Loop Induced Higgs Boson Pair Production

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Abstract

We discuss the loop induced production of Higgs boson pairs at high–energy e^+e^- colliders, both in the Standard Model and in its minimal supersymmetric extension. The cross sections are rather small, but these processes could be visible with high-enough luminosities and if longitudinal polarization is available.

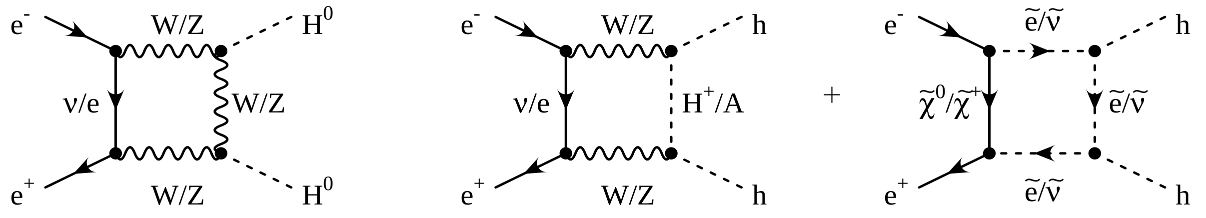
1. Introduction

If the genuine supersymmetric particles were too heavy to be kinematically accessible in collider experiments, the only way to distinguish between the Standard Model (SM) and the lightest Higgs boson of its minimal extension (MSSM) in the decoupling limit [where all the other MSSM Higgs bosons are heavy, and the lightest Higgs boson h has exactly the same properties [1] as the SM Higgs boson except that its mass is restricted to be smaller than $M_h \lesssim 140$ GeV], is to search for loop induced contributions of the supersymmetric particles, which could give rise to sizeable deviations from the predictions of the SM. Well known examples of this loop induced processes are the $\gamma\gamma$ widths of the Higgs particles [2] or the process $e^+e^- \to Z$+Higgs which in the MSSM receive extra contributions from supersymmetric gaugino and sfermion loops [3].

Another type of such discriminating processes is the pair production of Higgs bosons which will be analyzed here. In the SM, where it has been first discussed in Ref.[4], the process $e^+e^- \to H^0H^0$ is mediated only by W and Z boson loops, Fig.1a, while in the Minimal Supersymmetric extension, additional contributions to the corresponding process $e^+e^- \to hh$ will originate from chargino, neutralino, selectron and sneutrino loops, as well as loops built up by the associated A and $H^\pm$ bosons; Fig.1b. The cross sections for these two processes [as well as for the production of the heavy MSSM Higgs bosons, $e^+e^- \to HH, AA$ and hH] have been derived in [5] and here we will summarize the results.

2. SM Higgs Pair Production

In the SM, non–zero contributions to the process $e^+e^- \to H^0H^0$ can only come from one–loop diagrams, in the limit of vanishing electron mass. Among these, the diagrams involving the one–loop He^+e^- vertex [because $m_e \simeq 0$] and those with γ and Z boson s–channel exchanges [because of CP invariance] give zero–contribution; additional contributions from vertex diagrams involving the quartic WWH^0H^0/ZZH^0H^0 couplings are proportional m_e and also negligible. The only contribution to Higgs pair production in the SM will therefore come from W and Z box diagrams, Fig.1a. The expressions of the cross sections, allowing for longitudinal polarization of the initial beams are given in [5].



(a) (b)

Fig. 1: Feynman diagrams contributing to the Higgs boson pair production process in e^+e^- collisions in the SM (a) and in the MSSM (b).

The cross sections are shown in Fig.2 as a function of the Higgs boson mass for two center–of–mass energies, $\sqrt{s} = 500$ GeV and 1.5 TeV. Except when approaching the $2M_H$ threshold [and the small dip near the WW threshold], the cross sections are practically constant for a given value of the c.m. energy, and amount to $\sigma \sim 0.2$ fb at $\sqrt{s} = 500$ GeV in the unpolarized case. The decrease of the cross sections with increasing center–of–mass energy is very mild: at $\sqrt{s} = 1.5$ TeV, the cross section is still at the level of $\sigma \sim 0.15$ fb for Higgs boson masses less than $M_H \lesssim 350$ GeV.

With left–handed polarized electrons, the cross section $e^-_L e^+ \to H^0H^0$ is larger by a factor of two, while for left–handed electrons and right–handed positrons, the cross section $e^-_L e^+_R \to H^0H^0$ is larger by a factor of four, compared to the unpolarized case. Therefore, the availability of longitudinal polarization of the initial beams is very important. With integrated luminosities of the order of $\int \mathcal{L} \sim 100$ fb^{-1} which are expected to be available for future high–energy linear colliders, one could expect a few hundred events in the course of a few years, if both initial beams can be longitudinally polarized.

