Letter of Interest: physics potential with MEGII-fwd

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ABSTRACT: A new experimental setup for MEG II, the *MEGII-fwd*, with a forward calorimeter placed downstream from the muon stopping target could be used to search for light particles a in $\mu \to ea$ decays. Generic examples of such new particles are lepton flavor violating (LFV) axion-like particles (ALPs), which can be motivated by solutions to the Strong CP Problem, the observed Dark Matter abundance and/or the Standard Model (SM) Flavor Puzzle. The chiral structure of ALP couplings to leptons is model-dependent, with MEGII-fwd maximally sensitive to LFV ALPs that have nonzero couplings to right-handed leptons. The experimental set-up in MEGII-fwd suppresses the (left-handed) Standard Model background in the forward direction by controlling the polarization purity of the muon beam. With sufficient polarization purity and energy resolution MEGII-fwd could probe new parts of the theoretically interesting parameter space.

The main purpose of MEG II experiment is to search for the rare $\mu \to e\gamma$ transitions [1], with the first physics runs expected to begin in 2021. In this Letter of Interest we highlight that at the end of the $\mu \to e\gamma$ physics run MEG II could be repurposed as *MEGII-fwd* to search for $\mu \to ea$ decays, where a is a light particle that escapes the detector [2]. The experimental configuration of MEGII-fwd would resemble the one used in the experiment by Jodidio et al. [3], where $\mu^+ \to e^+ a$ decays were searched for in the forward direction. For highly polarized muons the SM background is then suppressed, see Fig. 1. There are two necessary requirements to realize this set-up. First, a forward detector to collect energetic forward positrons is needed. The final sensitivity to $\mu^+ \to e^+ a$ decays will depend on the detector energy resolution. For the projections we assume that a LYSO calorimeter (LYSO-ECAL) with a 10 cm diameter and high enough threshold for positron energies would have been installed in the forward direction, roughly 1.5 meters downstream from the muon stopping target. This is slightly larger but comparable with the largest crystal of 8.5 cm diameter soon available to MEG II. In the future one may consider ever larger calorimeters in the forward region, based on the efforts to produce bigger crystals in general [4, 5]. Second, a new configuration of the MEG II magnetic field will be needed in order to reduce depolarization effects, keeping the μ^+ spin antiparallel to the outgoing positron, and possibly focus an increased number of positrons in the forward direction.

Figure 2 shows the projected reach of MEGII-fwd after two weeks of running (corresponding to $\approx 10^{14}\,\mu^+$) for the case where a is a general lepton-flavor-violating (LFV) axion-like particle (ALP) with the effective Lagrangian involving the SM leptons given by

$$\mathcal{L}_{\rm eff} = \sum_i \frac{\partial_\mu a}{2f_a} \bar{\ell}_i C^A_{\ell_i\ell_i} \gamma^\mu \gamma_5 \ell_i + \sum_{i\neq j} \frac{\partial_\mu a}{2f_a}\, \bar{\ell}_i \gamma^\mu (C^V_{\ell_i\ell_j} + C^A_{\ell_i\ell_j}\gamma_5)\ell_j, \qquad i,j = e,\mu,\tau\,.$$

The angular distribution of the monochromatic positrons from $\mu^+ \to e^+ a$ is sensitive to the chirality of the $C^{V,A}_{\ell_i\ell_j}$ couplings. MEGII-fwd would be sensitive to the $\mu \to ea$ decay,

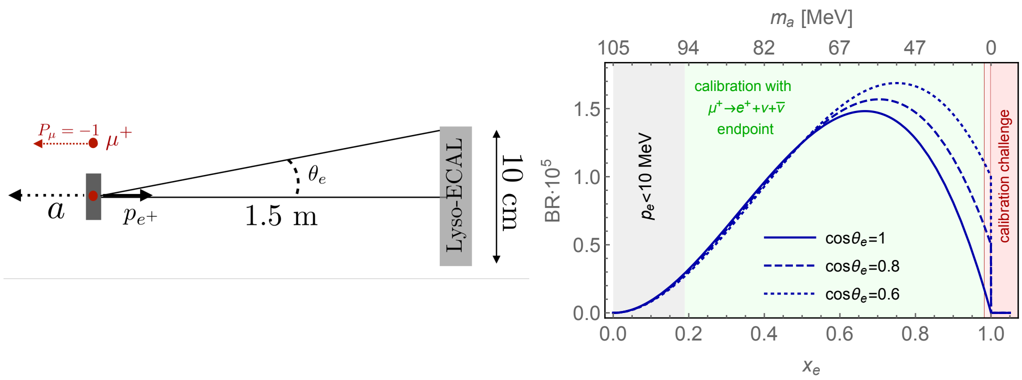

Figure 1. *Left:* The proposed MEGII-fwd set-up. A LYSO-ECAL detector of 10 cm in diameter is placed along the muon beam line 1.5 m downstream from the stopping point. The muon polarization P_μ is in the opposite direction than the detected positron. *Right:* Positron spectrum in the SM decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ for a fixed angle $\cos\theta_e = 1, 0.8, 0.6$. The muon beam is assumed to be 100% polarized ($\langle P_\mu\rangle = -1$), hence the e^+ spectrum drops towards the kinematical end point $x_e \equiv 2E_e/m_\mu = 1$, where the monochromatic signal from $\mu^+ \to e^+ a$ with a light ALP would be. Figures from [2].

