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Combined explanation of LHC multilepton, diphoton, and top-quark excesses

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In this article, we propose the Δ2HDMS as a combined explanation of several excesses and anomalies observed at the LHC. Especially, $t\bar{t}$ differential distributions point towards the associated production of new electroweak scale Higgs bosons decaying into bottom quarks and W bosons ($> 5\sigma$) with masses consistent with the diphoton excesses at ≈95 GeV and ≈151.5 GeV (3.8σ and 4.9σ, respectively). Furthermore, CMS found indications for resonant $t\bar{t}$ production at ≈400 GeV (3.5σ) and both ATLAS and CMS reported elevated four-top and $t\bar{t}W$ cross sections. The Δ2HDMS is obtained by supplementing the SM Higgs (H_2) with a second scalar doublet (H_1), real scalar singlet (S), and a Higgs triplet with zero hypercharge (Δ). We fix the masses of the neutral tripletlike and the singletlike scalars by the diphoton excesses, i.e., $m_{\Delta^0} = 151.5$ GeV and $m_S = 95$ GeV, respectively. H, the CP-even component of H_1, is produced via gluon fusion from a top-loop and decays dominantly to $S + \Delta^0$ whose subsequent decays to W^+W^- and $b\bar{b}$ explain the differential $t\bar{t}$ distributions for $\sigma(pp \to H \to S\Delta^0) \approx 5$ pb. Choosing the top-Yukawa of H_1 accordingly, the CP-odd Higgs boson A turns out to have the right production cross section to account for the resonant $t\bar{t}$ excess at 400 GeV, while the top-associated production of H and A results in new physics pollution of Standard Model $t\bar{t}W$ and $t\bar{t}t\bar{t}$ cross sections, as preferred by the data.

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I. INTRODUCTION

The Standard Model (SM) of particle physics describes the known fundamental constituents of matter and their interactions (excluding gravity) at subatomic scales. It has been extensively tested and verified by a plethora of measurements [1]. However, the minimality of the SM Higgs sector [2–5] remains unexplained: While we know that the observed 125 GeV boson [6,7] has properties and decay rates compatible with the SM expectations [8,9], no fundamental principle excludes the existence of additional scalar bosons.

In fact, resonant diphoton searches show intriguing indications for new Higgs bosons at the electroweak scale, both in the sidebands of SM Higgs analyses and in dedicated searches at 95 [10–14] and 151.5 GeV, with global significances of 3.8σ and 4.9σ [15,16], respectively. While the production mechanism for the 95 GeV scalar candidate is currently unknown, data imply that the 151.5 GeV boson is mainly produced in association, in particular with missing energy [17], but also leptons and (b) jets [18].

The mechanism of associated production provides the connection to the "LHC multilepton anomalies" [19–24]. These are processes involving multiple leptons and missing energy, with and without (b) jets, with SM signatures such as W^+W^-, WWW, Wh, tW, $t\bar{t}$, $t\bar{t}W$, and $t\bar{t}t\bar{t}$ (see Refs. [24,25] for a review) where deviations from the SM expectations have been observed. In particular, SM Higgs to W^+W^- analyses [26,27] prefer a new physics (NP) contribution, which is compatible with a ≈150 GeV scalar that is produced in association with missing energy [20,28]. Furthermore, the latest ATLAS analysis of the $t\bar{t}$ differential cross sections [29] prefers a NP contribution from the decay of a heavy new scalar into two lighter ones, which subsequently decay into W^+W^- and $b\bar{b}$ (see Fig. 1), over the SM hypothesis by at least 5.8σ [30]. Again, the masses are compatible with the hints for narrow resonances at 95 and 151.5 GeV which decay dominantly to $b\bar{b}$ and

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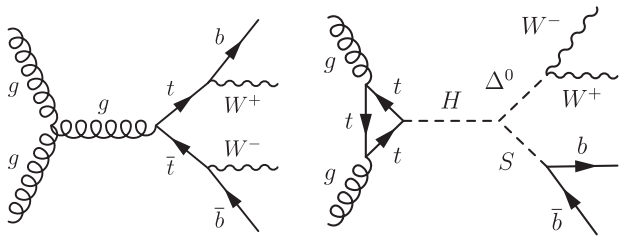

FIG. 1. Feynman diagrams showing the leading SM contribution (left) to top pair production and decay as well as the NP effect mimicking this process (right).

