Testing the Higgs Mechanism in the Lepton Sector with multi-TeV $e^+e^-$ Collisions

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Abstract. Multi-TeV $e^+e^-$ collisions provide with a large enough sample of $H^0$ bosons to enable measurements of its suppressed decays. Results of a detailed study of the determination of the muon Yukawa coupling at $\sqrt{s} = 3$ TeV, based on full detector simulation and event reconstruction, are presented. The muon Yukawa coupling can be determined with a relative accuracy of 0.04 to 0.08 for Higgs bosons masses from 120 GeV to 150 GeV, with an integrated luminosity of 5 ab$^{-1}$. The result is not affected by overlapping $\gamma\gamma \rightarrow$ hadrons background.

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1. Introduction

The detailed investigation of the Higgs sector is anticipated as one of the central themes of the accelerator particle physics program after the Higgs boson will have been observed, most likely at the LHC. The study of the Higgs profile will have to determine whether the observed particle is indeed responsible for generating the mass of gauge bosons, quarks and charged leptons. A significant corpus of studies, outlining strategies to test the Higgs mechanism for gauge bosons and quarks with accuracies down to a few percent, has already been assembled [1, 2] These rely on the combination of data from the LHC and an $e^+e^-$ linear collider operating at centre-of-mass energies $\sqrt{s} = 0.25$ TeV - 1.0 TeV. In this paper we discuss the feasibility of a test of the Higgs mechanism in the lepton sector, by verifying the scaling $g_{H\mu\mu}/g_{H\tau\tau}$, through a precise determination of the $g_{H\mu\mu}$ coupling in the $H^0 \rightarrow \mu^+\mu^-$ decay, in 3 TeV $e^+e^-$ collisions. At the LHC, the significance of an observation of the $H^0 \rightarrow \mu^+\mu^-$ decay is estimated to be only $\simeq 3 \sigma$ for $115 \text{ GeV} < M_H < 130 \text{ GeV}$, even when combining the CMS and ATLAS data on both the gluon and weak boson fusion production channels for 300 fb$^{-1}$ of integrated luminosity [3]. It further decreases for larger values of $M_H$. $e^+e^-$ collisions below 1.0 TeV should provide with determination of $g_{H\tau\tau}$ to a relative statistical accuracy
of $\simeq 0.035$ for a 120 GeV Higgs boson but, at best, with only a signal and not with a precision measurement in the $g_{H\mu\mu}$ Yukawa coupling [5]. The WW fusion process, $e^+e^- \rightarrow H^0\nu_{\ell}\bar{\nu}_{\ell}$, offers a large Higgs cross section, provided high enough $\sqrt{s}$ energies can be attained, to make this measurement possible. In this paper the detection of the $H^0 \rightarrow \mu^+\mu^-$ decay in high energy $e^+e^-$ collisions is studied using full Geant-4-based simulation and reconstruction. The paper is organized as follows. In section 2 we discuss the simulation of the $e^+e^- \rightarrow H^0\nu_{\ell}\bar{\nu}_{\ell}$, $H^0 \rightarrow \mu^+\mu^-$ process and of the relevant physics and machine-induced background. Section 3 describes the detector simulation and section 4 has the results.

2. $e^+e^- \rightarrow H^0\nu_{\ell}\bar{\nu}_{\ell}$, $H^0 \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 3$ TeV

Higgs boson production in $e^+e^-$ collisions proceeds through two main processes: the so-called Higgstrahlung, $e^+e^- \rightarrow H^0Z^0$, and the WW fusion, $e^+e^- \rightarrow H^0\nu_{\ell}\bar{\nu}_{\ell}$ reactions. While the associated production of the Higgs boson with a $Z^0$ has a number of advantages, including the possibility to tag the presence of the Higgs boson independent on its decay modes, WW fusion reaches the largest cross sections, due to its $\propto \log s$ rise, if large enough centre-of-mass energies can be obtained. This makes the $WW$ fusion process of special interest for the study of rare Higgs decays, such as $H^0 \rightarrow b\bar{b}$ at large Higgs boson masses, and $H^0 \rightarrow \mu^+\mu^-$. But as the energy increases, the $H^0$ production cross section is more and more peaked along the beam axis. Above $\simeq 3$ TeV, the further increase in production cross section is effectively lost, due to the limited detector acceptance in the very forward region. The production cross section at 3 TeV and 5 TeV is respectively 2.3 and 3.0 times larger compared to that at 1 TeV. However, restricting the acceptance to Higgs bosons produced at $|\cos \theta| < 0.99$ (0.92), the gains in cross section become 2.1 (1.7) and 2.4 (1.9), respectively. The possibility of achieving $e^+e^-$ collisions at multi-TeV energies, introduced by the CLIC concept [4], offers a real opportunity for observing this decay and measuring $g_{H\mu\mu}$ with enough accuracy to perform a significant test of the scaling of the Yukawa couplings in the lepton sector over a broad range of Higgs boson masses [5]. Multi-TeV $e^+e^-$ collisions become important not only for exploring the highest energy frontier but also for precision studies of suppressed Higgs decays.

