Higgcision in the Minimal Supersymmetric Standard Model

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Abstract

We perform global fits to the most recent data (after summer 2014) on Higgs boson signal strengths in the framework of the minimal supersymmetric standard model (MSSM). The heavy supersymmetric (SUSY) particles such as squarks enter into the loop factors of the $Hgg$ and $H\gamma\gamma$ vertices while other SUSY particles such as sleptons and charginos also enter into that of the $H\gamma\gamma$ vertex. We also take into account the possibility of other light particles such as other Higgs bosons and neutralinos, such that the 125.5 GeV Higgs boson can decay into. We use the data from the ATLAS, CMS, and the Tevatron, with existing limits on SUSY particles, to constrain on the relevant SUSY parameters. We obtain allowed regions in the SUSY parameter space of squark, slepton and chargino masses, and the $\mu$ parameter.
I. INTRODUCTION

The celebrated particle observed by the ATLAS [1] and the CMS [2] Collaborations at the Large Hadron Collider (LHC) in July 2012 is mostly consistent with the standard model (SM) Higgs boson than any other extensions of the SM [3, 4], at least in terms of some statistical measures. The SM Higgs boson was proposed in 1960s [5], but only received the confirmation recently through its decays into $\gamma\gamma$ and $ZZ^* \rightarrow 4\ell$ modes.

Although the data on Higgs signal strengths are best described by the SM, the other extensions are still viable options to explain the data. Numerous activities occurred in the constraining the SM boson [3, 6–23], higher dimension operators of the Higgs boson [24, 26], the two-Higgs doublet models [27–35], and in the supersymmetric framework [36–40]. A very recent update to all the data as of summer 2014 was performed in Ref. [4]. We shall describe the most significant change to the data set in Sec. III. In this work, we perform the fits in the framework of the minimal supersymmetric standard model (MSSM) to all the most updated data on Higgs signal strengths as of summer 2014.

In our previous analysis of the two-Higgs-doublet model (2HDM) [35], we do not specify which neutral Higgs boson is the observed Higgs boson, so that the whole scenario can be described by a small set of parameters. The bottom and leptonic Yukawa couplings are determined through the top Yukawa coupling, and the $HWW$ coupling is determined via $\tan\beta$ and top Yukawa, so that a minimal set of parameters includes only $\tan\beta$ and the top Yukawa coupling. We can easily include the effects of the charged Higgs boson by the loop factor in the $H\gamma\gamma$ vertex, and include possibly very light Higgs bosons by the factor $\Delta\Gamma_{\text{tot}}$. Here we follow the same strategy for the global fits in the framework of MSSM, the Higgs sector of which is the same as the Type II of the 2HDM, in order to go along with a minimal set of parameters, unless we specifically investigate the spectrum of supersymmetric particles, e.g., the chargino mass.

In this work, we perform global fits in the MSSM under various initial conditions to the most updated data on Higgs boson signal strengths. A few specific features are summarized here.

1. We use a minimal set of parameters without specifying the spectrum of the SUSY particles. For example, all up-, down- and lepton-type Yukawa couplings and the gauge-Higgs coupling are given in terms of the top Yukawa coupling, $\tan\beta$, and $\kappa_d$. 
where $\kappa_d$ is the radiative correction in the bottom Yukawa coupling defined later.

2. Effects of heavy SUSY particles appear in the loop factors $\Delta S^g$ and $\Delta S^\gamma$ of the $Hgg$ and $H\gamma\gamma$ vertices, respectively.

3. Effects of additional light Higgs bosons or light neutralinos that the 125.5 GeV Higgs boson can decay into are included by the deviation $\Delta \Gamma_{\text{tot}}$ in the Higgs boson width.

4. CP-violating effects can occur in Yukawa couplings, which are quantified by the CP-odd part of the top-Yukawa coupling. Effects of other CP sources can appear in the loop factor of $Hgg$ and $H\gamma\gamma$ vertices. We label them as $\Delta P^g$ and $\Delta P^\gamma$, respectively. In Ref. [41], we have computed all the Higgs-mediated CP-violating contributions to the electric dipole moments (EDMs) and compared to existing constraints from the EDM measurements of Thallium, neutron, Mercury, and Thorium monoxide. Nevertheless, we are content with CP-conserving fits in this work.

5. We impose the existing limits of chargino and stau masses when we investigate specifically their effects on the vertex of $H\gamma\gamma$. The current limit on chargino and stau masses are [42]

\[ M_{\tilde{\chi}^\pm} > 103.5 \text{ GeV}, \quad M_{\tilde{\tau}_1} > 81.9 \text{ GeV}. \]

Similarly, the current limits for stop and sbottom masses quoted in PDG are [42]

\[ M_{\tilde{t}_1} > 95.7 \text{ GeV}, \quad M_{\tilde{b}_1} > 89 \text{ GeV}, \]

which will be applied in calculating the effects in $H\gamma\gamma$ and $Hgg$ vertices. Note that the current squark mass limits from recent LHC searches in general reach the TeV range, but there often exist underlying assumptions on the mass of other SUSY particles. Therefore, we conservatively take the above mass limits on the stops and sbottoms in the following analysis.

The organization of the work is as follows. In the next section, we describe the convention and formulas for all the couplings used in this work. In Sec. III, we describe various CP-conserving fits and present the results. In Sec. IV, we specifically investigate the SUSY parameter space of charginos, staus, stops, and sbottoms. We put the synopsis and conclusions in Sec. V.
II. FORMALISM

For the Higgs couplings to SM particles we assume that the observed Higgs boson is a generic CP-mixed state without carrying any definite CP-parity. We follow the conventions and notation of CPsuperH \[43\].

A. Yukawa couplings

The Higgs sector of the MSSM is essentially the same as the Type II of the 2HDM. More details of the 2HDM can be found in Ref. \[35\]. In the MSSM, the first Higgs doublet couples to the down-type quarks and charged leptons while the second Higgs doublet couples to the up-type quarks only. After both doublets take on vacuum-expectation values (VEV) we can rotate the neutral components $\phi_1^0, \phi_2^0$ and $a$ into mass eigenstates $H_{1,2,3}$ through a mixing matrix $O$ as follows:

$$(\phi_1^0, \phi_2^0, a)^T = O_{\alpha i} (H_1, H_2, H_3)^T,$$

with the mass ordering $M_{H_1} \leq M_{H_2} \leq M_{H_3}$. We do not specify which Higgs boson is the observed one, in fact, it can be any of the $H_{1,2,3}$. We have shown in Ref. \[35\] that the bottom and lepton Yukawa couplings can be expressed in terms of the top Yukawa coupling in general 2HDM. We can therefore afford a minimal set of input parameters.

The effective Lagrangian governing the interactions of the neutral Higgs bosons with quarks and charged leptons is

$$\mathcal{L}_{Hff} = -\sum_{f=u,d,\ell} \frac{g_{mf}}{2M_W} \sum_{i=1}^{3} H_i \bar{f} \left( g_{H_i ff}^s + i g_{H_i ff}^p \gamma_5 \right) f.$$  \hspace{1cm} (1)

At the tree level, $(g^s, g^p) = (O_{\phi_1}, c_\beta, -O_{ai} \tan \beta)$ and $(g^s, g^p) = (O_{\phi_2}, s_\beta, -O_{ai} \cot \beta)$ for $f = (\ell, d)$ and $f = u$, respectively, and $\tan \beta \equiv v_2/v_1$ is the ratio of the VEVs of the two doublets. Threshold corrections to the down-type Yukawa couplings change the relation between the Yukawa coupling $h_d$ and mass $m_d$ as

$$h_d = \frac{\sqrt{2} m_d}{v \cos \beta \left( 1 + \kappa_d \tan \beta \right)}.$$  \hspace{1cm} (2)

\[1\] In general settings, $\kappa_d$ and $\kappa_s$ are usually the same, but $\kappa_b$ could be very different because of the third generation squarks. However, our main concern in this work is the third-generation Yukawa couplings. Thus, we shall focus on $\kappa_b$ although we are using the conventional notation $\kappa_d$. 
Thus, the Yukawa couplings of neutral Higgs-boson mass eigenstates $H_i$ to the down-type quarks are modified as

$$g^S_{H_i,dd} = \text{Re} \left( \frac{1}{1 + \kappa_d \tan \beta} \frac{O_{\phi_{1i}}}{\cos \beta} \right) + \text{Re} \left( \frac{\kappa_d}{1 + \kappa_d \tan \beta} \frac{O_{\phi_{2i}}}{\cos \beta} \right)$$

$$+ \text{Im} \left[ \frac{\kappa_d (\tan^2 \beta + 1)}{1 + \kappa_d \tan \beta} \right] O_{ai},$$

$$g^P_{H_i,dd} = -\text{Re} \left( \frac{\tan \beta - \kappa_d}{1 + \kappa_d \tan \beta} \right) O_{ai} + \text{Im} \left( \frac{\kappa_d \tan \beta}{1 + \kappa_d \tan \beta} \frac{O_{\phi_{1i}}}{\cos \beta} \right)$$

$$- \text{Im} \left( \frac{\kappa_d}{1 + \kappa_d \tan \beta} \frac{O_{\phi_{2i}}}{\cos \beta} \right).$$

(3)

In the MSSM, neglecting the electroweak corrections and taking the most dominant contributions, $\kappa_b$ can be split into [44]

$$\kappa_b = \epsilon_g + \epsilon_H,$$

where $\epsilon_g$ and $\epsilon_H$ are the contributions from the sbottom-gluino exchange diagram and from stop-Higgsino diagram, respectively. Their explicit expressions are

$$\epsilon_g = \frac{2\alpha_s}{3\pi} M^*_{3} \mu^* I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, |M_3|^2), \quad \epsilon_H = \frac{|h_t|^2}{16\pi^2} A^*_t \mu^* I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, |\mu|^2),$$

where $M_3$ is the gluino mass, $h_t$ and $A_t$ are the top-quark Yukawa and trilinear coupling, respectively.

