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CP violation in Supesymmetry and the LHC

R.M. Godbole[a]

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

ABSTRACT

In this talk I discuss possibilities of probing the CP violation (CPV) in the Minimal Supersymmetric Standard Model (MSSM), at the LHC as well as its effects on the LHC SUSY phenomenology. In the latter case I mainly discuss its effect on the Higgs-sector and hence on Higgs Phenomenology at the LHC. After outlining the possibilities that a study of the $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production at the LHC might offer, I will summarise the effects of the CPV in MSSM on the Higgs searches at the LHC. Further, I will discuss how a study of the process $H^{\pm} \to W^{+}\phi_1$ may be able to plug a 'hole" in the $\tan\beta$-m_{H^+} plane, where the LEP has no sensitivity and where the searches in the usual discovery channels at the LHC are likely to fail as well.

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Rohini M. Godbole

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

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1 Introduction

At present Particle Physics finds itself at a very interesting juncture. Almost all the experimental observations are explained, to a great precision of ~ 1 part per mill or more, in terms of the Standard Model (SM). The triumph of the gauge paradigm, in describing correctly the fundamental particles and interactions among them, is almost complete with the 2004 Nobel Prize being awarded for the discovery of Asymptotic Freedom. The Higgs boson still eludes direct experimental observation, but the current precision data and direct searches bound its mass (in the SM) in a range which is accessible perhaps to the Tevatron and definitely to the LHC. In spite of this tremendous success, the SM still does not give us a fundamental understanding of quite a few of its features. CP violation (CPV) in the SM happens to be one of them. The precision measurements by BABAR and BELLE at the $B-$ factories [1] show conclusively that *all* the CP violation observed experimentally so far, can be accurately described in terms of that in the up-quark mass matrix encoded in the phase in the Cabbibo-Kobayashi-Masakawa(CKM) quark-mixing matrix. However, this amount of CPV is not sufficient to provide a *quantitative* understanding of the observed Baryon Asymmetry(BA) i.e., $\frac{N_b}{N_\gamma} \sim 6.1 \times 10^{-10}$ *but* $\frac{N_{\bar{b}}}{N_\gamma} \sim 0$. This makes a source of CPV, beyond that in the SM, imperative. Hence it seems logical to investigate implications of such additional CPV for the various theoretical attempts that the Particle Physics community is investigating to go beyond the SM in order to cure its various deficiencies.

Supersymmetry(SUSY), by now almost the 'standard' Beyond the Standard Model (BSM) physics, is arguably the best option to stabilise the Higgs mass (and hence the EW scale) against radiative corrections [2]. SUSY phenomenology at the LHC occupies a place of pride in the LHC studies, next only to the Higgs physics. A discussion of CPV on SUSY phenomenology at the LHC therefore, forms a very important part of the studies. In the following I will first discuss general issues about CPV and the MSSM. Then I will discuss the effects of CPV in SUSY on MSSM phenomenology at the colliders and summarise the effects of the CPV in MSSM on the Higgs searches at the LEP and LHC. Further, I will discuss how a study of the process $H^\pm \to W^+\phi_1$ may be able to plug a 'hole" in the $\tan\beta$-m_{H^+} plane, where the LEP has no sensitivity and where the searches in the usual discovery channels at the LHC are likely to fail as well

2 MSSM and CPV.

CPV in SUSY has almost changed from an ugly duckling to a swan in the recent years. The most general supersymmetric version of the SM, a MSSM with complex SUSY parameters, contains 44 phases which can not be rotated away by a simple redefinition of the fields. In early days of SUSY, these phases were all tuned to zero so as to avoid unacceptably large electric dipole moments (EDM's) for fermions. However, a few years back it was noted [3] that it was possible to satisfy all the constraints on the EDM's with some of the phases of $\O(1)$, quite generally, provided the first two generations of squarks are heavy.

