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Learning from a Higgs-like scalar resonance

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Motivated by a diphoton anomaly observed by ATLAS and CMS we develop an SFitter analysis for a combined electroweak-Higgs sector, and a scalar portal at the LHC. The theoretical description is based on the linear effective Lagrangian for the Higgs and gauge fields, combined with an additional singlet scalar. The key target is the extraction of reliable information on the portal structure of the combined scalar potential. For the specific diphoton anomaly we find that the new state might well form such a Higgs portal. To obtain more conclusive results we define and test the connection of the Wilson coefficients in the Higgs and heavy scalar sectors, as suggested by a portal setup.

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I. INTRODUCTION

The discovery of a light Higgs boson [1,2] has opened a major new avenue in experimental and theoretical particle physics: comprehensive tests of a possible nonminimal fundamental scalar sector, for which there exists a plethora of motivations. While there has been a lot of progress in developing combined Higgs and gauge analysis strategies for the LHC Run II [3–6], there exists no general and proven analysis framework even for a Higgs portal model [7].

The announcement of an excess seen in the diphoton spectrum by both ATLAS and CMS [8–10], if confirmed by future data, suggests such an extended scalar sector. Taking as illustration the diphoton analysis we develop the suitable framework to study extended Higgs sectors in combination with Gauge-Higgs data. Beyond the diphoton anomaly we present the first full SFitter analysis of a Higgs portal allowing for higher-dimensional operators. Early studies of the anomaly in an effective theory framework can be found in Ref. [11]. Intriguingly, an additional scalar is not sufficient to explain the signal in complete models. The new scalar's sizable couplings to photons and gluons need to be induced by relatively light new particles [11,12]. For example in supersymmetric models, vectorlike matter added to the Minimal Supersymmetric Standard Model (MSSM) or nontrivial signatures in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) are necessary for a successful explanation of the excess [13]. In models in which these new states are connected to the Supersymmetry (SUSY) breaking sector the new scalar can be identified with the sgoldstino, implying a very low SUSY breaking scale [14]. Other extended spacetime symmetries give rise to dilaton [15] and radion interpretations [16], which imply similarly unintended consequences, such as low ultraviolet (UV) scales or a very large curvature of the extra dimension. Extra dimensional scalars not directly related to the compactification circumvent this problem [17] and can explain the localization of extra dimensional fermions, which makes the new scalar a localizer field [18]. Related models, which consider the electroweak scale (or the TeV scale) arising from composite dynamics are less constrained than the MSSM, due to the large number of potential scalar resonances and fermionic quark partners [19]. The possibility of the new resonance to be a spin 2 particle, associated with a higher-dimensional theory of gravity is strongly constrained by dilepton searches and just like the radion implies sizable curvature terms [20]. The large width of $\Gamma_S = 45$ GeV, as reported by ATLAS, can be addressed in some models [21,22]; while such a large width only slightly increases the statistical significance, if it is true, background interference effects are important [23]. In this case, it is well motivated to assume that the new scalar provides a portal to a dark sector, inducing a sizable width through invisible decays [24]. Alternatively, it might be the sign of cascade decays or other explanations not based on a single scalar resonance, which lead to cusps and endpoint structures that can fake a large width [25]. The very minimal, yet not perturbatively realizable assumption of photon fusion induced production cannot explain a large width [26]. The new resonance could also be related to the various, persistent flavor anomalies [27], to the mechanism behind the electroweak phase transition [28], the strong CP problem [29], or an underlying string theory [30]. Finally, a variety of models, motivated by different extensions of the Standard Model (SM) not fitting in the above categories, and further measurements testing the properties of the new resonance have been proposed [31].

In spite of all these considerations, the most obvious question is whether such an additional, likely scalar resonance can be part of an extended Higgs sector [32,33]. In a general case: under the hypothetical observation of a new scalar, how could we test whether it forms a Higgs portal, possibly to a new sector. To answer this question we will remain agnostic about the underlying physics, but assume that a resonantly produced narrow scalar singlet is responsible for the excess. We couple the new scalar to the SM through an effective Lagrangian. This assumption exactly corresponds to recent developments on how to describe deviations from the Standard Model Higgs sector at the LHC [3–6,34–37]. The combined Higgs portal Lagrangian is organized by the field content, the symmetry structure, and the mass dimension. This way we can contrast the apparent absence of dimension-six effects in the range $\Lambda \approx 300\ldots500$ GeV for the SM-like Higgs and gauge sector [5] with the need for higher-dimensional operators coupling to the new scalar with $\Lambda \lesssim 1$ TeV.

A. Theoretical framework

The most general linear effective Lagrangian up to dimension six and built from Standard Model particles and a new scalar singlet reads

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^H_{\text{dim-6}} + \mathcal{L}^S_{\text{dim}\le 5} + \mathcal{L}^S_{\text{dim-6}}. \tag{1}$$

Here, $\mathcal{L}_{\rm SM}$ stands for the renormalizable SM Lagrangian, while $\mathcal{L}^H_{\text{dim-6}}$ contains the dimension-six operators made out of SM fields. In the construction of the Lagrangian we implicitly assume that the new scalar lies below the cutoff scale of the effective expansion. Adopting the basis of our set of Higgs legacy papers [3–5], $\mathcal{L}^H_{\text{dim-6}}$ reads

$$\begin{aligned}\mathcal{L}^H_{\text{dim-6}} = {}& \frac{f_{BB}}{\Lambda^2}\phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi + \frac{f_{WW}}{\Lambda^2}\phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi - \frac{\alpha_s}{8\pi}\frac{f_{GG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{a\mu\nu} + \frac{f_{WWW}}{\Lambda^2}\mathrm{tr}(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho{}^\mu) \\ & + \frac{f_B}{\Lambda^2}(D_\mu\phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\phi) + \frac{f_W}{\Lambda^2}(D_\mu\phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\phi) + \frac{f_{\phi,2}}{\Lambda^2}\frac{1}{2}\partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi) \\ & + \left(\frac{f_\tau m_\tau}{v\Lambda^2}(\phi^\dagger\phi)(\bar{L}_3\phi e_{R,3}) + \frac{f_b m_b}{v\Lambda^2}(\phi^\dagger\phi)(\bar{Q}_3\phi d_{R,3}) + \frac{f_t m_t}{v\Lambda^2}(\phi^\dagger\phi)(\bar{Q}_3\tilde{\phi}u_{R,3}) + \text{H.c.}\right).\end{aligned} \tag{2}$$

The Higgs covariant derivative is $D_\mu\phi = (\partial_\mu + ig'B_\mu/2 + ig\sigma_a W^a_\mu/2)\phi$, and the field strengths are $\hat{B}_{\mu\nu} = ig'B_{\mu\nu}/2$ and $\hat{W}_{\mu\nu} = ig\sigma^a W^a_{\mu\nu}/2$ in terms of the Pauli matrices σ^a. The $SU(2)_L$ and $U(1)_Y$ gauge couplings are g and g', respectively. While the minimum independent set consists of 59 baryon number conserving operators, barring flavor structure and Hermitian conjugation [37], we follow the definition of the relevant operator basis describing Higgs coupling and triple gauge boson vertex (TGV) modifications at the LHC in Ref. [3]. In our construction we assume a narrow, CP-even Higgs, focusing on the minimal, Yukawa-like, couplings to the heavy fermions. We use the equations of motion to rotate to a basis where there are no blind directions linked to electroweak precision data. That way, we neglect all operators contributing to electroweak precision observables at tree level in our LHC analysis. For the Standard Model fit [3–5] we omit the operator $(\phi^\dagger\phi)^3$, which only contributes to the rather poorly measured triple Higgs coupling. In the Appendix we argue why even in the presence of an additional, mixing scalar, this operator will not add any extra relevant features to the fit.

Moving to the new scalar Lagrangian terms, we assume in the following that the additional singlet does not develop a vacuum expectation value (VEV), or that the Lagrangian can be redefined such that the VEV vanishes [33]. The effective Lagrangian of such an additional singlet scalar can be divided into two pieces. Following Refs. [18,33,38,39] we first write down a set of nonredundant, independent operators up to dimension five,

$$\begin{aligned}\mathcal{L}^S_{\text{dim}\le 5} &= \frac{1}{2}\partial_\mu S\partial^\mu S - a_1 S - \frac{M_S^2}{2}S^2 - a_3 S^3 - a_4 S^4 - \frac{f_5^S}{\Lambda}S^5 \\ &\quad - \mu_S S\phi^\dagger\phi - \frac{\lambda_{SH}}{2}S^2\phi^\dagger\phi - \frac{f_1^S}{\Lambda}S(\phi^\dagger\phi)^2 - \frac{f_3^S}{\Lambda}S^3\phi^\dagger\phi \\ &\quad + \frac{\alpha_s}{4\pi}\frac{f^S_{GG}}{\Lambda}SG^a_{\mu\nu}G^{a\,\mu\nu} + \frac{\alpha}{4\pi c_w^2}\frac{f^S_{BB}}{\Lambda}SB_{\mu\nu}B^{\mu\nu} \\ &\quad + \frac{\alpha}{4\pi s_w^2}\frac{f^S_{WW}}{\Lambda}SW^a_{\mu\nu}W^{a\mu\nu} \\ &\quad \times\left(-\frac{f_d^S}{\Lambda}S\bar{Q}_L\phi d_R - \frac{f_u^S}{\Lambda}S\bar{Q}_L\tilde{\phi}u_R - \frac{f_\ell^S}{\Lambda}S\bar{L}_L\phi\ell_R + \text{H.c.}\right).\end{aligned} \tag{3}$$

To be fully consistent with the Standard Model Lagrangian we could then add all dimension-six operators including at least one power of the new singlet scalar. The corresponding set of additional operators can be written as [38]

$$\begin{aligned}\mathcal{L}^S_{\text{dim-6}} &= \frac{f_\phi^{SS}}{\Lambda^2}\phi^\dagger\phi\partial_\mu S\partial^\mu S - \frac{f_6^S}{\Lambda^2}S^6 - \frac{f_4^S}{\Lambda^2}S^4\phi^\dagger\phi - \frac{f_2^S}{\Lambda^2}S^2(\phi^\dagger\phi)^2 \\ &\quad + \frac{f^{SS}_{GG}}{\Lambda^2}S^2G^a_{\mu\nu}G^{a\,\mu\nu} + \frac{f^{SS}_{BB}}{\Lambda^2}S^2B_{\mu\nu}B^{\mu\nu} + \frac{f^{SS}_{WW}}{\Lambda^2}S^2W^a_{\mu\nu}W^{a\,\mu\nu} \\ &\quad \times\left(-\frac{f_d^{SS}}{\Lambda^2}S^2\bar{Q}_L\phi d_R - \frac{f_u^{SS}}{\Lambda^2}S^2\bar{Q}_L\tilde{\phi}u_R \right. \\ &\quad \left. - \frac{f_\ell^{SS}}{\Lambda^2}S^2\bar{L}_L\phi\ell_R + \text{H.c.}\right).\end{aligned} \tag{4}$$

Nevertheless, given the singlet nature of the new scalar and neglecting lepton number violation, all dimension-six operators including the singlet are quadratic in the field S. Consequently, their phenomenological effects will be contributions to the mass terms (f_2^S/Λ^2), redefinitions of the S field to recover canonical kinetic terms (f_ϕ^{SS}/Λ^2), and the contributions to several vertices including two or more heavy scalars. After scalar-Higgs mixing, the two operators f_ϕ^{SS}/Λ^2 and f_2^S/Λ^2 will contribute to the SHH interaction as well. In the present analysis, restricted to trilinear S interactions, all these phenomenology features are already spanned by the free parameters in the Lagrangians of Eqs. (2) and (4). The addition of the dimension-six operators would only contribute to the analysis with extra blind parameters. Given these considerations, we neglect the explicit features induced by Eq. (4) for the time being. We give more details on the effective Lagrangian and the Higgs portal mixing in the Appendix.

B. Analysis framework

The set of analyses presented here are derived using the SFitter framework. SFitter allows us to study multidimensional parameter spaces in the Higgs sector [4,40], the gauge sector [5] and in new physics models like supersymmetry [41]. The fit procedure uses Markov chains to create an exclusive, multidimensional log-likelihood map, based on the available measurements and including all the relevant uncertainties and correlations. The construction of a profile likelihood with flat theory uncertainties leads to the RFit scheme [42]. The statistic uncertainties on the measurements, both for event rates and kinematic distributions, follow Poisson statistics, as do the background uncertainties. All systematic uncertainties are described by Gaussian distributions and can be correlated between the relevant channels. We show log-likelihood projections on two-dimensional planes after profiling over all other parameters. Here, red-yellow regions will illustrate points within $\Delta(-2\log\mathcal{L}) = 2.3$ of the best fit point log-likelihood (1σ in the Gaussian approximation), green regions indicate $\Delta(-2\log\mathcal{L}) = 6.18$ (2σ in the Gaussian limit), and black dots imply the $\Delta(-2\log\mathcal{L}) = 5.99$ exclusion limits (95% C.L. in the Gaussian case).

The implementation of experimental results in the SFitter framework is described in Ref. [4] for the Higgs measurements and in Ref. [5] for anomalous triple gauge boson coupling measurements. For the TGV analyses[1] the correlation of the theory uncertainties between the different bins of a given kinematic distribution is taken into account by flat profiled nuisance parameters [5], while for the different Higgs channels the theory uncertainties are considered uncorrelated without a sizable impact on the shown results [4]. For the Higgs portal analysis we take into account the constraints on a possible new resonance based on the data listed in Table I. For the new resonance we only implement inclusive measurements assuming a narrow width.

TABLE I. Experimental data on the heavy resonance included in our fit.

