Impact of the CDF $W$-mass anomaly on two Higgs doublet model

Yongtae Heo,$^{1,\text{a}}$ Dong-Won Jung,$^{1,\text{b}}$ and Jae Sik Lee$^{1,\text{c}}$

$^1$ Department of Physics, Chonnam National University, Gwangju 61186, Korea
$^2$ IUEP, Chonnam National University, Gwangju 61186, Korea
$^3$ Department of Physics, Yonsei University, Seoul 03722, Korea

(Dated: June 6, 2022)

Abstract

We consider the implication of the recent CDF $W$-mass anomaly in the framework of two Higgs doublet model. We find that the large deviation of the $S$ and $T$ parameters from their SM values of zero leads to the upper limit of about 1 TeV on the heavy charged and neutral Higgs bosons when it is combined with the theoretical constraints from the perturbative unitarity and for the Higgs potential to be bounded from below.
I. INTRODUCTION

Recently, using 8.8 fb\(^{-1}\) data collected at the Fermilab Tevatron collider with a center-of-mass energy of 1.96 TeV, the CDF collaboration has reported the result of the W boson mass measurement with unprecedented precision \([1]\)

\[
80.433.5 \pm 9.4 \text{ MeV},
\]

(1)

which, comparing with the SM expectation of 80.357 \(\pm 6 \text{ MeV}\) \([2]\), yields a difference with a significance of 7.0\(\sigma\). Performing a global fit of electroweak data with the high-precision CDF measurement while fixing \(U = 0\), one may find the large central values of the oblique parameters \(S\) and \(T\) together with the standard deviations such as \([3]\)

\[
(\hat{S}_0, \sigma_S) = (0.15, 0.08), \quad (\hat{T}_0, \sigma_T) = (0.27, 0.06),
\]

(2)

and a strong correlation \(\rho_{ST} = 0.93\) between them. We find other estimations such as \(S \approx 0.064 \pm 0.090\) and \(T \approx 0.14 \pm 0.064\) \([4]\), \(S \approx 0.100 \pm 0.074\) and \(T \approx 0.177 \pm 0.071\) \([5]\), \(S \approx 0.086 \pm 0.076\) and \(T \approx 0.167 \pm 0.059\) \([6]\), \(S \approx 0.17\) and \(T \approx 0.27\) \([7]\), \(T \approx 0.110 \pm 0.018\) \([8]\), and \(T : \{0.15949, 0.210177\}\) \([9]\). For further works involved with the \(W\)-mass anomaly, we refer to Refs. \([10–29]\).

In this Letter, taking the framework of two Higgs doublet model (2HDM), we report that the large deviation of the \(T\) parameter, especially, from its SM value of zero results in the upper limit of about 1 TeV on the masses of the heavy charged and neutral Higgs bosons when it is combined with the theoretical constraints from the perturbative unitarity and for the Higgs potential to be bounded from below.

II. FRAMEWORK

The general 2HDM scalar potential in the so-called Higgs basis \([30, 31]\) where only one doublet contains the non-vanishing vacuum expectation value \(v\) is given by

\[
V_{\mathcal{H}} = Y_1(\mathcal{H}_1^\dagger \mathcal{H}_1) + Y_2(\mathcal{H}_2^\dagger \mathcal{H}_2) + Y_3(\mathcal{H}_1^\dagger \mathcal{H}_2) + Y_3^*(\mathcal{H}_2^\dagger \mathcal{H}_1)
+ Z_1(\mathcal{H}_1^\dagger \mathcal{H}_1)^2 + Z_2(\mathcal{H}_2^\dagger \mathcal{H}_2)^2 + Z_3(\mathcal{H}_1^\dagger \mathcal{H}_1)(\mathcal{H}_2^\dagger \mathcal{H}_2) + Z_4(\mathcal{H}_1^\dagger \mathcal{H}_2)(\mathcal{H}_2^\dagger \mathcal{H}_1)
+ Z_5(\mathcal{H}_2^\dagger \mathcal{H}_2)^2 + Z_6^*(\mathcal{H}_2^\dagger \mathcal{H}_1)^2 + Z_7(\mathcal{H}_1^\dagger \mathcal{H}_1)(\mathcal{H}_2^\dagger \mathcal{H}_2) + Z_8(\mathcal{H}_1^\dagger \mathcal{H}_1)(\mathcal{H}_2^\dagger \mathcal{H}_1)
+ Z_9(\mathcal{H}_2^\dagger \mathcal{H}_2)(\mathcal{H}_1^\dagger \mathcal{H}_2) + Z_9^*(\mathcal{H}_1^\dagger \mathcal{H}_2)(\mathcal{H}_2^\dagger \mathcal{H}_1),
\]

