Electroweak Phase Transition in 2HDM under Higgs, Z-pole, and W precision measurements

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ABSTRACT: In this work we revisit the existence of a strong first order electroweak phase transition (SFOEWPT) and recent $m_W$ precision measurement in the Type-I and Type-II 2HDMs. The $\mathcal{O}(100)$ GeV new scalars in 2HDMs are favored by SFOEWPT, which is necessary for electroweak baryogenesis, and observed $m_W$ shift as well. We find that under current constraints, both Type-I and Type-II 2HDM can explain the SFOEWPT, Z-pole, Higgs precision measurements and $m_W$ precision measurement of CDF-II at same time, and all these precision measurements are sensitive to heavy Higgs mass splitting in 2HDM. The allowed regions are $\Delta m_{A/C} \in (-400, 400) \text{ GeV}, \tan \beta \in (1, 50)$, and $\Delta m_{A/C} \in (-200, 300) \text{ GeV}, \tan \beta \in (1, 12)$ for Type-I and Type-II 2HDM respectively. Furthermore future lepton collider measurements on Higgs and $Z$ boson properties can explore this scenario in more detail or even rule out it.
1 Introduction

With the discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012 [1, 2], particle physics has been entering a new era. Due to the lack of direct search result at LHC, precision studies of particle physics are becoming important. The current measurements of particle properties seem to be consistent with all other categories of experiments and can be described by the Standard Model (SM) quite well. Meanwhile there are compelling arguments, both from theoretical and observational viewpoints, in favor of new physics beyond the Standard Model (BSM). The CDF collaboration has recently reported a precise measurement of the $W$ boson mass, which indicates a significant tension with the previous measurements and the SM prediction [3]. Although this result needs to be further confirmed by other experiments, such as D0, ATLAS, and CMS, it is still an exciting possible signal indicating the existence of new physics at a place not far above the electroweak (EW) scale $^1$.

Given this possible signal, the following question is which new physics does this possible signal point to. Among different kinds of BSM new physics, electroweak baryogenesis (EWBG) [12, 13] is likely to be relevant to the current possible signal. EWBG was proposed to explain the observed baryon asymmetry of the universe (BAU). Through the baryon

$^1$Recent study on the new CDF result see [4–11].
number breaking sphaleron process \cite{14–16} and CP violated scattering with bubble wall, net baryon number can be produced during the nucleation process of Higgs field. To trigger the nucleation process and to prevent the generated net baryon being washed out, the electroweak phase transition (EWPT) needs to be a strong first order phase transition. However, due to current measured Higgs mass, the SM EWPT is not even first order \cite{17, 18}.

Therefore new particles are definitely required for a strong first order electroweak phase transition (SFOEWPT). Furthermore, new particles that help to trigger SFOEWPT can not be too heavy than EW scale, otherwise they will be decoupled in the thermal phase transition process and lose effect. Thus, the new measure W boson mass might be a hint of EWBG.

One method to trigger SFOEWPT is augmenting the SM Higgs sector via additional scalars, and it has been studied intensively in the literature \cite{19–31}. Extending the Higgs sector by a singlet scalar seems to be the simplest choice, but it is difficult for such model to explain the observed $m_W$ under current limits \cite{32}. In this work we choose Two-Higgs-Doublet Models (2HDMs) \cite{33, 34}, which extend the SM Higgs sector by another doublet, as the benchmark model to study the relationship between SFOEWPT and $m_W$. After electroweak symmetry breaking, in addition to the SM-like Higgs boson $h$, there are three non-SM Higgs bosons, $H/A/H^\pm$, which can have masses below TeV and couple to the SM-like Higgs $h$ to build an energy barrier between the symmetric and broken phase. Therefore the EW phase transition can be first order and strong enough for the baryogenesis \cite{27}. Furthermore, these light extra scalar can induce a positive $m_W$ shift \cite{35} and modify the predictions on the Z-pole observables like the oblique parameters $S$, $T$ and $U$ via one-loop contributions to the $W$ and $Z$ self-energies. The mixing between neutral scalars and extra loop corrections further reduce the Higgs couplings $\kappa_i = g_{Hii}^{2HDM}/g_{Hii}^{SM}$ relative to their SM expectations. Though the LHC measurements still give a large amount of available phase space of the 2HDM, future Higgs factories, e.g. ILC \cite{36}, FCC-ee \cite{37, 38} and CEPC \cite{39, 40} can measure them with unprecedented precision to further constrain the model.