Channel	Data Set	Reference
$S \to \gamma\gamma$	ATLAS 8 TeV	[9]
$S \to \gamma\gamma$	ATLAS 13 TeV	[9]
$S \to \gamma\gamma$	CMS 8 TeV	[43]
$S \to \gamma\gamma$	CMS 13 TeV	[10]
$S \to WW$	ATLAS 8 TeV	[44]
$S \to WW$	ATLAS 13 TeV	[45]
$S \to ZZ$	ATLAS 8 TeV	[46]
$S \to ZZ$	ATLAS 13 TeV	[47]
$S \to ZZ$	ATLAS 13 TeV	[48]
$S \to Z\gamma$	ATLAS 13 TeV	[49]
$S \to Z\gamma$	CMS 13 TeV	[50]
$S \to Z\gamma$	ATLAS 8 TeV	[51]
$S \to t\bar{t}$	ATLAS 8 TeV	[52]
$S \to jj$	CMS 8 TeV	[53]
$S \to hh$	ATLAS 13 TeV	[54]
$S \to hh$	CMS 8 TeV	[55]
$S \to \tau\bar{\tau}$	CMS 8 TeV	[56]

II. HIGGS PORTAL ANALYSIS

In the following we will use the SFitter effective Lagrangian framework to analyze a new gluon-fusion produced resonance[2] in combination with the electroweak gauge and Higgs sectors at the weak scale. In other words, we ask the question whether such a new particle could be part of an extended Higgs sector and what the allowed parameter space is. In Sec. II A we only include the dimension-five operators given in Eq. (3), restricting the analysis to the data in Table I. In Sec. II B we combine this analysis with the Higgs-electroweak measurements and the SFitter results induced by the dimension-six Lagrangian in Eq. (2). Finally we link the size of different operators to a common origin in Sec. II C.

A. Heavy scalar fit

As a first step we analyze only the measurements for the heavy scalar, as listed in Table I. In Fig. 1 we use this data to determine the five parameters

[1]Note that pair production of weak bosons at the LHC is a crucial ingredient to a Higgs fit based on an effective Lagrangian assuming a linear realization of electroweak symmetry breaking. Without taking these measurements into account the qualitative and quantitative outcome of the fit will be wrong [5].

[2]The assumption of a new narrow scalar, decaying to diphotons according to the observed excess and presumably produced through gluon fusion, suggests the name "Higgs-like" in the title of the paper, without implying any further connection to electroweak symmetry breaking.

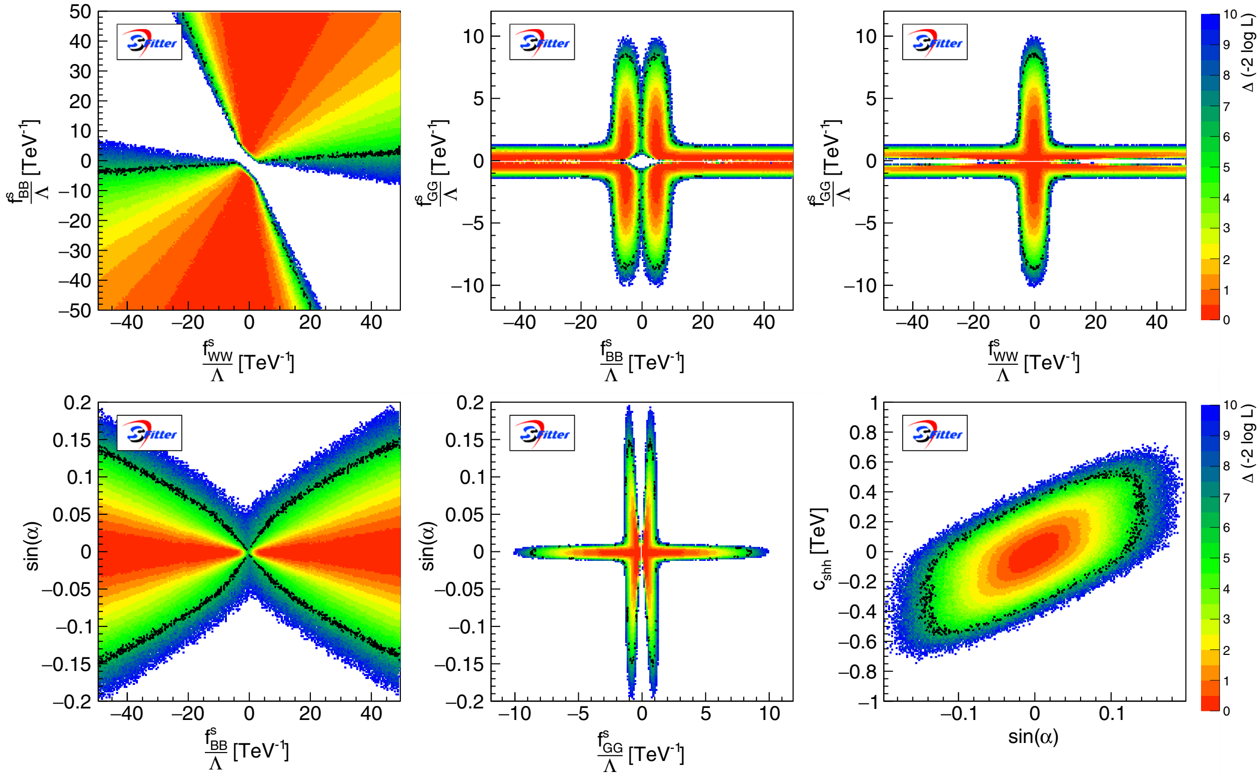

FIG. 1. Two-dimensional profile log-likelihoods for the analysis of the heavy scalar sector alone spanning f^S_{WW}, f^S_{BB}, f^S_{GG}, $\sin\alpha$, and c_{SHH}. The black points indicate $\Delta(-2\log L) = 5.99$.

$$\{f^S_{WW}, f^S_{BB}, f^S_{GG}, \sin\alpha, c_{SHH}\}. \tag{5}$$

In our parametrization c_{SHH} accounts for the independent contributions to the SHH vertex from the dimension-five Lagrangian beyond one of the terms partially responsible for generating the mixing, μ_S, as discussed in the Appendix.

The best fit point for this analysis has $-2\log L = 8.9$, while the SM point leads to $-2\log L = 28.2$, within a 3.1σ range for a 5-parameter study (in the Gaussian limit). In the upper left panel of Fig. 1 we can see that within the displayed range of parameters both f^S_{WW} and f^S_{BB} are strongly correlated, and they present a flat direction. The correlation reflects the fact that they are the only Wilson coefficients contributing to the diphoton decay of the new scalar at tree level. Because f^S_{WW} is constrained through the decay $S \to WW$, the diphoton excess cannot be accommodated through this coupling only. Due to that we find in the upper-center panel that $|f^S_{BB}/\Lambda| > 2\ \text{TeV}^{-1}$ at a C.L. higher than 99%. This is caused by the fact that f^S_{BB} does not contribute to the SWW vertex, and in addition its contribution to the SZZ vertex is suppressed by the weak mixing angle. This allows us to explain the observed excess without getting into conflict with the exclusion bounds, what makes $f^S_{WW} = 0$ compatible with the best fit point, as shown in the upper-right panel.

Looking at the results as a function of the mixing angle, and given the ranges spanned by f^S_{BB} and f^S_{WW} in the analysis, we find $\sin\alpha < 0.15$ at 95% C.L. as shown in the lower-left panel. This bound comes from the absence of a heavy scalar signal in WW and ZZ, but also in dijet, $t\bar{t}$, $\tau\bar{\tau}$, and hh decay channels. It is linked to maximum assumed values for f^S_{BB} and f^S_{WW}, because a larger mixing angle can be partially compensated by larger Wilson coefficients $f^S_{BB} + f^S_{WW}$. For large values of $f^S_{BB} + f^S_{WW}$ the diphoton branching ratio of the heavy scalar can exceed 50%, while the remaining decay channel modes are suppressed. In such cases the allowed values for the mixing angle $\sin\alpha$ can increase further without conflicting with data. If we allow for extreme values of $f^S_{BB}/\Lambda + f^S_{WW}/\Lambda \sim 250\ \text{TeV}^{-1}$, the upper bound on $\sin\alpha$ goes up to 0.3. However, such huge values would eventually conflict with the cutoff scale of the effective Lagrangian, as well as with the assumption of the new singlet being produced only through gluon fusion and not through photon fusion. For these reasons we decide to limit both f^S_{BB}/Λ and f^S_{WW}/Λ to values smaller than $50\ \text{TeV}^{-1}$ for all the results shown in the paper. In the lower-center panel we again observe two distinct regions in f^S_{GG}. The vertical region with $f^S_{GG}/\Lambda < 1.5\ \text{TeV}^{-1}$ is characterized by a large branching ratio for $S \to \gamma\gamma$, linked to large values of $f^S_{BB} + f^S_{WW}$. The horizontal region with $f^S_{GG}/\Lambda = 1.5\ldots10\ \text{TeV}^{-1}$ is characterized by a large production rate for the new scalar and a total decay width driven by f^S_{GG}. The upper limit on f^S_{GG} is set by dijet searches, and the mixing in this regime has to be small to respect the limits from other decay channels. Finally, in the lower-right panel we show the correlation between the mixing angle and c_{SHH} from the limit on the decay $S \to HH$. Fixing $c_{SHH} = 0$ and generating the SHH interaction through the mixing angle alone has no effect on any of the other correlations.

We proceed with an analysis allowing the new scalar to couple to the two fermions for which there are direct searches available. The analysis now includes

$$\{f^S_{WW}, f^S_{BB}, f^S_{GG}, \sin\alpha, c_{SHH}, f^S_t, f^S_\tau\}. \tag{6}$$

A selection of results is shown in Fig. 2. The fermionic Wilson coefficients f^S_t and f^S_τ are constrained by $t\bar{t}$ and $\tau^+\tau^-$ resonance searches, as well as from an upper limit $\Gamma_S < 25$ GeV which we assume throughout our analysis and which sets hard limits on f^S_t and f^S_τ. The upper limit on the total decay width is chosen to respect the narrow width hypothesis assumed on many of the experimental measurements included in the fit. The $t\bar{t}$ channel is the experimental mode with the most stringent experimental requirement on the narrow width assumption. The best fit point of this run is only mildly better than before, $-2\log L = 8.3$. The limits on these two fermion couplings are stronger for smaller f^S_{BB}, as illustrated for f^S_t in the upper-left panel, and f^S_τ in the upper-center one. The reason is that in those regions the partial decay width to photons becomes small, and the required diphoton branching ratio translates into small fermionic couplings. Conversely, larger fermionic Wilson coefficients now allow for best fit regions with large f^S_{GG} and f^S_{BB} at the same time, as shown in the upper-right panel of Fig. 2. This is the main difference with respect to the reduced analysis shown in Fig. 1. The rest of correlations remain qualitatively unchanged, as can be seen in the lower panels of Fig. 2. In particular the upper 95% C.L. limit on the mixing angle is still $\sin\alpha < 0.15$.

In passing we note that all the results shown so far have been derived assuming a CP-even new scalar. Nevertheless, for the analysis up to this point the results remain unchanged when instead we assume a heavy CP-odd scalar.

B. Combined Higgs portal fit

Next, we discuss the results for the general scenario, where we constrain the 17 parameters

$$\{f^S_{WW}, f^S_{BB}, f^S_{GG}, \sin\alpha, f^S_t, f^S_b, f^S_\tau, f_{WW}, f_{BB}, f_{GG}, f_W, f_B, f_{\phi,2}, f_{WWW}, f_t, f_b, f_\tau\} \tag{7}$$

from the combined measurements in the electroweak Higgs, and the heavy scalar sector. We have fixed $c_{SHH} = 0$ given its minor impact on the fit results.

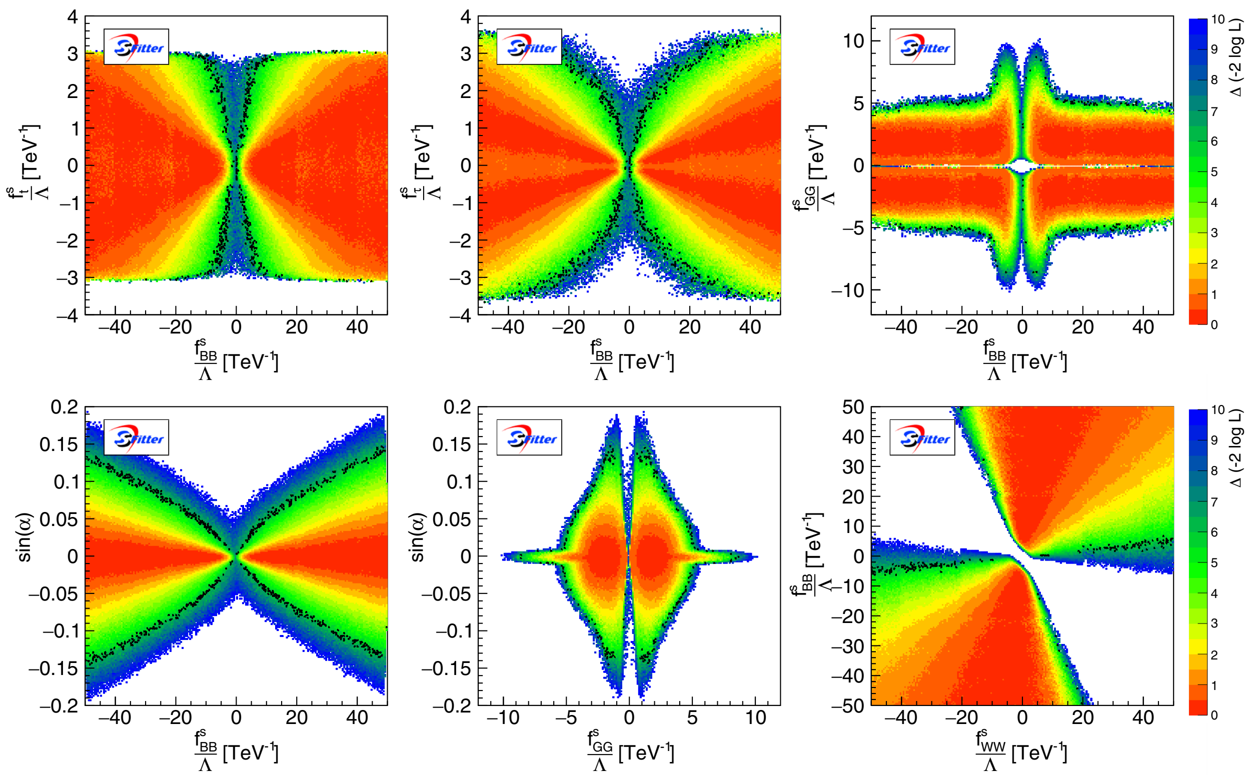

FIG. 2. Two-dimensional profile log-likelihoods for the analysis of the heavy scalar sector alone. In contrast to Fig. 1 we now include fermion couplings in our set of Wilson coefficients f^S_{WW}, f^S_{BB}, f^S_{GG}, $\sin\alpha$, c_{SHH}, f^S_t, and f^S_τ. The black points indicate $\Delta(-2\log L) = 5.99$.