B. Couplings to gauge bosons

- Interactions of the Higgs bosons with the gauge bosons $Z$ and $W^\pm$ are described by

$$\mathcal{L}_{HVV} = g M_W \left( W_\mu^+ W^{-\mu} + \frac{1}{2e_W^2} Z_\mu Z^\mu \right) \sum_i g_{H_i,\nu\nu} H_i$$

(4)

where

$$g_{H_i,\nu\nu} = c_\beta O_{\phi_{1i}} + s_\beta O_{\phi_{2i}}.$$

(5)

- Couplings to two photons: the amplitude for the decay process $H_i \rightarrow \gamma \gamma$ can be written as

$$\mathcal{M}_{\gamma\gamma H_i} = -\frac{\alpha M^2_{H_i}}{4\pi v} \left\{ S_{\gamma}(M_{H_i}) \left( \epsilon^*_1 \cdot \epsilon^*_2 \right) \right. - P_{\gamma}(M_{H_i}) \frac{2}{M^2_{H_i}} \left( \epsilon^*_1 \epsilon^*_2 k_1 k_2 \right) \left\}.$$
where \(k_{1,2}\) are the momenta of the two photons and \(\epsilon_{1,2}\) the wave vectors of the corresponding photons, \(\epsilon_{1}\perp = \epsilon_{1} - 2k_{1}(k_{2} \cdot \epsilon_{1})/M_{H_{i}}^{2}, \epsilon_{2}\perp = \epsilon_{2} - 2k_{2}(k_{1} \cdot \epsilon_{2})/M_{H_{i}}^{2}\) and \(\langle \epsilon_{1}\epsilon_{2}k_{1}k_{2}\rangle \equiv \epsilon_{\mu\nu\rho\sigma} \epsilon_{1} \epsilon_{2} k_{\rho} k_{\sigma}\). The decay rate of \(H_{i} \rightarrow \gamma\gamma\) is proportional to \(|S_{i}|^{2} + |P_{i}|^{2}\).

The form factors are given by

\[
S_{i}^\gamma(M_{H_{i}}) = 2 \sum_{f=h,t,\tau} N_{C} Q_{f}^{2} g_{H_{i}ff}^{S}(\tau_{f}) - g_{H_{i}V} F_{1}(\tau_{W}) + \Delta S_{i}^\gamma,
\]
\[
P_{i}^\gamma(M_{H_{i}}) = 2 \sum_{f=h,t,\tau} N_{C} Q_{f}^{2} g_{H_{i}ff}^{P}(\tau_{f}) + \Delta P_{i}^\gamma, \tag{7}
\]

where \(\tau_{x} = M_{H_{i}}^{2}/4m_{x}^{2}, N_{C} = 3\) for quarks and \(N_{C} = 1\) for taus, respectively. In MSSM, the factors \(\Delta S_{i}^\gamma\) and \(\Delta P_{i}^\gamma\) receive contributions from charginos, sfermions, and charged Higgs boson:

\[
\Delta S_{i}^\gamma = \sqrt{2}g \sum_{j=x_{1}^{\pm},x_{2}^{\pm}} g_{H_{i}ff}^{S} \frac{v}{m_{f}} F_{s_{f}}(\tau_{f})
\]
\[
- \sum_{j=t_{1},t_{2},b_{1},b_{2},t_{1},\bar{t}_{2}} N_{C} Q_{f}^{2} g_{H_{i}ff}^{S} \frac{v^{2}}{2m_{f}^{2}} F_{0}(\tau_{f}) - g_{H_{i}V} F_{1}(\tau_{W}) - \frac{v^{2}}{2M_{H_{\pm}}^{2}} F_{0}(\tau_{H\pm}),
\]
\[
\Delta P_{i}^\gamma = \sqrt{2}g \sum_{j=x_{1}^{\pm},x_{2}^{\pm}} g_{H_{i}ff}^{P} \frac{v}{m_{f}} F_{p_{f}}(\tau_{f}), \tag{8}
\]

where the couplings to charginos, sfermions, and charged Higgs are defined in the interactions:

\[
\mathcal{L}_{Hx^{+}x^{-}} = -\frac{g}{\sqrt{2}} \sum_{i,j,k} H_{k} x^{-}_{i} \left( g_{H_{i}x_{i}^{+}x_{j}}^{S} x_{j}^{-} + i\gamma_{5} g_{H_{i}x_{i}^{+}x_{j}}^{P} x_{j}^{-} \right),
\]
\[
\mathcal{L}_{Hf\bar{f}} = v \sum_{j=u,d} g_{H_{i}f_{j}\bar{f}_{j}}^{S} (H_{i} f_{j}^{\star} \bar{f}_{j}) + g_{H_{i}f_{j}\bar{f}_{j}}^{P} (H_{i} f_{j}^{\star} \bar{f}_{j}),
\]
\[
\mathcal{L}_{3H} = v \sum_{i=1}^{3} g_{H_{i}H+H^{-}} H_{i} H^{+} H^{-}. \tag{9}
\]

We shall describe the couplings of the Higgs boson to the charginos, sfermions, and charged Higgs boson a little later.

- Couplings to two gluons: similar to \(H \rightarrow \gamma\gamma\), the amplitude for the decay process \(H_{i} \rightarrow gg\) can be written as

\[
\mathcal{M}_{ggH_{i}} = -\frac{\alpha_{s} M_{H_{i}}^{2}}{4\pi v} \delta^{ab} \left\{ S^{g}(M_{H_{i}}) (\epsilon_{1}\perp \cdot \epsilon_{2}\perp) - P^{g}(M_{H_{i}}) \frac{2}{M_{H_{i}}^{2}} (\epsilon_{1}^{\star} \epsilon_{2} k_{1} k_{2}) \right\}, \tag{10}
\]
where \( a \) and \( b \) (\( a, b = 1 \) to \( 8 \)) are indices of the eight \( SU(3) \) generators in the adjoint representation. The decay rate of \( H_i \rightarrow gg \) is proportional to \(|S^g|^2 + |P^g|^2\). The fermionic contributions and additional loop contributions from squarks in the MSSM to the scalar and pseudoscalar form factors are given by

\[
S^g(M_{H_i}) = \sum_{f=b,t} g^S_{H_i fj} F_{sf}(\tau_f) + \Delta S^g_i ,
\]
\[
P^g(M_{H_i}) = \sum_{f=b,t} g^P_{H_i fj} F_{pf}(\tau_f) + \Delta P^g_i ,
\]

(11)

where
\[
\Delta S^g_i = - \sum_{\tilde{i}, \tilde{j}} g_{H_i \tilde{i}j}^{\tilde{g}} \frac{\nu^2}{4 m_{\tilde{i}}^2} F_0(\tau_{i \tilde{i}j}) ,
\]
\[
\Delta P^g_i = 0 ,
\]

(12)

where the \( \Delta P^g = 0 \) because there are no colored SUSY fermions in the MSSM that can contribute to \( \Delta P^g \) at one loop level.

C. Interactions of neutral Higgs bosons with charginos, sfermions, and charged Higgs

The interactions between the Higgs bosons and charginos are described by the following Lagrangian:

\[
\mathcal{L}_{\tilde{H}\tilde{\chi}^\pm} = - \frac{g}{\sqrt{2}} \sum_{i,j,k} H_k \bar{\tilde{\chi}}^+_i \left( g^S_{H_k \tilde{i}j} \tilde{\chi}^+_j + i \gamma_5 g^P_{H_k \tilde{i}j} \tilde{\chi}^-_j \right) \tilde{\chi}^-_j ,
\]

(13)

where \( G_{\phi^1} = (O_{\phi^1 k} - i s_\beta O_{ak}) \), \( G_{\phi^2} = (O_{\phi^2 k} - i c_\beta O_{ak}) \), \( i, j = 1, 2 \), and \( k = 1 - 3 \). The chargino mass matrix in the \((\tilde{W}^-, \tilde{H}^-)\) basis

\[
\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} M_W c_\beta \\ \sqrt{2} M_W s_\beta & \mu \end{pmatrix} ,
\]

