Compatibility of muon $g - 2$, $W$ mass anomaly in type-X 2HDM

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Recently CDF II Collaboration reported that they measured $W$ boson mass precisely. The measurement is deviated from the Standard Model (SM) Prediction at 7σ. Also, the recent FNAL measurement of the muon magnetic moment shows a 4.2σ deviation. To resolve the $W$ boson as well as the muon $(g - 2)$ anomalies, we explore the type-X two Higgs doublet model (2HDM). We analyze the $(m_A, \tan \beta)$ parameter space of the type-X 2HDM consistent with the muon $(g - 2)$, lepton universality test and recent $W$ boson mass measurements from the CDF II collaboration. We find that the measurement of the $h \to AA$ branching ratio gives a strong lower mass bound on $m_H$.

I. INTRODUCTION

The CDF experiment presented a high precision measurement of mass of the $W$ boson: $m_W^{CDF} = 80.4335 \pm 0.0094$ GeV, which is about $7\sigma$ away from the SM prediction [1]. Such deviation is in conflict experimental measurements of $m_W$ by Tevatron [2] and ATLAS [3]. Undeniably, we should interpret the deviation with caution as it might originate from systematic errors.

On the other hand, this result stands with the growing number of experimental anomalies, including the muon anomalous magnetic moment, $B$-anomalies etc. Hence it is worthwhile to reexamine the implication of the CDF result scenarios, which can explain other observed anomalies. The deviation in $W$ mass can originate from the quantum correction due to the presence of BSM particles which modifies the $S, T$ and $U$ parameters. Several analyses has been presented in this direction [4–68].

Here we are interested in the 2HDM of type-X, which can explain the muon $(g - 2)$ if the pseudoscalar ($A$) is much lighter than the other scalars. A considerable deviation in the $S$ and $T$ parameters is necessary to accommodate CDF results. We analyzed the parameter space which can simultaneously satisfy CDF measurement and $(g - 2)_\mu$. To explain $(g - 2)_\mu$, we require the pseudoscalar to be lighter than $m_h/2$ where $h$ is the SM Higgs bosons. And it opens up the $h \to AA$ decay model, which has been explored at LHC by CMS and ATLAS collaboration in various four-fermion final states, including $4\tau, 2\mu 2\tau$ [69–74]. We showed that the LHC limit puts a strong lower limit on the mass spectrum of the type-X 2HDM. Since the scalars are leptophobic in type-X 2HDM, strong constraint comes from the measurement of lepton universality in charged and neutral current processes. We have considered both the leptonic $Z$ decays and leptonic/semi-leptonic $\tau$ decays to constrain the available parameter space. We showed that it is possible to explain the $(g - 2)_\mu$ anomaly after satisfying all the experimental and theoretical constraints, including the CDF measurement. We found that the masses of the heavy BSM scalars are strongly restricted from below, and can LHC and ILC can explore the parameters space.

The paper is organized as follows: In Sec. II, we briefly summarize type-X 2HDM, muon $g - 2$ contribution, lepton universality test and oblique parameters. In Sec. III, we describe all of the theoretical and experiment constraints and find preferred region. We conclude in Sec. IV.

II. THE MODEL BASICS

In this section we briefly describe the necessary elements of the type-X 2HDM. For a detailed discussions about multi Higgs doublet model please see [75–77].

A. 2HDM with type-X Yuakwa interaction

The model contains two Higgs doublets $\Phi_1$ and $\Phi_2$ with $Y = 1/2$. Presence of two Higgs doublets where both the doublets couple to the fermions leads to flavour changing neutral current (FCNC) interaction at tree level. To avoid this, we impose a $Z_2$ symmetry such that $\Phi_1 \to -\Phi_1$ and $\Phi_2 \to \Phi_2$. The scalar potential can be written as,

$$V_{2HDM} = -m_{11}^2 \Phi_1^\dagger \Phi_1 - m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.\right] + \frac{1}{2} \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2} \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) + \frac{1}{2} \lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + h.c.\right.$$
After the electroweak symmetry breaking, the scalars $\Phi_1$ and $\Phi_2$ will acquire vacuum expectation values (VEV) $v_1$ and $v_2$ respectively. We can parameterize the doublets in the following way, $\Phi_j = (H^+_j, (v_j + h_j + i A_j)/\sqrt{2})^T$ and obtain the physical states $h$, $H$, $H^\pm$ by appropriately rotating the gauge eigenstates:

