Moderately light charged Higgs in $Q^P$ MSSM and NMSSM

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In this talk I discuss some aspects of the phenomenology of a moderately light charged Higgs with $130 \lesssim M_{H^\pm} \lesssim m_t$ GeV, lighter than the top quark, at the LHC. A charged Higgs in this mass range is still allowed in next-to-minimal Supersymmetric Standard Model (NMSSM) at low $\tan \beta$ as well as in CP-violating ($Q^P$) Minimal Supersymmetric Standard Model (MSSM) for a certain choice of $Q^P$ parameters, still respecting all the LEP-II bounds. In both the cases, the $H^\pm$ has a large branching ratio in the $W^\pm \phi$ channel, where $\phi$ denotes a generic Higgs which is dominantly pseudoscalar and hence may be substantially lighter than the LEP-II mass bound. This $\phi$ decays dominantly into a $b\bar{b}$ pair. Thus production of $H^\pm$ in the top decay gives a striking $tt$ signal at the LHC, where one of the top quarks decays into the $b\bar{b}bW$ channel, via $t \rightarrow bH^\pm, H^\pm \rightarrow \phi$ and $\phi \rightarrow b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $b\bar{b}bW$ invariant mass peaks helps reduce the Standard Model (SM) background very effectively. Further, in both the CPX-scenario, even after LEP-II constraints are taken into account. In both the cases, the NMSSM as well as the $Q^P$ MSSM, the $H^\pm$ has a large branching ratio in the $W^\pm \phi$ channel and the light $\phi$ decays dominantly into a $b\bar{b}$ pair. This thus gives a striking $tt$ signal at the LHC, where one of the top quarks decays into the $b\bar{b}bW$ channel, via $t \rightarrow bH^\pm, H^\pm \rightarrow \phi$ and $\phi \rightarrow b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $b\bar{b}bW$ invariant mass peaks helps reduce the SM background very effectively. Further, in the CPX-scenario this $\phi$ has reduced couplings to a $tt$ pair as well. As a result, in the above mentioned window in the parameter space, none of the usual search channels for the neutral Higgs will have a reach either at the Tevatron or at the LHC [8, 9]. The decay of a light $H^\pm$, produced in the $t$ decay, provides an additional channel to search for such a neutral scalar and help ‘fill’ this hole which exists in this case. For these low values of $\tan \beta$, the $H^\pm$ can not be searched via $H^\pm \rightarrow t\nu$, and there is no LHC reach for the $H^\pm$ as well. Thus the suggested topology can provide a signal for both the light charged $H^\pm$ and the light $\phi$ (which is mostly a pseudoscalar) in these regions of the parameter space, both for the NMSSM and the $Q^P$ MSSM.

I. INTRODUCTION

In this talk I discuss some aspects of the phenomenology of a moderately light charged Higgs with $130 \lesssim M_{H^\pm} \lesssim m_t$ GeV, lighter than the top quark, at the LHC. A charged Higgs in this mass range is still allowed in the NMSSM at low $\tan \beta$ as well as in CP-violating ($Q^P$) MSSM [2, 3], respecting all the LEP-II bounds [2, 3, 4, 5, 6]. In both cases, there exists a neutral Higgs boson, $\phi$, which is predominantly pseudoscalar and hence can be much lighter than the LEP-II bound of 90 GeV in the CP-conserving MSSM [6]. As a result, there exists a small window in the tan $\beta$–$M_\phi$ plane at low tan $\beta$ ($3 \lesssim \tan \beta \lesssim 5$) and $M_\phi < 50$ GeV [2, 3, 4, 5, 6], which is still allowed in the aforementioned CPX scenario, even after LEP-II constraints are taken into account. In both the cases, the NMSSM as well as the $Q^P$ MSSM, the $H^\pm$ has a large branching ratio in the $W^\pm \phi$ channel and the light $\phi$ decays dominantly into a $b\bar{b}$ pair. This thus gives a striking $tt$ signal at the LHC, where one of the top quarks decays into the $b\bar{b}W$ channel, via $t \rightarrow bH^\pm, H^\pm \rightarrow \phi$ and $\phi \rightarrow b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $b\bar{b}bW$ invariant mass peaks helps reduce the Standard Model (SM) background very effectively.

