

Studying the Higgs Sector at the CLIC Multi-TeV e^+e^- Collider

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Abstract

In this paper, we review the role of a multi-TeV e^+e^- linear collider to complete the mapping of the Higgs boson profile and studying heavier bosons in extended scenarios with more than one Higgs doublet.

1 Introduction

Understanding the origin of electro-weak symmetry breaking and mass generation stands as a central theme of the research programme in physics in the coming decades. The Standard Model (SM), successfully tested to an unprecedented level of accuracy by the LEP and SLC experiments, and now also by the B -factories, addresses this question with the Higgs mechanism [1]. The first manifestation of the Higgs mechanism through the Higgs sector is the existence of at least one Higgs boson, H^0 . The observation of a new spin-0 particle would represent a first sign that the Higgs mechanism of mass generation is realised in Nature. Present data indicates that it is heavier than 114 GeV and possibly lighter than about 195 GeV [2]. We expect the Higgs boson to be discovered at the TEVATRON or at the LHC, the CERN hadron collider, which will determine its mass and perform a first survey

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of its basic properties. A TeV-class linear collider, operating at centre-of-mass energies $350 \text{ GeV} < \sqrt{s} \leq 1 \text{ TeV}$, will bring the accuracy needed to further validate this picture and to probe the SM or extended nature of the Higgs sector. It will perform crucial measurements in a model-independent way and it will also complement the LHC in the search for heavy Higgs bosons. Their observation would provide direct evidence that nature has chosen a route different than the minimal Higgs sector of the SM. But neither the precision study of the Higgs profile nor the search for additional Higgs bosons will be completed at energies below 1 TeV. There are measurements which will be limited in accuracy or may be not feasible at all, due to limitations in both the available statistics and centre-of-mass energy. The two-beam acceleration scheme, presently developed within the CLIC study [3] at CERN, aims at collisions at $\sqrt{s}=3\text{-}5 \text{ TeV}$, representing a unique opportunity to extend e^+e^- physics to constituent energies of the order of the LHC energy frontier, and beyond, with very high luminosity. It is therefore important to assess the potential of a multi-TeV LC in complementing information that the LHC, and possibly a lower energy LC, will obtain.

2 Completing the Light Higgs Boson Profile

The TeV-class LC will perform highly accurate determinations of the Higgs profile. However, even at the high design luminosity of TESLA and the NLC there are properties which cannot be tested exhaustively. In fact, it is essential to ensure that

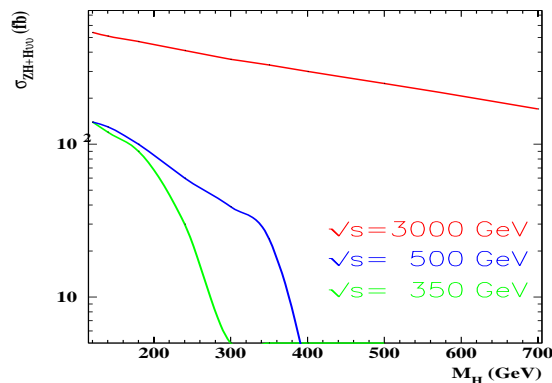


Figure 1: *Inclusive Higgs production cross section as a function of the Higgs mass M_H for three values of the e^+e^- centre-of-mass energy \sqrt{s} .*

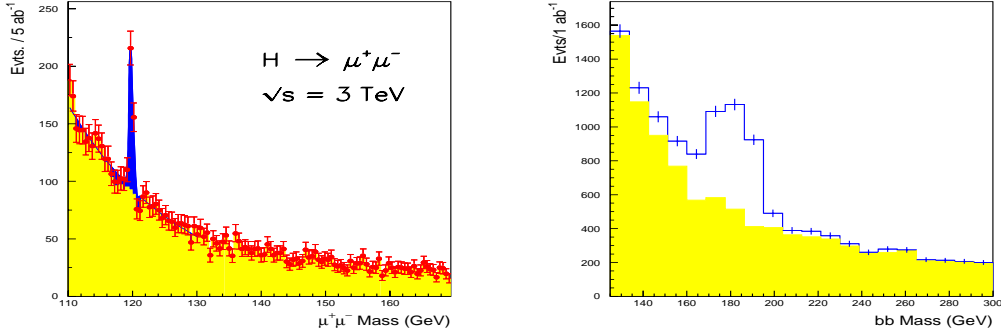


Figure 2: Reconstructed signals for $e^+e^- \rightarrow H^0 \rightarrow \mu^+\mu^-$ (left) and $e^+e^- \rightarrow H^0 \rightarrow b\bar{b}$ (right) for $M_H = 120 \text{ GeV}$ and 200 GeV respectively at $\sqrt{s}=3 \text{ TeV}$.