(3)
which contains 3 dimensionful quadratic and 7 dimensionless quartic parameters of which four parameters are complex. In this work we consider the CP-conserving case assuming \( \Im(Y_3) = \Im(Z_{5,6,7}) = 0 \) but without imposing the so-called \( Z_2 \) symmetry. \(^1\) The complex SU(2)\(_L\) doublets of \( \mathcal{H}_1 \) and \( \mathcal{H}_2 \) can be parameterized as

\[
\mathcal{H}_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + \varphi_1 + iG^0) \end{pmatrix}; \quad \mathcal{H}_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}} (\varphi_2 + iA) \end{pmatrix},
\]

where \( v = (\sqrt{2}G_F)^{-1/2} \approx 246.22 \) GeV and \( G^{\pm,0} \) and \( H^\pm \) stand for the Goldstone and charged Higgs bosons, respectively. For the neutral Higgs bosons, \( A \) denotes a CP-odd mass eigenstate and the two states \( \varphi_1 \) and \( \varphi_2 \) result in two CP-even mass eigenstates through mixing and one of them should play the role of the SM Higgs boson. The tadpole conditions relate the quadratic parameters \( Y_{1,3} \) to \( Z_{1,6} \) as follows:

\[
Y_1 + Z_1 v^2 = 0; \quad Y_3 + \frac{1}{2} Z_6 v^2 = 0.
\]

The 2HDM Higgs potential includes the mass terms which can be cast into the form consisting of three parts

\[
V_{\mathcal{H},\text{mass}} = M_{H_1}^2 H^+ H^- + \frac{1}{2} M_A^2 A^2 + \frac{1}{2} (\varphi_1 \varphi_2) M_0^2 \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix},
\]

in terms of the charged Higgs bosons \( H^\pm \), the neutral CP-odd Higgs boson \( A \), and the two neutral CP-even scalars \( \varphi_{1,2} \). The charged and CP-odd Higgs boson masses are given by

\[
M_{H^\pm}^2 = Y_2 + \frac{1}{2} Z_3 v^2, \quad M_A^2 = M_{H^\pm}^2 + \left( \frac{1}{2} Z_4 - Z_5 \right) v^2,
\]

while the \( 2 \times 2 \) mass-squared matrix of the neutral Higgs bosons \( M_0^2 \) takes the form

\[
M_0^2 = \begin{pmatrix} 0 & 0 \\ 0 & M_A^2 \end{pmatrix} + \begin{pmatrix} 2Z_1 & Z_6 \\ Z_6 & 2Z_5 \end{pmatrix} v^2.
\]

Note that the quartic couplings \( Z_2 \) and \( Z_7 \) have nothing to do with the masses of Higgs bosons and the mixing of the neutral ones. We further note that \( \varphi_1 \) does not mix with \( \varphi_2 \) in the \( Z_6 = 0 \) limit, and its mass squared is simply given by \( 2Z_1 v^2 \) which gives \( Z_1 \approx 0.13 \).

\(^1\) The \( Z_2 \) symmetry in the Higgs basis might be realized by requiring the invariance of the Higgs potential under the transformations \( \mathcal{H}_1 \to -\mathcal{H}_1 \) and \( \mathcal{H}_2 \to +\mathcal{H}_2 \). Therefore, by imposing it strictly, the \( Y_3 \), \( Z_6 \) and \( Z_7 \) terms have to be removed from the Higgs potential. Without imposing the \( Z_2 \) symmetry, there appear the Higgs-mediated flavor-changing neutral currents at tree level which could be avoided, for example, by considering the models in which the Yukawa matrices describing the couplings of the two Higgs doublets to the SM fermions are aligned in the flavor space. \(^{32,33}\)
With the $2 \times 2$ real and symmetric mass-squared $\mathcal{M}_0^2$ is given, the mixing is described by

$$(\varphi_1, \varphi_2)^T = O_{\alpha i} (h, H)^T_i,$$  \hspace{1cm} (9)

