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Letter

Explaining the $\gamma\gamma + X$ excesses at ≈151.5 GeV via the Drell-Yan production of a Higgs triplet

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ABSTRACT

The multi-lepton anomalies suggest the existence of a new scalar with a mass between 145 GeV and 155 GeV, which is compatible with indications of the associated production of a narrow resonance with a mass of ≈151 GeV. These anomalies require a sizable branching fraction of the new scalar to WW. However, because no ZZ signal at this mass has been observed, this implies that the new boson could be the neutral component of an $SU(2)_L$ triplet with zero hypercharge. This field leads to a positive definite shift in the W mass and is produced via the Drell-Yan process $pp \to W^* \to \Delta^0\Delta^\pm$. We use the side-bands of the ATLAS analysis [1] of the associated production of the Standard Model Higgs in the di-photon channel to search for this production mode of the triplet. Since the dominant decays of $\Delta^\pm$ depend only on its mass, the effect in the 22 signal categories considered by ATLAS is completely correlated. Combining all channels in a likelihood ratio test, we find that a non-zero $\mathrm{Br}[\Delta^0 \to \gamma\gamma]$, with a best-fit value of 0.66%, is preferred by $\approx 3\sigma$ for a mass of ≈151.5 GeV. While this mass is consistent with the multi-lepton anomalies, there is also an excess at ≈ 127 GeV with a significance of 3.6σ. However, the latter is inconsistent with the mass predicted by the multi-lepton anomalies and is in close proximity to the SM Higgs mass, suggesting the possibility of enhanced associated production of the SM Higgs.

1. Introduction

The Standard Model (SM) of particle physics is the established theoretical description of the fundamental constituents of matter and their interactions. It has been extensively and successfully tested at the precision frontier [2–4] and its last missing particle, the Brout-Englert-Higgs boson [5–8] has been discovered in 2012 at CERN [9–11]. In fact, this 125 GeV scalar has properties consistent with the ones predicted by the SM [12–16].

However, the minimality of the SM Higgs sector, i.e. a single $SU(2)_L$ doublet scalar that simultaneously gives masses to the electroweak (EW) gauge bosons and all (fundamental) fermions, is not guaranteed by any theoretical principle or symmetry. Therefore, a plethora of extensions has been proposed in the literature, including the addition of $SU(2)_L$ singlets [17–19], doublets [20–24] and triplets [25–30], as well as countless more models containing multiple new scalars.

To be viable, such extensions must respect the bounds from electroweak precision observables (particularly the ρ parameter), flavour observables and searches at the Large Hadron Collider (LHC). While flavour observables can be avoided if the new Higgses do not couple directly to SM fermions, the experimental average of the W mass [31] even suggests a positive new physics (NP) effect with 3.5σ significance

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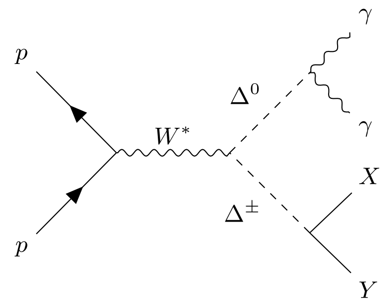

Fig. 1. Feynman diagram showing the Drell-Yan production of the triplet, $pp \to W^* \to (\Delta^\pm \to XY)(\Delta^0 \to \gamma\gamma)$, which can be searched for in the side-bands of the ATLAS analysis of the associated production of the SM Higgs [1]. Within our mass range, XY are dominantly $WZ, tb, cs, \tau\nu$ (see Fig. 2).

over the SM prediction [4].[1] Furthermore, an explanation of the multi-lepton anomalies[2] [35–42], in particular the very significant disagreement in the top quark differential distributions [39,42,43], requires that the new scalar which decays dominantly to WW lies in the mass range of 145 GeV to 155 GeV. In fact, we found that the side-bands of SM Higgs searches display increasing excesses for a new scalar at ≈151.5 GeV [44] (3.9σ) and hints for its decay to WW exist [45–47], while no ZZ excess at this mass is observed [48,49].

This suggests that the neutral component of the $SU(2)_L$ triplet with hypercharge $Y = 0$, which, at tree-level and in the absence of mixing, couples to W bosons but not to the Z, could be the ≈151 GeV boson.[3] This field, at the same time, predicts a positive definite shift in the W mass (w.r.t. the SM prediction) [50–62]. Furthermore, it cannot have tree-level couplings to SM fermions, such that it naturally avoids flavour bounds and has in general suppressed gluon and vector boson fusion production cross-sections, weakening or avoiding LHC bounds.

The triplet Higgs is produced via the Drell-Yan process $pp \to W^* \to \Delta^0\Delta^\pm$ at the LHC, i.e. together with additional particles. This has the potential to explain the hints for the ≈151 GeV boson, which are most pronounced in associated production channels. Note that these exclusive searches can significantly improve the new physics sensitivity by reducing the SM background: this is achieved by requiring the presence of additional particles or signatures in the final state, together with the ones from which the invariant mass is reconstructed.

The most extensive and complete search for the associated production of the SM Higgs was performed in Ref. [1]. In addition to the photon pair, from which the mass of the Higgs is reconstructed, ATLAS searched for 22 different signatures in its model-independent analysis, including leptons, jets, missing energy, *etc*. While no significant excess for $m_{\gamma\gamma} = 125$ GeV was found (in a single channel), the side-bands of this analysis can be used to search for the associated production of new Higgses in the 110 GeV–160 GeV range.

Therefore, we consider the process $pp \to W^* \to (\Delta^0 \to \gamma\gamma)(\Delta^\pm \to XY)$, see Fig. 1. For our mass range, $XY =, tb, WZ, \tau\nu$ (including that t, W or Z can be off-shell) are the dominant decay rates. Because $\Delta^\pm$ and Δ^0 turn out to be quasi-degenerate in mass and the branching ratios of $\Delta^\pm$ solely depend on it, $\text{Br}(\Delta^0 \to \gamma\gamma)$ is the only relevant additional free parameter for the analysis of $\gamma\gamma + X$ (for any given mass), making our setup very predictive. We can thus perform a global fit taking the full set of channels of Ref. [1] to test our conjecture that the neutral component of the $SU(2)_L$ triplet is the (hypothetical) ≈151.5 GeV boson.

2. Model and analysis

The SM extended with an $SU(2)_L$ triplet scalar (Δ) with hypercharge $Y = 0$ is commonly referred to as the ΔSM [63–70]. The most general scalar potential of this model is (see Appendix A for details)

$$V = -\mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_\Phi}{4}\left(\Phi^\dagger\Phi\right)^2 - \mu_\Delta^2 \text{Tr}\left(\Delta^\dagger\Delta\right) + \frac{\lambda_\Delta}{4}\left[\text{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + A\Phi^\dagger\Delta\Phi + \lambda_{\Phi\Delta}\Phi^\dagger\Phi\text{Tr}\left(\Delta^\dagger\Delta\right), \quad (1)$$

where all the couplings are assumed to be real, thereby making the potential CP-conserving. In addition to the SM Higgs h, this model contains a charged scalar ($\Delta^\pm$) and a neutral one (Δ^0). In the process of spontaneous electroweak symmetry breaking, the real component of the triplet acquires a vacuum expectation value (VEV) v_Δ, which maximally breaks custodial symmetry because it only contributes to the W mass but not to the Z mass.[4] Therefore, it leads to a positive definite shift in m_W (at tree-level) w.r.t. the SM prediction [4,71–80]. This is in agreement with the current global average [31], which indicates a positive effect of ≈44 MeV with a significance of 3.5σ w.r.t. the SM prediction [71].[5] While the exact value of v_Δ is immaterial for this work, the W-mass implies $v_\Delta \approx 4.1$ GeV.[6] The mass of $\Delta^\pm$ and Δ^0 can be expressed as

$$\begin{aligned} m_{\Delta_0}^2 &= \lambda_\Delta \frac{v_\Delta^2}{2} + \mu_\Delta \frac{v^2}{4v_\Delta} - \tan\alpha\left(\lambda_{\Phi\Delta} v_\Delta - \frac{A}{2}\right) v, \\ m_{\Delta^\pm}^2 &= \mu_\Delta \frac{v^2 + 4v_\Delta^2}{4v_\Delta}, \end{aligned} \quad (2)$$

where α is the mixing angle between h and Δ^0 and v is the VEV of the SM Higgs. Eq. (A.7) implies that the mass splitting between $\Delta^\pm$ and Δ^0 is of the order of v_Δ (for small α and the scalar self-couplings of $\mathcal{O}(1)$); see the discussion after Eq. (A.7). Therefore, we can assume them to be degenerate to a good approximation, *i.e.* $m_{\Delta^\pm} \approx m_{\Delta^0} \approx m_\Delta$. The mixing angle α impacts the branching ratios of Δ^0. However, we are only interested in $\Delta^0 \to \gamma\gamma$ which is loop induced and depends not only on α but also critically on $m_{\Delta^0} - m_{\Delta^\pm}$ (because it is related to the $\Delta^0\Delta^\pm\Delta^\mp$ coupling). Therefore, concerning the fit, we can subsume these parameters within $\text{Br}(\Delta^0 \to \gamma\gamma)$, which is the only relevant unknown quantity for analysing $\gamma\gamma + X$ (for any given mass). The decay rate for $\Delta^0 \to \gamma\gamma$, calculated as a function of the Lagrangian parameters, is given in Appendix A.

