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Excesses in the low-mass Higgs-boson search and the W-boson mass measurement

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Abstract The CDF collaboration recently reported a measurement of the W-boson mass M_W whose value shows a large upward deviation from the Standard Model (SM) prediction. The question arises whether such large values of M_W could be accommodated in extensions of the SM without violating other constraints and which phenomenological consequences this would have. A different type of deviation from the SM has been observed experimentally in the searches for light Higgs bosons. CMS has observed two excesses with a local significance of about $3\,\sigma$ in the $\gamma\gamma$ and $\tau^+\tau^-$ final states for a hypothetical Higgs-boson mass of approximately 95 GeV. These two excesses are compatible with the corresponding ATLAS limits. Earlier an excess was also observed in the Higgs-boson searches at LEP in the $b\bar{b}$ final state at the local $2\,\sigma$ confidence level at about the same mass. It was shown recently that the three excesses can be accommodated in a Two-Higgs-Doublet Model that is extended with a real singlet (N2HDM) of Yukawa type IV, while being in agreement with all other theoretical and experimental constraints. We demonstrate here that the region of the parameter space that describes the three excesses can also give rise to a large contribution to M_W in agreement with the recent CDF measurement. We discuss further phenomenological consequences of this scenario.

1 Introduction

The mass of the W boson M_W can be predicted from muon decay, which relates M_W to three extremely precisely measured quantities: the Fermi constant G_μ, the fine structure constant α, and the mass of the Z boson M_Z. Within the Standard Model (SM) and many extensions of it, this relation can be used to predict M_W via the expression

$$M_W^2 = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu\,M_Z^2}\,[1 + \Delta r(M_W, M_Z, m_t, \ldots)]} \right\}, \tag{1}$$

where the quantity Δr is zero at lowest order.[1] It comprises loop corrections to muon decay in the considered model, where the ellipsis in Eq. (1) denotes the specific particle content of the model.

The known contributions to the SM prediction for Δr include the complete one-loop [2,3] and the complete two-loop result [4–19], as well as partial higher-order corrections up to four-loop order [20–29]. This yields a prediction of

$$M_W^{\rm SM} = 80.353\,\text{GeV}\,, \tag{2}$$

where the implementation of Ref. [30] in the code `FeynHiggs` [31–33] has been used, and the input parameters have been chosen as in Ref. [34]. The remaining uncertainty from unknown higher-order corrections has been estimated in Ref. [35] to be about 4 MeV (see also Ref. [36]). Concerning the theoretical uncertainty that is induced by the experimental errors of the input parameters, in particular M_Z and the top-quark mass m_t are relevant. A variation of M_Z within its $\pm 1\,\sigma$ interval yields a shift of ± 2.7 MeV, while a variation of m_t by ± 0.5 GeV yields a shift of about ± 3 MeV. The SM prediction of Eq. (2) is somewhat lower than the current PDG average of the experimental results prior to the new

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[1] For an example of a model where the lowest-order prediction for M_W is modified, see for instance Ref. [1].

CDF measurement [37],

$$M_W^{\rm PDG} = 80.379 \pm 0.012\,\text{GeV}, \tag{3}$$

but in agreement at the level of about $2\,\sigma$.

Recently the CDF collaboration reported a new measurement using their full data set of $8.8\,\text{fb}^{-1}$ [38],

$$M_W^{\rm CDF-new} = 80.4335 \pm 0.0094\,\text{GeV}, \tag{4}$$

which deviates from the SM prediction by about $7\,\sigma$. The CDF collaboration also reported a combination of this new measurement with the other results from the Tevatron and with the measurements at LEP (but not with the results from the LHC),

$$M_W^{\rm Tev+LEP} = 80.4242 \pm 0.0087\,\text{GeV}. \tag{5}$$

In the future it will be mandatory to assess the compatibility of the different measurements of M_W with each other and to carefully analyze possible sources of systematic effects. The inclusion of the CDF measurement into a future world average is expected to give rise to an upward shift of the central value. Accordingly, the question arises whether extensions of the SM exist that can accommodate values between the central value of the current world average and the value measured by CDF without being in conflict with existing experimental and theoretical constraints, and which further phenomenological consequences arise from such scenarios. The implications of this new measurement for various scenarios of physics beyond the SM (BSM) have been discussed in Ref. [39–61].

Theories that could potentially accommodate a large contribution to M_W that shifts the predicted value towards $M_W^{\rm CDF-new}$ might also feature other direct signals of new physics that are detectable at the LHC. While so far no conclusive signs of BSM physics have been found at the LHC, both the measurements of the properties of the Higgs boson at 125 GeV (its couplings are known up to now to an experimental precision of roughly 10 to 20% [62,63]) and the existing limits from the searches for new particles leave ample room for BSM physics at (or below) the EW scale. In this paper we will study the possibility of an extended Higgs sector in which (as will be shown below) a value of M_W compatible with the CDF measurement can be realized by means of sizable corrections to Δr arising from mass splittings between the BSM Higgs bosons that have sizable couplings to the gauge bosons. A direct way of experimentally probing such a possibility consists of direct searches for the additional Higgs bosons at colliders, which have been performed at LEP [64–66], the Tevatron [67] and the LHC [68–72]. In this context one should note that, even though no detection of additional Higgs bosons has been made so far, several intriguing excesses in the searches for light Higgs bosons below 125 GeV have been observed.

Results based on the first year of CMS Run 2 data for Higgs-boson searches in the diphoton final state show a local excess of about $3\,\sigma$ at a mass of 95 GeV [69], where a similar excess of $2\,\sigma$ occurred in the Run 1 data at a comparable mass [73]. Combining 7, 8 and first year 13 TeV data (and assuming that the gg production dominates) the excess is most pronounced at a mass of 95.3 GeV with a local significance of $2.8\,\sigma$. First Run 2 results from ATLAS with $80\,\text{fb}^{-1}$ in the $\gamma\gamma$ searches below 125 GeV were reported in 2018 [71]. Although no significant excess above the SM expectation was observed in the mass range between 65 and 110 GeV, the limit on cross section times branching ratio obtained in the diphoton final state by ATLAS is substantially weaker than the corresponding upper limit obtained by CMS at and around 95 GeV.

