Growing Evidence for a Higgs Triplet

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Abstract

With the discovery of a Higgs boson with a mass of 125 gigaelectronvolts (GeV) at the Large Hadron Collider (LHC) at CERN in 2012, the Standard Model (SM) is complete, and despite intensive searches, no new fundamental particle has been observed since then. In fact, a discovery can be challenging without a predictive new physics model because different channels and observables cannot be combined directly and unambiguously. Furthermore, without supporting indirect hints, the signal space to be searched is huge, resulting in diluted significances due to the look-elsewhere effect.

Several LHC processes with multiple leptons in the final state point towards the existence of a new Higgs boson with a mass between 140 GeV to 160 GeV decaying mostly to \boldsymbol{W} bosons. While the former strongly reduces the look-elsewhere effect, the latter indicates that it could be a Higgs triplet with zero hypercharge. Within this simple and predictive extension of the Standard Model, we simulate and combine different channels of di-photon production in association with leptons, missing energy, jets, etc. Using the full run-2 results by ATLAS, including those presented recently at the Moriond conference, an increased significance of 4.3 standard deviations is obtained for a $\approx 152 \,\text{GeV}$ Higgs. Due to the previously predicted mass range, the look-elsewhere effect is negligible, and this constitutes the highest statistical evidence for a new narrow resonance obtained at the LHC. Furthermore, the model predicts a heavier-than-expected \boldsymbol{W} boson, as indicated by the global electroweak fit. If further substantiated, the discovery of a new Higgs would overthrow the SM, provide a compelling case for the construction of future particle colliders, and open the way to a novel understanding of the known shortcomings of the SM. In particular, the triplet Higgs field can lead to a strong first-order phase transition and could thus be related to the matter anti-matter asymmetry in our Universe.

Keywords: Higgs, Large Hadron Collider, Beyond the Standard Model, ${\pmb W}$ boson mass, Di-Photon, Matter-Antimatter Asymmetry

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1 Introduction

The established theoretical description of Nature at microscopic scales, the Standard Model (SM), with its gauge symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$ includes the strong, weak and electromagnetic interactions of matter particles (spin-1/2 fermions) via mediators (spin-1 particles, called gauge bosons). The gauge bosons of the electromagnetic and strong interactions—the photon and gluons—are massless, while those of the weak interactions, the W and Z bosons, are heavy.¹ The SM has been (with a few exceptions [1]) very successful in describing the results of the vast majority of particle physics experiments [2].

In 2012, the final missing particle of the SM, the Higgs boson, was observed by the ATLAS [3] and CMS [4, 5] collaborations at the Large Hadron Collider (LHC) at CERN. It is important to recall that this discovery took place several decades after the Higgs was predicted by the mechanism of spontaneous symmetry breaking via a scalar field, as proposed in 1964 by Brout and Englert [6], Higgs [7, 8] and Guralnik, Hagen and Kibble [9], and implemented in the SM by Glashow [10] Weinberg [11] and Salam [12]. The reason why finding the Higgs was so difficult is that its mass of 125 GeV lies beyond the reach of electron-positron colliders like LEP [13] at CERN, and its suppressed production cross-section prevented an observation at the Tevatron [14] at Fermilab. In fact, the Higgs discovery at the LHC was only possible this time

¹While the gluons (W bosons) originate only from the $SU(3)_c$ ($SU(2)_L$) factor, the photon (γ) and the Z are an admixture of hypercharge ($U(1)_Y$) and $SU(2)_L$.

²

because its signal strengths are predicted by the SM, so CMS and ATLAS were able to combine the di-photon $(\gamma\gamma)$ with the 4-lepton channel. Furthermore, the obtained Higgs mass was consistent with the expectation from the global electroweak fit, which provided a search range and indirect confirmation that it is really the SM Higgs. This substantiates the importance of an ultraviolet-complete and predictive model as well as indirect hints for new particles to facilitate discovery in statistically limited searches.

On the theoretical side, the Higgs boson of the SM is an elementary scalar, a type of particle that had never been observed before. It gives masses to the W and Z bosons while keeping the theory renormalizable (*i.e.* theoretically consistent) as shown by 't Hooft and Veltman [15, 16] in 1971. Furthermore, the elementary fermions acquire their masses via their so-called Yukawa interactions with the Higgs field [11, 17], which is an essential requirement for the existence of complex structures and processes in our Universe.

