Anomalous magnetic moments from asymptotic safety

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The measurements of the muon and electron anomalous magnetic moments hint at physics beyond the standard model. We show why and how models inspired by asymptotic safety can explain deviations from standard model predictions naturally. Our setup features an enlarged scalar sector and Yukawa couplings between leptons and new vectorlike fermions. Using the complete two-loop running of couplings, we observe a well-behaved high-energy limit of models including a stabilization of the Higgs. We find that a manifest breaking of lepton universality beyond standard model Yukawas is not necessary to explain the muon and electron anomalies. We further predict the tau anomalous magnetic moment and new particles in the TeV energy range, whose signatures at colliders are indicated. With small *CP* phases, the electron EDM can be as large as the present bound.

I. INTRODUCTION

Measurements of the electron and muon anomalous magnetic moments exhibit intriguing discrepancies from standard model (SM) predictions [1–3]. Adding uncertainties in quadrature, the deviations

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \times 10^{-11},$$
$$\Delta a_e \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = -88(28)(23) \times 10^{-14} \quad (1)$$

amount to 3.5σ (2.4σ) for the muon (electron). Recent theory predictions for a_μ find up to 4.1σ [4,5]. There are two stunning features in the data. First, the deviations Δa_μ and Δa_e have opposite sign. Second, their ratio $\Delta a_e/\Delta a_\mu = -(3.3 \pm 1.6) \times 10^{-4}$ is an order of magnitude smaller than the lepton mass ratio m_e/m_μ and an order of magnitude larger than the square of the mass ratio $(m_e/m_\mu)^2$. Theory explanations of the data (1), with either new light scalars [6–9], supersymmetry [10–12], bottom-up models [13,14], or others [15,16], manifestly break lepton flavor universality.

In recent years, asymptotic safety has been put forward as a new idea for model building [17,18]. It is based on the discovery [19] that particle theories may very well remain fundamental and predictive in the absence of asymptotic freedom due to interacting high-energy fixed points [20–22]. For weakly coupled theories, general theorems for

asymptotic safety are available [23,24] with templates covering simple [19,25,26], semisimple [27], and supersymmetric gauge theories [28]. Yukawa interactions and new scalar fields play a prominent role because they slow down the growth of asymptotically nonfree gauge couplings, which can enable interacting fixed points [23], including in extensions of the standard model [17,18,29,30].

In this paper, we show that asymptotically safe extensions of the SM may offer a natural explanation for the data (1). The primary reason for this is that Yukawa interactions, which help to generate interacting fixed points, can also contribute to lepton anomalous magnetic moments. We demonstrate this idea in two concrete models by introducing Yukawa couplings between ordinary leptons and new vectorlike fermions, and by adding new scalar fields which admit either a flavorful or flavor-universal ground state. Unlike in all previous works [6–16], we find that the data (1) can be accommodated without any explicit breaking of lepton universality. The stability of SM extensions all the way up to the Planck scale is exemplified using the renormalization group (RG) running of couplings for a wide range of BSM parameters.

II. NEW VECTORLIKE FERMIONS AND SCALAR MATTER

In the spirit of Ref. [19], we are interested in SM extensions involving N_F flavors of vectorlike color-singlet fermions ψ_i and N_F^2 complex scalar singlets S_{ij}. In their simplest form, the new fermions couple to SM matter only via gauge interactions [17,18]. The new ingredients in this paper are Yukawa couplings between SM and BSM matter. To make contact with SM flavor, we set $N_F = 3$. We then consider singlet or doublet models where the new fermions

are either $SU(2)$ singlets with hypercharge $Y = -1$, or $SU(2)$ doublets with $Y = -\frac{1}{2}$. In our conventions, electric charge Q and weak isospin T_3 relate as $Q = T_3 + Y$. Within these choices, and denoting the SM lepton singlets, doublets, and Higgs as E, L, and H, respectively, we find three possible Yukawa couplings κ, κ', and y with

