Unveiling the MSSM Neutral Higgs Bosons with Leptons and a Bottom Quark

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Abstract

We investigate the prospects for the discovery of neutral Higgs bosons produced with a bottom quark where the Higgs decays into a pair of tau leptons and the taus decay into an electron-muon pair, i.e. $bg \rightarrow b\phi^0 \rightarrow b\tau^+\tau^- \rightarrow b\ell^\pm\mu^\mp + E_T$, $\phi^0 = h^0, H^0, A^0$. Our study has been done within the framework of the Minimal Supersymmetric Standard Model. We consider the dominant physics backgrounds including the production of Drell-Yan processes ($b\tau^+\tau^-$ and $j\tau^+\tau^-$, $j = q, g$), top quark pair ($t\bar{t}$), $tW$ and $jWW$ with realistic acceptance cuts and efficiencies. We present $5\sigma$ discovery contours for the neutral Higgs bosons in the $(M_A, \tan \beta)$ plane as well as the region with a favored light Higgs mass ($123 \text{ GeV} \leq m_h \leq 129 \text{ GeV}$). Promising results are found for the CP-odd pseudoscalar ($A^0$) and the heavier CP-even scalar ($H^0$) Higgs bosons with masses up to 800 GeV and $\tan \beta \simeq 50$ at the LHC with a center of mass energy ($\sqrt{s}$) of 14 TeV and an integrated luminosity ($L$) of 300 fb$^{-1}$. With $\sqrt{s} = 14 \text{ TeV}$ and $L = 3000 \text{ fb}^{-1}$, LHC will be able to discover the Higgs pseudoscalar and the heavier Higgs scalar beyond $M_A = 1000 \text{ GeV}$.

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I. INTRODUCTION

Recent discovery of the Higgs boson by the ATLAS and the CMS experiments \cite{1, 2} has completed the remaining piece of the standard electroweak symmetry breaking (EWSB) puzzle and has one more time confirmed the success of the Standard Model (SM). Despite its success we know that the Standard Model is not a complete theory and there is new physics to be discovered at or beyond the electroweak scale. After this remarkable achievement, the goal is now to discover signs of new physics with particles and interactions beyond the Standard Model.

One of the most studied new physics candidate is the supersymmetric extension of the Standard Model. Supersymmetry (SUSY) is very well motivated both theoretically and phenomenologically and its realization with minimal particle content is called the Minimal Supersymmetric Standard Model (MSSM). The extensive search for the signs of SUSY and MSSM has so far only returned exclusion limits for SUSY particle masses. For simplified models, the current limits are above a TeV for gluinos and first/second generation squarks, and hundreds of GeV for electroweak gauginos \cite{3–5}.

The MSSM Higgs sector consists of two $SU(2)$ doublets $\phi_1$ and $\phi_2$ that couple to fermions with weak isospin $t_3 = -1/2$ and $t_3 = +1/2$, respectively \cite{6}. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of singly charged Higgs bosons $H^\pm$, two neutral CP-even scalars $H^0$ (heavier) and $h^0$ (lighter), and a neutral CP-odd pseudoscalar $A^0$. At the tree level, all properties of the Higgs sector are fixed by two parameters that are usually chosen to be the Higgs pseudoscalar mass ($m_A$) and the ratio of the vacuum expectation values of the two Higgs doublets ($\tan \beta \equiv v_2/v_1$). In the decoupling limit with $\tan \beta \gtrsim 10$ and $m_A \gtrsim 150$, the light Higgs scalar behaves like the SM Higgs boson, while the heavy Higgs scalar ($H^0$) and the Higgs pseudoscalar ($A^0$) are almost degenerate in mass with dominant decays into $b\bar{b}$ ($\sim 90\%$) and $\tau^+\tau^-$ ($\sim 10\%$) final states.

A supersymmetric light Higgs boson of mass 126 GeV implies large loop corrections to the tree level Higgs mass which requires a heavy stop and/or large trilinear couplings $\mu, \lambda$. These large loop corrections also indicate large fine tuning. Although low fine tuned MSSM is still a possibility, the available parameter space is shrinking. Non-observation of superpartners so far indicate a heavy SUSY particle spectrum which may be beyond the reach of the LHC or a relatively light but highly compressed spectrum with soft decay products that escape detection. MSSM Higgs searches are complementary to searches for colored scalars and electroweak gauginos.