such that $O^T \mathcal{M}_0^2 O = \text{diag}(M_h^2, M_H^2)$ with the orthogonal mixing matrix $O$ parameterized as

$$O = \begin{pmatrix}
c_\gamma & s_\gamma \\
-s_\gamma & c_\gamma
\end{pmatrix},$$  \hspace{1cm} (10)

introducing the mixing angle $\gamma$ between the two CP-even states $\varphi_1$ and $\varphi_2$. Then the quartic couplings $\{Z_1, Z_4, Z_5, Z_6\}$ are given by

$$Z_1 = \frac{1}{2v^2} \left( c_\gamma^2 M_h^2 + s_\gamma^2 M_H^2 \right), \quad Z_4 = \frac{1}{v^2} \left( s_\gamma^2 M_h^2 + c_\gamma^2 M_H^2 + M_A^2 - 2M_{H^\pm}^2 \right),$$

$$Z_5 = \frac{1}{2v^2} \left( s_\gamma^2 M_h^2 + c_\gamma^2 M_H^2 - M_A^2 \right), \quad Z_6 = \frac{1}{v^2} \left( -M_h^2 + M_H^2 \right) c_\gamma s_\gamma,$$  \hspace{1cm} (11)

in terms of the four masses $M_{h,H,A,H^\pm}$ and the mixing angle $\gamma$. We observe that, in the alignment limit of $\sin \gamma = 0$, $Z_1 = M_h^2/2v^2$ and $Z_6 = 0$ and $Z_4$ and $Z_5$ are determined by the mass differences of $M_H^2 + M_A^2 - 2M_{H^\pm}^2$ and $M_H^2 - M_A^2$, respectively [35–39]. For the study of the CP-conserving case, one may choose one of the following two equivalent sets:

$$\mathcal{I} = \{v, Y_2; M_{H^\pm}, M_h, M_H, M_A, \gamma; Z_2, Z_7\},$$

$$\mathcal{I}' = \{v; M_{H^\pm}, M_h, M_H, M_A, \gamma; Z_3, Z_2, Z_7\},$$  \hspace{1cm} (12)

each of which contains 9 real degrees of freedom, and the convention of $|\gamma| \leq \pi/2$ can be taken without loss of generality resulting in $c_\gamma \geq 0$ and $\text{sign}(s_\gamma) = \text{sign}(Z_6)$ assuming $M_H > M_h = 125.5$ GeV. The heavy Higgs masses squared are scanned up to $(1.5 \text{ TeV})^2$ and the quartic couplings $Z_2, |Z_3|$, and $|Z_7|$ up to 3, 10, 5, respectively.

III. ANALYSIS

First, we consider the perturbative unitarity (UNIT) conditions and those for the Higgs potential to be bounded from below (BFB) to obtain the primary theoretical constraints on the potential parameters or, equivalently, the constraints on the Higgs-boson masses including correlations among them and the mixing angle $\gamma$. For the unitarity conditions, we closely follow Ref. [40] taking into account three scattering matrices which are expressed in terms of the quartic couplings $Z_1$–$7$. Using the set $\mathcal{I}'$ in
Eq. (12) for the input parameters, all the seven quartic couplings are fixed exploiting the relations given by Eq. (11). For the details of the implementation of the UNIT conditions, we refer to Ref. [41]. For the BFB constraints, we require the following 5 necessary conditions for the Higgs potential to be bounded-from-below [42]:

\[ Z_1 \geq 0, \quad Z_2 \geq 0; \]
\[ 2\sqrt{Z_1 Z_2} + Z_3 \geq 0, \quad 2\sqrt{Z_1 Z_2} + Z_3 + Z_4 - 2|Z_5| \geq 0; \]
\[ Z_1 + Z_2 + Z_3 + Z_4 + 2|Z_5| - 2|Z_6 + Z_7| \geq 0. \tag{13} \]

