PROCEEDINGS OF SCIENCE

Higgs physics at a 10 TeV muon collider with the MUSIC detector

P. Andreetto,[a] **M. Casarsa,**[b,*] **A. Gianelle,**[a] **D. Lucchesi,**[a,c] **L. Palombini,**[a,c] **L. Sestini**[d] **and D. Zuliani**[a,c]

on behalf of the International Muon Collider Collaboration

[a] *INFN - Sezione di Padova, via F. Marzolo 8, 35131 Padua, Italy*
[b] *INFN - Sezione di Trieste, via A. Valerio 2, 34127 Trieste, Italy*
[c] *Università di Padova, via F. Marzolo 8, 35131 Padua, Italy*
[d] *INFN - Sezione di Firenze, via B. Rossi 3, 50019 Sesto Fiorentino, Florence, Italy*

E-mail: massimo.casarsa@ts.infn.it

This contribution outlines the physics potential of a future muon collider operating at a center-of-mass energy of 10 TeV for precision studies of the Higgs sector. A detailed detector simulation, incorporating the dominant sources of machine-induced background, is employed to assess the expected sensitivity to key Higgs processes. These include measurements of production cross sections for $H \to b\bar{b}$, $H \to WW^*$, and double-Higgs production $HH \to b\bar{b}b\bar{b}$. A central focus of the study is the determination of the Higgs boson trilinear self-coupling, a critical parameter for understanding the structure of the Higgs potential and the mechanism of electroweak symmetry breaking. The studies are based on the MUSIC (MUon System for Interesting Collisions) detector concept, specifically designed for the muon collider environment, and assumes two interaction points, each delivering an integrated luminosity of 10 ab^{-1} over five years. The results demonstrate the exceptional prospects of a multi-TeV muon collider in probing the Higgs potential with a precision unattainable by any other proposed future collider within a comparable timeframe.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

*Speaker

PoS(EPS-HEP2025)385

1. Introduction

The study of the Higgs boson is central to advancing our understanding of the fundamental interactions described by the Standard Model (SM). Since its discovery at the LHC in 2012 [1, 2], precise determination of its properties has become a primary goal of current and future collider programs. In this context, a muon collider [3] provides a particularly compelling opportunity to probe Higgs physics at multi-TeV energy scales, benefiting from well-defined initial states, low levels of physics backgrounds, and high production cross sections. At multi-TeV $\mu^+\mu^-$ collision energies, Higgs bosons are predominantly produced via vector-boson fusion (VBF), resulting in large cross sections, as shown in the left panel of Fig. 1. In particular, a 10 TeV muon collider is expected to deliver a dataset of 10 ab^{-1} over five years, corresponding to samples of about 10^7 single Higgs bosons and roughly 4×10^4 double Higgs bosons. These event yields enable high-precision measurements of Higgs couplings to fermions and bosons, and provide access to rare Higgs decay channels. The abundant production of multiple Higgs bosons further allows a direct determination of the trilinear, and potentially quartic, self-couplings, which are key parameters for understanding the structure of the Higgs potential and the mechanism of electroweak symmetry breaking.

The prospects of a muon collider for probing the Higgs sector have been demonstrated in numerous phenomenological studies [4], carried out with varying levels of sophistication in the event analysis. An example is presented in Fig. 1 (right), showing that sub-percent statistical precision can be achieved on the principal Higgs boson couplings. These studies typically account for the dominant physics backgrounds and employ parametric simulations to model the detector response. However, they do not incorporate the machine-induced background which, at a muon collider, reaches extremely high levels in the detector, with $O(10^8)$ soft-momentum particles entering at every beam crossing. Such background poses unique challenges to the experimental apparatus and could significantly jeopardize the collider's physics reach. The dominant sources of machine-induced background are the decay of muons circulating in the collider, referred to as beam-induced background (BIB), and the incoherent e^+e^- pair production (IPP) from interactions of real or virtual photons emitted by the colliding beams [5]. Their unprecedented nature makes it difficult to predict or model their effects on detector performance based on past experience, underscoring the need for detailed detector simulations.