(14)
is diagonalized by two different unitary matrices $C_R M C_L^\dagger = \text{diag}\{M_{\tilde{\chi}_1^\pm}, M_{\tilde{\chi}_2^\pm}\}$, where $M_{\tilde{\chi}_1^\pm} \leq M_{\tilde{\chi}_2^\pm}$. The chargino mixing matrices $(C_L)_{i\alpha}$ and $(C_R)_{i\alpha}$ relate the electroweak eigenstates to the mass eigenstates, via

$$
\tilde{\chi}_{\alpha L}^{-} = (C_L)^*_{i\alpha} \tilde{\chi}_{iL}^{-}, \quad \tilde{\chi}_{\alpha R}^{-} = (C_R)^*_{i\alpha} \tilde{\chi}_{iR}^{-};
\tilde{\chi}_{\alpha L}^{+} = (\bar{W}^{+}, \bar{H}^{+})^T_L,
\tilde{\chi}_{\alpha R}^{+} = (\bar{W}^{+}, \bar{H}^{+})^T_R.
$$

(15)

The Higgs-sfermion-sfermion interaction can be written in terms of the sfermion mass eigenstates as

$$
\mathcal{L}_{H\tilde{f}\tilde{f}} = v \sum_{f=u,d} g_{H,\tilde{f}_{1,2}} f^*_{1,2} (H f_{1,2}^* f_{1,2}),
$$

(16)

where

$$
v g_{H,\tilde{f}_{1,2}} = (\Gamma^a \tilde{f}_{1,2}^* \tilde{f}_{1,2})_{\beta j, \alpha i} O_{\alpha i} U_{\beta j}^* U_{\gamma k},
$$

with $\alpha = (\phi_1, \phi_2, a) = (1, 2, 3), \beta, \gamma = L, R, i = (H_1, H_2, H_3) = (1, 2, 3)$ and $j, k = 1, 2$.

The expressions for the couplings $\Gamma^a \tilde{f}_{1,2}^* \tilde{f}_{1,2}$ are shown in Ref. [43]. The stop and sbottom mass matrices may conveniently be written in the $(\tilde{q}_L, \tilde{q}_R)$ basis as

$$
\tilde{\mathcal{M}}^2_q = \begin{pmatrix}
M_{\tilde{q}_3}^2 + m_q^2 + c_2 \beta M_{\tilde{Z}}^2 (T_z^t - Q_s s_W^2) & h_q v_q (A_q^* - \mu R_q)/\sqrt{2} \\
h_q v_q (A_q - \mu^* R_q)/\sqrt{2} & M_{\tilde{R}_3}^2 + m_{\tilde{q}}^2 + c_2 \beta M_{\tilde{Z}}^2 Q_s s_W^2
\end{pmatrix},
$$

(17)

with $q = t, b, R = U, D, T_z^t = -T_z^b = 1/2$, $Q_t = 2/3$, $Q_b = -1/3$, $v_b = v_1$, $v_t = v_2$, $R_b = \tan \beta = v_2/v_1$, $R_t = \cot \beta$, and $h_q$ is the Yukawa coupling of the quark $q$. On the other hand, the stau mass matrix is written in the $(\tilde{\tau}_L, \tilde{\tau}_R)$ basis as

$$
\tilde{\mathcal{M}}^2_{\tilde{\tau}} = \begin{pmatrix}
M_{\tilde{\tau}_3}^2 + m_{\tilde{\tau}}^2 + c_2 \beta M_{\tilde{Z}}^2 (s_W^2 - 1/2) & h_{\tau} v_1 (A_{\tau}^* - \mu \tan \beta)/\sqrt{2} \\
h_{\tau} v_1 (A_{\tau} - \mu^* \tan \beta)/\sqrt{2} & M_{\tilde{\tau}_3}^2 + m_{\tilde{\tau}}^2 + c_2 \beta M_{\tilde{Z}}^2 s_W^2
\end{pmatrix}.
$$

(18)

The $2 \times 2$ sfermion mass matrix $\tilde{M}_f^2$ for $f = t, b$ and $\tau$ is diagonalized by a unitary matrix $U_{\tilde{f}}$:

$$
U_{\tilde{f}}^T \tilde{M}_f^2 U_{\tilde{f}} = \text{diag}(m_{f_1}^2, m_{f_2}^2) \text{ with } m_{f_1}^2 \leq m_{f_2}^2.
$$

The mixing matrix $U_{\tilde{f}}$ relates the electroweak eigenstates $\tilde{f}_{L,R}$ to the mass eigenstates $\tilde{f}_{1,2}$, via

$$
(\tilde{f}_L, \tilde{f}_R)^T = U_{\alpha i}^T (\tilde{f}_{1,2})^T_i.
$$

Interactions between the Higgs bosons and the charged Higgs boson can be found in Ref. [35].
III. DATA, FITS, AND RESULTS

A. Data

Our previous works [3, 35, 41] were performed with data of the Summer 2013. Very recently we have also updated the model-independent fits using the data of the Summer 2014 [4]. The whole set of Higgs strength data on \( H \rightarrow \gamma\gamma, ZZ^* \rightarrow 4\ell, WW^* \rightarrow \ell\nu\ell\nu, \tau\tau, \) and \( b\bar{b} \) are listed in Ref. [4]. The most significant changes since summer 2013 are the \( H \rightarrow \gamma\gamma \) data from both ATLAS and CMS. The ATLAS Collaboration updated their best-measured value from \( \mu_{ggH+ttH} = 1.6 \pm 0.4 \) to \( \mu_{\text{inclusive}} = 1.17 \pm 0.27 \) [15], while the CMS \( H \rightarrow \gamma\gamma \) data entertained a very dramatic change from \( \mu_{\text{untagged}} = 0.78^{+0.28}_{-0.26} \) to \( \mu_{ggH} = 1.12^{+0.37}_{-0.32} \) [46]. Other notable differences can be found in Ref. [4]. The \( \chi^2_{\text{SM}}/\text{d.o.f.} \) for the SM is now at 16.76/29, which corresponds to a \( p \)-value of 0.966.

B. CP-Conserving (CPC) Fits

We consider the CP-conserving MSSM and use the most updated Higgs boson signal strengths to constrain a minimal set of parameters under various conditions. Regarding the \( i \)-th Higgs boson \( H_i \) as the candidate for the 125 GeV Higgs boson, the varying parameters are:

- the up-type Yukawa coupling \( C_u^S \equiv g^S_{H,uu} = O_{\phi_2}/s_\beta \), see Eq. (1),
- the ratio of the VEVs of the two Higgs doublets \( \tan \beta \equiv v_2/v_1 \),
- the parameter \( \kappa_d \) (assumed real) quantifying the modification between the down-type quark mass and Yukawa coupling due to radiative corrections, as shown in Eq. (2),
- \( \Delta S_\gamma \equiv \Delta S_\gamma^i \) as in Eq. (8),
- \( \Delta S_\gamma \equiv \Delta S_\gamma^i \) as in Eq. (12), and
- the deviation in the total decay width of the observed Higgs boson: \( \Delta \Gamma_{\text{tot}} \).

The down-type and lepton-type Yukawa and the gauge-Higgs couplings are derived as

\[
C^S_d \equiv g^S_{H,dd} = \left( \frac{O_{\phi_1} + \kappa_d O_{\phi_2}}{1 + \kappa_d \tan \beta} \right) \frac{1}{\cos \beta},
\]
\[
C_{\ell}^S \equiv g_{H_{\ell}\ell} = \frac{O_{\phi_1i}}{\cos \beta},
\]
\[
C_v \equiv g_{H_{VV}} = c_{\beta}O_{\phi_1i} + s_{\beta}O_{\phi_2i}
\]  
(19)

with
\[
O_{\phi_1i} = \pm \sqrt{1 - s_{\beta}^2(C_u^S)^2}, \quad O_{\phi_2i} = C_u^S s_{\beta}.
\]  
(20)

In place of \(\tan \beta\) we can use \(C_v\) as a varying parameter, and then \(\tan \beta (t_{\beta})\) would be determined by
\[
t_{\beta}^2 = \frac{(1 - C_v^2)}{(C_u^S - C_v)^2} = \frac{(1 - C_v^2)}{[(C_u^S - 1) + (1 - C_v)]^2}.
\]  
(21)

We note that \(t_{\beta} = \infty\) when \((C_u^S - 1) = -(1 - C_v) < 0\) while \(t_{\beta} = 1\) when \((C_u^S - 1) = \pm \sqrt{1 - C_v^2} - (1 - C_v)\). Therefore \(t_{\beta}\) changes from \(\infty\) to 1 when \((C_u^S - 1)\) deviates from \(-(1 - C_v)\) by the amount of \(\pm \sqrt{1 - C_v^2}\). This implies that the value of \(t_{\beta}\) becomes more and more sensitive to the deviation of \(C_u^S\) from 1 as \(C_v\) approaches to its SM value 1.

We are going to perform the following three categories of CPC fits varying the stated parameters while keeping the others at their SM values.

