Sensitivity of the FCC-ee to axion-like particles at different center-of-mass energies

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There are some remaining open questions in particle physics, such as dark matter and the strong CP problem, which call for intensified collider exploration. The preferred option for the next generation of high-energy particle colliders is the Future Circular Collider (FCC) at CERN. The electron-positron stage of the FCC, FCC-ee, is proposed to run at or around four center-of-mass energies: the Z pole (91 GeV), the WW threshold (160 GeV), the ZH threshold (240 GeV), and the $t\bar{t}$ threshold (340–365 GeV). The clean and well-defined collision environment will allow for precision measurements sensitive to tiny deviations from the SM, while the high integrated luminosity makes FCC-ee an ideal facility for direct searches for rare new-physics (NP) processes.

Among the many NP scenarios accessible at FCC-ee, axion-like particles (ALPs) provide a useful benchmark because their collider phenomenology changes strongly with mass, lifetime, and electroweak gauge-boson couplings. The QCD axion, a pseudo-Nambu–Goldstone boson, was introduced to address the strong CP problem. More generally, ALPs (a) occur in theories with spontaneously broken global symmetries, with masses (m_a) and couplings to SM particles spanning many orders of magnitude. In certain regions of parameter space, ALPs can also be dark matter candidates or mediators. At FCC-ee, the high luminosity of the Z-pole run will allow us to probe small ALP couplings, while the higher center-of-mass energies extend the reach to larger m_a. Current exclusions and future sensitivity projections can be found in Ref. [1], while ALP signatures at current and future colliders are discussed in Refs. [2, 3].

In this study, the sensitivity of FCC-ee to ALPs is investigated at all planned center-of-mass energies, focusing on the case where the ALP couples primarily to electroweak gauge bosons at leading order. We study the associated production $e^+e^- \to a\gamma$, followed by the decay $a \to \gamma\gamma$, yielding a three-photon final state. The signal process and dominant irreducible background are shown in Fig. 1. This final state was previously studied at the Z pole in a more involved analysis [4], with sensitivity projections for m_a ranging from 0.1 to 85 GeV. Here, we update the Z-pole study and extend the analysis to the WW, ZH, and $t\bar{t}$ running stages, probing ALP masses up to 320 GeV. In the benchmark model considered, FCC-ee can probe the ALP-photon coupling down to a few 10^{-6} GeV^{-1} at the Z pole and about 10^{-5} GeV^{-1} at the higher-energy stages. The higher-energy stages extend the accessible mass range, while the Z-pole run provides the best sensitivity at low masses.

Beyond the benchmark scenario, we investigate how the sensitivity of the three-photon channel changes when the relative ALP couplings to the electroweak gauge fields are varied. Photon-fusion probes [5], $\gamma\gamma \to a \to \gamma\gamma$, are competitive in terms of sensitivity but

depend only on the ALP-photon coupling $C_{\gamma\gamma}$. In contrast, the $e^+e^- \to a\gamma$ production rate depends on both $C_{\gamma\gamma}$ and $C_{\gamma Z}$, while the ALP decay width can additionally depend on C_{WW} and C_{ZZ}. We study how these couplings affect the sensitivity across the different FCC-ee center-of-mass energies and find that the three-photon channel can provide information complementary to photon-fusion probes by probing the broader electroweak coupling structure of the ALP.

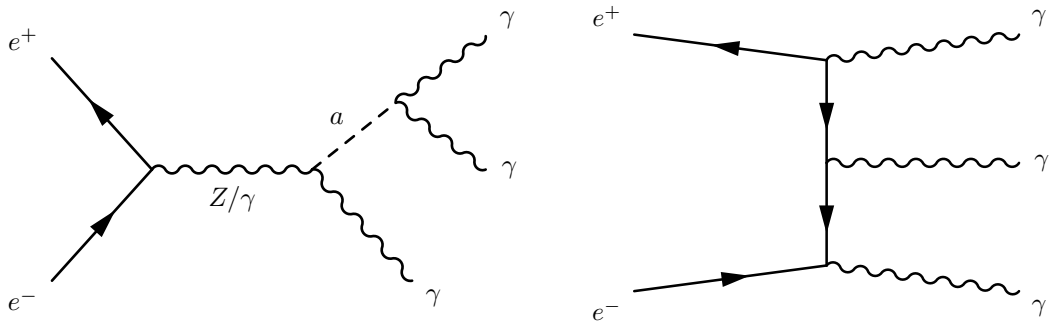

Abbildung 1: The diagrams for the signal process (left) and background process (right).

Literatur

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