A campaign of Higgs boson studies, documented in Ref. [6], was conducted for a 3 TeV muon collider. The present work reports the projected statistical precision attainable at a 10 TeV collider for cross-section measurements of Higgs decays to $b\bar{b}$ and WW^*, as well as for double-Higgs production into $b\bar{b}b\bar{b}$, and evaluates the sensitivity to the Higgs trilinear self-coupling. These projections are based on detailed detector simulations that include machine-induced background, assuming two interaction points (IPs), each collecting 10 ab^{-1} of data over five years.

2. Higgs boson studies with detailed detector simulation

The studies presented here are based on a detailed simulation of the MUSIC (MUon System for Interesting Collisions) detector concept, specifically designed for $\mu^+\mu^-$ collisions at a center-of-mass energy of 10 TeV. The detector adopts the typical cylindrical layout of multipurpose collider experiments, comprising an all-silicon tracking system, electromagnetic (ECAL) and hadronic (HCAL)

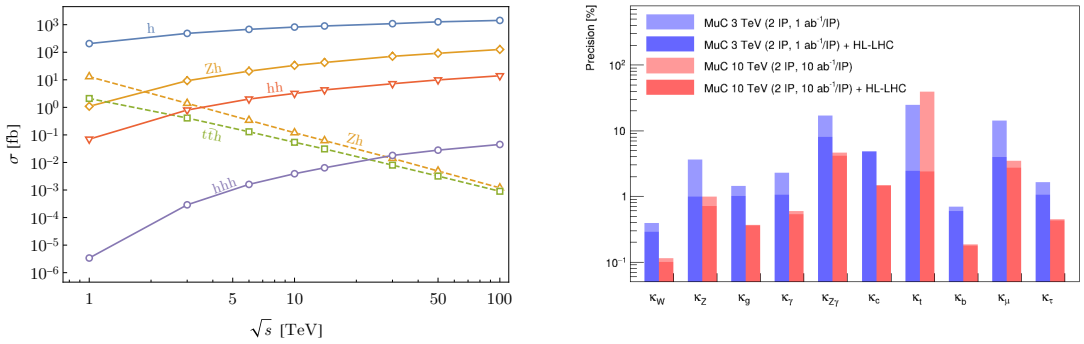

Figure 1: Left: Cross sections for the main Higgs boson production processes as a function of the center-of-mass energy $\sqrt{s}$ in $\mu^+\mu^-$ collisions, taken from Ref. [7]. Solid lines denote VBF processes, while dashed lines denote s-channel $\mu^+\mu^-$ annihilation. Initial-state radiation is not included. Right: Statistical precision on Higgs boson couplings at 3- and 10-TeV muon colliders, expressed as ratios κ_i to the SM expectations, under the assumption of no Higgs decays beyond the SM. Light-colored bars indicate the precision expected from the muon collider alone, while dark-colored bars show the precision when combined with HL-LHC results. The data are taken from Ref. [8] and have been rescaled to two IPs by the authors.

calorimeters, and an outer muon system. All MUSIC subdetectors feature high spatial granularity and advanced timing capabilities, providing a resolution of 100 ps or better. A superconducting solenoid, located between the ECAL and HCAL, generates a 5 T magnetic field to mitigate the impact of incoherent e^+e^- pair production on the innermost tracking layers. Along the beamline inside the detector, two conical tungsten shields with a 10° opening angle, referred to as "nozzles", are installed on either side of the interaction point to protect the detector from high-energy products of muon decays. Further details are provided in Ref. [9].

The Monte Carlo (MC) samples for the signal processes and associated physics backgrounds are produced with the WHIZARD generator [10], while particle hadronization and showering are handled by PYTHIA [11]. The samples are then processed through the detector simulation, based on GEANT4 [12], and reconstructed using the muon collider software framework [13]. Prior to reconstruction, BIB and IPP are overlaid onto the $\mu^+\mu^-$ hard-scattering events on an event-by-event basis. BIB is simulated with the FLUKA toolkit [14], modeling the machine lattice and machine-detector interface of a 10 TeV collider in the "EU24 lattice" configuration [5]. IPP is generated with Guinea-Pig [15], while the subsequent propagation and interactions of the resulting electrons and positrons with the nozzles are simulated using FLUKA.