the fundamental test of the scaling of Higgs couplings to fermions with their masses $\frac{g_{HXX}}{g_{HYY}} \propto \frac{M_X}{M_Y}$ can be performed with significant accuracy over a wide range of Higgs boson masses and for all particle species. At $\sqrt{s} = 350 - 500 \text{ GeV}$, the LC will test the couplings to gauge boson, and those to quarks if the Higgs boson is light. To complete this program for leptons and intermediate masses of the Higgs and to study the Higgs boson self-couplings, it is necessary to study rare processes, which need Higgs samples in excess to 10^5 events. As the cross section for $e^+e^- \rightarrow H^0\nu\bar{\nu}$ production increases with energy as $\log \frac{s}{M_H^2}$, it dominates at CLIC energies. The resulting large Higgs production rate at $\sqrt{s} \geq 3 \text{ TeV}$ and the expected luminosity, $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, yield samples of order of $0.5\text{-}1 \times 10^6$ decays of SM-like Higgs boson in 1-2 years (see Figure 1).

Measuring the muon Yukawa coupling by the determination of the $H^0 \rightarrow \mu^+\mu^-$ branching fraction completes the test of the coupling scaling for gauge bosons, quarks and leptons separately. This ensures that the observed Higgs boson is indeed responsible for the mass generation of all elementary particles. At $\sqrt{s}=3 \text{ TeV}$, the $H \rightarrow \mu^+\mu^-$ signal can be easily observed and the $g_{H\mu\mu}$ coupling measured to 4-11% accuracy for Higgs masses in the range $120 \text{ GeV} < M_H < 150 \text{ GeV}$, with 3 ab^{-1} . The sensitivity on the Higgs couplings to fermions also needs to be tested for heavier Higgs bosons. Beyond the $H \rightarrow WW$ threshold, the branching fractions $H \rightarrow f\bar{f}$ fall rapidly with increasing M_H values. $e^+e^- \rightarrow \nu\bar{\nu}H \rightarrow b\bar{b}$ at $\sqrt{s} \geq 1 \text{ TeV}$ offers a favourable signal-to-background ratio to probe g_{Hbb} for these intermediate-mass Higgs bosons. The $H^0 \rightarrow b\bar{b}$ decay can be measured for masses up to about 240 GeV and the accuracies are summarised in Table 1.

Table 1: *Signal significance and relative accuracy for the determination of the b Yukawa coupling for different values of the M_H mass at $\sqrt{s}=3$ TeV.*

M_H (GeV)	S/\sqrt{B}	$\delta g_{Hbb} / g_{Hbb}$
180	40.5	0.016
200	25.0	0.025
220	18.0	0.034

Table 2: *Relative accuracy for the determination of the triple Higgs coupling g_{HHH} for different values of the M_H mass at $\sqrt{s}=3$ TeV, assuming unpolarised beams.*

M_H (GeV)	Counting	Fit
120	± 0.131 (stat)	± 0.093 (stat)
180	± 0.191 (stat)	± 0.115 (stat)

Another fundamental test of the Higgs sector with a light Higgs boson, which significantly benefits from multi-TeV data, is the study of the Higgs self-couplings and the reconstruction of the Higgs potential. The triple Higgs coupling g_{HHH} can be accessed at a TeV-class LC in the double Higgs production processes $e^+e^- \rightarrow HHZ$ [4]. This measurement is made difficult by the tiny production cross section and by the dilution due to diagrams leading to double Higgs production, but not sensitive to the triple Higgs vertex. A LC operating at $\sqrt{s} = 500$ GeV can measure the HHZ production cross section to about 15% accuracy if the Higgs boson mass is 120 GeV, corresponding to a fractional accuracy of 23% on g_{HHH} [5]. Improvements can be obtained by performing the analysis at multi-TeV energies, through the process $e^+e^- \rightarrow HH\nu\bar{\nu}$ and by introducing observables sensitive to the presence of the triple Higgs vertex (see Table 2) [6]. On the contrary, the quartic Higgs coupling remains elusive, due to the smallness of the relevant triple Higgs production cross sections.