The production modes of the neutral MSSM Higgs bosons are similar to those of the SM Higgs boson with the most significant contributions coming from gluon fusion, weak boson fusion, and associated production with heavy quarks. The associated production with one $b$ quark \cite{12, 16} or two $b$ quarks \cite{17, 21} can be enhanced by a large $\tan \beta$ and can produce a large cross section for even a heavy pseudoscalar Higgs. These $\tan \beta$ enhanced production modes with Higgs decaying into bottom quark pairs \cite{22, 23} and muon pairs \cite{24}, as well as Higgs decaying into tau pairs \cite{25}, provide promising channels to discover the neutral Higgs bosons of the MSSM. The best tau pair discovery channel for Higgs bosons has one tau decaying into a tau-jet ($\pi, \rho$ or $a_1$) and another decaying into a light charged lepton ($\ell = e$ or $\mu$). ATLAS and CMS groups have also looked into these channels and set put limits on the masses and $\sigma \times Br$ of the neutral MSSM Higgs bosons \cite{26, 27}.

The inclusive tau pair discovery channel \cite{28, 31} ($pp \to \phi^0 \to \tau^+\tau^- + X, \phi^0 = h^0, H^0, A^0$) has been found to be very promising for the the search of neutral MSSM Higgs boson at the
LHC. In this article we study the associated production of neutral MSSM Higgs bosons with a single \( b \) quark with the Higgs decaying subsequently into \( \tau \) pairs followed by the decay of \( \tau \)'s into leptons (\( e^\pm \mu^\mp \)). Although the decay rate is lower compared to the \( \tau \)-jet + lepton channel, this channel does not suffer from the difficulties and uncertainties to tag a \( \tau \)-jet and provides an alternative with a cleaner signal containing two leptons. In the following sections we study the Higgs signal with SUSY correction as well as the physics background, describe the acceptance cuts we employ and exhibit the LHC discovery potential of the MSSM neutral Higgs bosons in this \( be\mu \) channel.

II. THE HIGGS SIGNAL WITH LEPTONS

The signal we consider is the associated production of a neutral MSSM Higgs boson with a single \( b \) quark followed by the decay of the Higgs into a \( \tau^+\tau^- \) pair and taus decaying into opposite sign different flavor leptons (\( e^\pm \mu^\mp \)) and neutrinos, i.e.

\[
bg \rightarrow b\phi^0 \rightarrow b\tau^+\tau^- \rightarrow be^\pm\mu^\mp + \not{E}_T
\]

where \( \phi^0 = h^0, H^0, A^0 \). This search channel is complementary to the other important final state with a larger branching fraction \( b\tau^+\tau^- \rightarrow bj\ell + \not{E}_T \). Furthermore, this \( be\mu \) discovery channel offers a cleaner signal without the uncertainties involved with tau tagging and avoids the physics background from \( Z \) decay and the QCD background involving jets.

We calculate the cross section of the Higgs signal in \( pp \) collisions \( \sigma(pp \rightarrow bA^0 \rightarrow b\tau^+\tau^- + X) \) with a Breit-Wigner resonance via \( bg \rightarrow bA^0 \rightarrow b\tau^+\tau^- \). In our parton level calculations we use the leading order (LO) parton distribution function of CTEQ6L1 [32]. To include the next-to-leading order (NLO) effects we choose both the factorization and renormalization scales to be \( M_{\phi}/4 \) [33–35] with a K factor to be one.

