2HD plus light pseudoscalar model for a combined explanation of the possible excesses in the CDF M_W measurement and $(g-2)_\mu$ with dark matter

Giorgio Arcadi[1] and Abdelhak Djouadi[2,3]

[1] *Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Universita degli Studi di Messina, Via Ferdinando Stagno d'Alcontres 31, I-98166 Messina, Italy*

[2] *CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain*

[3] *Laboratory of High Energy and Computational Physics, NICPB, Rävala pst. 10, 10143 Tallinn, Estonia*

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The new measurement of the W boson mass performed by the CDF experiment at the Tevatron shows a significant deviation not only with the expectation in the Standard Model but also with other precision measurements performed at LEP, the Tevatron, and the LHC. We nevertheless take this new measurement at face value and interpret it as an effect of new physics. We particularly try to link it with other possible anomalies such as the recent muon $g-2$ and consider a scenario that addresses some shortcomings of the Standard Model. We show that a version of a model with two doublets and a light pseudoscalar Higgs fields, supplemented by a stable isosinglet fermion, can simultaneously explain the possible M_W and $(g-2)_\mu$ anomalies and accounts for the weakly interacting massive particle that could be responsible of the dark matter in the universe.

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I. INTRODUCTION

The CDF experiment at the Tevatron has recently released a new measurement of the W boson mass [1]

$$M_W = 80.4335 \pm 0.0094 \text{ GeV}. \tag{1}$$

On the one hand, the combined statistical and systematical errors on this new measurement is smaller than that of the current world average value obtained when combining all former measurements from LEP, Tevatron, and the LHC, $M_W = 80.379 \pm 0.012$ GeV [2]. The central value of this average is more than 50 MeV lower than the CDF new value and, when one combines all available data, one obtains $M_W = 80.4133 \pm 0.0080$ GeV [3].

On the other hand, the new CDF value deviates from the expectation in the Standard Model (SM), as a recent global fit of all electroweak precision data gives [4]

$$M_W = 80.3545 \pm 0.0057 \text{ GeV}, \tag{2}$$

and this deviation from the theoretical prediction is huge, slightly more than 7σ. Even if one compares the prediction with the new averaged M_W value, the deviation is still at a very high level [3]. This new and unexpected development calls for great caution and confirmation (as it is customary to say, extraordinary claims require an extraordinary evidence) and, at least, a careful understanding of the differences between the various measurements is mandatory before any firm conclusion is made.

Nevertheless, as the main mission of a particle theorist is to interpret the experimental data without any qualms, one should take this new result at face value, put it in perspective and interpret it in the context of physics beyond the SM and/or infer its possible implications, as it was already done in many very recent analyses [5,6]. In particular, one should at least try to relate it to other observed anomalies and embed it in model extensions that address important shortcomings of the SM.

It would be particularly welcome if the new M_W value is connected with another recent discrepancy also observed at Fermilab, the one affecting the muon anomalous magnetic moment released a year ago by the Muon g–2 collaboration [7] and which exhibits a 4.2σ deviation from the SM expectation. There are also standing anomalies, albeit weaker, occurring in B-meson observables and some of them are also associated with muons, e.g., the semileptonic $b \to s\mu^+\mu^-$ decay rate [8].

In fact, in a recent paper [9], we correlated the above two anomalies in the context of a new physics model that also addresses a main concern of the SM, namely its inability to account for the dark matter (DM) in the universe. The model is based on an extension of the SM Higgs sector to contain two Higgs doublet fields and a light pseudoscalar a state with enhanced couplings to muons [10–12]. This particle then minimally couples to an additional SU(2) isosinglet fermion which is assumed to be stable and forms the DM. We have shown that a version of a 2HD + a model can cope with all existing constraints from collider and astroparticle physics and, at the same time, explains the deviations observed in the measurement of $(g-2)_\mu$ and $\mathrm{BR}(b \to s\mu^+\mu^-)$.

In this note, we reconsider this 2HD + a model and relax an assumption made to ease the numerical analysis, namely that the heavier Higgs—the CP-even H, CP-odd A. and two charged $H^\pm$—states are degenerate in mass to comply with electroweak precision data [13]. This will not affect the aspects related to DM and flavor physics, but introduces a correction to the ρ parameter that modifies the W mass value. We will show that the parameters of the model can be chosen in such a way that the CDF measurement is recovered without significantly impacting the other observables including the $(g-2)_\mu$ excess and allowing for a good DM candidate.

In the next section, we summarize our model and present two benchmarks in which the $(g-2)_\mu$ excess is resolved with collider and astroparticle physics constraints satisfied. In Sec. III, we discuss new contributions to M_W and show that the CDF value is reproduced in these benchmarks. A conclusion is given in Sec. IV.

