The 750 GeV diphoton excess and SUSY\textsuperscript{\textdagger}

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\textbf{Abstract}

The LHC experiments ATLAS and CMS have reported an excess in the diphoton spectrum at \( \sim 750 \) GeV. At the same time the motivation for Supersymmetry (SUSY) remains unbowed. Consequently, we review briefly the proposals to explain this excess in SUSY, focusing on “pure” (N)MSSM solutions. We then review in more detail a proposal to realize this excess within the NMSSM. In this particular scenario a Higgs boson with mass around 750 GeV decays to two light pseudo-scalar Higgs bosons. Via mixing with the pion these pseudo-scalars decay into a pair of highly collimated photons, which are identified as one photon, thus resulting in the observed signal.

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The LHC experiments ATLAS and CMS have reported an excess in the diphoton spectrum at \( \sim 750 \text{ GeV} \). At the same time the motivation for Supersymmetry (SUSY) remains unbowed. Consequently, we review briefly the proposals to explain this excess in SUSY, focusing on “pure” (N)MSSM solutions. We then review in more detail a proposal to realize this excess within the NMSSM. In this particular scenario a Higgs boson with mass around 750 GeV decays to two light pseudo-scalar Higgs bosons. Via mixing with the pion these pseudo-scalars decay into a pair of highly collimated photons, which are identified as one photon, thus resulting in the observed signal.

1. Motivation for SUSY

Theories based on Supersymmetry (SUSY) \([1,2]\) are widely considered as the theoretically most appealing extension of the Standard Model (SM). The Minimal Supersymmetric Standard Model (MSSM) constitutes, hence its name, the minimal supersymmetric extension of the SM. The number of SUSY generators is \( N = 1 \), the smallest possible value. In order to keep anomaly cancellation, contrary to the SM a second Higgs doublet is needed \([3]\). All SM multiplets, including the two Higgs doublets, are extended to supersymmetric multiplets, resulting in scalar partners for quarks and leptons (“squarks” and “sleptons”) and fermionic partners for the SM gauge boson and the Higgs bosons (“gauginos”, “higgsinos” and “gluinos”). So far, the direct search for SUSY particles has not been successful. One can only set lower bounds of \( \mathcal{O}(100 \text{ GeV}) \) to \( \mathcal{O}(1000 \text{ GeV}) \) on their masses \([4,5]\).

SUSY as such, and the MSSM as its simplest realization are considered as theoretically appealing for the following reasons:

- According to the Haag-Lopuszanski-Sohnius theorem \([6]\), SUSY offers the only non-trivial symmetry extension of the internal gauge symmetry of the SM.
Contrary to the SM, within the MSSM the three gauge couplings meet at a "Grand Unification" (GUT) scale of about $\sim 2 \times 10^{16}$ GeV, see, e.g., Ref. [7] (and references therein).

SUSY provides a way to cancel the quadratic divergences in the Higgs sector, hence stabilizing the huge hierarchy between the GUT and the electroweak (EW) scale.

Within SUSY theories the breaking of the electroweak symmetry is naturally induced at the EW scale.

The discovered Higgs boson at $\sim 125$ GeV can naturally be interpreted as the lightest (or the second lightest) Higgs boson in the MSSM [5]. The value of $\sim 125$ GeV is below the limit predicted in the year 2002 of $\sim 135$ GeV [9].

Over large parts of the SUSY parameter space the lightest Higgs boson behaves SM-like [10], in agreement with the experimental measurements [11].

Furthermore, in SUSY theories the lightest SUSY particle can be neutral, weakly interacting and absolutely stable, providing therefore a natural solution for the dark matter problem [12].

The two Higgs doublets in the MSSM result in five physical Higgs bosons instead of the single Higgs boson in the SM. In lowest order these are the light and heavy $CP$-even Higgs bosons, $h$ and $H$, the $CP$-odd Higgs boson, $A$, and two charged Higgs bosons, $H^{\pm}$. The Higgs sector of the MSSM is described at the tree level by two parameters: the mass of the $CP$-odd Higgs boson, $M_A$, and the ratio of the two vacuum expectation values, $\tan \beta \equiv v_2/v_1$. Higher-order contributions yield large corrections to the masses and couplings [13, 14].

