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Indirect bounds on heavy scalar masses of the two-Higgs-doublet model in light of recent Higgs boson searches

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ABSTRACT

We study an upper bound on masses of additional scalar bosons from the electroweak precision data and theoretical constraints such as perturbative unitarity and vacuum stability in the two-Higgs-doublet model taking account of recent Higgs boson search results. If the mass of the Standard-Model-like Higgs boson is rather heavy and is outside the allowed region by the electroweak precision data, such a discrepancy should be compensated by contributions from the additional scalar bosons. We show the upper bound on masses of the additional scalar bosons to be about 2 (1) TeV for the mass of the Standard-Model-like Higgs boson to be 240 (500) GeV.

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The Standard Model (SM) for elementary particles based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group has been tested accurately [1]. However, no Higgs boson has been confirmed yet. Discovery of the Higgs boson is the most important issue at the Fermilab Tevatron and the CERN Large Hadron Collider (LHC). Direct searches for the Higgs boson at CERN LEP have set a lower mass bound on the SM Higgs boson to be 114.4 GeV [2]. The Tevatron experiment has excluded the mass of the SM Higgs boson around 160 GeV [3]. Recently, the first results from the ATLAS and CMS experiments at the LHC have been reported [4,5]. The Higgs boson mass around 160 GeV and 300–450 GeV has been excluded by the data with the integrated luminosity of about 1 fb^{-1} .

It is well known that an upper bound on the mass of the Higgs boson is obtained by the tree level unitarity for elastic scattering processes of longitudinally-polarized vector bosons, such as $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$. In the SM, since the scattering amplitudes are proportional to the Higgs boson mass in the high energy limit, a large Higgs boson mass leads to a violation of the unitarity. Consequently the upper bound is obtained on the mass as about 710 GeV [6,7]. On the other hand, if the Higgs boson is absent, the scattering amplitudes grow for high energies. The violation of the tree level unitarity then occurs at $\sqrt{s} \sim 1.2 \text{ TeV}$, where \sqrt{s} is the

centre-of-mass energy of the WW scattering [8]. The LHC Higgs search experiment is expected to cover the entire range of the SM Higgs boson mass. Even if the Higgs boson is not found, some new physics beyond the SM must show up below the TeV scale. If we introduce the cutoff scale Λ into the model, more sensitive upper and lower bounds are obtained on the SM Higgs boson mass as a function of Λ [9–11].

From the electroweak precision data with the theoretical study for radiative corrections [12], the mass of the Higgs boson in the SM is indicated to be $m_h = 90_{-22}^{+27} \text{ GeV}$ and $m_h < 161 \text{ GeV}$ at the 95% Confidence Level (CL) [13]. Notice that this indirect bound on the mass cannot be applied if new physics exists below the TeV scale and affects the calculation for the radiative correction. In such a case, even if the Higgs boson is heavy, the electroweak precision data can be satisfied by the contribution from the new physics.

In the two-Higgs-doublet model (THDM), radiative corrections to the electroweak observables have already been calculated, and the possible allowed regions for the parameter space are evaluated under the electroweak precision data [14,15] and theoretical constraints [16–20]. Flavor physics data such as $b \rightarrow s\gamma$ [21,22], $B \rightarrow \tau\nu$ [23] and tau leptonic decays [24,25] in the THDM can further constrain the parameter space depending on types of Yukawa interactions. In particular, the mass of charged Higgs bosons is bounded from the $b \rightarrow s\gamma$ data to be greater than 295 GeV [26] by assuming the Type-II Yukawa interaction.

In this Letter, in light of recent Higgs boson searches, we re-analyze the constraint on the parameters in the THDM by using

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the electroweak precision data and the theoretical constraints from tree level unitarity and vacuum stability. In particular, we show an upper bound on the masses of the additional heavy scalar bosons can be obtained in the THDM depending on the mass of the SM-like Higgs boson. For a relatively large mass of the SM-like Higgs boson, a relatively large mass difference between the CP-odd Higgs boson and the charged Higgs boson is required in order to satisfy bounds from the electroweak precision data. They are bounded from above by the theoretical constraints. For an SM Higgs boson mass to be 240 (500) GeV, an upper bound on the mass of the CP-odd Higgs boson of about 2 (1) TeV is obtained.

