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Light New Physics coupling to τ

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Saturnalia '23
20-12-2023

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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 $a \to a + \mathrm{constant}$.

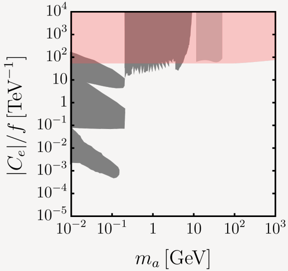
Axion-Like Particles

- 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 $m_a f_a \not\sim m_\pi f_\pi$.
- 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.

Photo: Sebastian Hoof

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

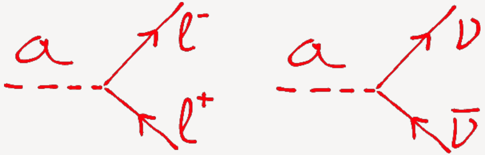
Light New Physics

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

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

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

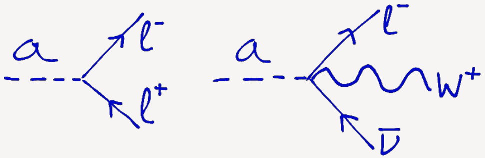
$m_a \in [1\,\mathrm{MeV}, 10\,\mathrm{GeV}]$, $f_a \sim 1\,\mathrm{TeV}$, flavour-universal $c^{ij} = c\delta^{ij}$ or τ-phillic $c^{ij} = c\delta^{i3}\delta^{j3}$.
Electroweak-preserving case: $c_{\ell\ell} - \bar{c}_{\ell\ell} + c_{\nu\nu} = 0$.



Light New Physics

After integration-by-parts and equations-of-motion

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



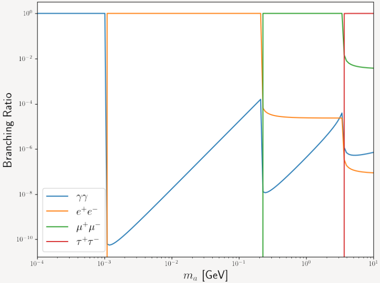
Particle decays

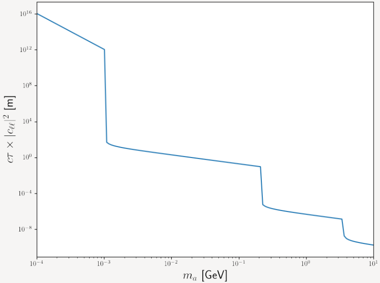
The ALP particles can decay to a pair of leptons

$$\Gamma(a \to \ell^+ \ell^-) = \frac{m_a}{8\pi} |c_{\ell\ell}|^2 \frac{m_\ell^2}{f_a^2} \left(1 - \frac{4m_\ell^2}{m_a^2}\right)^{1/2} ,$$

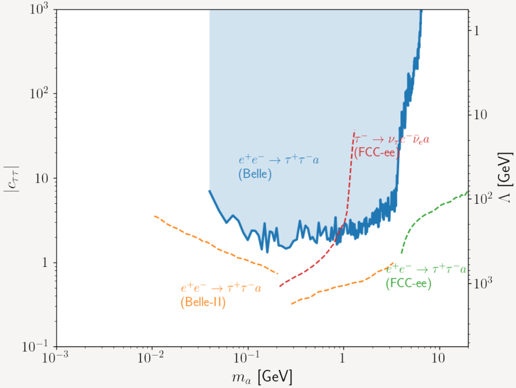
Also decays to 2γ through a lepton loop.

ALPs with $m_a > 2m_\mu$ will typically decay inside the detector.

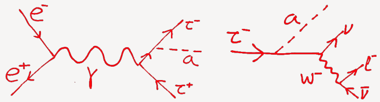




Collider searches



Production of visible ALPs in Belle, Belle-II and FCC-ee: the ALP decays into a pair of lighter leptons inside the detector.

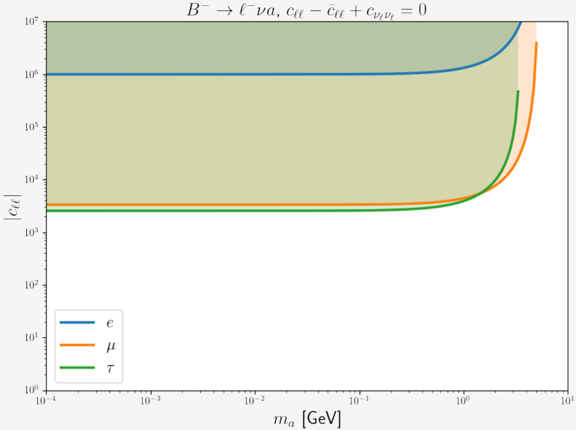


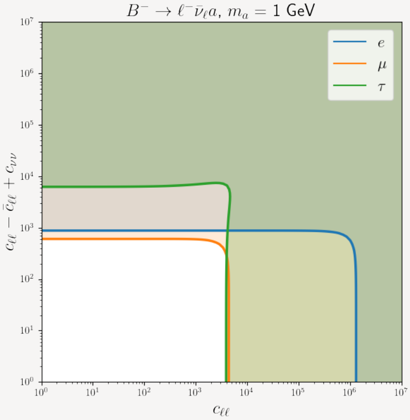
Bump searching at $m_{\ell\ell}^2 = m_a^2$.