$$\mathcal{L}_Y^{\text{singlet}} = -\kappa \bar{L} H \psi_R - \kappa' \bar{E} S^\dagger \psi_L - y \bar{\psi}_L S \psi_R + \text{H.c.},$$

$$\mathcal{L}_Y^{\text{doublet}} = -\kappa \bar{E} H^\dagger \psi_L - \kappa' \bar{L} S \psi_R - y \bar{\psi}_L S \psi_R + \text{H.c.}, \quad (2)$$

and flavor traces are understood to simplify the subsequent RG analysis. Effects of the Yukawa coupling y have been studied in Refs. [17,18,29]. The scalar potential of either model reads

$$V = \lambda (H^\dagger H)^2 + \delta H^\dagger H \text{Tr}[S^\dagger S]$$
$$+ u \text{Tr}[S^\dagger S S^\dagger S] + v (\text{Tr}[S^\dagger S])^2, \quad (3)$$

where u, v, λ, and δ are quartic and portal couplings. We further introduce mass terms for the scalars and vectorlike fermions. The potential (3) admits vacuum configurations V^+ and V^- characterized by

$$V^+: \begin{cases} \lambda > 0, \quad u > 0, \quad u + 3v > 0, \\ \delta > -2\sqrt{\lambda(u/3 + v)}, \end{cases}$$

$$V^-: \begin{cases} \lambda > 0, \quad u < 0, \quad u + v > 0, \\ \delta > -2\sqrt{\lambda(u + v)}. \end{cases} \quad (4)$$

Either of these allows for electroweak symmetry breaking. Moreover, in V^+, and for suitable mass parameters, the diagonal components of S each acquire the same vacuum expectation value $\langle S_{\ell\ell} \rangle \neq 0$, and the ground state is flavor universal. In V^-, a finite vacuum expectation value $\langle S_{\ell\ell} \rangle \neq 0$ arises only for one flavor direction, giving rise to a flavorful vacuum.

III. EXPLAINING ANOMALOUS MAGNETIC MOMENTS

We are now in a position to explain the data (1) in SM extensions with Eqs. (2) and (3). The relevant leading loop effects due to the couplings κ, κ', and δ are shown in Fig. 1, also using $S = \langle S \rangle + s$. Any lepton flavor $\ell = e$, μ, τ receives a contribution from BSM scalar-fermion loops with chiral flip on the lepton line induced by the coupling κ' [see Fig. 1(a)]. It scales quadratically with the lepton mass,

$$\Delta a_\ell = \frac{N_F \kappa'^2}{96\pi^2} \frac{m_\ell^2}{M_F^2} f_1 \left(\frac{M_S^2}{M_F^2} \right), \quad (5)$$

and represents a minimal lepton flavor dependence, with $f_1(t) = (2t^3 + 3t^2 - 6t^2 \ln t - 6t + 1)/(t - 1)^4$ positive for any t, and $f_1(0) = 1$. This manifestly positive contribution is the dominant one for a_μ. Contributions
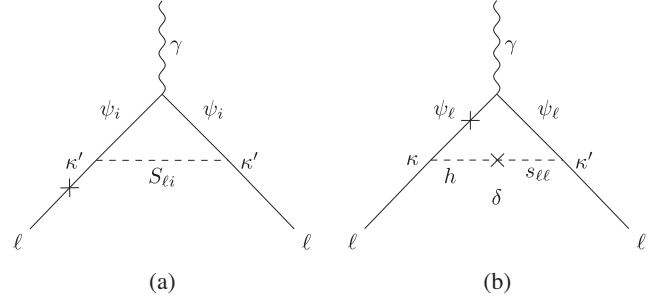

FIG. 1. Leading loop contributions to Δa_ℓ ($\ell = e, \mu, \tau$), including (a) BSM scalar fermion loops with a lepton chiral flip (cross on solid line), and (b) chirally enhanced contributions through scalar mixing (cross on dashed line), provided $\langle S_{\ell\ell} \rangle \neq 0$, and a BSM fermion ψ_ℓ chiral flip (cross on solid line).