The most general THDM with the doublet fields Φ_1 and Φ_2 are constrained by flavor changing neutral current (FCNC) processes. We here consider the model with the softly-broken discrete Z_2 symmetry under $\Phi_1 \rightarrow \Phi_1$ and $\Phi_2 \rightarrow -\Phi_2$ to avoid FCNC constraints [27]. There are four kinds of Yukawa interaction under the discrete symmetry [21]. In this Letter, we do not specify the type of the Yukawa interaction because it does not affect the following discussions. The Higgs potential is then given by

$$\begin{aligned} \mathcal{V}^{\text{THDM}} = & +m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_3^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2]. \end{aligned} \quad (1)$$

The soft-breaking mass parameter m_3^2 and the coupling constant λ_5 are complex in general. We here take them to be real assuming that CP is conserved in the Higgs sector.

The Higgs doublets Φ_i ($i = 1, 2$) can be written in terms of the component fields as

$$\Phi_i = \begin{pmatrix} i\omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i - iz_i) \end{pmatrix}, \quad (2)$$

where the vacuum expectation values (VEVs) v_1 and v_2 satisfy $\sqrt{v_1^2 + v_2^2} = v \simeq 246$ GeV. The mass eigenstates are obtained by rotating the component fields as

$$\begin{aligned} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} &= R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, & \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} &= R(\beta) \begin{pmatrix} z \\ A \end{pmatrix}, \\ \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} &= R(\beta) \begin{pmatrix} \omega^+ \\ H^+ \end{pmatrix}, \end{aligned} \quad (3)$$

where ω^\pm and z are the Nambu–Goldstone bosons, h , H , A and H^\pm are respectively two CP-even, one CP-odd and charged Higgs bosons, and

$$R(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}. \quad (4)$$

The eight parameters m_1^2 – m_3^2 and λ_1 – λ_5 are replaced by the VEV v , the mixing angles α and β ($= \tan^{-1} \frac{v_2}{v_1}$), the Higgs boson masses m_h , m_H , m_A and m_{H^\pm} , and the soft Z_2 breaking parameter $M^2 = m_3^2 / (\cos \beta \sin \beta)$. In particular, the quartic coupling constants are expressed in terms of physical Higgs boson masses, mixing angles and the soft Z_2 breaking mass parameter M^2 as

$$\lambda_1 = \frac{1}{v^2 \cos^2 \beta} (-M^2 \sin^2 \beta + m_H^2 \cos^2 \alpha + m_h^2 \sin^2 \alpha), \quad (5)$$

$$\lambda_2 = \frac{1}{v^2 \sin^2 \beta} (-M^2 \cos^2 \beta + m_H^2 \sin^2 \alpha + m_h^2 \cos^2 \alpha), \quad (6)$$

$$\lambda_3 = \frac{1}{v^2} \left[-M^2 + (m_H^2 - m_h^2) \frac{\sin 2\alpha}{\sin 2\beta} + 2m_{H^\pm}^2 \right], \quad (7)$$

$$\lambda_4 = \frac{1}{v^2} (M^2 + m_A^2 - 2m_{H^\pm}^2), \quad (8)$$

$$\lambda_5 = \frac{1}{v^2} (M^2 - m_A^2). \quad (9)$$

The coupling constants of the CP-even Higgs bosons with the weak boson hWW and HWW are proportional to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$. When $\sin(\beta - \alpha) = 1$, only h couples to the gauge bosons and behaves as the SM Higgs boson. We call this limit as the SM-like limit.

As discussed in Ref. [28], the masses of the heavy Higgs bosons (H , A and H^\pm) are expressed for $M \gtrsim v$ by

$$m_\Phi^2 \sim M^2 + \lambda_i v^2 [+O(v^4/M^2)], \quad (10)$$

while the mass of h is the SM-like form $\sim \lambda_i v^2$. When $M^2 \gg \lambda_i v^2$ the heavier Higgs bosons have the common mass $\sim M$. In this case, the effect of these bosons decouples in the large mass limit and the low energy theory becomes the SM with h being at the electroweak scale as the SM Higgs boson. On the contrary, when $M^2 \lesssim \lambda_i v^2$ the effect of these bosons does not decouple, and so-called non-decoupling effects appear in the low energy observables.¹ Notice that the mass difference between the heavy Higgs bosons is independent of M , so that the effect on the low energy observables can be large if the mass differences are not small. We also note that the mass difference between heavy Higgs bosons is related to the violation of the custodial $SU(2)$ symmetry [29,30], which causes significant deviation in the electroweak rho parameter from the SM prediction in the positive direction. As we see soon below, this positive contribution to the rho parameter (or the T parameter [12]) can be used to compensate the negative contribution of the heavy SM-like Higgs boson.

