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Sensitivity study of $\mu^+ \to e^+ a\gamma$ cLFV decay with the MEG II apparatus

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We report on a study of the Single Event Sensitivity (SES) of the MEG II apparatus in the search for the charged-lepton flavor-violating decay $\mu^+ \to e^+ a\gamma$, involving an Axion-like particle (ALP) in a V-A chirality configuration. While forbidden in the Standard Model (SM), this decay is predicted by several Beyond SM Physics scenarios. We performed Monte Carlo simulations with GEANT4 and analyzed data using the ROOT-Cern framework. Our results indicate that an optimized configuration, using a low muon beam rate ($R_\mu \simeq 1 \times 10^6\ \mu$/s) and a low photon energy threshold (10 MeV), maximizes experimental efficiency and the SES. With only a few days of data taking, MEG II can reach a sensitivity limit of $F_{V-A} \geq 2.3 \times 10^9$ GeV at 95% CL, improving upon the 2015 TWIST result of $F_{V-A} \geq 1.0 \times 10^9$ GeV at 95% CL. This study demonstrates the capability of MEG II to set world-leading constraints on this cLFV decay.

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1. Introduction

The Standard Model (SM) of particle physics presents many unanswered questions, such as the Flavor Puzzle. The SM features three generations of fermions connected by various accidental symmetries. In the case of spontaneous symmetry breaking, a set of Pseudo-Goldstone Bosons is expected to emerge as generators of the broken symmetries. In the leptonic sector, these new bosons can couple non-diagonally across the three fermion generations, enabling charged Lepton Flavor Violating (cLFV) interactions. These bosons, known as Axion-Like Particles (ALPs), can arise in several theoretical frameworks, such as the Peccei-Quinn symmetry in Quantum Chromo Dynamics (QCD) [1]. ALPs are particularly interesting as they can have extremely light masses and large decay constants, making them a compelling candidate for Dark Matter phenomena [2] [3] [4] [5]. The lepton-flavor-violating (LFV) vertex can be described by the following tree-level effective interaction [6]:

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \overline{\mu} \gamma^\mu (C^V_{\mu e} - C^A_{\mu e} \gamma^5) e + \text{h.c.} \tag{1}$$

where $C^{V(A)}_{\mu e}$ is the coupling that controls the vectorial (Axial) LFV interaction. Over the past years, several experiments have searched for processes involving ALPs, but no evidence has been found. The most stringent upper limit was set by the TWIST collaboration [7]. The decay process of interest for this study is $\mu^+ \to e^+ a\gamma$, which is formally realized by adding a Quantum Electro Dynamics (QED) vertex to the Lagrangian in Equation (1). This decay is referred to as the *Axion Radiative Muon Decay* (ARMD). The inclusion of a radiative correction is essential for detection with the MEG II apparatus, whose capabilities and performances are described in [8].

2. Single Event Sensitivity

The Single Event Sensitivity (SES) is defined as the branching ratio at which one signal event is expected:

$$SES = \frac{1}{k}, \quad \text{with} \quad k = \frac{N_{ev}}{\mathcal{BR}} \quad \text{and} \quad N_{ev} = 1 \quad \Longrightarrow \quad SES = \mathcal{BR}\,.$$

The normalization constant k depends on the reconstruction efficiencies, geometrical acceptances for the signal, trigger efficiencies, and data acquisition time. After computing the branching ratio of the decay using Monte Carlo simulations within the GEANT4 framework [9] integrated into the MEG II computing system, we model the behavior of the ARMD decay products and their associated distributions. This modeling enables us to estimate the experimental acceptances and reconstruction efficiencies required to determine k. In particular, we can relate the normalization for the MEG-like decay ($\mu^+ \to e^+\gamma$) [10] to that for the ARMD decay normalized to the standard muon decay ($\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$) through the relation

$$k_{ALP} = F \cdot k_{MEG\ II}\,,$$

where the proportionality factor F is affected by various experimental acceptance and efficiency factors that depend on the energy and angular distributions of the decay products. Figure 1 displays the complete behavior of F as a function of the photon energy trigger threshold: $F(E_\gamma)$. Lowering