CMS recently published the results for the search for additional Higgs bosons in the $\tau^+\tau^-$ channel [72]. Utilizing the full Run 2 data set the CMS collaboration reported an excess in the low-mass region assuming the gluon-fusion production mode and the subsequent decay into $\tau^+\tau^-$ pairs, where the mass range of the excess is compatible with the excesses that have been observed by CMS in the diphoton searches during Run 1 and Run 2. The excess in the $\tau^+\tau^-$ final state is most pronounced for a mass hypothesis of 100 GeV, with a local significance of $3.1\,\sigma$, while for a mass value of 95 GeV, i.e. closer to the most significant excess in the $\gamma\gamma$ search [69], CMS reports a local significance of $2.6\,\sigma$. So far there exists no corresponding result for the low-mass search in the $\tau^+\tau^-$ final state from the ATLAS collaboration in this mass range.

Searches for a low-mass Higgs boson that were previously carried out at LEP resulted in a $2.3\,\sigma$ local excess observed in the $e^+e^- \to Z(H \to b\bar{b})$ process [65] at a mass of about 98 GeV, where due to the $b\bar{b}$ final state the mass resolution was rather coarse. Because of this limited mass resolution in the $b\bar{b}$ final state at LEP this excess can be compatible with the slightly lower mass of 95 GeV favoured by the CMS excesses.

Since the reported excesses in the $\gamma\gamma$ and $\tau^+\tau^-$ channels at the LHC and the $b\bar{b}$ channel at LEP were found at approximately the same mass, the question of a possible common origin arises. Recently we demonstrated that indeed all three excesses can be described consistently in the N2HDM (the Two-Higgs-Doublet Model with an additional real singlet [74,75]) of Yukawa type IV [76].[2] In the present analysis we demonstrate that the parameter space that accommodates the three excesses can also give rise to a large contribution to M_W that can even bring the predicted value into agreement with the central value of the recent CDF measurement (as dis-

[2] Analyses in the N2HDM (and extensions) focusing only on the $\gamma\gamma$ and $b\bar{b}$ excesses can be found in Refs. [77–84].

cussed above, a future world average for M_W including the CDF measurement would be expected to lie in between the current world average and the central value reported by CDF). We discuss further phenomenological consequences of this scenario.

The paper is organized as follows. After introducing the model in Sect. 2.1 and the relevant theoretical and experimental constraints on the N2HDM parameter space in Sect. 2.2, the numerical results of our parameter scan are presented in Sect. 3, where also the future prospects are discussed. We summarize our results in Sect. 4.

2 Model definition, relevant constraints and the prediction for M_W

In the following we give a brief description of the N2HDM in order to define the necessary quantities and to introduce our notation. More details can be found in Ref. [76].

2.1 The N2HDM

The N2HDM is the simplest extension of a CP-conserving Two-Higgs doublet model (2HDM) in which the latter is augmented with a real scalar singlet Higgs field [74,75]. As in the 2HDM we define $\tan\beta := v_2/v_1$, the ratio of the vacuum expectation values (vev) of the two $SU(2)$ doublet fields Φ_1 and Φ_2. In order to avoid the occurrence of tree-level flavor-changing neutral currents (FCNC), a Z_2 symmetry is imposed under which either Φ_1 or Φ_2 changes the sign, and which is only softly broken by a bilinear term $m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})$. As in the 2HDM, one can have four variants of the N2HDM, depending on the Z_2 parities of the fermions. We will focus on type IV (flipped), which was shown to be capable of accommodating the three excesses at 95 GeV. In addition, the scalar potential is invariant under a second Z_2 symmetry acting only on Φ_S. This symmetry is spontaneously broken if the singlet acquires a vev v_S. The CP-even scalar spectrum contains a total of three physical Higgs bosons $h_{1,2,3}$, where we use the convention $m_{h_1} < m_{h_2} < m_{h_3}$. The relation between the states in the gauge eigenstate basis and the physical states can be expressed in terms of the 3×3 orthogonal matrix R, which can be parameterized by three mixing angles $-\pi/2 \le \alpha_1, \alpha_2, \alpha_3 \le \pi/2$ such that

$$R=\begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1}s_{\alpha_2}s_{\alpha_3}+s_{\alpha_1}c_{\alpha_3}) & c_{\alpha_1}c_{\alpha_3}-s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ -c_{\alpha_1}s_{\alpha_2}c_{\alpha_3}+s_{\alpha_1}s_{\alpha_3} & -(c_{\alpha_1}s_{\alpha_3}+s_{\alpha_1}s_{\alpha_2}c_{\alpha_3}) & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}, \tag{6}$$

where we use the short-hand notation $s_x = \sin x, c_x = \cos x$.

The couplings of the Higgs bosons to the fermions and gauge bosons are modified w.r.t. to the couplings of a Higgs boson as predicted by the SM. We express the couplings of the scalar mass eigenstates h_i, normalized to the corresponding SM couplings, in terms of the coupling coefficients $c_{h_i VV}$ and $c_{h_i f\bar{f}}$, such that the couplings to the massive vector bosons are given by

$$\left(g_{h_i WW}\right)_{\mu\nu} = \mathrm{i} g_{\mu\nu}\left(c_{h_i VV}\right) g M_W \quad \text{and}$$
$$\left(g_{h_i ZZ}\right)_{\mu\nu} = \mathrm{i} g_{\mu\nu}\left(c_{h_i VV}\right) \frac{g M_Z}{c_\mathrm{w}}, \tag{7}$$

where g is the $SU(2)_L$ gauge coupling, $c_\mathrm{w} = M_W/M_Z$ is the cosine of the weak mixing angle, and $s_\mathrm{w} = \sqrt{1-c_\mathrm{w}^2}$. The couplings of the Higgs bosons to the SM fermions are given by

$$g_{h_i f\bar{f}} = \frac{m_f}{v}\left(c_{h_i f\bar{f}}\right), \tag{8}$$

where m_f is the mass of the fermion, and $v = \sqrt{(v_1^2+v_2^2)} \approx$ 246 GeV is the SM vev. Analytical expressions for these coupling coefficients in terms of the mixing angles $\alpha_{1,2,3}$ and β can be found in Ref. [77].

