Single Heavy MSSM Higgs Production at e^+e^- Linear Collider

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(Dated:)

We briefly review the single heavy Higgs production at high energy e^+e^- linear collider, $\gamma\gamma$ collider and $e^-\gamma$ collider. We present the recent results for $e^+e^- \to W^\pm H^\mp$ in the Minimal Supersymmetric Standard Model and preliminary results for $e^+e^- \to \nu\bar{\nu}A^0$.

The measurement of the properties of the heavy Higgs bosons H^0, A^0 and $H^\pm$ of Minimal Supersymmetric Standard Model (MSSM) could tell us a lot about the MSSM parameters. The mass of the heavy Higgses are related to the overall scale m_{A^0} (CP-odd Higgs mass), with a distinctive mass relation between m_{A^0}, m_{H^0} and $m_{H^\pm}$ in MSSM. The heavy Higgs couplings to the fermions are sensitive to $\tan\beta$ (the ratio of the two Higgs vacuum expectation values) and Yukawa couplings, and its couplings to the sfermions are sensitive to the trilinear A-terms. Unlike the light CP-even Higgs h^0, whose couplings become increasingly insensitive to the MSSM parameters in the decoupling limit $(m_{A^0} \gg m_Z)$, the couplings of the heavy Higgs bosons are always sensitive to the MSSM parameters. Thus, measurements of the properties of the heavy MSSM Higgs bosons are very valuable, especially in the decoupling limit.

Discovery of the heavy Higgs bosons, however, poses a special challenge at future colliders, contrary to the case of the light CP-even Higgs h^0, when the discovery is almost certain at current and future collider experiments. Run II of the Fermilab Tevatron, now in progress, has a limited reach for the neutral heavy MSSM Higgs bosons H^0 and A^0 at small m_{A^0} and large $\tan\beta$. The charged Higgs boson $H^\pm$ can be discovered in top quark decays for $m_{H^\pm} \lesssim m_t$ and large $\tan\beta$ [1, 2]. The CERN Large Hadron Collider (LHC) has a much greater reach for heavy MSSM Higgs boson discovery at moderate to large values of $\tan\beta$ via the process of H^0 and A^0 decays to τ pairs [3, 4] and the charged MSSM Higgs boson $H^\pm$ mode: $gb \to tH^-$ with $H^- \to \tau\bar{\nu}$ [4, 5]. The absence of a Higgs boson discovery at the CERN LEP-2 experiments implies that $0.5 < \tan\beta < 2.4$ and $m_{A^0} < 91.9$ GeV are excluded at 95% confidence level [6]. This leaves a wedge-shaped region of parameter space at moderate $\tan\beta$ in which the heavy MSSM Higgs bosons could be missed at the LHC.

At a future high energy e^+e^- linear collider (LC), the heavy Higgs bosons will be produced in pairs, if it is kinematically allowed. The dominant production modes are $e^+e^- \to H^0A^0$ and $e^+e^- \to H^+H^-$. At large m_{A^0}, $m_{A^0} \simeq m_{H^0} \simeq m_{H^\pm}$ up to mass splittings of order m_Z^2/m_{A^0}, so that the pair-production modes are kinematically allowed only if $m_{A^0} \lesssim 0.5\sqrt{s}$. In particular, the pair-production modes are limited to $m_{A^0} \lesssim 250$ GeV ($m_{A^0} \lesssim 500$ GeV) at a LC with $\sqrt{s} = 500$ GeV ($\sqrt{s} = 1000$ GeV).

