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Higgs Physics at Multi-Tev Muon Collider

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At a center-of-mass energy of 10 TeV, muon collisions copiously produce Higgs bosons, enabling the measurement of their couplings with bosons and fermions with unprecedented accuracy, achievable with just 10 ab^{-1} of data. Additionally, pairs of Higgs bosons are produced with a significant cross-section, enabling the determination of the second term of the Higgs potential through measurements of the double Higgs production cross-section and the trilinear self-couplings. These collisions offer the possibility to study triple Higgs production, allowing the determination of the quadrilinear coupling and a deep investigation of the Higgs potential. The Muon Collider enables Higgs physics studies already at 3 TeV center-of-mass energy, laying the groundwork for the higher energy experiment. This contribution discusses the expected accuracy of Higgs measurements using detailed detector simulations, which include physics and machine backgrounds at both center-of-mass energies.

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1. Introduction

The measurement of Higgs boson couplings plays a pivotal role in testing the Standard Model (SM) and exploring potential new physics scenarios. Among these, the Higgs self-couplings are of particular interest, as any deviation from the SM predictions would have profound consequences for our understanding of the Higgs potential and the mechanism of electroweak symmetry breaking. While most of the Higgs couplings with fermions and vector bosons have already been measured at the LHC, future collider experiments hold the promise of pushing these precision measurements to below the 1% level [1]. So far, apart from the Higgs boson mass, no direct measurements of the Higgs potential have been made. In particular, the trilinear (λ_3) and quadrilinear (λ_4) Higgs self-couplings remain unmeasured at the LHC, as the production cross-sections for processes like HH and HHH are too low to be observed [2]. At a multi-TeV Muon Collider, a significant number of Higgs bosons could be produced primarily through WW fusion in the process $\mu\mu \to H\nu\nu$ as shown in Table 1, enabling detailed studies of their couplings. Furthermore, processes such as $\mu\mu \to HH\nu\nu$ and $\mu\mu \to HHH\nu\nu$ could be observed, allowing for the precise measurement of λ_3 and λ_4 with unprecedented accuracy [3]. Such a machine would offer the advantages of clean event environments similar to those in e^+e^- colliders, while also achieving the high collision energies characteristic of hadron colliders, thanks to the low synchrotron radiation losses of muon beams. Nevertheless, significant technological challenges must be addressed for both the machine and detectors before the feasibility of such a collider can be established.

Center-of-Mass Energy (TeV)	Luminosity (ab^{-1})	Higgs Events
3	1	5×10^5
10	10	9.5×10^6
14	20	2.2×10^7
30	90	1.2×10^9

Table 1: Projected Higgs event counts at different Muon Collider energy stages .

2. Description of muon collider and beam-induced background (BIB)

The performance of a Muon Collider could face significant limitations due to beam-induced background (BIB) effects [4]. The BIB arises from the decay of muons in the circulating beams, which produces electrons, positrons, and neutrinos. These particles can then interact with the accelerator components and the machine-detector interface (MDI), generating secondary particles such as photons, neutrons, electrons, or hadrons. The BIB at a Muon Collider exhibits distinctive characteristics: particles may reach the interaction point (IP) after traveling several meters, and their arrival is asynchronous to the bunch crossings. To mitigate the effects of BIB, advancements are required in the MDI, detector technology, and reconstruction algorithms. One proposed solution is the inclusion of two tungsten, cone-shaped nozzles along the beamline to reduce the BIB flux reaching the IP. Additionally, the detector could be equipped with advanced 5D sensors, which are capable of measuring energy, position, and timing to help distinguish and reject some of the BIB. The reconstruction algorithms will also need to be optimized to handle the combinatorial noise and false signals generated by BIB, while still maintaining high reconstruction performance.

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Given the complexity and novelty of the Muon Collider environment, it is essential to assess the physics performance of benchmark processes using full detector simulations. A prototype detector design, along with specialized reconstruction algorithms, has already been developed for a Muon Collider at 3 TeV [5, 6]. The detector and MDI optimisation for the 10 TeV case is in progress [7, 8].

3. Higgs physics at the 3 TeV Muon Collider

To evaluate the performance of Higgs physics at a Muon Collider, multiple Higgs decay channels have been analyzed using a detailed simulation of the detector. In particular, the 3 TeV case has been considered, as a proof of concept for multi-TeV stages: while in the 10 TeV case objects are more boosted towards the forward region, the transverse momentum distribution of objects such as the Higgs boson are rather similar in the 3 and 10 TeV case, as shown in Fig. 1. The Higgs decay processes under consideration include $H \to b\bar{b}$, $H \to WW$, $H \to ZZ$, $H \to \gamma\gamma$, and $H \to \mu^+\mu^-$. These analyses have been conducted for a Muon Collider operating at a collision energy of 3 TeV, which is projected to collect 1 ab^{-1} of integrated luminosity over five years of data-taking. The impact of the BIB is taken into consideration in all the analysis steps. Results obtained with full simulation are compared with parametric studies obtained with a Delphes card resembling the expected performance of a Muon Collider, showing good agreement. This proves that, while challenging, it is possible to keep the BIB under control. Figure 1 shows the impact of a 3 TeV and 10 TeV Muon Collider on the Higgs self-couplings.