Second, we consider the electroweak (ELW) oblique corrections to the so-called \( S, T \) and \( U \) parameters [43, 44] which provide significant constraints on the quartic couplings of the 2HDM. Fixing \( U = 0 \) which is suppressed by an additional factor \( M_Z^2/M_{BSM}^2 \) relative to \( S \) and \( T \), the \( S \) and \( T \) parameters are constrained as follows [2, 45]

\[
\frac{(S - \hat{S}_0)^2}{\sigma_S^2} + \frac{(T - \hat{T}_0)^2}{\sigma_T^2} - 2\rho_{ST} \frac{(S - \hat{S}_0)(T - \hat{T}_0)}{\sigma_S \sigma_T} \leq R^2 (1 - \rho_{ST}^2), \tag{14}
\]

with \( R^2 = 2.3, 4.61, 5.99, 9.21, 11.83 \) at 68.3%, 90%, 95%, 99%, and 99.7% confidence levels (CLs), respectively. For our numerical analysis, we take the 95% CL limit. For the central values \( \hat{S}_0 \) and \( \hat{T}_0 \) and the standard deviations \( \sigma_{S,T} \), we adopt those given in Ref. [3], see Eq. (2).

Using the set \( \mathcal{I}' \) for the input parameters, the \( S \) and \( T \) parameters take the following forms [42, 46–48]:

\[
S = -\frac{1}{4\pi} \left[ F'_\Delta(M_{H^\pm}, M_{H^\pm}) - c_\gamma^2 F'_\Delta(M_A, M_H) - s_\gamma^2 F'_\Delta(M_A, M_h) \right],
\]
\[
T = \frac{\sqrt{2}G_F}{16\pi^2\alpha_{EM}} \left[ F_\Delta(M_A, M_{H^\pm}) + c_\gamma^2 F_\Delta(M_H, M_{H^\pm}) + s_\gamma^2 F_\Delta(M_h, M_{H^\pm}) - c_\gamma^2 F_\Delta(M_A, M_H) - s_\gamma^2 F_\Delta(M_A, M_h) \right]. \tag{15}
\]

The one-loop functions are given by [3]

\[
F_\Delta(m_0, m_1) = F_\Delta(m_1, m_0) = \frac{m_0^2 + m_1^2}{2} - \frac{m_0^2 m_1^2}{m_0^2 - m_1^2} \ln \frac{m_0^2}{m_1^2},
\]
\[
F'_\Delta(m_0, m_1) = F'_\Delta(m_1, m_0) = -\frac{1}{3} \left[ 4 \left( \frac{2m_0 \ln (m_0^2 - m_1^2)}{m_0^2 - m_1^2} \right) - \frac{m_0^2 + m_1^2}{(m_0^2 - m_1^2)^2} F_\Delta(m_0, m_1) \right]. \tag{16}
\]

\(^2\) Here, \( M_{BSM} \) denotes some heavy mass scale involved with new physics beyond the Standard Model.

\(^3\) See, for example, Ref. [49].
With $F_\Delta(m, m) = 0$ and $F'_\Delta(m, m) = \frac{1}{3} \ln m^2$, we observe that $T$ is identically vanishing when $M_{H^\pm} = M_A$.

In the left panel of Fig. 1, we show the $S$ and $T$ parameters imposing the UNIT, BFB, and ELW constraints abbreviated by the combined UNIT$\oplus$BFB$\oplus$ELW$_{95\%}$ ones. Note that the 95% CL ELW limits are adopted and the heavy Higgs masses squared are scanned up to $(1.5\text{ TeV})^2$. We find that $S$ takes values in the range between $-0.03$ and $0.05$ whose absolute values are smaller than $\sigma_S = 0.08$, see Eq. (2). Note that the narrow region around 0 with radius about 0.004 is not allowed since the misalignment between $M_{H^\pm}$ and $M_A$ is required to achieve the sizable central value of the $T$ parameter, see the first line of Eq. (15). Note that $S$ is negative (positive) when $M_{H^\pm} > (\prec) M_A$. The $T$ parameter takes its value between $0.12$ and $0.24$. Note that $T$ is positive definite and sizable and, accordingly, $M_{H^\pm} = M_A$ is not allowed. Actually, we find that the region $-40 \lesssim (M_{H^\pm} - M_A)/\text{GeV} \lesssim 20$ is ruled out at 95% CL. In the right panel of Fig. 1 we show the correlations among the mass differences and the mixing angle $\gamma$. As $M_{H^\pm}$ increases, the mass difference between the charged and neutral Higgs bosons $|M_{H^\pm} - M_{A,H}|$ converges to the value of about 100 GeV. On the other hand, we find that $|M_H - M_A|/\text{GeV} \lesssim 250 (50) \text{ GeV}$ when $M_{H^\pm} > 500 (900) \text{ GeV}$.

