Supersymmetric Heavy Higgs Bosons at the LHC

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The search for heavy Higgs bosons is an essential step in the exploration of the Higgs sector and in probing the Supersymmetric parameter space. This paper discusses the constraints on the $M_A$ and $\tan\beta$ parameters derived from the bounds on the different decay channels of the neutral $H$ and $A$ bosons accessible at the LHC, in the framework of the phenomenological MSSM. The implications from the present LHC results and the expected sensitivity of the 14 TeV data are discussed in terms of the coverage of the $[M_A - \tan\beta]$ plane. New channels becoming important at 13 and 14 TeV for low values of $\tan\beta$ are characterised in terms of their kinematics and the reconstruction strategies. The effect of QCD systematics, SUSY loop effects and decays into pairs of SUSY particles on these constraints are discussed in details.

PACS numbers: 12.60.Jv, 14.80.Da

I. INTRODUCTION

With the observation of a light Higgs-like particle by the ATLAS and CMS experiments at the LHC [1, 2], the detailed exploration of the Higgs sector becomes one of the most compelling programs of collider physics. In particular, understanding whether this sector extends beyond that of the Standard Model (SM) and heavier Higgs bosons exist is of crucial importance for the viability of several models of new physics beyond the Standard Model, in primis of Supersymmetry (SUSY). This question can be answered either through a precision study of the couplings of the lightest boson, $h$, or by direct searches of the additional, heavier states which characterise extended Higgs models.

The LHC experiments have not only observed a light state and obtained the first determination of its decay rates to $\gamma\gamma$, $WW$ and $ZZ$. They have also performed several searches directly probing the possible production of heavy Higgs bosons and other searches, which can now be re-interpreted in order to set constraints on the production and decays of neutral heavy Higgs states. However, these data are still largely fragmentary.

Several studies of the MSSM heavy Higgs sector at LHC results have already been performed [3–7]. This paper intends to provide a comprehensive assessment of the present status and the future perspectives for the constraints on the MSSM Higgs sector parameters, from the identification of the main processes relevant to the LHC searches to a systematic study of the exclusion limits derived from the combination of the LHC results, in the context of the phenomenological MSSM (pMSSM) with the neutralino as the lightest SUSY particle (LSP) [8]. We perform this study taking the mass of the heavy pseudoscalar, $M_A$, and the ratio of the vacuum expectation value of the two Higgs doublets, $\tan\beta$, as the main parameters. We highlight the complex pattern of decays arising at low values of $\tan\beta$, values which are shown to be compatible with the present data and discuss the complementarity of decay modes such as $H \to ZZ$, $tt$ and $hh$ and $A \to Zh$.

The combination of the relevant decay channels to ex-
tend the sensitivity of the heavy Higgs searches over most of the \( [M_A - \tan \beta] \) was already discussed in \[9\]. Here, we use the published and preliminary results for the expected upper limits on the product of production cross section and decay branching fraction in several channels as constraints and extrapolate them to the full 2012 data set of 25 \( \text{fb}^{-1} \) experiment at 8 TeV and to 150 \( \text{fb}^{-1} \) of 14 TeV data.

In section II, we discuss the production and decays of the \( H \) and \( A \) neutral bosons, with special emphasis for the low \( \tan \beta \) region. Section III is devoted to presentation of the results of our systematic study of the indirect constraints derived from the latest measurements of the decay rates of the 126 GeV Higgs-like particle together with those obtained from direct searches for \( H/A \to \tau^+\tau^- \), \( H_{SM} \to ZZ, bbH \to bbbb \) and resonant \( tt \) production and their expected sensitivity on the 14 TeV LHC data. Then, we review additional decay modes, which have not yet been considered in the LHC searches but will become important at 14 TeV in the low \( \tan \beta \) region and characterise their kinematics and reconstruction strategies. Finally, we discuss the validity of these bounds when taking into account the production cross section uncertainties and the role of SUSY particles affecting the decays of heavy Higgs bosons, either in their direct decays to SUSY states or through loop corrections to their decay widths. Section IV has the conclusions.

II. THE HIGGS SECTOR AND THE \( M_A - \tan \beta \) PARAMETERS

A. \( H \) and \( A \) production and decays in the pMSSM

The MSSM neutral heavy Higgs bosons \( H \) and \( A \) have couplings modified compared to the SM Higgs state. In the decoupling limit \( (M_A \gg M_Z) \), the \( H/A \) coupling to the top quarks is suppressed by \( 1/\tan \beta \), while the couplings to bottom quarks and tau leptons are enhanced by \( \tan \beta \). As a consequence, the \( H/Att \) coupling is important only for \( \tan \beta \lesssim 10 \), those to \( bb \) and \( \tau\tau \) becoming dominant for larger values. On the other hand, the \( H \) couplings to vector bosons are suppressed by a factor \( \cos(\beta - \alpha) \), which in the large \( M_A \) and \( \tan \beta \) limit, decreases as \( 1/\tan \beta \). The situation is the same for the \( AhZ \) coupling, while there is no \( A \) coupling to vector bosons at tree level. Finally, the coupling of the \( H \) to \( hh \) also decreases in the large \( M_A \) and \( \tan \beta \) limit with \( 1/\tan \beta \). Hence, the description of the heavy Higgs sector in the large \( \tan \beta \) limit is simply dominated by the couplings to \( b \) and \( \tau \) fermions, whereas in the small \( \tan \beta \) regime, a rich phenomenology emerges, as the other couplings become important. A thorough discussion can be found in Ref. \[10\].

The \( H \) and \( A \) production cross section is dominated by the gluon fusion process and the associate Higgs production with \( b \) quarks. The relevant cross sections are shown in Fig. 1 for two values of the pseudoscalar Higgs mass \( (M_A = 300 \text{ and } 500 \text{ GeV}) \) at \( \sqrt{s} = 8 \) and 14 TeV, as a function of \( \tan \beta \).