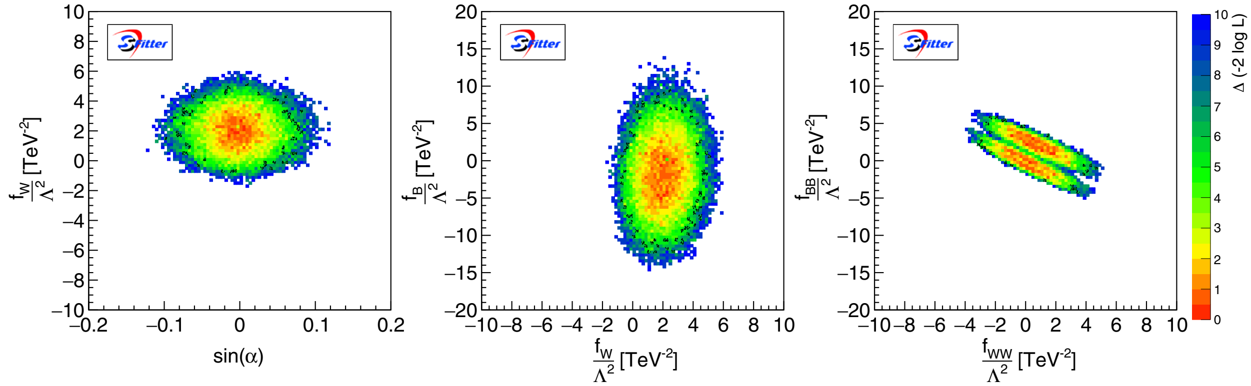

FIG. 3. Two-dimensional profile log-likelihoods for the combined Higgs, TGV, and heavy scalar sectors. The black points indicate $\Delta(-2\log L) = 5.99$.

In this case the best fit value has a likelihood of $-2\log L = 242.0$, for an analysis containing 252 measurements, while the Standard Model point leads to $-2\log L = 273.9$. In Fig. 3 we show a reduced selection of correlations between Wilson coefficients. When adding the heavy scalar to the combined Higgs and gauge boson analysis, the potentially largest change in the results appears for f_W and f_B. The twofold reason is illustrated in detail in the Appendix. First, focusing on the electroweak-Higgs phenomenology, while the contribution of f_W and f_B to the Higgs vertices is now weighted by the cosine of the mixing angle, their contribution to the triple gauge boson vertex is not. This generates a different pattern of Higgs-TGV correlations once we add the new scalar. Second, the mixing of the Higgs boson with the heavy scalar allows f_W and f_B to generate genuinely new Lorentz structure contributions to the SWW, SZZ and $SZ\gamma$ vertices, on top of the contributions from the rest of dimension-five and dimension-six operators.

The first effect turns out to be negligible, and given the small allowed size for the mixing angle, the electroweak-Higgs measurements are not precise enough to be sensitive to the scalar mixing contributions. Conversely, the second effect is more important. The mild preference for nonzero f_W values from the electroweak-Higgs measurements [5] causes the best fit regions to generate the new contribution to the decays $S \to WW$, ZZ, $Z\gamma$. These channels can be then better fit suppressing them further with a smaller mixing angle. The addition of the dimension-six operator causes then the upper bound on the scalar mixing to be mildly reduced with respect to the results in the previous section: now $\sin\alpha < 0.10$ at 95% C.L. This can be observed in the left panel of Fig. 3.

Apart from this effect, the small mixing angle causes a lack of sizable correlations between both the new scalar sector and the electroweak-Higgs sector. Consequently, the results and two-dimensional planes involving dimension-five operators are very similar to the ones shown in Fig. 2. The planes involving dimension-six operators remain unchanged with respect to the results shown in Ref. [5], something that we illustrate in the center and right panels of Fig. 3 for two of the dimension-six correlations.

C. A common origin of operators

When we split a common scalar potential for two mixing states into a set of dimension-five and dimension-six operators, the question becomes how different the higher-dimensional effects in the light and heavy scalar couplings can really be. In this section we assume that the set of heavy scalar couplings are directly tied to their Higgs-like counterparts,

$$\frac{f_{GG}}{\Lambda^2} = -2\frac{f^S_{GG}}{\Lambda}\left|\frac{f^S_{GG}}{\Lambda}\right| \qquad \frac{f_f}{\Lambda^2} = -\frac{v}{m_f}\frac{f^S_f}{\Lambda}\left|\frac{f^S_f}{\Lambda}\right|$$
$$\frac{f_{BB}}{\Lambda^2} = -\frac{1}{4\pi^2}\frac{f^S_{BB}}{\Lambda}\left|\frac{f^S_{BB}}{\Lambda}\right| \qquad \frac{f_{WW}}{\Lambda^2} = -\frac{1}{4\pi^2}\frac{f^S_{WW}}{\Lambda}\left|\frac{f^S_{WW}}{\Lambda}\right|, \tag{8}$$

for $f = b, t, \tau$. The relative signs and prefactors ensure that the underlying new physics scales are consistent, as defined in Eq. (3). For the fermion case, this is motivated by the need to have a minimal flavor violating structure in both dimension-five and dimension-six operators to avoid large flavor changing neutral currents [57]. For a given UV completion, the concrete relation between the operators will depend on the specific details of the model under consideration. In the following we impose the strict relations given in Eq. (8) as a way to illustrate the analysis features in an extreme scenario. The results can then be compared with the opposite extreme scenario, shown in the previous section, where no relations are present at all. We will comment on the effect of relaxing the relations in Eq. (8) at the end of the section, for cases where we are in an intermediate scenario. In a Bayesian language this approach would correspond to a Dirichlet prior, for example employed in the dark matter fit of Ref. [58], with an exponent parameter $\alpha \gg 1$.

After imposing the relations in Eq. (8), we proceed to perform the combined Higgs, triple gauge boson vertex and heavy scalar analysis spanning the 11 free parameters

$$\{f^S_{WW}, f^S_{BB}, f^S_{GG}, f^S_t, f^S_b, f^S_\tau, \sin\alpha, f_W, f_B, f_{\phi,2}, f_{WWW}\}. \tag{9}$$

We have again fixed $c_{SHH} = 0$, while f_{WW}, f_{BB}, f_{GG}, f_t, f_b and f_τ are set from Eq. (8). Interestingly, the best fit point is $-2\log L = 242.6$, i.e. within the analysis precision very close to the best fit point of the previous general scenario. This illustrates one of the most important conclusions: when dimension-five and dimension-six operators of a similar type are imposed to be related, there are still regions in the new physics parameter space which can accommodate the diphoton anomaly while respecting the constraints from the electroweak-Higgs measurements.

In Fig. 4 we again show a selection of two-dimensional correlations. In the upper-left panel we start with tight constraints on f^S_{BB} and also on f^S_{GG}. Now f^S_{BB}/Λ no longer presents an unconstrained direction, as the reduced allowed region for values around -10 TeV^{-1} is limited from the constraint that f_{BB} and hence f^S_{BB} is constrained by the Higgs measurements. Because of the minus signs in Eq. (8) the region of allowed values for both f^S_{BB} and f^S_{WW} corresponds to the solution that flips the sign of the $H\gamma\gamma$ vertex while respecting its measured size [5], as seen in the upper-center panel. In the case of f^S_{GG} and f_{GG} the several best fit regions are due to the measurement of a SM-like Higgs boson in gluon fusion production, the interference between f_{GG} and f_t [4], and the heavy scalar anomaly that excludes f_{GG} null values.

As seen in the upper-right panel, the stronger constraints on f^S_{BB} are directly translated into a stringent 95% C.L. bound on the mixing angle, $\sin\alpha < 0.02$. In the lower-left panel we show the impact of Eq. (8) on f^S_t. The fact that in this analysis f^S_{BB} is more constrained than in the general scenario implies that f^S_t is constrained to order-one values, as expected from the f^S_{BB} vs f^S_t correlation in Fig. 2. The solution for f_t that flips the sign of the Higgs-Yukawa present in Ref. [4] is excluded through f^S_t. This reduces the number of allowed regions for f_{GG}, as compared to the electroweak-Higgs fit [4]. In the case of f^S_τ and f^S_b, the allowed regions are limited by the $H\tau^+\tau^-$ and $Hb\bar{b}$ measurements. The v/m_f factors in Eq. (8) lead to reduced allowed ranges for f^S_τ in comparison to the previous general scenario.

We illustrate in the lower-center panel the allowed region for two of the dimension-six operators not involved in the simplifications of Eq. (8), f_W and f_B. They remain unaltered with respect to the general analysis or the electroweak-Higgs results [5]. Conversely, in the lower-right panel of Fig. 4 we illustrate the two parameter regions f_{BB} vs f_{WW}. There we see how the SM solution observed in the electroweak-Higgs analysis is now disfavored with respect to positive values for the Wilson coefficients.

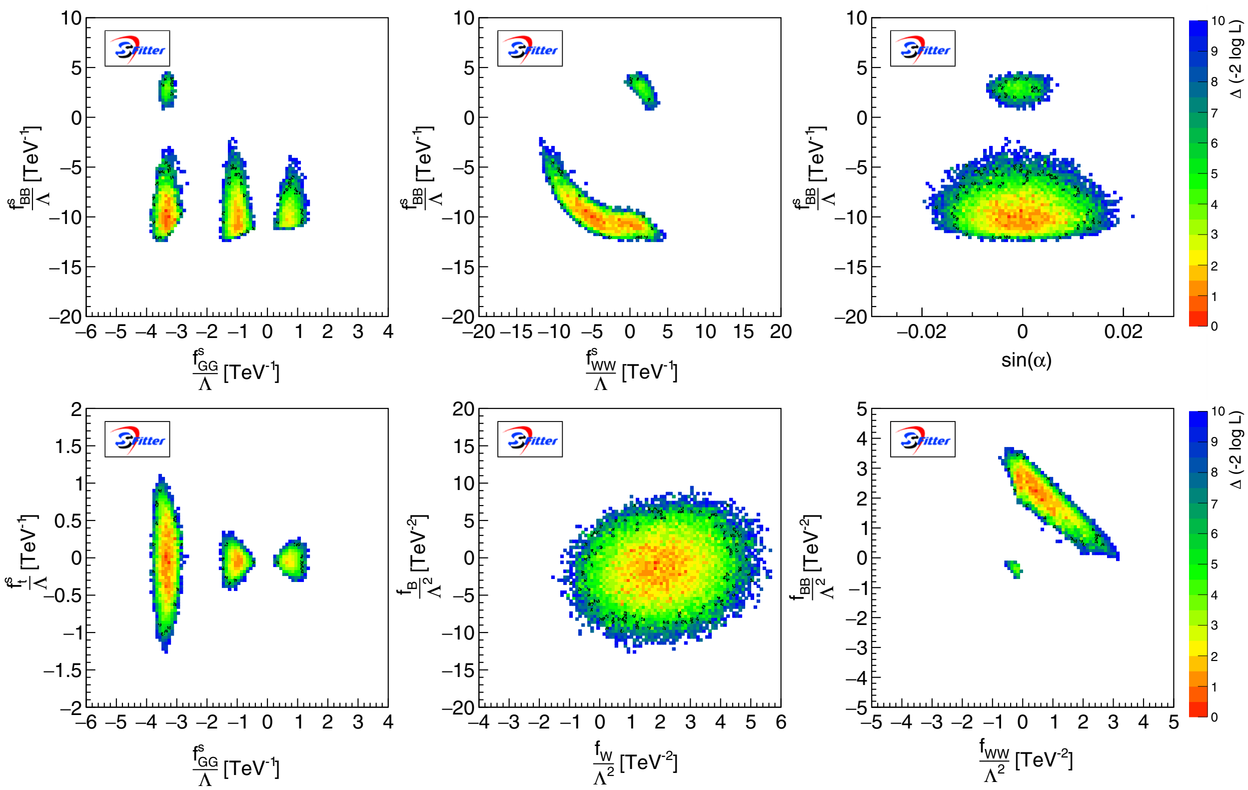

FIG. 4. Two-dimensional profile log-likelihoods for the combined Higgs, TGV, and heavy scalar fit, but assuming a common origin of operators as defined in Eq. (8). The black points indicate $\Delta(-2\log L) = 5.99$.

In this section we have illustrated the results of a constrained scenario imposing hard relations between the heavy scalar and Higgs operators in Eq. (8). Realistically, we would expect such relations to not be as strict. We therefore checked that relaxing Eq. (8) and allowing for order-one variations does not qualitatively change our conclusions. Numerically, the bound on the mixing angle $\sin\alpha$ becomes weaker once the relation $f_{BB} \propto f^S_{BB}|f^S_{BB}|$ is relaxed.

III. EPITAPH

We have developed the framework to perform a combined analysis of the electroweak-Higgs sector extended with a new scalar to test Higgs portal scenarios. The theoretical description we have studied is that of a linear effective Lagrangian extended with the addition of a singlet scalar.

The key question we face is the test of the portal structure hypothesis for an extended scalar sector. With that purpose we include a large set of Higgs event rates and kinematic distributions, combined with the recently implemented LHC triple gauge boson vertex distributions [5]. As a test of a Higgs portal scenario we study as illustration of the framework the possibility that a diphoton anomaly recently observed at the LHC [8–10] could be part of an extended Higgs sector. For that we include a selection of relevant experimental searches for heavy resonances as listed in Table I.

Analyzing first the new scalar sector only, we recover the result that a nonzero value for a reduced set of singlet scalar effective operators (f^S_{GG}, $f^S_{BB} + f^S_{WW}$) fits the observed anomaly in the diphoton channel, without conflicting with the lack of other positive observations, see Fig. 1. The mixing angle of the new singlet state with the Higgs boson can be sizable, the upper bound we find in the analysis is $\sin(\alpha) < 0.15$ at the 95% C.L. The addition of fermionic dimension-five operators increases the allowed parameter space regions for the bosonic operators. However it has no impact on the maximum allowed mixing angle value, see Fig. 2.

We then extend the analysis combining the new scalar sector with the electroweak-Higgs sector, using the Lagrangian description based on the dimension-six operators in Eq. (2). In this extended scenario the upper bound on the mixing angle is further reduced in order to suppress the new dimension-six contributions to the heavy scalar nonobserved decays. The upper bound is now $\sin(\alpha) < 0.1$ at 95% C.L., with a size still compatible with Higgs portal hypothesis. Beyond this change, the maximum allowed mixing angle reduces the correlations between the Higgs-electroweak phenomenology and the hypothetical heavy scalar interactions. This leads to results that in the most general scenario are very similar to the ones of the individual Higgs-electroweak [5], and heavy scalar analysis, respectively.