- **CPC.II**
  - **CPC.II.2**: \(C_u^S, \tan \beta (\kappa_d = \Delta \Gamma_{\text{tot}} = \Delta S^\gamma = \Delta S^g = 0)\)
  - **CPC.II.3**: \(C_u^S, \tan \beta, \kappa_d (\Delta \Gamma_{\text{tot}} = \Delta S^\gamma = \Delta S^g = 0)\)
  - **CPC.II.4**: \(C_u^S, \tan \beta, \kappa_d, \Delta \Gamma_{\text{tot}} (\Delta S^\gamma = \Delta S^g = 0)\)

- **CPC.III**
  - **CPC.III.3**: \(C_u^S, \tan \beta, \Delta S^\gamma (\kappa_d = \Delta \Gamma_{\text{tot}} = \Delta S^g = 0)\)
  - **CPC.III.4**: \(C_u^S, \tan \beta, \Delta S^\gamma, \kappa_d (\Delta \Gamma_{\text{tot}} = \Delta S^g = 0)\)
  - **CPC.III.5**: \(C_u^S, \tan \beta, \Delta S^\gamma, \kappa_d, \Delta \Gamma_{\text{tot}} (\Delta S^g = 0)\)

- **CPC.IV**
  - **CPC.IV.4**: \(C_u^S, \tan \beta, \Delta S^\gamma, \Delta S^g (\kappa_d = \Delta \Gamma_{\text{tot}} = 0)\)
  - **CPC.IV.5**: \(C_u^S, \tan \beta, \Delta S^\gamma, \Delta S^g, \kappa_d (\Delta \Gamma_{\text{tot}} = 0)\)

\(^2\) Note \(C_v \leq 1\) and positive definite in our convention.
Basically, the CPC.II, CPC.III, and CPC.IV fits vary \( (C_u^S, \tan \beta, \Delta S^\gamma) \), \( (C_u^S, \tan \beta, \Delta S^\gamma) \), and \( (C_u^S, \tan \beta, \Delta S^\gamma, \Delta S^g) \), respectively. Each category of CPC fits includes three fits: the second fit adds \( \kappa_d \) to the set of varying parameters and \( \Delta \Gamma_{\text{tot}} \) is further varied in the third one. The Arabic number at the end of each label denotes the total number of varying parameters.

The \( \Delta S^\gamma \) is the deviation in the \( H\gamma\gamma \) vertex factor other than the effects of changing the Yukawa and gauge-Higgs couplings, and it receives contributions from any exotic particles running in the triangular loop. For example, the charginos, charged Higgs bosons, sleptons, and squarks in the MSSM. Here we are content with a varying \( \Delta S^\gamma \) without specifying the particle spectrum of the MSSM. Later in the next section we shall specifically investigate the effects of charginos, staus, stops, and sbottoms.

In the MSSM, \( \Delta S^g \) receives contributions only from colored SUSY particles–squarks running in the \( Hgg \) vertex. The current limits on squark masses are in general above TeV such that \( \Delta S^g \) is expected to be small. Nevertheless, we do not restrict the size of \( \Delta S^g \) in this fit in order to see the full effect of \( \Delta S^g \).

The parameter \( \kappa_d \) arises from the loop corrections to the down-type Yukawa couplings. It changes the relation between the mass and the Yukawa coupling of the down-type quarks. We limit the range of \( |\kappa_d| < 0.1 \) as it is much smaller than 0.1 in most of the MSSM parameter space.

Although the charginos are constrained to be heavier than 103.5 GeV and sleptons to be heavier than 81.9 GeV [42], there are still possibilities that the decays of the 125.5 GeV Higgs boson into neutralinos and another neutral Higgs boson are kinematically allowed. These channels have not been explicitly searched for, but we can take them into account by the deviation \( \Delta \Gamma_{\text{tot}} \) in the total decay width of the observed Higgs boson.

The best-fit points for the fits are summarized in Table I. We see that the \( p \) values of the CPC.II.2, CPC.III.3, and CPC.IV.4 fits are the highest in each category. Also, the \( p \) value of the CPC.III.3 fit is slightly higher than that of the CPC.IV.4 fit, followed by the CPC.II.2 fit.
TABLE I. The best-fit values for various CPC fits. The SM chi-square per degree of freedom is $\chi^2_{SM}/\text{d.o.f.} = 16.76/29$, and p-value = 0.966.

| Fits   | $\chi^2$ | $\chi^2$/dof | p-value | $C^S_v$ | $\tan \beta$ | $\Delta S^\gamma$ | $\Delta S^g$ | $\kappa_d$ | $\Delta \Gamma_{\text{tot}}$ | $C_v$ | $C^S_d$ | $C^S_\ell$ |
|--------|----------|---------------|---------|---------|--------------|------------------|--------------|----------|-----------------|-------|-------|--------|
| CPC.II.2 | 16.74    | 0.620         | 0.937   | 1.011   | 0.111        | -                | -             | -         | -                | 1.000 | 1.000 | 1.000  |
| CPC.II.3 | 16.74    | 0.644         | 0.917   | 1.011   | 0.194        | -                | -             | 0.099     | -                | 1.000 | 1.000 | 1.000  |
| CPC.II.4 | 16.72    | 0.669         | 0.892   | 1.023   | 0.312        | -                | -             | -0.079    | 0.103            | 1.000 | 0.997 | 0.998  |
| CPC.III.3| 15.50    | 0.596         | 0.947   | -0.930  | 0.194        | 2.326            | -             | -         | -                | 0.932 | 1.003 | 1.003  |
| CPC.III.4| 15.48    | 0.619         | 0.929   | -0.948  | 0.180        | 2.402            | -             | -0.097    | -                | 0.940 | 1.036 | 1.002  |
| CPC.III.5| 15.43    | 0.643         | 0.907   | 1.061   | 0.100        | -0.938           | -             | 0.100     | 0.557            | 1.000 | 1.000 | 1.000  |
| CPC.IV.4 | 14.85    | 0.594         | 0.945   | -1.219  | 0.154        | 2.893            | 1.547         | -         | -                | 0.943 | 0.994 | 0.994  |
| CPC.IV.5 | 14.83    | 0.618         | 0.926   | -1.224  | 0.164        | 2.902            | 1.540         | 0.088     | -                | 0.935 | 0.962 | 0.993  |
| CPC.IV.6 | 14.83    | 0.645         | 0.901   | -1.213  | 0.173        | 2.868            | 1.528         | 0.082     | -0.071           | 0.929 | 0.962 | 0.993  |
| Fits    | $\chi^2$ | $\chi^2$/dof | $p$-value | $C_a^S$ | $\tan \beta$ | $\Delta S^y$ | $\Delta S^g$ | $\kappa_d$ | $\Delta \Gamma_{tot}$ | $C_v$ | $C_d^S$ | $C_{\ell}^S$ |
|---------|----------|--------------|-----------|---------|--------------|--------------|--------------|-----------|------------------|-------|---------|---------|
| CPC.III.3 | 15.68    | 0.603        | 0.944     | 1.000   | 34.58        | $-$0.853     | $-$          | $-$        | $-$              | 1.000 | 1.039   | 1.039   |
| CPC.III.4 | 15.59    | 0.624        | 0.926     | 0.999   | 9.332        | $-$1.026     | $-$          | $-$0.006   | $-$              | 0.976 | $-$1.170 | $-$1.051 |
| CPC.IV.4  | 15.23    | 0.609        | 0.936     | 1.000   | 5.681        | $-$1.127     | $-$0.057     | $-$        | $-$              | 0.940 | $-$1.002 | $-$1.002 |
| CPC.IV.4  | 15.23    | 0.609        | 0.936     | 1.000   | 5.695        | $-$1.126     | $-$1.395     | $-$        | $-$              | 0.940 | $-$1.002 | $-$1.002 |
| CPC.IV.5  | 15.22    | 0.634        | 0.914     | 1.000   | 5.423        | $-$1.128     | $-$0.062     | 0.002      | $-$              | 0.934 | $-$0.980 | $-$0.999 |
| CPC.IV.5  | 15.22    | 0.634        | 0.914     | 1.000   | 5.429        | $-$1.127     | $-$1.387     | 0.002      | $-$              | 0.934 | $-$0.980 | 0.999    |
C. Results

Before we present descriptions of the confidence regions and the correlations among the fitting parameters \( C_u^S \), \( \tan \beta \), \( \Delta S^\gamma \), \( \Delta S^g \), \( \kappa_d \), and \( \Delta \Gamma_{\text{tot}} \), we look into the behavior of \( \Delta \chi^2 \) versus \( C_u^S \) in each category of fits. In the \textbf{CPC.II} fits, the minimum \( \chi^2 \) values are 16.74 (\textbf{CPC.II.2}, \textbf{CPC.II.3}) and 16.72 (\textbf{CPC.II.4}) (see Table III), and \( \Delta \chi^2 \) versus \( C_u^S \) are shown in the upper row of Fig. I. The minima are located at \( C_u^S = 1.011 \) (\textbf{CPC.II.2}, \textbf{CPC.II.3}) and \( C_u^S = 1.023 \) (\textbf{CPC.II.4}) and the second local minima are developed around \( C_u^S = -1 \) but with \( \Delta \chi^2 \gtrsim 5 \). It is clear that \( C_u^S \approx 1 \) is preferred much more than the negative values. The \( \Delta \chi^2 \) dependence on \( C_u^S \) hardly changes by varying \( \kappa_d \) as shown in the upper-middle frame. With \( \Delta \Gamma_{\text{tot}} \) varying further, we observe the dependence of \( \Delta \chi^2 \) on \( C_u^S \) becomes broader by extending to the regions of \( |C_u^S| > 1 \) as shown in the upper-right frame. We also observe that the second local minimum around \( C_u^S = -1 \) disappears when \( \tan \beta \gtrsim 0.6 \).

