Higgs Bosons in B-L Supersymmetric Standard Model

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Abstract

In this review, we focus on the TeV scale B-L extension of the Minimal Supersymmetric Standard Model (BLSSM), which features a natural incorporation of a seesaw mechanism for generating light neutrino masses. We aim to explore the various phenomenological implications arising from the Higgs sector within this class of models. Specifically, we investigate the detection of a heavy neutral CP-even Higgs boson of the BLSSM, denoted as h', with a mass approximately of 400 GeV, at the Large Hadron Collider (LHC) via the channel $pp \to h' \to hh \to 2b + 2\ell$. Additionally, we assess the consistency of a light Higgs boson, with a mass around 90–95 GeV, with the results of a search conducted by the CMS collaboration in the diphoton channel.

Keywords: heavy Higgs, supersymmetric model, large hadron collider

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1. INTRODUCTION

Despite the lack of direct experimental evidence, Supersymmetry (SUSY) stands out as the most promising candidate for a unified theory beyond the Standard Model (SM). It offers an elegant solution to the quadratic divergence problem and provides a framework for relating bosons and fermions. The Minimal Supersymmetric Standard Model (MSSM) represents the simplest extension of the SM with supersymmetry. It is described by the superpotential [1]:

$$W = h_U Q_L U_L^c H_2 + h_D Q_L D_L^c H_1 + h_L L_L E_L^c H_1 + \mu H_1 H_2. \quad (1)$$

Additionally, the MSSM incorporates a set of soft SUSY breaking terms at the Grand Unified Theory (GUT) scale. These terms introduce deviations from exact symmetry and allow for the observation of different particle masses. The soft SUSY breaking terms can be classified into two categories: universal soft terms and nonuniversal soft terms. Universal soft terms, including the universal scalar mass (m_0), universal gaugino mass ($m_{1/2}$), and universal trilinear coupling (A_0), can be derived in certain specific scenarios such as minimal supergravity. However, it is important to note that these universal terms are based on simplified assumptions. On the other hand, nonuniversal soft terms introduce a larger number of free parameters, which leads to increased complexity and reduced predictability within the SUSY framework.

Due to the conservation of R-parity in supersymmetry, SUSY particles are always produced or destroyed in pairs. Among these particles, the Lightest Supersymmetric Particle (LSP) is particularly interesting as it is absolutely stable and considered a candidate for Dark Matter (DM) [2]. In the MSSM, a prediction arises regarding the upper bound of the Higgs boson's mass. This prediction asserts that the mass of the Higgs should not exceed approximately 130 GeV, as long as the scale of SUSY breaking remains of the order of the TeV scale. This result aligns well with the measured value of the Higgs mass at around 125 GeV obtained from experiments at the Large Hadron Collider (LHC). The relatively substantial mass of the Higgs boson within the framework of the MSSM implies that the SUSY particles, which are necessary to stabilize the Higgs mass, must be significantly heavier. This heaviness of SUSY particles can help explain the lack of their detection during the LHC's Run I and Run II, as they might be beyond the energy range that the LHC can currently explore.

When considering both collider and astrophysics constraints, the MSSM with universal soft SUSY breaking appears to be largely ruled out if SUSY particles at or below the TeV scale [3]. These constraints combine experimental observations and theoretical considerations to place limitations on the MSSM. To address the limitations of the MSSM, nonminimal supersymmetric extensions of the Standard Model have been proposed. These extensions can involve a larger particle content or a higher symmetry, allowing them to evade the issues faced by the MSSM. These nonminimal models are often motivated by Grand Unified Theories (GUTs) and offer a rich phenomenology to explore. Some examples of nonminimal SUSY models include those with an extended Higgs sector, such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [4], which introduces additional Higgs bosons. Another example is the nonminimal model with an extended gauge sector, known as the B-L Supersymmetric Standard Model (BLSSM) [5], where an additional gauge symmetry is introduced. These nonminimal SUSY models provide alternative frameworks to explore and offer potential solutions to the challenges faced by the MSSM, opening up new avenues for research and experimentation.

In this article, we briefly introduce the BLSSM and analyze its Higgs sector. We demonstrate that the BLSSM model includes three additional neutral Higgs fields, namely, h', H', and A', in addition to the Higgs fields present in the MSSM, h, H, and A. It is worth noting that the extra Higgs boson could be light with sufficient mixing with the SM-like h, thereby allowing sizable couplings to SM particles and the possibility of sticking signatures at the LHC. In this review, we will revisit and update our investigation into the significant signals associated with these additional Higgs bosons across a range of masses. Our aim is to highlight their potential in revealing new and intriguing phenomena at the Large Hadron Collider (LHC).

