Ultralight scalars in leptonic observables

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10.1007/JHEP03(2021)240 [2008.01099]

BSM - 2021

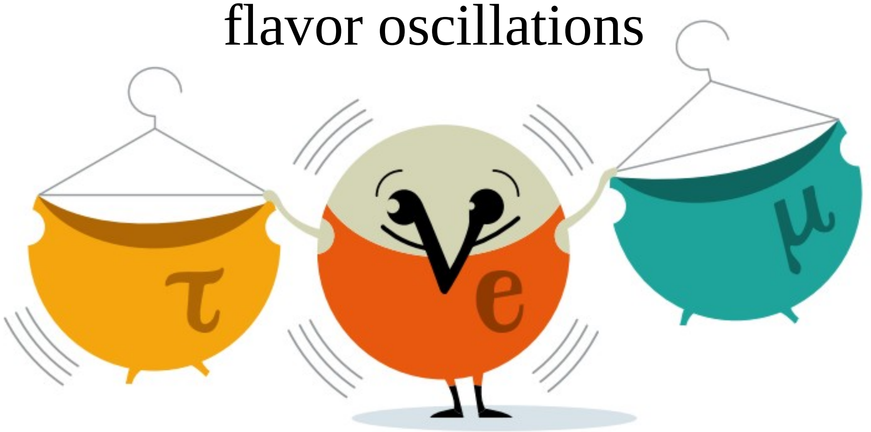
1. Introduction

Several modern experiments recently started taking data

New searches for lepton flavor violating processes

motivated by

- Experimental observation of neutrino flavor oscillations



More precise measurements of lepton flavor conserving observables

- Charged leptons anomalous magnetic moments.

Improved measurements expected at the Muon g-2 experiment

What type of new physics can be probed?

We will concentrate on ultralight scalars that couple to charged leptons

2. The effective Lagrangian

The general interaction between charged leptons and the real scalar is given by

Effective Lagrangian

$$\mathcal{L}_{\ell\ell\phi} = \phi\bar{\ell}_\beta \left(S_L^{\beta\alpha} P_L + S_R^{\beta\alpha} P_R \right) \ell_\alpha + \text{h.c.}$$

Possible flavor combinations: $\beta\alpha = \{ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau\}$

$m_\phi \ll m_e$ → in practice → $m_\phi \to 0$

Full Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\ell\ell\phi} + \mathcal{L}_{\ell\ell\gamma} + \mathcal{L}_{4\ell}$$

Dipole operators: $$\mathcal{L}_{\ell\ell\gamma} = \frac{e m_\alpha}{2} \bar{\ell}_\beta \sigma^{\mu\nu} \left[\left(K_2^L\right)^{\beta\alpha} P_L + \left(K_2^R\right)^{\beta\alpha} P_R \right] \ell_\alpha F_{\mu\nu} + \text{h.c.}$$

4-fermion operator $$\mathcal{L}_{4\ell} = \sum_{\substack{I=S,V,T \\ X,Y=L,R}} \left(A_{XY}^I\right)^{\beta\alpha\delta\gamma} \bar{\ell}_\beta \Gamma_I P_X \ell_\alpha \bar{\ell}_\delta \Gamma_I P_Y \ell_\gamma + \text{ h.c.}$$

→ $\Gamma_S = 1$, $\Gamma_V = \gamma_\mu$ and $\Gamma_T = \sigma_{\mu\nu}$

[Porod, Staub, Vicente, 1405.1434]

3. Bounds on the couplings: FCC

Stellar cooling

The production and emission of the scalar inside stars or in supernovae may constitute a powerful cooling mechanism

Sloan Digital Sky Survey and SuperCOSMOS Sky Survey

$\Rightarrow$ $\mathrm{Im}\, S^{ee} < 2.1 \times 10^{-13}$

[Calibbi, Redigolo, Ziegler, Zupan, 2006.04795]

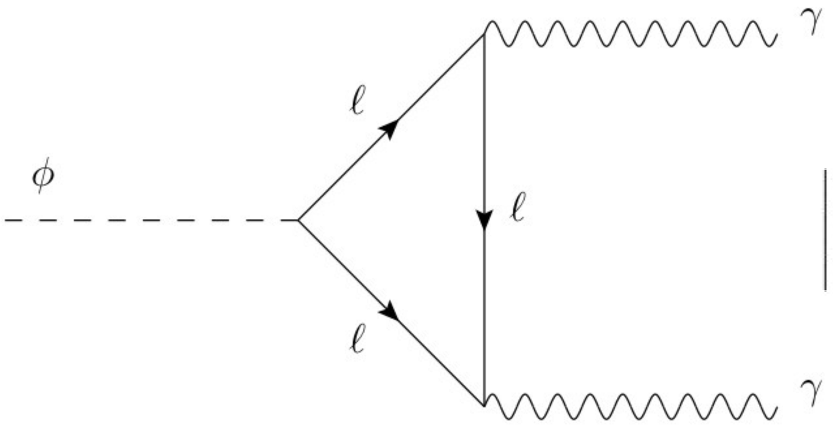
Supernova SN 1987A

$\Rightarrow$ $\mathrm{Im}\, S^{\mu\mu} < 2.1 \times 10^{-10}$

[Croon, Elor, Leane, McDermott, 2006.13942]

$$\Rightarrow \mathrm{Re}\, S^{\beta\beta} \lesssim \left[\mathrm{Im}\, S^{\beta\beta}\right]_{\max}$$