In the \textbf{CPC.III} fits, the minimum \( \chi^2 \) values are 15.50 (\textbf{CPC.III.3}), 15.48 (\textbf{CPC.III.4}), and 15.43 (\textbf{CPC.III.5}): see Table III and \( \Delta \chi^2 \) versus \( C_u^S \) are shown in the middle row of Fig. I. The minima are located at \( C_u^S = -0.930 \) (\textbf{CPC.III.3}), \( C_u^S = -0.948 \) (\textbf{CPC.III.4}), and \( C_u^S = 1.061 \) (\textbf{CPC.III.5}), and the second local minima are developed around \( C_u^S = 1 \) (\textbf{CPC.III.3} and \textbf{CPC.III.4}) and \( C_u^S = -1 \) (\textbf{CPC.III.5}), respectively. In contrast to the \textbf{CPC.II} fits, the \( \Delta \chi^2 \) difference between the true and local minima is tiny, \( \Delta \chi^2|_{\text{local}} - \Delta \chi^2|_{\text{true}} \lesssim 0.2 \): see Table III. The \( \Delta \chi^2 \) dependence on \( C_u^S \) hardly changes by varying \( \kappa_d \) additionally (shown in the middle-middle frame), but when \( \Delta \Gamma_{\text{tot}} \) is varied further, the dependence of \( \Delta \chi^2 \) on \( C_u^S \) becomes broader, the same as the \textbf{CPC.II} fits (see the middle-right frame). We observe the true/local minima around \( C_u^S = -1 \) disappear when \( \tan \beta \gtrsim 0.6 \).

In the \textbf{CPC.IV} fits, the minimum \( \chi^2 \) values are 14.85 (\textbf{CPC.IV.4}), 14.83 (\textbf{CPC.IV.5} and \textbf{CPC.IV.6}): see Table III and \( \Delta \chi^2 \) versus \( C_u^S \) are shown in the lower row of Fig. I. The minima are located at \( C_u^S = -1.219 \) (\textbf{CPC.IV.4}), \( C_u^S = -1.225 \) (\textbf{CPC.IV.5}), and \( C_u^S = -1.213, 1.022 \) (\textbf{CPC.IV.6}). The second local minima are developed for \textbf{CPC.IV.4} and \textbf{CPC.IV.5} at \( C_u^S = 1 \): see Table III. Similar to the \textbf{CPC.III} fits the \( \Delta \chi^2 \) difference between the true and local minima is tiny for \textbf{CPC.IV.4} and \textbf{CPC.IV.5}, \( \Delta \chi^2|_{\text{local}} - \Delta \chi^2|_{\text{true}} \sim 0.4 \): see Table III. On the other hand, in contrast to the \textbf{CPC.III} fits any values of \( C_u^S \) between \(-2 \) and \( 2 \) are allowed at 2-\( \sigma \) level and higher. The behavior of \( \Delta \chi^2 \) by additionally varying \( \kappa_d \) and \( \Delta \Gamma_{\text{tot}} \) is the same as in the previous cases. We again observe the true minima around
$C_u^S = -1$ disappear when $\tan \beta > \sim 0.6$.

We show the confidence-level regions on the $(C_u^S, \tan \beta)$ plane for three categories of CPC fits: CPC.II (upper row), CPC.III (middle row), and CPC.IV (lower row) in Fig. 2. The confidence level (CL) regions shown are for $\Delta \chi^2 \leq 2.3$ (red), 5.99 (green), and 11.83 (blue) above the minimum, which correspond to CLs of 68.3%, 95%, and 99.7%, respectively. The best-fit point is denoted by the triangle. We observe that the plots are very close to those of the Type II of the 2HDM [35], though the regions in general shrink by small amounts. First of all, the vertical 68.3% confidence (red) regions around $C_u^S = 1$ can be understood from Eq. (21) by observing that the value of $t_\beta$ changes from $\infty$ to 1 when $(C_u^S - 1)$ deviates from $-(1 - C_v)$ by the amount of $\pm \sqrt{1 - C_v^2}$ and there are generally many points around $C_v = 1$ as shown in Fig. 3.

In each category of fits, Fig. 1 is helpful to understand the basic behavior of the CL regions as $C_u^S$ is varied. In the CPC.II fits, the region around $C_u^S = 1$ is much more preferred. The negative $C_u^S$ values are not allowed at 68% CL. In the CPC.III fits, the region around $C_u^S = -1$ falls into the stronger 68.3% CL but $C_u^S = 0$ is not allowed even at 99.7% CL. On the other hand, the whole range of $-2 < C_u^S < 2$ is allowed at 95% CL for the CPC.IV fits though not at 68.3% CL. In all the fits, the negative values of $C_u^S$ are not allowed at 95% CL when $\tan \beta > 0.5$ is imposed, which is in general required by the perturbativity of the top-quark Yukawa coupling. The CL regions hardly change by varying $k_d$ additionally, but the CL regions can extend to the regions of $|C_u^S| > 1$ by further varying $\Delta \Gamma_{\text{tot}}$.

The CL regions on the $(C_u^S, C_v)$ plane are shown in Fig. 3 for the three categories of CPC fits: CPC.II (upper row), CPC.III (middle row), and CPC.IV (lower row). The CL regions are labeled in the same way as in Fig. 2. We observe $C_v > 0.75$ at 68.3% CL except in the CPC.IV.6 fit. Otherwise, one may make similar observations as in Fig. 2 for the behavior of the CL regions as $C_u^S$ is varied.

Figure 4 shows the CL regions on the $(C_u^S, C_d^S)$ plane in the same format as Fig. 2. $C_d^S \approx 1$ is preferred except for the CPC.IV.6 fit, in which the best-fit values of $C_d^S$ are about 0.96 and $-0.81$ when $C_u^S \sim -1.2$ and 1.0, respectively: see Table I. Nevertheless, the difference in $\Delta \chi^2$ between the true minima and the local minimum around the SM limit $(C_u^S, C_d^S) = (1, 1)$ is small. The CL regions, centered around the best-fit values, significantly expand as the fit progresses from CPC.II to CPC.III and from CPC.III to CPC.IV, as well as by adding $\Delta \Gamma_{\text{tot}}$ to the set of varying parameters.
We show the CL regions on the \((C_S^d, C_S^ℓ)\) plane in Fig. 5. The format is the same as in Fig. 2. At tree level without including \(κ_d\), \(C_S^d = C_S^ℓ = O_{φ_1}/\cos β\) as clearly seen in the left frames and the true and local minima are located at \((C_S^d, C_S^ℓ) = (1, 1)\) and \((-1, -1)\). The tree-level relation is modified by introducing \(κ_d\) and the local minima around \((C_S^d, C_S^ℓ) = (-1, 1)\) are developed as shown in the middle frames. Further varying \(ΔΓ_{tot}\), we observe that \(C_S^d = 0\) is allowed at the 99.7% CL but \(|C_S^ℓ| > 0\) always: see the right frames.

The CL regions involved with \(κ_d\) are shown in the left and middle frames of Fig. 6 for the CPC.II (upper), CPC.III (middle), and CPC.IV (lower) fits. We see any value of \(κ_d\) between \(-0.1\) and \(0.1\) is allowed.

Note that in the most recent update [4] when \(ΔΓ_{tot}\) is the only parameter allowed to vary, the fitted value of \(ΔΓ_{tot}\) is consistent with zero and is constrained by \(ΔΓ_{tot} < 0.97\) MeV at 95% CL. From the right frames of Fig. 6 we observe that the range of \(ΔΓ_{tot}\) at 95% CL (green region) varies from \(-2.4\) MeV to \(3.3\) MeV (CPC.II.4) and \(-2.9\) MeV to \(5.6\) MeV (CPC.III.5 and CPC.IV.6). Such a large range is not very useful in constraining the exotic decay branching ratio of the Higgs boson. Usually we have to limit the number of varying parameters to be small enough to draw a useful constraint on \(ΔΓ_{tot}\).

We show the CL regions on the \((C_u^S, ΔS^γ)\) plane in Fig. 7 for the CPC.III (upper) and CPC.IV (lower) fits. In the CPC.III fits, the range of \(ΔS^γ\) is from \(-2.5 (1)\) to \(0.3 (3.7)\) at 68.3% CL for the positive (negative) \(C_u^S\). In the CPC.IV fits, the range is a bit widened.

In Fig. 8 we show the CL regions of the CPC.IV fits on the \((C_u^S, ΔS^g)\) (upper) and \((ΔS^γ, ΔS^g)\) (lower) planes. We found that there are two bands of \(ΔS^g\) allowed by data, which are consistent with the results in the model-independent fits [3]. In the plots of \(ΔS^γ\) vs \(ΔS^g\) there are four almost degenerate solutions to the local minimum of \(χ^2\), which only differ from one another by a very small amount. It happens because \(ΔS^γ\) and \(ΔS^g\) satisfy a set of elliptical-type equations, which imply two solutions for each of \(ΔS^γ\) and \(ΔS^g\) [3].