through Z and W loops are parametrically suppressed as $\mathcal{O}(g_2^2)$ and by fermion mixing [31]. Comparing Eq. (5) with the muon data for a small scalar-to-fermion mass ratio $M_S^2/M_F^2 \ll 1$ yields the Yukawa coupling $\alpha_{\kappa'}$ within $(0.48 \pm 0.15)(\frac{M_F}{\text{TeV}})^2$, which is large for TeV-range fermion masses M_F. Fixing Δa_μ to the muon data (1) confirms that the corresponding contribution (5) for the electron would come out too small and with the wrong sign $\Delta a_e \simeq 6 \times 10^{-14}$ (see Fig. 2).

Additionally, chirally enhanced contributions, which are linear in the lepton mass, may arise through a portal-mediated scalar mixing where the chiral flip is shifted to a ψ line [Fig. 1(b)]. The key observation is that chiral enhancement naturally explains the electron data (Fig. 2). In practice, this can be realized with either V^+ or V^-. If the ground state is V^-, it must point in the electron direction (only $\langle S_{ee} \rangle \neq 0$), or else Eq. (1) cannot be satisfied. Overall, this leads to
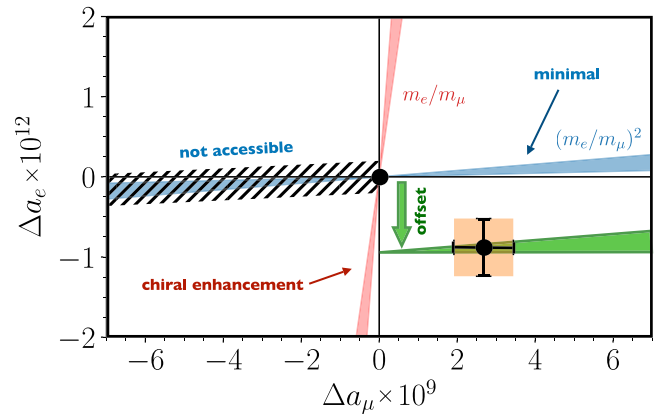

FIG. 2. Leading contributions to $\Delta a_{e,\mu}$ from Figs. 1(a) (blue band) and 1(b) (red band), which, in combination (green band), explain the electron and muon data (cross) simultaneously. The chirally enhanced offset is either flavor universal or points in the electron direction (green arrow). Band widths are indicative of a 20% mass splitting between fermion flavors from leading loops; the hatched region is inaccessible.
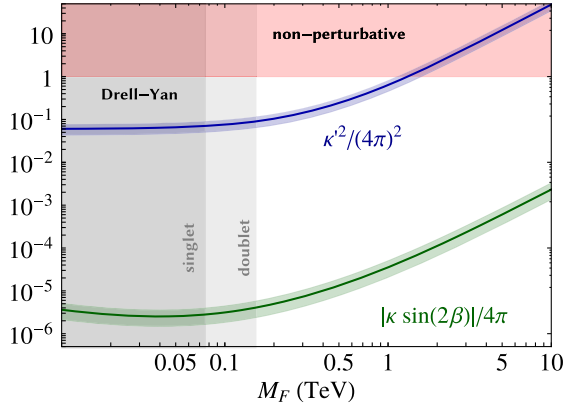
FIG. 3. Window for Yukawa and portal couplings which simultaneously explain the muon and electron data (1) as functions of the BSM fermion mass M_F ($M_S = 0.5$ TeV, band width 1σ). Gray-shaded areas are excluded by Drell-Yan searches, while the red-shaded area indicates strong coupling. All results refer to V^-; very similar ones are found for V^+ (not shown).

