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Higgs Physics at a Muon Collider with detailed detector simulation

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Muon collisions at multi-TeV center of mass energies are ideal for studying Higgs boson properties. At these energies the production rates will allow precise measurements of its couplings to fermions and bosons. In addition, the double Higgs boson production rate could be sufficiently high to directly measure the trilinear self-coupling, giving access to the determination of the Higgs potential. This contribution aims to give an overview of the results that have been obtained so far on Higgs couplings by studying the main Higgs decay channels. All the studies have been performed with a detailed simulation of the signal and physics backgrounds and by evaluating the effects of the beam-induced background on the detector performance. Estimates of Higgs boson couplings sensitivities and results on the uncertainty on double Higgs production cross section, together with the trilinear self-coupling, will be discussed at a center of mass energy of 3 TeV.

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1. Introduction

The measurements of Higgs boson couplings are fundamental to probe the Standard Model (SM) and to shed light on new physics scenarios. The Higgs self-couplings are of particular interest, since deviations from the SM have deep implications on the Higgs potential shape and on the electroweak simmetry breaking mechanism [1]. Most of the Higgs couplings with fermions and vector bosons have already been measured at LHC, but future colliders could push their precision below the 1% level [2]. Up to now there are no measurements of the Higgs potential, apart from the Higgs boson mass term. The trilinear (λ_3) and quadrilinear (λ_4) self-couplings cannot be measured at the LHC, due to the low cross-section of the HH and HHH productions [3]. The CLIC collaboration demonstrated that a e^+e^- linear collider could measure λ_3 with a precision in the order of 10% using collisions with a centre-of-mass energy of $\sqrt{s}$ =1.5 and 3 TeV [4]. The quadrilinear coupling λ_4 is difficult to be measured even at the ambitious FCC-hh project, where a limit at 68% Confidence Level (CL) in the interval [-2,+13] is expected to be set using pp collisions at 100 TeV and 20 ab^{-1} of integrated luminosity [5].

In a multi-TeV muon collider a significant number of Higgs bosons are produced mainly via WW-fusion with the reaction $\mu\mu \rightarrow H\nu\nu$, and they can be studied to measure the couplings. Moreover $\mu\mu \rightarrow HH\nu\nu$ and $\mu\mu \rightarrow HHH\nu\nu$ events could be produced, allowing the measurements of λ_3 and λ_4 [7, 8] with unprecedented precision. In this machine, clean events as in e^+e^- colliders are possible, and high collision energy as in hadron colliders could be reached, due to low synchrotron radiation losses of the muons beams. Nevertheless several technological challenges for both, machine and detectors, should be faced in order to demonstrate their feasibility.

2. Beam-induced background and detector challenges

The detector performance at a muon collider may be limited by the beam-induced background (BIB) [9]. The BIB is produced by the decays of muons in circulating beams, that generate electrons, positrons and neutrinos. Interactions of such particles with the machine and the machine-detector interface (MDI) can produce secondary particles like photons, neutrons, electrons or hadrons. Differently from other proposed future machines, the BIB at a muon collider shows unique features: particles can arrive to the interaction point (IP) from several meters of distance, and they are asynchronous with respect to the bunch-crossing. The MDI, the detectors and the reconstruction algorithms should be developed in order to mitigate the BIB. Two tungsten cone-shaped nozzles could be inserted in the detector along the beamline in order to reduce the BIB at the IP [10]. Moreover, the detector could employ 5D sensors that can measure the energy, position and time in order to reject part of the BIB. The reconstruction algorithms should also be defined in order to reduce the combinatorial and fake objects produced by the BIB, keeping the reconstruction performance at an adequate level. For these reasons and for the uniqueness of the muon collider environment, the physics performance on benchmark cases should be assessed by studying the full simulation of the experiment. A detector and dedicated reconstruction algorithms have been designed as explained in [12], where the reconstruction performance on key physics objects, like jets, muons and photons, is also discussed. Although the detector and the reconstruction algorithms are not fully optimized, the performance is already at the level of the LHC, but some work has to be done to arrive at the level of e^+e^- colliders. In this paper we are going to demonstrate that, with the state-of-the-art of muon collider detector, the sensitivity on the Higgs couplings is already competitive with that expected at the CLIC e^+e^- linear collider.

3. Measurement of the Higgs production cross-sections and couplings

In order to assess the Higgs Physics performance, several Higgs decay channels have been studied with the detailed simulation of the detector. The signals have been generated and reconstructed, as well as the expected backgrounds. The considered processes are $H \to b\bar{b}$, $H \to WW^*$, $H \to ZZ^*$, $H \to \gamma\gamma$ and $H \to \mu^+\mu^-$. These studies have been performed by considering a muon collider with 3 TeV collision energy, that is expected to collect 1 ab^{-1} of integrated luminosity in 5 years of data-taking.