Scalar interacting with a pair of photons



OSQAR experiment

[Ballou *et al.*, 2006.13942]

$$\left|\sum_\beta \frac{\mathrm{Re}\, S^{\beta\beta}}{m_\beta}\right|^2 < 3.8 \times 10^{-8}\ \mathrm{GeV}^{-2} \qquad \left|\sum_\beta \frac{\mathrm{Im}\, S^{\beta\beta}}{m_\beta}\right|^2 < 1.7 \times 10^{-8}\ \mathrm{GeV}^{-2}$$

$$\Rightarrow S^{ee} \lesssim 10^{-7} \text{ and } S^{\mu\mu} \lesssim 10^{-5}$$

Limits only valid if this diagram is the only contribution to the coupling to photons

3. Bounds on the couplings: FVC

$$\ell_\alpha \to \ell_\beta \, \phi$$

$$\Gamma\left(\ell_\alpha \to \ell_\beta \phi\right) = \frac{m_\alpha}{32\pi} \left|S^{\beta\alpha}\right|^2$$

$$\left|S^{\beta\alpha}\right| = \left(\left|S_L^{\beta\alpha}\right|^2 + \left|S_R^{\beta\alpha}\right|^2\right)^{1/2}$$

$$\alpha = \mu$$

TRIUMPH [Jodidio *et al.*, Phys.Rev.D 37, 237]

→ [Hirsch, Vicente, Meyer, Porod, 0902.0525] → $\mathrm{BR}\left(\mu \to e\,\phi\right) \lesssim 10^{-5}$

$$\Rightarrow \left|S^{e\mu}\right| < 5.3 \times 10^{-11}$$

$$\alpha = \tau$$

ARGUS [Albrecht *et al.*, Z. Phys. C 68, 25-28]

$$\frac{\mathrm{BR}\left(\tau \to e\,\phi\right)}{\mathrm{BR}\left(\tau \to e\,\nu\,\bar{\nu}\right)} < 0.015 \qquad \frac{\mathrm{BR}\left(\tau \to \mu\,\phi\right)}{\mathrm{BR}\left(\tau \to \mu\,\nu\,\bar{\nu}\right)} < 0.026$$

$$\Rightarrow \quad \left|S^{e\tau}\right| < 5.9 \times 10^{-7} \qquad \left|S^{\mu\tau}\right| < 7.6 \times 10^{-7}$$

These limits are weaker than those for muon decays, but still very stringent.
They are expected to be improved at Belle II.

4. Phenomenology: μ → e γ vs μ → 3 e

$$\ell_\alpha \to \ell_\beta \gamma$$

$$\Gamma\left(\ell_\alpha \to \ell_\beta \gamma\right) = \frac{e^2\, m_\alpha^5}{16\,\pi} \left[\left| \left(K_2^L\right)^{\beta\alpha} \right|^2 + \left| \left(K_2^R\right)^{\beta\alpha} \right|^2 \right]$$

$$\ell_\alpha^- \to \ell_\beta^- \ell_\beta^- \ell_\beta^+$$

NEW!

$$\Gamma_\phi\left(\ell_\alpha^- \to \ell_\beta^- \ell_\beta^- \ell_\beta^+\right) =$$

$$\frac{m_\alpha}{512\pi^3} \Bigg\{ \left(\left|S_L^{\beta\alpha}\right|^2 + \left|S_R^{\beta\alpha}\right|^2 \right) \left\{ \left|S^{\beta\beta}\right|^2 \left(4 \log \frac{m_\alpha}{m_\beta} - \frac{49}{6} \right) - \frac{2}{6} \left[\left(S^{\beta\beta *}\right)^2 + \left(S^{\beta\beta}\right)^2 \right] \right\}$$

$$- \frac{m_\alpha^2}{6} \Big\{ S_L^{\beta\alpha} S^{\beta\beta} A_{LL}^{S*} + 2 S_L^{\beta\alpha} S^{\beta\beta *} A_{LR}^{S*} + 2 S_R^{\beta\alpha} S^{\beta\beta} A_{RL}^{S*} + S_R^{\beta\alpha} S^{\beta\beta *} A_{RR}^{S*}$$