Motivated by a scalar portal scenario we define and test a hypothesis for a unique origin of the dimension-five and dimension-six operators studied in the analysis. Imposing Eq. (8) we find new physics regions of parameters that fit the diphoton anomaly while being consistent with the lack of deviations measured on the electroweak-Higgs measurements. The upper bound on the mixing angle is reduced in this case to $\sin(\alpha) < 0.02$, due to the strong constraints on the operators modifying $h \to \gamma\gamma$.

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Note added.—Recently, the partial analyses of Run II 2016 data by both ATLAS [59] and CMS [60] observed no significant excess over the background expectations, diluting the initial overexcitement the anomaly led to.

APPENDIX: HIGGS-SINGLET LAGRANGIAN

We describe here the main details of our effective Lagrangian analysis. We focus on the Higgs-scalar mixing and the combined phenomenology we derive. Following the Lagrangian in Eq. (3) of Sec. I A, both μ_S and f^S_1/Λ generate a mixing between the two interaction eigenstates H' and S'. In this appendix we denote interaction eigenstates as primed fields, while mass eigenstates after the rotation

$$\mathcal{L}_m = -\frac{1}{2}(H'S')\begin{pmatrix} M_H^2 & v\left(\mu_S + \frac{f^S_1 v^2}{\Lambda}\right)\left(1 - \frac{f_{\phi,2}v^2}{2\Lambda^2}\right) \\ v\left(\mu_S + \frac{f^S_1 v^2}{\Lambda}\right)\left(1 - \frac{f_{\phi,2}v^2}{2\Lambda^2}\right) & M_S^2 + \frac{\lambda_{SH} v}{2} \end{pmatrix}\begin{pmatrix} H' \\ S' \end{pmatrix}, \tag{A1}$$

are denoted by unprimed fields. The light mass term is $M_H^2 = 2\lambda_H v^2(1 - v^2 f_{\phi,2}/\Lambda^2)$, with the Higgs quartic coupling λ. The contribution proportional to $f_{\phi,2}/\Lambda^2$ originates from the Higgs kinetic term and the appropriate field redefinition [3]. The physical masses are

$$M_{1,2}^2 = \frac{M_S^2 + \frac{\lambda_{SH} v}{2} + M_H^2}{2} \mp \frac{1}{2}\sqrt{\left(M_S^2 + \frac{\lambda_{SH} v}{2} - M_H^2\right)^2 + 4v\left(\mu_S + \frac{f_1^S v^2}{\Lambda}\right)^2 \left(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2}\right)^2}, \tag{A2}$$

and the mixing angle as a function of the physical masses reads

$$\sin 2\alpha = \frac{2v(\mu_S + \frac{f_1^S v^2}{\Lambda})(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2})}{M_2^2 - M_1^2} \overset{f_1^S = 0}{\Rightarrow}$$
$$\mu_S = \sin 2\alpha \frac{M_2^2 - M_1^2}{2v}\left(1 + \frac{v^2}{2}\frac{f_{\phi,2}}{\Lambda^2}\right). \tag{A3}$$

The Higgs-scalar mixing affects many couplings of the mass eigenstates S and H. We first study the interactions of the light, Higgs-like, state. The admixture of the new scalar generates new interactions of the kind $s_\alpha f_j^S/\Lambda$, formally of dimension five, with an additional suppression by the mixing angle. Once we include the dimension-six operators of $\mathcal{L}_{\text{dim-6}}^H$, all mixing contributions can be absorbed in a redefinition of the effective Higgs Lagrangian, as long as we limit our analysis to trilinear interactions. For example, the physical Higgs-gluon coupling becomes

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\left(c_\alpha \frac{f_{GG} v}{\Lambda^2} + 2 s_\alpha \frac{f_{GG}^S}{\Lambda}\right) \equiv -\frac{\alpha_s}{8\pi}\frac{f'_{GG} v}{\Lambda^2}, \tag{A4}$$

where g_{Hgg} is defined through the term $g_{Hgg} H G_{\mu\nu}^a G^{a\mu\nu}$ in the Lagrangian [4]. Using this kind of redefinition the Higgs part of our analysis can be easily related to the results of Refs. [4,5].

As the Higgs-scalar mixing of Eq. (A1) is defined in the broken phase and does not affect the Goldstone modes, this kind of redefinition does not apply to the triple gauge vertices constrained by diboson production channels [4,5]. The contribution of f_W and f_B in the Higgs sector is weighted by c_α. For instance, the f_W contribution to the HWW interaction reads

$$\mathcal{L}^{HVV} \supset g_{HWW}^{(1)} (W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{H.c.}) \quad \text{with}$$
$$g_{HWW}^{(1)} = c_\alpha \frac{g^2 v}{2\Lambda^2}\frac{f_W}{2}. \tag{A5}$$

In contrast, the contributions of f_W and f_B to the triple gauge boson vertices are not modified by such a mixing angle and remain the same as in the Higgs-gauge analysis [5]. This way, a sizable mixing with the heavy scalar changes the pattern of Higgs-TGV correlations.

On the heavy scalar side, the interaction with the incoming gluons is

$$g_{Sgg} = -\frac{\alpha_s}{8\pi}\left(s_\alpha \frac{f_{GG} v}{\Lambda^2} - 2 c_\alpha \frac{f_{GG}^S}{\Lambda}\right) \equiv \frac{\alpha_s}{4\pi}\frac{f_{GG}^{s\prime}}{\Lambda}. \tag{A6}$$

While the contributions of $f_{WW} \leftrightarrow f_{WW}^S$, $f_{BB} \leftrightarrow f_{BB}^S$ and the fermionic interactions $f_f \leftrightarrow f_f^S$ follow this structure, the case of f_W and f_B is again special. Both Higgs-like operators generate new Lorentz structures in the heavy scalar sector. For example, the f_W contribution to the SWW vertex is

$$\mathcal{L}^{SVV} \supset g_{SWW}^{(1)} (W_{\mu\nu}^+ W^{-\mu} \partial^\nu S + \text{H.c.}) \quad \text{with}$$
$$g_{SWW}^{(1)} = s_\alpha \frac{g^2 v}{2\Lambda^2}\frac{f_W}{2}. \tag{A7}$$

Finally, the SHH interaction is generated through the terms

$$\mathcal{L} \supset \lambda^{SHH} SHH + \frac{f_{\phi,2}}{\Lambda^2} v s_\alpha c_\alpha^2 (S \partial^\mu H \partial_\mu H + 2H \partial^\mu S \partial_\mu H), \tag{A8}$$

where the momentum-independent coupling is composed of several terms in Eq. (2) and Eq. (3)

$$\begin{aligned}
\lambda^{SHH} &= -3 c_\alpha^2 s_\alpha v \lambda_H \left(1 - \frac{3 f_{\phi,2} v^2}{2\Lambda^2}\right) + \frac{1}{2}(2 c_\alpha s_\alpha^2 - c_\alpha^3)\mu_S \left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2}\right) + \frac{1}{2}(2 c_\alpha^2 s_\alpha - s_\alpha^3) v \lambda_{SH}\left(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2}\right) \\
&\quad - 3 c_\alpha s_\alpha^2 a_3 - \frac{3}{2} c_\alpha s_\alpha^2 v^2 \frac{f_3^S}{\Lambda} + \frac{3}{4}(c_\alpha s_\alpha^2 - c_\alpha^3)\frac{f_1^S v^2}{\Lambda}\left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2}\right) \\
&\equiv -3 c_\alpha^2 s_\alpha v \lambda_H \left(1 - \frac{3 f_{\phi,2} v^2}{2\Lambda^2}\right) + \frac{1}{2}(2 c_\alpha s_\alpha^2 - c_\alpha^3) s_{2\alpha} \frac{M_2^2 - M_1^2}{2v}\left(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2}\right) + c_{SHH}.
\end{aligned} \tag{A9}$$

There the Higgs self coupling λ_H can be expressed as

$$\lambda_H = \frac{s_\alpha^2 M_2^2 + c_\alpha^2 M_1^2}{2v^2}\left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2}\right), \tag{A10}$$

while the term c_{SHH} accounts for the contributions from λ_{SH}, a_3, and f_3^S, and the nonmixing induced f_1^S contributions to SHH. The dimension-6 operator $(\phi^\dagger\phi)^3$ would also contribute with an extra free parameter to c_{SHH}. In a simplified ansatz, we set $c_{SHH} = 0$, which corresponds to considering only the contributions of μ_S and $f_{\phi,2}$ to the SHH vertex. As commented in the text, besides the contribution to the S kinetic term, that will induce a contribution to all S couplings after the redefinition of the kinetic term to its canonical form, f_ϕ^{SS} will also contribute to the SHH vertex. It will contribute to the three kinematic structures in Eq. (A8) after taking into account the mixing between the two states.

[1] P. W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. **12**, 132 (1964); Broken Symmetries and the Masses of Gauge Bosons, Phys. Rev. Lett. **13**, 508 (1964); F. Englert and R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons, Phys. Rev. Lett. **13**, 321 (1964).

[2] G. Aad *et al.* (ATLAS Collaboration), 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**, 1 (2012); S. Chatrchyan *et al.* (CMS Collaboration), Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B **716**, 30 (2012).

[3] T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile, and M. C. Gonzalez-Garcia, Constraining anomalous Higgs interactions, Phys. Rev. D **86**, 075013 (2012); Robust determination of the Higgs couplings: Power to the data, Phys. Rev. D **87**, 015022 (2013); Determining Triple Gauge Boson Couplings from Higgs Data, Phys. Rev. Lett. **111**, 011801 (2013).

[4] T. Corbett, O. J. P. Eboli, D. Goncalves, J. Gonzalez-Fraile, T. Plehn, and M. Rauch, The Higgs legacy of the LHC Run I, arXiv:1505.05516; The nonlinear Higgs legacy of the LHC Run I, arXiv:1511.08188.

[5] A. Butter, O. J. P. boli, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, T. Plehn, and M. Rauch, The gauge-Higgs legacy of the LHC Run I, J. High Energy Phys. 07 (2016) 152.

[6] E. Massó and V. Sanz, Limits on anomalous couplings of the Higgs boson to electroweak gauge bosons from LEP and the LHC, Phys. Rev. D **87**, 033001 (2013); I. Brivio, T. Corbett, O. J. P. Eboli, M. B. Gavela, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, L. Merlo, and S. Rigolin, Disentangling a dynamical Higgs, J. High Energy Phys. 03 (2014) 024; G. Brooijmans *et al.*, Les Houches 2013: Physics at TeV colliders: New Physics Working Group report, arXiv:1405.1617; A. Falkowski and F. Riva, Model-independent precision constraints on dimension-6 operators, J. High Energy Phys. 02 (2015) 039; A. Falkowski, M. Gonzalez-Alonso, A. Greljo, and D. Marzocca, Global Constraints on Anomalous Triple Gauge Couplings in Effective Field Theory Approach, Phys. Rev. Lett. **116**, 011801 (2016); I. Brivio, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, and L. Merlo, The complete HEFT Lagrangian after the LHC Run I, Eur. Phys. J. C **76**, 416 (2016).

[7] See e.g. B. Patt and F. Wilczek, Higgs-field portal into hidden sectors, arXiv:hep-ph/0605188; R. Schabinger and J. D. Wells, Minimal spontaneously broken hidden sector and its impact on Higgs boson physics at the CERN Large Hadron Collider, Phys. Rev. D **72**, 093007 (2005); S. Bock, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, and P. M. Zerwas, Measuring hidden Higgs and strongly-interacting Higgs scenarios, Phys. Lett. B **694**, 44 (2010); C. Englert, T. Plehn, D. Zerwas, and P. M. Zerwas, Exploring the Higgs portal, Phys. Lett. B **703**, 298 (2011); C. Englert, T. Plehn, M. Rauch, D. Zerwas, and P. M. Zerwas, LHC: Standard Higgs and hidden Higgs, Phys. Lett. B **707**, 512 (2012); A. Djouadi, O. Lebedev, Y. Mambrini, and J. Quevillon, Implications of LHC searches for Higgs-portal dark matter, Phys. Lett. B **709**, 65 (2012); O. Lebedev, On stability of the electroweak vacuum and the Higgs portal, Eur. Phys. J. C **72**, 2058 (2012).

[8] G. Aad *et al.* (ATLAS Collaboration), Report No. ATLAS-CONF-2015-081; V. Khachatryan *et al.* (CMS Collaboration), Report No. CMS-PAS-EXO-15-004; A. Hoecker, Moriond Electroweak and Unified Theories 2016 - Experimental Summary, arXiv:1605.06042.

[9] M. Aaboud *et al.* (ATLAS Collaboration), Search for resonances in diphoton events at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 09 (2016) 001.

[10] V. Khachatryan *et al.* (CMS Collaboration), Search for Resonant Production of High-Mass Photon Pairs in Proton-Proton Collisions at $\sqrt{s} = 8$ and 13 TeV, Phys. Rev. Lett. **117**, 051802 (2016); Search for new physics in high mass diphoton events in 3.3 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV and combined interpretation of searches at 8 TeV and 13 TeV (unpublished).