New physics effects on the electroweak oblique parameters are parameterized by the S , T and U parameters [12]. By fixing $U = 0$, the central values of S and T are given by [1]

$$S = 0.03 \pm 0.09, \quad T = 0.07 \pm 0.08 \quad (\rho_{ST} = 0.87), \quad (11)$$

where ρ_{ST} is the correlation parameters for the χ^2 analysis. The origin $S = T = 0$ corresponds to the SM prediction for the reference value $m_h = 117$ GeV. The other SM parameters are chosen as $\hat{s}_2^2 = 0.23124 \pm 0.00016$, $\alpha_S = 0.01183 \pm 0.00016$, $m_t = 173 \pm 1.3$ GeV and $G_F = 1.16639 \times 10^{-5}$ GeV⁻².

In the THDM, the contributions to the electroweak parameters from the scalar boson loops are given by [14]

$$\begin{aligned} S_\Phi = & -\frac{1}{4\pi} [F'_\Delta(m_{H^\pm}, m_{H^\pm}) - \sin^2(\beta - \alpha) F'_\Delta(m_H, m_A) \\ & - \cos^2(\beta - \alpha) F'_\Delta(m_h, m_A)], \end{aligned} \quad (12)$$

$$\begin{aligned} T_\Phi = & -\frac{\sqrt{2}G_F}{16\pi^2\alpha_{\text{EM}}} \{ -F_\Delta(m_A, m_{H^\pm}) \\ & + \sin^2(\beta - \alpha) [F_\Delta(m_H, m_A) - F_\Delta(m_H, m_{H^\pm})] \\ & + \cos^2(\beta - \alpha) [F_\Delta(m_h, m_A) - F_\Delta(m_h, m_{H^\pm})] \}, \end{aligned} \quad (13)$$

where

¹ Even when $M \sim 0$, h can be decoupled from two gauge boson vertices if $\sin(\beta - \alpha) \sim 0$. A similar situation can be realized for small m_A in the minimal supersymmetric SM.

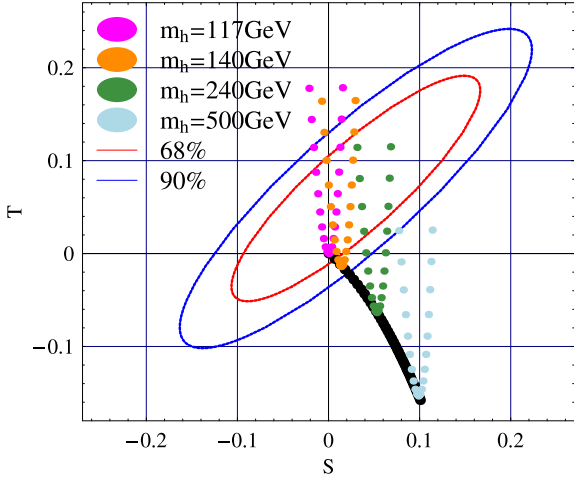


Fig. 1. The χ^2 analysis in the (S, T) plane is shown in the THDM where the SM-like Higgs boson is taken to be 117, 140, 240 and 500 GeV, with the SM-like limit $\sin(\beta - \alpha) = 1$ and $m_{H^\pm} = 300$ GeV. The mass of heavy neutral Higgs bosons $m_A = m_H$ is varied from 200 GeV to 400 GeV by the 10 GeV step (dots: from left to right). Ellipses correspond to electroweak precision limits with 68% ($\sqrt{2.30\sigma}$) and 90% ($\sqrt{4.61\sigma}$) confidence level.

$$F_\Delta(m_0, m_1) = F_\Delta(m_1, m_0) = \frac{m_0^2 + m_1^2}{2} - \frac{m_0^2 m_1^2}{m_0^2 - m_1^2} \ln \frac{m_0^2}{m_1^2}, \quad (14)$$

$$F'_\Delta(m_0, m_1) = F'_\Delta(m_1, m_0) = -\frac{1}{3} \left[\frac{4}{3} - \frac{m_0^2 \ln m_0^2 - m_1^2 \ln m_1^2}{m_0^2 - m_1^2} - \frac{m_0^2 + m_1^2}{(m_0^2 - m_1^2)^2} F_\Delta(m_0, m_1) \right]. \quad (15)$$

