Implications on the Heavy CP-even Higgs Boson
from Current Higgs Data

Jung Chang\textsuperscript{1}, Kingman Cheung\textsuperscript{1,2}, Po-Yan Tseng\textsuperscript{1}, and Tzu-Chiang Yuan\textsuperscript{3}

\textsuperscript{1} Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan
\textsuperscript{2} Division of Quantum Phases and Devices, School of Physics, Konkuk University, Seoul 143-701, Republic of Korea
\textsuperscript{3} Institute of Physics, Academia Sinica, Nangang, Taipei 11529, Taiwan

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Abstract

The current Large Hadron Collider data indicates that the newly observed resonance has the $WW$ and $ZZ$ modes consistent with the standard model Higgs boson, while the $\gamma\gamma$ mode is about $1.2 - 2$ times that of the standard model prediction and the tau-pair mode is suppressed. If this pattern persists in the upcoming data, it would be a sign for physics beyond the standard model.

In the type II two-Higgs-doublet model, it is the region where $\sin \alpha \approx 0$ and a moderately large $\tan \beta = 10 - 20$ that the lighter CP-even Higgs boson can accommodate the current data. We note that in this region the heavier CP-even Higgs boson must have a large decay branching ratio into tau pairs. We find that this heavier Higgs boson can be observable in the associated production with a $b\bar{b}$ pair and through the decay into a tau pair.
I. INTRODUCTION

It is of very high expectation that the observed particle at the Large Hadron Collider (LHC) [1,2] is the long-sought Higgs boson of the standard model (SM), which was proposed in 1960s [3]. At the end of 2011, both the ATLAS and CMS [1] experiments at the LHC have seen some excess of events of a possible Higgs boson candidate in the decay modes of $h \to \gamma\gamma$, $h \to WW^* \to \ell^+\nu\ell^−\bar{\nu}$ and $h \to ZZ^* \to 4\ell$ channels. Finally, the discovery was announced in July 2012 by ATLAS [1] and CMS [2]. The channels $WW$ and $ZZ$ are consistent with the predictions of the SM Higgs boson, while the $\gamma\gamma$ rate is somewhat higher than expectation. Some evidence is seen in the $b\bar{b}$ mode at the Tevatron [5], but the mass range is quite wide. On the other hand, the $\tau^+\tau^-$ mode appears to shy away from the detectors, albeit the data contain large uncertainties.

The diphoton production rate is about a factor of $1.2−2$ as much as that of the SM Higgs boson. A large number of models have been put forward to account for the observed particle at 125 GeV, including the SM, MSSM, NMSSM, $U(1)$-extended minimal supersymmetric standard model, and other MSSM-extended models, fermiophobic Higgs, 2HDM of various types, Randall-Sundrum radion, inert-Higgs doublet, triplet Higgs models (a summary of various models can be found in Ref. [6].) They all can explain the enhanced diphoton rate with some choices of parameter space. Nevertheless, the most peculiar observation is that the $\tau^+\tau^-$ mode is suppressed [7] in the data. If this picture persists in the upcoming data, it would be a sign for physics beyond the SM.

The two-Higgs-doublet model (2HDM) has enough free parameters that allow one to achieve a light CP-even Higgs boson of 125 GeV, for which the $WW^*$ and $ZZ^*$ modes are consistent with the SM Higgs boson, the diphoton mode is enhanced, and $\tau^+\tau^-$ mode is suppressed. This can be achieved in the type II 2HDM in the following parameter space

$$\sin\alpha \approx 0 \quad \text{and} \quad \tan\beta = 10−20.$$  

(1)

In this case, $\sin(\beta − \alpha) \approx \sin\beta$, which is close to 1 for large enough $\tan\beta$. Therefore, the $WW^*$ and $ZZ^*$ modes are about the same as the SM, and the $\tau^+\tau^-$ mode is highly suppressed. With a reduced total width the $\gamma\gamma$ branching ratio is enhanced. In fact, this

1 There was an update in November 2012: the $\tau\tau$ mode is measured to be $0.7 \pm 0.5$ (CMS) and $0.7 \pm 0.7$ (ATLAS) [7]. The $\tau\tau$ mode is still suppressed but with a large uncertainty.
is the favorable region for enhancement in the diphoton mode obtained in Ref. [8]. Other related works in 2HDM can be found in Refs. [9, 10].