The reconstruction algorithms for physics objects have been revised and optimized to mitigate machine-induced background, while preserving excellent performance for Higgs studies [9]. The analyses presented here focus on jets and muons. Jet reconstruction starts from charged-particle trajectories (tracks), reconstructed with a Combinatorial Kalman Filter in the ACTS package [16], and ECAL/HCAL clusters, which serve as input to the PandoraPFA particle-flow algorithm [17]. The resulting particle-flow objects are clustered into jets using the k_t algorithm [18] with $R = 0.5$, and jet four-momenta are obtained by summing the momenta of their constituents. Jet momenta are corrected to account for detector effects and biases, with additional angular adjustments applied in the barrel–endcap transition regions. Fake jets from machine-induced background are suppressed

$\sqrt{s}$ = 10 TeV, 2 IP, 10 ab^{-1}/IP		channel	σ_{eff} [fb]	ϵ_{sel} [%]	N_{evt}	$\Delta\sigma_H/\sigma_H$ [%]
$H \to b\bar{b}$	*S*:	$\mu^+\mu^- \to HX \to b\bar{b}X$	490	7.2	351518	0.20
	B:	$\mu^+\mu^- \to HX \to c\bar{c}X$	24.3	1.0	2422	
		$\mu^+\mu^- \to q\bar{q}'\nu_\ell\bar{\nu}_\ell$	2674	1.3	341598	
		$\mu^+\mu^- \to q\bar{q}'\ell\ell$	4339	0.024	10533	
		$\mu^+\mu^- \to q\bar{q}'\ell\nu_\ell$	9763	0.021	20974	
$H \to WW^*$	*S*:	$\mu^+\mu^- \to HX \to WW^*X \to q\bar{q}'\mu\nu_\mu X$	26.3	47.3	137493	0.41
	B:	$\mu^+\mu^- \to H\nu_\ell\bar{\nu}_\ell$	820	12.2	1000906	
		$\mu^+\mu^- \to H\ell\ell$	84.8	12.5	106226	
		$\mu^+\mu^- \to q\bar{q}'\ell\nu_\ell$	9763	11.4	11110294	
		$\mu^+\mu^- \to q\bar{q}'\nu_\ell\bar{\nu}_\ell$	2674	10.2	2731663	
		$\mu^+\mu^- \to q\bar{q}'\ell\ell$	4339	1.8	772342	
$HH \to b\bar{b}b\bar{b}$	*S*:	$\mu^+\mu^- \to HHX \to b\bar{b}b\bar{b}X$	1.1	18.5	2100	4.2
	B:	$\mu^+\mu^- \to Hq_h\bar{q}_hX \to b\bar{b}q_h\bar{q}_hX$	7.3	15.6	11307	
		$\mu^+\mu^- \to q_h\bar{q}_hq'_h\bar{q}'_hX$	10.9	9.0	9787	

Table 1: Summary of Higgs boson analyses based on a detailed detector simulation at a 10-TeV $\mu^+\mu^-$ collider, assuming two experiments each collecting 10 ab^{-1} of data. *S* and *B* denote the reconstructed Higgs boson channels and the main physics backgrounds, respectively. σ_{eff} is the effective cross section for the reconstructed final state, ϵ_{sel} the total selection efficiency, and N_{evt} the number of selected events. The last column shows the estimated relative statistical uncertainty on the Higgs boson production cross sections.

by requiring each jet to contain at least one track and that the highest-p_T track within the jet exceeds 2 GeV. Jets originating from b quarks are identified by exploiting characteristic signatures of b-hadron decays, such as displaced secondary vertices and associated muons, which are combined within deep neural networks. The jet-tagging algorithm working point is chosen to yield a b-jet efficiency of about 55%, with mis-tag rates of approximately 20% for c jets and 1% for light jets. Muons are identified by matching reconstructed tracks to hits in the outer muon system.

In the following, a representative subset of Higgs boson measurements is presented: the statistical sensitivity to the production cross section times branching ratio, $\sigma_H\,\mathcal{B}(H \to f)$ for $f = b\bar{b}$ and WW^*, as well as $\sigma_{HH}\,\mathcal{B}(HH \to b\bar{b}b\bar{b})$. Cross sections are determined as $N_S/(\epsilon_{\text{sel}}\,\mathcal{L}_{\text{int}})$, where N_S denotes the number of selected signal events, ϵ_{sel} the total signal selection efficiency, and $\mathcal{L}_{\text{int}}$ the integrated luminosity. The main features of the analyses are summarized in Tab. 1.