In this talk we consider the production of one of the heavy Higgs bosons in association

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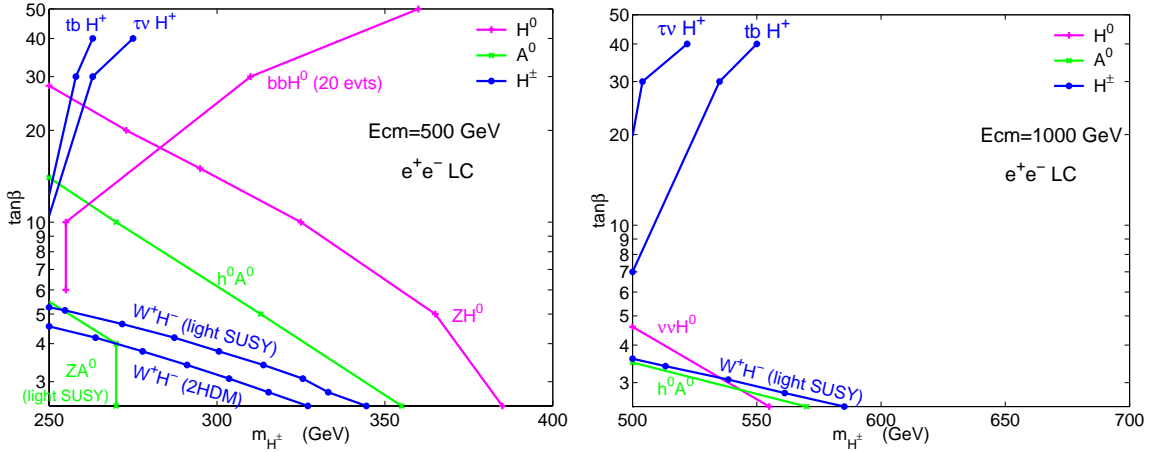[*]Electronic address: `shufang@theory.caltech.edu`

FIG. 1: Ten-event contours for single heavy Higgs boson production in unpolarized e^+e^- collisions for $\sqrt{s} = 500$ GeV (left), with 500 fb^{-1} of integrated luminosity and $\sqrt{s} = 1000$ GeV , with 1000 fb^{-1} of integrated luminosity (right). On the x-axis we plot the mass of the relevant heavy Higgs boson.

with lighter SM particles at the LC. While the cross sections for such production modes are typically very small, they offer the possibility of extending the reach of the LC to higher values of $m_{A^0, H^0, H^\pm} \gtrsim 0.5\sqrt{s}$. Single heavy Higgs boson production has been studied in the context of the MSSM or a general two Higgs doublet model (2HDM) in a number of processes at LC, $\gamma\gamma$ collider and $e^-\gamma$ collider. At a LC, the following final states have been considered:

(I) Tree-level processes suppressed by $\cos^2(\beta - \alpha)$, where α is the mixing angle that diagonalizes the CP-even neutral Higgs boson mass-squared matrix. Such processes includes the associated $h^0 A^0$ production $e^+e^- \to h^0 A^0$[7], Higgsstrahlung $e^+e^- \to ZH^0$[7], W and Z-boson fusion[8], $e^+e^- \to \nu\bar{\nu}H^0$; $e^+e^- \to e^+e^-H^0$. In the decoupling limit, $\cos^2(\beta - \alpha) \propto m_Z^4/m_{A^0}^4$, so these cross sections decrease rapidly as m_{A^0} increases.

(II) Production in association with pairs of third-generation fermions[9–12]: $e^+e^- \to b\bar{b}H^0$, $b\bar{b}A^0$, $\tau^-\bar{\nu}H^+$, and $\bar{t}bH^+$. The cross sections for the first three of these processes are strongly enhanced at large $\tan\beta$, and the fourth is enhanced at both large and small $\tan\beta$.

(III) Single heavy MSSM Higgs production modes that are zero at the tree level but arise at one loop: $e^+e^- \to ZA^0$[13, 14], $e^+e^- \to \gamma A^0$[13, 15, 16], $e^+e^- \to \nu\bar{\nu}A^0$[16–18] and $e^+e^- \to W^\pm H^\mp$[19–24].