The paper is organized as follows. Section 2 provides a concise introduction to the BLSSM. In Section 3, we undertake an in-depth analysis of the Higgs sector within this specific class of models. The exploration of the search for a heavy Higgs boson at the LHC is comprehensively presented in Section 4. Section 5 focuses on the diphoton decay of the light Higgs boson,

Superfield	Spin-0	Spin-$\frac{1}{2}$	Generations	$\mathbb{G}_{\rm SM} \otimes U(1)_{B\text{-}L}$
$\hat{Q}$	$\tilde{Q}$	Q	3	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}, \frac{1}{3}\right)$
$\hat{d}^c$	$\tilde{d}^c$	d^c	3	$\left(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, -\frac{1}{3}\right)$
$\hat{u}^c$	$\tilde{u}^c$	u^c	3	$\left(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, -\frac{1}{3}\right)$
$\hat{L}$	$\tilde{L}$	L	3	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -1\right)$
$\hat{E}^c$	$\tilde{e}^c$	e^c	3	$(\mathbf{1}, \mathbf{1}, 1, 1)$
$\hat{N}^c$	$\tilde{N}^c$	N^c	3	$(\mathbf{1}, \mathbf{1}, 0, 1)$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0\right)$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$\left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, 0\right)$
$\hat{\chi}_1$	χ_1	$\tilde{\chi}_1$	1	$(\mathbf{1}, \mathbf{1}, 0, -2)$
$\hat{\chi}_2$	χ_2	$\tilde{\chi}_2$	1	$(\mathbf{1}, \mathbf{1}, 0, 2)$

TABLE 1: Chiral superfields and their quantum numbers in the BLSSM.

shedding significant light on this phenomenon. Lastly, Section 6 encompasses our concluding remarks and observations.

2. THE BLSSM

The BLSSM [5], the minimal extension of MSSM, is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B\text{-}L}$. To address the cancellation of the associated B-L triangle anomaly, this extension introduces three extra chiral singlet superfields, one for each generation, possessing a B-L charge of -1. These superfields are denoted as N_i and correspond to the right-handed neutrinos. Furthermore, the breaking of the B-L symmetry at the TeV scale necessitates the inclusion of two chiral SM-singlet Higgs superfields, $\hat{\chi}_{1,2}$, each carrying B-L charges of ∓ 2. Additionally, the presence of a vector superfield, Z', becomes crucial for the gauging of $U(1)_{B\text{-}L}$. The quantum numbers of the chiral superfields with respect to the SM gauge group ($\mathbb{G}_{\rm SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$) and the $U(1)_{B\text{-}L}$ gauge group are presented in Table 1.

The BLSSM superpotential is given by

$$\begin{aligned} W = & Y_u^{ij} \hat{u}_i^c \hat{Q}_j \cdot \hat{H}_u - Y_d^{ij} \hat{d}_i^c \hat{Q}_j \cdot \hat{H}_d - Y_e^{ij} \hat{E}_i^c \hat{L}_j \cdot \hat{H}_d \\ & + Y_\nu^{ij} \hat{N}_i^c \hat{L}_j \cdot \hat{H}_u + \frac{1}{2} Y_N^{ij} \hat{N}_i^c \hat{\chi}_1 \hat{N}_j^c + \mu \hat{H}_u \cdot \hat{H}_d - \mu' \hat{\chi}_1 \hat{\chi}_2. \end{aligned} \tag{2}$$

The soft supersymmetry-breaking terms relevant to the BLSSM, under the usual universality assumptions at the Grand Unification Theory (GUT) scale, are expressed as follows:

$$\begin{aligned} -\mathcal{L}_{\rm soft} = & m_0^2 \sum_\phi |\phi|^2 + Y_u^A \tilde{Q} H_2 \tilde{U}^c + Y_d^A \tilde{Q} H_1 \tilde{D}^c \\ & + Y_e^A \tilde{L} H_1 \tilde{E}^c + Y_\nu^A \tilde{L} H_2 \tilde{\nu}^c + Y_S^A \tilde{\nu}^c \eta_1 \tilde{S}_2 \\ & + \Big[B\left(\mu H_1 H_2 + \mu' \eta_1 \eta_2\right) \\ & \quad + \frac{1}{2} m_{1/2} \left(\tilde{g}^a \tilde{g}^a + \tilde{W}^a \tilde{W}^a + \tilde{B}\tilde{B} + \tilde{B}'\tilde{B}'\right) + \text{h.c.} \Big], \end{aligned} \tag{3}$$

where the sum in the first term runs over $\phi = \tilde{Q}, \tilde{U}, \tilde{D}, \tilde{L}, \tilde{E}, \tilde{N}, H_{1,2}, \chi_{1,2}$ and $(Y_f^A)_{ij} \equiv A_0 (Y_f)_{ij}$ ($f = u, d, e, \nu, S$) is the trilinear scalar interaction associated with the fermion Yukawa coupling. The B-L symmetry can be radiatively broken by the following nonvanishing Vacuum Expectation Values (VEVs): $\langle \chi_1 \rangle = v'_1$ and $\langle \chi_2 \rangle = v'_2$. We define $\tan\beta'$ as the ratio of these VEVs ($\tan\beta' = v'_1/v'_2$) in analogy to the MSSM case ($\tan\beta = v_2/v_1$) [5].

