Phenomenology of Light MSSM Higgs Boson Scenario

Alexander Belyaev\textsuperscript{a, b}

School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, U.K.

Abstract. We have found that in the MSSM, the possibility for the lightest CP-even Higgs boson to be lighter than Z boson (as low as about 60 GeV) is, contrary to the usual belief, not yet excluded by LEP2 Higgs search nor any direct searches for supersymmetric particles at high energy colliders. The Light Higgs boson scenario (LHS) is realised when the \( Z \bar{h} \) coupling and the decay branching ratio \( \text{Br}(h/A \to bb) \) are simultaneously suppressed as a result of generic supersymmetric loop corrections. Consequently, the \( W^\pm H^\pm h \) coupling has to be large due to the sum rule of Higgs couplings to weak gauge bosons and as we demonstrate, the associate neutral and charged Higgs boson production process, \( pp \to H^\pm h(A) \), at the LHC can completely probe the LHS.

PACS. 14.80.Cp Non-standard-model Higgs bosons – 12.60.Jv Supersymmetric models

While the Standard Model (SM) of particle physics is consistent with existing data, there is a strong belief in a more complete description of the underlying physics. Supersymmetry (SUSY), as a good candidate for theory beyond the SM, solves principal theoretical problems of the SM such as hierarchy and fine tuning, as well as provides good dark matter candidate and potentially solves the problem of baryogenesis. In the minimal supersymmetric standard model (MSSM) the Higgs sector consists of two doublet fields \( h_d \) and \( h_u \) to generate masses for down- and up-type fermions, respectively, and to provide an anomaly-free theory. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of charged Higgs bosons \( H^\pm \), two neutral CP-even scalars \( H \) (heavier) and \( h \) (lighter), and a neutral CP-odd pseudoscalar \( A \). Higgs potential is constrained by supersymmetry such that all the tree-level Higgs boson masses and self-couplings are determined by only two independent unknown parameters, commonly chosen to be the mass of the CP-odd pseudoscalar \( M_A \) and the ratio of vacuum expectation values of neutral Higgs fields, denoted as \( \tan \beta \equiv \langle h_u \rangle / \langle h_d \rangle \).

The MSSM predicts a light neutral Higgs boson which is lighter than Z-boson at the tree level. However, large top quark and squark (stop) loop contributions induce significant radiative correction to the Higgs quartic coupling, such that the lighter neutral Higgs boson mass can be as large as 130 GeV \cite{[2, 3, 4, 5]}. The negative result of Higgs boson search at LEP2 via \( e^+e^- \to Zh \) production channel imposes a lower bound on the SM Higgs boson mass \( M_h > 114 \text{ GeV} \) \cite{[6]}, and excludes significant portion of MSSM parameter space.

The LEP2 collaborations have performed analyses for the MSSM \cite{[7]} using several benchmark scenarios that were considered as typical cases for the MSSM parameter space. The two complementary processes for MSSM Higgs boson search are \( e^+e^- \to Z h/A h \) \cite{[7]}, in which the first one occurs via \( Z \bar{h} \) coupling \( g_{ZZh} = \sin(\beta - \alpha) (\equiv s_{\beta\alpha}) \) while the second one via \( Z Ah \) coupling \( g_{ZAh} = \cos(\beta - \alpha) \). The obvious sum rule (\( g_{ZZh}^2 + g_{ZAh}^2 = 1 \)) puts strong constraints on the mass and couplings of the MSSM Higgs boson \( h \). For all studied benchmark scenarios at LEP2, \( M_h \) below about 90 GeV is excluded \cite{[7]}.

In this study, we propose a different region of the MSSM parameter space which has not been previously studied with deserved attention. We call this possibility light Higgs boson scenario (LHS), in which the Higgs boson \( h \) is lighter than the Z-boson and the \( Z h \) coupling is small enough to be consistent with the LEP2 data.

To satisfy the LEP2 constraint derived from the production channel \( e^+e^- \to Zh \) with \( M_h < M_Z \), the coupling \( g_{ZZh} \) (i.e. \( s_{\beta\alpha} \)) has to be small. Let us denote \( \mathcal{M}^2 \) as the 2 × 2 squared-mass matrix of the CP-even neutral Higgs bosons in the gauge eigenbasis (\( \text{Re} \ h_d^0, \text{Re} \ h_u^0 \)). The mass eigenstates \( (h, H) \) are given by the diagonalization of the matrix \( \mathcal{M}^2 \) with the definition:

\[
\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} -s_\alpha & c_\alpha \\ c_\alpha & s_\alpha \end{pmatrix} \begin{pmatrix} \text{Re} \ h_d^0 \\ \text{Re} \ h_u^0 \end{pmatrix},
\]

where \( c_\alpha \equiv \cos \alpha \) and \( s_\alpha \equiv \sin \alpha \) (with \(-\pi/2 \leq \alpha \leq \pi/2\)).