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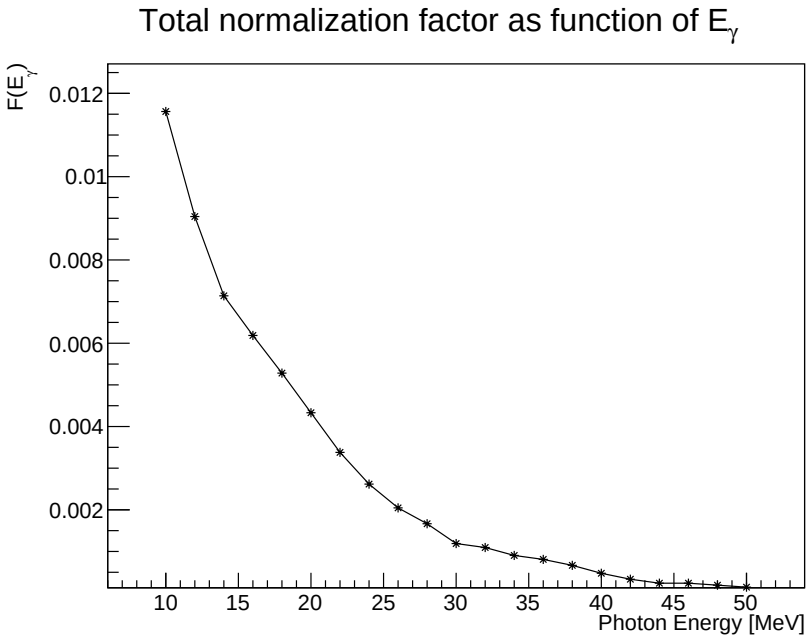

Figure 1: Normalization conversion factor from the $e\gamma$ signal to the $eA\gamma$ signal in MEG II as a function of the E_γ trigger threshold.

the photon energy cut increases $F(E_\gamma)$, which in turn enhances the normalization of the ARMD process and improves sensitivity. Operating at a high-intensity muon beam presents a significant challenge. Relaxing the photon energy cut threshold and eliminating the back-to-back topology requirement (necessary for the $e^+\gamma$ signal but not for a three-body decay) causes an exponential increase in the trigger rate mostly due to the infrared divergence. To keep the trigger rate below approximately 40 Hz, we reduce the muon beam intensity from $4 \times 10^7\, \mu/s$ (optimal for MEG II) to $\sim 1 \times 10^6\, \mu/s$. This reduction not only permits the relaxation of the conventional MEG trigger constraints, which are suboptimal for ARMD searches, but also decreases the number of accidental events (scaling as $\sim R_\mu^2$) relative to the Radiative Muon Decay (RMD: $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \gamma$) events (scaling as $\sim R_\mu$). Thus, a lower beam intensity is beneficial for background suppression in the ARMD search.

3. Expected normalization and data at low intensity beam rate

From 2021 to 2024, the MEG II collaboration collected several days of data at a low-intensity beam rate ($R_\mu \sim 1 \times 10^6\ \mu/s$) for trigger calibration purposes. Using the normalization measured from the 2022 low-intensity dataset, we estimate the normalization factors for the other data-taking periods. Furthermore knowing how the number of accidental and RMD background events scale with beam intensity, we can estimate the expected event rates and compositions over the four-year period from a small sample of the 2022 dataset. The estimated normalizations and events for the low intensity data acquisition periods are shown in Table 1.