For the case with $m_0 \approx m_1$, we have

$$F_\Delta(m_0, m_1) \approx \frac{2(m_0 - m_1)^2}{3} - \frac{(m_0 - m_1)^4}{30m_1^3} + \dots, \quad (16)$$

$$F'_\Delta(m_0, m_1) \approx +\frac{1}{3} \ln m_1^2 + \frac{m_0 - m_1}{6m_1} + \dots. \quad (17)$$

When all the additional heavy scalar bosons are degenerate $m_A = m_H = m_{H^\pm}$, we obtain $S_\Phi = T_\Phi = 0$. In the SM-like limit $\sin(\beta - \alpha) = 1$ with the further assumption $m_H = m_A$, we have

$$S_\Phi \approx -\frac{1}{12\pi} \ln \frac{m_{H^\pm}^2}{m_A^2}, \quad (18)$$

$$T_\Phi \approx +\frac{\sqrt{2}G_F}{12\pi^2\alpha_{EM}} (m_A - m_{H^\pm})^2. \quad (19)$$

In Fig. 1, we show predictions on the S and T parameters in the THDM together with the allowed regions from the precision data for each confidence level. The SM-like Higgs boson mass is varied from 117 GeV to 517 GeV (black curve: from up to down), and the SM-like limit $\sin(\beta - \alpha) = 1$ and $m_{H^\pm} = 300$ GeV are taken. We can see that electroweak precision data favor relatively light Higgs boson $m_h \lesssim 145$ GeV (90% CL). The degenerated mass of the heavy neutral Higgs bosons $m_A = m_H$ is varied from 200 GeV to 400 GeV by the 10 GeV step (dots: from left to right) for the given several values of the SM-like Higgs boson mass $m_h = 117, 140, 240$ and 500 GeV. The quadratic dependence on the mass difference between additional heavy scalar bosons can be easily understood by the approximate formula for $m_A \sim m_{H^\pm}$ in Eq. (19). Therefore, the deviation of the T parameter is insensitive to M .

In the SM, the mass of the Higgs boson is constrained due to tree level unitarity. It has been studied by considering 6×6 scattering matrix of two body scalar states ($hh, hz, zz, \omega^+\omega^-, h\omega^+, z\omega^+$) where each eigenvalues of scattering matrices are restricted to be less than a criteria ξ as $|a_0| \leq \xi$ [6] where a_0 is the S wave amplitude matrix. For $\xi = 1/2$, the Higgs boson mass is bounded to be less than about 710 GeV. In the THDM, there are 14 neutral [16], 8 singly charged and a doubly charged two body states [17]. In our numerical analysis, absolute values of all eigenvalues for the S wave amplitude matrix are required to be less than 1/2 as for a criteria to keep perturbativity [31]. For the constraint from vacuum stability, the Higgs potential is required to be positive for a large value of the order parameter. In the SM, this condition is expressed by $\lambda > 0$ at the tree level. In the THDM, the condition for vacuum stability is replaced by [18–20]

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \min[0, \lambda_4 - |\lambda_5|] > 0. \quad (20)$$

In Fig. 2, we show the regions excluded by various theoretical and experimental constraints in the THDM parameter space (on the $m_A - \Delta m$ plane) assuming the SM-like Higgs boson mass to be $m_h = 117, 140, 240$ and 500 GeV with $\sin(\beta - \alpha) = 1$, where $\Delta m = m_A - m_{H^\pm}$. The masses of neutral scalars and the soft-breaking mass parameter are taken to be degenerate $m_A^2 = m_{H^\pm}^2 = M^2$. Since quartic coupling constants λ_i are independent on $\tan\beta$ for $m_H = M$ with the SM-like limit, unitarity and stability bounds do not depend on $\tan\beta$ in the same limit. Regions excluded by the conditions from tree level unitarity and vacuum stability are shown as the green and yellow areas, respectively, while that excluded by the electroweak precision data at the 90% (68%) CL is indicated by the blue (light-blue) area. Although the bounds from perturbative unitarity, vacuum stability and the electroweak precision data with the oblique corrections do not depend on the type of Yukawa interaction, the direct search results for the charged Higgs boson depends on that via the decay process. The region with charged Higgs boson mass below 79.3 GeV [1] is shown as the gray area, which is excluded assuming $\mathcal{B}(H^+ \rightarrow \tau^+\nu) + \mathcal{B}(H^+ \rightarrow c\bar{s}) = 1$. Depending on the type of Yukawa interaction [21,32], we may have additional constraints from the flavor physics data analyses such as $B_s \rightarrow X_s \gamma$ [21,22,26], $B^+ \rightarrow \tau^+\nu$ [23] and $\tau \rightarrow \ell\nu\bar{\nu}$ ($\ell = e, \mu$) [24, 25]. We do not consider these constraints in Fig. 2 because they are model-dependent. In the upper two panels for $m_h = 117$ GeV and $m_h = 140$ GeV, entire regions of m_A (< 5 TeV) are allowed by all the constraints for a relatively small value for $|\Delta m|$. On the other hand, in the lower two panels for $m_h = 240$ GeV and $m_h = 500$ GeV, we can see that deviations from the allowed region by the electroweak precision data require new contributions to the electroweak precision parameters; i.e., a relatively large value of $|\Delta m|$. Since quartic coupling constants are constrained by the tree level unitarity, masses of heavy scalar bosons are essentially determined by the magnitude of M^2 for $M^2 \gg v^2$, where the mass difference Δm is expressed by $\Delta m \simeq (\lambda_i - \lambda_j)v^2/M$. For a given m_h , the magnitude of Δm is determined to satisfy the electroweak precision data via the new T parameter contribution, which is proportional to $(\Delta m)^2$. Consequently, m_A is constrained from above by unitarity bounds. For $m_h = 240$ GeV and $m_h = 500$ GeV cases, we have the upper bound to be 2 TeV and 1 TeV, respectively.