The production cross-sections for the Drell-Yan processes, $pp \to W^* \to \Delta^0\Delta^\pm$ and $pp \to Z^*, \gamma^* \to \Delta^\pm\Delta^\mp$ (where the asterisk denotes that the particle is off-shell), as a function of m_Δ are given in Fig. 2 (left). Here, we include the next-to-next-to leading log (NNLL) and NLO QCD correction factor of Refs. [88,89] (see also Ref. [90] for QCD corrections to charged Higgs production). Note that this is the dominant production mode in the limit of $\alpha \approx 0$[7] and $v_\Delta \ll v$. These processes

[1] However, note that the recent CMS value [32] not included in this average, is closer to the SM.

[2] The multi-lepton anomalies are LHC processes involving multiple leptons and missing transverse momentum in the final state (see Refs. [33,34] for recent reviews).

[3] In this work, we do not discuss the possibility that the neutral component of the triplet could be the 95 GeV boson [50]. Since the real triplet contains only one neutral component, it is, therefore, not possible to explain both excesses. However, it would be possible to extend the SM by two triplets so that the 151.5 GeV and 95 GeV excesses are not exclusive.

[4] For details on the model and its free parameters, see e.g. [50].

[5] The world W-mass fit [31] is based on the recent measurement from the CDF experiment [81] and previous measurements from the D0 experiment [82–85] at the Tevatron, the LHCb and ATLAS experiments at the LHC [84,86], and the LEP [87]. While there is a tension between the most precise measurement from the CDF and the rest, notice that even on excluding the former, a positive shift is preferred at ≈1.4σ.

[6] The world W-mass fit excluding the recent CDF measurement requires $v_\Delta \approx$ 2.7 GeV (see Appendix A).

[7] While the exact value of α is not relevant for our analysis, a value below ≈ 0.3 is generally compatible with SM Higgs signal strength measurements. This has

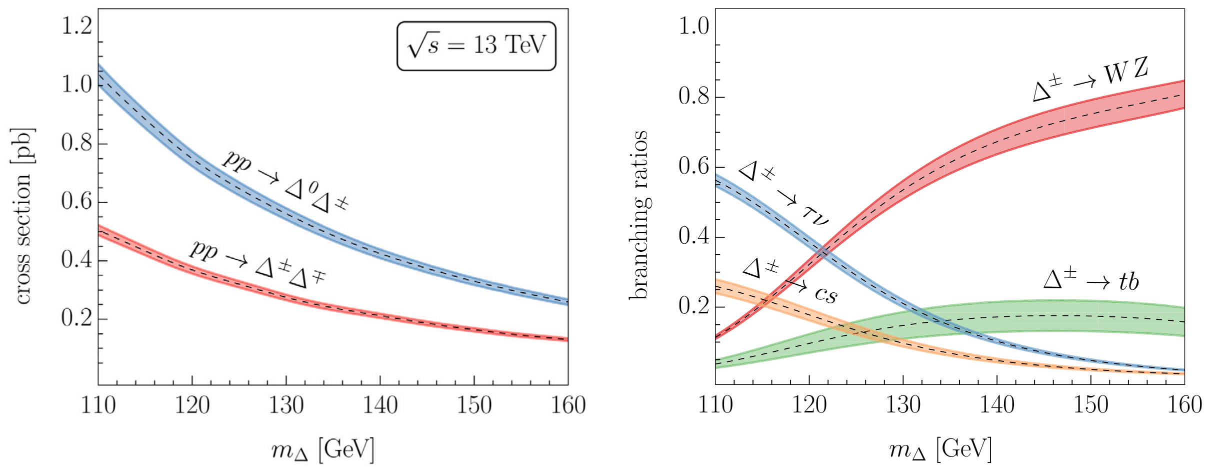

Fig. 2. Left: Production cross-section for $pp \to \Delta^0\Delta^\pm$ and $pp \to \Delta^\pm\Delta^\mp$ as a function of the triplet mass including the NNLL and NLO QCD correction factor of Refs. [88,89]. Right: Dominant branching ratios of the charged component $\Delta^\pm$ as a function of the mass.

were studied in detail in Ref. [91] finding that 4-lepton searches can only exclude masses between ≈160 GeV and ≈200 GeV.[8] However, the ATLAS analysis of the associated production of the SM Higgs [1] sensitive to $pp \to W^* \to \Delta^0\Delta^\pm$ with $\Delta^0 \to \gamma\gamma$ (shown in Fig. 1), was not included.

To determine the efficiency (including cuts and acceptance, *etc.*) we simulated $pp \to W^* \to (\Delta^\pm \to XY)(\Delta^0 \to \gamma\gamma)$ using `MadGraph5aMC@NLO` [92] with the parton shower performed by `Pythia8.3` [93] and carried out the detector simulation for the ATLAS detector [1] with `Delphes` [94]. The UFO model file at NLO for the ΔSM was built using `FeynRules` [95–97].[9] Note that the dominant branching fractions of $\Delta^\pm$ are induced by mixing with the SM Higgs doublet at tree level (scales as v_Δ/v) such that the dependence on it cancels. Therefore, we can show them as a function of m_Δ in Fig. 2 (right). The dominant final states for the mass range of interest are $XY = \tau\nu, cs, tb$ and WZ (including implicitly that t, W and Z can be off-shell).

Taking into account that Z and W bosons decay to leptons, missing energy and jets, we expect that the ATLAS signal regions targeting leptons, missing transverse energy ($E_T^{\rm miss}$) and high jet activity are the most important ones. Furthermore, at higher values of m_Δ, the categories addressing top quarks become relevant.

To obtain bounds on $\text{Br}(\Delta^0 \to \gamma\gamma)$ we perform a likelihood-ratio test using Poisson statistics. This means that we take the theory prediction for the number of events in a bin i as the mean of the Poisson distribution and calculate the ratio

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

where $\mathcal{L}$ is the likelihood described by the Poisson distribution, $N_i^{\rm SM,NP}$ is the number of expected events (which is a real number) in the SM (including the SM Higgs) or our ΔSM and $N_i^{\rm exp}$ is the number of events measured by ATLAS. Because $\mathcal{L}(N_i^{\rm NP}, N_i^{\rm exp})$ is a function of m_Δ and $\text{Br}(\Delta^0 \to \gamma\gamma)$, we can maximize it w.r.t. the latter for any given mass. This then corresponds to the maximum likelihood $\mathcal{L}_R^{\rm max}$ and thus to the best-fit value for $\text{Br}(\Delta^0 \to \gamma\gamma)$. Note that we allow for an unphysical negative branching ratio to take into account the effect of downward fluctuations of the background. The 68% and 95% confidence level (CL) regions are calculated in the asymptotic limit (where $\chi^2 = -2\ln(\mathcal{L}_R^{\rm max})$) by requiring that $\chi^2 = 1$ and $\chi^2 = 4$, respectively.

Table 1
Signal regions of the ATLAS analysis [1] that are most relevant for the Drell-Yan production of the triplet Higgs.

Target	Region	Detector level
High jet activity	$\geq 4j$	$n_{jet} \geq 4$, $\lvert\eta_{jet}\rvert < 2.5$
Top	ℓb	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$
	$t_{\rm lep}$	$n_{\ell=e,\mu} = 1$, $n_{\rm jet} = n_{b\text{-jet}} = 1$
	$t_{\rm had}$	$n_{\ell=e,\mu} = 0$, $n_{\rm jet} = 3$, $n_{b\text{-jet}} = 1$
Lepton	$\geq 1\ell$	$n_{\ell=e,\mu} \geq 1$
	2ℓ	ee, $\mu\mu$ or $e\mu$
	$\geq 3\ell$	$n_{\ell=e,\mu} \geq 3$
$E_{\rm T}^{\rm miss}$	$E_{\rm T}^{\rm miss} > 100$ GeV	$E_{\rm T}^{\rm miss} > 100$ GeV
	$E_{\rm T}^{\rm miss} > 200$ GeV	$E_{\rm T}^{\rm miss} > 200$ GeV
	$E_{\rm T}^{\rm miss} > 300$ GeV	$E_{\rm T}^{\rm miss} > 300$ GeV

3. Results

From the simulation, we obtain the effects in all 22 signal regions provided by ATLAS [1]. However, it turns out that only the 10 detained in Table 1 give relevant constraints on $\text{Br}(\Delta^0 \to \gamma\gamma)$.[10] The corresponding 95% CL bounds on $\text{Br}(\Delta^0 \to \gamma\gamma)$ are shown in Fig. 3. Interestingly, all relevant distributions, except $t_{\rm had}$, show a weakening of the limit around a mass of ≈150 GeV. Furthermore, a similar weakening of the limits is observed between 125 GeV and 130 GeV. Combing all signal regions in Fig. 3 by taking the product of the likelihood ratios, we obtain the best-fit value for $\text{Br}(\Delta^0 \to \gamma\gamma)$ as a function of the mass, as well the 68% CL and 95% CL regions, as shown in Fig. 4.[11] One can see that there is a preference for a non-zero signal both at around 125–130 GeV and at

an impact on the inclusive di-photon signal strength of the 151.5 GeV boson, which would become relevant for $\alpha > 0.1$.

