Synopsis

- Name: Priyotosh Bandyopadhyay
- Thesis title: Some studies on Higgs searches at the Large Hadron Collider in scenarios beyond the Standard Model
- Supervisor: Dr. Asesh Krishna Datta
- Submitted to Homi Bhabha National Institute (HBNI)

Predictions of the Standard Model (SM) of particle physics have now been verified at a remarkable level of precision in recent and ongoing experiments. Central to the SM is the issue of Electro-Weak Symmetry Breaking (EWSB) via the Higgs mechanism which predicts a massive scalar, the Higgs boson. Interestingly enough, this is the only particle of the SM spectrum which is yet to be discovered. Hence, search for the Higgs boson emerges as a priority programme at the running (like Tevatron) and the near-future (like the Large Hadron Collider or LHC) collider experiments.

However, although technically consistent in its formulation, the SM has got a rather unpleasant feature that screws up its scalar (Higgs) sector. The mass of the Higgs boson receives large quantum corrections ($\delta m^2_H$) which is quadratic in the cutoff scale up to which the SM remains the valid description of Nature. That the Higgs mass is not protected against quantum corrections is attributed to the fact that there is no corresponding symmetry for the scalar sector like the chiral symmetry and the gauge symmetry for the fermion-sector and the gauge-sector of the SM respectively which protect the masses of the fermions and gauge bosons against large radiative corrections. Thus, the mass-hierarchy gets destabilised in the scalar sector and the issue is known in the literature as the Hierarchy Problem. To ensure the Higgs mass to be of the electroweak scale, as is being indicated by several recent and on-going experiments, one thus requires an ‘unnatural’ amount of artificial fine-tuning. These are referred to as the Fine-tuning Problem and the Naturalness Problem pertaining to the Higgs sector of the SM. In fact, these problems are known to be very generic to any framework that involves fundamental scalar(s) in its spectrum.

On the other hand, ‘conspiring’ systematic cancellations between different contributions to ($\delta m^2_H$) might take place naturally in presence of a suitable symmetry. A space-time
symmetry like supersymmetry (SUSY), through a SUSY extension of the SM, offers such a possibility thus providing a technical resolution to the problem. Such an extension necessarily contains corresponding (super)partners (the superparticles or the sparticles) for all the SM excitations which differ by spin 1/2 from the latter. The quadratic divergences in context get exactly cancelled between diagrams containing the SM particles and the corresponding SUSY excitations.

Fundamental to a consistent minimal SUSY extension of the SM (the so called MSSM) is a construct called superpotential which preserves SUSY. For the framework to be well defined the superpotential should be an analytic function of the so-called chiral superfields which implies that two different Higgs doublets (with opposite hypercharges) are necessary to give masses to the up and down type quarks. Thus, the MSSM has necessarily an extended Higgs sector leading to a rich Higgs phenomenology. There are five physical Higgs bosons in the MSSM: two CP-even neutral ones \( h, H \), a CP-odd one \( A \) and two charged ones \( H^\pm \). Finding the signatures of these scalars gets inseparably linked to the search for SUSY at the upcoming LHC thanks to the subtle dynamics of the framework as a whole.

Search for the Higgs boson(s) at different ongoing (Tevatron) and recent (Large Electron Positron Collider or LEP) experiments has thus far yielded negative results. LEP came out with the most stringent lower bound on the SM Higgs mass which is \( m_H > 114.4 \) GeV. The same limit also holds for the lightest neutral Higgs boson \( h \) of the MSSM in the so-called decoupling limit, i.e., the limit in which the masses of all other Higgs bosons become very large compared to the mass of the \( Z \)-boson. Although smaller values of \( m_h \) (less than 114.4 GeV) are allowed away from the decoupling limit, the experimental lower bound on \( m_h \) is approximately the \( Z \)-mass. However, all these hold only when CP is a good symmetry in the MSSM framework.

