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

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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 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.

I. INTRODUCTION

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

$$M_W = 80.4335 \pm 0.0094 \text{ GeV}. \quad (1)$$

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, $M_W = 80.379 \pm 0.012 \text{ GeV}$ [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 $M_W = 80.4133 \pm 0.0080 \text{ GeV}$ [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]

$$M_W = 80.3545 \pm 0.0057 \text{ GeV}, \quad (2)$$

and this deviation from the theoretical prediction is huge, slightly more than 7$\sigma$. Even if one compares the prediction with the new averaged $M_W$ value, the deviation is still at a very high level [5]. 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 4.2$\sigma$ 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 semi-leptonic $b \to s \mu^+ \mu^-$ 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 such a 2HD+a model can easily cope with all existing constraints from collider and astroparticle physics and, at the same time, explains the deviations observed in the measurement of the $(g - 2)_{\mu}$ and $BR(b \to s \mu^+ \mu^-)$.

In this brief note, we reconsider this 2HD+a model and relax an assumption made to ease the numerical analysis, namely that the heavier Higgs states, the CP-even $H$, CP-odd $A$ and two charged $H^\pm$ bosons, 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 $\rho$ 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 all collider and astroparticle physics constraints satisfied. In section 3, we discuss new contributions to $M_W$ and show that the CDF value is reproduced in these benchmarks. A conclusion is given in section 4.
II. THE 2HD+A MODEL AND DARK MATTER

Models with two-Higgs doublet (2HDM) fields $H_1$ and $H_2$, acquiring non-zero 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 \cite{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 $A$ and two charged $H^\pm$ bosons. The main motivation of a 2HDM plus a light pseudoscalar $a$ boson is that it allows, in addition, to induce a gauge invariant interaction between the gauge singlet $a$ boson and pairs of SM fermions, as well as pairs of the fermionic singlet DM $\chi$, through the mixing with the $A$ state, described by the angle $\theta$ defined by

$$\tan 2\theta = 2v^2/(M_A^2 - M_a^2),$$

with $\kappa$ the coefficient of the term coupling the two doublets $H_1, H_2$ with the original singlet field. For $M_A \gg M_a$ and for a strong mixing $\sin 2\theta \approx 1$, there is an upper bound on $M_A$ from the requirement of perturbative unitarity in Higgs scattering amplitudes, $M_A \lesssim 1.4$ TeV \cite{11}.

In the simplest case in which the 2HDM sector is CP-conserving and possesses a $Z_2$ symmetry that forbids tree-level flavor-changing neutral currents, the model is 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 $\theta$ among the $a, A$ and $\alpha$ 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 $h a a$ states, $\lambda_{h a a} \lesssim 10^{-3}$. In order to cope with the LHC constraints which force the observed $h$ particle to have almost SM-like couplings to fermions and weak bosons \cite{10}, one can impose the so-called alignment limit, $\alpha = \beta - \frac{1}{2} \pi$.

Compared to the SM case \cite{15}, the Higgs couplings to the SM fermions are proportional to a factor $g_{Hff}$ where in the alignment limit one has $g_{Hff} = 1$ for the light $h$ while the ones of the other Higgs states are given by

$$g_{Hff} = \xi_f, \quad g_{Aff} = \cos \theta \xi_f, \quad g_{aff} = -\sin \theta \xi_f,$$

with the coefficients $|\xi_f| = \tan \beta$ or $\cot \beta$ depending on the type of the considered 2HDM \cite{14}. In the present situation, as we need enhanced couplings to the isospin $\frac{1}{2}$ muons, we will discuss only the so-called Type-II scenario with $|\xi_\tau| = |\xi_t| = 1/|\xi_i| = \tan \beta$ and the lepton–specific or Type–X scenario with $|\xi_\tau| = 1/|\xi_i| = 1/|\xi_t| = \tan \beta$. In both cases the non-standard Higgs states will have strongly enhanced couplings to charged leptons for values $\tan \beta \gg 1$ and, in Type-II, also to bottom quarks.

Finally, for what concerns the DM aspect, we will assume the presence of a stable fermion $\chi$ which is a SM singlet and hence does not couple to gauge bosons and couples to Higgs bosons only in pairs. In particular, there are no $\chi$ couplings to the CP-even $h, H$ bosons while its couplings to the two pseudoscalar bosons is given by

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

This model, recently discussed in Ref. \cite{9} to which we refer for further details, has remarkable virtues that we briefly summarize in the following.