W^+W^-, respectively. Since there is no indication for a 151.5 GeV boson decaying to ZZ, this suggests that it is the neutral component of a real $SU(2)_L$ triplet.

In this article, we propose a novel UV complete model that gives rise to these signatures and explains the $t\bar{t}$ differential distributions: the Δ2HDMS. It contains two scalar doublets, a real singlet, and a real triplet Higgs. We will show that it predicts the experimentally preferred $\gamma\gamma$ signal strengths for the 95 and the 151.5 GeV Higgs bosons and is compatible with the suggested signal in W^+W^- (with a full jet veto) if one includes decays of the 95 GeV state to invisible. Furthermore, it can account for the resonant $t\bar{t}$ excess at ≈400 GeV (3.5σ locally) [31] as well as the elevated four top, $t\bar{t}W$ and $t\bar{t}Z$ cross sections and predicts a positive shift in the W mass as suggested by the global fit.

II. MODEL

As outlined in the introduction, we propose the Δ2HDMS model. It contains two Higgs doublets with hypercharge $Y = +1/2$ (H_1 and H_2) and a real singlet (S). This means it corresponds to a 2HDMS [19,32–49], plus a real $SU(2)_L$ triplet (Δ) [50–57].[1] As in the 2HDMS, one can employ two Z_2 symmetries, one under which S and H_2 are odd, and one under which H_1 and Δ are odd, while all other fields are even. This removes trilinear coupling and thus most potential sources of CP violation.[2] Furthermore, this allows only one term which contains an odd number of any field[3]:

$$\mathcal{L}_{SH_1\Delta H_2} = -\lambda S H_1^\dagger \Delta H_2 + \text{H.c.}. \tag{1}$$

[1]A model with the same field content has been studied in Ref. [58] where it was shown that it can lead to electroweak baryogenesis. Supersymmetric versions of the model were considered in Refs. [59,60]. Reference [58] finds that electroweak baryogenesis can be achieved in a wide range of parameters, including the one studied here. Note that our LHC analysis is fully complementary to the one of Ref. [58]: Ref. [58] proposed the two-step mechanism for electroweak baryogenesis while we consider in detail the LHC phenomenology in light of the anomalies.

[2]Alternatively, one can employ a $U(1)'$ symmetry [61,62].

[3]The terms $\mu H_1 H_2^\dagger$ softly breaks the Z_2 symmetries but is usually included for phenomenological reasons.

TABLE I. Fields and their respective components in the limit of vanishing mixing angles. h corresponds to the SM Higgs and G^0 and $G^\pm$ to the Goldstone bosons. Note that, following the common 2HDM conventions [65], the SM Higgs boson h is contained within H_2 while the heavy doublet Higgs bosons H and A originate from H_1.

	S	H_1	H_2	Δ
$SU(2)_L$	1	2	2	3
$U(1)_Y$	0	1/2	1/2	0
Z_2^1	+	−	+	−
Z_2^2	−	+	−	+
Components	S	$H, A, H^\pm$	$h, G^0, G^\pm$	$\Delta^0, \Delta^\pm$

After electroweak symmetry breaking, in the approximation $v_\Delta, v_S, v_1 \ll v_2$ (where v_X is the vacuum expectation value of the field X), H_1, H_2, S, and Δ contain the mass eigenstates as given in Table I. Note that the term in Eq. (1) does not lead to mixing among the scalars in this limit, but it gives rise to the trilinear interactions $\mathcal{L}_{\phi^3} = -\frac{v}{4}\lambda\Delta^0 HS + \frac{v}{2}\lambda\Delta^+ H^- S + \text{H.c.}$ (assuming λ to be real and $v = \sqrt{v_1^2 + v_2^2} \approx v_2 \approx \sqrt{2}174$ GeV) where Δ decomposed according to the conventions of Refs. [63,64]. The former term leads to the desired decay of H into $S\Delta^0$ needed to obtain the associated production mechanism.

