Letter

$SU(2)_L$ triplet scalar as the origin of the 95 GeV excess?

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We explore the possibility that an $SU(2)_L$ triplet scalar with hypercharge $Y = 0$ is the origin of the 95 GeV diphoton excess. For a small mixing angle with the Standard Model Higgs, its neutral component has naturally a sizable branching ratio to $\gamma\gamma$ such that its Drell-Yan production via $pp \to W^* \to HH^\pm$ is sufficient to obtain the desired signal strength, where $H^\pm$ is the charged Higgs component of the triplet. The predictions of this setup are (1) The $\gamma\gamma$ signal has a p_T spectrum different from gluon fusion but similar to associated production. (2) Photons are produced in association with tau leptons and jets, but generally do not fall into the vector-boson fusion category. (3) The existence of a charged Higgs with $m_{H^\pm} \approx (95 \pm 5)$ GeV leading to $\sigma(pp \to \tau\tau\nu\nu) \approx 0.4$ pb, which is of the same level as the current limit and can be discovered with Run 3 data. (4) A positive definite shift in the W mass as suggested by the current global electroweak fit.

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Introduction. The Standard Model (SM) is the currently accepted theoretical description of the known constituents and interaction of matter. It has been successfully tested in precision experiments [1–3] and the Brout-Englert-Higgs boson [4–7], the last missing piece, was finally discovered in 2012 at CERN [8–10]. In fact, this 125 GeV particle has properties consistent with the ones predicted by the SM [11–15]. However, this does not exclude the existence of additional scalar bosons, as long as their role in electroweak symmetry breaking is subleading and their production cross sections are smaller than the ones of the SM-like Higgs [16,17].

The minimality of the SM Higgs sector, i.e., the existence of a single $SU(2)_L$ doublet scalar that simultaneously gives mass to the electroweak (EW) gauge bosons and all fermions, is not guaranteed by any theoretical principle or symmetry. A plethora of such extensions have been proposed in the literature, including the addition of $SU(2)_L$ singlets [18–20], doublets [21–25], and triplets [26–31].

While Large Hadron Collider (LHC) searches for new particles did not lead to any discovery (yet), there are interesting hints for new scalar bosons [32]. In particular, CMS [33–35] searches hint toward a neutral scalar H decaying into two photons at 95 GeV. This is compatible with the latest ATLAS result [36] and supported by Z-strahlung with $H \to b\bar{b}$ at LEP [37], as well as by $\tau\tau$ [35] and WW [38–40] searches. In fact, combining these channels results in a global significance of 3.8σ [41].

So far, explanations of the 95 GeV excesses in terms of $SU(2)_L$ singlets and/or $SU(2)_L$ doublets were proposed in the literature [42–67], which all respect custodial symmetry at tree-level. For higher dimensional $SU(2)_L$ representations, the measurement of the ρ-parameter restricts the vacuum expectation value (VEV) of the new scalar to be $\lesssim \mathcal{O}(1)$ GeV [3] and except for the $SU(2)_L$ triplet with hypercharge $Y = 0$ multiply charged scalars at the same