The scalar potential of the N2HDM comprises 11 free parameters. We use the public code `ScannerS` [75,85,86], with which the model can be explored in terms of the parameters

$$c_{h_2 t\bar{t}}^2,\ \ c_{h_2 VV}^2,\ \ \mathrm{sign}(R_{23}),\ \ R_{13},\ \ \tan\beta,\ \ v_S,$$
$$m_{h_{1,2,3}},\ \ m_A,\ \ m_{H^\pm},\ \ m_{12}^2. \tag{9}$$

Here, m_A, $m_{H^\pm}$ denote the masses of the physical CP-odd and charged Higgs bosons, respectively. We will identify the lightest CP-even Higgs boson h_1 with the one that could potentially be identified with the excesses at 95 GeV, labelled h_{95}. The second-lightest CP-even Higgs boson h_2 will be identified with the detected state at 125 GeV, labelled h_{125}. Besides the 11 free parameters mentioned above, Eq. (9) also contains the input parameter sign(R_{23}), which is used to lift a degeneracy arising from the dependence of the mixing angles α_i on the squared values of the coupling coefficients $c_{h_2 t\bar{t}}^2$ and $c_{h_2 VV}^2$ and the element of the mixing matrix R_{13}.

2.2 Theoretical and experimental constraints

In our analysis we apply several theoretical requirements to the parameter space of the N2HDM. We give here only a very brief description; more details can be found in Ref. [76].

In order to ensure that for the considered parameter point the electroweak minimum is physically viable it is required that the EW vacuum is either stable or meta-stable, i.e. sufficiently long-lived in comparison to the age of the universe. In particular, we apply conditions on the scalar couplings that exclude parameter points for which the scalar potential is not bounded from below [75,87]. For the calculation of the lifetime of the EW vacuum in case the electroweak minimum is not the global minimum of the potential, ScannerS provides an interface to the public code EVADE [88,89]. We also apply the tree-level perturbative unitarity conditions that ensure that in the high-energy limit the eigenvalues of the scalar 2×2 scattering matrix are smaller than $|8\pi|$ [75].

The experimental constraints are applied as follows. We verify the agreement of the selected points with the currently available measurements of the properties of the Higgs boson at about 125 GeV using the public code HiggsSignals v.2.6.1 [90–93]. The required theoretical predictions for the cross sections and the branching ratios of the scalars are obtained from the public codes SusHi [94,95] and N2HDECAY [75,96–99]. In the following we denote as χ^2_{125} the χ^2 contribution obtained from HiggsSignals. We demand that each point fulfills the condition

$$\chi^2_{125} - \chi^2_{125,\mathrm{SM}} \leq 5.99. \tag{10}$$

This corresponds to an exclusion limit on the model parameters in a joint estimation of two parameters at the 95% confidence level under the assumption that the SM fit result $\chi^2_{125,\mathrm{SM}}$ provides a good approximation for the best-fit χ^2_{125}-value of the N2HDM (see Ref. [93] for details).[3] We have checked explicitly that this is the case for our parameter scan. In order to test the parameter points against the exclusion limits from the Higgs-boson searches at LEP, the Tevatron and in particular from the LHC, we employ the public code HiggsBounds v.5.9.1 [100–105]. Constraints from flavor-physics observables are taken into account by the approach as implemented in ScannerS, where the 2HDM flavor constraints projected to the $\tan\beta$–$m_{H^\pm}$ plane as given in Ref. [106] are applied as approximation for the N2HDM, see e.g. the discussion in Ref. [84]. In particular, large tensions arise in 2HDM-like extensions of the SM for small values of $\tan\beta$ for the measurements of leptonic and radiative B-meson decays [106]. We will therefore use $\tan\beta = 1$ as a lower limit in our parameter scans. Contrary to previous analyses, we do not apply constraints from electroweak precision observables (EWPOs). Instead, we investigate whether agreement with the Tevatron measurement of M_W can be achieved, and we discuss the extent of compatibility with the experimental results for the effective leptonic weak mixing angle at the Z-boson resonance, see the next subsection.

2.3 Prediction for M_W

If new physics contributions to the EWPOs enter mainly through gauge boson self-energies, as it is the case for extended Higgs sectors, the BSM effects in the predictions for M_W and the Z-pole observables can in a simple approximation be expressed in terms of the oblique parameters S, T and U [107,108]. We make use of the implementation of the one-loop contributions to the oblique parameters for the N2HDM in ScannerS, which is based on generic results for extended Higgs sectors with an arbitrary number of Higgs doublets and singlets from Ref. [109]. In the framework of the oblique parameters, the W-boson mass can be calculated using the expression [109]

$$M_W^2 = \left(M_W^2\right)^{\mathrm{SM}} \left(1 + \frac{s_\mathrm{w}^2}{c_\mathrm{w}^2 - s_\mathrm{w}^2} \Delta r'\right), \tag{11}$$

with

$$\Delta r' = \frac{\alpha}{s_\mathrm{w}^2} \left(-\frac{1}{2} S + c_\mathrm{w}^2 T + \frac{c_\mathrm{w}^2 - s_\mathrm{w}^2}{4 s_\mathrm{w}^2} U\right). \tag{12}$$

Inserting the results for S, T and U obtained with ScannerS in the N2HDM yields our prediction for the mass of the W boson, in the following denoted by M_W^{N2HDM}.

Another very precisely known EWPO is the leptonic effective weak mixing angle at the Z-boson resonance, usually referred to as $\sin^2\theta_{\mathrm{eff}}$. M_W and $\sin^2\theta_{\mathrm{eff}}$ are the observables that by far have the largest impact on the electroweak fit, and we therefore do not include further Z-pole observables in our analysis. In fact, for the total width of the Z boson, Γ_Z, it was shown in Ref. [52] that the tension between the experimental value of Γ_Z and its theoretical prediction is only at the level of 1σ in the range of T that is required to predict a value of M_W in agreement with the CDF measurement.

