

RECEIVED: February 7, 2015

REVISED: April 5, 2015

ACCEPTED: April 20, 2015

PUBLISHED: May 7, 2015

A light pseudoscalar of 2HDM confronted with muon $g-2$ and experimental constraints

Lei Wang and Xiao-Fang Han

*Department of Physics, Yantai University,
Yantai 264005, P.R. China*

E-mail: leiwang@ytu.edu.cn, xfhan@mail.itp.ac.cn

ABSTRACT: A light pseudoscalar of the lepton-specific 2HDM can enhance the muon $g-2$, but suffer from various constraints easily, such as the 125.5 GeV Higgs signals, non-observation of additional Higgs at the collider and even $B_s \rightarrow \mu^+ \mu^-$. In this paper, we take the light CP-even Higgs as the 125.5 GeV Higgs, and examine the implications of those observables on a pseudoscalar with the mass below the half of 125.5 GeV. Also the other relevant theoretical and experimental constraints are considered. We find that the pseudoscalar can be allowed to be as low as 10 GeV, but the corresponding $\tan \beta$, $\sin(\beta - \alpha)$ and the mass of charged Higgs are strongly constrained. In addition, the surviving samples favor the wrong-sign Yukawa coupling region, namely that the 125.5 GeV Higgs couplings to leptons have opposite sign to the couplings to gauge bosons and quarks.

KEYWORDS: Higgs Physics, Beyond Standard Model

ARXIV EPRINT: [1412.4874](https://arxiv.org/abs/1412.4874)

Contents

| | | |
|----------|--------------------------------|----------|
| 1 | Introduction | 1 |
| 2 | L2HDM | 2 |
| 3 | Numerical calculations | 3 |
| 4 | Results and discussions | 5 |
| 5 | Conclusion | 9 |

1 Introduction

The ATLAS and CMS Collaborations found a 125.5 GeV Higgs boson at the LHC [1, 2]. The latest experimental data show that the properties of this particle agree with the Standard Model (SM) predictions. Especially the diphoton signal strength is changed from 1.6 ± 0.4 to 1.17 ± 0.27 for ATLAS [3] and from $0.78_{-0.16}^{+0.28}$ to $1.12_{-0.32}^{+0.37}$ for CMS [4], which are well consistent with the SM prediction within 1σ range. Thus, the 125.5 GeV Higgs signal data can give the strong constraints on the effects of new physics.

The two-Higgs-doublet model (2HDM) has very rich Higgs phenomenology, including two neutral CP-even Higgs bosons h and H , one neutral pseudoscalar A , and two charged Higgs H^\pm . The recent Higgs data have been used to constrain the 2HDM, see some recent examples [5–27]. In addition, a light pseudoscalar with a large $\tan\beta$ can account for the 3.1σ deviation between the SM predicted and measured values of the muon anomalous magnetic moment [28–32]. Due to the experimental constraints, the type-II 2HDM [33, 34] is very difficult to explain the muon g-2 anomaly [30, 32], but the lepton-specific 2HDM (L2HDM) [35–40] can still give a valid explanation [31, 32]. Compared to the recent study [32], we focus on a light pseudoscalar for which a relative small $\tan\beta$ is required to account for the muon g-2 anomaly. For a light pseudoscalar, the 125.5 GeV Higgs decay into the pseudoscalars is open, and the rare decay $B_s \rightarrow \mu^+\mu^-$ can obtain the additional important contributions from the very light pseudoscalar exchange diagrams. Therefore, the 125.5 GeV Higgs signal data and even $B_s \rightarrow \mu^+\mu^-$ can give the important constraints on the very light pseudoscalar. Also we consider the theoretical constraints, electroweak precision data, the non-observation of additional Higgs at collider, and the flavor observables $B \rightarrow X_s\gamma$, Δm_{B_s} and Δm_{B_d} .

Our work is organized as follows. In section 2 we recapitulate the L2HDM. In section 3 we introduce the numerical calculations. In section 4, we show the implications of muon g-2 and experimental data on the L2HDM. Finally, we give our conclusion in section 5.

2 L2HDM

The general Higgs potential is written as [41]

$$\begin{aligned}
 V = & m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - \left[m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) \right] \\
 & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
 & + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.} \right] + \left[\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \text{h.c.} \right] \\
 & + \left[\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.} \right].
 \end{aligned} \tag{2.1}$$

In this paper we focus on the CP-conserving case where all λ_i and m_{12}^2 are real. In the L2HDM, a discrete Z_2 symmetry is introduced to make $\lambda_6 = \lambda_7 = 0$, and allow for a soft-breaking term with $m_{12}^2 \neq 0$. The two complex scalar doublets have the hypercharge $Y = 1$,

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix}. \tag{2.2}$$

Where the vacuum expectation values (VEVs) $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$, and the ratio of the two VEVs is defined as usual to be $\tan \beta = v_2/v_1$. There are five mass eigenstates: two neutral CP-even h and H , one neutral pseudoscalar A , and two charged scalar H^\pm . We can rotate this basis to the Higgs basis by a mixing angle β , where the VEV of Φ_2 field is zero. In the Higgs basis, the mass eigenstates are obtained from

$$\begin{aligned}
 h &= \sin(\beta - \alpha)\phi_1^0 + \cos(\beta - \alpha)\phi_2^0, \\
 H &= \cos(\beta - \alpha)\phi_1^0 - \sin(\beta - \alpha)\phi_2^0, \\
 A &= a_2, \quad H^\pm = \phi_2^\pm.
 \end{aligned} \tag{2.3}$$

The right fields of the equations denote the interaction eigenstates in the Higgs basis. The corresponding masses and couplings of eq. (2.1) are changed in the Higgs basis [42]. For example, both λ_6 and λ_7 are taken as zero in the physics basis, but the rotation into the Higgs basis can generate non-zero values for λ_6 and λ_7 .