The \( bbH \) associate production is a tree level process, which increases as \( \tan^2 \beta \) and becomes dominant for \( \tan \beta \gtrsim 10 \). Instead, the gluon fusion processes \[11\], induced by top and bottom quark loops, have the top loops dominant at small \( \tan \beta \), resulting in a decrease of the total cross section with \( \tan \beta \) up to the point where the \( b \) loops take over and the total cross section increases. Finally, the \( ttH \) production mode is kinematically suppressed and decreases with \( 1/\tan^2 \beta \), while vector boson fusion and associate production with gauge bosons is not important, contrary to the case for the lightest Higgs boson.

The decay \( A/H \to \tau^+\tau^- \) is the main process for the LHC experiments to search for the neutral heavy Higgs bosons at the present LHC energy, the dominant decay into \( bb \) being overwhelmed by the SM multi-jet background. As such, the \( \tau\tau \) mode has so far attracted most of the attention in the LHC searches for heavy Higgs bosons. At intermediate to large values of \( \tan \beta \) the \( \tau\tau \) and \( bb \) channels saturate the decay widths of the \( A \) and \( H \). At low \( \tan \beta \) the decay pattern of the heavier MSSM Higgs particles becomes more complicated by the onset of several decay modes which compete with \( \tau\tau \), in particular \( WW, ZZ, tt \) and \( hh \). The branching fractions for the decays of \( H \) and \( A \) bosons are shown in Fig. 2 as a function of \( \tan \beta \) for two masses below (300 GeV) and above (500 GeV) the \( tt \) threshold.

The main features can be summarised as follows. Below the \( tt \) threshold, the \( H \) boson decays into gauge bosons \( H \to WW, ZZ \) and into pairs of the light...
Similarly the pseudoscalar with masses the \( M_A \) modified when some light SUSY particles are present in the BR(…)

The LHCb experiment has recently announced the first evidence for the \( B_s \to \mu^+\mu^- \) decay and measured its branching fraction to be in agreement with the SM expectation. This branching ratio is sensitive to the Higgs sector, in particular to \( M_A \) and \( \tan \beta \), proportional to \( \sim \tan^6 \beta / M_A^4 \) in the large \( \tan \beta \) limit. Complementary information is also obtained by dark matter direct detection experiments, in particular the latest XENON-100 limits, probing the scattering of neutralino with matter, which can be mediated by scalar particles.

The tools used to perform the scans and the analysis have been presented in Ref. [13, 18]. Most relevant to this study are the calculations of the Higgs decay branching fractions and production cross sections. The first are computed using the latest version of HDECAY (5.10) [19]. The cross section for \( gg \to H/A \) is computed at NNLO with HIGLU 3.1 [20, 21], that for \( tt \to H/A \) at NNLO with bbhMinlo [22] and that for \( pp \to bbH \) at LO with HQQ [23]. In addition, we compare the results for \( gg \) and \( bb \) processes from these programs to those from SusHi [24] and found an agreement within 10-15%. The Higgs and superparticle spectra are calculated with Softsusy 3.2.3 [26] and SuperIso Relic v3.2 [27] computing the dark matter relic density and flavour constraints and providing the central control program interfaced to the other codes.

B. SUSY Effects in \( H \) and \( A \) Decays

There are regions of the MSSM parameter space where the \( \tau\tau \) channel is suppressed and the limits derived in this channel are correspondingly relaxed. These may be due to direct decays of \( H/A \) to SUSY particles or to loop corrections to the \( H/Abb \) vertices, affecting the \( H/A \to \tau\tau \) branching fraction.

We consider first the decays of heavy neutral Higgs bosons into pairs of SUSY particles. The heavy Higgs bosons couple to charginos and neutralinos, primarily to identical particles for the mixed gaugino/higgsino states, and to different particles in case of pure gaugino or higgsino states. If the decay to charginos is allowed, it dominates over the decays to neutralinos. Heavy neutral Higgs bosons also couple to scalar fermions. However, decays to scalar fermions of the first two generations are suppressed and only significant at low \( \tan \beta \), where they are sub-dominant. For scalar fermions of the third genera-
tion the decay rates can be much larger, but they are suppressed at large \( \tan \beta \) for scalar top quarks, while they are enhanced for the scalar taus and scalar bottoms. Since the lightest scalar tau, \( \tilde{\tau}_1 \) is often the NLSP at large \( \tan \beta \), decays to staus are usually the dominant channel for decays into scalar fermions.

Figure 4 shows the decay branching fraction of \( H \) into any pair of SUSY particles calculated for the accepted pMSSM points for which at least one of these decay channels is kinematically allowed. In approximately 25% of these cases the branching fraction into SUSY particles is larger than 0.10.

The yield in the \( \tilde{\chi} \tilde{\chi} \) channels, representing the sum of all the kinematically accessible chargino and neutralino pairs, depends on the mass parameter \( M_2 \) and the Higgsino mass mixing parameter \( \mu \). Figure 5 shows the \( \sigma \times \text{BR} \) product in the \( [\mu - M_2] \) parameter plane to highlight the enhancement of this class of decays along the small \( M_2 \) or \( \mu \) regions.

The rates of decays into SUSY particles depend mostly on the difference between the masses of heavy boson and those of the SUSY particles. As the scale of the mass of the \( H \) and \( A \) bosons probed at the LHC increases, decays into SUSY particles become more likely and have to be carefully considered. The relevant mass patterns are extensively probed in our pMSSM scans. The increase in the branching fractions of any of these SUSY channels is correlated to the decrease of that for the \( \tau \tau \) mode, which can be suppressed by a factor of two, or more, compared to its average value at large \( M_A \) and \( \tan \beta \) values.