After B-L symmetry breaking, the new gauge boson, Z', acquires its mass from the kinetic term of the B-L Higgs fields, $\chi_{1,2}$. Namely, we have

$$M_{Z'}^2 = g_{BL}^2 v'^2 + \frac{1}{4} \tilde{g}^2 v^2. \tag{4}$$

In this expression, $\tilde{g}$ represents the coupling associated with the gauge kinetic mixing between $U(1)_Y$ and $U(1)_{B\text{-}L}$, while v' is defined as the square root of the sum of the squares of v'_1 and v'_2: $v' = \sqrt{v_1'^2 + v_2'^2}$. Furthermore, the mixing angle between the (SM) Z and (BLSSM) Z' states is given by

$$\tan 2\theta' = \frac{2\tilde{g}\sqrt{g_1^2 + g_2^2}}{\tilde{g}^2 + 16\left(\frac{v'}{v}\right)^2 g_{BL}^2 - g_2^2 - g_1^2}, \tag{5}$$

which should be $\lesssim 10^{-3}$ [6].

The BLSSM framework allows for the implementation of a type I seesaw mechanism, which can be achieved through specific components of the superpotential. The relevant part of the superpotential is denoted as

$$\mathcal{L}_{B\text{-}L} \supset Y_\nu \bar{l} H_2 \nu_R + \frac{1}{2} Y_N \bar{\nu_R^c} \chi_1 \nu_R^c + \text{h.c.}, \tag{6}$$

where Y_ν and Y_N are the Yukawa couplings associated with the neutrinos and right-handed neutrinos, respectively. Upon the breaking of the B-L symmetry, a Majorana mass term $M_R = Y_N \langle \chi_1 \rangle = Y_N v'$ is generated, with v' on the order of TeV and Y_N also of order unity, resulting in M_R being approximately TeV scale. Additionally, after electroweak symmetry breaking, a Dirac mass term $m_D = Y_\nu \langle H_2 \rangle = Y_\nu v$ arises. Combining these elements, the neutrino mass matrix M_ν is formed as

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}. \tag{7}$$

From this matrix, the light neutrino mass can be determined as

$$m_\nu = -m_D M_R^{-1} m_D^T. \tag{8}$$

By setting m_D to approximately 10^{-4} GeV, it follows that Y_ν is on the order of 10^{-6}, which is comparable to the Yukawa coupling Y_E associated with charged leptons. Consequently, m_ν is estimated to be around 1 eV.

It is worth noting that the BLSSM introduces several new particle contents that extend the SM of particle physics. These include the following: (i) extra neutral gauge boson called $Z_{B\text{-}L}$, denoted as Z', (ii) right-handed neutrinos and sneutrinos, (iii) extra neutralinos, which are superpartners of the extra neutral gauge boson and the extra Higgs bosons, and (iv) extra Higgs bosons beyond the ones present in the MSSM, namely, h', A', and H'. These extra scalars possess distinct properties and can have an impact on various processes. These new particle contents in the BLSSM lead to various signatures and implications in experimental observations. In the following sections, we will concentrate on the potential discovery signals of the relatively lighter exotic Higgs bosons h' and A' at the Large Hadron Collider (LHC). The observation of these particles in LHC experiments would provide compelling evidence for the existence of the BLSSM.

3. HIGGS BOSONS IN BLSSM

In the framework of the BLSSM, there are 2 Higgs doublet and 2 Higgs singlet superfields, which amount to a total of 12 degrees of freedom. However, four of these degrees of freedom have been absorbed by the gauge bosons $W^{\pm}$, Z, and Z'. The remaining particles in the model include two neutral pseudoscalar Higgs bosons denoted as A and A', two charged Higgs bosons denoted as $H^{\pm}$, and four neutral scalar Higgs bosons denoted as h, H, h', and H' [7]. One obtains the masses of the physical neutral BLSSM Higgs states in terms of the Higgs fields:

$$\begin{aligned} H^0_{1,2} &= \frac{1}{\sqrt{2}}\left(v_{1,2} + \sigma_{1,2} + i\phi_{1,2}\right), \\ \chi^0_{1,2} &= \frac{1}{\sqrt{2}}\left(v'_{1,2} + \sigma'_{1,2} + i\phi'_{1,2}\right), \end{aligned} \tag{9}$$

where the real and imaginary parts correspond to the CP-even (or scalar) and the CP-odd (or pseudoscalar) Higgs states. $v_{1,2}$ and $v'_{1,2}$ are the Vacuum Expectation Values (VEVs) of the Higgs fields $H_{1,2}$ and $\chi_{1,2}$, respectively.

The CP-odd neutral Higgs mass-squared matrix at the tree-level in the basis $(\phi_1, \phi_2, \phi'_1, \phi'_2)$ is given by

$$m^2_{A,A'} = \begin{pmatrix} B_\mu \tan\beta & B_\mu & 0 & 0 \\ B_\mu & B_\mu \cot\beta & 0 & 0 \\ 0 & 0 & B_{\mu'} \tan\beta' & B_{\mu'} \\ 0 & 0 & B_{\mu'} & B_{\mu'} \cot\beta' \end{pmatrix}. \tag{10}$$

This matrix illustrates that the MSSM-like CP-odd Higgs boson, denoted as A, is decoupled from the BLSSM-like CP-odd Higgs boson, denoted as A', at the tree level.