For the Yukawa Lagrangian, we take the right-handed up-type and down quarks to be odd under Z_2^2. Therefore, H_2 couples to all fermions, i.e., the Yukawa sector is the one of a type-I 2HDM. However, we also assume that the Z_2 symmetries of the Yukawa Lagrangian are broken in the top sector by the term

$$-\mathcal{L}_Y^{\not{Z}_2} = \mu_t \sqrt{2}\frac{m_t}{v}\bar{Q}_3 \tilde{H}_1 u_3. \tag{2}$$

We defined this term such that μ_t is the relative coupling strength compared to the SM Higgs.[4] Therefore, H and A can be produced from this coupling via gluon fusion induced by a top-quark loop. Furthermore, this coupling will lead to the top-associated production of H and A (see Fig. 2) as well as the tb associated production of $H^\pm$. Finally, we add neutral fermions χ (singlets under the SM gauge group) with the Yukawa coupling $Y_\chi S\bar{\chi}\chi$ to get a nonzero decay rate of S to invisible.

III. PHENOMENOLOGY

Here we study the phenomenology of our model in the limit of negligibly small mixing angles, i.e.,

[4]Note that if one defines this coupling in the down basis (i.e., Cabibbo Kobayashi Maskawa rotations appear associated with left-handed up quarks), the charged Higgs does not generate flavor violation in the down sector.

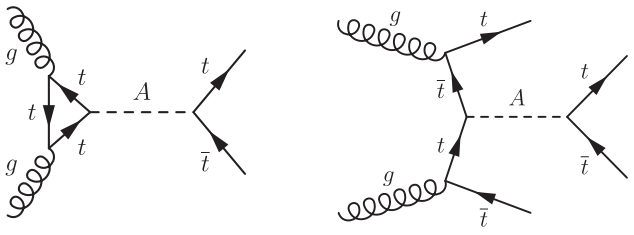

FIG. 2. Feynman diagrams showing the production of A via gluon fusion (left) and $t\bar{t}$ associated production (right) and its decays to top quarks.

$v_S, v_\Delta, v_1 \ll v_2$.[5] Note that v_Δ is naturally small due to the additional symmetry of the potential in case it goes to zero. Furthermore, v_Δ leads to a positive-definite shift in the W mass [64,66–73]. In fact, $v_\Delta \approx 2$ GeV is preferred by the current global fit [74–76] (driven by the CDF-II result [77]).[6]

In this limit, the only possible unsuppressed decays (i.e., tree-level decays via order one couplings) of H (A) are $t\bar{t}$ and $S\Delta^0$ ($t\bar{t}$, ZH and $W^\pm H^\mp$) while $H^\pm$ decays dominantly to tb and possibly to $\Delta^\pm S$.[7] In the following, we will assume $m_S < m_{\Delta^0} \ll m_H < m_A \approx m_{H^\pm}$ with m_H being below the top threshold. Note that a small value of v_Δ is preferred by the average [74,75,79] of the W mass measurements [77,77,80–82] (see Refs. [64,68–73,83–87]). Therefore, Δ^0 and $\Delta^\pm$ are quasidegenerate and being tripletlike, decay dominantly to W^+W^- and WZ, respectively. Since S is singletlike, it decays mainly (≈86%) to $b\bar{b}$ and has $\mathrm{Br}(S \to \gamma\gamma) = 1.4 \times 10^{-3}$ [88–103].

The main production mechanisms of H and A are gluon fusion and $t\bar{t}$ associated production, $H^\pm$ is produced in tb associated production while S and Δ^0 ($\Delta^\pm$) are produced from the decay of H ($H^\pm$). We fix m_S and m_{Δ^0} (and therefore $m_{\Delta^\pm}$) to the values suggested by the indications for narrow resonances, i.e., 95 and 151.5 GeV, respectively.