In the Higgs basis, the general Yukawa interactions with no tree-level FCNC are give [43]

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left[M'_d \bar{Q}_L(\Phi_1 + \kappa_d \Phi_2) d_R + M'_u \bar{Q}_L(\tilde{\Phi}_1 + \kappa_u \tilde{\Phi}_2) u_R + M'_\ell \bar{L}_L(\Phi_1 + \kappa_\ell \Phi_2) \ell_R \right] + \text{h.c.}, \tag{2.4}$$

where $\tilde{\Phi}_i(x) = i\tau_2 \Phi_i^*(x)$ and $M'_{d,u,\ell}$ are the Yukawa matrices. For the L2HDM,

$$\kappa_u = \kappa_d = \cot \beta, \quad \kappa_\ell = -\tan \beta. \tag{2.5}$$

The couplings of neutral Higgs bosons with respect to the SM Higgs boson are give by

$$\begin{aligned}
 y_V^h &= \sin(\beta - \alpha), & y_f^h &= \sin(\beta - \alpha) + \cos(\beta - \alpha)\kappa_f, \\
 y_V^H &= \cos(\beta - \alpha), & y_f^H &= \cos(\beta - \alpha) - \sin(\beta - \alpha)\kappa_f, \\
 y_V^A &= 0, & y_u^A &= -i\gamma^5 \kappa_u, & y_{d,\ell}^A &= i\gamma^5 \kappa_{d,\ell}.
 \end{aligned} \tag{2.6}$$

Where V denotes Z and W , and f denotes u , d and ℓ . The charged Higgs couplings are give as

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} [\kappa_d V_{CKM} M_d P_R - \kappa_u M_u V_{CKM} P_L] d + \varsigma_\ell \bar{\nu} M_\ell P_R \ell \right\} + h.c., \quad (2.7)$$

where M_f are the diagonal fermion mass matrices.

3 Numerical calculations

The in-house code is used to calculate the muon g-2, χ^2 fit to 125.5 GeV Higgs signal, $B_s \rightarrow \mu^+ \mu^-$, Δm_{B_s} and Δm_{B_d} . 2HDMC-1.6.5 [44, 45] is employed to implement the theoretical constraints from the vacuum stability, unitarity and coupling-constant perturbativity, and calculate the oblique parameters (S , T , U) and $\delta\rho$. SuperIso-3.4 [46] is used to implement the constraints from $B \rightarrow X_s \gamma$. HiggsBounds-4.1.3 [47, 48] is employed to implement the exclusion constraints from the neutral and charged Higgses searches at the LEP, Tevatron and LHC at 95% confidence level. Now we introduce the calculations of some constraints, which are the main motivations of this paper:

Muon g-2: the recent measurement on the muon anomalous magnetic moment is $a_\mu^{\text{exp}} = (116592091 \pm 63) \times 10^{-11}$ [49], which has approximately 3.1σ deviation from the SM prediction [50, 51], $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (262 \pm 85) \times 10^{-11}$ [32].

In the L2HDM, a_μ gets the additional contributions from the one-loop diagrams induced by the Higgs bosons and also from the two-loop Barr-Zee diagrams mediated by A , h and H . For the one-loop contributions [52–54],

$$\Delta a_\mu^{\text{2HDM}}(\text{1loop}) = \frac{G_F m_\mu^2}{4\pi^2 \sqrt{2}} \sum_j (y_\mu^j)^2 r_\mu^j f_j(r_\mu^j), \quad (3.1)$$

where $j = h, H, A, H^\pm$, $r_\mu^j = m_\mu^2/M_j^2$. For $r_\mu^j \ll 1$,

$$f_{h,H}(r) \simeq -\ln r - 7/6, \quad f_A(r) \simeq \ln r + 11/6, \quad f_{H^\pm}(r) \simeq -1/6. \quad (3.2)$$

For two-loop contributions,

$$\Delta a_\mu^{\text{2HDM}}(\text{2loop} - \text{BZ}) = \frac{G_F m_\mu^2}{4\pi^2 \sqrt{2}} \frac{\alpha_{\text{em}}}{\pi} \sum_{i,f} N_f^c Q_f^2 y_\mu^i y_f^i r_f^i g_i(r_f^i), \quad (3.3)$$

where $i = h, H, A$. m_f , Q_f and N_f^c are the mass, electric charge and number of color degrees of freedom of the fermion f in the loop. The functions $g_i(r)$ are [28–30]

$$g_{h,H}(r) = \int_0^1 dx \frac{2x(1-x) - 1}{x(1-x) - r} \ln \frac{x(1-x)}{r}, \quad g_A(r) = \int_0^1 dx \frac{1}{x(1-x) - r} \ln \frac{x(1-x)}{r}. \quad (3.4)$$

The contributions of the CP-even (CP-odd) Higgses to a_μ are negative (positive) at the two-loop level and positive (negative) at one-loop level. As m_f^2/m_μ^2 could easily overcome the loop suppression factor α/π , the two-loop contributions may be larger than one-loop ones. In the L2HDM, since the CP-odd Higgs coupling to the tau lepton is proportional to $\tan\beta$, the L2HDM can enhance sizably the muon g-2 for a light CP-odd Higgs with a large $\tan\beta$.

Global fit to the 125.5 GeV Higgs signal data: we take the light CP-even Higgs as the 125.5 GeV Higgs. Using the method taken in [55–60], we perform a global fit to the 125.5 GeV Higgs data of 29 channels after ICHEP 2014, which are summarized in the tables I-V of [61]. A number of new measurements or updates of existing ones were presented by ATLAS and CMS Collaborations [3, 4, 62–72]. The signal strength for the i channel is defined as

$$\mu_i = \epsilon_{ggh}^i R_{ggH} + \epsilon_{VBF}^i R_{VBF} + \epsilon_{VH}^i R_{VH} + \epsilon_{t\bar{t}H}^i R_{t\bar{t}H}. \quad (3.5)$$

Where $R_j = \frac{(\sigma \times BR)_j}{(\sigma \times BR)_j^{SM}}$ with j denoting the partonic processes ggH , VBF , VH , and $t\bar{t}H$. ϵ_j^i denotes the assumed signal composition of the partonic process j , which are given in tables I-V of [61]. For an uncorrelated observable i ,

$$\chi_i^2 = \frac{(\mu_i - \mu_i^{\text{exp}})^2}{\sigma_i^2}, \quad (3.6)$$

where μ_i^{exp} and σ_i denote the experimental central value and uncertainty for the i channel. We retain the uncertainty asymmetry in our calculations. For the two correlated observables, we take

$$\chi_{i,j}^2 = \frac{1}{1 - \rho^2} \left[\frac{(\mu_i - \mu_i^{\text{exp}})^2}{\sigma_i^2} + \frac{(\mu_j - \mu_j^{\text{exp}})^2}{\sigma_j^2} - 2\rho \frac{(\mu_i - \mu_i^{\text{exp}})(\mu_j - \mu_j^{\text{exp}})}{\sigma_i \sigma_j} \right], \quad (3.7)$$

where ρ is the correlation coefficient. We sum over χ^2 of the 29 channels, and pay particular attention to the surviving samples with $\chi^2 - \chi_{\min}^2 \leq 6.18$, where χ_{\min}^2 denotes the minimum of χ^2 . These samples correspond to the 95.4% confidence level regions in any two dimensional plane of the model parameters when explaining the Higgs data (corresponding to be within 2σ range).

