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# Tackling ALP searches in meson decays with ALP-aca: a phenomenological approach

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Part of the community has intensively searched for ALP signals, as well as conducted dedicated data analyses to identify potential evidence of New Physics compatible with an ALP, resulting in constraints on the ALP parameter space. Considering the advancements both in theoretical studies as well as experimental measurements, it is now the time to present a tool, ALP-aca , that facilitates the combination among the different information on ALP physics. We showcase a phenomenological analysis of the ALP theory using the most up-to-date data from flavour facilities, to show both the latest constraints and the potential of ALP-aca . The program is publicly available at ALP-aca .

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## 1. Introduction

Axions and axion-like particles (ALPs) have arisen as candidates to address some of the open problems of the Standard Model (SM) across different energy scales, such as the strong CP problem or the origin of Dark Matter. Searching for them in relation with mesons allows us to probe a mass range where the ALP is too heavy for astrophysical studies and too light to be tested at colliders, like the LHC. Additionally, flavour facilities now have a rich search programme rendering this avenue extremely interesting. Considering the work done in Refs. [1, 2], this proceeding aims to present a simplified analysis of ALP physics using `ALP-aca` , a tool that facilitates the combination of ALP theoretical predictions with the last experimental data from flavour facilities.

## 2. From the UV description to experimental analysis

The Axion-Like Particle (ALP) Lagrangian is usually defined as the $D \leq 5$ effective Lagrangian invariant under the constant shift symmetry of the ALP field, $a \to a + \epsilon$, only broken by gauge anomalous terms and by a light soft-breaking mass $m_a \ll f_a$ uncorrelated to the symmetry breaking scale $f_a$:

$$\begin{aligned}\mathcal{L}_{\rm ALP} =& \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f_a}\left(\frac{g'^2 c_B}{16\pi^2} B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_W}{16\pi^2} W^i_{\mu\nu}\tilde{W}^{i,\mu\nu} + \frac{g_s^2 c_G}{16\pi^2} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right) + \\ &+ \frac{\partial^\mu a}{f_a}\left(\bar{q}_L\, c_q \gamma_\mu q_L + \bar{u}_R\, c_u \gamma_\mu u_R + \bar{d}_R\, c_d \gamma_\mu d_R + \bar{\ell}_L\, c_\ell \gamma_\mu \ell_L + \bar{e}_R\, c_e \gamma_\mu e_R\right) + \mathcal{O}\left(\frac{a^2}{f_a^2}\right), \qquad (1)\end{aligned}$$

where $g_s$, $g$ and $g'$ stand for the strong, weak and hypercharge coupling respectively; $G^a_{\mu\nu}$, $W^i_{\mu\nu}$ and $B_{\mu\nu}$ are the $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ field strengths and $\tilde{X}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}X_{\rho\sigma}$, with $\epsilon^{0123} = 1$, their associated dual fields. The left- and right-handed (RH) fermions $f = \{q_L, u_R, d_R, \ell_L, e_R\}$ are triplets in flavour space, while the corresponding ALP couplings, $c_f = \{c_q, c_u, c_d, c_\ell, c_e\}$, are general $3 \times 3$ hermitian matrices. The resulting Lagrangian in Eq. (1) is valid at the UV scale $\Lambda = 4\pi f_a$. To be able to confront UV completions with experimental data, one has to perform the running of the Wilson coefficients, integrate out the heavy fields and match between EFTs at each relevant energy scale all the way down to energies $\sim \mathcal{O}(1)$ GeV. Fig. 1 shows a summary of the different EFTs, parameters and scales involved. This process is fully automated in `ALP-aca` .

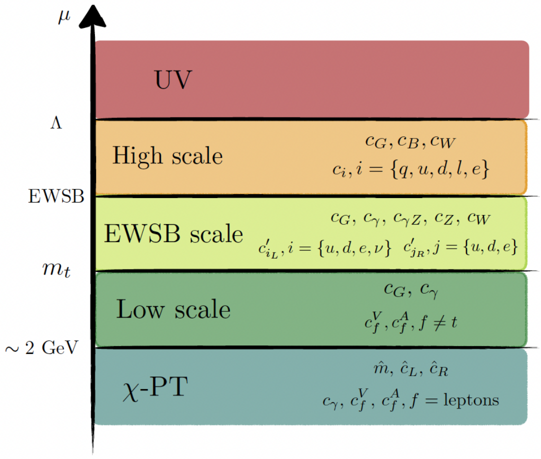

**Figure 1:** *Summary diagram of all scales and couplings implemented in* `ALP-aca` .

## 3. ALP-aca: a python package

`ALP-aca` is an easy-to-use Python package which provides a versatile tool for ongoing and future analyses of the physics involving ALPs since:

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- It allows one to test generic ALP-EFT Lagrangians as well as specific UV models.
- It permits one to define ALP couplings at arbitrary energy scales.
- It supports multiple operator bases, handling both flavour-universal and flavour-specific ALP couplings with fermions.
- It encodes the full 1-loop RGE of the shift-symmetric ALP couplings.
- It performs the matching and the running across various thresholds, from the UV scale $\Lambda$ down to meson-mass energies.
- It incorporates the routines to compute ALP decays into photons, hadrons and fermions. Particular attention is devoted to the hadronic decay treatment including the state-of-art $\chi$PT description, as well as VMD contributions.
- It accounts for various ALP production mechanisms, such as quarkonia radiative decays, FNCN meson decays, LFV decays and non-resonant production.
- It is equipped with the latest available experimental measurements.
- It handles prompt and displaced vertices, as well as invisible signatures.
- It includes statistical tools to compute likelihoods and confidence intervals.
- It scans over parameter spaces and allows to produce exclusion plots and signal regions.
- It integrates with the iNSPIRE-HEP REST API for automatic citation generation.

A detailed manual of all the functionalities is given in Ref. [1], where also a exhaustive list of all included experimental measurements is reported.

## 4. The Belle II anomaly: a case study

`ALP-aca` allows the user to perform a wide variety of phenomenological analyses. To showcase some of these functionalities, we will focus on the process $B^+ \to K^+\overline{\nu}\nu$[1]. The branching ratio was measured at Belle II [3], giving

$$\mathrm{BR}(B^+ \to K^+\overline{\nu}\nu) = \left[2.3 \pm 0.5\,(\mathrm{stat.})^{+0.5}_{-0.4}\,(\mathrm{syst.})\right] \times 10^{-5}, \tag{2}$$

which is in a 2.8 $\sigma$ tension with the SM. In Ref. [4], the authors claim that an ALP with $m_a = 2$ GeV could be compatible with this anomaly, by combining Belle II and BaBar data and assuming the following non-universal vector and axial ALP–quark couplings at the low energy scale $\mu_b \sim m_b$:

$$\mathcal{L}^{\mathrm{LE}}_{\mathrm{ALP}}(\mu_b) \supset \frac{\partial_\mu a}{f_a}\left(c^V_{sb}\bar{s}\gamma^\mu b + c^A_{sb}\bar{s}\gamma^\mu\gamma_5 b\right) + \mathrm{h.c.}\,. \tag{3}$$

Retaining only the ALP–quark couplings in Eq. (3) leads to a long-lived ALP that decays outside the Belle II and BaBar detectors, thus allowing to combine the two measurements directly.

We now attempt to explain this anomaly first in terms of an EFT description and then via specific UV completions. In Fig. 2, we plot the preferred parameter space in terms of the low-energy EFT

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[1] For a more comprehensive study of ALP searches in meson decays, please refer to Ref. [2].

Lagrangian of Eq. (3), where the measurement of $B^+ \to K^{*+}\nu\bar{\nu}$ places a direct constraint on the axial coupling, $|c^A_{sb}|/f_a \lesssim 1\times 10^{-8}$ GeV$^{-1}$, while the combined measurements of $B^+ \to K^+\nu\bar{\nu}$ point to a value for the vector coupling of $3\times 10^{-9}\,\mathrm{GeV}^{-1} \lesssim |c^V_{sb}|/f_a \lesssim 8\times 10^{-8}\,\mathrm{GeV}^{-1}$ in the $2\,\sigma$ region. These values agree with the ones reported in Ref. [4], thus being a cross-check of our results. In the same plot, we also show the predictions of different UV models, such as QED-DFSZ, Q-KSVZ, top-philic and a benchmark flaxion model[2], which lie along the diagonal, that is the blue line. For the models with no flavour-violating couplings at tree-level, namely QED-DFSZ, Q-KSVZ and top-philic, this follows from the fact that flavour violation is loop generated in the LH quark sector, thus implying $c^V_{sb} = -c^A_{sb}$. For the benchmark flaxion model considered this relation is a numerical accident. As can be seen, these models can easily generate the flavour-violating couplings at low-energy necessary to describe the Belle II anomaly. However, this is not enough to explain an excess corresponding to an "invisible" channel of an ALP since, apart from a suitable flavour-violating coupling, the ALP needs to be long-lived enough to escape the detector.