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Year	R_μ [μ/s]	DAQ Time (sec.)	$E_\gamma^{thr.}$ [MeV]	k_{ALP}	RMD	Accidentals
2021	1.0×10^6	322080 ($\sim 3.7\,d.$)	20.0	7.3×10^7	5424	1113
2022	8.7×10^5	193421 ($\sim 2.2\,d.$)	20.0	3.8×10^7	2833	506
2023	2.0×10^6	234790 ($\sim 2.7\,d.$)	18.0	1.3×10^8	7908	3246
2024	1.2×10^6	164299 ($\sim 1.9\,d.$)	14.0	8.3×10^7	6641	1636

Table 1: Summary of the normalizations and the number of events per type for the 2021, 2022, 2023 and 2024 data collection at low beam intensity.

4. Analysis and results

We can link the normalization and the ALP decay constant using

$$\begin{cases} \mathcal{BR} = SES(N_d) \cdot N_{ev} \\ \mathcal{BR} = \frac{C}{f_a^2}\mathcal{I} \end{cases} \quad \to f_a = \sqrt{\frac{C \cdot \mathcal{I}}{SES(N_d) \cdot N_{ev}}} \tag{2}$$

where $\mathcal{I} \cdot C = (30.61 \cdot 4.55 \times 10^{10})$ GeV^2 are the *Theoretical Integral* of the decay width and the product of a set of constants in the Branching Ratio calculation computed using *Mathematica* [11]. $SES(N_d)$ is the value of the *Single Event Sensitivity* for N_d number of days (inverse of the normalization in Table 1). N_{ev} represents the number of signal events reconstructed through a Likelihood Fit using the Background-Only Hypothesis that will be evaluated in the next paragraphs.

PDFs and discriminant distributions Since signal and backgrounds share the same chirality structure, the key discriminant distribution is the squared missing invariant mass. The ARMD signal appears as a resolution-smeared delta function centered at m_{ALP}, while the background from both accidental events and RMD events form a continuous distribution, in the latter case due to all possible combinations of the two neutrino energies. Using fully reconstructed Monte Carlo data and appropriate event selection, we obtain the distributions for the three event types in this variable. The Probability Density Functions (PDFs) are extracted by fitting the MC-reconstructed distributions using the *RooFit* analysis toolkit [12]. The ALP signal is modeled using a Double-Sided Crystal Ball function combined with a Gaussian, sharing the same mean. The RMD background is described as the sum of two Landau functions, while the accidental background is fitted with a single Landau function. The fitted distributions are shown in Figures 5, 3, 4.

Analysis framework To estimate the Upper Limits (UL) on the number of signal events at the 90% (95%) CL, we employed the *RooFit* and *RooStats* tools for data analysis. Unbinned fits were performed using a model defined as a linear combination of the PDFs defined before. To estimate the sensitivity, we used the *AsymptoticCalculator* class from *RooStats*, which performs hypothesis testing based on the asymptotic formulae for the profile likelihood ratio [13], allowing us to compute the CLs [14]. The upper limit is determined when this quantity equals 0.1 (90% CL) or 0.05 (95% CL). This fit was performed over 2000 toy experiments, with zero signal events, with the number of background events per type written in Table 1 and subject to Poisson fluctuations. The expected UL histogram and their medians are presented in Figure 2.

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Results and conclusions Using the results summarized in the previous section, we can provide a final estimate for the lower limit on the ALP decay constant $F_{V-A} = \frac{f_a}{\sqrt{2}}$ (f_a in Equation (2)) as

$$F_{V-A} \geq 2.5 \times 10^9 \text{ GeV @ 90 \% CL} \qquad F_{V-A} \geq 2.3 \times 10^9 \text{ GeV @ 95 \% CL}$$

These limits are achieved using just 10.5 days at low beam intensity, improving the best existing bound from TWIST [7] on the ALP decay constant in the $V - A$ chiral configuration. Future low-intensity data from calibration runs will further enhance this sensitivity, potentially leading to a major breakthrough in this field.