$$
\begin{pmatrix}
H \\
h
\end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\
h_2
\end{pmatrix}$$

$$A(H^\pm) = -s_\beta A_1(H^\pm_1) + c_\beta A_2(H^\pm_2),$$

where $s_\alpha = \sin \alpha$, $c_\beta = \cos \beta$ and $\tan \beta = v_2/v_1$. The CP-even state $h$ is identified with the SM-like Higgs with mass $m_h \approx 125$ GeV.

In this article we will consider the Type-X 2HDM where the RH leptons are odd under $\Z_2$ symmetry. The relevant Yukawa Lagrangian is given by,

$$-\mathcal{L}_Y = Y_u^c Q_L \tilde{u}_R + Y_d^c Q_L \tilde{d}_R + Y_e^c L_L \tilde{\ell}_R + \Phi_1 e_R + h.c.,$$

where $\tilde{Q}_2 = i \sigma_2 \Phi_2^*$. After symmetry breaking the Yukawa Lagrangian takes the form,

$$\mathcal{L}^{\text{Physical}}_{\text{Yukawa}} = -\sum_{f=u,d,\ell} \frac{m_f}{v} \left( \xi^f_\alpha h f + \xi^f_\beta H f - i \xi^f_\gamma f \gamma_5 A f \right) - \left\{ \frac{\sqrt{2} V_{ud}}{v} \pi \left[ \xi^l_\alpha m_u P_L + \xi^l_\beta m_d P_R \right] H^+ d + \frac{\sqrt{2} m_t}{v} \xi^t_\gamma \bar{t}_L H^+ t_R + h.c. \right\}.$$
As expected, only a small range of T parameter is allowed. We have satisfied the T parameter and found that the CP even heavy Higgs mass in the range of 200 to 400 GeV. As expected, only a small range of T parameter is allowed. We have satisfied the T parameter and found that the CP even heavy Higgs and the charged Higgs can not be degenerate. We plotted the mass difference between H and H± in Fig. 2. The mass difference has a mild dependence on the pseudoscalar mass.

\[ m_H \simeq m_{H^\pm} \leq \sqrt{\lambda_{\text{max}}} v = \sqrt{4\pi} v. \]  

Here we assumed the wrong sign scenario i.e \( \tan \beta \cos(\beta - \alpha) \approx 2 \).

The constrains from precision measurement are usually defined in terms of S,T and U parameters. As we have discussed in the introduction, the effect of newly measured \( m_W \) by CDF can be parametrized in terms of these parameters. Assuming \( \Delta U = 0 \) the allowed values of S and T parameters are discussed in Ref. [5], and the allowed range for S and T parameters are:

\[ S = 0.15 \pm 0.08, \quad T = 0.27 \pm 0.06. \]  

In the 2HDM, the contributions to oblique parameters induced by the scalar bosons are given by [81]

\[ S = -\frac{1}{4\pi} \left[ f_2(m_{H^\pm}, m_{H^\pm}) - \sin^2(\beta - \alpha) f_2(m_H, m_A) - \cos^2(\beta - \alpha) f_2(m_h, m_A) \right], \]

\[ T = -\frac{1}{32\pi^2\alpha_{EM} v^2} \left[ -f_1(m_A, m_{H^\pm}) + \sin^2(\beta - \alpha) \left( f_1(m_H, m_A) - f_1(m_H, m_{H^\pm}) \right) \right. \]

\[ \left. + \cos^2(\beta - \alpha) \left( f_1(m_h, m_A) - f_1(m_h, m_{H^\pm}) \right) \right], \]  

where

\[ f_1(m_1, m_2) = \frac{m_1^2 + m_2^2}{2} - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \log \frac{m_1^2}{m_2^2}, \]

\[ f_2(m_1, m_2) = \frac{1}{3} \left( \frac{4}{3} - \frac{m_1^2 \log m_1^2 - m_2^2 \log m_2^2}{m_1^2 - m_2^2} \right. \]

\[ \left. - \frac{m_1^2 + m_2^2}{(m_1^2 - m_2^2)^2} f_1(m_1, m_2) \right). \]  

The S parameter remains very small, and this strongly constrain the possible value of T parameter.