We show the correlations among the heavy Higgs-boson masses and the mixing angle $\gamma$ in the left
FIG. 2. The UNIT⊕BFB⊕ELW95% constraints (magenta) using $T'$, see Eq. 12. For comparisons, we also show the results after applying only the UNIT⊕BFB constraints (blue): (Left) Scatter plots of $M_A$ versus $M_H$ (upper left), $M_{H\pm}$ versus $M_H$ (upper right), $M_{H\pm}$ versus $M_A$ (lower left), and $M_{H\pm}$ versus $\gamma$ (lower right). (Right) The normalized distributions of the quartic couplings and the mixing angle $\gamma$.

panel of Fig. 2. Requiring the ELW constraint in addition to the UNIT⊕BFB ones, we find that $Z_1$ and $\gamma$ take values near to 0 less likely while $Z_5$ positive ones more likely, see the right panel of Fig. 2. On the other hand, the $Z_2$ and $Z_7$ distributions remain almost the same since they are irrelevant to the masses of Higgs bosons and the mixing angle $\gamma$. The $Z_3$ and $Z_6$ distributions undergo some changes but the $Z_4$ distribution changes most drastically excluding the region $|Z_4| \lesssim 1$. This could be understood by looking into the expression for $Z_4$ given in Eq. 11. Taking $\gamma = 0$ and $M_H = M_A$ for the convenience of discussion, one may have

$$Z_4 v^2 = 4 \Delta_M \overline{M},$$

with $\Delta_M \equiv M_A - M_{H\pm}$ and $\overline{M} \equiv (M_A + M_{H\pm})/2$. Therefore $Z_4$ can not vanish in the presence of the misalignment between $M_{H\pm}$ and $M_A$, which is required to achieve the sizable central value of the $T$ parameter. We recall that the mass difference $|\Delta_M|$ approaches to 100 GeV as $M_{H\pm}$ grows, see the right panel of Fig. 1. On the other hand, the above relation could be rewritten for $\overline{M}$ as

$$\overline{M} = \frac{Z_4 v^2}{4 \Delta_M} \leq \frac{v^2}{4} \left( \frac{Z_4}{\Delta_M} \right)_{\text{max}} \leq \frac{v^2}{4} \frac{|Z_4|_{\text{max}}}{|\Delta_M|_{\text{min}}},$$

which implies that there exists the absolute upper limit on the masses of the heavy charged and neutral Higgs bosons with $|Z_4|_{\text{max}}$ and $|\Delta_M|_{\text{min}}$ from the UNIT⊕BFB and ELW95% constraints, respectively. We observe that $|Z_4|$ tends to increase as $M_{H\pm}$ grows until it reaches $\sim 6$ where $M_{H\pm}$ takes its maximum
value of about 1 TeV. When $M_{H^\pm}$ approaches to 1 TeV, $|\Delta_M|$ converges to 100 GeV while taking its minimum value of about 30 GeV around $M_{H^\pm} = 450$ GeV, see the upper plots in the right panel of Fig. 1 and the plot of $M_{H^\pm}$ versus $M_A$ in the left panel of Fig. 2. Taking into account the full correlations among the masses of heavy Higgs bosons and the mixing angle, we find that $(Z_4/\Delta_M)_{\text{max}} \sim 6/(100 \text{ GeV})$ leading to the upper limit of about 1 TeV as clearly shown in the left panel of Fig. 2.

Finally, in order to assess the reliability of our main result, we consider the variation of the upper limit on the heavy Higgs-boson masses by shifting the central value of the $T$ parameter by the amount of $\pm \sigma_T$. We find that $M_{H^\pm} < 1,000^{+100}_{-400}$ GeV taking $\hat{T}_0 = 0.27 \pm 0.06$. We observe that the upper limit is quite stable when $\hat{T}_0$ is larger than the nominal value of 0.27 while it grows faster for the smaller values of $\hat{T}_0$.

IV. CONCLUSIONS

We consider the implication of the recent CDF $W$-mass anomaly in the framework of 2HDM. We find that the large deviation of the $S$ and $T$ parameters from their SM values of zero leads to the upper limit of about 1 TeV on the masses of the heavy charged and neutral Higgs bosons when it is combined with the theoretical constraints from the perturbative unitarity and for the Higgs potential to be bounded from below.