A quick summary of the CPC fits is in order here. The confidence regions in various fits are similar to the Type II of the 2HDM. When \(κ_d\) and \(ΔΓ_{tot}\) (not investigated in the previous 2HDM fits) are allowed to vary, the confidence regions are slightly and progressively enlarged due to more varying parameters. Especially the linear relation between \(C_d^S\) and \(C_ℓ^S\) are “diffused” when \(κ_d\) varies between \(±0.1\) as shown in Eq. (19). The two possible solutions for \(ΔS^γ\) in the CPC.III and CPC.IV cases are consistent with what we have found in previous works [3, 35]. The best-fit point of each fit is shown in Table I with the
corresponding $p$-value. It is clear that the SM fit provides the best $p$-value in consistence with our previous works [3, 4, 35]. Among the fits other than the SM one, the CPC.III.3 fit gives the smallest $\chi^2$ per degree of freedom and thus the largest $p$-value. It demonstrates that the set of parameters consisting of the top-Yukawa coupling $C_u^S$, $\tan \beta$ or equivalently the gauge-Higgs coupling $C_v$, and $\Delta S^\gamma$ is the minimal set of parameters that gives the best description of the data, other than the SM. In this fit, the $C_v = 0.93$ being very close to the SM value while $C_u^S$ takes on a negative value $-0.93$, which is then compensated by a relatively large $\Delta S^\gamma = 2.3$. The derived $C_d^S$ and $C_S^\ell$ are very close to the SM values. On the other hand, we show in Table II the other local minima for various CPC fits. We can see that the CPC.III.3 fit indeed has another local minimum, which has a $\chi^2$ very close to the true minimum, at which $C_u^S$, $C_v$, $C_d^S$, and $C_S^\ell$ are extremely close to their SM values while $\Delta S^\gamma = -0.85$.

IV. IMPLICATIONS ON THE MSSM SPECTRUM

Supersymmetric particles can enter into the picture of the observed Higgs boson via (i) exotic decays, e.g., into neutralinos, (ii) contributions to $\Delta S^\gamma$ by charginos, sleptons, squarks, and (iii) contributions to $\Delta S^g$ by squarks. Note that virtual effects are also present in $\kappa_d$. In this Section, since we are considering the explicit one-loop contributions of the SUSY particles to the $H\gamma\gamma$ and $Hgg$ vertices, we restrict $\tan \beta$ to be larger than $1/2$ so that the top-quark Yukawa coupling is supposed to be perturbative and the one-loop corrections remain reliable.

A. Charginos

We first investigate the effects of charginos. The lower mass limit of chargino is 103.5 GeV, so that the only place that it can affect the Higgs boson is in the loop factor $\Delta S^\gamma$. The MSSM parameters that affect the chargino mass and the interactions with the Higgs boson are: $M_2$, $\mu$, and $\tan \beta$, shown in Eqs. [13] and [14]. We show in Fig. 9 the confidence regions when we vary $C_u^S$, $\tan \beta$, $M_2$, and $\mu$ with the additional constraint on the chargino mass:

$$M_{\tilde{\chi}^\pm} > 103.5 \text{ GeV}.$$
TABLE III. The best-fit values for chargino contributions to $\Delta S^\gamma (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$. We imposed $M_{\tilde{\chi}_1^\pm}$ > 103.5 GeV and $\tan \beta > 1/2$. The parameters: $C_u^S$, $\tan \beta$, $M_2 \subset [-1 \text{TeV}, 1 \text{TeV}]$, $\mu \subset [0, 1 \text{TeV}]$ are scanned.

| Fits         | $\chi^2$ | $\chi^2$/dof | $p$-value | Best-fit values |
|--------------|----------|---------------|-----------|----------------|
| Charginos    | 15.78    | 0.631         | 0.921     | $C_u^S$ 0.992 $\tan \beta$ 1.513 $\kappa_d$ $\Delta S^\gamma$ $\Delta S^g$ $\Delta \Gamma_{\text{tot}}$ |

| Best-fit values | $C_v$ | $C_d^S$ | $C_{\ell}^S$ | $M_2$(GeV) | $\mu$(GeV) | $M_{\tilde{\chi}_1^\pm}$(GeV) | $M_{\tilde{\chi}_2^\pm}$(GeV) |
|-----------------|-------|---------|--------------|------------|------------|-------------------------------|-------------------------------|
|                 | 1.000 | 1.019   | 1.019        | 184        | 179        | 103.7                         | 261.3                        |

The results are analogous to those of the CPC.III.3 case if we do not impose the chargino mass constraint and the restriction of $\tan \beta > 1/2$. In the CPC.III.3 fit, $\Delta S^\gamma$ is free to vary both negatively and positively, while here the sign of the chargino contribution correlates with $C_u^S$ in the parameter space of $M_2$ and $\mu$. From the upper frames, we note that $C_u^S$ is always positive under the requirement of $\tan \beta > 1/2$ and $\Delta S^\gamma$ tends to be positive taking its value in the range between $-0.75$ and $1.7$ at 99.7% CL. In the lower-left frame, we show the $M_{\tilde{\chi}_1^\pm}$ dependence of the CL regions of $\Delta S^\gamma$. We observe that all the points fall into the 68.3% CL region of $-0.25 \lesssim \Delta S^\gamma \lesssim 0.43$ when $M_{\tilde{\chi}_1^\pm} \gtrsim 200$ GeV. We also observe that the $\mu$ parameter can be as low as 70 GeV when $M_2 < 0$ from the lower-right frame.

We show the best-fit point for the chargino contribution in Table III. The best-fit point gives $M_2 = 184$ GeV and $\mu = 179$ GeV, which give the lightest chargino mass $M_{\tilde{\chi}_1^\pm} = 103.7$ GeV, just above the current limit. The corresponding $\Delta S^\gamma \approx -0.68$. The $p$-value is slightly worse than the CPC.III.3 case.

**B. Scalar taus**

The staus contribute to $\Delta S^\gamma$ in a way similar to charginos. The SUSY soft parameters that affect the stau contributions are the left- and right-handed slepton masses $M_{L_3}$ and $M_{E_3}$, the $A$ parameter $A_\tau$, and the $\mu$ parameter. We are taking $\mu > 1$ TeV to avoid possibly large chargino contributions to $\Delta S^\gamma$. The $2 \times 2$ stau mass matrix is diagonalized to give two mass eigenstates $\tilde{\tau}_1$ and $\tilde{\tau}_2$, shown in [16] and [18]. The current mass limit on stau is
The best-fit values for stau contributions to $\Delta S^\gamma(\tilde{\tau}_1, \tilde{\tau}_2)$. We set $M_{E3} = M_{L3}$ and imposed $\tan \beta > 1/2$, $\mu > 1$ TeV, and $M_{\tilde{\tau}_1} > 81.9$ GeV. The scanning parameters are $C^S_u$, $\tan \beta$, $M_{L3} \subset [0, 1\text{TeV}]$, $\mu \subset [1, 2\text{TeV}]$, $A_\tau \subset [-1\text{TeV}, 1\text{TeV}]$.

| Fits            | $\chi^2$ | $\chi^2$/dof | p-value | Best-fit values |
|-----------------|-----------|--------------|---------|-----------------|
| Scalar taus     | 15.68     | 0.653        | 0.899   | $C^S_u$         |
|                 |           |              |         | $\tan \beta$    |
|                 |           |              |         | $\kappa_d$      |
|                 |           |              |         | $\Delta S^\gamma$ |
|                 |           |              |         | $\Delta S^g$    |
|                 |           |              |         | $\Delta \Gamma_{tot}$ |

Best-fit values

| $C_v$ | $C^S_d$ | $C^S_\ell$ | $M_{L3}$ (GeV) | $\mu$ (GeV) | $A_\tau$ (GeV) | $M_{\tilde{\tau}_1}$ (GeV) | $M_{\tilde{\tau}_2}$ (GeV) |
|-------|---------|------------|----------------|-------------|----------------|---------------------------|-----------------------------|
| 1.000 | 1.040   | 1.040      | 323            | 1075        | -43.2          | 132.3                     | 442.4                      |

$M_{\tilde{\tau}_1} > 81.9$ GeV \cite{42}.

We show in Fig. 10 the confidence regions when we vary $C^S_u$, $\tan \beta$, $M_{L3} = M_{E3}$, $\mu$, and $A_\tau$. Requiring $\tan \beta > 1/2$, $C^S_u > 0$ and most allowed regions are concentrated at $C^S_u \approx 1$ and $\Delta S^\gamma < 0$. Similar to the chargino case, $C^S_u$ and $\Delta S^\gamma$ correlate with each other in the parameter space. The “T” shape of the CL regions of $\Delta S^\gamma$ (upper-right) can be understood by observing that $C_v$ is constrained to be very close to 1 unless $C^S_u \approx 1$ when $C^S_u > 0$: see the CPC.III (middle) frames of Fig. 3. We observe that all the points fall into the 68.3% CL region of $-1.8 \lesssim \Delta S^\gamma \lesssim 0$ when $M_{\tilde{\tau}_1} \gtrsim 180$ GeV.