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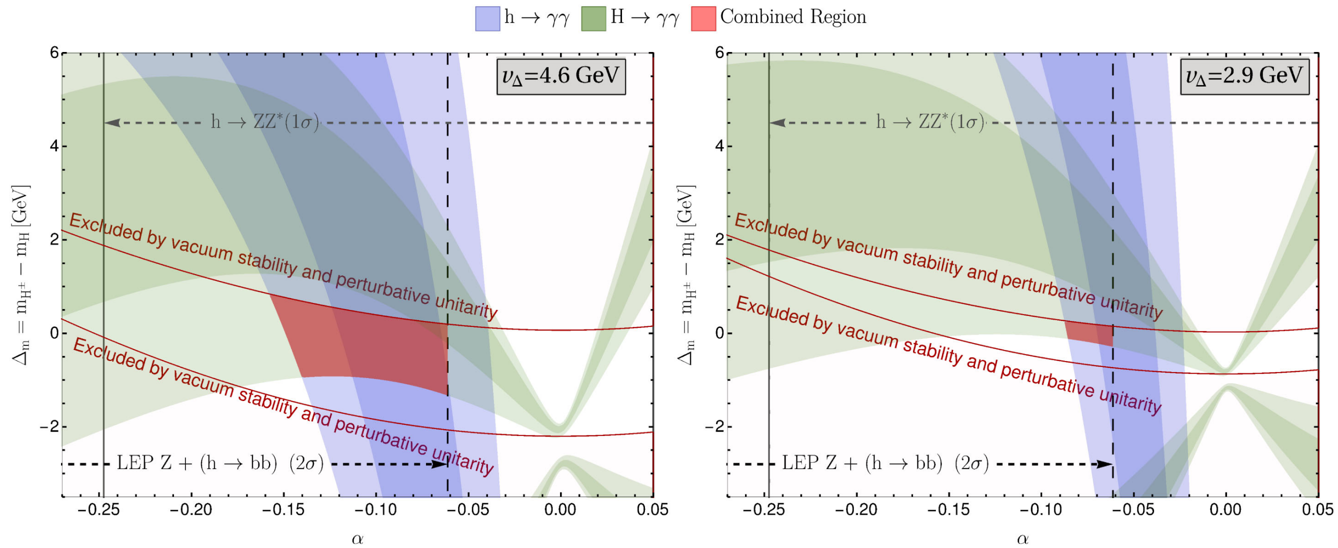

FIG. 1. Preferred regions (1σ and 2σ) by the $h \to \gamma\gamma$ signal strength (blue) and the 95 GeV $H \to \gamma\gamma$ excess (green) in the $\alpha - \Delta_m$ plane for the two values of v_Δ corresponding to the two m_W benchmark points. The region between the two red lines is allowed by vacuum stability and perturbative unitarity. The dashed vertical line indicates the region preferred by the LEP measurement of $Z + (H \to bb)$, and the region to the right of the solid vertical line is preferred by the $h \to ZZ^*$ signal strength at 1σ level.

mass scale are unavoidable which is problematic with respect to LHC searches [68–71].[1] It is well known that this field provides a positive definite shift in the W mass (with respect to the SM prediction) [80–91], as motivated by the current global electroweak fit [92–94] (driven by the CDF II result [95]). However, its collider phenomenology has been barely studied. In this article, we study the viability of $Y = 0$ triplet as an alternative in addressing the hints for a ≈95 GeV scalar.

Phenomenology. The SM extended with an $SU(2)_L$ triplet scalar with hypercharge 0, is commonly referred to as the ΔSM [96–103]. In contains an additional charged scalar $H^\pm$ and a neutral one H which acquires a vacuum expectation value v_Δ in the process of spontaneous symmetry breaking. Importantly, without mixing H couples only to W bosons at tree-level, while the CP-even mixing angle α induces couplings to SM fermions. Furthermore, charged Higgs loops modify both $h \to \gamma\gamma$ and $H \to \gamma\gamma$. A detailed description of the model is provided in the Supplemental Material [104].

Perturbative unitarity and vacuum stability: The ΔSM parameter space can be constrained by vacuum stability and perturbative unitarity. The region between the red lines in Fig. 1 is allowed by both criteria and the explicit calculation of the constraints is given in the Supplemental Material [104].