We have shown the results in the case with $\sin(\beta - \alpha) = 1$, and $m_H^2 = m_A^2 = M^2$ in Fig. 2. This choice of the parameters would be rather special in the sense that there is no $\tan\beta$ dependence in this case. In Eqs. (5) and (6) with $\sin(\beta - \alpha) = 1$, terms dependent on $\tan\beta$ are proportional to $m_{H^\pm}^2 - M^2$, and then one of λ_1 and λ_2 tends to large when $\tan\beta \neq 1$. Therefore, the parameter space is more restricted by the unitarity constraints in the case without

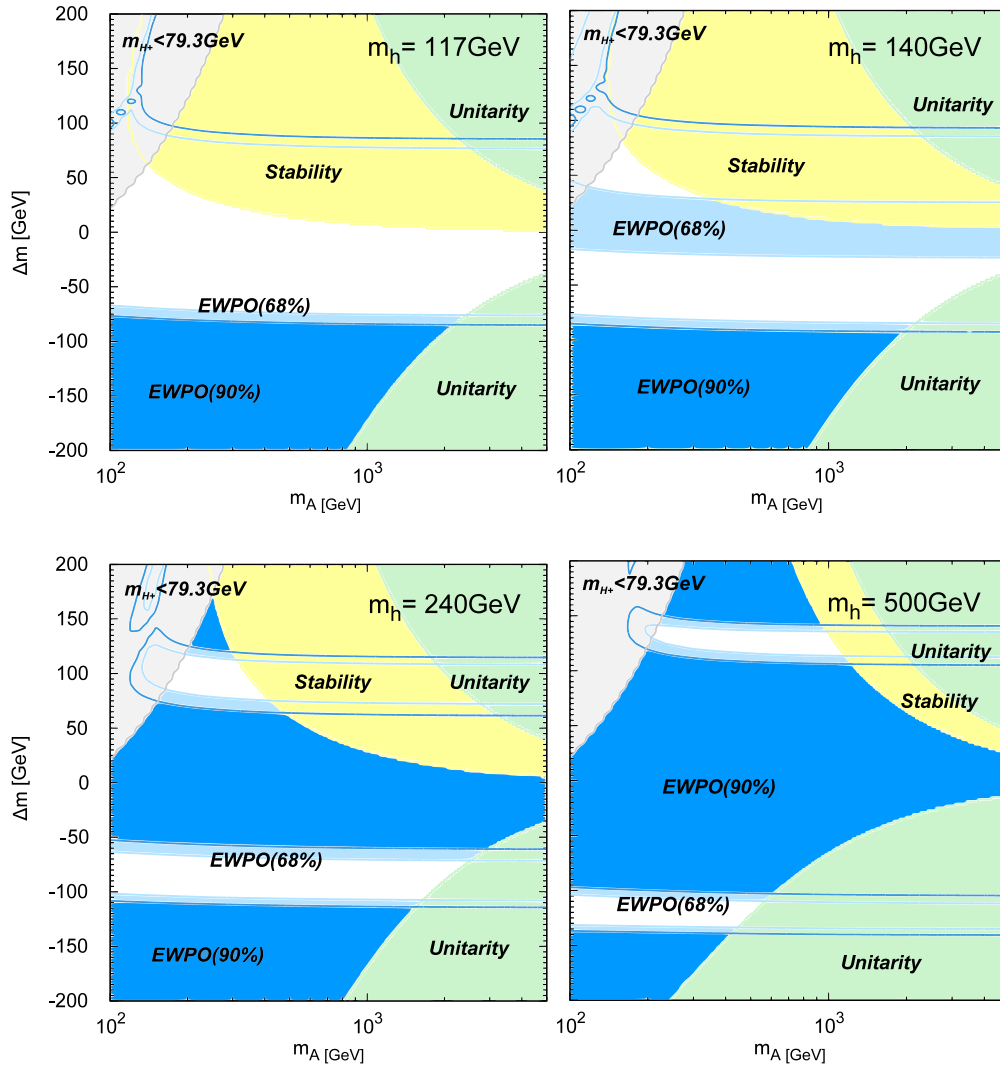


Fig. 2. Theoretical and experimental constraints in the parameter space of the THDM. Uncolored regions are allowed by all the constraints we here considered, i.e., tree level unitarity/stability and electroweak precision data, and direct search bound of charged Higgs boson, $m_{H^\pm} < 79.3$ GeV. The mass and mixing parameters are chosen as $M^2 = m_H^2 = m_A^2$, with the SM-like limit $\sin(\beta - \alpha) = 1$. In this limit, constraints are independent from $\tan\beta$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

degeneracy. Also when $\sin(\beta - \alpha) = 1$ is slightly relaxed, the bound from tree level unitarity becomes sensitive to $\tan\beta$. For larger values of $\tan\beta$, the bound becomes more restrictive. Consequently, the tree level unitarity bound shown in Fig. 2 can be regarded as the most conservative which is independent of the values of $\tan\beta$.

Finally, we shortly discuss the implication to the collider phenomenology. At the LHC, a heavy SM-like Higgs boson can be found via the gluon fusion $gg \rightarrow h$ or vector boson fusion $VV \rightarrow h$ ($V = W$ and Z) with the decays into $WW^{(*)}$ and $ZZ^{(*)}$ [33]. The additional neutral scalar bosons ϕ ($= H$ and A) would be produced via gluon fusion $gg \rightarrow \phi$ [34], associated production with heavy quarks $pp \rightarrow t\bar{t}\phi$, $b\bar{b}\phi$ [35], pair production $pp \rightarrow W^{\pm*} \rightarrow \phi H^\pm$ [32,36,37] and $pp \rightarrow Z^* \rightarrow