[11] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, and R. Torre, What is the $\gamma\gamma$ resonance at 750 GeV?, J. High Energy Phys. 03 (2016) 144; J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz, and T. You, On the interpretation of a possible ∼750 GeV particle decaying into $\gamma\gamma$, J. High Energy Phys. 03 (2016) 176; D. Buttazzo, A. Greljo, and D. Marzocca, Knocking on new physics' door with a scalar resonance, Eur. Phys. J. C **76**, 116 (2016); S. Knapen, T. Melia, M. Papucci, and K. Zurek, Rays of light from the LHC, Phys. Rev. D **93**, 075020 (2016); S. D. McDermott, P. Meade, and H. Ramani, Singlet scalar resonances and the diphoton excess, Phys. Lett. B **755**, 353 (2016); M. Low, A. Tesi, and L. T. Wang, A pseudoscalar decaying to photon pairs in the early LHC Run 2 data, J. High Energy Phys. 03 (2016) 108; Q. H. Cao, Y. Liu, K. P. Xie, B. Yan, and D. M. Zhang, A boost test of anomalous diphoton resonance at the LHC, arXiv:1512.05542; R. Martinez, F. Ochoa, and C. F. Sierra,

Diphoton decay for a 750 GeV scalar boson in an $U(1)'$ model, Nucl. Phys. **B913**, 64 (2016); L. Bian, N. Chen, D. Liu, and J. Shu, Hidden confining world on the 750 GeV diphoton excess, Phys. Rev. D **93**, 095011 (2016); P. Agrawal, J. Fan, B. Heidenreich, M. Reece, and M. Strassler, Experimental considerations motivated by the diphoton excess at the LHC, J. High Energy Phys. 06 (2016) 082; A. Falkowski, O. Slone, and T. Volansky, Phenomenology of a 750 GeV singlet, J. High Energy Phys. 02 (2016) 152; E. Gabrielli, K. Kannike, B. Mele, M. Raidal, C. Spethmann, and H. Veermäe, A SUSY inspired simplified model for the 750 GeV diphoton excess, Phys. Lett. B **756**, 36 (2016); A. Alves, A. G. Dias, and K. Sinha, The 750 GeV *S*-cion: Where else should we look for it?, Phys. Lett. B **757**, 39 (2016); W. Chao, Symmetries behind the 750 GeV diphoton excess, Phys. Rev. D **93**, 115013 (2016); I. Chakraborty and A. Kundu, Diphoton excess at 750 GeV: Singlet scalars confront triviality, Phys. Rev. D **93**, 055003 (2016); H. Han, S. Wang, and S. Zheng, Scalar explanation of diphoton excess at LHC, Nucl. Phys. **B907**, 180 (2016); M. x. Luo, K. Wang, T. Xu, L. Zhang, and G. Zhu, Squarkonium, diquarkonium, and octetonium at the LHC and their diphoton decays, Phys. Rev. D **93**, 055042 (2016); M. Dhuria and G. Goswami, Perturbativity, vacuum stability and inflation in the light of 750 GeV diphoton excess, Phys. Rev. D **94**, 055009 (2016); J. S. Kim, K. Rolbiecki, and R. R. de Austri, Model-independent combination of diphoton constraints at 750 GeV, Eur. Phys. J. C **76**, 251 (2016); L. Berthier, J. M. Cline, W. Shepherd, and M. Trott, Effective interpretations of a diphoton excess, J. High Energy Phys. 04 (2016) 084; S. M. Boucenna, S. Morisi, and A. Vicente, LHC diphoton resonance from gauge symmetry, Phys. Rev. D **93**, 115008 (2016); C. W. Murphy, Vector leptoquarks and the 750 GeV diphoton resonance at the LHC, Phys. Lett. B **757**, 192 (2016); J. Gu and Z. Liu, Physics implications of the diphoton excess from the perspective of renormalization group flow, Phys. Rev. D **93**, 075006 (2016); K. Das and S. K. Rai, 750 GeV diphoton excess in a U(1) hidden symmetry model, Phys. Rev. D **93**, 095007 (2016); J. Zhang and S. Zhou, Electroweak vacuum stability and diphoton excess at 750 GeV, Chin. Phys. C **40**, 081001 (2016); D. Chway, R. Dermisek, T. H. Jung, and H. D. Kim, Glue to Light Signal of a New Particle, Phys. Rev. Lett. **117**, 061801 (2016); G. Li, Y. n. Mao, Y. L. Tang, C. Zhang, Y. Zhou, and S. h. Zhu, Pseudoscalar Decaying Only via Loops as an Explanation for the 750 GeV Diphoton Excess, Phys. Rev. Lett. **116**, 151803 (2016); Q. H. Cao, Y. Liu, K. P. Xie, B. Yan, and D. M. Zhang, Diphoton excess, low energy theorem, and the 331 model, Phys. Rev. D **93**, 075030 (2016); J. Cao, L. Shang, W. Su, F. Wang, and Y. Zhang, Interpreting the 750 GeV diphoton excess within topflavor seesaw model, Nucl. Phys. **B911**, 447 (2016); J. Gao, H. Zhang, and H. X. Zhu, Diphoton excess at 750 GeV: Gluon-gluon fusion or quark-antiquark annihilation?, Eur. Phys. J. C **76**, 348 (2016); C. W. Chiang, M. Ibe, and T. T. Yanagida, Revisiting scalar quark hidden sector in light of 750-GeV diphoton resonance, J. High Energy Phys. 05 (2016) 084; S. Kanemura, N. Machida, S. Odori, and T. Shindou, Diphoton excess at 750 GeV in an extended scalar sector, arXiv:1512.09053; I. Low and J. Lykken, Implications of gauge invariance on a heavy diphoton resonance, arXiv:1512.09089; K. Kaneta, S. Kang, and H. S. Lee, Diphoton excess at the LHC Run 2 and its implications for a new heavy gauge boson, Int. J. Mod. Phys. A **31**, 1650159 (2016); A. Dasgupta, M. Mitra, and D. Borah, Minimal left-right symmetry confronted with the 750 GeV di-photon excess at LHC, arXiv:1512.09202.

[12] A. E. C. Hernandez and I. Nisandzic, LHC diphoton 750 GeV resonance as an indication of $SU(3)_c \times SU(3)_L \times U(1)_X$ gauge symmetry, Eur. Phys. J. C **76**, 380 (2016); K. M. Patel and P. Sharma, Interpreting 750 GeV diphoton excess in SU(5) grand unified theory, Phys. Lett. B **757**, 282 (2016); J. de Blas, J. Santiago, and R. Vega-Morales, New vector bosons and the diphoton excess, Phys. Lett. B **759**, 247 (2016); S. Chang, Simple $U(1)$ gauge theory explanation of the diphoton excess, Phys. Rev. D **93**, 055016 (2016); J. Chakrabortty, A. Choudhury, P. Ghosh, S. Mondal, and T. Srivastava, Di-photon resonance around 750 GeV: shedding light on the theory underneath, arXiv:1512.05767; D. Curtin and C. B. Verhaaren, Quirky explanations for the diphoton excess, Phys. Rev. D **93**, 055011 (2016); A. Pilaftsis, Diphoton signatures from heavy axion decays at the CERN Large Hadron Collider, Phys. Rev. D **93**, 015017 (2016); S. Di Chiara, L. Marzola, and M. Raidal, First interpretation of the 750 GeV diphoton resonance at the LHC, Phys. Rev. D **93**, 095018 (2016); R. S. Gupta, S. Jager, Y. Kats, G. Perez, and E. Stamou, Interpreting a 750 GeV diphoton resonance, J. High Energy Phys. 07 (2016) 145; A. Kobakhidze, F. Wang, L. Wu, J. M. Yang, and M. Zhang, 750 GeV diphoton resonance in a top and bottom seesaw model, Phys. Lett. B **757**, 92 (2016); Y. Bai, J. Berger, and R. Lu, 750 GeV dark pion: Cousin of a dark G-parity odd WIMP, Phys. Rev. D **93**, 076009 (2016); J. Chang, K. Cheung, and C. T. Lu, Interpreting the 750 GeV diphoton resonance using photon jets in hidden-valley-like models, Phys. Rev. D **93**, 075013 (2016); O. Antipin, M. Mojaza, and F. Sannino, Minimal Coleman-Weinberg theory explains the diphoton excess, Phys. Rev. D **93**, 115007 (2016); J. Cao, C. Han, L. Shang, W. Su, J. M. Yang, and Y. Zhang, Interpreting the 750 GeV diphoton excess by the singlet extension of the Manohar-Wise model, Phys. Lett. B **755**, 456 (2016); U. K. Dey, S. Mohanty, and G. Tomar, 750 GeV resonance in the dark left-right model, Phys. Lett. B **756**, 384 (2016); G. M. Pelaggi, A. Strumia, and E. Vigiani, Trinification can explain the di-photon and di-boson LHC anomalies, J. High Energy Phys. 03 (2016) 025; W. Altmannshofer, J. Galloway, S. Gori, A. L. Kagan, A. Martin, and J. Zupan, 750 GeV diphoton excess, Phys. Rev. D **93**, 095015 (2016); H. Davoudiasl and C. Zhang, 750 GeV messenger of dark conformal symmetry breaking, Phys. Rev. D **93**, 055006 (2016); N. Craig, P. Draper, C. Kilic, and S. Thomas, Shedding light on diphoton resonances, Phys. Rev. D **93**, 115023 (2016); J. E. Kim, Is an axizilla possible for di-photon resonance?, Phys. Lett. B **755**, 190 (2016); W. Chao, Neutrino catalyzed diphoton excess, Nucl. Phys. **B911**, 231 (2016); X. J. Bi, R. Ding, Y. Fan, L. Huang, C. Li, T. Li, S. Raza, X.-C. Wang, and B. Zhu, Promising interpretation of diphoton resonance at 750 GeV, Phys. Rev. D **94**, 015012 (2016); P. S. B. Dev,

R. N. Mohapatra, and Y. Zhang, Quark Seesaw, Vectorlike fermions and diphoton excess, J. High Energy Phys. 02 (2016) 186; S. Kanemura, K. Nishiwaki, H. Okada, Y. Orikasa, S. C. Park, and R. Watanabe, LHC 750 GeV diphoton excess in a radiative seesaw model, Prog. Theor. Exp. Phys. (**2016**) 123B04; A. E. C. Hernandez, A novel and economical explanation for SM fermion masses and mixings and its connection with the 750 GeV diphoton excess, Eur. Phys. J. C **76**, 503 (2016); L. Marzola, A. Racioppi, M. Raidal, F. R. Urban, and H. Veermäe, Non-minimal CW inflation, electroweak symmetry breaking and the 750 GeV anomaly, J. High Energy Phys. 03 (2016) 190.

[13] W. Chao, R. Huo, and J. H. Yu, The minimal scalar-stealth top interpretation of the diphoton excess, arXiv:1512.05738; S. Chakraborty, A. Chakraborty, and S. Raychaudhuri, Diphoton resonance at 750 GeV in the broken MRSSM, Phys. Rev. D **94**, 035014 (2016); Y. L. Tang and S. h. Zhu, NMSSM extended with vectorlike particles and the diphoton excess on the LHC, Phys. Rev. D **94**, 035010 (2016); B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze, T. Li, Q. Shafi, and J. W. Walker, Diphoton excess in consistent supersymmetric SU(5) models with vectorlike particles, arXiv:1601.00866; L. M. Carpenter, R. Colburn, and J. Goodman, Supersoft SUSY models and the 750 GeV diphoton excess, beyond effective operators, Phys. Rev. D **94**, 015016 (2016); H. P. Nilles and M. W. Winkler, 750 GeV diphotons and supersymmetric grand unification, J. High Energy Phys. 05 (2016) 182; M. Badziak, M. Olechowski, S. Pokorski, and K. Sakurai, Interpreting 750 GeV diphoton excess in plain NMSSM, Phys. Lett. B **760**, 228 (2016); G. Lazarides and Q. Shafi, Diphoton resonances in $U(1)_{B-L}$ extension of MSSM, Phys. Rev. D **93**, 111702 (2016); C. Han, T. T. Yanagida, and N. Yokozaki, Implications of the 750 GeV diphoton excess in gaugino mediation, Phys. Rev. D **93**, 055025 (2016); S. F. King and R. Nevzorov, 750 GeV Diphoton resonance from singlets in an exceptional supersymmetric standard model, J. High Energy Phys. 03 (2016) 139; W. Chao, The diphoton excess from an exceptional supersymmetric standard model, arXiv:1601.00633; L. J. Hall, K. Harigaya, and Y. Nomura, 750 GeV diphotons: Implications for supersymmetric unification, J. High Energy Phys. 03 (2016) 017; B. C. Allanach, P. S. B. Dev, S. A. Renner, and K. Sakurai, Diphoton excess explained by a resonant sneutrino in R-parity violating supersymmetry, Phys. Rev. D **93**, 115022 (2016); R. Ding, L. Huang, T. Li, and B. Zhu, Interpreting 750 GeV diphoton excess with R-parity violating supersymmetry, arXiv:1512.06560; T. F. Feng, X. Q. Li, H. B. Zhang, and S. M. Zhao, The LHC 750 GeV diphoton excess in supersymmetry with gauged baryon and lepton numbers, arXiv:1512.06696; U. Ellwanger and C. Hugonie, A 750 GeV diphoton signal from a very light pseudoscalar in the NMSSM, J. High Energy Phys. 05 (2016) 114; T. Cohen, G. D. Kribs, A. E. Nelson, and B. Ostdiek, 750 GeV diphotons from supersymmetry with Dirac gauginos, Phys. Rev. D **94**, 015031 (2016); D. M. Ghilencea and H. M. Lee, Diphoton resonance at 750 GeV in supersymmetry, arXiv:1606.04131; H. K. Dreiner, M. E. Krauss, B. O'Leary, T. Opferkuch, and F. Staub, On the validity of the CMSSM interpretation of the diphoton excess, arXiv:1606.08811.

[14] C. Petersson and R. Torre, 750 GeV Diphoton Excess from the Goldstino Superpartner, Phys. Rev. Lett. **116**, 151804 (2016); S. V. Demidov and D. S. Gorbunov, On the sgoldstino interpretation of the diphoton excess, JETP Lett. **103**, 219 (2016); J. A. Casas, J. R. Espinosa, and J. M. Moreno, The 750 GeV Diphoton Excess as a First Light on Supersymmetry Breaking, Phys. Lett. B **759**, 159 (2016); P. Baratella, J. Elias-Miro, J. Penedo, and A. Romanino, A closer look to the sgoldstino interpretation of the diphoton excess, J. High Energy Phys. 06 (2016) 086; R. Ding, Y. Fan, L. Huang, C. Li, T. Li, S. Raza, and B. Zhu, Systematic study of diphoton resonance at 750 GeV from sgoldstino, Int. J. Mod. Phys. A **31**, 1650151 (2016).

[15] J. Cao, L. Shang, W. Su, Y. Zhang, and J. Zhu, Interpreting the 750 GeV diphoton excess in the minimal dilaton model, Eur. Phys. J. C **76**, 239 (2016); E. Megias, O. Pujolas, and M. Quiros, On dilatons and the LHC diphoton excess, J. High Energy Phys. 05 (2016) 137; B. Agarwal, J. Isaacson, and K. A. Mohan, Minimal dilaton model and the diphoton excess, Phys. Rev. D **94**, 035027 (2016); D. K. Hong and D. H. Kim, Composite (pseudo) scalar contributions to muon $g-2$, Phys. Lett. B **758**, 370 (2016).

[16] P. Cox, A. D. Medina, T. S. Ray, and A. Spray, Diphoton excess at 750 GeV from a radion in the bulk-Higgs scenario, arXiv:1512.05618; A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion, and Y. Jiang, Higgs-radion interpretation of 750 GeV di-photon excess at the LHC, arXiv:1512.05771; E. E. Boos, V. E. Bunichev, and I. P. Volobuev, Can the 750 GeV diphoton LHC excess be due to a radion-dominated state?, arXiv:1603.04495; D. Bardhan, D. Bhatia, A. Chakraborty, U. Maitra, S. Raychaudhuri, and T. Samui, Radion Candidate for the LHC diphoton resonance, arXiv:1512.06674; M. Frank, K. Huitu, U. Maitra, and M. Patra, Probing Higgs-radion mixing in warped models through complementary searches at the LHC and the ILC, Phys. Rev. D **94**, 055016 (2016); F. Abu-Ajamieh, R. Houtz, and R. Zheng, Interpretation of 750 GeV diphoton resonance within the RS model and the associated radion phenomenology, arXiv:1607.01464.

