Probing the CP-even Higgs sector via H_{3}→H_{2}H_{1} in the natural next-to-minimal supersymmetric standard model

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Probing the CP-Even Higgs Sector via $H_3 \to H_2 H_1$ in the Natural NMSSM

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After the discovery of a Standard Model (SM) like Higgs boson, naturalness strongly favors the next to the Minimal Supersymmetric SM (NMSSM). In this letter, we point out that the natural NMSSM 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 top quark and can decay to $H_1 H_2$ with a large branching ratio. Using jet substructure we show that all 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. Especially, the LEP-LHC scenario with $H_1 \simeq 98$ GeV has a very good discovery potential.

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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 a SM like Higgs boson at the LHC with mass m_h around 126 GeV [1] has deep implications to 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 [2].). By contrast, the next-to-the MSSM (NMSSM) with an extra SM singlet Higgs field S is strongly favored by naturalness [3], due to originally its dynamically solution to the Higgs bilinear mass μ problem and now the SM-like Higgs boson mass enhancement via the relatively large Higgs trilinear Yukawa coupling λ in the superpotential and singlet-doublet mixing effect [4–7]. The natural NMSSM may leave hints at the light stop sector, but the LHC search is rather model dependent [8, 9] and barely has any relations with Higgs sector (Recently, an attempt to search for the light stop 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 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 di-photon 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 [14] (It receives some interests [15, 16] recently), or the possible LHC excess for the Higgs boson with mass around 113 GeV [17]. A scenario with two light Higgs fields and a low-mass pseudo-scalar in the NMSSM has been discussed in Ref. [18]. More noticeable features emerge when we take the heaviest CP-even Higgs boson H_3 into account. In this letter, we consider the full CP-even Higgs sector in the natural NMSSM. We point out that naturalness implies the mass of H_3 dominantly fall into $[300, 600]$ GeV and its significant triple Higgs coupling with H_1 and H_2. Such a structure of Higgs sector enable us to investigate the whole CP-even Higgs sector from the process $gg \to H_3 \to H_1 H_2$. Using jet substructure method, we show that all these 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.

Light Higgs Bosons in the Pushing-Upward Scenario: The SM-like Higgs boson can be accommodated without recurring severe fine-tuning, and we can show that the whole Higgs sector is light. Restricted to the Z_3-NMSSM, naturalness conditions point to a predictive parameter space [4]

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

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. Large λ and small $\tan\beta$ is required to obtain the 125 GeV SM-like Higgs mass without heavy stop, and μ should be at electroweak scale to avoid large fine-tuning in tadpole equations. The upper bound on λ is obtained by requiring perturbativ-

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ity up to the grand unified theory (GUT) scale. Also, the singlet cubic coupling κ in the superpotential is constrained by perturbativity, and typically is no more than half of λ. The stop sector should be sufficiently light, e.g., $m_{\tilde{t}_L} = m_{\tilde{t}_R} = 500$ GeV, and 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 square matrix in the Goldstone basis is

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

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. Ref. [4] found that, in the case with a large λ and small μ, the realization of pushing-upward scenario, which requires $(M_S^2)_{33} \lesssim (M_S^2)_{22}$, a cancellation condition is also necessary to reduce the large non-diagonal 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 less degree, by κ. It has to be noted that $(M_S^2)_{23}$ can not be exactly zero, but the above equation is sufficient to derive some approximate relations. Then we 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 with 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 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 $H_2 \to H_1 H_1$ (Ref. [19] considered such 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.

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

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

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

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

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 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 bottom quark is not enhanced so much. They have crucial implications to the collider phenomenology of H_3, e.g., it can be considerably produced at the LHC by virtue of the significant coupling to 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 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 $H_3 \to H_1 H_2$ decay width at the GeV scale and dominates over the H_3 decay. It will provides the most promising discovery prospect for H_3 and H_1. A similar channel has also been discussed in Ref. [13].

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 mass $\sim 95 - 100$

GeV (with an signal significance 2.3 σ) [14]. Although our discussions on 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

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

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.

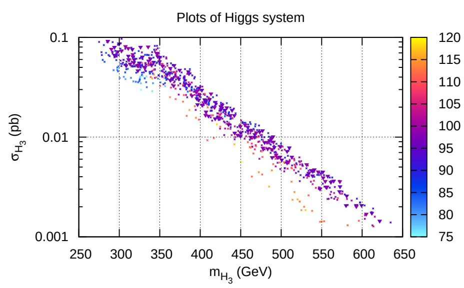

FIG. 1: A plot on the σ_{H_3}-m_{H_3} plane, with color code denoting m_{H_1}. Large inverted triangle points satisfy the LEP-LHC scenario. We use the NMSSMTools 3.2.1 [20], set $\frac{A_\lambda}{\mathrm{GeV}} \subset [300, 500]$, $\frac{A_\kappa}{\mathrm{GeV}} \subset [-300, 0]$, and require $\frac{m_{H_2}}{\mathrm{GeV}} \subset [125, 127]$ and signal strengths $R_{2,gg}(\gamma\gamma) \subset [1.4, 1.6]$, $R_{2,gg}(VV) \subset [1.0, 1.3]$.