The leading SM QCD and SUSY corrections to the bottom quark Yukawa coupling can be calculated by using an effective Lagrangian approach [36]. For large \( \tan \beta \), the effective Lagrangian expressed in terms of the physical Higgs fields is given by

\[
\mathcal{L} = \left( \frac{\tilde{m}_b}{v} \right) \left[ \left( \frac{\sin \alpha}{\cos \beta} - \Delta_b \right) \frac{\cos \alpha}{\sin \beta} \right] \bar{b}b h^0 - \left( \frac{\cos \alpha}{\cos \beta} + \Delta_b \right) \frac{\sin \alpha}{\sin \beta} \bar{b}b H^0 + i \tan \beta \bar{b}g b A^0 \right]\]

(1)

where \( \tilde{m}_b \) denotes the running bottom quark mass including SM QCD corrections which we evaluate with \( m_b(\text{pole}) = 4.7 \text{ GeV}, v \) is the Higgs vacuum expectation value (VEV), and \( \alpha \) is the mixing angle between the CP-even states \( h^0 \) and \( H^0 \). The function \( \Delta_b \) includes loop suppressed threshold corrections from sbottom-gluino and stop-higgsino loops. In the large \( M_{\text{SUSY}} \) and \( \tan \beta \) limit \( \Delta_b \) reads [37, 38]

\[
\Delta_b = \frac{2\alpha_{s}}{3\pi} \tilde{g}_{\beta} \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_i \mu \tan \beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)
\]

(2)

where the auxiliary function \( I \) is given by

\[
I(a, b, c) = -\frac{1}{(a^2 - b^2)(b^2 - c^2)(c^2 - a^2)} \left[ a^2 b^2 \log \frac{a^2}{b^2} + b^2 c^2 \log \frac{b^2}{c^2} + c^2 a^2 \log \frac{c^2}{a^2} \right].
\]

(3)

In our analysis of SUSY effects, we adopt the conventions in Refs. [14, 39]. The branching width of the neutral Higgs bosons into the \( bb \) final state is also affected by these SUSY
corrections which indirectly affect the branching width into the $\tau^+\tau^-$ final state as well. In the large tan $\beta$ limit, these branching ratios \[30\] are approximately given by

$$Br(A^0 \rightarrow b\bar{b}) \simeq \frac{9}{(1 + \Delta_b)^2 + 9}$$

(4)

$$Br(A^0 \rightarrow \tau^+\tau^-) \simeq \frac{(1 + \Delta_b)^2}{(1 + \Delta_b)^2 + 9}.$$  

(5)

Therefore the cross section of our Higgs signal is approximately

$$\sigma(bg \rightarrow bA^0 \rightarrow b\tau^+\tau^-) \simeq \sigma_{SM} \times \tan^2 \beta \frac{(1 + \Delta_b)^2}{(1 + \Delta_b)^2 + 9} \simeq \sigma(\Delta_b = 0) \times \left(1 + \Delta_b\right)^2 + 9$$  

(6)

which has only a mild dependence on $\Delta_b$. Depending on the sign of $\mu$, which determines the sign of $\Delta_b$, these SUSY corrections can enhance ($\mu < 0$) or suppress ($\mu > 0$) our signal. We study the neutral MSSM Higgs sector up to a TeV and assume all SUSY particles are heavy and above the Higgs sector. For $M_{\text{SUSY}} = m_{\tilde{q}} = m_{\tilde{g}} = A_t = 1 \text{ TeV}$, $\mu = +200 \text{ GeV}$ and $\tan \beta = 10 (50)$ this corresponds to a $\sim 1 \text{ (4)}\%$ drop in our signal cross section, for $M_{\text{SUSY}} = m_{\tilde{q}} = m_{\tilde{g}} = A_t = 2 \text{ TeV}$, $\mu = +1 \text{ TeV}$ and $\tan \beta = 10 (50)$ we get a suppression of $\sim 2 \text{ (9)}\%$. Since these effects are small for a large $M_{\text{SUSY}}$, we neglect them in the rest of our analysis.