Because detailed experimental studies of almost all of these processes are unavailable, we choose an optimistic standard of detectability to be 10 heavy Higgs boson production events in the LC data sample. We assume data samples of 500 fb^{-1} at $\sqrt{s} = 500$ GeV and 1000 fb^{-1} at $\sqrt{s} = 1000$ GeV. For neutral Higgs boson production, this 10-event standard corresponds to a cross section of 0.02 fb at $\sqrt{s} = 500$ GeV (0.01 fb at $\sqrt{s} = 1000$ GeV). For charged Higgs boson production, we add together the cross sections for H^+ and H^- production before applying the 10-event standard. In what follows we assume that the e^+ and e^- beams are unpolarized, and adapt the cross sections presented in the

literature accordingly. We consider only $\tan\beta$ values above the LEP lower bound of 2.4 [6] and heavy Higgs masses above $\sqrt{s}/2$. The comparison of various production modes in the reach of $m_H - \tan\beta$ plane is given in Fig. 1.

If the e^+e^- LC is converted into a photon collider through Compton backscattering of intense laser beams, the neutral heavy Higgs bosons H^0 and A^0 can be singly produced in the s-channel through their loop-induced couplings to photon pairs. This process appears to be very promising for detecting H^0 and A^0 with masses above $\sqrt{s}/2$ and moderate $\tan\beta$ values between 2.5 and 10 [25–27]. In particular, a recent realistic simulation of signal and backgrounds [25] showed that a 630 GeV e^+e^- LC running in $\gamma\gamma$ mode for three years would allow H^0, A^0 detection over a large fraction of the LHC wedge region (in which the heavy MSSM Higgs bosons would not be discovered at the LHC) for m_{A^0} up to the photon-photon energy limit of ~ 500 GeV. At a 1000 GeV LC, the mass reach is likely to be above 600 GeV [26].

The cross sections for production of $\tau^-\bar{\nu}H^+$ and $\bar{t}bH^+$ in $\gamma\gamma$ collisions [28] are expected to be larger than the corresponding cross sections in e^+e^- collisions at large $\tan\beta$. Production of W^+H^- in $\gamma\gamma$ collisions also occurs at the one-loop level[29], which is competitive with $e^+e^- \to W^+H^-$ in the MSSM for a TeV machine.

Finally, if the LC is run in $e^-\gamma$ mode, the process $e^-\gamma \to \nu H^-$ is possible. Unfortunately, with the typical expected $e^-\gamma$ luminosity of 100 fb^{-1}, the cross section for this process in the 2HDM is too small to be of interest [30]. This process could become promising in the MSSM if its cross section is enhanced by the contributions of light superpartners, or if the $e^-\gamma$ luminosity is increased.

Let us now focus on the two processes that we have studied: $e^+e^- \to W^\pm H^\mp$ and $e^+e^- \to \nu\bar{\nu}A^0$. The 2HDM contributions to $e^+e^- \to W^\pm H^\mp$ have been studied in [19], and we calculated the additional contributions from superparticles in MSSM. Details of the analysis can be found in [23]. Similar analysis has been done [22] and reported by O. Brein at this conference. There is no contribution at tree level due to the vanishing of γW^+H^- and ZW^+H^- couplings and the leading contribution appears at one-loop. Unlike the case of the non-supersymmetric 2HDM, in which the top/bottom quark loops give by far the largest contribution to the cross section, in the full MSSM the fermionic loops involving charginos/neutralinos and the bosonic loops involving stops/sbottoms also give contributions of similar size. Although the stop/sbottom loops are enhanced by the large $H^-\tilde{t}_R\tilde{b}_L^*$ coupling (which is proportional to the top quark Yukawa coupling), these diagrams are suppressed by higher powers of the superparticle masses than the fermionic loops.