For $M_H \lesssim 140$ GeV, the signal will mainly consist of four b quarks in the final state, $e^+e^- \to H^0H^0 \to b\bar{b}b\bar{b}$, since the dominant decay mode of the Higgs boson in this mass range is $H^0 \to b\bar{b}$. This calls for very efficient μ–vertex detectors to tag the b jets. Since these rare events will be searched for only after the discovery of the Higgs boson in the main production processes [5], M_H will be precisely known and the two mass constraints $m(b\bar{b}) = M_H$, together with the large number of final b quarks, give a reasonable hope to experimentally isolate the signals despite of the low rates. For $M_H \gtrsim 140$ GeV, since $H^0 \to W^+W^-$ and $H^0 \to ZZ$ will be the dominant decay modes of the Higgs boson, the signals will consist of four gauge bosons in the final state, $e^+e^- \to H^0H^0 \to VVVV$, leading to eight final fermions. These rather spectacular events should also help to experimentally isolate the signal.

3. MSSM Higgs Pair Production

For the pair production of the light CP–even Higgs boson of the MSSM, $e^+e^- \to hh$,

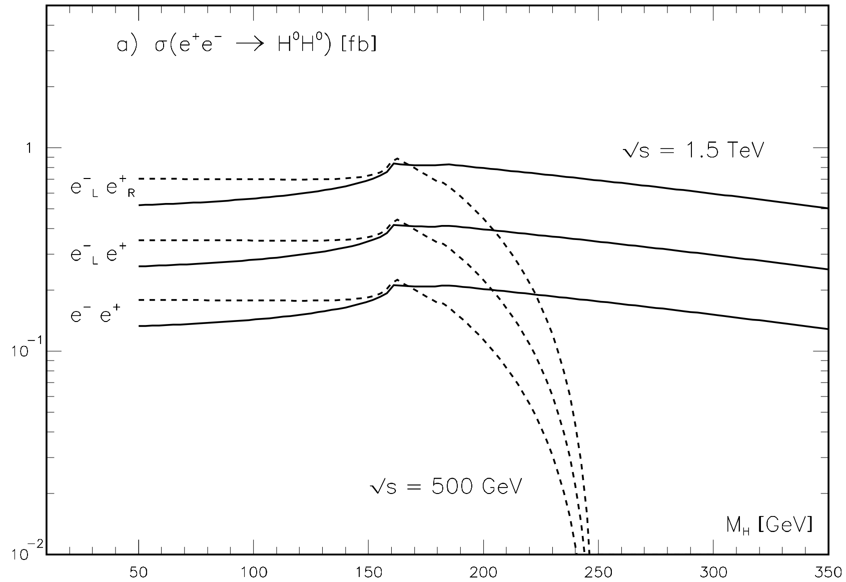
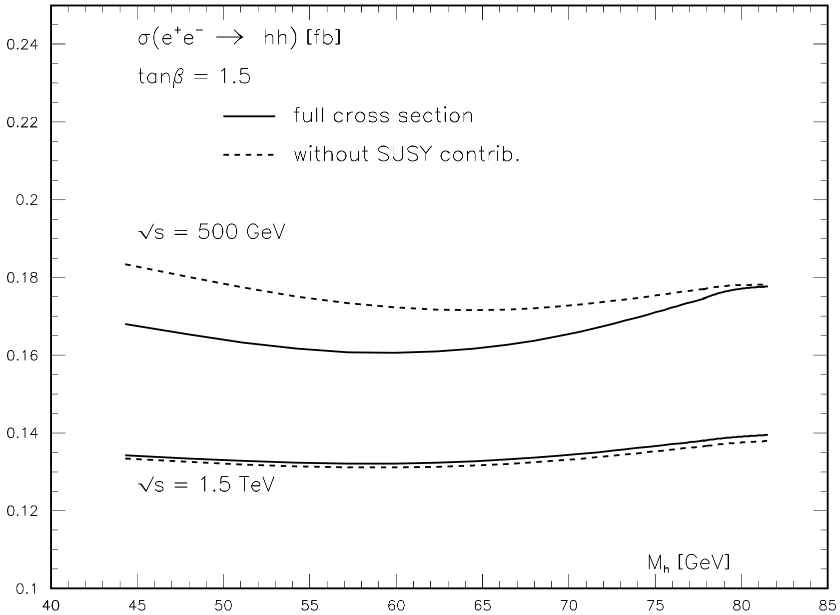


Fig. 2: The cross sections for, $e^+e^- \to H^0H^0$, as a function of M_H for $\sqrt{s} = 500$ GeV [dashed lines] and $\sqrt{s} = 1.5$ TeV [solid lines]. The lower, middle and upper curves correspond to the cross sections with unpolarized, e^-_L and $e^+_R e^-_L$ beams respectively.

several additional diagrams will contribute to the process; Fig.1b. Besides the W and Z boson box diagrams, one has the box diagrams with the exchange of the pseudoscalar and the charged Higgs bosons, A and $H^\pm$ and the box diagrams built up by chargino/sneutrino and neutralino/selectron loops. The analytical expressions of the cross sections, allowing for longitudinal polarization of the initial beams are also given in [5].