It is worth noting that the squared masses of these Higgs bosons, m^2_A and $m^2_{A'}$, are dependent on the parameters B_μ, $B_{\mu'}$, $\tan\beta$, and $\tan\beta'$. In particular, due to the dependence of B_μ on the vacuum expectation value v', both m^2_A and $m^2_{A'}$ are approximately on the order of 1 TeV, resulting in similar magnitudes. Due to the dependence of B_μ on v', $m^2_A = \frac{2B_\mu}{\sin 2\beta} \sim m^2_{A'} = \frac{2B_{\mu'}}{\sin 2\beta'} \sim \mathcal{O}(1\,\text{TeV})$.

The CP-even neutral Higgs mass-squared matrix at the tree level in the basis $(\sigma_1, \sigma_2, \sigma'_1, \sigma'_2)$ is given by

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}^2_{hH} & \mathcal{M}^2_{hh'} \\ \left(\mathcal{M}^2_{hh'}\right)^T & \mathcal{M}^2_{h'H'} \end{pmatrix}, \tag{11}$$

where $\mathcal{M}_{hH}$ is the MSSM CP-even mass matrix which results into an SM-like Higgs boson h with a mass $m_h \sim 125$ GeV and a heavy Higgs boson H with a mass $m_H \sim \mathcal{O}(1\,\text{TeV})$. The BLSSM mass matrix $\mathcal{M}_{h'H'}$ reads

$$\mathcal{M}^2_{h'H'} = \begin{pmatrix} m^2_{A'} c^2_{\beta'} + g^2_{BL} v'^2_1 & -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 \\ -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 & m^2_{A'} s^2_{\beta'} + g^2_{BL} v'^2_2 \end{pmatrix} \tag{12}$$

with $c_x = \cos x$ and $s_x = \sin x$. Thus, the eigenvalues of this matrix can be given as

$$m^2_{h',H'} = \frac{1}{2}\left\{ m^2_{A'} + m^2_{Z'} \mp \sqrt{\left(m^2_{A'} + m^2_{Z'}\right)^2 - 4 m^2_{A'} m^2_{Z'} \cos^2 2\beta'} \right\}. \tag{13}$$

It can be shown that the mass of h' is approximately given by

$$m_{h'} \simeq \left(\frac{m^2_{A'} M^2_{Z'} \cos^2 2\beta'}{m^2_{A'} + M^2_{Z'}} \right)^{\frac{1}{2}} \simeq \mathcal{O}(100\,\text{GeV}). \tag{14}$$

Finally, the matrix $\mathcal{M}_{hh'}$ can be denoted as

$$\mathcal{M}^2_{hh'} = \frac{1}{2} \tilde{g} g_{BL} \begin{pmatrix} v_1 v'_1 & -v_1 v'_2 \\ -v_2 v'_1 & v_2 v'_2 \end{pmatrix}. \tag{15}$$

This mixing is crucial for generating mixing between BLSSM Higgs bosons and MSSM-like Higgs states. The CP-even physical Higgs mass states can be obtained by diagonalizing the Higgs mass-squared matrix given by equation (11) with a unitary matrix $\mathcal{R}$ as

$$\mathcal{R} \mathcal{M}^2 \mathcal{R}^\dagger = \text{diag}\left\{ m^2_h, m^2_{h'}, m^2_H, m^2_{H'} \right\}. \tag{16}$$

A numerical scan confirms that when $\tan'\beta \leq 1.2$, the mass of the h' state can either be lighter or heavier than the mass of the SM-like Higgs boson. However, the other two CP-even states, H and H', are generally found to be quite heavy.

As an example of the benchmark point (BP) for the relevant parameters that leads to the SM Higgs mass of 125 GeV and second CP-even neutral Higgs, h', with a mass of approximately 400 GeV, we consider the following BP studied in [8]: $g_{BL} = 0.67$, $\tilde{g} = -0.64$, $\tan\beta = 11$, $\tan\beta' = 1.3$, and $v' = 4.8$ TeV. Additionally, the soft supersymmetry (SUSY) terms are given by $M_1 = 7.7 \times 10^2$ GeV, $M_2 = 8.5 \times 10^2$ GeV, $M_3 = 6.8 \times 10^2$ GeV, $M_{\tilde{B}'} = 1.5 \times 10^3$ GeV, and soft scalar masses of order 10^3 GeV.

4. HEAVY BLSSM HIGGS BOSON AT THE LHC

In this section, we focus on the production of a heavy BLSSM Higgs boson, h', at the LHC primarily through the gluon-gluon fusion process. In [8], our primary focus revolves around investigating the on-shell production of pairs of SM Higgs bosons from the new particle denoted as h'. This is followed by the decay process $h' \to hh \to bb\gamma\gamma$, which captures our particular interest.