The $H \to b\bar{b}$ process has been reconstructed in the dijet final state. The two jets are required to have a transverse momentum $p_T > 40$ GeV. A secondary vertex reconstructed from displaced tracks is required in both jets, in order to reduce the background from light jets. The main source of background is the decay of Z bosons: a number of 60×10^3 signal events and 66×10^3 background events are expected. The signal yield is extracted with an unbinned maximum likelihood fit to the dijet invariant mass, as shown in figure 1. The estimated relative statistical uncertainty on the event yield, and therefore on the $H \to b\bar{b}$ cross section, is 0.75%.

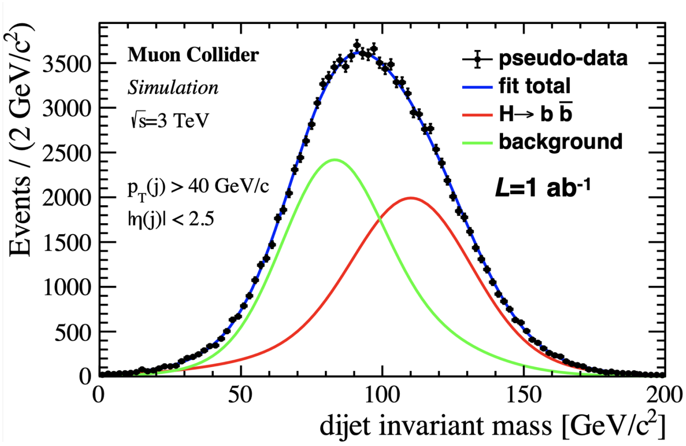

Figure 1: Expected b-dijet invariant mass distribution at the 3 TeV muon collider, and result of the fit performed to determine the sensitivity on the measurement of the $H \to b\bar{b}$ cross-section.

For the measurement of $H \to WW^*$ and $H \to ZZ^*$ processes the lepton(s)+jets final state is the one that gives the best signal/background ratio. For this reason two jets with $p_T > 10$ GeV, coming from the W/Z decay, are selected, as well as one or two muons coming from the decay of the other W or Z boson. Boosted Decision Trees have been trained having as input event kinematic variables, to distinguish the signal from backgrounds. Requirements are applied on the BDT outputs, resulting in 2400 (88) signal events and 2600 (850) background events for the $H \to WW^*(H \to ZZ^*)$ process. By considering a counting experiment, the relative uncertainty on the cross-sections is determined, obtaining 2.9% and 17% for $H \to WW^*$ and $H \to ZZ^*$ respectively.

The $H \rightarrow \gamma\gamma$ process has been studied by reconstructing two photons in the calorimeter, and high energy thresholds have been applied on calorimeter hits to remove most of the BIB contribution, that is assumed negligible. After the selection 700 signal events and 97×10^3 combinatorial events are expected. Again a BDT-requirement strategy is applied, and a relative uncertainty on the $H \rightarrow \gamma\gamma$ cross-section of 8.9% is obtained.

Finally, the $H \rightarrow \mu^+\mu^-$ has been studied: the two muons have been reconstructed by applying a tight requirement on the muon polar angle, to reduce BIB contaminations to a negligible level. BDTs are applied to remove the 2-muons and 4-muons combinatorial backgrounds resulting in 24 signal events and 1100 background events. By using and unbinned maximum-likelihood fit, a relative uncertainty of 38% on the $H \rightarrow \mu^+\mu^-$ cross-section is found.

The Higgs couplings to b, W, Z, γ and μ have been obtained by combining the measurements presented here, and using the relations between couplings and cross-sections. In this computation the $H \rightarrow WW^*$ process has a great importance, since it is the reverse reaction of the Higgs production mechanism via WW-fusion. The Higgs width Γ_H has been taken as a fixed value from the Standard Model expectation, but the determination of its uncertainty with full detector simulation at a muon collider is currently on-going. The results on the couplings sensitivity have been reported in table 1, where they are compared with what expected at CLIC. We should notice that the muon collider results have been obtained assuming a data-taking period of 5 years, while for CLIC 25 year of operations at several energy stages are considered. Nevertheless, we can see most of them are already competitive with CLIC. The largest difference has been found for the coupling with the Z boson, that is much better at CLIC, since it could take profit of studying the Higgsstrahlung production at lower collisions energies.

	Muon Collider 1 ab^{-1} @ 3 TeV	CLIC 0.5 ab^{-1} @ 350 GeV + 1.5 ab^{-1} @ 1.4 TeV + 2 ab^{-1} @ 3 TeV
Γ_H	5.5%	3.5%
g_{HZZ}	6.2%	0.8%
g_{HWW}	1.3%	0.9%
g_{Hbb}	1.6%	0.9%
$g_{H\mu\mu}$	18.7%	7.8%
$g_{H\gamma\gamma}$	6.7%	3.2%

Table 1: Expected sensitivity on the Higgs couplings measured at the muon Collider, compared with the sensitivity expected at CLIC [13].