[17] C. Cai, Z. H. Yu, and H. H. Zhang, 750 GeV diphoton resonance as a singlet scalar in an extra dimensional model, Phys. Rev. D **93**, 075033 (2016); S. Abel and V. V. Khoze, Photo-production of a 750 GeV di-photon resonance mediated by Kaluza-Klein leptons in the loop, J. High Energy Phys. 05 (2016) 063.

[18] M. Bauer, C. Hoerner, and M. Neubert, Diphoton resonance from a warped extra dimension, J. High Energy Phys. 07 (2016) 094; C. Csaki and L. Randall, A Diphoton Resonance from Bulk RS, J. High Energy Phys. 07 (2016) 061.

[19] K. Harigaya and Y. Nomura, A composite model for the 750 GeV diphoton excess, J. High Energy Phys. 03 (2016) 091; D. B. Franzosi and M. T. Frandsen, Symmetries and composite dynamics for the 750 GeV diphoton excess, arXiv:1601.05357; M. Son and A. Urbano, A new scalar resonance at 750 GeV: Towards a proof of concept in favor of strongly interacting theories, J. High Energy Phys. 05 (2016) 181; A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini, and H. Seradio, Singlets in composite Higgs models in light of the LHC diphoton searches, Phys. Rev. D **94**, 015004 (2016); Y. Nakai, R. Sato, and K. Tobioka,

Footprints of New Strong Dynamics via Anomaly and the 750 GeV Diphoton, Phys. Rev. Lett. **116**, 151802 (2016); J. M. No, V. Sanz, and J. Setford, See-saw composite Higgs model at the LHC: Linking naturalness to the 750 GeV diphoton resonance, Phys. Rev. D **93**, 095010 (2016); E. Molinaro, F. Sannino, and N. Vignaroli, Minimal Composite dynamics versus axion origin of the diphoton excess, Mod. Phys. Lett. A **31**, 1650155 (2016); N. D. Barrie, A. Kobakhidze, M. Talia, and L. Wu, 750 GeV composite axion as the LHC diphoton resonance, Phys. Lett. B **755**, 343 (2016); E. Molinaro, F. Sannino, and N. Vignaroli, Collider tests of (composite) diphoton resonances, Nucl. Phys. **B911**, 106 (2016); M. Redi, A. Strumia, A. Tesi, and E. Vigiani, Diphoton resonance and Dark Matter as heavy pions, J. High Energy Phys. 05 (2016) 078; K. Harigaya and Y. Nomura, Hidden pion varieties in composite models for diphoton resonances, Phys. Rev. D **94**, 075004 (2016); P. Ko, C. Yu, and T. C. Yuan, 750 GeV Diphoton excess as a composite (pseudo)scalar boson from new strong interaction, arXiv:1603.08802; B. Bellazzini, R. Franceschini, F. Sala, and J. Serra, Goldstones in Diphotons, J. High Energy Phys. 04 (2016) 072; P. Lebiedowicz, M. Luszczak, R. Pasechnik, and A. Szczurek, Can the diphoton enhancement at 750 GeV be due to a neutral technipion?, Phys. Rev. D **94**, 015023 (2016); W. Liao and H. q. Zheng, Scalar resonance at 750 GeV as composite of heavy vector-like fermions, Commun. Theor. Phys. **66**, 219 (2016); J. M. Cline and Z. Liu, LHC diphotons from electroweakly pair-produced composite pseudoscalars, arXiv:1512.06827; C. Han, K. Ichikawa, S. Matsumoto, M. M. Nojiri, and M. Takeuchi, Heavy fermion bound states for diphoton excess at 750 GeV–collider and cosmological constraints, J. High Energy Phys. 04 (2016) 159.

[20] M. T. Arun and P. Saha, Gravitons in multiply warped scenarios—at 750 GeV and beyond, arXiv:1512.06335; C. Han, H. M. Lee, M. Park, and V. Sanz, The diphoton resonance as a gravity mediator of dark matter, Phys. Lett. B **755**, 371 (2016); U. Danielsson, R. Enberg, G. Ingelman, and T. Mandal, The force awakens: The 750 GeV diphoton excess at the LHC from a varying electromagnetic coupling, arXiv:1601.00624; C. Q. Geng and D. Huang, Note on spin-2 particle interpretation of the 750 GeV diphoton excess, Phys. Rev. D **93**, 115032 (2016); S. B. Giddings and H. Zhang, Kaluza-Klein graviton phenomenology for warped compactifications, and the 750 GeV diphoton excess, Phys. Rev. D **93**, 115002 (2016); A. Falkowski and J. F. Kamenik, Diphoton portal to warped gravity, Phys. Rev. D **94**, 015008 (2016); A. Carmona, A 750 GeV graviton from holographic composite dark sectors, Phys. Lett. B **760**, 502 (2016); B. M. Dillon and V. Sanz, A little KK graviton at 750 GeV, arXiv:1603.09550; J. L. Hewett and T. G. Rizzo, 750 GeV diphoton resonance in warped geometries, arXiv:1603.08250; E. Alvarez, L. D. Rold, J. Mazzitelli, and A. Szynkman, A 750 GeV graviton and the Higgs as a pNGB, arXiv:1606.05326; A. Kobakhidze, K. McDonald, L. Wu, and J. Yue, Warped graviton couplings to bulk vectors with brane kinetic terms, arXiv:1606.08565.

[21] J. H. Davis, M. Fairbairn, J. Heal, and P. Tunney, The significance of the 750 GeV gluctuation in the ATLAS run 2 diphoton data, arXiv:1601.03153; B. J. Kavanagh, Reexamining the significance of the 750 GeV diphoton excess at ATLAS, arXiv:1601.07330.

[22] H. An, C. Cheung, and Y. Zhang, Broad diphotons from narrow states, arXiv:1512.08378; M. R. Buckley, Wide or narrow? The phenomenology of 750 GeV diphotons, Eur. Phys. J. C **76**, 345 (2016); D. Aloni, K. Blum, A. Dery, A. Efrati, and Y. Nir, On a possible large width 750 GeV diphoton resonance at ATLAS and CMS, J. High Energy Phys. 08 (2016) 017; A. Salvio, F. Staub, A. Strumia, and A. Urbano, On the maximal diphoton width, J. High Energy Phys. 03 (2016) 214.

[23] S. Jung, J. Song, and Y. W. Yoon, How resonance-continuum interference changes 750 GeV diphoton excess: Signal enhancement and peak shift, J. High Energy Phys. 05 (2016) 009; A. Djouadi, J. Ellis, and J. Quevillon, Interference effects in the decays of 750 GeV states into $\gamma\gamma$ and $t\bar{t}$, J. High Energy Phys. 07 (2016) 105; S. P. Martin, Signal-background interference for a singlet spin-0 digluon resonance at the LHC, Phys. Rev. D **94**, 035003 (2016); B. Hespel, F. Maltoni, and E. Vryonidou, Signal background interference effects in heavy scalar production and decay to a top-anti-top pair, J. High Energy Phys. 10 (2016) 016.

[24] M. Backovic, A. Mariotti, and D. Redigolo, Di-photon excess illuminates dark matter, J. High Energy Phys. 03 (2016) 157; F. D'Eramo, J. de Vries, and P. Panci, A 750 GeV portal: LHC phenomenology and dark matter candidates, J. High Energy Phys. 05 (2016) 089; M. T. Frandsen and I. M. Shoemaker, Asymmetric dark matter models and the LHC diphoton excess, J. Cosmol. Astropart. Phys. 05 (2016) 064; G. Arcadi, P. Ghosh, Y. Mambrini, and M. Pierre, Reopening dark matter windows compatible with a diphoton excess, J. Cosmol. Astropart. Phys. 07 (2016) 005; E. Morgante, D. Racco, M. Rameez, and A. Riotto, The 750 GeV diphoton excess, dark matter and constraints from the IceCube experiment, J. High Energy Phys. 07 (2016) 141; S. F. Ge, H. J. He, J. Ren, and Z. Z. Xianyu, Realizing dark matter and Higgs inflation in light of LHC diphoton excess, Phys. Lett. B **757**, 480 (2016); A. Hektor and L. Marzola, Di-photon excess at LHC and the gamma ray excess at the galactic centre, J. Cosmol. Astropart. Phys. 07 (2016) 042; Q. H. Cao, Y. Q. Gong, X. Wang, B. Yan, and L. L. Yang, One bump or two peaks: The 750 GeV diphoton excess and dark matter with a complex mediator, Phys. Rev. D **93**, 075034 (2016); P. Ko and T. Nomura, Dark sector shining through 750 GeV dark Higgs boson at the LHC, Phys. Lett. B **758**, 205 (2016); S. Bhattacharya, S. Patra, N. Sahoo, and N. Sahu, 750 GeV diphoton excess at CERN LHC from a dark sector assisted scalar decay, J. Cosmol. Astropart. Phys. 06 (2016) 010; A. Berlin, Diphoton and diboson excesses in a left-right symmetric theory of dark matter, Phys. Rev. D **93**, 055015 (2016); X. J. Huang, W. H. Zhang, and Y. F. Zhou, A 750 GeV dark matter messenger at the Galactic Center, Phys. Rev. D **93**, 115006 (2016); J. C. Park and S. C. Park, Indirect signature of dark matter with the diphoton resonance at 750 GeV, Phys. Dark Univ. **14**, 4 (2016); H. Han, S. Wang, and S. Zheng, Dark matter theories in the light of diphoton Excess, arXiv:1512.07992; P. S. B. Dev and D. Teresi, Asymmetric dark matter in the sun and the diphoton excess at the LHC, Phys. Rev. D **94**,

025001 (2016); X. J. Bi, Q. F. Xiang, P. F. Yin, and Z. H. Yu, The 750 GeV diphoton excess at the LHC and dark matter constraints, Nucl. Phys. **B909**, 43 (2016); D. Barducci, A. Goudelis, S. Kulkarni, and D. Sengupta, One jet to rule them all: Monojet constraints and invisible decays of a 750 GeV diphoton resonance, J. High Energy Phys. 05 (2016) 154; K. Ghorbani and H. Ghorbani, The 750 GeV diphoton excess from a pseudoscalar in fermionic dark matter scenario, arXiv:1601.00602; S. M. Choi, Y. J. Kang, and H. M. Lee, Diphoton resonance confronts dark matter, J. High Energy Phys. 07 (2016) 030.

[25] J. S. Kim, J. Reuter, K. Rolbiecki, and R. Ruiz de Austri, A resonance without resonance: Scrutinizing the diphoton excess at 750 GeV, Phys. Lett. B **755**, 403 (2016); J. Bernon and C. Smith, Could the width of the diphoton anomaly signal a three-body decay?, Phys. Lett. B **757**, 148 (2016); W. S. Cho, D. Kim, K. Kong, S. H. Lim, K. T. Matchev, J. C. Park, and M. Park, 750 GeV Diphoton Excess May Not Imply a 750 GeV Resonance, Phys. Rev. Lett. **116**, 151805 (2016); F. P. Huang, C. S. Li, Z. L. Liu, and Y. Wang, 750 GeV diphoton excess from cascade decay, Phys. Rev. D **94**, 055025 (2016); M. Chala, M. Duerr, F. Kahlhoefer, and K. Schmidt-Hoberg, Tricking Landau-Yang: How to obtain the diphoton excess from a vector resonance, Phys. Lett. B **755**, 145 (2016); J. Liu, X. P. Wang, and W. Xue, LHC diphoton excess from colorful resonances, arXiv:1512.07885; X. F. Han, L. Wang, L. Wu, J. M. Yang, and M. Zhang, Explaining 750 GeV diphoton excess from top/bottom partner cascade decay in two-Higgs-doublet model extension, Phys. Lett. B **756**, 309 (2016); V. De Romeri, J. S. Kim, V. Martin-Lozano, K. Rolbiecki, and R. R. de Austri, Confronting dark matter with the diphoton excess from a parent resonance decay, Eur. Phys. J. C **76**, 262 (2016); B. A. Dobrescu, P. J. Fox, and J. Kearney, Multistep production of a diphoton resonance, arXiv:1605.08772; B. M. Dillon, C. Han, H. M. Lee, and M. Park, Confronting diphoton resonance with cascade decays in warped gravity, arXiv:1606.07171.

[26] H. Ito, T. Moroi, and Y. Takaesu, Studying 750 GeV di-photon resonance at photon-photon collider, Phys. Lett. B **756**, 147 (2016); M. He, X. G. He, and Y. Tang, A $\gamma\gamma$ collider for the 750 GeV resonant state, Phys. Lett. B **759**, 166 (2016); S. Fichet, G. von Gersdorff, and C. Royon, Scattering light by light at 750 GeV at the LHC, Phys. Rev. D **93**, 075031 (2016); C. Csaki, J. Hubisz, S. Lombardo, and J. Terning, Gluon versus photon production of a 750 GeV diphoton resonance, Phys. Rev. D **93**, 095020 (2016); L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, The photon PDF in events with rapidity gaps, Eur. Phys. J. C **76**, 255 (2016); L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, The production of a diphoton resonance via photon-photon fusion, J. High Energy Phys. 03 (2016) 182; C. Csaki, J. Hubisz, and J. Terning, Minimal model of a diphoton resonance: Production without gluon couplings, Phys. Rev. D **93**, 035002 (2016); A. D. Martin and M. G. Ryskin, Advantages of exclusive $\gamma\gamma$ production to probe high mass systems, J. Phys. G **43**, 04LT02 (2016); F. Richard, Diphoton resonance at e^+e^- and photon colliders, arXiv: 1604.01640.