However, the SM cannot be the ultimate theory of Nature. For example, it does not account for the fact that more gravitationally interacting matter than visible matter is observed at astrophysical scales, leading to the conjecture of the existence of Dark Matter. Non-vanishing neutrino masses necessitated by neutrino oscillations also require an extension of the SM. Furthermore, the dominance of matter over anti-matter in the universe cannot be explained, and the SM does not include gravity. Therefore, it should be considered an effective description which needs to be superseded by a more comprehensive theory. While no unambiguous direction for such an extension has been established, any heavy new physics poses a problem for fundamental scalar particles because they are subject to quantum corrections involving the corresponding scale, which can be many orders of magnitude larger than the electroweak (EW) scale (~ 100 GeV). Therefore, the mass of the Higgs boson is puzzlingly small. Moreover, no theoretical principle or symmetry requirement guarantees the minimality of the SM Higgs sector. Solving these puzzles is part of the motivation for many new physics models and future experiments and accelerators.

Additional scalar bosons must play a subleading role in the spontaneous breaking of the weak interactions. One reason for this is that in the SM, the W mass can be calculated in terms of the Z mass and the weak and electromagnetic interaction strengths, and the result agrees well (on an absolute scale) with the corresponding measurement. Nonetheless, the W boson was found to be slightly heavier than expected by the CDF-II collaboration at Fermilab, which prefers a small new physics contribution.² In this context, the scalar $SU(2)_L$ triplet with hypercharge 0 [24–31] is particularly interesting since it is the most minimal extension of the SM which predicts a positive definite shift in the W mass at tree-level (*i.e.* at leading order in the expansion of quantum corrections) [32–44]. Furthermore, it has been shown that it can lead to a strong first-order phase transition [45–47] which is an essential ingredient of weakscale Baryogenesis, a mechanism that can explain the matter-antimatter asymmetry in the universe. Last but not least, the so-called "multi-lepton anomalies" [1, 48] suggest the existence of a new scalar with a mass range of 140 GeV to 160 GeV [49–52] which decays dominantly to W bosons and is produced in association with lepton,

²While the tension with the SM prediction is driven by the CDF-II result, the less precise LHC [18, 19] and LEP [20] values are in better agreement with the SM and in some conflict with the CDF result. Inflating the error according to the PDG method, a tension of 3.7σ is found [21–23].

³



Fig. 1: Feynman diagrams showing the Drell-Yan production and decays of the triplet Higgses: $pp \to W^* \to (\Delta^{\pm} \to tb, WZ)(\Delta^0 \to \gamma\gamma)$, which we search for using the sidebands of the SM Higgs analyses of ATLAS [56, 57].

bottom quarks and missing energy [53]. Both the production and decay modes are in agreement with the Y = 0 triplet hypothesis [54]. Importantly, these indirect hints for a new scalar reduce the look-elsewhere effect.

The SM extended by a $SU(2)_L$ triplet with zero hypercharge is a very predictive model since it contains (in addition to the SM) only one neutral and one charged scalar, without direct couplings to SM fermions. This leads to suppressed production rates such that it can evade LEP and current LHC bounds [55]. However, it has distinct collider signatures due to its unavoidable production in proton-proton collisions via off-shell EW gauge bosons and the photon, called Drell-Yan production. This leads to the associated production of di-photons with leptons, missing energy and/or jets [54] (see Fig. 1). Note that searching for these exclusive signatures significantly improves the new physics sensitivity by reducing the SM backgrounds due to the requirement of additional particles in the final state.

In this article, we search for the scalar triplet in associated production channels with di-photons in the mass range suggested by the multi-lepton anomalies. For this, we use the comprehensive ATLAS analysis of Ref. [56] as well as the latest result for di-photons plus single tau and single lepton channels of Ref. [57] presented at the Moriond conference.³

2 Model and Setup

The SM supplemented by a $SU(2)_L$ triplet scalar with hypercharge 0 is commonly referred to as the Δ SM [24–31].⁴ During spontaneous electroweak symmetry breaking, the $SU(2)_L$ doublet SM Higgs and the triplet Higgs acquire their vacuum expectation values v and v_{Δ} , respectively. While the former gives rise to both m_W and m_Z , the latter contributes only to m_W ; it is thus said to violate the custodial symmetry. More



³With respect to Ref. [54], we will not only include these new data but also perform background refitting and take into account the statistical correlations among the channels.

 $^{{}^{4}}$ For details and definitions of the model as well as the calculation of the branching ratios to photons, see Ref. [44].