II. LIGHT $H^\pm$ IN NMSSM.

In the MSSM $\mu$ is stabilized at the EW scale ‘naturally’, if one introduces an additional chiral superfield $\tilde{1}^1$, thus solving the so called $\mu$ problem. This class of Supersymmetric models, with additional singlet Higgs fields, is called the next-to-minimal supersymmetric standard model (NMSSM) [11, 12]. Further, the ‘little hierarchy’ problem caused by the non observation of the light neutral Higgs at LEP-II, may also be eased in the NMSSM [13]. While adding a singlet complex scalar field does not affect the charged Higgs boson pair $H^\pm$ of the MSSM directly, it has a strong indirect effect on the phenomenology of the $H^\pm$ boson. This effect comes from the modification of the MSSM mass relations between the doublet scalars $H^1_1, H^1_2$ and pseudoscalar $A^0_1$ and the resulting modification of the $H^0_1$ mass bound. Because of this modification it is possible to satisfy the LEP-2 limit on the $H^0_1$ mass even with a light $A^0_1$, which in turn implies a moderately light $H^\pm$ boson. The relaxation of the $A^0_1$ and $H^\pm$ mass limits of the MSSM is most pronounced in the moderate tan $\beta$ region. The superpotential of the NMSSM Higgs sector in terms of the singlet and doublet Higgs superfields, $S$ and $H_1, H_2$ respectively, can be written as [11]:

$$W = \lambda S H_1 H_2 - \frac{k}{3} S^3. \quad (1)$$

The resulting $F$ term of the Higgs potential is

$$V_F = \lambda^2 x^2 (v_2^2 + v_1^2) + \lambda^2 x^2 v_1^2 + k^2 x^4 - 2\lambda \kappa x^2 v_1 v_2, \quad (2)$$

where $x = \langle S \rangle$, $v_{1,2} = \langle H^0_{1,2} \rangle$ and $\tan \beta = v_2 / v_1$. The $D$-term is the same as in MSSM, i.e.

$$V_D = \frac{1}{8} (g_1^2 + g_2^2) (v_1^2 - v_2^2) + \frac{1}{2} g_1^2 v_1^2 v_2, \quad (3)$$
comparing the $F$-term of the MSSM, $V_F = \mu^2(v_1^2 + v_2^2)$, with Eq. 2 one gets

$$\mu = \lambda x \equiv \mu_{\text{eff}},$$

(4)

which naturally explains why the supersymmetric $\mu$ parameter has a relatively low value as required for EWSB. In fact this solution to the so called $\mu$-problem of the MSSM was the original motivation for the NMSSM. But the remaining terms of Eq. 2 lead to modifications of the neutral Higgs boson masses of the MSSM. In particular the resulting upper bound of the lightest Higgs scalar mass is $\{14, 15, 16, 18, 19\}$.

$$M_{H_1}^2 \leq M_Z^2 \cos^2(2\beta) + \frac{2\lambda^2 M_W^2}{g^2} \sin^2(2\beta) + \epsilon,$$

(5)

where the first term coming from the $V_D$ (Eq. 3) and the radiative correction $\epsilon$ are the same as in MSSM. But the additional contribution in the middle comes from the second term of $V_F$ (Eq. 2).

Note that this additional contribution is most pronounced in the low to moderate $\tan \beta$ region, where the MSSM mass bound coming from the first term of Eq. 2 is very small. Therefore it relaxes the MSSM bound on $M_{H_1}$ and hence the resulting lower limit on $M_A$ most significantly over this range of $\tan \beta$. This in turn relaxes the lower limit of the charged Higgs mass, which is related to the doublet pseudoscalar mass via

$$M_{H^+}^2 = M_A^2 + M_W^2 \left( 1 - \frac{2\lambda^2}{g^2} \right),$$

(6)

along with a small radiative correction. This is helped further due to the additional (negative) contribution in Eq. 6. Note that the additional contributions of Eqs. 5 and 6 depend only on the $SH_1H_2$ coupling $\lambda$, represented by the first term of the superpotential of Eq. 1. Therefore the Eqs. 5 and 6 hold also for the so called minimal nonminimal supersymmetric standard model (MNSSM), which assumes only the first term of the superpotential $[20, 21, 22]$.

