Abstract

This Habilitation à Diriger des Recherches (HDR) manuscript presents a systematic research program on the collider phenomenology and experimental search for the axion-like particles (ALPs) and related light dark sectors that I have conceived and led since 2019. ALPs, as pseudo-Nambu–Goldstone bosons emerging from spontaneously broken global symmetries, are promising candidates for physics beyond the Standard Model. While the QCD axion—a specific realization of the ALP paradigm—provides an elegant solution to the strong CP problem, general ALPs with independent mass and coupling parameters can address other fundamental problems such as dark matter and the matter–antimatter asymmetry.

The presented work describes the development of this research line, beginning with the exploration of established channels like ALP production with photons and jets at the LHC, and advancing towards more novel and complex signatures. We have systematically investigated the phenomenology of light, feebly coupled particles across a spectrum of production mechanisms at current and future colliders, employing a model-independent effective field theory framework. The LHC studies include detailed analyses of ALP production in association with dijets, single gauge bosons, electroweak boson pairs, and top quarks. A key aspect has been the consistent application of realistic detector simulations, background modeling, and advanced multivariate analysis techniques—methodologies I have developed and implemented to ensure the robustness and experimental relevance of our projections. In addition, a central component of this work is the direct experimental implementation of the invisible-ALP search strategy within the CMS experiment. Using the full Run-2 dataset at $\sqrt{s} = 13$ TeV, we performed an analysis of the rare SM process $t\bar{t}Z$ in the invisible decay channel $Z \to \nu\bar{\nu}$, a topology characterized by a top-quark pair recoiling against large missing transverse momentum. This measurement was reinterpreted in terms of collider-stable ALPs produced in association with top quarks, providing direct LHC constraints on ALP effective couplings and establishing a concrete bridge between phenomenological modeling and experimental measurements. An important part of this research program has been the training of early-career researchers, including the supervision of two PhD students and two postdoctoral researchers, who contributed to several of the studies presented in this manuscript. Looking beyond the LHC, this program has been extended to explore the physics potential of future colliders. First, we present a dedicated study on probing lepton-flavor-violating (LFV) ALP couplings at a high-energy muon collider, investigating the exotic decay $\tau \to \ell a$. Here, we developed a novel analysis strategy that uses polarized muon beams to suppress backgrounds. Second, to connect ALPs to broader theoretical frameworks, we have investigated light dark sector scenarios accessible via the Higgs portal at future e^+e^- colliders. We performed a dedicated analysis of invisible decays of both the SM-like Higgs boson and a dark Higgs state, demonstrating that the clean environment and precise recoil-mass techniques of lepton colliders can probe mixing angles and branching fractions far beyond the reach of the HL-LHC. Throughout this manuscript, we emphasize the complementarity between different search channels (for instance multi-lepton versus jets plus missing transverse energy) and between various facilities (LHC, HL-LHC, FCC-hh, muon, and e^+e^- colliders). This global approach enables combined analyses, deriving global constraints on the ALP and dark sector parameter space. Our results, which improve upon existing experimental bounds in several regions, provide a structured framework for future experimental investigations. We demonstrate that the ongoing and upcoming collider programs will be capable of probing ALP couplings to gluons, electroweak bosons, top quarks, and leptons—as well as Higgs portal parameters—with improved sensitivities, thereby providing a comprehensive collider framework for testing well-motivated extensions of the Standard Model.