IISc-CHEP/15/04
CERN-TH/2004-250
WUE-ITP-2004-037
hep-ph/0412193

Probing the CP-violating light neutral Higgs in the charged Higgs decay at the LHC

Dilip Kumar Ghosh[a], R.M. Godbole[b] and D.P. Roy[c,d]

[a] Institut für Theoretische Physik und Astrophysik,
Universität Würzburg, D-97074, Würzburg, Germany.

[b]Centre for High Energy Physics, Indian Institute of Science, Bangalore, 560 012, India.

[c]Department of Theoretical Physics, Tata Institute of Fundamental Research,
Homi Bhabha Road, 400 005 Mumbai, India.

[d] Theory Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland.

Abstract

The CP-violating MSSM allows existence of a light neutral Higgs boson ($M_{H_1} \lesssim 50$ GeV) in the CPX scenario in the low $\tan\beta(\lesssim 5)$ region, which could have escaped the LEP searches due to a strongly suppressed H_1ZZ coupling. This parameter space corresponds to a relatively light H^+ ($M_{H^+} < M_t$) , which is predicted to decay dominantly into the WH_1 channel. Thus one expects to see a striking $t\bar{t}$ signal at the LHC, where one of the top quarks decays into the $bb\bar{b}W$ channel, via $t \to bH^{\pm}, H^{\pm} \to WH_1$ and $H_1 \to b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $bb\bar{b}W$ invariant mass peaks is expected to make this signal practically free of the SM background. Our parton level Monte Carlo simulation yields upto 5000 events, for $\mathcal{L} = 30$ fb^{-1}, over the parameter space of interest, after taking into account the b-tagging efficiency for three or more b-tagged jets.

Introduction

The search for Higgs bosons and study of their properties is one of the main goals of physics studies at the Tevatron upgrade (Run 2) and the upcoming Large Hadron Collider (LHC). The precision measurements with Electro-Weak (EW) data indicate the existence of a light Higgs boson ($M_h <$ 246 GeV at 95% C.L.) whereas direct searches rule out the case $M_h < 114.4$ GeV [1] [2]. Naturalness arguments along with the indication of a light Higgs state suggest that Supersymmetry (SUSY) is a likely candidate for new physics Beyond the Standard Model (BSM). Even in the SUSY case, a mass for the lightest neutral Higgs smaller than ~ 90 GeV is ruled out [3] if the SUSY parameters as well as the SUSY breaking parameters are real and CP is conserved. However, in presence of CP-violation in the Higgs sector, the lower limit can get diluted due to a reduction in the H_1ZZ coupling [4].

CP violation, initially observed only in the K^0–$\bar{K}^0$ system, is one feature of the Standard Model (SM) that still defies clear theoretical understanding. It is in fact one of the necessary ingredients for generating the observed excess of baryons over antibaryons in the Universe [5, 6]. The amount of CP violation present in the quark sector described very satisfactorily in the CKM picture, is however, too small to generate a baryon asymmetry of the observed level of $N_B/N_\gamma \simeq 6.1 \times 10^{-10}$ [7]. New sources of CP violation *beyond* the SM are therefore a necessity [8].

The Minimal Supersymmetric Standard Model(MSSM), in principle, admits a large number of phases which can not be rotated away by a simple redefinition of the fields and hence provide new sources of CP-violation. A large number of these phases involving the first two generations of sparticles are strongly constrained by the electric dipole moments of the electron and neutron (EDMs)[9, 10] and mercury atoms [11]. However, these constraints are model-dependent. It has been demonstrated that cancellations among different diagrams allow certain combinations of these phases to be large in a general MSSM. Furthermore, if the sfermions of the first two generations are sufficiently heavy, above the 1 TeV range, the EDM constraints on the phase of the higgsino mass parameter $\mu = |\mu| e^{i\phi_\mu}$, in general constrained to $\phi_\mu \lesssim 10^{-2}$, get weaker; the sfermions of the third generation can still be light.

In a version of MSSM where the Higgsino mass term μ, the gaugino masses M_i and the trilinear couplings A_f are complex the Higgs sector, even with CP-conserving tree level scalar potential, has loop induced CP-violation [12, 13, 14, 15, 16, 17]. The LEP data can allow a much lighter Higgs with a mass $\lesssim$ 40–50 GeV [18, 19, 3] due to a reduction in the H_1ZZ coupling in the CPX scenario [13], which corresponds to a certain choice of the CP-violating SUSY parameters, chosen so as to showcase the CP-violation in the Higgs sector in this case. In a large portion of this region all the usual search channels of such a light Higgs at the LHC are also not expected to be viable [18] due to the simultaneous reduction in the coupling of the Higgs to a vector boson pair as well as the $t\bar{t}$ pair. As a matter of fact presence of CP-violation in Supersymmetry and hence the Higgs sector, can affect the Higgs decays as well as their production rates at the colliders substantially and has been a subject of many investigations [20, 18].

It is interesting to note that in the same region of the parameter space where the coupling of the lightest mass eigenstate H_1 to a pair of Z-bosons: the H_1ZZ coupling, is suppressed the $H^+W^-H_1$ coupling is enhanced because these two sets of couplings satisfy a sum-rule. The strong suppression of the H_1ZZ coupling also means that the H_1 is dominated by the pseudo-scalar component in this region and hence implies a light charged Higgs boson ($M_{H^+} < M_t$). These two features suggest that $H^\pm \rightarrow$

$H_1W^\pm$ is the dominant decay mode of the $H^\pm$ over the parameter space of interest. This motivated us to study the possibility of probing at the LHC, such a light Higgs scenario in CP violating MSSM Higgs model through the process $pp \to t\bar{t}X \to (bW^\pm)(bH^\mp)X \to (b\ell\nu)(bH_1W)X \to (b\ell\nu)(bb\bar{b})(jj)+X$ along with the hadronic and leptonic decays of the two W's interchanged. Thus the signal will consist of three or more b-tagged jets and two untagged jets along with a hard lepton and missing p_T. Similar studies have been done in the context of charged Higgs search in NMSSM model [21]. In the next section we present the notation and some details of the calculation, followed by presentation of the results in the section after that and we end by making some concluding remarks.