Finally the upper bound of Eq. 5 will only be useful if one can find an upper limit on $\lambda$. Such a limit can be derived $[14, 15, 16]$ from the requirement that all the couplings of the model remain perturbative up to some high energy scale, usually taken to be the GUT scale. Such an upper limit on $\lambda$ has been estimated in $[1]$ as a function of $\tan \beta$ using two-loop renormalization group equations. For quantitative evaluation of the NMSSM Higgs spectrum we consider the complete Higgs potential as given in terms of these parameters in $[23]$. The lower limit of the $H^\pm$ mass has been estimated as a function of $\tan \beta$ in $[1]$ by varying all these five NMSSM parameters over the allowed ranges, which include the constraints from LEP-2. The resulting $H^\pm$ mass limit is shown in Figure 1 by the dark solid curve along with the most conservative MSSM limit (shown by the dotted curve), corresponding to maximal stop mixing, which gives the largest radiative correction $\epsilon$. The NMSSM limit has practically no sensitivity to stop mixing. In addition the thin solid curve indicates the limit in the NMSSM where we require that the effective $\mu$ parameter given by Eq. 4 be bigger than 100 GeV as favoured by the chargino mass constraint from LEP-II. The LEP-2 mass limit from direct search of $H^+ \rightarrow \tau^+ \nu$ events is also shown by the dashed curve for comparison $[24]$.

In fact it might be interesting to check whether the flavour physics constraints allow this moderately light charged Higgs in this region of the parameter space. There is no limit from Tevatron in the moderate $\tan \beta$ region shown in Figure 1.

One sees from Figure 1 that even the most conservative MSSM limit implies $H^\pm$ mass $\geq 150$ GeV (175 GeV) for $\tan \beta \leq 6$ (4). In contrast in the NMSSM one can have a $H^\pm$ mass $\lesssim 120$ GeV over this moderate $\tan \beta$ region, going down to the direct LEP-2 limit of 86 GeV at $\tan \beta \simeq 2$. Note however that requiring that the effective $\mu$ parameter $\mu_{\text{eff}} = (S)\lambda$ be greater than 100 GeV, as favored by the LEP chargino search, increases this mass limit to $\gtrsim 120$ GeV $[21]$. The steep vertical rise at left reflects the well-known fixed-point solution at $\tan \beta = 1.55$, where the top Yukawa coupling blows up at the GUT scale. Thus allowing for possible intermediate scale physics one can evade the steep NMSSM mass limit at low $\tan \beta$ $[25]$. In contrast the MSSM limit holds independent of any intermediate scale physics ansatz.

We have investigated the neutral scalar and pseudoscalar Higgs spectrum of the NMSSM, when the $H^\pm$ lies near its lower mass limit ($M_{H^\pm} \simeq 120$ GeV). The lightest scalar is dominantly singlet ($M_{H_1} \simeq$...
TABLE I: Examples of dominant $H^\pm \to W A_1^0$ decay in the NMSSM. These decay branching fractions are shown along with the Higgs boson masses and the other model parameters.

| $\tan \beta$ | $M_{H^+}$ (GeV) | $M_{A_1^0}$ (GeV) | $B_{A_1^0}$ (%) | $\lambda, \kappa$ | $x = v_1/\sqrt{2}, A_\lambda, A_\kappa$ (GeV) |
|-------------|----------------|------------------|----------------|------------------|----------------------------------|
| 2           | 147            | 38               | 94             | .45,-.69         | 224,-8,2                          |
| 3           | 159            | 65               | 83             | .33,-.70         | 305,40,38                        |
| 4           | 145            | 48               | 89             | .28,-.70         | 563,170,85                       |
| 5           | 150            | 10               | 91             | .26,-.54         | 503,109,38                       |

100 GeV), while the doublet scalars are relatively heavy ($M_{H_{2,3}} > 120$ GeV). On the other hand there is often a light pseudoscalar ($M_{A_1^0} \approx 50$ GeV) with a very significant doublet component. Consequently a light charged Higgs boson of mass $\approx 120$ GeV is expected to decay dominantly via the standard $H^+ \to \tau^+\nu$ mode. Thus one can probe this mass range via the $t \to bH^+ \to bt^+\nu$ channel at Tevatron and especially at the LHC. On the other hand a somewhat heavier charged Higgs boson ($M_{H^+} > 130$ GeV) can dominantly decay via the $H^+ \to W^+ A_1^0$ channel [23]. In fact this seems to be a very favorable channel to probe for not only $H^+$ but also a light $A_1^0$ in the moderate $\tan \beta$ region, where the $A_1^0$ is expected to decay mainly in to the $bb$ mode. Table I shows some illustrative samples of NMSSM Higgs spectra where $H^+$ decays dominantly into the $W^+ A_1^0$ mode. These results are obtained by scanning the NMSSM parameter space. Note that in each case the effective parameter $\mu_{eff} = \lambda(S)$ is greater than 100 GeV as favored by the LEP chargino limit. The decay branching fractions are shown along with the Higgs boson masses and the other model parameters in Table I. We see indeed that $B(H^\pm \to A_1^0 W^\pm)$ can be substantial.