A. $t\bar{t}$ differential distributions

Next, we consider the production of H via top-quark-induced gluon fusion [88,104–113] and its subsequent decay to $\Delta^0 S$. Note that this is the only unsuppressed decay of H if its mass is below the $t\bar{t}$ threshold. With $S \to b\bar{b}$ and $\Delta^0 \to W^+W^-$, the resulting final state has the same signature as top-quark pair production and decay in the SM (see Fig. 1). In fact, as shown in Ref. [30], the tensions between the measured $t\bar{t}$ (normalized) differential cross sections observed by ATLAS [29] and the corresponding SM predictions (which are compatible with the earlier CMS results [114]),[8] can be removed if this NP process is added to the SM.[9] Using the most conservative estimate for the NP effect, i.e., the SM simulation among the set performed by ATLAS that is in the least tension with data,[10] a 5.8σ preference for NP with a best fit value of

$$\sigma(pp \to H \to \Delta^0 S \to W^+W^- b\bar{b}) \approx 5 \text{ pb}, \tag{3}$$

is found. Note that this result is approximately independent of m_H for 250 GeV $< m_H <$ 300 GeV. This translates to the preferred region (blue bands) for μ_t in Fig. 3.

B. Resonant $t\bar{t}$, $t\bar{t}t\bar{t}$, and $t\bar{b}H^\pm \to t\bar{b}b\bar{t}$

Because the CP-odd scalar A is (mainly) contained in H_1 together with H, they both have the same coupling strength to top quarks. However, since A couples axially, its production cross section from gluon fusion is ≈1.5 higher than the one of H for equal masses (see, e.g., Refs. [116,117]). If CP is conserved, as we assume, then A can neither decay to a pair of gauge bosons nor into two lighter Higgs bosons such that

$$\begin{aligned}
\Gamma(A \to t\bar{t}) &= \frac{3G_F m_A m_t^2 \mu_t^2}{4\sqrt{2}\pi}\sqrt{1-4\frac{m_t^2}{m_A^2}},\\
\Gamma(A \to HZ) &= \frac{G_F m_A^3}{8\sqrt{2}\pi}\lambda^{3/2}(m_H^2, m_Z^2; m_A^2),\\
\Gamma(A \to H^\pm W^\mp) &= \frac{G_F m_A^3}{4\sqrt{2}\pi}\lambda^{3/2}(m_{H^\pm}^2, m_{W^\mp}^2; m_A^2),
\end{aligned} \tag{4}$$

[5]Note that while Δ^0 has a very small mixing with the SM Higgs boson due to the Z_2 symmetries, S can in principle have a bigger mixing with h and thus relevant gluon fusion and Z Strahlung production.

[6]To be more specific, taking into account only the real Higgs triplet (i.e., disregarding the usually small effect of the mass splitting of the doublet components), the global fit [74–76] including the CDF-II measurement [77] prefers $v_\Delta = 3.4 \pm 1.0$ GeV, while excluding the CDF-II measurement one finds $v_\Delta = 2.3 \pm 1.7$ GeV.

[7]For a dominant decay $H \to S\Delta^0$, a coupling λ of order one is necessary. However, note that also the Higgs self-coupling in the SM is of order one and that this does not cause any theoretical problem related to perturbativity, unitarity, etc. Furthermore, the mass splitting among the components of the doublet is small enough to be consistent with perturbativity and vacuum stability as well [78].

[8]These findings are also compatible with the latest differential $t\bar{t}$ results of CMS [115]. However, since we are performing a Monte Carlo–based analysis, including the new CMS result would not have a significant impact because the SM prediction is the limiting factor and CMS performs a less detailed analysis than ATLAS in this respect. Furthermore, note that the $t\bar{t}$ differential distributions only provide the normalization of the total NP effect and a smaller effect would even be welcomed by data.

[9]Note that while in Ref. [30] we focus on the $m^{e\mu}$ and $|\Delta\phi^{e\mu}|$ distributions, we checked that the other (normalized) distributions that are in reasonable agreement with the SM predictions are only marginally affected by the NP contribution (see Fig. 4 of Ref. [30]).

[10]This is the Powheg+Pythia8 (rew) simulation, including the reweighting of the top p_T by using the NLO predictions (see Ref. [29] for details).