$B_s \rightarrow \mu^+ \mu^-$: the LHCb [73] and CMS [74] measurements lead to the weighted average, $\bar{B}(B_s \rightarrow \mu^+ \mu^-)_{\text{exp}} = (2.9 \pm 0.7) \times 10^{-9}$ [75], which is well agreement with the latest SM prediction, $\bar{B}(B_s \rightarrow \mu^+ \mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9}$ [76]. Recently, ref. [77] presents a complete one-loop calculation of the contributions of Aligned 2HDM to $B_s \rightarrow \mu^+ \mu^-$. Following the method taken in ref. [77], we define

$$\bar{R}_{s\mu} \equiv \frac{\bar{B}(B_s \rightarrow \mu^+ \mu^-)}{\bar{B}(B_s \rightarrow \mu^+ \mu^-)_{SM}} = \left[|P|^2 + \left(1 - \frac{\Delta\Gamma_s}{\Gamma_L^s}\right) |S|^2 \right], \quad (3.8)$$

where the CKM matrix elements and hadronic factors cancel out. Combining the SM prediction with the experimental result, $\bar{R}_{s\mu} = 0.79 \pm 0.2$ is required.

$$P \equiv \frac{C_{10}}{C_{10}^{SM}} + \frac{M_{B_s}^2}{2M_W^2} \left(\frac{m_b}{m_b + m_s} \right) \frac{C_P - C_P^{SM}}{C_{10}^{SM}}, \quad (3.9)$$

$$S \equiv \sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}} \frac{M_{B_s}^2}{2M_W^2} \left(\frac{m_b}{m_b + m_s} \right) \frac{C_S - C_S^{SM}}{C_{10}^{SM}}. \quad (3.10)$$

The 2HDM can give the additional contributions to coefficient C_{10} by the Z -penguin diagrams with the charged Higgs loop. Unless there are large enhancements for C_P and C_S , their contributions can be neglected due to the suppression of the factor $M_{B_s}^2/M_W^2$. For example, the C_P and C_S of type-II 2HDM can be dominant due to the enhancement of the large $\tan^2 \beta$ terms [78, 79]. Although such large $\tan^2 \beta$ terms are absent in the L2HDM, C_P can obtain the important contributions from the CP-odd Higgs exchange diagrams for m_A is very small. Such contributions are also sensitive to m_{H^\pm} and small $\tan \beta$. For the large $\tan \beta$, the terms proportional to $\cot \beta$ and the higher order terms can be neglected.

Using the formulas in [77], we calculate the parameter P and S in the L2HDM. Note that the mixing of two CP-even Higgses in this paper is different from [77], therefore some corresponding couplings need be replaced.

In our calculations, $m_h = 125.5$ GeV is fixed, and the input parameters are $\sin(\beta - \alpha)$, $\tan \beta$, the physical Higgs masses (m_H, m_A, m_{H^\pm}) and the coupling of hAA (λ_{hAA}), where λ_{hAA} is used to replace the soft-breaking parameter m_{12}^2 . We focus on $5 \text{ GeV} < m_A < 62.75 \text{ GeV}$, and such light CP-odd Higgs will be more strongly constrained, especially for the 125.5 GeV Higgs signal. Assuming that the Higgs couplings to fermions and gauge bosons are the same as the SM, $Br(h \rightarrow AA)$ is larger than 40% for $|\lambda_{hAA}| > 20 \text{ GeV}$ and $m_A < 62.5 \text{ GeV}$. Therefore, we scan λ_{hAA} in the range of $-20 \text{ GeV} \sim 20 \text{ GeV}$. In addition to that the theoretical constraints are satisfied, we require the L2HDM to explain the experimental data within the 2σ range, and fit the current Higgs signal data at the 2σ level. The experimental values of electroweak precision data, $B \rightarrow X_s \gamma$, Δm_{B_s} and Δm_{B_d} are taken from [80].

4 Results and discussions

Without the constraint of muon g-2, we find a surviving sample with a minimal value of χ^2 fit to the Higgs signal data, $\chi_{\min}^2 \simeq 16.95$, which is slightly smaller than SM value, 17.0. The corresponding input parameters are,

$$\begin{aligned} \sin(\beta - \alpha) &\simeq -0.999994, & \tan \beta &\simeq 5.16, & m_h &= 125.5 \text{ GeV}, & m_H &\simeq 130.35 \text{ GeV}, \\ m_A &= 61.50 \text{ GeV}, & m_{H^\pm} &= 146.21 \text{ GeV}, \\ \lambda_{hAA} &\simeq -0.47 \text{ GeV} & (m_{12}^2 &= 2174.84 \text{ GeV}^2). \end{aligned} \tag{4.1}$$

Our numerical results show that for the surviving samples within the 2σ range of χ^2 , $Br(h \rightarrow AA)$ is required to be smaller than 24%. Considering the constraint of muon g-2, the minimal value is $\chi_{\min}^2 \simeq 17.21$ and the input parameters are

$$\begin{aligned} \sin(\beta - \alpha) &\simeq 0.999712, & \tan \beta &\simeq 84.90, & m_h &= 125.5 \text{ GeV}, & m_H &\simeq 504.34 \text{ GeV}, \\ m_A &= 57.00 \text{ GeV}, & m_{H^\pm} &= 509.18 \text{ GeV}, \\ \lambda_{hAA} &\simeq -0.95 \text{ GeV} & (m_{12}^2 &= 2995.28 \text{ GeV}^2). \end{aligned} \tag{4.2}$$

In figure 1, we project the surviving samples on the plane of $\sin(\beta - \alpha)$ versus $\tan \beta$. Without the constraint of muon g-2, the surviving samples lie in two different regions. In

