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Light New Physics coupling to τ

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Why New Physics?

Our objective is to look for signs of New Physics, motivated by

- Theoretical questions: Flavour puzzle, dark matter, dark energy, unification with gravity, hierarchy problem, etc.
- Experimental anomalies: $(g-2)_\mu$, $R_{D^{(*)}}$, Cabbibo anomaly, etc.
- Elaboration of hypotheses.

Why Light New Physics?

- We could see it in the current particle colliders in the form of resonances ("visible" decays) or missing energy ("invisible" decays).
- Also in other experiments: helioscopes, astronomical observations, etc.
- Can not be described as an Effective Field Theory.
- Theoretical motivation: Dark Matter candidates, Strong CP problem, axiverse.

Strong CP problem

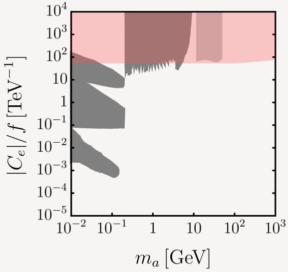
- Three discrete transformations: Charge conjugation (C), Parity (P) and Time reversal (T).
- Experimentally, C, P and CP are not symmetries of the SM.
- Strong interactions preserve CP, although we could write a CP-violating term $\theta G\tilde{G}$.
- Very strong experimental bounds from electric dipole moment of the neutron.
- **Peccei-Quinn mechanism:** A new pseudo-scalar field with anomalous couplings to gluons $aG\tilde{G}$ which develops a vev, dynamically erasing the CP violation. Its particle excitation is the axion.
- Characterized by energy scale f_a and mass $m_a f_a \sim m_\pi f_\pi$.
- Shift symmetry $a \to a + \mathrm{constant}$.

Axion-Like Particles

- Many beyond-SM models propose a new global $U(1)$ symmetry, spontaneously broken at energies $f_a \gg v$. The Nambu-Goldstone boson (NGB) associated to this symmetry would be an Axion-like particle (ALP).
- If the symmetry is also explicitly broken, the ALP is a pseudo-NGB, and $m_a f_a \sim m_\pi f_\pi$.
- As an example, string theory predicts the existence of many ALPs in a wide range of masses and energy scales as a result of the compactification of antisymmetric tensor fields.

Why coupling to τ?

- Many experimental constraints for couplings to photons and to quarks.
- The couplings to fermions are proportional to their mass, and τ is the heaviest lepton.
- New Physics in 3rd generation, consistent under RG flow.
- Improved experimental sensitivity to τ (e.g in Belle-II).



A. Biekötter, J. Fuentes-Martín, A. M. Galda and M. Neubert, arXiv:2307.10372

Light New Physics

Axion-like Particle coupled to a Peccei-Quinn current of leptons

$$\mathcal{L}_{\mathrm{ALP}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{2f_a}\partial_\mu a j^\mu_{\mathrm{PQ}}\,;$$

$$j^\mu_{\mathrm{PQ}} = \sum_{i,j}\left(c_{\ell\ell}^{ij}\bar{\ell}_i\gamma^\mu\gamma_5\ell_j + \bar{c}_{\ell\ell}^{ij}\bar{\ell}_i\gamma^\mu\ell_j + c_{\nu\nu}^{ij}\bar{\nu}_{\ell_i}\gamma^\mu P_L \nu_{\ell_j}\right)\,.$$

- $m_a \in [1\,\mathrm{MeV}, 10\,\mathrm{GeV}]$, $f_a \sim 1\,\mathrm{TeV}$, flavour-universal $c^{ij} = c\delta^{ij}$.
- $g_{\ell\ell} = c_{\ell\ell} m_\ell / f_a$.
- After integration-by-parts and equations-of-motion

$$\mathcal{L}_{\mathrm{ALP,int}} = \sum_\ell \left(i g_{\ell\ell}\bar{\ell}\gamma_5\ell a + \frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu\nu})(\bar{\ell}\gamma^\mu P_L\nu_\ell)W^-_\mu a + \mathrm{h.c.}\right) + (V\tilde{V}a)\,.$$

- Electroweak-preserving case: $g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu\nu} = 0$.

Light New Physics

Scalar ϕ and pseudo-scalar $\hat{\phi}$ bosons:

$$\mathcal{L}_{\text{lightNP}} \subset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}\partial_\mu\hat{\phi}\partial^\mu\hat{\phi} - \frac{1}{2}m_{\hat{\phi}}^2\hat{\phi}^2 - \sum_\ell \bar{\ell}(k_\ell\phi + i\hat{k}_\ell\hat{\phi}\gamma_5)\ell\,.$$

For the pseudo-scalar boson, we recover the EW-preserving ALP when the couplings are hierarchical $\hat{k}_\ell = g_\ell = c m_\ell/f_a$.

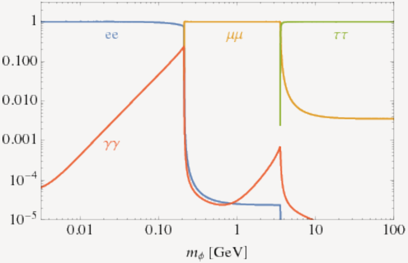
Particle decays

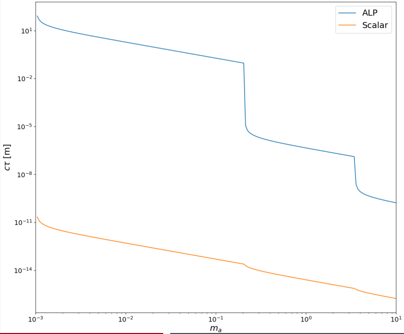
The NP particles can decay to a pair of leptons

$$\Gamma(S \to \ell^+\ell^-) = \frac{m_S}{8\pi}|K_\ell|^2 \left(1 - \frac{4m_\ell^2}{m_S^2}\right)^{\alpha_S} ,$$

with $K_\ell = g_{\ell\ell}$ and $\alpha_S = 1/2$ for $S = a$, and $K_\ell = k_\ell$ and $\alpha_S = 3/2$ for $S = \phi$.
Also decays to 2γ through a lepton loop.

ALPs with $m_a > 2m_e$ and scalars will typically decay inside the detector.





Leptonic B decays

$$\frac{\mathrm{BR}(B^- \to \ell^- \bar{\nu}_\ell a)}{\mathrm{BR}(B^- \to \ell^- \bar{\nu}_\ell)} \approx \frac{1}{1536\pi^2} \frac{m_B^4}{m_\ell^2 f_a^2} \left[(c_{\ell\ell} - \bar{c}_{\ell\ell} + c_{\nu\nu})^2 + \frac{16 m_\ell^2}{m_B^2} c_{\ell\ell}^2 \right]$$