In this Letter, we show that with the choice of the parameter space of Eq.(1) the lighter CP-even Higgs boson $h$ is consistent with the observed data, and the heavier CP-even Higgs boson $H$ can be observable through the associated production with a $b\bar{b}$ pair in the $b\bar{b}\tau^+\tau^-$ final state at the 8 TeV and 14 TeV LHC. This is the main result of the paper.

II. TWO-HIGGS-DOUBLET MODEL

Instead of one, the 2HDM employs two Higgs doublets. In order to avoid dangerous tree-level flavor-changing neutral currents, a discrete $Z_2$ symmetry is usually imposed in all the popular 2HDMs. A number of possible arrangements of the two doublets and various scenarios of the mass spectra for the Higgs bosons are recently analyzed in Refs. [11–16] in light of current data. In this work, we focus on the type II, which has the same Higgs sector as the MSSM. The Higgs sector consists of two Higgs doublets $H_u = (H_u^+ + H_u^0)\,^T$ and $H_d = (H_d^+ + H_d^0)\,^T$ where the subscripts $u,d$ denote the right-handed quark singlet fields that the Higgs doublets couple to. After electroweak symmetry breaking (EWSB), there are two CP-even, one CP-odd, and a pair of charged Higgs bosons. The parameters of the model in the CP-conserving case can be chosen as

$$m_h, m_H, m_A, m_{H^*}, \tan \beta \equiv \frac{v_u}{v_d}, \alpha$$

where $\alpha$ is the mixing angle between the two CP-even Higgs bosons. All these are free parameters of the model but subjected to theoretical and experimental constraints. With a common factor of $-igm_f/2m_W$ being suppressed, the couplings of the lighter and heavier CP-even Higgs bosons $h$ and $H$ to the tau, bottom and top quarks are, respectively, given by

$$
\begin{align*}
\tau^-\tau^+ & \quad b\bar{b} & \quad t\bar{t} \\
h: & -\sin\alpha/\cos\beta & -\sin\alpha/\cos\beta & \cos\alpha/\sin\beta \\
H: & \cos\alpha/\cos\beta & \cos\alpha/\cos\beta & \sin\alpha/\sin\beta
\end{align*}
$$

Other relevant couplings of $h$ and $H$ are those to the weak gauge bosons, which have a factor of $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ relative to the SM values, respectively.

$^2$ Though the type II model with the light CP-even Higgs $m_h \approx 125$ GeV is not the best fit to the current Higgs data, it still provides a decent good fit [14, 15].
Although $\sin \alpha \approx 0$ is chosen in Eq. (1), we do not consider the case when $\sin \alpha$ is fine-tuned to a value very close to zero, say smaller than $10^{-3}$. In such a case, the factor $-\sin \alpha / \cos \beta$ remains suppressed even if $\tan \beta$ is extremely large. In the case when the smallest value of $\sin \alpha$ is around $10^{-2}$ and $\tan \beta$ is larger than 20, the factor $-\sin \alpha / \cos \beta$ becomes substantial and so the lighter Higgs boson $h \to \tau^+ \tau^-$ is no longer suppressed [17]. Nevertheless, if $\sin \alpha$ is fine-tuned to $10^{-3}$, then $\tan \beta$ can be much larger than 20, and even around 60 the decay $h \to \tau^+ \tau^-$ is still strongly suppressed. On the other hand, if $\tan \beta < 10$ the factor $\cos (\beta - \alpha)$ is not suppressed enough such that the heavier Higgs boson $H \to ZZ^*(\rightarrow 4\ell)$ for $m_H = 130 - 600$ GeV might appear in the data. In this work, we use a small $\sin \alpha \sim 10^{-2}$ and $\tan \beta = 10 - 20$.