### III. HIGGS MASS RECONSTRUCTION

The $\tau^+\tau^-$ decay mode of the Higgs generates large missing transverse momentum due to the neutrinos in the final state which would normally make the mass reconstruction difficult. But since the neutral Higgs bosons are much more massive than $\tau$'s ($m_\phi \gg m_\tau$), $\tau$'s produced in a Higgs decay are highly boosted, and their decay products - leptons and neutrinos are almost collinear in the lab frame. We exploit this kinematic feature and reconstruct the Higgs mass in the collinear approximation \[40, 41\]. In the collinear limit, the decay product of each $\tau$ lepton can be identified by the fraction of energy it carries. Denoting these energy fractions with $x_1$ and $x_2$, the total missing transverse momentum can be expressed in terms of the transverse lepton momenta as

$$\vec{p}_T = \left[\frac{1}{x_1} - 1\right] \vec{p}_T(\ell_1) + \left[\frac{1}{x_2} - 1\right] \vec{p}_T(\ell_2).$$  

(7)

Given the measurements of the transverse momentum of charged leptons and the missing transverse momentum, the above relation can be used to determine the momenta of $\tau$'s:

$$p^\mu(\tau_i) = \frac{p^\mu(\ell_i)}{x_i}, \quad i = 1, 2.$$  

(8)

Thus the Higgs mass can be reconstructed from the invariant mass of the $\tau$ pairs \[41, 42\] as

$$M_\phi = \left[p(\tau_1) + p(\tau_2)\right]^2 = \left[\frac{p(\ell_1)}{x_1} + \frac{p(\ell_2)}{x_2}\right]^2.$$  

(9)

For a physical solution, $x_{1,2}$ should be between 0 and 1. This physical solution requirement is one of the most effective cuts to reduce the SM background. To avoid large determinants
that would also imply large uncertainties in the solution we require the leptons not to be back to back in the transverse plane \((\Delta \phi_T(e, \mu) < 175^\circ)\) \[43, 44\]. We also require the leptons not to be parallel in the transverse plane in order to reduce the Drell-Yan and \(t\bar{t}\) backgrounds \((\Delta \phi_T(e, \mu) > 5^\circ)\) \[43\].

\[
\begin{align*}
\text{FIG. 1: The invariant-mass distribution, } &\frac{d\sigma}{dM_{\tau\tau}}(pp \rightarrow b\tau^+\tau^- \rightarrow be^\pm\mu^\mp + E_T + X), \text{ for the Higgs signal (solid red) from } bg \rightarrow bA^0 \rightarrow \tau^+\tau^- \rightarrow be^\pm\mu^\mp + X \text{ with } M_A = 200 \text{ GeV and } \tan \beta = 10 \text{ as well as } M_A = 800 \text{ GeV for } \tan \beta = 10 \text{ and } \tan \beta = 50. \text{ Also shown is the physics background from the Drell-Yan process } bg \rightarrow b\tau^+\tau^- \rightarrow be^\pm\mu^\mp + X \text{ (dashed blue) and from the } t\bar{t} \text{ process (dotted blue).}
\end{align*}
\]

In Figure 1 we present the invariant mass distribution of the tau pairs for the Higgs signal \(pp \rightarrow bA^0 \rightarrow b\tau^+\tau^- + X\) via \(bg \rightarrow bA^0\), as well as the SM backgrounds due to Drell-Yan production and top pair production. In this figure we have applied all acceptance cuts discussed in the next two sections except the requirement on invariant mass.

**IV. THE PHYSICS BACKGROUND**

The physics background consists of the following processes

\[
\begin{align*}
bZ/\gamma^* &\rightarrow b\tau^+\tau^- \rightarrow be^\pm\mu^\mp + E_T \\
jZ/\gamma^* &\rightarrow j\tau^+\tau^- \rightarrow j_b e^\pm\mu^\mp + E_T \\
t\bar{t} &\rightarrow b_b e^\pm\mu^\mp + E_T \\
tW &\rightarrow b e^\pm\mu^\mp + E_T \\
jWW &\rightarrow j_b e^\pm\mu^\mp + E_T
\end{align*}
\]

where \(j = q, g\) represents a light jet. We use the notation of \(j_b\) to denote a light jet misidentified as a \(b\)-jet and \(b_b\) to denote a \(b\)-jet that escapes detection. At low mass, due to
the large Z mass peak the dominant background is the Drell-Yan process \( pp \to bZ/\gamma^* \to b\tau^+\tau^- + X \) and \( pp \to jZ/\gamma^* \to b\tau^+\tau^- + X \). At intermediate and high masses, Drell-Yan processes are suppressed as we move away from the Z pole and \( t\bar{t} \) and \( tW \) quickly become dominant. The \( jW W \) background is small due to the destructive interference between the Feynman diagrams that contribute to the same final states and due to the requirement of a light jet to be mistagged as a \( b \)-jet.

