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CP violation in supersymmetry, Higgs sector and the large hadron collider

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Abstract. In this talk I discuss some aspects of CP violation (CPV) in supersymmetry (SUSY) as well as in the Higgs sector. Further, I discuss ways in which these may be probed at hadronic colliders. In particular I will point out the ways in which studies in the $\tilde{\chi}^{\pm}, \tilde{\chi}_2^0$ sector at the Tevatron may be used to provide information on this and how the search can be extended to the LHC. I will then follow this by a discussion of the CP mixing induced in the Higgs sector due to the above-mentioned CPV in the soft SUSY breaking parameters and its effects on the Higgs phenomenology at the LHC. I would then point out some interesting aspects of the phenomenology of a moderately light charged Higgs boson, consistent with the LEP constraints, in this scenario. Decay of such a charged Higgs boson would also allow a probe of a light ($\lesssim$50 GeV), CP-violating (CPV) Higgs boson. Such a light neutral Higgs boson might have escaped detection at LEP and could also be missed at the LHC in the usual search channels.

Keywords. Supersymmetry; CP violation; Higgs sector; large hadron collider.

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1. Introduction

In spite of the unprecedented success that the Standard Model (SM) has had in providing a fundamental understanding of the elementary particles and the interactions among them, as well as in explaining *all* the high precision measurements in various high energy physics experiments, it suffers from certain theoretical deficiencies. Instability of the Higgs boson mass at the electroweak (EW) symmetry breaking scale and the resultant lack of naturalness and/or fine tuning, lack of a fundamental understanding of the mass differences among different fermions or in fact of the phenomenon of CP violation itself, are some of its most obvious lacunae. All the observed CPV in the laboratory to date, in the K_0–$\bar{K}_0$ system as well as in the B_0–$\bar{B}_0$ sector, can be explained in the SM in terms of the CKM picture [1,2]. The SM, however, cannot explain [3] *quantitatively* the so-called baryon asymmetry in the Universe (BAU), viz., the fact that $(N_b/N_\gamma) \sim 6.1 \times 10^{-10}$ while $(N_{\bar{b}}/N_\gamma) \sim 0$. If the particular beyond the SM (BSM) physics, which provides the mechanism of BAU generation, also has a source of CPV ($\not{C}\not{P}$) over and above the CKM phase present in the SM, it certainly makes it easier to generate the requisite

BAU. Hence it seems logical to investigate implications of such additional CPV for the various theoretical options of going beyond the SM, which the Particle Physics community is investigating, in order to cure the various deficiencies of the SM. $\not{CP}$ in the Higgs sector, possible only in the multi-Higgs doublet models, is one of the theoretically attractive sources of such additional CPV. A general two-Higgs doublet model seems to be able to generate adequate amount of BAU and be consistent with the current experimental constraints such as the electric dipole moments [4]. SUSY is arguably the most elegant and the popular option for extending the SM and any supersymmetric extension of the Standard Model, in fact, has to have at least two Higgs doublets [5]. Thus, with SUSY it may be possible to satisfy all the low energy constraints and still have sufficient $\not{CP}$ in the theory to explain the BAU quantitatively, without requiring fine tuning, at least in the non-minimal supersymmetric Standard Model (NMSSM) [6]. These $\not{CP}$ phases of the SUSY(breaking) parameters can have significant implications for the Higgs phenomenology at the colliders. Given the fact that Higgs search is 'raison d'être' for the current and future colliders, investigations of $\not{CP}$ in the Higgs sector are then phenomenologically very interesting indeed. Hence, the subject of $\not{CP}$ in the Higgs sector and supersymmetry has received a lot of attention in the recent times [7].

2. $\not{CP}$ and SUSY

2.1 *General remarks*

SUSY models suffer from an embarassment of riches when it comes to $\not{CP}$ phases. In the most general formulation there exists a large number, 44 to be precise, of phases of SUSY parameters which cannot be simply rotated away by a simple redefinition of fields. Matters are even worse as they also generate unacceptably large electric dipole moments (EDMs) for fermions. In the early days of SUSY the simplest solution was to fine tune all the phases to be zero or to make the sparticle masses very large. It has been observed in recent years [8,9] that it is possible to satisfy all the current experimental constraints and yet have some phases of $\mathcal{O}(1)$, provided the sparticles of the first two generations are heavy, i.e. the experimental constraints are satisfied more 'naturally'. Thus it may be possible to have adequate amount of BAU and at the same time be consistent with the present constraints.