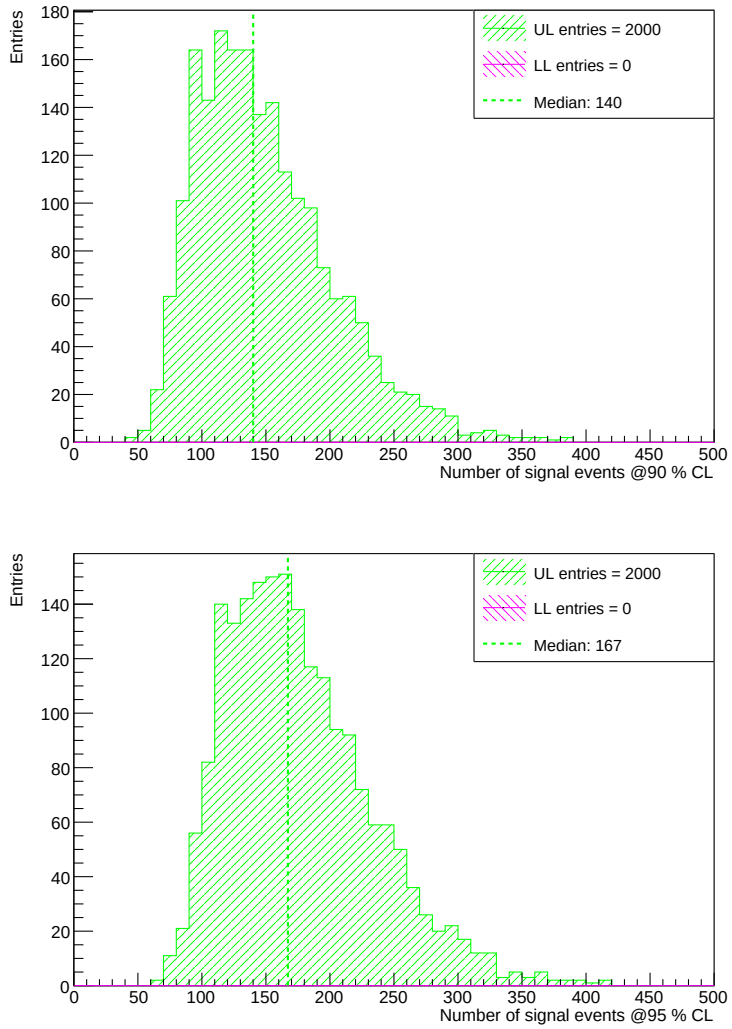

Figure 2: The left(right) figure displays the histogram of the upper limits at 90(95)% CL with its estimated sensitivity (Median).

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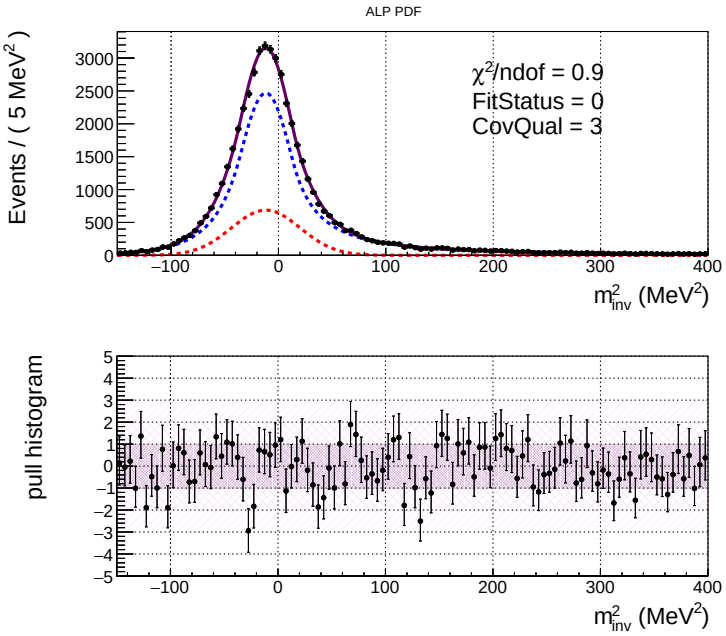

Figure 3: Unbinned fit result on the squared invariant missing mass distribution for the ALP signal. The top panel shows the total fit (violet) and the individual components. Black points indicate the unbinned Monte Carlo dataset. The bottom panel shows the normalized residuals, with shaded violet bands indicating 1σ, 2σ, and 3σ errors.

