Status of MSSM Higgs Sector using Global Analysis and Direct Search Bounds, and Future Prospects at the HL-LHC

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Abstract

In this paper, we search for the regions of the phenomenological minimal supersymmetric standard model (pMSSM) parameter space where one can expect to have moderate Higgs mixing angle ($\alpha$) with relatively light (up to 600 GeV) additional Higgses after satisfying the current LHC data. We perform a global fit analysis using most updated data (till December 2014) from the LHC and Tevatron experiments. The constraints coming from the precision measurements of the rare $b$-decays $B_s \rightarrow \mu^+\mu^-$ and $b \rightarrow s\gamma$ are also considered. We find that low $M_A (< 350)$ and high $\tan \beta (> 25)$ regions are disfavoured by the combined effect of the global analysis and flavour data. However, regions with Higgs mixing angle $\alpha \sim 0.1 - 0.8$ are still allowed by the current data. We then study the existing direct search bounds on the heavy scalar/pseudoscalar (H/A) and charged Higgs (H$^\pm$) masses and branchings at the LHC. It has been found that regions with low to moderate values of $\tan \beta$ with light additional Higgses (mass $\leq 600$ GeV) are unconstrained by the data, while the regions with $\tan \beta > 20$ are excluded considering the direct search bounds by the LHC-8 data. The possibility to probe the low $\tan \beta$ ($\leq 10$) region at the high luminosity run of LHC are also discussed and it has been found that even the high luminosity (3000 fb$^{-1}$) run of LHC may not have enough sensitivity to probe the entire region of parameter space.
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1 Introduction

The ATLAS and CMS collaborations have confirmed the discovery of a standard model (SM) like Higgs boson with mass close to 125 GeV [1, 2] at the end of 8 TeV run of LHC. The primary goal of 13/14 TeV run of LHC with increased integrated luminosity would be the more detailed study of various properties of the observed Higgs boson. The production modes of the observed Higgs boson that are analyzed at the LHC are the gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production with a W or Z, and associated production with a top-antitop pair. The decay modes of the Higgs boson that are studied by the ATLAS and CMS collaborations are $\gamma\gamma$, WW, ZZ, $b\bar{b}$ and $\tau^+\tau^-$. The di-photon and ZZ modes have been used to precisely measure the mass of the observed Higgs boson [15, 16]. The measurements by the ATLAS and CMS collaborations using LHC-8 data indicate that the couplings of the Higgs boson seem to agree with the SM predictions quite well. Tevatron have also reported the evidence of a SM-like Higgs boson with mass around 125 GeV [17]. Even though various coupling measurements at the LHC have already ruled out large deviations from the SM expectations, still the presence of uncertainties in coupling measurements do not rule out the possibility of having non-standard couplings of the observed Higgs boson. In fact, any small but statistically significant deviation from the SM expectations can be thought of as the first indication of new physics.

Supersymmetry (SUSY) [18–20] has been one of the most popular extensions of the SM, however a SUSY signature is yet to be observed at the LHC. Non-observation of sparticles at the LHC have placed severe constraints on the superparticle masses and couplings [21, 22]. The Higgs sector of the CP conserving minimal supersymmetric standard model (MSSM) contains two CP-even neutral Higgs bosons h and H, one CP-odd neutral Higgs boson A, and two charged Higgs bosons $H^\pm$. The lightest Higgs boson h can be identified with the observed 125 GeV Higgs boson. At the tree level, the Higgs sector of MSSM is described by two parameters: pseudoscalar mass $M_A$ and $\tan\beta$, where $\tan\beta$ is the ratio of the vacuum expectation values (vevs) of the two Higgs doublets. The mixing angle $\alpha$ between the neutral components of the two Higgs doublets can be determined in terms of $M_A$ and $\tan\beta$ at the tree level. However, radiative corrections to the Higgs boson mass matrix involving various SUSY parameters can modify the tree level value of $\alpha$. The couplings of $h$ with SM particles depend on $\alpha$ and $\beta$, hence global fit considering various Higgs coupling measurements at the LHC and Tevatron experiments can, in principle, constrain the MSSM parameter space.

Soon after the discovery of the 125 GeV Higgs boson, several analyses have been performed, for example, in the context of MSSM [23–38], general 2-Higgs doublet models [39–44], next-to minimal supersymmetric standard model (NMSSM) [45], effective theory framework [46–52]. However, in the last few months, both the ATLAS and CMS collaborations have updated some of their analyses on Higgs signal strength measurements. For example, ATLAS has updated their results for Higgs decay to $\mu^+\mu^-$ and $e^+e^-$ are also performed by both the ATLAS and CMS collaborations with 7+8 TeV LHC data [3, 4].
decaying to $\gamma\gamma$ [5], WW [7], ZZ [9], $b\bar{b}$ [11] channels, while CMS has published their new result for Higgs decaying to $\gamma\gamma$ [6]. In most of their analyses, the measure of uncertainty associated to various Higgs couplings have been now reduced by a sizable amount. A global analysis with all the most updated (up to December 2014) results on various Higgs coupling measurements at the LHC and Tevatron would be extremely useful to probe the MSSM parameter space.

In order to probe the Higgs sector of MSSM, the discovery/exclusion of additional Higgses is extremely crucial at the LHC. Besides the extensive study of the sparticles of the MSSM, both the ATLAS and CMS collaborations have performed dedicated searches of these additional Higgses in various possible final state signatures. Search for the heavy Higgs bosons (both H and A) are performed at the LHC with pair of $\tau$s in the final state [53, 54] considering both gluon-fusion and b-associated production modes. CMS and ATLAS has also searched for heavy resonances for the decay modes: $H \rightarrow \gamma\gamma$ [55], $H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ [56] and $H \rightarrow hh \rightarrow b\bar{b}b\bar{b}$ [57]. Heavy SM-like Higgs bosons decaying to pair of W bosons with final state consisting of one lepton, two jets and missing transverse energy has been studied by the CMS collaborations [58]. Heavy pseudoscalar Higgs boson (A) decaying to a Z boson and a light Higgs boson h has also been searched by the ATLAS and CMS collaborations at 19.7 fb$^{-1}$ luminosity at the 8 TeV run of LHC [59, 60]. In addition to that, both ATLAS and CMS have searched for the charged Higgs boson ($H^\pm$) decaying to $\tau\nu_\tau$, $c\bar{s}$ and $t\bar{b}$ when $H^\pm$ are produced via $t\bar{t}$ or in association with top quarks [61, 65]. So far, the ATLAS and CMS data have not revealed any signal and thus they put model-independent 95% C.L. upper limits on the production cross-section times branching ratios.

In the MSSM, the couplings of h with the SM electro-weak gauge bosons are proportional to $\sin(\beta - \alpha)$. The measured values of couplings of the observed 125 GeV Higgs boson with the $W/Z$ bosons are quite consistent with the SM expectations, which thus restricts the value of $\sin(\beta - \alpha)$ to unity. Non observation of additional Higgses (H, A and $H^\pm$) implies that their masses are possibly well above the electro-weak scale. One can satisfy both the above-mentioned observations by choosing $\alpha \sim 0$ and $\beta \sim \frac{\pi}{2}$ and/or $M_A >> M_Z$, which is generally known as the decoupling limit [20]. In this paper, however, we would like to address the following question: Is there any MSSM parameter space still allowed by the current LHC data where one can expect to have moderate Higgs mixing angle ($\alpha$) with relatively light (say, hundred to few hundred GeV) additional Higgses? In other words, we are looking for a feasible MSSM parameter space where the non-negligible Higgs mixing still exists, and simultaneously we have light additional scalar particles which can be probed at the run-II of LHC. Our strategy can summarized as follows:

- We first perform a $\chi^2$ analysis by scanning the relevant parameters of the MSSM Higgs sector and incorporating the updated Higgs signal strengths from the ATLAS, CMS and Tevatron experiments. The constraints coming from the precision measurements of rare decays like $B_s \rightarrow \mu^+\mu^-$ and $b \rightarrow s\gamma$ are also considered.

- We then impose the LHC direct search bounds on the heavy scalar/pseudoscalar Higgs (H/A)
and charged Higgs ($H^\pm$) masses and various branchings in the allowed parameter space.

- Finally, we study the possibility to probe the remaining parameter space in the high luminosity run of LHC.

In Sec. 2, we discuss the detailed prescription of our global fit analysis, followed by a brief outline of our parameter space scan. The favorable parameter space obtained after the global analysis is discussed in Sec. 2.2. In Sec. 3, we present the current limits on production cross-section times branching ratios obtained from the direct search of both neutral and charged Higgs bosons at the LHC. Future limits for the high luminosity run of LHC are discussed in Sec. 4. Finally in Sec. 5 we summarize our results.

2 Global analysis and available pMSSM parameter space

In this section, we discuss the details of our global fit analysis. Current bounds on various Higgs coupling measurements by the ATLAS and CMS collaborations at the LHC, and also by the CDF and D∅ collaborations at the Tevatron experiment are considered as the inputs to our global analysis. We also consider two important flavour physics constraints, namely $\text{BR}(b \to s \gamma)$ and $\text{BR}(B_s \to \mu^+ \mu^-)$ [66]. Finally, we discuss the features of the available parameter space satisfying the updated Higgs and flavour physics data.