$$\Delta a_e = \frac{m_e}{M_F} \frac{\kappa\kappa' \sin 2\beta}{32\pi^2} \left[f_2\left(\frac{m_s^2}{M_F^2}\right) - f_2\left(\frac{m_h^2}{M_F^2}\right) \right] + \frac{m_e^2}{m_\mu^2} \Delta a_\mu,$$

(6)

where $m_{h,s}$ are the Higgs and the BSM scalar mass, and the last term accounts for Eq. (5). The loop function $f_2(t) = (3t^2 - 2t^2 \ln t - 4t + 1)/(1-t)^3$ is positive for any t and $f_2(0) = 1$. The mixing angle β between the scalar $s_{\ell\ell}$ and the physical Higgs h is fixed via

$$\tan 2\beta = \frac{\delta}{\sqrt{\lambda(u+v)}} \frac{m_h}{m_s} (1 + \mathcal{O}(m_h^2/m_s^2)).$$

(7)

In Eq. (6), the term linear in the electron mass provides a unique offset for the electron Δa_e, sketched in Fig. 2. It dominates parametrically over the quadratic term and can have either sign set by the Yukawas κ, κ' and the portal coupling δ.

As an estimate, comparing Eq. (6) with the electron data, assuming $m_h^2/M_F^2 \ll 1$ and simultaneously fixing Eq. (5) to match the muon data, we find $|\kappa \sin 2\beta| \simeq (2.9 \pm 1.2) \times 10^{-4} (\frac{M_F}{\text{TeV}})^2$. The full parameter window explaining the data is indicated in Fig. 3 assuming V^-. Corrections from Z and W exchange, which contribute differently in the singlet and doublet models, are suppressed by small fermion mixing angles and are not sizeable enough to be seen in Fig. 3. Also shown are limits on M_F (gray) from Drell-Yan processes [30,32,33] and on perturbativity in $\alpha_{\kappa'}$ (red). We observe M_F within the range (0.05–2) TeV for $\alpha_{\kappa'}$ within (10^{-2}–1), with $\kappa \sin 2\beta/(4\pi)$ deeply perturbative (green) for small portal coupling δ. The dual parameter space ($\kappa' \ll \kappa$) where Fig. 1(a) is replaced by the corresponding Higgs-fermion loops, is ruled out by $Z \to \ell\ell$ data [1], which constrain

left-handed (right-handed) fermion mixing angles in the singlet (doublet) model to be of $\mathcal{O}(10^{-2})$ or smaller.

If the vacuum is V^+, all lepton anomalous magnetic moments receive a chirally enhanced contribution from Fig. 1(b), similar to the first term in Eq. (6). The offset in Fig. 2 is then slightly tilted and points along the direction of the red band. Due to the smallness of the tilt, results and constraints are similar to those for V^- in Fig. 3.

IV. RUNNING OF COUPLINGS UP TO THE PLANCK SCALE

We now turn to the RG running of couplings and conditions under which models are stable and predictive up to the Planck scale. We normalize couplings to loop factors,

$$\alpha_x = \frac{x^2}{(4\pi)^2}, \qquad \alpha_z = \frac{z}{(4\pi)^2},$$

(8)

where $x = g_1, g_2, g_3, y_t, y_b, y, \kappa, \kappa'$ are any of the gauge, top, bottom, or BSM Yukawa couplings, and $z = \lambda, u, v, \delta$ are the quartic and portal couplings. Models are matched onto the SM at the scale set by the fermion mass. For the running above M_F, we retain all 12 RG beta functions up to two-loop order in all couplings [34–37].