Denote \( x \equiv M_{11}^2 - M_{22}^2 \) and \( y \equiv M_{12}^2 \), in terms of the components of matrix \( \mathcal{M}^2 \). For relatively large
the neutral Higgs boson masses are approximately 114 GeV in order to agree with LEP2 data, since we obtain a small mass of the heavier CP-even Higgs boson over, the mass of the heavier CP-even Higgs boson which comes from the commonly discussed MSSM scenarios in unit of GeV. The MSSM parameters (at the weak scale) of an LHS sample point. The dimension of mass parameters is in units of GeV. $M_t(i=1, \ldots, 3)$, $M_Q$ and $A_3$ are gaugino masses, the universal soft-breaking sfermion mass and universal trilinear A-term for the third-generation at the weak scale, respectively. $M_{	ilde{X}^0}$, $M_{	ilde{X}^+}$ and $M_{	ilde{b}_i}$ are pole masses for the lightest chargino, stop and sbottom, respectively.

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Table 1. The MSSM parameters (at the weak scale) of an LHS sample point. The dimension of mass parameters is in units of GeV. $M_t(i=1, \ldots, 3)$, $M_Q$ and $A_3$ are gaugino masses, the universal soft-breaking sfermion mass and universal trilinear A-term for the third-generation at the weak scale, respectively. $M_{\tilde{X}^0}$, $M_{\tilde{X}^+}$ and $M_{\tilde{b}_i}$ are pole masses for the lightest chargino, stop and sbottom, respectively.

| $\tan \beta$ | $M_{H^+}$ | $\mu$ | $A_3$ | $M_{1/2}^H$ | $M_Q$ |
|-------------|---------|------|------|-----------|------|
| 35          | 135     | 890  | 750  | 100       | 600  |

\[M_h = 11, M_A = 113, M_H = 119, \]
\[\text{Br}(h/A/H \rightarrow b\bar{b}) = 0.65/0.64/0.03, \]
\[\text{Br}(h/A/H \rightarrow \tau^+\tau^-) = 0.25/0.34/0.54, \]
\[g_{Zh}^2 = 0.006, g_{Z\tilde{b}h} = g_{Z\tilde{b}H} = 0.994, \]
\[M_{\tilde{X}^0} = 100, M_{\tilde{X}^+} = 198, M_{\tilde{t}_1} = 126, M_{\tilde{b}_1} = 273, \]
\[\Delta \rho = 6.7 \times 10^{-4}. \]

\[\tan \beta \text{ (as preferred by the LHS)} \text{ and } y/x \approx 0, \text{ we find } s_{3\beta} \approx \frac{(y/x)^2}{\sqrt{2|x|}} \text{ which vanishes for } x < 0. \text{ Therefore, conditions } y/x \approx 0 \text{ and } x < 0 \text{ provide small values of } s_{3\beta}. \text{ The light Higgs boson } h \text{ mainly consists of } h_0^0, \text{ and the neutral Higgs boson masses are approximately } M_h^2 \approx M_{11}^2 \text{ and } M_H^2 \approx M_{22}^2. \text{ This feature is different from the usual scenarios in which } M_h^2 \approx M_{22}^2 \text{ and } M_H^2 \approx M_{11}^2. \text{ As it is well-known, } M_{22}^2 (\text{i.e., } h_u \text{-component}) \text{ receives large positive logarithmic correction from top and stop contributions. This correction, which helps to significantly increase the mass of } h \text{ in the usual scenarios, increases the mass of } H \text{ in the LHS and changes the sign of } x \text{ value from positive (at tree level) to negative when } M_A \sim M_Z. \text{ The condition } y/x \approx 0 \text{ (needed for the LHS)} \text{ can only be satisfied in some regions of MSSM parameter space which is studied below.}