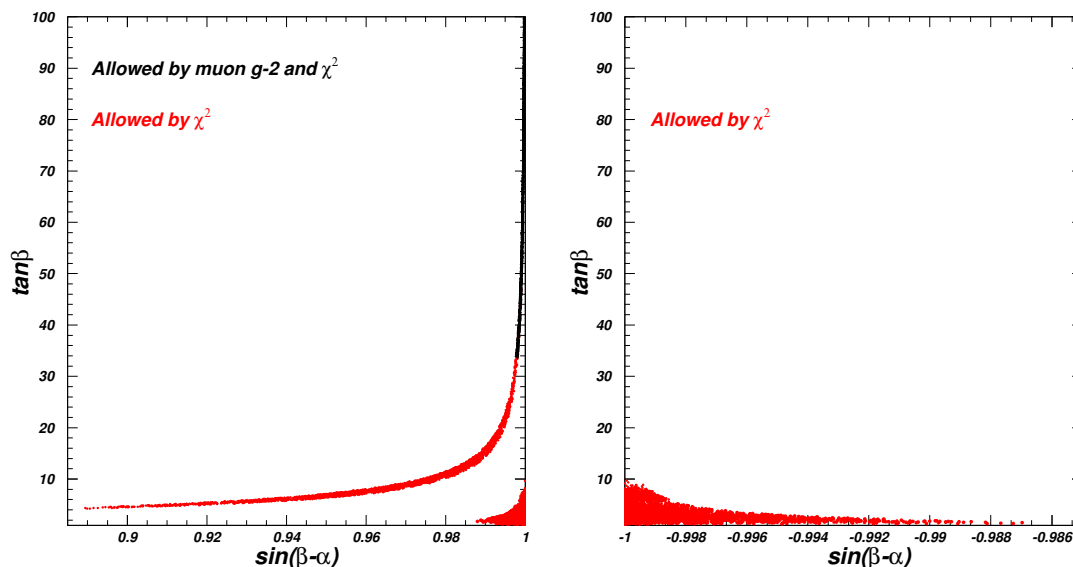


Figure 1. The scatter plots of surviving samples projected on the plane of $\sin(\beta - \alpha)$ versus $\tan \beta$.

one region, the 125.5 GeV Higgs couplings are near the SM values, called the SM-like region. In the other region, the Higgs couplings to leptons have opposite sign to the corresponding couplings to VV , called the wrong-sign Yukawa coupling region. In the SM-like region, the absolute value of $\sin(\beta - \alpha)$ is required to be larger than 0.986, while $\sin(\beta - \alpha)$ is allowed to have more sizable deviation from 1.0 in the wrong-sign Yukawa coupling region, $\sin(\beta - \alpha) > 0.89$. This can be understandable from the Higgs couplings to leptons. For the wrong-sign Yukawa coupling and SM-like Yukawa coupling, the Higgs couplings to lepton are respectively

$$\sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) = -1 + \varepsilon, \quad \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) = 1 - \varepsilon, \quad (4.3)$$

where the absolute value of ε is much smaller than 1.0. For $\sin(\beta - \alpha)$ approaches to 1.0, $\cos(\beta - \alpha)$ of the former is much larger than that of the latter for the same $\tan \beta$.

Including the constraint of muon g-2, the surviving samples favor the wrong-sign Yukawa coupling region. The corresponding $\sin(\beta - \alpha)$ approaches to 1.0 as increasing of $\tan \beta$, leading a small $\cos(\beta - \alpha)$ which ensures the absolute value of the coupling $h\ell\bar{\ell}$ around SM value. To account for the muon g-2, L2HDM has to provide a very large pseudoscalar coupling to lepton, and $\tan \beta$ is required to be larger than 34 as shown in the left panel of figure 1. For such large $\tan \beta$, eq. (4.3) shows that y_ℓ^h is much smaller than -1.0 for $\sin(\beta - \alpha)$ approaches to -1.0 . As a result, the absolute value of the 125.5 GeV Higgs couplings to leptons have the sizable deviations from SM predictions, which is excluded by the 2σ range of χ^2 . In addition, according to eq. (4.3), such large $\tan \beta$ leads to $y_\ell^h < 0$ although $\sin(\beta - \alpha)$ approaches to 1.0. Therefore, the surviving samples lie in the wrong-sign Yukawa coupling region.

In figure 2, the surviving samples are projected on the planes of Higgs couplings. The Higgs couplings to VV and quarks are very closed to SM values, but the Higgs couplings

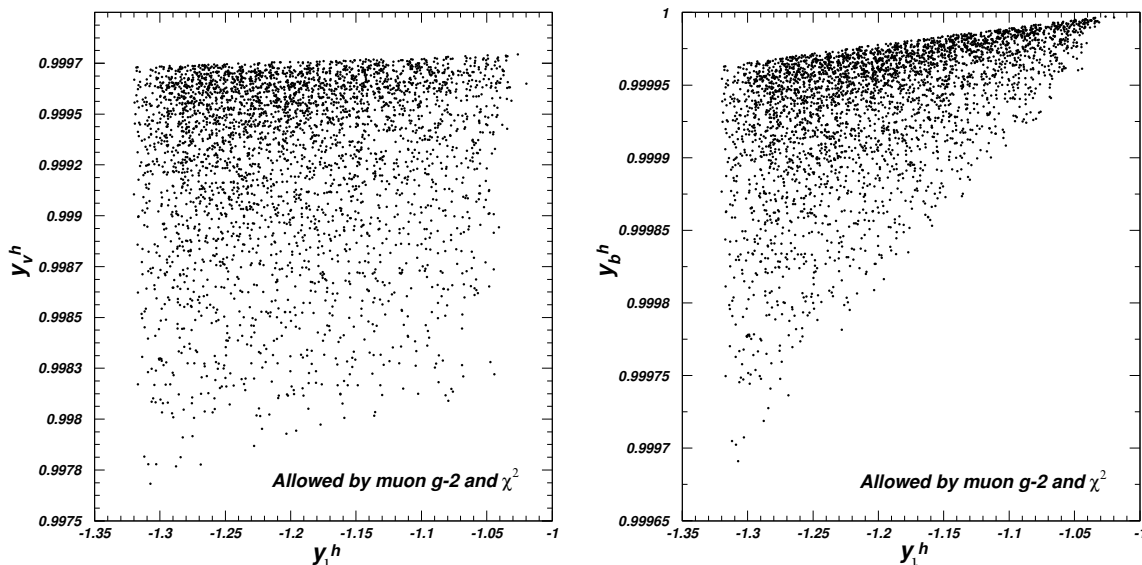


Figure 2. The scatter plots of surviving samples with the 2σ ranges of muon $g-2$ and χ^2 projected on the planes of the coupling $h\ell\bar{\ell}$ versus hVV , and $h\ell\bar{\ell}$ versus $hb\bar{b}$, respectively.