II. THE 2HD + A MODEL AND DARK MATTER

Models with two-Higgs doublet (2HDM) fields H_1 and H_2, acquiring nonzero expectation values v_1 and v_2 with $\sqrt{v_1^2+v_2^2} = v \simeq 246$ GeV and a ratio denoted by $\tan\beta = v_1/v_2$, are interesting and widely discussed extensions of the SM [14]. They lead to a richer Higgs spectrum consisting of two CP-even h, H bosons, with h assumed to be the state with a mass of 125 GeV observed at the LHC, a CP-odd A^0 and two charged $H^\pm$ bosons.

The presence of a Z_2 symmetry in the scalar sector is very often assumed to automatically prevent the emergence of tree-level flavor changing neutral currents. The 2HDM scalar potential in this case is given by:

$$\begin{aligned} V_{\rm 2HDM} = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2(\Phi_1^\dagger\Phi_2 + \mathrm{H.c.}) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + \frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2) + \mathrm{H.c.}) \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1). \end{aligned} \quad (3)$$

However, to accommodate the presence of DM in a viable way, we will consider in this work a Z_2 symmetric 2HDM sector extended with a light pseudoscalar singlet field a_0. The scalar potential of this 2HD + a model is the 2HDM one given above supplemented by the terms

$$\begin{aligned} V_{\rm 2HD+a} = {} & V_{\rm 2HDM} + \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{\lambda_a}{4}a_0^4 \\ & + \kappa(ia_0\Phi_1^\dagger\Phi_2 + \mathrm{H.c.}) + \lambda_{1P}a_0^2\Phi_1^\dagger\Phi_1 \\ & + \lambda_{2P}a_0^2\Phi_2^\dagger\Phi_2. \end{aligned} \quad (4)$$

The A^0 and a_0 states mix to give the mass eigenstates A and a; the mixing angle θ is defined by $\tan 2\theta = 2\kappa v/(M_A^2 - M_a^2)$, with κ the coefficient of the term coupling the two Higgs doublets with the singlet. Note that for $M_A \gg M_a$ and a strong mixing $\sin 2\theta \approx 1$, there is an upper bound from the requirement of perturbative unitarity in Higgs scattering amplitudes, $M_A \lesssim 1.4$ TeV [11].

Using the mixing angle α that diagonalizes the CP-even h and H mass matrix, which in the alignment limit becomes $\alpha = \beta - \frac{\pi}{2}$, and the abbreviation $M^2 = 2m_3^2/\sin 2\beta$, the 2HDM quartic couplings $\lambda_{i=1,5}$ can be reexpressed in terms of the physical Higgs masses as

$$\begin{aligned} \lambda_1 &= \frac{1}{v^2}\left(-\tan^2\beta M^2 + \frac{\sin^2\alpha}{\cos^2\beta}M_h^2 + \frac{\cos^2\alpha}{\cos^2\beta}M_H^2\right), \\ \lambda_2 &= \frac{1}{v^2}\left(-\frac{1}{\tan^2\beta}M^2 + \frac{\cos^2\alpha}{\sin^2\beta}M_h^2 + \frac{\sin^2\alpha}{\sin^2\beta}M_H^2\right), \\ \lambda_3 &= \frac{1}{v^2}\left(-M^2 + 2M_{H^\pm}^2 + \frac{\sin 2\alpha}{2\sin\beta}(M_H^2 - M_h^2)\right), \\ \lambda_4 &= \frac{1}{v^2}(M^2 + M_A^2\cos^2\theta + M_a^2\sin^2\theta - 2M_{H^\pm}^2), \\ \lambda_5 &= \frac{1}{v^2}(M^2 - M_A^2\cos^2\theta - M_a^2\sin^2\theta). \end{aligned} \quad (5)$$

This CP-conserving and Z_2 symmetric 2HD + a model is then characterized by the following set of input parameters: the five Higgs masses $M_h, M_H, M_{H^\pm}, M_A$ and M_a, the mixing angles θ among the a, A and α among the CP-even h, H states, $\tan\beta$ and three parameters of the scalar potential which enter only in the self-couplings among the Higgs bosons. The only requirement we will make on these last parameters is that they should lead to a very small coupling among the haa states, $\lambda_{haa} \lesssim 10^{-3}$.

We turn now to the Higgs couplings to fermions, which should be special in order to explain the $(g-2)_\mu$ anomaly in this 2HD + a model that also accommodates DM (for an explanation of $(g-2)_\mu$ alone, one can consider more elaborate 2HDMs such as a flavor aligned one [15] or exotic nonflavor aligned realizations [16]; see also Ref. [17]).