At this point it is also worth noting that the CPV in the Higgs sector is a very attractive source for the above mentioned additional CPV that is required for a quantitative explanation of the observed BA in the Universe. The $\not{CP}$ phases of the SUSY(breaking) parameters can induce, through loop effects, $\not{CP}$ in a Higgs sector which is CP-conserving at the tree level. Thus in the MSSM it maybe possible to satisfy all the EDM constraints and still have sufficient $\not{CP}$ in the theory to explain the BA quantitatively. Thus it is clear that $\not{CP}$ SUSY will also have implications for the Higgs Phenomenology at the colliders. Given the fact that Higgs searches is 'raison d'eˆtre' for the current and future Colliders, investigations of $\not{CP}$ in supersymmetric theories are phenomenologically very interesting indeed.

3 Phenomenology of the MSSM with CPV at the colliders.

3.1 General Remarks.

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 higssino mass term 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 also can 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. These phases can thus change even the CP-even variables such as the sparticle production rates, their decay widths and branching ratios. Of course the 'direct' measure of these phases will be the non-zero 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 [4]. Due to the high precision of the measurements that would be possible at the ILC [5], at times the CP-even variables like the branching ratios, cross-sections, polarisations of fermions in final state, will offer a better probe of the $\not{CP}$ phases than the CP-odd quantities constructed out of the final state momenta.

For the hadronic colliders the effects of CPV in MSSM on Higgs phenomenology have been studied in the context of Tevatron and the LHC [6, 7, 8, 9, 10, 11, 12, 13, 14], whereas that on the $\tilde{\chi}^{\pm}, \tilde{\chi}^{0}$ phenomenology has been studied mainly only in the context of the Tevatron [15]. I will begin with a brief discussion of the latter in the next subsection.

3.2 Effect of $\not{CP}$ on $\tilde{\chi}$ phenomenology at hadronic colliders

The end point of the invariant mass distribution of the dilepton pair produced in the three body decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-$, plays a very important role in SUSY phenomenology, particularly at the hadron colliders. Nonzero CPV phases can change this distribution substantially and thus can affect phenomenology of cascade decays of the sparticles. Further, this also opens up possibility of extracting information on the CPV phase if *all* the SUSY model parameters are known. At a $p\bar{p}$ collider, it is possible to construct CP-odd quantities, for $\tilde{\chi}^{\pm}, \tilde{\chi}^{0}$ system, producing a trilepton signal via $p\bar{p} \to \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \to l l' \bar{l}' + \not{E}_T$. Since the initial state is a CP-eigenstate, it is possible to construct T-odd variables using the initial (anti)proton direction. Some

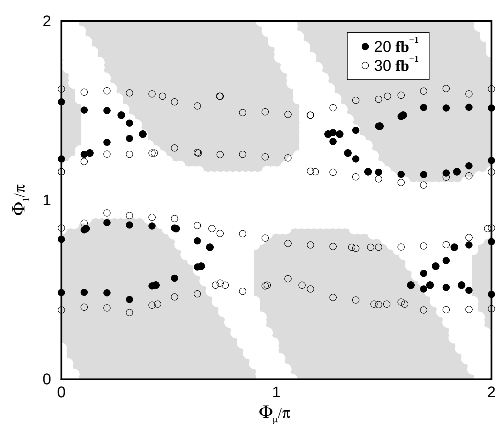


Fig. 1. Values of the $\not{CP}$ phases Φ_μ, Φ_1 that can be probed using the CP/T-violating asymmetries for the trilpeton signal, at 5σ level, for the luminosity indicated on the plot[15]. Shaded regions are ruled out by the EDM constraints.

of these variables are: $\mathcal{O}_T = \vec{p}_{\ell_1} \cdot (\vec{p}_{\ell_3} \times \vec{p}_{\ell_4})$ and $\mathcal{O}_T^{\ell\ell'} = \vec{p}_p \cdot (\vec{p}_{\ell} \times \vec{p}_{\ell'})$. In the first case $\ell_1 = \ell^-$ coming from the chargino decay $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \, \ell^- \bar{\nu}_\ell$, and $\ell_3 = \ell'^-$, $\ell_4 = \ell'^+$ coming from 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. The $\not{C}\not{P}$ phases also of course affect $\sigma(p\bar{p} \to \tilde{\chi}_1^- \tilde{\chi}_2^0)$, $\mathcal{B}(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \nu)$ and $\mathcal{B}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$. Fig. 1 illustrates what could be achieved at the Tevatron if an integrated Luminosity L = 20(30) fb^{-1}were to be available.