Fig. 2: Left: Production cross-section for $pp \to \Delta^0 \Delta^{\pm}$ and $pp \to \Delta^{\pm} \Delta^{\mp}$ as a function of the triplet mass including the NNLL and NLO QCD correction factor and uncertainties of Refs. [58, 59]. Right: Dominant branching ratios of the charged component Δ^{\pm} as a function of its mass. The errors are estimated from the decays for a SM Higgs with a higher (hypothetical) mass from $h \to tt^*, ZZ^*$ and $h \to cc$ [60]. While these uncertainties are sizable, we checked that their impact on the final significance is very small ($\approx 0.1\sigma$).

specifically, it leads to a positive definite shift in m_W :

$$m_W \approx m_W^{\rm SM} \left(1 + \frac{2v_\Delta^2}{v^2} \right),$$
 (1)

w.r.t. the SM prediction [2]. This is in agreement with the current global average for the W mass [2], which indicates a positive effect of $\approx 20 \text{ MeV}$ with a significance of 3.7σ [21]. This implies $v_{\Delta} \sim \mathcal{O}(\text{GeV})$ such that $v_{\Delta} \ll v$. Note that the exact value for v_{Δ} is immaterial for this work.

The Δ SM contains, in addition to the SM(-like) Higgs (h), a charged Higgs (Δ^{\pm}) and a neutral one (Δ^0) . Because h and Δ^0 have the same quantum numbers, they mix after EW symmetry breaking by an angle α , *i.e.* the mass eigenstates are linear superpositions of the neutral components of the triplet and doublet Higgses (the interaction eigenstates). However, since this mixing is generally small,⁵ we will use the same labels for the mass and interaction eigenstates. Furthermore, because the mass splitting between Δ^0 and Δ^{\pm} is of the order of v_{Δ} , we can assume both components to be degenerate, *i.e.* $m_{\Delta^0} \approx m_{\Delta^{\pm}} \equiv m_{\Delta}$, as far as LHC searches are concerned.

Due to its quantum numbers, the triplet Higgs cannot have direct couplings to quarks or leptons. Consequently, it is dominantly produced at the LHC via the Drell-Yan processes $pp \to W^* \to \Delta^0 \Delta^{\pm}$ and $pp \to Z^*/\gamma^* \to \Delta^{\pm} \Delta^{\mp}$,⁶ since it transforms non-trivially under $SU(2)_L$ (see Fig. 1). Because the couplings of Δ^{\pm} to SM particles are mixing-induced by v_{Δ} , the dominant decay modes are WZ, tb, $\tau\nu$ and cs, and

⁵Measurements of the SM Higgs signal strength, in particular $\gamma\gamma$ and $Z\gamma$, and theoretical constraints such as perturbative unitarity, restrict the mixing angle to be small.

⁶Note that vector-boson fusion is suppressed by v_{Δ}/v and/or α , while the latter also suppresses production via gluon fusion.

⁵

Target	Signal region	Detector level	Correlation
High jet activity[56]	$\geq 4j$	$n_{\mathrm jet}~\geq 4$, $ \eta_{\mathrm jet} ~<2.5$	_
Top[56]	$\ell b \ t_{ m lep}$	$\begin{array}{l} n_{\ell=e,\mu} \geq 1, n_{b\text{-jet}} \geq 1 \\ n_{\ell=e,\mu} = 1, n_{\text{jet}} = n_{b\text{-jet}} = 1 \end{array}$	_
Lepton	$2\ell[56]$ $1\ell[57]$	$ \begin{array}{l} ee, \mu\mu \mbox{ or }e\mu \\ n_{\ell=e,\mu} = 1, \ n_{\tau_{\rm had}} = 0, \ n_{b\text{-jet}} = 0, \\ E_{\rm T}^{\rm miss} > 35 \ {\rm GeV} \ ({\rm only \ for \ e\text{-channel}}) \end{array} $	< 26%
$E_{\mathrm{T}}^{\mathrm{miss}}[56]$	$\begin{array}{l} E_{\mathrm{T}}^{\mathrm{miss}} > 100 \ \mathrm{GeV} \\ E_{\mathrm{T}}^{\mathrm{miss}} > 200 \ \mathrm{GeV} \end{array}$	$\begin{split} E_{\rm T}^{\rm miss} &> 100~{\rm GeV} \\ E_{\rm T}^{\rm miss} &> 200~{\rm GeV} \end{split}$	29%
Tau [57]	$1 au_{ m had}$	$n_{\ell=e,\mu} = 0, n_{\tau_{\text{had}}} = 1, n_{b\text{-jet}} = 0, E_{\text{T}}^{\text{miss}} > 35 \text{ GeV}$	_