In the so-called constrained MSSM (CMSSM), the independent phases in the $\not{CP}$ MSSM that can be large (up to $\sim O(1)$), even after imposing the EDM constraints, are the phase of the Higgsino mass parameter μ, the trilinear coupling A_f as well as the gaugino masses $M_i, i = 1, 2$. In addition to this, the sfermion mass matrix can also have nonzero phases for each generation. These phases affect the masses of the sparticles and the Higgs bosons as well as their couplings to the SM particles and to each other. Thus their presence can affect the phenomenology of the sfermions, charginos/neutralinos and that of the Higgs bosons at the colliders. As mentioned above, these $\not{CP}$ phases in the soft SUSY breaking parameters induce CP-mixing in the Higgs sector radiatively, starting from a CP-conserving Higgs potential [10–14]. This as well as the above-mentioned effect of $\not{CP}$ on couplings, can affect the production rates of the Higgs bosons at the LHC [14,15]. These phases can thus change even the CP-even variables such as the sparticle production rates, their decay widths and branching ratios. Of course a 'direct' measure of these phases will be the nonzero value of CP-odd observables constructed out of the momenta of the final-state decay products.

Effects of nonzero $\not{CP}$ phases on the search and study of $\tilde{\chi}^{\pm}, \tilde{\chi}^0$, sfermions and the charged Higgses have been investigated in great detail [16]. Due to the high precision of the measurements that would be possible at the ILC [17], at times CP-even variables like the branching ratios, cross-sections, and polarisations of fermions in the final state may offer a better probe of the $\not{CP}$ phases than the CP-odd quantities constructed out of the final-state momenta.

The effects of CPV in MSSM on Higgs phenomenology have been studied in the context of LEP, Tevatron and the LHC [14,15,18–24], whereas those on the $\tilde{\chi}^{\pm}, \tilde{\chi}^0$ phenomenology have been studied mainly only in the context of the Tevatron [25,26].

2.2 *Effect of $\not{CP}$ phases in gaugino sector at the hadronic colliders*

In general, the size of the CP-violating observables is determined by the size of the interference between the CP-even and CP-odd quantities. The shape of the invariant mass distribution of the lepton pairs coming from the $\tilde{\chi}^{\pm}, \tilde{\chi}^0$ decays can be affected due to the presence of $\not{CP}$ violation. Thus $\not{CP}$ can affect their phenomenology very strongly and the study can afford information on the amount of $\not{CP}$ if the other SUSY parameters are known. Since the initial state in the case of a $p\bar{p}$ collider is a CP eigenstate, it is actually possible to construct $\not{CP}$ observables, which will be a direct measure of this $\not{CP}$. Choi *et al* [25] and Mrenna *et al* [26] studied the process $p\bar{p} \to \tilde{\chi}_2^0 \chi_1^{\pm}$. They constructed T-odd variables like $\mathcal{O}_T$ and $\mathcal{O}_T^{\ell\ell'}$ [25] using the initial (anti)proton direction and the momenta of the decay leptons given by

$$\begin{aligned} \mathcal{O}_T &= \vec{p}_{\ell_1} \cdot (\vec{p}_{\ell_3} \times \vec{p}_{\ell_4}); \\ \mathcal{O}_T^{\ell\ell'} &= \vec{p}_p \cdot (\vec{p}_\ell \times \vec{p}_{\ell'}) \,. \end{aligned} \tag{1}$$

Here, $\ell_1 = \ell^-$ of the chargino decay $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell$, and $\ell_3 = \ell'^-$, $\ell_4 = \ell'^+$ of the neutralino decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell'^- \ell'^+$. In the case of the second variable, the $\{\ell, \ell'\}$ stand for any combination of the two momenta among the three final-state leptons. Figure 1 illustrates what could be achieved at the Tevatron if an integrated luminosity $\mathcal{L} = 20(30)$ fb^{-1} were to be available. Of course, now that we know that the available luminosity at the Tevatron is going to be much less than this, the above becomes an academic exercise. It may be worthwhile to revisit the issue to look at the effect of the more recent analyses of the EDM constraints [9] on the issue.

