PROCEEDINGS OF SCIENCE

Overview for Axions/ALPs: theory perspective

Marvin Schnubel[a,b,*]

[a] Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA

[b] PRISMA+ Cluster of Excellence and Mainz Institute for Theoretical Physics Johannes Gutenberg University, 55099 Mainz, Germany

E-mail: mschnubel@bnl.gov

Axions and axion-like particles, commonly referred to as ALPs here, are among the most popular extensions of the Standard Model. They are as pseudo-Nambu-Goldstone bosons of a high energy global symmetry that is spontaneously broken naturally light and weakly coupled, presenting an interesting alternative to heavy new particles. In this short overview we present how ALPs can be added to the Standard Model. We then show how ALP couplings to SM particles evolve from high to lower energy scales. This scale running generates, independent from the specific UV coupling structure, flavour-changing ALP couplings in the down-type quark sector. Using that flavour-changing processes are experimentally well-constrained, we are then able to derive strong constraints on UV ALP couplings from flavour experiments that are complementary to astrophysics and collider searches. We present our findings in a benchmark scenario where at the UV scale we assume only the coupling to $SU(2)$ gauge bosons to be non-vanishing.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

*Speaker

PoS(LHCP2023)169

1. Introduction

The Standard Model of Particle Physics (SM) stands sound in its description of the smallest particles in nature and their interactions. Nevertheless, multiple experimental results as well as theoretical considerations suggest an extension of the SM. Examples include the empirical evidence of neutrino oscillations that prove that not all neutrinos can be massless, and the so-called strong CP problem, i.e. the question why the strong nuclear interactions obey CP symmetry, even though there is no profound theoretical principle dictating this behaviour. Among the most prominent beyond the SM (BSM) models are axions and axion-like particles, commonly referred to as ALPs in this article. They are pseudo-Nambu-Goldstone bosons (pNGBs) of a spontaneously broken approximate global $U(1)_{\rm PQ}$ symmetry that is realised at a scale Λ much larger than the electroweak scale [1–4]. In analogy with the pions of QCD that as pNGBs of the chiral symmetry are much lighter than the scale at which this symmetry is broken, ALPs are naturally much lighter than the scale of $U(1)_{\rm PQ}$ breaking. Since their couplings are typically suppressed by powers of the large scale Λ, ALPs as light and weakly coupled particles are an interesting alternative to heavy new physics. In the literature, many explicit models for ALPs apart from the initial QCD axion have been considered, e.g. heavy or composite QCD ALPs [5, 6], flavon and familon particles [7–9], and composite Higgs models [10, 11].

2. Effective field theory for ALPs

The most general effective Lagrangian including ALP couplings to the SM particles up to dimension 5 is given by [12]

$$\begin{aligned}\mathcal{L}_{\rm eff}^{D\leq 5} =& \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu}{f}\sum_F \bar{\psi}_F \mathbf{c}_F \gamma_\mu \psi_F + c_\phi \frac{\partial^\mu a}{f}\left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right) \\ &+ c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^{\mu\nu,a}\tilde{G}^a_{\mu\nu} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W^{\mu\nu,A}\tilde{W}^A_{\mu\nu} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B^{\mu\nu}\tilde{B}_{\mu\nu}\,. \end{aligned} \tag{1}$$

Here, $G^a_{\mu\nu}$, $W^A_{\mu\nu}$ and $B_{\mu\nu}$ are the field-strength tensors of $SU(3)_c$, $SU(2)_L$ and $U(1)_Y$, $\tilde{B}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}B_{\alpha\beta}$ and similar for the other gauge bosons are the dual tensors, and $\alpha_s = g_s^2/(4\pi)$, $\alpha_2 = g^2/(4\pi)$ and $\alpha_1 = g'^2/(4\pi)$ are the corresponding coupling parameters. The sum in the first line extends over all fermion multiplets, and $\mathbf{c}_F$ are hermitian 3×3 matrices in generation space. The Higgs doublet is denoted by ϕ. The suppression scale f of the ALP couplings is related to the scale of symmetry breaking by $f = 4\pi\Lambda$. Note that this Lagrangian has 50 real parameters[1]. The five $U(1)$ symmetries of the SM [2] can be used to remove five of these parameters. Canonically this is employed to eliminate the ALP-Higgs coupling c_ϕ, and we adopt this choice in this work as well.