It is now well-known that the bound from LEP on the mass of the lightest Higgs boson of the CP-conserving MSSM can get drastically reduced or even may entirely vanish if non-zero CP-violating phases are allowed for. This can happen through radiative corrections to the Higgs potential, whereby the phases, if any, of the Higgsino mass parameter \( \mu \) and the trilinear soft SUSY breaking parameter \( A \) enter the picture. The neutral Higgs states cease to be of definite CP property and they now can mix. The mixing depends on the values of these parameters and their phases. In particular, the scenario with a generic range of a suitable set of SUSY parameters for which the CP-violating effect turns out to be maximal is known in the literature as the ‘CPX’ scenario. Such a scenario serves as a useful benchmark for studying the CP-violating Higgs sector at the collider experiments. The couplings of the new Higgs eigenstates to gauge bosons as well as to fermions get modified depending on
the magnitude of the phases. Thus, there are three neutral states $h_i$ ($i=1,2,3$). The mass-bounds for all of them would get modified since the squared amplitudes for production via $WW$, $ZZ$ and $q\bar{q}$ couplings for all of them now consist of more than one term. Mutual cancellations among such terms can take place in certain regions of the parameter space thus resulting in reduced production rates and consequent weakening of different mass limits at collider experiments. In addition, complementary channels such as $e^+e^-\to h_1h_2$ suffer from coupling as well as phase-space suppressions. As a result, LEP experiments could not at all probe some regions in the CPX parameter space and hence no lower bound on the Higgs mass resulted in. These regions in $m_{H^\pm}$-$\tan\beta$ space are known in the literature as the ‘LEP holes’. One such extended hole is found for low to moderate $\tan\beta$ (3-10) and for charged Higgs mass lying between 30 and 50 GeV. However, a consensus over the exact span of this inaccessible region is still to be reached. We focus our study to this region.

It has been noted that although the hadron colliders can probe most of the parameter space of the CPX scenario and can indeed go beyond what already probed by the LEP searches, the lightest Higgs boson may still escape detection in the region of parameter space corresponding to the aforementioned hole. This is because not only $Z-Z-h_1$ but also the $W^+W^-h_1$ and $t\bar{t}h_1$ couplings tend to be very small within this hole. On the other hand, the relatively heavy neutral Higgs bosons $h_{2,3}$ couple to $W$, $Z$ and $t$ favourably, but they can decay in non-standard channels, thus requiring a modification in search strategies. Existing work that has compiled possible signals of the CPX scenario at the LHC is also restricted to the production of $h_i$ ($i=1,2,3$) bosons in SM-like channels. However, it looked into more decay channels of the $h_i$ bosons thus produced. It has been henceforth concluded that parts of the holes in the $m_{H^\pm}$-$\tan\beta$ or the $m_{h_1}$-$\tan\beta$ parameter space can be plugged, although considerable portions of the hole, especially for low $\tan\beta$, may still escape detection at the LHC even after accumulating 300 fb$^{-1}$ of integrated luminosity. Thus, it is important to look for other production channels for the scalars in the CPX region, especially by making use of the couplings of $h_1$ with the sparticles.

It is gratifying to note in this context that the $\tilde{t}_1\tilde{t}_1^*h_1$ coupling, where $\tilde{t}_1$ is the lighter top squark, indeed leads to such a discovery channel, in cases where the $t\bar{t}h_1$ and $W$-$W$-$h_1$, $Z$-$Z$-$h_1$ couplings are all highly suppressed. In fact, it has been observed that in a general CP-violating MSSM scenario, the cross section of $\tilde{t}_1\tilde{t}_1^*h_1$ production could be dramatically larger than that obtained by switching off the CP-violating phases. Since the trilinear SUSY breaking parameter $A_t$ is necessarily large in the CPX scenario, $\tilde{t}_1$ tends to be relatively light and may thus be produced at the LHC with large cross section. As a bonus, both $h_2$ and $h_3$ also couple favourably to the $t\bar{t}$ pair and can add modestly to the signal, although by themselves, they fail to produce a statistically significant signal. In this
work we investigate the implications of these couplings at the LHC, by concentrating on a specific signal arising from the associated production of the neutral Higgs bosons with a top-pair or a pair of lighter top squarks. The final state we study is $n$-jets (with $n \leq 5$ of which 3 are tagged $b$-jets) + dilepton + $\not{p_T}$. We have carried out a thorough analysis of the above final state taking into account the major backgrounds. We find that with an integrated luminosity of 30-50 fb$^{-1}$ the ‘hole’ can be probed fully with a healthy enough significance [1].

In a separate study [2,3] we concentrate on a different aspect of Higgs-search within a CP-conserving SUSY framework. Higgs bosons are expected to be looked for at the LHC in all probable channels to extract maximum possible information about the underlying framework through various consistency checks. This is also important since the SM-like production processes (with reference to which the current experimental constraints on the MSSM Higgs sector are derived) are known to be only sensitive to specific ranges of some SUSY parameters. For example, for most of the SM-like production processes like $gg \rightarrow h, H, A$, the associated production with heavy quarks like $gg, q\bar{q} \rightarrow h, H, A + t\bar{t}$ or $b\bar{b}$ for the neutral Higgs bosons and $t \rightarrow H^+b$ or associated production with top quarks like $gg/q\bar{q} \rightarrow H^+b$ for the charged Higgs bosons, the production processes are only enhanced for extreme values of $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets which are collectively responsible for the breaking of the electroweak symmetry in the MSSM. Another example of limitations of the SM-like production processes is as described earlier, when an otherwise viable signal of a Higgs boson produced in association with superparticles fails due to presence of CP-violation. Hence, other characteristic interactions of the MSSM Higgs bosons, if present, must be exploited for the purpose.