Notation and Formalism

As already mentioned in the introduction the non-vanishing phases of μ and/or the trilinear scalar couplings $A_{t,b}$ can induce explicit CP-violation in the Higgs sector via loop corrections. Thus the Higgs potential, even though invariant under CP-transformation at tree level, receives CP-violating contributions on loop corrections. Due to large Yukawa interactions of the Higgs bosons to top and bottom squarks, $\mathrm{Arg}(\mu)$ and $\mathrm{Arg}(A_t), \mathrm{Arg}(A_b)$ are the relevant CP phases. These generate contributions to the off diagonal block $\mathcal{M}^2_{\mathrm{SP}}$ in the 3×3 neutral Higgs boson mass-squared matrix $\mathcal{M}^2_{ij}$, mixing the scalar (S) and the pseudo-scalar (P) Higgs fields [12, 13, 14, 15, 16, 17]. These may be given approximately by [13]:

$$\mathcal{M}^2_{\mathrm{SP}} \approx \mathcal{O}\left(\frac{M_t^4 \mid \mu \mid\mid A_t \mid}{v^2 32\pi^2 M^2_{\mathrm{SUSY}}}\right)\sin\Phi_{\mathrm{CP}} \times \left[6, \frac{\mid A_t\mid^2}{M^2_{\mathrm{SUSY}}}, \frac{\mid \mu \mid^2}{\tan\beta M^2_{\mathrm{SUSY}}}, \frac{\sin 2\Phi_{\mathrm{CP}} \mid A_t \mid\mid \mu \mid}{\sin\Phi_{\mathrm{CP}} M^2_{\mathrm{SUSY}}}\right] \quad (1)$$

where $\Phi_{\mathrm{CP}} = \mathrm{Arg}(A_t\mu)$, $v = 246$ GeV. From the above expression it is clear that sizeable scalar-pseudo-scalar mixing is possible for large CP violating phase Φ_{CP}, $\mid \mu \mid$ and $\mid A_t \mid$ ($> M_{\mathrm{SUSY}}$). The mass scale M_{SUSY} is defined by $(m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2})/2$. After diagonalizing the 3×3 symmetric Higgs mass-squared matrix $\mathcal{M}^2_{ij}$ by an orthogonal matrix O, the physical mass eigenstates H_1, H_2 and H_3 (in ascending order of mass) are states of indefinite CP parity. In this case $M_{H^\pm}$ is more appropriate parameter for description of the MSSM Higgs-sector in place of the M_A used usually in the CP-conserving case.

As a result of the CP-mixing in the neutral Higgs sector, their couplings to the gauge bosons and the fermions get modified. For the purpose of illustration we provide the couplings of H_iVV, H_iH_jZ and $H_iH^\pm W^\mp$ below. More details can be found in Ref. [13].

$$\mathcal{L}_{H_iVV} = gM_W \sum_{i=1}^{3} g_{H_iVV}\, [H_i W^+_\mu W^{-,\mu} + \frac{1}{2c_W^2} H_i Z_\mu Z^\mu] \quad (2)$$

$$\mathcal{L}_{H_iH_jZ} = \frac{g}{2c_W} \sum_{j>i=1}^{3} g_{H_iH_jZ}\, (H_i \overleftrightarrow{\partial}_\mu H_j) Z^\mu \quad (3)$$

$$\mathcal{L}_{HH^\mp W^\pm} = \frac{g}{2c_W} \sum_{i=1}^{3} g_{H_iH^-W^+}\, (H_i \overleftrightarrow{\partial}_\mu H^-) W^{+,\mu} \quad (4)$$

where, g_{H_iVV}, $g_{H_iH_jZ}$ and $g_{H_iH^+W^-}$ are Higgs gauge boson couplings normalized to the standard model value and can be written as,

$$g_{H_iVV} = O_{1i}\cos\beta + O_{2i}\sin\beta, \quad (5)$$

$$g_{H_iH_jZ} = O_{3i}(\cos\beta O_{2j} - \sin\beta O_{1j}) - (i \leftrightarrow j) \quad (6)$$

$$g_{H_iH^+W^-} = O_{2i}\cos\beta - O_{1i}\sin\beta + iO_{3i} \quad (7)$$

These couplings obey the following sum rules:

$$\sum_{i=1}^{3} g^2_{H_iVV} = 1, \quad (8)$$

$$g^2_{H_iVV} + \mid g_{H_iH^+W^-} \mid^2 = 1, \quad (9)$$

$$g_{H_kVV} = \epsilon_{ijk} g_{H_iH_jZ} \quad (10)$$

From the above sum rules one can see that if two of the g_{H_iZZ} are known, then the whole set of couplings of the neutral Higgs boson to the gauge bosons are determined. It is interesting to see from Eq. (9) that in the presence of large CP-violating effects, with large scalar-pseudo-scalar mixing, the suppressed H_1VV coupling means an enhanced $H_1H^+W^-$ coupling. This enhancement will play a significant role in our analysis. Equally important is the correlation between the mass of the charged Higgs $M_{H^\pm}$ and that of the pseudo-scalar state that exists in the MSSM. A suppressed H_1VV coupling implies a light pseudo-scalar state, which in turn implies a light charged Higgs, with $M_{H^+} < M_t$.

As has been discussed before, the quantity $\sin\Phi_{\rm CP}/M^2_{\rm SUSY}$ needs to be large to get significant CP-mixing in the Higgs sector. The CP-*violating benchmark scenario* (CPX) has been suggested [13] to showcase this CP-violation and provides a suitable set of parameters which can be used to study the phenomenology of the CP-violating MSSM Higgs sector:

$$\widetilde{M}_Q = \widetilde{M}_t = \widetilde{M}_b = M_{\rm SUSY} \quad (11)$$

$$\mu = 4M_{\rm SUSY}, |A_t| = |A_b| = 2M_{\rm SUSY}, \quad (12)$$

$$\mathrm{Arg}(A_t) = \mathrm{Arg}(A_b) \quad (13)$$

In the next section we first summarize the current constraints from LEP on the MSSM parameter space and hence on the Higgs masses in the CPX scenario and then discuss the phenomenology of the charged and the neutral Higgs search in the region of the low M_{H_1} window that is still allowed by LEP [18, 19, 3] for the case of CP-violating MSSM.