Precision electro-weak data indicate that the Higgs boson must be lighter than about 195 GeV. However, this limit can be evaded if New Physics exists to cancel the effect of the heavy Higgs boson mass. In these scenarios, it is interesting to search for an heavier boson through the ZZ fusion process $e^+e^- \rightarrow H^0 e^+e^- \rightarrow X e^+e^-$, at high energies. Similarly to the associate HZ production in the Higgsstrahlung process at lower energies, this channel allows a model-independent search of Higgs boson, through the tag of the two forward electrons and the reconstruction

of their recoil mass [7]. This analysis needs to identify electrons, and measure their energy and direction down to $\simeq 100$ mrad, close to bulk of the $\gamma\gamma \rightarrow$ hadrons and pair backgrounds, making it a challenge for the forward tracking and calorimetric response of the detector. Preliminary results show that a clean Higgs signal can be extracted at $\sqrt{s}=3$ TeV for $M_H \leq 900$ GeV.

3 Testing New Physics in the Higgs Sector

If heavy Higgs bosons exist above pair-production threshold, they are accessible at the LC through the $e^+e^- \rightarrow H^0 A^0 \rightarrow b\bar{b}b\bar{b}, t\bar{t}t\bar{t}$ and $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}t\bar{b}$ processes, resulting in very distinctive, yet challenging, multi-jet final states with multiple b -quark jets, which must be efficiently identified and reconstructed. The

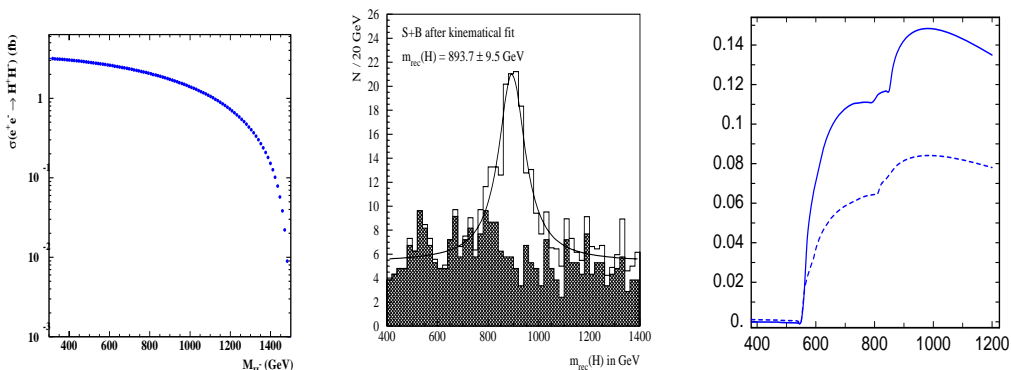


Figure 3: *Charged Higgs analysis at CLIC: $e^+e^- \rightarrow H^+H^-$ production cross section for $\sqrt{s}=3$ TeV as function of the charged Higgs mass (left). Signal reconstructed in the $H^+ \rightarrow t\bar{b}$ decay mode with the irreducible background overlaid (centre). Magnitude of the CP asymmetry $|\delta^{CP}|$ estimated as function of the charged Higgs mass (right).*

sizeable production cross sections provides sensitivity for masses up to 1 TeV and beyond for all values of $\tan \beta$, thus extending the LHC reach. A detailed analysis has been performed for the reconstruction of $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}t\bar{b}$ with $M_H=880$ GeV, corresponding to the CMSSM benchmark point J of reference [9], by identification of the $Wb\bar{b}Wbb$ final state, applying a mass constrained fit [8]. The irreducible SM $e^+e^- \rightarrow t\bar{b}t\bar{b}$ background and the overlay of accelerator-induced $\gamma\gamma \rightarrow$ hadrons events have been included. By reconstructing either both H^\pm s, or only one, the

analysis can be optimised in terms of efficiency and resolution for mass measurement, or for an unbiased study of H^\pm decays, respectively. Fractional accuracies of 1% on the heavy boson mass and of 5-10% on the product of production cross section and tb decay branching fraction are expected, with $\mathcal{L}=3 \text{ ab}^{-1}$ at $\sqrt{s} = 3 \text{ TeV}$.