3. Data Analysis

Signal events $e^+e^- \rightarrow H^0\nu_{\ell}\bar{\nu}_{\ell}$, $H^0 \rightarrow \mu^+\mu^-$ are generated with Pythia 6.205 [6], including beamstrahlung effects, at several Higgs boson mass values from 120 GeV up to 160 GeV. Cross sections are computed using CompHep 4.4.0 [7] and the Higgs decay branching fractions with HDECAY [8]. At $\sqrt{s} = 3$ TeV, the effective $e^+e^- \rightarrow H^0\nu_{\ell}\bar{\nu}_{\ell}$ production cross section, accounting for initial state radiation, is 0.48 pb to 0.45 pb and the decay branching fraction, $\text{BR}(H^0 \rightarrow \mu^+\mu^-) = 2.56 \times 10^{-4}$ to $6.47 \times 10^{-5}$, for $M_H$ in the range from 120 GeV to 150 GeV. The irreducible $\mu^+\mu^-\nu_{\ell}\bar{\nu}_{\ell}$ background is generated
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with CompHep 4.4.0 interfaced with Pythia 6.205. The total cross section of events with an invariant mass of the $\mu^+\mu^-$ system, $M_{\mu\mu}$, in the range $100 \text{ GeV} < M_{\mu\mu} < 400 \text{ GeV}$ is 5.31 fb. We assume to operate CLIC at centre of mass energy of 3 TeV for a total integrated luminosity of 5 ab$^{-1}$, which corresponds to $\approx$ eight years ($1 \text{ yr} = 10^7 \text{ s}$) of operation at its nominal luminosity of $6.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The CLIC anticipated parameters are given in [9], for this analysis we use the luminosity spectrum as in [10]. This provides with $\approx 2.3 \times 10^6 \, e^+e^- \rightarrow H^0\nu\bar{\nu}$ events, 620 to 150 of which are followed by the $H^0 \rightarrow \mu^+\mu^-$ decay, depending on the value of the Higgs bosons mass in the range from 120 GeV to 150 GeV. The machine induced background, which affects this analysis most, is due to parasitic $\gamma\gamma \rightarrow \text{hadrons}$ events occurring within the same time-stamp as a physics event. The anticipated average number of such events for the CLIC parameters is 3.2 BX$^{-1}$, or 161 events within a 25 ns time-stamp. $\gamma\gamma$ collisions are simulated using the GUINEAPIG program [11, 12] and the cross sections parametrised according to [13]. The hadronic final states are simulated using Pythia and overlayed to a signal event. The average visible energy deposited in the detector by $\gamma\gamma \rightarrow \text{hadrons}$ events is $\approx 90 \text{ GeV/BX}$.

Charged particles are reconstructed in a multi-layered main tracker, made of high resolution silicon strip detectors, and a precision vertex tracker in a 5 T solenoidal field. Discrete Si tracking, following the example of the CMS experiment at LHC, emerged as an appealing solution for CLIC, where local hit occupancy and two-track separation may limit the applicability of gaseous trackers [14, 10]. A large magnetic field is beneficial for ensuring an excellent momentum resolution for high $p_t$ particle tracks, as well as for confining low momentum charged particles from machine-induced backgrounds to small radii. This analysis is based on an implementation of the SiD detector [15], developed as a concept for the International Linear Collider (ILC) project, for the reconstruction of 3 TeV $e^+e^-$ events. The SiD concept has a five-layered Si main tracker which ensures a momentum resolution $\delta p_t/p_t^2 < 5 \times 10^{-5}$ and polar angle coverage down to $8.3^\circ$. The following assumptions on the detector response are made: the detection efficiency is 0.98 per layer, the point resolution 7 $\mu$m, which includes alignment effects, and the detector is capable of time-stamping hits with 25 ns resolution, corresponding to 50 bunch crossings (BX).