In order to investigate the corresponding shift in $\sin^2\theta_{\mathrm{eff}}$ that is induced via the BSM effects in terms of the oblique parameters as a consequence of sizable contributions to the prediction for M_W, we compute $\sin^2\theta_{\mathrm{eff}}$ according to [110]

$$\sin^2\theta_{\mathrm{eff}} = \sin^2\theta_{\mathrm{eff}}^{\mathrm{SM}} - \frac{\alpha(S - 4c_\mathrm{w}^2 s_\mathrm{w}^2 T)}{4(c_\mathrm{w}^2 - s_\mathrm{w}^2)}. \tag{13}$$

As will be shown below, the numerically relevant contribution arises from the $T (= \Delta\rho/\alpha)$ parameter. For the values of the SM parameters that enter in the prediction of M_W^{SM} and $\sin^2\theta_{\mathrm{eff}}^{\mathrm{SM}}$ we used the set of numerical values as given in Eq. (7) of Ref. [34], which were taken from Refs. [37,111]. The SM predictions for M_W and $\sin^2\theta_{\mathrm{eff}}$ obtained in this way are $M_W^{\mathrm{SM}} = 80.353$ GeV and $\sin^2\theta_{\mathrm{eff}}^{\mathrm{SM}} = 0.23156$.

2.4 Fitting the excesses at 95 GeV

In order to analyze whether the N2HDM can yield an upward shift in the prediction for M_W that is sufficiently large to make it compatible with the CDF measurement and simultaneously provide a possible explanation of the observed $\gamma\gamma$, $\tau^+\tau^-$ and $b\bar{b}$ excesses, we perform a χ^2-analysis quantifying the agreement between the theoretically predicted signal

[3] We checked that for all points $\chi^2_{125} > \chi^2_{125,\mathrm{SM}}$. Thus, the application of the condition shown in Eq. (10) is more restrictive than demanding that no parameter point is disfavoured at more than 95% confidence level compared to the best-fit point regarding χ^2_{125}.

rates and the experimentally observed values. Experimentally, it was determined that the excesses at 95 GeV were best described assuming signal rates of a scalar resonance of

$$\mu_{\gamma\gamma}^{\rm exp} \pm \Delta\mu_{\gamma\gamma}^{\rm exp} = 0.6 \pm 0.2 \ \ [69]\,, \tag{14}$$
$$\mu_{bb}^{\rm exp} \pm \Delta\mu_{bb}^{\rm exp} = 0.117 \pm 0.057 \ \ [64]\,, \tag{15}$$
$$\mu_{\tau\tau}^{\rm exp} \pm \Delta\mu_{\tau\tau}^{\rm exp} = 1.2 \pm 0.5 \ \ [72], \tag{16}$$

where the signal strengths are defined as the cross sections times branching ratios divided by the corresponding predictions for a hypothetical SM Higgs boson at the same mass, and the experimental uncertainties are given as 1 σ uncertainties. The theoretically predicted values $\mu_{\gamma\gamma}$, μ_{bb} and $\mu_{\tau\tau}$ were obtained by computing the gluon-fusion production cross section of h_{95} with the help of SusHi [94,95], and the branching ratios for the Higgs bosons were computed using N2HDECAY [75,96–99] (see Ref. [76] for more details). For each individual excess, we define the χ^2 contributions

$$\chi^2_{\gamma\gamma,\tau\tau,bb} = \frac{(\mu_{\gamma\gamma,\tau\tau,bb} - \mu^{\rm exp}_{\gamma\gamma,\tau\tau,bb})^2}{(\Delta\mu^{\rm exp}_{\gamma\gamma,\tau\tau,bb})^2}. \tag{17}$$

In order to assess the combined description of the three excesses, we define the total χ^2 contribution as

$$\chi^2_{\gamma\gamma+\tau\tau+bb} = \chi^2_{\gamma\gamma} + \chi^2_{\tau\tau} + \chi^2_{bb}, \tag{18}$$

where the results for the three channels in which the excesses were observed are treated as independent measurements, such that we can simply add the three individual χ^2 contributions. In the following numerical analysis, we will consider parameter points as providing a good description of the excesses if they account for the combined effect of the three excesses at the level of 1 σ or better. For three independent measurements, this translates into the requirement

$$\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53. \tag{19}$$

3 Numerical analysis

In this section we discuss our numerical analysis, where we investigate whether the N2HDM type IV parameter space that can describe the three excesses observed near 95 GeV can also yield a predicted value for the W-boson mass, $M_W^{\rm N2HDM}$, that is so large that it would be in agreement with the measured value as recently reported by CDF. We perform a random scan in the N2HDM type IV over the free parameters as defined in Eq. (9), where the scan ranges were chosen to be

$$\begin{aligned}
&94\,\text{GeV} \leq m_{h_1} \leq 98\,\text{GeV},\ m_{h_2} = 125.09\,\text{GeV},\\
&300\,\text{GeV} \leq m_{h_3} \leq 1000\,\text{GeV},\ 300\,\text{GeV} \leq m_A\\
&\leq 1000\,\text{GeV},\ 650\,\text{GeV} \leq m_{H^\pm} \leq 1000\,\text{GeV},\\
&1 \leq \tan\beta \leq 10, \quad 0 \leq m_{12}^2\\
&\leq 10^6\,\text{GeV}^2,\ 100\,\text{GeV} \leq v_S \leq 1500\,\text{GeV},\\
&0.6 \leq c^2_{h_2VV} \leq 0.9, \quad 0.6 \leq c^2_{h_2t\bar{t}} \leq 1.0,\\
&\text{sign}(R_{13}) = \pm 1, \quad -1 \leq R_{23} \leq 1.
\end{aligned} \tag{20}$$

It should be noted here that we focus our parameter scan on the parameter regions where h_{95}, corresponding to h_1, has a sufficiently large coupling to the gauge bosons and fermions so that it can give rise to the excesses that were observed in the Higgs searches near 95 GeV. Since h_{95} obtains its couplings to fermions and gauge bosons as a result of the mixing with the state h_2 that we identify with the observed Higgs boson h_{125}, we imposed an upper limit of $c_{h_2VV} \leq 0.9$ (see Ref. [76] for details). We use the public code ScannerS [75,85,86], which scans the parameters randomly over the given range and applies the theoretical and experimental constraints discussed in Sect. 2.2 (where we modified the routines for the check against the EWPO). We select parameter points with $M_W^{\rm N2HDM}$ within the 2 σ confidence-interval of the new CDF measurement given in Eq. (4). We thus only take into account points which fulfill

$$\chi^2_{M_W^{\rm CDF-new}} = \frac{(M_W^{\rm N2HDM} - M_W^{\rm CDF-new})^2}{(\Delta M_W^{\rm CDF-new})^2} \leq 4\,, \tag{21}$$

with $\Delta M_W^{\rm CDF-new} = 0.0094$ GeV.

