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Higgs physics at Muon Collider with detailed detector simulation

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Summary. — 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 parameters of trilinear self-couplings, giving access to the determination of the Higgs potential. This communication aims to give an overview of the results that have been obtained so far on Higgs couplings by studying the $\mu^+\mu^- \to H(b\bar{b})\nu\bar{\nu}$, $\mu^+\mu^- \to H(WW^*)\nu\bar{\nu}$ and $\mu^+\mu^- \to H(b\bar{b})H(b\bar{b})\nu\bar{\nu}$ processes. All the studies have been performed with a detailed simulation of the signal and physics background samples and by taking into account the effects of the beam-induced background on the detector performance. Evaluations of Higgs boson production cross-sections 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.

1. – Introduction

Understanding Higgs boson couplings is essential for probing the Standard Model and exploring potential new physics scenarios [1]. While the LHC has measured the most Higgs couplings with fermions and bosons, future colliders aim for precision below 1%, with a particular focus on elusive measurements of Higgs potential parameters, such as trilinear (λ_3) and quartic (λ_4) self-couplings [2]. Linear colliders like CLIC could achieve 10% precision in measuring λ_3 [3], but measuring λ_4 remains challenging. The FCC-hh project, using 100 TeV pp collisions and 20 ab^{-1} integrated luminosity, is expected to set limits on λ_4 at the 68% Confidence Level in the range [−2%, 13%] [4]. In a multi-TeV muon collider, Higgs bosons are mainly produced via WW-fusion, offering opportunities

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to study couplings. Events like $\mu^+\mu^- \to HH\nu\bar{\nu}$ and $\mu^+\mu^- \to HHH\nu\bar{\nu}$ allow unprecedented measurements of λ_3 and λ_4 [5, 6]. While muon colliders offer clean events like e^+e^- colliders and high collision energy like hadron colliders, addressing technological challenges in machine and detector development is crucial for their feasibility. The International Muon Collider Collaboration has foreseen a first stage at a center-of-mass energy of 3 TeV, followed by a subsequent stage at 10 TeV.

2. – The beam-induced background

Detectors at muon colliders confront challenges from beam-induced background (BIB) originating from muon decays within circulating beams, producing electrons, positrons, and neutrinos [7-9]. The electrons and positrons interact with the machine and the machine-detector interface (MDI), generating secondary particles like photons, neutrons, electrons, or hadrons, as shown in fig. 1. Unique to muon colliders, BIB exhibits distinct characteristics: particles enter the detector at significant distances from the interaction point (IP) and are asynchronous concerning bunch crossings [8]. To address BIB effects, advancements in MDI, detectors, and reconstruction algorithms are imperative. Strategies like inserting tungsten cone-shaped nozzles along the beamline and employing 5D sensors to measure energy, position, and time aid in BIB reduction. Refinement of reconstruction algorithms is essential to minimize combinatorial and fake objects produced by BIB while upholding reconstruction performance standards. Given the distinctive muon collider environment and BIB challenges, comprehensive studies involving full experiment simulations are necessary to assess physics performance on benchmark cases.

3. – Measurement of the Higgs production cross-sections

Various decay channels of the Higgs boson have been thoroughly investigated using detailed detector simulations in a muon collider setting with a collision energy of 3 TeV and an anticipated integrated luminosity of 1 ab^{-1} over 5 years. Key processes include $H \to b\bar{b}$, $H \to WW^*$, $H \to ZZ^*$, $H \to \gamma\gamma$, and $H \to \mu^+\mu^-$.

In the $H \to b\bar{b}$ channel, reconstruction targets the dijet final state requiring jets to have $p_T > 40$ GeV, resulting in an estimated relative statistical uncertainty of 0.75% on the event yield [10]. A fit to pseudo-data with $H \to b\bar{b}$ and backgrounds is shown in fig. 2, where the invariant mass resolution is due to BIB effects, but still allows to fit $H \to b\bar{b}$ over backgrounds.

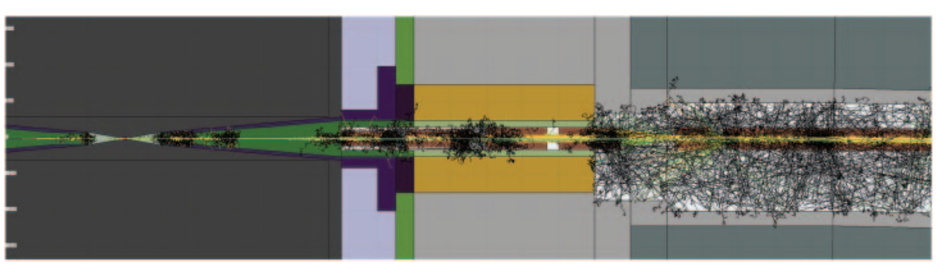

Fig. 1. – Pictorial view of tracks of secondary particles in the IP and in the first magnets around the IP in case of few muon decays. Figure taken from [9].