Note added: After the completion of our work, we have received Ref. [50] in which the CDF $W$-mass anomaly studied in the framework of 2HDMs. They also find the upper bounds of about 1 TeV on the masses of the heavy Higgs bosons by including phenomenological constraints from flavor observables, Higgs precision data, and direct collider search limits in addition to theoretical ones. We observe that the upper limit of about 1 TeV on the masses of heavy Higgs bosons are largely unaffected by the phenomenological constraints.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation (NRF) of Korea Grant No. NRF-2021R1A2B5B02087078 (Y.H., D.-W.J., J.S.L.). The work of D.-W.J. was also supported in part by the NRF of Korea Grant Nos. NRF-2019R1A2C1089334 and NRF-2021R1A2C2011003 and in part by

---

4 Note that the precise value of $|\Delta_M|$ and its parametric dependence depend on the order to which the $S$ and $T$ parameters are computed. In Ref. [3] from which we are adopting the central values and the standard deviations of the $S$ and $T$ parameters, the electroweak oblique parameters are computed at the one-loop order as in this work. In Ref. [26], a two-loop calculation of the $W$-boson mass has been performed and it is found that $|\Delta_M| \gtrsim 50$ GeV.
the Yonsei University Research Fund of 2022. The work of J.S.L. was also supported in part by the NRF of Korea Grant No. NRF-2022R1A5A1030700.

[1] T. Aaltonen et al. [CDF], “High-precision measurement of the W boson mass with the CDF II detector,” Science 376 (2022) no.6589, 170-176 doi:10.1126/science.abk1781
[2] P. A. Zyla et al. [Particle Data Group], “Review of Particle Physics,” PTEP 2020 (2020) no.8, 083C01 doi:10.1093/ptep/ptaa104
[3] C. T. Lu, L. Wu, Y. Wu and B. Zhu, “Electroweak Precision Fit and New Physics in light of W Boson Mass,” arXiv:2204.03796 [hep-ph].
[4] A. Strumia, “Interpreting electroweak precision data including the W-mass CDF anomaly,” arXiv:2204.04191 [hep-ph].
[5] J. de Blas, M. Pierini, L. Reina and L. Silvestrini, “Impact of the recent measurements of the top-quark and W-boson masses on electroweak precision fits,” arXiv:2204.04204 [hep-ph].
[6] A. Paul and M. Valli, “Violation of custodial symmetry from W-boson mass measurements,” arXiv:2204.05267 [hep-ph].
[7] P. Asadi, C. Cesarotti, K. Fraser, S. Homiller and A. Parikh, “Oblique Lessons from the W Mass Measurement at CDF II,” arXiv:2204.05283 [hep-ph].
[8] L. Di Luzio, R. Gröber and P. Paradisi, “Higgs physics confronts the $M_W$ anomaly,” arXiv:2204.05284 [hep-ph].
[9] K. S. Babu, S. Jana and V. P. K., “Correlating W-Boson Mass Shift with Muon $g-2$ in the 2HDM,” arXiv:2204.05303 [hep-ph].
[10] Y. Z. Fan, T. P. Tang, Y. L. S. Tsai and L. Wu, “Inert Higgs Dark Matter for New CDF W-boson Mass and Detection Prospects,” arXiv:2204.03693 [hep-ph].
[11] C. R. Zhu, M. Y. Cui, Z. Q. Xia, Z. H. Yu, X. Huang, Q. Yuan and Y. Z. Fan, “GeV antiproton/gamma-ray excesses and the W-boson mass anomaly: three faces of $\sim 60 – 70$ GeV dark matter particle?,” arXiv:2204.03767 [astro-ph.HE].
[12] P. Athron, A. Fowlie, C. T. Lu, L. Wu, Y. Wu and B. Zhu, “The W boson Mass and Muon $g-2$: Hadronic Uncertainties or New Physics?,” arXiv:2204.03996 [hep-ph].
[13] J. M. Yang and Y. Zhang, “Low energy SUSY confronted with new measurements of W-boson mass and muon $g-2$,” arXiv:2204.04202 [hep-ph].
[14] X. K. Du, Z. Li, F. Wang and Y. K. Zhang, “Explaining The Muon $g - 2$ Anomaly and New CDF II W-Boson Mass in the Framework of (Extra)Ordinary Gauge Mediation,” [arXiv:2204.04286 [hep-ph]].