In Fig. 1 we show the predicted values of M_W in the N2HDM for the parameter points of our scan as a function of the oblique parameter T. For the parameter points that provide a description of the collider excesses at 95 GeV at the level of 1 σ or better, i.e. $\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$, the color coding indicates the size of the oblique parameter S. The remaining parameter points are shown in gray. The light blue region shows the new CDF measurement within its $\pm 2\,\sigma$ band. The red dashed line indicates the SM prediction for the W-boson mass (see Sect. 1 for details). According to Eq. (11), one finds a nearly linear dependence of $M_W^{\rm N2HDM}$ on T, with a subleading contribution coming from S. The contributions from the oblique parameter U are found to be negligible. The color coding indicates that either values of $S \approx -0.020$ (dark blue) or $S \approx 0$ but positive (green) are found. The origin for the presence of these two separate branches will be further discussed below. It can be seen that the N2HDM of type IV can yield a prediction for M_W that agrees with the new M_W measurement from CDF, while simultaneously providing a good description of the three excesses at about 95 GeV, possessing a Higgs boson at 125 GeV whose properties are compatible with the LHC results, and which furthermore is in agreement with all the other constraints listed in Sect. 2.2.

As a consequence of the applied condition shown in Eq. (21), we enforce in our scan that all parameter points lie within the 2 σ uncertainty band of the CDF measure-

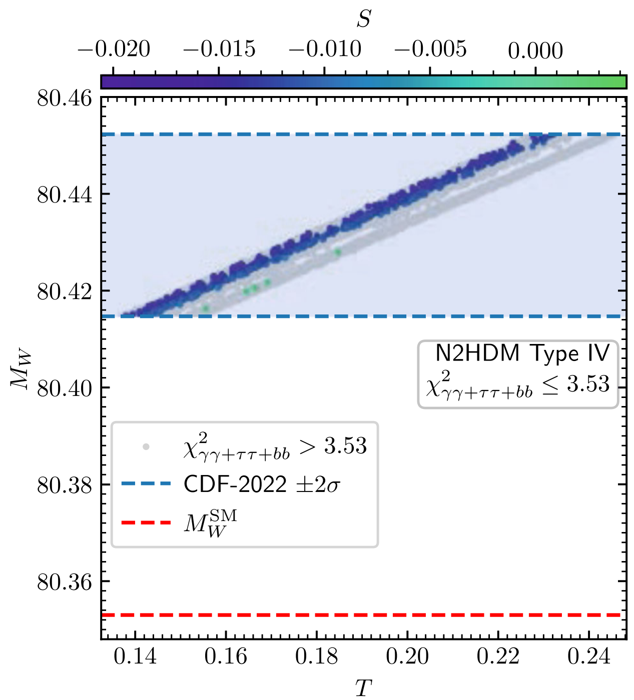

Fig. 1 The prediction for M_W in the N2HDM as a function of T, where the color coding indicates the size of S for the parameter points that describe the excesses at 95 GeV at the level of 1 σ or better, i.e. $\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$. The remaining parameter points are shown in gray. The light blue region corresponds to the new CDF measurement within $\pm 2\,\sigma$. All points lie within the light blue region, since in our scan we selected the points fulfilling the requirement $\chi^2_{M_W^{\rm CDF-new}} \leq 4$. The red dashed line shows the SM prediction for M_W

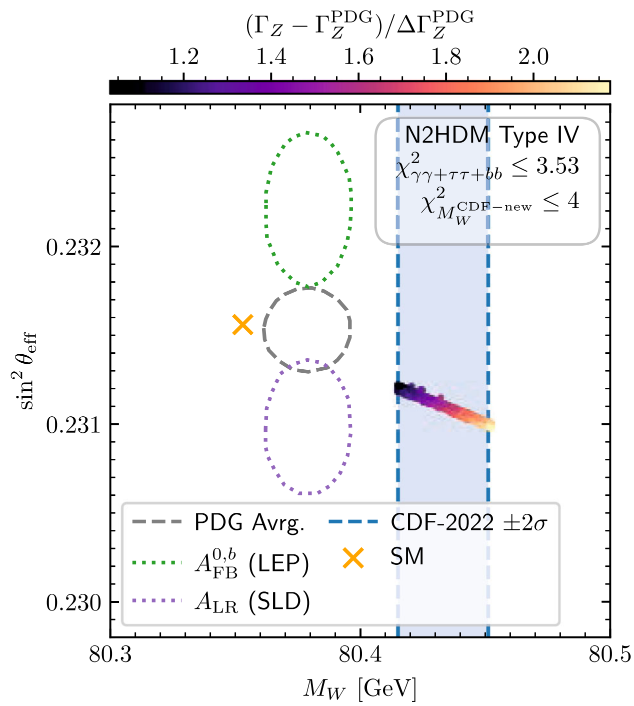

Fig. 2 The predictions for M_W and $\sin^2\theta_{\rm eff}$ in the N2HDM. The color coding of the points indicates the difference between the prediction for Γ_Z and the PDG average value $\Gamma_Z^{\rm PDG}$ divided by the experimental uncertainty $\Delta\Gamma_Z^{\rm PDG}$. The light blue region corresponds to the new CDF measurement within $\pm 2\,\sigma$. The green dotted and the purple ellipses indicate the 68% confidence level results from the two individually most precise measurements of $\sin^2\theta_{\rm eff}$ via $A_{\rm FB}^{0,b}$ at LEP and $A_{\rm LR}$ at SLD, respectively, whereas the gray dashed ellipse indicates the average of the LEP and SLD measurements [116–118]. Those ellipses are shown for the M_W value corresponding to the current world average. The orange cross indicates the SM prediction

ment. As such, our results demonstrate the compatibility of a description of the excesses at 95 GeV and a prediction for M_W that can be as large as the CDF result. However, we stress that parameter points that fit the collider excesses do not necessarily predict a value for M_W that would be inside the 2 σ uncertainty band of the CDF measurement. In fact, parameter regions yielding a good description of the collider excesses near 95 GeV can also give rise to smaller predicted values of M_W that are closer to the SM value. We would like to recall once more in this context that a potential new world average value of M_W, taking into account the CDF measurement and the previous measurements at LEP [112], the Tevatron [113] and the LHC [114,115], is expected to have a central value between the current world average and the CDF value. One can extrapolate from the slope of the line of points in Fig. 1 that a parameter scan targeting such a future average value (once it becomes available) would yield a preference for somewhat smaller values of the T parameter. Besides that, our conclusions regarding the compatibility of the description of the excesses at 95 GeV and a sizable positive shift to M_W in the direction of the CDF measurement are not affected.