AH$ [32,37], charged Higgs boson production would be via $gb \rightarrow H^\pm t$ [38], $pp \rightarrow W^\pm H^\mp$ [39] and $pp \rightarrow H^+ H^-$ [40]. As we discussed above, if the SM-like Higgs boson is heavy, a large mass splitting between additional heavy Higgs bosons H^\pm and A (or H) is required. In such a case, their decays into a lighter scalar boson associated with a weak gauge boson $H^\pm \rightarrow \phi W^\pm$ (or $\phi \rightarrow H^\pm W^\mp$) can be significant [41]. These decay modes are kinematically suppressed by the degeneracy of scalar boson masses in most of previous discussions, for example,

on Higgs boson decays in the minimal supersymmetric SM [42]. In addition, the one-loop induced decay process $H^\pm \rightarrow W^\pm Z$ can also be enhanced when the mass difference between A and H^\pm is large [43]. The bosonic decay branching fractions of scalar bosons can dominate over their fermionic decay modes. Therefore, detailed studies for these decay modes will be important to test the scenario with large mass splitting between additional heavy Higgs bosons [44].

In conclusion, we have analyzed theoretical bounds and experimental constraints in the THDM. For a given Higgs boson mass, the magnitude of the mass difference between additional heavy scalar bosons can be determined to satisfy the electroweak precision data. However, the mass difference requires a large coupling constant in the Higgs potential, and too large coupling constant violates tree level unitarity. Therefore, we have found that an upper bound on the additional heavy Higgs bosons is obtained when the SM Higgs boson is heavy. For example, m_A is bounded to be less than around 2 (1) TeV for $m_h = 240$ (500) GeV, where $M^2 = m_H^2 = m_A^2$ with the SM-like limit $\sin(\beta - \alpha) = 1$ is taken. Even if the SM-like Higgs boson is found to be light ($\lesssim 140$ GeV) our analysis shows a possible range of mass splitting in the heavy Higgs bosons in the THDM.

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