In the Z_2 symmetric realization of the 2HDM, these couplings are proportional to the SM Higgs Yukawa couplings. In the alignment limit in which the hff couplings (normalized to the SM Higgs couplings [18]) are SM-like,

$g_{hff} = 1$ as indicated by LHC Higgs data [19], the other Higgs couplings to fermions are such that $g_{Hff} = g_{A_0ff} = \xi_f$ with the coefficients $|\xi_f| = \tan\beta$ or $\cot\beta$ depending on the considered 2HDM type [14]. Only four configurations, dubbed Type-I, Type-II, Type-X, and Type-Y, properly describe these couplings.

In our 2HD + a model, one can choose a similar Z_2 symmetric realization as in the 2HDM above. In the limit $g_{hff} = 1$, the neutral Higgs couplings to fermions become

$$g_{Hff} = \xi_f, \qquad g_{Aff} = \cos\theta\xi_f, \qquad g_{aff} = -\sin\theta\xi_f, \qquad (6)$$

with the coefficients $|\xi_f| = \tan\beta$ or $\cot\beta$ depending on the type of the considered 2HDM [14]. As can be seen, the CP-even states have the same couplings as in the 2HDM while the CP-odd state A has analogous couplings as the one of the 2HDM but scaled by a factor $\cos\theta$. In the absence of mixing, $\theta \to 0$, the two couplings will coincide. In this limit, the additional a state will become a pure SM singlet. We can thus also define four types of 2HD + a models (I, II, X, and Y) as in the conventional 2HDM.

In our present case, as we need enhanced couplings to the isospin $-\frac{1}{2}$ muons to explain the $(g-2)_\mu$ excess, we will discuss only the so-called Type-II scenario with $|\xi_\tau| = |\xi_b| = 1/|\xi_t| = \tan\beta$ and the lepton–specific or Type-X scenario with $|\xi_\tau| = 1/|\xi_b| = 1/|\xi_t| = \tan\beta$. In both cases the nonstandard Higgs states will have strongly enhanced couplings to charged leptons for values $\tan\beta \gg 1$ and, in Type-II, also to bottom quarks.

The original motivation of a 2HDM plus a light pseudoscalar is that it allows to induce a gauge invariant interaction between the gauge singlet a and pairs of SM fermions, and through the mixing with the A state, to pairs of the fermionic singlet χ which is assumed to be stable and forms the DM. As χ is a SM singlet, it does not couple to gauge bosons and couples to Higgs bosons only in pairs. In particular, there are no χ couplings to the CP-even h, H bosons while its couplings to the two pseudoscalar Higgs bosons is given by [9]

$$\mathcal{L}_{\rm DM} = g_\chi(\cos\theta a + \sin\theta A)\bar{\chi} i\gamma_5\chi. \qquad (7)$$

In the next section we summarize the main relevant features of such a model.

III. FIT OF G-2 AND CONSTRAINTS

Following Ref. [9], to explain the excess observed at Fermilab in the measurement of $\Delta a_\mu = (g-2)_\mu$, we consider a 2HD + a model in which the 2HDM bosons except for h have masses above a few hundred GeV while the pseudoscalar boson a is light, with a mass below 100 GeV, and has a strong coupling $g_{a\mu\mu}$ to muons. The new physics contribution to Δa_μ is then mostly accounted for by one-loop and two-loop diagrams with the exchange of this a state, such as the ones shown in Fig. 1.

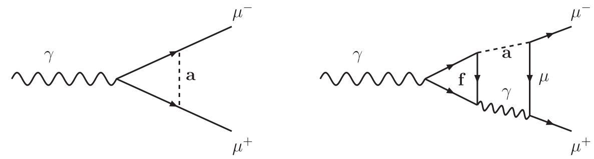

FIG. 1. Generic Feynman diagrams responsible for the one-loop (left) and two-loop (right) contributions of a neutral pseudoscalar Higgs boson to the $(g-2)_\mu$.

The corresponding contributions can be written as [20]

$$\Delta a_\mu^{1-\rm loop} \approx -\frac{\alpha}{8\pi\sin^2\theta_W}\frac{m_\mu^4}{M_W^2 M_a^2} g_{a\mu\mu}^2\left[\log\left(\frac{M_a^2}{m_\mu^2}\right) - \frac{11}{6}\right],$$
$$\Delta a_\mu^{2-\rm Loop} = \frac{\alpha^2}{8\pi^2\sin^2\theta_W}\frac{m_\mu^2}{M_W^2} g_{a\mu\mu}\sum_f g_{aff} N_c^f Q_f \frac{m_f^2}{M_a^2} F\left(\frac{m_f^2}{M_a^2}\right);$$
$$F(r) = \int_0^1 \mathrm{d}x \frac{\log(r) - \log[x(1-x)]}{r - x(1-r)}. \qquad (8)$$

where one includes in the last term only the contributions of the heavy third generation t, b, τ fermions with mass m_f, electric charge Q_f, and color number N_c^f.