III. EXPERIMENTAL CONSTRAINTS

The first constraint we must consider is the radiative decay of $B$ meson, $b \to s \gamma$, as well as the $B$-$\bar{B}$ mixing, both of which receive contributions from the charged Higgs boson. As shown in [18], we are safe if we take $m_{H^\pm} \geq 500$ GeV for $\tan \beta > 5$. Yet, the most important experimental constraint on the 2HDM comes from the $\rho$ parameter, which is theoretically and experimentally in the vicinity of 1, so that there is almost no room for deviations and it implies a strong restriction on the splitting of the Higgs boson masses. In 2HDM $\Delta \rho$ receives contributions from all Higgs bosons given by [18]

$$\Delta \rho^{2HDM} = \frac{\alpha_{em}}{4\pi \sin^2 \theta_W M_W^2} \left[ F(m_A, m_{H^+}) + \cos^2(\beta - \alpha) [F(m_{H^+}, m_h) - F(m_A, m_h)] 
+ \sin^2(\beta - \alpha) [F(m_{H^+}, m_h) - F(m_A, m_h)] 
+ \cos^2(\beta - \alpha) \Delta \rho^{SM}(m_h) + \sin^2(\beta - \alpha) \Delta \rho^{SM}(m_h) \right],$$

where

$$F(x, y) = \frac{1}{8} x^2 + \frac{1}{8} y^2 - \frac{1}{4} \frac{x^2 y^2}{x^2 - y^2} \log\left(\frac{x^2}{y^2}\right),$$

$$\Delta \rho^{SM}(M) = -\frac{\alpha_{em}}{4\pi \sin^2 \theta_W M_W^2} \left[ 3F(M, M_W) - 3F(M, M_Z) + \frac{1}{2}(M_Z^2 - M_W^2) \right].$$

The $\Delta \rho^{SM}(M)$ is rather small and can be ignored, but the other terms are sizable if the mass difference between the two mass arguments in $F(M_1, M_2)$ is large. Just the first term $F(m_A, m_{H^+})$ in Eq.(2) can be of order 0.01 for $m_A < 100$ GeV and $m_{H^\pm} = 500$ GeV. One
simple solution is to choose \( m_A \approx m_{H^\pm} \) and \( \cos(\beta - \alpha) \approx 0 \), then the 2HDM contributions to the \( \Delta \rho \) become miniscule.

Unless \( \tan \beta \) is of order 100 \([18]\), for Higgs boson masses larger than 100 GeV the contributions to the muon anomalous magnetic dipole moment is very small. We will ignore this constraint.

The next constraint is the current LHC data on the observed Higgs boson, defined by the signal strength parameter which is the production rate relative to the corresponding SM one:

\[
R_X^h \equiv \frac{\sigma(pp \to h) \times B(h \to X)}{\sigma(pp \to h_{SM}^{\text{SM}}) \times B(h_{SM} \to X)}
\]

for \( X = WW^*, ZZ^*, \gamma \gamma, \tau^+ \tau^- \). Here we take the observed boson to be the lighter CP-even Higgs \( h \). \([3]\)

The current values for \( R_{WW}^h \) and \( R_{ZZ}^h \) are consistent with the SM and \( R_{\gamma \gamma}^h \) is larger than 1, but \( R_{\tau^+ \tau^-}^h \) appears to be suppressed. Here we do not mean to perform a full scan of the parameter space, but only to emphasis that the parameter space of Eq.(1) would give an enhanced diphoton rate \( R_{\gamma \gamma}^h \) for the lighter CP-even Higgs boson while keeping the \( R_{WW}^h \) and \( R_{ZZ}^h \) intact with the SM values \([6, 8]\). The bonus is the suppressed \( R_{\tau^+ \tau^-}^h \), which appears to be consistent with both the CMS and ATLAS experiments that have reached the tau-pair detection sensitivity limit.