The study presented in [8] explored the decay channels of the Higgs-like particle h', specifically focusing on $h' \to W^+W^-$, $h' \to ZZ$, and $h' \to hh$. In this context, we will focus on the results obtained for the di-Higgs channel. Utilizing the BP mentioned earlier, the analysis determined that the branching ratio for $h' \to hh$ is $BR(h' \to hh) = 0.26$. Furthermore, the production cross section for the process $pp \to h'$ at a center-of-mass energy of $\sqrt{s} = 14$ TeV was found to be $\sigma(pp \to h') = 163.4$ fb. Considering the di-Higgs decay channel, the total cross section for the process $pp \to h' \to hh \to \bar{b}b\gamma\gamma$ is estimated to be of the order of 0.12 fb.

Although the cross section of this process, $\sigma(pp \to h' \to hh \to b\bar{b}\gamma\gamma)$, is smaller compared to $\sigma(pp \to h' \to hh \to 4b)$, we find it more promising due to several factors. The clean diphoton trigger offers excellent mass resolution and minimal background contamination, which enhances the signal sensitivity. In our analysis, we estimate $\sigma(pp \to h' \to hh \to b\bar{b}\gamma\gamma)$ as the product of the production cross section of the heavy BLSSM Higgs boson, $\sigma(pp \to h')$, and the branching ratio, $\text{BR}(h' \to hh \to b\bar{b}\gamma\gamma)$.

Cuts (select)	S	B	$S/\sqrt{B}$
Initial (no cut)	951	19951560	0.213
$E_T > 200\,\mathrm{GeV}$	933.18 ± 4.19	1476867.0 ± 1169.0	$0.768 \pm 2.88 \times 10^{-6}$
$M_{\gamma\gamma} > 120\,\mathrm{GeV}$	475.50 ± 15.40	165131.0 ± 404.0	$1.170 \pm 9.31 \times 10^{-5}$
$M_{\gamma\gamma} < 135\,\mathrm{GeV}$	474.80 ± 15.40	29023.0 ± 170.0	$2.787 \pm 5.23 \times 10^{-4}$
$M_{bb} > 50\,\mathrm{GeV}$	145.50 ± 11.10	3582.7 ± 59.9	$2.431 \pm 2.93 \times 10^{-3}$
$M_{bb} < 160\,\mathrm{GeV}$	134.70 ± 10.80	1944.9 ± 44.1	$3.055 \pm 5.03 \times 10^{-3}$
$\Delta R_{\gamma\gamma} < 3.5$	133.90 ± 10.7	1824.5 ± 42.7	$3.135 \pm 5.32 \times 10^{-3}$
$\Delta R_{b\bar{b}} < 3.5$	131.90 ± 10.7	1746.2 ± 41.8	$3.156 \pm 5.50 \times 10^{-3}$
$M_{\gamma\gamma\bar{b}b} > 360\,\mathrm{GeV}$	102.71 ± 9.57	686.4 ± 26.2	$3.920 \pm 1.14 \times 10^{-2}$
$M_{\gamma\gamma\bar{b}b} < 450\,\mathrm{GeV}$	98.5 ± 9.40	403.4 ± 20.1	$4.903 \pm 1.70 \times 10^{-2}$

TABLE 2: $pp \to h' \to hh \to b\bar{b}\gamma\gamma$ cut-flow at $L_{\text{int}} = 3000\,\mathrm{fb}^{-1}$.