The left panel of Fig. 4 shows benchmark trajectories up to the Planck scale M_{Pl} for models starting in the vacuum V^- at the scale M_F. For some initial conditions $\alpha_{\text{BSM}}|_{M_F}$ at the low scale, such as those used in Fig. 4, we find that the running is stable up to the Planck scale. We also observe from Fig. 4 that the Higgs potential becomes stable (remains metastable) in the singlet (doublet) model. Higgs stability in the doublet model can be achieved for larger portal and quartic couplings. Some couplings in Fig. 4 run slowly all the way up to the Planck scale. Others show a slow or fast crossover to near-constant values due to near-zeros of beta functions [38] which arise from a competition between SM and BSM matter. In the absence of quantum gravity, the evolution of couplings ultimately terminates in an interacting UV fixed point corresponding to asymptotic safety (singlet benchmark), with asymptotic freedom prevailing in the weak and strong sectors [17,18,23]. In some cases, trajectories remain safe up to the Planck scale (doublet benchmark) but blow up at trans-Planckian energies. For other initial conditions, we also find unsafe trajectories which terminate in sub-Planckian Landau poles (see Ref. [31] for a detailed study of initial conditions $\alpha_{\text{BSM}}|_{M_F}$).

The right panel of Fig. 4 shows the vacua of singlet and doublet models at the Planck scale in terms of the Yukawa couplings $(\alpha_\kappa, \alpha_{\kappa'})|_{M_F}$ at the matching scale. Integrating the RG between M_F and M_{Pl}, we find wide ranges of models whose vacua at the Planck scale are either V^+ (blue), or a stable V with a metastable Higgs sector ($\alpha_\lambda \gtrsim -10^{-4}$) such as in the SM (yellow) [39,40]. For other parameter ranges, we also find V^- (green), or unstable BSM potentials (gray), or Landau poles below the Planck scale (light red).
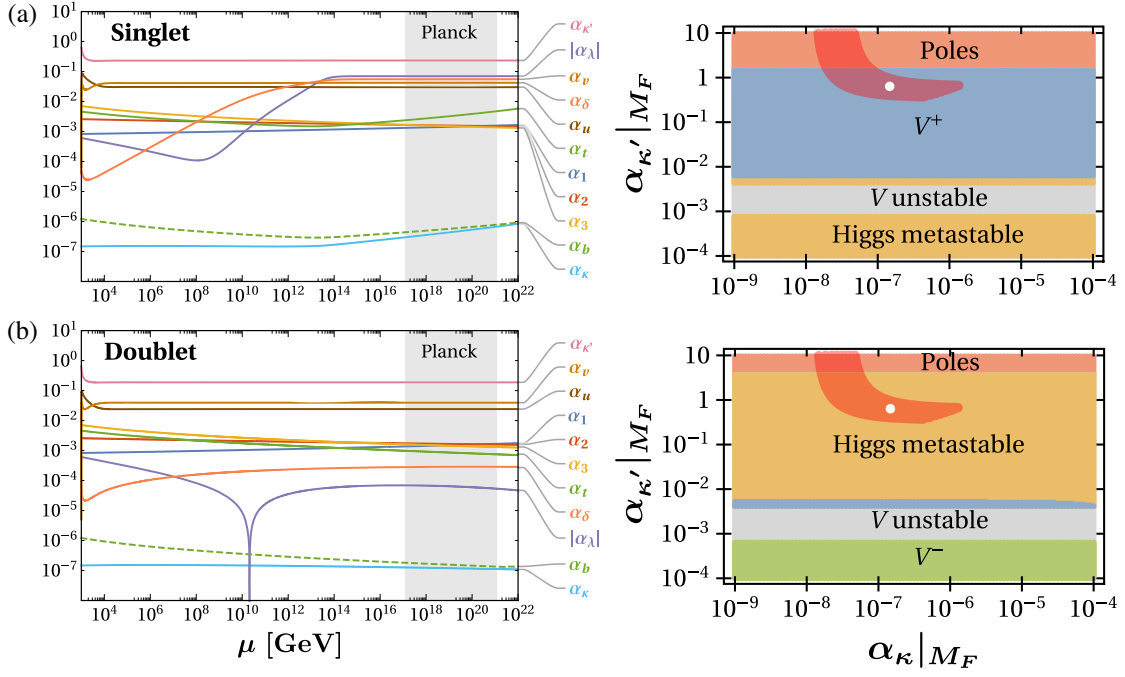
FIG. 4. Benchmark trajectories ($M_F = 2M_S = 1$ TeV) between the matching scale M_F and the Planck scale (left), and parameter scans of vacua at the Planck scale (right) for (a) the singlet model (top) and (b) the doublet model (bottom) using $(\alpha_\delta, \alpha_u, \alpha_v, \alpha_y)|_{M_F} = (5, -1, 4, 0) \times 10^{-5}$. High-scale vacua are shown as functions of the Yukawa couplings $(\alpha_\kappa, \alpha'_\kappa)|_{M_F}$. Parameters within the red-shaded areas are compatible with Eq. (1); white dots refer to the benchmarks on the left.