$H \to b\bar{b}$: Events with a Higgs boson decaying into a $b\bar{b}$ pair are selected by requiring two central high-p_T jets, with $p_T^{\text{jet}} > 40$ GeV and $10^\circ < \theta_{\text{jet}} < 170^\circ$. After b-flavor tagging of both jets, the only significant backgrounds that remain are $Z \to b\bar{b}$ and $Z \to c\bar{c}$. The signal yield is extracted from a fit to the dijet invariant mass distribution, shown in the left panel of Fig. 2. The statistical sensitivity of the yield is evaluated using a toy Monte Carlo study. Assuming negligible uncertainties on the selection efficiency and integrated luminosity, the relative statistical uncertainty on the production cross section is determined by the statistical sensitivity of the signal yield: 0.20%.

$H \to WW^*$: The WW^* channel is reconstructed in the semileptonic final state $q\bar{q}'\mu\nu_\mu$, which provides a favorable signal-to-background ratio. Candidates are defined by a high-p_T isolated prompt muon with $p_T^\mu > 10$ GeV and $10^\circ < \theta_\mu < 170^\circ$, together with two jets satisfying $p_T^{\text{jet}} > 20$ GeV and $10^\circ < \theta_{\text{jet}} < 170^\circ$. Two Boosted Decision Trees (BDTs) are trained to separate the signal from backgrounds containing a Higgs boson and from non-resonant processes. The BDT output distribution for the latter case is shown in Fig. 2 (right). Signal and background yields

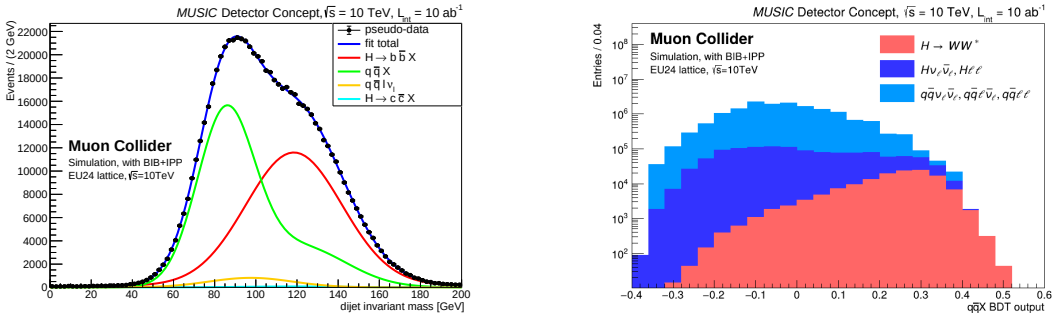

Figure 2: Left: Example of the dijet invariant mass fit for one of the pseudo-experiments used to extract the $H \to b\bar{b}$ yield. Right: Stacked distributions of the output of the BDT trained to separate the $H \to WW^*$ signal from non-resonant backgrounds.

are extracted from a fit to the two-dimensional distribution of the outputs of the two BDTs. The statistical sensitivity of the signal yield is assessed through a toy Monte Carlo study. Assuming negligible uncertainties on the selection efficiency and integrated luminosity, the relative statistical uncertainty on the $H \to WW^*$ production cross section is 0.41%.

$HH \to b\bar{b}b\bar{b}$: Double-Higgs production is studied in the all-hadronic final state $HH \to b\bar{b}b\bar{b}$. Selected events are required to contain at least four reconstructed jets with $p_T^{\text{jet}} > 20$ GeV and $10^\circ < \theta_{\text{jet}} < 170^\circ$. Jets are paired to form two Higgs candidates such that their invariant masses are closest to the nominal Higgs boson mass. Requiring b-tagging for at least one jet in each pair suppresses most backgrounds from light-quark jets. A multi-layer perceptron (MLP) is employed to discriminate signal from background, and its output distributions are fitted to extract the signal yield. The MLP outputs are subsequently used in a toy Monte Carlo study to evaluate the sensitivity to the double-Higgs production cross section, resulting in a statistical uncertainty of 4.2%.