Since LHC is a pp collider the initial state is not a CP eigenstate and hence a different set of variables needs to be constructed in order to probe the $\not{C}\not{P}$ phases in the $\tilde{\chi}$ studies at the LHC. Even more importantly, investigations into effects of these phases on the studies at the LHC using, say, the cascade decays, are needed and do not yet exist. Such studies are essential in order to assess the feasibility of determination of the SUSY parameters at the LHC from sparticle phenomenology, which involve sparticle mass measurements using end point of the dilepton invariant mass spectrum.

3.3 MSSM with CPV and Higgs phenomenology

CP violation in the Higgs-sector is possible only in the presence of multiple Higgs doublets, the simplest one being the two Higgs doublet model (2HDM). In the CP-conserving 2HDM there exist three neutral Higgs boson states: the CP-even h, H and CP-odd A. In presence of CP violation all these three mix and one has three states ϕ_1, ϕ_2, ϕ_3, none of which have a fixed CP property. Discussions of CP violation in the Higgs sector and hence of CP mixing among the neutral higgs boson states in a *model independent way*, existed in literature [16]. 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,

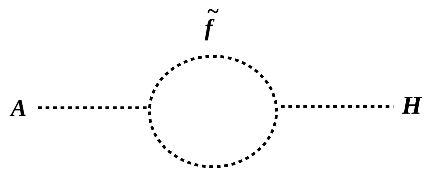
$$g^2_{\phi_i WW} + g^2_{\phi_j WW} + g^2_{\phi_k WW} = g^2 m_W^2, i \neq j \neq k.$$

As mentioned before the $\not{C}\not{P}$ phases of SUSY(breaking) parameters induce $\not{C}\not{P}$ violation in the Higgs sector, through loop corrections involving the third generation sfermions, even though the tree level scalar potential conserves CP. Thus a CPV MSSM is distinguished from a general CPV 2HDM, by the fact that the former has a prediction for the mixing in terms of SUSY(breaking) $\not{C}\not{P}$ phases of the MSSM mentioned before.

In general the scalar potential for a 2HDM can be written as

$$\begin{aligned} V &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.] \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + h.c. \right\} \end{aligned}$$

Unitarity implies that $V \in \Re$, which in turn means that $\{m_{11}, m_{22}, \lambda_{1-4}\} \in \Re$ and $\{m_{12}, \lambda_{5-7}\} \in \mathcal{C}$. In the MSSM various parameters in this potential can be expressed in terms of the gauge couplings and SUSY parameters μ, B, with $\lambda_5 = \lambda_6 = \lambda_7 = 0$. It can be shown in this case that any nonzero phase that m_{12}^2 may have can be rotated away by a redefinition of fields. Thus the tree level MSSM higgs potential can be CP-conserving even with nonzero phase of μ. However, at loop level, diagrams such as shown in Fig. 2 give non vanishing complex contribution



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

Fig. 2. Loop diagrams inducing CP-mixing in Higgs sector in the $\not{C}\!\not{P}$ MSSM

to m_{12}^2 which can not be any more rotated away as there is no freedom of field redefinition anymore. The CP-mixing in the Higgs sector can be parametrised by $\{\Phi_{A_f}, \Phi_3, \Phi_\mu\}$ [17, 18]. In certain regions of SUSY(breaking) parameter space the $\not{C}\!\not{P}$ phases can also induce CP violation in the sfermion-sfermion-Higgs vertex [6] and this in turn can give rise to EDM's of fermions which depends on $|A|, \Phi_\mu$ and Φ_A. Fig. 3 shows the constraints on the phases given by the EDM's for a given set of sparticle masses and SUSY parameters. Thus if this scenario is realised one will have to choose $|A|$ values to be greater than indicated on the contours so as to satisfy the EDM constraints and look at the effect of this CP-mixing on the Higgs boson phenomenology. The right panel of the figure shows that it is much more difficult to achieve consistency with the data for larger values of $\tan\beta$. In this case the allowed regions are due to accidental SUSY cancellations. For large values of $M_{\tilde{q}_3}$ and A, the loop induced CP-mixing mentioned earlier becomes dominant. In the so-called CPX scenario [18], designed to showcase this mixing one chooses: $M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY}, \mu = 4 M_{\rm SUSY}$, $|A_{t,b,\tau}| = 2 M_{\rm SUSY}$ and $|M_3| = 1 TeV$. Then the masses and couplings of the Higss bosons are studied as 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. The left panel of the Fig. 4 shows the masses for the lightest two Higgs-boson states and the right panel shows its couplings to a pair of vector boson V. It is to be noted that the Φ_3 has an effect on the masses at two loop level and hence the dependence on it is quite weak for small values of $\tan\beta$. Further it is also seen that for large phases of A_t, A_b, $g_{\phi_1 ZZ}$ decreases and it can even vanish for the case where ϕ_1 is mostly a pseudoscalar. For larger values of $\tan\beta$ effects of the phase Φ_3 can be significant and have been investigated in Ref. [11].