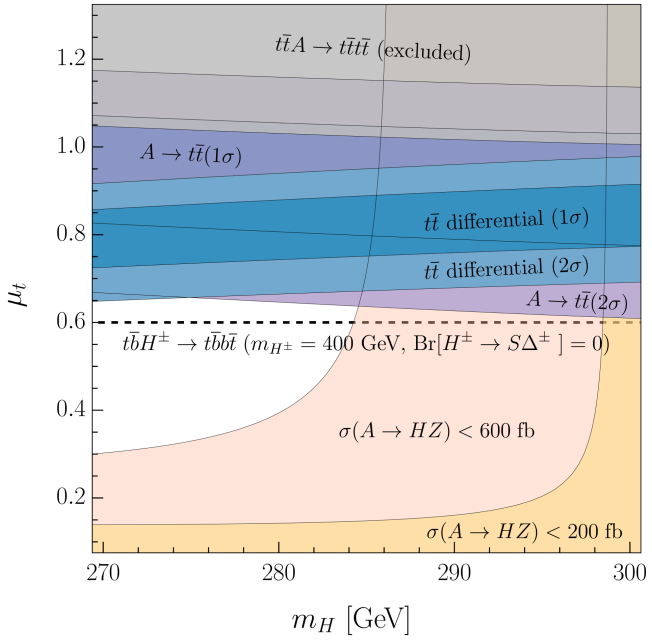

FIG. 3. Constraints and preferred regions in the m_H-μ_t plane from $t\bar{t}$ differential distributions, resonant $t\bar{t}$ production and $t\bar{t}A \to t\bar{t}t\bar{t}$ (see main text for details).

with

$$\lambda(x,y;z) = \left(1 - \frac{x}{z} - \frac{y}{z}\right)^2 - 4\frac{xy}{z^2} \tag{5}$$

are the dominant decay modes, with $\tan(\beta) = v_2/v_1$ and G_F being the Fermi constant.

To explain the CMS excess in resonant $t\bar{t}$ production at ≈400 GeV (3.5σ locally) [31] we set $m_A = 400$ GeV (see Fig. 2) and find[11]

$$\mu_t^2 = (0.82 \pm 0.23)/\mathrm{Br}(A \to t\bar{t}). \tag{6}$$

This results in the violet band in Fig. 3.[12]

The $t\bar{t}$ associated production of A is constrained by the ATLAS limit on $\sigma(pp \to At\bar{t} \to t\bar{t}t\bar{t})$ [119] (see Fig. 2). Here, a 2HDM of type II resulted in a 95% CL lower limit of $1 \lesssim \tan\beta$ for $m_A \approx 400$ GeV and thus $\mu_t \lesssim 1/\mathrm{Br}(A \to t\bar{t})$ (gray excluded region in Fig. 3). However, also the total four-top cross section $\sigma(pp \to t\bar{t}t\bar{t})$ at 13 TeV is measured by ATLAS [120] and CMS [121] to be $22.5^{+6.6}_{-5.5}$ fb and $17.7^{+6.0}_{-5.4}$ fb, respectively. In our model, the NP contribution to the total $t\bar{t}t\bar{t}$ cross section induced by $pp \to At\bar{t} \to t\bar{t}t\bar{t}$ can be obtained from the ATLAS analysis of $\sigma(pp \to At\bar{t} \to t\bar{t}t\bar{t})$: for $m_A \approx 400$ GeV, the 95% CL upper limit on the total cross section of 14.4 fb, corresponds to $\tan(\beta) > 1$ (see Fig. 8 in Ref. [119]). Therefore, $\sigma(pp \to At\bar{t} \to t\bar{t}t\bar{t}) \approx 14\mu_t^2$ fb and thus nicely compatible with the experimentally preferred NP contribution to the cross section.

ATLAS searches for the process $pp \to A \to ZH$ with $H \to t\bar{t}$ [122]. At the point in parameter space closest to our mass region, i.e., $m_A \approx 450$ GeV and $m_H \approx 350$ GeV, a limit of ≈600 fb is observed, compared to an expected limit of ≈400 fb. Even though we have $H \to W^+W^-b\bar{b}$ instead of $H \to t\bar{t}$, the signatures are similar and one can use these results to estimate a limit on $pp \to A \to ZH$ in our model (see yellow and pink region in Fig. 3).[13] Note that the top associated production of H leads to an effect in $t\bar{t}W$. While this effect goes in the direction preferred when comparing the SM prediction to the experimental value, it only gives a moderate effect.