[8] In fact, Ref. [91] used $m_{\Delta^0} = m_{\Delta^\pm} = 150$ GeV as a benchmark point.

[9] To 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. 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 in the extraction of the efficiency.

[10] The signal yields in the remaining signal regions are so small, compared to the corresponding background yields, that their inclusion in the combination has virtually no impact. Furthermore, the 2ℓ signal region is highly correlated (97%) with the 2ℓ-$\not{Z}$ (two-lepton signal region with a Z-veto) that we do not include the latter in our fit. It is important to note that whether these signal regions show an excess or deficit is irrelevant for our model-dependent analysis, since our predefined model predicts a negligible contribution in these signal regions.

[11] Note that there is a moderate correlation between the signal regions, in particular between the different $E_T^{\rm miss}$ categories. However, we checked that removing two of the three $E_T^{\rm miss}$ signal regions from the fit has a very small impact on the final result.

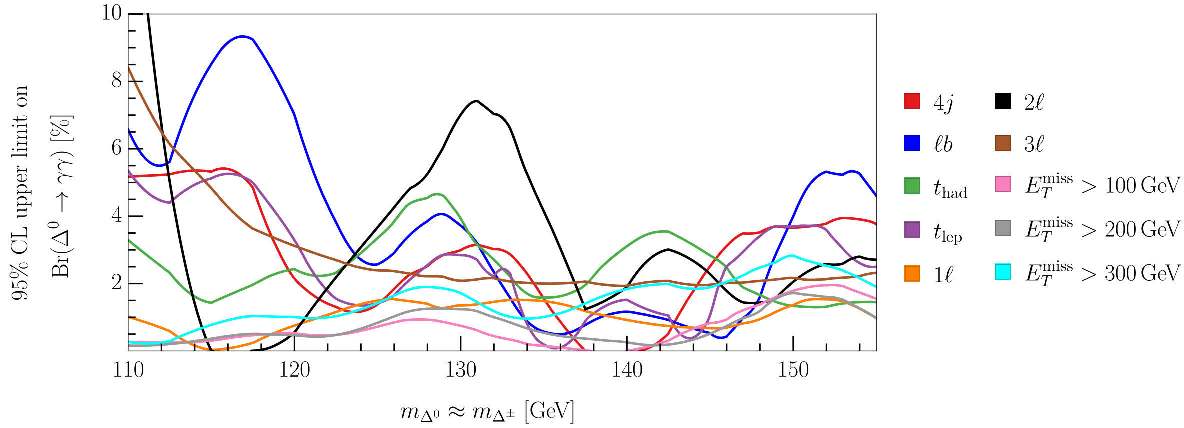

Fig. 3. 95% CL upper limits on Br($\Delta^0 \to \gamma\gamma$) for the 10 most relevant categories. Note that except for the t_{had} and 3ℓ signal regions, all categories show a weakening of the limit around 151.5 GeV.

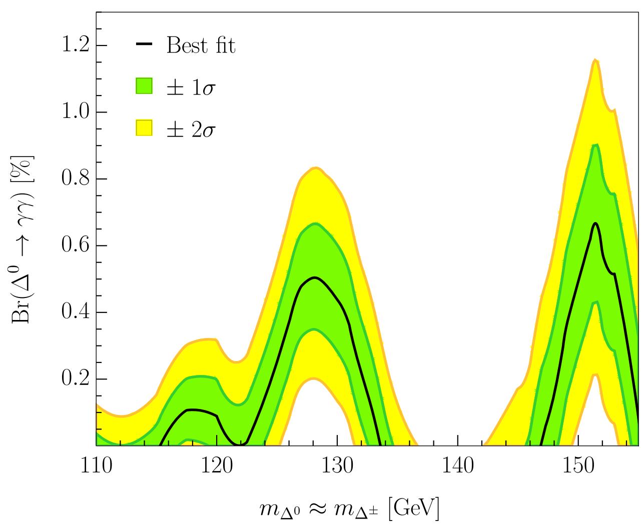

Fig. 4. Statistical combination of the relevant channels. Note that a non-zero branching ratio of $\Delta^0 \to \gamma\gamma$ is preferred at both ≈127 GeV (3.6σ) and ≈151 GeV (3σ). Note that the central value of around 0.6% at 151.5 GeV is compatible with all 95% CL limits in Fig. 3.

≈151.5 GeV. The latter has a significance of 3σ and shows the data consistency with the assumption that the (hypothetical) ≈151.5 GeV Higgs is the neutral component of a triplet with $Y = 0$.[12]

Furthermore, the excess in the 125 GeV–130 GeV range, with a significance of 3.6σ at ≈127 GeV, could be due to a triplet as well or point towards the enhanced associated production of the SM Higgs, since at 125 GeV the significance is still 1.8σ. However, the closeness to the SM Higgs makes it more prompt to systematic error and it is not consistent with the predictions of the multi-lepton anomalies. Finally, note that, in principle, the background would be lower if it were refitted in the presence of one or more additional resonances. This would, particularly for our two-peak structures with a deficit in events between them, further increase the significance.

In Fig. 5, we show the 1σ and 2σ preferred regions for Br($\Delta^0 \to \gamma\gamma$) in green in the α vs $m_{\Delta^\pm} - m_{\Delta^0}$ plane for $m_{\Delta^0} = 151.5$ GeV and $v_\Delta = 4.1$ GeV (top) and $v_\Delta = 2.7$ GeV (bottom), corresponding to the world W-mass fit including/excluding the recent CDF measurement. Also, shown in blue are the regions allowed by the SM Higgs to diphoton ($h \to \gamma\gamma$) [98,99] signal strength at 1σ, 2σ and 3σ. The $h \to ZZ^*$ signal strength restricts $|\alpha| \lesssim 0.25(0.38)$ at 1σ(2σ) level. See Appendix A for details on $h \to \gamma\gamma, ZZ^*$ constraints. Also shown are the regions (outside the two vertical red lines) excluded from the $H \to ZZ \to 4\ell, 2\ell 2q, 2\ell 2\nu$ search by CMS [100].[13]

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 $\Delta^\pm$ loop. The region between the two magenta lines satisfies perturbative unitarity, and the one below the blue line leads to a stable vacuum at the electroweak scale. Note that the part of the preferred region for Br($\Delta^0 \to \gamma\gamma$) overlapping with the region providing a stable vacuum entails a lower branching ratio than the central value.[14] Note that vacuum stability should not be treated on the same footing as an observable. Since it is sensitive to the non-decoupling effect, it could be restored by new physics without affecting low-energy phenomenology.

4. Conclusions and outlook

The multi-lepton anomalies [35–37,39,47], in particular the differential $t\bar{t}$ distributions [47], suggest the existence of a new scalar with a mass between 145 GeV and 155 GeV with a sizable branching fraction to WW. This is in agreement with the indications for a narrow resonance in $\gamma\gamma$ and $Z\gamma$ final states at ≈151 GeV we obtained in Ref. [44,105]). However, no excess in $ZZ \to 4\ell$ is observed [48,49]. This motivates the hypothesis that the ≈151 GeV Higgs could be the neutral component of an $SU(2)_L$ triplet with $Y = 0$, because it only couples to W bosons at tree-level (in the absence of mixing) but not to the Z. Furthermore, this field predicts a positive shift in m_W.

For small mixing angles, the main production mechanism of Δ^0 at the LHC is associated production together with the charged component $\Delta^\pm$ via the Drell-Yan process $pp \to W^* \to \Delta^0\Delta^\pm$. In this article, we use the sidebands of the model-independent ATLAS analysis [1] of the associated production of the SM Higgs in the di-photon channel, in order to search for this process. Because the leading branching fractions of $\Delta^\pm$ only depend on its mass, and it must be quasi-degenerate with the

[12] Note that while not all channels are in perfect agreement with each other, this is expected from statistics. There is also an excess in the $\gamma\gamma + \gamma$ signal region. However, this channel is not included in our fit since it is insensitive to our model. This means that the ΔSM predicts that this excess, which is anyway much below the 2σ level, is a statistical fluctuation.

[13] We use HiggsTools [101] to check possible exclusion of the model parameter space of our interest. We find that the resulting exclusion limits from HiggsSignals [102] of HiggsTools are less stringent than the ones we obtained by combining from the latest CMS and ATLAS measurements [98,99], while HiggsBounds [103] of HiggsTools excludes the region with sizeable α, e.g., $|\alpha| \gtrsim 0.15$ for $m_{\Delta^0} \approx 150$ GeV.

[14] We cross-checked our results with VEVACIOUS [104], finding differences of at most 10% which would have a negligible impact on our results.

