Investigating Resonant Higgs Production Cross-Section at FCC-ee: A Machine Learning-based Analysis for Semi-Leptonic W Boson Decay Channel

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ABSTRACT

This study examines the cross-section of Higgs production in the resonant s-channel during electron-positron collisions at the Future Circular Collider (FCC-ee). In this case, the Higgs boson decays into two W bosons, where one decays leptonically into the first or second-generation leptons with a neutrino and the other one decays hadronically, $e^+e^- \to H \to WW^* \to \ell\nu_\ell jj'$, at the center of mass energy of the Higgs boson mass. The main Standard Model background processes are taken into account, and an optimized machine learning-based analysis approach is performed to enhance the sensitivity of the signal events with respect to the backgrounds. The signal and backgrounds efficiencies and cross-sections, are estimated for two different scenarios according to whether the off-shell or on-shell W boson decays to two jets. The final Higgs production cross-section is comparable to prior studies.

Key words: Higgs boson, Standard Model, Future Circular Collider

I. INTRODUCTION

The study of Higgs boson production remains a cornerstone of modern particle physics, particularly in understanding the mechanisms of electroweak symmetry breaking [1]. One of the promising avenues for such investigations is the Future Circular Collider (FCC-ee), which offers the potential for high-precision measurements in electron-positron collision environments [2]. Measuring the Higgs production cross-section is critical for probing its properties, such as Yukawa couplings, to test the Standard Model (SM), and to investigate new physics beyond the Standard Model (BSM).

The resonant s-channel production of the Higgs boson during electron-positron collisions at the FCC-ee, with the Higgs boson decaying into two W bosons, where one W boson decays into a lepton accompanied by its neutrino, and the other W boson decays hadronically into two jets, is studied in Ref. [3], for all lepton families together. Specifically in this study, electron and muon are considered individually. In addition, different sub-channel decays of the on-shell and off-shell W boson (W*), are treated separately due to their different kinematics and cross-sections, which is discussed in the next section (II), beside the data simulation and the analysis strategy description.

The primary challenge in the analysis in section II, lies in distinguishing the Higgs signal from the predominant SM background processes. To address this, a machine learning-based approach utilizing multivariate analysis (MVA) via Boosted Decision Trees (BDTs) approach is employed [4]. This technique enables the optimization of signal sensitivity by effectively classifying and enhancing signal events relative to the background events. Previous studies have demonstrated the efficacy of BDTs in high-energy physics analyses, providing a robust framework for signal discrimination and background suppression. Finally in section III, the results are presented and discussed.

II. SIMULATION AND THE ANALYSIS STRATEGY

To investigate the resonant s-channel production of the Higgs boson at the FCC-ee, we detailed simulation using advanced computational techniques, which provide a comprehensive description of the final-state particles. This approach ensures high precision in modeling the Higgs boson production and its subsequent decay into W bosons. The signal and background events are generated using the Whizard framework. Parton Shower and hadronization processes are simulated with Pythia, and the detector response, reconstruction of particle tracks, and identification of final-state particles are modeled using Delphes, all within the FCC software framework, FCCSW, at $\sqrt{s} = m_H$. For the signal events, we consider two scenarios: in the first scenario, the W* decays leptonically, while in the second scenario, W* decays hadronically. In other words, in the first scenario, W* is decayed directly with Whizard into the correct fermion pair, and the on-shell W boson is decayed with Pythia. In the second scenario, the process is reversed, leading to different cross-sections and kinematics. Consequently, overall, four signal scenarios are taken into account: two for the electrons and two for the muons. The main background processes considered in this study are listed in Table 1, column 2, with their corresponding cross-sections, at 125 GeV center of mass energy.

The reconstructed events are analyzed to identify the Higgs boson semi-leptonic W boson decay channel, where two jets, one lepton (electron or muon) along with a neutrino are produced. To select signal events and remove backgrounds, each event requires to have exactly two jets and one isolated lepton, where electron and muon channel considered individually. Due to the presence of a neutrino in the signal process, events must have at least 2 GeV of missing transverse momentum [3]. To enhance the signal-background discrimination, we employ a MVA using the BDTs approach. Given the different kinematics of the two signal samples, different input variables are considered in the MVA for each. A list of input variables for one of the scenarios is shown in Figure 1.