Finally loop corrections to the \( H bb \) and \( Abb \) vertices, known as \( \Delta_b \) corrections [28], modify both the \( H/A \) production rates and their decay widths. In the decoupling limit, the \( H/A \) coupling to \( bb \) is modified by a factor \((1 + \Delta_b)^{-1}\), where

\[
\Delta_b \approx \frac{2 \alpha_s}{3\pi} \mu M_3 \frac{\tan \beta}{\max(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)} + \frac{\mu A_t}{16\pi^2} \frac{\tan \beta}{\max(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2)}.
\]

Full one loop corrections to the \( WW \) and \( ZZ \) decays have also been computed [29, 30]. We observe that the BR(\( H/A \to \tau \tau \)) is reduced as a result of the enhancement of BR(\( H/A \to bb \)) due to these corrections for SUSY parameters yielding a large \( \Delta_b \) of negative sign (see Figure 6). Such a large, negative \( \Delta_b \) term has also implications on the decay branching fractions of the lightest \( h \) boson. In the region where the \( H \to \tau \tau \) decay rate is reduced, the branching fraction BR(\( h \to bb \)) is also reduced and those for the other modes correspondingly increased.
These patterns might be tested through more precise determinations of the signal strengths of the lightest Higgs decays. In view of these effects, redundancy obtained through search in multiple channels sensitive in the same regions of the \([M_A - \tan \beta]\) parameter space appears to be essential.

![Figure 6: Correlation of the BR\((H \rightarrow \tau\tau)\) with BR\((H \rightarrow bb)\) (left) and with \(\Delta_b\) (right) for accepted pMSSM points. The correlated suppression of both the \(\tau\tau\) and \(bb\) branching fractions are due to additional decays into SUSY particles, while the decrease of \(\tau\tau\) with the increase of \(bb\) is due to \(\Delta_b\) effect.](image)

**C. Constraints from the h Mass and Decay Rates**

Assuming that the observed \(\sim 126\) GeV state is the lightest Higgs boson of the MSSM, \(h\), its mass \(M_h\) depends on several SUSY parameters, in particular \(M_A\), \(\tan \beta\) and the SUSY scale, \(M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}\). The LEP-2 \(M_A\), which are now significantly stronger than the LEP-2 limit. This is illustrated in Figure [7] which shows the values of \(\tan \beta\) vs. \(M_A\) for our pMSSM scans which are compatible with 121.5< \(M_h\) <129.9 GeV, for two intervals of values of the SUSY scale \(M_S\). Large enough \(M_S\) values rescue the MSSM scenarios at low values of \(\tan \beta\), provided we accept a high fine tuning parameter from the large scale of \(M_S\). This observation motivates the special attention we have chosen to devote to low \(\tan \beta\) scenarios in this study.

![Figure 7: The \([M_A - \tan \beta]\) parameter space compatible with 121.5 < \(M_h\) < 129.9 GeV for different SUSY scales \(M_S\). Distribution of the accepted pMSSM points in the \([M_A - \tan \beta]\) compatible with the \(M_h\) mass interval for 0.5< \(M_S\) <3.5 TeV (black dots) and 5< \(M_S\) <20 TeV (light grey dots).](image)

A second set of indirect constraints is derived by the measured \(h\) decay rates. For large \(M_A\) values, the couplings of the \(h\) boson can be expanded in powers of \(M_Z/M_A\) to obtain the following tree-level result [10]:

\[
g_{hVV}^{M_A \gg M_Z} 1 - \frac{M_Z^2}{8 M_A^2} \sin^2 4\beta \tan \beta \frac{\tan \beta \gg 1}{1 - \frac{2 M_Z^2}{M_A^2 \tan^2 \beta} (2)}
\]

For \(M_A \gg M_Z\), \(g_{hVV}\) reaches the SM value, more quickly if \(\tan \beta\) is large. The \(h\) couplings to up- and down-type fermions scale as [10]:

\[
g_{huu}^{M_A \gg M_Z} 1 + \frac{M_Z^2}{2 M_A^2} \sin 4\beta \tan \beta \frac{\tan \beta \gg 1}{1 - \frac{2 M_Z^2}{M_A^2 \tan^2 \beta} (3)}
\]

\[
g_{hdd}^{M_A \gg M_Z} 1 - \frac{M_Z^2}{2 M_A^2} \sin 4\beta \tan \beta \frac{\tan \beta \gg 1}{1 + \frac{2 M_Z^2}{M_A^2}} (4)
\]

The couplings of the \(h\) boson approach those of the SM Higgs boson for \(M_A \gg M_Z\) and these limits are reached at lower values of \(M_A\) for large \(\tan \beta\) (see Figure [8]). In practice, the ratio of branching fractions \(R_{XX} = BR(h \rightarrow XX)/BR(H_{SM} \rightarrow XX)\) or the signal strengths \(\mu_{XX} = \sigma(h)/\sigma(H_{SM}) \times R_{XX}\), where \(\sigma\) is the relevant production cross section, can be used to set constraints on the value of \(M_A\). The recent approximate N3LO calculation of the Higgs production cross section resulting in a 17% correction also needs to be taken into account [31]. The latest set of LHC results already allows us to evaluate some non-trivial constraints, as discussed in the next section.

![Figure 8: Scaling of the \(h\) branching fractions into \(bb\), \(\tau\tau\) and \(ZZ\) normalised to their SM value as a function of tan \(\beta\) for \(M_A = 300\) GeV (left panel) and as a function of \(M_A\) for \(\tan \beta = 10\) (right panel).](image)
III. CONSTRAINTS IN THE $M_A - \tan \beta$ PLANE

The LHC searches have gathered a significant corpus of results, which can be used to place some important constraints on the $H$ and $A$ bosons in a variety of channels. These results also allow us to study the expected sensitivity of data to be taken at 13 and 14 TeV from 2015. In the next two sections we discuss the current constraints and in the following we present the extrapolation to 14 TeV. There are important decay channels, such as $H/A \rightarrow hh$ and $A \rightarrow hZ$, for which no analysis has been performed yet on the LHC data. We characterise the kinematics and reconstruction strategy for these processes using parametrised simulation at the end of this section.