2.1 Experimental inputs and Global fit analysis

Both the ATLAS and CMS collaborations have published the results of the 125 GeV Higgs boson searches combining the 7+8 TeV data at the end of 8 TeV run of LHC [5–16]. Besides, the results of the SM Higgs boson search by the CDF and D∅ collaborations at the Tevatron experiment are also available in the literature [17,67]. In our global analysis, we consider the most updated Higgs data obtained from the LHC and Tevatron experiments. The Higgs bosons are produced at the LHC mainly via the gluon-gluon fusion (ggF) process. However, there exist other sub-dominant production mechanisms e.g., vector boson fusion (VBF), associated production with a $W/Z$ boson (Vh), associated production with pair of top quarks ($t\bar{t}h$). The decay modes of the Higgs boson which are analyzed are by the ATLAS and CMS collaborations are $h \to \gamma \gamma$ [5,6], $h \to WW^*$ [7,8], $h \to ZZ^*$ [9,10], $h \to b\bar{b}$ [11,12], and $h \to \tau^+ \tau^−$ [13,14], while the CDF and $D\emptyset$ collaborations have analyzed the $\gamma \gamma$, $WW^*$ and $b\bar{b}$ decay modes of the Higgs boson [17,67]. The experimental findings are usually presented in terms of the signal strength variable ($\mu$), which is defined as the ratio of the production cross-section ($\sigma$) times the branching ratio (BR) to a specific decay mode for a given new physics model normalized to the SM prediction. For example, when the Higgs boson is produced via gluon-gluon fusion process and it decays to a generic final state $XX$ (say $\gamma \gamma$, $WW^*$, ...
then one can define the signal strength variable $\mu$, assuming narrow-width approximation, as:

$$
\mu_{ggF}(X\bar{X}) = \frac{\Gamma(h \rightarrow gg)}{\Gamma(h_{SM} \rightarrow gg)} \times \frac{BR(h \rightarrow X\bar{X})}{BR(h_{SM} \rightarrow X\bar{X})},
$$

(1)

where $h$ is a observed 125 GeV Higgs boson and $h_{SM}$ is the SM Higgs boson. Similarly, if the Higgs boson is produced via VBF fusion process and it decays to $X\bar{X}$, then one can define,

$$
\mu_{VBF/VH}(X\bar{X}) = \frac{\Gamma(h \rightarrow WW)}{\Gamma(h_{SM} \rightarrow WW)} \times \frac{BR(h \rightarrow X\bar{X})}{BR(h_{SM} \rightarrow X\bar{X})}.
$$

(2)

From Eq. 1 and 2 it is evident that the signal strengths are functions of the partial decay widths and the total decay width of the Higgs boson. The presence of new particles/interactions in the new physics models lead to modifications in the partial/total decay widths, and thereby changes in the value of signal strength variables. Thus, precise measurement of these signal strength variables are extremely crucial as a small but statistically significant deviation from the SM expectation will hint at possible signatures of the new physics. Note that, in the timeline of the Moriond 2014 [68] workshop to the end of December 2014, significant changes have been observed in the measurement of various Higgs signal strengths. For example, ATLAS data for di-photon signal strength has changed from $1.57^{+0.33}_{-0.28}$ [68] to $1.17 \pm 0.27$ [5], while the same from the CMS has changed from $0.77 \pm 0.27$ [68] to $1.14^{+0.26}_{-0.23}$ [6]. Besides, both statistical and systematics uncertainties associated to some of these signal strengths have been reduced after the combination of (7+8) TeV LHC data. Near the end of last year, the CDF and $D\emptyset$ collaborations have also updated the constraints of 125 GeV Higgs boson couplings to fermions and vector bosons. We perform a global analysis considering all these most updated Higgs signal strengths as of the end of 2014. The available signal strength variables\(^2\), for different production and decay modes of the Higgs boson at the LHC are summarized in Tab. 1 to Tab. 5 while Tevatron Higgs data is shown in Tab. 6.

Let us now discuss the details of the MSSM parameter space scan. We do not consider any specific SUSY breaking scenario, rather we focus on the generic phenomenological MSSM (pMSSM) model with 19 free parameters and perform a random scan for approximately 100 million points. Those parameters that are relevant to the MSSM Higgs sector, namely pseudo-scalar mass parameter $M_A$, the ratio of the vacuum expectation values of two Higgs doublets $\tan \beta$, higgsino mass parameter $\mu$, the third generation squark trilinear couplings $A_t$ and $A_b$ (trilinear couplings of sleptons and first two generations squarks are set to zero), third generation squark soft mass parameters $M_{Q3}$, $M_{U3}$ and $M_{D3}$, are scanned in the following ranges:

$$(1 < \tan \beta < 50, \quad 100 \text{ GeV} < M_A < 600 \text{ GeV}),$$

\(^2\)For global fit analysis, we consider the signal strengths for different production modes as presented for individual decay channels. In other words, we do not consider the inclusive results for a given decay mode.
### Table 1: Signal strengths of $h \to \gamma\gamma$ channel as recorded by the ATLAS [5] and CMS [6] collaborations after 7+8 TeV run of LHC with 25 fb$^{-1}$ of luminosity. The amount of contribution to a given channel from each production modes are shown in Column 4-6. The total $\chi^2$ for the $\gamma\gamma$ channel with respect to the SM is $= 0.85$ (ATLAS) + 1.868 (CMS) = 2.718.

| Channel | Signal strength ($\mu$) | Production mode |
|---------|------------------------|-----------------|
|         | ATLAS | CMS | ggF | VBF | Vh |
| $\mu(ggh)$ | 1.32 ± 0.38 | 1.12$^{+0.37}_{-0.32}$ | 100% | - | - |
| $\mu(VBF)$ | 0.8 ± 0.7 | 1.58$^{+0.77}_{-0.68}$ | - | 100% | - |
| $\mu(Wh)$ | 1.0 ± 1.6 | -0.16$^{+1.16}_{-0.79}$ | - | - | 100% |
| $\mu(Zh)$ | 0.1$^{+3.7}_{-0.1}$ | - | - | - | 100% |

### Table 2: Signal strengths of $h \to ZZ^*$ channel as recorded by the ATLAS [9] and CMS [10] collaborations after 7+8 TeV run of LHC with 25 fb$^{-1}$ of luminosity. The amount of contribution to a given channel from each production modes are shown in Column 4-6. The total $\chi^2$ for the $ZZ^*$ channel with respect to the SM is $= 2.493$ (ATLAS) + 0.3 (CMS) = 2.793.

| Channel | Signal strength ($\mu$) | Production mode |
|---------|------------------------|-----------------|
|         | ATLAS | CMS | ggF | VBF | Vh |
| $\mu(ggh + bbh + tth)$ | 1.66$^{+0.51}_{-0.44}$ | 0.26$^{+1.64}_{-0.94}$ | 100% | - | - |
| $\mu(VBF + Vh)$ | 0.80$^{+0.46}_{-0.36}$ | 1.7$^{+2.2}_{-2.1}$ | - | 60% | 40% |

### Table 3: Signal strengths of $h \to WW^*$ channel as recorded by the ATLAS [7] and CMS [8] collaborations after 7+8 TeV run of LHC with 25 fb$^{-1}$ of luminosity. The amount of contribution to a given channel from each production modes are shown in Column 4-6. The total $\chi^2$ for the $WW^*$ channel with respect to the SM is $= 0.366$ (ATLAS) + 2.104 (CMS) = 2.470.

| Channel | Signal strength ($\mu$) | Production mode |
|---------|------------------------|-----------------|
|         | ATLAS | CMS | ggF | VBF | Vh |
| $\mu(ggF)$ | 1.02$^{+0.29}_{-0.26}$ | - | 100% | - | - |
| $\mu(VBF)$ | 1.27$^{+0.53}_{-0.45}$ | - | - | 100% | - |
| $\mu(0/1 \ jet)$ | - | 0.74$^{+0.22}_{-0.20}$ | 97% | 3% | - |
| $\mu$ (VBF tag) | - | 0.60$^{+0.57}_{-0.46}$ | 17% | 83% | - |
| $\mu$ (Vh tag (2l2\nu2j)) | - | 0.39$^{+1.97}_{-1.87}$ | - | - | 100% |
| $\mu$ (Wh tag(3l3\nu)) | - | 0.56$^{+1.27}_{-1.95}$ | - | - | 100% |
Table 4: Signal strengths of \( h \rightarrow b \bar{b} \) channel as recorded by the ATLAS [11] and CMS [12] collaborations after 7+8 TeV run of LHC with 25 fb\(^{-1}\) of luminosity. The amount of contribution to a given channel from each production modes are shown in Column 4-6. The total \( \chi^2 \) for the \( b \bar{b} \) channel with respect to the SM is \( = 1.50 \) (ATLAS) + 0.0 (CMS) = 1.5.

| Channel          | Signal strength (\( \mu \)) | ATLAS   | CMS   | Production mode |
|------------------|------------------------------|---------|-------|-----------------|
| \( \mu(\text{ggF}) \) | \( 1.93^{+1.45}_{-1.15} \) | -       | -     | 100%            |
| \( \mu(VBF + Vh) \) | \( 1.24^{+0.58}_{-0.54} \) | -       | -     | 60% 40%         |
| \( \mu (0\text{-jet}) \) | - \( 0.34 \pm 1.09 \) | \( 96.9\% \) | 1.0% | 2.1             |
| \( \mu (1\text{-jet}) \) | - \( 1.07 \pm 0.46 \) | \( 75.7\% \) | 14%  | 10.3           |
| \( \mu (\text{VBF tag}) \) | - \( 0.94 \pm 0.41 \) | \( 19.6 \) | 80.4 | -               |
| \( \mu (\text{Vh tag}) \) | - \( -0.33 \pm 1.02 \) | -       | -     | 100%            |

Table 5: Signal strengths of \( h \rightarrow \tau^+ \tau^- \) channel as recorded by the ATLAS [13] and CMS [14] collaborations after 7+8 TeV run of LHC with 25 fb\(^{-1}\) of luminosity. The amount of contribution to a given channel from each production modes are shown in Column 4-6. The total \( \chi^2 \) for the \( \tau^+ \tau^- \) channel with respect to the SM is \( = 0.857 \) (ATLAS) + 2.11 (CMS) = 2.967.