CMS [124] and ATLAS [125] searched for $t\bar{b}H^{\pm} \to t\bar{b}b\bar{t}$. They found a lower bound on $\tan(\beta)$ [corresponding to an upper bound on $Y_t^2 = 1/\tan^2(\beta)$] as a function of $m_{H^{\pm}}$. For $m_{H^{\pm}}$ the upper limit on μ_t is around 0.6. However, depending on the coupling λ, a sizable decay rate for $H^{\pm} \to \Delta^{\pm}S$ is possible. With $\Delta^{\pm} \to W^{\pm}Z$ and $S \to b\bar{b}$, this results in $t\bar{t}Z$ and $t\bar{t}W$-like signature. In fact, given that there is a preference for a ≈200 fb contribution in the latest $t\bar{t}W$ analysis of ATLAS [126], a NP contribution of around ≈400 fb is allowed at the 2σ level. Since the production cross section for $tbH^{\pm} \to t\bar{b}b\bar{t}$ is 600 fb for $m_{H^{\pm}} = 400$ GeV and $\mu_t = 1$, it is possible to evade the $t\bar{b}H^{\pm} \to t\bar{b}b\bar{t}$ bound, which is therefore only shown as a dashed line in Fig. 3.

C. 151.5 and 95 GeV signal strength

The main indications for a new resonance at ≈151.5 GeV are in inclusive $\gamma\gamma$ searches [17,127], $\gamma\gamma + (E_T^{\mathrm{miss}} > 90$ GeV) [128,129] and W^+W^- (without jets) [26,27], where E_T^{miss} stands for missing transverse energy. Reference [15] found $\sigma(pp \to \Delta^0 \to \gamma\gamma) \approx (6 \pm 3)$ fb and $\sigma(pp \to \Delta^0 \to \gamma\gamma + (E_T^{\mathrm{miss}} > 90\,\mathrm{GeV})) \approx (0.6 \pm 0.2)$ fb. The latter is obtained within the simplified model $pp \to (270\,\mathrm{GeV}) \to (151.5\,\mathrm{GeV} \to \gamma\gamma)(151.5^*\,\mathrm{GeV} \to \bar{\chi}\chi)$ where $m_\chi = 50$ GeV. The process W^+W^- with a full jet veto was studied for the direct production of a new scalar in

[11]Note that CMS only reported the p value as a function of μ_t while we assume a gaussian error for the cross section (and thus μ_t^2). The corresponding CMS analysis [118] is done with less integrated luminosity and reaches only down to 500 GeV. However, in the low mass region, a weaker-than-expected limit is observed.

[12]Note that the differential lepton distributions of resonant $t\bar{t}$ production via A are similar to the shapes within the SM. Their effect drops out to a good approximation in the normalized differential distributions studied above.

[13]Depending on m_H, we can have the decay $A \to ZH$ with $H \to \Delta^0 S \to W^+W^-b\bar{b}$ which could potentially contaminate the $t\bar{t}Z$ cross section measurement. The most precise measurement of the inclusive $t\bar{t}Z$ cross section to date stems from the ATLAS experiment [123], which is consistent with the SM. That said, all channels, except for one (four leptons with different flavor) rely on the use of machine learning. This will suppress the sensitivity to non-$t\bar{t}Z$ final states, such as $A \to ZH, H \to W^+W^-b\bar{b}$, in particular, for $m_H < m_{t\bar{t}}$.

