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Probing the CP-even Higgs sector via $H_3 \to H_2 H_1$ in the natural next-to-minimal supersymmetric standard model

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After the discovery of a standard model (SM)-like Higgs boson, naturalness strongly favors the next-to-minimal supersymmetric SM. In this letter, we point out that the natural next-to-minimal supersymmetric SM usually predicts the following CP-even Higgs H_i sector: (A) H_2 is the SM-like Higgs boson with mass pushed upward by a lighter H_1 with mass overwhelmingly within $[m_{H_2}/2, m_{H_2}]$; (B) $m_{H_3} \simeq 2\mu/\sin 2\beta \gtrsim 300$ GeV; (C) H_3 has a significant coupling to the top quark and can decay to $H_1 H_2$ with a large branching ratio. Using a jet substructure we show that these three Higgs bosons can be discovered via $gg \to H_3 \to H_1 H_2 \to b\bar{b}\ell\nu jj$ at the 14 TeV LHC. In particular, the LEP-LHC scenario with $H_1 \simeq 98$ GeV has a very good discovery potential.

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I. INTRODUCTION

Supersymmetry provides the most elegant solution to the gauge hierarchy problem in the standard model (SM). In the supersymmetric SMs (SSMs) with R parity, we can not only achieve the gauge coupling unification, but also have a cold dark matter candidate. Recently, the discovery of an SM-like Higgs boson at the LHC with mass m_h around 126 GeV [1] has deep implications for the SSMs. Although such a relatively heavy Higgs boson mass can be achieved in the minimal SSM (MSSM), it generically incurs a large fine-tuning. (For the possible solutions, see Ref. [2].) By contrast, the next-to-MSSM (NMSSM) with an extra SM singlet Higgs field S is strongly favored by naturalness [3], due originally to its dynamical solution to the Higgs bilinear mass μ problem, and now also to the SM-like Higgs boson mass enhancement via the relatively large Higgs trilinear Yukawa coupling λ in the superpotential and singlet-doublet mixing effect as well [4–7]. The natural NMSSM may leave hints at the light top-squark sector, but the LHC search is rather model dependent [8,9] and barely has any relations with the Higgs sector. (Recently, an attempt to search for the light top squark utilizing the properties of the SM-like Higgs boson was done in Ref. [10].)

In the natural NMSSM, the second lightest CP-even Higgs boson H_2 is identified as the SM-like Higgs boson, while the lightest CP-even Higgs boson H_1 is dominated by a singlet component. Thus, the H_2 mass can be *pushed upward* via the singlet-doublet mixing effect [4–7]. Such a scenario can also explain the possible diphoton excess from Higgs decays [4,11,12] since the significant mixing effect reduces the decay width of $H_2 \to b\bar{b}$ and the light charged Higgsino may increase the rate of Higgs decays to diphotons. Because H_1 has small doublet Higgs components, it might be able to interpret the slight LEP excess for the Higgs field with mass around 98 GeV [13] (see Refs. [14,15]), or the possible LHC excess for the Higgs boson with mass around 113 GeV [16]. A scenario with two light Higgs fields and a low-mass pseudoscalar in the NMSSM has been discussed in Ref. [17]. More noticeable features emerge when we take the heaviest CP-even Higgs boson H_3 into account. In this paper, we consider the full CP-even Higgs sector in the natural NMSSM. We point out that naturalness implies that the mass of H_3 dominantly falls into [300, 600] GeV and has a significant triple Higgs coupling with H_1 and H_2. Such a structure of the Higgs sector enables us to investigate the whole CP-even Higgs sector from the process $gg \to H_3 \to H_1 H_2$. Using the jet substructure method, we show that all three CP-even Higgs bosons H_i can be probed at the 14 TeV LHC. Our search strategy is especially suitable for the LEP-LHC Higgs bosons but also applies to the general pushing-upward scenario.