The Next-to-Minimal Supersymmetric Standard Model (NMSSM), see [15] for reviews, is a well-motivated extension of the MSSM. The original purpose of the NMSSM rests with the 'µ'-problem [16] of the simpler MSSM: this issue is addressed via the addition of a singlet superfield to the matter content of the MSSM, the 'µ'-parameter is then generated dynamically when the singlet takes a vacuum expectation value. Additionally, the NMSSM has received renewed attention due to its interesting features in terms of a SUSY interpretation of the observed Higgs signals, see [17] for a recent analysis and list of references. While several versions of the NMSSM can be formulated, we will focus here on the simplest one, characterized by a $Z_3$-symmetry and $CP$-conservation.

The NMSSM Higgs sector consists of two doublets and a singlet. The physical spectrum, besides the pair of charged states $H^{\pm}$, contains two doublet and one singlet $CP$-even degrees of freedom, $h_u$, $h_d$ and $h_s$, as well as one doublet and one singlet $CP$-odd components, $A_D$ and $A_S$. In addition, the SUSY partner of the singlet Higgs (called the singlino) extends the neutralino sector to a total of five neutralinos. In the $Z_3$- and $CP$-conserving version of the NMSSM in particular the (new) parameters $\lambda$, $\kappa$, $A_\kappa$ and $\mu = \lambda v_s$ appear, where $v_s$ denotes the vacuum expectation value of the Higgs singlet.
2. How to realize the 750 GeV excess in “minimal” SUSY models

The ATLAS [18] and CMS [19] experiments at the Large Hadron Collider (LHC) have both reported an excess in the diphoton channel at an invariant mass of about 750 GeV, corresponding to a local (global) significance of $3.6\sigma$ ($2.0\sigma$) and $2.6\sigma$ ($1.2\sigma$), respectively. The result is of course not conclusive, but if the excess were confirmed, this would be the first sign of new physics at terascale energies. The observed cross section with roughly $\sigma(pp \to \Phi_{750}) \times BR(\Phi_{750} \to \gamma\gamma) \sim O(5)\,\text{fb}$ is relatively large, such is the width preferred by the ATLAS measurements of $\sim 45$ GeV.

More than 300 articles appeared [20], trying to explain this “excess”, to analyze its compatibility with other experimental data, to propose future LHC measurements etc. From the literature it becomes clear that the observed diphoton rate cannot be explained with a SM-like Higgs boson because its tree level decays into third generation quarks and/or to gauge bosons are too large compared to the loop induced decays into diphoton final states. Furthermore, simple extension of the SM Higgs sector such as a singlet extension or Two-Higgs-Doublet Model (2HDM) are also plagued with too small diphoton rates and the way out is to introduce new vector-like fermions: see e.g. Refs. [21, 22]. Most explanations of a new resonance $\Phi_{750}$ require the ad-hoc introduction of new, additional particles into the spectrum [20].

There are only a few phenomenologically viable explanations within the framework of SUSY, and most of those go beyond the minimal models as motivated in the previous section. The “most minimal” explanations, i.e. within the minimal models without the ad-hoc introduction of new particles are the following:

- Within the MSSM the “excess” can be accomodated with the $\mathcal{CP}$-odd Higgs boson as the new state at $M_A \sim 750$ GeV. The large value of $\sigma \times BR$ is achieved by a (very fine-tuned) enhancement of $\Gamma(A \to \gamma\gamma)$ via charginos with $1/2M_Z \approx m_{\tilde{\chi}_2^\pm}$ [23].
- Alternatively, within the MSSM the “excess” can be described as a $\sim 750$ GeV heavy stop-antistop bound state (stoponium), where the light stop has a mass $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_2^0}$, only slightly above the lightest neutralino [24].
- Another description of the “excess” in the MSSM identifies the new resonance with the heavy $\mathcal{CP}$-even Higgs boson, $M_H \sim 750$ GeV. A sufficiently large value of $\Gamma(H \to \gamma\gamma)$ is reached via large trilinear couplings, together with a (very fine-tuned) enhancement of stop contributions to $\Gamma(H \to \gamma\gamma)$, as well as mixing with stoponium [25]. As in the previous example, also in this solution the light stop mass must only slightly above $m_{\tilde{\chi}_2^0}$.
- Within the “pure” NMSSM the “excess” can be accomodated with two $\mathcal{CP}$-even Higgs bosons with a masses $\sim 750$ GeV. These Higgs bosons can decay to a pair of light $\mathcal{CP}$-odd Higgs bosons with a mass of either $\sim 210$ MeV or $\sim 500\ldots 550$ MeV. Via mixing effects these highly boosted $\mathcal{CP}$-odd Higgs bosons...
bosons decay with a sufficiently high rate to two photons. Due to the strong boost these two photons are detected as one, thus resulting in the observed signal [26].