In this paper, we study the constraints from precision measurements (especially the new $W$ boson mass and future Higgs coupling measurements) on the 2HDM and explore the possible parameter space which could lead to a SFOEWPT. Our study shows that SFOEWPT is consistent with the new uplifted $m_W$ in a certain parameter space. But due to the close connection between $m_W$ and other precise measurements, the “SFOEWPT + $m_W$” scenario is in slight tension with current limits. Furthermore, the future precision lepton collider measurements of both Higgs and Z boson properties could fully rule out the alive parameters to fulfil SFOEWPT and $m_W$, provided the measured central values locate in the SM prediction. Conversely, if the “SFOEWPT + $m_W$” scenario in 2HDM is true, than a clear deviation from SM prediction will be observed at future lepton colliders.

The rest of the paper is organized as follows. In Section 2 we briefly introduce 2HDM models and related constraints. Description on EWPT is also given in Section 2. In Section 3 we perform parameter space scan on a wide range and present alive points, with future precise measurements included. We conclude this work in Section 4.
2 2HDM

2.1 A Review

In this section, we provide a brief review of the aspects of 2HDMs. For pedagogical introduction, see Ref. [34] and a recent review Ref. [41] in light of current experiments. The scalar sector of 2HDMs consists of two SU(2)_L doublets Φ_i, i = 1, 2, which can be parameterized as below,

\[ \Phi_i = \left( \frac{\phi_i^+ + iG_i}{\sqrt{2}} \right) \] (2.1)

where \( v_1 \) and \( v_2 \) are the vacuum expectation values (VEVs) of the neutral components, satisfying the relation \( v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV} \). Assuming CP-conserving and only a soft breaking of a discrete \( Z_2 \) symmetry allowed, the most general Higgs potential can be expressed as,

\[ V^0(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^+ \Phi_1 + m_{22}^2 \Phi_2^+ \Phi_2 - m_{12}^2 \left( \Phi_1^+ \Phi_2 + h.c. \right) + \frac{\lambda_1}{2} \left( \Phi_1^+ \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left( \Phi_2^+ \Phi_2 \right)^2 
+ \lambda_3 \left( \Phi_1^+ \Phi_1 \right) \left( \Phi_2^+ \Phi_2 \right) + \lambda_4 \left( \Phi_1^+ \Phi_2 \right) \left( \Phi_2^+ \Phi_1 \right) + \frac{\lambda_5}{2} \left[ \left( \Phi_1^+ \Phi_2 \right)^2 + h.c. \right] \] (2.2)

where there are eight real parameters, \( \{m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5\} \). After the electroweak symmetry breaking (EWSB), the scalar sector of a 2HDM consists of five mass eigenstates: a pair of neutral CP-even Higgses, \( h \) and \( H \), a CP-odd Higgs, \( A \), and a pair of charged Higgses \( H^\pm \). We can express these states as,

\[ h = -s_\alpha \phi_1 + c_\alpha \phi_2, \quad A = -s_\beta \varphi_1 + c_\beta \varphi_2, \]
\[ H = \quad c_\alpha \phi_1 + s_\alpha \phi_2, \quad H^\pm = -s_\beta \phi_1^\pm + c_\beta \phi_2^\pm. \] (2.3)

where we will identify \( h \) with the discovered SM-like 125 GeV Higgs without loss of generality.

For convenience, we will parametrize the potential of 2HDMs by the physical Higgs masses \( m_h, m_H, m_A \), and \( m_{H^\pm} \), the mixing angle between the two CP-even Higgses \( \alpha \), \( \tan \beta \equiv v_2/v_1 \), the electroweak VEV \( v \), and the soft \( Z_2 \) symmetry breaking parameter \( m_{12}^2 \). Note that the vacuum expectation value \( v \) and the mass of the SM-like Higgs, \( m_h \) are fixed to their known values 246 GeV and 125 GeV respectively, leaving the remaining six independent parameters.