W mass: The latest ATLAS update of $m_W = 80.360(16)$ [105] (superseding the 2017 result [106]) as well as the LHCb result $m_W = 80.354(32)$ [107] are significantly smaller compared to $m_W = 80.4335(94)$ GeV obtained by CDF II. When combined with D0 [95] and LEP [108], this lead to a naive global average of $m_W = 80.406(7)$ GeV. Because there is considerable tension between these measurements ($\chi^2/\mathrm{dof} = 4.3$), we inflate the error on m_W to 0.015 GeV to get a conservative average of [90][2]

$$m_W^{\mathrm{comb}} = (80.406 \pm 0.015)\ \mathrm{GeV}. \tag{1}$$

Comparing this with the SM prediction of $m_W^{\mathrm{SM}} = 80.3499(56)$ GeV [3,92,109–115], with $m_t = 172.5(0.7)$ GeV [3], the discrepancy of 56 MeV amounts to 3.7σ. If we disregarded the CDF II result, we find an average of

$$m_W^{\mathrm{comb(w/o\,CDFII)}} = (80.372 \pm 0.010)\ \mathrm{GeV}, \tag{2}$$

which corresponds to a discrepancy of 22 MeV (2.2σ).

In the ΔSM, we have

$$m_W^2 = \frac{g^2}{4}(v^2 + 4v_\Delta^2), \qquad m_Z^2 = \frac{g^2}{4\cos\theta_W^2}v^2. \tag{3}$$

Therefore, v_Δ of a few GeV can easily alter the m_W prediction in the desired direction. As such, m_W^{comb}

[1]For small mass-splitting among the $SU(2)_L$ components, LHC searches for multiply charged scalars would exclude scenarios with a neutral Higgs with a mass around ~95 GeV [72,73]. However, nondegenerate scenarios, with the heavier multiply charged Higgses decaying into (off-shell) neutral Higgses and W-bosons, could still be consistent with the LHC searches [74–77]. The phenomenology of such mass spectra has been studied in Refs. [78,79].

[2]This *naive* average agrees well with the one obtained in a sophisticated fit performed by HEPfit [92] prior to the ATLAS update.

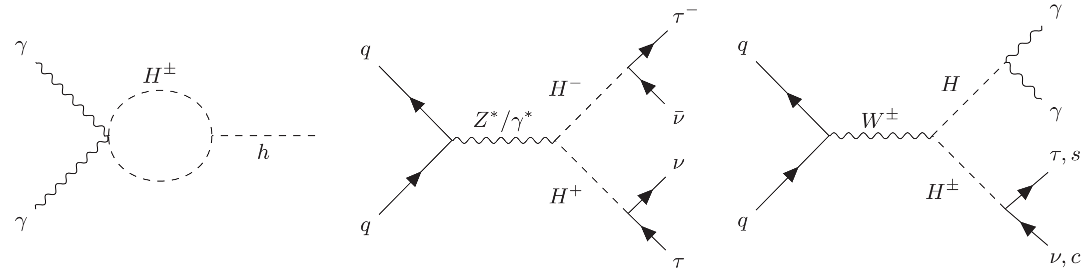

FIG. 2. Feynman diagrams showing the modification of $h \to \gamma\gamma$ (left), the DY processes $pp \to Z^*, \gamma^* \to H^+H^- \to \tau^+\tau^-\nu\bar{\nu}$ (middle), and $pp \to W^* \to H^\pm H^0$ (right).

requires $v_\Delta = 4.60^{+0.58}_{-0.66}$ GeV, while $m_W^{\mathrm{comb(w/o\,CDF\,II)}}$ requires $v_\Delta = 2.89^{+0.59}_{-0.75}$ GeV.

SM Higgs signal strength: Through the quartic interactions $H^\pm$ contributes to the diphoton decay rate of the SM Higgs h (see Fig. 2 left). The corresponding signal strength, with respect to the SM one, is given by

$$\mu_{h,\gamma\gamma} = \Gamma_{h\to\gamma\gamma}/\Gamma^{\mathrm{SM}}_{h\to\gamma\gamma} = |\kappa_\gamma^2|, \tag{4}$$

with

$$\kappa_\gamma \approx \cos\alpha + \frac{A_{hH^\pm H^\mp} v}{2m_{H^\pm}^2} \frac{\beta_H^0\left(\frac{4m_{H^\pm}^2}{m_h^2}\right)}{\frac{4}{3}\beta_H^{1/2}\left(\frac{4m_t^2}{m_h^2}\right) + \beta_H^1\left(\frac{4m_W^2}{m_h^2}\right)}, \tag{5}$$

and the loop functions [116] are given in Supplemental Material [104].