Results and discussion

Recently the OPAL Collaboration [19] reported their results for the Higgs boson searches in the CP-violating MSSM Higgs sector using the parameters defined in the CPX scenario as mentioned above and found that for certain values of phases and M_{H^+}, the lower mass limit on the neutral Higgs is diluted, at times vanishing completely. This results in windows in the $\tan\beta$–M_{H^+} plane which are

$\tan\beta$	2	2.2	2.5	3.0
$\mathrm{Br}(H^+ \to H_1 W^+)(\%)$	> 90 (83.5)	> 90(80.32)	> 90 (73.85)	> 90 (63.95)
$\mathrm{Br}(t \to bH^+)(\%)$	4.0 – 4.2	4.9 – 5.1	4.8 – 5.11	4.0 – 4.3
M_{H^+} (GeV)	$<$ 133.6 (135.1)	$<$ 122.7 (124.3)	$<$ 113.8 (115.9)	$<$ 106.6(109.7)
M_{H_1} (GeV)	$<$ 50.97 (54.58)	$<$ 39.0 (43.75)	$<$ 27.97 (35.44)	$<$ 14.28 (29.21)

Table 1: Range of values for BR ($H^+ \to H_1 W^+$) and BR ($t \to bH^+$) for different values of $\tan\beta$ corresponding to the LEP allowed window in the CPX scenario, for the common phase $\Phi_{\rm CP} = 60^\circ$, along with the corresponding range for the H_1 and H^+ masses. The quantities in the bracket in each column give the values at the edge of the kinematic region where the decay $H^+ \to H_1 W^+$ is allowed.

still allowed by the LEP data. The LEP bounds are essentially evaded in this window as the lightest state is largely a pseudo-scalar with highly suppressed coupling to the ZZ pair. There exist two programs; CPSuperH [22] and FeynHiggs 2.0 [23] to calculate the masses and mixing in the Higgs sector in the CP-violating case. Due to the different approximations made in the two calculations as well as differences in the inclusion of different higher order terms, at least in the CPX scenario, the two programs give somewhat different results and the experimentalists use the lower prediction of the two for the expected cross-sections to get the most conservative constraints. The constraints also depend sensitively on the mass of the top quark used in the calculation [3]. The preliminary results from a combined analysis of all the LEP results [3], provide exclusion regions in the $M_{H_1} - \tan\beta$ plane for different values of the CP-violating phases, for the following values of the parameters:

$$\mathrm{Arg}A_t = \mathrm{Arg}A_b = \mathrm{Arg}M_{\tilde{g}} = \Phi_{\rm CP}, \tag{14}$$

$$M_{\rm SUSY} = 0.5 \text{ TeV}, M_{\tilde{g}} = 1 \text{ TeV}, \tag{15}$$

$$M_{\tilde{B}} = M_{\tilde{W}} = 0.2 \text{ TeV}, \tag{16}$$

$$\Phi_{\rm CP} = 0^\circ, 30^\circ, 60^\circ, 90^\circ. \tag{17}$$

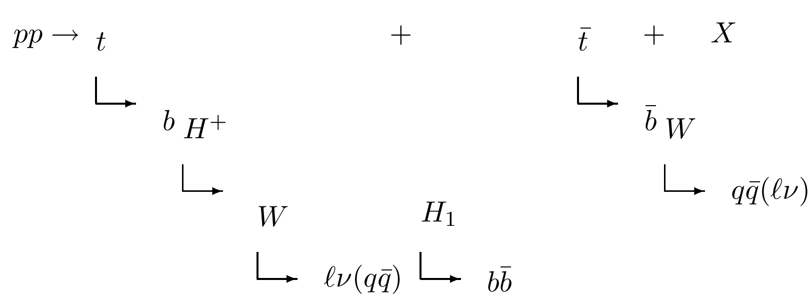
Combining the results of Higgs searches from ALEPH, DELPHI, L3 and OPAL, the authors in Ref.[18] have also provided exclusion regions in the M_{H_1}–$\tan\beta$ plane as well as M_{H^+}–$\tan\beta$ plane for the same set of parameters. While the exact exclusion regions differ somewhat in the three analyses [18, 19, 3] they all show that for phases $\Phi_{\rm CP} = 90^\circ$ and 60° LEP cannot exclude the presence of a light Higgs boson at low $\tan\beta$, mainly because of the suppressed $H_1 ZZ$ coupling. The analysis of Ref. [18] further shows that in the same region the $H_1 t\bar{t}$ coupling is suppressed as well. Thus this particular region in the parameter space can not be probed either at the Tevatron where the associated production W/ZH_1 mode is the most promising one; neither can this be probed at the LHC as the reduced $t\bar{t}H_1$ coupling suppresses the inclusive production mode and the associated production modes W/ZH_1 and $t\bar{t}H_1$, are suppressed as well. This region of Ref. [18] corresponds to $\tan\beta \sim 3.5 - 5, M_{H^+} \sim 125 - 140$

$\tan\beta$	3.6	4	4.6	5
$\text{Br}(H^+ \to H_1 W^+)(\%)$	$> 90(87.45)$	$> 90(57.65)$	> 90 (50.95)	$> 90(46.57)$
$\text{Br}(t \to bH^+)(\%)$	~ 0.7	$.7 - 1.1$	$0.9 - 1.3$	$1.0 - 1.3$
M_{H^+} (GeV)	< 148.5 (149.9)	< 139 (145.8)	< 130.1 (137.5)	$< 126.2(134)$
M_{H_1} (GeV)	< 60.62 (63.56)	< 49.51 (65.4)	< 36.62 (57.01)	$< 29.78(53.49)$

Table 2: Same as in Table 1 but for the value of common phase $\Phi_{\rm CP} = 90°$.

GeV, $M_{H_1} \lesssim 50$ GeV and $\tan\beta \sim 2-3, M_{H^+} \sim 105-130$ GeV, $M_{H_1} \lesssim 40$ GeV, for $\Phi_{CP} = 90°$ and $60°$ respectively. The code CPSuperH and $M_t = 175$ GeV has been used by them to calculate the couplings and the masses of the Higgs-bosons.

