Higgs and Electroweak Physics at the Muon Collider: Aiming for Precision at the Highest Energies

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Abstract *The discovery of the Higgs boson in 2012, and its subsequent measurement during run 1 and 2 of the LHC, have clarified the broad strokes of the mechanism of electroweak symmetry breaking (EWSB). The unique nature of the Higgs boson and its place at the heart of the Standard Model (SM) and many theories Beyond the SM (BSM) make it an extremely attractive target for further study. A muon collider [1, 2] provides an exciting set of new possible measurements at potentially higher energies than other facilities with relatively clean experimental environments, but studies of these measurements are thus far limited compared to those at other facilities. We aim to use the results of a dedicated object-performance study, separately submitted as an LoI, to characterize the performance of a potential detector at the Muon Collider. We will then report on new projections on the sensitivity of a muon collider, operating at a range of potential energies, on a range of important measurements related to the Higgs boson and EWSB.*

Higgs Couplings, Mass, and Width The characterization of the Higgs boson is one of the main experimental goals of all upcoming high energy facilities. Most e^+/e^- facilities propose to operate (at least at their start) at $\sqrt{s} = 250$ GeV, where the Higgs is produced mostly via Z-strahlung processes. A muon collider operating at $\sqrt{s} = 1.5$ TeV or higher, on the other hand, would produce Higgs bosons mostly via the vector-boson-fusion (VBF) process [3–5]. This VBF production mode allows for a set of Higgs couplings measurements complementary to other facilities, and allows for particularly effective measurements of the couplings to vector bosons. We will aim to benchmark sensitivity of a muon collider operating at a variety of energies for measuring the Higgs couplings to the various SM particles, in particular couplings to vector bosons (κ_V) and bottom quarks (κ_b) using WW^*/ZZ^* and $b\bar{b}$ decay modes, respectively. Couplings to the second generations of fermions can be quite challenging at both hadron and lepton colliders. However, they are of particular interest due to sensitivity to a whole class of new physics models (e.g. enhanced Yukawa in 2HDM) and potential connections with various muon anomalies. We will thus aim to study those couplings in detail.

It should be noted that a Muon Collider operating near $\sqrt{s} = 125$ GeV has the potential to perform a very precise measurement of the second generation lepton Yukawa coupling (κ_μ) using the s-channel production of the Higgs boson. In addition, it enables a unique measurement of the mass and width of the Higgs boson by scanning the beam energies across the resonance mass and directly measuring the total cross-section, similar to measurements of the Z boson at LEP. Measuring the width of the Higgs would help place important new constraints on the Higgs couplings to BSM particles. While the beam-induced-backgrounds, which increase at lower muon beam energies, are expected to be a challenging

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aspect of this measurement, the potential for a truly unique and model-independent measurement of the mass and width of the Higgs boson makes this an important benchmark to consider [4, 6–8].

Higgs Self-Coupling While the HL-LHC and other low energy lepton colliders are expected to measure the branching ratios of the Higgs boson extremely well, they are less well suited to measure the Higgs self-coupling [4,9]. The self-coupling, which arises as both cubic and quartic terms in the Higgs potential, is extremely difficult to measure because of the low cross-section of the di-Higgs and triple-Higgs final states that are sensitive to the coupling. The expected limits on the cubic-coupling from the HL-LHC and low energy e^+/e^- facilities are expected to be approximately 50%– significantly worse than all of the other Higgs couplings. Precise measurements of the self-coupling are, however, extremely important, as they can provide important statements on the nature of the electroweak phase transition which could be an important ingredient for baryogenesis, the stability of the vacuum, and more. The muon collider, with its potential higher energy range, can produce significant numbers of Higgs pairs and triplets. Moreover, a muon collider could have potentially lower backgrounds and cleaner experimental measurements than a high-pileup high-energy proton machine, and therefore access significantly more of the decay space [3, 4, 6]. Together with the precision Higgs coupling measurements the muon collider enables, it would allow a consistent extraction of the Higgs self-couplings [11]. Finally, as the main production mechanism for Higgs pairs at a high energy lepton collider is via VBF, there is also enhanced sensitivity to the direct four point $VVhh$ coupling [4]. We will aim to provide new projections on the sensitivity to the cubic, quartic, and $VVhh$ couplings of the Higgs boson using a variety of final states ($4b$, $bb\tau\tau$, $bbWW^*$, etc.) and at a range of possible muon collider energies.

Vector Boson Scattering The understanding of the EWSB does not only depend on the properties of the Higgs boson, but also the interactions between electroweak bosons. For example, deviation of the Higgs couplings from the SM expectation will leave its imprint on Vector Boson Scattering (VBS). We will need to study the VBS at the highest accessible energies because of the strong momentum transfer dependence of hints of new physics. In addition, the VBS process is also an exceptional tool to study trilinear and quartic electroweak gauge couplings, another ingredient to the EWSB. The LHC is the first machine able to access these couplings. However, to achieve precision, we need a collider going beyond the LHC. A muon collider operating in the multi-TeV regime will produce many VBS events. Contrary to other future colliders, the VBS process will be dominating over other multiboson processes, and so it will be significantly more powerful in studying this process. We propose to study the sensitivity to cubic and quartic gauge couplings as well as study how well different polarizations of the VBS process can be separated, and– in combinations with the aforementioned Higgs coupling studies– what information we can extract about the origin of EWSB.

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