We plotted the allowed space in S-T plane in Fig. 1 and the vertical bar shows the value of S parameter for heavy Higgs mass in the range of 200 to 400 GeV. As expected, only a small range of T parameter is allowed. We have satisfied the T parameter and found that the CP even heavy Higgs and the charged Higgs can not be degenerate. We plotted the mass difference between H and H± in Fig. 2. The mass difference has a mild dependence on the pseudoscalar mass.

\[ \Delta \equiv m_{H^\pm} - m_H \]

\[ \text{FIG. 2: Allowed range for T parameter in the 2HDM with } m_H = 200 \text{ GeV (purple), 300 GeV (blue), and 400 GeV (Red).} \]
From these observations, the limit on CMS and ATLAS have studied these channels [69–74].

This is due to the fact that the lepton universality mostly does not affect the lepton universality limits significantly.

H have recalculated the lepton universality limits for such result calls for a non-degenerate mass spectrum, and we come from the extra Higgs bosons through loop-level corrections.

So far in the literature the constraint on 2HDM-X coming from lepton universality has been calculated [84–86] assuming that H and $H^\pm$ degenerate. However, the CDF result calls for a non-degenerate mass spectrum, and we have recalculated the lepton universality limits for such a scenario. We found that unless H is relatively light ($m_H \sim 200$ GeV) the non-degenerate mass spectrum does not affect the lepton universality limits significantly. This is due to the fact that the lepton universality mostly depends on the mass gap between $m_A$ and $m_H$ when $H^\pm$ is heavier. Following the $\chi^2$-analysis in Ref.[85, 87], we obtain the limits on the lepton universality of $\tau$ and $Z$ decays.

In the large $\tan \beta$ limit, there are two important corrections. One correction is originated from the heavy charged Higgs boson at the tree-level. The other one comes from the extra Higgs bosons through loop-level corrections.

Since the pseudoscalar is lighter than $m_h/2$, the SM Higgs can decay to a pair of pseudoscalars. Since the pseudoscalar couples strong to leptons, the relevant signal at the LHC is $pp \to h \to AA \to 4\tau/2\mu 2\tau$. The both CMS and ATLAS have studied these channels [69–74]. From these observations, the limit on $BR(h \to AA)$ is as low as < 2% for $m_A = 9$ GeV. For most of the $m_A$ range, the limit is $BR(h \to AA) < 5\%$. We need to satisfy these constraints.

The relevant coupling for the Higgs decay to AA is given by [88],

$$\lambda_T = \frac{1}{4} s_2^2 \left( \lambda_1 + \lambda_2 \right) + (\lambda_3 + \lambda_4 + \lambda_5)s_4^2 c_5^2 - 2\lambda_5$$

$$\lambda_U = \frac{1}{2} s_2^2 \left( s_2^2 \lambda_1 - c_2^2 \lambda_2 + c_2^2 (\lambda_3 + \lambda_4 + \lambda_5) \right)$$

$$\lambda_{RAA} = -v (\lambda_T s_2 c_1 - \lambda_U c_2 c_1)$$

(13)
By rewriting \( \sin \alpha = \xi_h^2 \cos \beta \) and by inverting the quartic coupling to the relevant mass parameter we can calculate the branching ratio as a function of \( m_H, m_A, \xi_h^2 \). Figure 3 depicts the branching ratios. Evidently, \( BR(h \rightarrow AA) \) is close to 100% for most of the parameter space, unless the parameters are fine-tuned to cancel. This cancellation happens for a particular value of coupling modifier depending on the mass of heavy Higgs. The supression in the branching ratio does not depend on the quartic coupling \( \lambda_1 \), another free parameter of the model. From the Figure, it is evident that the parameter space is very strongly constrained. Since the coupling modifier dictates the deviation of Higgs Yukawa coupling, it is constrained by the measurement of Higgs coupling strength. The current measurement of these coupling strengths by CMS and ATLAS collaboration allows \( \xi_h^2 \) to be within 0.7 to 1.15 at 2\( \sigma \) [89, 90]. Thus, the combination of Higgs signal strength measurement with the measurement of Higgs branching ratio to light pseudoscalar puts a lower limit on the mass spectrum of 2HDM-X, and the CP even Higgs has to heavier than 300 GeV.