As mentioned already, in the same region of the parameter space where H_1ZZ coupling is suppressed, the $H^+W^-H_1$ coupling is enhanced because these two sets of couplings satisfy a sum-rule as shown in Eq.(9). Further, in the MSSM a light pseudo-scalar implies a light charged Higgs, lighter than the top quark. Tables 1 and 2 show the behaviour of the M_{H^+}, M_{H_1} and the BR $(H^+ \to H_1W^+)$, for values of $\tan\beta$ corresponding to the above mentioned window in the $\tan\beta$–M_{H_1} plane, of Ref. [18]. It is to be noted here that indeed the $H^\pm$ is light (lighter than the top) over the entire range, making its production in t decay possible. Further, the $H^\pm$ decays dominantly into H_1W, with a branching ratio larger than 47% over the entire range where the decay is kinematically allowed, which covers practically the entire parameter range of interest; viz. $M_{H_1} < 50(40)$ GeV for $\Phi_{\rm CP} = 90°(60°)$. It can be also seen from both the tables that the $\text{BR}(H^\pm \to H_1W)$ is larger than 90% over most of the parameter space of interest. So not only that H^+ can be produced abundantly in the t decay giving rise to a possible production channel of H_1 through the decay $H^\pm \to H_1W^\pm$, but this decay mode will be the only decay channel to see this light $(M_{H^\pm} < M_t)$ $H^\pm$. The traditional decay mode of $H^\pm \to \tau\nu$ is suppressed by over an order of magnitude and thus will no longer be viable. Thus the process



will allow a probe of both the light H_1 **and** a light $H^\pm$ in this parameter window in the CP-violating

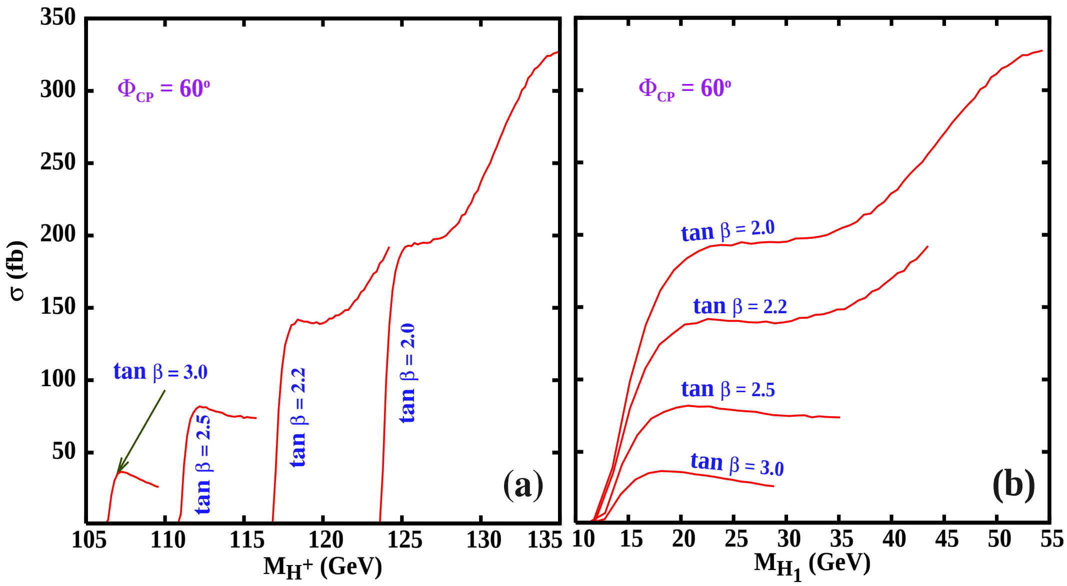


Figure 1: Variation of the expected cross-section with M_{H^+} (a) and M_{H_1} (b) for four values of $\tan\beta = 2, 2.2, 2.5$ and 3. The CP-violating phase $\Phi_{\rm CP}$ is 60°. See text for the values of the remaining MSSM parameters. The cross-sections are obtained after applying the mass window cuts as mentioned in the text. These numbers should be multiplied by ~ 0.5 to get the signal cross-section as explained in the text.

MSSM in the CPX scenario. The signal will consist of three or more b-tagged and two un-tagged jets along with a hard lepton and missing p_T. For a b tagging efficiency e, the suppression factor SF due to the demand of three or more tagged b jets is given by

$$SF = 4e^3(1-e) + e^4.$$

Assuming $e = 0.5$ we get 5/16 for this suppression factor.

In our parton-level Monte Carlo analysis we employ following strategies to identify final state jets and leptons:

1. $\mid \eta \mid < 2.5$ for all jets and leptons, where η denotes pseudo-rapidity,
2. p_T of the hardest three jets to be higher than 30 GeV,
3. p_T of all the other jets, lepton, as well as the missing p_T to be larger than 20 GeV,
4. A minimum separation of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4.$ between the lepton and jets as well as each pair of jets. If ΔR between two partons is less than 0.4 we merge them into a single jet.

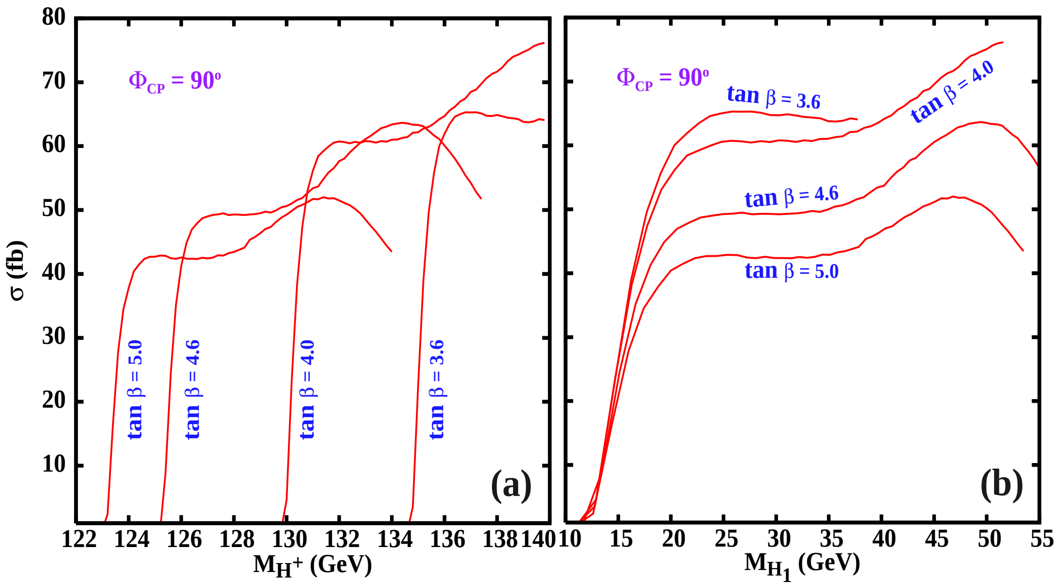


Figure 2: Variation of the cross-section with M_{H^+} (a) and M_{H_1} (b) for four values of $\tan\beta = 3.6, 4, 4.6$ and 5. The CP-violating phase $\Phi_{\rm CP}$ is 90°. The other MSSM parameters are same as in Figure 1. These numbers should be multiplied by ~ 0.5 to get the signal cross-section as explained in the text. The same mass window cuts as mentioned in Figure 1 have been used in this case.