As evident from the previous expressions, both the 1-loop and 2-loop contributions to Δa_μ should be accounted for, since the latter features an m_f^2/m_μ^2 enhancement which can compensate the suppression due to the additional power in the electroweak coupling. A viable fit of the $(g-2)_\mu$ anomaly is obtained for a light M_a, of the order of 10 GeV, with a substantial doublet component, i.e., $\sin\theta \gtrsim 0.5$, and enhanced couplings to muons, hence for the Type-II or Type-X configurations for the Yukawa couplings. The other nonstandard Higgs bosons, which have been assumed to be heavy, also contribute to Δa_μ via Barr–Zee type diagrams [20] but only marginally. We have included such contributions in our numerical computation but, for shortness, we do not report here the corresponding lengthy analytical expressions.

Nevertheless, to be viable, the model has to obey several rather stringent constraints. It has first to fulfill several theoretical constraints, in particular the ones on the various quartic couplings of the 2HD + a scalar potential given in Eq. (4) that we briefly summarize below (for more details see, e.g., Refs. [21–23]).

Using the relations between the quartic couplings and the Higgs masses displayed in Eq. (5), one can describe the 2HD + a model by adopting the set of parameters $(M_h, M_H, M_{H^\pm}, M_A, M_a, M, \lambda_{1P}, \lambda_{2P}, \lambda_a, \sin\theta)$. For theoretical consistency, the latter are first subject to the requirement that the scalar potential is bounded from below which leads to the constraints

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \lambda_a > 0,$$
$$\sqrt{\lambda_1\lambda_2} + \lambda_3 + \min(0, \lambda_4 - |\lambda_5|) > 0,$$
$$\sqrt{\frac{\lambda_1\lambda_a}{2}} + \lambda_{1P} > 0, \qquad \sqrt{\frac{\lambda_2\lambda_a}{2}} + \lambda_{2P} > 0,$$
$$\sqrt{\lambda_1}\lambda_{1P} + \sqrt{\lambda_2}\lambda_{2P} \geq 0. \tag{9}$$

In addition, there is the requirement of perturbative unitarity that leads to the following bounds on the couplings

$$|x_i| < 8\pi, |\lambda_{1,2P}| < 4\pi, |\lambda_3 \pm \lambda_4| < 4\pi,$$
$$\left|\frac{1}{2}(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2})\right| < 8\pi,$$
$$\left|\frac{1}{2}(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2})\right| < 8\pi,$$
$$|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| < 8\pi, \qquad |\lambda_3 \pm \lambda_5| < 8\pi, \tag{10}$$

where the x_i's are the solutions of the equation

$$0 = x^3 - 3(\lambda_a + \lambda_1 + \lambda_2)x^2 + (9\lambda_1\lambda_a + 9\lambda_2\lambda_a - 4\lambda_{1P}^2 - 4\lambda_{2P}^2 - 4\lambda_3^2 - 4\lambda_3\lambda_4 - \lambda_4^2 + 9\lambda_1\lambda_2)x + 12\lambda_{2P}^2\lambda_1 + 12\lambda_{1P}^2\lambda_2 - 16\lambda_{1P}\lambda_{2P}\lambda_3 - 8\lambda_{1P}\lambda_{2P}\lambda_4 + (-27\lambda_1\lambda_2 + 12\lambda_3^2 + 12\lambda_3\lambda_4 + 3\lambda_4^2)\lambda_a. \tag{11}$$

Bounds like the ones given in Eqs. (9) and (10) will constrain the mass splitting among the different Higgs bosons and will thus, as will be seen in the next section, have an impact on the interpretation of the M_W anomaly.

Together with these theoretical constraints, potential collider constraints should also be accounted for. Most of the constraints on the signal strength of the 125 Higgs boson h [19] are avoided by limiting the deviations from the alignment limit, $\alpha = \beta - \frac{\pi}{2}$. However, even in this limit, the h total decay width is modified by the decay $h \to aa$ when kinematically accessible. To ensure that $\mathrm{BR}(h \to aa)$ does not exceed the experimental limit, one has to impose constraints on the 2HD + a scalar potential such that the resulting haa coupling is small enough.

Moving to the masses and couplings of the extra heavy Higgs states of the model, we have different constraints from LHC searches depending on the configurations of the Yukawa couplings, namely, the Type-II or Type-X.