III. LIGHT $H^\pm$ IN CP-VIOLATING MSSM

Interestingly one can have a similar signal in the CP-violating MSSM due to large scalar-pseudoscalar mixing. In this case, the $h$, $H$ and $A$ of the MSSM are no longer mass eigenstates, even if we start with a tree level scalar potential which is CP-conserving. Loop effects mix them and the mass eigenstates $H_1$, $H_2$ and $H_3$ (ordered according to their masses) no longer have a definite CP [23]. 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. The light charged $H^+$ decays dominantly into the $WH_1$ channel giving rise to a striking $t\bar{t}$ signal at the LHC, where one of the top quarks decays into the $b\bar{b}W$ channel, via $t \to bH^+, H^+ \to WH_1$ and $H_1 \to b\bar{b}$. The characteristic correlation between the $b\bar{b}$, $b\bar{b}W$ and $b\bar{b}W$ invariant mass peaks helps reduce the SM background, drastically [27]. Note that this signal is identical to the NMSSM case discussed above. As already mentioned, a combined analysis of all the LEP results, shows that a light neutral Higgs is still allowed in the CPX scenario in the CPV-MSSM. The experiments provide exclusion regions in the $M_{H_1} - \tan \beta$ plane for different values of the CP-violating phase, with the various parameters taking the following values:

$$\text{Arg} A_t = \text{Arg} A_\lambda = \text{Arg} M_b = \phi_{CP},$$

$$M_{\text{Susy}} = 0.5 \text{TeV}, M_b = 1 \text{TeV},$$

$$M_{\bar{b}} = M_{\tilde{W}} = 0.2 \text{TeV},$$

$$\phi_{CP} = 0^\circ, 30^\circ, 60^\circ, 90^\circ.$$  

Combining the results of Higgs searches from

![FIG. 2: The LEP exclusion region taken from [8]. The light green (medium grey) and dark green (dark grey) regions are the exclusion regions in the $\tan \beta - m_{H_1}$ plane, at 95 %CL and 99.7 %CL respectively. More conservative of the two theoretical calculations was used at each point in the parameter space in this figure. For details such as values of $m_t$ used and the dependence of the exclusion region on them, see Ref. [8]. The dashed lines indicate the boundaries of the regions expected to be excluded at 95% CL.](image-url)

ALEPH, DELPHI, L3 and OPAL, the authors in Ref.[2,5,6,8] have provided exclusion regions in the $M_{H_1} - \tan \beta$ plane as well as in the $M_{H_1} - \tan \beta$ plane. While the exact exclusion regions differ somewhat in different analysis [2,5,6,8] and depend on the value of the top quark mass $m_t$, as well as the programs used.
TABLE II: Range of values for BR \( H^+ \to H_1W^+ \) 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 \( \Phi_{CP} = 90^\circ \), 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 \( H^+ \to H_1W^+ \) is allowed.

| \( \tan \beta \) | 3.6 | 4 | 5 |
|------------------|-----|---|---|
| \( B(H^+ \to H_1W^+) \) \( (%) \) | \( > 90(87.45) \) | \( > 90(57.65) \) | \( > 90(46.57) \) |
| \( B(t \to bH^+) \) \( (%) \) | \( \sim 0.7 \) | \( 0.7 - 1.1 \) | \( 1.0 - 1.3 \) |
| \( M_{H^+} \) \( (GeV) \) | \( < 148.5 \) (149.9) \( < 139 \) (145.8) \( < 126.2 \) (134) |
| \( M_{H_1} \) \( (GeV) \) | \( < 60.62 \) (63.56) \( < 49.51 \) (65.4) \( < 29.78 \) (53.49) |

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. \( M_{H_1} < 50 \) GeV for \( \Phi_{CP} = 90^\circ \). It can be also seen from the table that the BR(\( H^\pm \to H_1W^\pm \)) is larger than 90\% over most of the parameter space of interest. So not only that \( H^\pm \) 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 a 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

\[ p\bar{p} \to t(\to bH^+ \to bW^+H_1)\bar{t}(\to bW^- \to b\ell\nu/qq') , \]

with the \( H_1 \) further decaying into a \( b\bar{b} \) pair and the \( W^\pm \) decaying into a \( l\nu(q\bar{q}') \) pair will allow a probe of both the light \( H_1 \) and a light \( H^\pm \) in this parameter window in the CP-violating MSSM in the CPX scenario.