4. Measurement of the HH cross-section and determination of the trilinear Higgs self-coupling

The measurement of the HH cross-section is the first step for the determination of the Higgs trilinear coupling λ_3. In this study we consider the process $\mu\mu \rightarrow H(\rightarrow b\bar{b})H(\rightarrow b\bar{b})\nu\nu$, with four b-jets in the final state, at $\sqrt{s} = 3$ TeV. The signal and the backgrounds, $\mu\mu \rightarrow b\bar{b}b\bar{b}\nu\nu$ and $\mu\mu \rightarrow Hb\bar{b}\nu\nu$, have been simulated and reconstructed. Other background sources are considered negligible, since at least one b-tag per Higgs candidate is required. A number of 50 HH events and 430 background events are expected. Different kinematic observables are given in input to a BDT trained to separate the signal from the background, and a fit to this BDT distribution is performed to extract the uncertainty on the number of HH signal events, that is found to be 30%. The output of the BDT and the fit result are shown in Fig. 2. This uncertainty is of the same order of that obtained by CLIC (20%) in the same final state [13]. In order to extract the trilinear coupling, two

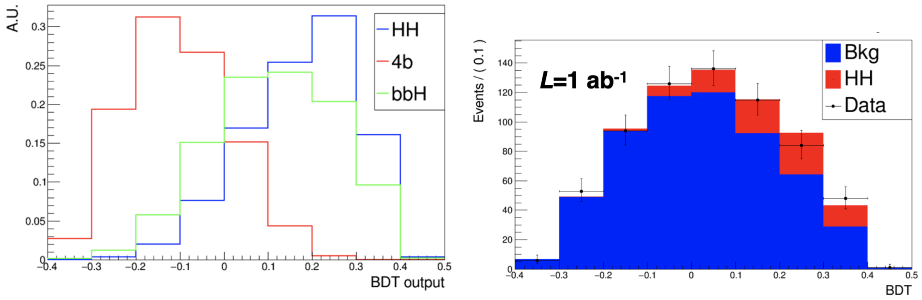

Figure 2: (Left) distribution of the BDT output and (right) fit for the extraction of the HH production cross-section. The signal is coloured in red, the background in blue, black points with errors bars represent the pseudodataset.

BDTs are employed, one for separating the HH from the backgrounds, and a second one to separate the trilinear component of the HH production from the inclusive HH. Several BDTs distributions are obtained by generating samples with different trilinear coupling hypotheses. Such distributions are compared to the pseudo-dataset obtained by assuming the Standard Model value. A likelihood scan is performed as shown in figure 3, and the 1-σ confidence level is determined, obtaining an uncertainty of about 20% on λ_3. It is higher than the result obtained by CLIC, $[-8\%, +11\%]$ at 1-σ level, that assumes a total integrated luminosity of 7.5 ab^{-1}, compared to the 1 ab^{-1} at the 3-TeV muon collider.

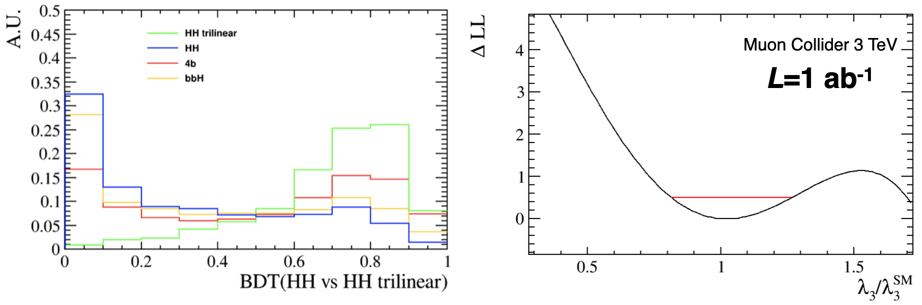

Figure 3: Left: distribution of the BDT output for the separation of the trilinear HH component from the inclusive HH. Right: likelihood scan for the uncertainty on the determination of λ_3.

5. Conclusions

In this paper the expected sensitivity on the Higgs couplings measurements at a muon collider have been presented. These studies have been done with the detailed simulation of the detector, and a collision center of mass energy of 3 TeV has been considered. Most of the measurements of the Higgs couplings are competitive with those expected at CLIC. The sensitivity on the trilinear Higgs coupling is at the same level of CLIC, if it is scaled to the same integrated luminosity. The 3 TeV collisions represent just the first stage of a muon collider, but collisions at 10 TeV and above are possible. For this reason it is necessary to develop a detector for the 10 TeV case, and assess the physics performance that includes the impact of the beam-induced background. Moreover the reconstruction algorithms, that now are very simple, will be improved in the future by using more sophisticated techniques, *e.g.* using machine-learning algorithms for jet identification.

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