Study of Higgs to WW Coupling Measurement Performance through $e^+e^- \to \nu\bar{\nu}b\bar{b}$ at Future Circular Colider - Electron Positron

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This investigation seeks to evaluate the potential performance capabilities of the measurment of Higgs to WW coupling and the total Higgs decay width at the FCC-ee - a future e^+e^- collider. The signal process used in the investigation is $e^+e^- \to \nu\bar{\nu}b\bar{b}$ through WW Fusion, and considers various backgrounds. Unlike previous studies, this investigation closely evaluates the effect of detector performance on the coupling uncertainty. The uncertainty on the measurement of $\sigma_{\nu\bar{\nu}H}$ x BR $(H \to b\bar{b})$ is found to be 2.3% at $\sqrt{s} = 350$GeV and 3.8% at $\sqrt{s} = 240$GeV, leading to a model-independent uncertainty on Higgs to WW coupling of 0.8% and 1.1% respectively, and an uncertainty on the total Higgs decay width of 1.1% and 1.4%, respectively.

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I. INTRODUCTION

To continue the search for physics beyond the standard model, precision knowledge of standard-model particles and their properties is required to measure deviations at higher energy scales. In investigating the Higgs boson, evidence for new physics at an energy scale of 1 TeV is expressed in deviations of the Higgs boson coupling to gauge bosons and fermions of up to 5% relative to Standard Model predictions, and scales as $1/\Lambda^2$ [**?**]. It is therefore necessary to measure Higgs boson couplings to per-cent accuracy or better to be sensitive to new physics at 1 TeV, and to per-mil accuracy or better to be sensitive to new physics at multi-TeV.

Among the possible machines proposed for a precision study of the standard model particles, the FCC-ee (Future Circular Collider electron-positron) stands out as the tool of choice. A circular e^+e^- collider provides a high-luminosity higgs factory with a clean detection environment useful for studying various higgs properties as well as Z and W bosons and the top-quark [**?**].

Constraining the Higgs to W boson coupling (g_{HWW}) and the total Higgs boson width (Γ_{tot}) is a top priority.

One path for this measurement is through studying the process $e^+e^- \to \nu\bar{\nu}b\bar{b}$. This final state occurs through two processes, Higgs-strahlung (HZ) (Figure 1) where the Z decays into a neutrino pair, and WW fusion (Figure 2).

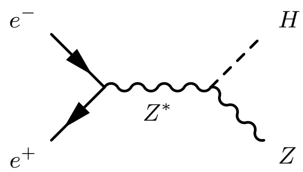

Figure 1: Higgs-strahlung

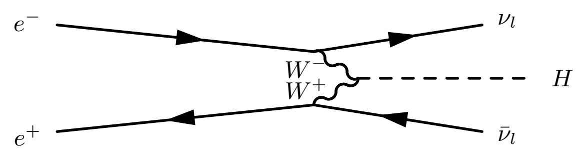

Figure 2: WW Fusion

The measurement of $\sigma_{\nu\bar{\nu}H}$ x BR ($H \to b\bar{b}$) contributes to the calculation of the total Higgs boson width, given by

$$\Gamma_{\text{tot}} = \frac{\Gamma(\text{H} \to \text{W W})}{\text{BR}(\text{H} \to \text{W W})} \tag{1.1}$$

The uncertainty of the measurement of $\sigma_{\nu\bar{\nu}H}$ x BR ($H \to b\bar{b}$), determined by fittting the WW Fusion profile to a Monte Carlo (MC) simulation of the $\nu\bar{\nu}b\bar{b}$ signal and backgrounds, can therefore be combined with previously published uncertainty calculations on Higgs branching ratios to determine the potential precision of the Higgs boson total width measurement at the FCC-ee.

