



Light New Physics coupling to τ

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

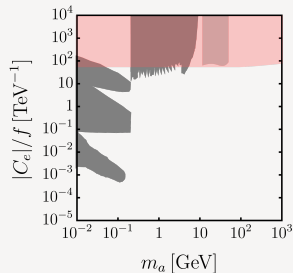
- Theoretical questions: Flavour puzzle, dark matter, dark energy, unification with gravity, hierarchy problem, etc.
- Experimental anomalies: $(g - 2)_\mu$, $R_{D^{(*)}}$, Cabbibo anomaly, etc.
- Elaboration of hypotheses.

- 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.

- 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 $a \rightarrow a + \text{constant}$.

- 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 $m_a f_a \approx m_\pi f_\pi$.
- 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.

- 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

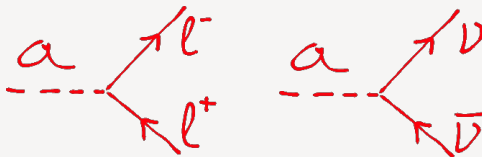
Axion-like Particle coupled to a Peccei-Quinn current of leptons

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{2f_a} \partial_\mu a j_{\text{PQ}}^\mu;$$

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

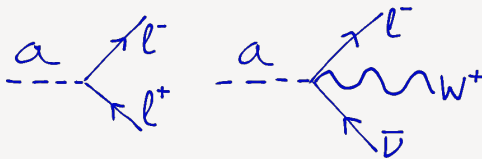
$m_a \in [1 \text{ MeV}, 10 \text{ GeV}]$, $f_a \sim 1 \text{ TeV}$, flavour-universal $c^{ij} = c \delta^{ij}$ or τ -phillic $c^{ij} = c \delta^{i3} \delta^{j3}$.

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



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

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

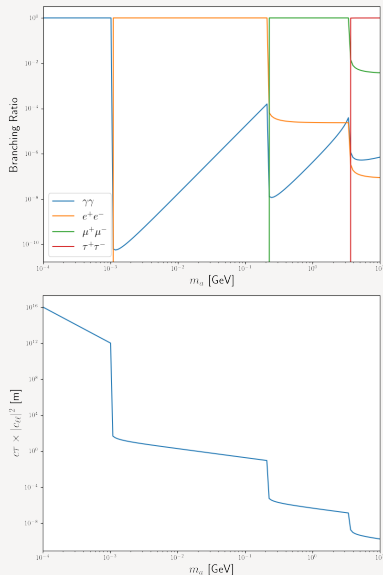


The ALP particles can decay to a pair of leptons

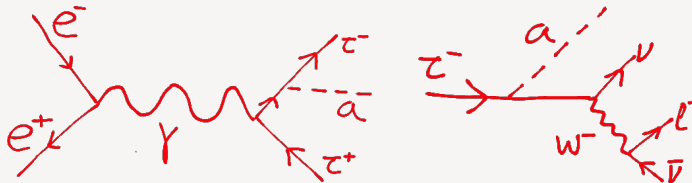
$$\Gamma(a \rightarrow \ell^+ \ell^-) = \frac{m_a}{8\pi} |c_{\ell\ell}|^2 \frac{m_\ell^2}{f_a^2} \left(1 - \frac{4m_\ell^2}{m_a^2}\right)^{1/2},$$

Also decays to 2γ through a lepton loop.

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



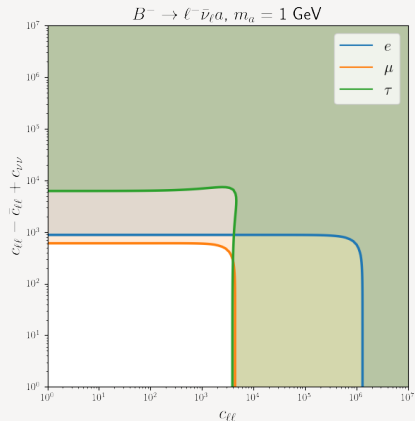
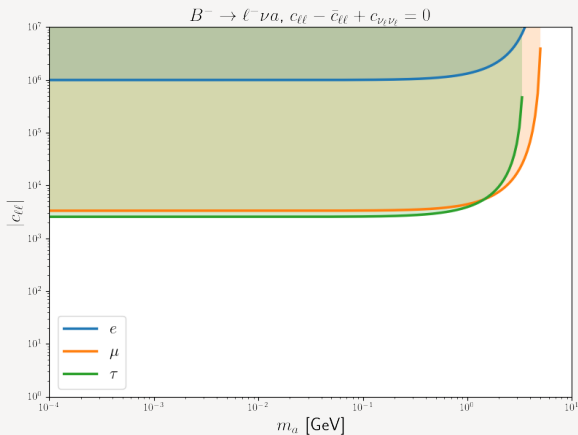
Production of visible ALPs in Belle, Belle-II and FCC-ee: the ALP decays into a pair of lighter leptons inside the detector.

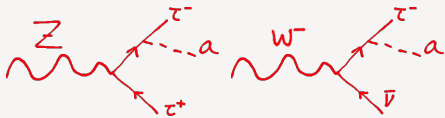


Bump searching at $m_{\ell\ell}^2 = m_a^2$.