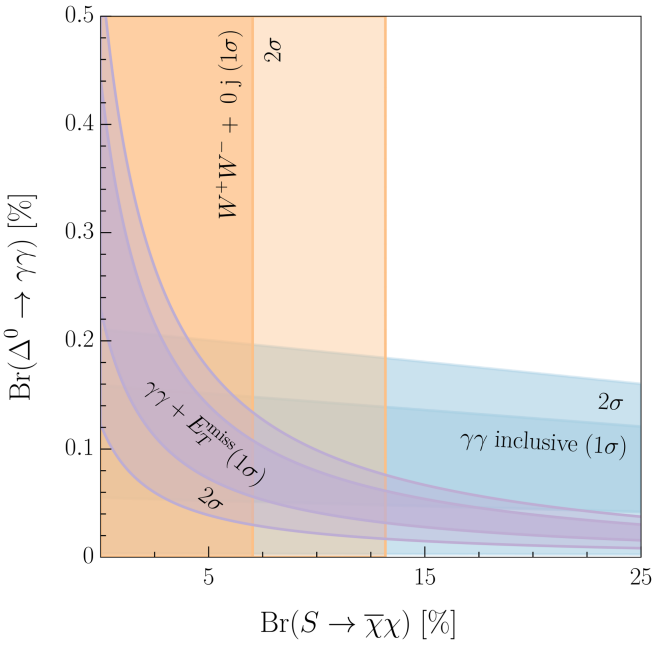

FIG. 4. Preferred regions from signal strength measurements of $\gamma\gamma$ (inclusive), $\gamma\gamma + (E_T^{\mathrm{miss}} > 90\ \mathrm{GeV})$ and W^+W^- (jet veto) of the 151.5 GeV boson Δ^0 as a function of its branching ratio to $\gamma\gamma$ and the branching ratio of the 95 GeV boson S to invisible, for $m_H = 290$ GeV.

Ref. [28] finding $\approx 2\sigma$ significance for a nonzero cross section of ≈ 1 pb at ≈ 151.5 GeV. In our model, Δ^0 is produced in association with S and therefore mainly with b jets, taus, and leptons. Thus, a nonzero branching ratio of $S \to$ invisible, $\mathrm{Br}(S \to \bar{\chi}\chi)$, is needed to pass the full jet veto and to give rise to $\gamma\gamma + E_T^{\mathrm{miss}}$. We simulated both $\gamma\gamma + E_T^{\mathrm{miss}}$ and $W^+W^- + E_T^{\mathrm{miss}}$ in our model to obtain the efficiency and the significances for $S \to E_T^{\mathrm{miss}}$, i.e., $m_\chi < 95/2$ GeV.[14] The results for the three regions $\gamma\gamma$ (inclusive), $\gamma\gamma + (E_T^{\mathrm{miss}} > 90\ \mathrm{GeV})$, and $W^+W^- + 0$ jets are shown in Fig. 4 for $m_H = 290$ GeV. One can see that all three signal strengths are nicely compatible for $\mathrm{Br}(S \to \bar{\chi}\chi) \approx 5\%$ and $\mathrm{Br}(\Delta^0 \to \gamma\gamma) \approx 0.1\%$. Note that the latter value is within the natural expectations for the scalar triplet with hypercharge $Y = 0$ [133].

Finally, the diphoton signal strength for S (≈ 95 GeV) induced via $pp \to H \to \Delta^0 S$ [30] of $\mu_{\gamma\gamma} \approx 0.1$ (with respect to a hypothetical SM Higgs-like boson with the same mass) is at the low side of the preferred range $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ [134]. However, one could allow for a moderate mixing angle with the SM Higgs boson of around 0.2, which is possible if v_S is non-negligible. In this setup, one would be close to the central value while being consistent with SM Higgs boson signal strength measurements and at the same time explaining (partially) the LEP excess in Z Strahlung as well as the indications for $\tau\tau$ [135] and W^+W^- [28].

[14]For the simulations, we employed MadGraph5aMC@NLO [130] with the parton shower performed by Pythia8.3 [131] and the detector simulation carried out with Delphes [132]. We validated our analysis of $\gamma\gamma + E_T^{\mathrm{miss}}$ by comparing it against the ATLAS simulation in Ref. [17]. To correct for our fast simulation vs the full detector simulation of ATLAS, we added a 15 GeV smearing on the missing transverse energy (excluding jets) and on the jet energies. Note that also Drell-Yan production, i.e., $pp \to W^* \to \Delta^\pm \Delta^0$ with $\Delta^0 \to ZW$ and $Z \to \nu\nu$ and/or $W \to \ell\nu$, contributes to $\gamma\gamma + (E_T^{\mathrm{miss}} > 90)$ which is responsible for a nonvanishing cross section at $\mathrm{Br}(S \to \bar{\chi}\chi) = 0$ in Fig. 4.