For the Drell-Yan processes, the different flavor leptons that we require in the final state can only be produced through an initial \( \tau \) pair. But for the remaining background processes they can be produced directly from \( W \)'s or indirectly by intermediate \( \tau \)'s. The branching ratio for leptonically decaying \( \tau \) (\( \tau \to e\tilde{\nu}_e \nu_e \tau/\mu\tilde{\nu}_\mu \nu_\tau \)'s) is about 17\%. Hence each intermediate \( \tau \) suppresses a channel approximately by the same amount. We calculate all the contributions (0,1,2 intermediate \( \tau \) ) except for the \( jW W \) background for which we only consider \( W \)'s decaying directly into \( e \) or \( \mu \) since the cross section of this process is already quite small.

V. ACCEPTANCE CUTS

To simulate the detector effects, we apply Gaussian smearing with the energy measurement uncertainty parametrized by an energy dependent term and an energy independent term added in quadrature as

\[
\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b \tag{11}
\]

where we use \( a = 60\%(25\%) \) and \( b = 3\%(1\%) \) for jets (leptons) following the ATLAS and CMS TDR [45,46]. We assume a constant \( b \)-tagging efficiency throughout the detector with the rate \( \epsilon_b = 60\% \), and constant mistagging rates of \( c \)-jets and light jets as \( b \)-jets with the rates \( \epsilon_c = 14\% \) an \( \epsilon_j = 1\% \).

| Acceptance cuts (LL,HL) |
|-------------------------|
| \( p_T(b) > (20,30) \text{ GeV} \)                                      | \( |\eta(b,e,\mu)| < 2.5 \) |
| \( p_T(e,\mu) > (15,20) \text{ GeV} \)                                 | \( \Delta R(b,e,\mu) > 0.4 \) |
| \( E_T > (20,40) \text{ GeV} \)                                       | \( 5^\circ < \Delta\phi_T(e,\mu) < 175^\circ \) |
| \( |M_{\tau\tau} - M_A| < (0.15,0.20) \times M_A \)                    | \( 0 < x_{1,2} < 1 \) |

TABLE I: Acceptance cuts for low and high luminosity (LL,HL). We veto two jet events for which \( p_T(b_1,b_2) > 20 \text{ GeV} \) and \( |\eta| < 4.5 \).

In order to account for the noisy detector environment due to pile-up, we employ two sets of cuts specific for low and high luminosity (LL,HL). We require exactly one high transverse momentum \( b \)-tagged jet and two opposite sign different flavor leptons in the event. The \( b \)-jet is required to have \( p_T > 20 \text{ GeV} \) (LL) or \( p_T > 30 \text{ GeV} \) (HL) and \( |\eta| < 2.5 \). To reduce the \( t\bar{t} \) background we veto two jet events with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 4.5 \) [47]. We require both leptons to be isolated by imposing \( \Delta R > 0.4 \) and to have \( p_T > 15 \text{ GeV} \) (LL) or \( p_T > 20 \text{ GeV} \) (HL). We apply a 20 GeV (LL) and 40 GeV (HL) cut on the missing transverse momentum which we define as the negative sum of the transverse momenta of the visible objects in the
event. We finally require the reconstructed Higgs mass to be within 15% (LL) or 20% (HL) of the pseudoscalar Higgs mass $M_A$. A summary of the basic cuts we employed is displayed in Table I.

We use MadGraph [48] to generate HELAS [49] subroutines to compute the matrix elements for the tree level signal and background processes. We introduce the NLO corrections to the SM background processes as $K$ factors. We apply a $K$ factor 1.3 for the Drell-Yan processes [50], a $K$ factor of 2 for top pair production [51, 52], a $K$ factor of 1.58 for $tW$ production [53], and a $K$ factor of 1 for $jWW$ background. Cross sections and signal significance for benchmark points are displayed in Table II.