Most importantly, the anomalous magnetic moments (1) are matched for couplings in the red-shaded areas which cover the 1σ band. Constraints from Higgs signal strength [1] imply an upper bound on α_κ, corresponding to a lower bound for the scalar mass of about 226 GeV (for $M_F = 1$ TeV). Similar results are found for V^+ at the low scale (not shown), except that regions with V^- in Fig. 4 turn into V^+. We conclude that models are stable and Planck-safe for a range of parameters $\alpha_{\text{BSM}}|_{M_F}$.

V. COLLIDER PRODUCTION AND DECAY

Models predict new scalars and fermions in the TeV energy range. Their phenomenology is characterized by an enlarged flavor sector with a large Yukawa coupling κ' and moderate or small couplings κ, δ. We identify collider signatures through production and decay [31]. We denote the fermions in the singlet model by ψ_s^{-1} and the isospin components in the doublet model by ψ_d^0 and ψ_d^{-1}; superscripts show electric charge. The ψ_d^0 is lighter than the ψ_d^{-1} by $\Delta m = M_{\psi^{-1}} - M_{\psi^0} = g_2^2 \sin\theta_W^2 m_Z/(8\pi) \simeq 0.4$ GeV [41]. All fermion flavors can be pair-produced in pp and $\ell\ell$ machines via s-channel γ or Z exchange, and through $W^\pm$ exchange at pp colliders (doublet model only). Lepton colliders allow for pair production from t-channel S at order κ'^2, which is sizable (see Fig. 3). Single-ψ production together with a lepton arises from s-channel Z- and W-boson contributions via fermion mixing. S production occurs only via the Higgs portal,

or at lepton colliders with t-channel ψ in association with h at order $\kappa\kappa'$ or in pairs at order $(\kappa')^2$.

If kinematically allowed, the charged fermions decay as $\psi^{-1} \to S\ell$, and the neutral ones as $\psi_d^0 \to S\nu$. If these channels are closed, the ψ^{-1} decays to a Higgs plus a lepton instead. The decay rate $\Gamma(\psi^{-1} \to h\ell^-) = \frac{\kappa^2}{64\pi} M_F(1 - m_h^2/M_F^2)^2$ provides the lifetime estimate $\Gamma^{-1} \sim 10^{-27}(1/\alpha_\kappa)(1/M_F[\text{TeV}])$ s. The neutral fermion ψ_d^0 cascades down slower, yet still promptly through W emission with $\psi_{d,i}^0 \to \psi_{d,i}^{-1*} W^{+*} \to h\ell_i^- W^{+*}$. If kinematically allowed, the BSM scalars S undergo tree-level decay into $\psi\bar\psi$ via y, and into $\psi\ell$ via κ'. At one loop, the decays $S \to \gamma\gamma$, ZZ, $Z\gamma$, and $S \to WW$ (doublet model only) arise from y. Although there is no genuine lepton flavor violation (LFV), as flavor in the S-decay process is conserved, the mixing between the ψ and the SM leptons introduces very distinct LFV-like final states $S_{ij} \to \ell_i^\pm \ell_j^\mp$. The LFV-like decays at the order $\kappa\kappa' v_h/M_F$ or $(\kappa')^2 (v_s v_h/2M_F)^2$ are the leading ones for negligible y and $M_S/M_F \ll 1$.