As a remnant of the UV $U(1)_{\rm PQ}$ symmetry, the ALP Lagrangian inherits a shift symmetry $a \to a$+constant. The symmetry is manifest in the derivative couplings of the ALP and for the couplings to $SU(2)_L$ and $U(1)_Y$ gauge bosons its effect can be absorbed using field redefinitions. The coupling to QCD gauge bosons only preserves a discrete version of the shift symmetry. In a general set-up, we also allow for a direct soft breaking of the shift symmetry by including a mass

[1] 1 (ALP-mass) + 1 (ALP-Higgs coupling) + 3 (ALP-gauge boson couplings) + 5×9 (ALP-fermion couplings)

[2] the individual lepton numbers, baryon number and hypercharge

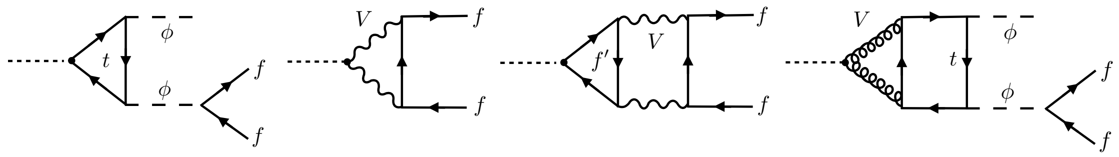

Figure 1: Feynman diagrams contributing to the RG evolution of flavour-diagonal ALP-fermion couplings.

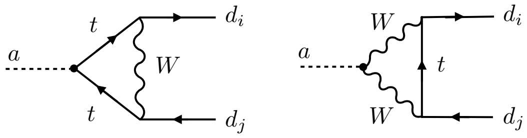

Figure 2: Feynman diagrams contributing to the RG evolution of flavour-changing ALP-fermion couplings.

term in the Lagrangian. Taking effects from QCD instantons into account, the physical ALP mass is given by [13–16]

$$m_a^2 = m_{a,0}^2 \left[1 + O\left(\frac{f_\pi^2}{f^2}\right)\right] + c_{GG}^2 \frac{f_\pi^2 m_\pi^2}{f^2} \frac{2 m_u m_d}{(m_u + m_d)^2}\,, \tag{2}$$

where m_π and f_π are the pion mass and decay constant.

For ALPs lighter than the EW scale, it is necessary to evolve their couplings to SM particles down to the respective scale using RG methods [16–18]. At the EW scale, the heavy SM particles, i.e. the top quark, the Higgs boson and the W and Z bosons, are integrated out and the theory is matched onto a low-energy EFT without these fields present as propagating degrees of freedom. Just below the EW scale, this necessarily generates flavour-diagonal couplings of ALPs to all SM particles via diagrams as exemplary given in figure 1. Since the SM also features flavour-changing W boson interactions, these effects can implement themselves through scale evolution and matching onto the EFT, such that at the lower energy scale of experiments ALPs have tree-level flavour-changing couplings even though the UV theory might be flavour-blind or -diagonal. Exemplary diagrams contributing to the generation of flavour-changing couplings are shown in figure 2. We find it instructive to give a representative numerical approximation of the strength of these induced flavour-changing effects. Assuming a flavour-diagonal UV coupling structure $\mathbf{c}_F = c_F \mathbb{I}$, we define the flavour changing coupling in the down-type sector as $\mathbf{k}_D = \mathbf{U}_d^\dagger \mathbf{c}_Q \mathbf{U}_d$, where $\mathbf{U}_d^\dagger \mathbf{Y}_d \mathbf{W}_d = \mathbf{Y}_d^{\text{diag}}$ diagonalises the down-type Yukawa matrix. $\mathbf{V} = \mathbf{U}_u^\dagger \mathbf{U}_d$ is the CKM matrix. We then find for the off-diagonal elements (with $i \neq j$)

$$\begin{aligned} k_D(m_t)_{ij} \simeq & 10^{-5} V_{ti}^* V_{tj} \big[-6.1 c_{GG} - 2.8 c_{WW} - 0.02 c_{BB} \\ & - 1.9 \times 10^3 c_Q + 1.9 \times 10^3 c_u - 9.2 c_d + 4.2 c_L - 0.05 c_e \big]\,. \end{aligned} \tag{3}$$