$$- 12 \left(S_L^{\beta\alpha} S^{\beta\beta} A_{LL}^{T*} + S_R^{\beta\alpha} S^{\beta\beta *} A_{RR}^{T*} \right) - 4 \left(S_R^{\beta\alpha} S^{\beta\beta} A_{RL}^{V*} + S_L^{\beta\alpha} S^{\beta\beta *} A_{LR}^{V*} \right)$$

$$+ 6 e^2 \left[S_R^{\beta\alpha} S^{\beta\beta} \left(K_2^L\right)^{\beta\alpha *} + S_L^{\beta\alpha} S^{\beta\beta *} \left(K_2^R\right)^{\beta\alpha *} \right] + \text{c.c.} \Big\} \Bigg\}$$

$$S^{\beta\beta} = S_L^{\beta\beta} + S_R^{\beta\beta *}$$

Simplified Effective Lagrangian

$$\mathcal{L}_{\text{LFV}}^{\text{simp}} = \frac{e\, m_\alpha \, \left(K_2^L\right)^{\beta\alpha}}{2} \, \bar{\ell}_\beta \, \sigma^{\mu\nu} \, P_L \, \ell_\alpha F_{\mu\nu} + S_L^{\beta\alpha} \, \phi \, \bar{\ell}_\beta \, P_L \, \ell_\alpha + \text{h.c.}$$

It only includes left-handed photonic dipole and scalar-mediated operators.
Here we assume the dipole contributions to be independent from the scalar induced ones.

$\boldsymbol{\ell_\alpha^- \to \ell_\beta^- \ell_\beta^- \ell_\beta^+}$

$$\Gamma\left(\ell_\alpha^- \to \ell_\beta^- \ell_\beta^- \ell_\beta^+\right) =$$

$$\frac{m_\alpha}{512\pi^3}\left\{\left|S_L^{\beta\alpha}\right|^2 \left\{\left|S_L^{\beta\beta}\right|^2 \left(4\log\frac{m_\alpha}{m_\beta} - \frac{49}{6}\right) - \frac{2}{6}\left[\left(S_L^{\beta\beta *}\right)^2 + \left(S_L^{\beta\beta}\right)^2\right]\right\}\right.$$

$$\left. + m_\alpha^4 \, e^4 \left|K_2^L\right|^2 \left(\frac{16}{3}\log\frac{m_{\ell_\alpha}}{m_{\ell_\beta}} - \frac{22}{3}\right)\right\}$$

Simplified Effective Lagrangian

$$\mathcal{L}_{\rm LFV}^{\rm simp} = \frac{e\, m_\alpha\, \left(K_2^L\right)^{\beta\alpha}}{2}\, \bar{\ell}_\beta\, \sigma^{\mu\nu}\, P_L\, \ell_\alpha F_{\mu\nu} + S_L^{\beta\alpha}\, \phi\, \bar{\ell}_\beta\, P_L\, \ell_\alpha + \text{h.c.}$$

We will make use of the parametrization [Gouvea, Vogel, 1303.4097]

$$e\left(K_2^L\right)^{\beta\alpha} \equiv \frac{1}{(\kappa+1)\Lambda^2}, \quad S_L^{\beta\alpha} \equiv m_\alpha \frac{\kappa}{(\kappa+1)\Lambda}, \quad S_L^{\beta\alpha} = S_L^{\beta\beta}$$

- Λ is dimensionful. Energy scale at which the coefficients are induced.
- κ is dimensionless. Accounts for the relative intensity of both interactions.