5. We impose Gaussian smearing on energies, with $\Delta E/E = 0.6/\sqrt{E}$ for jets.

6. We demand three or more tagged b-jets in the final state assuming a b-tagging efficiency of 50%.

7. The missing p_T is obtained by vector summation of the transverse momenta of the lepton and the jets after Gaussian smearing.

Below we outline the mass reconstruction strategy we employ. The leptonically decaying W in the above decay chain is reconstructed from the lepton momentum p_l and the missing transverse momentum p_T within a quadratic ambiguity using the constraint that the invariant mass of the $\ell\nu$ pair $m_{\ell\nu} = M_W$. In case of complex solutions the imaginary part is discarded and the two solutions coalesce. The hadronically decaying W is reconstructed from that pair of untagged jets, whose invariant mass is closest to M_W. One top is then reconstructed from one of the reconstructed W's and one of the remaining jets chosen such that the invariant mass $m_{W jet}$ is closest to M_t. Similarly the H_1 is then reconstructed from a pair from among the remaining jets, such that the invariant mass of the pair is closest to M_{H_1}. Then the $H^{\pm}$ is reconstructed from this H_1 and the remaining reconstructed W. In case of a quadratic ambiguity for the latter, the one giving invariant mass closer to $M_{H^{\pm}}$ is chosen.

Although the masses of the H_1 and $H^\pm$ may not be known, one can select the right combinations on the basis of a clustering algorithm. Finally the second top is reconstructed by combining this $H^\pm$ with the remaining jet.The signal cross-sections shown in Figs 1 and 2 are obtained using mass window cuts of $M_W \pm 15$ GeV, $M_t \pm 25$ GeV, $M_{H_1} \pm 15$ GeV and $M_{H^\pm} \pm 25$ GeV on the reconstructed W, t, H_1 and $H^\pm$ masses. Only the M_W and M_t mass window cuts are retained in Figures 3 and 4, showing the distributions in the reconstructed H_1 and H^+ masses.

In Figure 1 we show the variation of the cross-section with M_{H^+} (a) and M_{H_1} (b) for the CP-violating phase $\Phi_{\rm CP} = 60^\circ$ while the choice of other MSSM parameters are defined through Eqs.(11-16). We have used the CPSuperH program [22] with $M_t = 175$ GeV, to calculate the masses and the couplings of the Higgs-bosons in the CPX scenario. We have used the CTEQ 4L parametrisation of the parton density distributions and the QCD scale chosen is $2M_t$. The numbers presented in the figure contain neither the suppression factor due to b–tagging efficiency nor the K–factor(1.3–1.4) due to the NLO corrections to the $t\bar{t}$ cross-sections. Taking into account both, the numbers in the figure should be multiplied by $5/16 \times 1.3$–$1.4 \sim 0.5$ to get the signal cross-section at the LHC. It may also be stated that the expected cross-sections at the Tevatron are far too small for this process to be useful there.

As can be seen from the figure the signal cross-section decreases with increase in $\tan\beta$. This can be explained by the fact that $H^+ \to H_1 W^+$ as well as $t \to bH^+$ branching ratio decreases with the increase in $\tan\beta$ for a fixed H_1 mass. In this scenario, the largest signal cross-section (~ 160 fb) can be obtained for $\tan\beta = 2$ and $M_{H^+} = 135$ GeV, which corresponds to $M_{H_1} = 54.3$ GeV. The cross-section is ~ 125 fb for $M_{H^+} = 130$ GeV corresponding to $M_{H_1} = 40$ GeV. In principle there exists a physics background to the signal arising from the decay $H^\pm \to W^\pm \bar{b}b$, via the virtual tb channel, but over this particular range of $M_{H^\pm}$ and $\tan\beta$ the corresponding branching ratio is negligibly small [24].

In Figure 2, we show variation of the signal cross-section with M_{H^+} (a) and M_{H_1} (b) for the CP-violating phase $\Phi_{\rm CP} = 90^\circ$ keeping other MSSM parameters fixed as in Figure 1. Apart from the choice of the phase, the main difference from Figure 1 is in the values of $\tan\beta$. In this case we have somewhat larger values of $\tan\beta$, namely $3.6, 4., 4.6$ and $5.$, corresponding to the light Higgs window of Ref. [18] for $\Phi_{\rm CP} = 90^\circ$. The largest signal cross-section in this case is ~ 38 fb. Note that in both cases the signal cross-section is $\gtrsim 20$ fb for $M_{H_1} \gtrsim 15$ GeV.

In Figure 3 (a) we show the three-dimensional plot for the correlation between $m_{b\bar{b}}$ and $m_{b\bar{b}W}$ invariant mass distribution for $\Phi_{CP} = 60^\circ, \tan\beta = 2$ and $M_{H^+} = 125.6$ GeV. The light Higgs mass corresponding to this set of input parameter is 24.8 GeV. It is clear from Figure 3 that there is simultaneous clustering in the $m_{b\bar{b}}$ distribution around $\simeq M_{H_1}$ and in the $m_{b\bar{b}W}$ distribution around $M_{H^\pm}$. Figure 3(b) shows the same, in terms of cross-section distribution in $b\bar{b}$, $b\bar{b}W$ and $b\bar{b}Wb$ invariant masses for the signal. The clustering feature can be used to distinguish the signal over the standard model background. As a matter of fact we estimated the background to the signal coming from the QCD production of $t\bar{t}b\bar{b}$. Even though the starting LO cross-section for $t\bar{t}b\bar{b}$ production is as high as ~ 8.5 pb, once all the cuts (including the mass window cuts) are applied we are left with a contribution to the signal type events of less than 0.5 fb. The major reduction is brought about by requiring that the invariant mass of the $bbbW$ be within 25 GeV of M_t[1]. This makes it very clear that the detectability