Table 1: The signal regions of the ATLAS analyses [56, 57] which are sensitive to the Drell-Yan production of the scalar triplet within our mass range of interest. E_T^{miss} stands for missing transverse energy, t for the top quark and $\ell = e, \mu$ for an electron or a muon. $n_{(b)}$ -jet denotes the number of (bottom quark-initiated) jets and η_{jet} the rapidity of the jet. The subscripts 'had' and 'lep' stand for the corresponding hadronic decays of tau leptons and the leptonic decays of top quarks.

the only free parameter is m_{Δ} entering through phase space factors.⁷ The resulting branching ratios are shown in Fig. 2. The dominant decay widths of Δ^0 (WW, bb and ZZ for our mas range of interest) depend on v_{Δ} and α . However, we are interested in $\Delta^0 \to \gamma \gamma$ which constitutes a particularly clean signature with controlled backgrounds in experiments. This decay is loop-induced and depends, in addition to α and v_{Δ} , critically on $m_{\Delta^0} - m_{\Delta^{\pm}}$ (because the mass difference is related to the trilinear couplings $\Delta^0 \Delta^{\pm} \Delta^{\mp}$).⁸ Therefore, in the following, we subsume these parameter dependencies into the di-photon branching ratio $\operatorname{Br}(\Delta^0 \to \gamma \gamma)$ and consider the latter as a free parameter.

3 Analysis and results

We consider searches for the production of photon pairs (di-photons) at the LHC in association with additional particles or missing energy.⁹ Since we are interested in

⁷Note that for our mass range of interest, the top and either Z or W are off-shell. However, for convenience, we omitted the asterisk signalling this. In the simulation, we generated both $\Delta^{\pm} \rightarrow W^*Z$ and $\Delta^{\pm} \rightarrow WZ^*$ weighted by their branching ratios. ⁸Furthermore, this decay is sensitive to extensions of the Δ SM, which is neither the case for the DY

⁸Furthermore, this decay is sensitive to extensions of the Δ SM, which is neither the case for the DY production mechanism nor for the decays of the charged Higgs (which happen at tree-level).

⁹Multi-lepton final states originating from the decays of the triplet Higgses to WW, ZW and tb were studied in detail in Ref. [55] finding that they can only exclude masses between $\approx 160 \text{ GeV}$ and $\approx 200 \text{ GeV}$. In fact, Ref. [55] used $m_{\Delta 0} = m_{\Delta \pm} = 150 \text{ GeV}$ as a benchmark point.



Fig. 3: Di-photon invariant mass distributions for eight relevant signal regions. The data (black) is shown together with the continuum background (blue) from the ATLAS analyses and the total Δ SM events (red). The latter is comprised of the refitted background (not shown for brevity), the predicted SM Higgs signals at 125 GeV (magenta) and 152 GeV signal (green).

the on-shell production of a new Higgs that decays to photons, we can look for a peak in the invariant mass spectrum of the di-photons. In this context, an extensive analysis of the associated production of the SM Higgs was performed in Ref. [56], containing 22 different channels ($\gamma\gamma + X$ where X stands for leptons, missing energy, jets, *etc.*). In addition, recently, ATLAS released another search targeting various channels, including $\gamma\gamma + \tau$ [57], which was not included in Ref. [56].¹⁰ The figures given in the ATLAS papers [56, 56] show the observed and expected number of events as a function of the invariant mass of the di-photon system between 105 GeV and 160 GeV, therefore covering our region of interest motivated by the multi-lepton anomalies.¹¹

We simulated the processes $pp \to W^* \to (\Delta^{\pm} \to XY)(\Delta^0 \to \gamma\gamma)$, with Δ^{\pm} decaying according to its (mass-dependent) branching ratios (see Fig. 2) using MadGraph5aMC@NLO [61] with the parton showering performed by Pythia8.3 [62] and carried out the simulation for the ATLAS detector [56] with Delphes [63]. The UFO model file at NLO for the Δ SM was built using FeynRules [64–66].¹² Taking into account that Z and W bosons decay (according to their known branching ratios) to leptons, missing energy and jets, we expect that the ATLAS signal regions targeting leptons, missing transverse energy (E_T^{miss}) and high jet activity are the most sensitives ones. Furthermore, at higher values of m_{Δ} , the categories addressing top quarks become relevant.¹³ In fact, we find that, of the 23 categories, the 8 listed in Table 1 turn out to be relevant in our model for the mass range under consideration. The di-photon invariant mass distributions for these relevant signal regions are shown in Fig. 3.