**IV. THE HEAVIER CP-EVEN HIGGS BOSON**

The scenario defined by the parameter space of Eq.(1) would give an interesting signature for the heavier CP-even Higgs boson. Since \( \cos(\beta - \alpha) \approx 1/\tan \beta \) for a large enough \( \tan \beta \) and \( \sin \alpha \approx 0 \), the heavier CP-even Higgs \( H \) couples very mildly to \( WW \) and \( ZZ \) while the decays into \( \tau^+ \tau^- \) and \( b \bar{b} \) are enhanced by \( \tan \beta \). Therefore, the current constraint of \( h_{SM} \to ZZ^* \to 4\ell \) does not apply to \( H \), so that its mass \( m_H \) can be anywhere between 130 GeV and 1 TeV. \([4]\) We show the decay branching ratios of \( H \) versus \( m_H \) in Fig. 1 where we have used \( \sin \alpha = 0.01 \) and \( \tan \beta = 10 \) (top) and 20 (bottom). Note that both the \( \gamma \gamma \) and \( Z \gamma \) branching ratios are below \( 10^{-5} \) in this case and not shown. The \( \tau^+ \tau^- \) branching ratio

\[3\] There are a number of works in 2HDM or supersymmetry frameworks that take the heavier CP-even Higgs boson or the pseudoscalar boson as the observed particle \([10, 19]\); or both CP-even Higgs bosons are nearly degenerate \([20]\). We do not pursue these possibilities here.

\[4\] Similar idea was considered in Ref. \([21]\).
varies from 5% to 10%, and the $WW^{(*)}$ and $ZZ^{(*)}$ are sub-leading as long as $\tan\beta$ is large enough. Note that if $\tan\beta < 10$, the $H \to ZZ^{(*)} \to 4\ell$ mode is not small enough such that

\[ \text{BR}(H \to XX) \]

![Graph showing decay branching ratios for the heavier CP-even Higgs boson $H$ versus its mass $m_H$.](image)

FIG. 1. Decay branching ratios for the heavier CP-even Higgs boson $H$ versus its mass $m_H$. The parameters for the 2HDM are chosen as $\sin\alpha = 0.01$ and $\tan\beta = 10$ (top) and 20 (bottom).

...
large enough enhancement for $\tan \beta = 10 - 20$ to make up for the mass suppression factor from $m_b$. Therefore, the gluon fusion cross section would be at least a factor of 4 smaller than that of the SM Higgs boson. The channel $gg \rightarrow H \rightarrow \tau^+\tau^-$ would be buried under the current $\tau^+\tau^-$ data.

On the other hand, the $pp \rightarrow b\bar{b}H$ receives a large $\tan \beta$ enhancement. We show the production cross sections for $pp \rightarrow b\bar{b}H$ at the 8 and 14 TeV LHC for $\sin\alpha = 0.01$ and $\tan \beta = 10, 20$ in Fig. 2. The cross section can reach a level of $10 - 100$ pb for $m_H = 130$ GeV.

![Production cross sections for $pp \rightarrow b\bar{b}H$ at the 8 TeV and 14 TeV LHC. The parameters for the 2HDM are chosen as $\sin\alpha = 0.01$ and $\tan \beta = 10$ (dashed) and 20 (solid).](image)

**FIG. 2.** Production cross sections for $pp \rightarrow b\bar{b}H$ at the 8 TeV and 14 TeV LHC. The parameters for the 2HDM are chosen as $\sin\alpha = 0.01$ and $\tan \beta = 10$ (dashed) and 20 (solid).

V. SIGNAL-BACKGROUND ANALYSIS

In the following, we present the signal and backgrounds of $b\bar{b}\tau^+\tau^-$ final state in detector-simulation level by employing the Delphes package [22] inside MADGRAPH [23], with the most general settings for the LHC.