A. Present Constraints (7 and 8 TeV)

1. Indirect Constraints from the light Higgs signal

The ATLAS and CMS collaboration have recently updated their determination of the mass and signal strengths of the Higgs-like particle. In particular, results for the $\gamma \gamma$ [35, 36], $ZZ$ [27, 38] and $WW$ [39, 40] channels have been reported by both collaborations for the full 8 TeV data set, corresponding to integrated luminosities of up to 25 fb$^{-1}$. In addition, CMS has updated the search in the $\tau\tau$ channel at low mass [41]. Here we use the weighted averages for the mass and signal strengths in these preliminary results, as summarised in Table I. For the important $\gamma\gamma$ channel we average the preliminary results of the multi-variate and cut-based analyses of CMS accounting for the quoted correlation [48]. The results of the two collaborations are only marginally consistent and we therefore rescale the error of the combined result according to the prescriptions of the Particle Data Group [42]. We use these new inputs and perform an analysis of the regions of MSSM parameter space favoured by these data. The analysis follows the strategy discussed in [13]. We define the 90% C.L. region corresponding to observables given in Table I by constructing the corresponding $\chi^2$ probability. We account for the theory uncertainties on the MSSM $h$ mass, $\pm 1.5$ GeV, and the Higgs production rates, $\pm 20\%$. No signal evidence has been reported for the $bb$, where we also include the combined estimate on $\mu_{bb}$ obtained by CDF and D0 at the Tevatron [43], and the $\tau^+\tau^-$ channels. For these we add the contribution to the total $\chi^2$ only when the respective $\mu$ value is outside the $\pm 1.5 \sigma$ interval from the measured central value. Compared to the results available at the end of 2012, we register a marked realignment of the average values for the $\mu_{XX}$ signal strengths from the ATLAS and CMS results around the SM values. This has important consequences on the constraints derived. In particular, the $M_A$ bound derived from the new data is about 100 GeV lower compared to that obtained on the first preliminary results on part of the 8 TeV data released at the end of 2012, without the CMS re-analysis of the $\gamma\gamma$ channel [13]. This clearly shows that it is difficult to predict the sensitivity achievable in future for these indirect limits, which depends not only on the accuracy of the inputs but also rather critically on the measured values.

| Parameter | Value      | Experiment               |
|-----------|------------|--------------------------|
| $M_h$ (GeV) | 125.7±0.4  | ATLAS [36] + CMS [38]    |
| $\mu_{\gamma\gamma}$ | 1.20±0.30  | ATLAS [39] + CMS [30]    |
| $\mu_{ZZ}$  | 1.10±0.22  | ATLAS [37] + CMS [38]    |
| $\mu_{WW}$  | 0.77±0.21  | ATLAS [39] + CMS [40]    |
| $\mu_{bb}$  | 1.12±0.45  | ATLAS [13] + CMS [44] + (CDF+D0) [45] |
| $\mu_{\tau\tau}$ | 1.01±0.36  | ATLAS [44] + CMS [41]    |

TABLE I: Input values for the average values of the $h$ mass and signal strengths used for this study with their statistical accuracies. Systematic uncertainties are discussed in the text.

We consider points compatible at 90% C.L. with these inputs accounting for theory uncertainties. We observe that these account for 76% of the accepted pMSSM points, up from the 30% obtained in the same analysis performed on the earlier data. For all these points the $\sim 126$ GeV state observed by ATLAS and CMS is the lightest Higgs, $h$. Therefore we confirm the results from our previous analysis where we did not find any pMSSM solution compatible with the LHC Higgs results where the 126 GeV particle is either the $H$ or the $A$ boson. This result provides an answer to the question of [49]. Figure 9 shows this fraction as a function of $[M_A - \tan \beta]$ (left) and $[\mu - M_2]$ (right).

FIG. 9: Fractions of pMSSM points compatible at 90% C.L. with the constraints of Table I in the $[M_A - \tan \beta]$ (left) and $[\mu - M_2]$ (right).

2. Direct Constraints from MSSM Higgs Searches

Searches for the $H/A \rightarrow \tau^+\tau^-$ process have been conducted by the ATLAS with 4.7 fb$^{-1}$ at 7 TeV [50] and CMS with 4.8+12.2 fb$^{-1}$ at 7 and 8 TeV [51]. The CMS
sensitivity corresponds to an expected upper limit on the product of production cross section and decay branching fraction of \( \sim 80 \) fb at 300 GeV and 20 fb at 500 GeV. In this study, we impose the expected CMS 95% C.L. limit on the product of production cross section and decay branching fraction, which is weaker than the observed limit, on our pMSSM points.