We have investigated the signal over the entire parameter range of the ‘hole’ in the \( \tan \beta - m_{H_1} \) plane of the Figure 2. We show our results in Figures 3 and 4 for common \( \mathcal{Q} \) phase \( \Phi_{CP} = 90^\circ \). As can be seen from the Figure 3 the largest signal cross-section case is \( \sim 38 \) fb and the signal cross-section is \( \geq 20 \) fb for \( M_{H_1} \geq 15 \) GeV. It is clear from the right panel of the Figure 4 that there is simultaneous clustering in the \( m_{b\bar{b}} \) distribution around \( \sim M_{H_1} \) and in the \( m_{bbH_1} \) distribution around \( M_{H^\pm} \). It should be mentioned here that the combinatorial background has already been included in the inclusive \( bb \) and \( bbW \) invariant mass distributions plotted in right hand panel in Figure 4 whereas the three dimensional plot showing the correlation does not include this. The clustering feature can be used to distinguish the signal over the standard model background. Technically the most useful in this are the mass window cuts (\( M_W \pm 15 \) 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) employed in the mass reconstruction procedure as described in Ref. [27]. As a matter of fact the estimated background coming from the QCD production of \( t\bar{b}b \) once all the cuts (including the mass window cuts) are applied, to the signal type events is less than 0.5 fb, in spite of a starting cross-section of 8.5 pb. The major reduction is brought about by requiring that the invariant mass of the \( bbW \) be within 25 GeV of \( M_t \). Preliminary studies in ATLAS collaboration presented at Les Houches Workshop [28] also show that this background can be suppressed to negligible levels by similar requirements. This makes it very clear that the detectability of the signal is controlled primarily by the signal size. It is also clear from Figure 3 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 \( \mathcal{Q} \) to compute the Higgs masses in terms of the model parameters, they all show that for phases \( \Phi_{CP} = 90^\circ \) and \( 60^\circ \) LEP cannot exclude the presence of a light Higgs boson at low \( \tan \beta \), mainly because of the suppressed \( H_1ZZ \) coupling.

The analysis of Ref. [8, 9] further shows that in the same region the \( H_1tt \) 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 \( ttH_1 \) coupling suppresses the inclusive production mode and the associated production modes \( W/ZH_1 \) and \( ttH_1 \), are suppressed as well. This region of Ref. [8] corresponds to \( \tan \beta \sim 3.5 - 5, M_{H^\pm} \sim 125 - 140 \) GeV, \( M_{H_1} \sim 50 \) GeV and \( \tan \beta \sim 2 - 3 \), \( M_{H^\pm} \sim 105 - 130 \) GeV, \( M_{H_1} \sim 40 \) GeV, for \( \Phi_{CP} = 90^\circ \) and \( 60^\circ \) respectively. 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. Further, in the MSSM a light pseudo-scalar implies a light charged Higgs, lighter than the top quark. The comment about possible constraints on a moderately light charged Higgs from flavour physics, made in the context of the NMSSM applies in this case as well.

Table I shows the behaviour of the \( M_{H^\pm}, M_{H_1} \) 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. [8]. 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 \( H_1W \),
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 \( H^\pm \rightarrow \nu \tau \) is suppressed by over an order of magnitude.

Note further, that the correlation between a light \( \phi \), a moderately light \( H^\pm \) and the large branching ratio for \( H^\pm \rightarrow \phi W^\pm \) follows in the MSSM and in the NMSSM, due to some simple sum rules. Hence it may be a generic feature of any scenario, which allows a light charged Higgs in spite of the LEP-II constraints, so that \( t \rightarrow bH^\pm \) is not negligible and further \( H^\pm \rightarrow \phi W^\pm \) is possible, \( \phi \) being a light neutral Higgs which dominantly decays into a \( bb \) pair.

IV. SUMMARY

Thus in conclusion, both in the NMSSM and in the CPV-MSSM the moderately light charged Higgs that is allowed at moderately low values of \( \tan \beta \), provides interesting and novel phenomenology at the LHC. It would be interesting to investigate whether the flavour physics constraints allow a light charged Higgs in the mass range that attains in these regions of the parameter space in the two cases.