[27] C. Bonilla, M. Nebot, R. Srivastava, and J. W. F. Valle, Flavor physics scenario for the 750 GeV diphoton anomaly, Phys. Rev. D **93**, 073009 (2016); D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, Toward a coherent solution of diphoton and flavor anomalies, J. High Energy Phys. 08 (2016) 035; F. F. Deppisch, S. Kulkarni, H. Päs, and E. Schumacher, Leptoquark patterns unifying neutrino masses, flavor anomalies and the diphoton excess, Phys. Rev. D **94**, 013003 (2016); G. Belanger and C. Delaunay, Dark sector for $g_\mu - 2$, R_K and a diphoton resonance, Phys. Rev. D **94**, 075019 (2016); M. Bauer and M. Neubert, Flavor anomalies, the diphoton excess and a dark matter candidate, Phys. Rev. D **93**, 115030 (2016); F. Goertz, J. F. Kamenik, A. Katz, and M. Nardecchia, Indirect constraints on the scalar di-photon resonance at the LHC, J. High Energy Phys. 05 (2016) 187.

[28] M. Perelstein and Y. D. Tsai, 750 GeV Di-photon Excess and Strongly First-Order Electroweak Phase Transition, Phys. Rev. D **94**, 015033 (2016); W. Chao, The Diphoton Excess Inspired Electroweak Baryogenesis, arXiv:1601.04678; A. Ghoshal, On Electroweak Phase Transition and Di-photon Excess with a 750 GeV Scalar Resonance, arXiv:1601.04291.

[29] Q. H. Cao, S. L. Chen, and P. H. Gu, Strong *CP* Problem, Neutrino masses and the 750 GeV diphoton resonance, arXiv:1512.07541; P. Draper and D. McKeen, Diphotons, new vacuum angles, and strong *CP*, J. High Energy Phys. 04 (2016) 127; C. W. Chiang, H. Fukuda, M. Ibe, and T. T. Yanagida, 750 GeV diphoton resonance in a visible heavy QCD axion model, Phys. Rev. D **93**, 095016 (2016); T. Higaki, K. S. Jeong, N. Kitajima, and F. Takahashi, The QCD axion from aligned axions and diphoton excess, Phys. Lett. B **755**, 13 (2016); S. Dimopoulos, A. Hook, J. Huang, and G. Marques-Tavares, A collider observable QCD axion, J. High Energy Phys. 11 (2016) 052.

[30] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze, and T. Li, Interpretation of the diphoton excess at CMS and ATLAS, Phys. Rev. D **93**, 055032 (2016); L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust, and T. R. Taylor, 750 GeV diphotons from closed string states, Phys. Lett. B **755**, 312 (2016); T. Li, J. A. Maxin, V. E. Mayes, and D. V. Nanopoulos, 750 GeV diphoton excesses in a realistic D-brane model, Phys. Rev. D **94**, 025002 (2016); L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust, and T. R. Taylor, Update on 750 GeV diphotons from closed string states, Phys. Lett. B **759**, 223 (2016); G. K. Leontaris and Q. Shafi, Diphoton resonance in F-theory inspired flipped SO(10), Eur. Phys. J. C **76**, 574 (2016); M. Cvetic, J. Halverson, and P. Langacker, Addendum: String consistency, heavy exotics, and the 750 GeV diphoton excess at the LHC, Fortschr. Phys. **64**, 748 (2016); A. E. Faraggi and J. Rizos, The 750 GeV di-photon LHC excess and extra Z's in heterotic-string derived models, Eur. Phys. J. C **76**, 170 (2016); A. Karozas, S. F. King, G. K. Leontaris, and A. K. Meadowcroft, 750 GeV diphoton excess from E_6 in F-theory GUTs, Phys. Lett. B **757**, 73 (2016); E. Palti, Vectorlike exotics in F-theory and 750 GeV diphotons, Nucl. Phys. **B907**, 597 (2016); M. Cvetic, J. Halverson, and P. Langacker, String consistency, heavy exotics, and the 750 GeV diphoton excess at the LHC, Fortschr. Phys. **64**, 748 (2016); J. J. Heckman, 750 GeV diphotons from a D3-brane, Nucl. Phys. **B906**, 231 (2016); L. E. Ibanez and V. Martin-Lozano, A megaxion at 750 GeV as a first hint of low scale string theory, J. High Energy Phys. 07 (2016) 021;

J. Ashfaque, L. D. Rose, A. E. Faraggi, and C. Marzo, The LHC di-photon excess and gauge coupling unification in extra Z' heterotic-string derived models, Eur. Phys. J. C **76**, 570 (2016); A. Belhaj and S. E. Ennadifi, On 750 GeV diphoton resonance in stringy standard-like models, arXiv:1606.02956.

[31] T. Nomura and H. Okada, Four-loop neutrino model inspired by diphoton excess at 750 GeV, Phys. Lett. B **755**, 306 (2016); P. Ko, Y. Omura, and C. Yu, Diphoton excess at 750 GeV in leptophobic $\mathrm{U}(1)'$ model inspired by E_6 GUT, J. High Energy Phys. 04 (2016) 098; A. E. C. Hernandez, I. d. M. Varzielas, and E. Schumacher, The 750 GeV diphoton resonance in the light of a 2HDM with S_3 flavour symmetry, arXiv:1601.00661; R. Barbieri, D. Buttazzo, L. J. Hall, and D. Marzocca, Higgs mass and unified gauge coupling in the NMSSM with vector matter, J. High Energy Phys. 07 (2016) 067; T. Modak, S. Sadhukhan, and R. Srivastava, 750 GeV diphoton excess from gauged $B-L$ symmetry, Phys. Lett. B **756**, 405 (2016); F. F. Deppisch, C. Hati, S. Patra, P. Pritimita, and U. Sarkar, Implications of the diphoton excess on left-right models and gauge unification, Phys. Lett. B **757**, 223 (2016); H. Zhang, 750 GeV diphoton excess: Who introduces it?, Phys. Rev. D **93**, 114032 (2016); I. Sahin, Semi-elastic cross section for a scalar resonance of mass 750 GeV, arXiv:1601.01676; D. Borah, S. Patra, and S. Sahoo, Subdominant left-right scalar dark matter as origin of the 750 GeV di-photon excess at LHC, Int. J. Mod. Phys. A **31**, 1650097 (2016); D. Stolarski and R. Vega-Morales, Probing a virtual diphoton excess, Phys. Rev. D **93**, 055008 (2016); M. Fabbrichesi and A. Urbano, Breaking of the $SU(2)_L \times U(1)_Y$ symmetry: The 750 GeV resonance at the LHC and perturbative unitarity, Phys. Rev. D **94**, 035004 (2016); C. Hati, Explaining the diphoton excess in alternative left-right symmetric model, Phys. Rev. D **93**, 075002 (2016); J. H. Yu, Hidden gauged U(1) model: Unifying scotogenic neutrino and flavor dark matter, Phys. Rev. D **93**, 113007 (2016); R. Ding, Z. L. Han, Y. Liao, and X. D. Ma, Interpretation of 750 GeV diphoton excess at LHC in singlet extension of color-octet neutrino mass model, Eur. Phys. J. C **76**, 204 (2016); I. Dorsner, S. Fajfer, and N. Kosnik, Is symmetry breaking of SU(5) theory responsible for the diphoton excess?, Phys. Rev. D **94**, 015009 (2016); T. Nomura and H. Okada, Four-loop radiative seesaw model with 750 GeV diphoton resonance, arXiv:1601.04516; H. Okada and K. Yagyu, Renormalizable model for neutrino mass, dark matter, muon $g-2$ and 750 GeV diphoton excess, Phys. Lett. B **756**, 337 (2016); U. Aydemir and T. Mandal, Interpretation of the 750 GeV diphoton excess with colored scalars in $\mathbf{SO(10)}$ grand unification, arXiv:1601.06761; A. Djouadi, J. Ellis, R. Godbole, and J. Quevillon, Future collider signatures of the possible 750 GeV state, J. High Energy Phys. 03 (2016) 205; T. Nomura and H. Okada, Generalized Zee-Babu model with 750 GeV diphoton resonance, Phys. Lett. B **756**, 295 (2016); E. Bertuzzo, P. A. N. Machado, and M. Taoso, Diphoton excess in the 2HDM: Hasting towards the instability and the nonperturbative regime, Phys. Rev. D **94**, 115006 (2016); J. Kawamura and Y. Omura, Diphoton excess at 750 GeV and LHC constraints in models with vectorlike particles, Phys. Rev. D **93**, 115011 (2016); I. Ben-Dayan and R. Brustein, Hypercharge axion and the diphoton 750 GeV resonance, arXiv:1601.07564; L. Aparicio, A. Azatov, E. Hardy, and A. Romanino, Diphotons from diaxions, J. High Energy Phys. 05 (2016) 077; T. Li, J. A. Maxin, V. E. Mayes, and D. V. Nanopoulos, A flippon related singlet at the LHC II, J. High Energy Phys. 06 (2016) 167; S. I. Godunov, A. N. Rozanov, M. I. Vysotsky, and E. V. Zhemchugov, New Physics at 1 TeV?, JETP Lett. **103**, 557 (2016); C. Arbelez, A. E. C. Hernandez, S. Kovalenko, and I. Schmidt, Linking radiative seesaw-type mechanism of fermion masses and nontrivial quark mixing with the 750 GeV diphoton excess, arXiv:1602.03607; C. Gross, O. Lebedev, and J. M. No, Drell-Yan constraints on new electroweak states and the di-photon anomaly, arXiv:1602.03877; Y. Hamada, H. Kawai, K. Kawana, and K. Tsumura, Models of LHC diphoton excesses valid up to the Planck scale, Phys. Rev. D **94**, 014007 (2016); F. Goertz, A. Katz, M. Son, and A. Urbano, Precision Drell-Yan measurements at the LHC and implications for the diphoton excess, J. High Energy Phys. 07 (2016) 136; C. Delaunay and Y. Soreq, Probing new physics with isotope shift spectroscopy, arXiv:1602.04838; S. F. Mantilla, R. Martinez, F. Ochoa, and C. F. Sierra, Diphoton decay for a 750 GeV scalar boson in a $SU(6) \otimes U(1)_X$ model, Nucl. Phys. **B911**, 338 (2016); Y. J. Zhang, B. B. Zhou, and J. J. Sun, The fourth generation quark and the 750 GeV diphoton excess, arXiv:1602.05539; F. Staub *et al.*, Precision tools and models to narrow in on the 750 GeV diphoton resonance, Eur. Phys. J. C **76**, 516 (2016); S. Baek and J. h. Park, LHC 750 GeV diphoton excess and muon $(g-2)$, Phys. Lett. B **758**, 416 (2016); P. Ko, T. Nomura, H. Okada, and Y. Orikasa, Confronting a new three-loop seesaw model with the 750 GeV diphoton excess, Phys. Rev. D **94**, 013009 (2016); J. Ren and J. H. Yu, $\mathrm{SU}(2)\times\mathrm{SU}(2)\times\mathrm{U}(1)$ Interpretation on the 750 GeV diphoton excess, arXiv:1602.07708; J. F. Kamenik and M. Redi, Back to 1974: The $\mathcal{Q}$-onium, Phys. Lett. B **760**, 158 (2016); Y. Kats and M. J. Strassler, Resonances from QCD bound states and the 750 GeV diphoton excess, J. High Energy Phys. 05 (2016) 092; A. Ahriche, G. Faisel, S. Nasri, and J. Tandean, Addressing the LHC 750 GeV diphoton excess without new colored states, Nucl. Phys. **B916**, 64 (2017); J. Bernon, A. Goudelis, S. Kraml, K. Mawatari, and D. Sengupta, Characterising the 750 GeV diphoton excess, J. High Energy Phys. 05 (2016) 128; G. Panico, L. Vecchi, and A. Wulzer, Resonant diphoton phenomenology simplified, J. High Energy Phys. 06 (2016) 184; A. Bharucha, A. Djouadi, and A. Goudelis, Threshold enhancement of diphoton resonances, Phys. Lett. B **761**, 8 (2016); W. Lu, Electroweak and Majorana sector Higgs bosons and pseudo-Nambu-Goldstone bosons, arXiv:1603.04697; D. T. Huong and P. V. Dong, Left-right asymmetry and 750 GeV diphoton excess, Phys. Rev. D **93**, 095019 (2016); J. F. Kamenik, B. R. Safdi, Y. Soreq, and J. Zupan, Comments on the diphoton excess: Critical reappraisal of effective field theory interpretations, J. High Energy Phys. 07 (2016) 042; X. Liu and H. Zhang, RG-improved prediction for 750 GeV resonance production at the LHC, arXiv:1603.07190; S. Di Chiara, A. Hektor, K. Kannike, L. Marzola, and M. Raidal, Large loop-coupling enhancement of a 750 GeV pseudoscalar from a light dark