II. LIGHT HIGGS BOSONS IN THE PUSHING-UPWARD SCENARIO

The SM-like Higgs boson can be accommodated without recurrent severe fine-tuning, and we can show that the whole Higgs sector is light. Restricted to the

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Z_3—NMSSM, naturalness conditions point to a predictive parameter space [4]

$$\begin{aligned} &\lambda{:}0.6\text{–}0.7, \qquad \tan\beta{:}1.3\text{–}3.0, \\ &\mu = \lambda v_s{:}100\ \text{GeV–}200\ \text{GeV}, \end{aligned} \tag{1}$$

where $\tan\beta$ is the ratio of the vacuum expectation values for two Higgs doublets, and λ is the singlet-doublet cubic coupling in the superpotential. A large λ and small $\tan\beta$ is required to obtain the 125 GeV SM-like Higgs mass without a heavy top squark, and μ should be at the electroweak scale to avoid large fine-tuning in tadpole equations. The upper bound on λ is obtained by requiring perturbativity up to the grand unified theory scale. Also, the singlet cubic coupling κ in the superpotential is constrained by perturbativity, and typically is no more than half of λ. The top-squark sector should be sufficiently light, e.g., $m_{\tilde{t}_L} = m_{\tilde{t}_R} = 500$ GeV, and as a flavor-safe choice $A_t = -500$ GeV. Their concrete values will not qualitatively affect our following discussions.

Moreover, A_λ can be determined in the pushing-upward mixing scenario. The Higgs mass-squared matrix in the Goldstone basis is

$$\begin{aligned} (M_S^2)_{11} &= M_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta, \\ (M_S^2)_{12} &= -\frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta, \\ (M_S^2)_{13} &= -\frac{1}{2}(M_A^2 \sin 2\beta + 2\lambda\kappa v_s^2)\cos 2\beta \frac{v}{v_s}, \\ (M_S^2)_{22} &= m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \\ (M_S^2)_{23} &= \frac{1}{2}(4\lambda^2 v_s^2 - M_A^2 \sin^2 2\beta - 2\lambda\kappa v_s^2 \sin 2\beta)\frac{v}{v_s}, \\ (M_S^2)_{33} &= \frac{1}{4}M_A^2 \sin^2 2\beta\left(\frac{v}{v_s}\right)^2 + 4\kappa^2 v_s^2 + \kappa A_\kappa v_s \\ &\quad - \frac{1}{2}\lambda\kappa v^2 \sin 2\beta, \end{aligned} \tag{2}$$

where $M_A^2 = 2\lambda v_s(A_\lambda + \kappa v_s)/\sin 2\beta$ defines the largest scale among these elements. The orthogonal matrix diagonalizing M_S^2 will be denoted by O: $O^T \mathrm{Diag}(m_{H_3}^2, m_{H_2}^2, m_{H_1}^2) O = M_S^2$. The singlet-doublet mixing effect can be studied approximately by decoupling the entries involving the first state. Reference [4] found that, in the case with a large λ and small μ, for the realization of the pushing-upward scenario—which requires $(M_S^2)_{33} \lesssim (M_S^2)_{22}$—a cancellation condition is also necessary to reduce the large nondiagonal element $(M_S^2)_{23}$,

$$1 - (A_\lambda/2\mu + \kappa/\lambda)\sin 2\beta \simeq 0. \tag{3}$$

Thus, A_λ is largely determined by μ and $\tan\beta$, and to a lesser degree by κ. It has to be noted that $(M_S^2)_{23}$ cannot be exactly zero, but the above equation is sufficient to derive some approximate relations. We then have

$$m_{H_3}^2 \approx M_A^2 \simeq \left(\frac{2\mu}{\sin 2\beta}\right)^2\left(1 - \frac{\kappa}{\lambda}\frac{\sin 2\beta}{2}\right). \tag{4}$$

Recall that $\kappa < \lambda$, so, to a good approximation, we get $m_{H_3} \simeq M_A \simeq 2\mu/\sin 2\beta$, which is about 2.5μ. Thus, the H_3 mass is directly related to the weak-scale naturalness.