While the SiD is designed for the reconstruction of events at centre-of-mass energies below 1 TeV, its geometry is well suited for the study of simple events, as those of our signal, up to multi-TeV energies. Full event simulation is performed using the SiD model implemented in the Mokka 06-03 program [17] based on Geant-4 [18]. Simulation results are saved in the lcio format [19] and used as input to the event reconstruction. This is performed using a set of dedicated processors implemented in the Marlin reconstruction and analysis framework [20]. The reconstruction starts from hits generated in the sensitive layers along the track. The track pattern recognition is performed from the outermost main tracker hits and extends inwards to the vertex tracker. After the first stage of pattern recognition hit bundles are fitted using a simple helix. A second stage pattern recognition is performed using hits left unassociated after
the first stage. Reconstructed particle tracks are requested to have more than 4 hits and associated hits on at least 70% of the number of sensitive surfaces traversed, depending on their polar angle, $\theta$, $\chi^2$ fit probability in excess of 0.01, $|\cos \theta| < 0.98$, and impact parameter significance below 3.5 times the extrapolation resolution, in both coordinates. These cuts remove poorly measured particle tracks. The momentum resolution of the reconstructed muon tracks is $\delta p_t/p_t^2 = (3.46 \pm 0.10) \times 10^{-5}$, in agreement with the SiD specifications. Events with two, oppositely charged muon candidate tracks with momentum exceeding 10 GeV and below 750 GeV and event energy in charged particles $100 \text{ GeV} < E_{\text{charged}} < 1.5 \text{ TeV}$ are selected.

4. Results

The invariant mass distribution of the selected di-muon pairs is shown in Figure 1. The distribution is fitted with a Gaussian curve to describe the signal and an exponential background. The mass resolution $\sigma_{M_H}/M_H$ for signal events is 0.0034, which corresponds to 0.40 GeV for $M_H=120$ GeV. The signal region is defined by a $\pm 2 \sigma_{M_H}$ interval around the fitted mass peak position and a binned $\chi^2$ fit is performed to extract the number of signal and background events. Results are summarised in Table I. We obtain $\frac{\Delta BR(H^0 \rightarrow \mu\mu)}{BR(H^0 \rightarrow \mu\mu)} = 0.086$ and 0.160 for $M_H = 120$ GeV and 150 GeV, respectively. These results correspond to a determination of $g_{H\mu\mu}$ with a relative accuracy of 0.04 to 0.08. A significant signal for the decay can be obtained up to $M_H = 155$ GeV, when its branching fraction is only $4\times10^{-5}$, due to the rapid turn on of the $WW$ decay channel of the Higgs boson. The analysis is repeated by overlaying the $\gamma\gamma \rightarrow$ hadrons background on signal events, for $M_H = 120 \text{ GeV}/c^2$. No degradation of the reconstruction efficiency and

![Figure 1. Reconstructed invariant mass distribution for signal and background $\mu^+\mu^-$ + $E_{\text{missing}}$ events with $M_H = 130$ GeV and 5 ab$^{-1}$ of integrated luminosity.](image)


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| $M_H$ (GeV) | Nb. Signal Evts. | Nb. Bkg. Evts. | $S/\sqrt{B}$ | $\delta BR/BR$ |
|-------------|-----------------|----------------|--------------|--------------|
| 120         | 229.6           | 161.1          | 18.1         | 0.086        |
| 130         | 153.1           | 88.1           | 16.3         | 0.101        |
| 140         | 103.2           | 64.3           | 12.9         | 0.125        |
| 150         | 68.1            | 58.1           | 9.5          | 0.160        |
| 155         | 68.1            | 58.0           | 5.2          | 0.253        |
| 160         | 12.1            | 33.0           | 2.1          |              |

resolution is observed for the amount of hadronic background corresponding to 50 BX (see Figure 2).

![Reconstructed invariant mass distribution](image)

**Figure 2.** Reconstructed invariant mass distribution for signal events with $M_H$ =120 GeV without (histogram) and with (points with error bars) $\gamma\gamma \rightarrow$ hadrons background overlayed.

5. Conclusions

The determination of the muon Yukawa coupling $g_{H\mu\mu}$ in $e^+e^-$ collisions at centre-of-mass energies of 3 TeV at CLIC has been studied through the $e^+e^- \rightarrow H^0\nu_e\bar{\nu}_e$, $H^0 \rightarrow \mu^+\mu^-$ process using full simulation and event reconstruction. The process is observable for Higgs mass values up to 155 GeV and the $g_{H\mu\mu}$ Yukawa coupling can be determined with a relative statistical accuracy of 0.04 to 0.08 for masses from 120 GeV to 150 GeV with an integrated luminosity of 5 ab$^{-1}$. The superposition of machine-induced $\gamma\gamma \rightarrow$ hadrons background corresponding to 50 bunch crossings overlayed on a single $\mu^+\mu^-\nu\bar{\nu}$ event does not affect these results.
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