In Fig.3, we show the cross section for the process $e^+e^- \to hh$ as a function of M_h for two c.m. energies $\sqrt{s} = 500$ GeV and 1.5 TeV and two values of $\tan\beta = 1.5$ and 50. The solid lines are for the full cross sections, while the dashed lines are for the cross sections without the SUSY contributions. To include the latter we have chosen the parameters $M_2 = -\mu = 150$ GeV, while the common slepton and squark masses are taken to be $M_L = 300$ GeV and $M_S = 500$ GeV; the parameter A_t and A_b are set to zero. Only the unpolarized cross sections are discussed: as mentioned previously, they are simply increased by a factor of 2(4) when the initial beam(s) are longitudinally polarized.

Let us first discuss the case where the supersymmetric contributions are not included, for small $\tan\beta$ the cross section is of the same order as the SM cross section and does not strongly depend on M_h especially at very high–energies. Although the WWh/Zhh couplings are suppressed by $\sin(\beta-\alpha)$ factors, the suppression is not very strong and the W/Z box contributions are not much smaller than in the SM; the diagrams where $A/H^\pm$ are exchanged will give compensating contributions since the $hAZ/hH^\pm W$ couplings are proportional to the complementary factor $\cos(\beta-\alpha)$. As in the SM case, the cross sections slightly decrease with increasing energy. For large $\tan\beta$ values, the factors sin / $\cos(\beta-\alpha)$ vary widely when M_h is varied. For small M_h, the factor $\sin(\beta-\alpha) \to 0$, and the



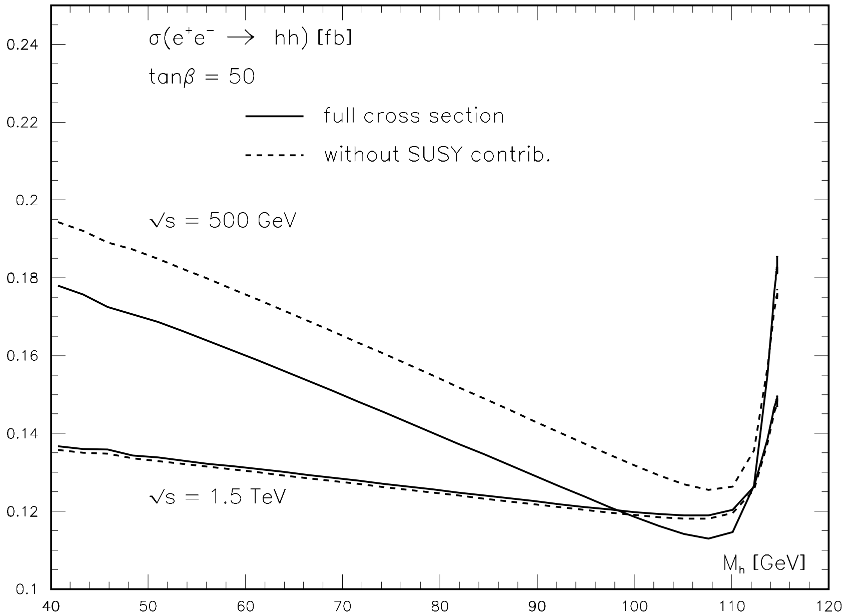


Fig. 3: The cross sections for $e^+e^- \to hh$ in the MSSM, as a function of M_h for $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1.5$ TeV and for $\tan\beta = 1.5$ and 50. The solid curves correspond to the full cross sections, while the dashed curves correspond to the cross sections without the SUSY contributions.

contribution of the diagrams with $A/H^{\pm}$ exchange dominates. The latter contribution decreases with increasing M_h [i.e. with decreasing $\cos(\beta-\alpha)$], until the decoupling limit is reached for $M_h \simeq 110$ GeV. In this case, the factor $\sin(\beta-\alpha) \to 1$ and the W/Z boson loops are not suppressed anymore; one then obtains the SM cross section.

The contributions of the chargino/selectron and neutralino/sneutrino loops lead to a destructive interference. At high–energies, the supersymmetric boxes practically do not contribute; but at low energies, and especially below the decoupling limit, the SUSY contributions can be of the order of $\sim 10\%$. We have scanned the SUSY parameter space, and the maximum contribution of the SUSY loops that we have found was about $\sim -15\%$. In the decoupling limit, the SUSY contributions are, at most, of the order of a few percent. Because of the rather low production rates, it will therefore be difficult to experimentally see this effect.

4. Summary

We have discussed the one–loop induced production of Higgs boson pairs at future high–energy e^+e^- colliders in the SM and the MSSM. In the SM, the unpolarized cross section is rather small, of the order 0.1–0.2 fb. The longitudinal polarization of both the e^- and e^+ beams will increase the cross section by a factor of 4. With integrated luminosities $\int \mathcal{L} \gtrsim 100$ fb^{-1} as expected to be the case for future high–energy linear colliders, one could expect a few hundred events in the course of a few years if longitudinal polarization is available. The final states are rather clean, giving a reasonable hope to isolate the signals experimentally. In the MSSM, additional contributions to the processes $e^+e^- \to hh$ come from chargino/ neutralino and slepton loops. For hh production, the contributions of the supersymmetric loops are in general rather small, being of the order of a few percent; the cross sections are therefore of the same order as in the SM. For the processes involving heavy Higgs bosons, the cross sections are even smaller than for $e^+e^- \to hh$, and the signals will be hard to be detected experimentally.

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