III. NUMERICAL RESULTS AND DISCUSSIONS

In the previous section we have discussed the relevant parameter space and the contraines coming from various theoretical as well as experimental observatios. We scanned the parameter space in the following range:

\[
m_A : 10 - 90 \text{ GeV}, \tan \beta : 20 - 90, m_H : 300 \& 400 \text{ GeV}
\]

(14)

The allowed parameter and the constraints are shown in Fig. 4 where the top(bottom) panel corresponds to \( m_H = 300(400) \text{ GeV} \). To explain \( (g - 2)_\mu \), we neet light pseudoscalar and large \( \tan \beta \) and the parameter space is strongly constrained by the measurement of lepton universality. However, small parameter space with \( m_A \) between 10 to 50 GeV is still allowed when \( \tan \beta \) in the range 40 – 60 GeV.

Since the BSM scalars are hadrophobic, the present limit on the scalars of type-X 2HDM is rather weak. The existing LHC limits originate from the fermionic interactions of the BSM scalars, i.e. the existing search strategy looks for BSM scalars produced via gluon fusion and decay to \( b\bar{b} \) or \( \tau\tau \). Since the quark coupling to the new scalars is proportional to \( \cot \beta \), there is no limit on BSM scalars if \( \tan \beta \) is greater than 10. The parameter space of this model is well restricted, and the non-fermionic decay mode should be studied to probe the allowed parameter space.

IV. CONCLUSION

In this work, we explored type-X 2HDM to constrain the \((m_A, \tan \beta)\) parameter region with the recent measurement obtained by CDF II collaboration. To resolve the W boson mass discrepancy, the mass difference between \( m_H \) and \( m_{H^+} \) are the order of \( O(10) \text{GeV} \) due to enhancement in the oblique correction, \( T \sim 0.1 - 0.2 \). We calculated constraints coming from the lepton universality test and measurement of Higgs signal strength at the LHC. We found that the CDF measurement does not constrain the 2HDM-X parameter space, which can explain...
the muon $(g - 2)$ anomaly. Interestingly, the Higgs signal strength measurement, specifically the measurement of $BR(h \to AA)$, put a stronger lower limit on the mass of the heavy Higgs boson, which should be heavier than 200 GeV.

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[1] CDF Collaboration, T. Aaltonen et al., “High-precision measurement of the W boson mass with the CDF II detector,” Science 376 (2022) no. 6589, 170–176.

[2] CDF, D0 Collaboration, T. A. Aaltonen et al., “Combination of CDF and D0 W-Boson Mass Measurements,” Phys. Rev. D 88 (2013) no. 5, 052018, arXiv:1307.7627 [hep-ex].

[3] ATLAS Collaboration, M. Aaboud et al., “Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” Eur. Phys. J. C 78 (2018) no. 2, 110, arXiv:1701.07240 [hep-ex]. [Erratum: Eur.Phys.J.C 78, 898 (2018)].

[4] 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].

[5] 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].

[6] 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].

[7] 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].

[8] 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].

[9] 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].

[10] A. Strumia, “Interpreting electroweak precision data including the W-mass CDF anomaly,” arXiv:2204.04191 [hep-ph].

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

[12] 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].

[13] K. Sakurai, F. Takahashi, and W. Yin, “Singlet extensions and W boson mass in the light of the CDF II result,” arXiv:2204.04477 [hep-ph].

[14] 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].

[15] 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].

[16] 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].

[17] 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].

[18] 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:2204.05301 [hep-ph].

[19] 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].

[20] L. Di Luzio, R. Gröber, and P. Paradisi, “Higgs physics confronts the $M_W$ anomaly,” arXiv:2204.05284 [hep-ph].

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

[22] 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].

[23] A. Paul and M. Valli, “Violation of custodial symmetry from W-boson mass measurements,” arXiv:2204.05267 [hep-ph].

[24] T. Biekötter, S. Heinemeyer, and G. Weiglein, “Excesses in the low-mass Higgs-boson search and the W-boson mass measurement,” arXiv:2204.05975 [hep-ph].