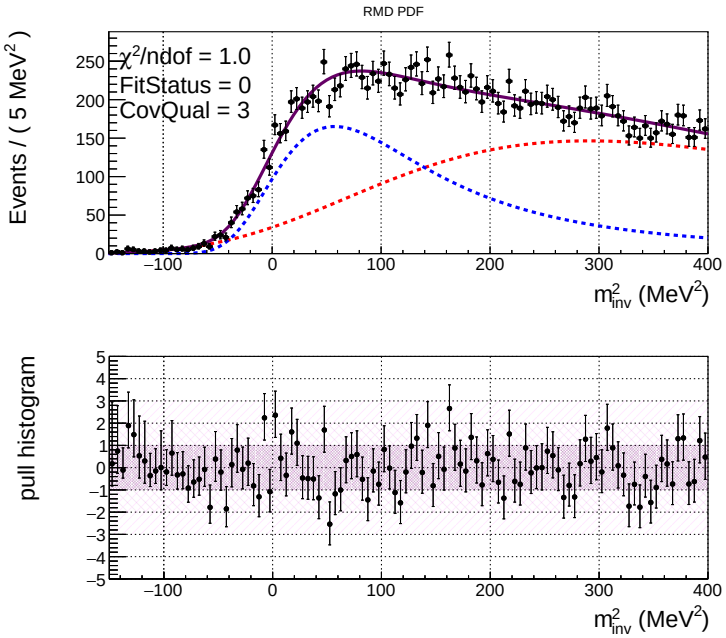

Figure 4: Unbinned fit result on the squared invariant missing mass distribution for the RMD background. The top panel shows the total fit (violet) and the individual components. Black points indicate the unbinned Monte Carlo dataset. The bottom panel shows the normalized residuals, with shaded violet bands indicating 1σ, 2σ, and 3σ errors.

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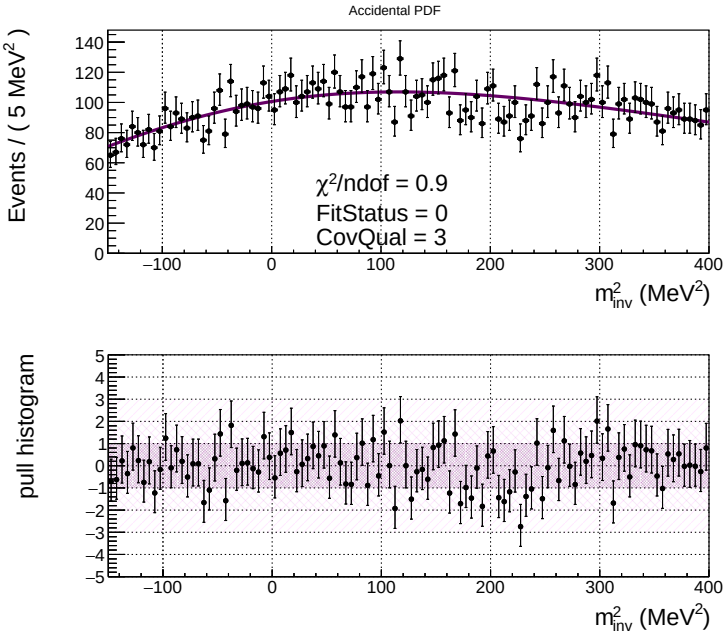

Figure 5: Unbinned fit result on the squared invariant missing mass distribution for the accidental background. The top panel shows the total fit (violet). Black points indicate the unbinned Monte Carlo dataset. The bottom panel shows the normalized residuals, with shaded violet bands indicating 1σ, 2σ, and 3σ errors.

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