Next we turn to the compatibility with the most sensitive Z-pole observable, $\sin^2\theta_{\rm eff}$. In Fig. 2 we show the predictions for M_W and $\sin^2\theta_{\rm eff}$ in the N2HDM for all points with $\chi^2_{125} - \chi^2_{125,\rm SM} \leq 5.99$, $\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$ and $\chi^2_{M_W^{\rm CDF-new}} \leq 4$. One can see that the parameter points that fit the new CDF measurement of the W-boson mass feature also sizable modifications of $\sin^2\theta_{\rm eff}$ compared to the SM prediction. It should be noted that without the restriction of the displayed points to those for which the predicted value for M_W is compatible at the 2 σ level with the new CDF measurement the displayed scan points in Fig. 2 would extend further to the left, i.e. into the direction towards the SM prediction that is indicated by an orange cross in the figure. According to Eq. (13), the predicted values of $\sin^2\theta_{\rm eff}$ featured for the displayed parameter points of our scan are smaller than the SM value, and they do not touch the current 1 σ ellipse based on the PDG average values of M_W (which does not contain the new CDF measurement) and $\sin^2\theta_{\rm eff}$. However, here it should be kept in mind that the PDG average of $\sin^2\theta_{\rm eff}$ is composed of different measurements, where the two most precise ones are compatible with each other only at the level of about 3 σ: the one based on the forward–backward asymmetry of the bottom quarks measured at LEP [118], and the one obtained from the left-right asymmetry measured at SLD [118]. It can be observed that the data points preferred by the M_W measurement of CDF are in better agreement with the SLD measurement based on $A_{\rm LR}$, whereas the tension increases with the value of $\sin^2\theta_{\rm eff}$ extracted at LEP based on measurements of $A_{\rm FB}^{0,b}$. Similar observations were made in Refs. [39,44,52], and the correlation between the effective weak mixing angle and the mass of the W boson is expected to arise generically in models in which the shift in the prediction for M_W towards the new CDF measurement of M_W is accommodated mainly via the breaking of the custodial symmetry by means of a non-zero T parameter (and not via, e.g., BSM vertex and box contributions to muon decay). The fact that the points in Fig. 2 lie along an approximately straight line is an indication of the strong dependence on the T-parameter, whereas the impact of the non-zero values of the S-parameter on the prediction for $\sin^2\theta_{\rm eff}$ is very small in our scan.

While the ellipse indicating the current world average for M_W and $\sin^2\theta_{\rm eff}$ as well as the two ellipses indicating the measurements of $\sin^2\theta_{\rm eff}$ via $A_{\rm FB}^{0,b}$ at LEP and $A_{\rm LR}$ at SLD are all shown for the current world average of M_W that does not contain the new CDF measurement, it becomes clear from the plot that for a future world average value of M_W located in between the current world average and the new CDF measurement the displayed ellipses would be accordingly shifted to the right (and modified in order to account for the combined experimental error of the new world average). The tendency towards a better agreement of the N2HDM predictions with the SLD measurement of $\sin^2\theta_{\rm eff}$ based on $A_{\rm LR}$ will become more pronounced the closer the future world average for M_W will be to the new CDF measurement. Finally, it should be noted that, while we only show in Fig. 2 the parameter points for which the excesses in the low-mass Higgs searches near 95 GeV are well described, the other parameter points that are in agreement with the CDF result for M_W would be located at essentially the same region in the M_W–$\sin^2\theta_{\rm eff}$ plane.[4]

Finally, we discuss the compatibility of the parameter region of the N2HDM yielding predictions for M_W close to the CDF measurement with the experimentally measured value of the width of the Z boson, Γ_Z. The color coding of the points in Fig. 2 indicates the difference between the prediction for Γ_Z and the PDG average value $\Gamma_Z^{\rm PDG}$ divided by the experimental uncertainty $\Delta\Gamma_Z^{\rm PDG}$ [37]. Our N2HDM prediction for $\Gamma_Z = \Gamma_Z^{\rm SM} + \Delta\Gamma_Z$ is based on the SM prediction computed according to Ref. [119] and using the input parameters as discussed in Sect. 2.3. The shift $\Delta\Gamma_Z$ is obtained using the fit formula given in Ref. [120], where we took into account the numerically relevant terms depending on S and T. One can see that a prediction for M_W in agreement with the 2 σ uncertainty band of the CDF measurement in combination with a good description of the excesses at 95 GeV is possible with a tension for Γ_Z which is only slightly above 1 σ. For parameter points that predict a value of M_W that is even larger than the central value of the CDF measurement, the tension for Γ_Z grows to the level of more than 2 σ. Here we stress again that a future world average value of M_W taking into account the CDF measurement would lie below the CDF measurement, with potentially much larger uncertainties reflecting the low level of compatibility between the CDF result and the most precise other measurements of the W-boson mass. Thus, an analysis based on such a future world average value would be expected to yield a prediction for Γ_Z that agrees with the experimental value at the level of 1 σ or better.

In order to shed more light on the N2HDM parameter space regions that can give rise to a value of M_W that is in agreement with the CDF measurement, we show in Fig. 3 the parameter points in the plane of the mass differences between h_3 and $H^\pm$ on the horizontal axis and between A and $H^\pm$ on the vertical axis. For the points with $\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$, the color coding indicates the value of $\chi^2_{\gamma\gamma+\tau\tau+bb}$ in the left plot and of m_A in the right plot. The remaining points are shown in gray (as throughout our analysis, the condition of Eq. (10) is applied for the displayed points). One can see that most of the parameter points have a mass hierarchy in which h_3 and A are either both lighter or both heavier than the charged Higgs bosons $H^\pm$. The separation of the parameter points into these two distinct mass hierarchies that are visible in Fig. 3 is also the reason for the presence of the two separate branches of points that are visible in Fig. 1. The fact that the presence of these two mass hierarchies facilitates a prediction of the W-boson mass that is in agreement with the recent CDF measurement is in line with the results of Ref. [52], where the compatibility of the 2HDM of type I in the alignment limit with the CDF measurement of M_W was investigated. We note that in contrast to the results in the alignment limit of the 2HDM, in the present analysis we also find parameter points with a predicted value of M_W in agreement with the CDF measurement featuring a different mass hierarchy, namely $m_A < m_{H^\pm} < m_{h_3}$, as indicated by the displayed parameter points in the lower right parts of the plots in Fig. 3. Most