The production and decay pattern of the heavy MSSM neutral Higgs bosons crucially depend on the value of \( \tan \beta \), as discussed above. The LHC data at 7 and 8 TeV, probe relatively large values, \( \tan \beta \gtrsim 5–10 \). For these values, their couplings to \( b \) quarks and \( \tau \) leptons, proportional to \( \tan \beta \), are strongly enhanced, and those to top quarks and massive bosons, proportional to \( \approx 1/\tan \beta \), are suppressed. Therefore the \( \tau \tau \) channel is presently the single most constraining decay mode. It defines a region of the \( [M_A - \tan \beta] \) parameter space which is probed also by the \( B_s \to \mu \mu \) rare decay and by dark matter direct detection experiments [14] [15], but the \( H/A \to \tau \tau \) LHC searches at 7 and 8 TeV set the tightest constraints. In addition to it, preliminary results have been reported for the first search for \( H/A \to bb \) in association production with \( b \) jets \( bbH/A \to bbbb \) based on the 7 TeV CMS data [52], which has sensitivity at large values of \( \tan \beta \) with an expected upper limit of 8 pb on \( \sigma \times BR \) at 300 GeV. The analyses of the decays of the SM Higgs \( H_{SM} \to ZZ \) have set constraints on the product of production cross section and decay branching fraction \( \sigma(gg \to H_{SM}) \times BR(H_{SM} \to ZZ) \) for Higgs masses up to 1 TeV [53] [54]. These can now be used to constrain the decay of the heavy SUSY \( H/A \to ZZ \), with upper limits of \( \sim 1.9 \) and 1.4 fb at 200 and 300 GeV, respectively. Finally, the decay \( H/A \to tt \) can be constrained through the cross section bounds obtained for the production of a narrow resonance decaying into top quark pairs, interpreted in the original studies in the context of the searches for the production of a lepto-photonic \( Z' \) gauge boson, KK resonances or other exotic narrow resonances. Results have been reported by both ATLAS [55] and CMS [56] for the 7 TeV data with cross section upper limits of order of 3 pb and 0.8 pb at resonance masses of \( \sim 500 \) GeV and 800 GeV, respectively.

First, we study the value of the product of production cross section and decay branching fraction in several channels by scanning over the pMSSM parameters. Figure 10 shows the regions of the \( [M_A - \tan \beta] \) parameter space where the product \( \sigma \times BR \) exceeds 1, 10 and 100 fb at 8 TeV for the \( gg \to H/A \) and \( bb \to H/A \) production processes and the \( H/A \to ZZ, H/A \to WW \) and \( H/A \to tt \) decays. Finally, we combine the constraints derived in the various channels. We take the expected upper limits on the products \( \sigma \times BR \) in the various channels for both (a) the present status of the results and (b) their extrapolation to the full 8 TeV data set, 25 fb\(^{-1}\). When limits are only available for the 7 TeV data set, we compute the expected limit at 8 TeV by taking the ratio of production cross sections at the two energies, as a function of the \( H/A \) mass, into account. For each channel, we consider the contours in the \( [M_A - \tan \beta] \) plane where more than 95% of the selected pMSSM points are excluded by these constraints. Alongside the \( \tau \tau \) channel, the \( ZZ \) and \( bbbb \) channels also offer sensitivity on the 7 and 8 TeV data. For the \( ZZ \) channel we use the upper limits on \( \sigma \times BR \) from [54] These limits define an excluded region which connects with the \( \tau \tau \) constraint at low masses and extends up to \( M_A \simeq 550 \) GeV for \( \tan \beta = 3-4 \). The \( bbbb \) channels is based on the preliminary result on the 7 TeV CMS data [62] extrapolated to the full 8 TeV data set. We include also the constraint derived from the signal strengths, \( \mu \), obtained in the ATLAS and CMS SM Higgs analyses for the \( \gamma \gamma, WW, ZZ \) channels and the limits for \( bb \) and \( \tau \tau \), as discussed above, interpreting the observed particle as the SUSY lightest Higgs, \( h \). Results are summarised in Figure 11 The combination of the \( H/A \to \tau \tau \) channel and the mass and \( \mu \) values for the lightest \( h \) boson exclude the region with \( M_A > 320 \) GeV for all values of \( \tan \beta \). For the current results, the \( \mu \) values defines this lower bound in the region of \( \tan \beta = 2-15 \), where the direct search sensitivity is weaker. The sensitivity of the direct \( H/A \) searches should approach this bound down to \( \tan \beta \simeq 10 \), once the full 2012 data is analysed. The

![Figure 10: Product of production cross section and decay branching fraction for \( H \to ZZ \) (left), \( H \to WW \) (upper centre) and \( H \to t\bar{t} \) (right) at 8 TeV in the \( [M_A - \tan \beta] \) parameter plane. The dots in the light shade show all the selected pMSSM points and those in darker shades of colour the points having \( \sigma \times BR \) larger than 1, 10 and 100 fb. The lines superimposed on the left panel show the expected (dashed) and observed (continuous) 95% C.L. upper limits obtained in the \( H/A \to \tau \tau \) search of [51]. Entries below threshold in the \( t\bar{t} \) channel are due to off-shell decays.](image-url)
FIG. 11: Combination of the expected constraints on the $[M_A - \tan \beta]$ parameter plane from the $\tau\tau$ and $ZZ$ channels for (a) the current results (upper panel) and (b) their extrapolation to the full 8 TeV data set (lower panel). The colour scale gives the fraction of pMSSM points excluded at each $M_A$ and $\tan \beta$ value. The contours show the limits corresponding to 95% or more of the points excluded. The 90% C.L. constraint from the Higgs signal strengths is also shown. The expected and observed upper limits on $\tan \beta$ obtained in the MSSM $M_h^{max}$ scenario from the $\tau\tau$ channel search of $[51]$ are indicated by the grey dotted and continuous lines, respectively, on the upper plot. The grey region has no accepted pMSSM points after the $B_s \to \mu\mu$, direct DM searches and $M_h$ constraints.

$ZZ$ channel, and to a lesser extent the $WW$, should close the low $M_A$ corner from $\tan \beta \simeq 2$ up to the $\tau\tau$ limit for $M_A \lesssim 230$ GeV with the full 8 TeV data. The upper limits from the $tt$ channel, for which only results at 7 TeV have been reported, are still below the expected values for $H/A$ production in the MSSM, even by extrapolating them to the full 8 TeV data set. Instead, this channel will become essential at 13 and 14 TeV. The combination of these constraints from the Higgs sector provide limits on $M_A$ and $\tan \beta$, which are significantly tighter compared to those derived from flavour physics, such as the BR$(B_s \to \mu\mu)$ for which the first measurement has recently been reported by LHCb $[16]$ (see Figure 11).