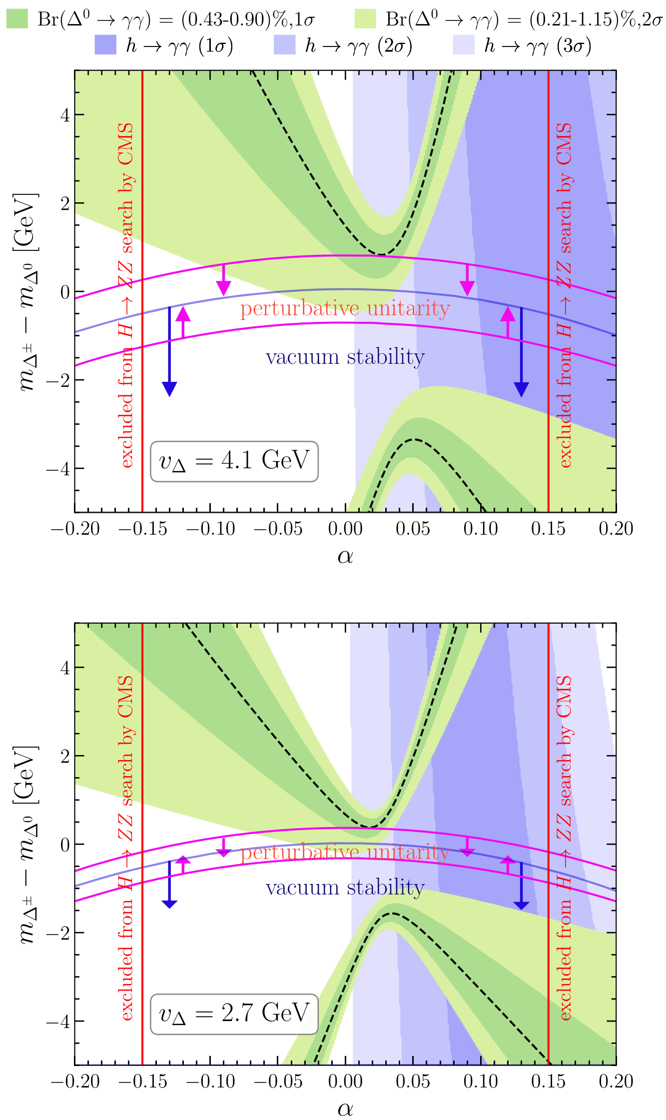

Fig. 5. Preferred regions in the α vs $m_{\Delta^\pm} - m_{\Delta^0}$ plane for $m_{\Delta^0} = 151.5$ GeV and $v_\Delta = 4.1$ GeV (top) and $v_\Delta = 2.7$ GeV (bottom). The 1σ and 2σ regions for $\mathrm{Br}(\Delta^0 \to \gamma\gamma)$ are shown in green, with the dashed black line denoting the central value. The band between the two magenta lines satisfies perturbative unitarity, and the one below the blue line leads to a stable vacuum. The blue regions are allowed by the $h \to \gamma\gamma$ signal strength at 1σ (1.02-1.15), 2σ (0.96-1.22) and 3σ (0.90-1.29) levels. The regions outside the two vertical red lines are excluded from the $H \to ZZ \to 4\ell, 2\ell 2q, 2\ell 2\nu$ search.

neutral component ($m_{\Delta^\pm} \approx m_{\Delta^0} \approx m_\Delta$), $\mathrm{Br}(\Delta^0 \to \gamma\gamma)$ is the only free parameter of interest (for a given mass). Within the mass range 110 GeV–156 GeV, 10 out of the 22 signal regions of the ATLAS analysis [1] give relevant constraints on $\mathrm{Br}(\Delta^0 \to \gamma\gamma)$. Furthermore, 9 of them show a weakening of the 95% CL limit at ≈145 GeV to ≈155 GeV. In fact, combining all channels in a likelihood ratio test leads to the preference of non-zero $\mathrm{Br}(\Delta^0 \to \gamma\gamma)$, with a significance of 3σ for $m_\Delta \approx$151.5 GeV and a best-fit value of $\mathrm{Br}(\Delta^0 \to \gamma\gamma) = 0.66\%$. This shows that the strong indications for the associated production of the ≈151 GeV scalar are consistent with the assumption that it is the neutral component of a Higgs triplet.

Moreover, a similar excess (3.6σ) is obtained at 127 GeV, i.e. near the SM Higgs boson mass. While it could in principle be due to a triplet as well, it is not compatible with the mass range expected from the multi-lepton anomalies. Furthermore, it could also originate (partially) from the associated production of the SM Higgs. In this case, the significance reduces to 1.8σ. This option is particularly interesting since it was already pointed out in Ref. [40] that there are hints for a non-zero new physics contribution to $h + W$, which constitutes an overlapping signal.[15] Furthermore, the enhanced associated production of the SM Higgs is expected in the Δ2HDMS [107], which was recently proposed as a combined explanation of the multi-lepton anomalies, the hints for new Higgses at 151.5 GeV and 95 GeV and the resonant $t\bar{t}$ excess at 400 GeV [108].

While in this article, we accumulated evidence that the (hypothetical) ≈151.5 GeV Higgs is the neutral component of the triplet with $Y = 0$, this does not exclude a more complicated scalar sector, and additional production mechanisms are required to explain the multi-lepton anomalies. To disentangle them, we are eagerly waiting for the analysis of LHC run-3 data, and a comprehensive analysis of associated Higgs production by CMS, in the spirit of Ref. [1], would be very welcome. Furthermore, the Drell-Yan production of $\Delta^\pm\Delta^\mp$ can lead to WWW-like signatures, where an $\approx 2\sigma$ higher cross-section than expected in the SM is observed [109,110]. Finally, we remark that 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) [111,112], the Compact Linear Collider (CLIC) [113], the Future Circular Collider (FCC-ee) [114,115] and the International Linear Collider (ILC) [116,117].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. $Y = 0$ Higgs triplet model

The most general scalar potential of the ΔSM model involving the SM Higgs doublet Φ and the $Y = 0$ Higgs triplet Δ is given by

$$V = -\mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_\Phi}{4}\left(\Phi^\dagger\Phi\right)^2 - \mu_\Delta^2 \mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \frac{\lambda_\Delta}{4}\left[\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + A\Phi^\dagger\Delta\Phi + \lambda_{\Phi\Delta}\Phi^\dagger\Phi\mathrm{Tr}\left(\Delta^\dagger\Delta\right), \tag{A.1}$$

with Φ and Δ parametrised as

$$\Phi = \begin{pmatrix} h_\Phi^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi^0 + iG^0) \end{pmatrix},$$

$$\Delta = \frac{1}{2}\begin{pmatrix} v_\Delta + h_\Delta^0 & \sqrt{2}h_\Delta^+ \\ \sqrt{2}h_\Delta^- & -(v_\Delta + h_\Delta^0) \end{pmatrix},$$

where $h^-_{\Phi,\Delta} = (h^+_{\Phi,\Delta})^*$, and $v_\Phi \approx 246$ GeV and v_Δ are the respective VEVs. Without loss of generality, all the scalar couplings in Eq. (A.1) can be assumed to be real-valued. Consequently, the potential is CP-conserving. Though the dimensionful coupling A can be negative, the

[15] In our follow-up work. [106], we found that this excess disappears once the new ATLAS result of $\gamma\gamma + \tau$ is included and the background is refitted.

sign can always be absorbed in the Δ field redefinition. For definiteness, one can assume $A > 0$. Minimising the potential in Eq. (A.1), we find

$$\mu_\Phi^2 = -\frac{Av_\Delta}{2} + \frac{1}{4}v_\Phi^2\lambda_\Phi + \frac{1}{2}\lambda_{\Phi\Delta}v_\Delta^2,$$
$$\mu_\Delta^2 = -\frac{Av_\Phi^2}{4v_\Delta} + \frac{1}{2}v_\Phi^2\lambda_{\Phi\Delta} + \frac{1}{4}\lambda_\Delta v_\Delta^2.$$