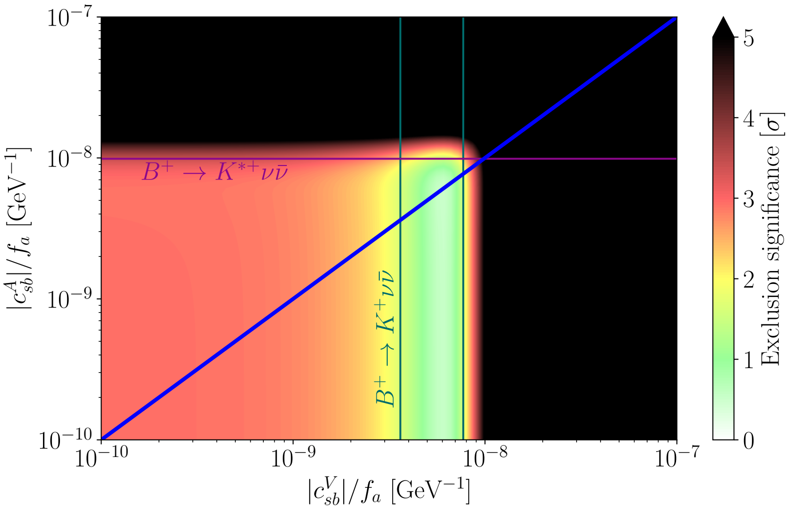

**Figure 2:** *Preferred region of parameter space $c^V_{sb}/f_a$ vs. $c^A_{sb}/f_a$ to explain the Belle II anomaly. The line in blue highlights where the couplings generated by the benchmarks lie. The mass of the ALP is set to $m_a = 2\,\mathrm{GeV}$.*

To emphasise this point, we plot in Fig. 3 the partial width $\Gamma(B^+ \to K^+ a)$ and $P_{\mathrm{inv}}$, running implicitly as a function of $f_a$, $f_a \in [100, 10^{10}]$ GeV. The region that would explain the Belle II anomaly is shaded in blue, while the red-shaded area is excluded by the requirement that $\Gamma(B^+ \to K^+ a) < \Gamma_B$, the total decay width of the $B$ meson. As we can see, the QED-DFSZ, Q-KSVZ and top-philic models fail as the loop-induced coupling requires a scale $f_a$ incompatible with an invisible ALP. Moreover, in the flaxion model studied here, flavour violation is slightly suppressed due to Cabibbo factors, making again the scale too small for the ALP to be long-lived. Notice that it is possible to reconcile these models with the Belle II measurement, assuming that the ALP can decay into a Dark Sector (DS) with BR$(a \to \mathrm{DS}) \gtrsim \mathcal{O}(10^{-3})$ (dashed lines). We do not

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[2] Ref. [2] has a detailed discussion on the characteristics and couplings of the models, as well as additional UV scenarios.

discuss here the non-universal DFSZ (light green) and $sb$-philic scenarios due to space constraints, but a detailed analysis can be found in Ref. [2].

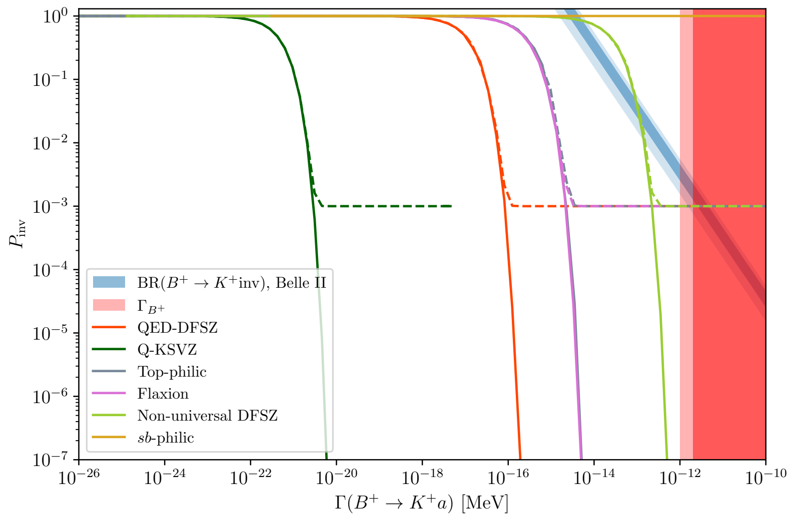

**Figure 3:** *Probability of invisible decay as a function of the decay width of* $B^+ \to K^+ a$ *for the different models studied for a branching ratio to a dark sector of* 0 ($10^{-3}$) *for the continuous (dashed) lines. We set* $m_a = 2\,\mathrm{GeV}$. *The blue-shaded region represents the branching ratio obtained experimentally at Belle II, while the red-shaded region is excluded by the decay width of* $B^+$.

From these simplified benchmark models we learn that if we see a missing energy signal compatible with an ALP, the model must either exhibit flavour violation relatively unsuppressed, or certain channels must be cancelled at low energies to make the particle invisible. In many cases, both conditions are necessary.

## 5. Conclusions

We have presented ALP-aca , an user-friendly Python package that provides the tools to perform present and future phenomenological analyses of ALPs in meson searches. As a showcase of all the possibilities it has, we studied the Belle II anomaly and found that our EFT results agree with those in Ref. [4], while the benchmark models we highlighted need to have a branching ratio to a dark sector in order to accommodate the experimental data.

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