In the case of the Type-II scenario, there are strong limits from the search of the $H, A, H^\pm$ states at the LHC [24,25]. In the limit $M_A \approx M_H \approx M_{H^\pm}$ one can adapt to the present 2HD + a case the constraints on the $[M_A, \tan\beta]$ parameter plane derived in the context of the MSSM [26]. In this latter case, values $\tan\beta \gtrsim 10$ are excluded for $M_H = M_A \lesssim 1$ TeV from $pp \to H/A \to \tau^+\tau^-$ searches [24], while values $\tan\beta \gtrsim 30$ are excluded by $pp \to H^\pm \to tb$ searches for $M_{H^\pm} \lesssim 700$ GeV [25]. The latter searches also excludes low values of $\tan\beta$, namely $\lesssim 2$ for $M_{H^\pm} \lesssim 1.2$ TeV. However, in our case, given the presence of additional decay channels such as $H \to aa$, $A \to ah$, $H \to Za$, and $H^\pm \to aW$, we expect weaker limits than in the MSSM. In Ref. [9], it has been found that a value $M_A \gtrsim 1$ TeV would allow for high enough values of $\tan\beta$ to be compatible with a fit of $(g-2)_\mu$.

Besides limits from heavy resonances, one has to cope as well with the constraint from a light a decaying into muon pairs [27] which has a large production times decay rate, $\sigma(pp \to a \to \mu^+\mu^-)$ at high $\tan\beta$ [27,28]. In the large $\tan\beta$ regime, preferred by $g-2$), only a narrow window of values of M_a, around 10 GeV, would survive.

In summary, within a Type-II Yukawa configuration, a viable interpretation of the $(g-2)_\mu$ anomaly can be achieved only in very constrained regions of the parameters spaces which would be soon probed by a further increase of the sensitivity of collider searches.

A viable fit of $(g-2)_\mu$ is much easier to achieve in the case of the Type-X scenario. Thanks to the suppressed coupling with all quarks at high $\tan\beta$, the aforementioned constraints do not apply. Other searches, such as heavy Higgs production in pairs, $pp \to HA, H^+H^-$ with possibly exotic Higgs decays into a gauge and a lighter Higgs boson would be required; for a recent discussion, see, e.g., Ref. [29]. In any case, masses of a few hundred GeV for the $H, A, H^\pm$ states are still allowed in this configuration. On should note that for a light a state, severe constraints on the Type-X scenario come also from lepton universality in Z-boson and τ-lepton decays [2].

Flavor physics is also a relevant source of constraints as the rate of decays of K mesons and above all, B mesons [30] are sensitive to the presence of additional Higgs bosons. In our scenario, the $B_s \to \mu^+\mu^-$ process is particularly important since it could receive significant contributions from the light a state, possibly emitted on mass-shell, with enhanced couplings to muons [31]. Particularly relevant is also, for the Type-II case, the bound $M_{H^\pm} > 570$ GeV [32] from the $b \to s\gamma$ radiative decay.

Finally, for what concerns the DM issue, two ingredients make that the χ state with a $\mathcal{O}(100\ \mathrm{GeV})$ mass provides the correct cosmological relic density as measured by the PLANCK satellite [33] and chiefly passes the stringent constraints from experiments in direct detection such as XENON1T [34] and indirect detection such as FERMI-LAT [35]. First, χ does not couple to the CP-even h and H states hence forbidding spin-independent interactions at tree-level and, second, new $\chi\chi$ annihilation channels involving the light a are present and allow for an efficient annihilation into lighter particles.

In the discussion of experimental limits above, a major assumption has been made to ease numerical analyses, namely that the heavier Higgs states are degenerate in mass, $M_H = M_A = M_{H^\pm}$, as is naturally the case in models such as the MSSM in the decoupling regime [26]. This was the simplest way to avoid large contributions to electroweak precision observables [13] and, in particular, the W mass to which we turn our attention now.

IV. IMPACT ON THE W BOSON MASS

The leading radiative corrections to M_W can be approximated by the one affecting the ρ parameter which measures the strength of the neutral to the charged currents ratio at zero-momentum transfer [36],

$$\frac{\Delta M_W}{M_W} \simeq \frac{1}{2}\frac{M_W^2}{2M_W^2 - M_Z^2}\Delta\rho \approx \frac{3}{4}\Delta\rho,$$
$$\Delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}, \tag{12}$$

where Π_{VV} are the transverse parts of the $V = W, Z$ boson self-energies. In our 2HD $+\,a$ model, the additional contributions due to the extra Higgs states (we ignore the SM-like contribution of the h boson which is included in the fit of the SM data) is given, in the alignment limit, by (see also Ref. [37] in which the contributions in a 2HDM were first discussed and Ref. [5] in which they were interpreted in this new M_W context):

$$\Delta\rho = \frac{\alpha}{16\pi^2 M_W^2(1 - M_W^2/M_Z^2)}[f(M_{H\pm}^2, M_H^2) + \cos^2\theta f(M_{H\pm}^2, M_A^2) + \sin^2\theta f(M_{H\pm}^2, M_a^2) - \cos^2\theta f(M_A^2, M_H^2) - \sin^2\theta f(M_a^2, M_H^2)], \tag{13}$$

where α is the fine structure constant and θ the Aa mixing angle. The function f is given by

$$f(x, y) = x + y - \frac{2xy}{x - y}\log\frac{x}{y}, \tag{14}$$

and vanishes if the two particles running in the loop are degenerate in mass $f(x, x) = 0$ while, in the limit of a large mass splitting, one has $f(x, 0) = x$ instead. Hence, in the case where the members of an SU(2) doublet have masses that are quite different, contributions which are quadratic in the mass of the heaviest particle appear.

