E_\gamma < 55.0\text{ MeV}$ and $52.5 < E_{e^+} < 53.2\text{ MeV}$, which have signal efficiencies of 93% and 97%, respectively, are applied for the $(\cos \Theta_{e^+\gamma}, t_{e^+\gamma})$ -plane. The signal PDF contours (1σ , 1.64σ and 2σ) are shown

6 Conclusions and perspectives

This letter presents the result of a search for the $\mu^+ \rightarrow e^+\gamma$ decay using data collected in 2021–2022 by the MEG II experiment, based on a blind analysis procedure and a maximum-likelihood statistical analysis.

The sensitivity is $\mathcal{S}_{90} = 2.2 \times 10^{-13}$; the improvement in sensitivity compared to [5] amounts to a factor 2.4 within

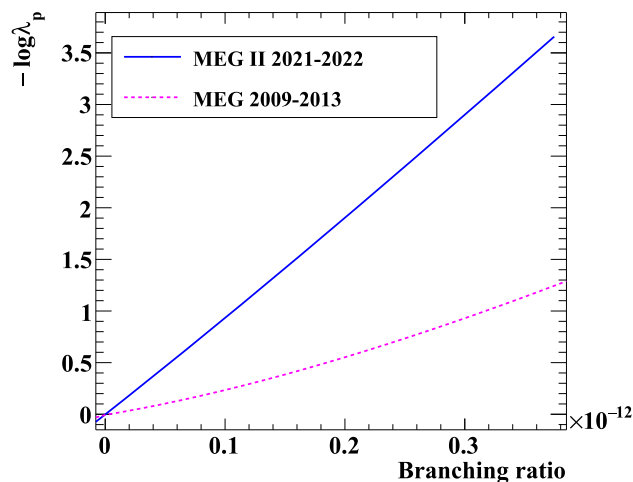


Fig. 3 The negative log likelihood-ratio λ_p , versus the branching ratio. The blue solid (magenta dashed) curve corresponds to the MEG II 2021–2022 data (the MEG full dataset [5])

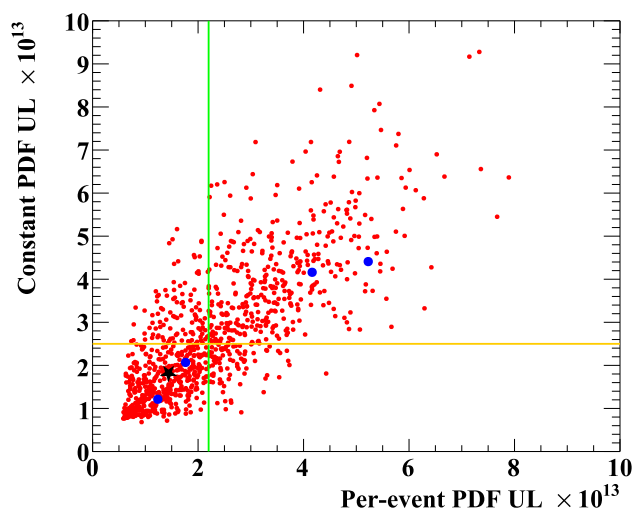


Fig. 4 Scatter plot of the 90 % C.L. upper limits computed for an ensemble of pseudo-experiments with a null-signal hypothesis for the two analyses. The blue dots and the black star are the upper limits measured in the time side-bands as described in the text and in the signal region, respectively. The vertical green and horizontal orange lines represent the sensitivities of the per-event and constant PDF analyses

a data taking period of about one fourth. The result is compatible with the expected background and establishes a 90% C.L. upper limit on the branching ratio $\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 1.5 \times 10^{-13}$, which is the most stringent to date. The MEG II collaboration has continued to take data during 2023 and 2024, with a projected statistic 1.5-fold (1.3 (2023) + 0.2 (2024)) larger than in 2021–2022. The collaboration plans to take data in the years 2025–2026 with an additional expected 2.6-fold increase in statistics, with the goal of reaching a sensitivity to the $\mu^+ \rightarrow e^+\gamma$ decay of $\mathcal{S}_{90} \sim 6 \times 10^{-14}$. In addition, a machine learning based algorithm has recently been developed to be introduced in the positron reconstruction.

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Data Availability Statement Data will be made available on reasonable request. [Authors' comment: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.]

Code Availability Statement This manuscript has no associated code/software. [Authors' comment: Code/Software generated or analysed during the current study is available on reasonable request.]

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References

1. S.T. Petcov, The processes $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\nu' \rightarrow \nu + \gamma$ in the Weinberg-Salam model with neutrino mixing. *Sov. J. Nucl. Phys.* **25**, 340 (1977). Erratum *ibid.* **25**, 698 (1977)
2. R. Barbieri, L.J. Hall, Signals for supersymmetric unification. *Phys. Lett. B* **338**(2–3), 212–218 (1994). [https://doi.org/10.1016/0370-2693\(94\)91368-4](https://doi.org/10.1016/0370-2693(94)91368-4). [arXiv:hep-ph/9408406](https://arxiv.org/abs/hep-ph/9408406)
3. J. Hisano, D. Nomura, T. Yanagida, Atmospheric neutrino oscillation and large lepton flavor violation in the SUSY SU(5) GUT. *Phys. Lett. B* **437**, 351–358 (1998). [https://doi.org/10.1016/S0370-2693\(98\)00929-0](https://doi.org/10.1016/S0370-2693(98)00929-0). [arXiv:hep-ph/9711348](https://arxiv.org/abs/hep-ph/9711348)
4. K. Afanaciev et al. (MEG II), A search for $\mu^+ \rightarrow e^+\gamma$ with the first dataset of the MEG II experiment. *Eur. Phys. J. C* **84**(3), 216 (2024). <https://doi.org/10.1140/epjc/s10052-024-12416-2>. [arXiv:2310.12614](https://arxiv.org/abs/2310.12614)
5. A.M. Baldini et al. (MEG Collaboration), Search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$ with the full dataset of the MEG experiment. *Eur. Phys. J. C* **76**(8), 434 (2016). <https://doi.org/10.1140/epjc/s10052-016-4271-x>
6. K. Afanaciev et al. (MEG II), Operation and performance of the MEG II detector. *Eur. Phys. J. C* **84**(2), 190 (2024). <https://doi.org/10.1140/epjc/s10052-024-12415-3>. [arXiv:2310.11902](https://arxiv.org/abs/2310.11902)
7. A.M. Baldini et al., Performances of a new generation tracking detector: the MEG II cylindrical drift chamber. *Eur. Phys. J. C* **84**(5), 473 (2024). <https://doi.org/10.1140/epjc/s10052-024-12711-y>
8. K. Yamamoto et al., Photon energy reconstruction with the meg ii liquid xenon calorimeter. *EPJ Web Conf.* **320**, 00030 (2025). <https://doi.org/10.1051/epjconf/202532000030>
9. G.J. Feldman, R.D. Cousins, Unified approach to the classical statistical analysis of small signals. *Phys. Rev. D* **57**(7), 3873–3889 (1998). <https://doi.org/10.1103/PhysRevD.57.3873>
10. S. Navas et al. (Particle Data Group), Review of particle physics. *Phys. Rev. D* **110**(3), 030001 (2024). <https://doi.org/10.1103/PhysRevD.110.030001>
11. J. Neyman, E.S. Pearson, IX. On the problem of the most efficient tests of statistical hypotheses. *Philos. Trans. R. Soc. Lond.* **231**(694–706), 289–337 (1933)