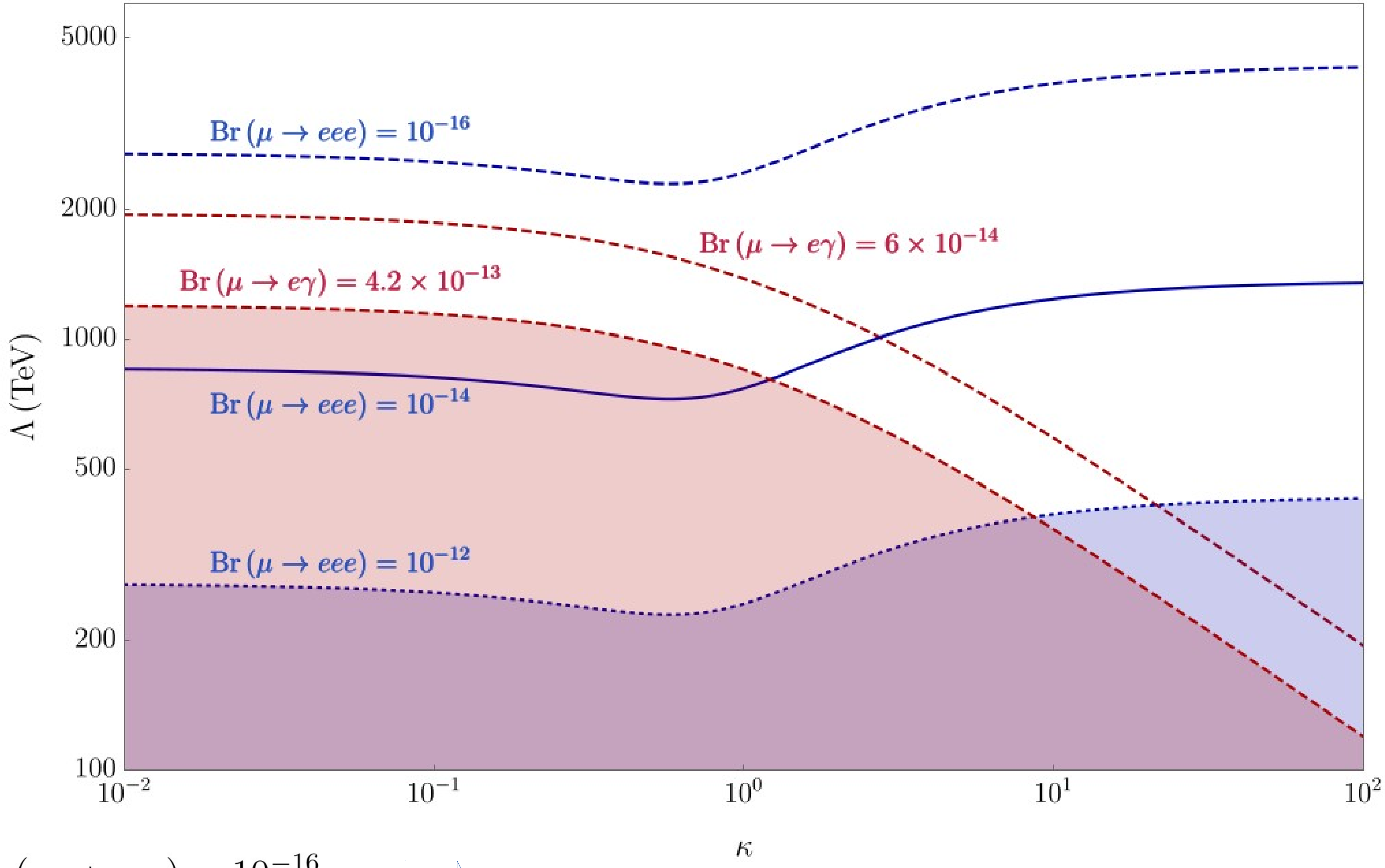
κ << 1 → Dipole operator dominates

κ >> 1 → Scalar mediated contribution dominates

⇨ $$\Gamma\left(\ell_\alpha \to \ell_\beta \gamma\right) = \frac{m_\alpha^5}{16\pi} \frac{1}{(\kappa+1)^2 \Lambda^4}$$

⇨ $$\Gamma\left(\ell_\alpha^- \to \ell_\beta^- \ell_\beta^- \ell_\beta^+\right) = \frac{m_\alpha^5}{512\pi^3}\left[\frac{\kappa^2}{(\kappa+1)^4\Lambda^4}\left(4\log\frac{m_\alpha}{m_\beta} - \frac{53}{6}\right) + \frac{e^2}{(\kappa+1)^4\Lambda^4}\left(\frac{16}{3}\log\frac{m_{\ell_\alpha}}{m_{\ell_\beta}} - \frac{22}{3}\right)\right]$$

4. Phenomenology: μ → e γ vs μ → 3 e



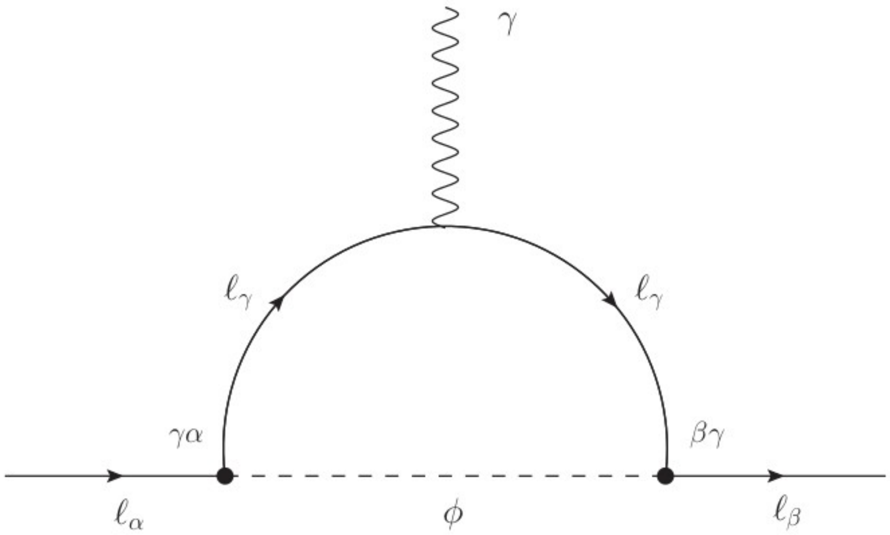
$\mathrm{Br}(\mu \to eee) = 10^{-16}$
$\mathrm{Br}(\mu \to e\gamma) = 6 \times 10^{-14}$ ⇒ Future sensitivities for the MEG-II and Mu3e experiments