B -meson leptonically decaying into an invisible ALP.

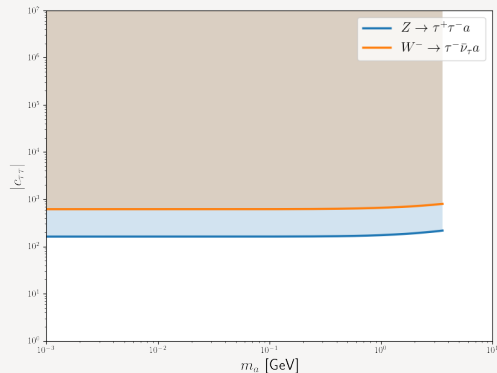
$$\frac{\text{BR}(B^- \rightarrow \ell^- \bar{\nu}_\ell a)}{\text{BR}(B^- \rightarrow \ell^- \bar{\nu}_\ell)} \approx \frac{1}{1536\pi^2} \frac{m_B^4}{m_\ell^2 f_a^2} \left[(c_{\ell\ell} - \bar{c}_{\ell\ell} + c_{\nu\nu})^2 + \frac{16m_\ell^2}{m_B^2} c_{\ell\ell}^2 \right]$$

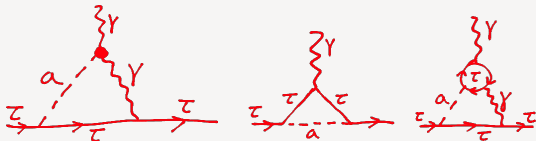




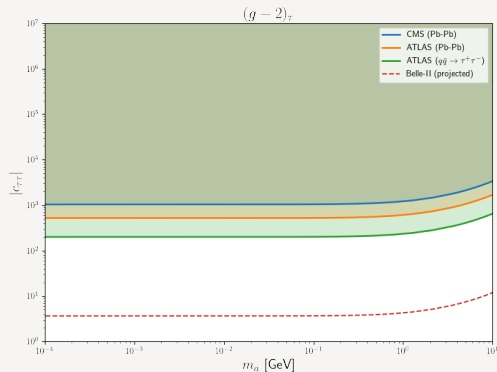
Production of invisible ALP in $Z \rightarrow \tau^+ \tau^- a$
and $W^- \rightarrow \tau^- \bar{\nu}_\tau a$.

For the W decays there are additional terms in
the case of EW-violating interactions.

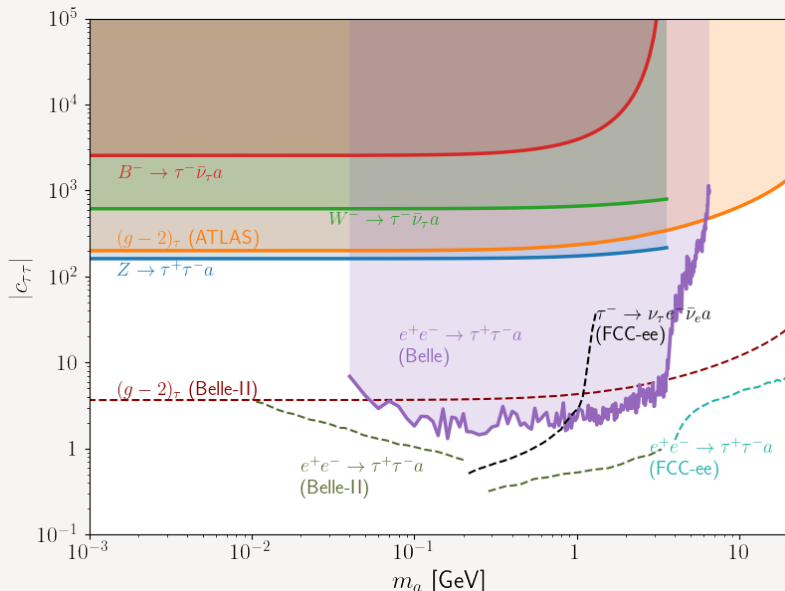




- New (2022-23) measurements of $(g - 2)_\tau$ at LHC
- Still not very precise ($|a_\tau| < 1.8 \times 10^{-3}$)
- Belle-II is expected to achieve a precision of $\sim 10^{-6}$



Bounds for couplings to τ leptons



- 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 $B^- \rightarrow \tau^- \bar{\nu}_\tau a$, $W^- \rightarrow \tau^- \bar{\nu}_\tau a$ and $Z \tau^- \tau^+ a$ complement direct searches for lighter ALPs.
- Loop effects in $(g - 2)_\tau$, will drastically improve in Belle-II.

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

- JA, A. Guerrera, S. Peñaranda and S. Rigolin: “Leptonic meson decays into invisible ALP”. Nucl.Phys.B 979 (2022) 115791, arXiv: 2111.02536 [hep-ph]
- W. Altmannshofer, J. A. Dror, and S. Gori, “New Opportunities for Detecting Axion-Lepton Interactions” Phys. Rev. Lett. 130 no. 24, (2023) 241801, arXiv:2209.00665 [hep-ph]
- D. Biswas et al. (Belle), “Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair in e^+e^- annihilation at center-of-mass energies near 10.58 GeV” arXiv:2207.07476 [hep-ex]