In particular, there exist nontrivial interaction-vertices among the electroweak gauginos/higgsinos (the charginos and the neutralinos) and the MSSM Higgs bosons. These imply that decays of charginos/neutralinos may as well lead to Higgs bosons. On the other hand, the major source of charginos and neutralinos at the LHC would be the cascades of squarks and gluinos which are expected to be produced copiously at the LHC via strong interactions. It has already been demonstrated in earlier works that the overall suppression due to different branching fractions along a SUSY-cascade leading to Higgs bosons could be more than compensated for by the strong production cross section at the top of the cascade. Hence, the strong production of squarks and gluinos may eventually turn out to be a major source of Higgs bosons at the LHC under such cascades. The compositions and the masses of the charginos and the neutralinos play a big role in the process. These, in turn, are determined by the values of the $U(1)$ and the $SU(2)$ gaugino masses ($M_1$ and $M_2$ respectively, which break SUSY softly) and the value of $\mu$, the SUSY-conserving higgsino-mass...
parameter appearing in the superpotential. On the other hand, the soft-SUSY breaking $SU(3)$ gaugino mass ($M_3$) determines the mass of the gluino which controls the strong production rates to a significant extent. Thus, it is clear that a correlation existing among these masses would play a crucial role in the phenomenology of Higgs bosons under SUSY cascades.

Canonical SUSY studies at colliders work in a paradigm that assumes high scale universality among different gaugino masses. Although highly economic and thus predictive (and hence, popular as well), there is no deep reason as to why such a universality should be robust. In contrary, it is now known that such universality is a result of a trivial form of the so-called gauge kinetic function from which the common gaugino mass arises at a high scale as SUSY breaks in the hidden sector. In particular, this happens when the gauge kinetic function involves a combination of hidden sector fields which is singlet under the underlying gauge group of the SUSY Grand Unified Theory (SUSY-GUT). However, contributions from the non-singlet higher GUT representations or from the linear combinations of the singlet and possible non-singlet representations may effectively induce non-universality in the soft masses for the gauginos at the high scale itself. Such triggering of non-universality at the high scale would distort the spectrum of the gaugino masses at the weak scale with respect to one obtained with universality condition intact at the high scale. This leads to a modification in the compositions of the charginos and neutralinos and alterations in relative masses for all of them including the gluino. As indicated in the last paragraph, this is bound to have a significant impact on the resulting phenomenology at colliders including Higgs searches at the LHC under SUSY cascades.

Thus, SUSY cascade decays are mainly governed by the soft-SUSY breaking gaugino mass parameters $M_1, M_2, M_3$ and $\mu$. Assumption of a universal gaugino mass at a high scale (GUT scale) leads to a particular ratio among the three gaugino masses at the weak scale which is $M_1 : M_2 : M_3 = 1 : 2 : 6$. In other words, this weak scale ratio among the three gaugino masses reflects the universality of them at the high scale. Any departure from this ratio could very well signal a non-universality of gaugino masses at the high scale. Hence, high scale non-universality among the gaugino masses can be effectively realised by freely varying $M_1, M_2$ and $M_3$ at the weak scale. We considered such departures from universality and studied their implications for Higgs boson productions under cascade decays of the SUSY particles in the framework of MSSM. We then contrast them with results expected from a scenario with universal gaugino masses. The situation for smaller and somewhat large charged Higgs masses, viz., the cases with $m_{H^\pm}=180$ GeV and 250 GeV respectively, are also discussed. Remarkably enough, the cross-sections of the lightest neutral Higgs boson and that of the charged Higgs bosons, when plotted as functions of
$M_2$ or $\mu$, show a “cross-over” behaviour. We use this relative event-rates for the neutral and the charged Higgs bosons as a tool to distinguish between the universal and the non-universal scenarios. Complete scans over the $M_2-\mu$ parameter space are undertaken for some appropriately chosen benchmark points to highlight the contrast. Signal topology and cuts are suitably chosen to ensure a healthy significance for the signal. In the neutral Higgs sector we reconstruct the $b\bar{b}$ invariant mass peak and study its significance over the backgrounds. On a detailed analysis it is observed that, for the universal case, more or less all benchmark scenarios would have signals with $5\sigma$ significance for an integrated luminosity of 10 fb$^{-1}$, whereas for the non-universal case, some points fail to achieve that. On the other hand, for the charged Higgs boson, we carry out our analysis in two different modes: (i) $H^\pm \rightarrow \tau^\pm \nu_\tau$ for a lighter charged Higgs boson ($m_{H^\pm} = 180$ GeV) and (ii) $H^\pm \rightarrow t\bar{b}$ for a somewhat heavy charged Higgs boson ($m_{H^\pm} = 250$ GeV). We find that complementary to the neutral Higgs case, here it is the non-universal scenario which can have a significance of $5\sigma$ or above even with an early data from the LHC (with an integrated luminosity of 10 fb$^{-1}$). Thus, Higgs production under SUSY cascades can effectively shed light on the issue of actual universality/non-universality of the gaugino masses at a high scale.