2.3 *Effects of $\not{CP}$ in MSSM on the Higgs sector*

There are many interesting studies about how to search for the effects of $\not{CP}$ in SUSY by looking at its influence on sparticle phenomenology at the ILC [27]. However,

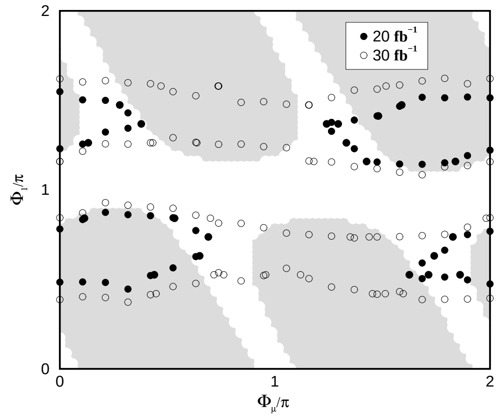
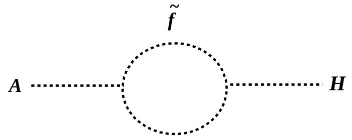


Figure 1. Values of the $\not{CP}$ phases Φ_μ, Φ_1 that can be probed using the CP/T-violating asymmetries for the trilpeton signal, at 5σ level, for the luminosity indicated on the plot [25]. Shaded regions are ruled out by the EDM constraints.



$$\propto \frac{m_f^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \Im m(A_f \mu)$$

Figure 2. Loop diagrams inducing CP-mixing in Higgs sector in the $\not{CP}$ MSSM.

the most interesting one, in my opinion, is the very nontrivial effect that the CP-violating phases in the parameters of the MSSM have on the phenomenology and the search prospects of the Higgs bosons at the colliders. As has been already mentioned before, the $\not{CP}$ phases in the MSSM induce CPV in the Higgs sector, even when the tree level potential is CP-conserving. As a result, the CP-even h, H and the CP-odd A of the MSSM mix and give rise to mass eigenstates ϕ_1, ϕ_2, ϕ_3, where $m_{\phi_1} < m_{\phi_2} < m_{\phi_3}$. Indeed, model-independent discussions of CP violation in the Higgs sector and hence of CP-mixing among the neutral Higgs boson states have existed in literature [28] since long. The special feature of the current studies is the definitive linking between the $\not{CP}$ in MSSM and the one in Higgs sector. Effect of this mixing on the couplings of the mixed CP states ϕ_1, ϕ_2, ϕ_3 with a pair of gauge bosons/fermions, i.e., $\phi_i f\bar{f}$, $\phi_i VV$, can change the Higgs phenomenology profoundly. It can be shown that various sum rules exist for these and we have, for example,

$$g_{\phi_i WW}^2 + g_{\phi_j WW}^2 + g_{\phi_k WW}^2 = g^2 m_W^2, \quad i \neq j \neq k.$$