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 hadronic decaying W boson and denote W_ℓ as leptonic decaying W boson. The existence of W_ℓ will suppress the enormous QCD backgrounds. The total cross section is

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

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 vary within only a few times), in particular for heavy H_3.

We implement the simplified model for Higgs bosons in FeynRules [21] to generate the UFO format of the effective model for MadGraph5 [22], where the parton-level signatures are generated.

The semi-leptonic $t\bar{t}$ pair production is the dominant background (BG), with the NNLO cross section ≈ 240 pb [23]. The subdominant BG $W_\ell + b\bar{b}$+jets has cross section depending on the renormalization scale, roughly, about 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 [24] with xqcut $= 15$ GeV. For the latter BG, we include up to 2 additional jets and set the $k-$factor to be 2.

We use PYTHIA6.420 [25] for particle decay, parton-shower and hadronization. However, in order to employ the BDRS procedure later, we turn off the $B-$hadrons decays in Pythia. The final state particles, which satisfy $p_T > 0.1$ GeV and $|\eta| < 5.0$, are recorded with the HepMC [26] format and passed to Fastjet 3.0 [27] 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 partilces 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 other light quark mis-b-tagged probability of 1%. We choose the C/A algorithm [29] with radius R=1.4 and p_T>40 GeV to cluster the final states besides isolated leptons to form fat jets. Following BDRS [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 μ=0.667 and not too asymmetric splitting, i.e., $y = \min(p^2_{T,j_1},\ p^2_{T,j_2})\Delta R^2_{j_1,j_2}/m^2_j > y_{cut}$ with y_{cut}=0.09 ($\Delta R^2_{j_1,j_2}$ is the angular distance), are required. If the above criteria are not satisfied, we will set $j = j_1$ and come back to decomposition. Finally, we filter the Higgs neighbourhood 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 recognised as the negative vector sum of all p_T of reconstructed leptons and filtered jets. We will not consider effects of detector resolution in present paper, which is of course very important in a detailed experimental study.

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 highest p_T is regarded as the W_h-jet [30]. 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. Fig. 2 shows the distributions of some important kinematic variables. In terms of the plots, we display the cut flow

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

- Cut2: It is observed that the longitudinal momentum of the neutrino from W decay is generically small, hence $m_{H_{2,3}}$ can be approximately reconstructed by assuming $p_{z,\nu} = 0$. Practically, cuts based on this assumption are satisfactory. Then

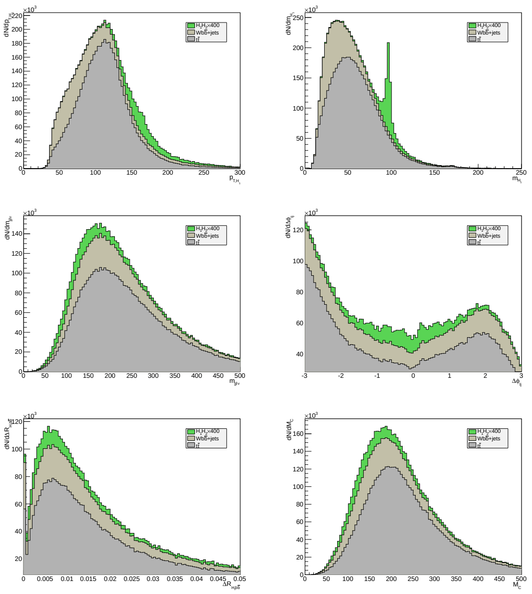

FIG. 2: Distribution for triggered signal and background of p_{T,H_1}, m_{H_1}, $m_{jjl\nu}$, $\Delta\phi_{lj}$, $\Delta R_{H_1 b\bar{b}}$, and M_C. The number of events has been normalised to 14 TeV 500 fb^{-1}, and the signal is 400 times amplified.

we impose: $95\,\text{GeV} < m_{H_1} < 100\,\text{GeV}$, $m_{jj\ell\nu} < 150\,\text{GeV}$, and $m_{b\bar{b}jj\ell\nu} < 440\,\text{GeV}$.

- 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 the azimuthal angles difference between the signal lepton and (one) jet being sufficiently small.

- 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 W_h-jet is much larger. Thus, we require $\Delta R_{H_1,b\bar{b}} < 0.01$, and $2.6 < \Delta R_{H_1 W_h} < 3.4$.

- Cut5: We also impose the cluster transverse mass of decay products of the H_2: $M_C = \sqrt{p^2_{T,jj\ell} + m^2_{jj\ell}} + \not{E}_T < 220$ GeV.

With the cuts above, we obtain the signal significance of 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 behaviour, the whole parameter space with pushing-upward effect can be explored. Using BDT analysis [31], 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)

	$t\bar{t}$	$W(\to l\nu jj)b\bar{b} + jets$	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

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 to 4.02 and with the precise 4.42 σ excess for the LEP-LHC benchmark point.

Increasing 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 relatively light H_1 have the most promising discovery potential; (C) Most of the parameter space is discoverable except for simultaneously light H_3 and heavy H_1, e.g., the benchmark point B1, despite of a rather large cross section, it has a quite low signal significance.

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 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 it for a future work.

	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

TABLE II: Discovery signal significances for 6 representative points at 14 TeV 500 fb^{-1}. We design 25 kinematic variables for BDT analysis [31]: $\not{E}_T$, $p_{T,W}$, 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}.

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

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