These can be used to replace the mass terms μ_Φ^2 and μ_Δ^2 in the Lagrangian. The mass matrices for the CP-even neutral and charged Higgses read

$$M_0^2 = \begin{pmatrix} \frac{\lambda_\Phi v_\Phi^2}{2} & \left(\lambda_{\Phi\Delta}v_\Delta - \frac{A}{2}\right)v_\Phi \\ \left(\lambda_{\Phi\Delta}v_\Delta - \frac{A}{2}\right)v_\Phi & \frac{\lambda_\Delta v_\Delta^2}{2} + \frac{Av_\Phi^2}{4v_\Delta} \end{pmatrix},$$
$$M_\pm^2 = \begin{pmatrix} Av_\Delta & \frac{Av_\Phi}{2} \\ \frac{Av_\Phi}{2} & \frac{Av_\Phi^2}{4v_\Delta} \end{pmatrix},$$

in the interaction basis $(h_\phi^{0,\pm}, h_\Delta^{0,\pm})$. We diagonalize these mass matrices by rotating the interaction bases to the physical bases:

$$\begin{pmatrix} h \\ \Delta^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h_\Phi^0 \\ h_\Delta^0 \end{pmatrix},$$
$$\begin{pmatrix} G^\pm \\ \Delta^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} h_\Phi^\pm \\ h_\Delta^\pm \end{pmatrix},$$

that the masses of the physical Higgs states are

$$m_h^2 = \frac{\lambda_\Phi v_\Phi^2}{2} + \tan\alpha\left(\lambda_{\Phi\Delta}v_\Delta - \frac{A}{2}\right)v_\Phi, \tag{A.2}$$

$$m_{\Delta^0}^2 = \frac{\lambda_\Delta v_\Delta^2}{2} + \frac{Av_\Phi^2}{4v_\Delta} - \tan\alpha\left(\lambda_{\Phi\Delta}v_\Delta - \frac{A}{2}\right)v_\Phi, \tag{A.3}$$

$$m_{\Delta^\pm}^2 = A\frac{v_\Phi^2 + 4v_\Delta^2}{4v_\Delta}, \tag{A.4}$$

and the mixing angles are

$$\tan 2\alpha = \frac{4v_\Phi v_\Delta\left(2\lambda_{\Phi\Delta}v_\Delta - A\right)}{2\lambda_\Phi v_\Phi^2 v_\Delta - 2\lambda_\Delta v_\Delta^3 - Av_\Phi^2}, \tag{A.5}$$

$$\tan 2\beta = -\frac{4v_\Phi v_\Delta}{v_\Phi^2 - 4v_\Delta^2}. \tag{A.6}$$

Here, the mass state h is identified as the 125 GeV Higgs observed at the LHC, and the state $G^\pm$ corresponding to the zero eigenvalue of $M_\pm^2$ is the charged Goldstone boson, while we do not mention the neutral Goldstone G^0 purely coming from the doublet Higgs.

Now, we can trade the trilinear and quartic couplings of the Lagrangian with the physical masses, the triplet VEV and the mixing angle as follows.

$$\lambda_\Phi = \frac{2}{v_\Phi^2}\left[\cos^2\alpha\ m_h^2 + \sin^2\alpha\ m_{\Delta^0}^2\right],$$

$$\lambda_\Delta = \frac{2}{v_\Delta^2}\left[\sin^2\alpha\ m_h^2 + \cos^2\alpha\ m_{\Delta^0}^2 - \frac{v_\Phi^2}{v_\Phi^2 + 4v_\Delta^2}m_{\Delta^\pm}^2\right],$$

$$\lambda_{\Phi\Delta} = \frac{1}{2v_\Phi v_\Delta}\left[\sin 2\alpha\left(m_h^2 - m_{\Delta^0}^2\right) + \frac{4v_\Phi v_\Delta}{v_\Phi^2 + 4v_\Delta^2}m_{\Delta^\pm}^2\right],$$

$$A = \frac{4v_\Delta}{v_\Phi^2 + 4v_\Delta^2}m_{\Delta^\pm}^2.$$

Therefore, we have four free parameters in the Higgs sector of our model: $m_{\Delta^0}, m_{\Delta^\pm}, \alpha$ and v_Δ.

From Eq. (A.3) and Eq. (A.4), we have

$$m_{\Delta^\pm}^2 - m_{\Delta^0}^2 = Av_\Delta - \frac{\lambda_\Delta v_\Delta^2}{2} + \tan\alpha\left(\lambda_{\Phi\Delta}v_\Delta - \frac{A}{2}\right)v_\Phi. \tag{A.7}$$

Therefore, as it turns out, Δ^0 and $\Delta^\pm$ are nearly mass-degenerate for small (or vanishing) α and v_Δ. Though non-zero (or sufficiently large) α and v_Δ break this mass-degeneracy and can, in principle, induce sizable mass-splitting among them, the requirement of vacuum stability and perturbative unitarity (spelt out later in this section) restricts the mass-splitting to a few GeV.

Note that the Higgs triplet does not couple to the SM fermions at the renormalizable level. Therefore, the Yukawa Lagrangian is the same as that of the SM (before EW symmetry breaking), with the only difference arising from the mixing of the scalar states. The gauge-kinetic Lagrangian for Δ is

$$\mathcal{L} \supset \mathrm{Tr}[|D_\mu\Delta|^2], \tag{A.8}$$

where $D_\mu\Delta = \partial_\mu\Delta + ig\left[\frac{1}{2}\sigma^k W_\mu^k, \Delta\right]$, g is the $SU(2)_L$ gauge coupling, σ^k are the Pauli matrices, and the square bracket denotes the commutator.

W mass

Once the EW symmetry is broken, the Higgs triplet contributes to the W-boson mass at the tree level

$$m_W^2 = \frac{1}{4}g^2(v_\Phi^2 + 4v\Delta^2) = \left(m_W^{\rm SM}\right)^2\left(1 + \frac{4v_\Delta^2}{v_\Phi^2}\right). \tag{A.9}$$

That is, it leads to a positive definite shift in m_W as required by the world W-mass fit. As such, the world average (including the CDF II measurement) requires $v_\Delta = 4.1 \pm 1.2$ GeV, while excluding the CDF II measurement, one requires $v_\Delta = 2.7 \pm 2.0$ GeV.

Vacuum stability and perturbative unitarity

Requiring the potential to be bounded from below in all field directions, one gets the following conditions

$$\lambda_\Phi > 0, \quad \lambda_\Delta > 0, \quad 2\lambda_{\Phi\Delta} + \sqrt{\lambda_\Phi\lambda_\Delta} > 0,$$

while requiring that perturbative unitarity is respected in all $2 \to 2$ scalar scattering processes, one gets

$$|\lambda_\Phi| \le 32\pi, \quad |\lambda_\Delta| \le 32\pi, \quad |\lambda_{\Phi\Delta}| \le 16\pi,$$
$$|6\lambda_\Phi + 5\lambda_\Delta \pm \sqrt{(6\lambda_\Phi - 5\lambda_\Delta)^2 + 192\lambda_{\Phi\Delta}^2}| \le 128\pi.$$

Note that the conditions $|\lambda_\Delta| \le 32\pi$ and $|\lambda_{\Phi\Delta}| \le 16\pi$ restricts the triplet-like Higgs states Δ^0 and $\Delta^\pm$ to be quasi-mass-degenerate.

SM Higgs signal strengths

The triplet-like Higgs states contribute to the SM Higgs decays through the trilinear and quartic interactions. In particular, $h \to \gamma\gamma$ and $h \to ZZ^*$ can provide nontrivial constraints on the model parameter space. The $h \to \gamma\gamma$ signal strength is given by

$$\mu_{\gamma\gamma} \approx \left|\cos\alpha + \frac{\lambda_{h\Delta^+\Delta^-}v}{2m_{\Delta^\pm}^2}\frac{\beta^0\left(\frac{4m_{\Delta^\pm}^2}{m_h^2}\right)}{\frac{4}{3}\beta^{1/2}\left(\frac{4m_t^2}{m_h^2}\right) + \beta^1\left(\frac{4m_W^2}{m_h^2}\right)}\right|^2, \tag{A.10}$$

where

$$\lambda_{h\Delta^+\Delta^-} = \sin\alpha\left\{\frac{\lambda_\Delta}{2}v_\Delta\cos^2\beta + \left(\lambda_{\Phi\Delta}v_\Delta + \frac{A}{2}\right)\sin^2\beta\right\} \tag{A.11}$$

$$+ \cos\alpha\left\{\frac{\lambda_\Phi}{2}v_\Phi\sin^2\beta + \lambda_{\Phi\Delta}v_\Phi\cos^2\beta - \frac{A}{2}\sin 2\beta\right\}, \tag{A.12}$$

and the loop functions are given by [118]

$$\beta^0(x) = -x\,[1 - x f(x)]\,,$$
$$\beta^{1/2}(x) = 2x\,[1 + (1-x) f(x)]\,,$$
$$\beta^1(x) = -\,[2 + 3x + 3x(2-x) f(x)]\,.$$

Combining the most recent measurements of CMS [98] and ATLAS [99], $\mu^{\text{CMS}}_{h,\gamma\gamma} = 1.12^{+0.09}_{-0.09}$ and $\mu^{\text{ATLAS}}_{h,\gamma\gamma} = 1.04^{+0.10}_{-0.09}$, respectively, we get the inverse weighted average

$$\mu^{\text{exp}}_{h,\gamma\gamma} = 1.08^{+0.07}_{-0.06}. \tag{A.13}$$

The other SM Higgs signal strengths ($b\bar{b}$, $c\bar{c}$, $\tau\tau$, gg, WW^* and ZZ^*) are given by $\cos^2\alpha$ to a very good approximation. The PDG average [4] of the $h \to ZZ^*$ signal strength based on the LHC measurements [14, 48,49] gives

$$\mu^{\text{LHC}}_{ZZ^*} = 1.02 \pm 0.08. \tag{A.14}$$

While the $h \to ZZ^*$ signal strength simply puts a constraint on the mixing angle α:

$$|\alpha| \lesssim 0.25(0.38) \text{ at } 1\sigma(2\sigma) \text{ level}, \tag{A.15}$$

the $h \to \gamma\gamma$ signal strength puts non-trivial constraints on m_{Δ^0}, $m_{\Delta^\pm} - m_{\Delta^0}$ and α. Note that their dependence on $m_{\Delta^\pm} - m_{\Delta^0}$ stems via the coupling $\lambda_{h\Delta^+\Delta^-}$.