- Similarly to the above explanation, another solution, somewhat more robust against experimental constraints, can be found if the light \( \mathcal{CP} \)-odd Higgs bosons have a mass \( \sim m_\pi \) [27]. The mixing with the pion results in a nearly purely two-photon decay of each of the light \( \mathcal{CP} \)-odd Higgs bosons. A possible mass difference of the two \( \mathcal{CP} \)-even Higgs bosons was shown to yield an “effective width” at the same level as preferred by the ATLAS data [27].

- Other explanations with the (N)MSSM require additional couplings or particles in the spectrum. Examples are solutions in the \( R \)-parity violating MSSM [28], or a very low SUSY-breaking scale, where the sgoldstino is identified with \( \Phi_{750} \) [29], or within the NMSSM turning non-perturbative at \( O(10 \text{ TeV}) \) [30].

3. Realization within the NMSSM

Here we will review the explanation of the “excess” as presented in Ref. [27], which in our view constitutes the most robust description within the “pure (N)MSSM”. Let us stress again that within this solution no new exotic matter is included, but it relies strictly on the simple matter content of this model. The Feynman diagram for the “mechanism” invoked here to reproduce the “excess” is shown in Fig. 1.

![Feynman diagram](image)

**Fig. 1.** The resonant production of \( \Phi \) (\( \mathcal{CP} \)-even Higgs bosons) followed by the decay to two \( \Sigma \) scalars (the light \( \mathcal{CP} \)-odd Higgs boson) and then to photons. The final state photons are pairwise collimated.
3.1. The NMSSM parameter space

In Ref. [27] it is detailed which part of the NMSSM parameter space results in the desired signal: two $\mathcal{CP}$-even Higgs bosons around 750 GeV, a light $\mathcal{CP}$-odd Higgs $A_1$ with a mass $\sim m_\pi$, $\sigma \times \text{BR} \sim 5 \text{ fb}$, as well as agreement with the measured signal rates of the SM-like Higgs boson, $H_{\text{SM}}$, at $\sim 125$ GeV. The favoured parameter space is given as follows.

- $M_A \simeq 750$ GeV enables a sizable production of the state(s) at $\sim 750$ GeV via a significant doublet component;
- $\kappa \simeq \frac{\lambda}{2 \tan 2 \beta}$ ensures a suppressed decay $H_{\text{SM}} \to A_1 A_1$; furthermore, $\kappa \gtrsim 0.1$ allows for a competitive $\Gamma(h_s \to A_1 A_1)$ as compared to the fermionic decays of the doublet component. Consequently, the two Higgs bosons at $\sim 750$ GeV have to be strongly mixed doublet-singlet states. Finally, $\kappa$ determines the separation in mass for the states at $\sim 750$ GeV;
- $\mu \sim M_A \sin 2 \beta$ is fixed both by the requirement $2 \kappa \mu \simeq 750$ GeV, conditioning the presence of a singlet-like component at $\sim 750$ GeV, with the significant decay to pseudo-scalars, and by the condition on $H_{\text{SM}} \to A_1 A_1$;
- $\lambda$ is bounded as $\frac{0.4 \tan \beta}{1+\tan^2 \beta} \lesssim \lambda \lesssim \frac{2 \sqrt{2} \tan \beta}{\sqrt{1+18 \tan^2 \beta+\tan^4 \beta}}$: this results from the conditions of a suppressed decay $H_{\text{SM}} \to A_1 A_1$, which would spoil the interpretation of the LHC Run-I results, of perturbativity up to the GUT scale and of a sizable $\Gamma(h_s \to A_1 A_1)$; moreover, the light $\mathcal{CP}$-odd Higgs would be long-lived if $\lambda$ were too small;
- $\tan \beta \lesssim 15$ is constrained by the lower bound on chargino searches $\mu \gtrsim 100$ GeV, as the result of the various correlations; note that $\tan \beta = \mathcal{O}(10)$ satisfies the requirements on the fermionic decays of the states at $\sim 750$ GeV – which should remain moderate;
- $A_\kappa \lesssim \mathcal{O}(0.1)$ GeV conditions a light $\mathcal{CP}$-odd singlet; the specific value of $A_\kappa$ determines $m_{A_1} \sim m_\pi$. It should be noted that, together with the requirement $A_\kappa \to 0$ which, in our scenario, follows the assumptions on $\kappa$, $\lambda$, $\mu$ and $M_A$, $A_\kappa \to 0$ places us in the approximate $R$-symmetry limit of the NMSSM, and that $A_1$ thus appears as the pseudo-Goldstone boson of this $R$-symmetry.