We now summarize the Higgs spectra in the natural NMSSM under consideration. First, all the Higgs fields are properly light. H_3 and its $SU(2)_L$ partners—the charged Higgs bosons $H^\pm$ and the heavy CP-odd Higgs A_2—take roughly degenerate masses M_A. H_2 is SM-like with a mass around 125 GeV. H_1 is SM singlet-like and should be allowed by the LEP experiment. Note that m_{H_1} is likely to fall into the region $[m_h/2, m_h]$ with the lower bound set by forbidding the decay $H_2 \to H_1 H_1$. (Reference [18] considered such a case.) Otherwise, it tends to be the dominant decay mode of H_2. In addition, the lightest CP-odd Higgs boson A_1 has a mass around the weak scale. Moreover, at least one chargino and three neutralinos, consisting of the Higgsinos and singlino, are light as well. All of them may be detectable at the LHC and here we will focus on the CP-even Higgs bosons.

III. H_i—COUPLINGS

The Higgs signals at colliders are sensitive to their mixing angles which can be described by the tree-level Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{tree}} \supset\ & r_{i,Z}\frac{M_Z^2}{\sqrt{2}v}H_i ZZ + r_{i,W}\frac{\sqrt{2}M_W^2}{v}H_i W^+ W^- \\ & - r_{i,f}\frac{m_f}{\sqrt{2}v}H_i \bar{f} f + \mu_{ijk}H_i H_j H_k, \end{aligned} \tag{5}$$

with $v \approx 174$ GeV. $r_{i,V}$ and $r_{i,f}$ encode the deviations of the couplings of H_i from h_{SM}. For instance, we have

$$r_{1,V} = O_{32}, \qquad r_{2,V} = O_{22}, \qquad r_{3,V} = O_{12}. \tag{6}$$

We have also included the triple Higgs couplings, which will play a crucial role in the Higgs boson searches.

We now present the features of the H_3 couplings. Firstly, note that $(M_S^2)_{12}$ is a small entry and m_{H_3} is a few times larger than $m_{H_{2,1}}$; it is not difficult to obtain the upper bound on O_{12},

$$O_{12} = -s_{\theta_1} \lesssim (M_S^2)_{12}/m_{H_3}^2 \sim (M_S^2)_{12}/(M_S^2)_{11}, \tag{7}$$

where we have used the fact that $(M_S^2)_{11}$ gives the dominant contribution to m_{H_3}. Therefore, the couplings between H_3 and the weak gauge bosons are negligibly small. Next, the reduced couplings of H_3 to the bottom and top quarks are given by

$$\begin{aligned} C_{3,b} &= -O_{11}\tan\beta + O_{12} \approx -O_{11}\tan\beta, \\ C_{3,t} &= O_{11}\cot\beta + O_{12} \approx O_{11}\cot\beta. \end{aligned} \tag{8}$$

Owing to a relatively small $\tan\beta$ in the natural NMSSM, the coupling of H_3 to the top quark is significant while the coupling to the bottom quark is not enhanced that much. They have crucial implications for the collider phenomenology of H_3, e.g., it can be considerably produced at the LHC by virtue of the significant coupling to the gluon,

$$C_{3,g} = 1.03 C_{3,t} - 0.06 C_{3,b} \approx O_{11} \cot\beta. \tag{9}$$

Finally, the triple Higgs coupling $H_3 H_2 H_1$ is greatly enhanced by a large λ and A_λ,

$$\mu_{123} \sim -\frac{\lambda A_\lambda}{\sqrt{2}}\left(1 + 2\frac{\kappa}{\lambda}\frac{\mu}{A_\lambda}\right) \simeq -\frac{\lambda A_\lambda}{\sqrt{2}}, \tag{10}$$

which will lead to an $H_3 \to H_1 H_2$ decay width at the GeV scale and dominates over the H_3 decay. It will provide the most promising discovery prospect for H_3 and H_1. A similar channel has also been discussed in Ref. [19].