Assigning different \( Z_2 \) parities to the SM fermions, there are four types of 2HDMs. However, in this study, we focus on the so-called Type-I and Type-II 2HDMs, where all fermions obtain their masses from a single Higgs doublet in Type-I model while up- and down-type fermions obtain their masses from different Higgs doublets in Type-II model. In the Type-II model the couplings between \( A/H \) and down-type fermions are enhanced by \( \tan \beta \) and therefore it is usually more constrained by experiments when \( \tan \beta \) is large.

2.2 Theoretical Constraints on 2HDMs

The parameter spaces of 2HDMs are already constrained by theoretical consideration without experimental results.
• **Vacuum stability** In order to make the vacuum stable, the scalar potential should be bounded from below [42]:

\[
\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_4 + \lambda_5 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2} \tag{2.4}
\]

• **Perturbativity and unitarity** Requiring perturbativity, we must have \(|\lambda_i| \leq 4\pi\). And requiring tree-level unitarity of the scattering in the 2HDM scalar sector imposes the following additional mass constraints [43]:

\[
\begin{align*}
3(\lambda_1 + \lambda_2) &\leq \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2} < 16\pi, \tag{2.5} \\
(\lambda_1 + \lambda_2) &\leq \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2} < 16\pi, \tag{2.6} \\
(\lambda_1 + \lambda_2) &\leq \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2} < 16\pi, \tag{2.7} \\
|\lambda_3 + 2\lambda_4 + 3\lambda_5| &< 8\pi, \quad |\lambda_3 \pm \lambda_4| < 8\pi, \quad |\lambda_3 \pm \lambda_5| < 8\pi \tag{2.8}
\end{align*}
\]

To understand these constraints, it is useful to consider the relations between the quartic couplings and the physical masses

\[
v^2\lambda_1 = m_h^2 - \frac{t_\beta (m_{12}^2 - m_H^2 s_\beta c_\beta)}{c_\beta^2} + (m_h^2 - m_H^2) \left[ c_\beta - a (t_\beta^2 - 1) - 2t_\beta s_\beta - a c_\beta - a \right],
\]

\[
v^2\lambda_2 = m_h^2 - \frac{m_{12}^2 - m_H^2 s_\beta c_\beta}{t_\beta s_\beta^2} + (m_h^2 - m_H^2) \left[ c_\beta - a \left(t_\beta^2 - 1\right) + 2t_\beta^{-1} s_\beta - a c_\beta - a \right],
\]

\[
v^2\lambda_3 = m_h^2 + 2m_{H^+}^2 - 2m_H^2 - \frac{m_{12}^2 - m_H^2 s_\beta c_\beta}{s_\beta c_\beta} - (m_h^2 - m_H^2) \left[ 2c_\beta^{-a} + s_\beta - a c_\beta - a \left(t_\beta - t_\beta^{-1}\right) \right],
\]

\[
v^2\lambda_4 = m_A^2 - 2m_{H^+}^2 + m_H^2 - \frac{m_{12}^2 - m_H^2 s_\beta c_\beta}{s_\beta c_\beta},
\]

\[
v^2\lambda_5 = m_H^2 - m_A^2 - \frac{m_{12}^2 - m_H^2 s_\beta c_\beta}{s_\beta c_\beta}. \tag{2.9}
\]

We can introduce \(\lambda v^2 \equiv m_H^2 - m_{12}^2 / (s_\beta c_\beta)\) following Ref. [44]. The above expression indicates that the unitarity and perturbativity set up upper bounds on the mass splittings, which can be roughly taken as \(\lambda v^2 < 4\pi v^2\), \(m_A^2 - m_H^2 \lesssim O(4\pi v^2 - \lambda v^2)\), \(m_{H^+}^2 - m_H^2 \lesssim O(4\pi v^2 - \lambda v^2)\) and \(\max\{t_\beta, \cot \beta\} \lesssim \sqrt{8(8\pi v^2)} / (3\lambda v^2)\). Generally speaking, large mass splitting among non-SM Higgses are not allowed for large values of \(\lambda v^2\) and/or non-SM Higgs masses.

### 2.3 Direct searches at LEP and LHC

The search for pair-produced charged Higgs bosons at the Large Electron-Positron Collider (LEP) imposes a lower bound of 80 GeV on the mass of the charged Higgs boson [45], and LEP searches for \(AH\) production constrain the sum of the masses \(m_H + m_A > 209\) GeV [46].