| Channel          | Signal strength (\( \mu \)) | ATLAS   | CMS   | Production mode |
|------------------|------------------------------|---------|-------|-----------------|
| \( \mu(\text{H} \rightarrow \gamma \gamma) \) | \( 6.14^{+3.25}_{-3.19} \) | -       | -     | 78% 5% 17%      |
| \( \mu(\text{H} \rightarrow WW^*) \) | \( 0.85^{+0.88}_{-0.81} \) | -       | -     | 78% 5% 17%      |
| \( \mu(\text{H} \rightarrow b \bar{b}) \) | \( 1.59^{+0.69}_{-0.72} \) | -       | -     | 100%            |

Table 6: Signal strengths of \( h \rightarrow \gamma \gamma, WW^*, \) and \( b \bar{b} \) channel as recorded by the CDF and \( D\emptyset \) collaborations at the Tevatron with 10 fb\(^{-1}\) of luminosity at \( \sqrt{s} = 1.96 \) TeV [17,67]. The amount of contribution to a given channel from each production modes are shown in Column 4-6. The total \( \chi^2 \) for the above three modes with respect to the SM is \( = 3.296 \).

\[
-8000 \text{ GeV} < A_t, A_b < 8000 \text{ GeV}, \quad 100 \text{ GeV} < \mu < 8000 \text{ GeV},
\]
\[
100 \text{ GeV} < M_{Q3}, M_{U3} < 8000 \text{ GeV}, \quad 100 \text{ GeV} < M_{D3} < 8000 \text{ GeV},
\] (3)
while we fix the following parameters since they have little impact on our analysis,

\[ M_1 = 100 \text{ GeV}, \quad M_2 = 2000 \text{ GeV}, \quad M_3 = 3000 \text{ GeV}, \]
\[ M_{L_{1,2,3}} = M_{E_{1,2,3}} = 3000 \text{ GeV}, \quad M_{Q_{1,2}} = 3000 \text{ GeV}, \quad M_{U_{1,2}} = M_{D_{1,2}} = 3000 \text{ GeV}, \]

where \( M_{1,2,3} \) are the gaugino mass parameters, \( M_{L_i} \) and \( M_{E_i} \) \((i = 1, 2, 3)\) are the left and right handed slepton soft SUSY breaking mass parameters, and \( M_{Q_i}, M_{U_i}, M_{D_i} \) \((i = 1, 2)\) are the first two generation squark soft SUSY breaking mass parameters.

We scan the third generation trilinear couplings \( (A_t \text{ and } A_b) \) and soft masses \( (M_{Q_3}, M_{U_3}, M_{D_3}) \) over a wide range in order to obtain the lightest MSSM Higgs boson mass in the range of 125 ± 3 GeV assuming 3 GeV uncertainty in Higgs mass calculation [69]. Since we are interested in the possibility of having light additional Higgses, we restrict \( M_A \) up to 600 GeV. From the above choices of the model parameters, it is evident that we do not consider the possibility of the decay of \( h \) to MSSM particles. We use SUSPECT (version 2.43) [70] to scan the MSSM parameter space and SuperIso (version 3.4) [71] to calculate the flavour physics observables, while the branching ratios of the lightest Higgs boson are evaluated using HDECAY (version 6.41) [72].

Now, to combine the available information on different signal strength variables from the ATLAS, CMS and Tevatron, and to compare with the MSSM expectations, we compute \( \chi^2 \) for all the scanned parameter space points, defined as below:

\[
\chi^2 = \sum_i \frac{(\mu_i - \bar{\mu}_i)^2}{\Delta \mu_i^2},
\]

where \( \mu_i \) is the experimentally observed signal strength for a particular production/decay mode \( i \), and \( \bar{\mu}_i \) is the value predicted for the same channel for a chosen MSSM parameter space point with \( \Delta \mu_i \) being the measure of the experimental error associated to that channel. The sum over \( i \) takes into account of all the experimentally measured production and decay modes of the Higgs boson.

It is to be noted that, different production processes can, in principle, contribute to a particular experimental search channel, thereby while calculating the signal strengths for a parameter space point, one needs to consider the contributions coming from different production processes. Following the procedure of Ref. [29], we implement this modification in our analysis as follows:

\[
\bar{\mu}_i = \sum_j T_{ij} \hat{\mu}_j,
\]

where \( T_{ij} \) denotes the amount of contribution that can originate from the production mode \( j \) to the category/channel \( i \) with \( \hat{\mu}_i \) being the signal strength corresponding to the MSSM parameter space point. For example, the category \( \mu(VBFtag) \), as introduced in Tab. 3, receives 17% and 83% contributions from the ggF and VBF processes respectively [73]. So, we calculate \( \hat{\mu}_{ggF} \) and \( \hat{\mu}_{VBF} \), and then scale them with 0.17 and 0.83 (the \( T_{ij} \)'s here) respectively to obtain the proper signal strength \( (\bar{\mu}) \) corresponding to VBFtag category. To obtain the contributions coming from
different production processes to a given decay mode/category, we use LHC Higgs cross-section working group report [73].

We consider altogether 28 data points (i.e., experimental inputs, see Tab. 1 - 6) combining the CMS and ATLAS and Tevatron Higgs data. We calculate $\chi^2$ for all the scanned parameter space points and find the minimum of $\chi^2$. We call this minimum as the approximate minima ($\chi^2_{\text{approx}}$). In order to obtain the true $\chi^2$ minimum ($\chi^2_{\text{min}}$), we vary the parameters around their approximated values i.e., values corresponding to the approximate $\chi^2$ minimum. We present the parameter space that is available after the global analysis considering the 1$\sigma$ and 2$\sigma$ intervals with $\chi^2 = \chi^2_{\text{min}} + 2.3$ and $\chi^2 = \chi^2_{\text{min}} + 6.18$ respectively in $M_A - \tan\beta$ plane [74]. The “best fit” value corresponds to $M_A \sim 584$ GeV and $\tan\beta \sim 36$. To determine how a set of experimental data is well represented by any given model, one usually calculates the chi-square per degrees of freedom (d.o.f) i.e., $\chi^2$/d.o.f. The minimum value of $\chi^2$ obtained from the analysis for SM is 15.744 with $\chi^2$/d.o.f = $\chi^2$/28 = 0.562, while for MSSM we obtain $\chi^2_{\text{min}} = 15.013$ with $\chi^2$/d.o.f = $\chi^2$/20 = 0.75.

2.2 Available MSSM parameter space

Before we proceed to discuss our findings, let’s review our methodology once more. We first perform a $\chi^2$ analysis using a random scan of the parameters relevant to the MSSM Higgs sector, then we find the true $\chi^2_{\text{min}}$ to get the “best-fit” values of those parameters. The points with $\chi^2$ within 2$\sigma$ of the true $\chi^2_{\text{min}}$ are only considered for further analysis. We impose the two most stringent rare b-decay constraints, namely BR($b \rightarrow s\gamma$) and BR($B_s \rightarrow \mu^+\mu^-$), and allow 2$\sigma$ deviation of these two branching ratios from the central value [66],

$$2.77 \times 10^{-4} < \text{BR}(B_s \rightarrow X_s\gamma) < 4.09 \times 10^{-4}$$
$$1.0 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+\mu^-) < 5.2 \times 10^{-9}.$$ (7)

In Fig.1, we show the parameter space in the $M_A - \tan\beta$ plane obtained from the global fit analysis and also satisfying the flavour physics constraints on BR($b \rightarrow s\gamma$) and BR($B_s \rightarrow \mu^+\mu^-$). Magenta (black) coloured triangle (circle) shaped points represent 2$\sigma$ (1$\sigma$) allowed parameter space. The region with $M_A \leq 350$ GeV and $\tan\beta \geq 20$ are excluded by the stringent BR($B_s \rightarrow \mu^+\mu^-$) constraint, which is expected to dominate for regions with large $\tan\beta$ and relatively smaller $M_A$. However, for significantly larger $M_A$ i.e., $M_A \geq 425$ GeV, the effect of this constraint is negligible. Besides, most of the points in the region with $M_A \leq 400$ GeV with $\tan\beta \leq 8$ are excluded by the BR($b \rightarrow s\gamma$) constraint.

In order to display the interplay of two flavour physics constraints, in Fig. 2(a) we first show the parameter space obtained after the global analysis with Higgs mass constraint (122 GeV $\leq M_h \leq 128$ GeV) only, without imposing any flavor physics constraint. In the middle panel (b), we then show the same distribution but now imposing the BR($b \rightarrow s\gamma$) constraint, while in right-most figure (c) the same correlation with BR($B_s \rightarrow \mu^+\mu^-$) constraint only is shown. The effect of the
Figure 1: Parameter space allowed in $M_A$ vs $\tan\beta$ plane from our global fit analysis and also satisfying the flavour physics constraints on $Br(b \to s\gamma)$ and $Br(B_s \to \mu^+\mu^-)$. Magenta (black) coloured triangle (circle) shaped points represent $2\sigma$ ($1\sigma$) allowed parameter space from global fits of 125 GeV Higgs data after Run-I of LHC. In rest of our analysis, while presenting the direct search constraints and the future limits on the heavy Higgs masses and BRs, we would consider these $2\sigma$ points which satisfies our global fit analysis and the updated flavour data.

Figure 2: Scatter plots in the (a) $M_A - \tan\beta$ plane without any flavor constraint (left panel), (b) $M_A - \tan\beta$ plane only after imposing $Br(b \to s\gamma)$ constraint (middle panel) and (c) $M_A - \tan\beta$ plane after imposing only $Br(B_s \to \mu^+\mu^-)$ constraint (right panel). In Fig. 1, we show the same correlation after the imposition of both $Br(b \to s\gamma)$ and $Br(B_s \to \mu^+\mu^-)$ constraints.
Figure 3: Left panel (a) shows the allowed parameter space in $\tan \beta - \alpha$ plane after the global fit analysis and also satisfying the flavour physics constraints. Colour conventions are same as Fig. 1. In the right panel (b), we display the same allowed parameter space but now are presented in the $M_A - \alpha$ plane.