Δ^0 *decays*

The dominant tree-level decay rates $f\bar{f}$, $WW^{(*)}$, $ZZ^{(*)}$ can be obtained by rescaling the SM-like Higgs decays widths by g^2_{ff}, g^2_{WW} and g^2_{ZZ}. These couplings are given by

$$g_{ff} \approx -\sin\alpha,$$
$$g_{WW} \approx -\sin\alpha + \frac{4v_\Delta}{v}\cos\alpha,$$
$$g_{ZZ} \approx -\sin\alpha,$$

if they are normalized to unity in the SM. The $\Delta^0 \to \gamma\gamma$ decay rate is given by

$$\Gamma(\Delta^0 \to \gamma\gamma) = \frac{\alpha^2 g_2^2 m^3_{\Delta^0}}{1024\pi^3 m^2_W}\left|g_{\Delta^0\gamma\gamma}\right|^2,$$

where the electromagnetic constant α is taken at the scale $q^2 = 0$ since the final state photons are real, and

$$g_{\Delta^0\gamma\gamma} \approx -\frac{4}{3}\sin\alpha\;\beta^{1/2}\left(\frac{4m_t^2}{m^2_{\Delta^0}}\right) + (-\sin\alpha + \frac{4v_\Delta}{v}\cos\alpha)\beta^1\left(\frac{4m_W^2}{m^2_{\Delta^0}}\right) + \frac{\lambda_{\Delta^0\Delta^+\Delta^-}v}{2m^2_{\Delta^\pm}}\beta^0\left(\frac{4m^2_{\Delta^\pm}}{m^2_{\Delta^0}}\right),$$

with

$$\lambda_{\Delta^0\Delta^+\Delta^-} = \cos\alpha\left\{\frac{\lambda_\Delta}{2}v_\Delta\cos^2\beta + \left(\lambda_{\Phi\Delta}v_\Delta + \frac{A}{2}\right)\sin^2\beta\right\} - \sin\alpha\left\{\frac{\lambda_\Phi}{2}v_\Phi\sin^2\beta + \lambda_{\Phi\Delta}v_\Phi\cos^2\beta - \frac{A}{2}\sin 2\beta\right\}.$$

Data availability

The data used are extracted from the publicly available ATLAS publications.

References

[1] ATLAS Collaboration, G. Aad, et al., Model-independent search for the presence of new physics in events including $H \to \gamma\gamma$ with $\sqrt{s}$ = 13 TeV pp data recorded by the ATLAS detector at the LHC, J. High Energy Phys. 07 (2023) 176, arXiv:2301.10486 [hep-ex].
[2] ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group, S. Schael, et al., Precision electroweak measurements on the Z resonance, Phys. Rep. 427 (2006) 257–454, arXiv:hep-ex/0509008.
[3] HFLAV Collaboration, Y.S. Amhis, et al., Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021, Phys. Rev. D 107 (5) (2023) 052008, arXiv:2206.07501 [hep-ex].
[4] Particle Data Group Collaboration, R.L. Workman, et al., Review of particle physics, PTEP 2022 (2022), 083C01.
[5] P.W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. 12 (1964) 132–133.
[6] F. Englert, R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. 13 (1964) 321–323.
[7] P.W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. 13 (1964) 508–509.
[8] G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Global conservation laws and massless particles, Phys. Rev. Lett. 13 (1964) 585–587.
[9] ATLAS Collaboration, G. Aad, et al., Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1–29, arXiv:1207.7214 [hep-ex].
[10] CMS Collaboration, S. Chatrchyan, et al., Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30–61, arXiv:1207.7235 [hep-ex].
[11] CDF, D0 Collaboration, T. Aaltonen, et al., Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the tevatron, Phys. Rev. Lett. 109 (2012) 071804, arXiv:1207.6436 [hep-ex].
[12] CMS Collaboration, S. Chatrchyan, et al., Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs, Phys. Rev. Lett. 110 (8) (2013) 081803, arXiv:1212.6639 [hep-ex].
[13] ATLAS Collaboration, G. Aad, et al., Evidence for the spin-0 nature of the Higgs boson using ATLAS data, Phys. Lett. B 726 (2013) 120–144, arXiv:1307.1432 [hep-ex].
[14] ATLAS, CMS Collaboration, G. Aad, et al., Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV, J. High Energy Phys. 08 (2016) 045, arXiv:1606.02266 [hep-ex].
[15] ATLAS, CMS Collaboration, J.M. Langford, Combination of Higgs measurements from ATLAS and CMS: couplings and k- framework, PoS LHCP2020 (2021) 136.
[16] ATLAS Collaboration, Combined measurements of Higgs boson production and decay using up to 139 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13, TeV collected with the ATLAS experiment.
[17] V. Silveira, A. Zee, Scalar phantoms, Phys. Lett. B 161 (1985) 136–140.
[18] M. Pietroni, The electroweak phase transition in a nonminimal supersymmetric model, Nucl. Phys. B 402 (1993) 27–45, arXiv:hep-ph/9207227.
[19] J. McDonald, Gauge singlet scalars as cold dark matter, Phys. Rev. D 50 (1994) 3637–3649, arXiv:hep-ph/0702143.
[20] T.D. Lee, A theory of spontaneous T violation, Phys. Rev. D 8 (1973) 1226–1239.
[21] H.E. Haber, G.L. Kane, The search for supersymmetry: probing physics beyond the standard model, Phys. Rep. 117 (1985) 75–263.
[22] J.E. Kim, Light pseudoscalars, particle physics and cosmology, Phys. Rep. 150 (1987) 1–177.
[23] R.D. Peccei, H.R. Quinn, CP conservation in the presence of instantons, Phys. Rev. Lett. 38 (1977) 1440–1443.
[24] N. Turok, J. Zadrozny, Electroweak baryogenesis in the two doublet model, Nucl. Phys. B 358 (1991) 471–493.
[25] W. Konetschny, W. Kummer, Nonconservation of total lepton number with scalar bosons, Phys. Lett. B 70 (1977) 433–435.
[26] T.P. Cheng, L.-F. Li, Neutrino masses, mixings and oscillations in SU(2) x u(1) models of electroweak interactions, Phys. Rev. D 22 (1980) 2860.
[27] G. Lazarides, Q. Shafi, C. Wetterich, Proton lifetime and fermion masses in an SO(10) model, Nucl. Phys. B 181 (1981) 287–300.
[28] J. Schechter, J.W.F. Valle, Neutrino masses in SU(2) x U(1) theories, Phys. Rev. D 22 (1980) 2227.
[29] M. Magg, C. Wetterich, Neutrino mass problem and gauge hierarchy, Phys. Lett. B 94 (1980) 61–64.
[30] R.N. Mohapatra, G. Senjanovic, Neutrino masses and mixings in gauge models with spontaneous parity violation, Phys. Rev. D 23 (1981) 165.
[31] LHC-TeV MW Working Group Collaboration, S. Amoroso, et al., Compatibility and combination of world W-boson mass measurements, Eur. Phys. J. C 84 (5) (2024) 451, arXiv:2308.09417 [hep-ex].
[32] CMS Collaboration, V. Chekhovsky, et al., High-precision measurement of the W boson mass with the CMS experiment at the LHC, arXiv:2412.13872 [hep-ex].
[33] O. Fischer, et al., Unveiling hidden physics at the LHC, Eur. Phys. J. C 82 (8) (2022) 665, arXiv:2109.06065 [hep-ph].