LHC are also looking for direct productions of exotic Higgses via including \(A/H \to \mu \mu\) [47, 48], \(A/H \to bb\) [49, 50], \(A/H \to \tau \tau\) [51–53], \(A/H \to \gamma \gamma\) [54–58], \(A/H \to tt\) [59],
Table 1. Estimated $S$, $T$, and $U$ ranges and correlation matrices $\rho_{ij}$ from Z-pole precision measurements of the current results [78].

|   | Current | CEPC | FCC-ee | ILC |
|---|---------|------|--------|-----|
|   | $\sigma$ (10^{-2}) | $\sigma$ (10^{-2}) | $\sigma$ (10^{-2}) | $\sigma$ (10^{-2}) |
| $S$ | $0.04 \pm 0.11$ | $1.82$ | $0.370$ | $2.57$ |
| $T$ | $0.09 \pm 0.14$ | $2.56$ | $0.514$ | $3.59$ |
| $U$ | $-0.02 \pm 0.11$ | $1.83$ | $0.416$ | $2.64$ |

$H \to ZZ$ [60, 61], $H \to WW$ [62, 63], $A \to hZ \to b\bar{b}\ell\ell$ [64–67], $A \to hZ \to \tau\tau\ell\ell$ [66, 68, 69], $H \to hh$ [70–73], and $A/H \to HZ/AZ$ [74, 75]. The null results have already ruled out a significant portion of parameter space of 2HDM. For a typical mass splitting $m_A - m_H = m_{H^\pm} - m_H = 200$ GeV, the exotic decay channel $A \to HZ$ has already excluded a neutral Higgs with mass less than $2m_t$ for $\tan \beta < 5$ in Type-I model and for $0.5 < \tan \beta < 15$ in Type-II model. For large $\tan \beta$ region ($\tan \beta > 15$) in Type-II model, this channel puts the mass of neutral scalar $H$ to be above 600 GeV. Top quarks search channels, $4t$ and $A/H \to tt$, rule out $m_H < 800$ GeV for $\tan \beta < 0.3$ and $m_H < 650$ GeV for $\tan \beta < 1.1$ in both two types of 2HDMs. While $A/H \to \tau\tau, \gamma\gamma$ can exclude the region $m < 350$ GeV, $\tan \beta < 1$ in Type-I and -II models, $A/H \to \tau\tau$ could fully exclude $m_H$ larger than 800 GeV when $\tan \beta > 10$ in Type-II 2HDM. For a complete recasting the LHC direct search results in the 2HDM, we refer the readers to Ref. [27, 41, 76].

2.4 Z-pole and Higgs precision measurements

Measurements of Z-pole observables at the Large Electron-Positron Collider (LEP) impose strong constraints on the 2HDM [77]. Satisfying Z-pole constraints requires the charged scalar mass to be close to one of the heavy neutral scalar masses: $m_{H^\pm} \simeq m_H$ or $m_{H^\pm} \simeq m_A$. In our analysis, we simply take the $S,T,U$ data at 95% Confidence Level (C.L.) in Tab. 1 to capture the dominant contributions from Z-pole measurements. Note that a global analysis to recast the $S,T,U$ parameters is needed by including both Z-pole observables and latest $W$ mass measurement [3], here for simplicity we just take them as two separate measurements and are going to discuss more on the $W$ boson mass effects in Sec. 2.5.

Figure 1. Current oblique constraints $S,T,U$ in the plane of $\Delta m_A - \Delta m_C$ with $m_H = 700$ GeV, $\tan \beta = 3$ in the alignment limit $\cos(\beta - \alpha) = 0$. The colors are for corresponding parameter value.
To reveal the relation between non-SM Higgs spectra and \( S, T, U \), we define following mass splitting parameters:

\[
\Delta m_A = m_A - m_H, \quad \Delta m_C = m_{H^+} - m_H
\]  

(2.10)

In Fig. 1 we present the \( S, T, U \) deviation from their SM value as functions of \( \Delta m_A \) and \( \Delta m_C \). Current measure uncertainty for \( S, T, U \) are around 10\%, so it can be seen that \( T \) parameter provides the most stringent limit on non-SM Higgs mass splitting.