We now turn our attention to the lightest Higgs boson H_1. Interestingly, the LEP Collaboration reported a slight excess for the Higgs boson with a mass of ~95–100 GeV (with a signal significance of 2.3σ) [13]. Although our discussions of the Higgs bosons and the ensuing search strategies are not restricted to this case, it is tempting to interpret H_1 as the source of this excess. So we have

$$C_{1,V}^2 \frac{\mathrm{Br}(H_1 \to b\bar{b})}{\mathrm{Br}_{\mathrm{SM}}(H_1 \to b\bar{b})} \sim 0.1\text{–}0.25. \tag{11}$$

For $m_H \lesssim 100$ GeV, its decay to $b\bar{b}$ nearly determines its total width. Thus, the LEP requires $C_{H_1,VV} \sim 0.3$, which is a typical value expected from the mixing Higgs sector.

IV. SIGNATURE AND BACKGROUNDS

In light of the previous analysis, the signature $gg \to H_3 \to H_1(\to b\bar{b})H_2(\to W_h W_\ell)$ is promising, where we denote W_h as the hadronic decaying W boson and denote W_ℓ as the leptonic decaying W boson. The existence of W_ℓ will suppress the enormous QCD backgrounds. The total cross section is

$$\sigma_{H_3} = 0.2\left(\frac{C_{3,g}}{0.4}\right)^2 \frac{\mathrm{Br}(H_3 \to H_1 H_2)}{20\%} \frac{\mathrm{Br}(H_1 \to b\bar{b})}{90\%} \times \frac{\mathrm{Br}(H_2 \to W_\ell W_h)}{28\%} \frac{\sigma_{\mathrm{GF}}(h_{\mathrm{SM}})}{10\ \mathrm{pb}}\ \mathrm{pb}, \tag{12}$$

where $\ell = e, \mu$. The numerical results are shown in Fig. 1. It can be seen that the production cross section of H_3 is stable for a given m_{H_3} (typically varying only a few times), in particular for a heavy H_3.

We implement the simplified model for Higgs bosons in FEYNRULES [20] to generate the universal FEYNRULES output format of the effective model for MADGRAPH5 [21], where the parton-level signatures are generated.

The semileptonic $t\bar{t}$ pair production is the dominant background (BG), with the next-to-next-to-leading-order cross section ≈240 pb [22]. The subdominant BG $W_\ell + b\bar{b}$ + jets has a cross section depending on the renormalization scale, which is roughly 40 pb. Other BGs can be neglected in our signal region. BGs are generated using MADGRAPH5. To avoid double counting, we adopt the modified version of MLM matching [23] with xqcut = 15 GeV. For the latter BG, we include up to two additional jets and set the k factor to be 2.

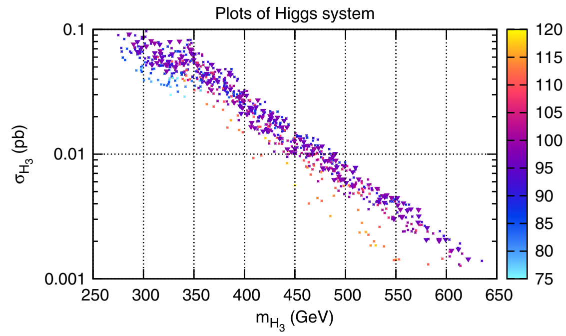

FIG. 1 (color online). A plot in the $\sigma_{H_3} - m_{H_3}$ plane, with the color code denoting m_{H_1}. Large inverted triangle points satisfy the LEP-LHC scenario. We use the NMSSMTOOLS 3.2.1 [31], set $\frac{A_\lambda}{\mathrm{GeV}} \subset [300, 500]$ and $\frac{A_\kappa}{\mathrm{GeV}} \subset [-300, 0]$, and require $\frac{m_{H_2}}{\mathrm{GeV}} \subset [125, 127]$ and the signal strengths $R_{2,gg}(\gamma\gamma) \subset [1.4, 1.6]$, $R_{2,gg}(VV) \subset [1.0, 1.3]$.