Dominant backgrounds come from $Zb\bar{b}$ and $Zjj$ (when the light-flavored quark jet or gluon jet is misidentified as a $b$ quark) production followed by $Z \rightarrow \tau^+\tau^-$. We employ the
B-tagging with a constant efficiency of 60% and the mistag efficiency from a light-flavored quark or a gluon to be 1% \cite{24}. The selection cuts are

\[
E_{T,j,b} > 30 \text{ GeV}, \; |\eta_{j,b}| < 2.5, \; \Delta R_{jj} > 0.5 \\
p_{T,\tau} > 30 \text{ GeV}, \; |\eta_{\tau}| < 2.5, \; \Delta R_{\tau j} > 0.5
\]  

(5)

We calculate the differential cross sections under these cuts and B-tagging efficiency, and use the Delphes for detector simulation and reconstruction of the tau leptons, b-jets, and the Higgs boson and Z boson peaks.\footnote{The $p_T$ reconstruction requirements for the tau leptons coming from the Higgs decay and from the background are treated differently, in order to correctly reconstruct the mass peak of the Higgs boson and the Z boson. We rescale the distributions to their corresponding cross sections before adjusting the $p_T$.}

We show the continuum background for the sum of $b\bar{b}\tau^+\tau^-$ and $jj\tau^+\tau^-$ versus $M_{\tau^+\tau^-}$ in Fig. 3. The majority of the background comes from the Z boson with a peak around $m_Z$ in the figure. Hypothetical signals of $m_H = 130$ GeV and 300 GeV are added to the background in the figure. The $jj\tau^+\tau^-$ background decreases to a negligible level while the dominant background comes from $b\bar{b}\tau^+\tau^-$. However, the signal for $\tan \beta = 10$ stands somewhat above the background and the signal for $\tan \beta = 20$ is unambiguously discernible. The cross sections under the 130 GeV and 300 GeV Higgs boson $H$ at the 8 TeV LHC are 10 and 1 fb, respectively, for $\tan \beta = 10$, and about a factor of 4 larger for $\tan \beta = 20$. The cross section under the Higgs boson peak should be large enough for observation.

VI. DISCUSSION

We offer a few comments as follows.

1. The process $pp \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\tau^+\nu_\tau\bar{b}\tau^-\bar{\nu}_\tau$ would also give a $b\bar{b}\tau^+\tau^-$ final state, but it can be reduced to a negligible level by requiring no $p_T$ missing.

2. The mass range hinted by the $b\bar{b}$ excess at the Tevatron \cite{5} might be explained by the heavy CP-even Higgs boson $H$ in this scenario with a wide mass range peaked at around 135 GeV.

3. In this work, the $\tau$ identification and reconstruction are taken into account in the Delphes, which has an efficiency similar to actual experiments. The tau efficiency
FIG. 3. Differential cross section $d\sigma/dM_{\tau^+\tau^-}$ versus $M_{\tau^+\tau^-}$ for the continuum background coming from $b\bar{b}\tau^+\tau^-$ and $jj\tau^+\tau^-$ and for the hypothetical signals of the heavier CP-even Higgs boson $H$ of 130 and 300 GeV. Details of detector simulations and normalization are described in the text.

obtained by experiments is around 50% - 60% with the fake rate from jets around 1% [25].

4. The process $pp \rightarrow b\bar{b}H \rightarrow b\bar{b}\tau^+\tau^-$ is also interesting and expected to be enhanced in the model. However the severe QCD continuum background and the combinatorics must also be scrutinized.

5. If the $\tau^+\tau^-$ and $b\bar{b}$ modes continue to be suppressed in the observed 125 GeV Higgs boson, there must be another Higgs-like boson that couples to $b$ and $\tau$. Therefore, $pp \rightarrow b\bar{b}H$ production followed by $H \rightarrow \tau^+\tau^-$ in the $b\bar{b}\tau^+\tau^-$ final state is a rather general channel to probe this scenario. In particular, the $b$ coupling in 2HDM is enhanced by $\tan\beta$ such that the $H$ can be observable at the LHC.

We have shown that if the observed Higgs boson continues to give an enhanced $\gamma\gamma$ rate but a suppressed $\tau^+\tau^-$ rate, it is likely that there exists another heavier CP-even Higgs boson decaying into $\tau^+\tau^-$. We showed in the 2HDM that using the associated production
$bbH$ followed by $H \rightarrow \tau^+\tau^-$ we can detect this heavier CP-even Higgs boson at the LHC. It is of the highest priority that the LHC experiments now search for the $b\bar{b}\tau^+\tau^-$ final state to uncover another Higgs boson.

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