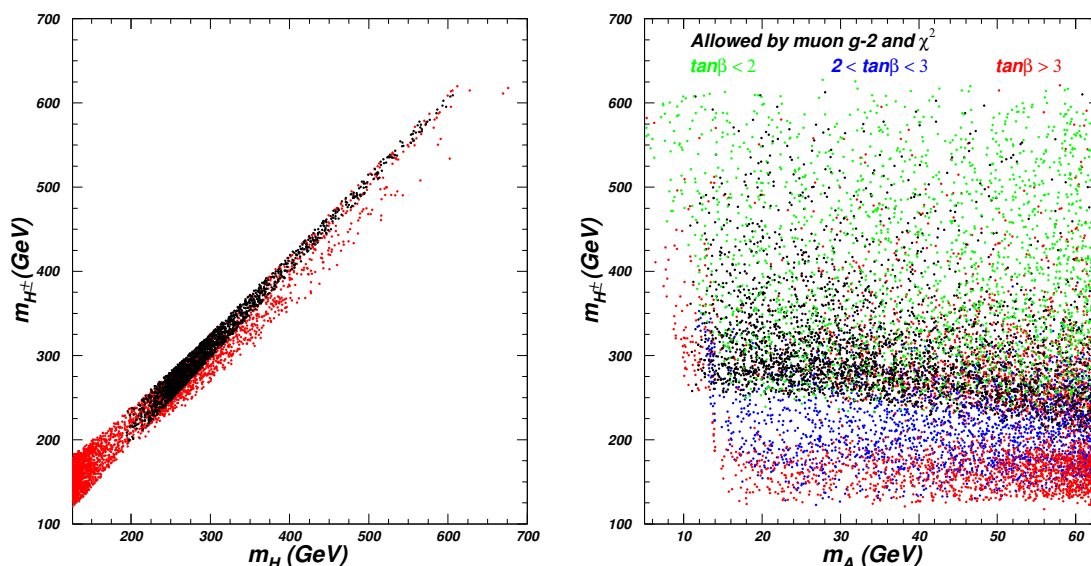


Figure 3. Left panel: same as figure 1, but projected on the plane of m_H versus m_{H^\pm} . Right panel: The scatter plots of surviving samples within the 2σ range of χ^2 projected on the plane of m_A versus m_{H^\pm} .

to leptons have the opposite sign to the SM values, and over 30% deviation from the SM values.

In figure 3, the surviving samples are projected on the planes of m_H versus m_{H^\pm} and m_A versus m_{H^\pm} , respectively. The left panel shows that there is a small mass difference between m_H and m_{H^\pm} for the surviving samples, especially for including the constraint of muon $g-2$. Such small mass difference is mainly required by the electroweak parameter ρ to produce a pseudoscalar with mass in the range of $5 \text{ GeV} \sim 62.75 \text{ GeV}$. As shown in figure 1,

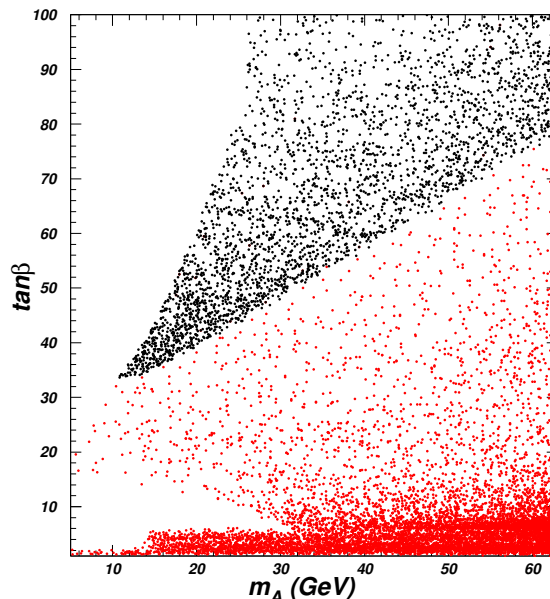


Figure 4. Same as figure 1, but projected on the plane of m_A versus $\tan\beta$.

the experimental data of muon $g-2$ require $\tan\beta > 34$. For such large $\tan\beta$, the charged Higgs has a very large coupling to lepton, and the search experiments of charged Higgs give the lower bound of the charged Higgs mass, $m_{H^\pm} > 200$ GeV. Due to the small mass difference between m_H and m_{H^\pm} induced by the parameter ρ , m_H is required to be larger than 200 GeV. In ref. [32], the authors took the limiting case of $\beta - \alpha = \frac{\pi}{2}$ and several fixed values of $m_H - m_{H^\pm}$ and λ_1 , and found that the theoretical constraints and electroweak precision data give the upper bound of charged Higgs, $m_{H^\pm} \leq 200$ GeV for $m_A < 100$ GeV. In this paper, we scan the whole parameter space, and find that m_{H^\pm} is allowed to be as high as 600 GeV. Our results are consistent with those of many other papers, such as ref. [6], ref. [18] and ref. [31].

The right panel shows that $\tan\beta$ is required to be larger than 2.0 for $m_{H^\pm} < 230$ GeV, and the main constraints are from the flavor observables Δm_{B_s} and Δm_{B_d} . In addition, for $m_A < 16$ GeV, there is strong correlation between m_A and m_{H^\pm} due to the constraint of $B_s \rightarrow \mu^+\mu^-$. In particular, m_{H^\pm} is required to be larger than 450 GeV for $\tan\beta < 2$ and $m_A < 10$ GeV, and m_{H^\pm} is allowed to be sharply decreased with the increasing of m_A . For $m_A > 20$ GeV, the contributions from the exchange of A diagrams to the coefficient C_P are difficult to overcome the suppression factor $M_{B_s}^2/M_W^2$, therefore $B_s \rightarrow \mu^+\mu^-$ is not sensitive to m_A . Also the constraint of $B_s \rightarrow \mu^+\mu^-$ on m_A and m_{H^\pm} can be relaxed by a modest large $\tan\beta$, but not sensitive to the enough large $\tan\beta$. Including the constraint of muon $g-2$, m_A is allowed to be as low as 10 GeV, but the corresponding m_{H^\pm} is required to be larger than 250 GeV.

In figure 4, the surviving samples are projected on the plane of m_A versus $\tan\beta$. For $m_A < 26$ GeV, the upper bound of $\tan\beta$ is strongly constrained by the exclusion experiments of Higgs at the collider, and some intermediate values are excluded by the 2σ constraint of χ^2 fit to the Higgs signal. Including the constraint of muon $g-2$, the range of $\tan\beta$ is sizably narrowed with m_A approaching to 10 GeV.

5 Conclusion

In the L2HDM, a light pseudoscalar with a large $\tan\beta$ can account for the muon g-2 anomaly. Assuming that the light CP-even Higgs is the 125.5 GeV Higgs, we study the implications of the relevant theoretical and experimental constraints on a pseudoscalar with the mass below the half of 125.5 GeV, especially for the muon g-2 anomaly, 125.5 GeV Higgs signal and $B_s \rightarrow \mu^+\mu^-$. We find that the pseudoscalar can be allowed to be as low as 10 GeV, and $\tan\beta$ is required to be larger than 34. As the increasing of $\tan\beta$, $\sin(\beta - \alpha)$ is very closed to 1.0. For m_A approaches to 10 GeV, the range of $\tan\beta$ is sizably narrowed, and m_{H^\pm} is required to be larger than 250 GeV. In addition, the 125.5 GeV Higgs couplings to leptons are favored to have opposite sign to the couplings to gauge bosons and quarks, and over 30% deviation from the SM values.