Of recent, in a separate study [4], we look into the prospects of uncovering the Higgs sector of the Universal Extra Dimensions (UED) with one extra spatial dimension. In such a scenario, all the SM particles including the Higgs boson can propagate into the bulk. Compactification of the extra spatial dimension via orbifolding (a $S_1/Z_2$ orbifold, to ensure chiral fermions in usual 4-dimensions) leads to an expected tower of the Kaluza-Klein (KK) excitations for all the SM particles including the Higgs boson. This makes the Higgs sector of the UED phenomenologically rich with four Higgs excitations appearing at the first KK-level. These are one CP-even Higgs boson, one CP-odd Higgs boson and two charged Higgs bosons.

In the framework of the so-called minimal UED (mUED) with conserved KK-parity $[K_p = (-1)^n$, a $Z_2$ parity, where $n$ is the KK-level in reference], precision electroweak data restrict $R^{-1}$ to $R^{-1} \gtrsim 300$ GeV where $R$ is the radius of compactification. The scenario, in particular its Higgs sector, is specified by the following four input parameters: $R^{-1}$, the effective cutoff of the theory ($\Lambda$), the mass of the SM Higgs boson (i.e., KK level-0 Higgs boson) and $\tilde{m}_h^2$, the so-called boundary mass-squared term for the excited scalars. The salient features of the UED-Higgs sector turn out to be the following: (i) In the minimal scenario with $\tilde{m}_h^2 = 0$, the masses of the KK-Higgs bosons are predominantly determined by $R^{-1}$ for its values ($\mathcal{O}(1\,\text{TeV})$) that are theoretically allowed and phenomenologically interesting. They are thus nearly degenerate to each other and also to the KK-excitations of the SM-gauge bosons and the SM-leptons from the same level. (ii) The four Higgs bosons
from the first KK-level could very well be the only kinematically accessible Higgs excitations at the LHC along with the (level ‘0’) SM Higgs boson. At this point, these five Higgs bosons are reminiscent of five such Higgs bosons of the MSSM. (iii) An important difference, however, is that all the level-1 KK-Higgs bosons have odd KK-parity and thus would be produced only in association with another heavy (KK-odd) level-1 UED excitation, i.e., they cannot be singly produced thus resulting in their generic production rates smaller than the corresponding MSSM Higgs bosons. The heavi-ness coupled with imposed KK-parity of the UED Higgs bosons along with the prevailing degeneracy in the KK-spectrum makes the production and detection (because of softer visible decay products) of the KK-Higgs bosons a challenging proposition. Thus, we also try to see into the possibility of having non-zero values of $\bar{m}_h^2 = 0$ which may bring out appreciable splitting between the UED Higgs bosons and other UED excitations at a given KK level thus influencing the Higgs phenomenology at the LHC.

In our work we quantitatively estimate the situation by calculating the production cross-sections and decay rates for the KK Higgs bosons in different possible modes. The direct production rates for these level-one Higgs bosons turn out to be very low as they are to be produced in association with a suitable level-1 excitation, both of which are heavy and, also that the processes are mostly going to be electroweak in nature. Associated productions of the KK Higgs bosons with excitations of the third generations fermions (top, bottom and tau) are also being investigated. On the other hand, at the LHC, the strongly interacting level one excitations ($g_1 g_1, g_1 q_1, q_1 q_1$, etc.) can be copiously produced when $R^{-1}$ is in the ballpark of 1 TeV. This opens up the possibility of Higgs production under the cascade decays of UED excitations similar to the case in MSSM discussed earlier. Our initial focus is on the charged Higgs production under such UED cascades. With $\bar{m}_h^2 = 0$, as indicated above, the prospects of detecting the excited Higgs-bosons tend to diminish due to their dominant decays to rather soft ($\sim 10$ GeV) $\tau$-s. While one starts to have harder $\tau$-s with increasing $R^{-1}$, this in turn lowers the production cross-sections at the top of the cascade in the first place thus making the early detection of KK-Higgs bosons very difficult for phenomenologically interesting values of $R^{-1}$ [4] and for $\bar{m}_h^2 = 0$. Thus, a detailed study of the prospects of the LHC in probing the UED Higgs sector with non-vanishing $\bar{m}_h^2$ turns out to be a highly relevant exercise.