In the $\not{CP}$ MSSM we have definite prediction for this mixing in terms of the $\not{CP}$ in the MSSM. This happens as the scalar potential of the MSSM is completely specified in terms of the gauge couplings and the Higgsino mass parameter μ. At tree level, enough freedom exists to rotate away the phase of μ if any. However, at loop level, diagrams such as shown in figure 2 give nonvanishing complex contributions to the scalar potential which cannot be any more rotated away as there is no freedom of field redefinition. The contribution of the loop diagram is $\propto \frac{m_f^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \Im m(A_f \mu)$. The CP-mixing in the Higgs sector can be parametrised by $\{\Phi_{A_f}, \Phi_3, \Phi_\mu\}$ [10–14]. For a specific scenario [11], called CPX scenario, the effect on the couplings of $\phi_i, i = 1,3$ to a VV pair, $V = W/Z$, can be really drastic and the lightest state becomes almost CP-odd, thus becoming decoupled from a VV sector. This corresponds to a choice of the MSSM parameters: $M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY}, \mu = 4M_{\rm SUSY}$, $|A_{t,b,\tau}| = 2M_{\rm SUSY}$ and $|M_3| = 1$ TeV. The Higgs masses and couplings are functions of $\tan\beta, M_{H^\pm}, \Phi_{A_f}, \Phi_\mu, \Phi_3$ as well as the SUSY scale $M_{\rm SUSY}$. In this case the EDM constraints are easily satisfied for the chosen parameters and hence the phases Φ can be varied freely. For obvious reasons the phases Φ_{A_t}, Φ_{A_b} dominantly affect the masses and couplings of the mixed Higgs boson states. Figure 3 taken from ref. [13] shows this strong dependence clearly. Thus in this CPX scenario [11] the lightest Higgs boson ϕ_1 may have missed being discovered at the LEP due to its reduced couplings to ZZ. As a matter of fact, the nonobservation of a Higgs boson signal in the direct searches at the LEP now needs to be reinterpreted in the MSSM with CP violation. The recent analysis from OPAL [29] shows that indeed there are 'holes' in the excluded region at small $\tan\beta$ and m_{ϕ_1} in the $\tan\beta$–m_{ϕ_1} plane that are allowed even with the nonobservation of the signal at LEP. Figure 4 shows a plot taken from first of the refs. [29] wherein the hole can be seen very clearly. This corresponds to the case of a ϕ_1 decoupled from ZZ as mentioned above.

2.4 *Effect of CP-mixing on Higgs searches at Hadronic Collider*

At the Tevatron and at the LHC, gluon fusion provides the main production mode for the Higgs. The loop-induced $gg\phi_i$ coupling is dominated by the $t, \tilde{t}$ and $\tilde{b}$ loops. CP violation in the MSSM can have effects on this loop-induced coupling and thus affect the Higgs production rates at the hadronic colliders. In [15] the authors consider a situation where the loop-induced mixing between h, H and A is not significant but the effect on the Higgs production rate due to the effect of $\not{C}\not{P}$ squark–squark–Higgs vertex on the $gg\phi_1$ coupling is large. In figure 5 the contours of ratios of h, H production rates in the CP-violating MSSM to those without CP violation are shown. This corresponds to the case where the $\not{C}\not{P}$ in the MSSM induces CPV $\tilde{q}\tilde{q}h(H)$ couplings. As expected from the sum rule we find that whereas the h production rate increases in the allowed region, the H production rate decreases. As can be seen from the figure the effects can be considerable.

In the case of loop-induced CP-mixing in the Higgs sector [10–14], a complete analysis involving all the three colliders LEP, Tevatron and LHC was performed [14]. Figure 6 shows their results. In addition to the gaps in the LEP coverage for small Higgs masses which is already evident in the OPAL results of figure 4, this figure also shows that neither the Tevatron nor the LHC have reach in the same region due to a reduced $t\bar{t}\phi$ coupling, along with a reduction in $VV\phi$ coupling there. Thus the issue of light Higgs searches at the LHC needs to be revisited for the CP-violating