Acknowledgments

We would like to thank Xin-Qiang Li for helpful discussions. This work was supported by the National Natural Science Foundation of China (NNSFC) under grant No. 11105116.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [[arXiv:1207.7235](https://arxiv.org/abs/1207.7235)] [[INSPIRE](#)].
- [2] ATLAS collaboration, *Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [[arXiv:1207.7214](https://arxiv.org/abs/1207.7214)] [[INSPIRE](#)].
- [3] ATLAS collaboration, *Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, *Phys. Rev. D* **90** (2014) 112015 [[arXiv:1408.7084](https://arxiv.org/abs/1408.7084)] [[INSPIRE](#)].
- [4] CMS collaboration, *Observation of the diphoton decay of the Higgs boson and measurement of its properties*, *Eur. Phys. J. C* **74** (2014) 3076 [[arXiv:1407.0558](https://arxiv.org/abs/1407.0558)] [[INSPIRE](#)].
- [5] J. Bernon, J.F. Gunion, Y. Jiang and S. Kraml, *Light Higgs bosons in two-Higgs-doublet models*, *Phys. Rev. D* **91** (2015) 075019 [[arXiv:1412.3385](https://arxiv.org/abs/1412.3385)] [[INSPIRE](#)].
- [6] B. Dumont, J.F. Gunion, Y. Jiang and S. Kraml, *Constraints on and future prospects for two-Higgs-doublet models in light of the LHC Higgs signal*, *Phys. Rev. D* **90** (2014) 035021 [[arXiv:1405.3584](https://arxiv.org/abs/1405.3584)] [[INSPIRE](#)].
- [7] P.M. Ferreira, R. Guedes, M.O.P. Sampaio and R. Santos, *Wrong sign and symmetric limits and non-decoupling in 2HDMs*, *JHEP* **12** (2014) 067 [[arXiv:1409.6723](https://arxiv.org/abs/1409.6723)] [[INSPIRE](#)].
- [8] P.S.B. Dev and A. Pilaftsis, *Maximally symmetric two Higgs doublet model with natural standard model alignment*, *JHEP* **12** (2014) 024 [[arXiv:1408.3405](https://arxiv.org/abs/1408.3405)] [[INSPIRE](#)].

- [9] L. Wang and X.-F. Han, *Study of the heavy CP-even Higgs with mass 125 GeV in two-Higgs-doublet models at the LHC and ILC*, *JHEP* **11** (2014) 085 [[arXiv:1404.7437](#)] [[INSPIRE](#)].
- [10] L. Wang and X.-F. Han, *A simplified 2HDM with a scalar dark matter and the galactic center gamma-ray excess*, *Phys. Lett. B* **739** (2014) 416 [[arXiv:1406.3598](#)] [[INSPIRE](#)].
- [11] B. Grzadkowski, O.M. Ogreid and P. Osland, *Measuring CP-violation in Two-Higgs-Doublet models in light of the LHC Higgs data*, *JHEP* **11** (2014) 084 [[arXiv:1409.7265](#)] [[INSPIRE](#)].
- [12] S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, *Fingerprinting nonminimal Higgs sectors*, *Phys. Rev. D* **90** (2014) 075001 [[arXiv:1406.3294](#)] [[INSPIRE](#)].
- [13] A. Kobakhidze, L. Wu and J. Yue, *Anomalous top-Higgs couplings and top polarisation in single top and Higgs associated production at the LHC*, *JHEP* **10** (2014) 100 [[arXiv:1406.1961](#)] [[INSPIRE](#)].
- [14] B. Hespel, D. Lopez-Val and E. Vryonidou, *Higgs pair production via gluon fusion in the two-Higgs-doublet model*, *JHEP* **09** (2014) 124 [[arXiv:1407.0281](#)] [[INSPIRE](#)].
- [15] J. Baglio, O. Eberhardt, U. Nierste and M. Wiebusch, *Benchmarks for Higgs boson pair production and heavy Higgs boson searches in the two-Higgs-doublet model of type II*, *Phys. Rev. D* **90** (2014) 015008.
- [16] K. Cheung, J.S. Lee and P.-Y. Tseng, *Higgcision in the two-Higgs doublet models*, *JHEP* **01** (2014) 085 [[arXiv:1310.3937](#)] [[INSPIRE](#)].
- [17] P.M. Ferreira, J.F. Gunion, H.E. Haber and R. Santos, *Probing wrong-sign Yukawa couplings at the LHC and a future linear collider*, *Phys. Rev. D* **89** (2014) 115003 [[arXiv:1403.4736](#)] [[INSPIRE](#)].
- [18] B. Coleppa, F. Kling and S. Su, *Constraining type II 2HDM in light of LHC Higgs searches*, *JHEP* **01** (2014) 161 [[arXiv:1305.0002](#)] [[INSPIRE](#)].
- [19] X.-D. Cheng, Y.-D. Yang and X.-B. Yuan, *Phenomenological discriminations of the Yukawa interactions in two-Higgs doublet models with Z_2 symmetry*, *Eur. Phys. J. C* **74** (2014) 3081 [[arXiv:1401.6657](#)] [[INSPIRE](#)].
- [20] Y.-n. Mao and S.-h. Zhu, *Lightness of Higgs boson and spontaneous CP-violation in the Lee model*, *Phys. Rev. D* **90** (2014) 115024 [[arXiv:1409.6844](#)] [[INSPIRE](#)].
- [21] N. Chen, J. Li, Y. Liu and Z. Liu, *LHC searches for the CP-odd Higgs by the jet substructure analysis*, *Phys. Rev. D* **91** (2015) 075002 [[arXiv:1410.4447](#)] [[INSPIRE](#)].
- [22] A. Celis, V. Ilisie and A. Pich, *Towards a general analysis of LHC data within two-Higgs-doublet models*, *JHEP* **12** (2013) 095.
- [23] C.-Y. Chen and S. Dawson, *Exploring two Higgs doublet models through Higgs Production*, *Phys. Rev. D* **87** (2013) 055016 [[arXiv:1301.0309](#)] [[INSPIRE](#)].
- [24] V. Barger, L.L. Everett, H.E. Logan and G. Shaughnessy, *Scrutinizing the 125 GeV Higgs boson in two Higgs doublet models at the LHC, ILC and Muon Collider*, *Phys. Rev. D* **88** (2013) 115003 [[arXiv:1308.0052](#)] [[INSPIRE](#)].
- [25] X.-F. Wang, C. Du and H.-J. He, *LHC Higgs signatures from topflavor seesaw mechanism*, *Phys. Lett. B* **723** (2013) 314 [[arXiv:1304.2257](#)] [[INSPIRE](#)].
- [26] T. Abe, N. Chen and H.-J. He, *LHC Higgs signatures from extended electroweak gauge symmetry*, *JHEP* **01** (2013) 082 [[arXiv:1207.4103](#)] [[INSPIRE](#)].