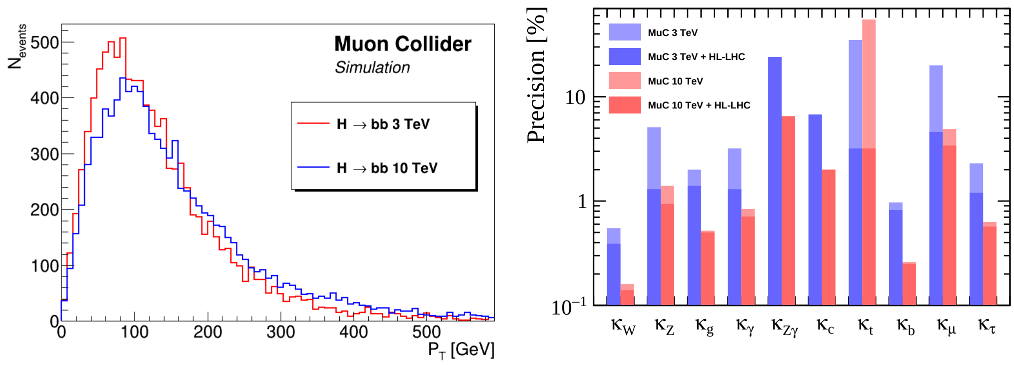

Figure 1: Left: Higgs boson transverse momentum distribution at 3 TeV (red) and 10 TeV (blue) case. Right: comparison of Higgs couplings precision for a 3 TeV and 10 TeV Muon Collider, in combination with expected results coming from HL-LHC.

4. Double Higgs production and self-coupling

The sensitivity to the trilinear Higgs self-coupling, denoted as κ_{λ_3}, has been derived through parametric simulations of a Muon Collider [9]. These studies present the 68% confidence level (CL) bounds for a center-of-mass energy of $\sqrt{s} = 3$ TeV with an integrated luminosity $\mathcal{L} = 1$ ab^{-1}. The result consists of two disconnected intervals: $0.73 < \kappa_{\lambda_3} < 1.35$ and $1.85 < \kappa_{\lambda_3} < 1.94$, highlighting the presence of two distinct minima in the likelihood function. The same analysis has been performed in the full simulation context described before. The analysis proceeds by measuring the double Higgs production cross-section (HH) as an intermediate step towards the extraction of the trilinear coupling [10].

4.1 $HH \to b\bar{b}b\bar{b}$ cross-section determination

The measurement of double-Higgs production is a crucial first step toward extracting the value of the trilinear Higgs self-coupling, as double Higgs production is sensitive to this coupling. In this study, the HH production process is studied where both Higgs bosons decay to $b\bar{b}$. The $HH \to b\bar{b}b\bar{b}$ channel provides the highest event yield, making it ideal for precision studies. The reconstruction of HH events begins by forming all possible pairs of two-jet combinations, with the condition that at least one jet in each pair is tagged as a b-jet. Higgs boson candidates are selected from the pair of jets whose invariant masses, m_{12} and m_{34}, minimize the figure of merit

$$F = \sqrt{(m_{12} - m_H)^2 + (m_{34} - m_H)^2} \tag{1}$$

where m_H is the known Higgs boson mass.

The primary physics background in this analysis comes from processes where four heavy-quark jets ($q_h\bar{q}_h q_h\bar{q}_h$) are produced, mainly via the decay of intermediate electroweak gauge bosons. Another major background arises from $\mu^+\mu^- \to Hq_h\bar{q}_h X \to b\bar{b}q_h\bar{q}_h X$, where single Higgs production mimics the signal but does not involve the trilinear Higgs coupling.

To mitigate these backgrounds, advanced tagging algorithms are employed, and backgrounds involving light-quark jets and fake jets are assumed to be negligible, as they can be effectively vetoed using jet substructure techniques and machine learning methods. To improve the signal-to-background separation, we use a Multilayer Perceptron (MLP) trained on twelve observables, including invariant masses of jet pairs, transverse momenta, and angular correlations. The resulting MLP output is shown in Fig.2, where a clear separation between the HH signal and the $q_h\bar{q}_h q_h\bar{q}_h X$ background is observed.