[4] In Ref. [82] a complex singlet field was considered instead of the real singlet of the N2HDM. There it was shown that the imaginary part of the singlet can give rise to a valid dark-matter candidate whose annihilation can also account for the so-called galactic-center excess, while the real component of the singlet field gives rise to the state at 95 GeV that accounts for the collider excesses as in the N2HDM. Therefore, a combined description of the prediction for the W-boson mass, the excesses in the Higgs searches near 95 GeV and the galactic-center excess should also be possible (see Refs. [45,60] for discussions of the M_W prediction and the galactic-center excess in the inert 2HDM).

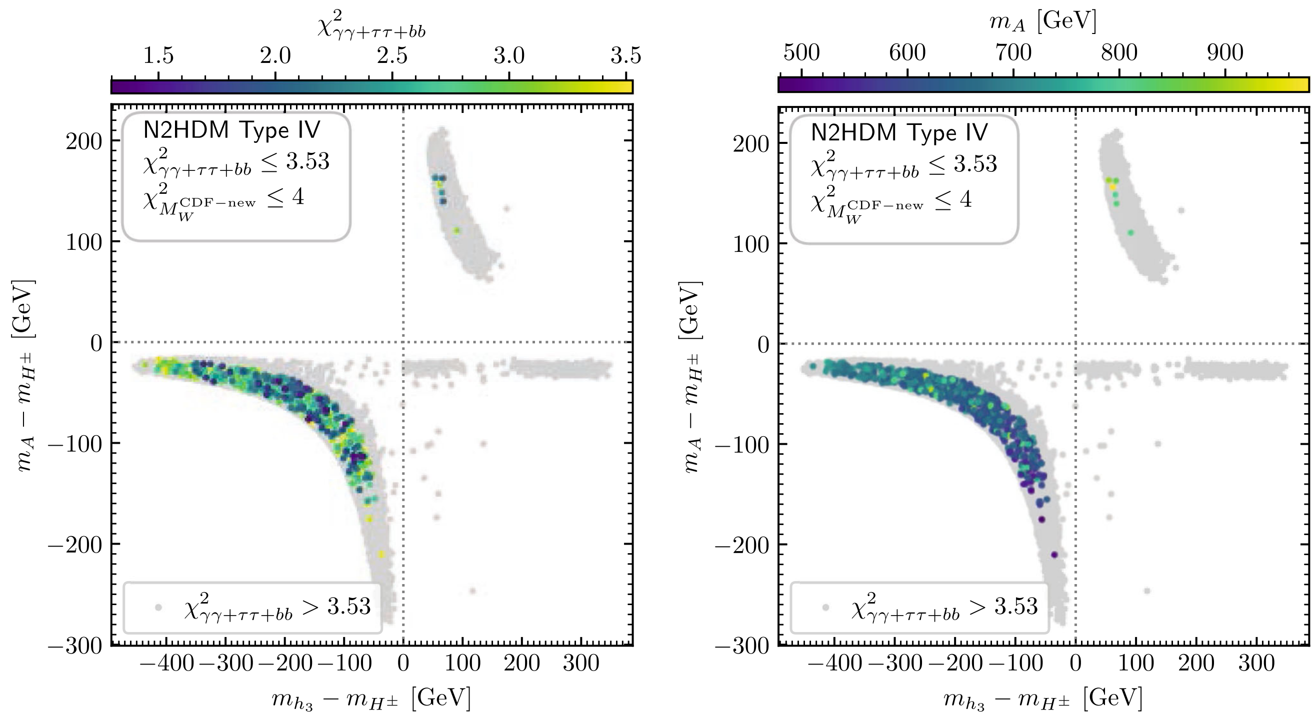

Fig. 3 Parameter points in the plane of the mass differences $m_{h_3} - m_{H^\pm}$ (horizontal axis) and $m_A - m_{H^\pm}$ (vertical axis). The color coding indicates the value of $\chi^2_{\gamma\gamma+\tau\tau+bb}$ in the left plot and of m_A in the right plot for the parameter points that describe the excesses at 95 GeV at the level of 1 σ or better, i.e. $\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$. The remaining parameter points are shown in gray

of these points – which are all displayed in gray, indicating that they are not compatible with the excesses observed in the Higgs searches near 95 GeV at the 1 σ level – are located on a horizontal branch where A and $H^\pm$ are close in mass. For these points, the heavy state h_3 is dominantly singlet-like. Thus, this part of the N2HDM parameter space resembles the one of a 2HDM with the doublet-like states h_{95} and h_{125} (scenarios of this kind, where the second-lightest CP-even Higgs boson corresponds to the observed state at about 125 GeV, have been investigated in Refs. [121–123]) which is supplemented by the heavier singlet-like state h_3. Consequently, in this case the large upward shift in the prediction of M_W results from the large mass splitting between h_{95}, h_{125} and the states A and $H^\pm$. The fact that the points in the horizontal branch with $m_A \approx m_{H^\pm}$ are shown in gray indicates that for a dominantly doublet-like state h_{95} the three excesses observed in the low-mass Higgs-boson searches cannot be described simultaneously. We therefore do not discuss these points any further in the following.

For the parameter points that accommodate the excesses in the low-mass Higgs searches at the level of $\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$, one can see from the left plot of Fig. 3 that both the mass hierarchies $m_{h_3}, m_A < m_{H^\pm}$ and $m_{h_3}, m_A > m_{H^\pm}$ can be realized. For the points in the upper right part of the plots for which the charged Higgs bosons are lighter than the heavy neutral states, our scan resulted in only a small number of parameter points that comply with the various constraints. While we expect that a more detailed scan would give rise to a somewhat larger allowed parameter region in the upper right part of the plots, we do not attempt a detailed discussion of the correlation between $\chi^2_{\gamma\gamma+\tau\tau+bb}$ and the precise values of the mass splittings. However, it is obvious from the displayed gray points that even without imposing the constraint on $\chi^2_{\gamma\gamma+\tau\tau+bb}$ the parameter region in this branch giving rise to a prediction for M_W that is compatible with the new CDF value is more restricted than for the points that feature $H^\pm$ as the heaviest particle (lower left branch of points). Here it is important to note that the mixing of the singlet field with the doublet fields in the N2HDM gives rise to additional theoretical constraints on the scalar couplings, in particular from perturbative unitarity, as compared to the 2HDM. As a result of these additional constraints in combination with the requirement $c^2_{h_{125}VV} < 0.9$ (see Eq. (20)) and experimental constraints from flavor-physics observables, we find that parameter points with $m_{h_3} - m_{H^\pm} \gtrsim 150$ GeV in this branch are excluded.