Leptonic B decays

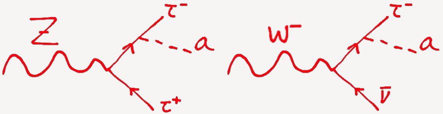
B-meson leptonically decaying into an invisible ALP.

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

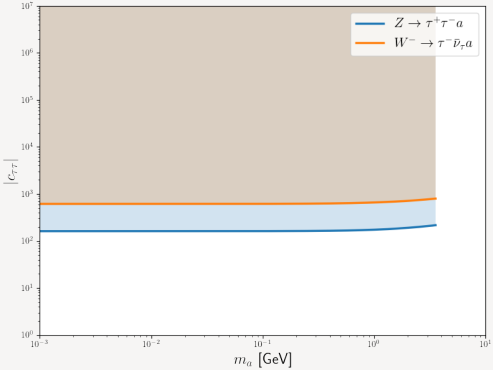




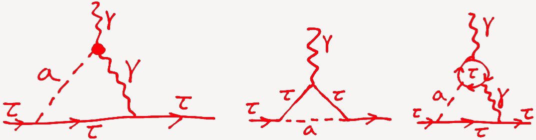
Gauge boson decays



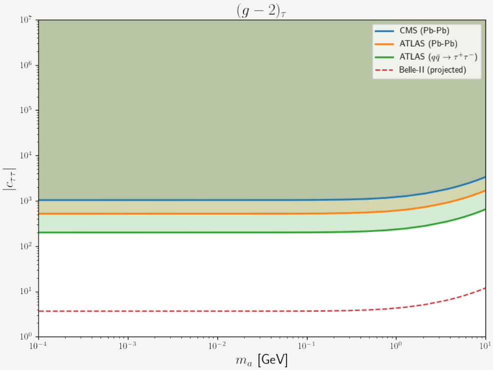
Production of invisible ALP in $Z \to \tau^+\tau^- a$ and $W^- \to \tau^- \bar{\nu}_\tau a$.
For the W decays there are additional terms in the case of EW-violating interactions.



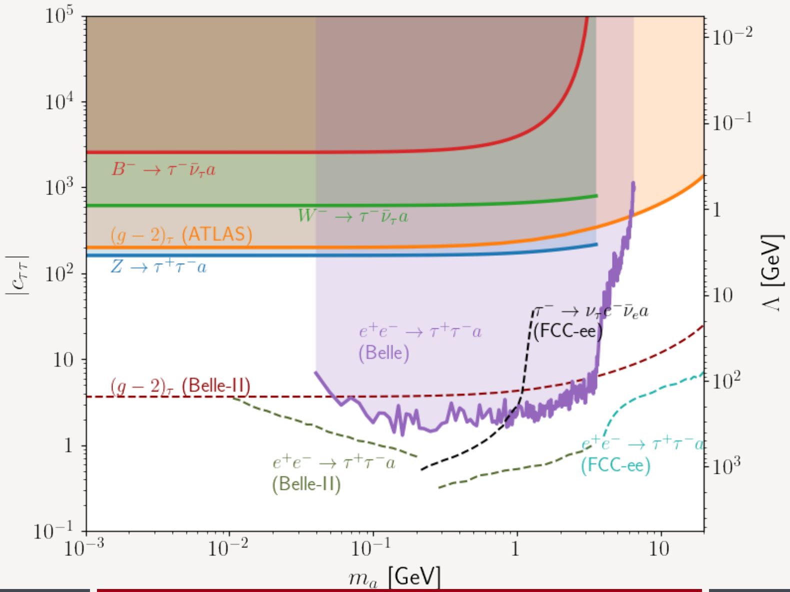
$(g-2)_\tau$



- New (2022-23) measurements of $(g-2)_\tau$ at LHC
- Still not very precise ($|a_\tau| < 1.8 \times 10^{-3}$)
- Belle-II is expected to achieve a precision of $\sim 10^{-6}$



Bounds for couplings to τ leptons



Conclusions

- ALPs are a well-motivated extension of the SM with a new light pseudoscalar particle.
- We studied ALPs coupling to τ, both in LFU and τ-phillic scenarios.
- Production of “visible” ALPs in colliders:
  - Dedicated search at Belle.
  - Belle-II will improve the bounds, and FCC-ee will explore heavier ALP masses.
- “Invisible” ALPs in $B^- \to \tau^- \bar{\nu}_\tau a$, $W^- \to \tau^- \bar{\nu}_\tau a$ and $Z\tau^-\tau^+ a$ complement direct searches for lighter ALPs.
- Loop effects in $(g-2)_\tau$, will drastically improve in Belle-II.

Outlook

- Still Work in Progress
- Invisible ALPs in $e^+e^- \to \tau^+\tau^- a$.
- $B \to D^{(*)}\tau^-\bar{\nu}_\tau a$ and $R_{D^{(*)}}$?
- Generalization to other light NP particles: scalars, dark photons, etc.

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