Figure 2 shows the signal and background cross sections with $\sqrt{s} = 14$ TeV and acceptance cuts for low luminosity (LL) and high luminosity (HL) as a function of the pseudoscalar Higgs mass $M_A$. The signal is shown for $\tan \beta = 10$ and 50, with a common mass for scalar quarks, scalar leptons, gluino, and the $\mu$ parameter from the Higgs term in the superpotential, $m_\tilde{q} = m_\tilde{g} = m_\tilde{\ell} = \mu = 1$ TeV. All tagging efficiencies and $K$ factors discussed above are included.

\[
\hat{s}_{\text{min}}^{1/2} = \sqrt{E^2 - P_z^2} + \sqrt{E_T^2 + M_{\text{inv}}^2}
\]  

where $M_{\text{inv}}$ is the total mass of all invisible particles produced in an event. In our case the invisible particles are neutrinos hence we set $M_{\text{inv}} = 0$.

For the Higgs signal, the mass of the Higgs particle determines the minimum center of mass energy of the process since the Higgs is mostly on-shell. Similarly for the background,
TABLE II: Signal and SM background cross sections in femtobarns and signal significance, i.e. \( \sigma_S/\sqrt{\sigma_S + \sigma_B} \) for \( \sqrt{s} = 14 \text{ TeV} \) and \( L = 30 \text{ fb}^{-1} \). \( K \) factors are included in the signal significance values.

| \( M_A(\text{GeV}) \) | 100  | 200  | 400  | 800  |
|-----------------------|-----|------|------|------|
| \( \sigma(\text{signal}) \) [\( \tan \beta = 10 \)] | 15.85 | 8.847 | 1.176 | 0.052 |
| \( \sigma(\text{signal}) \) [\( \tan \beta = 50 \)] | 344.0 | 196.8 | 29.82 | 1.496 |
| \( \sigma(\text{Drell-Yan}) \) | 57.40 | 0.517 | 0.061 | 0.004 |
| \( \sigma(\bar{t}t) \) | 2.867 | 9.158 | 10.25 | 5.792 |
| \( \sigma(tW) \) | 4.884 | 14.96 | 14.71 | 7.521 |
| \( \sigma(jWW) \) | 0.054 | 0.153 | 0.144 | 0.067 |
| \( N_{\text{sig}} \) [\( \tan \beta = 10 \)] | 8.513 | 6.745 | 0.959 | 0.059 |
| \( N_{\text{sig}} \) [\( \tan \beta = 50 \)] | 90.64 | 69.65 | 19.02 | 1.637 |

intermediate on-shell particles determine the mass scale. For the main \( t\bar{t} \) background the mass scale is \( 2m_t \). So this variable is effective in reducing the \( t\bar{t} \) and \( tW \) backgrounds in the high mass region where \( M_A > 2m_t \). What we actually get from \( s_{1/2}^{1/2} \) is not exactly the mass of the intermediate particles but an event by event lower bound of the center of mass energy of the hard interaction. Therefore we expect this variable to be effective well above the \( 2m_t \) threshold. To optimize our cut, we determine the \( s_{1/2}^{1/2} \) value for which the cut

\[
\hat{s}_{1/2}^{1/2} > s_{1/2}^{1/2}
\]

maximizes the signal significance, i.e. \( \sigma_S/\sqrt{\sigma_S + \sigma_B} \). Since the mass scale for the Higgs signal changes with \( M_A \), the optimum cut \( s_{1/2}^{1/2} \) depends on \( m_A \) as well. To determine its \( M_A \) dependence we do a scan over \( M_A \) in the range [500 GeV, 1000 GeV] for \( \tan \beta = 10, 50 \) and compute the optimum \( s_{1/2}^{1/2} \) cut. We display the result of this scan in Figure 3.