The best-fit values are shown in Table IV. The $\chi^2$ is just slightly worse than that of the CPC.III.3 case and the $p$ value is lowered because of more varying parameters. The values for $C^S_u$, $C_v$, $C^S_\ell$ and $C^S_d$ are very close to their SM values. The lightest stau has a mass of 132.3 GeV.

C. Stops and sbottoms

Here we investigate the effects on $\Delta S^\gamma$ and $\Delta S^g$ from squark contributions, namely, the stop and sbottom contributions are the relevant ones. We adopt a rather loose mass limits quoted in PDG \cite{42}

\begin{equation}
M_{\tilde{t}_1} > 95.7 \text{ GeV} , \quad M_{\tilde{b}_1} > 89 \text{ GeV} .
\end{equation}

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In order to fully understand the stop and sbottom contributions, we separate the stop and sbottom contributions, and show the results of sbottoms in Tables V and VI while those of stops in Table VII and in Fig. 12. We are taking $\mu > 1\text{ TeV}$ to avoid possibly large chargino contributions to $\Delta S^\gamma$.

1. Sbottom only

Corresponding plots are shown in Fig. 11 and the best fit point is shown in Table V. In this case, the $\Delta S^\gamma$ and $\Delta S^g$ are related by a linear relation $\Delta S^\gamma = 2N_C Q_b^2 \Delta S^g = \frac{2}{3} \Delta S^g$: see Eqs. (8) and (12). Most allowed regions are concentrated at $C_u^S \approx 1$ and along the $\Delta S^\gamma = 0$ line except for a small island where $\Delta S^\gamma \approx -0.86$ and accordingly $\Delta S^g \approx -1.3$. In fact, the

| Fits   | $\chi^2$ | $\chi^2$/dof | p-value | Best-fit values |
|--------|----------|--------------|---------|----------------|
| $C_u^S$ | tan $\beta$ | $\kappa_d$ | $\Delta S^\gamma$ | $\Delta S^g$ | $\Delta \Gamma_{tot}$ |
| Sbottoms | 15.84 | 0.660 | 0.894 | 1.000 | 64.98 | 0.037 | -0.858 | -1.29 | - |

| Fits   | $\chi^2$ | $\chi^2$/dof | p-value | Best-fit values |
|--------|----------|--------------|---------|----------------|
| $C_u^S$ | tan $\beta$ | $\kappa_d$ | $\Delta S^\gamma$ | $\Delta S^g$ | $\Delta \Gamma_{tot}$ |
| Sbottoms | 16.74 | 0.697 | 0.860 | 1.011 | 0.501 | 0.026 | -0.00046 | -0.00069 | - |

| Fits   | $\chi^2$ | $\chi^2$/dof | p-value | Best-fit values |
|--------|----------|--------------|---------|----------------|
| $C_u^S$ | tan $\beta$ | $\kappa_d$ | $\Delta S^\gamma$ | $\Delta S^g$ | $\Delta \Gamma_{tot}$ |
| Sbottoms | 15.84 | 0.660 | 0.894 | 1.000 | 64.98 | 0.037 | -0.858 | -1.29 | - |

TABLE V. Only sbottom contributions to $\Delta S^\gamma(\tilde{b}_1, \tilde{b}_2)$, $\Delta S^g(\tilde{b}_1, \tilde{b}_2)$, $\kappa_d$. $M_{D3} = M_{Q3}$, $M_3 = 1\text{ TeV}$, and imposing $M_{\tilde{t}_1} > 95.7\text{ GeV}$ and $M_{\tilde{b}_1} > 89\text{ GeV}$. We also impose $\tan \beta > 1/2$ and $\mu > 1\text{ TeV}$.

TABLE VI. The same as in Table V but imposing $M_{\tilde{b}_1} > 120\text{ GeV}$.

TABLE VII. The same as in Table V but imposing $M_{\tilde{t}_1} > 120\text{ GeV}$.

TABLE VIII. The same as in Table V but imposing $M_{\tilde{t}_2} > 120\text{ GeV}$.
best fit point is located at the island as shown in Table V and the lightest sbottom mass is only 96 GeV. The presence of the island can be understood by observing that $\Delta \chi^2$ quickly grows along the $\Delta S^\gamma = \frac{2}{3} \Delta S^g$ line: see Fig. 8. When the line cuts across the 68.3% (red) CL region at $\Delta S^\gamma \sim -0.8$, the island comes into existence but it quickly disappears as $M_{\tilde{b}_1}$ increases since such a large value of $\Delta S^\gamma \sim -0.8$ can only be attainable when the sbottom is as light as $\sim 100$ GeV. From the lower frames, we observe that the island disappears if we impose $M_{\tilde{b}_1} \gtrsim 120$ GeV, and all the couplings will then be very close to the SM values as shown in Table VI and $-0.12(-0.04) \lesssim \Delta S^\gamma \lesssim 0.015(0.015)$ at 99.7% (68.3%) CL.

2. Stop only

The stop-only case can be compared with the CPC.IV.4 case, where $C_u^S$, $\tan \beta$, $\Delta S^\gamma$, and $\Delta S^g$ are independent parameters. However, due to the strong correlation between the $\Delta S^\gamma$ and $\Delta S^g$ given by $\Delta S^\gamma = 2N_C Q_t^2 \Delta S^g = \frac{8}{3} \Delta S^g$, somewhat different pattern in ($C_u^S, \Delta S^\gamma$) from that of the CPC.IV.4 case is generated. Furthermore, the requirement of $\tan \beta > 1/2$ completely removes the negative $C_u^S$ region at 95% CL: see the upper frames of Fig. 12. There are two disconnected long-stripe regions in the plot of ($C_u^S, \Delta S^\gamma$), instead of a single connected island in the ($C_u^S, \Delta S^\gamma$) panels of CPC.IV cases in Fig. 7. We observe that all the points fall into the 68.3% CL region of $-1 \lesssim \Delta S^\gamma \lesssim 0.2$ when $M_{\tilde{t}_1} \gtrsim 350$ GeV. The best fit is shown in Table VII. The lightest stop mass stands at 401 GeV, and both $\Delta S^g$ and $\Delta S^\gamma$ are rather small. The $p$ value is slightly worse than the CPC.IV.4 case.

V. SYNOPSIS AND CONCLUSIONS

We have analyzed the relevant parameter space in the MSSM with respect to the most updated data on Higgs boson signal strength. The analysis is different from the model-independent one [4] mainly because $\Delta S^\gamma$ and $\Delta S^g$ are related by a simple relation, and up-type, down-type and leptonic Yukawa couplings are also related to one another, such that they are no longer independent. We have shown in Figs. 1 to 8 the confidence-level regions in the parameter space for the cases of CPC.II to CPC.IV fits by varying a subset or all of the following parameters: $C_u^S$, $\tan \beta$ (or equivalently $C_v$), $\kappa_d$, $\Delta S^\gamma$, $\Delta S^g$, and $\Delta \Gamma_{\text{tot}}$. This set of parameters is inspired by the parameters of the general MSSM. Since the Higgs
TABLE VII. Only stop contributions to $\Delta S^\gamma(\tilde{t}_1,\tilde{t}_2)$, $\Delta S^g(\tilde{t}_1,\tilde{t}_2)$, $\kappa_d$. $M_{U3} = M_{Q3}$, $M_3 = 1$ TeV, and imposing $M_{\tilde{t}_1} > 95.7$ GeV and $M_{\tilde{b}_1} > 89$ GeV. We also impose $\tan\beta > 1/2$ and $\mu > 1$ TeV.

Scanning parameters: $C^S_u$, $\tan\beta$, $M_{Q3} \subset [0,1$ TeV$]$, $\mu \subset [1,2$ TeV$]$, $A_t \subset [-1$ TeV$,$ 1 TeV$]$.

| Fits | $\chi^2$ | $\chi^2$/dof | $p$-value | Best-fit values |
|------|----------|--------------|-----------|----------------|
|      |          |              |           | $C^S_u$ | $\tan\beta$ | $\kappa_d$ | $\Delta S^\gamma$ | $\Delta S^g$ | $\Delta \Gamma_{\text{tot}}$ |
| **Stops** | 16.26   | 0.678        | 0.878     | 1.224  | 0.500     | -0.017  | -0.462    | -0.173   | - |

Best-fit values:

| $C_v$ | $C^S_d$ | $C^S_\ell$ | $M_{Q3}$(GeV) | $\mu$(GeV) | $A_t$(GeV) | $M_{\tilde{t}_1}$ | $M_{\tilde{t}_2}$ | $M_{\tilde{b}_1}$ | $M_{\tilde{b}_2}$ |
|-------|--------|-------------|--------------|-----------|-----------|----------------|----------------|----------------|----------------|
| 0.993 | 0.933  | 0.936       | 797          | 1080      | -675      | 401.4         | 1078            | -              | -              |

sector of the MSSM is the same as the 2HDM type II, the down-type and the leptonic Yukawa couplings are determined once the up-type Yukawa couplings are fixed. It implies that $C^S_u$ and $\tan\beta$ (or equivalently $C_v$) can determine all the tree-level Yukawa and gauge-Higgs couplings. The effects of SUSY spectrum then enter into the parameters $\kappa_d$, $\Delta S^\gamma$, and $\Delta S^g$ through loops of colored and charged particles.