Since the production of Higgs boson at all the colliders utilises its large couplings with the Z/W bosons as well the heavy fermions, it is clear that the above

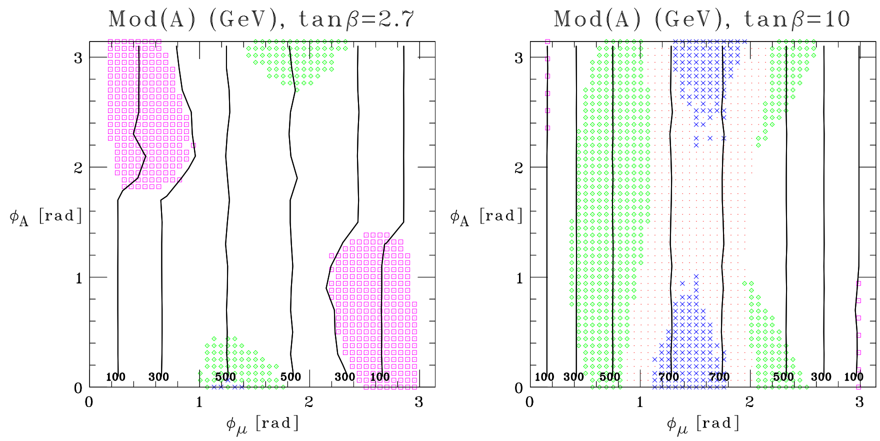


Fig. 3. Contours of $|A|$ in GeV in the Φ_μ–Φ_A plane along with the regions excluded by constraints on the EDM's indicated by the shaded area [6]. The plot in the left panel is for $\tan\beta = 2.7, |\mu| = 600\text{GeV}, \mathrm{M}_{\tilde{q}_{1,2}} = 1000\text{GeV}, \mathrm{M}_{\tilde{q}_3} = 300\text{GeV}, \mathrm{M}_{\tilde{g}} = 300\text{GeV}$ and $M_A = 200\text{GeV}$, whereas for the right panel $\tan\beta = 10$, $M_{\tilde{q}_{1,2}} = 300\text{GeV}$.

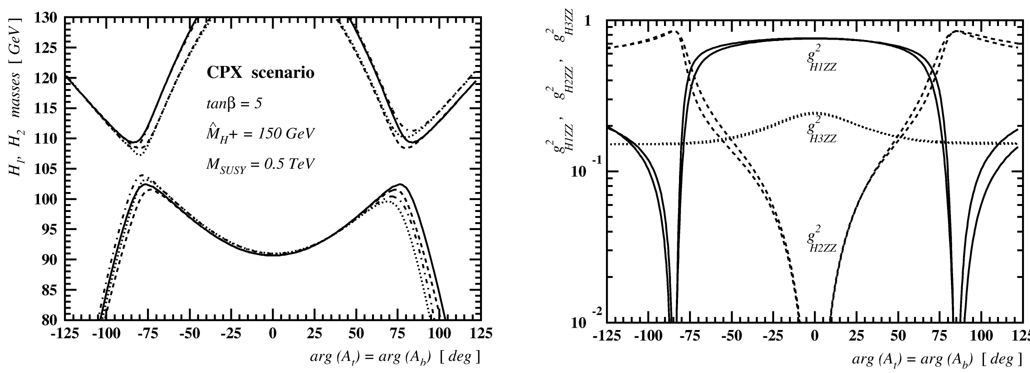


Fig. 4. Variation of M_{ϕ_i} and $g^2_{\phi_i VV}$ with $\Phi_{A_t} = \phi_{A_b}$. $\Phi_\mu = 0$ and $\Phi_3 = 0(\pi/2)$. Values of all the other relevant parameters are indicated on the figure and correspond to the case where the ϕ_3 is also light with a mass ~ 150 GeV [10].