3. Probing ALPs with flavour physics

The lightest of ALPs $m_a \leq 100$ MeV are typically well-constrained by astrophysical observations such as supernovae and axion halo- and helioscopes. In contrast, ALPs with masses ≤ 10 GeV

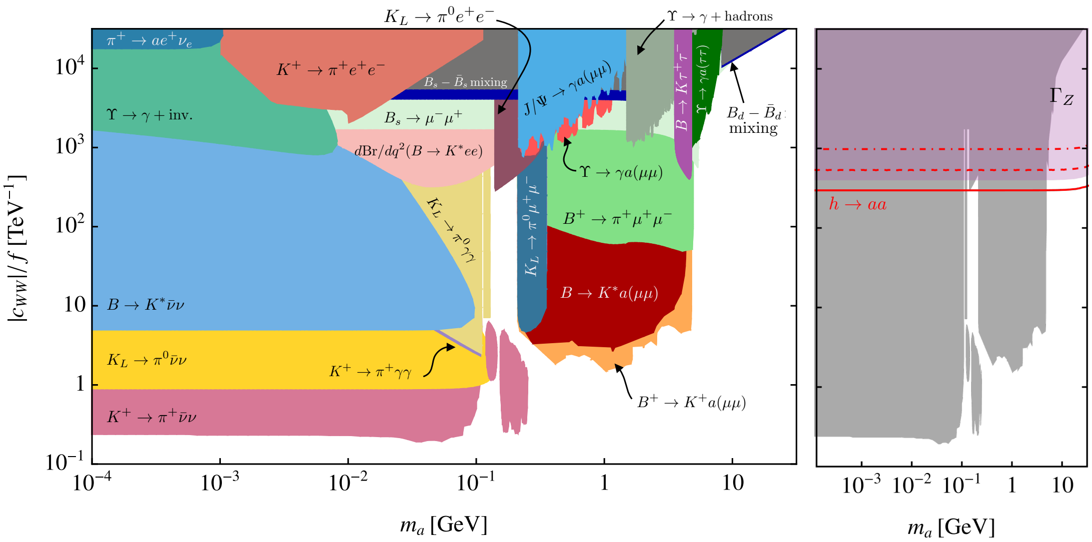

Figure 3: Excluded parameter space in the benchmark scenario where the ALP only couples to $SU(2)_L$ gauge bosons is non-vanishing at the high energy scale. For details on how the individual constraints were derived, see [19]. On the right-hand side we compare flavour constraints with constraints from exotic Higgs and Z decay searches.

are best probed by direct resonance searches at colliders or searches for rare Higgs and Z boson decays. In the SM, flavour-changing currents are well-constrained. It is therefore possible to derive strong constraints on flavour-changing ALP couplings, and through equation (3) relate them to UV ALP-Lagrangian parameters. Here we show that flavour physics are therefore predestined to neatly fill in the previously unprobed parameter space of intermediate ALP masses 100 MeV $< m_a <$ 10 GeV. We study the reach of these experiments within a benchmark scenario where only the coupling to $SU(2)_L$ gauge bosons is non-vanishing at the UV scale, and all other couplings including flavour-changing ones are generated radiatively. We present our findings in figure 3. Details on how to derive the individual bounds can be found in [19]. On the right hand side of this figure we compare the flavour bounds with the reach of exotic Higgs and Z decay searches from [20]. When the ALP is light $m_a \lesssim 5$ GeV, flavour constraints are clearly dominant. The same exercise was repeated in [19] for the benchmark scenarios where the ALP only has a coupling to $SU(3)_c$ gauge bosons, $U(1)_Y$ gauge bosons, or one of the SM fermion multiplets. While the individual constraints and relative strength of the bounds vary among the scenarios, the general shape is the same and provides important constraints for 'medium-heavy' ALPs that are complementary to other experimental searches.