[25] R. Balkin, E. Madge, T. Menzo, G. Perez, Y. Soreq, and J. Zupan, “On the implications of positive W mass shift,” arXiv:2204.05992 [hep-ph].

[26] L. Di Luzio, M. Nardecchia, and C. Toni, “Light vectors coupled to anomalous currents with harmless Wess-Zumino terms,” arXiv:2204.05945 [hep-ph].

[27] K. Cheung, W.-Y. Keung, and P.-Y. Tseng, “Iso-doublet Vector Leptoquark solution to the Muon $g - 2$ Anomaly and New CDF II W-Mass Measurement at CDF,” arXiv:2204.05302 [hep-ph].

[28] M. Endo and S. Mishima, “New physics interpretation of W-boson mass anomaly,” arXiv:2204.05965 [hep-ph].

[29] A. Crivellin, M. Kirk, T. Kitahara, and F. Mescia, “Correlating $t \to c Z$ to the W Mass and B Physics with Vector-Like Quarks,” arXiv:2204.05962 [hep-ph].
G. Arcadi and A. Djouadi, "The 2HD+a model for a \textit{W} mass anomaly on two Higgs doublet model," arXiv:2204.05728 [hep-ph].

Y. H. Ahn, S. K. Kang, and R. Ramos, "Implications of New CDF-II W Boson Mass on Two Higgs Doublet Model," arXiv:2204.06485 [hep-ph].

M.-D. Zheng, F.-Z. Chen, and H.-H. Zhang, "The $W\nu$-vertex corrections to $W$-boson mass in the R-parity violating MSSM," arXiv:2204.06541 [hep-ph].

P. Perez Fileviez, H. H. Patel, and A. D. Plascencia, "On the W-mass and New Higgs Bosons," arXiv:2204.07144 [hep-ph].

A. Ghoshal, N. Okada, S. Okada, D. Raut, Q. Shafi, and A. Thapa, "Type III seesaw with R-parity violation in light of $m_W$ (CDF)," arXiv:2204.07138 [hep-ph].

Z. Péli and Z. Trócsányi, "Vacuum stability and scalar masses in the superweak extension of the standard model," arXiv:2204.07100 [hep-ph].

J. Kawamura, S. Okawa, and Y. Omura, "W boson mass and muon $g - 2$ in a lepton portal dark matter model," arXiv:2204.07022 [hep-ph].

S. Kanemura and K. Yagyu, "Implication of the W boson mass anomaly at CDF II in the Higgs triplet model with a mass difference," arXiv:2204.07511 [hep-ph].

K. I. Nagao, T. Nomura, and H. Okada, "A model explaining the new CDF II W boson mass linking to muon $g - 2$ and dark matter," arXiv:2204.07411 [hep-ph].

P. Mondal, "Enhancement of the W boson mass in the Georgi-Machacek model," arXiv:2204.07844 [hep-ph].

K.-Y. Zhang and W.-Z. Feng, "Explaining W boson mass anomaly and dark matter with a (1|1) dark sector," arXiv:2204.08067 [hep-ph].

L. M. Carpenter, T. Murphy, and M. J. Smylie, "Changing patterns in electroweak precision with new color-charged states: Oblique corrections and the W boson mass," arXiv:2204.08546 [hep-ph].

O. Popov and R. Srivastava, "The Triplet Dirac Seesaw in the View of the Recent CDF-II W Mass Anomaly," arXiv:2204.08568 [hep-ph].

G. Arcadi and A. Djouadi, "The 2HD+a model for a combined explanation of the possible excesses in the CDF $M_W$ measurement and $(g - 2)_\mu$ with Dark Matter," arXiv:2204.08406 [hep-ph].

T. A. Chowdhury, J. Heeck, S. Saad, and A. Thapa, "W boson mass shift and muon magnetic moment in the Zee model," arXiv:2204.08390 [hep-ph].

D. Borah, S. Mahapatra, D. Nanda, and N. Sahu, "Type II Dirac Seesaw with Observable $\Delta N_{ee}$ in the Light of W-mass Anomaly," arXiv:2204.08266 [hep-ph].

V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, and T. Tong, "Beta-decay implications for the W-boson mass anomaly," arXiv:2204.08440 [hep-ph].