Combining the most recent measurements of CMS [117] and ATLAS [118], $\mu^{\mathrm{CMS}}_{h,\gamma\gamma} = 1.12^{+0.09}_{-0.09}$ and $\mu^{\mathrm{ATLAS}}_{h,\gamma\gamma} = 1.04^{+0.10}_{-0.09}$, respectively, we get the weighted average

$$\mu^{\mathrm{exp}}_{h,\gamma\gamma} = 1.08^{+0.07}_{-0.06}. \tag{6}$$

The resulting preferred regions at the 1σ and 2σ level are shown in blue in Fig. 1.

While the $h \to \gamma\gamma$ signal strength is the most precise measured one, it is affected by h-H mixing and the $H^\pm$-loop contribution so that cancellations occur. Therefore, the second-best measured SM Higgs signal $h \to ZZ^*$ [119,120] provides a complementary constraint of [3]

$$\mu^{\mathrm{exp}}_{h,ZZ^*} = 1.02 \pm 0.08, \tag{7}$$

which, to a very good approximation, is only sensitive to the mixing angle α. The region on the right of the solid vertical line in Fig. 1 is compatible with $\mu^{\mathrm{exp}}_{h,ZZ^*}$ at the 1σ level.

Diphoton excess: While nearly all relevant decay modes of H can be obtained from a rescaling of the widths of a SM-like Higgs with a mass of 95 GeV by multiplying with $\sin^2\alpha$, the decay $H \to WW^*$ is already generated at tree-level via v_Δ and $H \to \gamma\gamma$ receives loop contributions from the charged Higgs as well as from W loops[3]:

$$\Gamma(H\to\gamma\gamma) \approx \frac{\alpha_{\mathrm{em}}^2 g_2^2 m_H^3}{1024\pi^3 m_W^2}\left| -\frac{4}{3}\sin\alpha\beta_H^{1/2}\left(\frac{4m_t^2}{m_H^2}\right) + \left(-\sin\alpha + \frac{4v_\Delta}{v}\cos\alpha\right)\beta_H^1\left(\frac{4m_W^2}{m_H^2}\right) + \frac{A_{HH^\pm H^\mp} v}{2m_{H^\pm}^2}\beta_H^0\left(\frac{4m_{H^\pm}^2}{m_H^2}\right)\right|^2. \tag{8}$$

Here, α_{em} at $q^2 = 0$ numerically approximates well the NLO QED corrections.

For a small mixing angle α, H is mainly produced via the Drell-Yan (DY) process $pp \to W^* \to H^\pm H$ (see Fig. 2 right) with a leading order (LO) cross section of 1.77 pb for $m_{H^\pm} \approx m_H = 95$ GeV. While the QCD corrections have not been estimated so far for the ΔSM, it is obvious that they pertain dominantly to the hadronic ends of the processes and are thus expected to be the same as for sleptons or $SU(2)_L$ triplet leptons. The latter has been calculated in Ref. [121], resulting in a correction factor of 1.15, by which we naively rescale the LO cross section (computed with MadGraph5AMC@NLO [122]) to obtain $\approx$2 pb. In addition, H is also produced via gluon-gluon fusion (ggF) and vector boson fusion (VBF) processes through the mixing with h. The corresponding cross section is calculated by multiplying the production cross section of a SM-like 95 GeV Higgs by α^2. Neglecting the subdominant contribution from VBF, and using $\sigma[pp \to h(95)] \approx$ 68 pb [123–133], we thus have

$$\sigma[pp \to H \to \gamma\gamma] \approx \mathrm{Br}[H\to\gamma\gamma] \times (2 + 68\alpha^2)\ \mathrm{pb}. \tag{9}$$

Normalizing the signal strength to the one of a hypothetical SM-like Higgs with the same mass [123], we find numerically