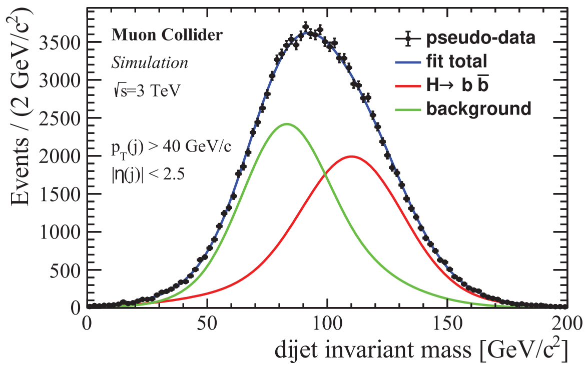

Fig. 2. – A fit to pseudo-data with $H \to b\bar{b}$ and backgrounds, where the invariant mass resolution is due to BIB effects. Figure taken from [10].

For $H \to WW^*$ and $H \to ZZ^*$, lepton(s)+jets final state provides the best signal-to-background ratio. Boosted Decision Trees are employed to separate signal and background, yielding significant signal events compared to background events. In the $H \to \gamma\gamma$ process, reconstruction involves identifying two photons in the calorimeter, with a relative uncertainty of 7.6% on the cross-section. $H \to \mu^+\mu^-$ process employs stringent requirements on muon polar angle and utilizes BDTs to remove physics backgrounds, resulting in a 38% relative uncertainty on the cross-section. A comparison with CLIC's results is presented in table I: the CLIC experiment assumes a center-of-mass energy of 3 TeV and a total integrated luminosity of 2 ab^{-1}, collected in five years. Results from the Muon Collider are comparable with CLIC's results, while also showing room for improvement.

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

The determination of the Higgs trilinear coupling λ_3 involves measuring the HH cross-section, focusing on the process $\mu^+\mu^- \to H(b\bar{b})H(b\bar{b})\nu\bar{\nu}$ at $\sqrt{s} = 3$ TeV, where four b-jets are present in the final state. Both signal and background processes, $\mu\mu \to bbbb\nu\nu$ and $\mu\mu \to Hb\bar{b}\nu\bar{\nu}$, are simulated and reconstructed, with other background sources deemed

TABLE I. – *Comparison between Muon Collider and CLIC sensitivities on Higgs production cross-sections.*

Physics process	Muon Collider	CLIC
$H \to b\bar{b}$	0.75%	0.3%
$H \to WW^*$	2.9%	0.7%
$H \to ZZ^*$	17%	3.9%
$H \to \mu^+\mu^-$	38%	25%
$H \to \gamma\gamma$	7.6%	10%

negligible due to the requirement of at least one b-tag per Higgs candidate. A Boosted Decision Tree (BDT) discriminates between signal and background, with a subsequent fit to the BDT distribution determining an uncertainty of 30% on the number of HH signal events, closely aligning with CLIC's uncertainty in the same final state. To extract the trilinear coupling, two BDTs separate HH from backgrounds and distinguish the trilinear component of HH production from inclusive HH. Various BDT distributions generated using samples with different trilinear coupling hypotheses are compared to a pseudo-dataset assuming the Standard Model value. A likelihood scan yields a 1-σ confidence level uncertainty of about 20% on λ_3, comparable to CLIC's 22% result at the 1-σ level, assuming a total integrated luminosity of 2 ab^{-1} [11]. In this study, backgrounds coming from the mistag of c and light jets are considered negligible, with a more accurate study in progress.

5. – Conclusions

This paper outlines the projected sensitivity for Higgs production cross-sections measurements at a muon collider, employing detailed detector simulations and a center-of-mass collision energy of 3 TeV. Results indicate that most Higgs coupling measurements are on par with those expected at CLIC. Notably, the sensitivity on the trilinear Higgs coupling matches that of CLIC when scaled to the same integrated luminosity. Results have been also compared with studies performed using parametric simulations, showing reasonable agreement [12]. While the 3 TeV collisions represent a possible initial phase of a muon collider, there exists a potential for collisions at higher energies, which could reach 10 TeV and beyond. Consequently, there is a necessity to develop detectors tailored for the 10 TeV scenario and evaluate the physics performance, considering the impact of beam-induced background. Furthermore, advancements are anticipated in reconstruction algorithms, currently basic, with future enhancements likely incorporating more sophisticated techniques such as machine-learning algorithms for jet identification.

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