- It passes all collider constraints on the 2HDM bosons if one is in the alignment limit which forces the $h$ particle to be SM-like \cite{16} and the heavier $H, A$ and $H^\pm$ states to be heavy enough to escape direct detection at the LHC \cite{17} \cite{18}. In the case of the Type-II model, assuming $M_A \approx M_H \approx M_{H^\pm}$ which is the simplest way to avoid the occurrence of large corrections to electroweak observables, one can adapt to the present 2HD+a case the constraints on the $[M_A, \tan \beta]$ plane derived for the MSSM \cite{19}. In the MSSM, values $\tan \beta \gtrsim 10$ are excluded for $M_H = M_A \lesssim 1$ TeV from $pp \to H/A \to \tau^+ \tau^-$ searches \cite{17}, while values $\tan \beta \gtrsim 50$ are excluded by $pp \to H^\pm \to t\bar{t}$ searches for $M_{H^\pm} \lesssim 700$ GeV \cite{18}. However, in our case, given the presence of additional decay channels, such as $H \to aa, A \to ab, H \to Za$ and $H^\pm \to aW$, we expect weaker limit than in the MSSM. In Ref. \cite{9}, we have thus assumed the value $M \gtrsim 1$ TeV. In the Type–X model, since all production vertices of the new Higgs bosons at the LHC are suppressed at high $\tan \beta$, the interpretation of the $g - 2$ excess is much easier and it is possible to lower the value of $M$ down to a few hundreds of GeV despite of the constraints from $H/A$ production.

- For the light $a$ state, one needs to have small $a b b$ and $a \tau \tau$ couplings to evade LEP bounds \cite{20} and a tiny $h a a$ coupling, $\lesssim 10^{-3}$, to sufficiently suppress the LHC constrained additional $h \to aa$ boson decays \cite{21}. In the range of small Higgs boson masses considered for the Type–X model, severe constraints come also from lepton universality in $Z$-boson and $\tau$-lepton decays \cite{2}.

- Flavor physics is also a relevant source of constraints as the rate of decays of $K$ mesons and above all, $B$ mesons \cite{22} are sensitive to the presence of additional Higgs bosons. In our scenario, the $B_\tau \to \mu^+ \mu^-$ 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 \cite{24}. Particularly relevant is also, for the Type–II case, the bound $M_{H^\pm} > 570$ GeV \cite{23} from the $b \to s \gamma$ radiative decay.

- For a few GeV mass and in Type-II and Type–X scenarios with large enough $\tan \beta$ values, the $a$ boson can give the required contribution to the $(g - 2)_\mu$ through Barr–Zee type diagrams occurring at the two–loop level \cite{25} that allow to explain the 4.2$\sigma$ deviation of the Fermilab measurement from the SM expectation. There are also one loop contributions of the $a$ and 2HDM Higgs states but they are suppressed compared to the above.

Finally, for what concerns the DM issue, two ingredients make that the $\chi$ state with a $\mathcal{O}(100$ GeV) mass provides the correct cosmological relic density as measured by the PLANCK satellite \cite{26} and chiefly passes
FIG. 1. A summary of the various constraints in the \([M_a, \tan \beta]\) plane for the 2HD+\(a\) model in the Type-II (left panel) and Type-X (right panel) scenarios for the assignments of the \((m_\chi, g_\chi, \sin \theta)\) parameters displayed on top of the corresponding panels. The colored black bands correspond to regions in which the correct DM relic density is obtained, the green and yellow bands are when a fit of the \((g - 2)\) measurement is achieved within 1 \(\sigma\) and 2 \(\sigma\), the red areas are those in which the decay rate of \(B_s \to \mu^+ \mu^-\) exceeds the experimental limit, the purple hatched region is excluded mainly by the LHC searches of \(H/A\) bosons decaying into \(\tau\) pairs. In the bottom panel, the regions above the dot-dashed gray (magenta) contours are excluded by bounds on lepton universality violation in \(Z\)-boson (\(\tau\)) decays. We have taken the 2HDM mass scale to be \(M = 1.2\) (0.5) TeV for the Type-II (Type-X) cases.

In the previous discussion, a major assumption has been made to ease the numerical analysis, namely that the heavier \(H, A, H^\pm\) states are degenerate in mass, \(M_H = M_A = M_{H^\pm} = M\), as is naturally the case in some models, such as the MSSM in the decoupling regime \([19]\). 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.