Moreover, the requirements of a $\sim 125$ GeV mass for the SM-like Higgs state and flavor physics constrain the squark spectra, while $(g-2)_\mu$ and slepton searches impact the slepton spectrum. We stress that the singlino and higgsino masses are essentially determined by the choices in the Higgs sector and that light higgsinos (constituting the LSP in the simplest configuration) appear as a trademark of this scenario.

Naturally, certain attractive features of the NMSSM Higgs sector, such as the possibility of a light $\mathcal{CP}$-even singlet, appear as a necessary sacrifice in order to conciliate an interpretation of the $\sim 750$ GeV excess with the parameter space and
constraints of the NMSSM. Moreover, it could be argued that the mechanisms which is invoked – from the sizable singlet-doublet mixing at \( \sim 750 \text{ GeV} \), or the condition of a \( A_1-\pi^0 \) interplay, to the collimated diphoton decays, indistinguishable from a single photon – are quite elaborate. Still, it is remarkable that all the necessary properties to fit the signal can be united in a phenomenologically realistic way within as theoretically simple a model as the NMSSM, without e.g. requiring additional ad-hoc matter.

3.2. How to test this scenario?

The scenario reviewed in the previous subsection offers several distinctive tests at the LHC. We start with the fact that the width of the signal could be reproduced by two \( CP \)-even Higgs bosons with mass difference of the same order as the favored width (by ATLAS) \[18\]. In Fig. 2, we show the diphoton invariant mass distribution of the diphoton signal for two different bin sizes. We consider a benchmark point (P6, see Ref. \[27\] for details) for illustration. The distribution with the large bin size of 40 GeV corresponds to the experimental bin size of the ATLAS study \[18\], as shown in the left panel. The experimental photon energy resolution of about 5–10% would allow for a higher precision \[31\], but due to the small statistical sample, both experiments choose a rather large bin size. One can clearly see that for the benchmark point the two scalars cannot be distinguished from a wide resonance with the current data. For comparison we have included into this plot the original data from ATLAS after subtracting the expected background. One can see that the events predicted for this benchmark point provide a good reproduction of the experimental shape. We also display in the right panel of Fig. 2 the invariant mass distribution with a 5 GeV binning. While currently the experimental resolution in \( m_{\gamma\gamma} \) exceeds 10 GeV, one can speculate that further improvements during the current LHC run will be made. With the accuracy of \( \sim 5 \text{ GeV} \) and an increased luminosity, the broad excess, provided it is real, might be resolved as two narrow resonances \[32\].