Let us first evaluate the impact of the new M_W measurement in the Type-II benchmark. As discussed in Refs. [11,12], in Type-II 2HDMs and for large Higgs masses, only a limited mass splitting between the $H/A/H^{\pm}$ states is allowed when one requires compatibility with theoretical constraints from perturbativity and unitarity such as those that apply on the quartic couplings of the scalar potential. This is particularly true when the alignment limit, $\cos(\beta - \alpha) = 0$, is imposed.

In the present case, we will simply consider the minimal option of a splitting between M_A, M_H, and $M_{H^\pm}$, assume again the alignment limit and perform a scan over the possible values of $M_H, M_{H^\pm}$ and, also varying M_a in the range of a few 10 GeV and $\tan\beta$ in the perturbative range allowed for the bottom Yukawa coupling,

$$M_a \in [10, 100]\ \text{GeV}, \qquad \tan\beta \in [1, 60]. \tag{15}$$

We also account for the theoretical bounds on the couplings as given by Eqs. (9) and (10). Following Ref. [9], we also impose $\text{BR}(h \to aa) < 0.2$ to cope with the LHC constraint on invisible decay of the SM-like Higgs boson [38].

The result is shown in Fig. 2 for $|M| = M_H = M_A = 1.2$ TeV and $\sin\theta = 0.5$. As can be seen, almost independently from the value of M_a, at least within the considered range, the CDF measurement can be successfully interpreted simply by considering a splitting $M_A - M_{H^\pm} \approx 100$–220 GeV. This mass difference has no impact neither in the new physics contribution to Δa_μ, dominated in this setup by the contribution of the light a state, nor on the DM observables, since the latter does not couple to the charged Higgs. The results obtained in Ref. [9] hence directly apply also in this case.

As already pointed out, the Type-II scenario is severely constrained by collider data. While our choice of $M_{A,H}$ and $\sin\theta$ allows to avoid bounds from heavy Higgs searches at the LHC, the parameter space of the model is affected by the limits from the search of light resonances, which allow only for values $M_a \gtrsim 75$ GeV and a narrow strip around $M_a \simeq 10$ GeV. While for $M_a \gtrsim 75$ GeV it is still possible to have a viable interpretation of the CDF anomaly, a combined explanation of the $(g-2)_\mu$ would require lighter a masses. A reasonable fit would be then possible only for very specific choices and tuning of the model parameter and would be most probably ruled out by a slight future increase of the experimental sensitivity.

Moving to the Type-X scenario, a somewhat more extensive analysis can be conducted. Indeed, theoretical

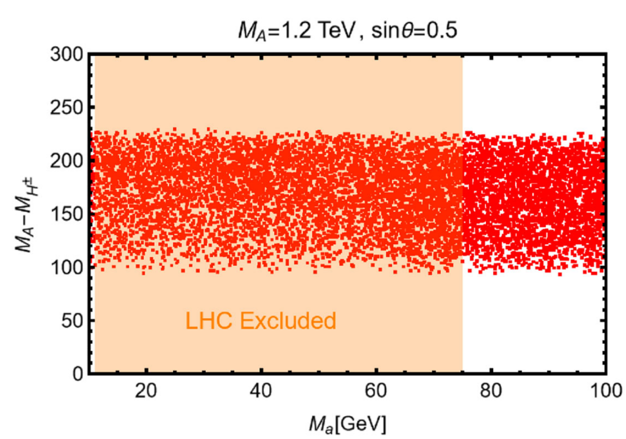

FIG. 2. Range of values of the difference $M_A - M_{H^\pm}$ as a function of M_a when considering $\tan\beta \in [1, 60]$ and $M_A = 1.2$ TeV in Type-II models that account for the deviation in the value of M_W as reported by CDF.

constraints allow for higher Higgs mass splitting in this case and, moreover, small deviations from the alignment limit can be considered. Assuming two fixed values for the heavy pseudoscalar Higgs state, $M_A = 300$ GeV and $M_A = 500$ GeV, we have varied the other Higgs sector parameters in the following ranges

$$M_a \in [10, 100]\ \text{GeV}, \qquad \tan\beta \in [1, 150],$$
$$M_{H,H^\pm} \in [100, 1000]\ \text{GeV}, \qquad |\cos(\beta-\alpha)| < 0.2,$$
$$\sin\theta \in [0.5, 0.7]. \qquad (16)$$

We display in the panels of Fig. 3, the model points that are compatible with the various theoretical and experimental constraints discussed in the previous section and, at the same time, giving a deviation to $\Delta\rho$ compatible with the CDF measured M_W value. In the left (right) panels, the input value $M_A = 300(500)$ GeV is used.