Y.-P. Zeng, C. Cai, Y.-H. Su, and H.-H. Zhang, "Extra boson mix with Z boson explaining the mass of W boson," arXiv:2204.09487 [hep-ph].

M. Du, Z. Liu, and P. Nath, "CDF W mass anomaly in a Stueckelberg extended standard model," arXiv:2204.09024 [hep-ph].

K. Ghorbani and P. Ghorbani, "W-Boson Mass Anomaly from Scale Invariant 2HDM," arXiv:2204.09001 [hep-ph].

A. Bhaskar, A. A. Madathil, T. Mandal, and S. Mitra, "Combined explanation of W-mass, muon $g - 2$, $R_K^{(*)}$ and $R_{D^{(*)}}$ anomalies in a singlet-triplet scalar leptoquark model," arXiv:2204.09031 [hep-ph].

S. Baek, "Implications of CDF W-mass and $(g - 2)_\mu$ on $U(1)_{\mu - \tau}$ model," arXiv:2204.09585 [hep-ph].

J. Cao, L. Meng, L. Shang, S. Wang, and B. Yang, "Interpreting the W mass anomaly in the vectorlike quark models," arXiv:2204.09477 [hep-ph].

D. Borah, S. Mahapatra, and N. Sahu, "Singlet-Doublet Fermion Origin of Dark Matter, Neutrino Mass and W-Mass Anomaly," arXiv:2204.09671 [hep-ph].

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].

E. d. S. Almeida, A. Alves, O. J. P. Eboli, and M. C. Gonzalez-Garcia, "Impact of CDF-II Measurement of $M_W$ on the electroweak legacy of the LHC Run II," arXiv:2204.10130 [hep-ph].

Y. Cheng, X.-G. He, F. Huang, J. Sun, and Z.-P. Xing, "Dark photon kinetic mixing effects for CDF W mass excess," arXiv:2204.10156 [hep-ph].

A. Addazi, A. Marciano, A. P. Morais, R. Pasechnik, and H. Yang, "CDF II W-mass anomaly faces first-order electroweak phase transition," arXiv:2204.10315 [hep-ph].

J. Heeck, "W-boson mass in the triplet seesaw model," arXiv:2204.10274 [hep-ph].

H. Abouabid, A. Arhrib, R. Benbrik, M. Krab, and M. Ouchemouh, "Is the new CDF $M_W$ measurement consistent with the two higgs doublet model?", arXiv:2204.12018 [hep-ph].

H. B. T. Tan and A. Derevianko, "Implications of W-boson mass for atomic parity violation," arXiv:2204.11991 [hep-ph].

A. E. Faraggi and M. Guzzi, "Z's and sterile neutrinos from heterotic string models: exploring Z' mass exclusion limits," arXiv:2204.11974 [hep-ph].

A. Batra, S. K. A, S. Mandal, H. Prajapati, and R. Srivastava, "CDF-II W Boson Mass Anomaly in the Canonical Scotogenic Neutrino-Dark Matter Model," arXiv:2204.11945 [hep-ph].

R. Benbrik, M. Boukidi, and B. Manaut, "W-mass and 96 GeV excess in type-III 2HDM," arXiv:2204.11755 [hep-ph].

C. Cai, D. Qiu, Y.-L. Tang, Z.-H. Yu, and H.-H. Zhang, "Corrections to electroweak precision observables from mixings of an exotic vector boson in light of the CDF W-mass anomaly," arXiv:2204.11570 [hep-ph].

R. Dermisek, J. Kawamura, E. Lunghi, N. McGinnis, and S. Shin, "Leptonic cascade decays of a heavy Higgs boson through vectorlike leptons at the LHC," arXiv:2204.13272 [hep-ph].

T.-K. Chen, C.-W. Chiang, and K. Yagyu, "Explanation of the W mass shift at CDF II in the Georgi-Machacek Model," arXiv:2204.12898 [hep-ph].

R. S. Gupta, "Running away from the T-parameter solution to the W mass anomaly," arXiv:2204.13690 [hep-ph].

ATLAS Collaboration, G. Aad \textit{et al.}, "Search for Higgs bosons decaying to $aa$ in the $\mu\mu\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment," \textit{Phys. Rev. D} \textbf{92} (2015) no. 5, 052002, arXiv:1505.01609 [hep-ex].
[70] CMS Collaboration, V. Khachatryan et al., “Search for light bosons in decays of the 125 GeV Higgs boson in proton-proton collisions at $\sqrt{s} = 8$ TeV,” *JHEP* **10** (2017) 076, arXiv:1701.02032 [hep-ex].