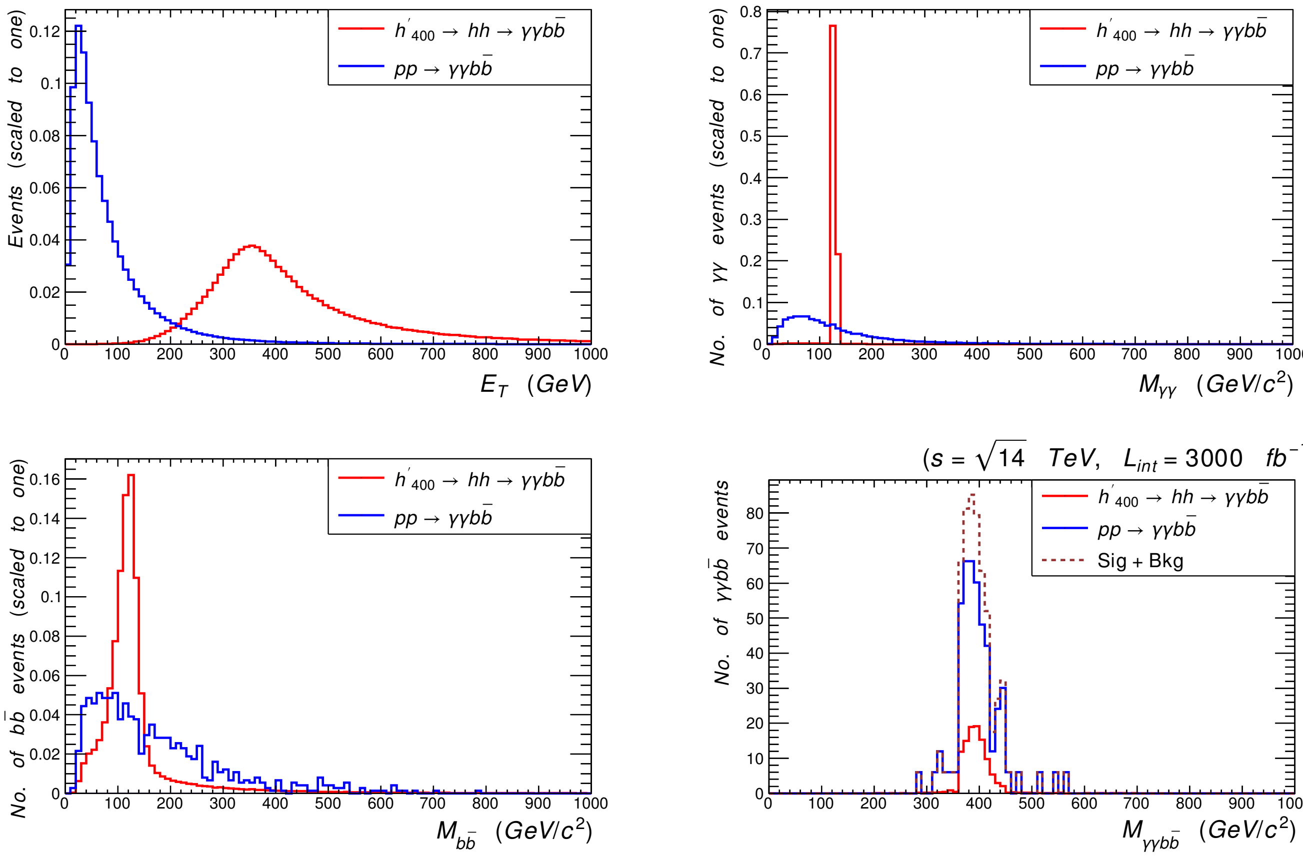

FIGURE 1: Signal and background versus the variables: E_T, $M_{\gamma\gamma}$, $M_{b\bar{b}}$, and $M_{\gamma\gamma b\bar{b}}$.

As emphasized in [8], our analysis involved a series of computational procedures carried out as follows. Firstly, the BLSSM model was implemented using the SARAH package. Subsequently, SPheno was utilized to generate the particle spectrum based on the implemented model. For event analysis and the examination of the corresponding background, MadGraph and MadAnalysis were employed. To carry out this study, we utilize a High-Luminosity LHC (HL-LHC) luminosity of $L_{\text{int}} = 3000\,\mathrm{fb}^{-1}$ since this specific channel is not accessible during Run 3. Our investigation into this process aims to contribute valuable insights into the properties of the heavy BLSSM Higgs boson and its interactions.

In Figure 1, we present the distributions of the signal, denoted as S, and background, denoted as B, with respect to various variables: E_T (transverse energy), $M_{\gamma\gamma}$ (diphoton invariant mass), $M_{b\bar{b}}$ (b-jet invariant mass), and $M_{\gamma\gamma b\bar{b}}$ (diphoton and b-jet invariant mass combination). It is important to note that the event rates shown in the figures have been calculated after applying acceptance cuts. These cuts help select events that meet specific criteria, ensuring that only relevant events are considered in the analysis. By implementing these acceptance cuts, we can effectively study the signal and background processes while reducing noise and irrelevant contributions, leading to more precise and meaningful results.

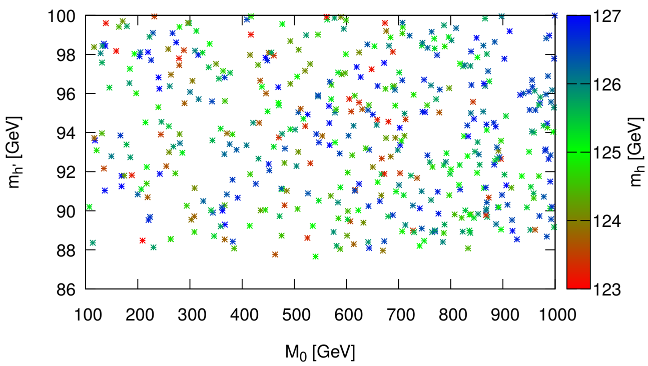

FIGURE 2: $m_{h'}$ as function of M_0, with randomly varying other parameters. Adapted from [12].

5. DIPHOTON DECAY OF A LIGHT HIGGS STATE

In 2018, the CMS collaboration reported an excess near 95 GeV in the diphoton final state resulting from the gluon fusion initiated channel ($gg \to h' \to \gamma\gamma$) [9]. Their latest results, released in March 2023, reaffirmed the presence of this excess by employing advanced analysis techniques and incorporating data from multiple years of Run 2. The combined data revealed an excess with a local significance of 2.9σ at a mass of $m_{\gamma\gamma} = 95.4$ GeV.

Similarly, the ATLAS collaboration recently published their latest findings in the diphoton channel, utilizing the complete Run 2 data set [10]. Their updated analysis showcased improved sensitivity compared to their previous study, which had a smaller data sample. ATLAS identified an excess with a local significance of 1.7σ in the diphoton channel at an invariant mass of 95 GeV, aligning with the observation reported by CMS that indicates a 2.8σ deviation at mass equal to 95.3 GeV [9].