- If $\kappa \gg 1$ and $\mathrm{Br}(\mu \to eee) > 10^{-16} \longrightarrow \Lambda < 4000\,\mathrm{TeV}$
- If $\kappa \ll 1$ and $\mathrm{Br}(\mu \to e\gamma) > 10^{-14} \longrightarrow \Lambda < 2000\,\mathrm{TeV}$

The search for the scalar mediated contribution in Mu3e will be very constraining in all the parameter space

4. Phenomenology: μ → e γ vs μ → 3 e

Generation of dipole operators by loops involving the ultralight scalar as shown here



- We assume that the scalar provides the dominant contribution to dipole operators.
- Only the electron diagonal coupling and the electron – muon couplings are allowed not to be zero and are considered to be real.

Approximated expressions

NEW!

$$(K_2^L)^{e\mu} = \frac{S^{ee}}{96\pi^2\, m_\mu^3}\Big\{3\, m_\mu\, S_R^{e\mu} + m_e\left(-6\, S_L^{e\mu} + 2\,\pi^2\, S_L^{e\mu} + 3\, S_R^{e\mu}\right) + 3\, m_e S_L^{e\mu} \log\left(-\frac{m_e^2}{m_\mu^2}\right)\left[1 + \log\left(-\frac{m_e^2}{m_\mu^2}\right)\right]\Big\}$$

$$(K_2^R)^{e\mu} = \frac{S^{ee}}{96\pi^2\, m_\mu^3}\Big\{3\, m_\mu\, S_L^{e\mu} + m_e\left(-6\, S_R^{e\mu} + 2\,\pi^2\, S_R^{e\mu} + 3\, S_L^{e\mu}\right) + 3\, m_e S_R^{e\mu} \log\left(-\frac{m_e^2}{m_\mu^2}\right)\left[1 + \log\left(-\frac{m_e^2}{m_\mu^2}\right)\right]\Big\}$$

4. Phenomenology: μ → e γ vs μ → 3 e

$$R_{\alpha\beta} = \frac{\mathrm{BR}(\ell_\alpha \to \ell_\beta \ell_\beta \ell_\beta)}{\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma)}$$

- Scenario 1: $S_L^{e\mu} = 0$ or $S_R^{e\mu} = 0$

$$R_{\mu e}^{(1)} \approx \frac{4\pi r}{3\alpha} \frac{12 \log r - 53}{|\log(-r)|^4 + r} \approx 3.2 \cdot 10^4$$

- Scenario 2: $S_L^{e\mu} = S_R^{e\mu}$

$$R_{\mu e}^{(2)} \approx \frac{4\pi r}{3\alpha} \frac{12 \log r - 53}{|\log^2(-r) + \sqrt{r}|} \approx 1.9 \cdot 10^4 \qquad r = \frac{m_\mu^2}{m_e^2};$$

- Scenario 3: $S_L^{e\mu} = -S_R^{e\mu}$

$$R_{\mu e}^{(3)} \approx \frac{4\pi r}{3\alpha} \frac{12 \log r - 53}{|\log^2(-r) - \sqrt{r}|} \approx 1.1 \cdot 10^5$$

⇨ R >> 1 in all the cases, since the decay in the numerator is induced at tree level, while the one in the denominator takes place at loop order.

⇨ The three scenarios lead to different predictions for the ratio and could allow us to determine the nature of the scalar if both processes are observed.

Anomalous magnetic moments (AMM)