We use PYTHIA6.420 [24] for particle decay, the parton shower, and hadronization. However, in order to employ the Butterworth-Davison-Rubin-Salam procedure later, we turn off the B-hadron decays in PYTHIA. The final-state particles, which satisfy $p_T > 0.1$ GeV and $|\eta| < 5.0$, are recorded with the HEPMC [25] format and passed to FASTJET 3.0 [26] for clustering. The signal leptons are required to have $p_T > 10$ GeV, $|\eta| < 2.5$, and pass the isolation criteria, which means the scalar sum of p_T of the final particles inside a cone of $R = 0.15$ around the lepton should be less than 10% of $p_{T,l}$. We assume a b-tagging efficiency of 70% with a probability that other light quarks are incorrectly b-tagged of 1%. We choose the C/A algorithm [27] with radius $R = 1.4$ and $p_T > 40$ GeV to cluster the final states besides isolated leptons to form fat jets. Following Butterworth-Davison-Rubin-Salam [28], we first break the hard fat jets into subjets $j_{1,2}$ with masses $m_{j_{1,2}}$. Next, a significant mass drop $m_{j_1} < \mu m_j$ with $\mu = 0.667$ and a not too asymmetric splitting, i.e., $y = \min(p_{T,j_1}^2, p_{T,j_2}^2)\Delta R_{j_1,j_2}^2/m_j^2 > y_{\mathrm{cut}}$ with $y_{\mathrm{cut}} = 0.09$ ($\Delta R_{j_1,j_2}^2$ is the angular distance), are required. If the above criteria are not satisfied, we will set $j = j_1$ and come back to the decomposition. Finally, we filter the Higgs neighborhood by resolving the fat jets on a finer angular scale $R_{\mathrm{filt}} = \min(0.35, R_{j_1 j_2}/2)$ and taking the three hardest objects, with the remains identified as the underlying event contamination.

The transverse momentum of the neutrino can be recognized as the negative vector sum of all p_T's of the reconstructed leptons and filtered jets. We do not consider effects of detector resolution in the present paper, which is of course very important in a detailed experimental study.

V. EVENT SELECTIONS AND RESULTS

Two basic cuts are imposed to trigger our events. First, at least two filtered fat jets are required. One of them has two leading subjets which are b-tagged and satisfy $|\eta| < 2.5$, and then the fat jet is identified as the H_1 jet. Among the remaining fat jets, the one with the highest p_T is regarded as the W_h jet [29]. Second, the events must contain exactly one isolated lepton.

For illumination, we will take a benchmark point inspired by the LEP-LHC Higgs scenario: $m_{H_1} = 98$ GeV, $m_{H_2} = 125$ GeV, as well as $m_{H_3} = 400$ GeV. Figure 2 shows the distributions of some important kinematic variables. In terms of the plots, we display the cut flow as follows.

(i) Cut1: The relatively large mass splitting between H_3 and H_1 gives H_1 a boost. Therefore, we require $p_{T,b\bar{b}} > 150$ GeV, $p_{T,jj\ell\nu} > 120$ GeV, and $|p_{T,b\bar{b}} - p_{T,jj\ell\nu}| < 20$ GeV.

(ii) Cut2: It is observed that the longitudinal momentum of the neutrino from W decay is generically small, and hence $m_{H_{2,3}}$ can be approximately reconstructed by assuming $p_{z,\nu} = 0$. Practically, cuts based on this assumption are satisfactory. Then we impose 95 GeV $< m_{H_1} <$ 100 GeV, $m_{jj\ell\nu} < 150$ GeV, and $m_{b\bar{b}jj\ell\nu} < 440$ GeV.