The LHC has also performed high precision tests on the Higgs couplings, which indicates all the measurable couplings \( \kappa_i \) are close to their SM values. Future Higgs factories will further improve the precision of measurements in the Higgs sector, and we therefore include hypothetical future lepton collider results in our study. We adopt the Higgs measurements results presented in Table 3 in Ref. [79]. Note that for future experiments, we assume there is no deviation from the SM in Higgs measurements.

2.5 \( m_W \) in the 2HDM

As an important observable used in the SM precise test, \( m_W \) is closely related to Z boson mass \( m_Z \), Fermi constant \( G_F \), and fine structure constant \( \alpha \)

\[
m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r)
\]

(2.11)

where \( \Delta r \) corresponds to quantum corrections [35]. In the 2HDM, \( m_W \) correction can be represented by [80]

\[
m_W^{2\text{HDM}} = m_W^{2\text{SM}} \left[ 1 + \frac{\alpha c_W^2}{2 (c_W^2 - s_W^2)} T (1 + \delta \rho^{2\text{HDM}}) + \frac{\alpha}{8 s_W^2} U - \frac{\alpha}{4 (c_W^2 - s_W^2)} S \right]
\]

(2.12)

to the \( \mathcal{O}(\alpha^2) \). Here \( m_W^{2\text{SM}} = 80.357 \text{GeV} \pm 4 \text{input} \pm 4 \text{theory} \text{MeV} \) [3], \( S, T, U \) are oblique parameters in the 2HDM [78], and \( \delta \rho^{2\text{HDM}} = \frac{\lambda_{hhh}^{2\text{HDM}}}{16 \pi^2 m_h^2} \) are higher order 2HDM effects from enhanced Higgs boson self-interactions. Currently \( \kappa_{hhh} = \lambda_{hhh}^{2\text{HDM}} / \lambda_{hhh}^{\text{SM}} \in (-1.0, 6.6) \) [81] is already strongly constrained, thus the higher order effect \( \delta \rho^{2\text{HDM}} \) up to \( \mathcal{O}(0.01) \) is weak.

For convenient, we define

\[
\Delta m_W^{2\text{HDM}} = m_W^{2\text{HDM}} - m_W^{2\text{SM}}
\]

(2.13)

In the left panel of Fig. 2 where we take \( \Delta U = 0 \) as a benchmark case, we show the general picture of \( \Delta m_W^{2\text{HDM}} \) in the plane of \( \Delta T - \Delta S \) based on the allowed region shown in the Fig. 1. The colors show values of \( \Delta m_W^{2\text{HDM}} \), varying from -50 MeV to 50 MeV. We have 5 black dash-dotted lines for \( \Delta m_W^{2\text{HDM}} = -40, -20, 0, 20, \) and 40 MeV. Generally speaking, \( \Delta m_W^{2\text{HDM}} \) mainly depends on \( \Delta T \), and the larger \( \Delta T \) and smaller \( \Delta S \) result in large \( \Delta m_W^{2\text{HDM}} \). This result can be easily understood with the sizes of the coefficients in front of \( S, T, U \) in Eq. (2.12).

In the right panel, we take the benchmark spectrum of Fig. 1 with \( m_H = 700 \text{GeV} \) and
Figure 2. (Left): general picture of $\Delta m_{W}^{2\text{HDM}}$ in the plane of $\Delta T - \Delta S$ with $\Delta U = 0$. The colors are values of $\Delta m_{W}^{2\text{HDM}}$, varying from -50 MeV to 50 MeV. We have 5 black dash-dotted lines for $\Delta m_{W}^{2\text{HDM}} = -40, -20, 0, 20,$ and 40 MeV. (Right): $m_{W}^{2\text{HDM}}$ in the plane of $\Delta m_{A} - \Delta m_{C}$ with same benchmark spectrum $m_{H} = 700$ GeV as Fig. 1. The colors are same to the left panel.