B. Perspectives at 14 TeV

The increase of the production cross sections moving from 7 to 14 TeV is a factor of 4.5 to 9 for $gg \to H/A$ and 5 to 12 for $bb \to H/A$ in the mass range 300 to 800 GeV. Figure 12 shows the regions of the $[M_A - \tan \beta]$ parameter space where the product $\sigma \times \text{BR}$ exceeds 1, 10 and 100 fb for the $gg \to H/A$ and $bb \to H/A$ production processes and the $H/A \to ZZ$, $H/A \to WW$, $H/A \to hh$, $A \to hZ$, $H/A \to tt$ and the inclusive decays $H/A \to \text{SUSY}$ particles. At the high mass end the product $\sigma \times \text{BR}$ of $\sim 10$ fb, corresponding to the current sensitivity at 800 GeV in the $\tau\tau$ channel, is obtained beyond $M_A = 1$ TeV. At 13 and 14 TeV the sensitivity extends to mass values above the $hh$, $hZ$ and the $tt$ production thresholds at small to intermediate values of $\tan \beta$, which make these channels relevant to the LHC searches. In this region the $\tau\tau$ channel alone cannot ensure the coverage of the $[M_A - \tan \beta]$ plane and these additional channels need to be included. The $ZZ$ channel provides redundancy while the $tt$ decay is most important, in particular at large $M_A$ and low $\tan \beta$ values. The $WW$ channel has more limited interest, since its sensitivity is lower than $ZZ$. The combination of the $\tau\tau$, $ZZ$ and $tt$ modes covers the $[M_A - \tan \beta]$ parameter plane up to $M_A \simeq 700$ GeV for any value of $\tan \beta$, as shown in Figure 13.

1. Characterisation of $hZ$ and $hh$ channels

The decays $H \to hh$ and $A \to hZ$ are important in providing redundancy at low values of $\tan \beta$ and intermediate $M_A$ masses. They also result in rather distinctive $bbb$, $bb\tau\tau$ and $bb\ell\ell$ ($\ell = e, \mu$) final states, which should be investigated in the high energy LHC runs. Since these modes have not yet been searched for in the LHC data, we characterise here their decay kinematics and study the reconstruction strategies using a simple analysis for signal events.

These events are generated using Pythia 8.1 $[57]$ at 14 TeV and scaled to an integrated luminosity of 150 fb$^{-1}$. For this study, we have chosen $M_A = 400$ and 500 GeV, $\tan \beta = 5$ with branching fractions of 0.12 for $H \to hh$ and $A \to hZ$. The detector response simulation is performed using Delphes 3.0 $[58]$. Jets are reconstructed using the anti-kt algorithm $[59]$ implemented in FastJet $[60]$, requiring their pseudo-rapidity, $\eta$, not to exceed 2.4 and transverse momentum $p_T > 20$ GeV. Electrons and muons are accepted for $|\eta| < 2.4$ and $p_T > 20$ GeV. $b$-jets are accepted at $\eta < 2.5$, assuming a tagging efficiency of 75% per jet. In both channels, $b$-jets are rather soft, with the transverse energy distributions peaking around 50 GeV, thus emphasising $b$ tagging at relatively small transverse energies (see Figures 14 and 15). Similarly low is the transverse energy distribution of leptons from the $Z$ decay in the $A$ channel, which has its most probable value just above the $p_T$ cut applied in this analysis (see Figure 15).
$H \rightarrow hh \rightarrow bbbb$ events are reconstructed by requiring at least three $b$-tagged jets. The pairing of four $b$ jets, or three $b$ jets with any of the reconstructed jets, which minimizes the mass difference of the two di-jet pairs and their difference from the $h$ mass of 126 GeV is selected. The di-jet invariant mass distribution is shown in Figure 14. The invariant mass resolution obtained with the fast simulation is comparable to that reported for the $H_{SM} \rightarrow bb$ search. The four-jet invariant mass, $M_{bbbb}$ shows a clear peak corresponding to the generated $H$ mass as shown in Figure 14. The efficiency of this selection for the signal mass region of $300 < M_{bbbb} < 500$ GeV is $\simeq 16\%$ at both values of $M_H$.

$H \rightarrow \ell\ell b\bar{b}$ we select events with two, oppositely charged, electrons or muons with two or more jets, of which at least one $b$ tagged. The $\ell\ell$ invariant mass is required to be consistent with that of the $Z$ within the resolution. If the event contains exactly two $b$-tagged jets, the invariant mass of the pair is required to be con-

FIG. 12: Product of production cross section and decay branching fraction for $H \rightarrow ZZ$ (upper left), $H \rightarrow WW$ (upper centre), $H \rightarrow hh$ (upper left), $A \rightarrow hZ$ (bottom right), $H \rightarrow tt$ (bottom centre) and $H \rightarrow$ SUSY particles (bottom left), at 14 TeV in the $[M_A - \tan \beta]$ parameter plane. The colour coding is given in the legend and it is the same as in Figure 10.

FIG. 13: Combination of the expected constraints on the $[M_A - \tan \beta]$ parameter plane from the $\tau\tau$, $ZZ$ and $tt$ channels as in Figure 11 extrapolated to 150 fb$^{-1}$ at 14 TeV. The colour scale gives the fraction of pMSSM points excluded at each $M_A$ and $\tan \beta$ value. The grey region has no accepted pMSSM points after the $B_s \rightarrow \mu\mu$, direct DM searches and $M_h$ constraints.

FIG. 14: Reconstruction of $H \rightarrow hh \rightarrow bbbb$ events at 14 TeV for $M_H = 400$ GeV: distribution of the $b$-jet transverse energy $E_T$ (upper right) and energy $E$ (lower left), invariant mass of $bb$ pairs (lower left) and $bbbb$ invariant mass (lower right). A BR$(H \rightarrow hh) = 0.12$ has been assumed.
consistent with 126 GeV within the resolution. If there is only one $b$-tagged jet, but it has a mass consistent with 126 GeV, this is also accepted. The final mass is computed by combining the di-leptons with the di-jet pair.