The $\text{BR}(B_s \to \mu^+\mu^-)$ constraint in the low $M_A$ and large $\tan \beta$ region, and the impact of $\text{BR}(b \to s\gamma)$ in low $M_A$ and low $\tan \beta$ is now clearly visible for these plots. Once we impose both the Higgs mass and flavour physics constraints, the available parameter space has already been shown in Fig. 1. Note that, in rest of our analysis, we name these 2$\sigma$ allowed points collectively as the “scanned data set” and present the direct search constraints and the future limits on the heavy Higgs masses and couplings using this data set.

In Fig. 3, we show the scatter plots in the (a) $\alpha - \tan \beta$ and (b) $\alpha - M_A$ planes, where $\alpha$ is the Higgs mixing angle. In order to understand the important features of Fig. 3(a), let’s concentrate on three different regions of $\tan \beta$, namely $\tan \beta < 5$, $5 < \tan \beta < 20$, and $\tan \beta > 20$. The region with $\tan \beta < 5$ corresponds to $\alpha > -0.2$ radian. Now, $\tan \beta = 5$ implies $\beta = 1.373$ radian, which means $(\beta - \alpha) = 1.573$ radian or, around 90 degree with $\alpha = -0.2$ radian, so here we are near the alignment limit $(\beta - \alpha = \pi/2)$ [75]. The region with $\tan \beta > 20$ corresponds to very small $\alpha$ (< -0.05 radian), and thereby $(\beta - \alpha) \sim \pi/2$ i.e., we again achieve the alignment limit. The intermediate regime with $5 < \tan \beta < 20$ also satisfies the criteria of alignment. However, we see that in this alignment limit, $M_A$ can be as light as 300-400 GeV with relatively large $\alpha$ (see Fig. 3(b)) satisfying current data. This scenario can be thought of as the “alignment without decoupling” scenario, as discussed in Ref. [76–78]. In fact, in order to make a more quantitative statement, In Fig. 4 we the
allowed parameter space in the \((\beta - \alpha) - \tan \beta\) plane with different choices of \(M_A\). We divide the entire \(M_A\) region in four parts, namely \(200 < M_A < 300\) GeV (red/square), \(300 < M_A < 400\) GeV (black/circle), \(400 < M_A < 500\) GeV (green/triangle), and \(500 < M_A < 600\) GeV (blue/cross), while the red horizontal line at \((\beta - \alpha) = 1.571\) indicates its exact value at the alignment limit. From Fig. 3 and Fig. 4 it is clear that regions with relatively light \(M_A\) \((\leq 400\) GeV) satisfying the alignment limit is perfectly allowed by current data, one is not always forced to be in the decoupling limit to comply with LHC data.

![Figure 4: The allowed parameter space in the \((\beta - \alpha) - \tan \beta\) plane are presented with different choices of \(M_A\). The entire \(M_A\) region is divided in four parts, namely \(200 < M_A < 300\) GeV (red/square), \(300 < M_A < 400\) GeV (black/circle), \(400 < M_A < 500\) GeV (green/triangle), and \(500 < M_A < 600\) GeV (blue/cross). The red horizontal line at \((\beta - \alpha) = 1.571\) indicates the value of \((\alpha - \beta)\) at the alignment limit. We see that regions with light \(M_A\) \((\leq 400\) GeV) satisfying the alignment limit is allowed by current data.](image)

Before we end this section, we would like to discuss the correlation between various Higgs signal strength variables. Fig. 5 shows the scatter plots in \(\mu_{ZZ} - \mu_{\gamma\gamma}\) (left), \(\mu_{ZZ} - \mu_{\tau^+\tau^-}\) (middle) and \(\mu_{ZZ} - \mu_{bb}\) (right) planes. The partial decay width \(\Gamma(h \rightarrow ZZ)\) remains unaltered compared to the SM value, however \(\Gamma(h \rightarrow bb)\) and total decay width of Higgs (\(\Gamma_{tot}\)) have increased while \(\Gamma(h \rightarrow gg)\) has decreased for most of the scanned data points. We know that when the total decay width increases, the sub-leading decay modes like \(\gamma\gamma, gg, ZZ, WW\) decreases. Hence, the suppression in the \(\mu_{ZZ}/\mu_{\gamma\gamma}\) can be thought of as the interplay of two effects: the increase in total decay width (or, decrease in \(h \rightarrow ZZ/ h \rightarrow \gamma\gamma\) branching ratio) and decrease in \(\Gamma(h \rightarrow gg)\) with respect to the SM.
Figure 5: Signal strength correlation in (a) $\mu_{ZZ} - \mu_{\gamma\gamma}$, (b) $\mu_{ZZ} - \mu_{\tau^+\tau^-}$ and (c) $\mu_{ZZ} - \mu_{b\bar{b}}$ plane. Magenta (black) coloured triangle (circle) shaped points represent $2\sigma$ ($1\sigma$) allowed points of our “scanned data set”.

3 Bounds on MSSM heavy Higgses from direct searches

In previous section, we first describe the global fit analysis, and then show that the signal strength measurements of the SM-like Higgs boson with different possible final state signatures do not exclude the possibility of having additional light Higgses (say $\leq$ 400 GeV) with moderate values of Higgs mixing angle $\alpha$. One can ask whether these light MSSM Higgses are still allowed satisfying the direct search bounds at the LHC-8, this is precisely the goal of this section. Here we will impose the bounds set by the ATLAS and CMS collaborations on the masses and branching ratios of the neutral and charged Higgs bosons at the end of 8 TeV run of LHC. Note that, we do not attempt to combine the 7 and 8 TeV data, rather in our analysis we consider the LHC-8 data only. We expect that inclusion of LHC-7 data will not change our results significantly. We calculate the production cross-section of the neutral heavy Higgses ($H$ and $A$) using SuShi (version 1.4.1) [79] and charged Higgs ($H^\pm$) using PYTHIA6 (version 6.4.28) [80]. The branching ratios of both the charged and neutral Higgses are evaluated using HDECAY (version 6.41) [72].

3.1 Neutral Higgs boson searches

3.1.1 Search for $H$ with $\gamma\gamma$ final states

The di-photon invariant mass distribution plays an important role to discover the 125 GeV Higgs boson at the LHC. However, the sensitivity of this channel falls rapidly with the increase of the SM Higgs boson mass and become vanishingly small beyond 150 GeV [55]. In models with additional Higgses, di-photon mode can be an useful probe to search for these heavy resonances. The CMS collaboration has searched for the CP-even heavy MSSM Higgs $H$ using the di-photon invariant
mass distribution with 19.7 fb\(^{-1}\) of data at the 8 TeV run of LHC. They assume that the Higgs is produced via gluon-gluon fusion process. Both narrow and wide width heavy resonances are investigated with widths ranging from 0.1 to several GeV and Higgs masses varying in the range of 150 GeV to 850 GeV. No excess over the SM background has been found, and thus 95\% C.L. upper bounds have been set on the production cross-section times branching ratio in the above-mentioned Higgs mass range. In Fig. 6(a), we show the distribution of the quantity \(\sigma \times \text{BR}(H \rightarrow \gamma\gamma)\) for all the points of our scanned data set (i.e., 2\(\sigma\) allowed points obtained after the global analysis with various Higgs signal strengths and flavour data, see Sec. 2). We then superimpose the bounds set by the CMS collaboration for two different choices of the Higgs decay width. The red solid line in Fig. 6(a) represents the case where Higgs decay width is 10\% of the Higgs boson mass, while the blue dashed line represents the same but with fixed value of the Higgs decay width \(\Gamma = 0.1\) GeV. From the figure, one can see that all the points of our scanned data set satisfy the CMS bounds. A further investigation reveals that the Higgs to \(\gamma\gamma\) branching ratio varies between \(10^{-6} - 10^{-7}\) for all the points, and thus makes the quantity \(\sigma \times \text{BR}(H \rightarrow \gamma\gamma)\) small enough to evade the CMS bound.

### 3.1.2 Search for \(H\) with \(WW\) final states

In the SM, the decay of Higgs boson to electro-weak gauge bosons (\(W/Z\)) provides interesting signatures at the LHC. In fact, the \(ZZ\) mode has very good sensitivity to precisely measure the Higgs boson mass and its spin and parity [15,16]. The CMS collaboration has searched for a SM-like Higgs boson decaying to pair of W bosons with \((5 + 19.3)\) fb\(^{-1}\) data collected at \(\sqrt{s} = (7 + 8)\) TeV at the LHC [58]. Analyzing the data with lepton, jets plus missing transverse energy final state signature, CMS exclude SM-like Higgs bosons in the mass ranges 170-180 GeV and 230-545 GeV at 95\% C.L.. One can translate the bound on the cross-sections obtained from \(WW\) channel into a model with additional Higgses. We calculate the product of production cross-section and \(WW\) branching ratio \(\sigma \times \text{BR}(H \rightarrow WW)\) for our scanned points and then compare our findings with the upper limit cross-sections obtained by the CMS collaboration. Note that we do not combine the 7 and 8 TeV data of LHC, rather we consider the exclusion limits of the 8 TeV data only. In Fig. 6(b), we superimpose the CMS exclusion limit on the 2\(\sigma\) allowed points obtained from global fit analysis. We find that updated CMS bound on production cross-section with Higgs decaying to pair of Ws is not sensitive enough to exclude the scanned parameter space. As we have already discussed, for almost all the points we are near the alignment limit (i.e. \((\beta - \alpha) \sim \frac{\pi}{2}\)), which results into highly suppressed branching ratio of Higgs to the \(WW\) mode, \(\text{BR}(H \rightarrow WW) \sim 10^{-2} - 10^{-4}\). This is the reason why the quantity \(\sigma \times \text{BR}(H \rightarrow WW)\) is very small, and thus become insensitive to CMS bounds. We also find that even if we consider the \((7+8)\) TeV combined CMS exclusion limit the parameter space will still remain allowed by the LHC data.
Figure 6: (a) Left: Scatter plot in $M_H - [\sigma \times \text{BR}(H \to \gamma\gamma)]$ plane assuming gluon-gluon fusion production process. The solid red (blue dashed) line represents the observed upper limits on $\sigma \times \text{BR}(H \to \gamma\gamma)$ at 95% C.L. by the CMS collaboration [55] using LHC-8 data with $\Gamma_H = 0.1 \times M_H$ (0.1 GeV). Magenta coloured triangle shaped points represent 2$\sigma$ allowed parameter space from global fits satisfying flavour constraints (see Fig 1). (b) Right: Scatter plot in $M_H - [\sigma \times \text{BR}(H \to WW)]$ plane when the H is produced via ggF. The red solid line indicates the observed upper limits on $\sigma \times \text{BR}(H \to WW)$ at the 95% C.L. by the CMS collaboration [58] using LHC-8 data.