$\tan \beta = 3$, and show $\Delta m_{W}^{2\text{HDM}}$ in the plane of $\Delta m_{A} - \Delta m_{C}$. We can see that, under current various constraints, the benchmark spectrum here can supply for the theoretical correction meeting the new experimental measurement at CDF-II [3]. Since in the 2HDM, $\Delta m_{W}^{2\text{HDM}}$ is directly relevant to oblique parameters, and oblique parameters further depend on non-SM Higgs mass splitting $\Delta m_{A}$ and $\Delta m_{C}$. So it is clear that $\Delta m_{W}^{2\text{HDM}}$ is sensitive to non-SM Higgs mass splitting.

2.6 Flavour constraints

The charged Higgs $H^{\pm}$ boson couples to both up and down type fermions, which can lead to flavor changing processes strongly constrained by flavor physics observations. The most stringent of limits comes from the measurements of B-meson decays (e.g. $b \to s\gamma$ and $B^{+} \to \tau \nu$), which disfavor $m_{H^{\pm}} < 580$ GeV and large values of $\tan \beta$ respectively in Type-II 2HDM [82, 83], or $m_{H^{\pm}} < 1$ TeV and small values of $\tan \beta$ ($\tan \beta < 1$) in Type-I model [83]. However, flavor constraints can be alleviated with contributions from other sectors of the BSM models [84]. In this paper, we only focus on the constraints from $B$-physics on the scalar sector.

2.7 Phase transition in the 2HDM

To study EWPT, we need to know the thermal effective potential, which is the free-energy density, as the function of scalar VEVs. The thermal effective potential $V(\phi_{1}, \phi_{2}, T)$ can be schematically expressed as:

$$V(\phi_{1}, \phi_{2}, T) = V^0(\phi_{1}, \phi_{2}) + V^{\text{CW}}(\phi_{1}, \phi_{2}) + V^{\text{CT}}(\phi_{1}, \phi_{2}) + V^{T}(\phi_{1}, \phi_{2}, T).$$

(2.14)
Here $\phi_i$ are scalar VEVs, $T$ is the temperature of thermal system, $V^0(\phi_1, \phi_2)$ is the tree-level potential, $V^{\text{CW}}(\phi_1, \phi_2)$ and $V^{\text{CT}}(\phi_1, \phi_2)$ are Coleman-Weinberg potential and counter term respectively, and $V^T(\phi_1, \phi_2, T)$ is thermal correction. Detailed formulas can be found in the literature [25, 26].

In the very early universe, temperature $T$ is much higher than all the particles’ mass in our model. The large effective thermal mass keep $\phi_i$ at zero and thus maintain the EW-symmetry. And when $T$ become much lower than EW scale, the global minimum position of $V(\phi_1, \phi_2, T)$ on $\phi_1 - \phi_2$ plane must move to a place where $\phi_1^2 + \phi_2^2 \neq 0$ to break EW-symmetry. To know whether this phase transition process is first-order, we can track the minimum point with $T$ decreasing. If the minimum point (which locates in zero point when $T$ is very large) “jump to” a non-zero point discontinuously at critical temperature $T_c$, then the EWPT should be first-order. This method has been numerically implemented in public package BSMPT [85]. We will use this package in this work.

Furthermore, to prevent baryon number being washed out inside Higgs bubble, the “wash out” parameter [24] $\xi_c \equiv v_c/T_c$ ($v_c$ is the Higgs VEV at $T_c$) should roughly be larger than 1. Considering the uncertainty in $\xi_c$ calculation [28, 29], we use a slightly looser criteria for SFOEWPT:

$$\xi_c \equiv \frac{v_c}{T_c} > 0.9$$ (2.15)

3 Study results

In this section, we try to explore the SFOEWPT under various current and future constraints. Specially we have a detailed study about the latest $m_W$ result at CDF-II.

We will firstly have a large amount of random scan points, and our study include the theoretical constraints, $B$-physics, LHC Run-II direct searches, current precision measurement of Higgs and $Z$-pole physics. Then the further study is performed at future Higgs factories, including CEPC, FCC-ee and ILC as shown in Tab. 1, to confront the SFOEWPT and $m_W$ anomaly. Our study of Higgs precision measurements will deep into one-loop level.

