Muon Collider: Study of Higgs couplings and self-couplings precision

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Abstract

The Higgs boson can be considered as a portal to new physics. The determination of its couplings to fermions and bosons and of its self-couplings constitute one of the fundamental tests of the mechanism at the basis of the Electroweak Symmetry Breaking. While the formers are expected to be measured with the necessary precision at any future collider, the latter, i.e. the full determination of the Higgs potential will be extremely challenging. In this letter we propose to determine the accuracy that could be reached at a muon collider on the Higgs couplings to b-quarks, W and Z bosons and to demonstrate that it will be possible to determine the Higgs potential by using the full simulation of the detector and taking into account the beam-induced background at $\sqrt{s} = 1.5$ TeV, $\sqrt{s} = 3.0$ TeV, and $\sqrt{s} = 10$ TeV.

State of the art

A major leap forward in understanding the electroweak symmetry breaking will be the verification of the shape of the Higgs scalar potential. In the Standard Model (SM), the scalar potential is completely fixed by the Higgs boson mass m_H and the vacuum expectation value $v = 1/\sqrt{\sqrt{2}G_F} \approx 246\ GeV$, where G_F is the Fermi constant. At low energy, it can be parametrized in terms of the trilinear (λ_3) and quadrilinear (λ_4) Higgs self-couplings:

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 \quad \text{with} \quad \lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}.$$

The experimental extraction/determination of λ_3, λ_4 will be of paramount importance, since the actual nature of the observed Higgs particle might be hidden into the shape of the Higgs scalar potential [1], [2]. It can also dramatically affect the dynamics of the early Universe being related to the electroweak phase transition. A nonstandard shape might allow baryogenesis to take place as a result of a 1st order electroweak phase transition.

The simplest mechanism for obtaining information on the Higgs self-couplings is the measurement of the production of double and triple Higgs final states, that being characterized by exceedingly small cross sections, require collisions at very high energy, much higher than what has been reached so far.

During the process of the Update of the European Strategy for Particle Physics, the precision on the Higgs couplings to bosons and fermions has been evaluated for all the proposed future accelerators but the muon collider case was missing [3]. The effect of the beam-induced background (BIB) on some of the physics objects has been studied only recently [4] by using the full simulation for a collider at $\sqrt{s} = 1.5$ TeV. At the same center of mass energy, still using the full simulation, it has been demonstrated that even a challenging process like $\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ can be efficiently reconstructed [5]. The precision on the Higgs coupling to b-quark was calculated at $\sqrt{s} = 1.5$ TeV and then extrapolated at $\sqrt{s} = 3.0$ TeV, and $\sqrt{s} = 10$ TeV. A recent work shows that the number of triple Higgs events produced at a muon collider could be enough to reach a good precision on the quartic self-coupling [6], which opens the possibility to fully determine the Higgs potential shape. (See also Sec. 5.2 of [7]). A full simulation study has started on double Higgs production and preliminary results on cross section precision have been presented at ICHEP2020 [8].

Proposed activities

During the next year, the full simulation of the detector will be improved and solidified (see Muon Collider: solidifying the physics case LoI). Tracks, muons, jets and b-jets will be available to reconstruct W, Z and H bosons. The following main activities are foreseen:

1. Determination of the accuracy on the coupling of the Higgs boson to W and Z bosons, to the b-quark and to the muon at $\sqrt{s} = 1.5$ TeV for which we already have the BIB and then at $\sqrt{s} = 3.0$ TeV where the BIB will be simulated as Snowmass activity (see Muon Collider: Machine Detector Interface Studies LoI) and extrapolated to $\sqrt{s} = 10$ TeV.
2. Estimation of the accuracy of the trilinear Higgs coupling measurement from double Higgs production:
    a. Sample of double Higgs events decaying to $b\bar{b}b\bar{b}$ will be generated by using WHIZARD/MadGraph at the three center of mass energies together with the relevant physics background.
    b. Signal and physics background events will be fully simulated and reconstructed, in particular new b-jet tagging techniques based on advanced AI method will be used.
    c. The uncertainty on λ_3 will be evaluated from the uncertainty on the HH production cross section, that will be determined by using advanced AI methods to separate signal from background and trilinear from no self-interaction processes.
3. Determination of the quadrilinear Higgs self-coupling accuracy. The extraction of the quadrilinear Higgs self-coupling, λ_4, and its accuracy, is more challenging. The production cross section $\sigma\left(\mu^+\mu^- \to HHH\upsilon_\mu\bar{\upsilon}_\mu\right)$ has contributions from double Higgs production (subsequently radiating a further Higgs boson) with and without self-coupling including therefore also λ_3. Other contributions come from diagrams with three Higgs bosons not involving λ_4.A similar situation is present also in the double Higgs production, but in the case of HHH the sensitivity to the quadrilinear coupling is not very high. Here we plan to:
    a. Generate a sample of $HHH \to b\bar{b}b\bar{b}b\bar{b}$ at the three different center of mass energies and reconstruct them following procedure similar to what will be done for HH, with the additional requirement of separate HHH from HH.

b. Find a way to generate the physics background constituted by 6 b-jets+ $\nu\bar{\nu}$ and/or a combination of b-jets with untagged jets for a total of 6 jets $+\nu\bar{\nu}$, in any case events with 8 objects in the final state.
c. Study and identify the physics observables sensitive to trilinear and quadrilinear self-couplings and finally, fit to these quantities for the determination of the accuracy on λ_3 and λ_4.

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