[1]Preliminary studies in ATLAS collaboration presented at Les Houches Workshop [25] also find that this background

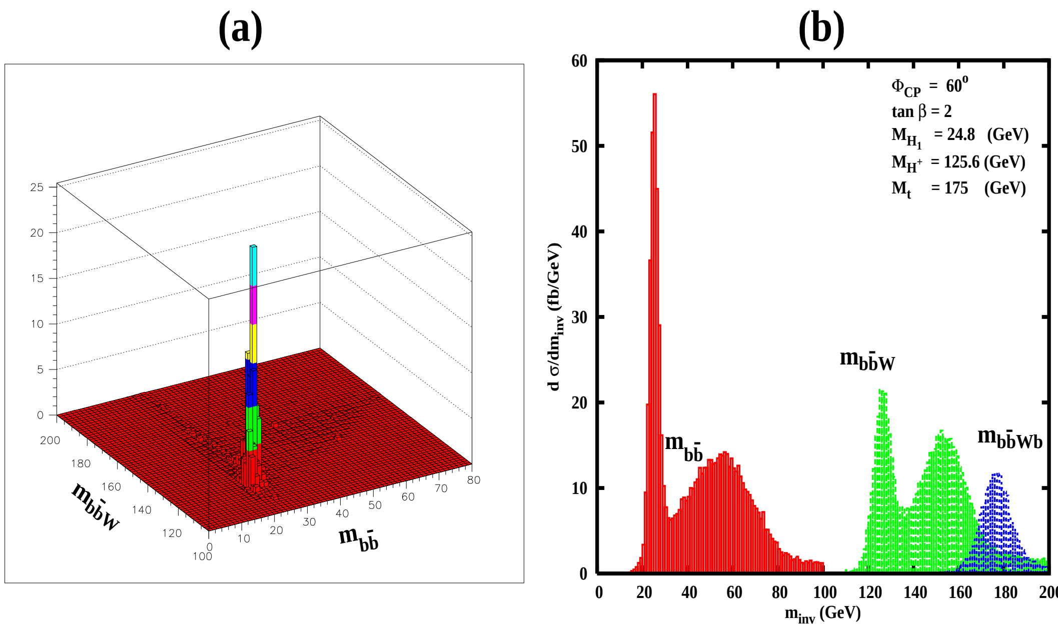


Figure 3: Clustering of the $b\bar{b}, b\bar{b}W$ and $b\bar{b}bW$ invariant masses: (a) three-dimensional plot for the correlation between $m_{b\bar{b}}$ and $m_{b\bar{b}W}$ invariant mass distribution; (b) $m_{b\bar{b}}, m_{b\bar{b}W}$ and $m_{b\bar{b}Wb} = M_t$ invariant mass distributions for $\Phi_{\rm CP} = 60^\circ$. M_t, M_W mass window cuts have been applied as explained in the text. The other MSSM parameters are $\tan\beta = 2, M_{H^+} = 125.6$ GeV and the corresponding light Higgs mass is $M_{H_1} = 24.8$ GeV.

of the signal is controlled primarily by the signal size. It is also clear from Figures 1 and 2 that indeed the signal size is healthy over the regions of interest in the parameter space. Thus using this process one can cover the region of the parameter space in $\not{C}\not{P}$ MSSM, in the $\tan\beta - M_{H_1}$ plane which can not be excluded by LEP-2 and where the Tevatron and the LHC have no reach via the usual channels. Note further that this process would be the only channel of discovery for the charged Higgs-boson $H^\pm$ as well in this scenario, as the traditional decay mode of $H^\pm \to \nu\tau$ is suppressed by over an order of magnitude.

Figure 4(a) shows the three-dimensional plot for the correlation between $m_{b\bar{b}}$ and $m_{b\bar{b}W}$ invariant mass distribution for $\Phi_{CP} = 90^\circ$, and somewhat higher values of $\tan\beta$ and $M_{H^+}, \tan\beta = 5$ and $M_{H^+} = 133$ GeV. The light Higgs mass corresponding to this set of input parameter is 51 GeV. The Figure 4(b) shows the same, in terms of cross-section distribution in $b\bar{b}$, $\bar{b}bW$ and $\bar{b}bbW$ invariant

can be suppressed to negligible levels by similar requirements.