The limits derived above do not account for the effects of theoretical uncertainties, affecting the Higgs production cross section and decay branching fractions, and of SUSY contributions. First, the $gg \to H/A$ and $bb \to H/A$ cross sections have sizeable QCD uncertainties from the factorisation and renormalisation scales, parton distribution functions (PDFs) and parametric systematics from $\alpha_s$ and the heavy quark masses. We estimate the parametric systematics on the cross section for $\alpha_s = 0.118 \pm 0.0012$, $m_t(m_t) = (172.9 \pm 1.5)$ GeV and those from the PDFs by taking the largest difference between different sets of functions. The latter is the dominant contribution. The combination of the uncertainties on the quark masses, PDFs and $\alpha_s$ leads to an estimated systematic uncertainty on the $pp \to H/A$ rate of $\pm 24\%$ at 8 TeV and $\pm 20\%$ at 14 TeV, dominated by the PDFs and scale, and comparable to those for $pp \to H_{SM}$ production.

In order to evaluate their impact on the exclusion contours in the $[M_A - \tan \beta]$ plane, we repeat our study while changing the production cross section by $\pm 25\%$ and compare the constraints obtained to that corresponding to the central values for the production cross sections. Figures 17 and 18 show the fractions of excluded points in the $[M_A - \tan \beta]$ plane and their projections as a function of $M_A$ for the fixed value of $\tan \beta = 15$ at 8 and 14 TeV, respectively, and includes the effect of the $\pm \sigma_{QCD}$ change of the cross sections by the QCD uncertainties. The effect is a shift of the excluded $M_A$ mass by $\pm 45$ GeV at 8 TeV and by $\pm 55$ GeV at 14 TeV at $\tan \beta = 15$ and larger for higher values of $\tan \beta$.

Then, we observe that, there is a significant smearing of the curve giving the fraction of excluded pMSSM points as a function of $M_A$, even if the systematics on the production cross section are ignored. In fact, the exclusion curve goes from 10% to 90% of the points excluded over a range of $M_A$ values spanning $\sim 90$ GeV at 8 TeV and $\sim 150$ GeV at 14 TeV, as a result of the variation of other pMSSM parameters. This range, which is comparable to that corresponding to the QCD uncertainty obtained above, is intrinsic to the pMSSM and includes contributions such as the loop effect through the $\Delta s$ term discussed in section II.B.

Finally, we consider quantitatively the region of the
The search for heavy Higgs bosons represents a next frontier in the understanding of the Higgs sector after the discovery of the Higgs-like state at 126 GeV at the LHC and the first results on its decays, spin and parity. The combination of the indirect limits from the $h$ signal strengths and the direct searches in the $\tau\tau$ and $ZZ$ channels should impose an exclusion limits in $[M_A - \tan\beta]$ plane around $M_A \gtrsim 320$ GeV for the $7+8$ TeV data, determined by the indirect limit from the rates of the observed Higgs boson.

As the mass sensitivity of the LHC searches increases with the energy and integrated luminosity, more final states than $\tau\tau$ become relevant to effectively constrain the supersymmetric parameter space, in particular at low to moderate values of $\tan\beta$. In fact, low values of $\tan\beta$ are still viable, after incorporating the $M_h$ constraint, provided high SUSY scales, $M_S$, are chosen and they represent a scenario, rich in decays into $t\bar{t}$ and $ZZ$, $hh$ and $hZ$ boson pairs, which should be carefully explored at the LHC at 13 and 14 TeV. The $M_S$ bound will reach $M_A \gtrsim 800$ GeV for any value of $\tan\beta$ with $150$ fb$^{-1}$ of data at 14 TeV, determined by the direct searches for heavy Higgs states. The effects of the SUSY particle spectrum, other SUSY parameters and the QCD theoretical uncertainties need to be carefully considered. SUSY loops and QCD effects on the $M_A$ bounds are found to be quite comparable in size. However, scenarios where decays into SUSY particles are important, or even dominant, exist and these channels need to be accounted for in the LHC searches at 13 and 14 TeV.

The constraints derived by the study of the Higgs sector are becoming an essential part of the probe of the SUSY parameter space at the LHC and offer an essential complement to the searches for strongly interacting SUSY particles and gauginos.

Acknowledgments

We are grateful to Abdelhak Djouadi who provided us with inspiration for several parts of this study, in particular the interest for the low $\tan\beta$ region and the use of the $ZZ$ and $tt$ analyses to constrain heavy Higgs production. We wish to thank also Benjamin Allanach for discussion and support with the use of Softsusy, Robert Harlander with that of SusHi and Stefan Dittmaier for discus-
wishes to thank the Galileo Galilei Institute for Theoretical Physics for the hospitality and INFN for partial support during the early stages of this work.