There are improvements in all the CPC fits since our analysis of 2HDM [35] a year ago. The most significant changes in the Higgs-boson data from 2013 to 2014 were the diphoton signal strengths measured by both ATLAS and CMS [45, 46] while all other channels were moderately improved. Overall, all fitted couplings are improved by about 10% and the SM Higgs boson enjoys a large $p$ value close to 1 [4].

The SUSY particles enter the analysis mainly through the loop effects of the colored and charged particles into the parameters such as $\Delta S^\gamma$, $\Delta S^g$, and $\kappa_d$ while light neutralinos with mass less than $m_h/2$ can enter into $\Delta \Gamma_{\text{tot}}$. We have analyzed the effects of the SUSY spectrum with the direct search limits quoted in PDG [42]. We offer the following comments concerning the MSSM spectrum.

1. The effect of $\kappa_d$ on the CL regions is insignificant, which can be seen easily when we go across from the first column to the second column in Figs. 2 to 4. On the other hand, the effect of $\Delta \Gamma_{\text{tot}}$ is relatively large, which can be seen by going across from the second column to the last column in Figs. 2 to 4.

2. The squark cases, the stop-only and the sbottom-only, are special cases of CPC.IV.4.
in which $\tan\beta$ (or equivalently $C_v$, $C_u^S$, $\Delta S^\gamma$, and $\Delta S^g$ are varied. In the stop and sbottom cases, because $\Delta S^\gamma$ and $\Delta S^g$ are related by a linear relation, and thus they are strongly correlated. Therefore, the fits of stop and sbottom are not as good as the CPC.IV.4.

3. In the sbottom-only case, there is a fine-tuned allowed region, in which the lightest sbottom mass is only 96 GeV and $\Delta S^\gamma \approx -0.8$. On the other hand, if we merely impose $M_{b_1} > 120$ GeV this fine-tuned region is completely gone, and the best fit parameters are very close to the SM ones.

4. The chargino and stau cases are special cases of CPC.III.3 in which $\tan\beta$ (or equivalently $C_v$, $C_u^S$, and $\Delta S^\gamma$ are varied. Nevertheless, the $\Delta S^\gamma$ is restricted by the SUSY parameters $\mu$, $\tan\beta$, and $M_2$ or $M_{L_3,E_3}$ in such a way that $\Delta S^\gamma$ is not entirely free to vary. The resulting fits are not as good as the CPC.III.3 case.

5. In all SUSY cases that we considered in this work, including chargino, stau, stop, and sbottom, the preferred $C_u^S$ is larger than zero, indeed close to 1, and $C_v$ is also close to 1.

6. The contributions to $\Delta S^\gamma$ from charginos, staus, stops, and sbottoms are not of the same sign. We show the $\Delta S^\gamma$ versus $\Delta S^g$ for chargino-only, stau-only, stop-only, and sbottom-only cases in Fig. 13. It is clearly that $\Delta S^\gamma \gtrsim -0.7$ for chargino-only case, $\Delta S^\gamma \lesssim 0.3$ for stau-only case. On the other hand, $\Delta S^\gamma$ can extend to large values in the stop case but it is limited by small Yukawa coupling in the sbottom case. It is possible that various contributions can cancel among one another in general.

7. The direct search limits on charginos and staus prevent the $\Delta S^\gamma$ from becoming too large while those on stops and sbottoms prevent both $\Delta S^\gamma$ and $\Delta S^g$ from becoming too large.

8. Imposing $\tan\beta > 1/2$, all the points fall into the 68.3% CL region of the current Higgs data when the lightest chargino, stau, or stop is heavier than 200 GeV, 180 GeV, or 350 GeV, respectively, under the assumption that one of them is dominantly contributing to $\Delta S^\gamma$ and/or $\Delta S^g$. While, the sbottom contributions are negligible when $M_{b_1} > 120$ GeV.
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FIG. 1. Plots of $\Delta \chi^2$ vs $C_u^S$ for three categories of CPC fits: CPC.II (upper row), CPC.III (middle row), and CPC.IV (lower row). The left frames show the cases of CPC.II.2 (varying $C_u^S$, $\tan \beta$), CPC.III.3 (varying $C_u^S$, $\tan \beta$, $\Delta S^\gamma$), and CPC.IV.4 (varying $C_u^S$, $\tan \beta$, $\Delta S^\gamma$, $\Delta S^9$). In the middle frames, the cases CPC.II.3, CPC.III.4, CPC.IV.5 are shown by adding $\kappa_d$ to the corresponding set of varying parameters. The right frames are for the cases of CPC.II.4, CPC.III.5, and CPC.IV.6 in which $\Delta \Gamma_{\text{tot}}$ is further varied. In each frame, each different color corresponds to a different range of $\tan \beta$: $0.1 < \tan \beta < 0.4$ (red), $0.4 < \tan \beta < 0.6$ (magenta), $0.6 < \tan \beta < 1$ (yellow), and $1 < \tan \beta$ (gray).
FIG. 2. The confidence-level regions on the \((C_S^u, \tan \beta)\) plane for three categories of CPC fits: CPC.II (upper row), CPC.III (middle row), and CPC.IV (lower row) fits. The left frames show the cases of CPC.II.2 (varying \(C_S^u\), \(\tan \beta\)), CPC.III.3 (varying \(C_S^u\), \(\tan \beta\), \(\Delta S^\gamma\)), and CPC.IV.4 (varying \(C_S^u\), \(\tan \beta\), \(\Delta S^\gamma\), \(\Delta S^g\)). In the middle frames, the cases CPC.II.3, CPC.III.4, CPC.IV.5 are shown by adding \(\kappa_d\) to the corresponding set of varying parameters. The right frames are for the cases of CPC.II.4, CPC.III.5, and CPC.IV.6 in which \(\Delta \Gamma_{\text{tot}}\) is further varied. The confidence regions shown are for \(\Delta \chi^2 \leq 2.3\) (red), 5.99 (green), and 11.83 (blue) above the minimum, which correspond to confidence levels of 68.3%, 95%, and 99.7%, respectively. The best-fit point is denoted by the triangle.
FIG. 3. The same as in Fig. 2 but on the \((C_u^S, C_v)\) plane.
FIG. 4. The same as in Fig. 2 but on the $(C_u^S, C_d^S)$ plane.
FIG. 5. The same as in Fig. 2 but on the $(C_s^d, C_s^\ell)$ plane.
FIG. 6. The confidence-level regions on the $(C_u^S, \kappa_d)$ (left and middle) and the $(C_u^S, \Delta \Gamma_{\text{tot}})$ (right) planes. The left frames show the cases of CPC.II.3, CPC.III.4, CPC.IV.5 and the middle and right frames are for the cases of CPC.II.4, CPC.III.5, and CPC.IV.6. The labeling of confidence regions is the same as in Fig. 2.
FIG. 7. The upper frames show the confidence-level regions on the \((C^S_u, \Delta S^\gamma)\) plane for the CPC.III.3 (left), CPC.III.4 (middle), and CPC.III.5 (right) fits. The lower frames are for the CPC.IV.4 (left), CPC.IV.5 (middle), and CPC.IV.6 (right) fits. The labeling of confidence regions is the same as in Fig. 2.

FIG. 8. The confidence-level regions on the \((C^S_u, \Delta S^g)\) (upper) and the \((\Delta S^\gamma, \Delta S^g)\) (lower) planes for the CPC.IV.4 (left), CPC.IV.5 (middle), and CPC.IV.6 (right) fits. The labeling of confidence regions is the same as in Fig. 2.
FIG. 9. **Charginos**: The confidence-level regions of the fit by varying $C_S^u$, $\tan \beta$, $M_2$, and $\mu$ with $\tan \beta > 1/2$ and $M_{\tilde{\chi}^\pm} > 103.5$ GeV. The description of the confidence regions is the same as Fig. 2.
FIG. 10. **staus**: The confidence-level regions of the fit by varying $C_u^S$, $\tan \beta$, $M_{L3} = M_{E3}$, $\mu$, and $A_\tau$ with the restrictions: $\tan \beta > 1/2$, $\mu > 1$ TeV, and $M_{\tilde{\tau}_1} > 81.9$ GeV. The description of the confidence regions is the same as Fig. [2]
FIG. 11. **Sbottoms**: The confidence-level regions of the fit by varying $C_u^S$, $\tan \beta$, $M_{Q_3} = M_{D_3}$, $\mu$, and $A_b$ with the restrictions: $\tan \beta > 1/2$, $\mu > 1$ TeV, and $M_{b_1} > 89$ GeV. The description of the confidence regions is the same as Fig. 2.
FIG. 12. **Stops:** The confidence-level regions of the fit by varying $C_u^S$, $\tan \beta$, $M_{Q_3} = M_{U_3}$, $\mu$, and $A_t$ with the restrictions: $\tan \beta > 1/2$, $\mu > 1$ TeV, and $M_{\tilde{t}_1} > 95.7$ GeV. The description of the confidence regions is the same as Fig. [2]
FIG. 13. The $\Delta S^\gamma$ versus $\Delta S^g$ for chargino-only, stau-only, stop-only, and sbottom-only cases. The additional black region denotes $\Delta \chi^2 \leq 1.0$. 