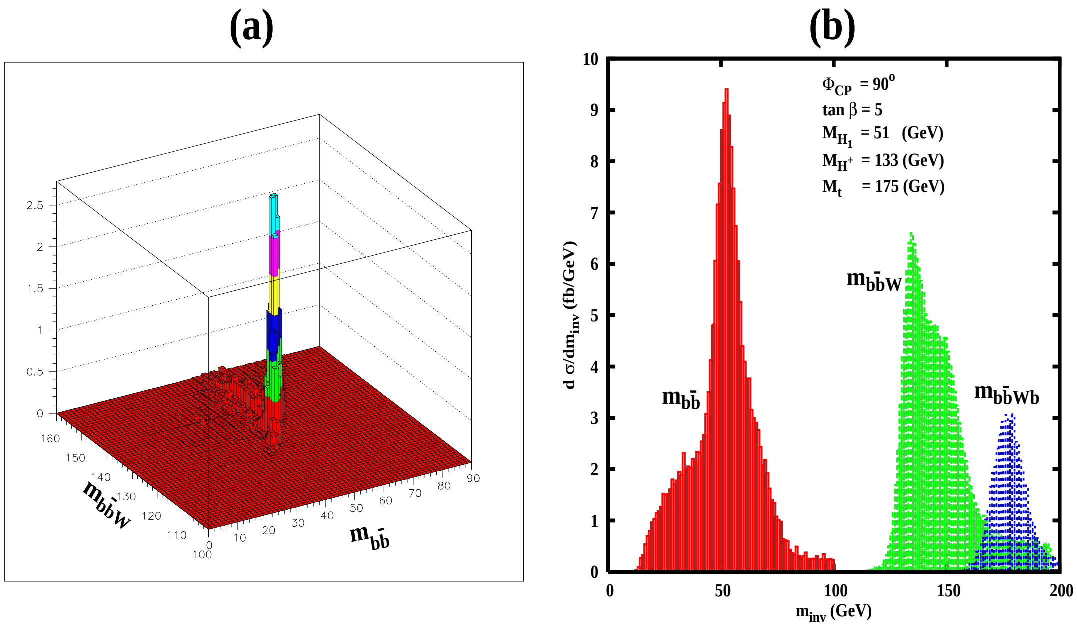


Figure 4: Clustering of the $b\bar{b}, b\bar{b}W$ and $b\bar{b}bW$ invariant masses. (a) three-dimensional plot for the correlation between $m_{b\bar{b}}$ and $m_{b\bar{b}W}$ invariant mass distribution. (b) $m_{b\bar{b}}, m_{b\bar{b}W}$ and $m_{b\bar{b}Wb} = M_t$ invariant mass distributions for $\Phi_{\rm CP} = 90°$. M_t, M_W mass window cuts have been applied as explained in the text. The other MSSM parameters are $\tan\beta = 5, M_{H^+} = 133$ GeV, corresponding to a light neutral Higgs H_1 with mass $M_{H_1} = 51$ GeV.

masses for the signal. Both these figures show similar clustering of the $b\bar{b}$, $b\bar{b}W$ invariant masses at values corresponding to M_{H_1} and M_{H^+} respectively as in Figure 3.

It should be mentioned here that the combinatorial background has already been included in the inclusive $b\bar{b}$ and $b\bar{b}W$ invariant mass distributions plotted in Figures 3-4 whereas the three dimensional plots showing the correlation do not include this. Within the framework of the mass reconstruction strategy outlined before, after the reconstruction of $t \to bW$, one is left with three b jets and a W. The former correspond to three possible invariant $b\bar{b}$ masses for each MC point. It is seen from Figures 3 and 4 that even after inclusion of all the possible pairs at each point the peak at the H_1 mass is clearly visible. Now for further reconstruction one can choose the pair with invariant mass closest to the peak and then calculate the $b\bar{b}W$ invariant mass by combining this pair with the remaining W. In case of quadratic ambiguity for the W both the values for the $Wb\bar{b}$ invariant mass are retained. Again, we see a clear peak at the H^+ mass. Finally combining this with the remaining b gives the $Wbbb$ invariant mass which peaks at M_t. In case of quadratic ambiguity for the W we have chosen the Wbb combination with invariant mass closer to the H^+ mass peak. In the three dimensional plot of Figures 3-4 we show the pair of invariant masses corresponding to this combination of Wbb as well as the $b\bar{b}$ invariant mass closest to H_1 mass. We have found that about 50% of the signal events will have more than one combination of the $b\bar{b}$ and $b\bar{b}W$ invariant masses in the window $M_{H_1} \pm 15$ GeV and $M_{H^+} \pm 25$ GeV respectively, when one includes all the combinations. Thus the combinatorial background is important but does not seem to overwhelm the signal.

A comment about the M_t dependence of our results is in order. If the value of M_t used is increased from 175 to 178 GeV, typically the mass difference M_{H^+}–M_{H_1} goes up by about 7–8 GeV and thus the curves in Figures 1 and 2 will extend to M_{H_1} values higher by about 7–8 GeV. We, however, have used the more conservative value of 175 GeV for M_t. as the window in the $\tan\beta$– M_{H^+} window which we explore, has been obtained using $M_t = 175$ GeV in Ref. [18]. Since the size of the window where LEP has no reach also gets bigger with an increased value of M_t [19, 3], the above observation simply implies that the region which the process $t \to bH^\pm \to bH_1W \to bb\bar{b}W$ can probe will also be bigger in that case.

Conclusions

Thus we have looked in the CPX scenario, in the CP-violating MSSM, at the region in the $\tan\beta$–$M_{H^\pm}$ plane, where a light H_1 signal might have been lost at LEP due to strong suppression of the H_1ZZ coupling and where the Tevatron and the LHC will have no reach due to a simultaneous suppression of the $H_1t\bar{t}$ coupling as well. Specifically, we concentrated in the MSSM parameter space $3.5 < \tan\beta < 5, M_{H_1} \lesssim 50$ GeV and $2 < \tan\beta < 3, M_{H_1} \lesssim 40$ GeV, for the common CP violating phase $\Phi_{\rm CP} = 90^\circ$ and 60° respectively, which correspond to the light H_1 window of [18]. We find that a light charged Higgs ($M_{H^\pm} < M_t$) with a large value for the branching ratio for the decay $H^\pm \to H_1W$ is realised almost over the entire parameter space that we considered. We find that such a light H_1 and light $H^\pm$, can be probed at the LHC in $t\bar{t}$ signal where one of the top quarks decays into the $bb\bar{b}W$ channel, via $t \to bH^\pm, H^\pm \to WH_1$ and $H_1 \to b\bar{b}$. Our parton-level Monte Carlo yields upto $\sim$ 1100–5000 events for a $\mathcal{L} = 30$ fb^{-1} corresponding to the CP-violating phase $\Phi_{\rm CP} = 90^\circ$ and 60° respectively. The events will show a very characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $bb\bar{b}W$ invariant mass peaks, indicating that the SM background may be negligible. Further, in a considerable part of this region, the branching ratio for the $H^\pm \to \tau\nu$ channel, that is normally used for the charged Higgs search, is reduced by over an order of magnitude. Thus, this $t\bar{t}$ signal will be a probe of **both** a light neutral H_1 and a light charged Higgs $H^\pm$. It is imperative that this investigation is followed up with a more exact simulation using event generator level Monte Carlo and detector acceptance effects, which is beyond our means. We hope that the encouraging results from this parton level Monte Carlo study will induce the CMS and the ATLAS collaborations to undertake such investigations.

Acknowledgements

We wish to thank the organisers of the Workshop on High Energy Physics Phenomenology 8 (WHEPP8) in Mumbai, India (Jan. 4-15, 2004) where this work was started and the Board for Research in Nuclear Sciences (BRNS) in India, for its support to organise the Workshop. The work of DKG is supported by the Bundesministerium für Bildung und Forschung Germany, grant

05HT1RDA/6. DKG would also like to thank US DOE contract numbers DE-FG03-96ER40969 for financial support during the initial stages of this work.