### 3.1.3 Search for $H$ with $hh$ final states

The Higgs pair production cross-section in the SM is very small, around 10 fb at $\sqrt{s} = 8$ TeV [56]. However, well-motivated BSM physics models predict the decay of narrow-width heavy resonances to pair of 125 GeV Higgses, and thus one can expect enhancement in the 125 GeV Higgs pair production cross-section. Search for these heavy resonances decaying to pair of h, i.e. $pp \to X \to hh$ with X being the new heavy resonance, is performed by the CMS collaboration in the mass range of 260 - 1100 GeV with 19.7 fb$^{-1}$ of data at $\sqrt{s} = 8$ TeV [56, 57] The final state signatures that have been investigated by the CMS collaboration are: (i) $b\bar{b}b\bar{b}$ where both the Higgses decaying to $b\bar{b}$, and (ii) $b\bar{b}\gamma\gamma$ where one of the Higgs decays to $b\bar{b}$ while other decays to pair of photons. The reconstruction of heavy resonance is possible in both the above-mentioned signatures, however 4$b$ final state is experimentally challenging while $b\bar{b}\gamma\gamma$ channel has less background contamination and very good di-photon mass resolution. The observations by the CMS collaborations are consistent
with the SM, and so 95% upper limit on the production cross-section is placed for the entire mass range of the heavy resonance. At the LHC, the MSSM heavy CP even Higgs (H) can be generously produced from the ggF process, which then decays to a pair of 125 GeV Higgses. So, the bounds on the production cross-section of new heavy resonances can be directly used to probe/exclude certain mass range of the heavy Higgs boson. To do so, we calculate the quantities $\sigma(pp \rightarrow H) \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ and $\sigma(pp \rightarrow H) \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma)$ for all our scanned data set.

Figure 7: (a) Left: Scatter plot in $M_H - [\sigma \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}b\bar{b})]$ plane assuming gluon-gluon fusion production process for 2$\sigma$ allowed parameter space (represented by magenta points). The solid red line represents the observed upper limits on $\sigma \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ at 95% C.L. by the CMS collaboration [57] using 8 TeV data. (b) Right: Scatter plot in $M_H - [\sigma \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma)]$ for ggF production mode. The red solid line indicates the observed upper limits on $\sigma \times \text{BR}(H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma)$ at the 95% C.L. by the CMS collaboration [56] using LHC 8 TeV data.

In Fig. 7(a) and Fig. 7(b), we show the distributions of those two quantities respectively, and also display the 95% C.L. upper limits (solid red line) imposed by the CMS collaborations on the respective distributions. The branching of MSSM heavy Higgs H to hh becomes sizable only for small tan$\beta$ ($\leq 5$) and low $M_A$ region [20]. Once $M_A$ becomes $\geq 350$ GeV, the $t\bar{t}$ decay opens up and dominates in the parameter space. We find that CMS data can not exclude the 2$\sigma$ allowed parameter space. The regions close to CMS exclusion lines corresponds to smaller values of tan$\beta$, and so with one/two orders of improved measurement of di-Higgs production cross-section
at the Run-II of LHC, one can probe/exclude such regions of the parameter space. The ATLAS collaborations also searched for the heavy resonances (Kaluza-Klein excitation mode graviton) decaying to a pair of SM Higgses with both the Higgs decaying to pair of b-quarks in the context of the Randall-Sundrum model [81]. The 95% exclusion limits set by the ATLAS collaboration are sensitive for heavy resonances (mass > 500 GeV) only, and thus is not directly applicable to the parameter space of interest, so we do not consider them in our analysis.

3.1.4 Search for $H/A$ with $\tau^+\tau^-$ final states

The coupling of MSSM heavy Higgs ($H$) and pseudoscalar Higgs ($A$) with down type fermion $f_d$ (say bottom quark, tau lepton) is proportional to $\cos \alpha/\cos \beta$ and $\tan \beta$ respectively. For fixed value of Higgs mixing angle $\alpha$, both the couplings $Hf_d\bar{f}_d$ and $Af_d\bar{f}_d$ increases with $\tan \beta$. Thus for large values of $\tan \beta$ (say $\geq 10$), both $H$ and $A$ dominantly decays to $b\bar{b}$ ($\sim 90\%$) and $\tau^+\tau^-$ ($\sim 10\%$), resulting into strong suppression in all other decay modes [20]. The production of the MSSM heavy Higgses is also primarily controlled by $\tan \beta$. The Higgses are dominantly produced via gluon-gluon fusion process and associated production with b-quarks i.e., $b\bar{b}\Phi$ ($\Phi = H,A$). All other production processes like VBF, associated production with gauge bosons, associated production with top quarks are dominantly suppressed for the heavy Higgses $H/A$ due to small $HVV/AVV$ and $Ht\bar{t}/At\bar{t}$ couplings [20]. The ATLAS and CMS collaborations at the LHC have studied the signatures of these heavy Higgses ($H/A$) produced via ggF and b-quark associated production process, and decays to pair of $\tau$-leptons [53,54]. No excesses are observed over the SM backgrounds, and thus model independent bounds are placed on the production cross-section times branching ratio $\sigma \times \text{BR}(\Phi \to \tau^+\tau^-)$ for different values of $M_\Phi$ with $\Phi = H/A$. In Fig. 8(a) and Fig. 8(b), we display our scanned points along with the upper limit on production cross-section by the ATLAS and CMS collaboration for two dominant production modes, left panel corresponds to the ggF process while right panel represents the associated production process $b\bar{b}\Phi$, $\Phi = H,A$. In order to compare our findings with the ATLAS [53] and CMS [54] data, in Fig. 8(a) and Fig. 8(b) we show the distributions of $\sigma \times \text{BR}(\Phi \to \tau^+\tau^-)$ combining the contributions of both $H$ and $A$ for the two different production mechanism.

It is evident from Fig. 8 that the LHC data from the $H \to \tau^+\tau^-$ channel have significant impact on the 2$\sigma$ allowed parameter space. In fact, the entire region with $\tan \beta > 20$ and significant amount of parameter space with $\tan \beta > 10$ are excluded when the Higgs is produced via $b\bar{b}\Phi$ process. However, sensitivity of this channel with ggF production process is negligible. For a better understanding of the sensitivity of $\tau^+\tau^-$ channel, we display the scanned dataset with explicit $\tan \beta$ dependence, regions with $30 < \tan \beta < 50$, $20 < \tan \beta < 30$, $10 < \tan \beta < 20$ and $1 < \tan \beta < 10$ are shown in pink (cross), green (triangle), blue (circle) and violet (square) respectively. One can now clearly see that the regions with large $\tan \beta$ implies large coupling with $b$ and $\tau$s and so large $\sigma \times \text{BR}$, and thus more stringent constraint by the LHC data.
Figure 8: Scatter plot in $M_H - [\sigma \times \text{BR}(\Phi \rightarrow \tau^+\tau^-)]$ plane where $\Phi = H, A$ produced via (a) gluon fusion and (b) in association with $b$-quarks. The solid red (black dashed) line represents the observed upper limits on $\sigma \times \text{BR}(\Phi \rightarrow \gamma\gamma)$ at 95% C.L. by the ATLAS (CMS) collaboration using LHC-8 data [53, 54]. Combined contributions of $\sigma \times \text{BR}(\Phi \rightarrow \tau^+\tau^-)$ of both $H$ and $A$ for the $2\sigma$ allowed parameter space with $30 < \tan \beta < 50, 20 < \tan \beta < 30, 10 < \tan \beta < 20$ and $1 < \tan \beta < 10$ are shown in pink (cross), green (triangle), blue (circle) and violet (square) respectively.