The backgrounds (including the SM Higgs for our purpose) given by ATLAS were obtained under the hypothesis that there is only a single resonance at 125 GeV. Since we assume, in addition, a second resonance with a different mass and signal strength, the background has to be redetermined. For this, we subtract from the measured number of events per bin (N_i^{exp}) the predicted number of SM Higgs events as well as the new physics signal (depending on m_{Δ} and $\text{Br}[\Delta^0 \to \gamma \gamma]$) and fit this the continuous function

$$\left(1 - \frac{m}{s}\right)^b + (m/s)^{a_0 + a_1 \log(m/s)} \tag{2}$$

with the free parameters a_0, a_1 and b, and s = 13 TeV being the LHC run-2 center-ofmass energy, and m the invariant mass of the di-photon pair. In Fig. 3, we show the fit to the di-photon invariant mass distributions for eight relevant signal regions. The continuum backgrounds taken from the ATLAS analyses are in blue, and the overall

¹⁰Ref. [56] was done in the context of a non-resonant di-Higgs analysis and used a boosted decision tree (BDT) for categorizing events. To recast this analysis, we took the conservative approach to add the events of all three BDT cuts to recover the data set obtained by applying the event selection cuts.
¹¹We solely rely on ATLAS results here, because, unfortunately, no competitive CMS analysis for the

¹¹We solely rely on ATLAS results here, because, unfortunately, no competitive CMS analysis for the associated production of a Higgs within our mass range of interest exists.

¹²To reduce the computational resources needed for our scan, we performed the simulations at leading order but rescaled the production cross-section to account for the NLO and NNLL effect following Refs. [58, 59]. Furthermore, we simulated the 4-jet category at NLO, where gluon radiation is particularly important, and included it via a correction factor of 1.2.

¹³We did not include the signal region targeting hadronically decaying top quarks in our analysis. Here, ATLAS uses a BDT which targets top-pair production with a tight cut on the BDT score of 0.9. Because our signal consisting of a bottom quark and an off-shell top is quite different from this, the resulting efficiency is expected to be very small. Furthermore, we also used the single lepton category from Ref. [56], since the bottom-quark jet veto leads to a nearly uncorrelated data set w.r.t. the lb category of Ref. [56].



Fig. 4: Preferred range for the branching ratio of $\Delta^0 \to \gamma \gamma$ for the 8 signal regions which are sensitive to the signal of our model.

fitted Δ SM signal-plus backgrounds are in red. Also shown are the 125 GeV SM Higgs and 152 GeV triplet Higgs signals.



Fig. 5: Statistical combination of the 8 relevant channels including their correlations within the Δ SM. Note that a non-zero branching ratio of $\Delta^0 \rightarrow \gamma \gamma$ is preferred at $m_{\Delta} \approx 152 \text{ GeV}$ with a significance of 4.3σ .

To find (for a given mass) the preferred range for $Br(\Delta^0 \to \gamma \gamma)$, we perform for each signal region a likelihood-ratio test using Poisson statistics. Thus, the theory prediction for the number of events in a bin *i* (including the continuous background of Eq. (2), the SM Higgs signal and the new physics signal from the triplet Higgs) corresponds to the mean of the Poisson distribution, and we calculate the ratio

$$\mathcal{L}_R = \Pi_i \left[\mathcal{L}(N_i^{\text{SM}}, N_i^{\text{exp}}) / \mathcal{L}(N_i^{\text{NP}}, N_i^{\text{exp}}) \right].$$
(3)

Here \mathcal{L} is the likelihood described by the Poisson distribution, $N_i^{\text{SM}}(N_i^{\text{NP}})$ is the number of expected events in the SM (Δ SM) and N_i^{exp} is the number of events measured by ATLAS.

The resulting 68% and 95% confidence level (CL) regions of $\operatorname{Br}(\Delta^0 \to \gamma \gamma)$, calculated by requiring that $\Delta \chi^2 = -2 \ln(\mathcal{L}_R) = 1$ and $\Delta \chi^2 = -2 \ln(\mathcal{L}_R) = 4$, respectively, are shown in Fig. 4.¹⁴ Interestingly, all relevant distributions display a preference for a non-zero decay rate to $\gamma \gamma$ at $\approx 152 \,\text{GeV}$. Combing all 8 signal regions, including the relevant correlations among them, we obtain the best-fit range for $\operatorname{Br}(\Delta^0 \to \gamma \gamma)$ as a function of m_{Δ} in Fig. 5. One can see a strong preference for a non-zero signal strength, which is most pronounced at $\approx 152 \,\text{GeV}$ with a corresponding significance of 4.3σ .