The observables $\sigma_H \mathcal{B}(H \to f)$ are sensitive to the Higgs boson couplings to SM fermions and bosons. The precision of these couplings is typically estimated through a global fit to the cross sections. However, the studies performed so far with detailed detector simulations do not yet cover all of the most relevant Higgs decay modes; therefore, a coupling fit is not yet feasible.

$HH \to b\bar{b}b\bar{b}$ provides direct access to the Higgs boson trilinear self-coupling λ_3. Its measurement requires disentangling double-Higgs events produced via an intermediate off-shell H^* from other HH production mechanisms. The statistical sensitivity to λ_3 has been estimated following Ref. [6]: eleven $HH \to b\bar{b}b\bar{b}$ samples are generated with WHIZARD for $\kappa_{\lambda_3} = \lambda_3/\lambda_3^{SM}$ values between 0.2 and 1.8, with $\kappa_{\lambda_3} = 1$ corresponding to the SM. Two independent MLPs are trained: one to separate the SM signal from physics backgrounds, and another to distinguish HH events produced via an off-shell H^* using angular and helicity observables. For each κ_{λ_3} hypothesis, two-dimensional templates of signal and background are constructed from the MLP outputs, and pseudo-datasets are generated for the SM case. A likelihood scan is then performed to extract the 68% C.L. interval. The resulting precision is $0.958 < \kappa_{\lambda_3} < 1.057$, achievable with two experiments and 10 ab^{-1} of data per experiment in about five years.

3. Summary

A 10 TeV muon collider is expected to provide abundant samples of single and double Higgs bosons, enabling precision studies of Higgs properties. Studies based on detailed detector simulations, assuming two experiments each collecting 10 ab^{-1} of data over five years and including machine-induced background, indicate that the production cross sections for $H \to b\bar{b}$ and $H \to WW^*$ can be measured with permille precision, while the trilinear Higgs self-coupling can be determined at the percent level using only $HH \to b\bar{b}b\bar{b}$. Machine-induced background effects are successfully mitigated, and the precision levels projected in parametric analyses are achievable. Work is ongoing to extend these studies to all major Higgs channels.

Acknowledgments

This work was supported by the European Union's Horizon 2020 and Horizon Europe Research and Innovation programs through the Marie Skłodowska-Curie RISE Grant Agreement No. 101006726 and the Research Infrastructures INFRADEV Grant Agreement No. 101094300.

References

[1] G. Aad *et al.*, Phys. Lett. B 716, 1 (2012).

[2] S. Chatrchyan *et al.*, Phys. Lett. B 716, 30 (2012)

[3] C. Accettura *et al.*, Eur. Phys. J. C 83, 864 (2023).

[4] C. Accettura *et al.*, arXiv:2504.21417 (2025).

[5] D. Calzolari *et al.*, PoS ICHEP2024, 819 (2025).

[6] P. Andreetto *et al.*, Eur. Phys. J. C 85, 221 (2025).

[7] H.A. Ali *et al.*, 2022 Rep. Prog. Phys. **85** 084201.

[8] M. Forslund and P. Meade, J. High Energ. Phys. 08, 185 (2022).

[9] P. Andreetto *et al.*, PoS EPS-HEP2025, 515 (2026).

[10] W. Kilian, T. Ohl, and J. Reuter, Eur. Phys. J. C 71, 1742 (2011).

[11] T. Sjöstrand *et al.*, Comput. Phys. Commun. 191, 159 (2015).

[12] S. Agostinelli *et al.*, Nucl. Instrum. Meth. A 506, 250 (2003).

[13] The Muon Collider software, `github.com/MuonColliderSoft`.

[14] C. Ahdida *et al.*, Front. Phys. 9, 788253 (2022).

[15] C. Rimbault *et al.*, EUROTEV-REPORT-2005-016 (2005).

[16] X. Ai *et al.*, Comput. Softw. Big Sci. 6, 8 (2022).

[17] M. Thomson, Nucl. Instrum. Meth. A 611, 25 (2009).

[18] S.D. Ellis and D.E. Soper, Phys. Rev. D 48, 316 (1993).