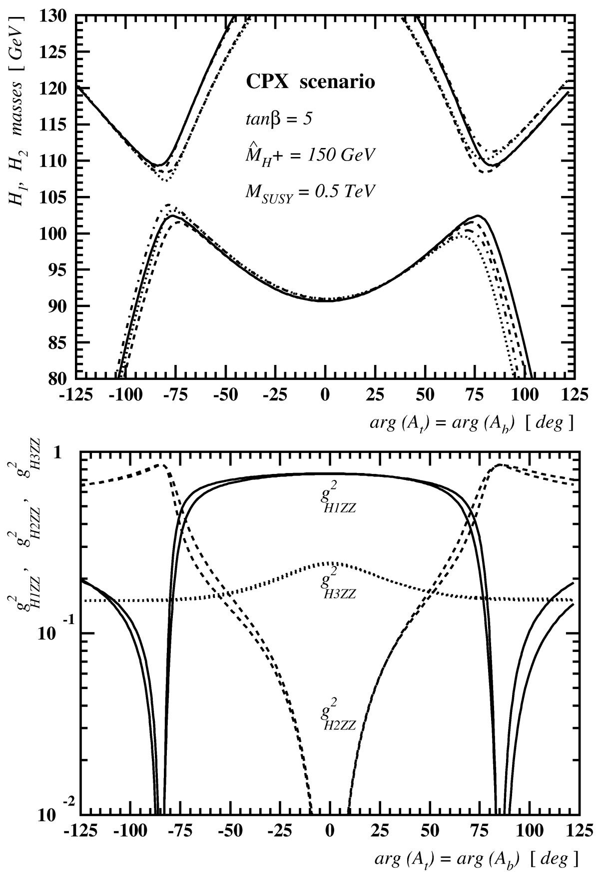


Figure 3. Variation of M_{ϕ_i} and $g^2_{\phi_i VV}$ with $\Phi_{A_t} = \Phi_{A_b}$. $\Phi_\mu = 0$ and $\Phi_3 = 0(\pi/2)$. Values of all the other relevant parameters are indicated on the figure and correspond to the case where ϕ_3 is also light with a mass ~150 GeV [13].

MSSM. Preliminary analyses by ATLAS Collaboration [30] seems to confirm this result of the theory analysis.

2.5 *Search for a light ϕ_1 in $H^\pm$ decay at the LHC*

One possible way this ‘hole’ could be probed is by searching for a light ϕ_1 in the decay of the charged Higgs $H^\pm$ [23,24]. The parameter space where the hole occurs corresponds to a relatively light $H^\pm$ ($M_{H^\pm} < M_t$), which is predicted to decay dominantly into the $W\phi_1$ channel. This happens due to a sum rule

$$g^2_{\phi_i VV} + |g_{\phi_i H^+ W}|^2 = 1.$$

Since the couplings of ϕ_1 with VV, gg, $t\bar{t}$ are suppressed, ϕ_1 coupling to H^+W is large. Thus, in the small $\tan\beta, M_{H^+}$ hole, where ϕ_1 may have been missed at the

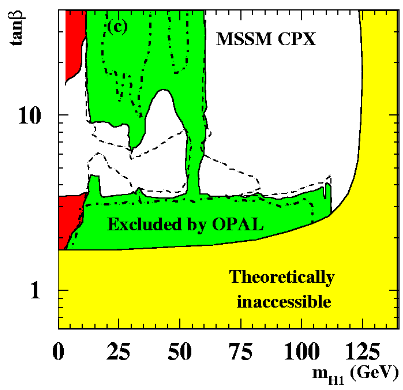


Figure 4. Regions in the $\tan\beta$–m_{ϕ_1} plane disallowed theoretically or excluded by the current LEP searches [29]. The allowed 'hole' at the low $m_{H^+}, \tan\beta$ values can be seen very clearly.

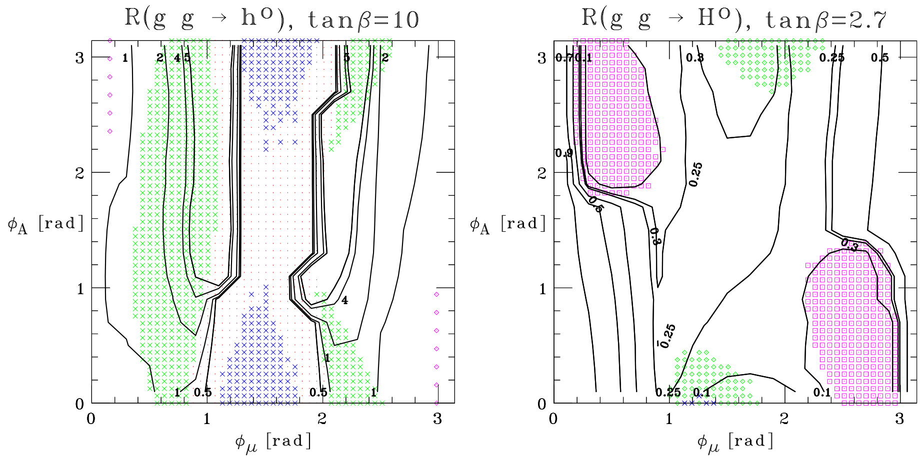


Figure 5. Contours of ratio of Higgs production to that expected in the CP conserving case, as a function of Φ_μ and Φ_A [15]. The left panel is for h and $\tan\beta = 10$ and the right panel is for H and for $\tan\beta = 2.7$. Also shown are the regions disallowed by the EDM constraints.