VI. DISCUSSION

We have shown that extensions of the standard model with new vectorlike leptons and singlet matrix scalar fields (2) and (3) explain the muon and electron anomalous magnetic moments (1) simultaneously. Yukawa couplings mixing SM and BSM matter and a Higgs portal coupling are instrumental to generate both minimal (5) and chirally enhanced (6) contributions, which, when taken together,

match the present data (Fig. 2). Also, the mechanism generating anomalous magnetic moments is rather natural and not fine-tuned to the data. In fact, our models can in principle accommodate deviations Δa_μ and Δa_e in the half-plane spanned by the minimal and chirally enhanced contributions, as indicated in Fig. 2.

Further features unlike the SM are a stable Higgs potential and well-behaved running couplings up to the Planck scale. This includes asymptotically safe extensions of the SM which, for the first time, match the measured values of all gauge couplings and the Higgs, top, and bottom masses, and models which may run into poles or instabilities at trans-Planckian energies. Also, some parameter settings can explain the data but are unsafe at high energies due to poles prior to the Planck scale (Fig. 4). We thus see very clearly how the high-energy behavior offers an additional selection criterion for models and their low-energy BSM parameters. Further predictions are a strongly and a weakly coupled Yukawa sector, and new matter fields with masses in the TeV range (Fig. 3), which can be tested at colliders.

From the viewpoint of lepton universality, it is worth noting that a manifest breaking has been instrumental in all previous models explaining both anomalies. As a proof of principle, however, our models find that any breaking beyond SM Yukawas is not mandatory. In a related vein, we also stress that lepton universality in itself is not key for asymptotic safety. In fact, it would be straightforward to explicitly break lepton flavor universality in alterations of models while maintaining predictions for both anomalies, and without spoiling a well-behaved high-energy behavior.

Another aspect which sets our models apart from any previous ones explaining both anomalies is that we also predict the deviation of the tau anomalous magnetic moment from its standard model value. This can be done solely using the data and the vacuum, and is insensitive to any other details. Specifically, provided the ground state distinguishes electron flavor, we have

$$\Delta a_\tau \equiv a_\tau^{\exp} - a_\tau^{\mathrm{SM}} = (7.5 \pm 2.1) \times 10^{-7}, \qquad (9)$$

and $\Delta a_\tau = (8.1 \pm 2.2) \times 10^{-7}$ otherwise. Although the present limit on Δa_τ is 4 orders of magnitude away [1], it would be very interesting to test these predictions in the future. We also note that with small CP phases, the electric dipole moment of the electron can be as large as the present bound, $d_e < 1.1 \times 10^{-29}$ ecm [42]. In settings with flavor-universal vacua, the bound extends to all lepton electric dipole moments d_ℓ, which would make an experimental check for the muon and the tau very challenging.

Finally, we comment on asymptotic safety as a guiding principle for model building. Vectorlike fermions alongside singlet matrix scalar fields and their Yukawa interactions are established ingredients in settings with perturbatively exact asymptotic safety, and appear prominently in templates for asymptotically safe SM extensions. Here, we have extended earlier ideas by additionally allowing for new Yukawa and portal interactions between SM and BSM matter. Curiously, these new interactions not only improve the high-energy behavior (Fig. 4) in the spirit of asymptotic safety, but also generate anomalous magnetic moments (Fig. 1) which can match the data naturally (Fig. 2). It would thus seem interesting to further explore the potential of models inspired by asymptotic safety for flavor and particle physics.

Note added.—The possibility of rendering Δa_μ insignificant has recently been suggested by a lattice determination of the hadronic vacuum polarization [43]. Note, though, that these findings are in tension with electroweak data [44,45] and other lattice studies, which requires further scrutiny [46].

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