Two center-of-mass energies are considered - $\sqrt{s}$ = 350GeV and $\sqrt{s}$ = 240GeV. 240 GeV is the center-of-mass energy proposed for the FCC as a Higgs factory, which balances the Higgs production cross section with the FCC-ee luminosity profile as a function of energy. While the Higgs cross-section peaks at 255 Gev, the FCC-ee luminosity decreases with increasing energy due to bremsstrahlung, leading to a maximum luminosity at $\sqrt{s}$ = 240GeV. It is proposed to run the FCC-ee at $\sqrt{s}$ = 240GeV for five years, leading to a total integrated luminosity of 10 ab$^-$1 with four interaction points. The FCC-ee proposal also includes a five-year run at the $t\bar{t}$ threshold of $\sqrt{s} = 350$GeV with an integrated luminosity of 2.6 ab$^-$1. For this investigation, while large luminosity is preferable and decreases statistical uncertainty, the shape separation between the WW Fusion profile and its most similar background, ZH, increases as the available phase space of the missing mass increases. While the missing mass of the ZH background clusters around the Z boson mass of 91 GeV, the missing mass of the WW Fusion signal peaks at around $\sqrt{s}$ - m$_H$. A larger difference between the shape of the WW Fusion signal and its backgrounds leads to a lower uncertainty in the signal fit to the simulated data, thereby decreasing the uncertainty of the measurements.

In the course of this study, the effects of detector performance on the precision of coupling measurements is investigated, and compared against detectors simulated in previous studies investigating Higgs decays at the ILC [**?**], at TLEP [**?**] and at LEP3 using the CMS detector [**?**].

II. OBJECTS

The signal process investigated is $e^+e^- \to \nu\bar{\nu}b\bar{b}$ through WW fusion. The visible decay products are two b-quarks, which hadronize into two jets of particles, and are the objects detected and reconstructed by the detector. Neutrinos escape the detector and are searched for through the profile of the missing four-momentum calculated from the two reconstructed jets.

Jet reconstruction was first performed using the antikt algorithm included with the default Delphes distribution (`https://arxiv.org/pdf/0802.1189.pdf`). This algorithm defines a jet by the cluster of particles around a point with some cutoff distance. This is not optimized for the FCC, however, since our signal will contain only particles which come from one of the two jets and nothing else. Thus, it is better to define the two jets as a grouping of all the particles seen by the detector into exactly two jets. This is accomplished by the inclusive ee-kt algorithm which is included in Fastjet (`https://arxiv.org/pdf/1111.6097.pdf`). To do this, the Delphes installation was modified to interface a broader selection of algorithms. The modified code can be found in (`https://github.com/aandriat/MIT-FCCee/tree/master/jet_algs`) with FastJetFinder.cc being the crucial element, located in the Delphes/modules directory of your Delphes installation.

III. MC EVENT GENERATION AND DETECTOR SIMULATION

The generation of signal and background events was performed through Whizard [?] which is a next-to-leading order tool and includes initial state radiation. Parton showering and hadronization was done using Pythia 8 [3]. Detector simulation was done using Delphes [4]. A card was made to simulate an optimal detector for Higgs precision studies at the FCCee.

The signal event produced is $\nu\bar{\nu}b\bar{b}$ through WW Fusion. The background events considered are $\nu\bar{\nu}b\bar{b}$ through ZH, $\nu\bar{\nu}c\bar{c}$, $\nu\bar{\nu}q\bar{q}(q \neq b, c)$, $q\bar{q}l^+l^-$, $q\bar{q}l^-\nu$, $q\bar{q}q\bar{q}$, $q\bar{q}$, and $q\bar{q}\gamma$.

Update: To more inclusively account for possible background processes, the background collection was changed to $e^+e^- \to q\bar{q}$, $e^+e^- \to W^+W-$, and $e^+e^- \to ZZ$. However, I had trouble implementing this in Whizard becasue of on-shell constraints and double-counting if considering the final states of these processes.