[34] A. Crivellin, B. Mellado, Anomalies in particle physics and their implications for physics beyond the standard model, Nat. Rev. Phys. 6 (5) (2024) 294–309, arXiv:2309.03870 [hep-ph].
[35] S. von Buddenbrock, N. Chakrabarty, A.S. Cornell, D. Kar, M. Kumar, T. Mandal, B. Mellado, B. Mukhopadhyaya, R.G. Reed, The compatibility of LHC runs 1 data with a heavy scalar of mass around 270\, GeV, arXiv:1506.00612 [hep-ph].
[36] S. von Buddenbrock, N. Chakrabarty, A.S. Cornell, D. Kar, M. Kumar, T. Mandal, B. Mellado, B. Mukhopadhyaya, R.G. Reed, X. Ruan, Phenomenological signatures of additional scalar bosons at the LHC, Eur. Phys. J. C 76 (10) (2016) 580, arXiv:1606.01674 [hep-ph].
[37] S. von Buddenbrock, A.S. Cornell, A. Fadol, M. Kumar, B. Mellado, X. Ruan, Multi-lepton signatures of additional scalar bosons beyond the standard model at the LHC, J. Phys. G 45 (11) (2018) 115003, arXiv:1711.07874 [hep-ph].
[38] S. von Buddenbrock, A.S. Cornell, E.D.R. Iarilala, M. Kumar, B. Mellado, X. Ruan, E.M. Shrif, Constraints on a 2HDM with a singlet scalar and implications in the search for heavy bosons at the LHC, J. Phys. G 46 (11) (2019) 115001, arXiv:1809.06344 [hep-ph].
[39] S. Buddenbrock, A.S. Cornell, Y. Fang, A. Fadol Mohammed, M. Kumar, B. Mellado, K.G. Tomiwa, The emergence of multi-lepton anomalies at the LHC and their compatibility with new physics at the EW scale, J. High Energy Phys. 10 (2019) 157, arXiv:1901.05300 [hep-ph].
[40] Y. Hernandez, M. Kumar, A.S. Cornell, S.-E. Dahbi, Y. Fang, B. Lieberman, B. Mellado, K. Monnakgotla, X. Ruan, S. Xin, The anomalous production of multi-lepton and its impact on the measurement of Wh production at the LHC, Eur. Phys. J. C 81 (4) (2021) 365, arXiv:1912.00699 [hep-ph].
[41] S. von Buddenbrock, R. Ruiz, B. Mellado, Anatomy of inclusive $t\bar{t}W$ production at hadron colliders, Phys. Lett. B 811 (2020) 135964, arXiv:2009.00032 [hep-ph].
[42] S. Banik, G. Coloretti, A. Crivellin, B. Mellado, Uncovering new higgses in the LHC analyses of differential $t\bar{t}$ cross sections, arXiv:2308.07953 [hep-ph].
[43] ATLAS Collaboration, G. Aad, et al., Inclusive and differential cross-sections for dilepton $t\bar{t}$ production measured in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector, J. High Energy Phys. 07 (2023) 141, arXiv:2303.15340 [hep-ex].
[44] A. Crivellin, Y. Fang, O. Fischer, S. Bhattacharya, M. Kumar, E. Malwa, B. Mellado, N. Rapheeha, X. Ruan, Q. Sha, Accumulating evidence for the associated production of a new Higgs boson at the LHC, Phys. Rev. D 108 (11) (2023) 115031, arXiv:2109.02650 [hep-ph].
[45] CMS Collaboration, A. Tumasyan, et al., Measurements of the Higgs boson production cross section and couplings in the W boson pair decay channel in proton-proton collisions at $\sqrt{s}$ = 1TeV, Eur. Phys. J. C 83 (7) (2023) 667, arXiv:2206.09466 [hep-ex].
[46] ATLAS Collaboration, G. Aad, et al., Measurements of Higgs boson production by gluon-gluon fusion and vector-boson fusion using $H \to WW^* \to e\nu\mu\nu$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D 108 (2023) 032005, arXiv:2207.00338 [hep-ex].
[47] G. Coloretti, A. Crivellin, S. Bhattacharya, B. Mellado, Searching for low-mass resonances decaying into W bosons, Phys. Rev. D 108 (3) (2023) 035026, arXiv:2302.07276 [hep-ph].
[48] CMS Collaboration, A. Tumasyan, et al., A portrait of the Higgs boson by the CMS experiment ten years after the discovery, Nature 607 (7917) (2022) 60–68, arXiv:2207.00043 [hep-ex], Erratum: Nature 623 (2023).
[49] ATLAS Collaboration, G. Aad, et al., Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at $\sqrt{s}$ =13 TeV with the ATLAS detector, Eur. Phys. J. C 80 (10) (2020) 957, arXiv:2004.03447 [hep-ex], Erratum: Eur. Phys. J. C 81 (29) (2021) 398.
[50] S. Ashanujjaman, S. Banik, G. Coloretti, A. Crivellin, B. Mellado, A.-T. Mulaudzi, SU(2) L triplet scalar as the origin of the 95 GeV excess?, Phys. Rev. D 108 (9) (2023) L091704, arXiv:2306.15722 [hep-ph].
[51] M. Chabab, M.C. Peyranère, L. Rahili, Probing the Higgs sector of $Y = 0$ Higgs triplet model at LHC, Eur. Phys. J. C 78 (10) (2018) 873, arXiv:1805.00286 [hep-ph].
[52] P. Fileviez Perez, H.H. Patel, A.D. Plascencia, On the W mass and new Higgs bosons, Phys. Lett. B 833 (2022) 137371, arXiv:2204.07144 [hep-ph].
[53] Y. Cheng, X.-G. He, F. Huang, J. Sun, Z.-P. Xing, Electroweak precision tests for triplet scalars, Nucl. Phys. B 989 (2023) 116118, arXiv:2208.06760 [hep-ph].
[54] T.-K. Chen, C.-W. Chiang, K. Yagyu, Explanation of the W mass shift at CDF II in the extended Georgi-Machacek model, Phys. Rev. D 106 (5) (2022) 055035, arXiv:2204.12898 [hep-ph].
[55] T.G. Rizzo, Kinetic mixing, dark Higgs triplets, and MW, Phys. Rev. D 106 (3) (2022) 035024, arXiv:2206.09814 [hep-ph].
[56] W. Chao, M. Jin, H.-J. Li, Y.-Q. Peng, Y. Wang, Axionlike dark matter from the type-II seesaw mechanism, Phys. Rev. D 109 (11) (2024) 115027, arXiv:2210.13233 [hep-ph].
[57] J.-W. Wang, X.-J. Bi, P.-F. Yin, Z.-H. Yu, Electroweak dark matter model accounting for the CDF W-mass anomaly, Phys. Rev. D 106 (5) (2022) 055001, arXiv:2205.00783 [hep-ph].
[58] Y. Shimizu, S. Takeshita, W boson mass and grand unification via the type-II seesaw-like mechanism, Nucl. Phys. B 994 (2023) 116290, arXiv:2303.11070 [hep-ph].
[59] G. Lazarides, R. Maji, R. Roshan, Q. Shafi, Heavier W boson, dark matter, and gravitational waves from strings in an SO(10) axion model, Phys. Rev. D 106 (5) (2022) 055009, arXiv:2205.04824 [hep-ph].
[60] G. Senjanović, M. Zantedeschi, SU(5) grand unification and W-boson mass, Phys. Lett. B 837 (2023) 137653, arXiv:2205.05022 [hep-ph].
[61] A. Crivellin, M. Kirk, A. Thapa, Minimal model for the W-boson mass, $(g-2)_\mu$, $h \to \mu^+\mu^-$ and quark-mixing-matrix unitarity, Phys. Rev. D 108 (3) (2023) L031702, arXiv:2305.03081 [hep-ph].
[62] T.-K. Chen, C.-W. Chiang, K. Yagyu, CP violation in a model with Higgs triplets, J. High Energy Phys. 06 (2023) 069, arXiv:2303.09294 [hep-ph], Erratum: J. High Energy Phys. 07 (2023) 169.
[63] D.A. Ross, M.J.G. Veltman, Neutral currents in neutrino experiments, Nucl. Phys. B 95 (1975) 135–147.
[64] J.F. Gunion, R. Vega, J. Wudka, Higgs triplets in the standard model, Phys. Rev. D 42 (1990) 1673–1691.
[65] P.H. Chankowski, S. Pokorski, J. Wagner, (Non)decoupling of the Higgs triplet effects, Eur. Phys. J. C 50 (2007) 919–933, arXiv:hep-ph/0605302.
[66] T. Blank, W. Hollik, Precision observables in SU(2) x U(1) models with an additional Higgs triplet, Nucl. Phys. B 514 (1998) 113–134, arXiv:hep-ph/9703392.
[67] J.R. Forshaw, A. Sabio Vera, B.E. White, Mass bounds in a model with a triplet Higgs, J. High Energy Phys. 06 (2003) 059, arXiv:hep-ph/0302256.
[68] M.-C. Chen, S. Dawson, T. Krupovnickas, Higgs triplets and limits from precision measurements, Phys. Rev. D 74 (2006) 035001, arXiv:hep-ph/0604102.
[69] R.S. Chivukula, N.D. Christensen, E.H. Simmons, Low-energy effective theory, unitarity, and non-decoupling behavior in a model with heavy Higgs-triplet fields, Phys. Rev. D 77 (2008) 035001, arXiv:0712.0546 [hep-ph].
[70] P. Bandyopadhyay, A. Costantini, Obscure Higgs boson at colliders, Phys. Rev. D 103 (1) (2021) 015025, arXiv:2010.02597 [hep-ph].
[71] J. de Blas, M. Pierini, L. Reina, L. Silvestrini, Impact of the recent measurements of the top-quark and W-boson masses on electroweak precision fits, Phys. Rev. Lett. 129 (27) (2022) 271801, arXiv:2204.04204 [hep-ph].
[72] P. Athron, M. Bach, D.H.J. Jacob, W. Kotlarski, D. Stöckinger, A. Voigt, Precise calculation of the W boson pole mass beyond the standard model with FlexibleSUSY, Phys. Rev. D 106 (9) (2022) 095023, arXiv:2204.05285 [hep-ph].
[73] E. Bagnaschi, J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You, SMEFT analysis of m_W, J. High Energy Phys. 08 (2022) 308, arXiv:2204.05260 [hep-ph].
[74] A. Sirlin, On the O(alpha**2) corrections to tau (mu), m (W), m (Z) in the SU(2)-L x U(1) theory, Phys. Rev. D 29 (1984) 89.
[75] A. Djouadi, C. Verzegnassi, Virtual very heavy top effects in LEP / SLC precision measurements, Phys. Lett. B 195 (1987) 265–271.
[76] L. Avdeev, J. Fleischer, S. Mikhailov, O. Tarasov, $0(\alpha\alpha_s^2)$ correction to the electroweak ρ parameter, Phys. Lett. B 336 (1994) 560–566, arXiv:hep-ph/9406363, Erratum: Phys. Lett. B 349 (1995) 597–598.
[77] K.G. Chetyrkin, J.H. Kuhn, M. Steinhauser, QCD corrections from top quark to relations between electroweak parameters to order alpha-s**2, Phys. Rev. Lett. 75 (1995) 3394–3397, arXiv:hep-ph/9504413.
[78] K.G. Chetyrkin, J.H. Kuhn, M. Steinhauser, Corrections of order $\mathcal{O}(G_F M_t^2 \alpha_s^2)$ to the ρ parameter, Phys. Lett. B 351 (1995) 331–338, arXiv:hep-ph/9502291.
[79] M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Precise prediction for the W boson mass in the standard model, Phys. Rev. D 69 (2004) 053006, arXiv:hep-ph/0311148.
[80] G. Degrassi, P. Gambino, P.P. Giardino, The $m_W - m_Z$ interdependence in the standard model: a new scrutiny, J. High Energy Phys. 05 (2015) 154, arXiv:1411.7040 [hep-ph].
[81] CDF Collaboration, T. Aaltonen, et al., High-precision measurement of the W boson mass with the CDF II detector, Science 376 (6589) (2022) 170–176.
[82] D0 Collaboration, V.M. Abazov, et al., Measurement of the W boson mass, Phys. Rev. Lett. 103 (2009) 141801, arXiv:0908.0766 [hep-ex].
[83] D0 Collaboration, V.M. Abazov, et al., Measurement of the W boson mass with the D0 detector, Phys. Rev. D 89 (1) (2014) 012005, arXiv:1310.8628 [hep-ex].
[84] LHCb Collaboration, R. Aaij, et al., Measurement of the W boson mass, J. High Energy Phys. 01 (2022) 036, arXiv:2109.01113 [hep-ex].
[85] ATLAS Collaboration, M. Aaboud, et al., Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, Eur. Phys. J. C 78 (2) (2018) 110, arXiv:1701.07240 [hep-ex], Erratum: Eur. Phys. J. C 78 (898) (2018) 898.
[86] ATLAS Collaboration, Improved W boson Mass Measurement using 7 TeV Proton-Proton Collisions with the ATLAS Detector.
[87] ALEPH, DELPHI, L3, OPAL, LEP Electroweak Collaboration, S. Schael, et al., Electroweak measurements in electron-positron collisions at W-boson-pair energies at LEP, Phys. Rep. 532 (2013) 119–244, arXiv:1302.3415 [hep-ex].
[88] R. Ruiz, QCD corrections to pair production of type III seesaw leptons at hadron colliders, J. High Energy Phys. 12 (2015) 165, arXiv:1509.05416 [hep-ph].
[89] A.H. Ajjath, B. Fuks, H.-S. Shao, Y. Simon, Precision predictions for exotic lepton production at the large hadron collider, Phys. Rev. D 107 (7) (2023) 075011, arXiv:2301.03640 [hep-ph].
[90] A. Djouadi, M. Spira, SUSY - QCD corrections to Higgs boson production at hadron colliders, Phys. Rev. D 62 (2000) 014004, arXiv:hep-ph/9912476.
[91] J. Butterworth, H. Debnath, P. Fileviez Perez, F. Mitchell, Custodial symmetry breaking and Higgs boson signatures at the LHC, Phys. Rev. D 109 (9) (2024) 095014, arXiv:2309.10027 [hep-ph].
[92] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].