The number of HH events is extracted by fitting the MLP output distribution with pseudo-datasets generated based on expected event yields. The corresponding statistical uncertainty on the $HH \to b\bar{b}b\bar{b}$ cross-section, assuming negligible uncertainties on selection efficiency and integrated luminosity is

$$\frac{\Delta\sigma(HH \to b\bar{b}b\bar{b})}{\sigma(HH \to b\bar{b}b\bar{b})} = 33\%. \tag{2}$$

4.2 Determination of the trilinear Higgs coupling

The double-Higgs production cross section is sensitive to the trilinear Higgs self-coupling λ_3. The Feynman diagram where the Higgs pair is produced via an off-shell Higgs boson (H^*) is directly dependent on the value of λ_3. This kinematic feature is exploited to extract the value of λ_3. The strategy for determining the uncertainty on λ_3 proceeds as follows:

- Double-Higgs events are generated for different values of $\kappa_{\lambda_3} = \lambda_3/\lambda_3^{SM}$: 0.2, 0.4, 0.6, 0.8, 0.9, 1.0, 1.1, 1.2, 1.4, 1.6, and 1.8, where the case $\kappa_{\lambda_3} = 1$ corresponds to the SM.
- Two separate MLP classifiers are trained: the first is identical to that used for the HH cross section measurement, while the second is trained specifically to separate HH events produced

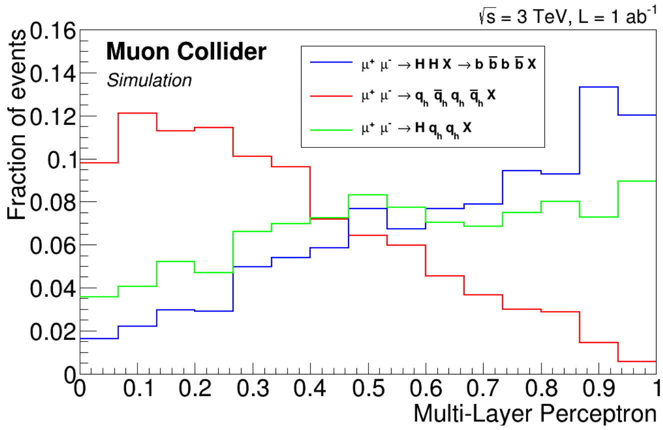

Figure 2: Distributions of the MLP output for the HH signal and the main background contributions. The distributions are normalized to unit area. [10]

via an off-shell H^* from other double-Higgs production mechanisms. The latter is trained using kinematic variables sensitive to the production mechanism, such as the angle between the Higgs bosons and the helicity angles of the jet pairs.

- For each κ_{λ_3} hypothesis, 2D templates of the MLP scores are constructed for both signal and background events. Pseudo-datasets are generated from these templates, and the likelihood function is calculated as a function of κ_{λ_3} by comparing the pseudo-data to the templates.

- The likelihood profile is fitted using a fourth-degree polynomial, and the uncertainty on κ_{λ_3} is determined by finding the 68% CL interval around $\kappa_{\lambda_3} = 1$.

The result of the maximum-likelihood template fit is shown in Fig. 3, where the log-likelihood difference ΔLL is presented as a function of the ratio between the Higgs self-coupling λ_3 and its SM prediction, showing a good comparison with respect to expectations from phenomenological studies. Improvements in jet reconstruction performance can significantly enhance the precision of the trilinear coupling measurement. With advanced b-tagging techniques, the performance of the Muon Collider could approach the theoretical limits.

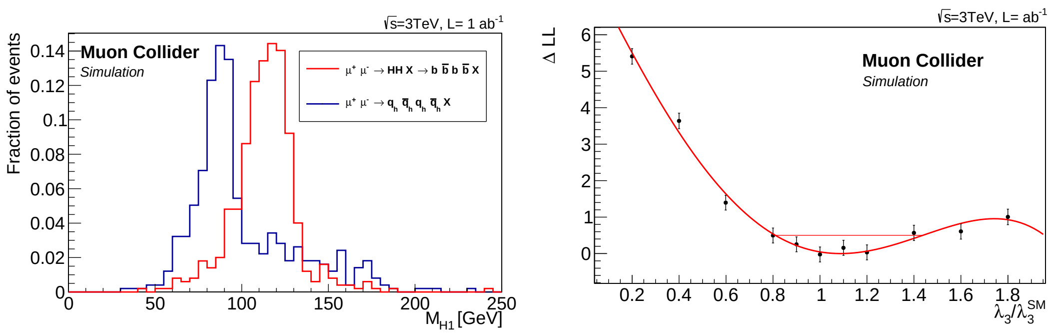

Figure 3: Left: Invariant mass of the leading Higgs candidate compared between HH events and background events. Right: ΔLL as a function of κ_{λ_3} hypothesis for samples reconstructed without the BIB [10].

5. Conclusion

The Muon Collider stands out as a feasible and competitive option for advancing Higgs physics. The Muon Collider paves the way for a new era in particle physics research by achieving precision in Higgs coupling measurements and exploring double Higgs production. In particular, we have proved that it is possible to achieve competitive performance at 3 TeV using a full simulation framework, taking into consideration the presence of the BIB. Going to the 10 TeV stage, there are several places where improvements can be obtained, starting from the MDI and detector optimizations, up to the usage of algorithms tailored for the Muon Collider physics cases. Upcoming studies at 10 TeV will further refine these findings, making the Muon Collider a compelling prospect among future colliders.

Acknowledgments

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