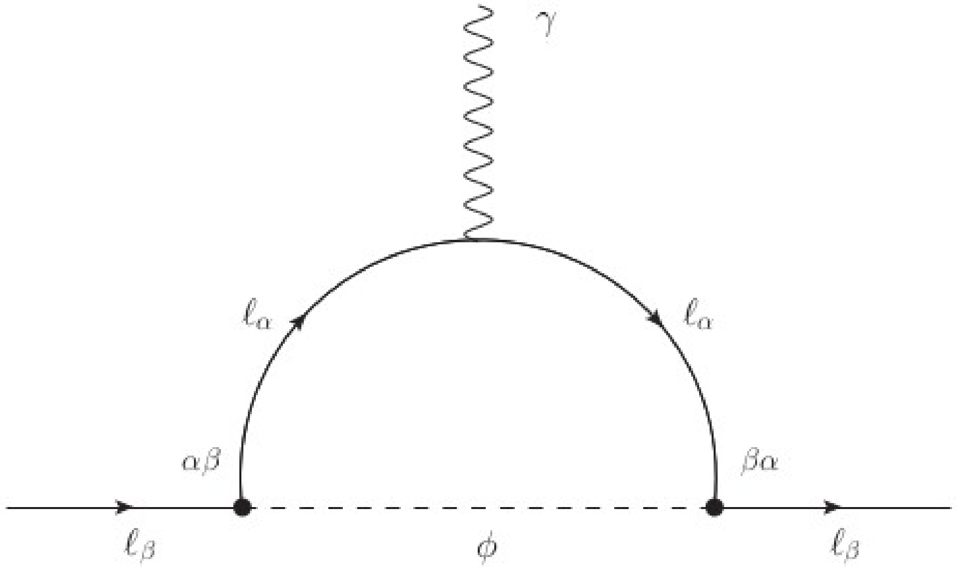
$$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = (-87 \pm 36) \times 10^{-14}$$
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (27.1 \pm 7.3) \times 10^{-10}$$

$$a_\beta = \frac{g_\beta - 2}{2}$$

Electric dipole moments (EDM)

$$|d_e| < 1.1 \times 10^{-29}\, e\,\text{cm}$$
$$|d_\mu| < 1.5 \times 10^{-19}\, e\,\text{cm}$$