[15] T. P. Tang, M. Abdughani, L. Feng, Y. L. S. Tsai and Y. Z. Fan, “NMSSM neutralino dark matter for $W$-boson mass and muon $g - 2$ and the promising prospect of direct detection,” [arXiv:2204.04356 [hep-ph]].

[16] G. Cacciapaglia and F. Sannino, “The W boson mass weighs in on the non-standard Higgs,” [arXiv:2204.04514 [hep-ph]].

[17] M. Blennow, P. Coloma, E. Fernández-Martínez and M. González-López, “Right-handed neutrinos and the CDF II anomaly,” [arXiv:2204.04559 [hep-ph]].

[18] F. Arias-Aragón, E. Fernández-Martínez, M. González-López and L. Merlo, “Dynamical Minimal Flavour Violating Inverse Seesaw,” [arXiv:2204.04672 [hep-ph]].

[19] K. Sakurai, F. Takahashi and W. Yim, “Singlet extensions and W boson mass in the light of the CDF II result,” [arXiv:2204.04770 [hep-ph]].

[20] J. Fan, L. Li, T. Liu and K. F. Lyu, “W-Boson Mass, Electroweak Precision Tests and SMEFT,” [arXiv:2204.04805 [hep-ph]].

[21] X. Liu, S. Y. Guo, B. Zhu and Y. Li, “Unifying gravitational waves with W boson, FIMP dark matter, and Majorana Seesaw mechanism,” [arXiv:2204.04834 [hep-ph]].

[22] H. M. Lee and K. Yamashita, “A Model of Vector-like Leptons for the Muon $g - 2$ and the W Boson Mass,” [arXiv:2204.05024 [hep-ph]].

[23] Y. Cheng, X. G. He, Z. L. Huang and M. W. Li, “Type-II Seesaw Triplet Scalar and Its VEV Effects on Neutrino Trident Scattering and W mass,” [arXiv:2204.05031 [hep-ph]].

[24] H. Song, W. Su and M. Zhang, “Electroweak Phase Transition in 2HDM under Higgs, Z-pole, and W precision measurements,” [arXiv:2204.05085 [hep-ph]].

[25] E. Bagnaschi, J. Ellis, M. Madigan, K. Mimasu, V. Sanz and T. You, “SMEFT Analysis of $m_W$,” [arXiv:2204.05260 [hep-ph]].

[26] H. Bahl, J. Braathen and G. Weiglein, “New physics effects on the $W$-boson mass from a doublet extension of the SM Higgs sector,” [arXiv:2204.05269 [hep-ph]].

[27] P. Athron, M. Bach, D. H. J. Jacob, W. Kotlarski, D. Stöckinger and A. Voigt, “Precise calculation of the W boson pole mass beyond the Standard Model with FlexibleSUSY,” [arXiv:2204.05285 [hep-ph]].

[28] J. Gu, Z. Liu, T. Ma and J. Shu, “Speculations on the W-Mass Measurement at CDF,” [arXiv:2204.05296 [hep-ph]].

[29] J. J. Heckman, “Extra W-Boson Mass from a D3-Brane,” [arXiv:2204.05302 [hep-ph]].
[30] J. F. Donoghue and L. F. Li, “Properties of Charged Higgs Bosons,” Phys. Rev. D 19 (1979), 945 doi:10.1103/PhysRevD.19.945

[31] H. Georgi and D. V. Nanopoulos, “Suppression of Flavor Changing Effects From Neutral Spinless Meson Exchange in Gauge Theories,” Phys. Lett. B 82 (1979), 95-96 doi:10.1016/0370-2693(79)90433-7

[32] A. V. Manohar and M. B. Wise, “Flavor changing neutral currents, an extended scalar sector, and the Higgs production rate at the CERN LHC,” Phys. Rev. D 74 (2006), 035009 doi:10.1103/PhysRevD.74.035009 arXiv:hep-ph/0606172 [hep-ph].

[33] A. Pich and P. Tuzon, “Yukawa Alignment in the Two-Higgs-Doublet Model,” Phys. Rev. D 80 (2009), 091702 doi:10.1103/PhysRevD.80.091702 arXiv:0908.1554 [hep-ph].