3.1.5 Search for $A$ with $Zh$ final states

Similar to the case where we discussed the possibility of heavy resonances decaying to pair of MSSM lightest Higgs bosons (see Sec. 3.1.3), one can also consider the possibility of having $h$ in association with $Z$ boson from the decay of pseudoscalar Higgs boson $A$ when $M_A$ is greater than $(M_h + M_Z)$. However, the decay rate $\Gamma(A \rightarrow Zh)$ is appreciable only at very low values of $\tan \beta (< 10)$ and for $M_A$ below the $t\bar{t}$ threshold i.e., approx. 350 GeV. Once the $t\bar{t}$ decay opens up, it dominates for all values $M_A > 350$ GeV and $\tan \beta < 10$ [20]. The CMS collaboration at the LHC has searched for the heavy pseudoscalar Higgs bosons when it decay to a $Z$ boson and a light Higgs boson ($h$). The final state includes two opposite sign leptons (from $Z$ decay) and two $b$-quarks (from $h$ decay). Thus, one can fully reconstruct the mass of $A$ using the four momentum information of the final state leptons and $b$-jets. In fact three clear distinguishable resonance peaks, at $M_Z$, $M_h$ and $M_A$, are expected for the signal events. Both the ATLAS and CMS collaborations have performed the search for the heavy pseudoscalar Higgs bosons at the 8 TeV run of LHC [59, 60]. No significant excesses over SM background are observed in the ATLAS and CMS data. Thus model independent 95% C.L.
upper limits are imposed on the production cross-section of $A$ times $\text{BR}(A \to Zh)$. In Fig. 9(a) and (b), we present the $2\sigma$ allowed scanned data points along with the CMS and ATLAS exclusion limits respectively. The solid red exclusion line in Fig. 9(a) assume narrow-width resonance, while the blue dashed line consider the 30 GeV decay width of $A$ boson. The ATLAS collaboration has also performed their study with narrow width approximation, however they have analyzed two possible decay modes of the Higgs boson, namely $b\bar{b}$ and $\tau^+\tau^-$. In Fig. 9(b) we display the allowed parameter space with $b\bar{b}$ final state, while Fig. 9(c) shows the same but with $\tau^+\tau^-$ final state. As we already mentioned, this decay mode plays an important role only in the region with small $\tan \beta$ and low $M_A$. We find that in the parameter space of our interest, ATLAS and CMS data are not sensitive enough to impose any additional constraints. We expect these heavy pseudoscalar Higgses will be probed with improved measurement of these decay modes in the run-II of LHC.
3.2 Charged Higgs boson searches

3.2.1 Search for \( H^\pm \) with \( \tau \nu \) and \( c\bar{s} \) final states

The SM particle content does not include a charged scalar particle, however models with additional Higgs doublets predict charged Higgs bosons (\( H^\pm \)). Thus the discovery of a charged scalar particle is a clear signature of BSM physics. The large electron positron collider (LEP) searched for the charged bosons with center-of-mass energy \( \sqrt{s} = 209 \) GeV. LEP did not found any signal of charged Higgs boson which then leads to put bounds on mass of the charged Higgs boson \( M_{H^\pm} > 78.6 \) GeV [82]. The production and decay of \( H^\pm \) primarily depend on \( M_{H^\pm} \) and top quark mass, more precisely on whether \( M_{H^\pm} < M_{\text{top}} \) or \( M_{H^\pm} > M_{\text{top}} \). If the charged Higgs bosons are lighter than the top quarks, i.e., \( M_{H^\pm} < (m_t - m_b) \), then \( H^\pm \) is mostly produced from the \( t\bar{t} \) process. The decay of \( H^\pm \) depends on the coupling of the charged Higgs boson with the fermions which is mainly controlled by \( \tan\beta \). The coupling is large for very low and very large values of \( \tan\beta \) and small for intermediate values. Thus, for light enough \( H^\pm \) it is primarily produced from the \( t\bar{t} \) process and dominantly decays into \( \tau\nu_\tau \) final states. It is to be noted that light charged Higgs bosons (\( M_{H^\pm} < M_t \)) can also decay to a charm and a anti-strange quark, and thus in certain regions of parameter space one can expect some competition between the \( c\bar{s} \) and \( \tau\nu_\tau \) decay modes. Now, if the \( H^\pm \) is heavy i.e., \( M_{H^\pm} > M_{\text{top}} \), then they are mainly produced in associated production with a top quark i.e., \( pp \to tH^\pm + X \). For small \( \tan\beta \), \( H^\pm \) exclusively decays to a top and bottom quark, however for large values of \( \tan\beta \) the decay of \( H^\pm \) to \( \tau\nu_\tau \) is not negligible i.e., \( \text{BR}(H^\pm \to \tau^\pm\nu_\tau) \sim 10\% \) [20].

Both CMS and ATLAS collaborations have searched for the charged Higgs bosons at the 8 TeV run of LHC using the top-quark pair production process and associated production of \( H^\pm \) with a top quark. Search for the light charged Higgs bosons decaying to a \( \tau \) and a tau-neutrino (\( \nu_\tau \)), and/or to a charm and strange quark are presented by the ATLAS and CMS collaborations [61–64]. The results seem to agree with the SM predictions and non observation of the excesses leads to 95% C.L. exclusion limits on the production cross-section times branching ratios for different values of \( M_{H^\pm} \).

Now, we find that all the points of the scanned data set corresponds to \( M_{H^\pm} > 200 \) GeV and thereby the decay \( t \to bH^\pm \) is kinematically forbidden, and so ATLAS and CMS bounds on \( M_{H^\pm} \) using the \( t\bar{t} \) sample have no effect on the parameter space of interest. However, we do impose the ATLAS and CMS bounds on \( M_{H^\pm} \) considering the production of charged Higgs boson in association to a top and bottom quark with \( H^\pm \) decaying to \( \tau^\pm\nu_\tau \). In Fig.10(a), we superimpose the ATLAS and CMS bounds on the points corresponding to our data set. We check that the bounds using the \( c\bar{s} \) mode are not applicable. From Fig.10(a) one can infer that one/two orders of improvement in cross-section and branching ratio measurement might help to probe the parameter space of interest.
3.2.2 Search for $H^\pm$ with $t\bar{b}$ final states

As we already mentioned, the decay of $H^\pm$ to a top and bottom quark dominates in the regions with $M_{H^\pm} > M_t$. They are primarily produced via $gg \rightarrow tbH^\pm$ process. However processes like $q\bar{q} \rightarrow H^+H^-$, associated production with neutral Higgses can give small contributions to the dominant $tbH^\pm$ process. The decay of $H^\pm$ is completely controlled by the single parameter $\tan \beta$. For small values of $\tan \beta$ it is the dominant decay mode (branching ratio is close to unity), however at high $\tan \beta$ the branching ratio decreases slightly $\text{BR}(H^\pm \rightarrow t\bar{b}) \sim 90\%$ while $\text{BR}(H^\pm \rightarrow \tau^\pm\nu_\tau) \sim 10\%$.

The CMS collaborations have searched for the charged Higgs bosons with $H^\pm$ decaying to a top and bottom quark \cite{65}. The process under consideration looks like $gg \rightarrow H^+tb \rightarrow (\ell\nu_bb)(\ell'\nu_bb)b$, with $\ell, \ell'$ being an electron or a muon. The search is performed with 19.7 fb$^{-1}$ of data at $\sqrt{s} = 8$ TeV. No evidence for a charged Higgs signal is found and thus upper limits on the production rate are placed for $H^\pm$ masses in the range of 180-600 GeV. We calculate the $gg \rightarrow tbH^\pm$ production cross-section for all our valid points, and then impose the CMS bounds. We present our results in From Fig. 10(b), where the solid red line indicates the CMS exclusion limit. It is evident from the
figure that $t\bar{b}$ mode is not sensitive enough to put any strong bound on the parameter space.

4 SUSY Higgs : Future limits

4.1 Heavy Higgs search

In the last section we have discussed the limits on the allowed parameter space of the MSSM Higgs sector coming from the direct searches at LHC run-I. We show that significant amount of parameter space with additional light Higgses are still allowed by the LHC data. We find that the production of heavy Higgs bosons in association with the bottom quarks with its decay to $\tau^+\tau^-$ provides the most stringent bound on our parameter space and the regions with large values of $\tan\beta$ ($> 20$) are excluded by this channel. Our naive estimation indicates that the high luminosity run of LHC (HL-LHC)$^3$ will be sensitive enough to probe the parameter space with $\tan\beta \sim 10$. Hence, the region with $\tan\beta < 10$ requires special attention. In this section, we discuss the reach of HL-LHC for the decay modes $H \rightarrow hh$, $H \rightarrow t\bar{t}$, $A \rightarrow Zh$ as these channels are most sensitive at the low $\tan\beta$ region. Additionally, we also consider the decay $H \rightarrow ZZ$ following the ATLAS and CMS analysis $[86,87]$ at 14 TeV run of LHC with 3000 fb$^{-1}$ of integrated luminosity.

4.1.1 Search for $H$ with $4\ell$ final states

Both the ATLAS and CMS collaborations have looked for the heavy Higgs bosons decaying into $ZZ$ ($Z \rightarrow \ell\ell$, $\ell = e, \mu$) via ggF production mechanism at 14 TeV HL-LHC $[86,87]$. In their analyses, the ATLAS collaboration has considered the decay width of $H$ to be the same as that of a SM-like Higgs boson for a given mass, while the CMS collaboration calculated the width of $H$ assuming $\tan\beta = 1$ and $\cos(\beta - \alpha) = -0.06$. The expected 95% C.L. exclusion limits on $\sigma \times \text{BR}(H \rightarrow ZZ \rightarrow 4\ell)$ at $\mathcal{L} = 3000$ fb$^{-1}$ by the ATLAS and CMS collaborations are quite similar as shown in Fig. 11 by red solid and blue dashed line respectively. We calculate the quantity $\sigma \times \text{BR}(H \rightarrow ZZ \rightarrow 4\ell)$ for all the points in our scanned data set and then compare our results with ATLAS and CMS predictions $[86,87]$. In Fig. 11 we overlay the experimental predictions with our scanned data set shown in magenta triangles. We find that in most of the parameter space, even the points with large production cross section, the branching ratio $\text{BR}(H \rightarrow ZZ)$ is very small ($\sim 10^{-3}$ to $10^{-5}$)$^4$, which results into smaller values of $\sigma \times \text{BR}(H \rightarrow ZZ \rightarrow 4\ell)$. We thus find that most of the parameter space points are beyond the reach of HL-LHC for $H \rightarrow 4\ell$ final state.
4.1.2 Search for pseudoscalar $A$ with $\ell^+\ell^-b\bar{b}$ final states

In the region below the $t\bar{t}$ threshold, and small tan $\beta$ the pseudoscalar Higgs $A$ decays to $Zh$ with an appreciable amount. Another interesting feature of this decay mode with $Z \rightarrow \ell^+\ell^-$ and $h \rightarrow b\bar{b}$ is that one can fully reconstruct the mass $A$ using the four momentum of the leptons and b-jets. ATLAS and CMS collaborations have analysed the sensitivity of this channel at the HL-LHC via ggF process [86, 87]. To represent the expected 95% C.L. exclusion limits ATLAS has assumed a narrow width approximation (i.e., width of $A$ is much smaller than the experimental resolution) while CMS has calculated the width of $A$ by assuming $\tan \beta = 1$ and $\cos(\beta - \alpha) = -0.06$. In Fig. 12, we show the distribution of $\sigma \times \text{Br}(H \rightarrow ZZ \rightarrow \ell^+\ell^-)\ell^+\ell^-$ for all the points in the scanned data set, and then overlay the 95% C.L. upper limits by the ATLAS (red solid line) and CMS (blue dashed line) [86,87] at 14 TeV LHC with $\mathcal{L} = 3000 \text{ fb}^{-1}$. We find that the ATLAS limits are more stronger (by almost one order) than the CMS, although the reason behind this is apparently not clear. From the Fig. 12 it is clear that only a very small region of parameter space will be excluded by the HL-LHC data, in fact to probe the remaining parameter space few orders of magnitude

Future reach of MSSM heavy Higgses have been discussed in the context of 14 TeV run of LHC, for details see Refs. [83–85].