So far it was assumed that our scenario mimics the diphoton signal since the two collimated photons of the light pseudo-scalar decay are indistinguishable from an isolated photon. However, if the four photon final state was discriminated from the diphoton signature, it would be a strong hint at our scenario. Refs. \[33, 35\] considered photon jets (two or more collimated photons) at hadron colliders. In particular, Ref. \[35\] discussed the possibility of photon conversion into \( e^+e^- \) pairs and its discriminating power between photon jets and isolated photons. For a photon jet, the probability of photon conversion is higher than for a single photon, and Ref. \[35\] showed that already several tens of events are sufficient to discriminate between both hypotheses and a few hundred events allow for a 5\( \sigma \) discrimination assuming prompt photons. However, their conclusions assume a pseudo-scalar mass of 1 GeV and the results are very sensitive to this parameter. For long lived pseudoscalars, the discriminating power is reduced since photon conversion cannot start
As discussed previously, the light pseudo-scalar, $A_1$, has a small branching fraction of $\lesssim 1\%$ for decays to electron pairs. Because of its short life-time it would typically decay promptly to a highly collimated $e^+e^-$ pair, so-called “electron-jet”. Such electron-jets, prompt and displaced, were searched for by the LHC experiments. In our case, two signatures can appear: two high-$p_T$ electron jets or one electron jet and an energetic photon. The searches for the direct production of the scalar decaying to two electron-jets could thus provide further constraints, but the limits have been obtained only for the light SM-like Higgs boson $\sim 750$ GeV. While the discussed 8 TeV searches lack the sensitivity to constrain our scenario now, they clearly offer interesting prospects for observing electron decay modes of $A_1$ (possibly accompanied by the photon-jet from the opposite decay chain) at the increased center-of-mass energy and high luminosity run of the LHC.

The proposed scenario can also be probed via the “classic signature” for additional heavy neutral Higgs bosons, $pp \rightarrow \Phi \rightarrow \tau^+\tau^-$, where the limits are set in the $m_\Phi$-$\tan\beta$ space. Within the MSSM, assuming the additional Higgs bosons at a mass around $\sim 750$ GeV, the (expected) limits on $\tan\beta$ are around $\sim 35$ based on Run I data [38, 39] (see also Ref. [40]). In our NMSSM scenario there are three Higgs bosons with a mass around 750 GeV contributing to this search channel, $H_2$, $H_3$ and $A_2$, where the overall number of $\tau^+\tau^-$ events is roughly 25% lower than in the MSSM, mainly due to the decay of $H_{2,3} \rightarrow A_1A_1$. Consequently, a similar, but slightly higher limit on $\tan\beta$ can be set in our NMSSM scenario. With increasing luminosity this limit could roughly improve to $\tan\beta \sim 5$–10 at the LHC after collecting 300–3000/fb of integrated luminosity (see also [41]). Therefore, the proposed scenario could eventually lead to an observable signal in the $\tau^+\tau^-$ searches for heavy Higgs bosons at the LHC, depending on the details of the scenario (value of $\tan\beta$, masses of electroweak particles etc.). It should furthermore be noted that
in our scenario no significant decay of the Higgs bosons at $\sim 750$ GeV to $WW$, $ZZ$ or $Z\gamma$ should be observed.

Another prediction that arises from the preferred parameter space discussed in the previous subsection are light higgsinos. With the masses of 100–300 GeV they are well within the kinematic reach of the LHC. However, the small mass differences, $O(10 \text{ GeV})$, within the light higgsino sector hinder their observation at the LHC. If all the non-higgsino SUSY particles are sufficiently far in mass, the decay of the second neutralino, $\tilde{\chi}_2^0$ proceeds almost exclusively via the light pseudo-scalar $A_1$. With the following significant branching ratio to soft $\gamma\gamma$ pair the observation in the soft di- and trilepton searches [42, 43] becomes practically impossible. The radiative production at a high-energy $e^+e^-$ collider remains a valid possibility though [44, 45].

4. Conclusions

The LHC experiments ATLAS and CMS have reported an excess in the diphoton spectrum at $\sim 750$ GeV. At the same time the motivation for Supersymmetry (SUSY) remains unbowed. Accordingly, we have reviewed briefly the proposals to explain this excess in the (N)MSSM. Here we have focused on (N)MSSM solutions that do not require the addition of new particles or couplings. Solutions in the MSSM rely either on a strong enhancement of the coupling a Higgs boson at $\sim 750$ GeV to photons via (fine-tuned) SUSY particle contributions. Alternatively, a stoponium bound state at $\sim 750$ GeV is used to accommodate the observed “excess”.

Within the NMSSM a new possibility arises. Here one or two Higgs bosons with a mass $\sim 750$ GeV can decay to two very light pseudo-scalar Higgs bosons. Via mixing effects these highly boosted $CP$-odd Higgs bosons decay with a sufficiently high rate to two photons. Due to the strong boost these two photons are detected as one, thus resulting in the observed signal.

