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Charged and neutral minimal supersymmetric standard model Higgs boson decays and measurement of tan β at the compact linear collider

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Abstract. The minimal supersymmetric extension of the standard model (MSSM) predicts the existence of new charged and neutral Higgs bosons. The pair creation of these new particles at the multi-TeV e^+e^- compact linear collider (CLIC), followed by decays into standard model particles, were simulated along with the corresponding background. High-energy beam–beam effects such as ISR, beamstrahlung and hadronic background were included. We have investigated the possibility of using the ratio between the number of events found in various decay channels to determine the MSSM parameter tan β and we have derived the corresponding statistical error from the uncertainties on the measured cross-sections and Higgs boson masses.

Keywords. Minimal supersymmetric standard model; heavy Higgs bosons; compact linear collider.

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1. Introduction

In the standard model (SM), one doublet of scalar Higgs fields is needed to break the electroweak gauge symmetry. On the other hand, in several extensions of the SM, and in particular supersymmetry, the Higgs sector may consist of at least two isodoublets of scalar fields. The theoretical framework of this study is the minimal supersymmetric extension of the standard model (MSSM), where the symmetry breaking through two complex Higgs doublets leads to five physical states. Two of them are charged (H^+, H^-) and, among the three neutral Higgs bosons, two are CP-even states, h^0 and H^0, and one is CP-odd, A^0. At tree level, the MSSM Higgs sector is entirely determined with only two independent parameters, generally taken as the mass m_A and the ratio of the two vacuum expectation values tan β. In this paper, we consider the production of charged and neutral Higgs bosons at the compact linear collider (CLIC) [1], through $e^+e^- \rightarrow H^+H^-$ and $e^+e^- \rightarrow A^0H^0$. These two processes were already analysed separately in previous studies [2,3].

Here, we consider all hadronic decays of the charged and neutral Higgs bosons, either via a pair of third generation quarks or via final states with one or two τ-leptons decaying into hadrons. We present a combined sensitivity study of the two processes at CLIC, with an updated description of the beam–beam effects and of the various background processes. In addition, we estimate the accuracy with which various cascade decays of H^+H^- and A^0H^0 can be measured, and we discuss the derivation of $\tan\beta$ from these measurements.

2. Discovery limits for charged and neutral MSSM Higgs bosons at CLIC

In e^+e^- collisions, charged and neutral Higgs bosons can be produced in pairs via an intermediate photon or Z boson. At CLIC, prior to the initial state radiation of photons (ISR), one must take into account several high-energy beam–beam effects, which lead in particular to a long low-energy tail in the center-of-mass energy spectrum via emission of beamstrahlung photons at the interaction point. In turn, high-energy collisions between the beamstrahlung photons may lead to the production of additional hadrons. With the beam parameters considered for this study [4], the nominal center-of-mass energy is 3 TeV, the luminosity is 6.5×10^{34} cm^{-2} s^{-1}, the average energy loss of a beam particle due to beamstrahlung is 16%, and one expects 0.73 hadronic events per bunch crossing (we integrate the hadronic background over 75 bunch crossings, i.e. 20 ns). After the generation of A^0H^0 and H^+H^- pairs with PYTHIA, a fast detector simulation is performed with SIMDET [6] using its default parametrizations for CLIC. The b- and τ-tagging efficiencies are both set to 70% and are implemented by hand in the reconstruction procedure.

2.1 *Estimation of the SM backgrounds*

The most significant SM background processes for the pair production and hadronic decays of MSSM charged and neutral Higgs bosons are those which lead to genuine $bbbb$, $tttt$, $bb\tau\tau$, $tt\tau\tau$, $tbtb$ and $tb\tau\nu_\tau$ final states. MadGraph and MadEvent [7] were used to generate the SM background processes and to calculate the associated cross-sections (a separate Monte-Carlo program was written to include the energy spectrum of the incoming electrons and positrons). Then, the quark fragmentation and the inclusion of final state radiation (FSR) effects are performed using the relevant PYTHIA subroutines, prior to fast detector simulation and event reconstruction with SIMDET.