Extensions of the SM may introduce new sources of CP violation, through additional physical phases whose effects can be searched for in the Higgs sector. Supersymmetric one-loop contributions can lead to differences in the decay rates of $H^+ \rightarrow t\bar{b}$ and $H^- \rightarrow \bar{t}b$, in the MSSM with complex parameters [10]. This CP asymmetry is expressed as: $|\delta^{CP}| = \frac{|\Gamma(H^- \rightarrow b\bar{t}) - \Gamma(H^+ \rightarrow t\bar{b})|}{\Gamma(H^- \rightarrow b\bar{t}) + \Gamma(H^+ \rightarrow t\bar{b})}$ and it can amount to up to $\simeq 15\%$ as shown in Figure 3. The leading contributions, from loops with \tilde{t} , \tilde{b} and \tilde{g} , δ^{CP} , are sensitive to the masses of these sparticles. With the expected statistics of $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}\bar{t}b$ at $\sqrt{s}=3 \text{ TeV}$ and assuming realistic charge tagging performances, a 3σ effect would be observed with $\mathcal{L}=5 \text{ ab}^{-1}$, for an asymmetry $|\delta^{CP}|=0.10$.

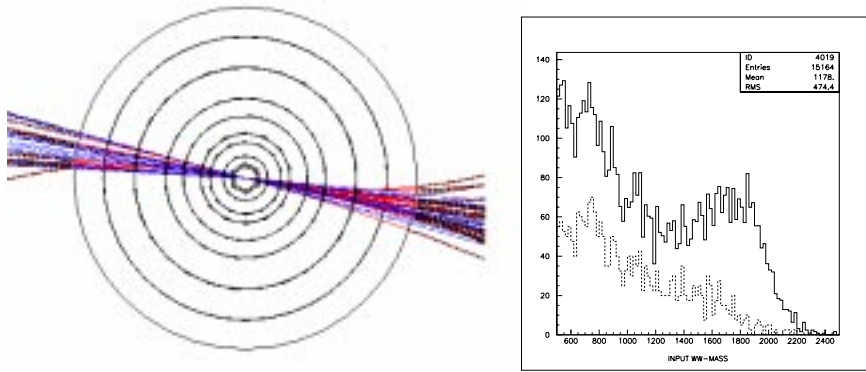


Figure 4: *Left: Display of a $e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$ event at 3 TeV reconstructed in a multi-layered Si Tracker. Right: Distribution of the reconstructed WW mass in a SSB model with a 2 TeV resonance. The background is overlaid.*

4 EWSB without the Higgs Boson

If the breaking of the electro-weak symmetry is not due to the Higgs mechanism, then the $e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$ and $Z^0Z^0\nu\bar{\nu}$ processes may reveal new dynamics of gauge boson interactions [11]. In fact when no elementary Higgs boson exists with

$M_H \leq 700$ GeV, we expect W^\pm and Z^0 bosons to develop strong interactions at a scale $\simeq 1$ TeV. The experimental signatures are represented both by deviations of the $e^+e^- \rightarrow W_L W_L \nu\nu$ cross section from its SM expectation and also by the possible formation of vector resonances at masses beyond 1 TeV (see Figure 4). Clean final states can be reconstructed using $W \rightarrow q\bar{q}'$ and the resonant components identified also when accounting for backgrounds and detector response [12].

5 Conclusions

A Multi-TeV e^+e^- LC, such as CLIC, has the potential to complete the study of the Higgs boson and to investigate an extended Higgs sector over a wide range of model parameters. Preserving the LC signature properties of clean events, with well defined kinematics, at a Multi-TeV LC will require a substantial effort of machine parameter optimisation, detector design and data analysis techniques. However, exploratory studies, accounting for realistic experimental conditions, confirm that CLIC will perform precision measurements and push its sensitivity up to the kinematical limits. While the main motivation for experimentation at a Multi-TeV LC arise from the

Table 3: Comparison of expected accuracies on Higgs couplings at CLIC and at the VLHC hadron colliders [13]

\sqrt{s} $\int \mathcal{L}$	CLIC 3 TeV 5 ab ⁻¹	VLHC-I 40 TeV 300 fb ⁻¹	VLHC-II 200 TeV 300 fb ⁻¹
$\delta g_{Htt}/g_{Htt}$	0.05-0.10 (?)	0.05-0.10	0.01-0.02
$\delta g_{Hbb}/g_{Hbb}$	0.01-0.03	-	-
$\delta g_{H\mu\mu}/g_{H\mu\mu}$	0.03-0.10	0.15-0.25	0.10-0.13
$\delta g_{HHH}/g_{HHH}$	0.07-0.09	???	0.10-0.30 (?)
g_{HHHH}	$\neq 0$ (?)	-	-

search of new phenomena, its role in studying the Higgs sector will also be crucial in completing the mapping of the H^0 Boson profile, studying heavy Higgs bosons in extended scenarios or explore otherwise the origin of symmetry breaking, if no elementary Higgs boson is observed. In this way, the CLIC multi-TeV LC project ensures a continue competitive e^+e^- physics program through two generation of projects and of physics questions.

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