- [27] J. Shu and Y. Zhang, *Impact of a CP-violating Higgs sector: from LHC to baryogenesis*, *Phys. Rev. Lett.* **B 111** (2013) 091801.
- [28] D. Chang, W.-F. Chang, C.-H. Chou and W.-Y. Keung, *Large two loop contributions to $g-2$ from a generic pseudoscalar boson*, *Phys. Rev.* **D 63** (2001) 091301 [[hep-ph/0009292](#)] [[INSPIRE](#)].
- [29] K.-m. Cheung, C.-H. Chou and O.C.W. Kong, *Muon anomalous magnetic moment, two Higgs doublet model and supersymmetry*, *Phys. Rev.* **D 64** (2001) 111301 [[hep-ph/0103183](#)] [[INSPIRE](#)].
- [30] K. Cheung and O.C.W. Kong, *Can the two Higgs doublet model survive the constraint from the muon anomalous magnetic moment as suggested?*, *Phys. Rev.* **D 68** (2003) 053003 [[hep-ph/0302111](#)] [[INSPIRE](#)].
- [31] J. Cao, P. Wan, L. Wu and J.M. Yang, *Lepton-specific two-Higgs doublet model: experimental constraints and implication on Higgs phenomenology*, *Phys. Rev.* **D 80** (2009) 071701 [[arXiv:0909.5148](#)] [[INSPIRE](#)].
- [32] A. Broggio, E.J. Chun, M. Passera, K.M. Patel and S.K. Vempati, *Limiting two-Higgs-doublet models*, *JHEP* **11** (2014) 058 [[arXiv:1409.3199](#)] [[INSPIRE](#)].
- [33] L.J. Hall and M.B. Wise, *Flavor changing Higgs-boson couplings*, *Nucl. Phys.* **B 187** (1981) 397 [[INSPIRE](#)].
- [34] J.F. Donoghue and L.F. Li, *Properties of charged Higgs bosons*, *Phys. Rev.* **D 19** (1979) 945 [[INSPIRE](#)].
- [35] V.D. Barger, J.L. Hewett and R.J.N. Phillips, *New constraints on the charged Higgs sector in two Higgs doublet models*, *Phys. Rev.* **D 41** (1990) 3421 [[INSPIRE](#)].
- [36] J. Bagger, E. Poppitz and L. Randall, *The R axion from dynamical supersymmetry breaking*, *Nucl. Phys.* **B 426** (1994) 3 [[hep-ph/9405345](#)] [[INSPIRE](#)].
- [37] A.G. Akeroyd and W.J. Stirling, *Light charged Higgs scalars at high-energy e^+e^- colliders*, *Nucl. Phys.* **B 447** (1995) 3 [[INSPIRE](#)].
- [38] A.G. Akeroyd, *Nonminimal neutral Higgs bosons at LEP-2*, *Phys. Lett.* **B 377** (1996) 95 [[hep-ph/9603445](#)] [[INSPIRE](#)].
- [39] A.G. Akeroyd, *Fermiophobic and other nonminimal neutral Higgs bosons at the LHC*, *J. Phys.* **G 24** (1998) 1983 [[hep-ph/9803324](#)] [[INSPIRE](#)].
- [40] M. Aoki, S. Kanemura, K. Tsumura and K. Yagyu, *Models of Yukawa interaction in the two Higgs doublet model and their collider phenomenology*, *Phys. Rev.* **D 80** (2009) 015017 [[arXiv:0902.4665](#)] [[INSPIRE](#)].
- [41] R.A. Battye, G.D. Brawn and A. Pilaftsis, *Vacuum topology of the two Higgs doublet model*, *JHEP* **08** (2011) 020 [[arXiv:1106.3482](#)] [[INSPIRE](#)].
- [42] S. Davidson and H.E. Haber, *Basis-independent methods for the two-Higgs-doublet model*, *Phys. Rev.* **D 72** (2005) 035004 [[hep-ph/0504050](#)] [[INSPIRE](#)].
- [43] A. Pich and P. Tuzon, *Yukawa alignment in the two-Higgs-doublet model*, *Phys. Rev.* **D 80** (2009) 091702 [[arXiv:0908.1554](#)] [[INSPIRE](#)].
- [44] D. Eriksson, J. Rathsman and O. Stål, *2HDMC — Two-Higgs-doublet model calculator*, *Chin. Phys.* **C 181** (2010) 189 [*Erratum ibid.* **C 181** (2010) 985].
- [45] D. Eriksson, J. Rathsman and O. Stål, *2HDMC — Two-Higgs-doublet model calculator*, *Chin. Phys.* **C 181** (2010) 833.