References

[1] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716 (2012) 1 [arXiv:1207.7214 [hep-ex]].
[2] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716 (2012) 30 [arXiv:1207.7235 [hep-ex]].
[3] J. Baglio and A. Djouadi, [arXiv:1103.6247 [hep-ph]].
[4] M. Carena, P. Draper, T. Liu and C. Wagner, Phys. Rev. D 84 (2011) 095010 [arXiv:1107.4354 [hep-ph]].
[5] N. D. Christensen, T. Han and S. Su, Phys. Rev. D 85 (2012) 115018 [arXiv:1203.3207 [hep-ph]].
[6] J. Chang, K. Cheung, P.-Y. Tseng and T.-C. Yuan, Phys. Rev. D 87 (2013) 035008 [arXiv:1211.3849 [hep-ph]].
[7] M. Carena, S. Heinemeyer, O. Stal, C. E. M. Wagner and G. Weiglein, [arXiv:1302.7033 [hep-ph]].
[8] A. Djouadi et al. [Les Houches MSSM Working Group], [hep-ph/9901246].
[9] [ATLAS Collaboration], CERN/LHCC 99-14.
[10] A. Djouadi, Phys. Rept. 459 (2008) 1 [hep-ph/0503173].
[11] M. Muhlleitner, H. Rzehak and M. Spira, DESY-PROC-2010-01.
[12] A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, JHEP 1209 (2012) 107 [arXiv:1207.1348 [hep-ph]].
[13] A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, Phys. Lett. B 720 (2013) 153 [arXiv:1211.4004 [hep-ph]].
[14] A. Arbey, M. Mahmoudi, and F. Mahmoudi, Eur. Phys. J. C 72 (2012) 1906 [arXiv:1112.3032 [hep-ph]].
[15] A. Arbey, M. Battaglia, F. Mahmoudi and D. Martinez Santos, Phys. Rev. D 87 (2013) 035026 [arXiv:1212.4887 [hep-ph]].
[16] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 110 (2013) 021801 [arXiv:1211.2674 [hep-ex]].
[17] E. Aprile et al. [XENON100 Collaboration], Phys. Rev. Lett. 109 (2012) 181301.
[18] A. Arbey, M. Battaglia and F. Mahmoudi, Eur. Phys. J. C 72 (2012) 1847 [arXiv:1110.3726 [hep-ph]].
[19] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. 108 (1998) 56.
[20] M. Spira, A. Djouadi, D. Graudenz and P. M. Zerwas, Nucl. Phys. B 453 (1995) 17 [hep-ph/9504378].
[21] M. Spira, Nucl. Instrum. Meth. A 389 (1997) 357 [hep-ph/9610350].
[22] R.V. Harlander and W.B. Kilgore, Phys. Rev. D 68 (2003) 013001 [hep-ph/0304035].
[23] M. Spira, Fortschr. Phys. 46 (1998) 203 [hep-ph/9705337].
[24] R. V. Harlander, S. Liebler and H. Mantler, arXiv:1212.3249 [hep-ph].
[25] B.C. Allanach, Comput. Phys. Commun. 143 (2002) 305 [hep-ph/0104145 [hep-ph]].
[26] F. Mahmoudi, Comput. Phys. Commun. 178 (2008) 745 [arXiv:0710.2067 [hep-ph]]; idem, Comput. Phys. Commun. 180 (2009) 1579 [arXiv:0805.1444 [hep-ph]].
[27] A. Arbey and F. Mahmoudi, Comput. Phys. Commun. 181 (2010) 1277 [arXiv:0906.0389 [hep-ph]].
[28] D. M. Pierce, J. A. Bagger, K. T. Matchev, R.-j. Zhang and , Nucl. Phys. B 491 (1997) 3 [hep-ph/9606211].
[29] W. Hollik and J.-H. Zhang, Phys. Rev. D 84 (2011) 055022 [arXiv:1109.4781 [hep-ph]].
[30] P. Gonzalez, S. Palmer, M. Wiebusch and K. Williams, arXiv:1211.3079 [hep-ph].
[31] R. Barate et al. [ALEPH, DELPHI, L3 and OPAL Collaborations and LEP Working Group for Higgs boson searches], Phys. Lett. B 565 (2003) 61 [hep-ex/0306033].
[32] S. Schael et al. [ALEPH, DELPHI, L3 and OPAL Collaborations and LEP Working Group for Higgs Boson Searches], Eur. Phys. J. C 47 (2006) 547 [hep-ex/0602042].
[33] M. S. Carena, S. Heinemeyer, C. E. M. Wagner, G. Weiglein and , Eur. Phys. J. C 26 (2003) 601 [hep-ph/0202167].
[34] R. D. Ball, M. Bonvini, S. Forte, S. Marzani and G. Ridolfi, [arXiv:1303.3590 [hep-ph]].
[35] [ATLAS Collaboration], Note ATLAS-CONF-2013-012.
[36] [CMS Collaboration], Note CMS PAS HIG-2013-001.
[37] [ATLAS Collaboration], Note ATLAS-CONF-2013-013.
[38] [CMS Collaboration], Note CMS PAS HIG-2013-002.
[39] [ATLAS Collaboration], Note ATLAS-CONF-2013-030.
[40] [CMS Collaboration], Note CMS PAS HIG-2013-004.
[41] J. Behringer et al. [Particle Data Group Collaboration], Phys. Rev. D 86 (2012) 010001.
[42] [ATLAS Collaboration], Note ATLAS-CONF-2012-161.
[43] [CMS Collaboration], Note CMS PAS HIG-2012-044.
[44] T. Aaltonen et al. [CDF and D0 Collaborations], Phys. Rev. Lett. 109 (2012) 071804 [arXiv:1207.6436 [hep-ex]].
[45] [ATLAS Collaboration], Note ATLAS-CONF-2013-014.
[46] [ATLAS Collaboration], Note ATLAS-CONF-2012-161.
[47] M. Schmelling, Phys. Scripta 51 (1995) 676.
[48] P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein and L. Zeune, arXiv:1211.1955 [hep-ph].
[49] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 705 (2011) 174 [arXiv:1107.5003 [hep-ex]].
[50] [CMS Collaboration], Note CMS PAS HIG-2012-050.
[51] J. Behr et al. [arXiv:1301.4412 [hep-ex]].
[52] [ATLAS Collaboration], Note ATLAS-CONF-2012-169.
[53] [CMS Collaboration], Note CMS PAS HIG-2012-041.
[54] G. Aad et al. [ATLAS Collaboration], JHEP 1209 (2012) 041 [arXiv:1207.2409 [hep-ex]].
[55] S. Chatrchyan et al. [CMS Collaboration], arXiv:1211.3338 [hep-ex].
[63] A. Arbey, M. Battaglia and F. Mahmoudi, arXiv:1212.6865 [hep-ph].