[3]Only $Z\gamma$ also receives an additional direct contribution from the W loop, which is already present for $\sin\alpha = 0$, but the corresponding branching ratio is negligibly small.

$$\mu_{H,\gamma\gamma} \approx (21.5 + 719\alpha^2) \times \mathrm{Br}[H \to \gamma\gamma]. \quad (10)$$

This has to be compared to the combination of the CMS and ATLAS analyses of a low mass $\gamma\gamma$ searches of [65][4]

$$\mu^{\mathrm{exp}}_{H,\gamma\gamma} = 0.27^{+0.10}_{-0.09}. \quad (11)$$

The resulting preferred regions are shown in green in Fig. 1.[5]

Zbb, *WW* and $\tau\tau$: While $\mathrm{Br}[H \to WW]$ is large for a very small mixing angle α, the resulting effect in $\gamma\gamma$ would be too high if one aims at the central value of the cross section of Ref. [40]. Therefore, α cannot be too small, and it is possible to explain the *Zbb* excess of LEP which requires

$$\mu^{\mathrm{exp}}_{bb} = \frac{\sigma^{\mathrm{exp}}(e^+e^- \to ZH)}{\sigma^{\mathrm{SM}}(e^+e^- \to ZH)} \mathrm{Br}(H \to b\bar{b}) = 0.117 \pm 0.057. \quad (12)$$

For tau decays, the central values of the signal strength $\mu^{\mathrm{exp}}_{\tau\tau} = 1.2 \pm 0.5$ cannot be fully explained, which is a general feature of most SM extensions addressing the 95 GeV excess [58], the error is too large to draw a conclusion here.

$pp \to H^+H^- \to \tau^+\tau^-\nu\bar{\nu}$: The charged Higgs in general dominantly decays to $\tau\nu$. Therefore, its pair production and subsequent decays, i.e., $pp \to Z^*, \gamma^* \to H^+H^- \to \tau^+\tau^-\nu\bar{\nu}$ (see Fig. 2, middle), leads to a collider signature searched for in the context of supersymmetric tau partners [135–138]. While CMS [137] provides an upper bound on the cross section and observes a weaker limit than expected, ATLAS [138] observes a stronger limit than expected but does not provide a bound on the total cross section. Since both bounds deviate from the expected limit by $\approx 1\sigma$ level, but in opposite directions, we will thus use the expected limit on the cross section provided by CMS [137] of $0.34^{+0.24}_{-0.12}$ pb. Using once more MadGraph5AMC@NLO at LO, we find a production cross section of 0.86 pb which we again multiply by a factor 1.15 [121,139] to include NLO QCD effects.

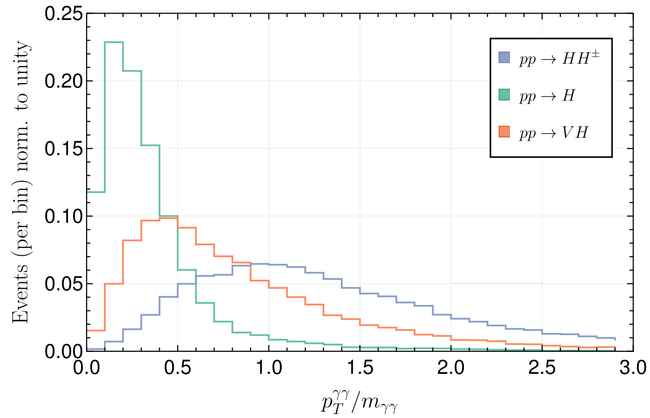

FIG. 3. Transverse momentum normalized to the invariant mass of the photon pair system for different production mechanisms of a 95 GeV scalar H: VH (orange), ggF (green), DY production in the triplet model (blue).

Taking into account that CMS and ATLAS assume a 100% branching ratio of the stau to tau and neutralino, while we have $\mathrm{Br}[H^\pm \to \tau^\pm\nu_\tau] \approx 0.66 \pm 0.03$ [123,140–154],[6] a cross section of $\approx 0.44 \pm 0.03$ pb is predicted. This is in slight tension with the 95% exclusion limit.