2.2 *Charged Higgs boson discovery contour*

In order to reconstruct $e^+e^- \to H^+H^- \to tbtb$ events, which can occur for all values of $\tan\beta$, we proceed as follows. First, the presence of two W bosons decaying hadronically is tested and t quarks are reconstructed from a W candidate paired with one of the four b-tagged jets. After assignment of the t candidates and the remaining b jets to their correct H^+H^- pair, a mass constrained kinematical fit is applied. Some cuts on $m_{\rm rec}(tt)$ and $m_{\rm rec}(bb)$ allow to further reduce the SM background. As for $e^+e^- \to H^+H^- \to tb\tau\nu_\tau$, which has a significant branching ratio for the large values of $\tan\beta$ only, we first search for one charged Higgs boson decaying into tb. Then, since a full reconstruction of the other charged Higgs boson is not possible due to the presence of missing transverse energy in the final state, we reconstruct its transverse mass $m_{\rm T}$ instead. In that case, the dominant background is $e^+e^- \to tb\tau\nu_\tau$, which mostly arises from the pair production of top quarks, where one of them decays through $t \to bW \to b\tau\nu_\tau$. However, it is efficiently reduced by appropriate cuts, in particular on the missing transverse energy and $m_{\rm T}$. The left-hand side plot of figure 1 shows how the CLIC discovery limit varies with $\tan\beta$ for $H^+H^- \to tbtb$, $H^+H^- \to tb\tau\nu_\tau$ and the combination of these two processes. The discovery limit for charged Higgs bosons at CLIC lies between 1.22 TeV and 1.25 TeV.

2.3 *Neutral Higgs boson discovery contour*

After the discovery of heavy charged Higgs bosons at CLIC, one should explore the neutral Higgs sector. For this purpose, we focus on the three cascade decays leading to t and/or b quarks in the final state. One major challenge in the Higgs sector is to reduce not only the SM background, but also the background arising from $e^+e^- \to H^+H^-$ events, for which the production cross-section is about 2.5 times larger than for $e^+e^- \to A^0H^0$. For small values of $\tan\beta$, both A^0 and H^0 mainly decay into a tt pair and, after reduction of all backgrounds, one expects a CLIC discovery limit of 0.97 TeV. At large $\tan\beta$, the search for $A^0H^0 \to bbbb$ events yields a higher discovery limit, namely 1.30 TeV. Finally, for the intermediate values of $\tan\beta$, some $e^+e^- \to A^0H^0$ events lead to $ttbb$ final states, just like most of the $e^+e^- \to H^+H^-$ events. However, in order to reconstruct the neutral Higgs bosons, one pairs two t candidates on the one hand and two b-tagged jets on the other hand, while two tb pairs are searched for when reconstructing the charged Higgs bosons. At $\tan\beta \simeq 7.6$, where the fraction of A^0H^0 pairs decaying into $ttbb$ final states is the largest, the discovery limit is 0.89 TeV. The CLIC discovery contour associated to these three cascade decays of the A^0H^0 pairs is shown in the right-hand side plot of figure 1.

3. Estimation of the signal rates and measurement of $\tan\beta$

The decay widths of the MSSM charged and neutral Higgs bosons depend directly on $\tan\beta$ [8], and so do the number of observed events for each cascade decay. In order to minimize the effect of luminosity and cross-section uncertainties for $\tan\beta$ determination, we consider the ratio between two decay widths (i.e. between two signal rates of the same Higgs boson pair). The statistical uncertainty on m_A was derived from a χ^2-analysis. Since it usually remains smaller than 1%, it does not significantly affect the $\tan\beta$ determination. Figure 2 shows the expected positive