Figures 2 show the dependence of the $e^+e^- \to W^+H^-$ cross section on the charged Higgs mass for $\tan\beta = 2.5$, $\sqrt{s} = 500$ GeV (left) and $\sqrt{s} = 1000$ GeV (right). Solid lines are the contributions from the non-SUSY 2HDM with the Higgs sector constrained by the MSSM mass and coupling relations. The dotted (dashed) lines show the cross sections in the full MSSM, including the contributions from all the superparticles, for $A_t = A_b = 0$ ($A_t = A_b = 200$ GeV). We compare the cross sections with 80% left-handed e^- polarization, no polarization, and 80% right-handed e^- polarization, which are denoted in each plot by the same type of lines, from top to bottom. Left-handed e^- polarization always gives a larger cross section. The additional SUSY contributions
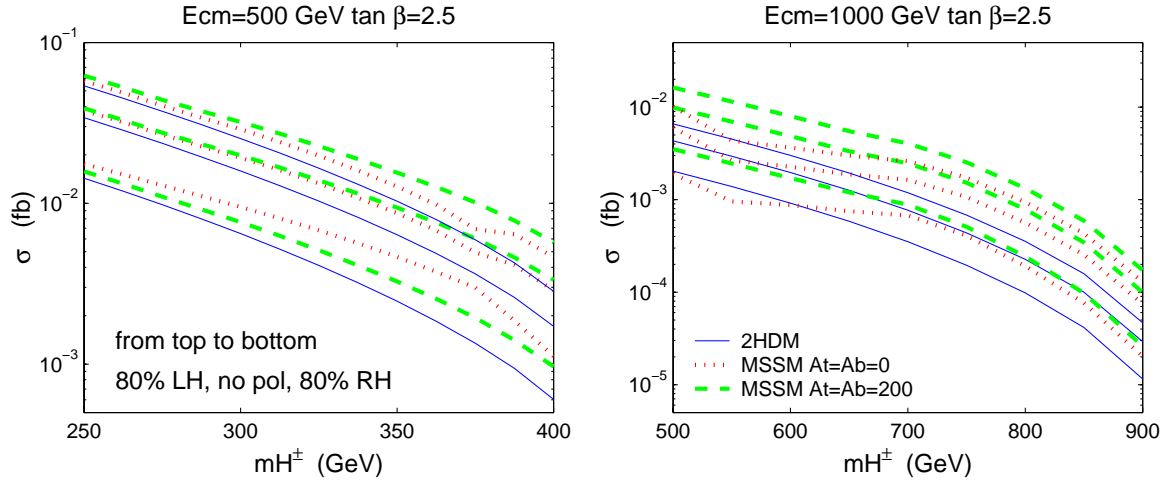
FIG. 2: The $e^+e^- \to W^+H^-$ cross section as a function of $m_{H^\pm}$ for $\tan\beta = 2.5$, at $\sqrt{s} = 500$ GeV (left) and 1000 GeV (right). The trilinear couplings are chosen as $A_t = A_b = 0$ (dotted lines) and 200 GeV (dashed lines). The rest of the SUSY parameters are chosen to be $M_{\mathrm{SUSY}} = 200$ GeV, $2M_1 = M_2 = 200$ GeV, and $\mu = 500$ GeV. The solid lines show the cross section in the non-SUSY 2HDM (with MSSM relations for the Higgs sector).
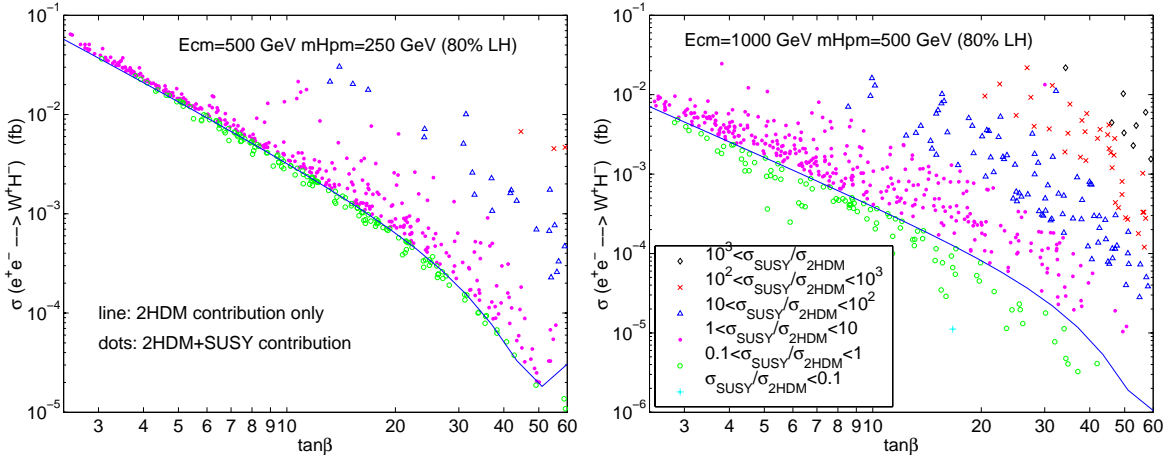