3.1 Study method

We perform a 6 parameters random scan for both Type-I and Type-II, and the scan regions are:

$$\tan \beta \in (0.2, 50), |\cos(\beta - \alpha)| < 0.5, m_{A/H^\pm} \in (10, 1500) \text{ GeV },$$

$$m_{12}^2 \in (0, 1500^2) \text{ GeV}^2, m_H \in (130, 1500)\text{GeV}.$$ (3.1)

The number of samples allowed by current various (except for $m_W$ from CDF-II) is more than 1 million ( of 1 billion points in total). After considering the SFOEWPT, it is about a few hundreds of thousands points allowed for Type-I, but much less for Type-II to be shown in Fig. 3 as grey dots.
Figure 3. The allowed parameter space in the plane of $m_H - \tan \beta$ (left), $\Delta m_A - \Delta m_C$ (right). The grey points survive all theoretical constraints, current experimental constraints, and the conditions of SFOEWPT. The top and bottom panels are for Type-I and Type-II respectively. The green ones are able to provide a $m_W$ by CDF-II, while the red ones are allowed by future Higgs and Z-pole precision measurements from CEPC. The red and green points do not cover each other.

To incorporate in the $m_W$ at CDF-II, here in the 2HDM based on Eq. (2.12), we take the $m_W$ data at 95% Confidence Level (C.L.) with the $\chi^2$ profile-likelihood fit,

$$
\chi^2 = \frac{(m_W^{2HDM} - m_W^{obs})^2}{\sum \sigma^2_{m_W}},
$$

(3.2)
After taking into account of experiment uncertainties, we have
\[ \Delta m_W^{2\text{HDM}}|_{\text{ex}} \in (36.3, 103.4) \text{ MeV}, \] (3.3)
and if considering SM theoretical uncertainties as well, it is \( \Delta m_W^{2\text{HDM}}|_{\text{th+ex}} \in (31.1, 108.9) \text{ MeV} \) for the 6 parameter scan at 95% C.L. We will only take \( \Delta m_W^{2\text{HDM}}|_{\text{ex}} \) as condition of \( m_W \) for CDF-II in the following study\(^2\).

### 3.2 SFOEWPT under LHC measurements

As discussed above, after scanning the entire parameter space of Type-I and Type-II 2HDM, we obtain the sector which is allowed by current limits and also satisfy the SFOEWPT requirement.

As shown in Fig. 3, the grey points meet all the conditions of current various measurements(except for \( m_W \) at CDF-II) and SFOEWPT in both types. For Type-I and Type-II, favored mass region are different:

- **Type-I**: To satisfy SFOEWPT and current limits, \( m_H \) distributes in region \((125, 1000) \text{ GeV} \) with \( \tan \beta \) varying from 1 to 50. Mass splitting \( m_{H^\pm} - m_H \) and \( m_A - m_H \) distribute in region \((-400, 400) \text{ GeV} \).

- **Type-II**: Compared with Type-I, Type-II is more limited due to the limited \( \tan \beta \) region. \( m_H \) distributes in region \((125, 1000) \text{ GeV} \), while \( \tan \beta \) is limited to \((1, 12) \). Mass splitting \( m_{H^\pm} - m_H \) and \( m_A - m_H \) vary in region \((-200, 300) \text{ GeV} \).

To summarize, SFOEWPT require the mass of non-SM Higgs \( H/A/H^\pm \) to be smaller than 1 TeV and a certain amount of splitting between them. Comparing with the right panel of Fig. 2, it is clear that the uplifted \( m_W \) is consistent with SFOEWPT requirement.

### 3.3 SFOEWPT under Higgs, Z and W precision measurements

As discussed above, SFOEWPT, Higgs precision measurements at one-loop level, and Z-pole physics (oblique parameter \( S,T,U \)) are all connected by heavy Higgs mass splitting. In more detail, Fig. 2 and Eq. (2.12) tells that non-zero \( \Delta S/T \) is needed for uplifting \( m_W \). But Higgs and Z-pole physics have strong constraints on the value of \( \Delta S/T \). As presented in Fig. 3, the green points meet all these Higgs, Z-pole, \( m_W \) and SFOEWPT conditions. Compared to the grey points, we can see the allowed \( \tan \beta, m_H, \Delta m_A \) and \( \Delta m_C \) region of green points does not change a lot. Another feature is they mainly locate around the boundary region, which is mainly because current electroweak measurements is not precise enough, so the uplifted \( m_W \) in need can still be satisfied within 2HDM framework. As shown in our benchmark case Fig. 1, specific \( \Delta T \) is in need. Since oblique parameters is type universal, thus Type-I and Type-II have similar features for green region.