We observe that the shape of the \( s_{1/2}^{1/2} \) distribution for the SM background does not change significantly with our Higgs mass window cut, but for the Higgs signal it shifts towards higher values with increasing Higgs mass while broadening due to more missing energy carried away by neutrinos. This results in an almost linear relation between the optimum \( s_{1/2}^{1/2} \) cut and \( M_A \) which we determine to be \( s_{1/2}^{1/2} = 0.71 \times M_A - 29 \text{ GeV} \). As can be seen from Figure 3 the optimum value has a small \( \tan \beta \) dependence as well. In the rest of our analysis we use \( s_{1/2}^{1/2} = 0.7 \times M_A \) for simplicity.

VI. THE DISCOVERY POTENTIAL AT THE LHC

To calculate the LHC reach, we scan the \( (M_A, \tan \beta) \) plane and display the discovery contours for \( \sqrt{s} = 8 \text{ TeV} \) with an integrated luminosity \( L = 25 \text{ fb}^{-1} \) as well as \( \sqrt{s} = 14 \text{ TeV} \) with integrated luminosities \( L = 30 \text{ fb}^{-1}, 300 \text{ fb}^{-1}, 3 \text{ ab}^{-1} \) in Figures 4 and 5. In addition, we also show the improvement with the addition of the \( s_{1/2}^{1/2} \) cut.
FIG. 3: Optimal $s_{min}^{1/2}$ cut as a function of the pseudoscalar Higgs mass $M_A$ for $\tan \beta = 10$ (green triangles) and $\tan \beta = 50$ (red circles). The best fit is approximately given by $s_{min}^{1/2} = 0.7 \times M_A$.

We define the signal to be observable if the lower limit on the signal plus background is larger than the corresponding upper limit on the background \[55, 56\], namely,

$$L(\sigma_S + \sigma_B) - N\sqrt{L(\sigma_S + \sigma_B)} > L\sigma_B + N\sqrt{L\sigma_B},$$

which corresponds to

$$\sigma_S > \frac{N^2}{L} \left[ 1 + 2\sqrt{L\sigma_B}/N \right].$$

Here $L$ is the integrated luminosity, $\sigma_S$ is the signal cross section, and $\sigma_B$ is the background cross section. Both cross sections are taken to be within a bin of width $\pm \Delta M_{\tau\tau}$ centered at $M_A$. In this convention, $N = 2.5$ corresponds to a $5\sigma$ signal.

For $\tan \beta \gtrsim 10$, $M_A$ and $M_H$ are almost degenerate when $M_A \gtrsim 125$ GeV, while $M_A$ and $M_h$ are very close to each other for $M_A \lesssim 125$ GeV \[57, 58\]. Therefore, when computing the realistic discovery reach, we add the cross sections of the $A^0$ and the $h^0$ for $M_A < 125$ GeV and those of the $A^0$ and the $H^0$ for $M_A \geq 125$ GeV \[59\].

We use FeynHiggs \[60\] to calculate the light Higgs mass at two loop level \[61, 63\]. To cope with the remaining theory uncertainty in the light Higgs mass which is about 2-3 GeV \[63\], we define a favored light Higgs mass band (for a 126 GeV light Higgs) to be the range $123 \text{ GeV} \leq m_h \leq 129 \text{ GeV}$.

Figure 4 shows the $5\sigma$ discovery contour in the $(M_A, \tan \beta)$ plane for the neutral MSSM Higgs bosons at the LHC with $\sqrt{s} = 8$ TeV and $L = 25 \text{ fb}^{-1}$. Also shown is the parameter region excluded by LEP II \[64\]. In addition, we present the favored region of a light Higgs boson (123 GeV $\leq m_h \leq 129$ GeV) for $M_{\text{SUSY}} = \tilde{m} = \tilde{m}_{\tilde{q}} = \tilde{m}_{\tilde{g}} = \mu = 1 \text{ TeV}$ and $X_t = A_t - \mu \cot \beta = 2 \text{ TeV}$, where $A_t$ is the trilinear coupling for scalar top.
FIG. 4: The $5\sigma$ discovery contour at the LHC with $\sqrt{s} = 8$ TeV and a luminosity of $L = 25$ fb$^{-1}$. The discovery region is the part of the parameter space above the contour. Also shown are (a) the region excluded by LEP II (green, lower shaded), (b) the region excluded by LHC Higgs searches (cyan, upper shaded), and (c) the region with a favored light Higgs mass of $123$ GeV $\leq m_h \leq 129$ GeV (orange, hatched) and the central value of 126 GeV (dotted).