FIG. 3: MSSM cross section as a function of $\tan\beta$ for $\sqrt{s} = 500$ GeV and $m_{H^\pm} = 250$ GeV (left) and $\sqrt{s} = 1000$ GeV and $m_{H^\pm} = 500$ GeV (right). The different symbols show the enhancement of the MSSM cross section relative to the 2HDM. The solid line shows the 2HDM cross section.

generally enhance the cross section. The cross sections decline as $m_{H^\pm}$ increases; however, reasonable cross sections can be obtained for $m_{H^\pm} > \sqrt{s}/2$, especially for small $\tan\beta$.

In Fig. 3 we compare the cross section in the MSSM with that in the 2HDM as a function of $\tan\beta$, for $\sqrt{s} = 500$ and 1000 GeV. We fix $m_{H^\pm}$ to a single value, $m_{H^\pm} = \sqrt{s}/2$, in order to more clearly illustrate the effect of the MSSM contributions. The rest of the MSSM parameters are chosen randomly within 1 TeV, taking into account
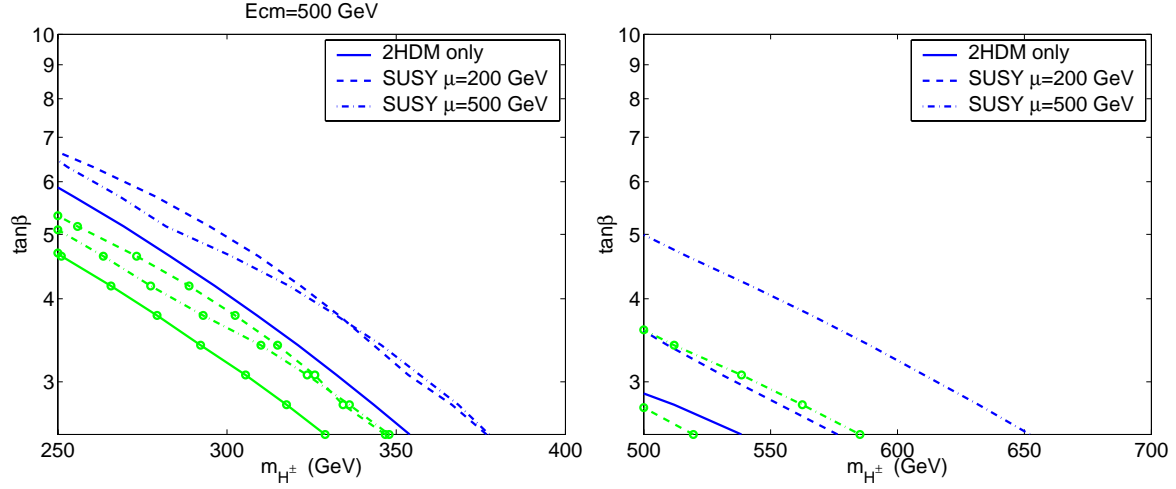
FIG. 4: Ten-event contours for $e^+e^- \to W^\pm H^\mp$ for $\sqrt{s} = 500$ GeV with 500 fb^{-1} (left) and $\sqrt{s} = 1000$ GeV with 1000 fb^{-1} (right). The SUSY parameters are chosen to be $M_{\text{SUSY}}^{tb} = 1000$ GeV for the top and bottom squarks, $M_{\text{SUSY}} = 200$ GeV for the rest of the squarks and the sleptons, $2M_1 = M_2 = 200$ GeV, $M_{\tilde{g}} = 800$ GeV, $A_t = A_b = 2M_{\text{SUSY}}^{tb}$, and $\mu = 200$ GeV (dashed lines) and 500 GeV (dot-dashed lines). Solid lines show the 2HDM result. Light (green) lines show the unpolarized cross section and dark (blue) lines show the cross section with an 80% left-polarized e^- beam.