change in the couplings can affect the Higgs boson phenomenology at all the colliders drastically. The non observation of a Higgs boson signal in the direct searches at the LEP needs to be reinterpreted in the MSSM with CP violation. The recent analysis from OPAL [19] 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 with the non-observations of the signal at LEP. Essentially the lightest mass eigenstate is dominantly a pseudoscalar in this case and hence does not couple to a ZZ pair very effectively.

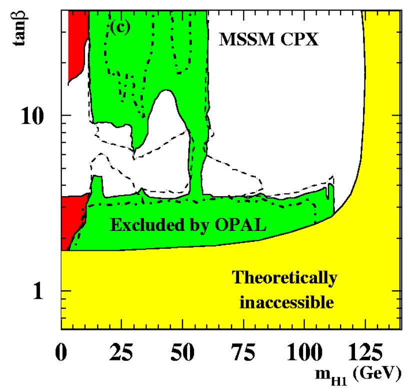


Fig. 5. Regions in the $\tan\beta$–m_{ϕ_1} plane disallowed theoretically or excluded by the current LEP searches[19]. The allowed 'hole' at the low m_{H^+}, $\tan\beta$ values can be seen very clearly.

3.4 Effect of CP mixing on Higgs searches at Hardonic 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 Fig. 6 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 increase in the allowed region, the H production rate decreases.

In case of loop induced CP mixing in the Higgs sector [17, 18] a complete analysis involving all the three colliders LEP,Tevatron and LHC was performed [10]. In addition to the gaps in the LEP coverage for small Higgs masses which is already evident in the OPAL results of Fig 5, 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 MSSM. Preliminary analyses by ATLAS collaboration [20] seems to confirm this result of the theory analysis.

3.5 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 $H^\pm$ [13, 14]. 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. Thus one expects to see a striking $t\bar{t}$

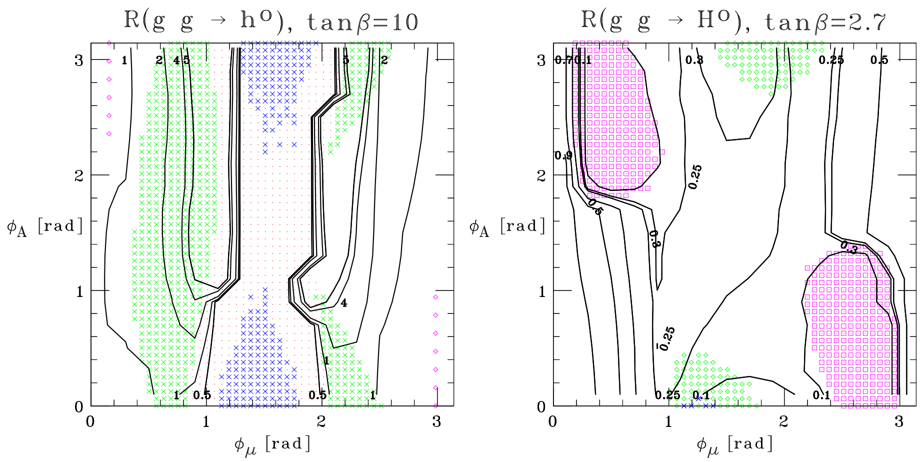


Fig. 6. Contours of ratio of Higgs production to that expected in the CP conserving case, as a function of Φ_μ and Φ_A[6]. The left panel is for h and $\tan\beta = 10$ and the right panel is for H and for $\tan\beta = 2.7$. Also shown are the regions disallowed by the EDM constraints.

