Beyond the Standard Model with High-Energy Lepton Colliders

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September 1, 2020

Abstract

We propose an aspirational theory case underlining the physics potential of a high-energy lepton collider. Exploring the coverage of motivated scenarios for physics beyond the Standard Model and highlighting unique opportunities afforded by energetic lepton beams, we aim to identify energy and luminosity goals that would position such a collider as a natural successor to the LHC and proposed electron-positron Higgs factories.

The physics case for proposed electron-positron Higgs factories such as the ILC[1], CLIC[2], FCC-ee[3], and CEPC[4] is robust, demonstrating the clear potential to illuminate the properties of the Higgs boson with current and near-future technology. The path to higher energies remains somewhat less clear, particularly on the ∼few-decade timescale. While FCC-hh[5] and SPPC[6] offer a number of exciting possibilities, high energy lepton colliders have become increasingly compelling, with the potential to surpass the effective reach of the LHC while comprehensively probing the electroweak and dark sector well above the TeV scale. Candidates include both multi-TeV circular muon colliders[7] and electron-based plasma wakefield accelerators (PWFAs). While there are enormous differences in the technical challenges associated with the two different technologies, for the purpose of beyond-the-Standard Model (BSM) physics we expect very similar reaches for the same energy and luminosity.

The 2021 Snowmass process provides an ideal setting in which to develop the physics case of these colliders, not least because high-energy lepton collider R&D in the United States could strongly complement partnership in a Higgs factory and ultimately lead to the construction of a frontier-defining collider on US soil. Here we advocate for an aspirational approach to developing the theory case for a high-energy lepton collider, in which the coverage of motivated scenarios for physics within and beyond the Standard Model guides the energy and luminosity targets. For the sake of concreteness we will focus on the prospects for a high-energy muon collider, in part because it may be achievable on a shorter timescale than PWFA.

In the interest of letting the physics case guide the accelerator parameters, we propose to study the physics potential of muon colliders across a wide range of center-of-mass energies, from $\sqrt{s} = 1 - 100$ TeV. While the upper end of this scale lies on the extreme edge of existing proposals[8], it may well be motivated by the most compelling physics case. Our study will cover a range of compelling scenarios related to naturalness, dark matter, and electroweak symmetry breaking, as well as bottom-up simplified models spanning the relevant signature space. Where possible, we will highlight the potential for direct tests of BSM physics that may be suggested by indirect evidence at Higgs factories as well as future flavor, EDM, and gravitational wave experiments. We will also highlight novel opportunities afforded by high-energy lepton beams, including higher-order processes providing increased sensitivity to new colored particles. Interleaving simulation and analytic approaches, we will map out the computational techniques required for the faithful treatment of various SM and BSM processes as a function of energy. The ultimate goal is to provide a comprehensive view of the physics case for a high-energy lepton collider, engaging the US HEP community and laying down a marker for accelerator design.

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