4 Discussion, Conclusions and Outlook

The obtained 4.3σ for a new Higgs at $\approx 152 \text{ GeV}$ within the ΔSM is the highest significance for a narrow resonance at the LHC within a simple but ultraviolet-complete extension of the SM. Note that, due to the mass range and the final state signatures predicted by the multi-lepton anomalies, the look-elsewhere effect is negligible. Consequently, we were able to combine the different channels without a penalty for additional degrees of freedom. Furthermore, the ΔSM can account for the observed positive shift

 $^{^{14}{\}rm Note}$ that we allow for an unphysical negative branching ratio to take into account the effect of downward fluctuations of the background.



Fig. 6: Preferred regions in the α vs $m_{\Delta^{\pm}} - m_{\Delta^0}$ plane for $m_{\Delta^0} = 152$ GeV and two values of v_{Δ} : 4.6 GeV (left) and 2.9 GeV (right), corresponding to the central value obtained from the global electroweak fit with and without including the CDF-II measurement. The band between the two orange lines satisfies perturbative unitarity and the one below the blue line leads to a stable vacuum at the electroweak scale. The green regions are allowed by the SM Higgs signal strength to photons $(h \to \gamma \gamma)$ [68, 69] signal strength at 1σ (1.02-1.15), 2σ (0.96-1.22) and 3σ (0.90-1.29) levels. The 1σ , 2σ and 3σ regions for Br($\Delta^0 \to \gamma \gamma$) are shown in violet. Note that both Br($\Delta^0 \to \gamma \gamma$) and Br($h \to \gamma \gamma$) are sensitive to the mass splitting since this determines the tri-linear Higgs coupling which enters the processes via the Δ^{\pm} loop.

in W and lead to a strong first-order phase transition required for generating a matter anti-matter asymmetry via Baryogenesis.

So far, we have subsumed the free parameters of our model into $\operatorname{Br}[\Delta^0 \to \gamma \gamma]$. Let us now have a closer look at how the preferred decay rate for photons can be obtained. $\operatorname{Br}[\Delta^0 \to \gamma \gamma]$ is only a function of the mixing angle α and the mass splitting between the charged and neutral components of the triplet (for a given mass and v_{Δ}). Looking at the corresponding parameter space for two representative values of v_{Δ} shown in Fig. 6, one can see that the 2σ region preferred by the associated di-photon production can lead to an unstable vacuum and only slightly overlaps within the nonperturbative regime. This indicates that while we have growing evidence for a 152 GeV Higgs produced via Drell-Yan in association with leptons (e, μ and τ), missing energy and b quarks, the Δ SM should be extended. In fact, while it can lead to a strong firstorder phase transition, it cannot account for the additional charge-parity violation [67] to obtain Baryogenesis since the triplet interactions are all real. This means that while the Δ SM is not expected to be the final theory of Nature, also because it does not solve several of the problems of the SM mentioned in the introduction, it provides an important indication of the direction in which the SM should be extended.

A more comprehensive model addressing these problems could be the Δ 2HDMS model, where the SM is extended not only by a triplet but also by a singlet and a second doublet. This model can successfully give rise to weak-scale Baryogenesis [70]

and explain the tensions between the theory predictions of the differential top-quark distribution and their measurements [71] which are part of the multi-lepton anomalies. Furthermore, the charged Higgs coming from the second $SU(2)_L$ doublet can modify $Br(\Delta^0 \to \gamma\gamma)$ significantly (via the tri-linear term $H_1^{\dagger}\Delta^0 H_2$) to avoid problems with vacuum stability and perturbative unitariy.

Finally, a new Higgs boson in general, and our Δ SM in particular, significantly strengthens the physics case for future particle experiments. The charged component of the triplet could be examined with great precision at future e^+e^- accelerators, such as the Circular Electron-Positron Collider (CEPC) [72, 73], the Compact Linear Collider (CLIC) [74], the Future Circular Collider (FCC-ee) [75, 76] and the International Linear Collider (ILC) [77, 78]. Furthermore, these colliders can be used to determine the properties of the SM Higgs very precisely (which are, in general, altered in our model), produce many top quarks within a clean environment to test the related multilepton anomalies and clarify the preference of new physics in the global electroweak fit, in particular the W mass where a positive-definite shift w.r.t. the SM is predicted.

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