Although these findings are still in the preliminary stage, they have garnered significant attention in the particle physics community. Several beyond the Standard Model (BSM) explanations have already been proposed to account for this potential new resonance [11], and references therein. Confirming these observations with future data would provide substantial direct evidence of new physics.

In this section, our main objective is to investigate the potential compatibility of a light BLSSM Higgs boson, with a mass in the range of 90–97 GeV, with the results obtained from a diphoton channel search conducted independently by the CMS and ATLAS collaborations. To initiate our analysis, we present the plot shown in Figure 2, sourced from [12]. This plot depicts the scan for $m_{h'}$ as a function of the universal soft SUSY breaking parameter, m_0, while allowing other related terms to vary randomly.

As can be seen from this plot, $m_{h'} \simeq 95$ GeV is quite plausible in the BLSSM. The Higgs signal strength is a measurement that compares the observed production and decay rates of the Higgs boson to the predictions of the Standard Model. In the case of the Higgs, h', decay to diphoton ($h' \to \gamma\gamma$), the signal strength is defined as

$$\mu_{\gamma\gamma} = \frac{\sigma\left(gg \to h'\right)}{\sigma\left(gg \to h_{\rm SM}\right)} \times \frac{{\rm BR}\left(h' \to \gamma\gamma\right)}{{\rm BR}\left(h_{\rm SM} \to \gamma\gamma\right)}. \quad (17)$$

BP	m_0	$M_{\frac{1}{2}}$	$\tan\beta$	A_0	μ	μ'
1	998	2141	29.9	3837	1849	2020
2	359	3103	31.2	3705	2561	1247
3	146	3351	44.7	3736	2739	1162
4	874	2450	11.4	3709	2092	1770
5	870	4014	57.4	3477	3222	1522
6	363	4234	40.2	3744	3386	1237

$m_{h'}$	m_h	$\sigma(pp \to h' \to \gamma\gamma)$	$\sigma(pp \to h \to \gamma\gamma)$
95.3	125.9	13.1	43.5
94.2	125.3	8.6	49.3
96.3	125.4	10.0	49.0
96.6	125.3	13.0	44.7
89.7	125.7	9.7	49.3
90.0	126.2	8.7	47.6

TABLE 3: Benchmark points for $m_{h'} \sim 95$ GeV, where mass parameters (m_0, $M_{1/2}$, A_0, μ, μ', m_h, and $m_{h'}$) are given in terms of GeV, while the cross sections are given in terms of fb.

Combining the experimental measurements from both ATLAS and CMS, the measured signal strength for the diphoton channel is:

$$\mu_{\gamma\gamma} = 0.27^{+0.10}_{-0.09}. \quad (18)$$

This would be compatible with an additional Higgs-like particle that decays to diphoton final states.

In [12], the six benchmark points for $m_{h'}$ around 95 GeV, displayed in Table 3 have been investigated.

In Figure 3, we present a comparison of the number of observed events for BP5 and BP6 with the experimental data from the CMS detector at a center-of-mass energy of 13 TeV. The data points are color-coded for clarity: yellow points correspond to the specific process $h' \to \gamma\gamma$, pink points represent the decay of the SM Higgs boson ($h \to \gamma\gamma$), and the red points illustrate the background events originating from other SM processes. These figures demonstrate the distinctions between the signal arising from h' and the SM Higgs boson decay signal, as well as the background events, all in the context of the diphoton ($\gamma\gamma$) invariant mass spectrum. The detailed analysis of this data is of utmost importance to experimental physicists, as it enables them to explore the existence of new physics beyond the SM and to probe the unique properties of the h' particle.

6. CONCLUSIONS

We have demonstrated that the BLSSM, a theoretically well-motivated realization of supersymmetry, holds the potential to produce detectable signals of a heavy neutral CP-even Higgs boson at both the LHC during Run 3 and the subsequent HL-LHC phase. These signals stem from the lightest (neutral) Higgs state in the BLSSM model, denoted as h', which exhibits a significant B-L composition. In contrast, the discovered Higgs boson with a mass of $m_h = 125$ GeV corresponds to the lightest (neutral) Higgs state primarily governed by MSSM characteristics, referred to as h.