FIG. 5: The $5\sigma$ discovery contours at the LHC with $\sqrt{s} = 14$ TeV and a luminosity of $L = 30,300,3000$ fb$^{-1}$. The dashed lines show the improvement obtained with the aid of the $s_{\min}^{1/2}$ cut. The discovery region is the part of the parameter space above the contours. Also shown are (a) the region excluded by LEP II (green, lower shaded), and (b) the region with a favored light Higgs mass of $123$ GeV $\leq m_h \leq 129$ GeV (orange and yellow, hatched and shaded) and the central value of 126 GeV (dotted and dashed).
Figure 5 shows the $5\sigma$ discovery contours for the MSSM Higgs bosons at the LHC with $\sqrt{s} = 14$ TeV with $L = 30, 300$ and $3000 \, \text{fb}^{-1}$. We display again the regions with a favored light Higgs mass ($123$ GeV $\leq m_h \leq 129$ GeV) for $M_{\text{SUSY}} = 1$ TeV (2 TeV) and $X_t = 2 \, \text{TeV}(\sqrt{6} \, M_{\text{SUSY}})$. We find that the discovery contour even dips below $\tan\beta = 10$ for $100 \, \text{GeV} < M_A < 300 - 400 \, \text{GeV}$ depending on luminosity. Below $\tan\beta = 10$ our approximation of mass degeneracy of MSSM Higgs bosons breaks down; therefore we include only one Higgs boson ($A^0$) in our calculations to simplify the numerical analysis. For $M_A, M_H \gtrsim 400 \, \text{GeV}$ the Higgs cross section becomes kinematically suppressed while for lower masses ($M_A \lesssim 300 \, \text{GeV}$), the Higgs cross section is reasonably large. Therefore, for $M_A \lesssim 300 \, \text{GeV}$ even the CP-odd pseudoscalar alone can lead to an observable signal with $5 < \tan\beta < 10$. High mass regions with $M_A, M_H \gtrsim 400$ can be probed if $\tan\beta$ is large. Specifically for $M_A = 1$ TeV and $\tan\beta = 60$, MSSM neutral Higgs bosons can provide a $5\sigma$ discovery signal with an integrated luminosity of $L \simeq 300 \, \text{fb}^{-1}$.

VII. CONCLUSIONS

We have studied the production of neutral MSSM Higgs bosons at the LHC associated with a single $b$ quark followed by Higgs decay into tau pairs and tau leptons decaying to electron-muon pairs. This production channel is enhanced for large $\tan\beta$ and this specific final state offers a clean signal albeit a smaller branching ratio compared to the more promising tau pair discovery channel with $b\tau^+\tau^- \to bj\ell + E_T$. The $be\mu$ channel does not require tau jet tagging hence eliminates the uncertainties involved with it, and the physics background for our signal from $Z$ decay and the QCD backgrounds containing light jets are more suppressed.

Motivated with the latest non-observation of super partners, we have considered a heavy SUSY spectrum with squarks, sleptons and the gluino above the Higgs sector. After all the cuts are applied, the Higgs signal cross section is about $1.5 \, \text{fb}$ for $M_A = 800 \, \text{GeV}$ and $\tan\beta = 50$ at the LHC running at 14 TeV center of mass energy. We have calculated the relevant background processes which are Drell-Yan, $t\bar{t}$, $tW$ and $jWW$ productions with full spin correlation. The Drell-Yan background is dominant at low mass and $t\bar{t}/tW$ backgrounds are dominant at high mass regions. Our calculation shows that the discovery contour for an integrated luminosity of $L = 300 \, \text{fb}^{-1}$ extends to $M_A = 800 \, \text{GeV}$ for $\tan\beta = 50$ and up to almost $M_A = 1$ TeV for $\tan\beta = 60$ with the help of the $s_{\text{min}}^{1/2}$ variable.

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