References

[1] S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592**, 1 (2004), see also `http://pdg.lbl.gov`.

[2] ALEPH, DELPHI, L3, OPAL, The LEP Higgs Working Group for Higgs Boson Searches, Phys. Lett. B **565** 61, (2003). `CERN-EP-2003-011`.

[3] LEP SUSY Working Group, `http://lepsusy.web.cern.ch/lepsusy`; LEP Higgs Working Group, `LHWG-Note 2004-01`.

[4] J. F. Gunion, B. Grzadkowski, H. E. Haber and J. Kalinowski, Phys. Rev. Lett. **79**, 982 (1997), [arXiv:hep-ph/9704410].

[5] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967); JETP Lett. 6, 24 (1967).

[6] For a recent summary, see A. D. Dolgov, [arXiv:hep-ph/0211260].

[7] C. L. Bennett *et al.*, Astrophys. J. Suppl. **148**, 1 (2003) [astro-ph/0302207].

[8] For a review, see e.g. M. Dine and A. Kusenko, Rev. Mod. Phys. **76**, 1 (2004) [arXiv:hep-ph/0303065].

[9] P. Nath, Phys. Rev. Lett. **66**, 2565 (1991); Y. Kizukuri and N. Oshino, Phys. Rev. D **46**, 3025 (1992); T. Ibrahim and P. Nath Phys. Lett. B **418**, 98 (1998), [arXiv:hep-ph/9707409]; Phys. Rev. D **57**, 478 (1998), [arXiv:hep-ph/9708456]; *ibid* D **58**, 019901(E) (1998); *ibid* D **60**, 079903 (1999); *ibid* D **60**, 119901 (1999); M. Brhlik, G.J. Good and G.L. Kane, Phys. Rev. D **59**, 115004 (1999) , [arXiv:hep-ph/9810457]; A. Bartl, T. Gajdosik, W. Porod, P. Stockinger and H. Stremnitzer, Phys. Rev. D **60**, 073003 (1999), [arXiv:hep-ph/9903402]; D. Chang, W.-Y. Keung and A. Pilaftsis, Phys. Rev. Lett. **82**, 900 (1999), [arXiv:hep-ph/9811202]; S. Pokorski, J. Rosiek and C.A. Savoy, Nucl. Phys. B **570**, 81 (2000), [arXiv:hep-ph/9906206]; E. Accomando, R. Arnowitt and B. Dutta, Phys. Rev. D **61**, 115003 (2000), [arXiv:hep-ph/9907446]; S. Abel, S. Khalil and O. Lebedev, Nucl. Phys. B **606**, 151 (2001), [arXiv:hep-ph/0103320]; U.Chattopadhyay, T.Ibrahim and D.P.Roy, Phys. Rev. D **64**, 013004 (2001), [arXiv:hep-ph/0012337]; D. A. Demir, M. Pospelov and A. Ritz, Phys. Rev. D **67**, 015007 (2003), [arXiv:hep-ph/0208257].

[10] A. Pilaftsis, Nucl. Phys. B **644**, 263 (2002), [arXiv:hep-ph/0207277].

[11] T. Falk, K. A. Olive, M. Pospelov and R. Roiban, Nucl. Phys. B **560**, 3 (1999), [arXiv:hep-ph/9904393].

[12] A. Pilaftsis, Phys. Rev. D **58**, 096010 (1998),[arXiv:hep-ph/9803297] and Phys. Lett. B **435**, 88 (1998), [arXiv:hep-ph/9805373].

[13] A. Pilaftsis and C. E. Wagner, Nucl. Phys. B **553**, 3 (1999) , [arXiv:hep-ph/9902371].

[14] D. A. Demir, Phys. Rev. D **60**, 055006 (1999), [arXiv:hep-ph/9901389].

[15] S. Y. Choi, M. Drees and J. S. Lee, Phys. Lett. B **481**, 57 (2000), [arXiv:hep-ph/0002287].

[16] M. Carena, J. R. Ellis, A. Pilaftsis and C. E. Wagner, Nucl. Phys. B **586**, 92 (2000), [arXiv:hep-ph/0003180].

[17] G. L. Kane and L. -T. Wang, Phys. Lett. B **488**, 383 (2000), [arXiv:hep-ph/0003198].

[18] M. Carena, J. R. Ellis, S. Mrenna, A. Pilaftsis and C. E. Wagner, Nucl. Phys. B **659**, 145 (2003), [arXiv:hep-ph/0211467].

[19] G. Abbiendi *et al.* [OPAL Collaboration], *Eur. Phys. J. C* **37**, 49 (2004).

[20] A. Dedes and S. Moretti, Phys. Rev. Lett. **84**, 22 (2000), [arXiv:hep-ph/9908516], Nucl. Phys. B **576**, 29 (2000), [arXiv:hep-ph/990941]; S. Y. Choi, K. Hagiwara and J.S. Lee, Phys. Rev. D **64**, 032004 (2001), [arXiv:hep-ph/0103294], Phys. Lett. B **529**, 212 (2002), [arXiv:hep-ph/0110138]; A. G. Akeroyd and A. Arhrib, Phys. Rev. D **64**, 095018 (2001),[arXiv:hep-ph/0107040]; A. Arhrib, D. K. Ghosh and O. C. W. Kong, Phys. Lett. B **537**, 217 (2002) [arXiv:hep-ph/0112039]; S. Y. Choi, M. Drees, J. S. Lee and J. Song, Eur. Phys. J. C **25**, 307 (2002) [arXiv:hep-ph/0204200].

[21] M. Drees, M. Guchait and D.P. Roy, Phys. Lett. B **471**, 39 (1999), [arXiv:hep-ph/9909266].

[22] J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. **156**, 283 (2004) [arXiv:hep-ph/0307377].

[23] S. Heinemeyer, Eur. Phys. J. C **22**, 521 (2001) [arXiv:hep-ph/0108059].

[24] E. Ma, D. P. Roy and J. Wudka, Phys. Rev. Lett. **80**, 1162 (1998) [arXiv:hep-ph/9710447].

[25] Talk presented by Markus Schumacher at the Workshop at TeV colliders at Les Houhces, May 1-21, 2005, Summary in the talk by T. Lari, url: `http://agenda.cern.ch/askArchive.php?base=agenda&categ=a053250&id=a053250s10t1/moreinfo`.