The result is consistent with the alignment limit.
improvement in cross-section measurement is required.

4.1.3 Search for H with di-higgs ($H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$) final states

In this subsection we discuss the possibility of observing the heavy CP even Higgs boson ($H$) at HL-LHC with its decay to a pair of SM-like Higgses ($h$) with one Higgs decaying to $b\bar{b}$ and other to $\gamma\gamma$ modes. Single $H$ production cross section can be up to two orders of magnitude larger compared to the direct $h$ pair production cross section (see Tab. 1 of Ref. [88]) depending on the choice of model parameters and it can also have non-trivial effects on the self coupling measurement of the 125 GeV Higgs [88].

In the MSSM, the production cross-section of $H$ and its decay to a pair of SM-like Higgses crucially depends on the SUSY parameter space, mainly $M_A$ and $\tan\beta$. More precisely, below the $t\bar{t}$ threshold (350 GeV), the decay rate $\Gamma(H \rightarrow hh)$ is substantial only for smaller values of $\tan\beta$. The dominant production mode of $H$ is the ggF fusion, which after being produced decays to a pair of $h$. The final state signature, depending on the decay of the SM-like Higgses, includes, for example, $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $bbW^+W^-$, $b\bar{b}\gamma\gamma$ etc. Among all these possibilities, $b\bar{b}b\bar{b}$ final state has

5The SM Higgs pair production cross section at next to leading order is about 34 fb at 14 TeV LHC for $M_h = 125$ GeV [89].
the largest cross-section. However, due to enormous QCD background this is one of the most challenging scenarios to be observed at the LHC. On the other hand, even though the branching ratio for $b\bar{b}\gamma\gamma$ channel is very small (about 0.27 %), it is the most promising channel due to large photon identification efficiency and very good resolution in the photon energy measurement. Hence using the di-photon invariant mass distribution one can easily reconstruct the Higgs boson mass and at the same time separate the signal from the SM background\(^6\).

![Figure 13: Sensitivity of di-Higgs final state in $M_A - \tan\beta$ plane at HL-LHC from $b\bar{b}\gamma\gamma$ channel with $L = 3000 fb^{-1}$. The magenta coloured points are 2σ allowed points from global analysis and the black circled points are expected to be probed at HL-LHC (see Sec.4.1.3 for details).](image)

A detailed signal-background analysis of heavy Higgs production and its decay to a pair of 125 GeV Higgs in $b\bar{b}\gamma\gamma$ channel has been already performed in Ref. [88]. Here we use their results to constrain our parameter space\(^7\). Events with two $b$-jets, two photons and no isolated leptons are selected after imposing the basic selection cuts following the ATLAS collaboration [90]. Using the four momentum information of the $b\bar{b}$ and $\gamma\gamma$ system, the invariant mass of the heavy Higgs boson can be reconstructed assuming $M_{b\bar{b}\gamma\gamma}$ is $M_H \pm 50$ GeV.

Let us now estimate the sensitivity of the HL-LHC to probe the parameter space in the $b\bar{b}\gamma\gamma$. In Ref. [88], authors considered few representative benchmark points with heavy Higgs mass $M_H$ in the range of 275 - 600 GeV and performed a detailed realistic collider analysis. We should note

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\(^6\)In this case, the dominant backgrounds are $t\bar{t}h$ and the direct Higgs pair production ($hh$). Note that, the production cross-section for both the Higgs pair and $t\bar{t}h$ processes depend on the MSSM parameters, however, here we assume SM cross-sections for $hh$ and $t\bar{t}h$ processes.

\(^7\)The analysis for $b\bar{b}\gamma\gamma$ channel was first introduced in the Ref. [91]

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that the cut efficiencies do not change radically in the entire region of 275 - 600 GeV. The number of background events ($N_B$) and the cut efficiencies as a function of $M_H$ are taken from Ref. [88]. We estimate the number of signal events ($N_S$) for the all the points in the scanned data set by multiplying the cut efficiencies with the production cross-sections, and then calculate the signal significance $S = N_S/\sqrt{N_B}$. In Fig. 13, we present the sensitivity of the $b\bar{b}\gamma\gamma$ channel at HL-LHC where magenta triangles corresponds to our scanned data set, while the black circles represent the points with $S > 2\sigma$. In other words, these are the points (black circle) with low tan $\beta$ ($< 10$) that are expected to be probed at the HL-LHC. The lack of sensitivity of HL-LHC in the regions of parameter space with tan $\beta > 10$ is due to the fact that both the ggF production cross-section and BR($H \rightarrow hh$) decreases with the increase of tan $\beta$ forcing this portion of parameter space to go beyond the reach of HL-LHC. From the Fig. 13, one can note that future run of LHC might not be able to exclude the entire region below $M_H \lesssim 425$ GeV and tan $\beta \lesssim 8$.

4.1.4 Search for $H/A$ with $t\bar{t}$ final state

Above the kinematic threshold of $t\bar{t}$ ($\sim 350$ GeV), $H$ and $A$ can decay into $t\bar{t}$ pair. For $M_A > 350$ GeV and low to moderate values of tan $\beta$, it is indeed the dominant decay mode of $H/A$. Besides, the production cross-section of the heavy Higgs $H$ via ggF process also becomes large in the low tan $\beta$ regime. Hence, assuming the narrow width approximation, one can expect to observe a resonance peak at $M_{H/A}$ in the $t\bar{t}$ invariant mass distribution. However, the main drawback of such a bump hunting is that it is extremely difficult to extract the $t\bar{t}$ resonance peak from the huge SM $t\bar{t}$ continuum background. We perform a detailed signal-background analysis in the context of HL-LHC and study the sensitivity of HL-LHC to probe the region of parameter space of our interest.

We analyze the production of heavy Higgs $H$ via ggF process and its decay to $t\bar{t}$

Semileptonic decay of top quark is considered here. So, the final state signature includes one isolated lepton (electron or muon), at least four jets among them at least two are $b$-jets and missing transverse energy ($E_T$). We use PYTHIA (version 6.4.28) [80] to generate both the signal and dominant SM background, e.g., $t\bar{t}$ events. Electrons are selected with $p_T > 20$ GeV and $|\eta| < 2.47$, while we choose muons with $p_T > 20$ GeV and $|\eta| < 2.4$. We select jets with $p_T > 30$ GeV and $|\eta| < 2.8$. A jet is called a “b-jet” if the angular separation $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ in the $\eta - \phi$ plane between the jet and a $B$-hadron is less than 0.2. Following the ATLAS collaborations, we also assume 70% $b$-tagging efficiency irrespective of the $p_T$ of the $b$-jets [92]. In our analysis, we implement the methodology of lepton isolation and lepton-jet identification following the ATLAS study [93]. Although it is possible to reconstruct leptonically decaying top quark within a quadratic ambiguity, for simplicity we use the parton level four momentum information of the neutrino to reconstruct

As $H$ and $A$ are almost degenerate, one might not be able to distinguish them in $t\bar{t}$ invariant mass distribution. Here we consider only the production of the heavy Higgs $H$ from the ggF process for simulation purpose.
We are now in a position to describe the details of our simulation procedure as well as the kinematic selection cuts for our signal and the backgrounds. We choose three representative benchmark points with $M_H = 400$ GeV (green), 500 GeV (blue), 600 GeV (red) and SM $t\bar{t}$ background (black). The distribution has been drawn before applying the cut on invariant mass ($C_5$) in signal region SR-loose (see text for details) for integrated luminosity $\mathcal{L} = 3000$ fb$^{-1}$. We consider NNLO+NNLL cross-section for SM $t\bar{t}$ production at 14 TeV LHC (966 pb) and for signal the no of events has been estimated/provided assuming single $H$ production cross-section to be 1 pb with $BR(H \to t\bar{t}) = 100%$.

The $H$ mass.

We denote the signal region $SR-medium$ with the same set of cuts as that of $SR-loose$ but with $E_T > 100$ GeV. In order to probe higher values of $M_H$, we define the signal region $SR-tight$ where
the cuts on $p_T$ of the jets and $E_T$ are stronger. For example, for $SR$-tight, events are selected with $p_T$ of the first two leading jets greater than 100 GeV while the missing transverse energy $E_T > 100$ GeV.

| Channel         | Number of Events at 3000 $fb^{-1}$ |
|-----------------|-----------------------------------|
|                 | $M_H = 400$ GeV | $M_H = 500$ GeV | $M_H = 600$ GeV |
| $SR$-loose      | Signal | $tt$ | Signal | $tt$ | Signal | $tt$ |
|                 | 1268   | 104612 | 9658   | 420572 | 26842   | 563452 |
| $SR$-medium     | 8      | 1741   | 1584   | 69232  | 9656    | 194698 |
| $SR$-tight      | -      | -      | 4      | 637    | 2296    | 44894  |

Table 7: Number of signal ($H$ production via ggF) and SM $t\bar{t}$ events after applying the final cuts in $SR$-Loose, $SR$-Medium and $SR$-Tight signal region at 14 TeV LHC with $\mathcal{L} = 3000$ $fb^{-1}$. For $t\bar{t}$, we have used NNLO cross-section [94]. For the signal estimation we have presented the number assuming $\sigma(pp \to H)_{NLO} \times BR(H \to t\bar{t}) = 1$ pb.