Turning now to the points with the mass hierarchy $m_{h_3}, m_A < m_{H^\pm}$ that are visible in the lower left part of the plots, one can see that the mass splitting between $H^\pm$ and A is restricted to be below about 200 GeV for the points describing the excesses in the low-mass Higgs searches at the 1 σ level, while the mass splitting between $H^\pm$ and h_3 can be even larger than 400 GeV. In the latter parameter region A and $H^{\pm}$ are almost degenerate, while h_3 is substantially lighter. The fact that this particular mass hierarchy allows for a good description of the excesses at 95 GeV was already noted in Ref. [76] (see Fig. 5 therein). It is remarkable that the same mass hierarchy, as demonstrated here, can also give rise to a prediction of M_W in agreement with the CDF measurement. Furthermore, for this mass hierarchy the strongest first-order electroweak phase transition can be accommodated in the (N)2HDM [124,125], and as such the respective parameter space regions might be suitable for the realization of electroweak baryogenesis or for the production of an observable primordial gravitational-wave background.

From the right plot of Fig. 3 one can infer that in the lower left branch of points where m_A is significantly smaller than $m_{h_3} \approx m_{H^{\pm}}$ the presence of a CP-odd Higgs boson with a mass of 400 GeV $\lesssim m_A \lesssim$ 500 GeV is compatible with a prediction of the W-boson mass in agreement with the new CDF value and with the presence of a Higgs boson at 95 GeV that is in fairly good agreement with the measured signal rates in the three respective decay modes. This is of particular interest in view of the fact that the local 3.5 σ excess observed at about 400 GeV by the CMS collaboration in searches for additional Higgs bosons in di-top final states [126] can be described by means of the CP-odd Higgs boson A of the type IV N2HDM, while at the same time the $\gamma\gamma$ excess and the $b\bar{b}$ excess at 95 GeV can be described by the singlet-like Higgs boson as shown in Ref. [84]. The presence of parameter points with $m_A \lesssim$ 500 GeV, as shown in the right plot of Fig. 3, that also accommodate the more recently observed $\tau^+\tau^-$ excess at 95 GeV and the CDF measurement of M_W leave room for the possibility that additionally also the $t\bar{t}$ excess at about 400 GeV can be accommodated. We leave a more detailed investigation of this very interesting scenario for future work.

4 Conclusions

The recently reported measurement of the W-boson mass M_W by the CDF collaboration deviates significantly from the SM prediction. A future world average for M_W that includes the previous measurements of M_W as well as the new CDF result will have to be based on a careful analysis of the systematic uncertainties of the different measurements and will have to account for the observed spread between the different results. If the future world average moves significantly towards the central value reported by the recent CDF measurement, the presence of sizable contributions from BSM physics to the prediction for M_W would be favored. In this paper we have discussed whether a prediction for M_W that would be compatible with the recent CDF measurement and simultaneously a description of recently reported excesses in low-mass Higgs boson searches near 95 GeV can be accommodated in a simple extension of the SM without being in conflict with existing experimental and theoretical constraints. Specifically, we have focused on a Two-Higgs-Doublet Model that is extended with an additional real singlet scalar (N2HDM) of Yukawa type IV, which we had identified in a recent publication [76] to be suitable for the description of the reported excesses in the search for light Higgs bosons at around 95 GeV. These excesses were found in the $\gamma\gamma$, the $\tau^+\tau^-$ and the $b\bar{b}$ decay modes and can be described in the N2HDM by means of a singlet-like Higgs boson at this mass that mixes with the detected Higgs boson at 125 GeV.

We have demonstrated that in the N2HDM a prediction of the value of M_W in agreement with the CDF measurement is compatible with a good description of the collider excesses at 95 GeV. We have shown that the parameter regions giving rise to those features are in agreement with the various theoretical and experimental constraints on the model parameters. In the parameter regions that we have determined the heavy neutral scalars h_3 and A are either both lighter or both heavier than the charged states $H^{\pm}$. Furthermore, we have pointed out that the parameter region featuring a sizable mass splitting between the third CP-even Higgs boson h_3 and the approximately mass-degenerate CP-odd Higgs boson A and the charged Higgs bosons $H^{\pm}$, i.e. $m_{h_3} < m_A \approx m_{H^{\pm}}$ (with $m_A < m_{H^{\pm}}$), naturally gives rise to sizable values of the T parameter and thus to an enhancement of M_W compared to the SM prediction. It is interesting to note that this is also the mass hierarchy which is favoured by the requirement of realizing a strong first-order electroweak phase transition (which may give rise to an observable gravitational wave signal) in the N2HDM. Concerning the effective weak mixing angle, the parameter space preferred by the new M_W measurement from CDF is well compatible with the $\sin^2\theta_{\rm eff}$ value extracted from $A_{\rm LR}$ at SLD, while there is some tension with the value obtained from $A_{\rm FB}^{0,b}$ at LEP.

Finally, we note that a possible future world average value, taking into account the previous measurements of M_W at LEP, the Tevatron and the LHC in combination with the new CDF result, would be expected to have a somewhat lower central value for M_W than the one reported by CDF and potentially a significantly larger uncertainty reflecting the low level of compatibility between the CDF result and the most precise previous measurements. Such a central value of M_W between the current world average and the CDF value would yield a preference for smaller and somewhat less restricted values of the T parameter. These smaller values of T would correspond to slightly smaller mass splitting of the heavy BSM Higgs bosons. We stress that our qualitative results indicating the compatibility of the description of the collider excesses at 95 GeV with a sizable upward shift in the prediction for M_W would remain unchanged in such a scenario.

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