- [46] F. Mahmoudi, *SuperIso v2.3: a program for calculating flavor physics observables in supersymmetry*, *Chin. Phys. C* **180** (2009) 1579.
- [47] P. Bechtle et al., *HiggsBounds: confronting arbitrary Higgs sectors with exclusion bounds from LEP and the Tevatron*, *Chin. Phys. C* **181** (2010) 138.
- [48] P. Bechtle et al., *HiggsBounds-4: improved tests of extended Higgs sectors against exclusion bounds from LEP, the Tevatron and the LHC*, *Eur. Phys. J. C* **74** (2014) 2693 [[arXiv:1311.0055](#)] [[INSPIRE](#)].
- [49] MUON G-2 collaboration, G.W. Bennett et al., *Final report of the muon E821 anomalous magnetic moment measurement at BNL*, *Phys. Rev. D* **73** (2006) 072003 [[hep-ex/0602035](#)] [[INSPIRE](#)].
- [50] F. Jegerlehner and A. Nyffeler, *The muon $g - 2$* , *Phys. Rev.* **477** (2009) 1 [[arXiv:0902.3360](#)] [[INSPIRE](#)].
- [51] A. Kurz, T. Liu, P. Marquard and M. Steinhauser, *Hadronic contribution to the muon anomalous magnetic moment to next-to-next-to-leading order*, *Phys. Lett. B* **734** (2014) 144 [[arXiv:1403.6400](#)] [[INSPIRE](#)].
- [52] B. Lautrup, A. Peterman and E. de Rafael, *The muon $g - 2$ precession experiments: past, present and future*, *Phys. Rept.* **3** (1972) 193.
- [53] J.P. Leveille, *The second order weak correction to $g - 2$ of the muon in arbitrary gauge models*, *Nucl. Phys. B* **137** (1978) 63 [[INSPIRE](#)].
- [54] A. Dedes and H.E. Haber, *Can the Higgs sector contribute significantly to the muon anomalous magnetic moment?*, *JHEP* **05** (2001) 006 [[hep-ph/0102297](#)] [[INSPIRE](#)].
- [55] J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, *Fingerprinting Higgs suspects at the LHC*, *JHEP* **05** (2012) 097.
- [56] G. Bélanger, B. Dumont, U. Ellwanger, J.F. Gunion and S. Kraml, *Higgs couplings at the end of 2012*, *JHEP* **02** (2013) 053 [[arXiv:1212.5244](#)] [[INSPIRE](#)].
- [57] P.P. Giardino, K. Kannike, M. Raidal and A. Strumia, *Reconstructing Higgs boson properties from the LHC and Tevatron data*, *JHEP* **06** (2012) 117 [[arXiv:1203.4254](#)] [[INSPIRE](#)].
- [58] B. Dumont, S. Fichet and G. von Gersdorff, *A bayesian view of the Higgs sector with higher dimensional operators*, *JHEP* **07** (2013) 065 [[arXiv:1304.3369](#)] [[INSPIRE](#)].
- [59] J.-J. Cao, Z.-X. Heng, J.M. Yang, Y.-M. Zhang and J.-Y. Zhu, *A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM*, *JHEP* **03** (2012) 086 [[arXiv:1202.5821](#)] [[INSPIRE](#)].
- [60] K. Cheung, J.S. Lee and P.-Y. Tseng, *Higgs precision (higgcision) era begins*, *JHEP* **05** (2013) 134 [[arXiv:1302.3794](#)] [[INSPIRE](#)].
- [61] K. Cheung, J.S. Lee and P.-Y. Tseng, *Higgs precision analysis updates 2014*, *Phys. Rev. D* **90** (2014) 095009 [[arXiv:1407.8236](#)] [[INSPIRE](#)].
- [62] ATLAS collaboration, *Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data*, *Phys. Rev. D* **90** (2014) 052004 [[arXiv:1406.3827](#)] [[INSPIRE](#)].
- [63] C. Mills, *Measurement of cross sections and couplings of the Higgs boson in the WW decay channel using the ATLAS detector*, talk given at the 37th International Conference on High Energy Physics (ICHEP2014), July 2–9, Valencia, Spain (2014).

- [64] E. Shabalina, *Search for Higgs Bosons produced in association with top quarks with the ATLAS detector*, talk given at the 37th International Conference on High Energy Physics (ICHEP2014), July 2–9, Valencia, Spain (2014).
- [65] M. Kado, *Physics of the Brout-Englert-Higgsboson in ATLAS*, talk given at the 37th International Conference on High Energy Physics (ICHEP2014), July 2–9, Valencia, Spain (2014).
- [66] CMS collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state*, *Phys. Rev. D* **89** (2014) 092007 [[arXiv:1312.5353](#)] [[INSPIRE](#)].
- [67] CMS collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, *JHEP* **01** (2014) 096 [[arXiv:1312.1129](#)] [[INSPIRE](#)].
- [68] CMS collaboration, *Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks*, *Phys. Rev. D* **89** (2014) 012003 [[arXiv:1310.3687](#)] [[INSPIRE](#)].
- [69] CMS collaboration, *Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons*, *JHEP* **05** (2014) 104 [[arXiv:1401.5041](#)] [[INSPIRE](#)].
- [70] CMS collaboration, *Search for $t\bar{t}H$ production using the matrix element method*, [CMS-PAS-HIG-14-010](#) (2014).
- [71] A. David, *Physics of the Brout-Englert-Higgsboson in CMS*, talk given at the 37th International Conference on High Energy Physics (ICHEP2014), July 2–9, Valencia, Spain (2014).
- [72] K. Herberichs, *Studies of the Higgs boson properties at D0*, talk given at the 37th International Conference on High Energy Physics (ICHEP2014), July 2–9, Valencia, Spain (2014).
- [73] LHCb collaboration, *Measurement of the $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+\mu^-$ decays at the LHCb experiment*, *Phys. Rev. Lett.* **111** (2013) 101805 [[arXiv:1307.5024](#)] [[INSPIRE](#)].
- [74] CMS collaboration, *Measurement of the $B_s \rightarrow \mu^+\mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+\mu^-$ with the CMS experiment*, *Phys. Rev. Lett.* **111** (2013) 101804 [[arXiv:1307.5025](#)] [[INSPIRE](#)].
- [75] CMS and LHCb collaborations, *Combination of results on the rare decays $B_{(s)}^0 \rightarrow \mu^+\mu^-$ from the CMS and LHCb experiments*, [CMS-PAS-BPH-13-007](#) (2014).
- [76] C. Bobeth et al., *$B_{s,d} \rightarrow l^+l^-$ in the standard model with reduced theoretical uncertainty*, *Phys. Rev. Lett.* **112** (2014) 101801 [[INSPIRE](#)].
- [77] X.-Q. Li, J. Lu and A. Pich, *$B_{s,d}^0 \rightarrow \ell^+\ell^-$ decays in the aligned two-Higgs-doublet model*, *JHEP* **06** (2014) 022 [[arXiv:1404.5865](#)] [[INSPIRE](#)].
- [78] H.E. Logan and U. Nierste, *$B_{s,d} \rightarrow \ell^+\ell^-$ in a two Higgs doublet model*, *Nucl. Phys. B* **586** (2000) 39 [[hep-ph/0004139](#)] [[INSPIRE](#)].
- [79] C.-S. Huang, W. Liao and Q.-S. Yan, *The promising process to distinguish supersymmetric models with large $\tan\beta$ from the standard model: $B \rightarrow X_s\mu^+\mu^-$* , *Phys. Rev. D* **59** (1999) 011701 [[hep-ph/9803460](#)] [[INSPIRE](#)].
- [80] PARTICLE DATA GROUP collaboration, K.A. Olive et al., *Review of particle physics*, *Chin. Phys. C* **38** (2014) 090001.