As an illustration, we present in Table 1 one LHS sample point where the gaugino masses (with $M_2 = 2M_1$), the supersymmetric Higgs mass $\mu$-parameter ($\mu$), the universal soft-breaking sfermion mass ($M_Q$), and the trilinear A-term ($A_3$) for the third-generation at the weak scale are all at (or below) TeV scale. For our numerical analysis, we use CPsuperH program [8] and assume CP is conserved. For the LHS sample point specified in Table 1, $x > 0$, $y/x \approx -0.2$ and $s_{3\beta} \approx 0.98$ at tree level. After including radiative corrections, the Higgs mass matrix elements in the effective potential become $M_{11}^2 \approx (71.0 \text{ GeV})^2$, $M_{22}^2 \approx (119.7 \text{ GeV})^2$, and $M_{33}^2 \approx -(19.5 \text{ GeV})^2$, hence, $x < 0$ and $y/x \approx 0.041$. (The mass of top quark is taken to be 172.5 GeV.) Consequently, we obtain a small $s_{3\beta_0} \approx 0.069$. Note that in the LHS, the lighter Higgs boson mass is close to its tree-level value $M_h \approx \sqrt{M_{11}^2} \sim M_Z$ when $M_A \sim M_Z$. This feature is qualitatively very different from the commonly discussed MSSM scenarios in which $M_h$ receives large radiative corrections. Moreover, the mass of the heavier CP-even Higgs boson $H$ must receive large radiative corrections to exceed about 114 GeV in order to agree with LEP2 data, since the $ZZH$ coupling is close to the SM value.

To find the allowed parameter space for the LHS with $\mu > 0$, we scan the following set of MSSM parameters: $\tan \beta [1.1, 50]$, $(M_{H^+}/\text{TeV}) [0.1, 2]$, $(M_A/\text{TeV}) [-2, 2]$, $(M_t/\text{TeV}) [0.05, 1]$, $(M_b/\text{TeV}) [0.05, 1]$, $(M_Q/\text{TeV}) [0.05, 1]$ and $(\mu/\text{TeV}) [0, 3M_Q]$, within the range denoted in brackets. Since a too large $\mu$-parameter induces not only the color breaking vacuum in the general direction of the scalar potential but also the fine-tuning in the Higgs mass parameter, we require $\mu$ to be less than $3M_Q$ in our analysis [9, 10]. Then, we check the LHS parameter space against the full set of the experimental and theoretical constraints. They are: (1) LEP2 $Z\ell\ell/Z\ell \ell$ and $A\ell/\ell$ constraints, cf. Tables 14 and 17 of Ref. [7]; (2) Chargino ($M_{\tilde{X}^+}$), stop ($M_{\tilde{t}_1}$), sbottom ($M_{\tilde{b}_1}$) and gluino ($M_3$) mass limits: $M_{\tilde{X}^0} \geq 103 \text{ GeV}$ [11], $M_{\tilde{t}_1} > 96 \text{ GeV}$ [11], $M_{\tilde{b}_1} > 220 \text{ GeV}$ for $M_{\tilde{X}^0} < 90 \text{ GeV}$ and $M_{\tilde{b}_1} - M_{\tilde{X}^0} > 6 \text{ GeV}$ (where $M_{\tilde{X}^0}$ is the lightest neutralino mass) [12] or $M_{\tilde{b}_1} > 100 \text{ GeV}$ for all other regions [11], and $M_3 > 270 \text{ GeV} \text{ for } M_{\tilde{b}_1} < 220 \text{ GeV} \text{ and } M_3 - M_{\tilde{b}_1} > 6 \text{ GeV}$ [13] or $M_3 > 240 \text{ GeV}$ for all other regions [14]; (3) electroweak constraint: one-loop stop contributions to $\rho$-parameter $|\Delta \rho_{\tilde{t} \tilde{t}}| < 2 \times 10^{-3}$ [15]; (4) color breaking constraint: $A_3^2 < 3(M_Q^2 + M_{\tilde{t}_1}^2 + \mu^2)$ where $M_{\tilde{t}_1}$ is the soft-breaking mass for Higgs $h_0$ [9, 10].

Our result is shown in Fig. 1 where blue (darker) and green (lighter) color indicates allowed parameter space with $M_b < M_Z$ and $M_b > M_Z$, respectively.

Fig. 1. Projected planes of scanned parameter space indicating the LHS region in accord with experimental data. (See detail explanation in the text.)
Moreover, its couplings to down-type fermions are further suppressed, as indicated in Fig. 1f. Therefore, the LHS, which is realized in intermediate-to-high tan β region, can be potentially probed even at the Tevatron via several tan β-enhanced processes, such as $p\bar{p} \rightarrow h(A)$ (produced via gluon-gluon fusion process) with $h/A \rightarrow \tau\tau$, $p\bar{p} \rightarrow b\bar{b}h(A)$, as well as $p\bar{p} \rightarrow t\bar{t}$ with $t \rightarrow H^+b$. At present luminosity, those processes are sensitive only to very large values of $\tan \beta \gtrsim 45$—50, while at 10 fb$^{-1}$, $\tan \beta \gtrsim 30$ could be probed [20, 21]. At the LHC, a smaller tan β value ($\lesssim 10$) of the LHS can be tested via the tan β-enhanced processes, such as $p\bar{p} \rightarrow (h, A) \rightarrow \tau\tau$ [22]. Furthermore, given the expected large number ($\sim 10^8$) of top quark pairs produced at the LHC, the LHC can manifest itself in the copious $t \rightarrow H^+b$ decays as long as $M_{H^+}$ is not too large (below about 140 GeV) [23].