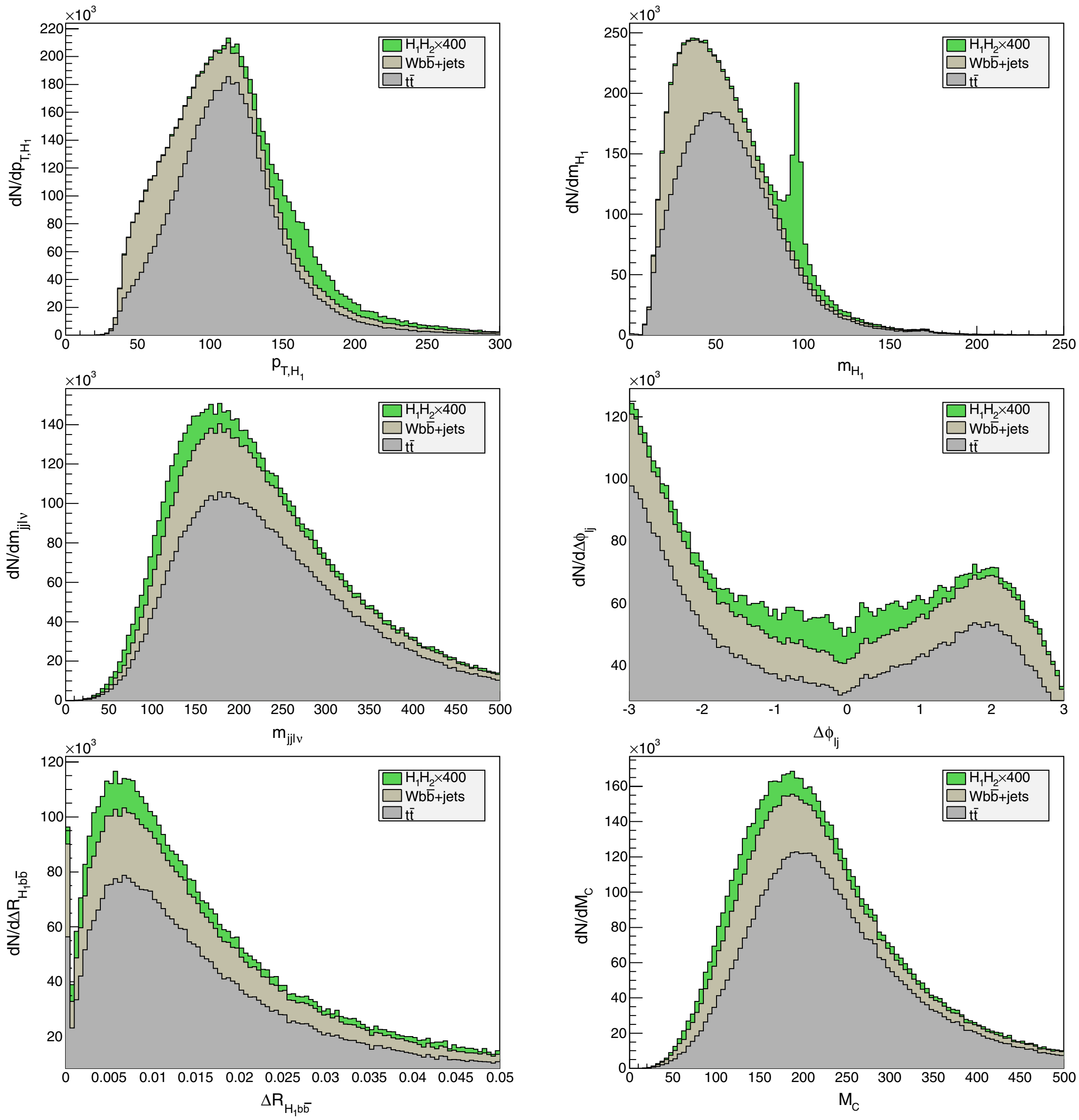

FIG. 2 (color online). Distribution for the triggered signal and background of p_{T,H_1}, m_{H_1}, $m_{jjl\nu}$, $\Delta\phi_{lj}$, $\Delta R_{H_1 b\bar{b}}$, and M_C. The number of events has been normalized to 14 TeV 500 fb^{-1}, and the signal is amplified 400 times.

TABLE I. Number of events after each cut for background and signal (normalized to 500 fb^{-1}). The signal significance $S/\sqrt{S+B}$ has reached 4.02 with the precise 4.42σ excess for the LEP-LHC benchmark point.