In the top panels we show the simultaneous values of $M_{H^\pm} - M_A$ and $M_{H^\pm} - M_H$ which allow to obtain the desired contribution to the W boson mass. These include small $M_{H^\pm}$ values, close to the exclusion limit from the LEP experiment, $M_{H^\pm} \gtrsim M_W$ [2]. The subsequent lower panels show that a small deviation from the alignment limit, $\cos(\beta-\alpha) \neq 0$, can still account for the CDF M_W value even if the $M_{H^\pm} - M_A$ difference is significant.

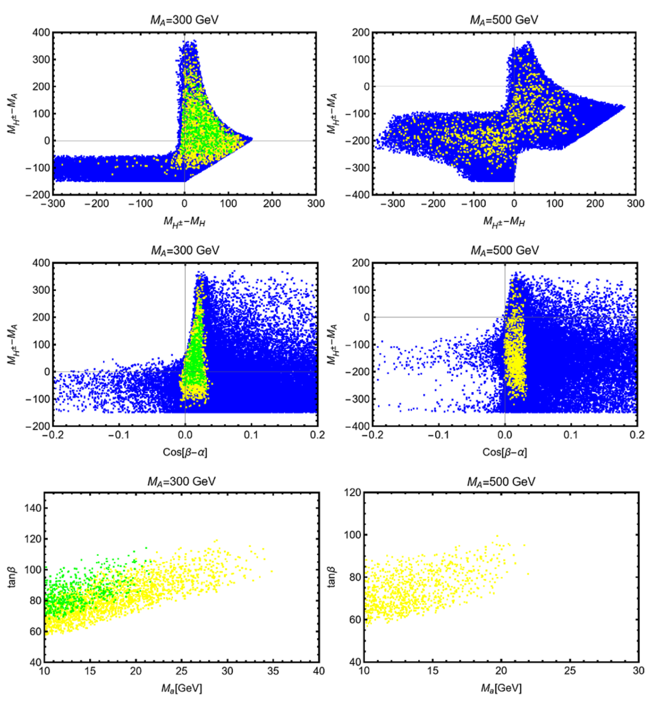

FIG. 3. Outcome of the scans of the Type-X 2HD + a parameter space in the planes, from top to bottom, $[M_{H^\pm} - M_H, M_{H^\pm} - M_A]$, $[\cos(\beta-\alpha), M_{H^\pm} - M_A]$ and $[M_a, \tan\beta]$ when fixing the input values $M_A = 300$ GeV (left column) and $M_A = 500$ GeV (right column). The green (yellow) points provide a fit within $1(2)\sigma$ of the $(g-2)_\mu$ anomaly.

Furthermore, we have highlighted with different colors the points which, together with the CDF M_W value and the different constraints, provide a viable fit of the $(g-2)_\mu$ anomaly. More specifically, the yellow points are compatible with $(g-2)_\mu$ at the 2σ level, while the green ones represent an agreement within 1σ. As can be seen, there are regions of the 2HD + a parameter space, with not too large Higgs mass splittings and close to the decoupling limit, in which this is indeed possible.

Finally the lower panels show the points complying with the $(g-2)_\mu$ anomaly in the $[M_a, \tan\beta]$ plane. As can be seen, for $M_A = 500$ GeV, only very few points lead to the experimentally measured Δa_μ at the 1σ level. This is due to the fact that the bounds from lepton universality in Z and τ decays exclude most of the viable parameter space, as they disfavor a too pronounced hierarchy between the light M_a and heavy $M_{H,A,H^\pm}$ masses. For this reason, setting $M_A =$ 300 GeV instead, makes it is easier to have a 1σ fit of $(g-2)_\mu$ as shown in the figure.

Concerning collider limits, besides $h \to aa$, it has been shown that searches of heavy and light neutral resonances decaying into fermions do not affect the scenario under consideration [9]. However, having relaxed the requirements of the $H, A, H^\pm$ mass degeneracy and the alignment limit, searches of Z/h, H might become relevant as well. As shown, e.g., in Ref. [39], these will constrain the Type-X model only at low $\tan\beta$ values, $\tan\beta \lesssim 10$, and hence, do not affect the combined explanation of the M_W and $(g-2)_\mu$ anomalies which favors high $\tan\beta$.