III. IMPACT ON THE W BOSON MASS

The leading radiative corrections to \(M_W\) can be approximated by the one affecting the \(\rho\) parameter which measures the strength of the neutral to the charged currents ratio at zero–momentum transfer \([29]\),

\[
\frac{\Delta M_W}{M_W} \approx \frac{1}{2} \frac{M_W^2}{2M_W^2 - M_Z^2} \Delta \rho \approx \frac{3}{4} \Delta \rho ,
\]

where \(\Pi_{VV}(0)\) 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. \([30]\) in which the contributions in a 2HDM,
were first discussed and Ref. \[5\] in which they were interpreted in this new \(M_W\) context:

\[
\Delta \rho = \frac{\alpha}{16\pi^2} \frac{M^2_W}{M^2_W(1 - M^2_W/M^2_Z)} \left[ f(M^2_H \pm M^2_A) + \cos^2 \theta f(M^2_H \pm M^2_A) + \sin^2 \theta f(M^2_H \pm M^2_A) - \cos^2 \theta f(M^2_A, M^2_H) - \sin^2 \theta f(M^2_A, M^2_H) \right],
\]

where \(\alpha\) is the fine structure constant and \(\theta\) the \(Aa\) mixing angle. The function \(f\) is given by

\[
f(x, y) = x + y - \frac{2xy}{x - y} \log \frac{x}{y},
\]

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,

\[M_a \in [10, 100] \text{ GeV}, \ \tan \beta \in [1, 60],\]

accounting also for the theoretical bounds on the couplings of the scalar potential \[12\]. The result is shown in Fig. 2 for \(M = M_H = M_A = 1.2\) TeV and \(\sin \theta = 0.5\).

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 \(M - M_{H^\pm} \approx 100 - 300\) GeV. This Higgs mass difference has no impact on the observables shown in Fig. 1 which then remain the same also in the light of the deviation from the SM of the CDF \(M_W\) value, if indeed confirmed.

Moving to the Type-X scenario, a slightly more extensive analysis can be conducted. Indeed, theoretical constraints allow for higher Higgs mass splitting in this case and, moreover, small deviations from the alignment limit can be considered. Assuming a fixed value for the mass of the heavy pseudoscalar Higgs state, \(M_A = 500\) GeV and choosing again \(\sin \theta = 0.5\), we have varied the other Higgs sector parameters as follows

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

\[M_{a,H,H^\pm} \in [100, 1000] \text{ GeV}, \ |\cos(\beta - \alpha)| < 0.2.\]
We display in the three panels of Fig. 3 the model points that are compatible with the theoretical constraints discussed in Refs. 10,11 and giving a deviation to $\Delta \rho$ compatible with the CDF measured $M_W$ value. In the left panel of Fig. 3, we simply repeat the Type-II analysis and show the results in the $[M_A, M_{H^\pm} - M]$ plane. In the Type-X scenario, in addition to the fact that smaller 2HDM Higgs masses can be considered, the range of mass splitting that allows to explain the new $M_W$ value is relatively wider; again, the impact of $M_a$ in the considered $10-100$ GeV range is rather small.

In the middle panel, 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. And these include small $M_{H^\pm}$ values, close to the exclusion limit from the LEP experiment, $M_{H^\pm} \gtrsim M_W^2$. Finally, the right panel shows that a small deviation from the alignment limit, $\cos(\beta - \alpha) \neq 0$, can still account for the CDF value even if the $M_{H^\pm} - M_A$ difference is significant.

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 after shortly the CDF announcement. Most of these analyses made use of the Peskin-Takeuchi formalism 31 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. 3 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 same model points already presented in Fig. 3 but in the $[T, \Delta a_\mu/(10^{-11})]$ bidimensional plane, with $a_\mu = 1/2 (g-2)_\mu$. The figure highlights the $1\sigma$ (in green) and $2\sigma$ (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

$$T \in [0.16, 0.21],$$

which has been proposed in Ref. 32 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 non zero overlapping region nevertheless exists.

**IV. 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 (and a measurement from the CMS collaboration would be welcome) 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 brief note, 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. We show that under some conditions, the anomalous contribution to $M_W$ can be reproduced by allowing some mass non-degeneracy for the heavier Higgs bosons. At the same time, one can explain the excess observed in the value of the muon anomalous magnetic moment (if it is indeed also real) and comply with $B$-meson physics constraints such as those originating from $b \to s\gamma$ and $b \to s\mu^+\mu^-$ decay rates. All this while satisfying the direct and indirect light and heavy Higgs searches at the LHC and elsewhere, as well as the astrophysical constraints from direct and indirect detection of a DM with the observed cosmological density.

Such a scenario can be probed already at the next LHC run and with a slight increase of sensitivity of astrophysical experiments searching for thermal dark matter.

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