Lepton conserving contributions

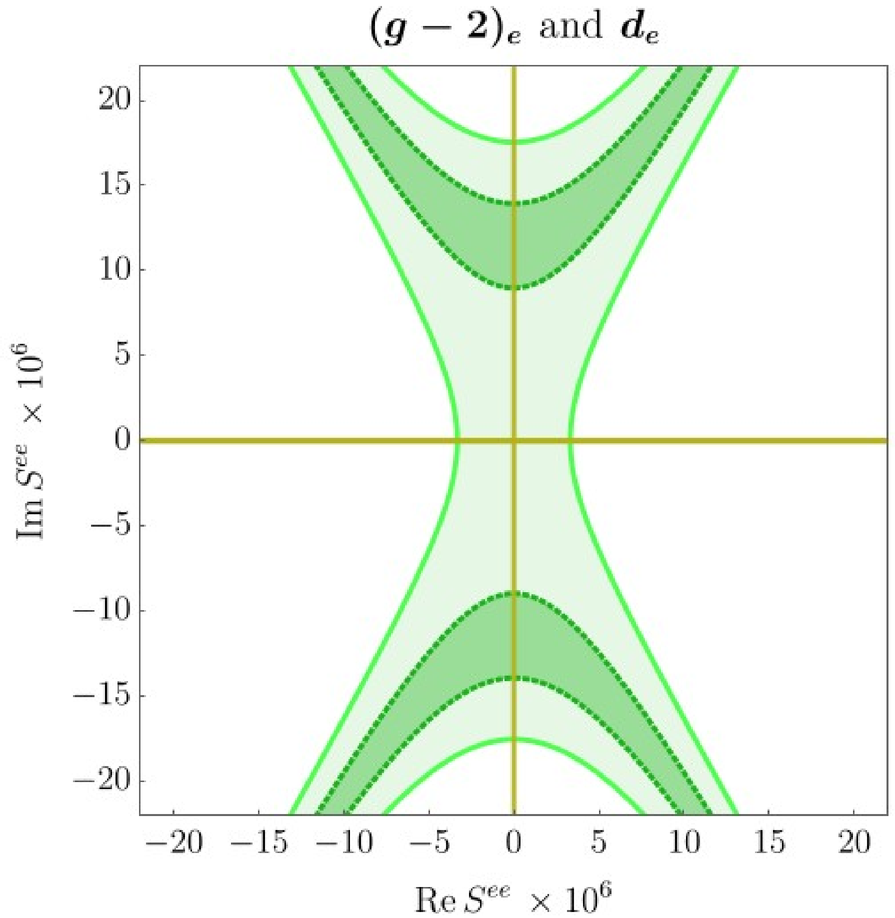


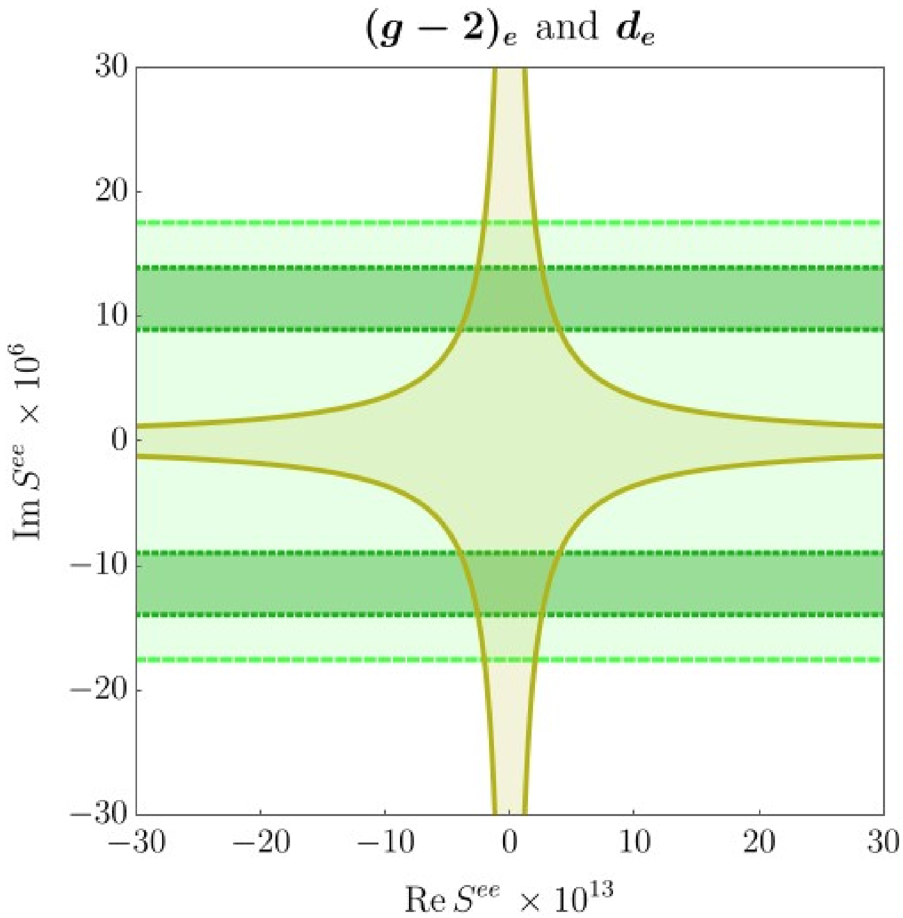
$$\Delta a_\alpha = \frac{1}{16\pi^2}\left[3\,(\text{Re}\,S^{\alpha\alpha})^2 - (\text{Im}\,S^{\alpha\alpha})^2\right]$$

$$d_\alpha = -\frac{e}{8\,\pi^2\,m_\alpha}\,(\text{Re}\,S^{\alpha\alpha})\,(\text{Im}\,S^{\alpha\alpha})$$

Too high values for the off-diagonal couplings would be necessary to fully explain the anomalies, and these are excluded by LFV observations.