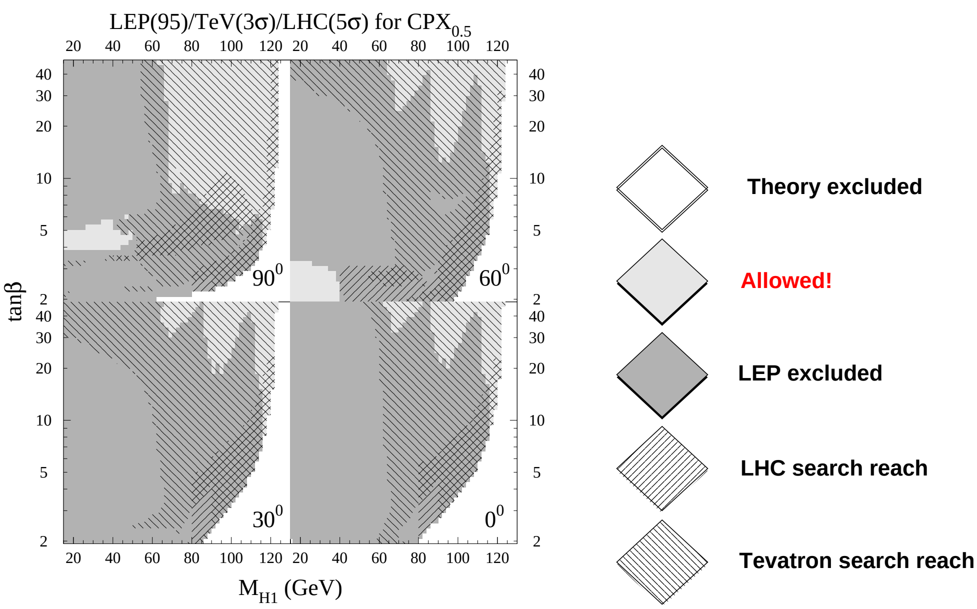


Fig. 7. Coverage of LEP,Tevaron and the LHC for the Higgs searches in CPX scenario[10]

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 $\phi_1 \to b\bar{b}$. 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 up to 4500 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. 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 Fig 8 taken from Ref. [14]. This result needs to be confirmed by experimental simulations. including detector effects.

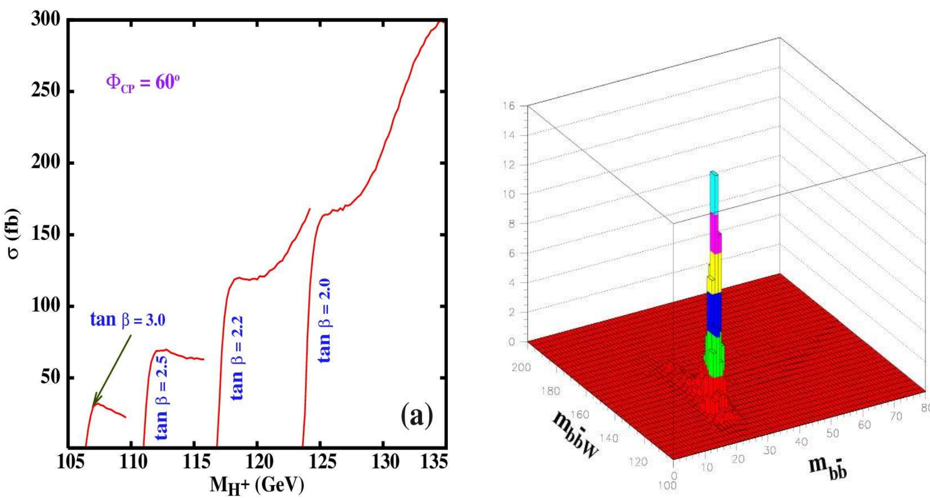


Fig. 8. Left panel shows variation of the expected cross-section with M_{H^+} for four values of $\tan\beta = 2, 2.2, 2.5$ and 3. The CP-violating phase $\Phi_{\rm CP}$ is 60°. The right panel shows lustering of the $b\bar{b}, b\bar{b}W$ and $b\bar{b}bW$ invariant masses in the three-dimensional plot for the correlation between $m_{b\bar{b}} \equiv M_{H_1}$ and $m_{b\bar{b}W} \equiv M_{H^+}$ invariant mass distribution. Details of the parameters used are given in [14].

4 Conclusion

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 [18] 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 low $\tan\beta(\lesssim 5)$ region and 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 the 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 $\phi_1 \to b\bar{b}$.

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