However, future lepton colliders, such as CEPC, ILC, and FCC-ee, will measure electroweak parameters to unprecedented precision. As presented in Tab. 1, uncertainties of

\(^2\)There is no apparent difference found for \( \Delta m_W^{2\text{HDM}}|_{\text{ex}} \) and \( \Delta m_W^{2\text{HDM}}|_{\text{th+ex}} \) in our study.
oblique measurements in CEPC can be reduced to 1% level, which one order smaller than current uncertainties. For the Higgs precision measurements, the works [44, 78, 79] have discussed them for the case of 2HDM systematically. Provided that there is no apparent deviation of Higgs and Z-pole proprieties to the SM predictions observed, or in other words, the future measurements turn out to be consistent with SM prediction, we take CEPC precision measurements as an example to study the impact from future lepton colliders. Finally as shown in Fig. 3, the red points represent spectrum meeting conditions of Higgs, Z-pole measurements, and SFOEWPT. We can see, the red region is strongly restricted to $\Delta m_A = 0$ or $\Delta m_C = \Delta m_A$ for both types. For Type-I, it is $\Delta m_C = \Delta m_A, |\Delta m_A| \in (150, 350)$GeV, or $\Delta m_C = 0, |\Delta m_A| \in (150, 350)$GeV. While for Type-II, it is $\Delta m_C = \Delta m_A$ and $\Delta m_A \in (150, 250)$GeV. In both types, the red region and green region are separate from each other, which means Higgs+Z-pole measurements at CEPC can exclude the region for $m_W$ at CDF-II.

On the other hand, if SFOEWPT with uplifted $m_W$ in 2HDM is the true BSM scenario, deviations from SM prediction will be observed at future measurements with high confidence level.

4 Conclusion

In this work, we revisited the existence of a strong first order electroweak phase transition (SFOEWPT) in the Type-I and Type-II 2HDMs as the grey points in Fig. 3. At the same time, the latest precision measurement of the $m_W$ at CDF-II, indicates possible existence of new particles with mass around electroweak scale. We studied them all in the framework of 2HDM.

In detail, we carried out a global analysis, including $W$ boson mass $m_W$, SFOEWPT requirements, direct searches of scalar resonances at the LHC, and current LHC and future Higgs and Z-pole precision measurements at lepton colliders such as CEPC, ILC, FCC-ee. We found that,

1. Since in the 2HDM, $\Delta m_W^{2HDM}$ is directly relevant to oblique parameters as discussed, which is dependent on the heavy Higgs mass splitting of $\Delta m_A = m_A - m_H$and $\Delta m_C = m_{H^\pm} - m_H$, we can see $\Delta m_W^{2HDM}$ is sensitive to heavy Higgs mass splitting. As a result, all these precision measurements and SFOEWPT in 2HDM are sensitive to non-SM Higgs mass splitting in 2HDM.

2. Under current constraints, both Type-I and Type-II 2HDM can explain the SFOEWPT, Z-pole, Higgs precision measurements and $m_W$ precision measurement of CDF-II at same time. In the Fig. 3, we have the green points satisfying all of them, under current various constraints. Generally the allowed region are

   \[ m_H \in (125, 950) \text{ GeV} , \Delta m_{A/C} \in (-400, 400) \text{ GeV}, \tan \beta \in (1, 50) \]

   for Type-I,

   \[ m_H \in (125, 900) \text{ GeV} , \Delta m_{A/C} \in (-200, 300) \text{ GeV}, \tan \beta \in (1, 12) \]
for Type-II.

3. With future precision measurements at CEPC, ILC, or FCC-ee, if there is no deviation to SM observed at Higgs or Z-pole physics, SFOEWPT is still allowed, but $m_W$ from CDF-II can not explained anymore by 2HDM. In other words, if 2HDM is the true BSM scenario after lepton colliders run, deviations from SM prediction will be observed at future measurements with high confidence level.

Such a constrained parameter space points out a clear direction for experimental studies and also theoretical explorations for explaining other phenomenology.

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