We have reviewed in more detail a proposal to realize this “excess” within the NMSSM, as presented in Ref. [27]. In this particular scenario two $CP$-even Higgs bosons have a mass around $\sim 750$ GeV. Once one of them is produced, it can decay to two light pseudo-scalar Higgs bosons. Via mixing with the pion these pseudo-scalars decay into a pair of highly collimated photons, which are identified as one photon, thus resulting in the observed signal. The mass difference of the two $CP$-even Higgs bosons can mimic a larger width as preferred by the ATLAS data.

We have discussed several possibilities to test this scenario in the upcoming LHC runs. These include a possible double peak structure in the invariant $\gamma\gamma$ mass spectrum, due to the fact that two Higgs bosons contribute to the signal. Also an enhanced observation of electron-jets could be a clear signal of this scenario. Concerning the more “classic” heavy Higgs boson searches, we expect that the relevant parameter space can be covered in the $\tau^+\tau^-$ searches, where the 750 GeV Higgs bosons should become detectable. On the other hand, in our scenario no substantial decays of the Higgs bosons at $\sim 750$ GeV to $WW$, $ZZ$ or $Z\gamma$ should be observed.
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References

[1] H. Nilles, Phys. Rept. 110 (1984) 1; H. Haber and G. Kane, Phys. Rept. 117 (1985) 75; R. Barbieri, Riv. Nuovo Cim. 11 (1988) 1.
[2] M. Drees, R. Godbole and P. Roy, Hackensack, USA: World Scientific (2004) 555 p.
[3] S. Glashow and S. Weinberg, Phys. Rev. D 15 (1977) 1958.
[4] C. Young, talk given at “Moriond EW”, March 2016, see: https://indico.in2p3.fr/event/12279/session/12/contribution/194/material/slides/0.pdf.
[5] J. Lorenz, talk given at “Moriond QCD”, March 2016, see: http://moriond.in2p3.fr/QCD/2016/MondayMorning/Lorenz.pdf; G. Della Porta, talk given at “Moriond QCD”, March 2016, see: http://moriond.in2p3.fr/QCD/2016/MondayMorning/Porta.pdf; M. Franco Sevilla, talk given at “Moriond QCD”, March 2016, see: http://moriond.in2p3.fr/QCD/2016/MondayMorning/Sevilla.pdf.
[6] R. Haag, J. Lopuszanski and M. Sohnius, Nucl. Phys. B 88 (1975) 257.
[7] U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. B 260 (1991) 447.
[8] S. Heinemeyer, O. Stäl and G. Weiglein, Phys. Lett. B 710 (2012) 201 [arXiv:1112.3026 [hep-ph]].
[9] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, Eur. Phys. J. C 28 (2003) 133 [arXiv:hep-ph/0212020].
[10] J. Gunion and H. Haber, Phys. Rev. D 67 (2003) 075019 [arXiv:hep-ph/0207010]; H. Haber, arXiv:hep-ph/9505240.
[11] S. Zenz, talk given at “Moriond EW”, March 2016, see: https://indico.in2p3.fr/event/12279/session/5/contribution/176/material/slides/0.pdf; L. Dell’Asta, talk given at “Moriond EW”, March 2016, see: https://indico.in2p3.fr/event/12279/session/5/contribution/202/material/slides/0.pdf.
[12] H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419; J. Ellis, J. Hagelin, D. Nanopoulos, K. Olive and M. Srednicki, Nucl. Phys. B 238 (1984) 453.
[13] S. Heinemeyer, Int. J. Mod. Phys. A 21 (2006) 2659 [arXiv:hep-ph/0407244].
[14] A. Djouadi, Phys. Rept. 459 (2008) 1 [arXiv:hep-ph/0503173].