[71] ATLAS Collaboration, M. Aaboud et al., “Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV,” *JHEP* **06** (2018) 166, arXiv:1802.03388 [hep-ex].

[72] CMS Collaboration, A. M. Sirunyan et al., “Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state of two muons and two $\tau$ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *JHEP* **11** (2018) 018, arXiv:1805.04865 [hep-ex].

[73] CMS Collaboration, A. M. Sirunyan et al., “Search for light pseudoscalar boson pairs produced from decays of the 125 GeV Higgs boson in final states with two muons and two nearby tracks in $p\bar{p}$ collisions at $\sqrt{s} = 13$ TeV,” *Phys. Lett. B* **800** (2020) 135087, arXiv:1907.07235 [hep-ex].

[74] CMS Collaboration, A. M. Sirunyan et al., “Search for a light pseudoscalar Higgs boson in the boosted $\mu\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *JHEP* **08** (2020) 139, arXiv:2005.08694 [hep-ex].

[75] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, *The Higgs Hunter’s Guide*, vol. 80. 2000.

[76] A. Djouadi, “The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model,” *Phys. Rept.* **459** (2008) 1–241, arXiv:hep-ph/0503173.

[77] 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, arXiv:1106.0034 [hep-ph].

[78] Muon g-2 Collaboration, B. Abi et al., “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm,” *Phys. Rev. Lett.* **126** (2021) no. 14, 141801, arXiv:2104.03281 [hep-ex].

[79] J. Haller, A. Hoecker, R. Kogler, K. Mönig, T. Peiffer, and J. Stelzer, “Update of the global electroweak fit and constraints on two-Higgs-doublet models,” *Eur. Phys. J. C* **78** (2018) no. 8, 675, arXiv:1803.01853 [hep-ph].

[80] L. Wang and X.-F. Han, “A light pseudoscalar of 2HDM confronted with muon g-2 and experimental constraints,” *JHEP* **05** (2015) 039, arXiv:1412.4874 [hep-ph].

[81] D. Toussaint, “Renormalization Effects From Superheavy Higgs Particles,” *Phys. Rev. D* **18** (1978) 1626.

[82] ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group Collaboration, S. Schael et al., “Precision electroweak measurements on the Z resonance,” *Phys. Rept.* **427** (2006) 257–454, arXiv:hep-ex/0509008.

[83] HFLAV Collaboration, Y. Amhis et al., “Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of summer 2016,” *Eur. Phys. J. C* **77** (2017) no. 12, 895, arXiv:1612.07233 [hep-ex].

[84] T. Abe, R. Sato, and K. Yagyu, “Lepton-specific two Higgs doublet model as a solution of muon $g - 2$ anomaly,” *JHEP* **07** (2015) 064, arXiv:1504.07059 [hep-ph].

[85] E. J. Chun and J. Kim, “Leptonic Precision Test of Two Higgs-Doublet Models,” *JHEP* **07** (2016) 110, arXiv:1605.06298 [hep-ph].

[86] E. J. Chun, J. Kim, and T. Mondal, “Electron EDM and Muon anomalous magnetic moment in Two-Higgs-Doublet Models,” *JHEP* **12** (2019) 068, arXiv:1906.00612 [hep-ph].

[87] E. J. Chun, A. Das, J. Kim, and J. Kim, “Searching for flavored gauge bosons,” *JHEP* **02** (2019) 093, arXiv:1811.04320 [hep-ph]. [Erratum: *JHEP* 07, 024 (2019)].

[88] 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, arXiv:hep-ph/0207010.

[89] CMS Collaboration, “Measurements of Higgs boson production in the decay channel with a pair of $\tau$ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV,” arXiv:2204.12957 [hep-ex].

[90] ATLAS Collaboration, G. Aad et al., “Measurements of Higgs boson production cross-sections in the $H \to \tau^+\tau^-$ decay channel in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” arXiv:2201.08269 [hep-ex].