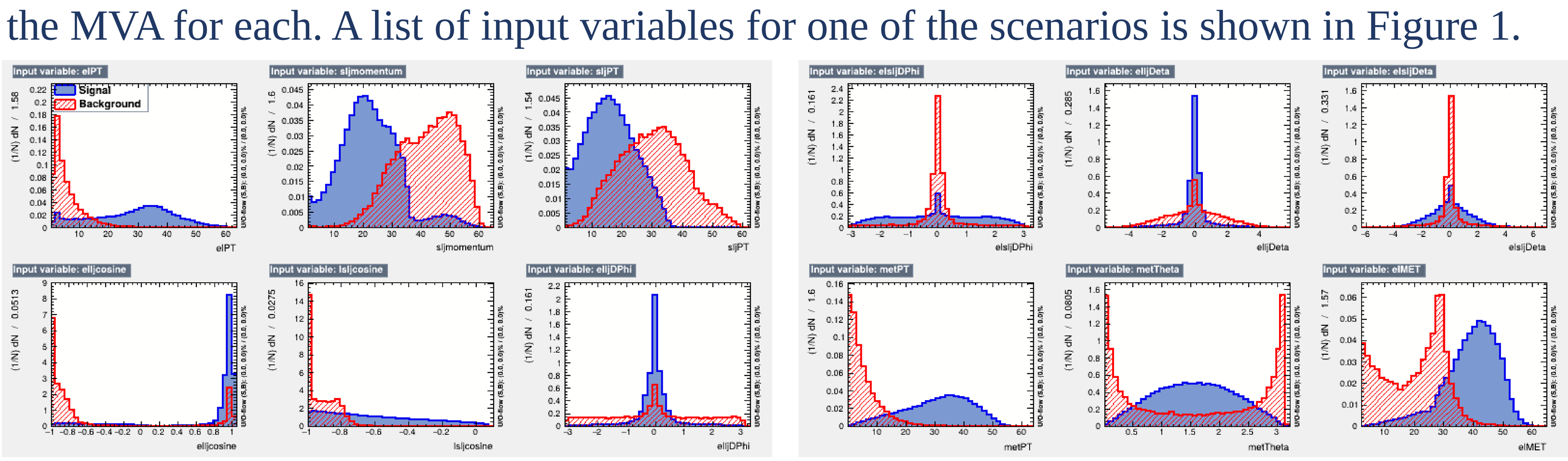

Figure 1. The representative histograms of input variables imported to MVA for the electron channel

The BDTs output for the two scenarios in the electron channel are depicted in Figure 2. To further improve significance, an optimization approach is applied on the outputs. The main outcome is the estimation of the efficiencies of the signal and background events, which leads to the maximum significance, is discussed in the following.

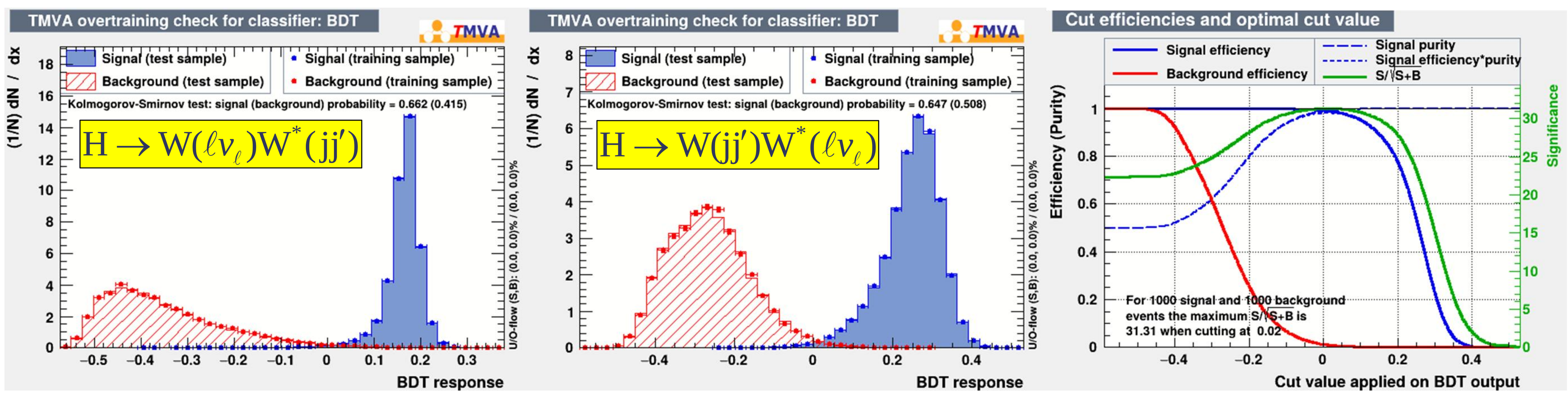

Figure 2. BDTs classification output for the electron channel, when W* decays hadronically (**left**), when W* decays leptonically (**middle**); Cut efficiency classifier plot (**Right**).