[15] U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. 496 (2010) 1 [arXiv:0910.1785 [hep-ph]]; M. Maniatis, Int. J. Mod. Phys. A 25 (2010) 3505 [arXiv:0906.0777 [hep-ph]].
[16] J. Kim and H. Nilles, Phys. Lett. B 138 (1984) 150.
[17] F. Domingo and G. Weiglein, arXiv:1509.07283 [hep-ph].
[18] The ATLAS Collaboration, ATLAS-CONF-2015-081.
[19] The CMS Collaboration, CMS PAS EXO-15-004.
[20] See: http://inspirehep.net/search?ln=en&p=refersto%3Arefer%3A1410174.
[21] A. Angelescu, A. Djouadi, and G. Moreau, Phys. Lett. B 756 (2016) 126 [arXiv:1512.04921 [hep-ph]].
[22] A. Falkowski, O. Slone, and T. Volansky, *JHEP* **1602** (2016) 152 [arXiv:1512.05777 [hep-ph]].
[23] A. Bharucha, A. Djouadi and A. Goudelis, arXiv:1603.04464 [hep-ph].
[24] D. Choudhury and K. Ghosh, arXiv:1605.00013 [hep-ph].
[25] A. Djouadi and A. Pilaftsis, arXiv:1605.01040 [hep-ph].
[26] U. Ellwanger and C. Hugonie, *JHEP* **1605** (2016) 114 [arXiv:1602.03344 [hep-ph]].
[27] F. Domingo, S. Heinemeyer, J. S. Kim and K. Rolbiecki, *Eur. Phys. J. C* **76** (2016) no.5, 249, [arXiv:1602.07691 [hep-ph]].
[28] R. Ding, L. Huang, T. Li and B. Zhu, arXiv:1512.06560 [hep-ph]; B. Allanach, P. Dev, S. Renner and K. Sakurai, arXiv:1512.07645 [hep-ph].
[29] S. Demidov and D. Gorbunov, *JETP Lett.* **103** (2016) no.4, 219 [arXiv:1512.05723 [hep-ph]]; J. Casas, J. Espinosa and J. Moreno, arXiv:1512.07895 [hep-ph]; P. Baratella, J. Elias-Miro, J. Penedo and A. Romanino, arXiv:1603.05682 [hep-ph].
[30] M. Badziak, M. Olechowski, S. Pokorski and K. Sakurai, arXiv:1603.02203 [hep-ph].
[31] G. Aad et al. [ATLAS Collaboration], *Eur. Phys. J. C* **74** (2014) 10, 3071 [arXiv:1407.5063 [hep-ex]].
[32] Q. Cao, Y. Gong, X. Wang, B. Yan and L. Yang, *Phys. Rev. D* **93** (2016) no.7, 075034 [arXiv:1601.06374 [hep-ph]].
[33] S. Ellis, T. Roy and J. Scholtz, *Phys. Rev. D* **87** (2013) 1, 014015 [arXiv:1210.3657 [hep-ph]].
[34] S. Ellis, T. Roy and J. Scholtz, *Phys. Rev. Lett.* **110** (2013) 12, 122003 [arXiv:1210.1855 [hep-ph]].
[35] B. Dasgupta, J. Kopp and P. Schwaller, arXiv:1602.04692 [hep-ph].
[36] G. Aad et al. [ATLAS Collaboration], *JHEP* **1411** (2014) 088 [arXiv:1409.0746 [hep-ex]].
[37] G. Aad et al. [ATLAS Collaboration], *JHEP* **1602** (2016) 062 [arXiv:1511.05542 [hep-ex]].
[38] V. Khachatryan et al. [CMS Collaboration], *JHEP* **1410** (2014) 160 [arXiv:1408.3316 [hep-ex]]; The CMS Collaboration, CMS-PAS-HIG-14-029.
[39] G. Aad et al. [ATLAS Collaboration], *JHEP* **1411** (2014) 056 [arXiv:1409.6064 [hep-ex]].
[40] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, *Eur. Phys. J. C* **75** (2015) 9, 421 [arXiv:1507.06706 [hep-ph]].
[41] A. Holzner [ATLAS and CMS Collaborations], arXiv:1411.0322 [hep-ex].
[42] V. Khachatryan et al. [CMS Collaboration], arXiv:1512.08002 [hep-ex].
[43] M. van Beekveld, W. Beenakker, S. Caron and R. R. de Austri, *JHEP* **1604** (2016) 154 [arXiv:1602.00590 [hep-ph]].
[44] M. Berggren et al., *Eur. Phys. J. C* **73** (2013) 12, 2660 [arXiv:1307.3566 [hep-ph]].
[45] G. Moortgat-Pick et al., *Eur. Phys. J. C* **75** (2015) 8, 371 [arXiv:1504.01726 [hep-ph]].