We have specifically investigated the process $gg \to h' \to hh \to b\bar{b}\gamma\gamma$ with a benchmark point illustratively chosen to have a mass of $m_{h'} = 400$ GeV. Our focus has been on the potential to detect this signal at the HL-LHC, presenting a promis-

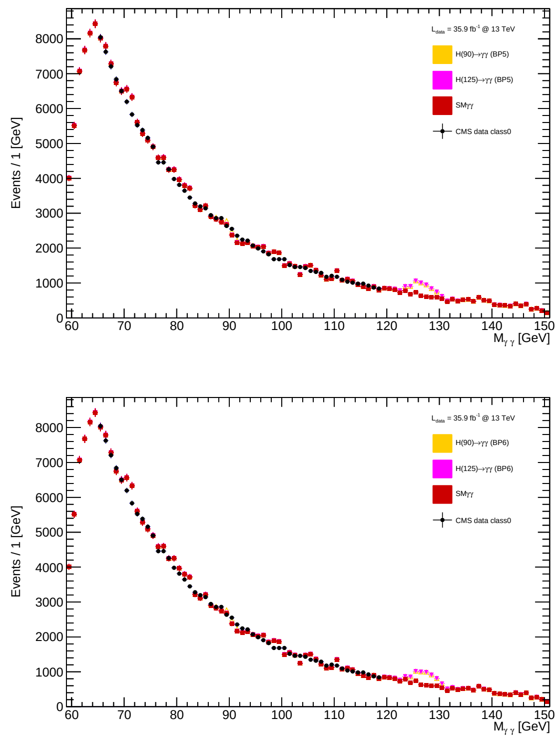

FIGURE 3: Signal and background versus the variables: E_T, $M_{\gamma\gamma}$, $M_{b\bar{b}}$, and $M_{\gamma\gamma b\bar{b}}$.

ing opportunity to distinguish the BLSSM hypothesis from alternative scenarios also based on supersymmetry.

Furthermore, we were motivated by a $\sim$2.8σ excess observed by the CMS experiment in the di-photon channel at an integrated luminosity of 35.9 fb^{-1} and a center-of-mass energy of $\sqrt{s} = 13$ TeV (including a moderate contribution from 8 TeV data) within the mass range of approximately 90–97 GeV. Consequently, we conducted an analysis to explore the discovery potential of a light neutral Higgs boson, denoted as h', within the context of the BLSSM during Run 2 of the LHC.

In summary, our findings underscore the significance of the BLSSM model in generating observable signals of a heavy neutral CP-even Higgs boson, providing a promising avenue for experimental verification and distinguishing it from other supersymmetric frameworks.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

References

[1] S. Moretti and S. Khalil, "Supersymmetry Beyond Minimality: From Theory to Experiment," CRC Press, 2019, ISBN 978-0-367-87662-3.

[2] G. Jungman, M. Kamionkowski, and K. Griest, "Supersymmetric dark matter," Phys. Rept. **267** (1996), 195–373 doi:10.1016/0370-1573(95)00058-5 [arXiv:hep-ph/9506380 [hep-ph]].

[3] W. Abdallah and S. Khalil, "MSSM Dark Matter in Light of Higgs and LUX Results," Adv. High Energy Phys. **2016** (2016), 5687463 doi:10.1155/2016/5687463 [arXiv:1509.07031 [hep-ph]].

[4] U. Ellwanger, M. Rausch de Traubenberg, and C. A. Savoy, "Particle spectrum in supersymmetric models with a gauge singlet," Phys. Lett. B **315** (1993), 331–337 doi:10.1016/0370-2693(93)91621-S [arXiv:hep-ph/9307322 [hep-ph]].

[5] S. Khalil and A. Masiero, "Radiative B-L symmetry breaking in supersymmetric models," Phys. Lett. B **665** (2008), 374–377 doi:10.1016/j.physletb.2008.06.063 [arXiv:0710.3525 [hep-ph]].

[6] V. V. Andreev and A. A. Pankov, "Constraints on the Z-Z-prime mixing angle from data measured for the process $e^+e^- > W^+W^-$ at the LEP2 collider," Phys. Atom. Nucl. **75** (2012), 76–89 doi:10.1134/S1063778812010024.

[7] B. O'Leary, W. Porod, and F. Staub, "Mass spectrum of the minimal SUSY B-L model," JHEP **05** (2012), 042 doi:10.1007/JHEP05(2012)042 [arXiv:1112.4600 [hep-ph]].

[8] M. Ashry, S. Khalil, and S. Moretti, "Searching for a Heavy Neutral CP-Even Higgs Boson in the BLSSM at the LHC Run 3 and HL-LHC," [arXiv:2305.11712 [hep-ph]].

[9] A. M. Sirunyan et al. [CMS], "Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV," Phys. Lett. B **793** (2019), 320–347 doi:10.1016/j.physletb.2019.03.064 [arXiv:1811.08459 [hep-ex]].

[10] C. Arcangeletti on behalf of ATLAS collaboration: `https://indico.cern.ch/event/1281604/attachments/2660420/\\4608571/LHCSeminarArcangeletti-final.pdf`,7th of June, 2023.

[11] A. Belyaev, R. Benbrik, M. Boukidi, M. Chakraborti, S. Moretti, and S. Semlali, "Explanation of the Hints for a 95 GeV Higgs Boson within a 2-Higgs Doublet Model," [arXiv:2306.09029 [hep-ph]].

[12] A. A. Abdelalim, B. Das, S. Khalil, and S. Moretti, "Diphoton decay of a light Higgs state in the BLSSM," Nucl. Phys. B **985** (2022), 116013 doi:10.1016/j.nuclphysb.2022.116013 [arXiv:2012.04952 [hep-ph]].