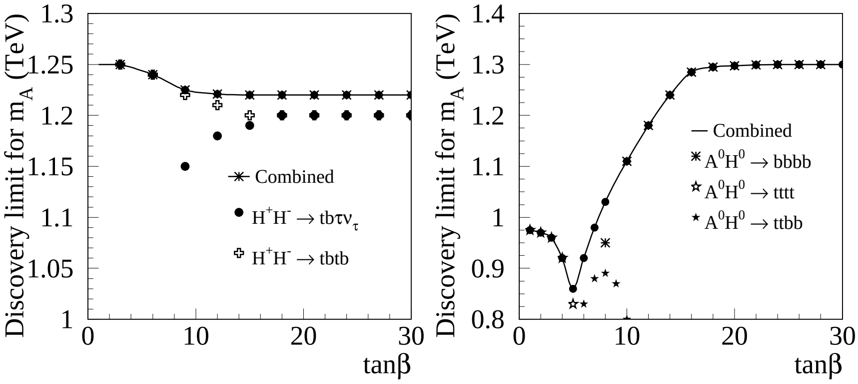

Figure 1. Discovery contours of charged and neutral Higgs bosons at CLIC, with an integrated luminosity of 3000 fb^{-1}: for a discovery, one requires the signal S to be at least ten events and it must exceed five statistical fluctuations of the background B.

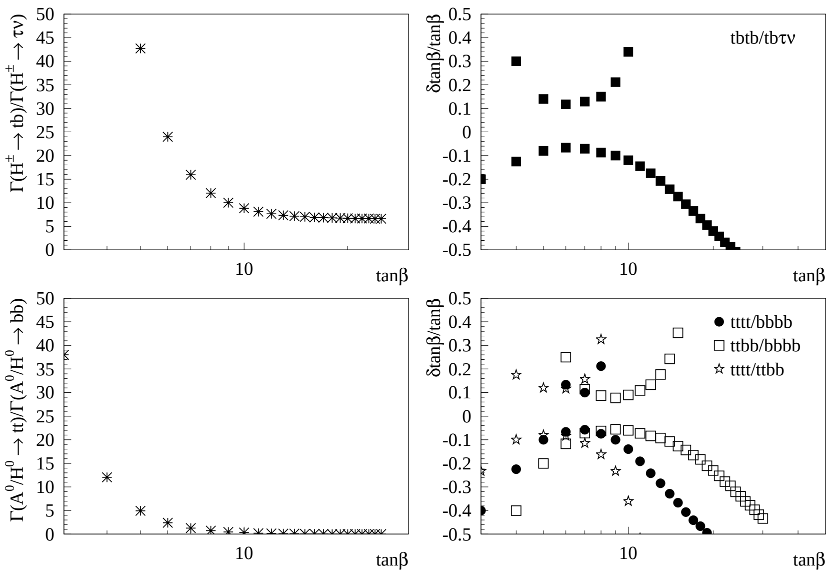

Figure 2. Variation with $\tan\beta$ of the expected statistical error on $\tan\beta$ when deriving this parameter from the ratio between various signal rates, for $m_A = 700$ GeV and an integrated luminosity of 3000 fb^{-1}.

and negative relative uncertainties on $\tan\beta$. We neglect the relative error on the luminosity, and so the signal rate uncertainty is $\sqrt{S+B}/S$.

The statistical errors on $\tan\beta$ are always smallest for values of $\tan\beta$ in the 5–8 region. For other $\tan\beta$ values, the relative error on the ratio of the signal rates is much larger, either because one of the cascade decays has a vanishing cross-section, or because of the asymptotic behaviour of the ratio between the signal rates (especially at large $\tan\beta$).

4. Conclusion

The discovery limit for MSSM charged and neutral Higgs bosons at CLIC lies beyond 1 TeV and, in contrast to the LHC, does not significantly depend on $\tan\beta$. In addition, by comparing the signal rates of different cascade decays, one may be able to measure $\tan\beta$ with a good accuracy in the intermediate region, which is not accessible through standard decays of the MSSM Higgs bosons at the LHC.

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