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[1] M. Drees, E. Ma, P. N. Pandita, D. P. Roy and S. K. Vempati, Phys. Lett. B 433, 346 (1998) [arXiv:hep-ph/9805242].

[2] For a review and more detailed references, see, E. Accomando et al., Report of the “Workshop on CP studies and non-standard Higgs physics,”
FIG. 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 $\Phi_{\text{CP}} = 90^\circ$. 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. $M_t, M_W$ mass window cuts have been applied\cite{27}.

\[ \text{arXiv:hep-ph/0608079} \]

\[ \text{[3]} \] A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B 553, 3 (1999) [arXiv:hep-ph/9902371].

\[ \text{[4]} \] M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Phys. Lett. B 495, 155 (2000) [arXiv:hep-ph/0009212].

\[ \text{[5]} \] G. Abbiendi et al. [OPAL Collaboration], Eur. Phys. J. C 37, 49 (2004) [arXiv:hep-ex/0406057].

\[ \text{[6]} \] S. Schael et al. [ALEPH Collaboration], Eur. Phys. J. C 47, 547 (2006) [arXiv:hep-ex/0602042].

\[ \text{[7]} \] R.M. Godbole and D.P. Roy, in Ref. [2].

\[ \text{[8]} \] M. Carena, J. R. Ellis, A. Pilaftsis and C. E. M. Wagner, Nucl. Phys. B659, 145 (2003), arXiv:hep-ph/0211467.

\[ \text{[9]} \] M. Schumacher, in Ref. [2].

\[ \text{[10]} \] See, for example, M. Drees, R. M. Godbole and P. Roy, Theory and Phenomenology of Sparticles, World Scientific, Singapore (2005).

\[ \text{[11]} \] H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B 120, 346 (1983).

\[ \text{[12]} \] H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B 124, 337 (1983).

\[ \text{[13]} \] R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005) [arXiv:hep-ph/0502105].

\[ \text{[14]} \] M. Drees, Int. J. Mod. Phys. A 4, 3635 (1989).

\[ \text{[15]} \] S. F. King and P. L. White, Phys. Rev. D 52 (1995) 4183 [arXiv:hep-ph/9505326].

\[ \text{[16]} \] S. F. King and P. L. White, Phys. Rev. D 53 (1996) 4049 [arXiv:hep-ph/9508346].

\[ \text{[17]} \] U. Ellwanger and M. Rausch de Traubenberg, Z. Phys. C 53 (1992) 521.

\[ \text{[18]} \] P. N. Pandita, Z. Phys. C 59 (1993) 575.

\[ \text{[19]} \] T. Elliott, S. F. King and P. L. White, Phys. Rev. D 49 (1994) 2435 [arXiv:hep-ph/9308309].

\[ \text{[20]} \] C. Panagiotakopoulos and K. Tamvakis, Phys. Lett. B 469 (1999) 145 [arXiv:hep-ph/9908351].

\[ \text{[21]} \] C. Panagiotakopoulos and A. Pilaftsis, Phys. Lett. B 505 (2001) 184 [arXiv:hep-ph/0101266].

\[ \text{[22]} \] C. Panagiotakopoulos and A. Pilaftsis, Phys. Rev. D 63 (2001) 055003 [arXiv:hep-ph/0008268].

\[ \text{[23]} \] M. Bastero-Gil, C. Hugonie, S. F. King, D. P. Roy and S. Vempati, Phys. Lett. B 489 (2000) 359 [arXiv:hep-ph/0006198].

\[ \text{[24]} \] W. M. Yao et al. [Particle Data Group], J. Phys. G 33 (2006) 1.

\[ \text{[25]} \] M. Masip, R. Munoz-Tapia and A. Pomarol, Phys. Rev. D 57 (1998) 5340 [arXiv:hep-ph/9804437].

\[ \text{[26]} \] M. Drees, M. Guchait and D. P. Roy, Phys. Lett. B 471 (1999) 39 [arXiv:hep-ph/9909266].

\[ \text{[27]} \] D. K. Ghosh, R. M. Godbole and D. P. Roy, Phys. Lett. B 628 (2005) 131 [arXiv:hep-ph/0412193].

\[ \text{[28]} \] 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 (please see \cite{27} for the reference to url).

\[ \text{[29]} \] $H_1$ here is synonymous with $\phi$ of earlier discussion in the Introduction.