sector, arXiv:1603.07263; K. Howe, S. Knapen, and D. J. Robinson, Diphotons from an electroweak triplet-singlet, Phys. Rev. D **94**, 035021 (2016); J. H. Collins, C. Csaki, J. A. Dror, and S. Lombardo, Novel kinematics from a custodially protected diphoton resonance, Phys. Rev. D **93**, 115001 (2016); N. Liu, W. Wang, M. Zhang, and R. Zheng, 750 GeV diphoton resonance in a vector-like extension of Hill model, Int. J. Mod. Phys. A **31**, 1650145 (2016); G. Cynolter, J. Kovacs, and E. Lendvai, Diphoton excess and VV-scattering, Mod. Phys. Lett. A **31**, 1650133 (2016); T. Gherghetta, N. Nagata, and M. Shifman, Visible QCD axion from an enlarged color group, Phys. Rev. D **93**, 115010 (2016); M. Chala, C. Grojean, M. Riembau, and T. Vantalon, Deciphering the *CP* nature of the 750 GeV resonance, Phys. Lett. B **760**, 220 (2016); R. S. Chivukula, A. Farzinnia, K. Mohan, and E. H. Simmons, Diphoton resonances in the renormalizable coloron model, Phys. Rev. D **94**, 035018 (2016); A. Y. Kamenshchik, A. A. Starobinsky, A. Tronconi, G. P. Vacca, and G. Venturi, Vacuum energy, Standard Model physics and the 750 GeV diphoton excess at the LHC, arXiv:1604.02371; N. D. Barrie, A. Kobakhidze, S. Liang, M. Talia, and L. Wu, Heavy leptonium as the origin of the 750 GeV diphoton excess, arXiv:1604.02803; A. Kusenko, L. Pearce, and L. Yang, Leptogenesis via the 750 GeV pseudoscalar, Phys. Rev. D **93**, 115005 (2016); H. Ito and T. Moroi, Production and decay of diphoton resonance at future e^+e^- colliders, Phys. Rev. D **94**, 015021 (2016); A. Bolanos, J. L. Diaz-Cruz, G. Hernandez-Tome, and G. Tavares-Velasco, Has a Higgs-flavon with a 750 GeV mass been detected at the LHC13?, Phys. Lett. B **761**, 310 (2016); R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, F. Riva, A. Strumia, and R. Torre, Digamma, what next?, J. High Energy Phys. 07 (2016) 150; M. Duerr, P. Fileviez Perez, and J. Smirnov, New forces and the 750 GeV resonance, arXiv:1604.05319; S. Iwamoto, G. Lee, Y. Shadmi, and R. Ziegler, Diphoton signals from colorless hidden quarkonia, Phys. Rev. D **94**, 015003 (2016); S. Fichet, G. von Gersdorff, and C. Royon, Measuring the Diphoton Coupling of a 750 GeV Resonance, Phys. Rev. Lett. **116**, 231801 (2016); Y. Cai, J. D. Clarke, R. R. Volkas, and T. T. Yanagida, TeV-scale pseudo-Dirac seesaw mechanisms in an E_6 inspired model, Phys. Rev. D **94**, 033003 (2016); R. Sato and K. Tobioka, LHC future prospects of the 750 GeV resonance, Phys. Lett. B **760**, 590 (2016); J. M. No, Is it $SU(2)_L$ or just $U(1)_Y$? 750 GeV di-photon probes of the electroweak nature of new states, Phys. Rev. D **94**, 035020 (2016); M. A. Ebert, S. Liebler, I. Moult, I. W. Stewart, F. J. Tackmann, K. Tackmann, and L. Zeune, Exploiting jet binning to identify the initial state of high-mass resonances, Phys. Rev. D **94**, 051901 (2016); R. Nevzorov and A. W. Thomas, Diphoton signature of neutral pseudo-Goldstone boson in the E6CHM at the CERN LHC, arXiv:1605.07313; K. Kannike, G. M. Pelaggi, A. Salvio, and A. Strumia, The diphoton as the Higgs of the Higgs, J. High Energy Phys. 07 (2016) 101; T. Appelquist, J. Ingoldby, M. Piai, and J. Thompson, A spartan model for the LHC diphoton excess, arXiv:1606.00865; A. Carmona, F. Goertz, and A. Papaefstathiou, Uncovering the relation of a diphoton scalar resonance to the Higgs boson, arXiv:1606.02716; M. Dalchenko, B. Dutta, Y. Gao, T. Ghosh, and T. Kamon, Exploring the jet multiplicity in the 750 GeV diphoton excess, arXiv:1606.03067; C. H. Chen and T. Nomura, 750 GeV diphoton resonance and the implications in an $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ model, arXiv:1606.03804; L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and M. Spannowsky, Jet activity as a probe of diphoton resonance production, arXiv:1606.04902; O. Antipin, P. Culjak, K. Kumericki, and I. Picek, Radiative neutrino models in light of diphoton signals, arXiv:1606.05163; A. Alves, A. G. Dias, and K. Sinha, Diphotons at the Z-pole in models of the 750 GeV resonance decaying to axion-like particles, arXiv:1606.06375; M. Carena, P. Huang, A. Ismail, I. Low, N. R. Shah, and C. E. M. Wagner, A second peak in diphoton (or diboson) resonances, arXiv:1606.06733; A. Efrati, J. F. Kamenik, and Y. Nir, The phenomenology of the di-photon excess and $h \to \tau\mu$ within 2HDM, arXiv:1606.07082; C. Royon, Forward physics at the LHC: From the structure of the Pomeron to the search for γ-induced resonances, arXiv:1606.07675; U. K. Dey, S. Mohanty, and G. Tomar, Leptoquarks: 750 GeV diphoton resonance and IceCube events, arXiv:1606.07903; A. Di Iura, J. Herrero-Garcia, and D. Meloni, Phenomenology of SU(5) low-energy realizations: The diphoton excess and Higgs flavor violation, arXiv:1606.08785; S. Banerjee, D. Barducci, G. Blanger, and C. Delaunay, Implications of a high-mass diphoton resonance for heavy quark searches, arXiv:1606.09013; K. Das, T. Li, S. Nandi, and S. K. Rai, A new proposal for diphoton resonance from E_6 motivated extra $U(1)$, arXiv:1607.00810; M. Bauer, M. Neubert, and A. Thamm, The "forgotten" decay $S \to Z + h$ as a CP analyzer, arXiv:1607.01016.

[32] D. Becirevic, E. Bertuzzo, O. Sumensari, and R. Z. Funchal, Can the new resonance at LHC be a *CP*-odd Higgs boson?, Phys. Lett. B **757**, 261 (2016); S. Ghosh, A. Kundu, and S. Ray, Potential of a singlet scalar enhanced standard model, Phys. Rev. D **93**, 115034 (2016); R. Benbrik, C. H. Chen, and T. Nomura, Higgs singlet boson as a diphoton resonance in a vectorlike quark model, Phys. Rev. D **93**, 055034 (2016); X. F. Han and L. Wang, Implication of the 750 GeV diphoton resonance on two-Higgs-doublet model and its extensions with Higgs field, Phys. Rev. D **93**, 055027 (2016); W. C. Huang, Y. L. S. Tsai, and T. C. Yuan, Gauged two Higgs doublet model confronts the LHC 750 GeV diphoton anomaly, Nucl. Phys. **B909**, 122 (2016); S. Moretti and K. Yagyu, 750 GeV diphoton excess and its explanation in two-Higgs-doublet models with a real inert scalar multiplet, Phys. Rev. D **93**, 055043 (2016); M. Badziak, Interpreting the 750 GeV diphoton excess in minimal extensions of two-Higgs-doublet models, Phys. Lett. B **759**, 464 (2016); K. Cheung, P. Ko, J. S. Lee, J. Park, and P. Y. Tseng, Higgs precision study of the 750 GeV diphoton resonance and the 125 GeV standard model Higgs boson with Higgs-singlet mixing, Phys. Rev. D **94**, 033010 (2016); A. Salvio and A. Mazumdar, Higgs stability and the 750 GeV diphoton excess, Phys. Lett. B **755**, 469 (2016); N. Bizot, S. Davidson, M. Frigerio, and J.-L. Kneur, Two Higgs doublets to explain the excesses $pp \to \gamma\gamma(750\ \mathrm{GeV})$ and $h \to \tau^\pm\mu^\mp$, J. High Energy Phys. 03 (2016) 073; S. K. Kang and J. Song, Top-phobic heavy Higgs boson as the 750 GeV diphoton resonance, Phys. Rev. D **93**, 115012 (2016); F. Wang, W. Wang, L. Wu, J. M. Yang, and M. Zhang, Interpreting 750 GeV diphoton resonance as degenerate

Higgs bosons in NMSSM with vectorlike particles, arXiv:1512.08434; F. Wang, L. Wu, J. M. Yang, and M. Zhang, 750 GeV diphoton resonance, 125 GeV Higgs and muon $g-2$ anomaly in deflected anomaly mediation SUSY breaking scenarios, Phys. Lett. B **759**, 191 (2016); X. F. Han, L. Wang, and J. M. Yang, An extension of two-Higgs-doublet model and the excesses of 750 GeV diphoton, muon g-2 and $h \to \mu\tau$, Phys. Lett. B **757**, 537 (2016); C. W. Chiang and A. L. Kuo, Can the 750-GeV diphoton resonance be the singlet Higgs boson of custodial Higgs triplet model?, Phys. Lett. B **760**, 634 (2016); M. J. Dolan, J. L. Hewett, M. Krämer, and T. G. Rizzo, Simplified models for Higgs physics: Singlet scalar and vector-like quark phenomenology, J. High Energy Phys. 07 (2016) 039; S. Gopalakrishna and T. S. Mukherjee, The 750 GeV diphoton excess in a two Higgs doublet model and a singlet scalar model, with vectorlike fermions, unitarity constraints, and dark matter implications, arXiv:1604.05774.

[33] S. Dawson and I. M. Lewis, Singlet model interference effects and a 750 GeV diphoton resonance, Phys. Rev. D **95**, 015004 (2017).

[34] S. Weinberg, Effective gauge theories, Phys. Lett. B **91**, 51 (1980); S. R. Coleman, J. Wess, and B. Zumino, Structure of phenomenological lagrangians. I, Phys. Rev. **177**, 2239 (1969); C. G. Callan, Jr., S. R. Coleman, J. Wess, and B. Zumino, Structure of Phenomenological Lagrangians. II, Phys. Rev. **177**, 2247 (1969).

[35] C. J. C. Burges and H. J. Schnitzer, Virtual effects of excited quarks as probes of a possible new hardonic mass scale, Nucl. Phys. **B228**, 464 (1983); C. N. Leung, S. T. Love, and S. Rao, Low-energy manifestations of a new interactions scale: Operator analysis, Z. Phys. C **31**, 433 (1986); W. Buchmüller and D. Wyler, Effective lagrangian analysis of new interactions and flavour conservation, Nucl. Phys. **B268**, 621 (1986); W. Kilian, Electroweak symmetry breaking: The bottom-up approach, Springer Tracts Mod. Phys. **198**, 1 (2003); A. De Rujula, M. Gavela, P. Hernandez, and E. Masso, The self-couplings of vector bosons: does LEP-1 obviate LEP-2?, Nucl. Phys. **B384**, 3 (1992); K. Hagiwara, R. Szalapski, and D. Zeppenfeld, Anomalous Higgs boson production and decay, Phys. Lett. B **318**, 155 (1993); K. Hagiwara, S. Matsumoto, and R. Szalapski, Constraints on new physics in the electroweak bosonic sector from current data and future experiments, Phys. Lett. B **357**, 411 (1995); M. C. Gonzalez-Garcia, Anomalous Higgs couplings, Int. J. Mod. Phys. A **14**, 3121 (1999); G. Passarino, NLO inspired effective Lagrangians for Higgs physics, Nucl. Phys. **B868**, 416 (2013). K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Low energy effects of new interactions in the electroweak boson sector, Phys. Rev. D **48**, 2182 (1993); K. Hagiwara, T. Hatsukano, S. Ishihara, and R. Szalapski, Probing nonstandard bosonic interactions via W boson pair production at lepton colliders, Nucl. Phys. **B496**, 66 (1997); R. Alonso, M. B. Gavela, L. Merlo, S. Rigolin, and J. Yepes, The effective chiral Lagrangian for a light dynamical "Higgs particle", Phys. Lett. B **722**, 330 (2013); Erratum, Phys. Lett. B**726**, 926(E) (2013); G. Buchalla, O. Catà, and C. Krause, Complete electroweak chiral Lagrangian with a light Higgs at NLO, Nucl. Phys. **B880**, 552 (2014); M. B. Gavela, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, L. Merlo, S. Rigolin, and J. Yepes, *CP* violation with a dynamical Higgs, J. High Energy Phys. 10 (2014) 44.

[36] C. Englert, A. Freitas, M. M. Mühlleitner, T. Plehn, M. Rauch, M. Spira, and K. Walz, Precision measurements of Higgs couplings: implications for new physics scales, J. Phys. G **41**, 113001 (2014).

[37] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, Dimension-six terms in the standard model Lagrangian, J. High Energy Phys. 10 (2010) 085.

[38] B. Gripaios and D. Sutherland, An operator basis for the Standard Model with an added scalar singlet, J. High Energy Phys. 08 (2016) 103.

[39] J. F. Kamenik, B. R. Safdi, Y. Soreq, and J. Zupan, Comments on the diphoton excess: Critical reappraisal of effective field theory interpretations, J. High Energy Phys. 07 (2016) 042.

[40] R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, and M. Dührssen, Measuring the Higgs sector, J. High Energy Phys. 08 (2009) 009; M. Klute, R. Lafaye, T. Plehn, M. Rauch, and D. Zerwas, Measuring Higgs Couplings from LHC Data, Phys. Rev. Lett. **109**, 101801 (2012); T. Plehn and M. Rauch, Higgs couplings after the discovery, Europhys. Lett. **100**, 11002 (2012).

[41] R. Lafaye, T. Plehn, M. Rauch, and D. Zerwas, Measuring supersymmetry, Eur. Phys. J. C **54**, 617 (2008).

[42] A. Höcker, H. Lacker, S. Laplace, and F. Le Diberder, A new approach to a global fit of the CKM matrix, Eur. Phys. J. C **21**, 225 (2001).

[43] V. Khachatryan *et al.* (CMS Collaboration), Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B **750**, 494 (2015).

[44] G. Aad *et al.* (ATLAS Collaboration), Search for a high-mass Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 01 (2016) 032.

[45] ATLAS Collaboration, Search for a high-mass Higgs boson decaying to a pair of W bosons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Report No. ATLAS-CONF-2016-021.

[46] G. Aad *et al.* (ATLAS Collaboration), Search for an additional, heavy Higgs boson in the $H \to ZZ$ decay channel at $\sqrt{s} = 8$ TeV in pp collision data with the ATLAS detector, Eur. Phys. J. C **76**, 45 (2016).

[47] M. Aaboud *et al.* (ATLAS Collaboration), Report No. ATLAS-CONF-2016-016.

[48] ATLAS Collaboration, Report No. ATLAS-CONF-2016-012.

[49] M. Aaboud *et al.* (ATLAS Collaboration), Report No. ATLAS-CONF-2016-010.

[50] V. Khachatryan *et al.* (CMS Collaboration), Report No. CMS-PAS-EXO-16-019.

[51] G. Aad *et al.* (ATLAS Collaboration), Search for new resonances in $W\gamma$ and $Z\gamma$ final states in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B **738**, 428 (2014).

[52] G. Aad *et al.* (ATLAS Collaboration), A search for $t\bar{t}$ resonances using lepton-plus-jets events in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 08 (2015) 148.

[53] V. Khachatryan *et al.* (CMS Collaboration), Search for narrow resonances in dijet final states at $\sqrt{s} = 8$ TeV with the novel CMS technique of data scouting, arXiv: 1604.08907.
[54] ATLAS Collaboration, Report No. ATLAS-CONF-2016-017.
[55] V. Khachatryan *et al.* (CMS Collaboration), Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 8 TeV, Phys. Lett. B **749**, 560 (2015).
[56] CMS Collaboration, Report No. CMS-PAS-HIG-14-028.
[57] F. Goertz, Indirect Handle on the Down-Quark Yukawa Coupling, Phys. Rev. Lett. **113**, 261803 (2014).
[58] S. Liem, G. Bertone, F. Calore, R. R. de Austri, T. M. P. Tait, R. Trotta, and C. Weniger, Effective field theory of dark matter: A global analysis, J. High Energy Phys. 09 (2016) 077.
[59] ATLAS Collaboration, Report No. ATLAS-CONF-2016-059.
[60] CMS Collaboration, Report No. CMS-PAS-EXO-16-027.