[93] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159–177, arXiv:1410.3012 [hep-ph].

[94] DELPHES 3 Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, M. Selvaggi, DELPHES 3, a modular framework for fast simulation of a generic collider experiment, J. High Energy Phys. 02 (2014) 057, arXiv:1307.6346 [hep-ex].

[95] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, T. Reiter, UFO - the universal FeynRules output, Comput. Phys. Commun. 183 (2012) 1201–1214, arXiv:1108.2040 [hep-ph].

[96] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr, B. Fuks, FeynRules 2.0 - a complete toolbox for tree-level phenomenology, Comput. Phys. Commun. 185 (2014) 2250–2300, arXiv:1310.1921 [hep-ph].

[97] C. Degrande, Automatic evaluation of UV and R2 terms for beyond the standard model Lagrangians: a proof-of-principle, Comput. Phys. Commun. 197 (2015) 239–262, arXiv:1406.3030 [hep-ph].

[98] CMS Collaboration, A.M. Sirunyan, et al., Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2021) 027, arXiv:2103.06956 [hep-ex].

[99] ATLAS Collaboration, G. Aad, et al., Measurement of the properties of Higgs boson production at $\sqrt{s} = 13$ TeV in the $H \to \gamma\gamma$ channel using 139 fb^{-1} of pp collision data with the ATLAS experiment, J. High Energy Phys. 07 (2023) 088, arXiv:2207.00348 [hep-ex].

[100] CMS Collaboration, A.M. Sirunyan, et al., Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 06 (2018) 127, arXiv:1804.01939 [hep-ex], Erratum: J. High Energy Phys. 03 (2019) 128.

[101] H. Bahl, T. Biekötter, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, J. Wittbrodt, HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals, Comput. Phys. Commun. 291 (2023) 108803, arXiv:2210.09332 [hep-ph].

[102] P. Bechtle, S. Heinemeyer, T. Klingl, T. Stefaniak, G. Weiglein, J. Wittbrodt, HiggsSignals-2: probing new physics with precision Higgs measurements in the LHC 13 TeV era, Eur. Phys. J. C 81 (2) (2021) 145, arXiv:2012.09197 [hep-ph].

[103] H. Bahl, V.M. Lozano, T. Stefaniak, J. Wittbrodt, Testing exotic scalars with HiggsBounds, Eur. Phys. J. C 82 (7) (2022) 584, arXiv:2109.10366 [hep-ph].

[104] J.E. Camargo-Molina, B. O'Leary, W. Porod, F. Staub, **Vevacious**: a tool for finding the global minima of one-loop effective potentials with many scalars, Eur. Phys. J. C 73 (10) (2013) 2588, arXiv:1307.1477 [hep-ph].

[105] S. Bhattacharya, G. Coloretti, A. Crivellin, S.-E. Dahbi, Y. Fang, M. Kumar, B. Mellado, Growing excesses of new scalars at the electroweak scale, arXiv:2306.17209 [hep-ph].

[106] A. Crivellin, S. Ashanujjaman, S. Banik, G. Coloretti, S.P. Maharathy, B. Mellado, Growing evidence for a Higgs triplet, arXiv:2404.14492 [hep-ph].

[107] G. Coloretti, A. Crivellin, B. Mellado, Combined explanation of LHC multilepton, diphoton, and top-quark excesses, Phys. Rev. D 110 (7) (2024) 073001, arXiv:2312.17314 [hep-ph].

[108] ATLAS Collaboration, G. Aad, et al., Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production in the multilepton final state in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 07 (2023) 203, arXiv:2211.01136 [hep-ex].

[109] CMS Collaboration, A.M. Sirunyan, et al., Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV, Phys. Rev. Lett. 125 (15) (2020) 151802, arXiv:2006.11191 [hep-ex].

[110] ATLAS Collaboration, G. Aad, et al., Observation of WWW production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. Lett. 129 (6) (2022) 061803, arXiv:2201.13045 [hep-ex].

[111] CEPC Study Group Collaboration, M. Dong, et al., CEPC conceptual design report: volume 2 - physics & detector, arXiv:1811.10545 [hep-ex].

[112] F. An, et al., Precision Higgs physics at the CEPC, Chin. Phys. C 43 (4) (2019) 043002, arXiv:1810.09037 [hep-ex].

[113] CLICdp, CLIC Collaboration, T.K. Charles, et al., The compact linear collider (CLIC) - 2018 summary report, arXiv:1812.06018 [physics.acc-ph].

[114] FCC Collaboration, A. Abada, et al., FCC-ee: the lepton collider: future circular collider conceptual design report volume 2, Eur. Phys. J. Spec. Top. 228 (2) (2019) 261–623.

[115] FCC Collaboration, A. Abada, et al., FCC physics opportunities: future circular collider conceptual design report volume 1, Eur. Phys. J. C 79 (6) (2019) 474.

[116] ILC Collaboration, The international linear collider technical design report - volume 2: physics, arXiv:1306.6352 [hep-ph].

[117] The International Linear Collider Technical Design Report - Volume 3.I: Accelerator \& in the Technical Design Phase, arXiv:1306.6353 [physics.acc-ph].

[118] J.F. Gunion, H.E. Haber, G.L. Kane, S. Dawson, The Higgs Hunter's Guide, vol. 80, 2000.