IV. CANDIDATE SELECTION

To select the WW Fusion $\nu\bar{nu}b\bar{b}$ signal, first a sample is created which groups all detected particles into exactly two jets reconstruccted using the ee-k_T algorithm. The jets are b-tagged with an efficiency specified by the Delphes deterctor simulation. Only events containing two jets which are both b-tagged are allowed. Events with isolated leptons are omitted.

Next, kinematic cuts are applied based on the distribution of various properties. The optimal cuts were determined both by visual inspection of N-1 cut distributions, and through a BDT rectangular cut optimization tool in TMVVA. The visible mass of the system is required to be between 99 and 140 GeV since the visible mass from the signal comes only from the Higgs. The visible PT of the system is required to be less than 140 GeV. The visible PZ is required to be less than 130 GeV. The number of charged tracks in the two jets is required to be between 6 and 40. Lab angle between 1.5 and 3. Other parameters considered were the acoplanarity angle, and the CosTheta of the jet with respect to the beam axis, but were found to have negligible impact on the elimination of backgrounds. The visible energy of the system and recoil mass of the di-jet system are not considered for cuts because the uncertainty in the cross section and branching ratio of the Higgs bb system is given by the shape fit of the recoil mass, so the full distribution is left for the signal extraction. The implementation of cuts in the analysis code can be found in (`https://github.com/aandriat/MIT-FCCee/blob/master/vvbb_complete/install/treecutter_tree.C#L90`).

V. STATISTICAL METHOD

The uncertainty in the quanitity of interest, $\sigma_{\nu\bar{\nu}H}$ x Br ($H \to b\bar{b}$) is found using a Maximum Likelihood tool from HiggsAnalysis/CombinedLimit [**?**]. This measurement is then combined with other measurements necessary to arrive at a total higgs width in a coupling tool [**?**].

The Maximum Likelihood tool allows the specification of systematic uncertainties. The unertainties used are a lognormal systematic uncertainty of 2.6% on luminosity and an individual lognormal uncertainty of 1% on each of the backgrounds and signal. As an additional feature, the ZH process can be considered as a second signal and is left with a floating normalization uncertainty, so that assumptions about the shape of the ZH distribution do not contribute to the measurement of the WW uncertainty. The setup for this measurement is shown in (`https://github.com/aandriat/MIT-FCCee/blob/master/vvbb_complete/install/xsection_tool.txt`).

The analysis gives a total uncertainty of 2.29% in $\sigma_{\nu\bar{\nu}H} xBr(H \to b\bar{b})$. Compare this to an uncertainty of 10.5% at 240 GeV and 0.66% at 500 GeV given by the ILD paper [**?**].

The total higgs width was calculated to be !!! and the higgs WW coupling is calculated as !!!.

VI. RESULTS

The uncertainty on the measurement of $\sigma_{\nu\bar{\nu}H}$ x Br ($H \to b\bar{b}$) is found to be 2.3% at $\sqrt{s} = 350$GeV and 3.8% at $\sqrt{s} = 240$GeV, (compare to 0.6% and 2.2% in the TLEP paper) leading to a model-independent uncertainty on Higgs to WW coupling of 0.8% and 1.1%! respectively, and an uncertainty on the total higgs width of 1.1% and 1.4%, respectively (compare to 1.2% and 2.4% in the TLEP paper).

The results found in this analysis suggests an improvement in the potential precision of Higgs to WW coupling measurements using an FCCee - specific detector, and improves the physics case for a circular electron positron precision higgs factory.

VII. CONCLUSION

This will be the conclusion.

[1] CERN, The FCC-ee design study, `http://tlep.web.cern.ch/`
[2] J. Alwall *et al.*, *JHEP* **07** (2014) 079.
[3] T. Sjostrand, S. Mrenna, and P.Z. Skands, Comput. Phys. Commun. **178** (2008) 852–867.
[4] J. de Favereau *et al.* [DELPHES 3 collaboration], *JHEP* **02** (2014) 057.