[34] A. Peñuelas and A. Pich, “Flavour alignment in multi-Higgs-doublet models,” JHEP 12 (2017), 084 doi:10.1007/JHEP12(2017)084 arXiv:1710.02040 [hep-ph].

[35] J. F. Gunion and H. E. Haber, “The CP conserving two Higgs doublet model: The Approach to the decoupling limit,” Phys. Rev. D 67 (2003), 075019 doi:10.1103/PhysRevD.67.075019 arXiv:hep-ph/0207010 [hep-ph].

[36] N. Craig, J. Galloway and S. Thomas, “Searching for Signs of the Second Higgs Doublet,” arXiv:1305.2424 [hep-ph].

[37] M. Carena, I. Low, N. R. Shah and C. E. M. Wagner, “Impersonating the Standard Model Higgs Boson: Alignment without Decoupling,” JHEP 04 (2014), 015 doi:10.1007/JHEP04(2014)015 arXiv:1310.2248 [hep-ph].

[38] P. S. Bhupal Dev and A. Pilaftsis, “Maximally Symmetric Two Higgs Doublet Model with Natural Standard Model Alignment,” JHEP 12 (2014), 024 [erratum: JHEP 11 (2015), 147] doi:10.1007/JHEP12(2014)024 arXiv:1408.3405 [hep-ph].

[39] J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, “Scrutinizing the alignment limit in two-Higgs-doublet models: m_h=125 GeV,” Phys. Rev. D 92 (2015) no.7, 075004 doi:10.1103/PhysRevD.92.075004 arXiv:1507.00933 [hep-ph].

[40] D. Jurčiukonis and L. Lavoura, “The three- and four-Higgs couplings in the general two-Higgs-doublet model,” JHEP 12 (2018), 004 doi:10.1007/JHEP12(2018)004 arXiv:1807.04244 [hep-ph].

[41] S. Y. Choi, J. S. Lee and J. Park, “Yukawa Alignment in the Higgs Basis,” arXiv:2110.03908 [hep-ph].

[42] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, “Theory and phenomenology of two-Higgs-doublet models,” Phys. Rept. 516 (2012), 1-102 doi:10.1016/j.physrep.2012.02.002 arXiv:1106.0034 [hep-ph].
[43] M. E. Peskin and T. Takeuchi, “A New constraint on a strongly interacting Higgs sector,” Phys. Rev. Lett. 65 (1990), 964-967 doi:10.1103/PhysRevLett.65.964

[44] M. E. Peskin and T. Takeuchi, “Estimation of oblique electroweak corrections,” Phys. Rev. D 46 (1992), 381-409 doi:10.1103/PhysRevD.46.381

[45] J. S. Lee and A. Pilaftsis, “Radiative Corrections to Scalar Masses and Mixing in a Scale Invariant Two Higgs Doublet Model,” Phys. Rev. D 86 (2012), 035004 doi:10.1103/PhysRevD.86.035004 [arXiv:1201.4891 [hep-ph]].

[46] D. Toussaint, “Renormalization Effects From Superheavy Higgs Particles,” Phys. Rev. D 18 (1978), 1626 doi:10.1103/PhysRevD.18.1626

[47] W. Grimus, L. Lavoura, O. M. Ogreid and P. Osland, “A Precision constraint on multi-Higgs-doublet models,” J. Phys. G 35 (2008), 075001 doi:10.1088/0954-3899/35/7/075001 [arXiv:0711.4022 [hep-ph]].

[48] W. Grimus, L. Lavoura, O. M. Ogreid and P. Osland, “The Oblique parameters in multi-Higgs-doublet models,” Nucl. Phys. B 801 (2008), 81-96 doi:10.1016/j.nuclphysb.2008.04.019 [arXiv:0802.4353 [hep-ph]].

[49] S. Kanemura, Y. Okada, H. Taniguchi and K. Tsumura, “Indirect bounds on heavy scalar masses of the two-Higgs-doublet model in light of recent Higgs boson searches,” Phys. Lett. B 704 (2011), 303-307 doi:10.1016/j.physletb.2011.09.035 [arXiv:1108.3297 [hep-ph]].

[50] S. Lee, K. Cheung, J. Kim, C. T. Lu and J. Song, “Status of the two-Higgs-doublet model in light of the CDF $m_W$ measurement,” arXiv:2204.10338 [hep-ph].