LEP and where LHC detection in the usual modes may be difficult, the branching ratio of H^+ into ϕ_1 is rather large.

Table 1 shows the variation of the branching ratios over this entire region. The value of the common CPV phase here is 60°. We see clearly from table 1 that the low mass of the moderately light charged Higgs allows it to be produced in the $t/\bar{t}$ decay, which further decays into ϕ_1. Note that BR$(H^\pm \to \phi_1 W) > 47\%$ over the *entire* kinematic region in the light ϕ_1 window still allowed by LEP.

A few points are worth noticing. Due to the rather small value of $\tan\beta$ the usual $\tau\nu_\tau$ decay mode for H^+ is also not available for the H^+ search in this case. Thus in this region of the MSSM parameter space, the above process provides a search

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 $\Phi_{\rm CP} = 60°$, 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.

$\tan\beta$	2	2.2	2.5	3.0
Br($H^+ \phi_1 W$)(%)	> 90 (83.5)	> 90 (80.32)	> 90 (73.85)	> 90 (63.95)
Br(tbH^+)(%)	4.0–4.2	4.9–5.1	4.8–5.11	4.0–4.3
M_{H^+}	< 133.6 (135.1)	< 122.7 (124.3)	< 113.8 (115.9)	< 106.6 (109.7)
M_{H_1}	< 50.97 (54.58)	< 39.0 (43.75)	< 27.97 (35.44)	< 14.28 (29.21)

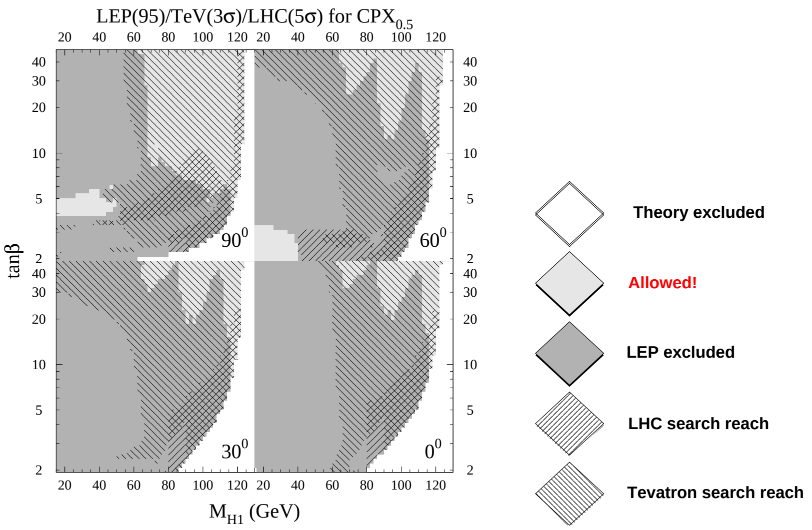


Figure 6. Coverage of LEP, Tevatron and the LHC for the Higgs searches in CPX scenario [14]

prospect not just for the light neutral state which might have been missed at the LEP, but also the light charged Higgs H^+. Secondly, a similar situation obtains in NMSSM as well [31].

Thus one can look at:

$$pp \to t \quad + \quad \bar{t} \quad + \quad X$$

$$t \hookrightarrow b\, H^+, \quad H^+ \hookrightarrow W\; H_1, \quad W \hookrightarrow \ell\nu(q\bar{q}), \quad H_1 \hookrightarrow b\bar{b}$$

$$\bar{t} \hookrightarrow \bar{b}\, W, \quad W \hookrightarrow q\bar{q}(\ell\nu)$$