Before closing this discussion, let us note that the implications for the M_W value of the mass splitting of the scalars in a 2HDM has been also discussed in the series of papers of Ref. [5] that appeared shortly after the CDF announcement. Most of these analyses made use of the Peskin-Takeuchi formalism [40] in which, besides the T parameter that is equivalent to the $\Delta\rho$ correction, $T \propto \Delta\rho$, and which has the biggest impact, also the S parameter was considered (the parameter U gives too small contributions that were neglected in most cases).

While we qualitatively agree with the results of Refs. [5], the situation is more complicated in our case since we have the additional contribution of the light a state which, from the start, has a very large mass splitting compared to M_A, M_H, and $M_{H^\pm}$. The presence of this light a boson will require a slightly smaller mass splitting $M_H - M_{H^\pm}$ and $M_A - M_{H^\pm}$ to comply with the new M_W value, compared to the 2HDM case.

Finally, to conclude our analysis with an explicit illustration, we show in Fig. 4 the correlation between the deviations of the CDF M_W and the muon $(g-2)$ measurements from the SM expectation using the S, T, U formalism. We display the Type-X model points (for simplicity we considered just the $M_A = 300$ GeV case) in the $[T, \Delta a_\mu/(10^{-11})]$ plane, with $a_\mu = \frac{1}{2}(g-2)_\mu$.

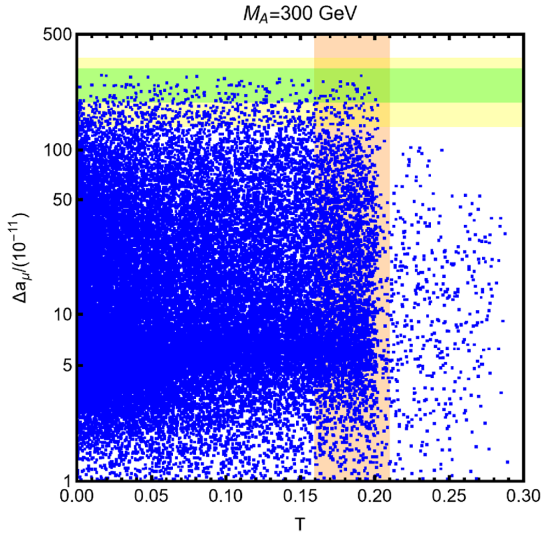

FIG. 4. Type-X model points in the $[T, \Delta a_\mu/(10^{-11})]$ bidimensional plane that comply with the various constraints. The green and yellow horizontal bands represent the 1σ and 2σ allowed ranges for Δa_μ while the orange vertical band represent the range of values of T given in Eq. (17).

The figure highlights the 1σ (in green) and 2σ (in yellow) horizontal regions corresponding to the $(g-2)_\mu$ anomaly and, as a vertical band depicted in orange, the range of values of the T parameter

$$T \in [0.16, 0.21], \tag{17}$$

which has been proposed in Ref. [41] to explain the CDF measurement of M_W. As can be seen, it is in general rather difficult to simultaneously accommodate the CDF M_W and the Fermilab $(g-2)_\mu$ measured values, but a nonzero overlapping region nevertheless exists.

V. CONCLUSIONS

The new measurement of the W mass reported by the CDF collaboration features a large deviation from the theoretical expectation in the SM, but is also widely different from previous measurements made at LEP, the Tevatron and LHC. While a detailed and careful analysis of the various systematical errors that affect the different M_W measurements is required before drawing a definite conclusion, one can nevertheless speculate about the possibility that this deviation could be due to new physics beyond the SM and, eventually, relate it to additional anomalies observed in other measurements.

In this paper, we have considered a two Higgs doublet model supplemented by a light pseudoscalar Higgs boson to which we add a new stable singlet fermion to account for the dark matter. Two Z_2 symmetric configurations have been considered for the Yukawa couplings of the Higgs bosons and both of them allow to reproduce the M_W value measured by CDF, when a nondegeneracy in the masses of the new heavy Higgs bosons is assumed.

In the case of the Type-II possibility, these masses are required to be above the TeV scale to avoid the constraints from LHC Higgs searches. A combined explanation of the M_W and $(g-2)_\mu$ anomalies is further disfavored by LHC constraints on searches of light a resonances.

More appealing and viable is, instead, the situation in the Type-X configuration. The previously mentioned LHC constraints are indeed avoided and, at high $\tan\beta$ values, one can obtain a combined explanation of the M_W and $(g-2)_\mu$ anomalies for $M_a \simeq 10$–20 GeV and $M_A = 300$ GeV. If M_A is raised to 500 GeV, the agreement of $(g-2)_\mu$ with experiment occurs only at the 2σ level.

The considered scenarios comply with B-meson physics constraints and allow to accommodate a DM candidate which satisfy the cosmological requirements and pass all constraints from current astrophysical searches.

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