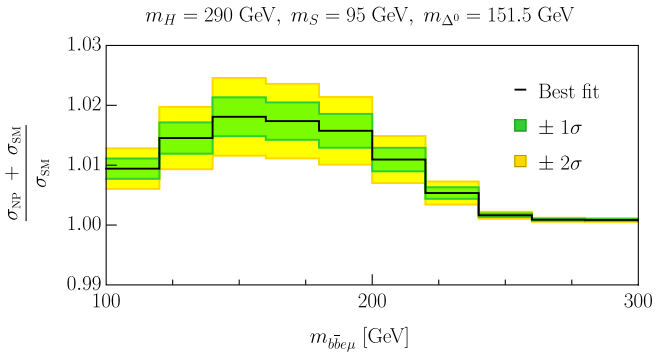

FIG. 5. Predicted deviations from the SM predictions in the invariant mass distribution of the $b\bar{b}e\mu$ system for our benchmark point. Note that these results are in agreement with the preliminary ATLAS results of Ref. [143].

IV. CONCLUSIONS AND OUTLOOK

We propose the Δ2HDMS as a combined explanation of the LHC multilepton anomalies, the resonant diphoton (≈ 95 GeV and ≈ 151.5 GeV) and top quark excesses (≈ 400 GeV) with significances of $> 5\sigma$, $3\sigma - 5\sigma$, and 3.4σ, respectively. The model is obtained by extending the SM with a second Higgs boson doublet as well as a real $SU(2)_L$ singlet and a real $SU(2)_L$ triplet and naturally predicts (at tree level) a positive shift in the W mass in agreement with the current global fit for $v_\Delta = O(1\ \mathrm{GeV})$. In particular, a benchmark points with

$$\begin{aligned} &m_{\Delta^\pm} \approx m_{\Delta^0} = 151.5\,\mathrm{GeV}, \quad m_S = 95\,\mathrm{GeV}, \\ &m_{H^\pm} \approx m_A \approx 400\,\mathrm{GeV}, \quad v_\Delta \approx 2\,\mathrm{GeV}, \quad v_S = O(\mathrm{GeV}), \\ &m_H = 290\,\mathrm{GeV}, \quad \mu_t = 0.7, \lambda = O(1), \quad \tan\beta \gtrapprox 5 \end{aligned} \tag{7}$$

is consistent with all signals and bounds.

While we provided proof of principle that all these anomalies can be explained without violating other bounds, in the future, a detailed examination of the NP effects in the differential $t\bar{t}W$ and $t\bar{t}Z$ distributions would be very interesting. Additionally, note that, e.g., the disappearance of the resonant $t\bar{t}$ would not falsify the model: if A were lighter, i.e., below the top threshold, then it could contribute to the differential $t\bar{t}$ distributions via $pp \to A \to W^\pm H^\mp$ with $H^\pm \to tb$, which would supplement the effect of $pp \to H \to \Delta^0 S \to W^+W^- b\bar{b}$. This

would allow for an explanation of the anomaly with a small top Yukawa coupling and H could be lighter since $\mathrm{Br}(A \to ZH)$ would be smaller, and thus the $t\bar{t}Z$-like signal is reduced.

Our model can be tested in multiple ways with forthcoming measurements. For example, it predicts deviations from the SM predictions in the invariant mass of the $b\bar{b}e\mu$ system in the differential $t\bar{t}$ analyses (see Fig. 5) and in asymmetric Higgs signals, e.g., in $\gamma\gamma bb$. Furthermore, it opens a window of opportunity for the exploration and observation of new bosons at the electroweak scale at future e^+e^- accelerators, in particular the charged component of the triplet ($\Delta^{\pm}$), such as the Circular Electron-Positron Collider [136,137], the Compact Linear Collider [138], the Future Circular Collider [139,140], and the International Linear Collider [141,142].

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