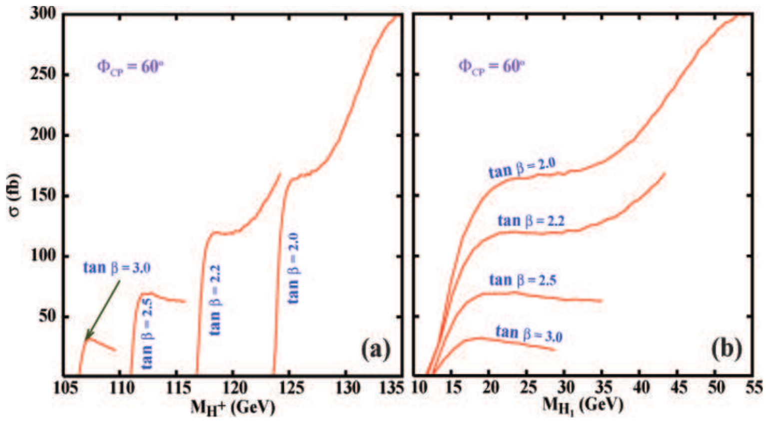


Figure 7. The left and right panel shows variation of the expected cross-section with M_{H^+} and M_{H_1} respectively for different values of $\tan\beta$ for CP-violating phase $\Phi_{\rm CP}$ 60°, respectively. Details of the parameters used are given in [24].

The process thus gives rise to very striking signal in $t\bar{t}$ production with: $t \to bH^+ \to b\phi_1 W \to bb\bar{b}W$ and $\bar{t} \to \bar{b}W$, with one W decaying leptonically and the other hadronically. Hence both $W's$ can be reconstructed. One can look at the $WWbbbb$ events, demanding three tagged $b's$. Our parton level Monte Carlo shows that the mass of the $b\bar{b}$ pair with the smallest value will cluster around m_{ϕ_1} and $b\bar{b}W$ around M_{H^+}.

Figure 7 shows that the cross-sections, even after including the b-tagging efficiency as well as putting cuts on various kinematic variables, are substantial and for $\mathcal{L} = 30\ \text{fb}^{-1}$ luminosity, one expects about 1000–5000 events. Further, the clustering of the invariant mass of the $b\bar{b}$ pair with the smallest value around m_{ϕ_1} and that of the $b\bar{b}W$ invariant mass around M_{H^+} can be seen from figure 8 taken from ref. [24]. As a matter of fact, this very clear clustering can make the signal almost background free. This result needs to be confirmed by experimental simulations including detector effects. We have checked that the QCD background can be removed by demanding that $bbbW$ mass be within 25 GeV of m_t. For example, possible QCD background coming from $t\bar{t}b\bar{b}$ production with a starting cross-section as high as 8.5 pb, is reduced to only about 0.5 fb with these cuts and reconstruction.

3. Determination of the CP-mixing at the LHC

While it is clear that the LHC can indeed search for a SM Higgs over the entire mass range that is allowed theoretically, determination of its profile is perhaps not very easy for the LHC. While it may be possible to distinguish between the CP-even and CP-odd nature of the Higgs boson at the LHC, the prospects of measuring the CP-mixing, should it be a state with indefinite CP, have not been yet fully explored [32]. The best bet for the determination of the CP nature of the Higgs is offered by the use of its couplings to a pair of gauge bosons either in production [34]