Conclusions: We have shown that in the MSSM the possibility for the CP-even Higgs boson $h$ to be lighter than $Z$-boson (as low as about 60 GeV) is, contrary to the usual belief, not yet excluded by the existing direct search experiments. The characteristic of the light Higgs boson scenario (LHS) is that the $ZZh$ coupling and the decay branching ratio $Br(h/A \rightarrow b\bar{b})$ are simultaneously suppressed as a result of SUSY loop corrections. We would also note that the region of MSSM parameter space considered for explaining the non-conclusive LEP2 excess of the $\sim 98$ GeV 'Higgs-like' events [6], as studied in the literature (see, e.g., [24, 25]), is a subset of the more generic LHS parameter space that we have found in this paper. Our result would be useful for clarifying the parameter space responsible for this excess.

The implications of the LHS to the usual LHC (and Tevatron) search strategies for the lighter CP-even Higgs boson ($h$) can be summarized as follows. In view of its production mechanisms, both the vector boson fusion process and the associated production of $h$ with vector boson are largely suppressed, while the associated production of $h$ and $H^+$ is enhanced by the large $W^-h-H^+$ coupling. In view of its decay channels, the decay branching ratio of $h$ into $b\bar{b}$ mode is reduced and the $\tau^+\tau^-$ mode is enhanced. Also, as compared to the SM rates, the $gg \rightarrow h \rightarrow \gamma\gamma$ rate is reduced by a couple of orders of magnitudes and the $gg \rightarrow h \rightarrow \tau^+\tau^-$ rate is enhanced by about an order of magnitude for $h$ around 60 GeV. Since the mass of

![Fig. 2](image-url) Rates for $p\bar{p} \rightarrow H^+h(A) \rightarrow \tau^+\nu\bar{b} \rightarrow \pi^+\nu\bar{b}\bar{b}$ signature at the Tevatron and the LHC.
the heavier CP-even Higgs boson is below 130 GeV in the LHS, there is no resonance enhanced $hh$ pair production from $gg$ fusion process. The only large Higgs pair production rate at the LHC is via $p p \rightarrow H^\pm h(A)$ whose production cross sections are sizable (above a few hundreds fb) and insensitive to the value of $\tan \beta$. (The tree level $AAH^\pm$ rate is independent of $\tan \beta$.) Hence, if this production channel is not observed at the LHC, it would undoubtedly exclude the LHS. On the other hand, if this production channel is detected, a large production rate of the heavier Higgs boson $H$ via vector boson fusion process is expected in the LHS.

Finally, we note that in the LHS, $B$ physics processes at $B$-factories, Tevatron and LHC, such as $b \rightarrow s\gamma$, $B^+ \rightarrow \tau^-\nu\tau$, $B_d\rightarrow \mu^+\mu^-$ and $B_s \rightarrow J/\psi K_S$ oscillation measurements, could be largely modified due to the sizable contributions from light (neutral and charged) Higgs bosons. Since the predictions on those processes could strongly depend on the flavor structure of the SUSY breaking parameters, we do not impose any constraints from flavor physics to further restrict the allowed MSSM parameter space of the LHS presented in this work. A detailed study of the constraints from flavor physics, under a specific assumption of the flavor structure, is interesting and deserves a separate study.

Our preliminary study [19] shows that even for the commonly discussed minimal-flavor-violation (MFV) scenario in which flavor violation is solely generated by SM Cabibbo-Kobayashi-Maskawa (CKM) matrix, the LHS can be consistent with all the present $B$-physics data though its parameter space is largely reduced. In Fig. 3 we present the allowed LHS parameter space indicated by green area after application $B$-physics constraints (black and gray areas) combined with LEP2 constraints (red, dark red and yellow areas). The blue color indicates the allowed parameter space for $m_{h} > M_Z$. All other colors indicate the excluded regions. One can see that $m_h$ is required to be larger than about 80 GeV while $\tan \beta$ is bounded to be less than about 20, mainly due to the $B_{d,s} \rightarrow \mu^+\mu^-$ constraint represented by black area. Hence, it is expected that the MSSM LHS would require a non-MFV flavor sector, should $h$ boson be much lighter than $Z$ boson. Its detail will be published in a forthcoming paper [19].

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