In Fig. 14, we display the $t\bar{t}$ invariant mass distribution for the three representative benchmark points with $M_H = 400$ GeV (green), 500 GeV (blue), 600 GeV (red), and also overlay the same for the SM $t\bar{t}$ background (black line). We show the invariant mass distribution for the signal region $SR$-loose with an integrated $\mathcal{L} = 3000$ $fb^{-1}$. To estimate the number of background events, we use the $t\bar{t}$ cross-section at next-to next-to leading order (NNLO) $\sigma_{NLO}^{t\bar{t}} = 966$ pb [94]. For simplicity, we assume that for all the benchmark points $BR(H \to t\bar{t})$ is 100% and the next-to leading order production cross-section $\sigma(pp \to H)$ is 1 pb. Note that, we make such a conservative choice just to keep our analysis simple, one can easily scale our numbers with the actual production cross-sections. Although one can see clear resonance peaks at the $M_H$ masses (see Fig. 14), enormous SM $t\bar{t}$ background makes it very challenging to observe a clear signal of heavy Higgs in the $t\bar{t}$ invariant mass distribution. To make more quantitative statement, we count the number of signal and background events for three signal regions $SR$-loose, $SR$-medium and $SR$-tight after C5, and then calculate the statistical significance $S = N_s/\sqrt{N_B}$. In Tab. 7, we present the number of signal and background events for three benchmark points and the SM $t\bar{t}$ backgrounds at the 14 TeV run of LHC with $\mathcal{L} = 3000$ $fb^{-1}$. From Tab. 7 one can see that $N_s/N_B$ ratio is very small for all the benchmark points and irrespective the signal regions. We find that the statistical significances $S$ for $M_H = 600$ GeV are 36, 22 and 11 for the three signal regions $SR$-loose, $SR$-medium and $SR$-tight respectively. However, even with 5% systematic uncertainty these numbers reduces to 0.95, 0.99, 1.02 respectively.

In Fig. 15 we show the distribution of $\sigma \times BR(H, A \to t\bar{t})$ assuming production of both $H$ and $A$ via ggF for all the points in our scanned data set. We find that $\sigma \times BR(H, A \to t\bar{t})$ lies mostly in the region $0.5 - 0.0001$ pb. The red solid line in Fig. 15 represents $\sigma \times BR(H, A \to t\bar{t}) = 1$ pb. This
red solid line indicates that for most the points in our scanned data set the quantity cross-section times \( BR(H, A \rightarrow t\bar{t}) \) is 10 - 1000 times smaller, and thus the the numbers in Tab. 7 represent a too much optimistic scenario. In other words, even HL-LHC might not be sensitive enough to probe such a region of parameter space.

Recently, it has been shown that using angular cuts, the signal significance can be improved [95]. However, one should note that the inclusion of systematic uncertainties may change the significance drastically and it is not possible to predict the reach of the \( t\bar{t} \) channel at the HL-LHC without the precise knowledge of the systematic uncertainties. We end this section by mentioning that the observation of a heavy Higgs in \( H \rightarrow t\bar{t} \) channel at the HL-LHC is really a challenging task and it needs special attention and more detailed studies.

5 Conclusion

A scalar particle with mass close to 125 GeV has been discovered at the LHC. Measurements of spin-parity and various couplings seem to agree with the SM expectations. In the minimal extension of SM, namely MSSM, one can identify the observed 125 GeV Higgs boson as the lightest Higgs boson among the five MSSM Higgses \( h, H, A \) and \( H^\pm \). In the MSSM, the couplings of \( h \) with SM electro-weak gauge bosons (\( W/Z \)) are proportional to \( \sin(\beta - \alpha) \) where \( \tan \beta \) is the ratio of
vevs of two Higgs doublets while $\alpha$ is the Higgs mixing angle. Precise measurements of various couplings of the observed Higgs boson with $W/Z$ bosons by the ATLAS and CMS collaborations imply $\sin(\beta - \alpha) \sim 1$. At the tree level, the Higgs mixing angle can be derived using pseudoscalar Higgs mass parameter $M_A$ and $\tan\beta$, however if we include radiative corrections, $\alpha$ becomes a non-trivial function of various SUSY parameters. The ATLAS and CMS collaborations have also searched for the heavy Higgs bosons ($H, A, H^\pm$), however absence of any signal puts strong bounds on the masses/branchings of these heavy Higgses. One can easily satisfy the current LHC data by taking $\alpha \to 0$, and $\beta \to \pi/2$ with $M_A >> M_Z$, which is generally known as the decoupling limit of MSSM. In this limit, the lightest MSSM Higgs boson behaves exactly like SM Higgs and masses of other Higgs bosons ($H, A, H^\pm$) are pushed well above LHC reach. In this paper we study the possibility of having light additional MSSM Higgs bosons, preferably below 600 GeV, with moderate Higgs mixing angle $\alpha$, being consistent with the SM Higgs data and also direct search limits on the MSSM heavy Higgses.

We restrict ourselves in the 19 dimensional pMSSM framework and scan the parameters that are relevant for the MSSM Higgs sector. We perform a global fit analysis using most updated data (till December 2014) from the LHC and Tevatron experiments and also consider the flavor physics constraints. The region with $M_A \leq 350$ GeV and $\tan\beta \geq 25$ are excluded by the BR($B_s \to \mu^+\mu^-$) while $M_A \leq 350$ GeV with $\tan\beta \leq 8$ is not favoured by the BR($b \to s\gamma$) constraint. The regions with large $M_A$ value ($> 400$ GeV) are not much constrained by the data. An interesting point to note that regions with $200 < M_A < 400$ can have moderate values of the Higgs mixing angle $\alpha = 0.2$, while for relatively large values of $M_A$, $\alpha$ can be as large as $\sim 0.8$ with small $\tan\beta$. Thus, one is not always forced to be in the decoupling limit to comply with the LHC data and light additional Higgses ($M_A$) is still allowed by current data. Moreover, 10 - 20% deviations from the SM expectations are also observed for various Higgs signal strength variables.

We next study the impact of current bounds on the MSSM heavy Higgs boson ($H, A$ and $H^\pm$) masses and couplings from the direct search at the LHC. We analyze the following decay modes of the MSSM heavy Higgses: $H \to \gamma\gamma$, $H \to WW$, $H \to hh \to b\bar{b}b\bar{b}$, $H \to hh \to b\bar{b}\gamma\gamma$, $H/A \to \tau^+\tau^-$, $A \to Zh$, $H^\pm \to \tau^\pm\nu$ and $H^+ \to t\bar{b}$. As we have already mentioned, most of the regions of parameter space satisfy the alignment limit ($\beta - \alpha \sim \pi/2$), the 7+8 TeV LHC data on $H \to WW$ channel is not sensitive enough to constrain the parameter space of our interest. Except $H/A \to \tau^+\tau^-$, LHC bounds on the production cross-section times branching ratios for other decay modes of $H, A$ and $H^\pm$ are also one/two orders of magnitude larger compared to the MSSM expectations. The 7+8 TeV LHC data on MSSM heavy Higgs decay $\Phi(= H/A) \to \tau^+\tau^-$ put the most stringent bound on our parameter space. The entire region with $\tan\beta > 20$ is excluded when the heavy Higgses $\Phi = H/A$ are produced via $b\bar{b}\Phi$ process. The reason being large $\tan\beta$ (typically $> 20$) implies large BR($H/A \to \tau^+\tau^-$), typically $\sim 10\%$, and large cross-section for associated production of $H/A$ with bottom quarks, and thus stronger constraint on the quantity $\sigma \times BR$. 

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We also study the prospect of probing the allowed parameter space, mostly low tan $\beta$ region at the high luminosity run of LHC (HL-LHC). We impose the ATLAS and CMS preliminary results on $H \to ZZ$ and $A \to Zh$ at the HL-LHC. The impact of the future limits from the $H \to ZZ$ and $A \to Zh$ channels are on the allowed parameter space is found to be marginal at $L = 3000 \, fb^{-1}$. Searches via $H \to hh$ at the HL-LHC can only probe a small part of the parameter space with low tan $\beta$. Among several other possible decay modes, $H \to t\bar{t}$ dominates in the low tan $\beta$ region for $M_H > 350 \, GeV$. We perform a dedicated signal-background analysis on the $H \to t\bar{t}$ channel by choosing a few representative MSSM benchmark points. We find that for $H \to t\bar{t}$ channel the signal to background ratio can be very small. A more detailed analysis is required, for example one can use the jet substructure technique, spin correlation technique to achieve better sensitivity in this channel. We discuss that so far the combined 7+8 TeV LHC data on the $H/A \to \tau^+\tau^-$ channel has the best sensitivity to place constraints on the MSSM parameter space of interest. Thus, one may expect to find stronger constraints on the MSSM parameter space from the $\tau^+\tau^-$ mode at the HL-LHC. It is beyond the scope of this paper, we leave this discussion for future.

In summary, we find that regions with low to moderate values of tan $\beta$ with light additional Higgses (mass $\leq 600 \, GeV$) remain unconstrained by the current data. Even the high luminosity run of LHC may not have enough sensitivity to probe the entire low tan $\beta$ region of parameter space. However, the proposed $e^+e^-$ international linear collider (ILC) will be an ideal machine to study this scenario. With the expected accuracies of the determinations of various partial decay widths of the Higgs boson and also the possibility of producing some of the heavy MSSM Higgses directly, one might be able the probe the remaining region of the allowed parameter space with $\sqrt{s} = 1000 \, GeV$ with higher luminosities at the ILC.

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