the experimental lower limit on the superparticle searches. Details of the analysis can be found at [24]. While the 2HDM cross section falls rapidly with increasing $\tan\beta$, the MSSM contributions depend much more weakly on $\tan\beta$, especially at $\sqrt{s} = 1000$ GeV, where the maximum cross section is almost independent of $\tan\beta$. This implies that the largest relative cross section enhancements due to MSSM contributions occur at large $\tan\beta$, as shown by the different symbols in Fig. 3. At a 500 GeV machine, an enhancement of more than a factor of 10 can occur for $\tan\beta > 10$, while a factor of 100 can occur for $\tan\beta > 40$. At a 1000 GeV machine, the enhancements can be even larger. At low $\tan\beta$, cross section enhancements of roughly 50% are typical.

The maximum 10-event reaches in $m_{H^\pm}$ and $\tan\beta$ is shown in Fig. 4. In all cases considered, the MSSM contributions increase the 10-event reach over that in the 2HDM: the reach in $m_{H^\pm}$ is increased by about 20 GeV at $\sqrt{s} = 500$ GeV, and by about 40 GeV or more at $\sqrt{s} = 1000$ GeV. At $\sqrt{s} = 1000$ GeV, increasing the μ parameter from 200 to 500 GeV with other SUSY parameters held fixed increases the reach by about 70 GeV in $m_{H^\pm}$, and by about 1 unit in $\tan\beta$. At $\sqrt{s} = 500$ GeV, the μ dependence is much weaker. For either value of μ, using an 80% left-polarized e^- beam increases the reach compared to using unpolarized beams by about 30 GeV in $m_{H^\pm}$ at $\sqrt{s} = 500$ GeV and by twice that at $\sqrt{s} = 1000$ GeV; at either center-of-mass energy the reach in $\tan\beta$ increases by about 1 unit.