III. RESULTS AND DISCUSSION

By leveraging the advanced capabilities of the FCC-ee and sophisticated analysis techniques, this study aims to contribute valuable insights into Higgs boson physics and pave the way for future explorations in this field.

In the electron channel (Table 1), columns 2,3 and 4, the signal and background initial cross-sections, efficiencies after pre-selection cuts, and after performing BDTs are presented, respectively, when the W* decays to two jets (first signal scenario). In the last column final cross-sections as the output of the MVA are estimated, which leads to the calculation of Higgs properties, such as muon and electron Yukawa. Table 2 shows the results similar to the Table 1, but for the second signal scenario, when the W* decays leptonically. As it is shown in both tables, and also in Figure 2, the results for two signal scenarios, *i.e.* whether W* decays into leptons or jets, are different due to various kinematics. The hadronic decay of W* boson scenario gives a better sensitivity. In addition, since an optimization approach is applied on the BDTs output, the most sensitivity of signal area is achieved, which leads to the maximum possible significance.

Process ($e^+e^- \to$)	**Cross Section (initial) [fb]**	**pre-selection Efficiency**	**Final Efficiency (after MVA)**	**Cross Section (final) [fb]**
(signal) $H \to W(\ell\nu_\ell)W^*(jj')$	4.58×10^{-2}	0.268	0.253	1.16×10^{-2}
$H \to WW^* \to \ell\nu_\ell\ell'\nu_{\ell'}$	3.19×10^{-2}	0.282	0.027	8.72×10^{-4}
$e^{+(-)}\bar{\nu}_e(\nu_e)jj'$	13.82	0.649	0.178	2.45
$\mu^{+(-)}\bar{\nu}_\mu(\nu_\mu)jj'$	6.71	0.023	0.004	2.72×10^{-2}
$\tau^{+(-)}\bar{\nu}_\tau(\nu_\tau)jj'$	6.76	0.124	0.043	0.29
$e^+e^-\nu_e\bar{\nu}_e$	336.4	0.018	0.003	0.96
$\mu^+\mu^-\nu_\mu\bar{\nu}_\mu$	220.2	0	0	0
$\tau^+\tau^-\nu_\tau\bar{\nu}_\tau$	42.65	0.036	0.004	0.18
$\ell\nu_\ell\ell'\nu_{\ell'}$	5.80	0.461	0.114	0.66
jj'	363100	0.065	8.28×10^{-5}	30.05
$H \to gg$	7.38×10^{-2}	0.013	8.33×10^{-7}	6.15×10^{-8}

Table 1. Signal and backgrounds cross-sections, efficiencies after pre-selection cuts, and after BDTs, when the W* decays to two jets.

Process ($e^+e^- \to$)	**Cross Section (initial) [fb]**	**pre-selection Efficiency**	**Final Efficiency (after MVA)**	**Cross Section (final) [fb]**
(signal) $H \to W(jj')W^*(\ell\nu_\ell)$	3.18×10^{-2}	0.255	0.243	7.75×10^{-3}
$H \to WW^* \to \ell\nu_\ell\ell'\nu_{\ell'}$	3.19×10^{-2}	0.282	5.48×10^{-4}	1.75×10^{-5}
$e^{+(-)}\bar{\nu}_e(\nu_e)jj'$	13.82	0.649	0.011	0.15
$\mu^{+(-)}\bar{\nu}_\mu(\nu_\mu)jj'$	6.71	0.023	4.72×10^{-4}	3.17×10^{-3}
$\tau^{+(-)}\bar{\nu}_\tau(\nu_\tau)jj'$	6.76	0.124	1.4×10^{-3}	9.88×10^{-3}
$e^+e^-\nu_e\bar{\nu}_e$	336.4	0.018	0	0
$\mu^+\mu^-\nu_\mu\bar{\nu}_\mu$	220.2	0	0	0
$\tau^+\tau^-\nu_\tau\bar{\nu}_\tau$	42.65	0.036	5.91×10^{-6}	2.52×10^{-4}
$\ell\nu_\ell\ell'\nu_{\ell'}$	5.80	0.461	5.50×10^{-5}	3.19×10^{-4}
jj'	363100	0.065	1.21×10^{-3}	44.05
$H \to gg$	7.38×10^{-2}	0.013	2.19×10^{-3}	1.62×10^{-4}

Table 2. As same as Table 1, but for the case where the W* decays leptonically.

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