Acknowledgements

The author wishes to thank M. Bauer, M. Neubert, S. Renner and A. Thamm for the exciting work on this project and the organisers of LHCP2023 for the invitation. This work was by the Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter (PRISMA$^+$ – EXC 2118/1) within the German Excellence Strategy (project ID 39083149).

References

[1] R. D. Peccei and H. R. Quinn, *CP Conservation in the Presence of Instantons*, *Phys. Rev. Lett.* **38** (1977) 1440–1443.

[2] R. D. Peccei and H. R. Quinn, *Constraints Imposed by CP Conservation in the Presence of Instantons*, *Phys. Rev.* **D16** (1977) 1791–1797.

[3] S. Weinberg, *A New Light Boson?*, *Phys. Rev. Lett.* **40** (1978) 223–226.

[4] F. Wilczek, *Problem of Strong P and T Invariance in the Presence of Instantons*, *Phys. Rev. Lett.* **40** (1978) 279–282.

[5] M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez and R. Del Rey, *Color unified dynamical axion*, *Eur. Phys. J. C* **78** (2018) 972, [1805.06465].

[6] P. Agrawal and K. Howe, *Factoring the Strong CP Problem*, *JHEP* **12** (2018) 029, [1710.04213].

[7] Y. Ema, K. Hamaguchi, T. Moroi and K. Nakayama, *Flaxion: a minimal extension to solve puzzles in the standard model*, *JHEP* **01** (2017) 096, [1612.05492].

[8] L. Calibbi, F. Goertz, D. Redigolo, R. Ziegler and J. Zupan, *Minimal axion model from flavor*, *Phys. Rev.* **D95** (2017) 095009, [1612.08040].

[9] T. Alanne, S. Blasi and F. Goertz, *Common source for scalars: Flavored axion-Higgs unification*, *Phys. Rev. D* **99** (2019) 015028, [1807.10156].

[10] B. Gripaios, A. Pomarol, F. Riva and J. Serra, *Beyond the Minimal Composite Higgs Model*, *JHEP* **04** (2009) 070, [0902.1483].

[11] G. Ferretti and D. Karateev, *Fermionic UV completions of Composite Higgs models*, *JHEP* **03** (2014) 077, [1312.5330].

[12] H. Georgi, D. B. Kaplan and L. Randall, *Manifesting the Invisible Axion at Low-energies*, *Phys. Lett. B* **169** (1986) 73–78.

[13] M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, *Can Confinement Ensure Natural CP Invariance of Strong Interactions?*, *Nucl. Phys. B* **166** (1980) 493–506.

[14] W. A. Bardeen, S. H. H. Tye and J. A. M. Vermaseren, *Phenomenology of the New Light Higgs Boson Search*, *Phys. Lett. B* **76** (1978) 580–584.

[15] P. Di Vecchia and G. Veneziano, *Chiral Dynamics in the Large n Limit*, *Nucl. Phys. B* **171** (1980) 253–272.

[16] M. Bauer, M. Neubert, S. Renner, M. Schnubel and A. Thamm, *The Low-Energy Effective Theory of Axions and ALPs*, *JHEP* **04** (2021) 063, [2012.12272].

[17] M. Chala, G. Guedes, M. Ramos and J. Santiago, *Running in the ALPs*, *Eur. Phys. J. C* **81** (2021) 181, [2012.09017].

[18] K. Choi, S. H. Im, C. B. Park and S. Yun, *Minimal Flavor Violation with Axion-like Particles*, *JHEP* **11** (2017) 070, [1708.00021].

[19] M. Bauer, M. Neubert, S. Renner, M. Schnubel and A. Thamm, *Flavor probes of axion-like particles*, *JHEP* **09** (2022) 056, [2110.10698].

[20] M. Bauer, M. Neubert and A. Thamm, *Collider Probes of Axion-Like Particles*, *JHEP* **12** (2017) 044, [1708.00443].