Comparing to the other single charged Higgs production modes at LC collider, we see that while $e^+e^- \to \tau\bar{\nu}H^+$ and $e^+e^- \to \bar{t}bH^+$ is promising at large $\tan\beta$, W^+H^- production is the only channel in e^+e^- collisions analyzed to date that yields ≥ 10
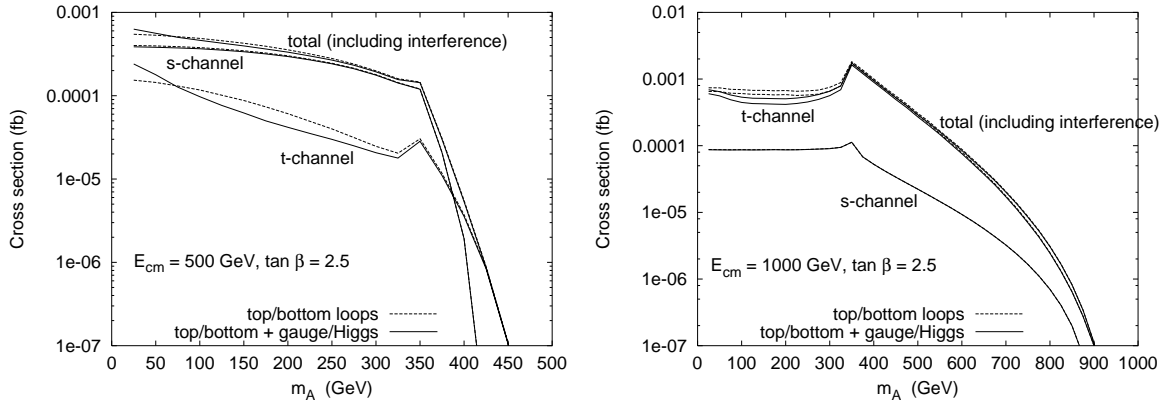
FIG. 5: Cross section of $e^+e^- \to \nu\bar{\nu}A^0$ for $\tan\beta = 2.5$, $\sqrt{s} = 500$ GeV (left) and $\sqrt{s} = 1000$ GeV (right) with s-channel, t-channel and $s+t$ contributions, respectively. Solid lines show the total contributions from top/bottom quarks, Higgs bosons and gauge bosons, while the dashed lines show the top/bottom quark contribution only. Non-supersymmetric 2HDM contributions are included and MSSM mass relation for the Higgs sector is imposed.

events containing charged Higgs bosons at low $\tan\beta$ values for $m_{H^\pm} \geq \sqrt{s}/2$.

For the single CP-odd Higgs production mode $e^+e^- \to \nu\bar{\nu}A^0$, the leading contribution from top and bottom quark correction to the WWA^0 vertex has been reported in [16]. Details of the full 2HDM contributions can be found in [17]. Part of the SUSY contributions including CP violation phases has been done in [18] and reported by A. Arhrib at this conference. In addition to the t-channel W fusion contributions, there are diagrams of s-channel Z boson exchange. For on-shell intermediate Z, such process is the same as $e^+e^- \to ZA^0$ with Z decaying into neutrinos, which has been calculated for 2HDM and full MSSM in [13, 14] and the production cross section is found to be small. Moreover, Z resonance portion can be removed experimentally by the recoil reconstruction. However, for off-shell intermediate Z^*, such processes have the same $\nu\bar{\nu}A^0$ final state, which interfere with the t-channel diagrams and have to be included in our calculation. Fig. 5 show the cross section for 2HDM contributions, for 500 GeV and TeV LC. The cross section is too small to be observed for $m_{A^0} > \sqrt{s}/2$ [16].

In summary, we can see that the single heavy Higgs production could be important at LC when the heavy Higgs mass is larger than half of the center of mass energy. The production modes $e^+e^- \to ZH^0, h^0A^0, W^\pm H^\mp$ and $b\bar{b}H^0$ at 500 GeV machine and $e^+e^- \to W^\pm H^\mp, h^0A^0, \nu\bar{\nu}H^0$ and $t\bar{b}H^-$ at TeV machine has reasonable 10-event reach in $m_{H^\pm} - \tan\beta$ plane. At low $\tan\beta$, SUSY contributions from light superparticles and using left-polarized electron beam could enhance the cross section for $e^+e^- \to W^\pm H^\mp$. While for $e^+e^- \to \nu\bar{\nu}A^0$, the non-supersymmetric 2HDM contribution seems to be too small to be interesting. A few additional processes that have not yet been computed may be promising for single heavy Higgs boson production at an e^+e^- collider, for example, the weak boson fusion process $e^+e^- \to \bar{\nu}e^-H^+$ at $\sqrt{s} \sim 1000$ GeV. Also, to have a realistic analysis of the reach for various single heavy Higgs production modes, the background study is important and necessary.

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