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Light Axion-Like Particles at Future Lepton Colliders

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Axion-like particles (ALPs) are well-motivated extensions of the Standard Model (SM) that appear in many new physics scenarios, with masses spanning a broad range. In this work, we systematically study the production and detection prospects of light ALPs at future lepton colliders, including electron-positron and multi-TeV muon colliders. At lepton colliders, light ALPs can be produced in association with a photon or a Z boson. For very light ALPs, the ALPs are typically long-lived and escape detection, leading to a mono-V (V=photon,Z) signature. In the long-lived limit, we find that the mono-photon channel at the Tera-Z stage of future electron-positron colliders provides the strongest constraints on ALP couplings to SM gauge bosons, thanks to the high luminosity, low background, and resonant enhancement from on-shell Z bosons. At higher energies, the mono-photon cross section becomes nearly energy-independent, and the sensitivity is governed by luminosity and background. At multi-TeV muon colliders, the mono-Z channel can yield complementary constraints. For heavier ALPs that decay promptly, mono-V signatures are no longer valid. In this case, ALPs can be probed via non-resonant vector boson scattering (VBS) processes, where the ALP is exchanged off-shell, leading to kinematic deviations from SM expectations. We analyze constraints from both light-by-light scattering and electroweak VBS, the latter only accessible at TeV-scale colliders. While generally weaker, these constraints are robust and model-independent. Our combined analysis shows that mono-V and non-resonant VBS channels provide powerful and complementary probes of ALP-gauge boson interactions.

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