Let us therefore consider the option to reduce $\mathrm{Br}[H^\pm \to \tau\nu]$ by increasing the mass splitting Δm such that $\mathrm{Br}[H^\pm \to HW^*]$ becomes sizable[7]:

$$\Gamma(H^\pm \to HW^*) = \frac{9g^4 m_{H^\pm}}{512\pi^3} \lambda^2_{HH^\pm W} G\left(\frac{m_H^2}{m_{H^\pm}^2}, \frac{m_W^2}{m_{H^\pm}^2}\right), \quad (13)$$

where $\lambda_{HH^\pm W} = 2\cos\alpha\cos\beta - \sin\alpha\sin\beta$, and the loop function $G(x,y)$ is given in the Supplemental Material [104].

As one can see in Sec. III in the Supplemental Material [104], choosing $v_\Delta = 0.86$ GeV as a benchmark point, allows for a small region in parameter space with sizable mass splitting, that is allowed by the vacuum stability and perturbative unitarity[8] as well as compatible with $h \to \gamma\gamma, ZZ^*$, $H \to \gamma\gamma$, and *Zbb*. Note that this scenario predicts a small positive shift in the W mass.

Conclusions and outlook. In summary, the predictions if the neutral component of the $SU(2)_L$ triplet with hypercharge 0 is the origin of the 95 GeV excess are

(i) LHC Run 3 shows a stau-like excess.
(ii) Positive shift in the W mass.
(iii) H is produced in association with jets and τ leptons.

[4]Note that the signal strength of H is normalized with respect to an SM-like Higgs with the same mass. While the latter is mainly produced via ggF and VBF processes, the former is dominantly produced via the DY process $pp \to W^* \to H^\pm H$ while the other production modes are too a good approximation only induced via the mixing with h. Note that, while in the limit of zero mixing between the SM Higgs and the triplet Higgs, H is fermiophobic, this region in parameter space is, contrary to the setup of Ref. [134], not excluded due to the charged Higgs contribution to $H \to \gamma\gamma$. Furthermore, for $\alpha \neq 0$, couplings to fermions are induced.

[5]Note that our model has similarities with one of the "square" benchmark scenarios of Ref. [44], where the 95 GeV excess was studied in the context of the type-I two-Higgs-doublet model. There, in the fermiophobic limit, $pp \to W^{\pm*} \to H^\pm H$ is the dominant production mode. However, the model in Ref. [44] predicts an additional pseudoscalar with ≈ 80 GeV while the Higgs potential allows for more freedom than our setup.

[6]Since in our case the branching ratio is dominated by $\tau\nu$ and cs, the error on $\mathrm{Br}[H^\pm \to cs]$ is dominating the error of $\mathrm{Br}[H^\pm \to \tau^\pm\nu_\tau]$.

[7]Note that $\mathrm{Br}[H^\pm \to H^*W]$ is much smaller such that it can be neglected.

[8]Note that, for sizeable α, the requirements of vacuum stability and perturbative unitarity dictate that $\Delta_m \approx 22\alpha$–3.75 GeV.

(iv) A charged Higgs with a mass below ≈100 GeV which could be very well studied at future e^+e^- colliders [155–158].

(v) A significantly broader p_T spectrum of the diphoton system compared to ggF, as shown in Fig. 3.[9]

[9]While this information is currently not available, it can be used in future analyses as a discriminator. To compare the p_T of the diphoton system of the ΔSM to the SM, we generated 100 k events at NLO using MadGraph5AMC@NLO with the parton shower performed by PYTHIA8.3 [159] and the detector simulation for the CMS detector [34], carried out with DELPHES [160]. The UFO model file at NLO of the ΔSM was built using FeynRules [161–163] and to increase the efficiency of the simulation, the decay of H to a photon pair was forced using MadSpin [164].

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