	$t\bar{t}$	$W(\to l\nu jj)b\bar{b}$ + jets	Signal
Total	1.2×10^8	1.91×10^7	1.25×10^4
Trigged	4.95×10^6	1.45×10^6	1456.75
Cut1	3.77×10^5	1.61×10^5	639.5
Cut2	1932	203	119.75
Cut3	1512	155.2	105.5
Cut4	108	47.75	56.25
Cut5	84	47.75	55

(iii) Cut3: Because H_2 has spin-0 and W only couples to the left-handed fermions, the lepton from W_ℓ will align with one of the jets from W_h decay. It allows us to impose a cut $|\Delta\phi_{\ell j}| < 1.5$, namely, that the difference of the azimuthal angles between the signal lepton and (one) jet is sufficiently small.

(iv) Cut4: The filtered H_1 jet actually contains three subjets, the $b\bar{b}$, and a radiated gluon. So the H_1 jet and its $b\bar{b}$ subsystem must have a very small angle distance. By contrast, the angle distance between the H_1 jet and the W_h jet is much larger. Thus, we require $\Delta R_{H_1,b\bar{b}} < 0.01$ and $2.6 < \Delta R_{H_1 W_h} < 3.4$.

(v) Cut5: We also impose the cluster transverse mass of the decay products of the H_2, $M_C = \sqrt{p_{T,jj\ell}^2 + m_{jj\ell}^2} + \not{E}_T < 220$ GeV.

With the cuts above, we obtain the signal significance of a 4.42σ excess for the LEP-LHC benchmark point at 14 TeV 500 fb^{-1}. The cut efficiency and the number of signal and background events are presented in Table I.

Since Fig. 1 shows an obvious converged behavior, the whole parameter space with the pushing-upward effect can be explored. Using a boosted-decision-trees analysis [30], we consider six representative points to demonstrate the search prospect, and the signal significance for each point is given in Table II. Some observations can be made. (A) For a given m_{H_3}, a lighter H_1 shows a better discovery potential. (B) Increasing the H_3 mass helps to boost H_1 but the production cross section is reduced. Thus, a moderately heavy $H_3 \sim 400$ GeV and a relatively light H_1 have the most promising discovery potential. (C) Most of the parameter space is discoverable except for a simultaneously light H_3 and a heavy H_1, e.g., the benchmark point B1, despite having a rather large cross section, has a rather low signal significance.

TABLE II. Discovery signal significances for six representative points at 14 TeV 500 fb^{-1}. We design 25 kinematic variables for boosted-decision-trees analysis [30]: $\not{E}_T$, $p_{T,W}$, m_W, n_{jet}, p_{T,b_1}, p_{T,b_2}, $p_{T,\ell}$, $m_{T,\ell\nu}$, $p_{T,wj\ell}$, p_{T,wj_2}, $p_{T,jj\ell\nu}$, $\Delta R_{\ell j}$, $\Delta\phi_{lw}$, p_{T,H_3}, $m_{\ell\nu}$, $E_{l\nu}$, and m_{H_3}.

	m_{H_1} (GeV)	m_{H_3} (GeV)	σ (fb)	$\frac{S}{\sqrt{S+B}}$
B1	100	300	70	0.81
B2	65	300	50	3.84
B3	98	400	25	4.73
B4	65	400	20	7.68
B5	100	600	2	2.79
B6	65	600	2	4.99

The situation can be further improved when we take $H^\pm$ into account. $H^\pm$ can be produced associated with a single top quark, with a moderately large cross section at the small-$\tan\beta$ region. Moreover, it can decay to H_1 and W with a substantial branching ratio and hence provide a way to probe both H_1 and $H^\pm$. In this case a lighter $H^\pm$ can be produced with a larger p_T, which is not very sensitive to m_{H_1}, so it can provide a complementary channel for the pushing-upward scenario search. We leave this for a future work.

VI. CONCLUSION

We have pointed out the specific features in the CP-even Higgs sector of the natural NMSSM, and showed that all three CP-even Higgs bosons H_i can be probed at the 14 TeV LHC.

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