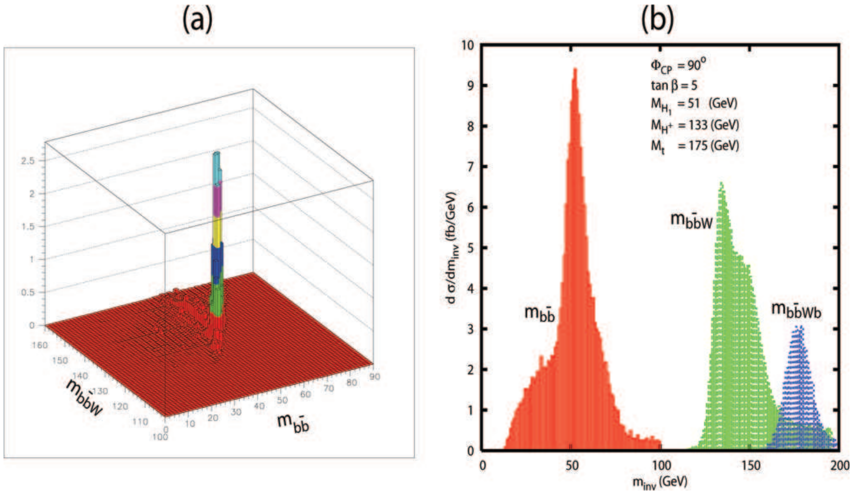


Figure 8. Clustering of the $b\bar{b}$, $b\bar{b}W$ and $b\bar{b}bW$ invariant masses and the three-dimensional plot showing correlation between the $m_{b\bar{b}} \equiv M_{H_1}$ and $m_{b\bar{b}W} \equiv M_{H^+}$ invariant masses. Details of the parameters used are given in [24].

or in the decay [33]. However, these are essentially tests which distinguish between the different tensor structures that a CP-even or CP-odd scalar can have with a pair of gauge bosons. The CP-mixing between the CP-even and CP-odd states in the Higgs sector induced by the $\not{CP}$ in the MSSM, only changes the normalisation of the $g_{\mu\nu}$ coupling and does nothing to the tensor structure. Hence methods based on the $VV\phi_1$ couplings do not probe this CP violation. In this case the best bet is indeed to make use of the $t\bar{t}\phi_i$ couplings. At the LHC, the $t\bar{t}$ final state produced in the decay of an inclusively produced Higgs can provide knowledge of the CP nature of the $t\bar{t}\phi$ coupling through spin–spin correlations [35] whereas $t\bar{t}\phi$ production can allow a determination of the relative strength of the scalar and the pseudoscalar coupling of ϕ_i with a $t\bar{t}$ pair [36]. The discussions in ref. [35] are in the context of a general 2-Higgs doublet model (2HDM); the ones in ref. [36] look simply at it in a model independent way. In the context of the specific model of CP-mixing induced by $\not{CP}$ MSSM parameters, the effects of CP violation in the $\tau\bar{\tau}\phi_1$ coupling on the τ polarisation at the LHC, have been discussed [37]. Some of these issues have been part of the Working Group activities at the workshop and hence have been discussed in detail in the WG report. I do not, therefore, discuss it further here.

4. Conclusions

Thus we note that the possibilities of probing the CP-violating phases in the MSSM in sparticle production and decays at the LHC have yet to be explored fully. These CPV phases can, in principle, affect the shape of dilepton invariant mass spectrum for the dilepton pair produced in the decay of $\tilde{\chi}_2^0$ and thus affect the sparticle mass determination accuracy etc. Further, these modifications may be a probe of the CPV phases if remaining SUSY parameters are known. CP-conserving quantities such as cross-sections, branching ratios are sensitive to the CPV phases, but for direct measurements CPV variables need be constructed. This task has still to be done for the LHC.

CP violation in MSSM can affect the Higgs search possibilities at the LEP and LHC profoundly. For low m_A and not too heavy squarks, $\not{C}\not{P}$ MSSM parameters can induce CPV in the $\tilde{q}\tilde{q}\phi$ vertex, which in turn can affect the Higgs production rate through gluon fusion, by as much as a factor 10, for values of CPV phases which are consistent with the EDM constraints. In the CPX scenario [11] chosen to showcase the $\not{C}\not{P}$ in the MSSM, existence of a light neutral Higgs boson ($M_{\phi_1} \lesssim 50$ GeV) is allowed at low $\tan\beta(\lesssim 5)$ region. It could have escaped the LEP searches due to a strongly suppressed $\phi_1 ZZ$ coupling. Even the LHC might miss discovering such a ϕ_1 due to the suppression of the $t\bar{t}\phi_1$ coupling as well. In this situation, decay of the light $H^\pm \to \phi_1 W$ may provide a signal for ϕ_1 through its $b\bar{b}$ decay. 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 $t \to bH^\pm, H^\pm \to W\phi_1$ and $\phi_1 \to b\bar{b}$. This provides a search channel not just for the light ϕ_1 which would be allowed to exist in this scenario, but also for the light H^+ which also must exist in this case.

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