4. Phenomenology: AMM and EDM



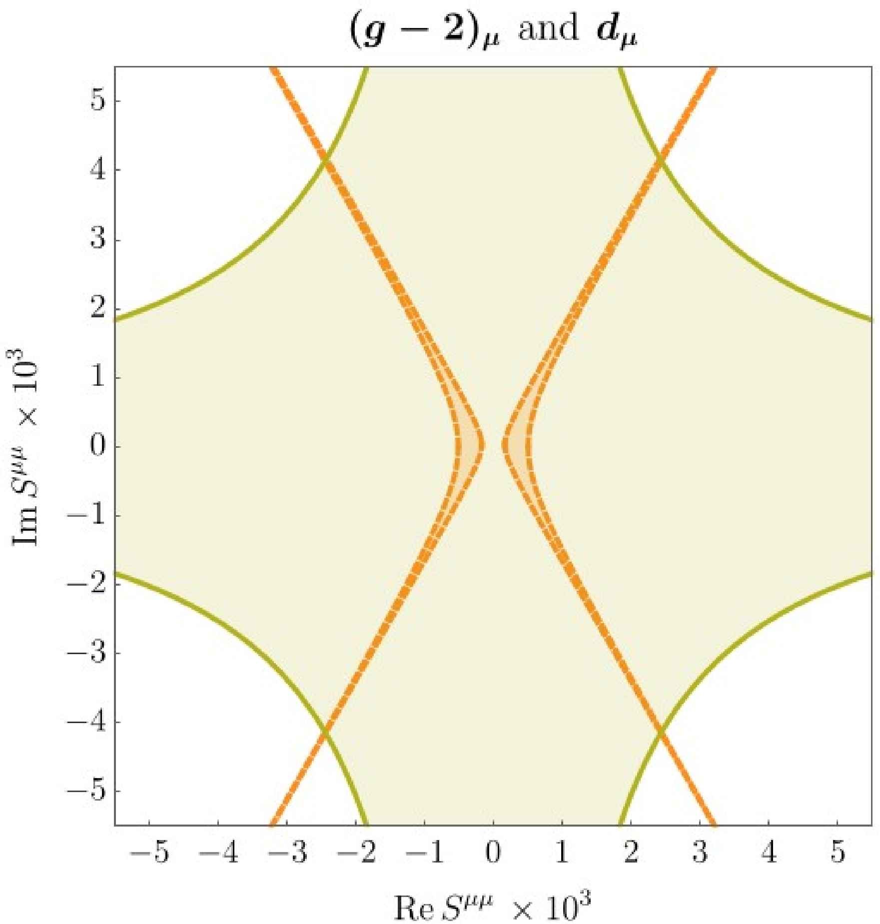


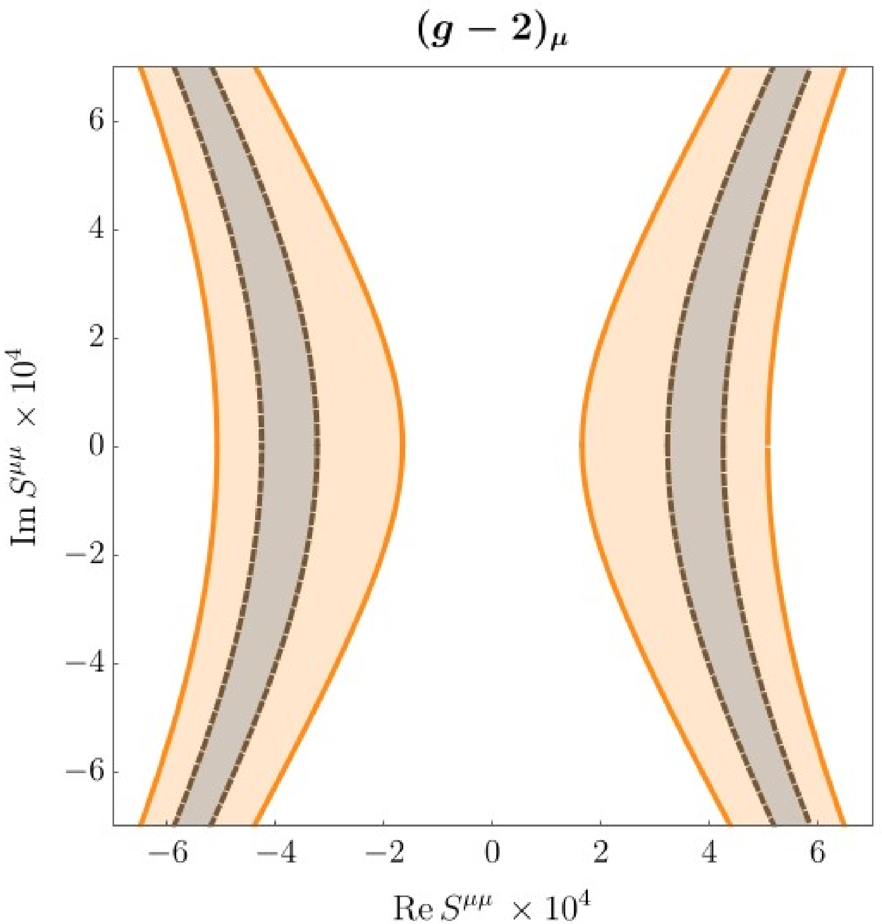
- The electron EDM strongly constraints the coupling, making it essentially purely real or purely imaginary.

- We can find regions that explain the g-2 anomaly compatible with the bound for the EDM

  - Even with $S^{ee} = 0$, we stay in the 3 σ region.
  - We achieve agreement at the 1 σ level if $Re(S^{ee}) \leq 10^{-13}$ and $Im(S^{ee}) \sim 10^{-5}$

4. Phenomenology: AMM and EDM





- The muon EDM does not impose strong restrictions on the parameter space.
- Larger couplings, $S^{\mu\mu} \sim 10^{-4}$, are necessary to explain the muon anomaly.

In both cases, the required values for the couplings are in conflict with the current bounds. A mechanism to suppress the processes from which the bounds are derived would be necessary for the scalar to be able to provide an explanation to the anomalies.

6. Summary and discussion

- Ultralight scalars appear in a wide variety of SM extensions.
  - As very light states
  - As exactly massless Goldstone bosons
- We have explored the impact of ultralight scalars adopting a model independent general approach, taking into account scalar and pseudoscalar interactions.
- We have briefly reviewed the current bounds on the scalar-charged leptons couplings.
- We have obtained analytical expressions for several observables and we explored some phenomenological aspects of this scenario.
- We have shown that an explanation to the g-2 anomalies can be possible if some mechanisms exist to suppress the processes from which the diagonal bounds are obtained.
- Also, the observables discussed in the paper are complementary.
- The scalar could also couple to quarks, opening many hadronic and semi-leptonic channels.