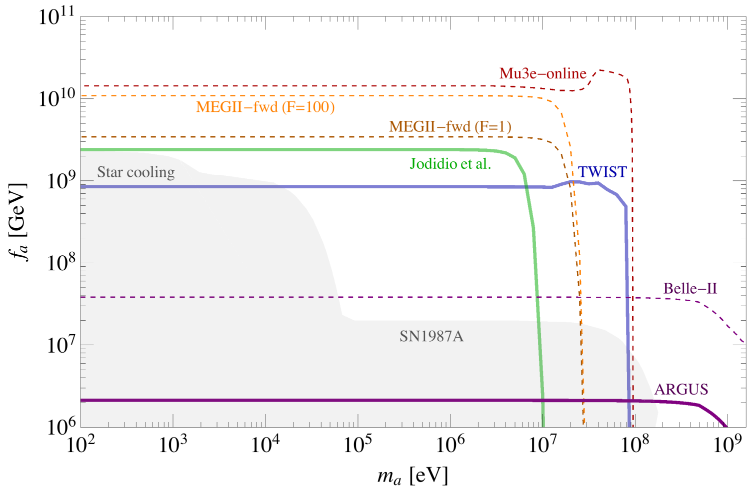

Figure 2. Summary of the present (solid lines) bounds and future (dashed lines) projections for an ALP with flavor-violating couplings to leptons ($C^A_{\ell_i\ell_j} = 1$). The gray shaded regions are excluded by the astrophysical bounds from star cooling and SN1987A due to the coupling C^A_{ee} [2]. The green (blue) line is the exclusion from searches for $\mu^+ \to e^+ a$ with an isotropic ALP by Jodidio et al. [3] (TWIST [6]). The dark orange dashed line is the MEGII-fwd projection for an isotropic ALP with no magnetic focusing, while for the orange dashed line the focusing is assumed to increase the luminosity in the forward direction by a factor of 100. The dark red dashed line is the Mu3e projection from [7]. The purple (dashed) solid line is the bound from the $\tau \to ea$ search by the ARGUS collaboration [8] (projected reach at Belle-II [2]).

unless the ALP couples only to the $V - A$ current. In Fig. 2, for illustration purposes, all axial couplings, flavor conserving and flavor violating, were set to 1 ($C^A_{\ell_i\ell_j} = 1$), while all vector couplings were set to 0 ($C^V_{\ell_i\ell_j} = 0$), such that the $\mu^+ \to e^+ a$ decay is isotropic [2]. The MEGII-fwd projections are shown for two different sets of assumptions. For the dark orange line, labeled "MEGII-fwd (F=1)", we assume the relative positron energy resolution to be $\delta x_e = 10^{-2}$, the μ^+ polarization to be $\langle P_\mu \rangle - 1 = 10^{-2}$, and that there is no magnetic focusing. For the orange line, labeled "MEGII-fwd (F=100)", we set the focusing to $F = 100$ (with F defined as the increase over the purely geometrical acceptance), roughly what was achieved in the 1986 experiment by Jodidio et al. [3]. In both cases the expected reach surpasses the previous experimental bounds, and goes well beyond the astrophysical bounds [2]. Fig. 2 also shows as a dark red line the expected reach of the planned Mu3e experiment at PSI whose main goal is to search for $\mu^+ \to e^+e^-e^+$ decays [9, 10], but can also be used to search for $\mu \to ea$ decay using online event reconstruction [11].

Finally, MEG II can also be used to search for other decays, for instance for $\mu \to ea$ transitions where a decays to electrons or photons inside the detector [12]. Another complementary probe is the $\mu^+ \to e^+\gamma a$ decay which is less dependent on the chiral structure of the ALP couplings than the $\mu \to ea$ search. Naively, the MEG II luminosity will exceed the one of Crystal Box [13] by at least 3 orders of magnitude. In optimal conditions one could thus probe new parameter space beyond the current TWIST bound for the $V - A$ ALPs. The combination of the two searches, $\mu \to ea\gamma$ and $\mu \to ea$ at MEGII-fwd, would then fully cover the possible chiral structures of the ALP couplings.

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